From T2K to Hyper-K

Journées prospectives du LLR 2019

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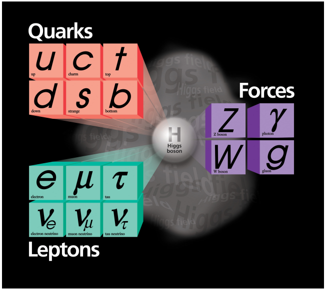
Neutrinos in the Standard Model... and beyond



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

oscillations ⇒ neutrinos have (different) mass

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

flavour "interaction"

mass "propagation"

$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix}1 & 0 & 0\\0 & \cos\theta_{23} & \sin\theta_{23}\\0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\text{atmospheric } \Delta m^2_{31}}\begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13}\\0 & 1 & 0\\-e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\underbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\-\sin\theta_{12} & \cos\theta_{12} & 0\\0 & 0 & 1\end{pmatrix}}_{\text{solar } \Delta m^2_{21}}$$

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

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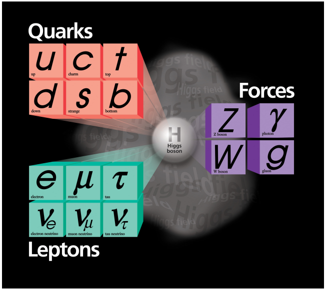

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atmospheric Δm^2_{31}

solar Δm^2_{21}

reactors

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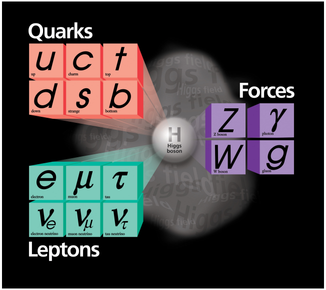

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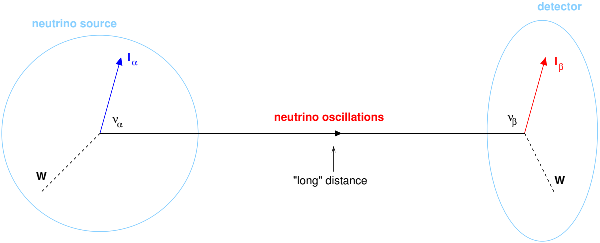
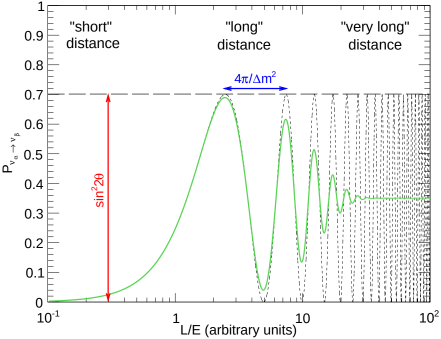
accelerators

reactors

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

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 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?

Three flavour oscillation parameters summary

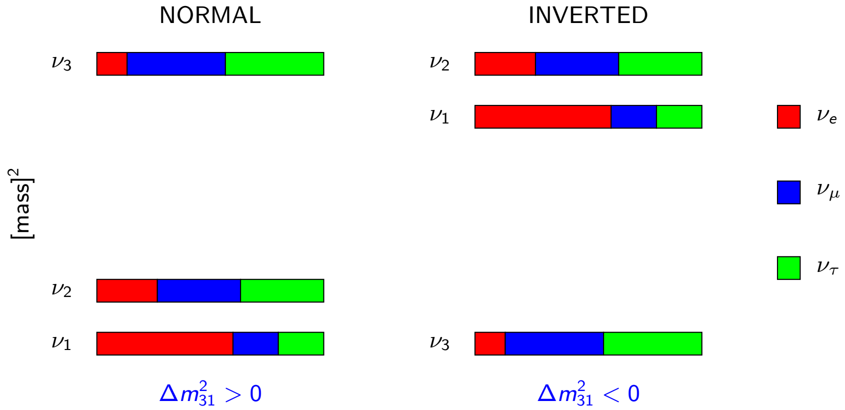
From NuFIT 4.1 (2019), `www.nu-fit.org`

Parameter	bfp$\pm1\sigma$	1σ acc.	Experiment	Comment
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	4.2%	KamLAND, SK, SNO	unitarity?
Δm^2_{21} [10^{-5} eV^2]	$7.39^{+0.21}_{-0.20}$	2.8%	KamLAND, SK, SNO	
$\sin^2\theta_{23}$	NH: $0.563^{+0.018}_{-0.024}$ IH: $0.565^{+0.017}_{-0.022}$	4.3%	T2K, NOνA, SK	unitarity? octant? ($\theta_{23}>45^\circ$ or $<45^\circ$?)
$\Delta m^2_{3\ell}$ [10^{-3} eV^2]	NH: $\Delta m^2_{31}=2.528^{+0.029}_{-0.031}$ IH: $\Delta m^2_{32}=-2.510^{+0.030}_{-0.031}$	1.2%	T2K, NOνA, SK, Daya Bay	mass hierachy?
$\sin^2\theta_{13}$	NH: $0.02237^{+0.00066}_{-0.00065}$ IH: 0.02259 ± 0.00065	3.0%	Daya Bay, RENO, Double Chooz	unitarity?
$\delta_{\rm CP}$ [degree]	NH: 221^{+39}_{-28} IH: 282^{+23}_{-25}	-	T2K, NOνA (w/ θ_{13} constraint)	3σ measurement? CP violation?

Open questions in neutrino oscillations : mass hierarchy, θ_{23} octant, value of $\delta_{\rm CP}$, unitarity?

What is the mass hierarchy?

