Current status and Physics Potential of the **Hyper-Kamiokande Experiment**

La Thuile 2023 - Les Rencontres de Physique de la Vallée d'Aoste

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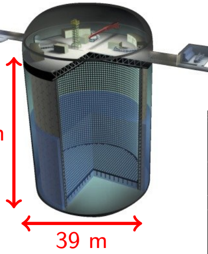
March 7, 2023

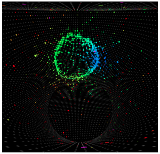
Hyper-Kamiokande

The Hyper-Kamiokande detector

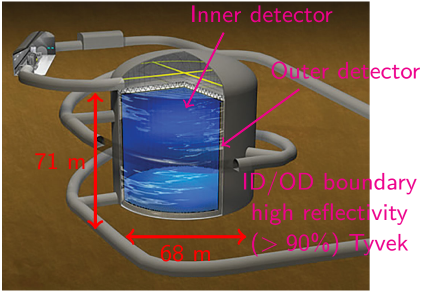
Super-Kamiokande

Running for 30 years and still has a lot to teach!





Hyper-Kamiokande

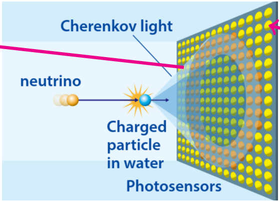


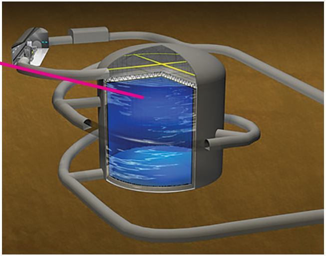
	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% ($\times$2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton

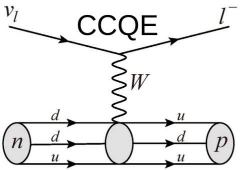
Hyper-Kamiokande will begin taking data in 2027

Neutrino detection with water Cherenkov detectors

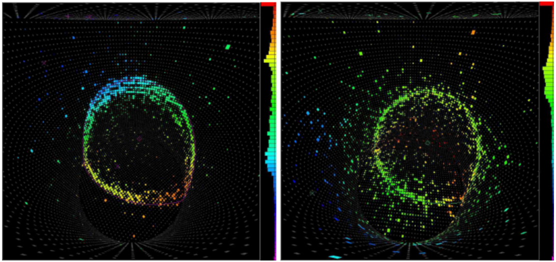
PhotoMultiplier Tube (PMT)







Muon Electron



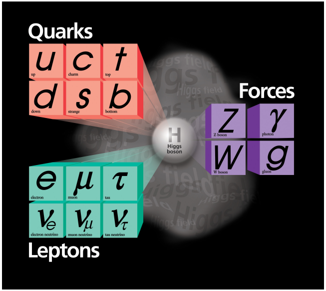
courtesy of SK collaboration

The Hyper-Kamiokande collaboration

- Around 500 collaborators from all around the world working together, sharing expertise and building a milestone in particle physics

- This week: First in-person meeting since Feb. 2020

Neutrinos in the Standard Model... and beyond



Super-Kamiokande (1998) + SNO (2001) :

oscillations ⇒ neutrinos have (different) mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavour "interaction" — mass "propagation"

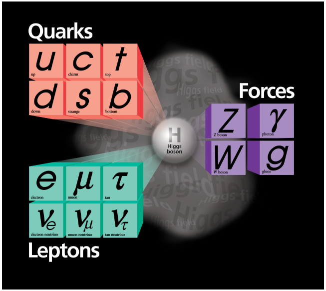
$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric Δm^2_{31} — solar Δm^2_{21}

3 mixing angles, 2 squared mass differences, 1 CP violation phase

open questions: mass hierarchy? $\theta_{23} > 45^\circ$ or $< 45^\circ$? value of δ_{CP}? unitarity?

Neutrinos in the Standard Model... and beyond



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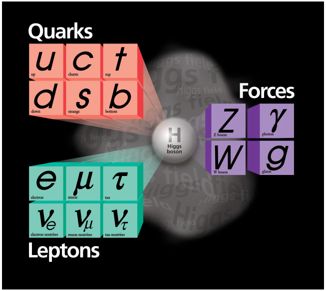

Super-Kamiokande (1998) + SNO (2001) :

oscillations $\Rightarrow$ neutrinos have (different) <u>mass</u>

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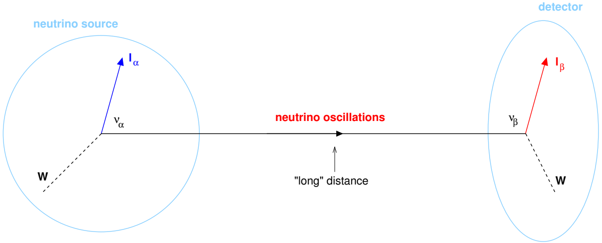
atmospheric Δm^2_{31} — solar Δm^2_{21}

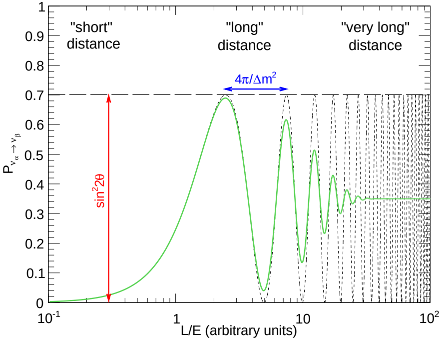
accelerators — reactors

3 mixing angles, 2 squared mass differences, 1 CP violation phase

open questions: mass hierarchy? $\theta_{23} > 45^\circ$ or $< 45^\circ$? value of δ_{CP}? unitarity?

