KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Prospects for CP violation measurements with the Hyper-Kamiokande experiment

Benjamin Quilain (Kavli IPMU, The University of Tokyo)
for the Hyper-Kamiokande proto-collaboration

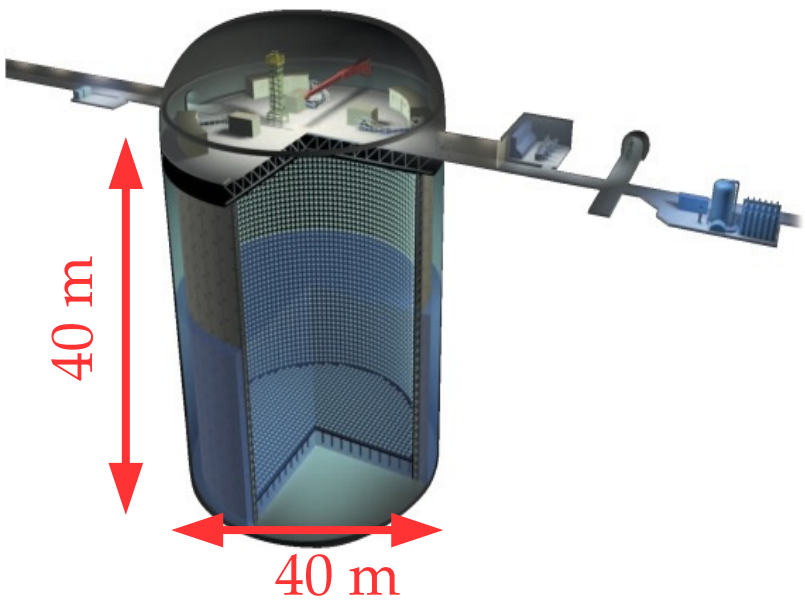
Hyper-Kamiokande

EPS meeting, Ghent, 2019/07/12

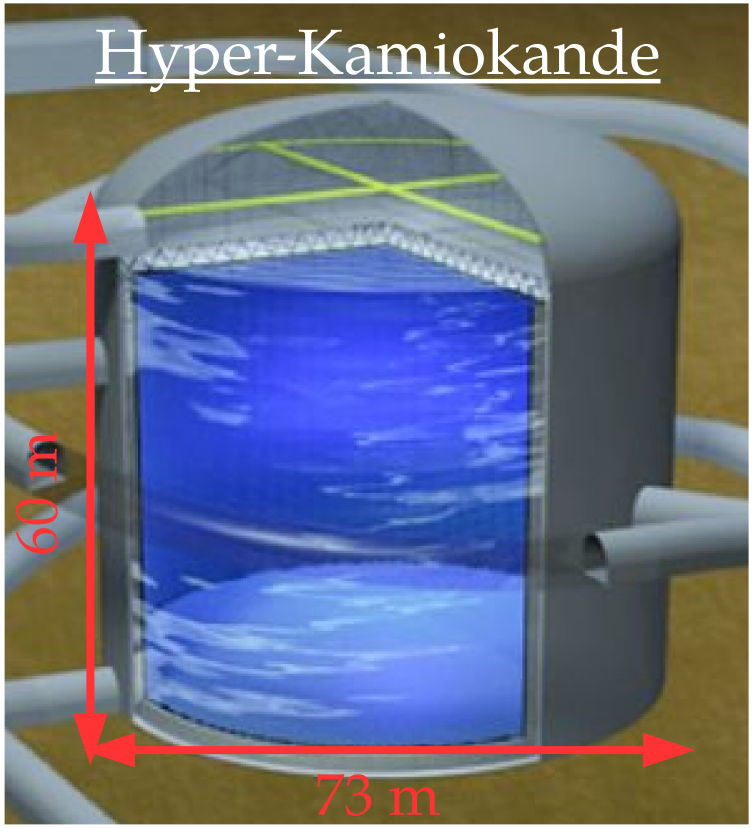
What ?

- Next generation of neutrino observatory in Japan→ construction 2020-26 → A 260 kton water Cherenkov detector → <u>Fiducial Mass ~ 8 x SK.</u>

<u>Super-Kamiokande</u>



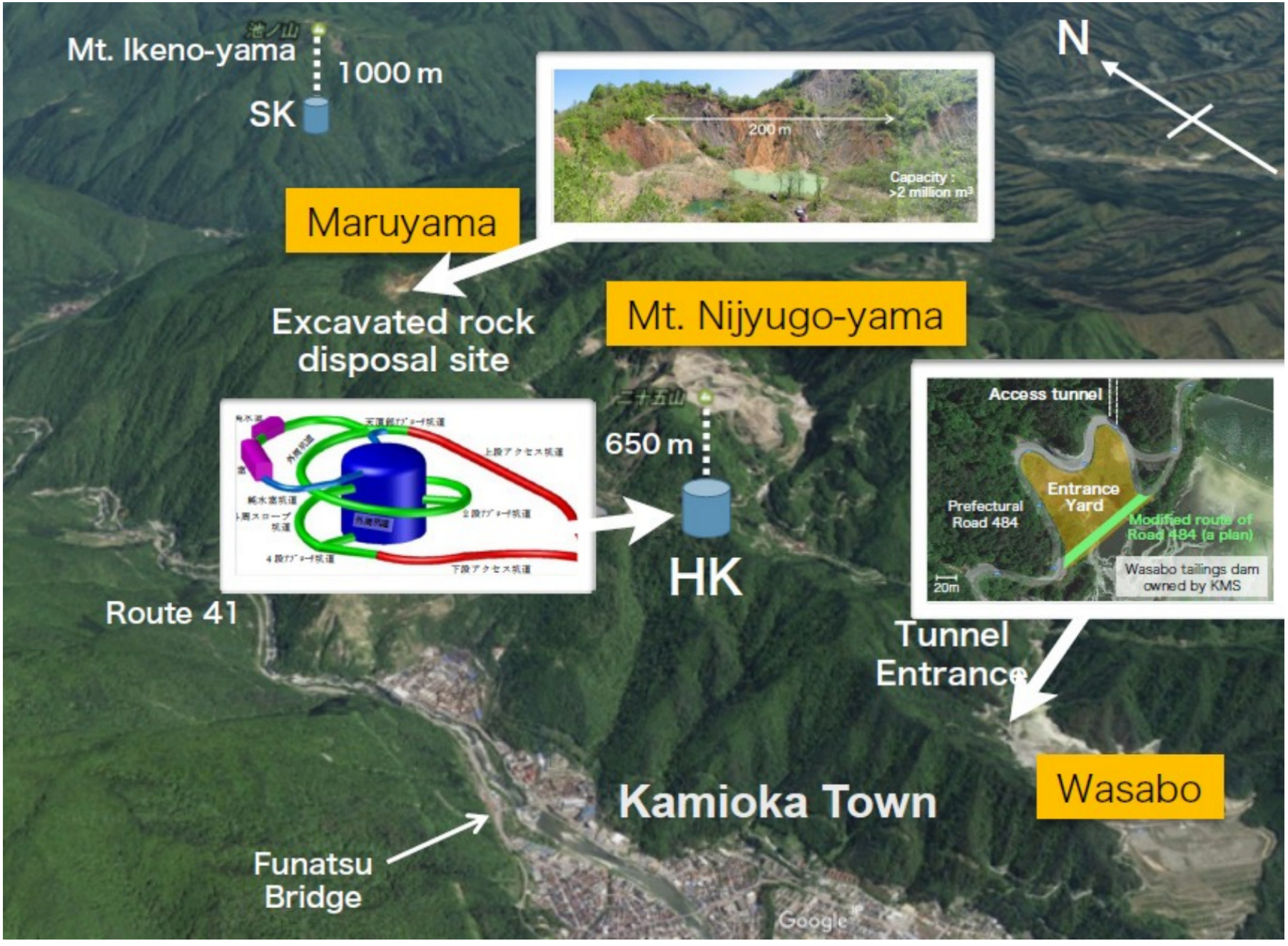
<u>Hyper-Kamiokande</u>



	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	11,129	40,000
Photo-coverage	40%	40% (×2 sensitivity)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

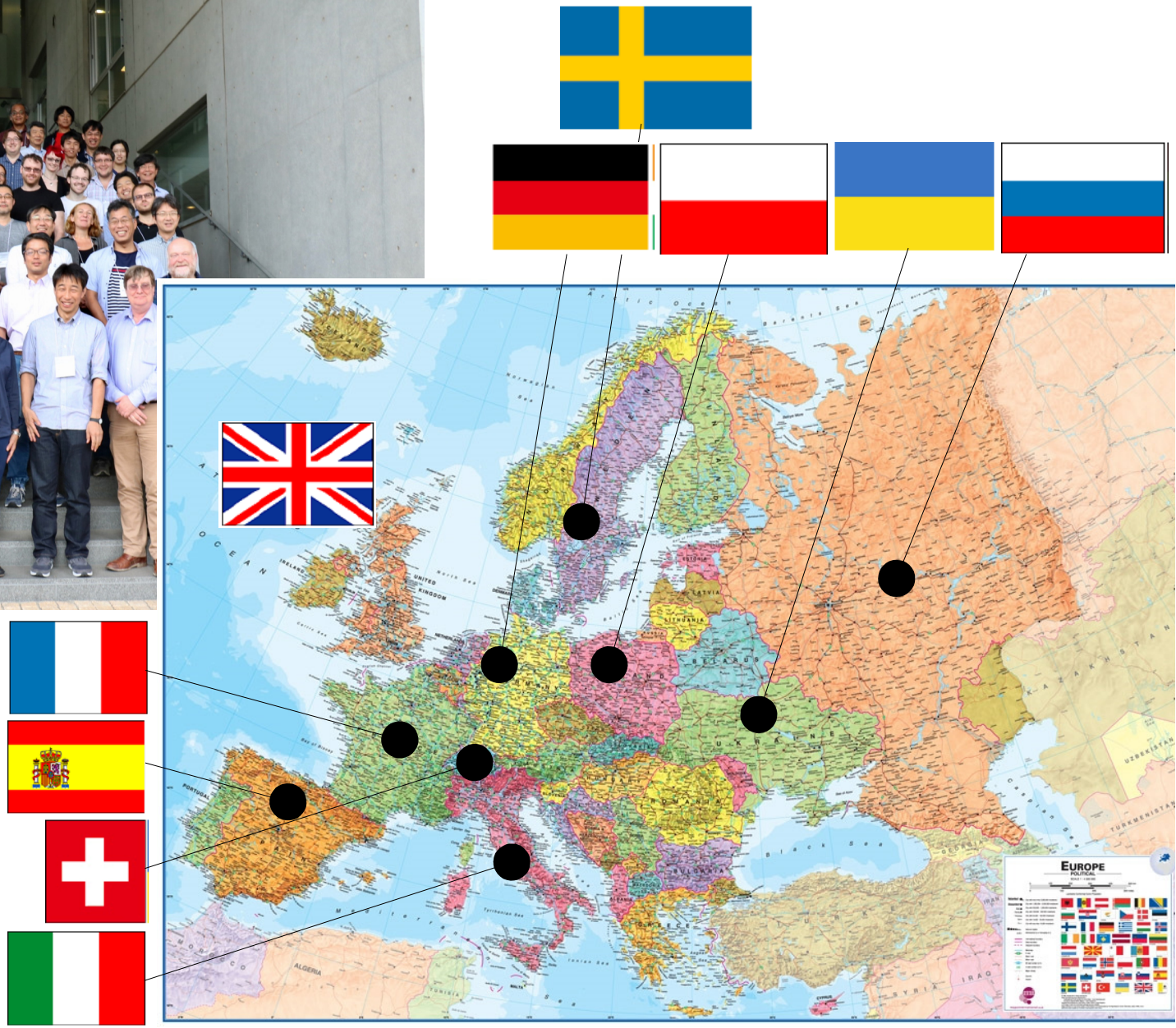
Where ?

- In Japan, ~10km away from the current Super-Kamiokande detector



Who ?

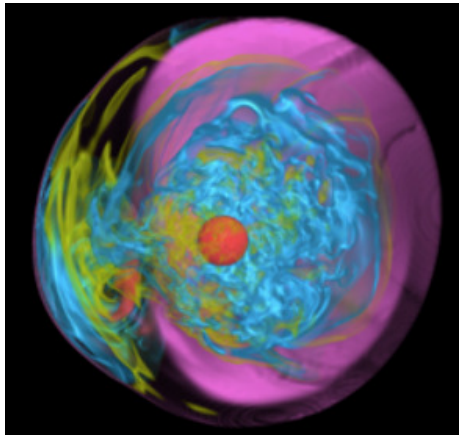
- A world-wide collaboration of 17 countries & 82 institutes: ~300 members



- Already involving
  10 countries in Europe

Why ?

- To tackle a very rich and unique physics program :



Solar neutrino (Low energy):

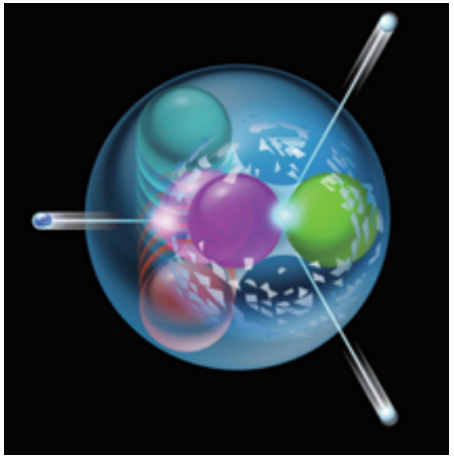
MSW effect in the Sun

Non-standard interaction in the Sun etc.

Astrophysics neutrino (Low energy) :

Constrains Supernovae models.

Constrains cosmic star formation history.



Proton decay (High energy)

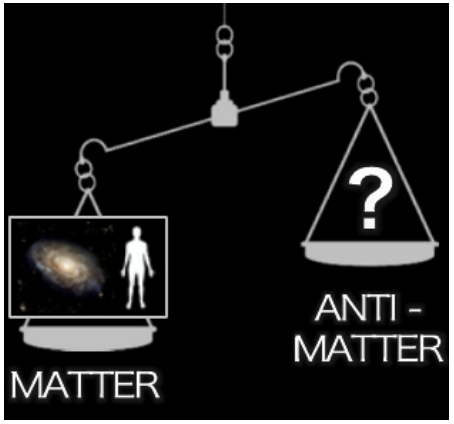
Direct probe for Grand Unified Theories through world best sensitivity on proton decay

CP violation (High energy)

High sensitivity to ν mass ordering.

Observe CP violation in the lepton sector for the 1st time.

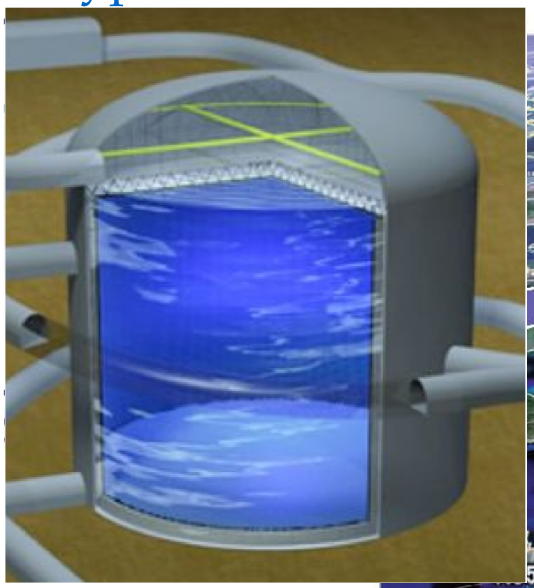
High precision measurement of δ_{CP} parameter.

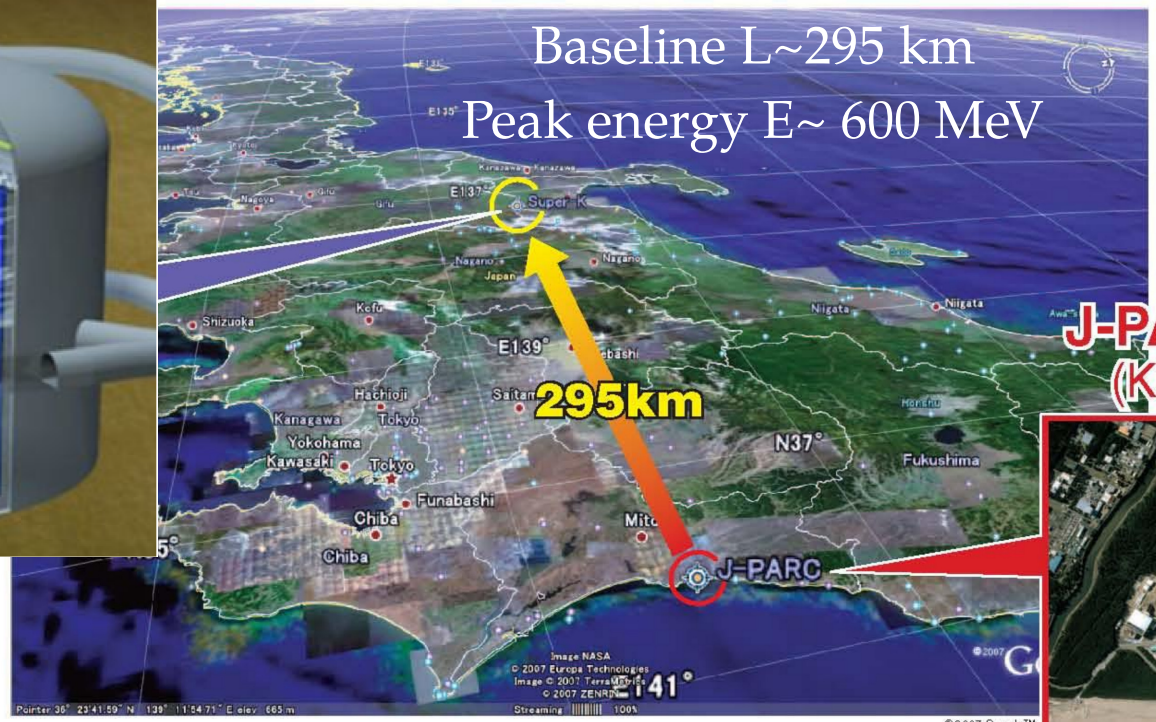


How ?

