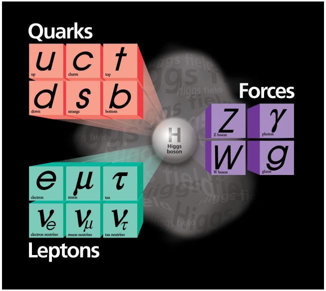
Latest results and perspectives for Super-Kamiokande and T2K experiments
UC Louvain

Thomas Mueller

Laboratoire Leprince-Ringuet

January 30, 2024



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

oscillations ⇒ neutrinos have (different) mass

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

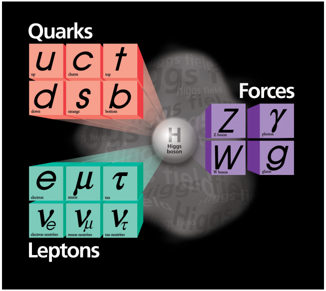
flavour "interaction" — mass "propagation"

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

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?



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

reactors

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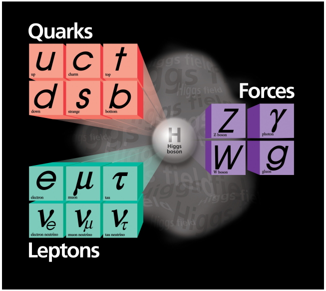

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atmospheric Δm^2_{31} — solar Δm^2_{21}

accelerators — reactors

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

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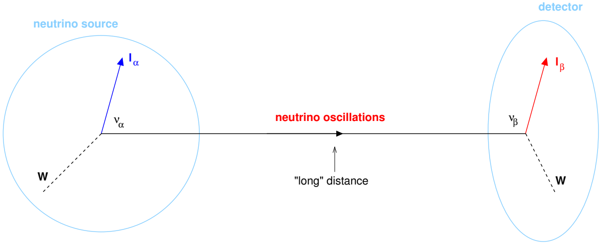
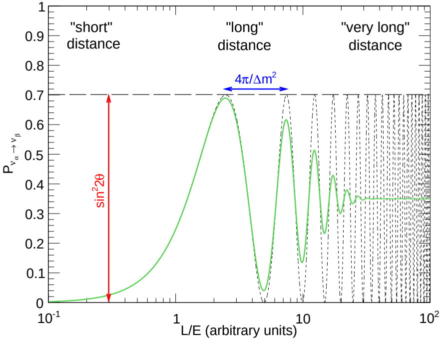
Neutrino oscillation in a nutshell





2-flavour approximation:

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

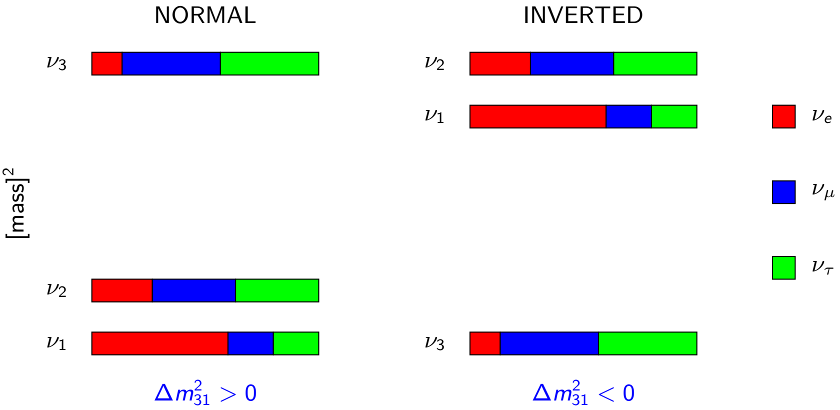
3 flavours : much longer to write...
but the same basic principle

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

Matter-antimatter asymmetry?

What is the mass hierarchy?

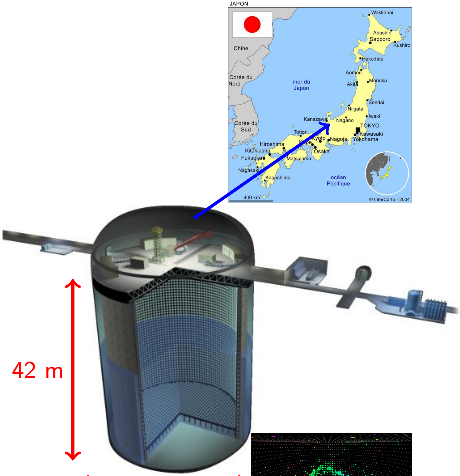
two possibilities for the neutrino mass spectrum

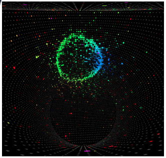


NB: we know that the mass state containing most ν_e is the lighter of the two "solar mass" states $\Delta m^2_{21} \equiv m^2_2 - m^2_1 > 0$ and $\theta_{12} < 45^\circ$ thanks to the observation of the matter effect in the Sun

- 50 kton water Cherenkov detector (currently doped with Gd)
- Located in Kamioka, Japan, under Mt. Ikenoyama : 1 km rock overburden (2.7 km water equivalent)
- Optically divided into an inner detector (ID) with a fiducial volume of 22.5 kton and an outer detector (OD), instrumented with
  - ID : $\sim$ 11000 inward facing large 20"-PMTs, 40% photo-coverage
  - OD : 1885 8"-PMTs primarily used as veto

Running for more than 25 years and still has a lot to teach !





The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~230 collaborators from 51 institutes in 11 countries

Detector phases

- SK experiment has collected data during 7 phases

Phase	Period	Event
SK-I	1996.4 to 2001.7	Start of the experiment
SK-II	2002.10 to 2005.10	20% photo-coverage after accident
SK-III	2006.7 to 2008.8	Full photo-coverage (40%) restored
SK-IV	2008.9 to 2018.5	Upgraded electronics
SK-V	2019.1 to 2020.8	Detector upgraded for Gd-loading
SK-VI	2020.8 to 2022.6	0.01% Gd-doping
SK-VII	since 2022.6	0.03% Gd-doping

- Highly versatile multi-purpose experiment in the MeV - TeV range: solar & atmospheric neutrinos, supernovae neutrinos, diffuse supernova neutrino background (DSNB), neutrino astrophysics, proton-decay, dark matter, beam neutrino (T2K)
- In this talk, status and perspectives for the physics analysis of solar, atmospheric and beam neutrino oscillations and the search for the DSNB

Latest SK published physics results (selected pieces)

- **Solar neutrinos**

  Solar neutrino measurements using the full data period of Super-Kamiokande-IV
  K. Abe et al., arXiv:2312.12907 [hep-ex]

  Search for Periodic Time Variations of the Solar ^{8}B Neutrino Flux Between 1996 and 2018 in Super-Kamiokande
  K. Abe et al., arXiv:2311.01159 [hep-ex]

- **Atmospheric neutrinos**

  Atmospheric neutrino oscillation analysis with neutron tagging and an expanded fiducial volume in Super-Kamiokande I-V
  T. Wester et al., arXiv:2311.05105 [hep-ex]

- **Supernovae neutrinos**

  Searching for Supernova Bursts in Super-Kamiokande IV
  M. Mori et al., Astrophys.J. 938 (2022) 1, 35

  Pre-supernova Alert System for Super-Kamiokande
  L. N. Machado et al., Astrophys.J. 935 (2022) 1, 40

- **DSNB**

  Search for Astrophysical Electron Antineutrinos in Super-Kamiokande with 0.01% Gadolinium-loaded Water
  M. Harada et al., Astrophys.J.Lett. 951 (2023) 2, L27

  Diffuse Supernova neutrino background search at Super-Kamiokande
  K. Abe et al., Phys.Rev.D 104 (2021) 12, 122002

- **Neutrino astrophysics**

  Search for neutrinos in coincidence with gravitational wave events from the LIGO-Virgo O3a Observing Run with the Super-Kamiokande detector
  K. Abe et al., Astrophys.J. 918 (2021) 2, 78

  Search for tens of MeV neutrinos associated with gamma-ray bursts in Super-Kamiokande
  A. Orii et al., PTEP 2021 (2021) 10, 103F01

- **Proton-decay and other baryon number violating processes**

  Search for proton decay via $p \to \mu K^0$ in 0.37 megaton-years exposure of Super-Kamiokande
  R. Matsumoto et al., Phys.Rev.D 106 (2022) 7, 072003

  Neutron-antineutron oscillation search using a 0.37 megaton-years exposure of Super-Kamiokande
  K. Abe et al., Phys.Rev.D 103 (2021) 1, 012008

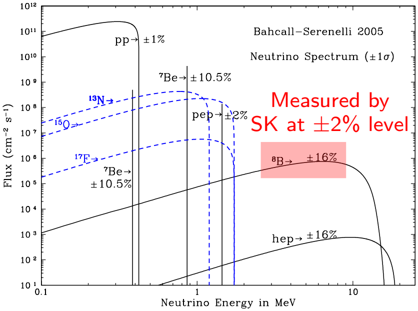
- **Dark matter**

  Search for Cosmic-Ray Boosted Sub-GeV Dark Matter Using Recoil Protons at Super-Kamiokande
  K. Abe et al., Phys.Rev.Lett. 130 (2023) 3, 031802