Neutrino oscillation in a nutshell





2-flavour approximation:

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

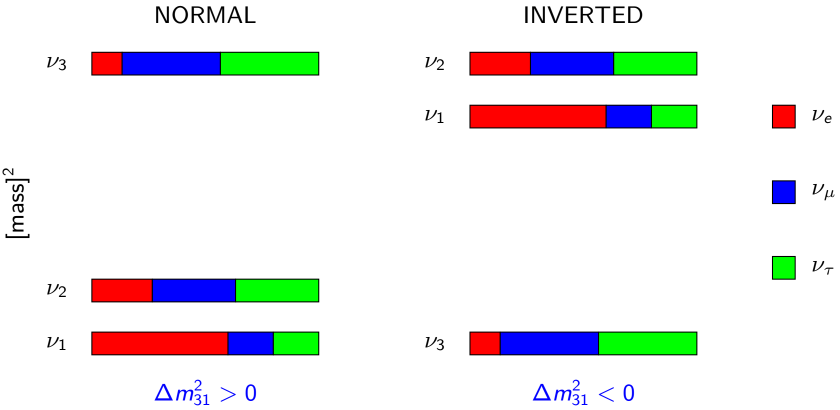
3 flavours : much longer to write...
but the same basic principle

$\delta_{CP} \neq 0 \Rightarrow P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

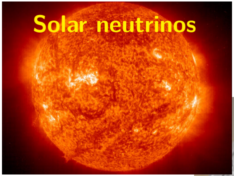
Matter-antimatter asymmetry?

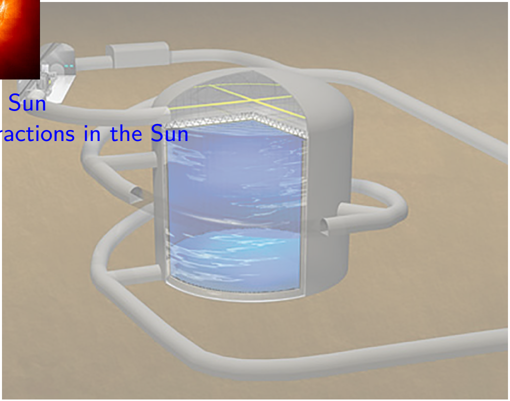
What is the mass hierarchy?

two possibilities for the neutrino mass spectrum



NB: we know that the mass state containing most ν_e is the lighter of the two "solar mass" states $\Delta m^2_{21} \equiv m^2_2 - m^2_1 > 0$ and $\theta_{12} < 45^\circ$ thanks to the observation of the matter effect in the Sun



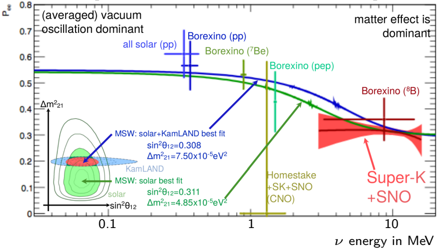


MSW effect in the Sun
Non standard interactions in the Sun

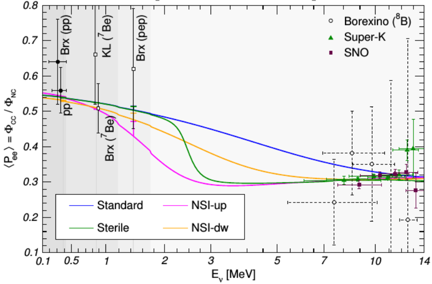
Solar neutrinos

- SK/SNO found high matter effect in the Sun $\Leftrightarrow$ P_{ee} upturn shifted to low energies

[Ikeda M., SK, Neutrino 2018]

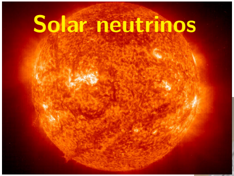


[arXiv:1507.0587]



- SK deviates from "standard" upturn scenario by $> 2\sigma$
- Statistical fluctuation? Light sterile neutrino? Non Standard Interaction (NSI) in the Sun?
- Hyper-Kamiokande solar ν physics : explore upturn region, probe day/night asymmetry (matter effects in the Earth), solve tension w/ KamLAND results

HK physics case



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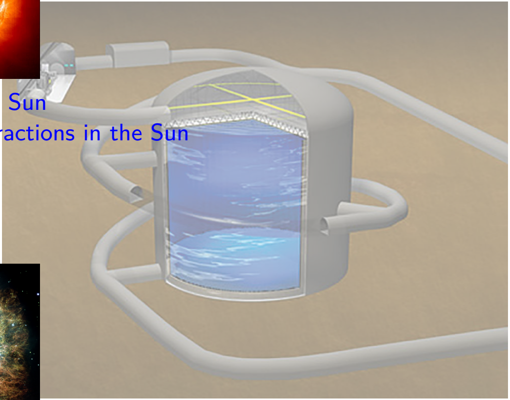
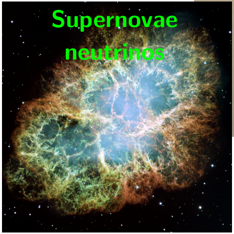
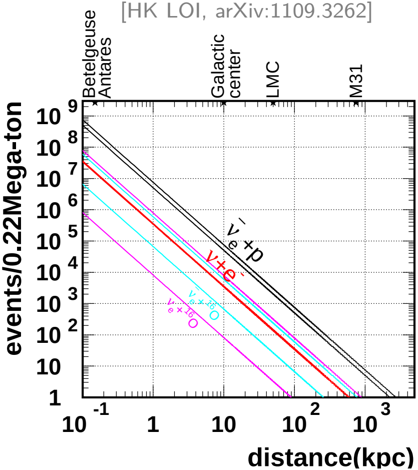




Constraints SN models
Constraints star formation history

- 99% of the gravitational energy of a SN is released into neutrinos ⇒ knowledge about the mechanisms in the core of the collapsing star
- SK only sensitive to galactic SN ($\sim$ 8000 events) which are extremely rare (few times per century) so far only SN1987a in LMC (12 events in Kamiokande)
- HK sensitive to extra-galactic SN (Andromeda)
- If SN in the galactic center, $\sim$ 50k events ⇒ unprecedented constraints in both time and energy [K. Abe et al. ApJ 916 15 (2021)]
- Directional resolution of 1° @ 10 kpc ⇒ multi-messengers astronomy

[HK LOI, arXiv:1109.3262]