- CP violation search essentially based on accelerator ν : T2HK

Hyper-Kamiokande





Produce ν_μ / $\bar{\nu}_\mu$

Detect

ν_μ, ν_e / $\bar{\nu}_\mu, \bar{\nu}_e$

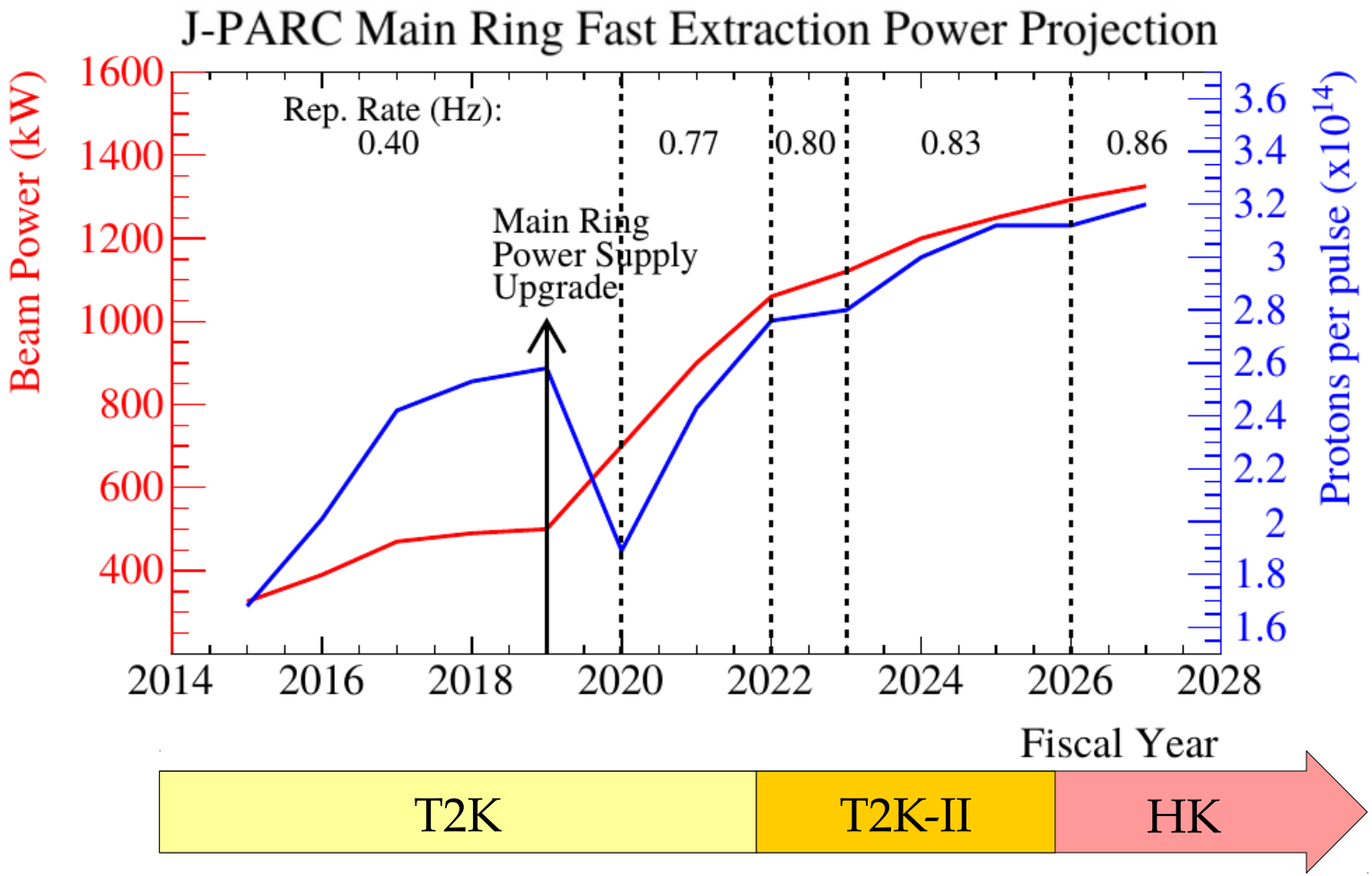
- ν_e appearance in a ν_μ beam and ν_μ disappearance & $\bar{\nu}$ equivalents.
- Detector technologies, calibration, analyses well-proven by T2K&SK.
- ⟹ Quick start ! Which relies on 2 milestones :

  1. ↓ time to accumulate statistics.
  2. ↓ systematic uncertainties.

Statistics: JPARC accelerator upgrade

- T2K so far: 490kW continuous run
  → 2.4sec cycle

- 750kW : T2K designed intensity
  → 1.3sec cycle
  → Magnet power-supplies updates : Funded



- 1.3MW: 1.16sec cycle
  → 1.1 MW demonstrated already (1 shot instead of 8)
  → > 1.3 MW Requires Main ring RF cavity upgrade.
  → KEK listed « JPARC-upgrade for HK » as the 1st priority since 2016

Systematics: Near detector upgrades

- Need to reduce uncertainties from 5% (T2K) to 3% (HK)

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

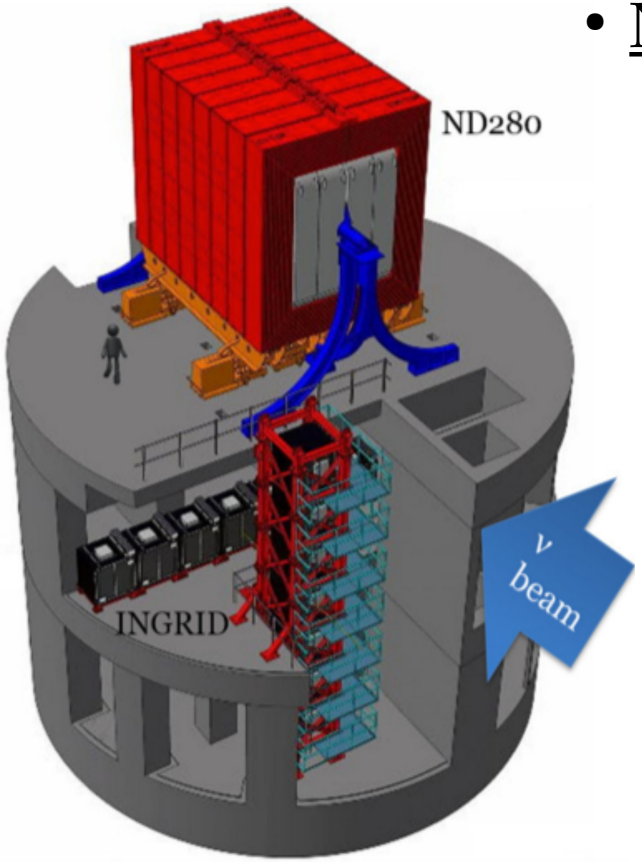
- SK detector & FSI etc.: ↓ using same detector technology for near/far

- Uncertainty on extrapolation of ND280 constraints to SK :
  → Can be reduced using same flux, target, acceptance between near/far.
  → And increasing the separation of cross-section's channels.

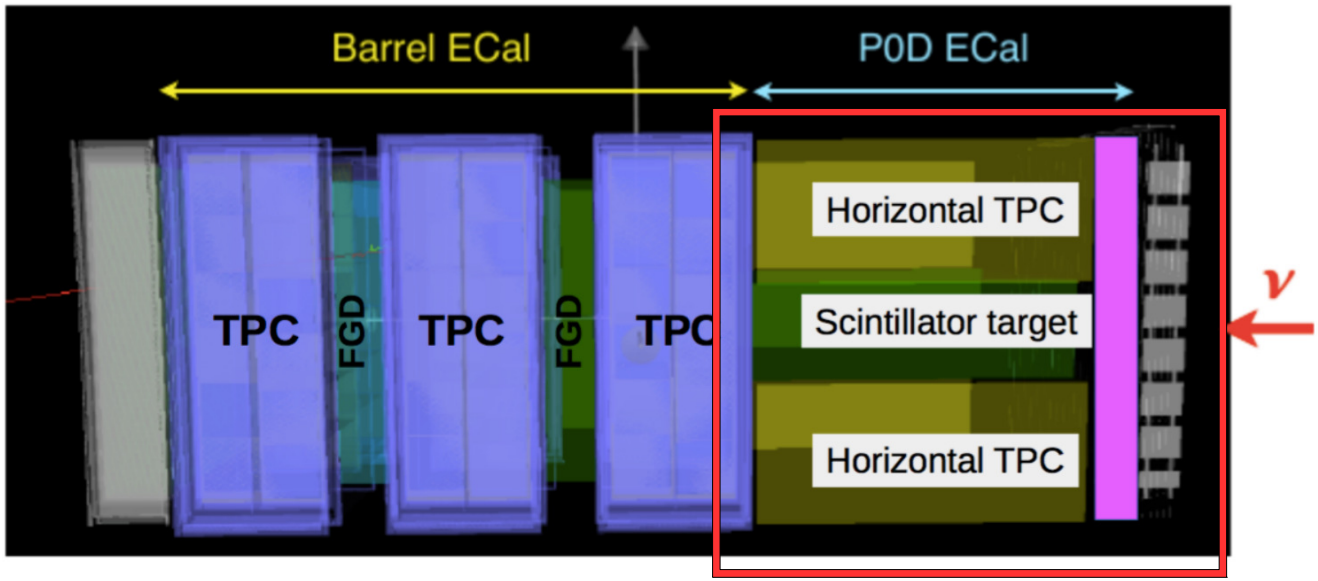
- $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$ is crucial for CPV determination.
  → Detector capable of high ν_e - ν_μ CC, ν_μ NC, γ separation.

The ND280 detector upgrade

- 2. a : Existing near detector complex @280m : ND280 + INGRID



- ND280 is being upgraded now for T2K-II :



- New horizontal TPCs up / down

  → ~4π acceptance for μ as SK /HK

- Improved tracker : Lower hadron threshold.

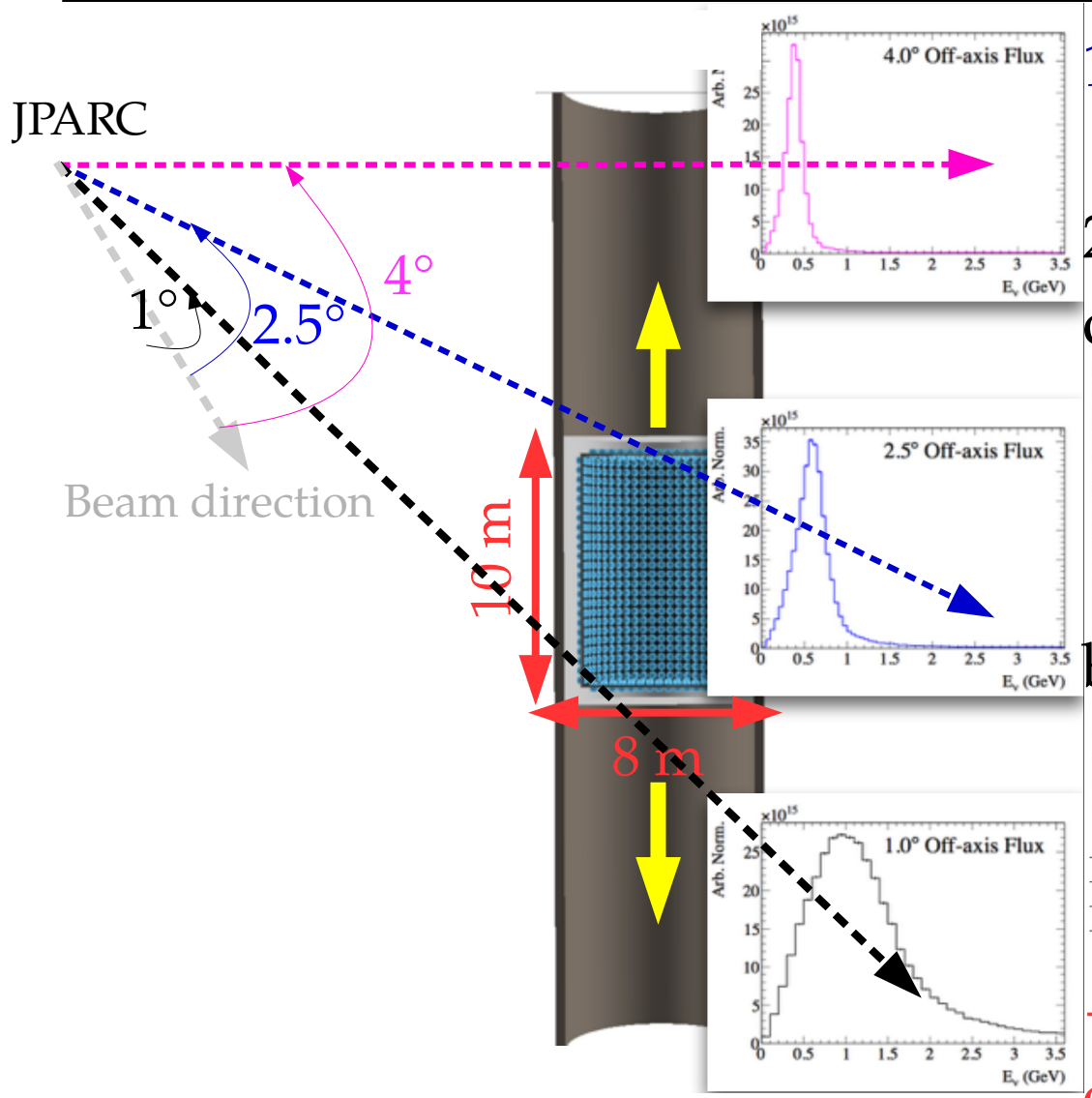
  → ↑ ID of cross-section models (CCQE, 2p-2h etc.)

- Improved tracker's E-resolution => e/1-track-γ separation possible

  → ↓ systematics on $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$

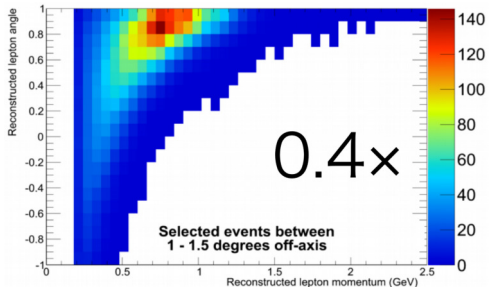
Intermediate Water Cherenkov Detector

- 2.b. New Intermediate Water Cherenkov Detector located @750m - 2km:

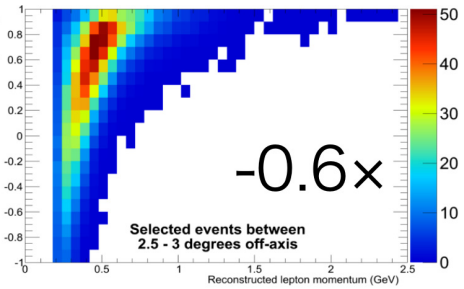


1. Same technology far / near.

2. a. HK flux = linear combination of different off-axis angles.



b. Take same combination of reconstructed number of ν (e.g. in p_μ/θ_μ)



→Drastically ↓ use (so systematics) of cross-section models !

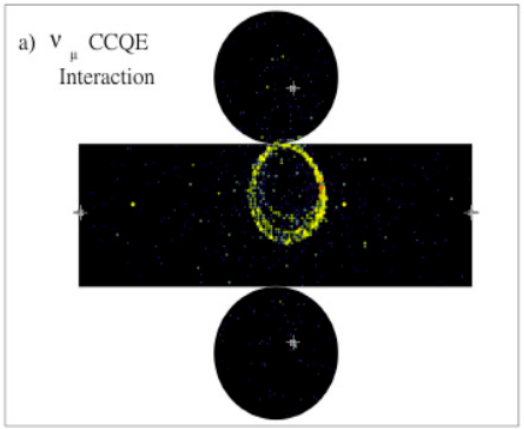
3. WC => Excellent ν_e / ν_μ separation => (ν_e / ν_μ) / ($\bar{\nu}_e$ / $\bar{\nu}_\mu$).

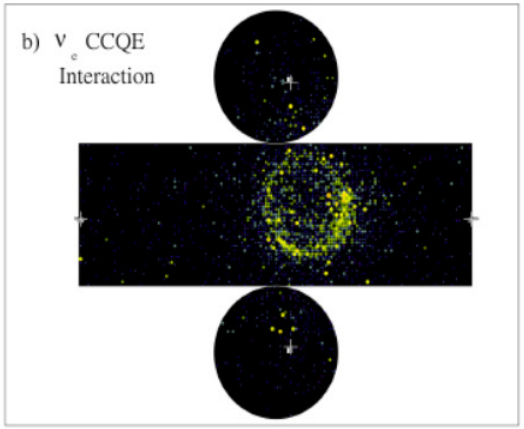
→ ND280&IWCD necessary & complementary to reach systematics ≤ 3 %.