Solar neutrinos

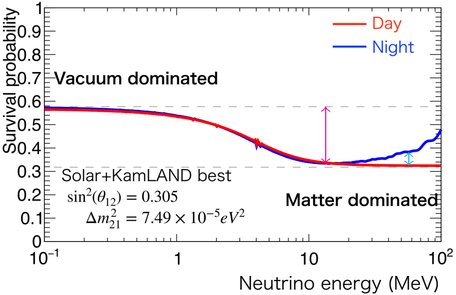
- Sun is powered by 2 groups of thermonuclear reaction the *pp* chain and CNO cycle
- Solar ν oscillations are affected by matter effects in the Sun / Earth

Standard Solar Model (SSM)



$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e + Q$$

Neutrino oscillations (LMA-MSW)



Matter effects in the Sun

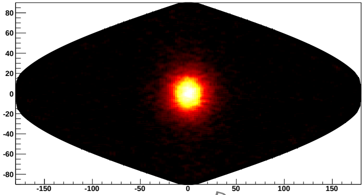
Matter effects in the Earth

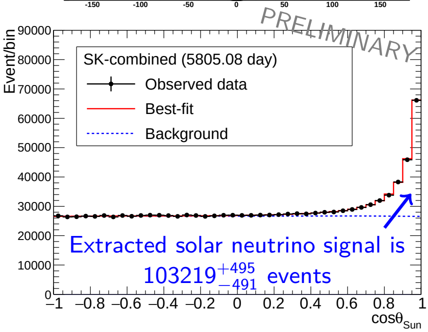
Solar neutrinos detection at SK

- Solar neutrinos detected through ES:

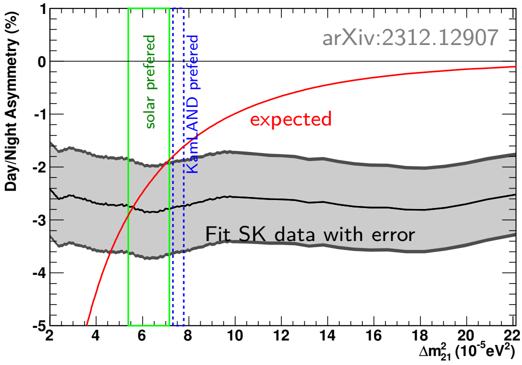
$$\nu + e^- \rightarrow \nu + e^-$$

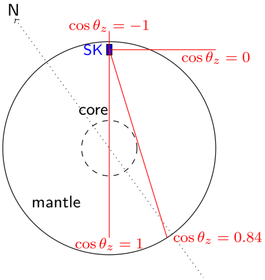
- Advantages of SK:
  - Large volume
  - Realtime measurements
  - Precise energy determination
  - Precise determination of direction
- Physics program:
  - Oscillation parameter determination
  - Day/Night (matter effects in Earth) + seasonal flux variation
  - Precise ^{8}B measurement (metallicity of the Sun)
  - Investigate exotic scenarios

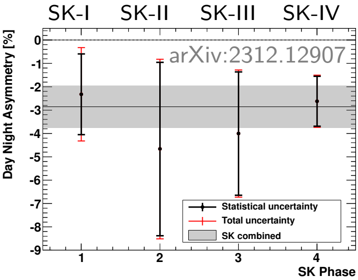




Day-Night asymmetry



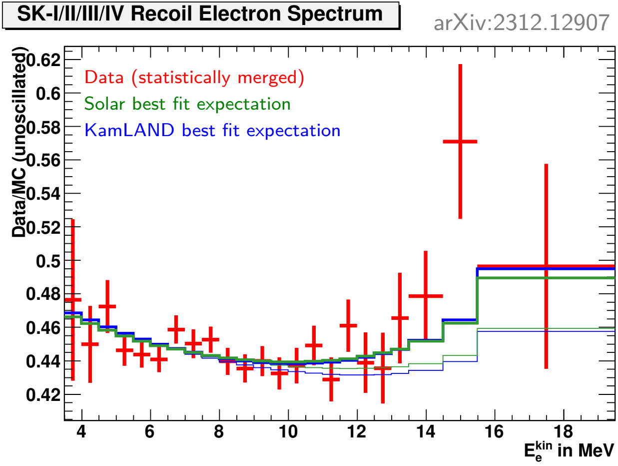




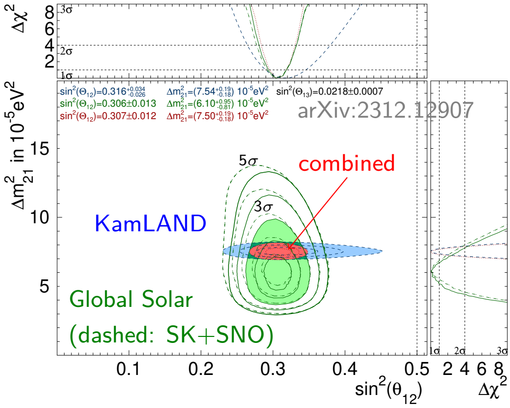
Significance of D/N asymmetry:

- 3.2σ for solar best fit
- 3.1σ for global best fit

Energy spectrum



Slightly favors up-turn, though need more data

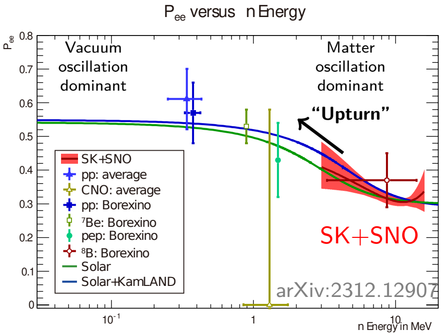


Experiment	$\sin^2\theta_{12}$	Δm^2_{21}
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}\times10^{-5}$ eV^2
Global solar	0.306 ± 0.013	$6.10^{+0.95}_{-0.81}\times10^{-5}$ eV^2
Combined	0.307 ± 0.012	$7.50^{+0.19}_{-0.18}\times10^{-5}$ eV^2

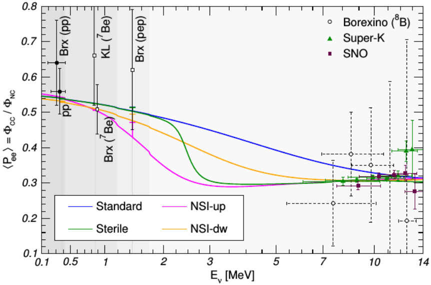
1.5 σ tension between global solar and KamLAND in Δm^2_{21}

Exploration of the upturn region

- SK and SNO found high matter effect in the Sun ⇔ P_{ee} upturn shifted to low energies



Eur. Phys. J. A 52 (2016) 87



- SK is trying to measure the "upturn" → light sterile neutrino? Non Standard Interaction (NSI) in the Sun?

- Neutrinos produced by the interaction of primary cosmic rays (mostly protons) with Earth's atmosphere

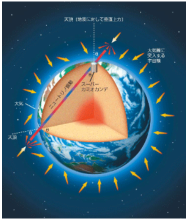
- Wide range of energies from about 100 MeV to 100 GeV

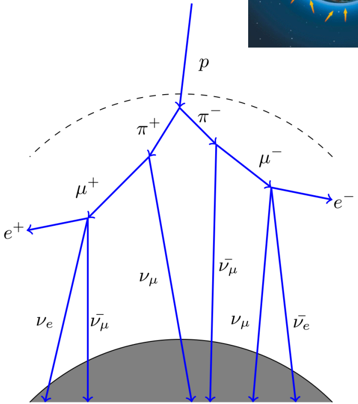
- Produced at $\mathcal{O}(10\text{ km})$ above the surface and coming from all directions $\Rightarrow$ wide range of baselines from 10 to 10^4 km

- Flavor content :

$$\frac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} \simeq 2 \text{ below 1 GeV}$$

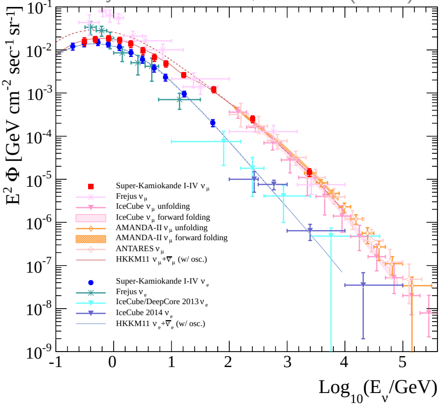
$$\frac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} > 2 \text{ above 1 GeV}$$





- Detailed simulations are required to compute the neutrino flux taking into account cosmic ray flux, complex hadron interactions, geomagnetic field, solar activity, etc...
- On top of that, oscillations !
  - complicated matter effect of neutrinos travelling through Earth
  - appearance of the third kind of neutrinos ν_τ
- 1998, observation of a deficit of atmospheric upward-going vs. downward going ν_μ $\Rightarrow$ discovery of neutrino oscillations (model-independent) 2015 Nobel prize

Phys. Rev. D 94, 052001 (2016)