- Neutrinos produced by all of the supernova explosions since the beginning of the universe
- Detection channel IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$
- First detection in SK-Gd? Gd has very large n capture cross section and a very distinctive γ signature [arXiv:0309300] Lastest results for DSNB search at SK [K. Abe et al. PRD 104 (2021)]
- Shape of the spectrum with HK!
- Dependency with the redshift $\Rightarrow$ rate as a function of time
- Sensitivity to fraction of failed SN *i.e.* neutron star vs BH (harder spectrum)

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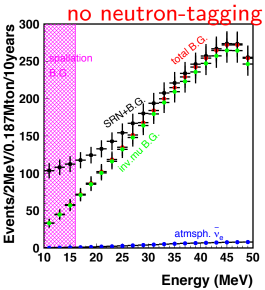

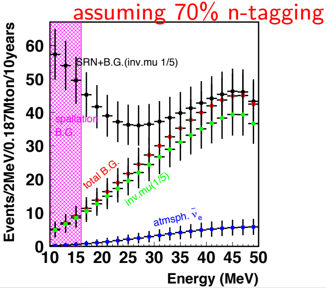

Diffuse Supernovae Neutrino Background

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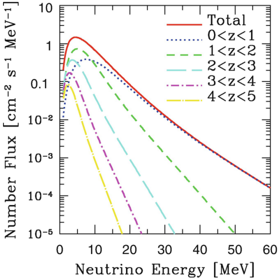
[Astrophys. J 607, 20 (2004)]



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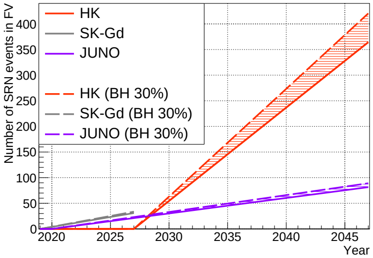
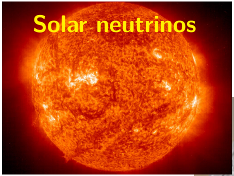
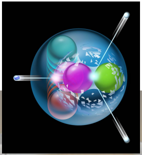


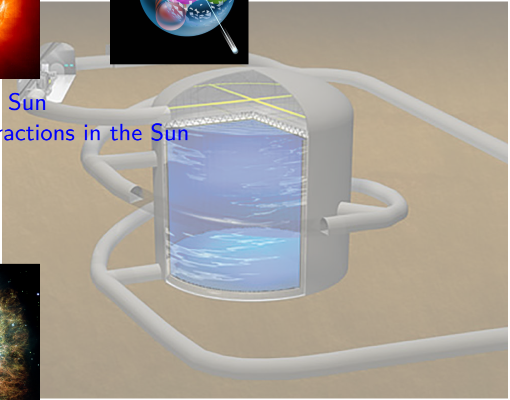
HK physics case

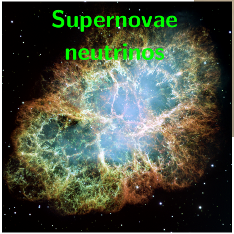




Proton
decay (GUT)

MSW effect in the Sun
Non standard interactions in the Sun

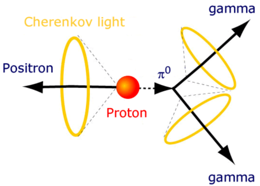


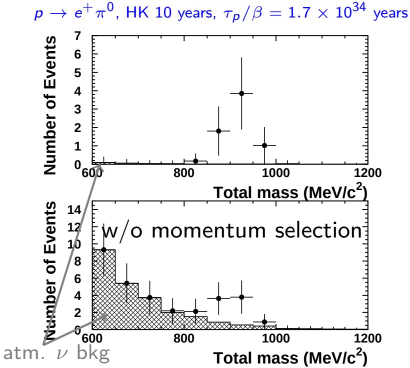


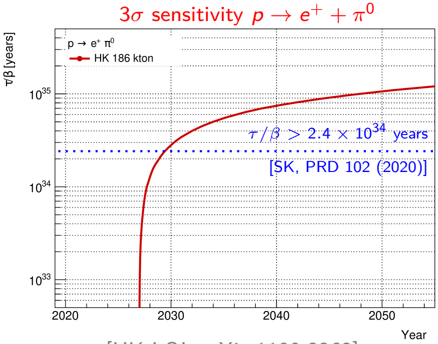
Constraints SN models
Constraints star formation history

GUT and proton decay

- Probe Grand Unified Theories at a new scale through proton decay
- Golden channel : $p \to e^+ + \pi^0$, very clean event topology, almost background free (dominant bkg is atmospheric ν producing a π^0)
- Second channel $p \to \bar{\nu} + K^+$







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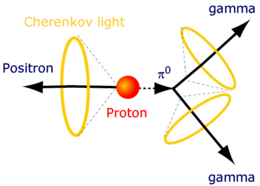
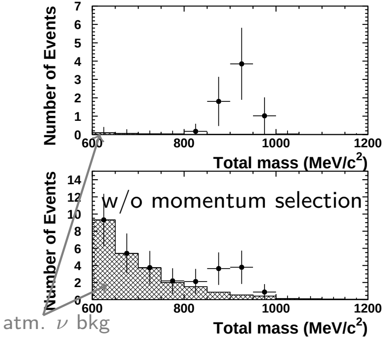
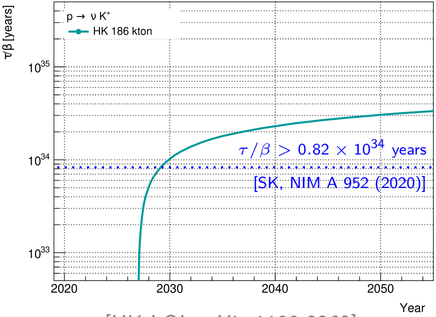


$p \to e^+\pi^0$, HK 10 years, $\tau_p/\beta = 1.7 \times 10^{34}$ years



3σ sensitivity $p \to \nu + K^+$



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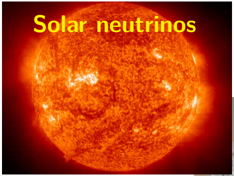