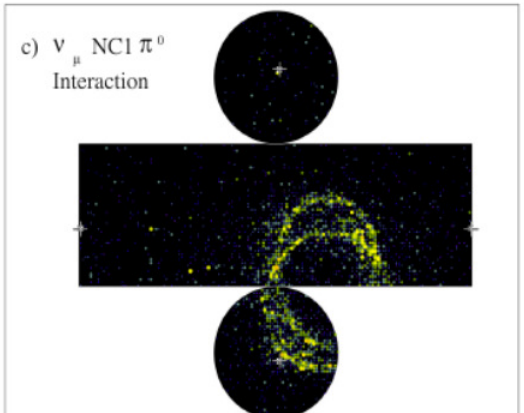
Event selection at far detector

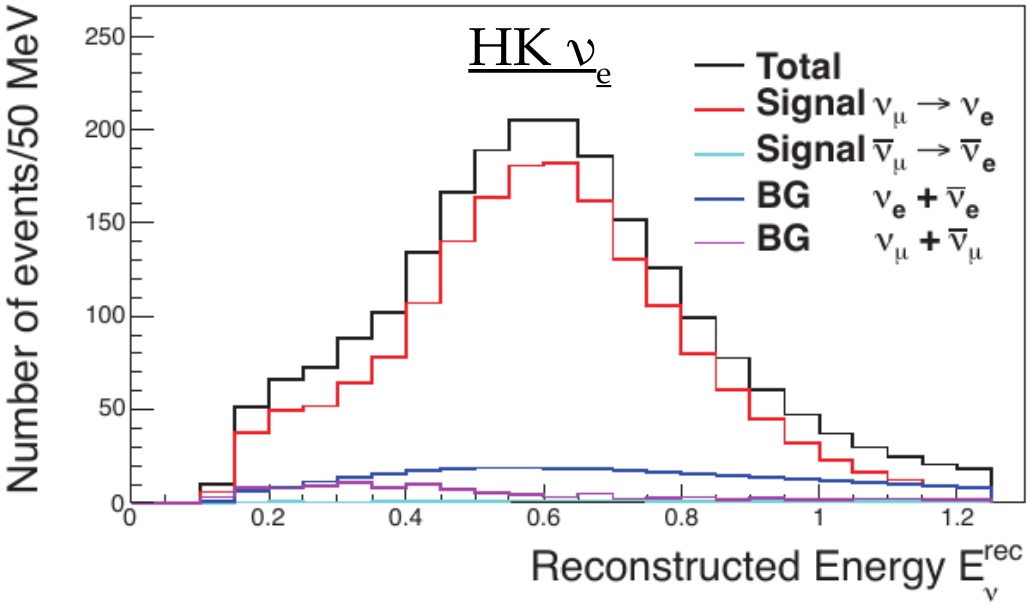
- <u>Before ν_e selection:</u>
- Main background from ν_μ-CC (70%)
  → ID with ring shape & decay-e.

- Second background from ν_μ-NC (25 %, mainly NCπ^0)
  → ID with number of rings (π^0 - 2 rings).
  → ID π^0 – 1 ring with π^0 cut.





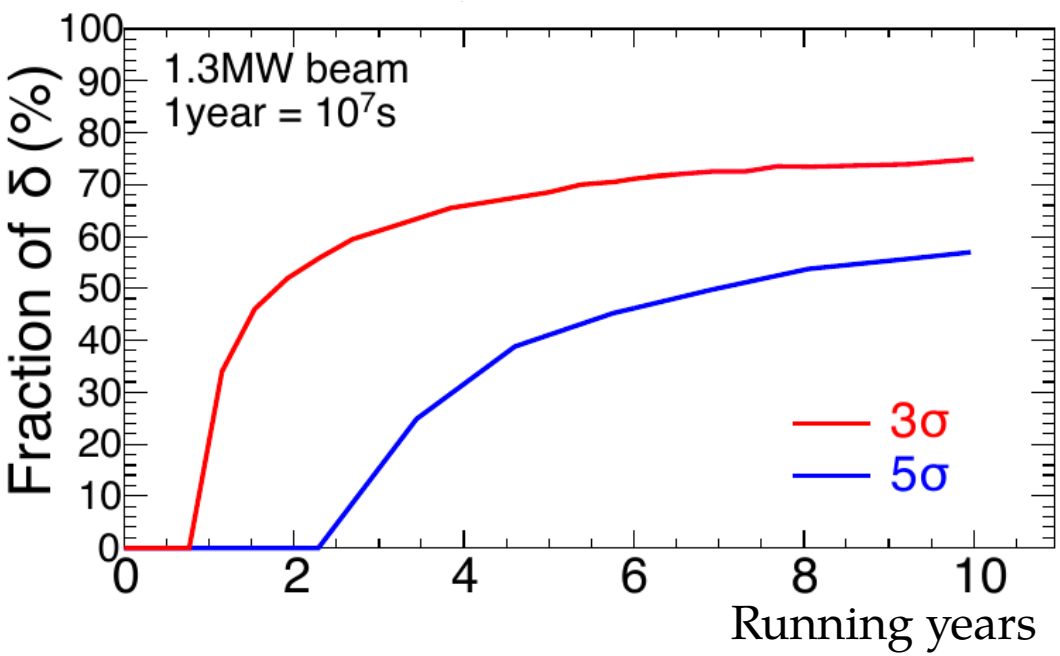


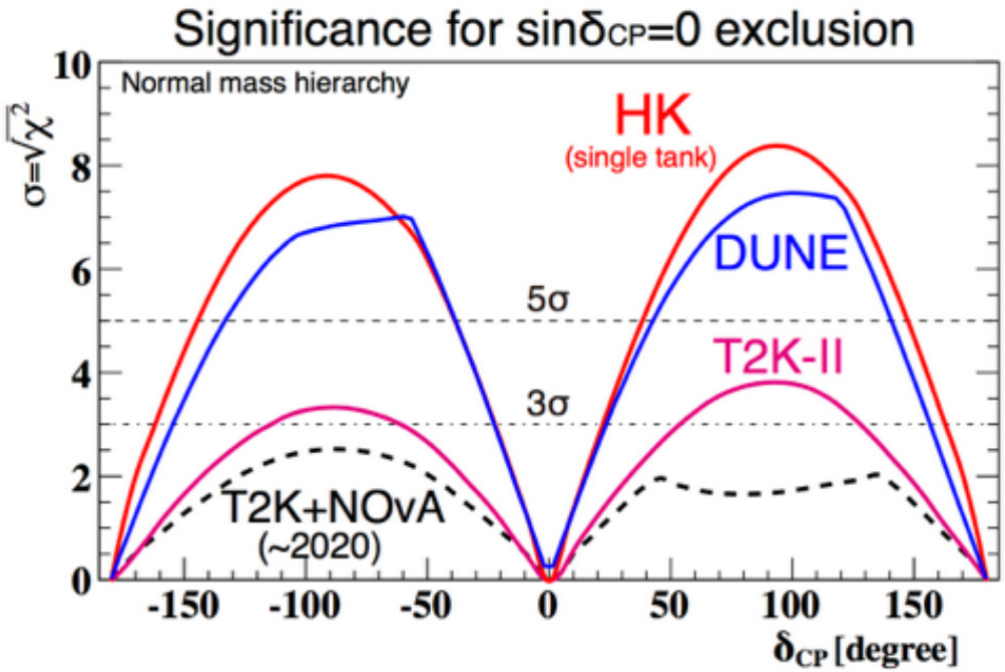


- Selection purity = 80 %
- Selection efficiency = 65 %.

Sensitivity to CPV with beam ν only

- Assume $\nu:\bar{\nu}$ = 1:3 running @1.3MW (operation can be adjusted).





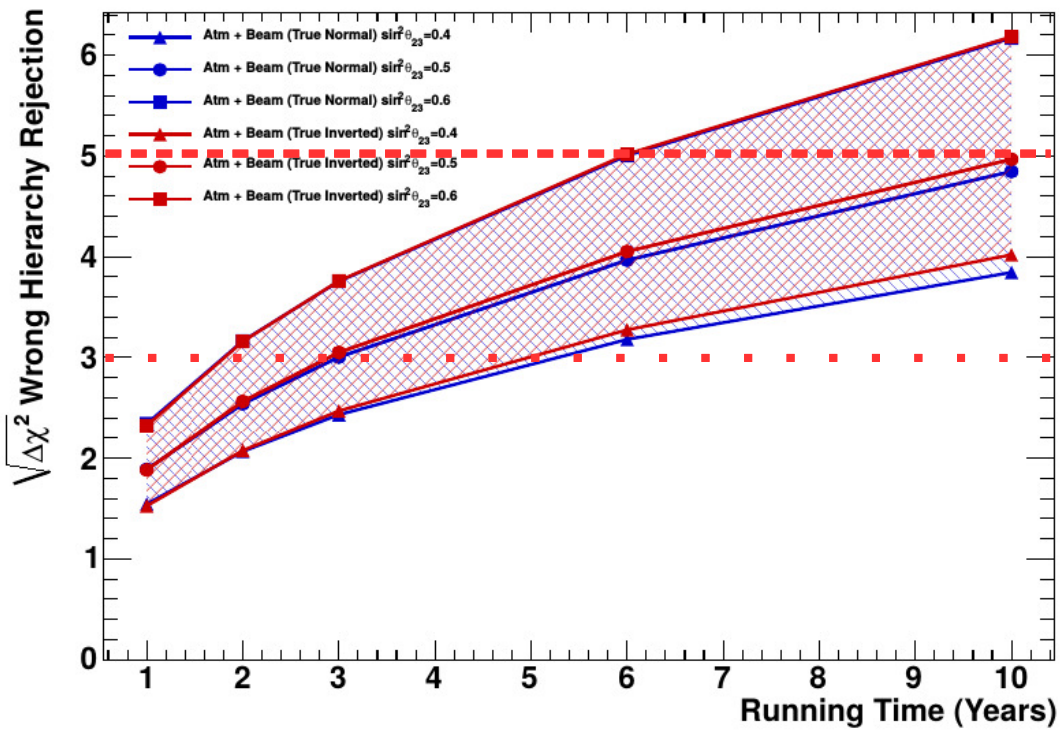
- <u>If maximal CP violation :</u> 5σ after 2.5 years !

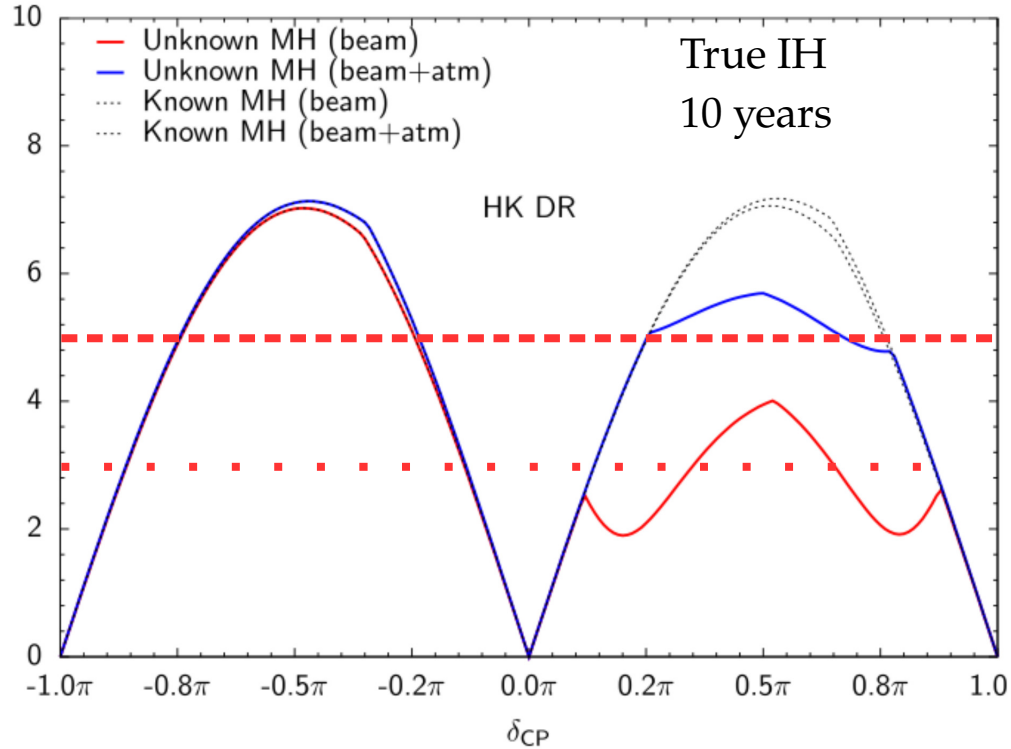
- Probe 55% of δ_{CP} phase-space after 10 years w/ 5σ sensitivity !

- … assuming the Mass Hierarchy is known
  → The sensivity on CP violation highly depends on MH determination, if we only use beam neutrinos.

Combining beam + atmospheric neutrinos

- Mass Hierarchy can be determined mostly using atmospheric neutrinos





- Even if MH not determined at that time, HK-only can determine the MH 5σ after ≥ 6 years.

- The sensitivity highly depends on θ_{23} value.

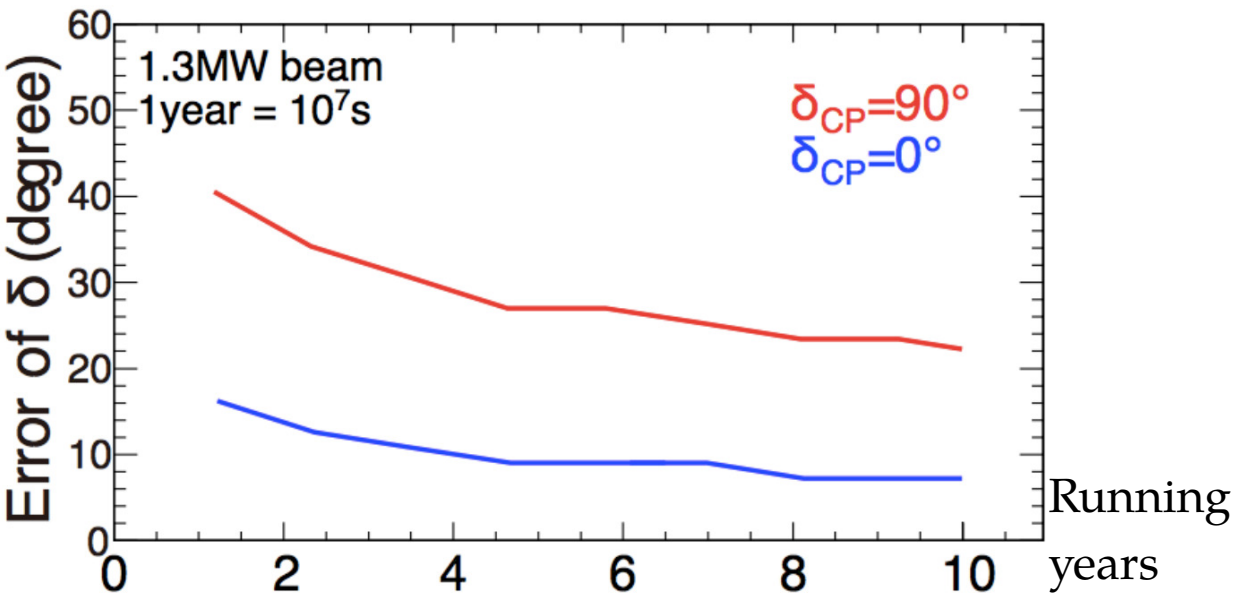
- Which highly helps to recover the CPV sensitivity.

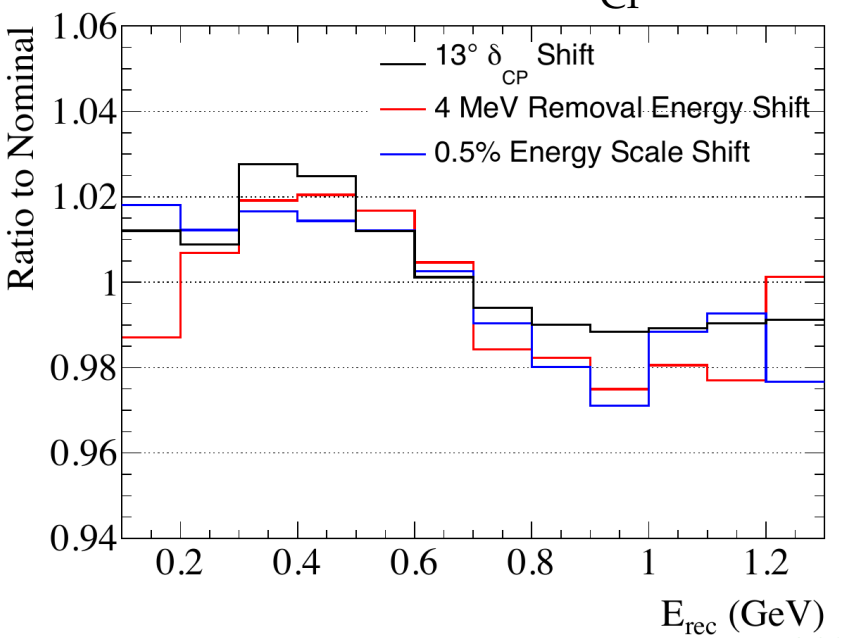
Sensitivity to δ_{CP} value

- After CPV is determined, accurate measurement of δ_{CP} will be crucial

→ Maximal CPV, leptogenesis, symetries of lepton's generations ...

- <u>Sensitivity will be limited by systematics :</u>
  - If δ_{CP}~0°, systematics are the same as for CPV (ν_e/ν_μ / $\bar{\nu}_e/\bar{\nu}_\mu$ etc.)
  - If δ_{CP}~90°, dominant systematics are those who mimics $\cos\delta_{CP}$ term.