Atmospheric neutrinos flux

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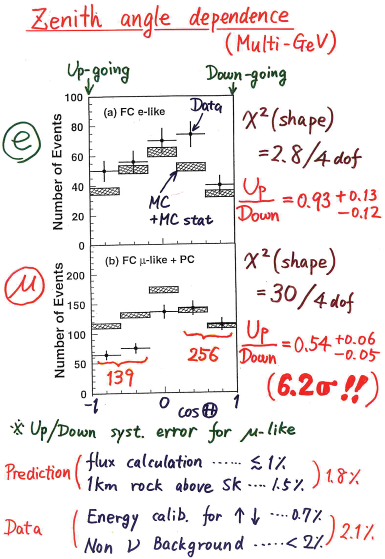
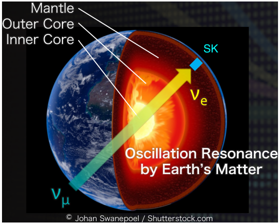
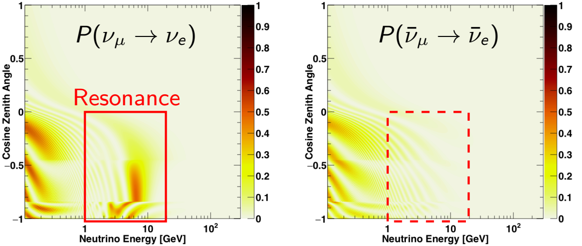


Atmospheric neutrinos and mass-hierarchy determination

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



Normal Hierarchy

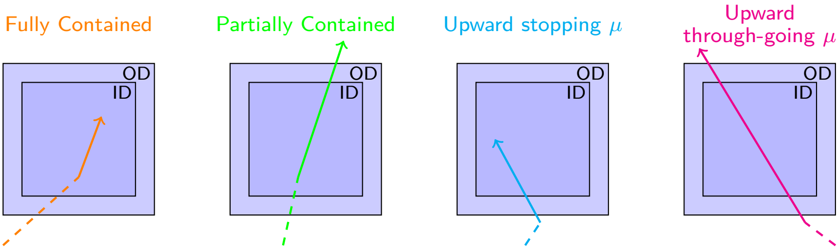


Phys. Rev. D97, 072001 (2018)

- Mass-hierarchy determined with upward-going multi-GeV ν_e sample:
  - Normal hierarchy : enhancement of $P(\nu_\mu \to \nu_e)$
  - Inverted hierarchy : enhancement of $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

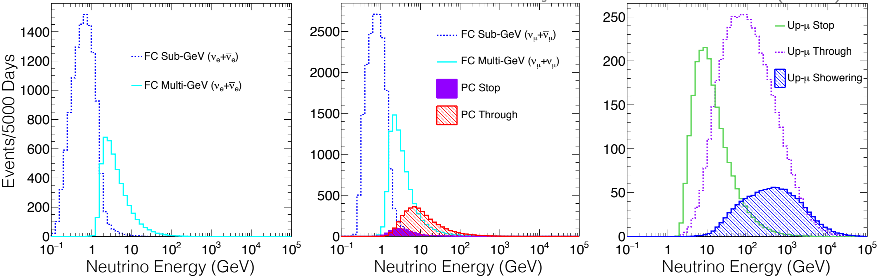
- Sensitivity enhanced if $\nu/\bar{\nu}$ separation

Depending on the topology and ID and OD activities

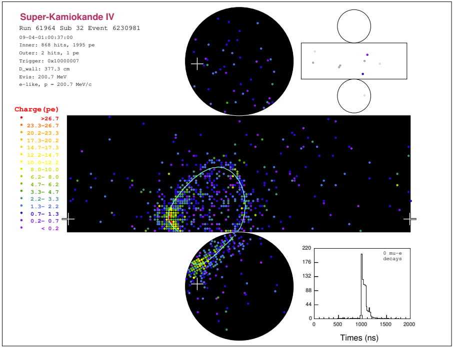


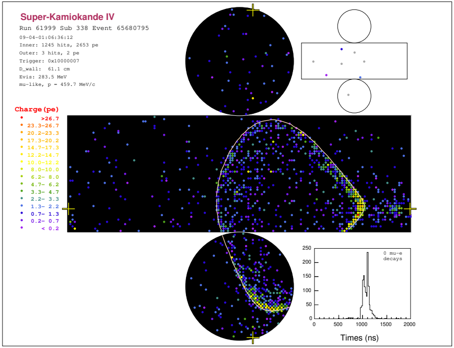
MC simulations

Phys. Rev. D97, 072001 (2018)



- SK excellent PID allows for a clear favour separation

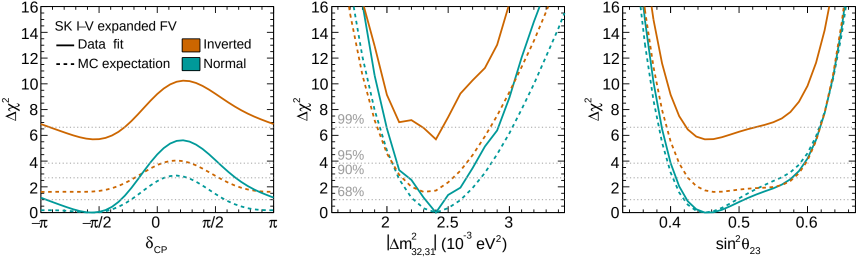




- Events are further categorized according to energies, number of rings, number of decay-electrons, π^0 likelihood (+ neutron tagging in SK-IV only) $\Rightarrow$ 20 samples in the end

SK atmospheric neutrinos results

arXiv:2311.05105

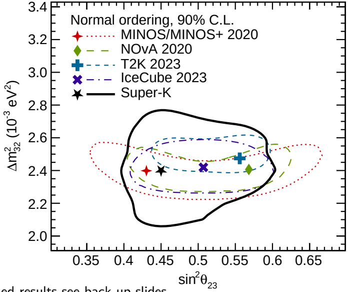


Data favors first octant for θ_{23}

Data favors NH at $\sim 2\sigma$

δ_{CP} best fit agrees with that of T2K

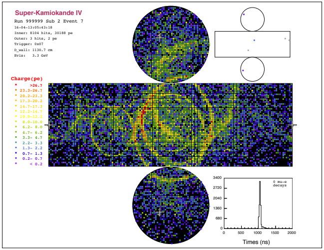
Some constraining power over θ_{13} consistent with LBL results

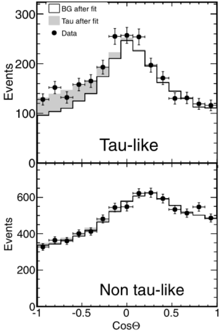


Results shown here are with θ_{13} constrained by reactor experiments, for unconstrained results see back-up slides

ν_τ appearance at Super-Kamiokande

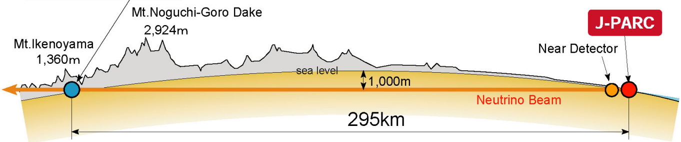
- Results taken from Phys.Rev.D 98 (2018) 5, 052006
- τ leptons produced in CC ν_τ interactions decay quickly to secondary particles $\Rightarrow$ not possible to directly detect τ in SK
- Leptonic τ decay look quite similar to atmospheric CC ν_e or ν_μ
- Hadronic decays are dominant and produce one or more pions $\Rightarrow$ allows separation of CC ν_τ signal from CC ν_μ, CC ν_e and NC background
- Results excludes no-tau appearance at 4.6σ





T2K experiment in a nutshell

1) 30 GeV protons, 760 kW reached on 25 dec. 2023 !!!



3) well-defined ν_μ / $\bar{\nu}_\mu$ beam + 2.5° off-axis

2) near detector complex at 280 m

4) Super-Kamiokande as far detector

ν_e or $\bar{\nu}_e$ appearance: leading order θ_{13}, sub-leading δ_{CP}

ν_μ or $\bar{\nu}_\mu$ disappearance: "atmospheric" parameters ($\sin^2 2\theta_{23}, \Delta m^2_{31}$)

T2K a big international collaboration of neutrino LBL

~575 physicists, 75 institutions, 14 countries

Canada
TRIUMF
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

CERN

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
Keio U.
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tohoku U.
Tokyo Institute Tech
Tokyo Metropolitan U.
Tokyo U of Science
U. Tokyo
Yokohama National U.
ILANCE

United Kingdom
Imperial C. London
King's College London
Lancaster U.
Oxford U.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

Hungary
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Neutrino appearance and disappearance at T2K

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

- Precision measurement of θ_{23} and Δm^2_{31}
- CPT test with antineutrino mode ($\bar\nu_\mu \to \bar\nu_\mu$)

$$P(\nu_\mu \to \nu_e) = 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{31}L}{4E} \times \left[1 \pm \frac{2a}{\Delta m^2_{31}}\left(1-2s^2_{13}\right)\right]$$
θ_{13} driven

$$+ 8c^2_{13}s_{12}s_{13}s_{23}\left(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}\right)\cos\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E}$$
CP even

Change sign by changing ν to $\bar\nu$

$$\mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E}$$
CP odd

$$+ 4s^2_{12}c^2_{13}\left(c^2_{12}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right)\sin\frac{\Delta m^2_{21}L}{4E}$$
Solar driven

$$\mp 8c^2_{13}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\frac{aL}{4E}\left(1-2s^213\right)$$
Matter effect (CP odd)