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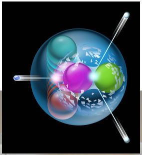

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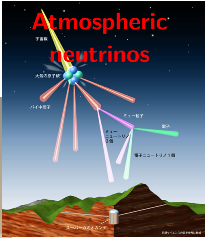
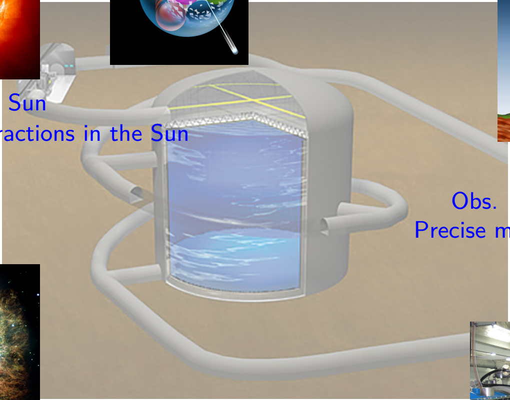
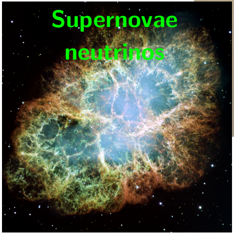




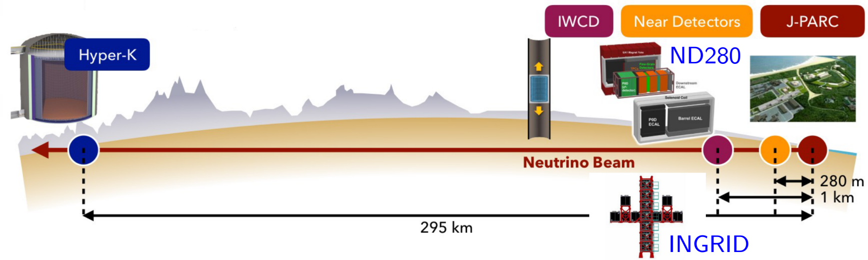
Obs. CP violation at 5σ
Precise measurement of δ_{CP}
Mass hierarchy



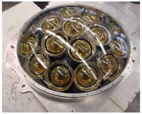
Constraints SN models
Constraints star formation history

Hyper-Kamiokande long-baseline program

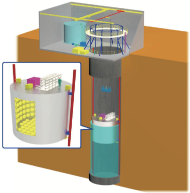
- Search for ν_μ ($\bar{\nu}_\mu$) disappearance $\Rightarrow$ precise measurement of atmospheric parameters
- Search for ν_e ($\bar{\nu}_e$) appearance $\Rightarrow$ search for CP violation in the lepton sector
- Upgraded beam power to 1.3 MW w.r.t. T2K ($\sim$ 500 kW)
- Upgraded ND280 (off-axis detector of T2K)
- New Intermediate Water Cherenkov Detector @ 1 km

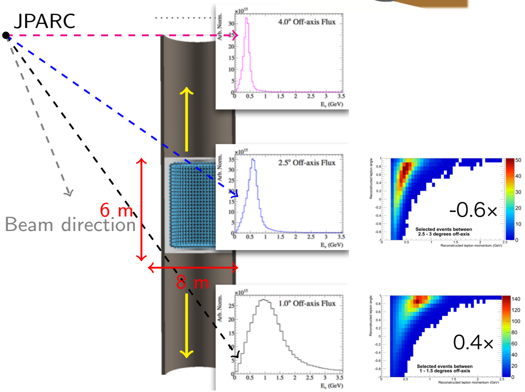


Intermediate Water Cherenkov Detector (IWCD)



Multi-PMTs : better timing and spatial res. than 20"-PMTs

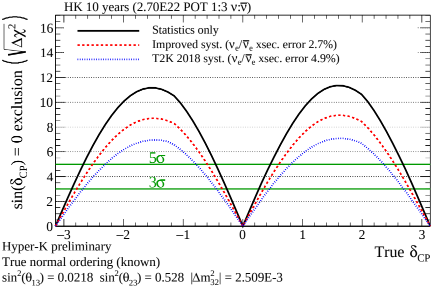


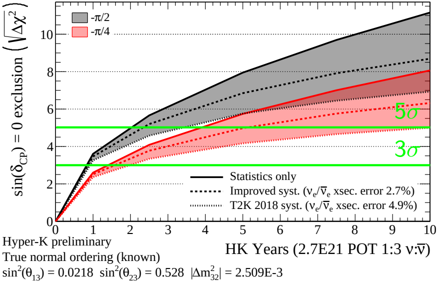


- Solid angle different at near and far detector
- Take a combination of reconstructed number of neutrinos (*e.g.* in p/θ) to correctly predict the flux at HK $\Rightarrow$ helps in reducing systematics related to cross-section models
- Water Cherenkov $\Rightarrow$ same as HK, excellent PID
- Distance $\sim$ 1 km
- Loaded w/ Gd for n tagging?
- ND280 + IWCD complementary to reach $\leq 3\%$ syst.

Sensitivity to CP violation

- Assumption ν:$\bar{\nu}$ = 1:3 with beam @ 1.3 MW

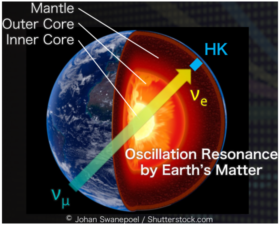




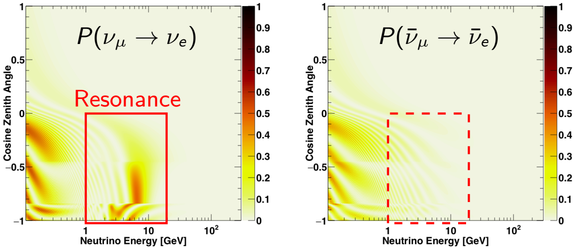
- If $\delta_{CP} = -\pi/2$: 5σ after 2-4 years of data taking, independent from ↘ systematics
- 5σ sensitivity on 60% of δ_{CP} values in 10 years
- HK has world-best sensitivity to CP violation... if MH is known