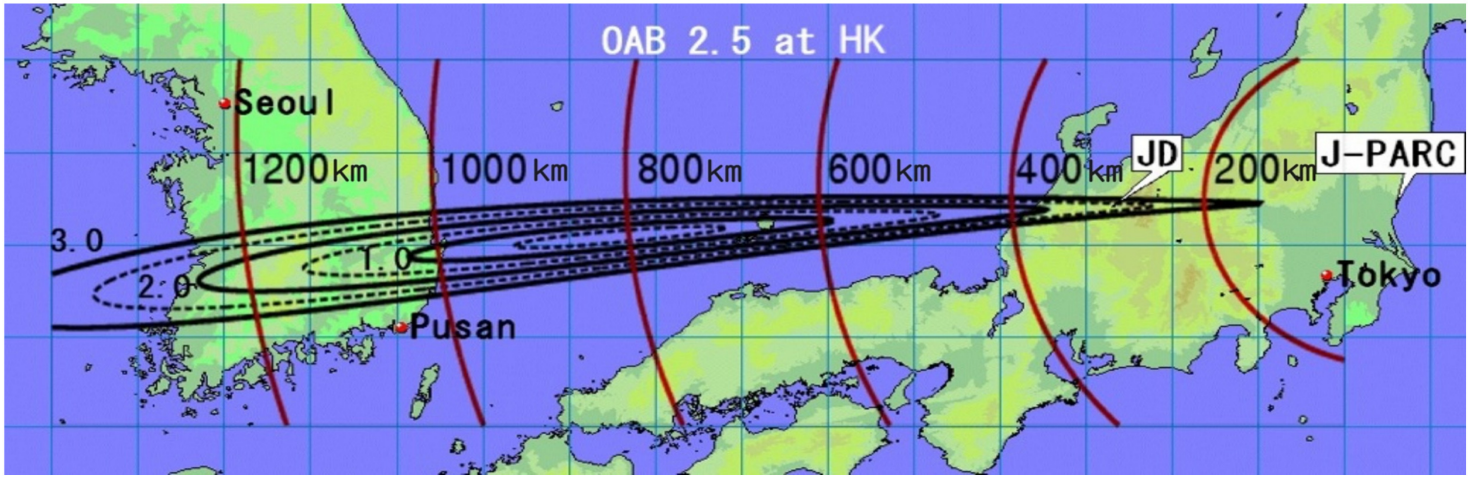
- <u>13° shift of δ_{CP}~ :</u> 0.5 % shift in E-scale (*IWCD*), 4 MeV shift in nucleus binding E (*ND280*), 5 % change in fraction of non QE interactions (*IWCD, ND280*), Off-axis angle shift by 0.6 mrad (*INGRID*) → Need the combination of all 3 near detectors !

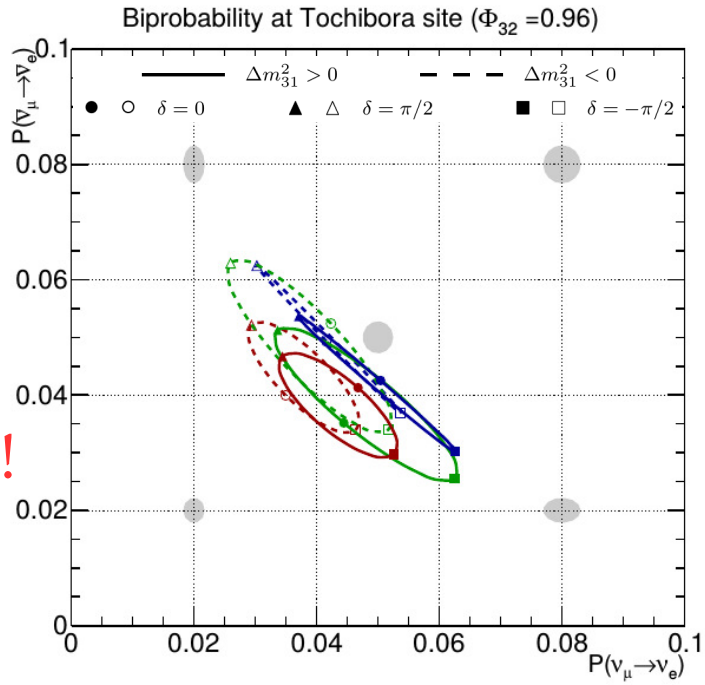
Perspectives towards δ_{CP} improvements

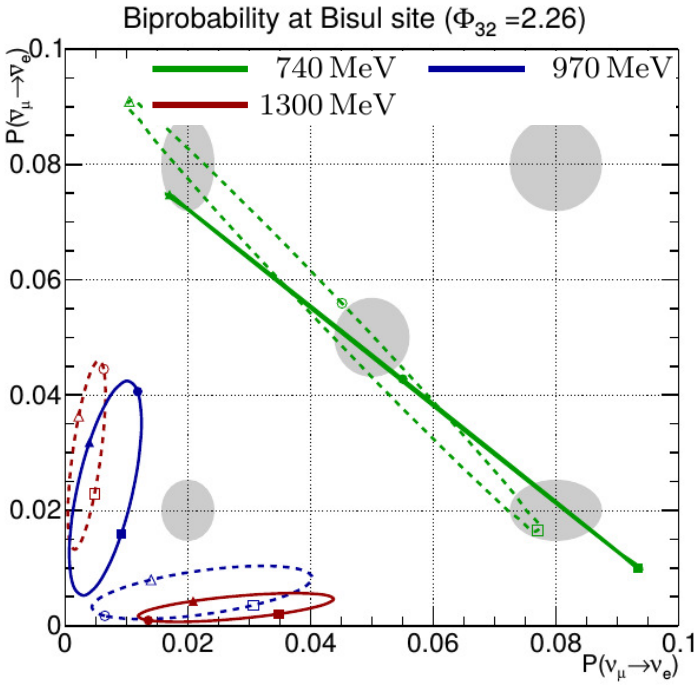
- Reduce the systematic uncertainties → Calibrate IWCD w/ test beam…

- Or, increase the δ_{CP} impact on oscillations ! → Go at the 2nd maximum !

→ Install a 2nd detector in Korea !
→ Baseline>1000 km
→ Off-axis angle could be 1.3°.





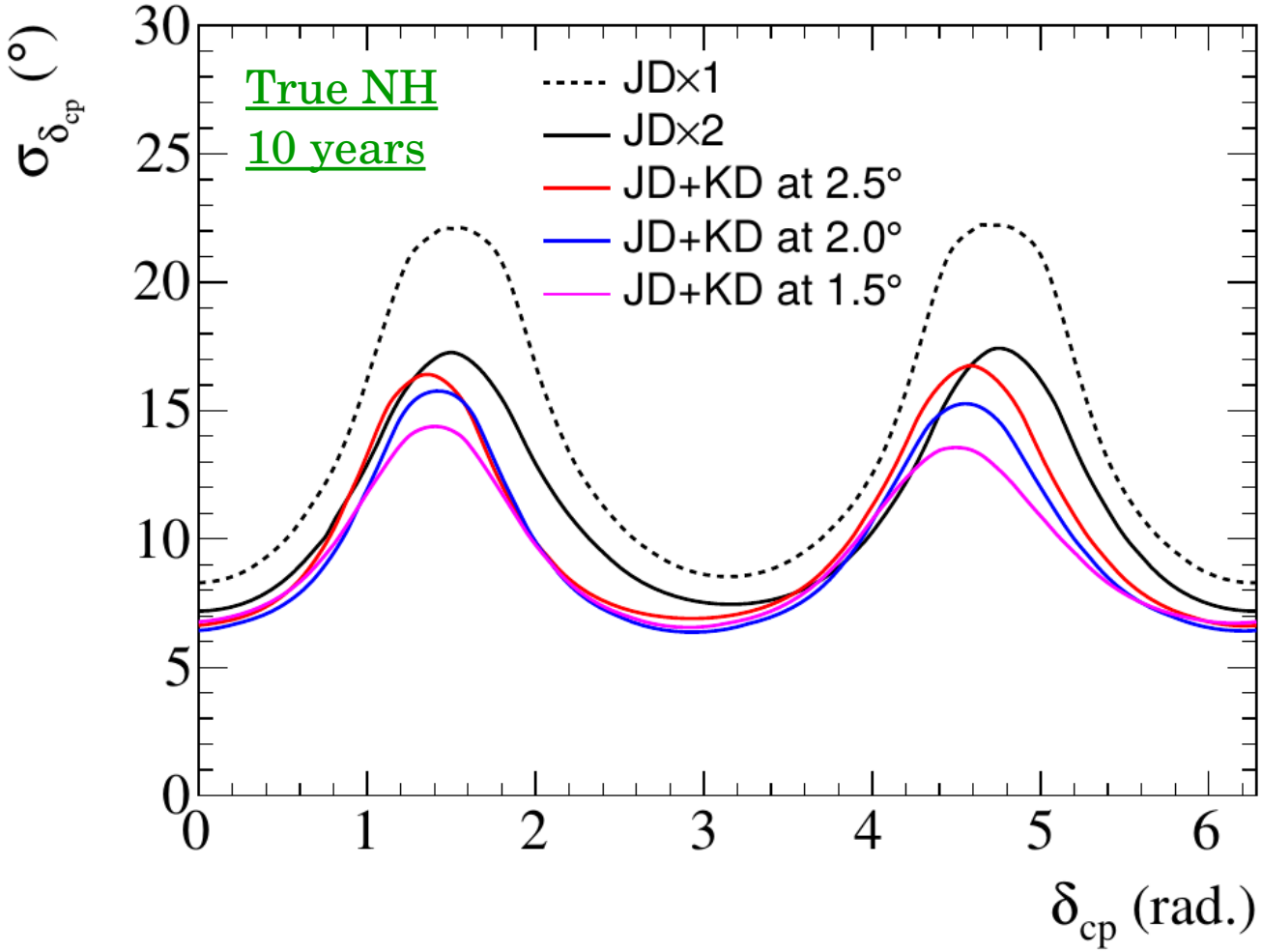


- Improved MH sensitivity !

- Enhanced δ_{CP} impact !

Perspectives towards δ_{CP} improvements

- Which would lead to a large improvement on δ_{CP} sensitivity.



- Could allow to reach a resolution of 13° even at maximal CPV !

- Unique constraints on δ_{CP} , and so on some models of maximal CPV, and some models of leptogenesis or symetries of lepton's generations…

Conclusions

- Hyper-Kamiokande is the next generation of ν observatory in Japan
  $\rightarrow$ Has a unique program expanding from solar ν to p-decay and CPV

- Allow to reach 5σ determination of CPV after 2.5 years (if $\delta_{CP} = -\pi/2$)…
  + measure δ_{CP} with a resolution from 9° ($\delta_{CP} = 0$) to 23° ($\delta_{CP} = -\pi/2$).

- Which can be improved to 7° to 13° ($\delta_{CP} = -\pi/2$) w/ the Korean detector

- <u>To achieve these tasks, we are relying on the expertize built in T2K…</u>
  - … while upgrading the accelerator to reach 1.3MW.
  - … and reducing systematic uncertainties from 5 % to 3 %
    by upgrading the existing near detector complex and building a new intermediate water Cherenkov detector.

- HK construction starts in April next year, and data taking in 2026.

Thank you very much !

Additional slides

Status of the project in Japan

HYPER-KAMIOKANDE EXPERIMENT TO BEGIN CONSTRUCTION IN APRIL 2020

Posted on SEPTEMBER 19, 2018 5:01 PM by ADMIN

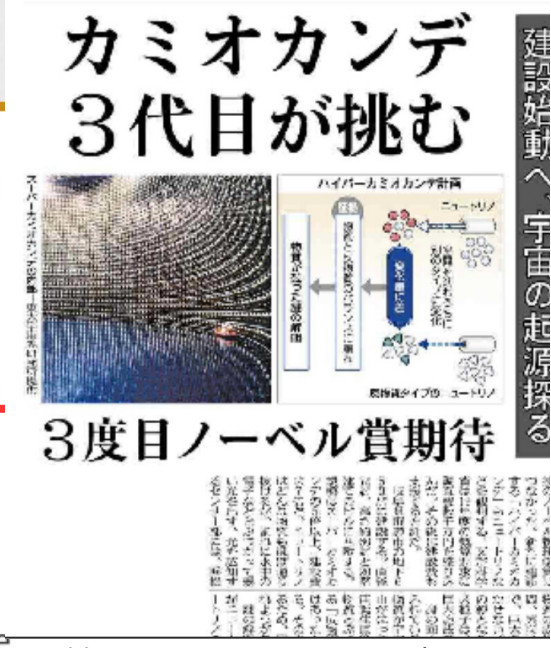
Last week at the 7th Hyper-Kamiokande proto-collaboration meeting, a statement was issued by the University of Tokyo recognizing the significant scientific discoveries which the planned Hyper-Kamiokande experiment would enable.

It states that, based on these exciting prospects, the University of Tokyo will ensure that construction of the experiment will begin in 2020. Hyper-Kamiokande now moves from planning to a real experiment.

The Hyper-Kamiokande proto-collaboration welcomes this exciting endorsement of the project and the boost it will give to increasing even further the international contributions and participation in the experiment. Introducing the statement, Professor Takaaki Kajita, Director of the Institute for Cosmic Ray Research at the University of Tokyo and 2015 Nobel Laureate in Physics, pointed out that the Japanese funding agency MEXT has included seed funding for Hyper-Kamiokande in its JFY 2019 budget request. He illustrated with many examples that it is standard in Japan for large projects to begin with a year of seed funding, and said that in any case the University of Tokyo commitment meant that Hyper-Kamiokande construction will begin in April 2020.

The Hyper-Kamiokande Proto-Collaboration will now work to finalize designs, and is very open to more international partners to join in this far-reaching new experiment.

Night/morning news after MEXT decision (T. Kajita)


カミオカンデ
3代目が挑む

3度目ノーベル賞期待

Nikkei newspaper Aug. 24 (evening edition)

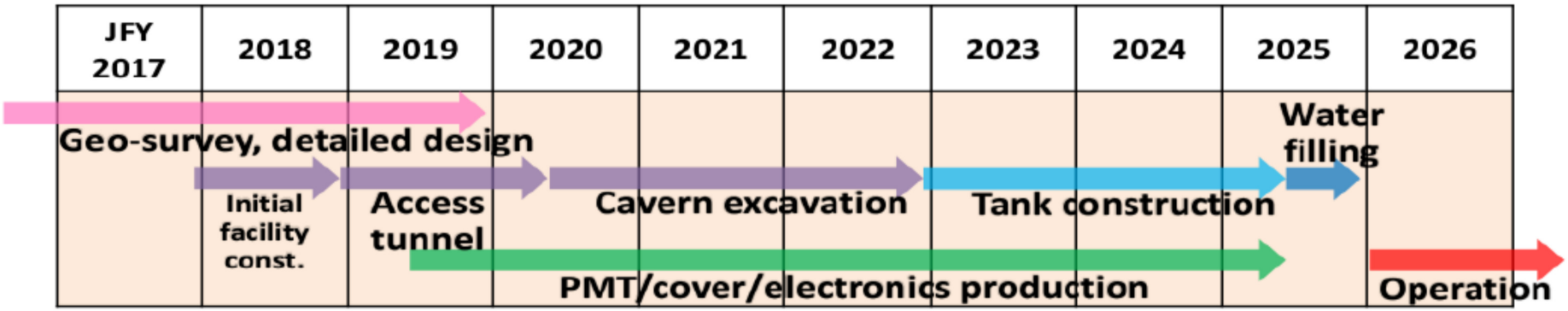
- 3rd generation of Kamiokand
- Unvealing the mystery of the origin of the Universe.
- The construction will begin.
- 3rd Nobel prize expected.

Aiming for 2026 start of

Conclusions

- HK will allow to explore fascinating windows on the universe with unprecedented precision :
  → CP violation in lepton sector, Cosmic star formation, GUT etc.

- <u>September 2018 :</u> the project will receive seed funding in 2019 and full funding for construction from 2020 ! → HK expect starts in 2026 !



- Tons of possible contributions combining hard-/soft-ware.
  → Invite each of you to think about this new tremendous physics accessible to us…
  → And contact me/HK collaborators for any questions/ideas ! → M. Gonin

Beamline upgrade

Beam Power	490kW (achieved)	750kW (proposed) [original]	1.1MW (demonstrated)	1.3MW (proposed)
# of protons/ pulse	2.5×10^{14}	2.0×10^{14} [3.3×10^{14}]	2.7×10^{14} [2.6×10^{14}]	3.2×10^{14}
Operation cycle	2.48 s	1.32 s [2.1 s]	1shot [50shots]	1.16 s

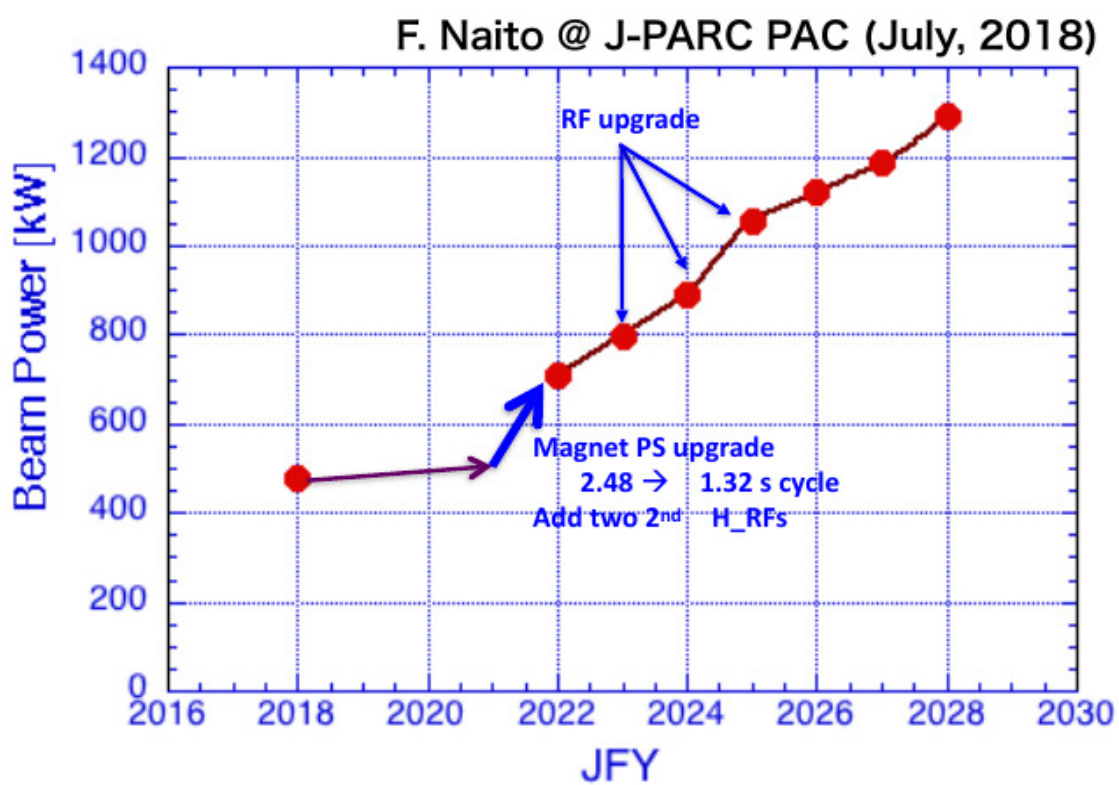
+26% +19%

Method

- Increase repetition rate
  - 2.48s → 1.3s → 1.16s
  - MR magnet PS upgrade
- Increase beam intensity
  - $2.5\times10^{14} \rightarrow 3.2\times10^{14}$ ppp
  - MR RF system upgrade