$a[\text{eV}^2] = 2\sqrt{2}G_F n_e E = 7.6 \times 10^{-5}\rho[\text{g/cm}^3]E[\text{GeV}]$

- θ_{13} dependence of the leading term and θ_{23} dependence of the leading term (octant)
- CP violation: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar\nu_\mu \to \bar\nu_e)$ if $\sin\delta \neq 0$
- Matter effect: ν_e ($\bar\nu_e$) appearance enhanced in normal (inverted) mass hierachy

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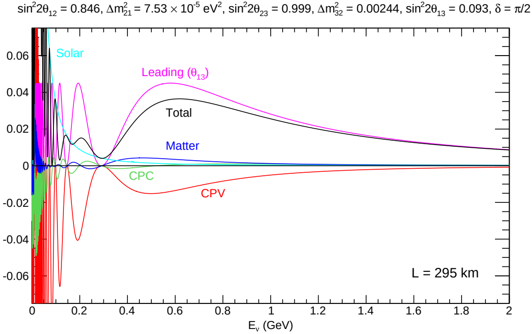

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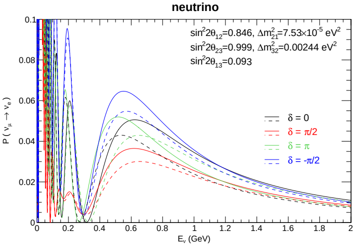
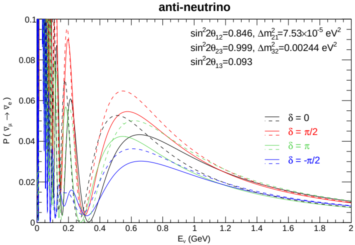
- Matter effect: ν_e ($\bar{\nu}_e$) appearance enhanced in normal (inverted) mass hierachy

Learning from ν_e ($\bar{\nu}_e$) appearance

- $\sin^2 2\theta_{13}$ and $\sin^2 2\theta_{23}$ enhance/suppress both ν_e and $\bar{\nu}_e$ appearance
- CP-violating phase $\delta_{\rm CP}$, up to $\pm 30\%$ effect at T2K
  - $\delta_{\rm CP} = 0, \pi \Rightarrow$ no CP violation, $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in vacuum
  - $\delta_{\rm CP} \sim -\pi/2$ enhances $\nu_\mu \to \nu_e$ and suppresses $\bar{\nu}_\mu \to \bar{\nu}_e$
  - $\delta_{\rm CP} \sim +\pi/2$ suppresses $\nu_\mu \to \nu_e$ and enhances $\bar{\nu}_\mu \to \bar{\nu}_e$
- Matter effects, $\pm 10\%$ effect at T2K
  - Normal Hierarchy: enhances $\nu_\mu \to \nu_e$ and suppresses $\bar{\nu}_\mu \to \bar{\nu}_e$
  - Inverted Hierarchy: suppresses $\nu_\mu \to \nu_e$ and enhances $\bar{\nu}_\mu \to \bar{\nu}_e$





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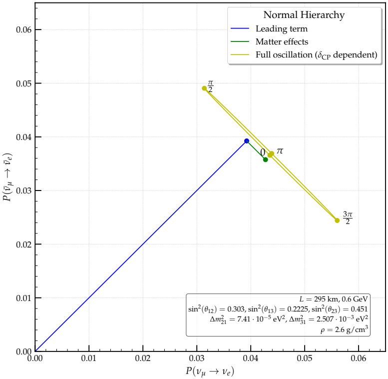

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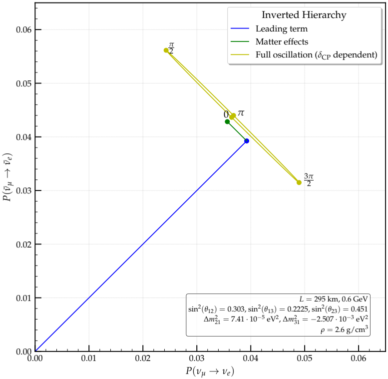
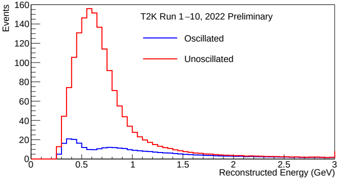
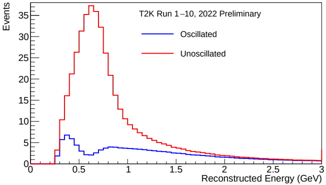


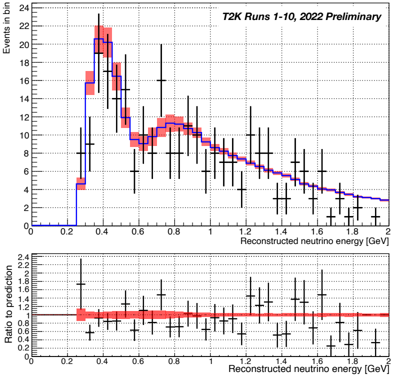
ν_μ $(\bar{\nu}_\mu)$ disappearance @ T2K

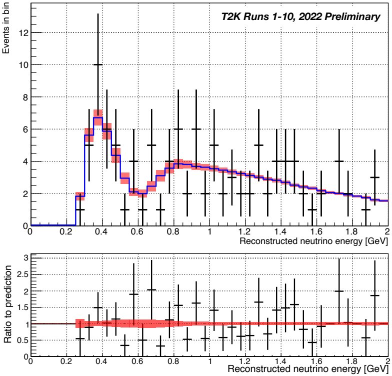




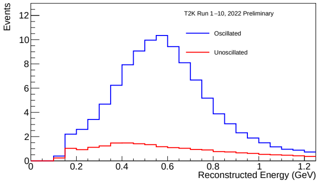
FHC 1Rμ

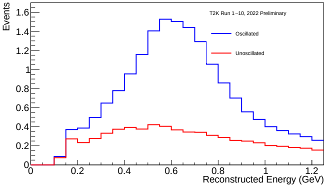
RHC 1Rμ





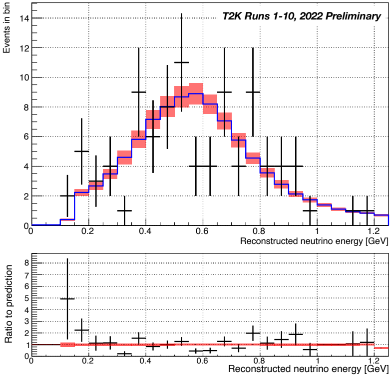
ν_e $(\bar{\nu}_e)$ appearance @ T2K

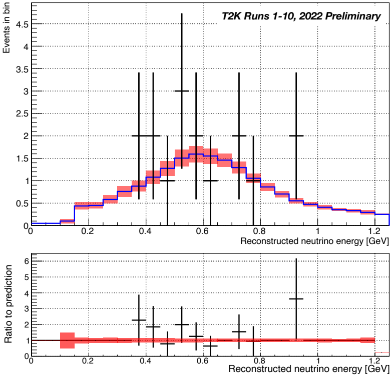




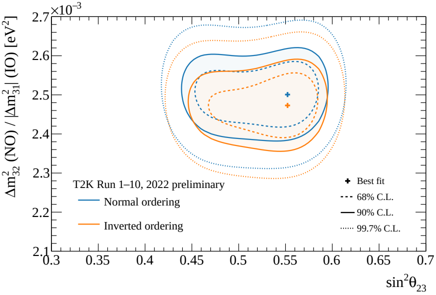
FHC 1Re

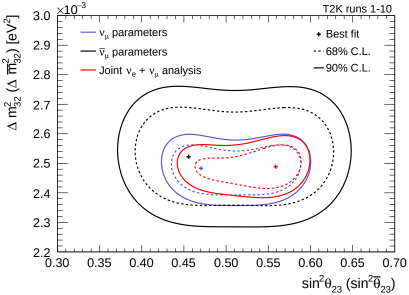
RHC 1Re





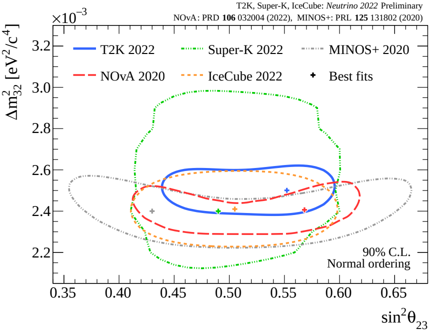
T2K "atmospheric" results





- World leading measurement of $\sin^2 2\theta_{23}$
- Results consistent with maximal mixing
- No significant differences between ν and $\bar{\nu}$
- Reactor contraint applied ($\sin^2 2\theta_{13} = 0.0861 \pm 0.0027$)

T2K "atmospheric" results



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- Results consistent with maximal mixing
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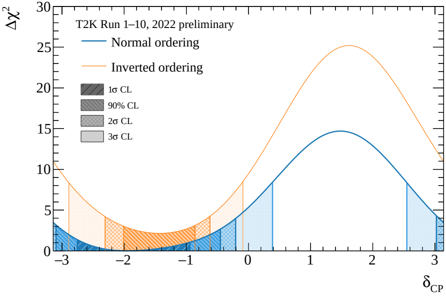
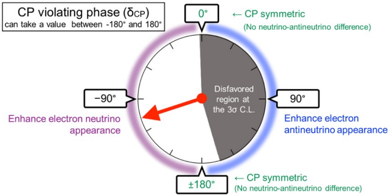
Towards a measurement of CP violation?