Atmospheric neutrinos and mass-hierarchy determination

- Mass-hierarchy can be accessed through matter effects, the longer the baseline, the higher the effects

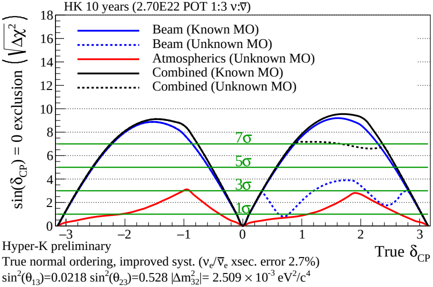


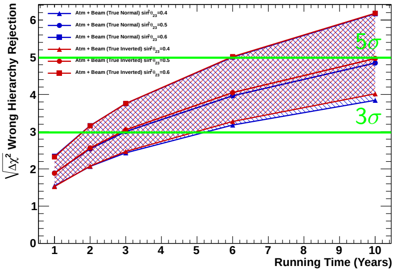
Normal Hierarchy



[PTEP 2019 (2019) no.5, 053F01]

- Mass-hierarchy determined with upward-going multi-GeV ν_e sample: atm. baseline $\leq$ 130000 km $\gg$ 295 km accelerator baseline
  - Normal hierarchy: enhancement of $P(\nu_\mu \to \nu_e)$
  - Inverted hierarchy: enhancement of $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- Sensitivity enhanced if $\nu/\bar{\nu}$ separation $\Rightarrow$ neutron capture [ν ($\bar{\nu}$) interactions on nuclei produce a p (n)]

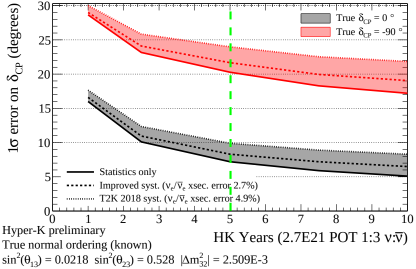




- Even if MH is not known when HK starts, sensitivity to CP violation is little affected if we use atmospheric ν
- MH will be determined $\leq$ 6-10 years through atmospheric ν oscillations

Precision of δ_{CP} measurement

- After CPV is determined, accurate measurement of δ_{CP} will be crucial
$\Rightarrow$ maximal CPV, constrain leptogenesis scenarios, symmetries of lepton's generation,...



	HK precision	
	5 years	10 years
CP conservation ($\delta_{CP} = 0$)	8°	6°
Max. CP violation ($\delta_{CP} = -\pi/2$)	25°	19°

- HK will be the leading experiment for CPV & δ_{CP} measurements in the next 20 years

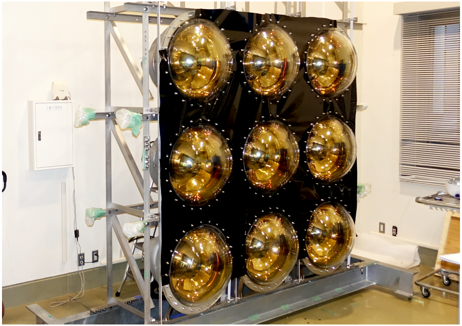
Beginning of HK construction

Access tunnel entrance when the excavation just started on May 6, 2021

Beginning of HK construction

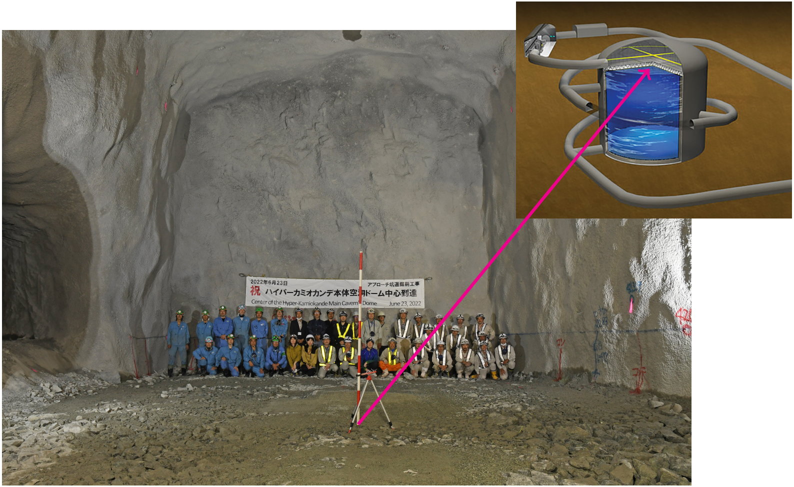
Groundbreaking ceremony held online on May 28, 2021

PMT production and delivery



Total 3772 PMTs ($\sim$ 20%)
delivered by April 2022

Current status of HK construction



Center of the future HK main cavern's dome reached on June 23, 2022

Summary and conclusion

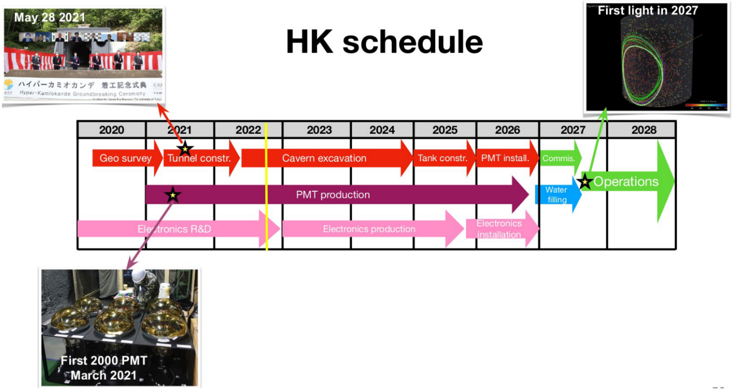
- Hyper-Kamiokande is a next-generation neutrino experiment built on the success of Super-Kamiokande with $8\times$ larger fiducial volume and improved PMTs
- Upgraded beam program with 1.3 MW beam power, upgraded near detectors and new Intermediate Water Cherenkov Detector $\Rightarrow$ towards discovery of CP violation in the lepton sector
- Extraordinary research project with extraordinary scientific significance
- Highly versatile multi-purpose experiment, with capability to explore variety of topics in the MeV - TeV energy range: beam neutrinos, solar and atmospheric neutrinos, supernovae neutrinos, DSNB, neutrino astrophysics, dark matter, proton decay and other baryon number-violating processes, ...