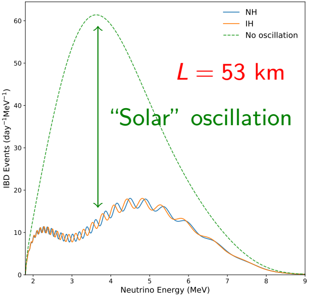
two possibilities for the neutrino mass spectrum



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

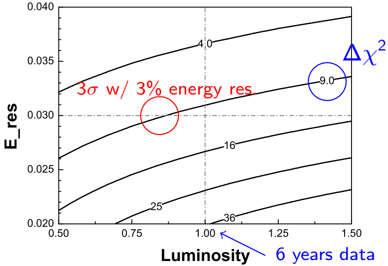
JUNO, towards a measurement of the MH

- Main goal: determine Mass Hierarchy with reactor $\bar{\nu}_e$ disappearance @ 53 km
- Very unique and complemntary to long-baseline measurement of the MH
- In order to disentangle NH from IH ($\Delta m^2_{21}/\Delta m^2_{31} \sim 3\%$), one needs :
  - 3% energy resolution @ 1 MeV
  - $< 1\%$ non-linearity accuracy
- 6 years data taking to achieve 3σ / 4σ possible if progress in accelerator experiments



$L = 53$ km

"Solar" oscillation



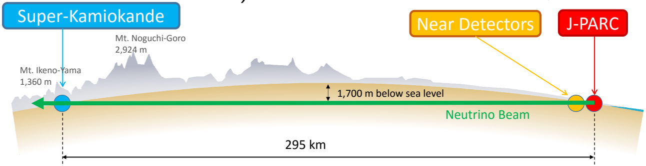
$\Delta\chi^2$

3σ w/ 3% energy res.

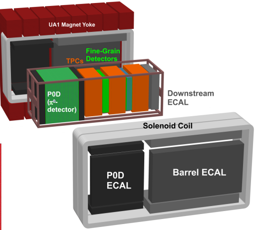
6 years data

Overview of the T2K experiment

1) J-PARC accelerator 450 kW, 30 GeV protons



2) High intensity ν_μ beam ($> 99\%$ purity), 600 MeV, narrow band (1^{st} off-axis exp.)



4) Super-Kamiokande : 50 kt water Cerenkov detector

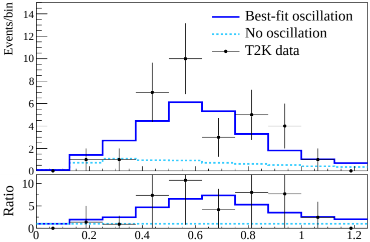
3) Near detector
at 280 m

Observation of $\nu_e \,/\, \bar{\nu}_e$ appearance : θ_{13} and δ_{CP}

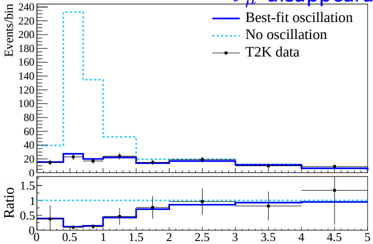
Precise measurement of $\nu_\mu \,/\, \bar{\nu}_\mu$ disappearance : “atmospheric” parameters $(\theta_{23}, \Delta m^2_{32})$

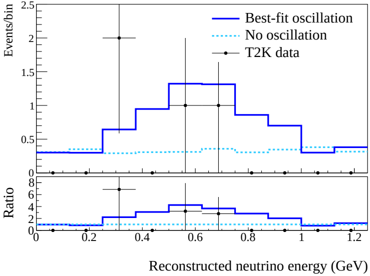
Appearance and disappearance results [Phys.Rev D96 (2017)]

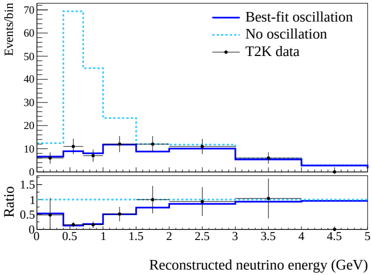
ν_e appearance



ν_μ disappearance







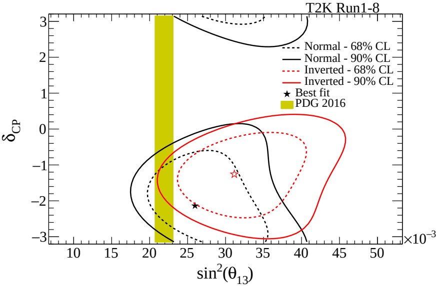
$\bar{\nu}_e$ appearance

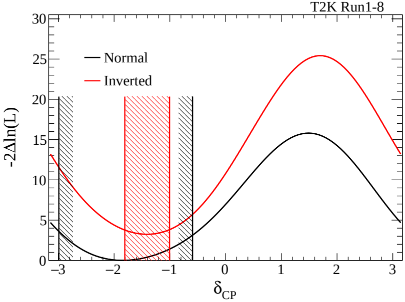
$\bar{\nu}_\mu$ disappearance

First hints on δ_{CP} [Phys.Rev.Lett. 121 (2018)]

- Thanks to antineutrino data T2K alone is sensitive to δ_{CP}
- Adding reactor constraints we can exclude CP conservation at 2σ
- Can we do even better?

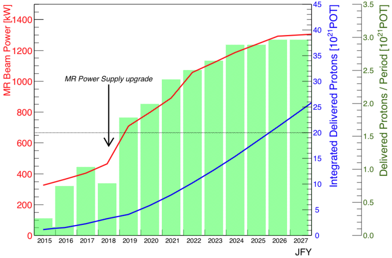
	δ_{CP}	ν_e CCQE	ν_e CC1π^+	$\bar{\nu}_e$ CCQE
	$-\pi/2$	73.5	6.9	7.9
Normal	0	61.4	6.0	9.0
Ordering	$\pi/2$	49.9	4.9	10.0
	π	61.9	5.8	8.9
	$-\pi/2$	64.9	6.2	8.5
Inverted	0	54.4	5.1	9.8
Ordering	$\pi/2$	43.5	4.3	10.9
	π	54.0	5.3	9.7
Observed		74	15	7





T2K-II

- T2K is expected to complete data taking by 2020 with a total exposure of 7.8×10^{21} POT
- Next generation long baseline experiments (HK and/or DUNE) won't start data taking before 2028
- T2K has been extended for a running period (T2K-II) to go up to 20×10^{21} POT (6 years, 5 months beam / year, assuming J-PARC power upgrade)



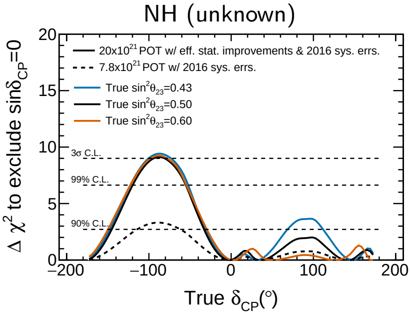
- In the meantime, we expect to increase SK selections eff. by ∼ 20% (new algorithms)