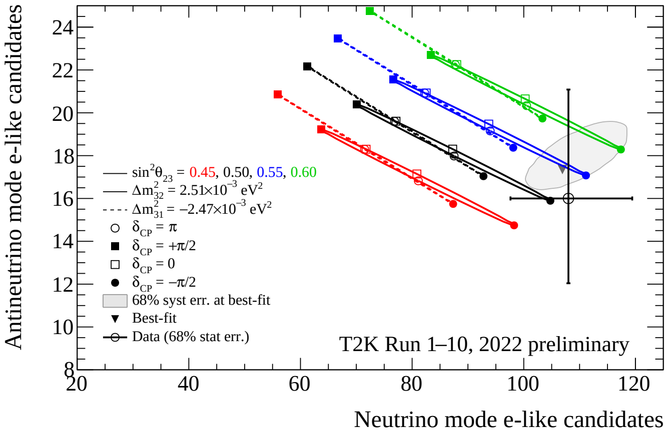


Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.75, -0.94]$	
90%	$[-3.10, -0.45]$	$[-2.01, -0.86]$
2σ	$[-\pi, -0.21] \cup [3.02, \pi]$	$[-2.31, -0.62]$
3σ	$[-\pi, 0.39] \cup [2.55, \pi]$	$[-2.89, -0.09]$

T2K Run 1-10, preliminary

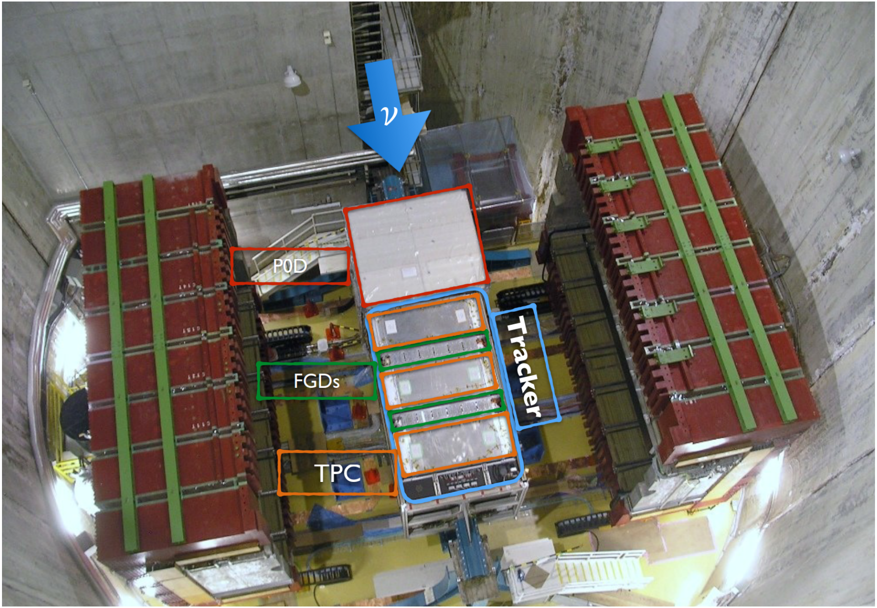
- CP conservation excluded at 90% C.L.
- Large region of δ_{CP} values excluded at 3σ
- Preference for maximal CP violation ($\delta_{CP} \sim -\pi/2$)

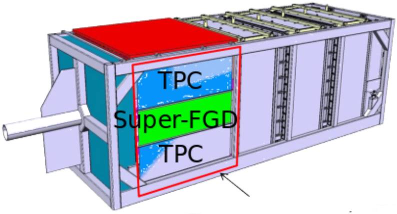
Summary of oscillation results

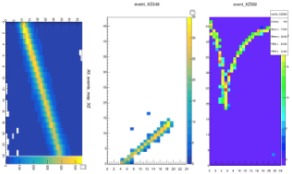


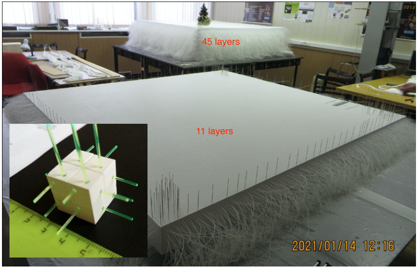
- Oscillation parameters at the limit :
  maximal mixing in θ_{23} + maximal ν_e / $\bar{\nu}_e$ asymmetry
- Consistent w/ PMNS, within statistical + systematic errors

The "old" ND280 detector complex







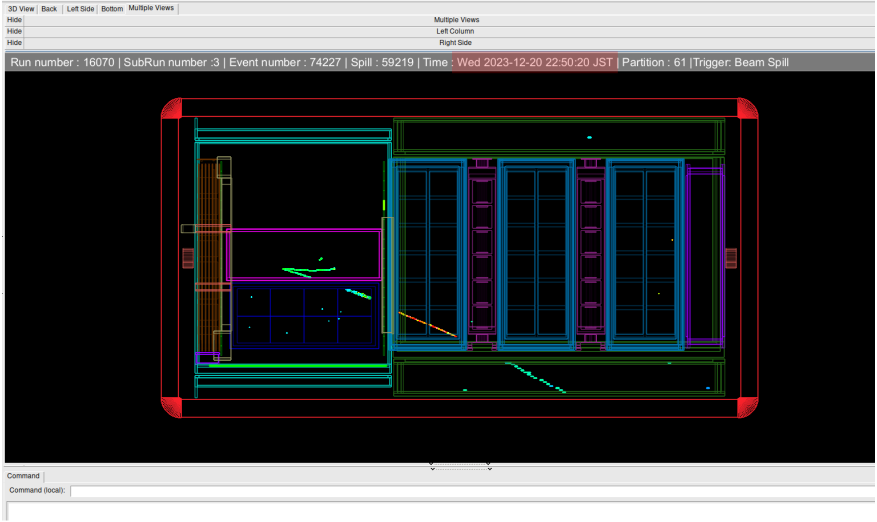


Test of the prototype at CERN & LANL

Fully active target of 2000000 plastic scintillator cubes of 1 cm^3
highly granular + (quasi-)3D readout: 56000 fibres WLS + MPPCs

⇒ measurement of the kinematics of the outgoing particles from neutrino interactions, and particularly hadrons, with an unprecedented precision

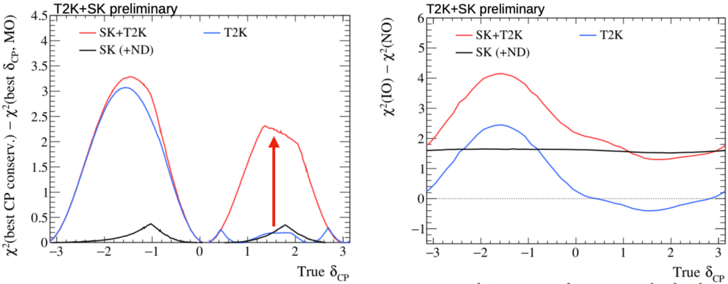
The Super-FGD, one of the very first event display



T2K-SK joint fit

- SK is a common detector for both experiments $\Rightarrow$ strong correlations in detector systematics, and also a common neutrino interaction model.
- δ_{CP} sensitivity mainly driven by T2K.
- SK covers large range of neutrino energies and baselines, hence better mass hierarchy sensitivity.

Ability to reject (left) CP conservation and (right) wrong mass ordering as a function of true δ_{CP}

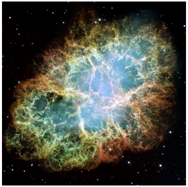


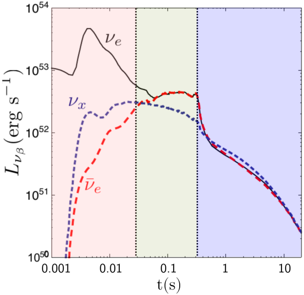
"SK (+ND)": SK-only fit with T2K ND constraint on the low-E cross-section model. True values assumed: $\sin^2\theta_{23} = 0.528$, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2, $\sin^2\theta_{13} = 0.0218$, NO

- Joint fit breaks the degeneracy between δ_{CP} and MO, and increases the ability to reject CP conservation beyond the simple sum of two experiments in some regions.