Construction on-going! Data taking in 2027!

New collaborators welcome!

BACK-UP SLIDES

HK schedule


May 28 2021
ハイパーカミオカンデ 着工記念式典
Hyper-Kamiokande Groundbreaking Ceremony
HK schedule
First light in 2027
2020
2021
2022
2023
2024
2025
2026
2027
2028
Geo survey
Tunnel constr.
Cavern excavation
Tank constr.
PMT install.
Commis.
PMT production
Water filling
Operations
Electronics R&D
Electronics production
Electronics installation
First 2000 PMT
March 2021

Three flavour oscillation parameters summary

From NuFIT 5.0 (2020), `www.nu-fit.org`

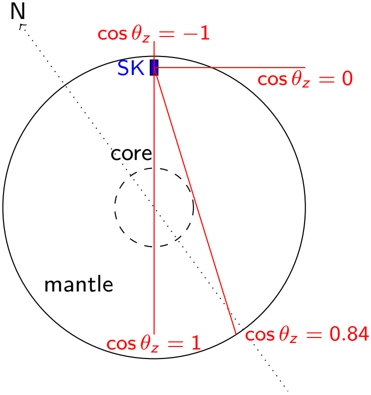
Parameter	bfp$\pm 1\sigma$	1σ acc.	Experiment	Comment
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	4.2%	KamLAND, SK, SNO	unitarity?
Δm^2_{21} $[10^{-5}$ eV$^2]$	$7.42^{+0.21}_{-0.20}$	2.8%	KamLAND SK, SNO	
$\sin^2\theta_{23}$	NH: $0.573^{+0.016}_{-0.020}$ IH: $0.575^{+0.016}_{-0.019}$	4.3%	T2K, NOνA, SK	unitarity? octant? ($\theta_{23}>45^\circ$ or $<45^\circ$?)
$\Delta m^2_{3\ell}$ $[10^{-3}$ eV$^2]$	NH: $\Delta m^2_{31} = 2.517^{+0.026}_{-0.028}$ IH: $\Delta m^2_{32} = -2.498^{+0.028}_{-0.028}$	1.2%	T2K, NOνA, SK, Daya Bay	mass hierachy?
$\sin^2\theta_{13}$	NH: $0.02219^{+0.00062}_{-0.00063}$ IH: $0.02238^{+0.00063}_{-0.00062}$	3.0%	Daya Bay, RENO, Double Chooz	unitarity?
δ_{CP} [degree]	NH: 197^{+27}_{-24} IH: 282^{+26}_{-30}	-	T2K, NOνA (w/ θ_{13} constraint)	3σ measurement? CP violation?

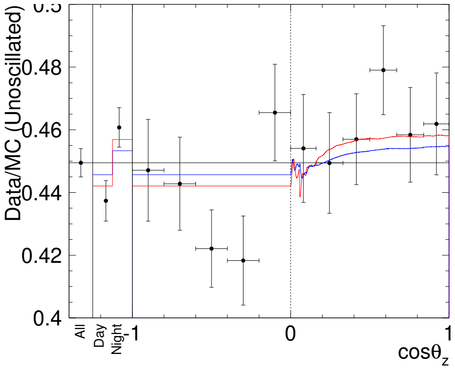
Open questions in neutrino oscillations : mass hierarchy, θ_{23} octant, value of δ_{CP}, unitarity?

Regeneration of solar ν_e's in the Earth?

During day solar ν's cross atmosphere + thin part of crust $\Rightarrow$ negligible matter effects

During night they come from below, passing through the Earth $\Rightarrow$ matter effects (density in the core $\sim$ 0.01 Sun)

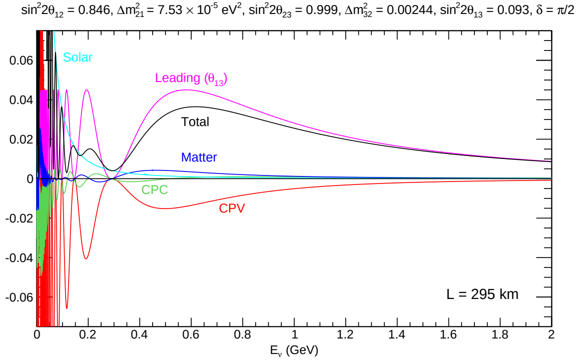




$$A_{\mathrm{DN}} = \big(-4.9 \pm 1.8(\mathrm{stat.}) \pm 1.4(\mathrm{syst.})\big)\%$$

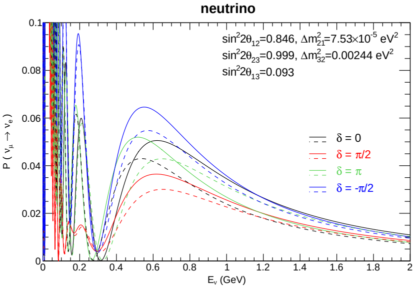
$$A_{\mathrm{DN}}^{\mathrm{fit,SK}} = \big(-3.3 \pm 1.0(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})\big)\%$$

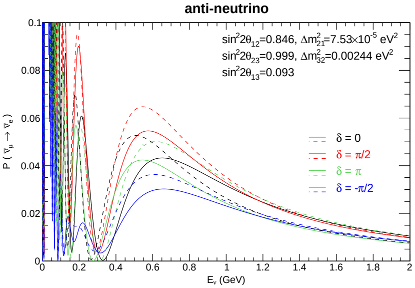
$$P(\nu_\mu \to \nu_e) = \boxed{4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}}$$
$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$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