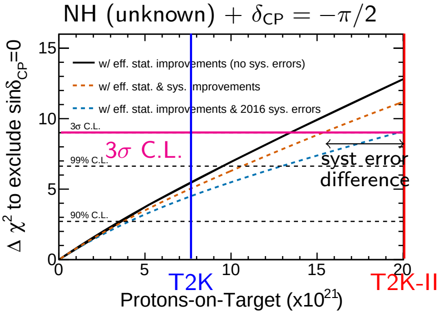
	True δ_{CP}	Total	Signal	Signal	Beam CC	Beam CC	NC
			$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}\mu$	
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

Simulation with 10^{21} POT for ν + 10^{21} POT for $\bar{\nu}$

T2K-II and needs for systematics reduction

- T2K phase II ⇒ increase statistics to 20×10^{21} POT
- Motivations for T2K phase II : 1st experiment to exclude CP conservation $> 3\sigma$
- Limited by our current systematics in far detector (SK) : from 5.1% to 6.8%





- w/o decreasing current systematics: phase space very limited even for 20×10^{21} POT ⇒ a 3σ exclusion possible almost only if $\delta_{\mathrm{CP}} = -\pi/2$ and Normal Hierarchy
- Decreasing systematics to 4% ⇔ 5×10^{21} POT ($>$ 2 times current T2K statistics)

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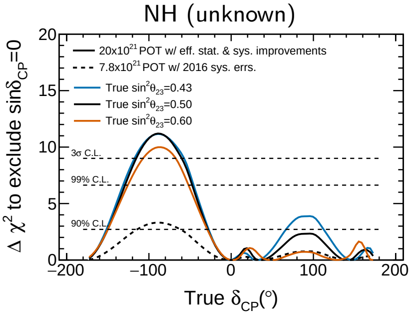

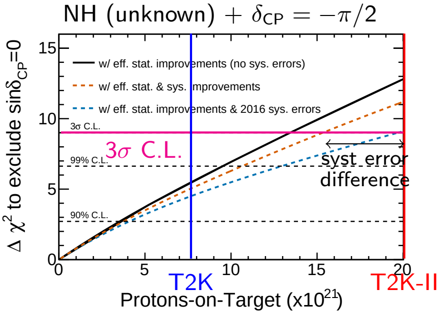

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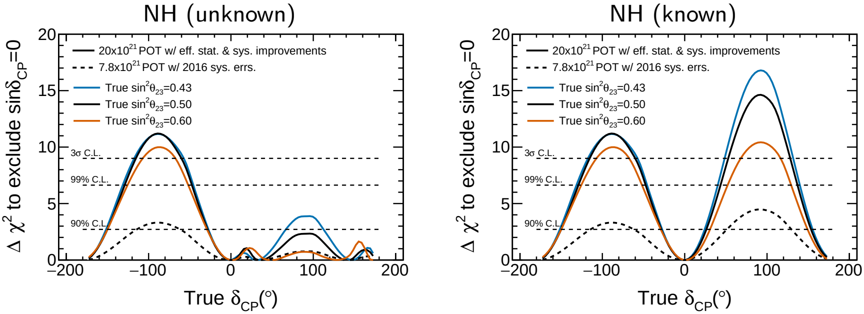

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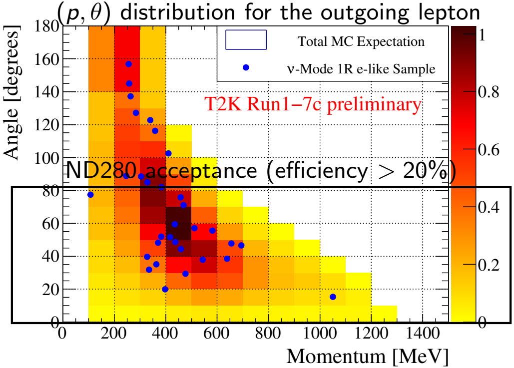
Towards systematics reduction

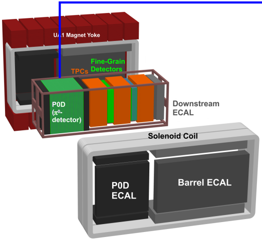


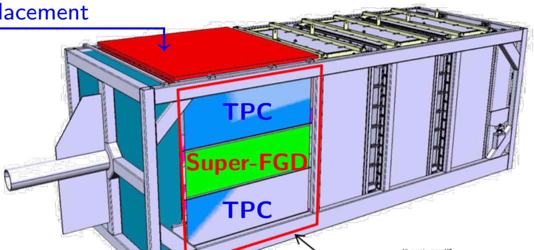
- Need a measurements with :
  1. Similar target nucleus as SK : independent of cross section models
  2. 4π acceptance as SK for lepton kinematics : efficiency corrections not needed
  3. High granularity to identify interaction final states (track low momenta hadrons) : improve energy reconstruction

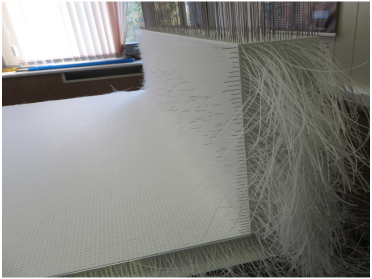
⇒ goal of ND280 upgrades (and of the WAGASCI detector!)

The ND280 upgrade (2021-...)