Supernovae physics

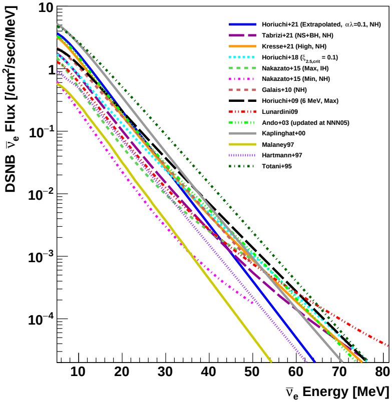
- Core-collapse supernovae are among the most cataclysmic phenomena in the Universe and essential elements of the dynamics of the cosmos
- Underlying mechanism still poorly understood and requires knowledge of the core of the collapsing star
- 10^{58} neutrinos emitted in a burst (99% of gravitational energy) $\Rightarrow$ information about this core
- So far, only SN1987a in LMC has been detected by neutrino experiments
- If burst in the galatic center $\Rightarrow \sim 8000$ neutrinos in SK ... but only few times per century in our galaxy





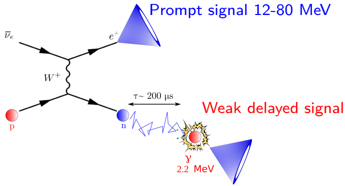
$\Rightarrow$ quest for the Diffuse Supernova Neutrino Background (DSNB)

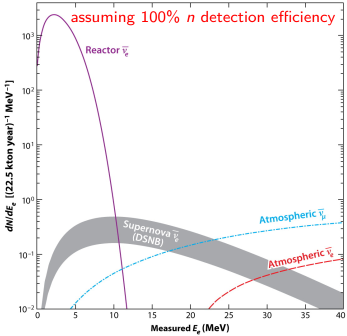
- Composed by neutrinos of all past SN of all flavors whose energies have been redshifted when propagating to the Earth ⇒ information not only on the SN neutrino emission process but also star formation and Universe expansion history
- Normalisation mostly determined by SN rate, related to cosmic star formation rate
- Shape depends on many parameters : fraction of BH-forming SN, effective neutrino energies (core temperature), and sub-dominantly on the expansion of the Universe (red-shift) and neutrino mass-hierarchy



DSNB detection at Super-Kamiokande

- Detection channel in SK : inverse β-decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$
- Searched at $\mathcal{O}(10)$ MeV, bounded by reactor + spallation background at lower energy and atmospheric neutrinos at higher energies
- In order to disentangle signal from backgrounds, neutron detection in coincidence with the positron is mandatory $\Rightarrow$ BDT developped
- Neutron doesn't produce Cherenkov light but its capture on H (timescale of 200 μs) produce a 2.2 MeV gamma. Neutron detection efficiency of 25% in SK-IV (improved electronics)

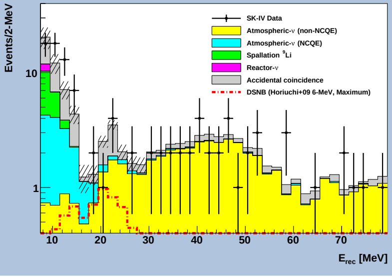


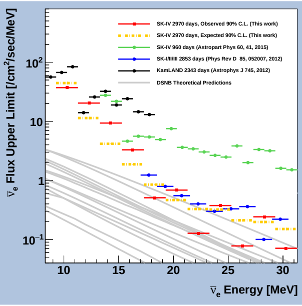


Beacom JF. 2010.
Annu. Rev. Nucl. Part. Sci. 60:439–62

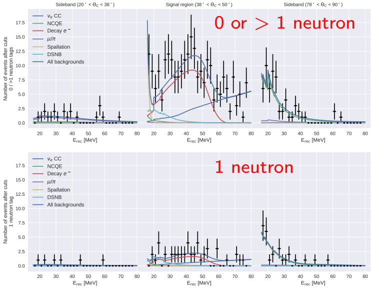
Latest results with SK-IV data [Phys.Rev.D 104 (2021) 12, 122002]

Binned, model-independent
required 1-tagged neutron





Unbinned spectral fit

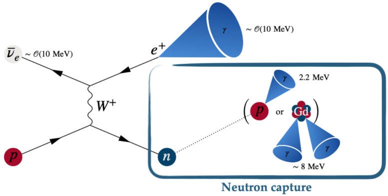


$\overline{\nu_e}$/cm²/s > 17.3 MeV	90% CL upper limit			Pred.
Model	**SK4**	**SK1-4**	**Sens.**	
Kaplinghat+00, max	3.7	2.6	1.3	3.00
Horiuchi+09 6 MeV, max	3.8	2.7	1.5	1.94
Ando+03 (updated 05)	3.8	2.7	1.5	1.74
Kresse+20 (High, NH)	3.7	2.7	1.5	1.57
Lunardini09 Failed SN	3.8	2.7	1.5	0.72
Nakazato+15 (max, IH)	3.8	2.7	1.5	0.53

World best sensitivity to DSNB

comparable to the predictions of various models

The SK-Gd upgrade



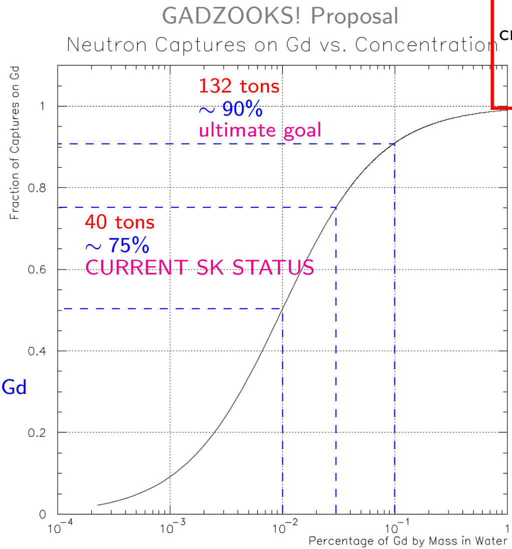
Motivations

- Improve neutron detection at SK
- SK-IV: neutron tagging possible but inefficient
- Dissolve Gd sulfate in water to enhance neutron signal : very high neutron capture cross-section + 8 MeV photon cascade

Upgrade process

- 2002: first proof of concept
- 2009: small scale prototype detector started (EGADS)
- 2018: SK detector refurbishment (SK-V)
- 2020: SK detector w/ 0.01% Gd (SK-VI)
- 2022: SK detector w/ 0.03% Gd (SK-VII, currently running)
- SK detector w/ 0.1% Gd?

Gd thermal neutron cross section : 49.7 kb ($\sigma_H = 0.33$ b)
8 MeV γ cascade



13.2 tons of $Gd_2(SO_4)_3 8H_2O$
in 50 ktons water
~ 50% capture on Gd
August 2020

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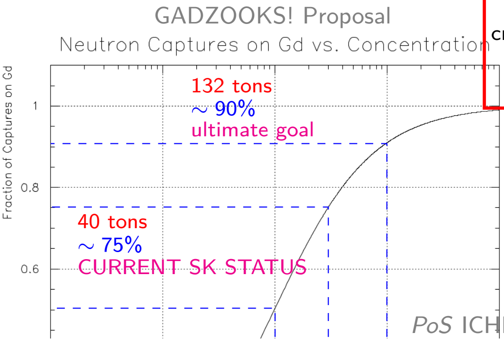

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PoS ICHEP2020 (2021) 164

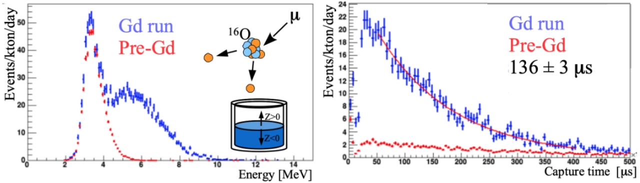
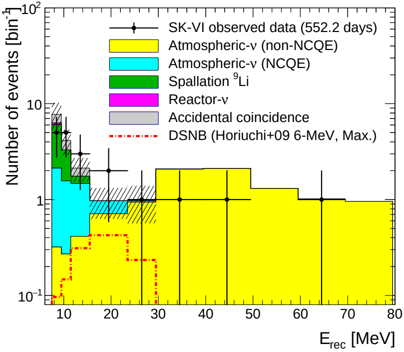
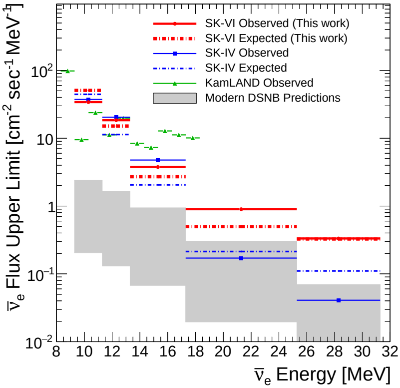


Figure 5: Reconstructed energy for spallation neutrons candidates for runs with and without Gd in the lower region of the detector (left) and capture time of the neutron candidates (right).