Beam focuse / trajectory curve

Proton acceleration



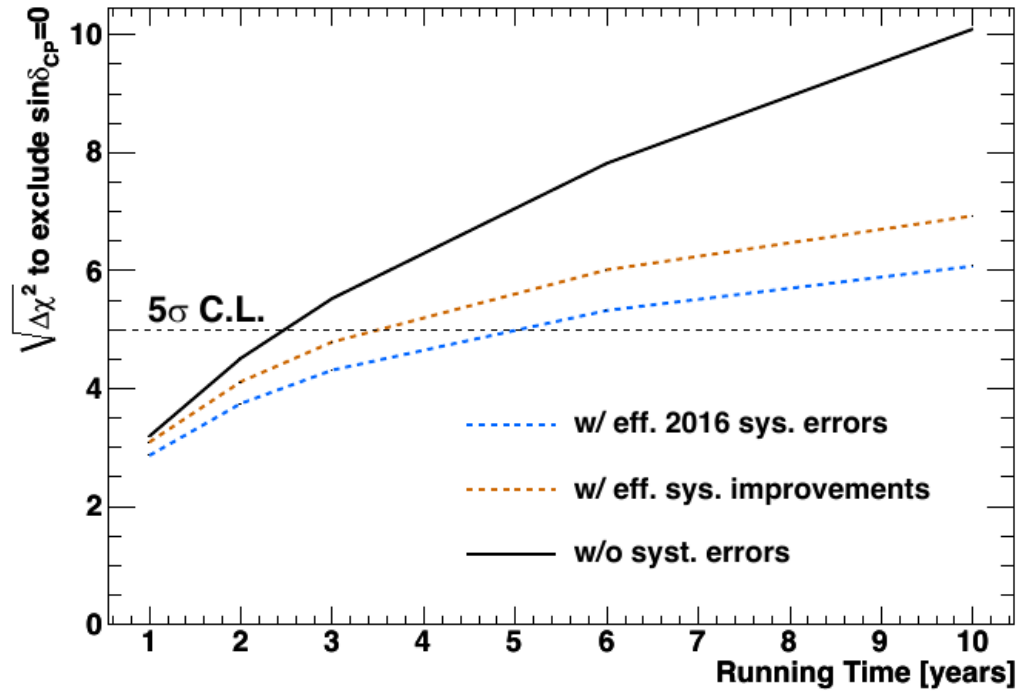
Beamline upgrade

Necessary upgrade toward >1.3MW

- **Primary beamline**
  - **Beam monitor upgrade**
  - Remote maintenance in FF section
  - Larger aperture magnets and/or upgraded collimators may be needed
- **DAQ**
  - **DAQ/control system upgrade** for higher rep. rate and safety operation
- **Secondary beamline**
  - **Target/beam window upgrade**
  - **Higher current** horn operation (250kA → **320kA**)
  - **Cooling capacity** upgrade
  - Upgrade for **radiation protection/treatment**
  - Radiation damage studies and develop more radiation-resistant beamline components (target/beam window, etc)

Accelerator systematic uncertainties

Hyper-K sensitivity to CP violation assuming true $\delta_{CP} = \pi/2$

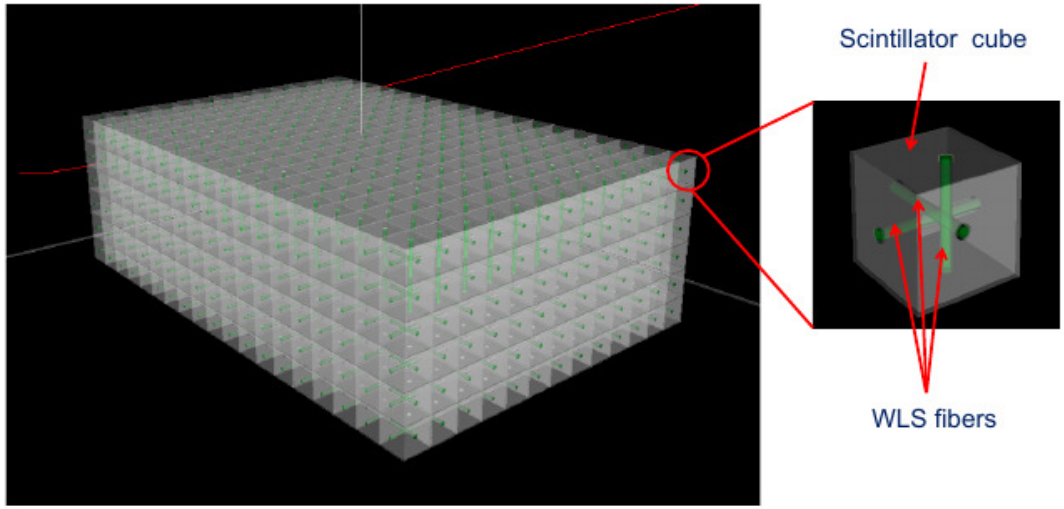


Systematic uncertainties on number of events at HK

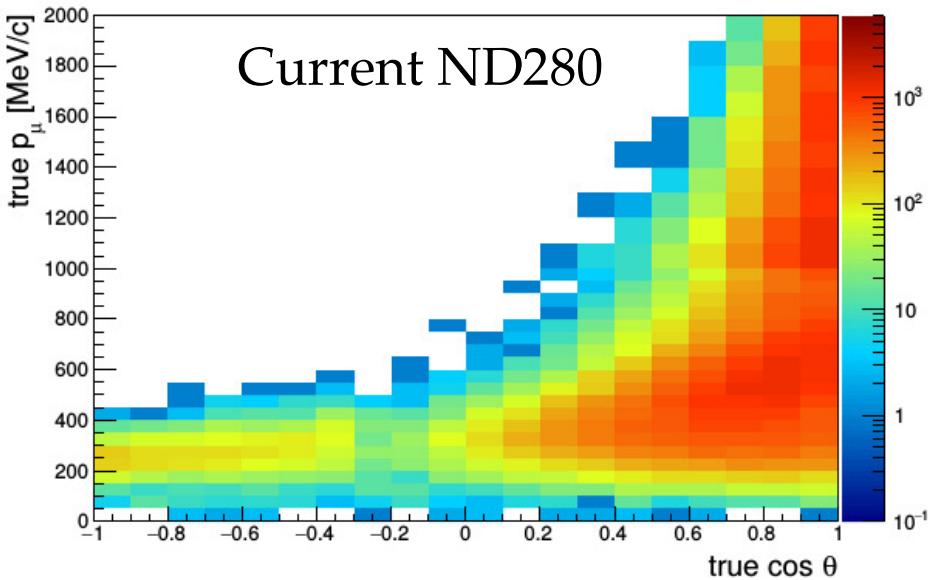
		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0%	0.5%	0.7%	3.2%
	Disappearance	3.3%	0.9%	1.0%	3.6%
$\bar{\nu}$ mode	Appearance	3.2%	1.5%	1.5%	3.9%
	Disappearance	3.3%	0.9%	1.1%	3.6%

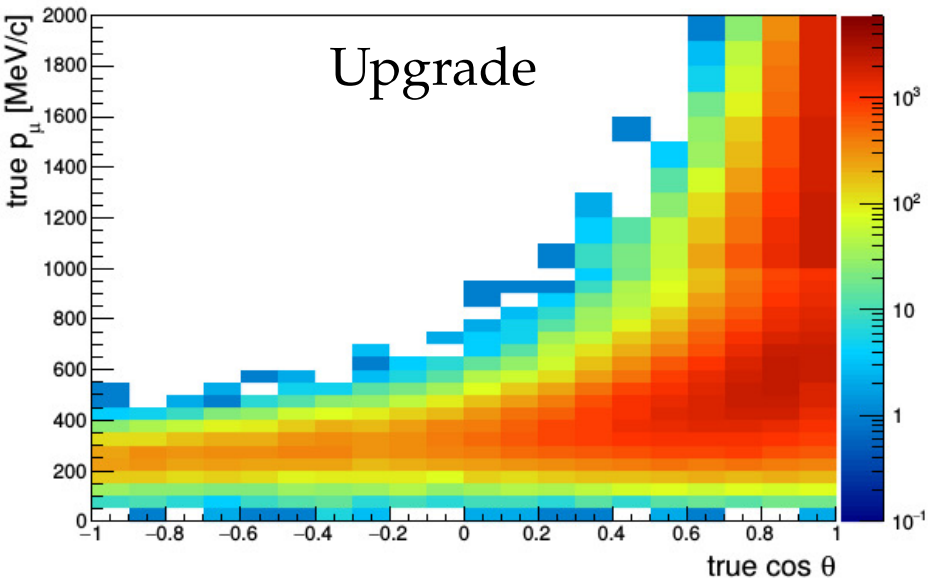
2nd : Systematic error reduction

Super-FGD tracker



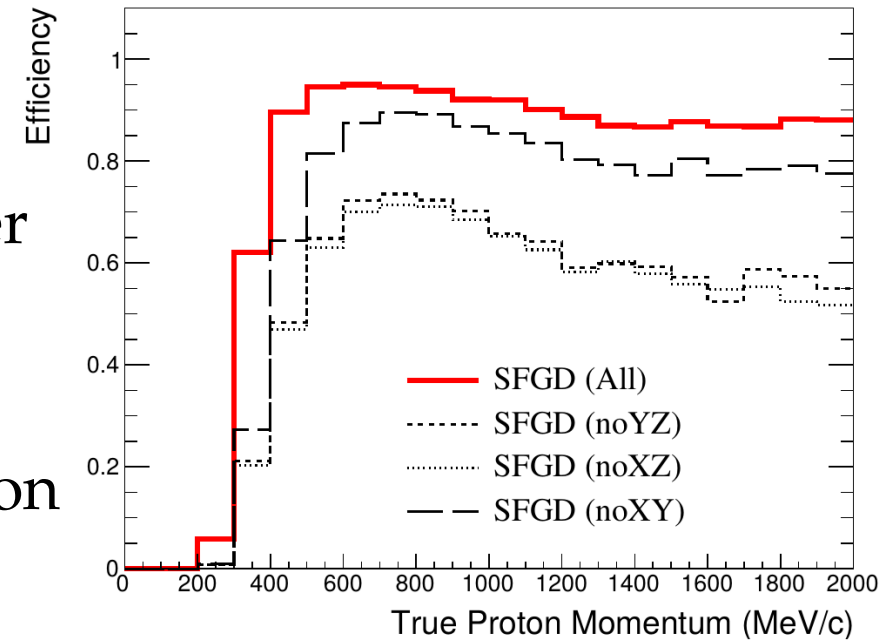
- 1 cm³ scintillating cubes.
- Readout in 3 directions → Improved tracking & E-resolution
- Allows a 4π acceptance for π, p & low energy μ.



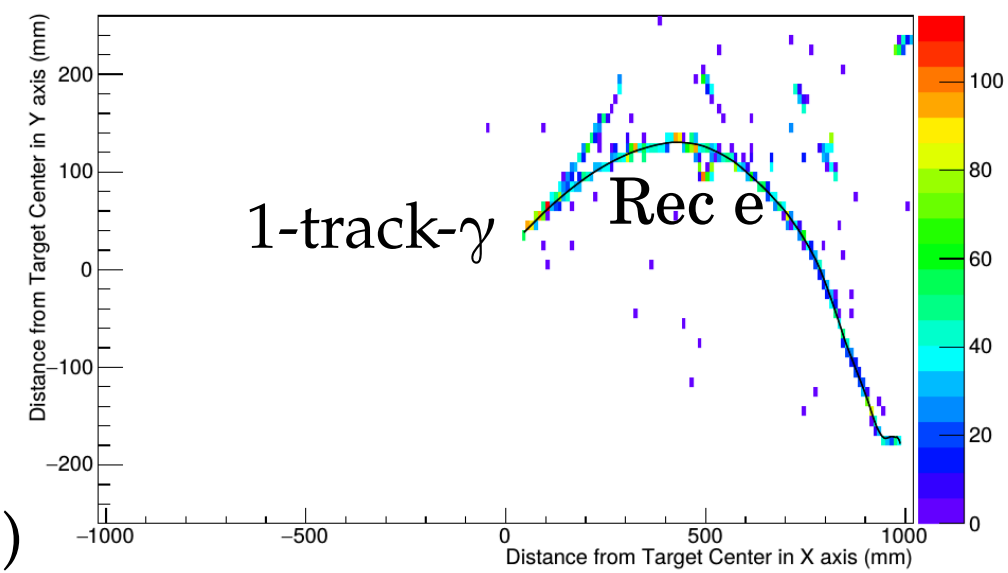


2nd : Systematic error reduction

- Current ND280 : p-threshold limited to 450 MeV/c
- Upgrade : Improved tracking => Lower hadron threshold.
  p-threshold : 450 → 300 MeV/c
  → Larger ability to identify cross-section models (CCQE, 2p-2h etc.)
  → Lower systematics in rate and E.



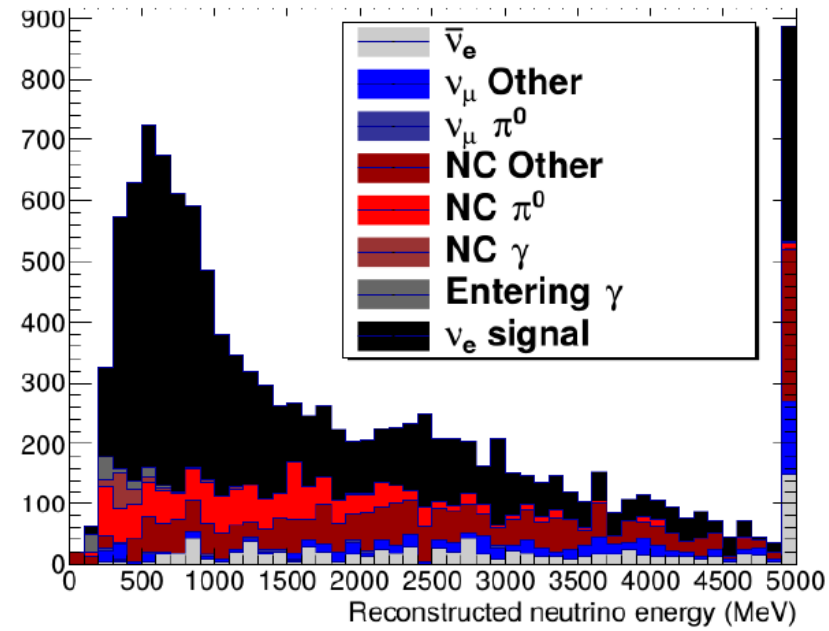
- Current ND280 : γ bkg limit ν_e measurements < 1 GeV.
- Upgrade : Improved E-resolution => e/1-track-γ separation possible
  → Constraints on $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$



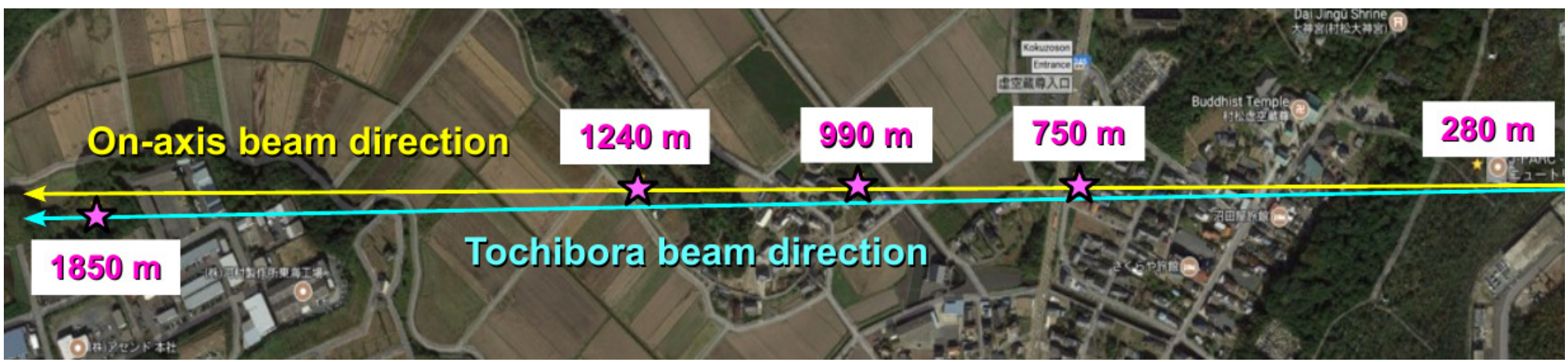
2nd : Systematic error reduction

- WC => Excellent ν_e / ν_μ separation
  => $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$.