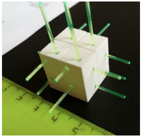
Upgrade → P0D replacement

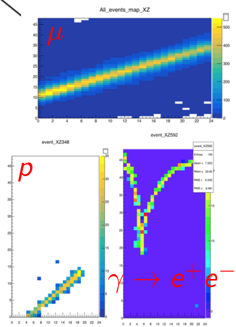






Super-FGD:
- $2M \times 1$ cm^3
- $\sim 60k$ channels

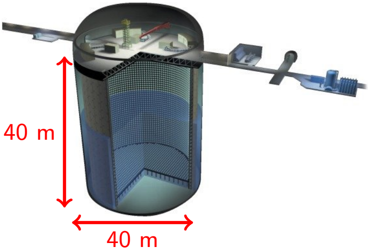




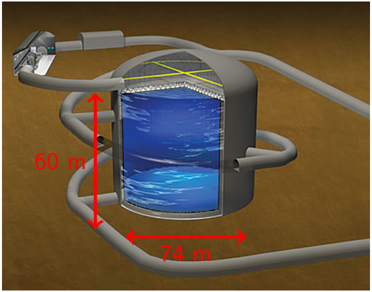
Events from prototype data

The Hyper-Kamiokande detector

HK = next generation of large water Cherenkov observatory in Japan



Super-Kamiokande



Hyper-Kamiokande

	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	11129	40000
Photo-coverage	40%	40% (×2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	260 kton / 187 kton

The Hyper-Kamiokande detector

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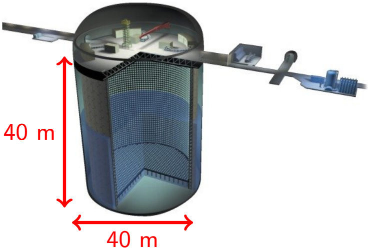

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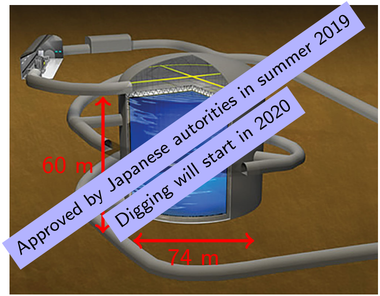

Approved by Japanese autorities in summer 2019

Digging will start in 2020

Hyper-Kamiokande

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Site	Mozumi	Tochibora
Number of ID PMTs	11129	40000
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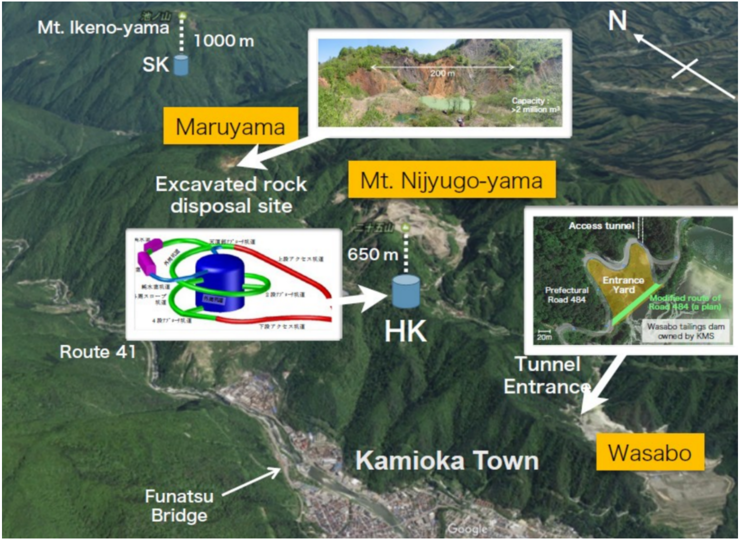
Hyper-Kamiokande location

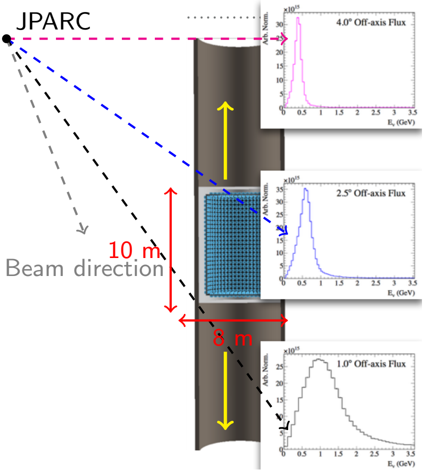


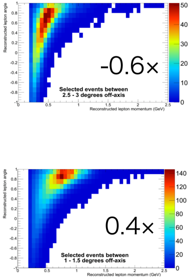
Same off-axis angle, less overburden

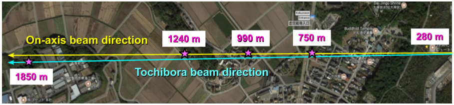
HK with a neutrino beam

- Main goals: CP violation search based on accelerator ν and high precision on "atmospheric" parameters
- ν_e appearance and ν_μ disappearance from a ν_μ beam (and their antineutrino equivalent)
- Well proven detector technologies, calibration and analyses by T2K
- Relies on two milestones :
  1) J-PARC accelerator upgrade to 1.3 MW
  2) reduced systematic uncertainties from 5% to 3%
- Syst. reduction ⇒ ND280 upgrade!!
  flux + cross-sections ✓
  $\sigma(\nu_\mu)/\sigma(\nu_e)$, $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ ✓
  SK detector, SK FSI+SI+PN ✖ detector still different...

Intermediate Water Cherenkov Detector: NuPrism (E61)





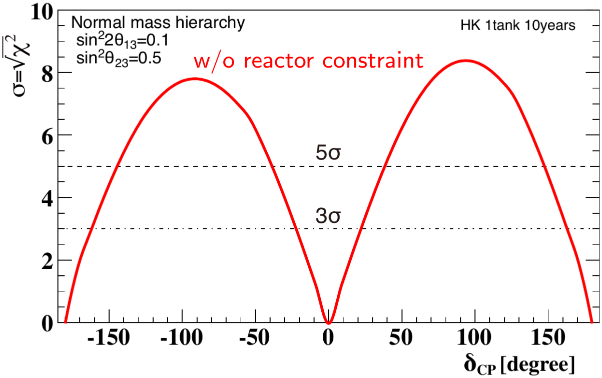


- Solid angle different at near and far detector
- Take a combination of reconstructed number of neutrinos (*e.g.* in p/θ) to correctly predict the flux at HK $\Rightarrow$ drastically reduce the use of cross-section models
- WC $\Rightarrow$ same than SK, excellent PID
- Loaded w/ Gd for n tagging ?
- Site under survey (event rate / pile-up vs pit depth)

  $\Rightarrow$ ND280 + IWCD complementary to reach $\lesssim 3\%$ syst.