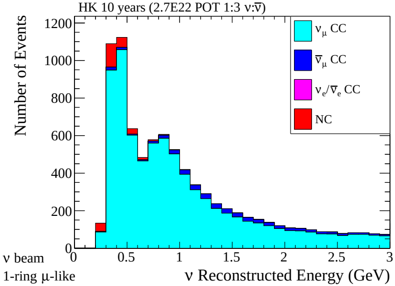
$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$
$$+8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$
$$\boxed{-8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32} \sin\Delta_{31}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

$$\boxed{P(\bar\nu_\mu \to \bar\nu_e) \qquad a \to -a \qquad \delta \to -\delta}$$

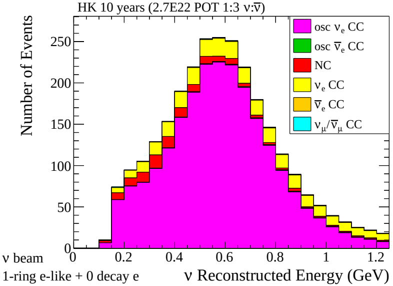




Beam only ν mode

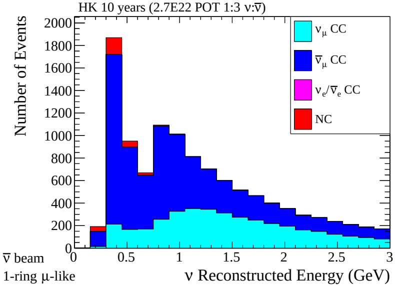


Beam only ν mode

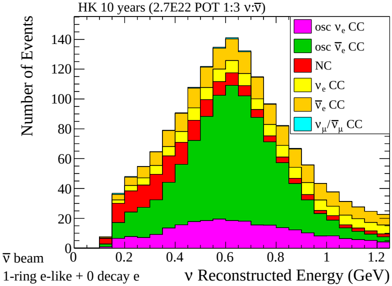


Reconstructed neutrino beam event samples disappearance (left) and appearance (right)

Beam only $\bar{\nu}$ mode

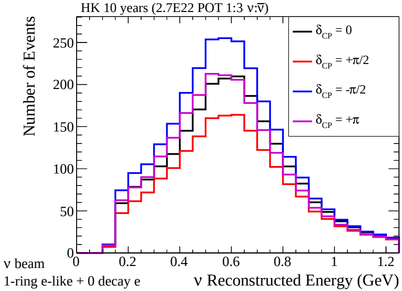


Beam only $\bar{\nu}$ mode

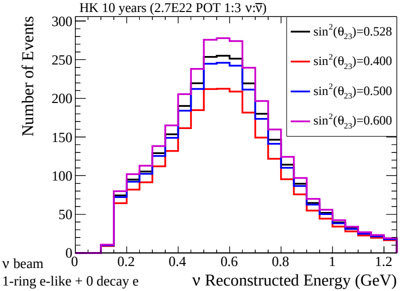


Reconstructed antineutrino beam event samples disappearance (left) and appearance (right)

Beam only ν mode



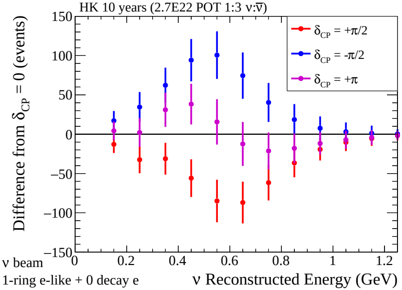
Beam only ν mode



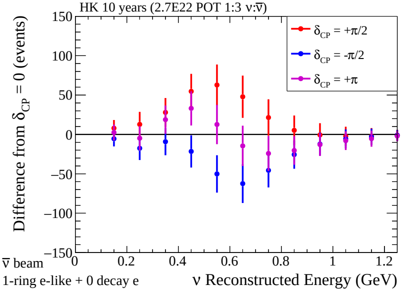
Appearance channel is sensitive to the value of CP
<u>but</u> needs the precise measurement of other parameters, *e.g.* θ_{23}

Hyper-Kamiokande prospects for the CP phase (4)

Beam only ν mode



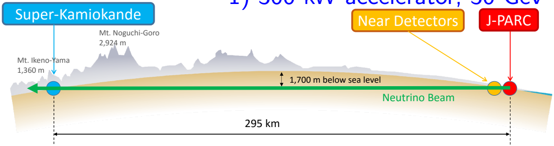
Beam only $\bar{\nu}$ mode



Operating the beam in neutrino and antineutrino modes and the various muon and electron-like samples help solving degeneracies

As so does the input from atmospheric neutrinos

1) 300 kW accelerator, 30 GeV protons



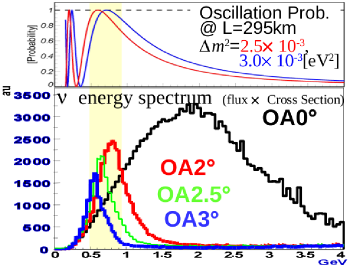
3) well-defined ν_μ beam (purity $> 99\%$)

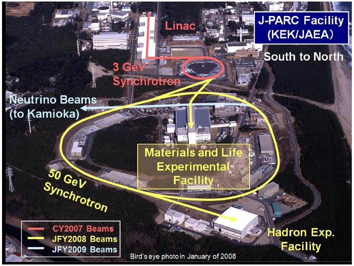
2) near detectors at 280 m

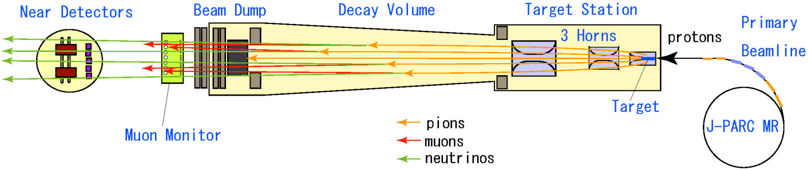
4) far detector 50 kton Water Cherenkov

ν_e appearance: leading order θ_{13}, sub-leading δ_{CP}

ν_μ disappearance: atm. parameters



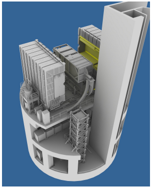


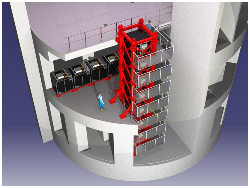


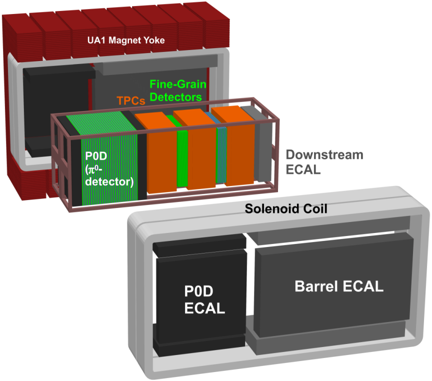
first off-axis experiment (beam @ 2.5°)

energy tuned for oscillation maximum, 0.5% ν_e contamination

The near detector complex (INGRID + ND280)