- Loaded with Gd for n-tagging
  → Enhanced $\nu/\bar{\nu}$ separation.
  → Measure n-multiplicy



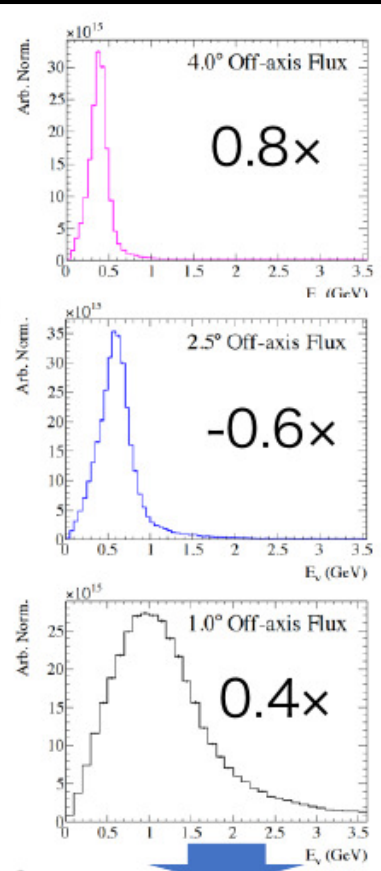
- Sites under survey (balance between event rate / pile-up vs pit depth)

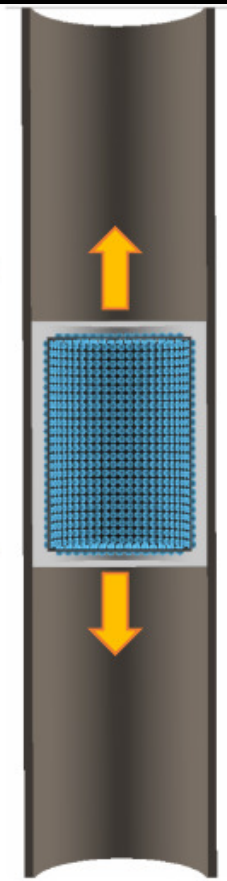


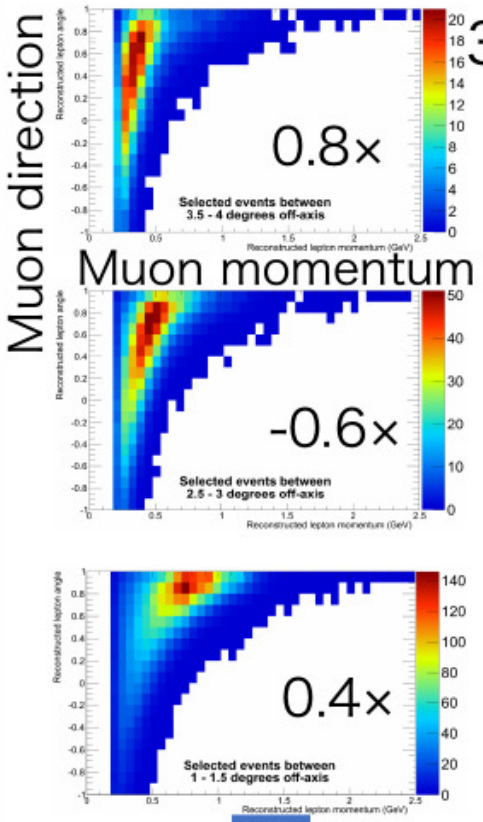
- ND280 + IWCD totally complementary to reach systematics ≤ 3 %.

Linear combination of measurements

1. Separate detector volume to 30 off-axis slices.
2. Take a linear combination of off-axis slices to reproduce desired spectrum.

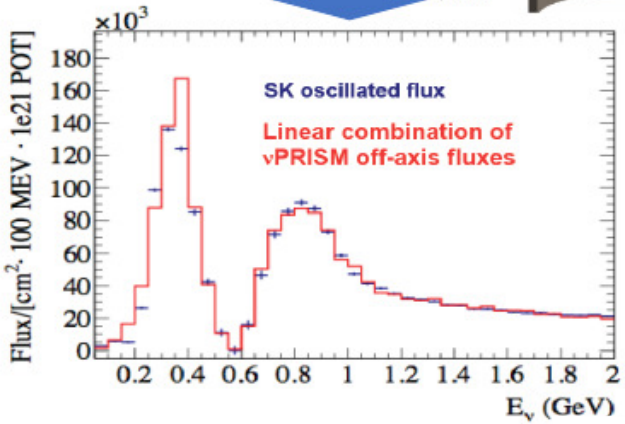


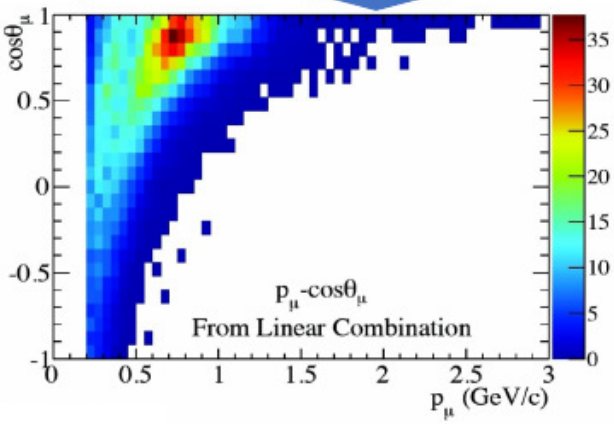




3. Take the same linear combination of observed variables to predict the distribution corresponding to that spectrum.

Example: Oscillated far detector spectrum





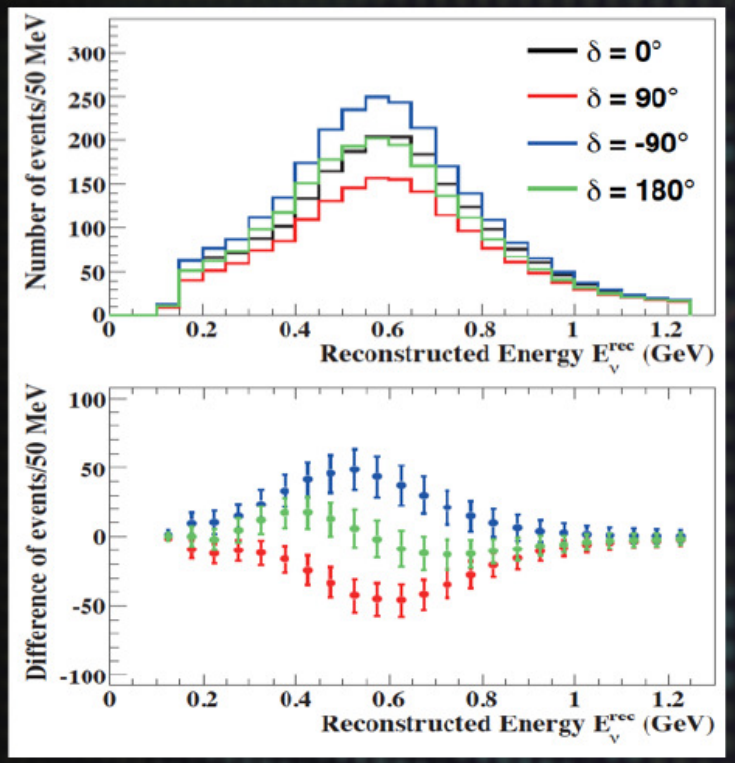
Enables data driven fit less-dependent on interaction models. Some ND-independent systematics can be canceled.

Accelerator neutrino physics : T2HK

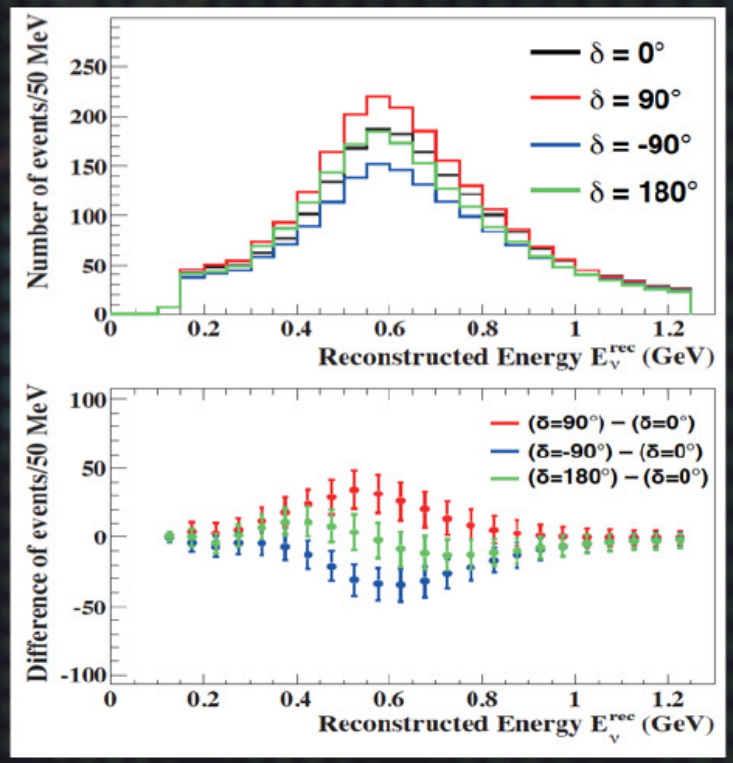
Number of signal candidate events, 1.3 MW × 10 years (10^8 sec), $\nu:\bar{\nu}$ = 1:3

for δ_{CP} = 0	Signal $\nu_\mu \rightarrow \nu_e$ CC	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	Beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	1,643	15	7	259	134
$\bar{\nu}$ beam	1,183	206	4	317	196

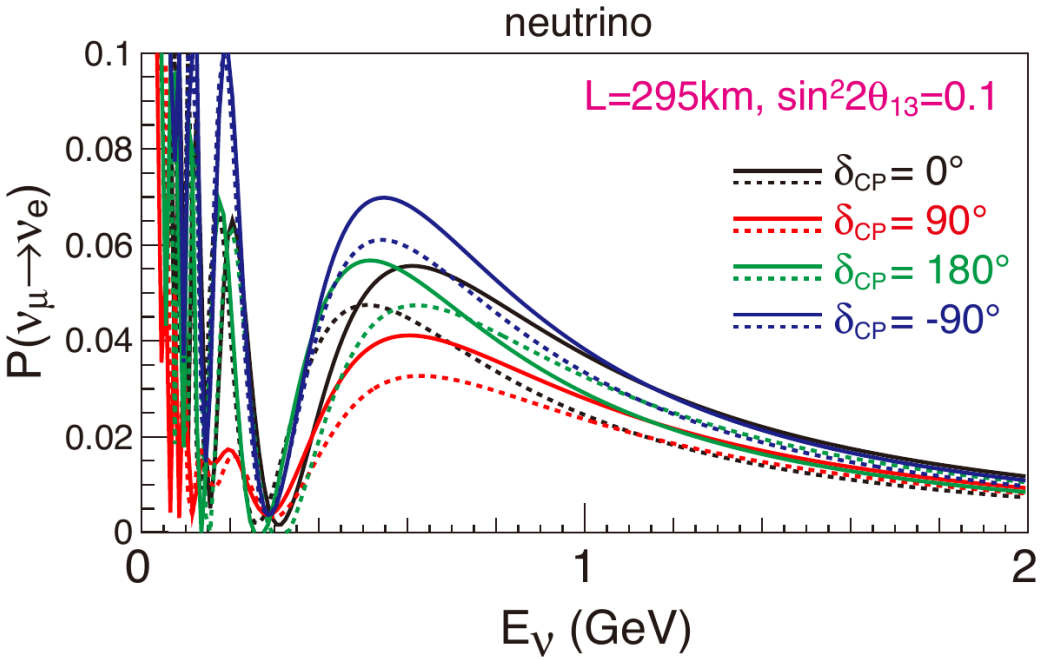
ν beam ν_e appearance

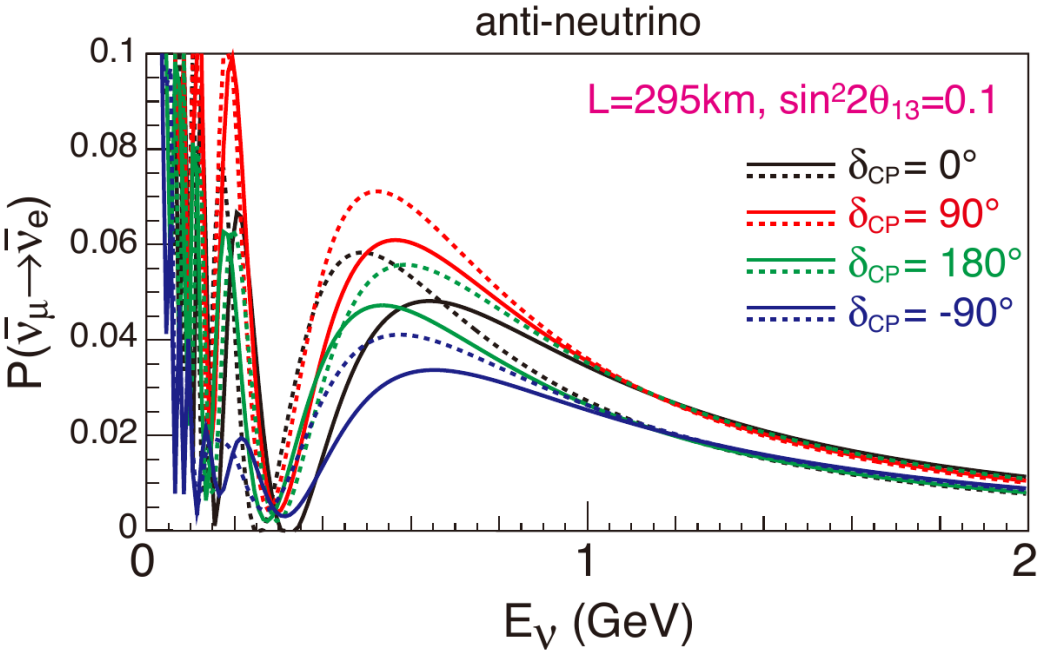


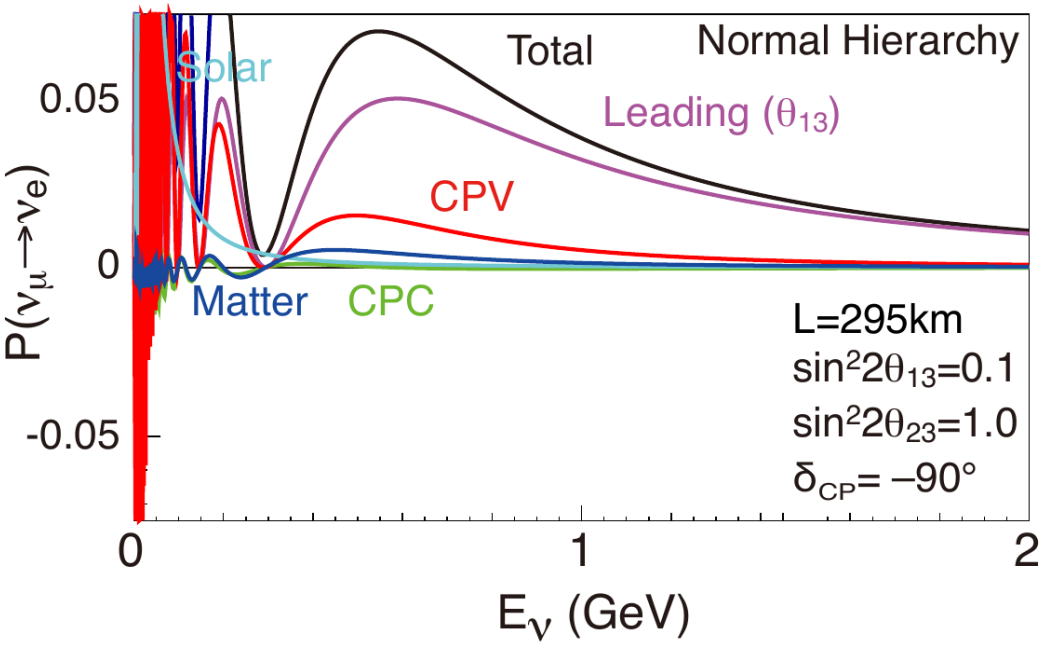
$\bar{\nu}$ beam $\bar{\nu}_e$ appearance