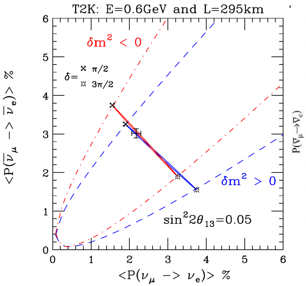
Sensitivity to CP violation

- Assume ν:$\bar{\nu}$ = 1:3 running @ 1.3 MW



- Probe 58% (76%) of $\delta_{\rm CP}$ phase-space after 10 years w/ 5σ (3σ) sensitivity
- If maximal CP violation, 5σ discovery in 2 years!

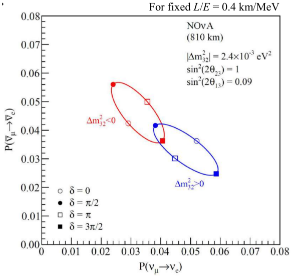
Sensitivity to mass hierarchy



T2K / HK:

$L = 295$ km

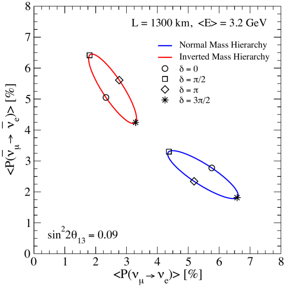
$E = 600$ MeV



NOνA:

$L = 810$ km

$E = 2$ GeV



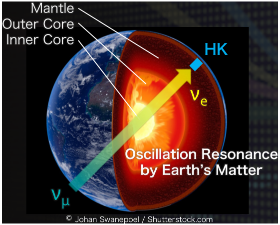
DUNE:

$L = 1300$ km

$E = 3$ GeV

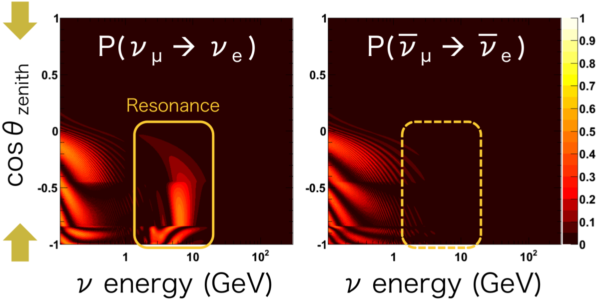
- Hyper-Kamiokande sensitivity to mass hierarchy with neutrino beam is limited
- Use atmospheric neutrinos w/ or w/o other experimental results
- A second HK tank could be installed in Korea (1000-1200 km baseline) ⇒ enough matter effects to measure the MH

MH through atmospheric neutrinos



© Johan Swanepoel / Shutterstock.com

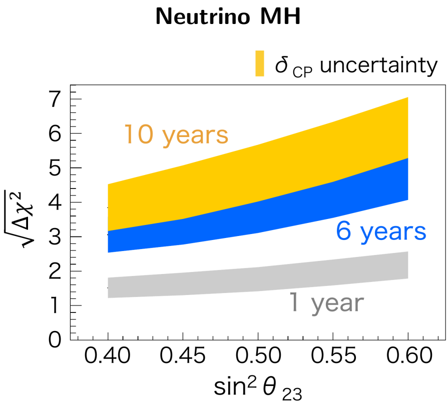
Normal Hierarchy case

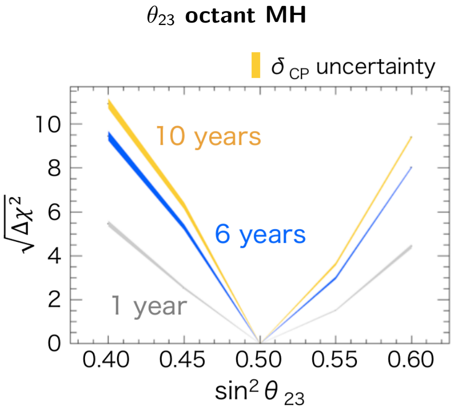


- Mass hierarchy accessible through matter effect (MSW) in upward going multi-GeV sample :
  - If NH, enhancement of $\nu_\mu \rightarrow \nu_e$
  - If IH, enhancement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- No magnetic field, only statistical analysis $\Rightarrow$ sensitivity enhanced by using neutron tagging (ν_e / $\bar{\nu}_e$ separation)

Mass hierachy and atmospheric parameters

- Combined analysis with accelerator + atmospheric neutrinos

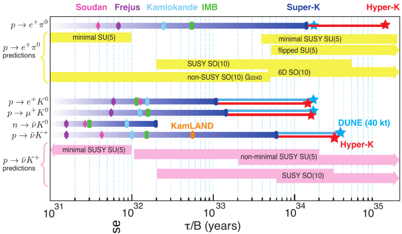




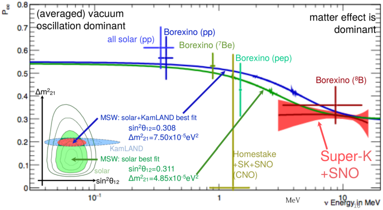
- Very high sensitivity to θ_{23} octant ⇒ determination within few years
- 4 to 5σ sensitivity to mass hierarchy in 10 years

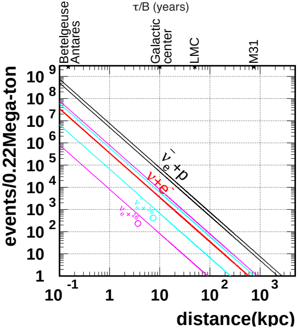
Low energy physics at HK and other stuff...

Search for *p*-decay

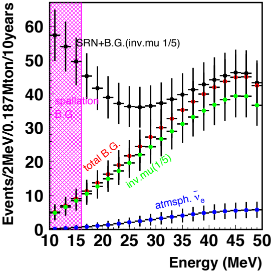


Search for solar oscillations





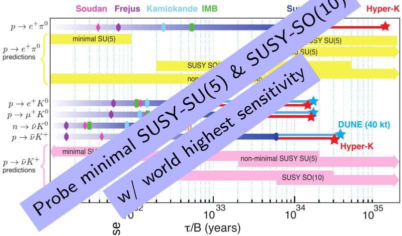
Search for SN neutrinos



Search for DSNB neutrinos

Low energy physics at HK and other stuff...