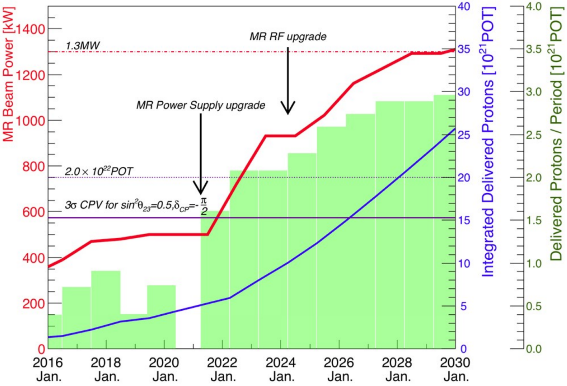


- INGRID @ on-axis:
  $\rightarrow$ ν beam monitoring
- ND280 @ 2.5° :
  $\rightarrow$ Normalisation of neutrino flux
  $\rightarrow$ Measurement of ν cross-sections
  - UA1 dipole magnet (0.2 T),
  - P0D (π^0 detector)
  - FGD+TPC (target + tracking)
  - ECAL (EM calorimeter),
  - Side-μ-range detector

* Beam currently capable of 450-500kW stable running

* Beam line upgrade in 2021
  - Nd280 upgrade will happen at the same time

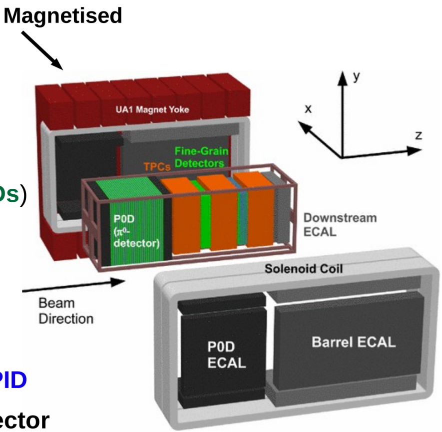
* target power: 1.3MW

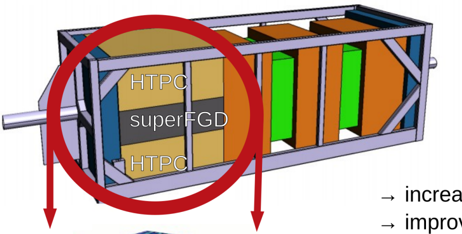


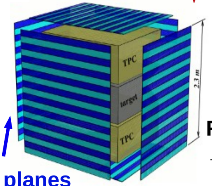
ND280

Same off-axis angle as SK

- Active target mass → 2 x scintilltors (**FGDs**)
  → vertex reconstruction
- 3 Time projection chambers (**TPC**)
  → **momentum** reconstruction
  → **charge** identification
  → Particle identification (**PID**)
- Electromagnetic calorimeters (**Ecal**) → **PID**
- **π^0 detector** and **side muon range detector**







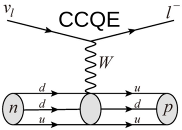
6 ToF planes

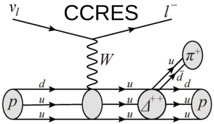
Pi0 detector is being replaced by
*** SuperFGD**
- higher granularity, 3D readout

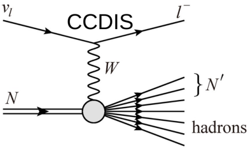
*** Horizontal TPCs (HTPCs)**
*** Time of Flight (ToF) planes**

→ increases active target **mass** for oscillation analysis
→ improved **angular acceptance**
→ able to reconstruct **low energy short tracks**
  → improved hadronic information
  → better $\gamma \rightarrow e^{+} e^{-}$ identification

Reduce systematic uncertainty to 4%
→ 3σ exclusion of CP conservation for 36% of the δ_{cp} phase space (if mass hierarchy is known)



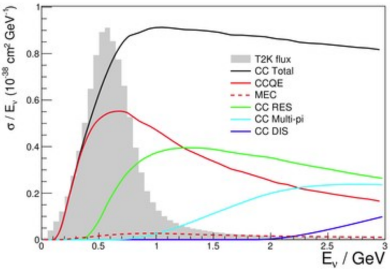




NC interactions also important

e.g. NCπ^0, NC1γ

→ background



Interactions occur with nucleons bound inside a nucleus

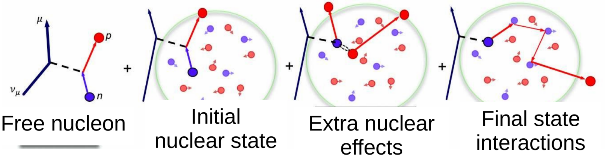
→ **Nuclear effects!!**

We only measure particles that exit the nucleus

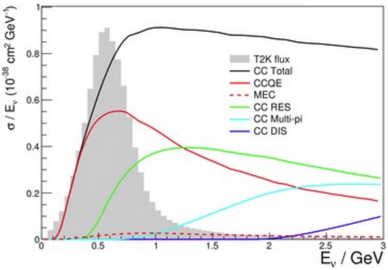
→ lose information about the initial interaction

→ can create a bias in energy reconstruction

Neutrino interactions (2)



Interaction modes and Nuclear models tuned to external data



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