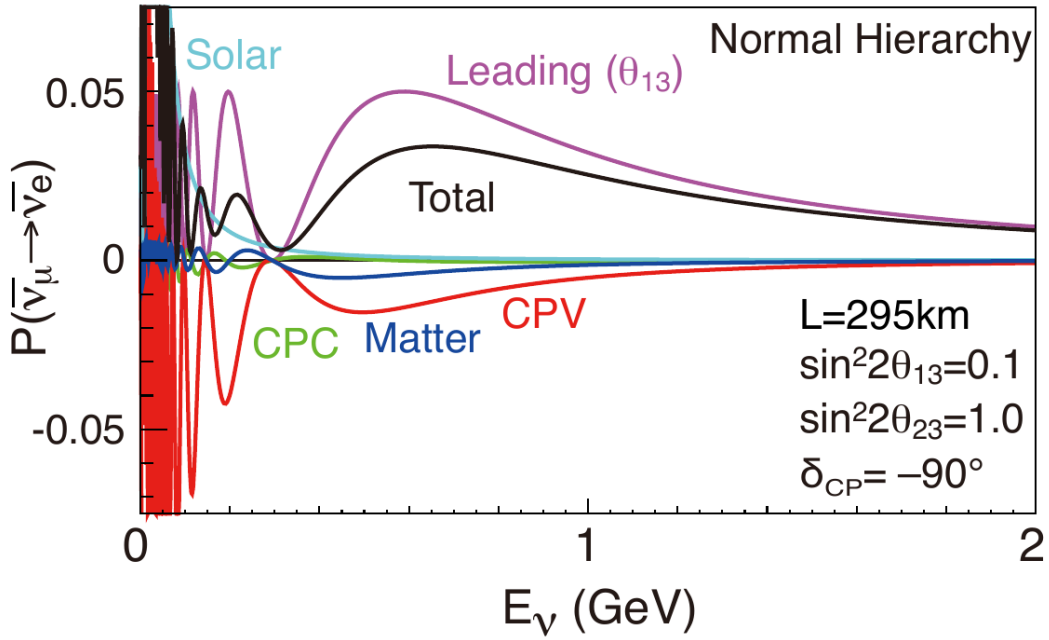


Accelerator neutrino physics : T2HK

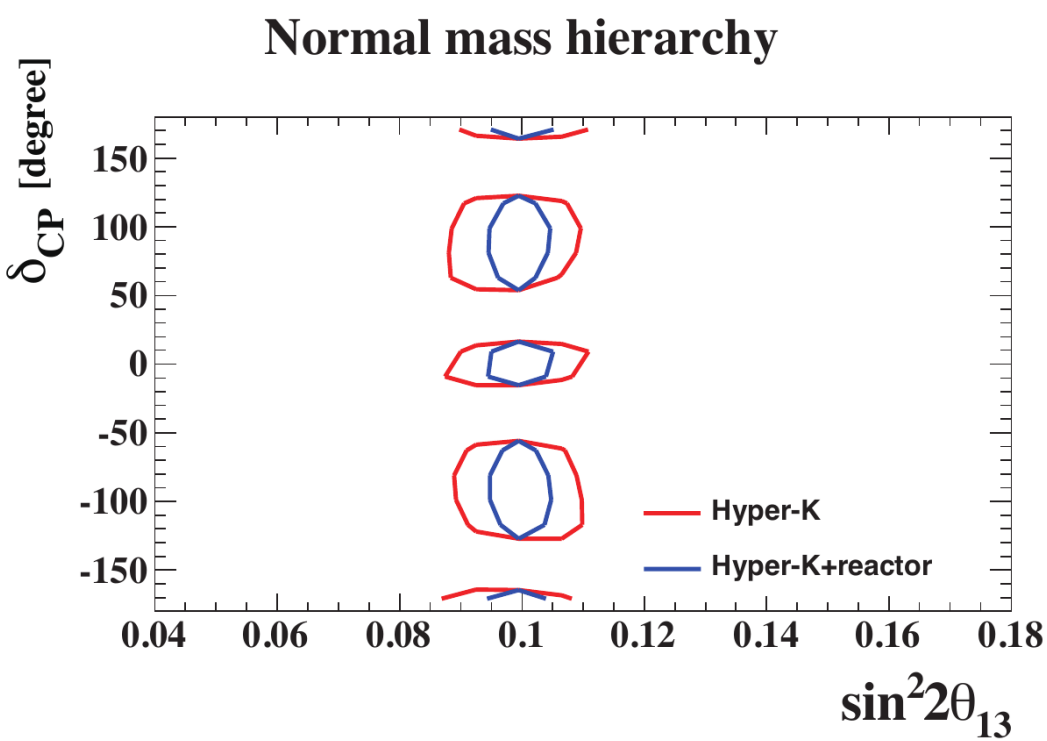


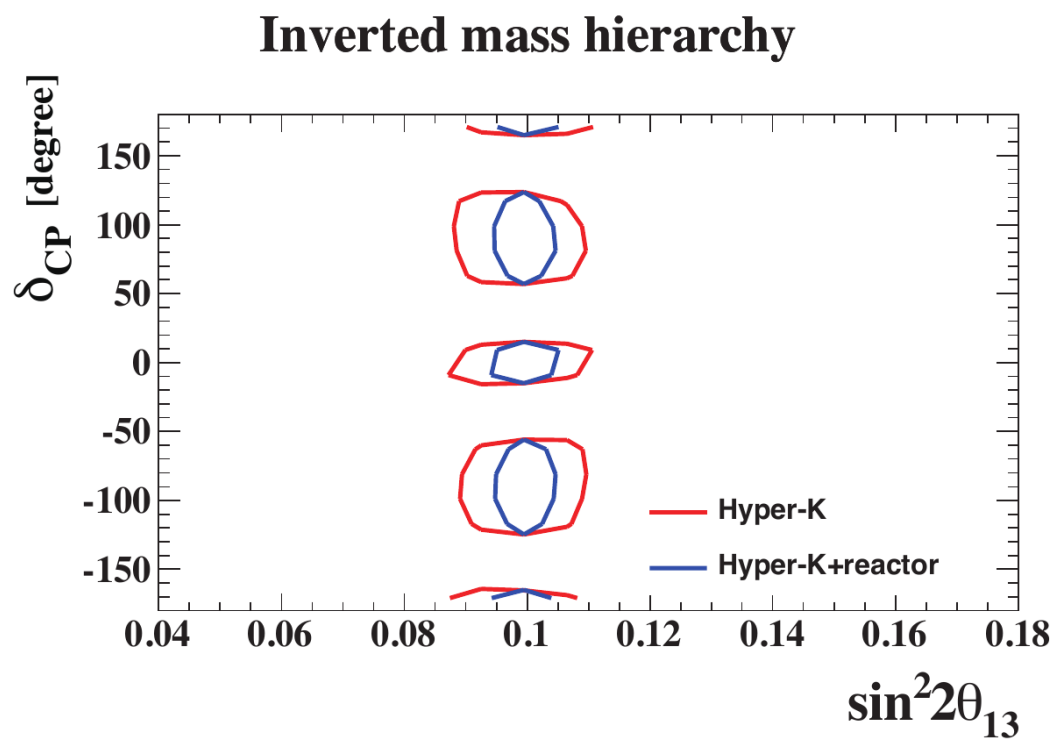


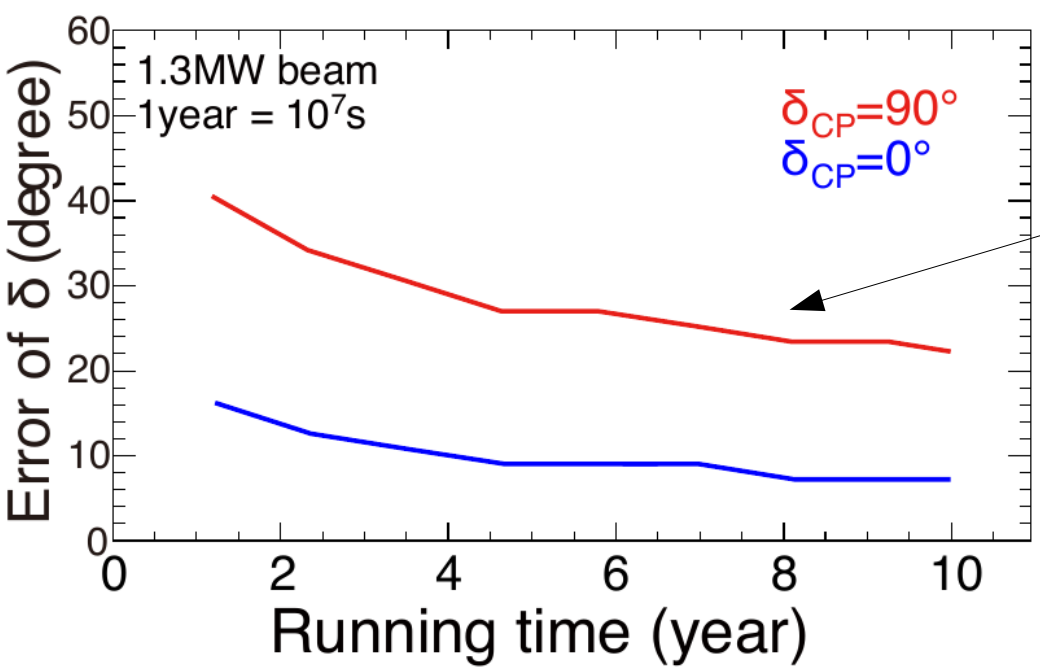




Impact at high energy

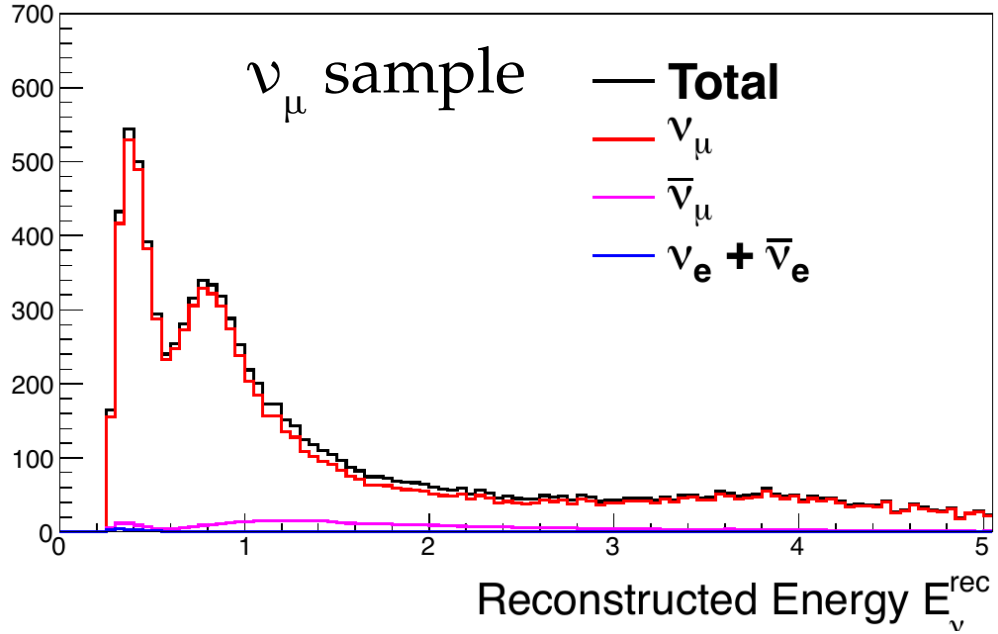




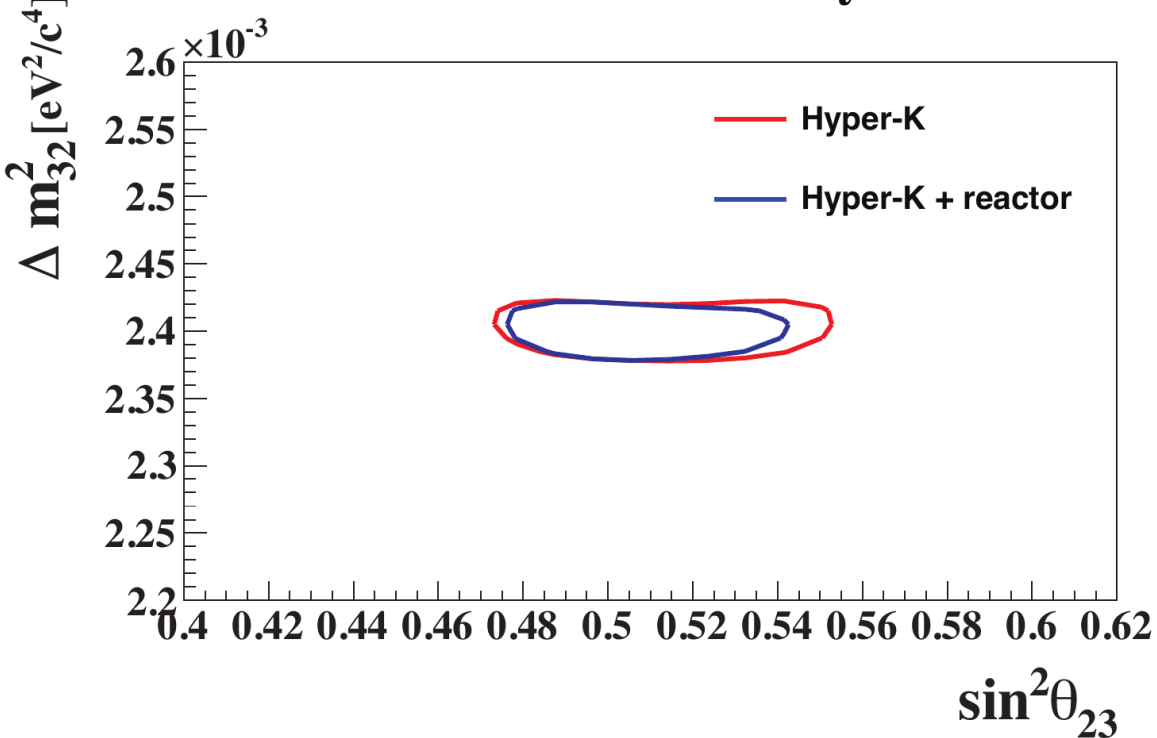


$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$
$$\boxed{+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$+4s_{12}^2 c_{13}^2(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$
$$-8c_{13}^2 s_{12}^2 s_{23}^2 \frac{aL}{4E}(1-2s_{13}^2)\cos\Delta_{32}\sin\Delta_{31}$$
$$+8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2s_{13}^2)\sin^2\Delta_{31}$$

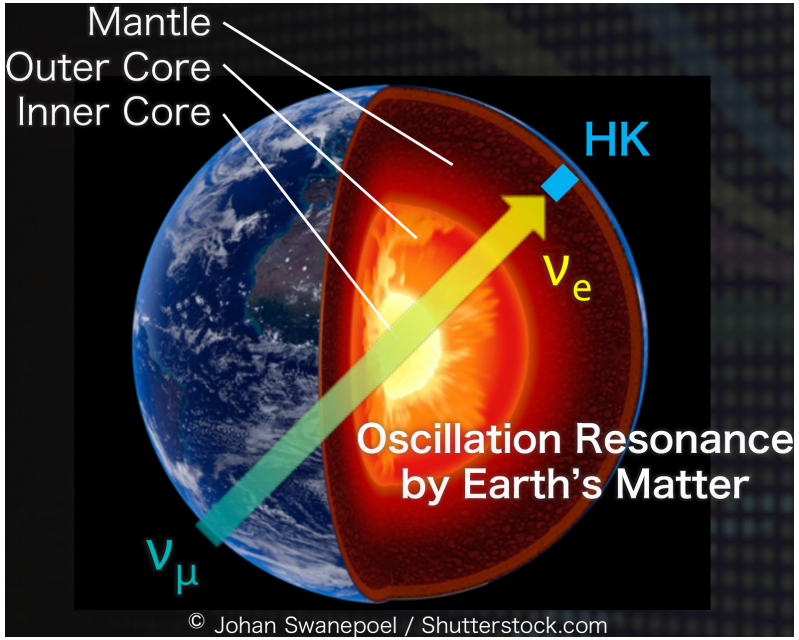
Impact at high energy

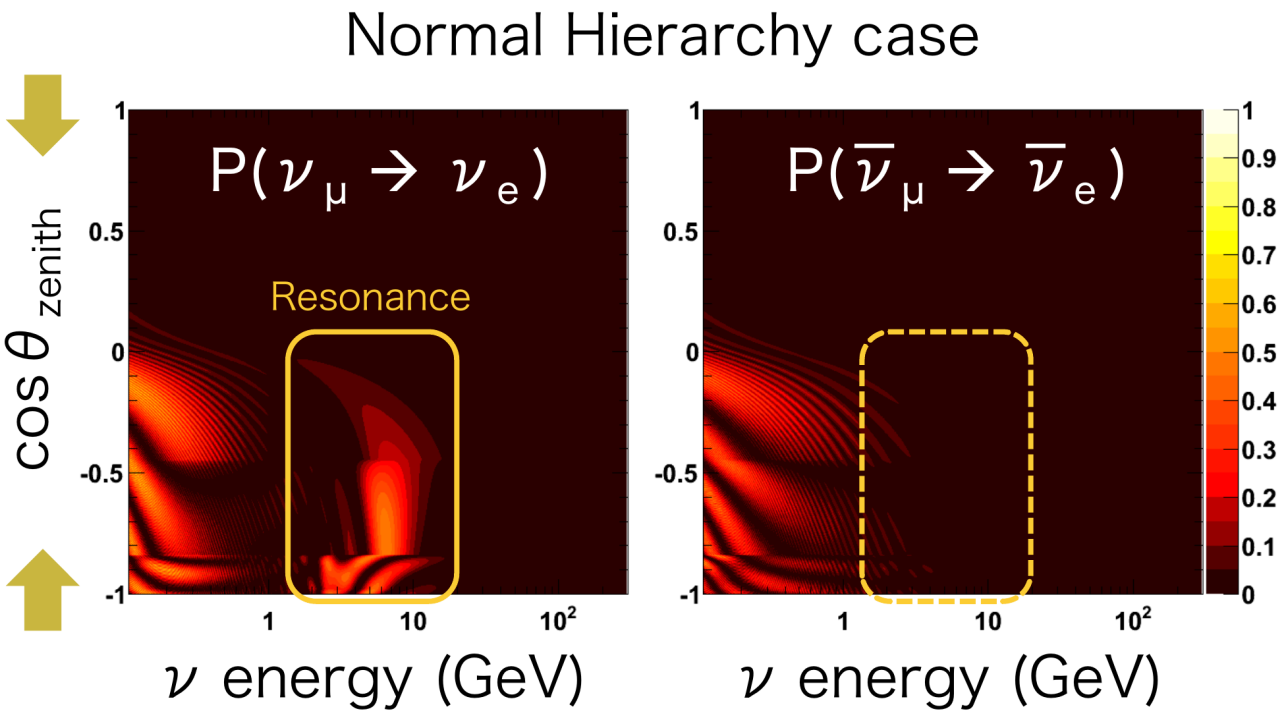


Normal mass hierarchy



Atmospheric neutrinos





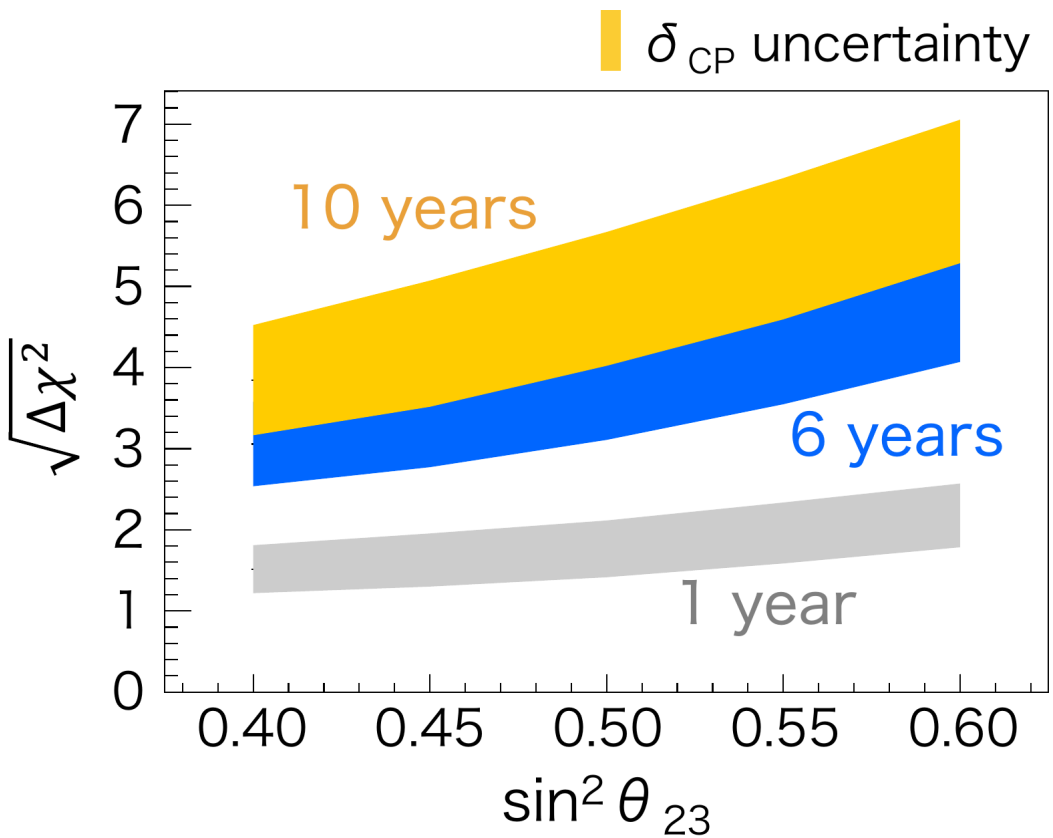
- Mass hierarchy accessible through MSW effect in upward-going multi-GeV ν_e sample :
  - <u>Normal hierarchy :</u> enhancement of $\nu_\mu \rightarrow \nu_e$.
  - <u>Inverted hierarchy :</u> enhancement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