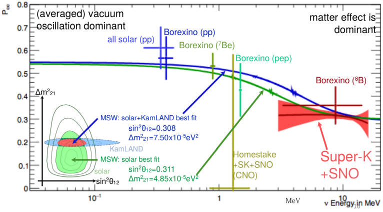
Search for *p*-decay

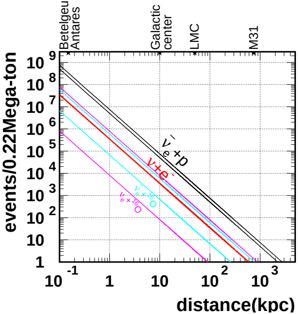


Probe minimal SUSY-SU(5) & SUSY-SO(10)

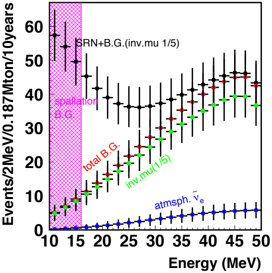
w/ world highest sensitivity

Search for solar oscillations





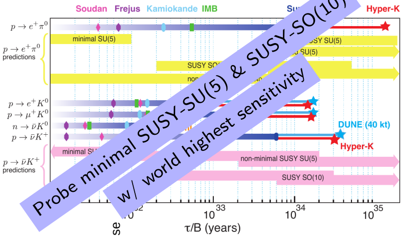
Search for SN neutrinos



Search for DSNB neutrinos

Low energy physics at HK and other stuff...

Search for *p*-decay



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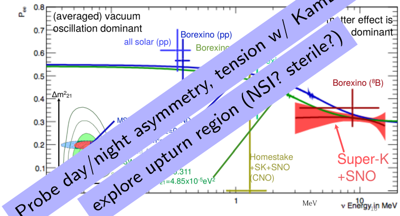
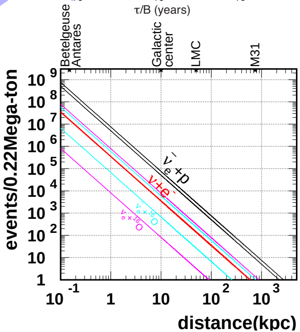
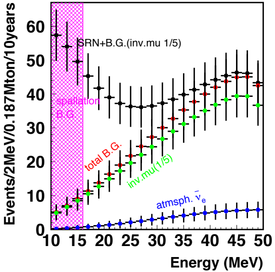


Probe day/night asymmetry, tension w/ KamLAND,

explore upturn region (NSI? sterile?)



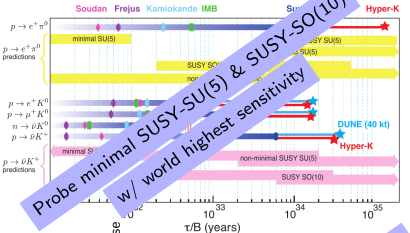
Search for SN neutrinos



Search for DSNB neutrinos

Low energy physics at HK and other stuff...

Search for *p*-decay



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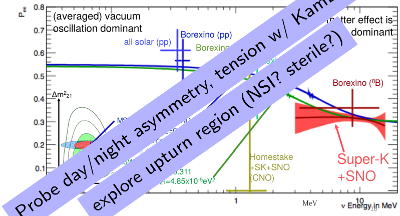

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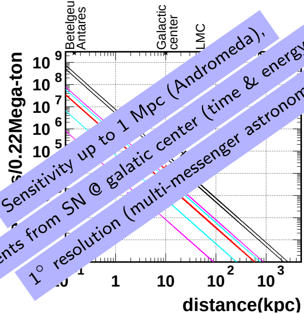
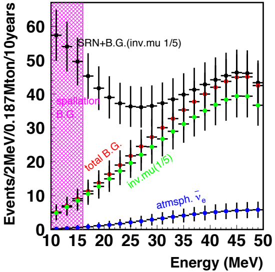


Sensitivity up to 1 Mpc (Andromeda),

50k events from SN @ galatic center (time & energy profile)

1° resolution (multi-messenger astronomy)

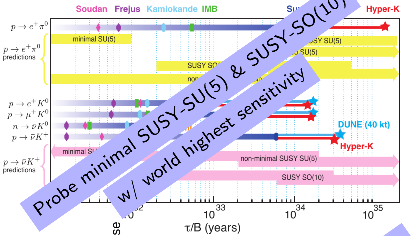
Search for SN neutrinos



Search for DSNB neutrinos

Low energy physics at HK and other stuff...

Search for *p*-decay



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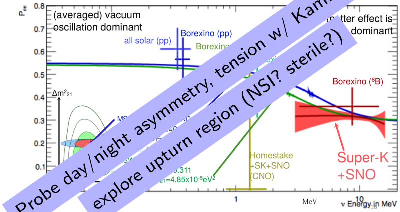
w/ world highest sensitivity

Search for solar oscillati



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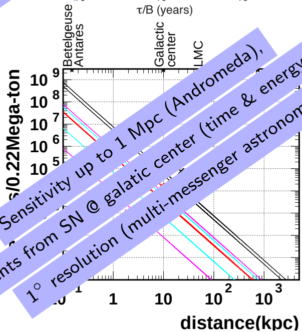

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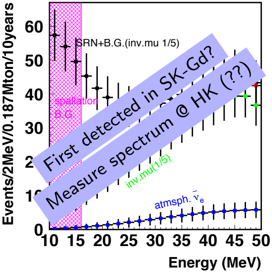


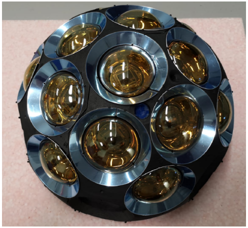
First detected in SK-Gd?

Measure spectrum @ HK (??)

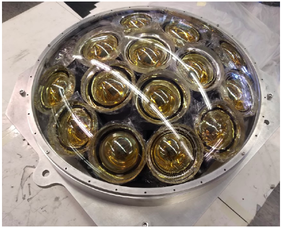
Search for DSNB neutrinos

mPMT modules for Hyper-K / IWCD?