The very first results with Gadolinium (0.01%)

- M. Harada et al., Astrophys.J.Lett. 951 (2023) 2, L27





- Cut-based neutron tagging

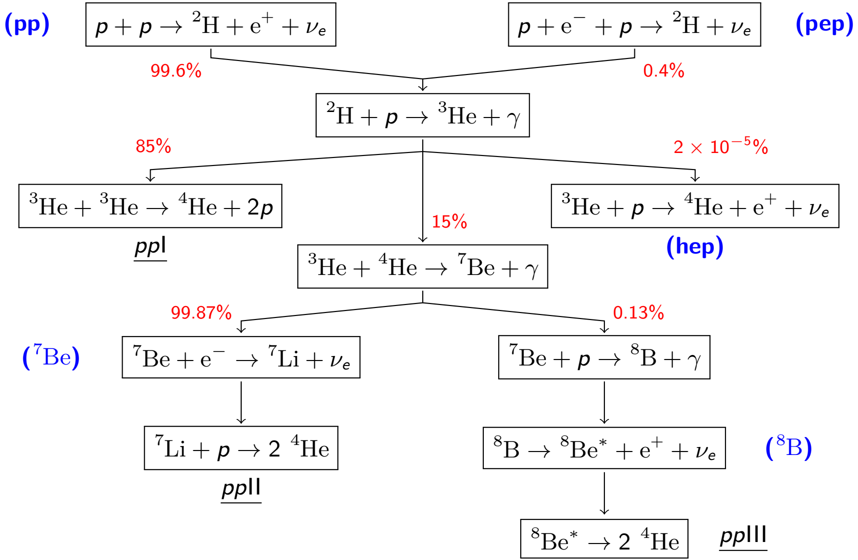
Perspectives for physics analysis with Gd

- Many analyses highly affected by limited ability to distinguish between neutrinos and antineutrinos (though already excellent sensitivity) $\Rightarrow$ Gd has lifted this limitation!
- For solar neutrinos: Better efficiency of cosmogenic neutron tagging = better spallation cut
- For atmospheric neutrinos
  - Limited effect for multi-GeV samples (to be studied), limited effect on the MH determination in the sub-GeV sample
  - Enhancement of δ_{CP} determination in the sub-GeV sample
  - Atmospheric parameters determination ($+\delta_{CP}$) will benefit from joint T2K-SK fit
- For DSNB neutrinos
  - Very promising perspectives for the DSNB search $\Rightarrow$ increased statistics
  - 8 MeV γ cascade (compared to 2.2 MeV for H) will help lowering the threshold down to 12 MeV where ^{9}Li decays will start to dominate (17.3 MeV currently) by removing almost all spallation background (accidentals)
  - Locating muon-induced showers using neutrons will become especially powerfull
  - After eliminating spallation, NCQE interactions dominate $\Rightarrow$ new dedicated techniques under study

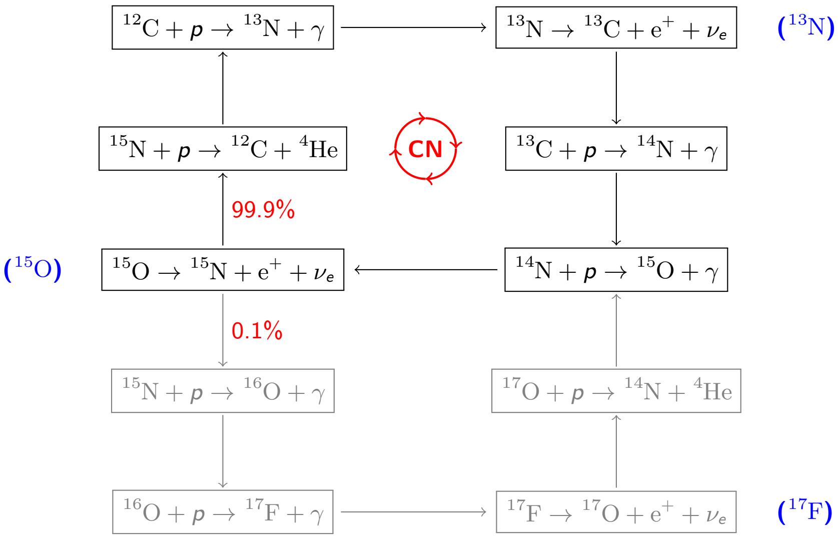
- Super-Kamiokande is running for more than 25 years and still has a lot to teach
- World leading results on atmospheric (6511 live days SK-I to SK-V) and solar neutrino oscillation as well as DSNB (5805 live days SK-I to SK-IV)
- The new phase (SK-Gd) has started in 2020, clear neutron signals have been observed in SK-VI and SK-VII

We are entering an era of extraordinary research with the new phase of Super-Kamiokande detector (and very soon with Hyper-Kamiokande)... **Stay tuned!**

The *pp* chain of stellar thermonuclear reactions

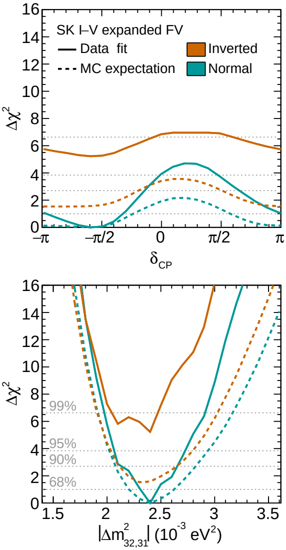


The CNO cycle of stellar thermonuclear reactions



SK atmospheric neutrinos results - θ_{13} unconstrained

arXiv:2311.05105



Most sensitive sub-samples

Phys. Rev. D97, 072001 (2018)

Sample	Energy bins	$\cos\theta_z$ bins	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	CC ν_τ	NC	Data	MC
Fully Contained (FC) Sub-GeV									
e-like, Single-ring									
0 decay-e	5 $e^\pm$ momentum	10 in $[-1, 1]$	0.717	0.248	0.002	0.000	0.033	10294	10266.1
1 decay-e	5 $e^\pm$ momentum	single bin	0.805	0.019	0.108	0.001	0.067	1174	1150.7
μ-like, Single-ring									
0 decay-e	5 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.041	0.013	0.759	0.001	0.186	2843	2824.3
1 decay-e	5 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.001	0.000	0.972	0.000	0.027	8011	8008.7
2 decay-e	5 $\mu^\pm$ momentum	single bin	0.000	0.000	0.979	0.001	0.020	687	687.0
π^0-like									
Single-ring	5 $e^\pm$ momentum	single bin	0.096	0.033	0.015	0.000	0.856	578	571.8
Two-ring	5 π^0 momentum	single bin	0.067	0.025	0.011	0.000	0.897	1720	1728.4
Multi-ring			0.294	0.047	0.342	0.000	0.318	(1682)	(1624.2)
Fully Contained (FC) Multi-GeV									
Single-ring									
ν_e-like	4 $e^\pm$ momentum	10 in $[-1, 1]$	0.621	0.090	0.100	0.033	0.156	705	671.3
$\bar{\nu}_e$-like	4 $e^\pm$ momentum	10 in $[-1, 1]$	0.546	0.372	0.009	0.010	0.063	2142	2193.7
μ-like	2 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.003	0.001	0.992	0.002	0.002	2565	2573.8
Multi-ring									
ν_e-like	3 visible energy	10 in $[-1, 1]$	0.557	0.102	0.117	0.040	0.184	907	915.5
$\bar{\nu}_e$-like	3 visible energy	10 in $[-1, 1]$	0.531	0.270	0.041	0.022	0.136	745	773.8
μ-like	4 visible energy	10 in $[-1, 1]$	0.027	0.004	0.913	0.005	0.051	2310	2294.0
Other	4 visible energy	10 in $[-1, 1]$	0.275	0.029	0.348	0.049	0.299	1808	1772.6
Partially Contained (PC)									
Stopping	2 visible energy	10 in $[-1, 1]$	0.084	0.032	0.829	0.010	0.045	566	570.0
Through-going	4 visible energy	10 in $[-1, 1]$	0.006	0.003	0.978	0.007	0.006	2801	2889.9
Upward-going Muons (Up-μ)									
Stopping	3 visible energy	10 in $[-1, 0]$	0.008	0.003	0.986	0.000	0.003	1456.4	1448.9
Through-going									
Non-showering	single bin	10 in $[-1, 0]$	0.002	0.001	0.996	0.000	0.001	5035.3	4900.4
Showering	single bin	10 in $[-1, 0]$	0.001	0.000	0.998	0.000	0.001	1231.0	1305.0

δ_{CP}: Sensitive to δ_{CP} (signal) would benefit from $\nu/\bar{\nu}$ separation (FC Sub-GeV e-like, Single-ring, 0 and 1 decay-e)

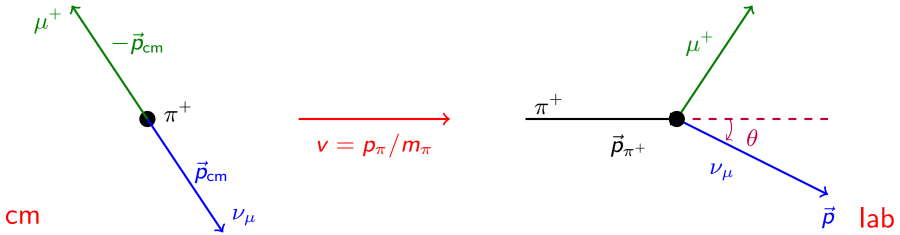
Sensitive to δ_{CP} flux normalization (FC Sub-GeV μ-like, Single-ring, 0 and 1 decay-e)

MH: Sensitive to MH, discrimination by number of decay-e (FC Multi-GeV Single-ring ν_e-like, $\bar{\nu}_e$-like)

Sensitive to MH, discrimination w/ 4 variables MVA : transverse mom., mom. fraction of most energetic ring, number of rings, number of decay-e (FC Multi-GeV Multi-ring ν_e-like, $\bar{\nu}_e$-like)

TABLE II. Sample purity broken down by neutrino flavor assuming neutrino oscillations with $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$ and $\sin^2\theta_{23} = 0.5$. The data and MC columns refer to the total number of observed and expected events, respectively, including oscillations but before fitting, for the full 328 kiloton-year exposure. Sub-GeV multi-ring interactions are not used in the present analysis. The numbers of observed and expected events in this sample are enclosed in parenthesis.