- => Sensitivity enhanced if separation ν_e / $\bar{\nu}_e$

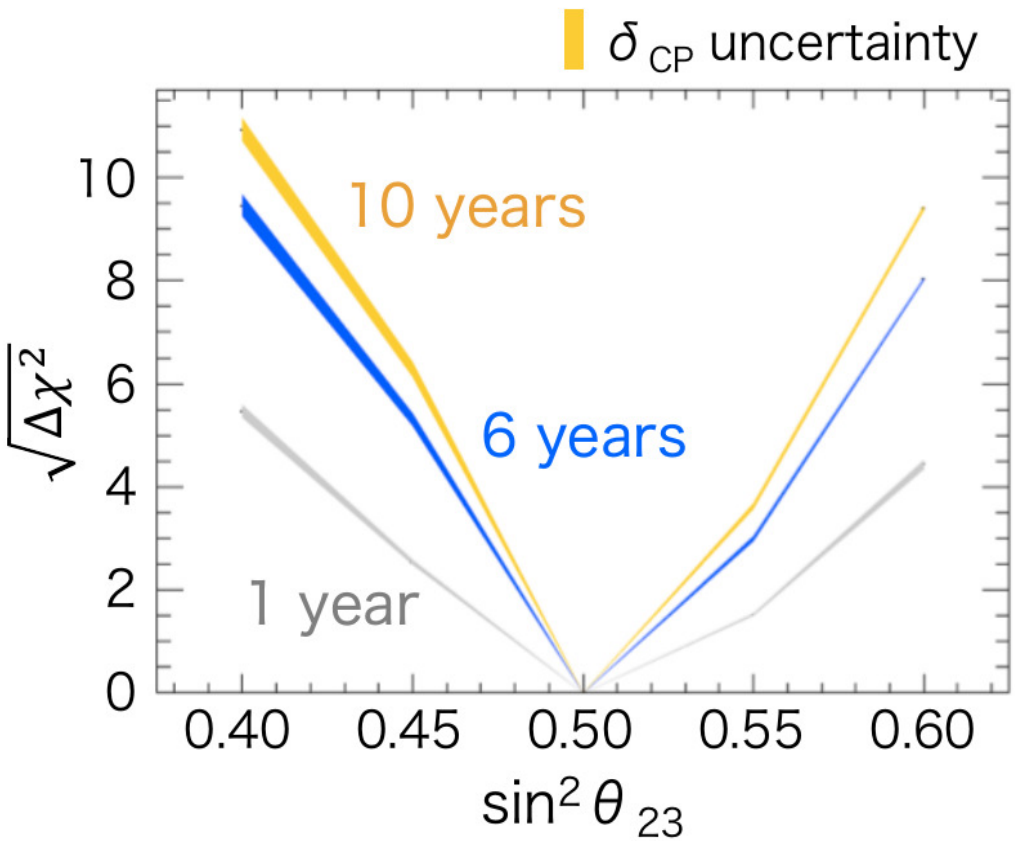
Mass hierarchy & atmospheric parameters

- Combined analysis with accelerator + atmospheric neutrinos.

Neutrino mass hierarchy



θ_{23} octant

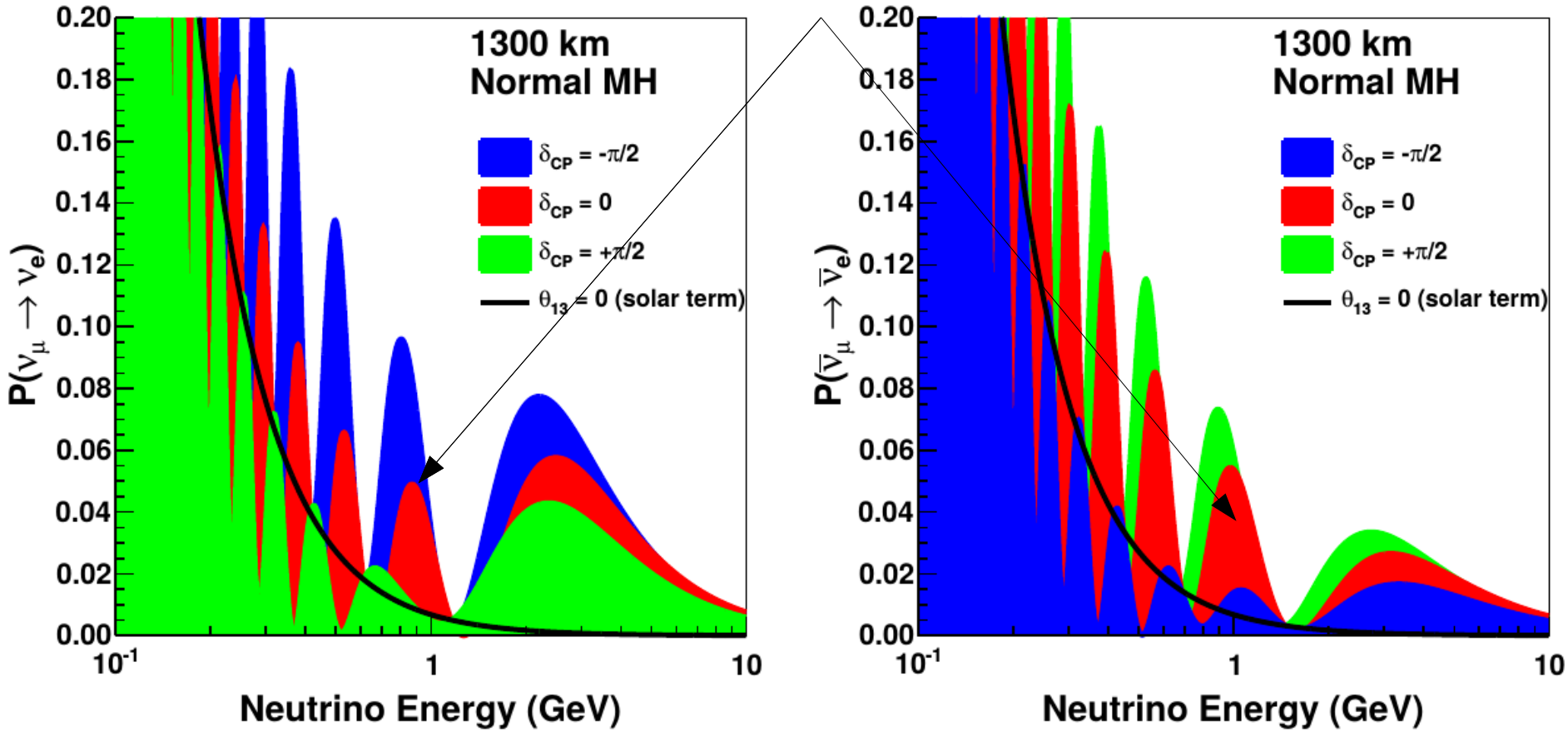


- Very high sensitivity to θ_{23} octant → determination within few years.

- High sensitivity to Mass hierarchy → reach 4 to 5σ in 10 years.

A. Impacts des oscillations : apparition ν_e

- Mais DUNE peut aussi voir le premier minimum :

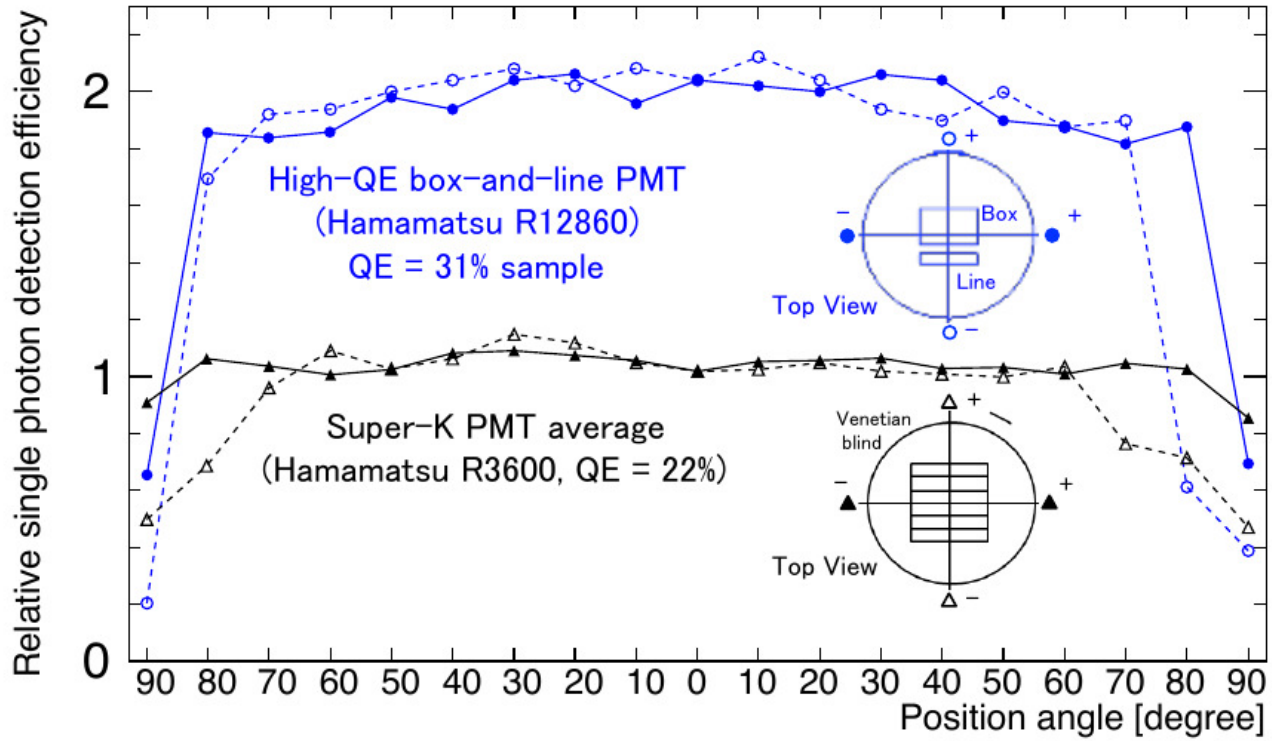


- Effet sur le taux bien plus fort au premier (~50% max) qu'au second minimum (~30 % max)

- <u>Shifte en energie egalement bien plus prononce au premier minimum :</u>
  → Permet une excellente mesure de la CPV et davantage, de la valeur de la phase CP.

HK photo-detectors

- New 20'' High-quantum efficiency Box&Line PMT :

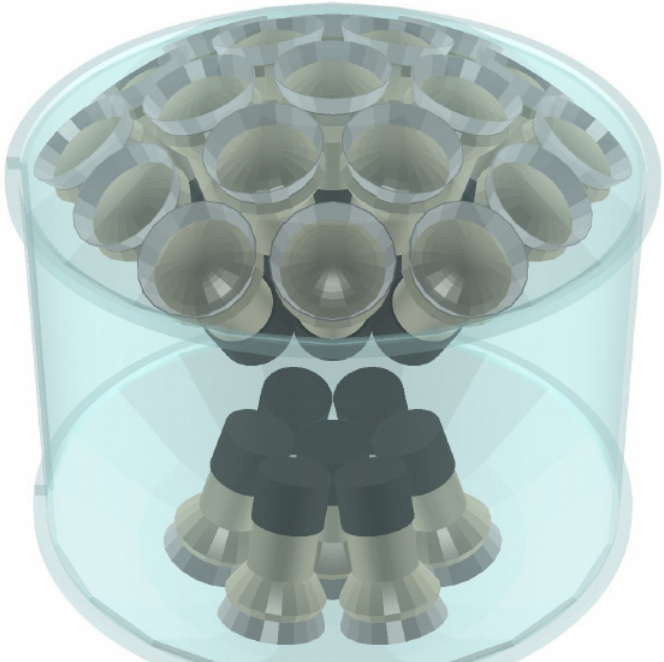


	SK PMTs	HK B&L PMT	
Photo-cathode diameter	20''	20''	
Quantum efficiency	22 %	31 % (QE x CE = 2 x SK)	✓
Transit Time spread (TTS)	5 ns	2.6 ns	✓
Dark rate @13 degrees	4 kHz	8.4 kHz (goal : 4 kHz)	✗

Multi-PMT modules for HK

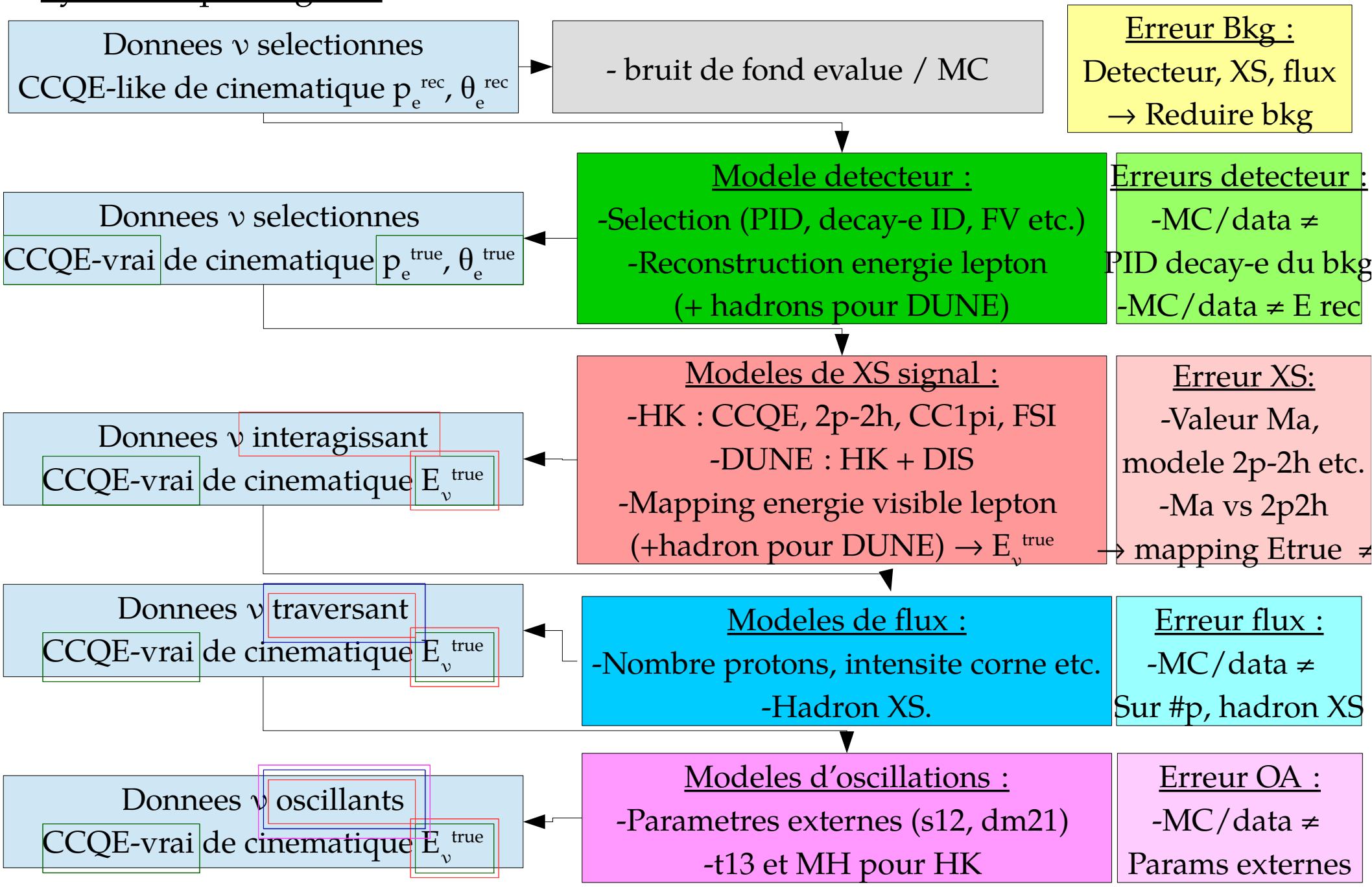
- Study other PMTs complementary to 20′′ to enhance HK physics.
  → multi-PMTs modules (19 x 3′′ PMTs)

Multi-PMT (19 PMTs)



3” PMT

- Smaller size : Better reconstruction near wall
  → Increase FV.
- Better timing resolution: better vertex resolution → enhanced momentum resolution.
- Dark rate in negative HV = 200Hz:
  → Signal/Noise ratio ~ 20′′.
- Dark rate in positive HV = 100Hz:
  S/N ~ 2 x 20′′→ Can probe lower energies ?

D. Erreurs systematiques et ND

- Systematiques signal : viennnent des corrections d'efficacite :