- HK base design : new 20" high-quantum eff. box&line PMT (QE×CE=2×SK)
- Add mPMT as a complement for low energy physics? What for IWCD?
- 2 designs under study (19 × 3")



Italian design (KM3Net-based)
half sphere, integrated charge/timing



Canadian design
tuned for HK & flash ADC (waveforms)

- Better timing resolution (2.6 ns for B&L vs 1.5 ns for mPMT), smaller size, directionality, dark rate < 100 Hz ⇒ better vertex resolution (increase FV !!), better PID, probe lower energies
- Proposal for joined test (LLR, LPNHE) and analysis using MEMPHYNO @ APC

Conclusions

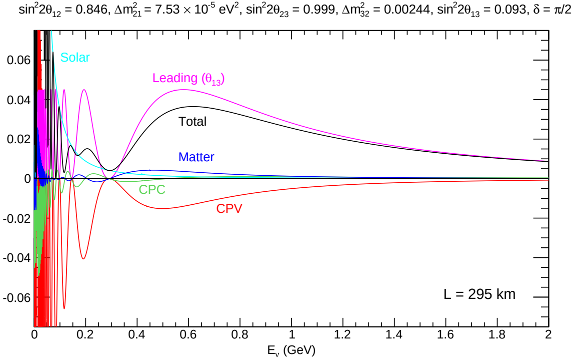
- Missing pieces in neutrino oscillations: measurement of the θ_{23} octant, measurement of the CP violation phase, determination of the mass hierarchy + unitarity tests
- JUNO will start measuring MH end 2021 at earliest
- T2K-II will start data taking en 2021 at earliest
- HK (very well proven technology, already 2 nobel prizes) will allow to explore fascinating windows on the Universe with unprecedented precision ⇒ CP violation in the lepton sector, cosmic star formation, GUT, ...
- DUNE will measure δ_{CP}, probe MH, PMNS unitarity w/ higher sensitivity but represents a much higher technological challenge ⇒ HK and DUNE are complementary projects

HK has a exceptionnal potential of exceptionnal discoveries for the next 10 to 20 years

Back-up Slides

ν_e appearance in accelerator experiments (1)

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

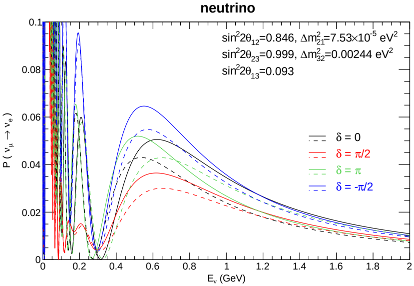


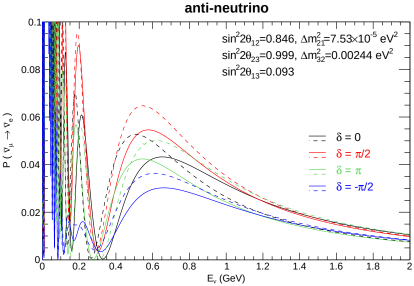
$\sin^2 2\theta_{12} = 0.846$, $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2, $\sin^2 2\theta_{23} = 0.999$, $\Delta m^2_{32} = 0.00244$, $\sin^2 2\theta_{13} = 0.093$, $\delta = \pi/2$

ν_e appearance in accelerator experiments (2)

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

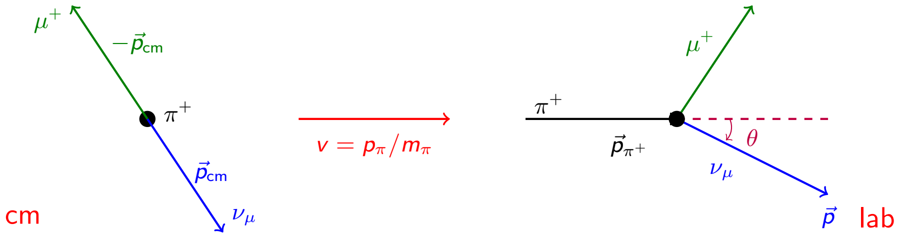
$$\boxed{P(\bar{\nu}_\mu \to \bar{\nu}_e) \qquad a \to -a \qquad \delta \to -\delta}$$





Off-axis experiments (1)

high intensity WB beam
detector shifted by a small angle from axis of beam
almost monochromatic neutrino energy



Neutrino energy in cm frame : $E_{\rm cm} = p_{\rm cm} = \frac{m_\pi}{2}\left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \simeq 29.79$ MeV

$$\gamma = (1 - v^2)^{-1/2} = E_\pi / m_\pi \gg 1$$

$$\begin{cases} E = \gamma(E_{\rm cm} + v p^z_{\rm cm}) \\ p^z = \gamma(v E_{\rm cm} + p^z_{\rm cm}) \end{cases}$$

$$p^z = p\cos\theta \qquad \Rightarrow \qquad E = \frac{E_{\rm cm}}{\gamma(1 - v\cos\theta)}$$

Off-axis experiments (2)

using $\cos\theta \simeq 1-\theta^2/2$ and $v \simeq 1$

$$E = \frac{E_{\rm cm}}{\gamma(1-v\cos\theta)} \simeq \frac{\gamma(1+v)}{1+\gamma^2\theta^2 v(1+v)/2}E_{\rm cm} \simeq \frac{2\gamma}{1+\gamma^2\theta^2}E_{\rm cm}$$

$$E \simeq \left(1-\frac{m_\mu^2}{m_\pi^2}\right)\frac{E_\pi}{1+\gamma^2\theta^2} = \left(1-\frac{m_\mu^2}{m_\pi^2}\right)\frac{E_\pi m_\pi^2}{m_\pi^2+E_\pi^2\theta^2}$$

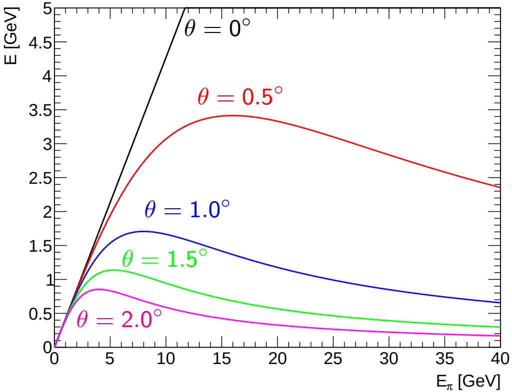
- $\theta = 0 \Rightarrow E \propto E_\pi$ WB beam
- $E_\pi\theta \gg m_\pi \Rightarrow E \propto \frac{m_\pi^2}{E_\pi\theta^2}$ high-energy π^+ give low-energy ν_μ

$$\frac{dE}{dE_\pi} \simeq \left(1-\frac{m_\mu^2}{m_\pi^2}\right)\frac{1-\gamma^2\theta^2}{(1+\gamma^2\theta^2)^2}$$