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



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

$$\gamma = (1 - v^2)^{-1/2} = E_\pi / m_\pi \gg 1 \qquad \begin{cases} E = \gamma(E_{\mathrm{cm}} + v p^z_{\mathrm{cm}}) \\ p^z = \gamma(v E_{\mathrm{cm}} + p^z_{\mathrm{cm}}) \end{cases}$$

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

Off-axis experiments (2)

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

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

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

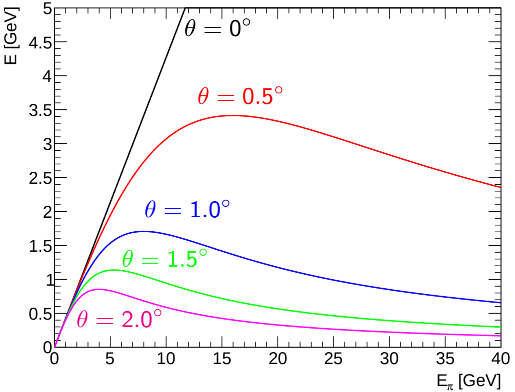
- $\theta = 0 \Rightarrow E \propto E_\pi$ WB beam
- $E_\pi\theta \gg m_\pi \Rightarrow E \propto \frac{m_\pi^2}{E_\pi\theta^2}$ high-energy π^+ give low-energy ν_μ

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

$\frac{dE}{dE_\pi} \simeq 0$ 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)

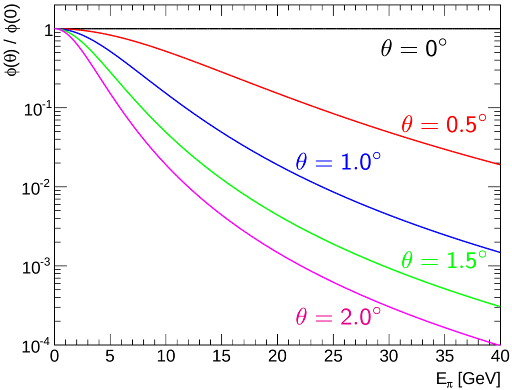
off-axis angle $\theta \simeq m_\pi / \langle E_\pi \rangle \Rightarrow E \simeq \frac{29.79\ \text{MeV}}{\theta}$



- 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

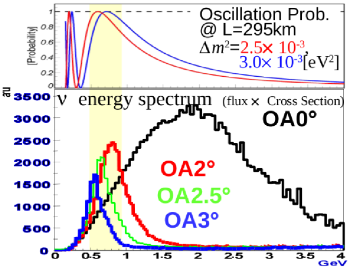
Off-axis experiments (4)

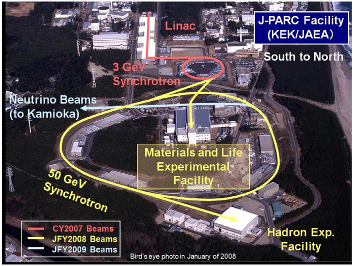
$$\frac{\phi(\theta)}{\phi(0)} = \left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$

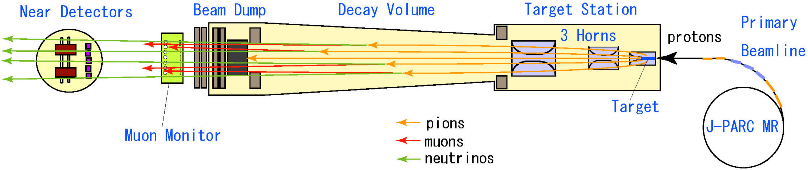


flux suppression requires high-intensity beams

Intense & high quality ν_μ beam



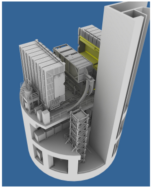


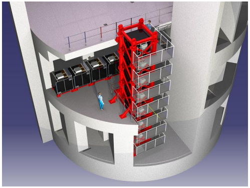


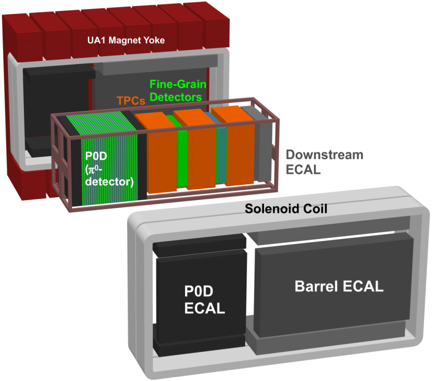
first off-axis experiment (beam @ 2.5°)

energy tuned for oscillation maximum, 0.5% ν_e contamination

The near detector complex (INGRID + ND280)





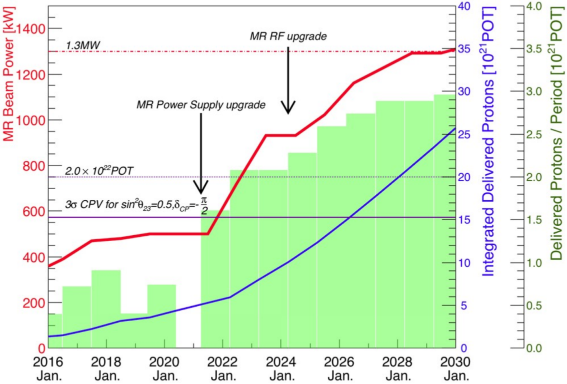


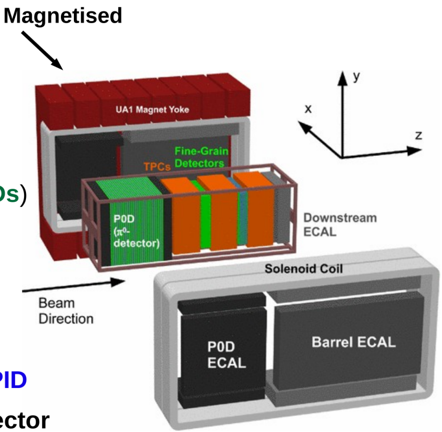
- INGRID @ on-axis:
  $\rightarrow$ ν beam monitoring
- ND280 @ 2.5° :
  $\rightarrow$ Normalisation of neutrino flux
  $\rightarrow$ Measurement of ν cross-sections
  - UA1 dipole magnet (0.2 T),
  - P0D (π^0 detector)
  - FGD+TPC (target + tracking)
  - ECAL (EM calorimeter),
  - Side-μ-range detector

* 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

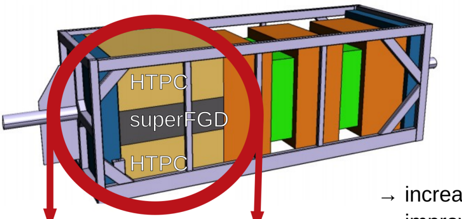


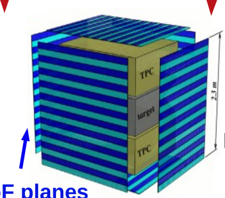


ND280

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**

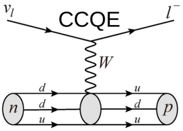
  → improved hadronic information

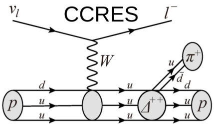
  → better $\gamma \rightarrow e^+ e^-$ identification

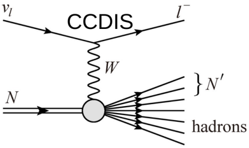
Reduce systematic uncertainty to 4%

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

Neutrino interactions (1)



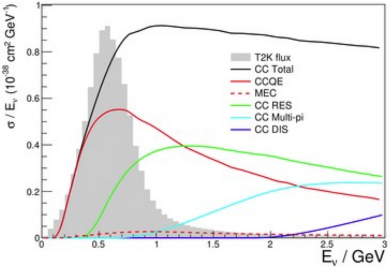




NC interactions also important

e.g. NCπ^0, NC1γ

→ background



Interactions occur with nucleons bound inside a nucleus

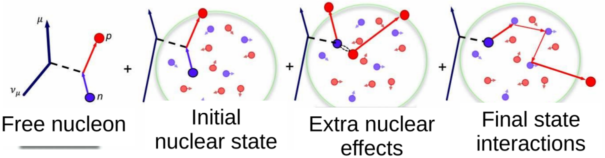
→ **Nuclear effects!!**

We only measure particles that exit the nucleus

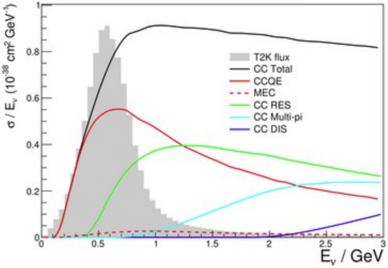
→ lose information about the initial interaction

→ can create a bias in energy reconstruction

Neutrino interactions (2)



Interaction modes and Nuclear models tuned to external data



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Oscillation analysis strategy