$\frac{dE}{dE_\pi} \simeq 0$ for $\theta = \gamma^{-1} = \frac{m_\pi}{E_\pi} \Rightarrow E \simeq \left(1-\frac{m_\mu^2}{m_\pi^2}\right)\frac{m_\pi}{2\theta} \simeq \frac{29.79\text{ MeV}}{\theta}$

Off-axis experiments (3)

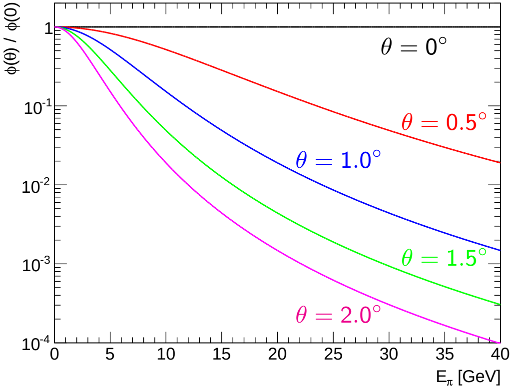
off-axis angle $\theta \simeq m_\pi / \langle E_\pi \rangle \Rightarrow E \simeq \frac{29.79\text{ MeV}}{\theta}$



- E can be tuned on oscillation peak $E_{\text{peak}} = \Delta m^2 L / 2\pi$
- small $E \Rightarrow$ short $L_{\text{osc}} = \frac{4\pi E}{\Delta m^2} \Rightarrow$ sensitivity to small value of Δm^2

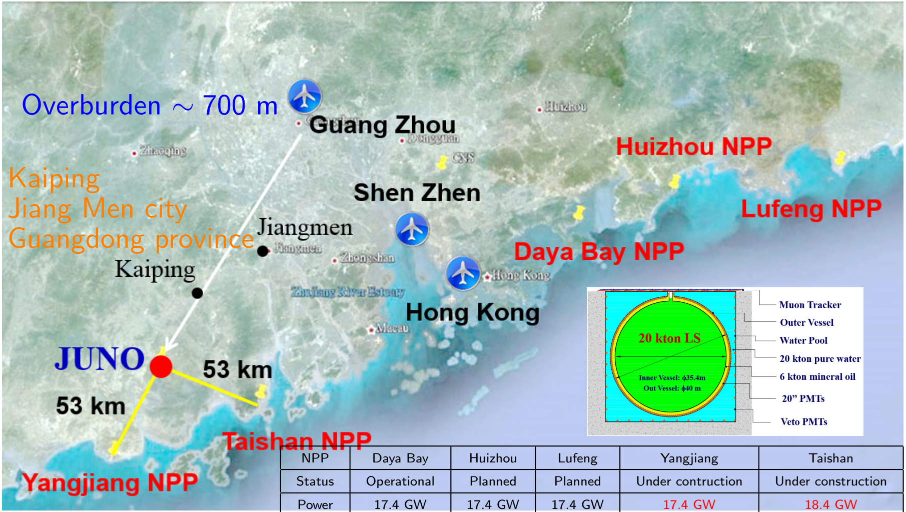
Off-axis experiments (4)

$$\frac{\phi(\theta)}{\phi(0)} = \left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$



flux suppression requires high-intensity beams

JUNO location

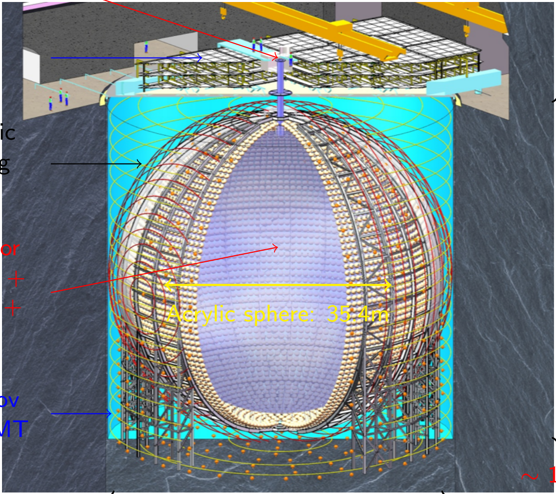


Overburden ∼ 700 m

Kaiping
Jiang Men city
Guangdong province

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under contruction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW
					26.6 GW by 2020

JUNO detector, data taking by 2021



Calibration

Top Tracker

Earth magnetic
Field shielding
coils

Central detector
Steel structure +
Acrylic sphere +
20 kt LS

Water Cerenkov
∼ 2400 20" PMT

LS / Water
filling room

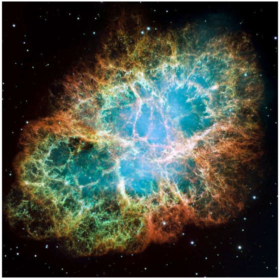
Water pool height: 44 m

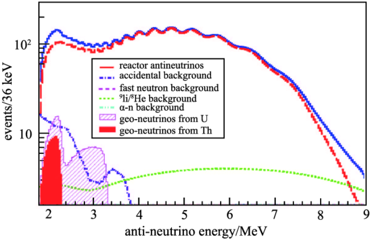
∼ 18000 20" PMT
+ ∼ 25000 3" PMT

Water pool diameter: 43.5m

JUNO physics summary

- Mass Hierarchy!
- Precise measurement of 3 mixing parameters $< 1\%$
  - Several atmospheric ν per day
  - Reactor ν, 60/day
  - Solar ν, 10-1000/day
- Supernova ν : burst 5-7k in 10s from 10 kpc + DSNB
- Geo-neutrinos 1.1/day
- Nucleon decay
- Exotic searches





The solar “tension”