Super-Kamiokande Recent results on Atmospheric neutrinos

Jun Kameda
(Institute for Cosmic Ray Research, Univ. of Tokyo)
for Super-Kamiokande collaboration

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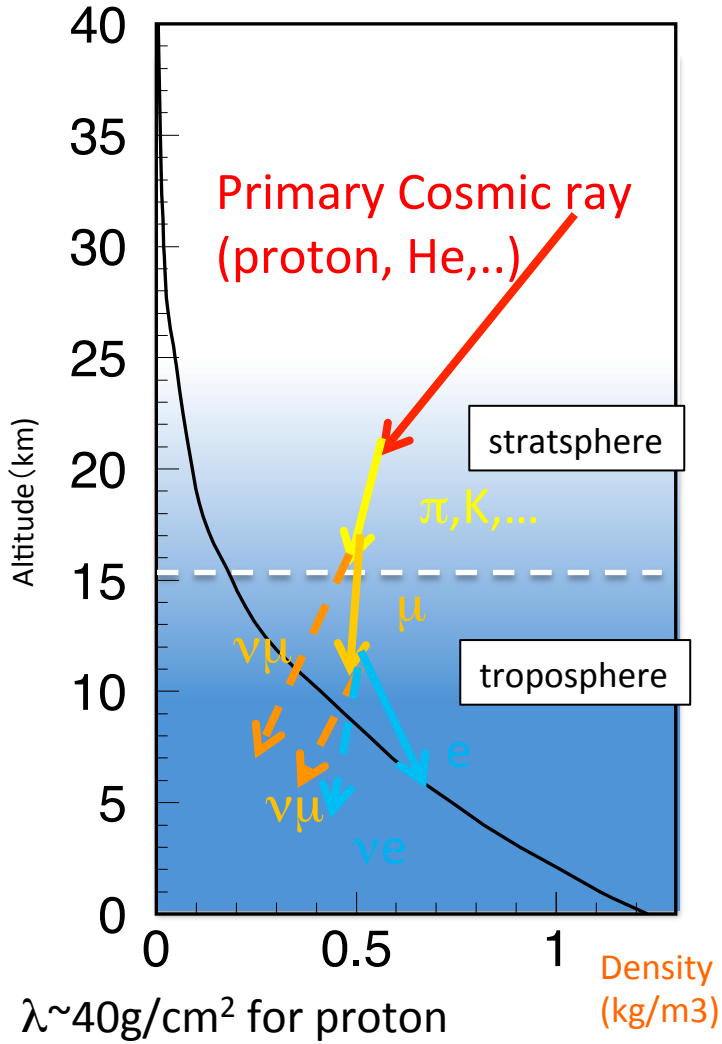
Outline

- Introductions on
  - Atmospheric neutrinos
  - Neutrino oscillation
  - Super-Kamiokande (Super-K)
- Recent result of ν oscillation study with atmospheric neutrinos
- A Future project in SK
- Summary

Atmospheric neutrinos

= Secondary products of primary cosmic rays in the atmosphere



λ~40g/cm^2 for proton
→L~15km

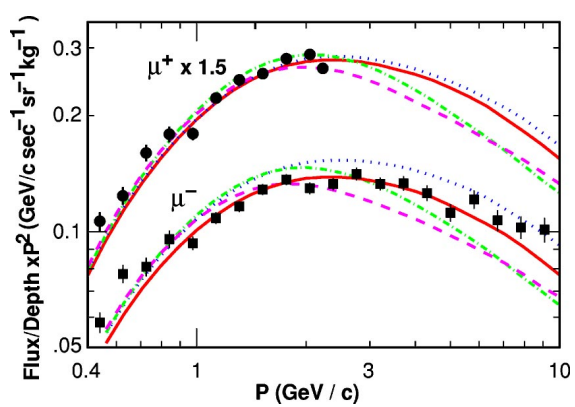
p + A → π's, ...

$$\pi^{\pm} \rightarrow \mu^{\pm} + \boxed{\nu_{\mu}}(\bar{\nu}_{\mu})$$

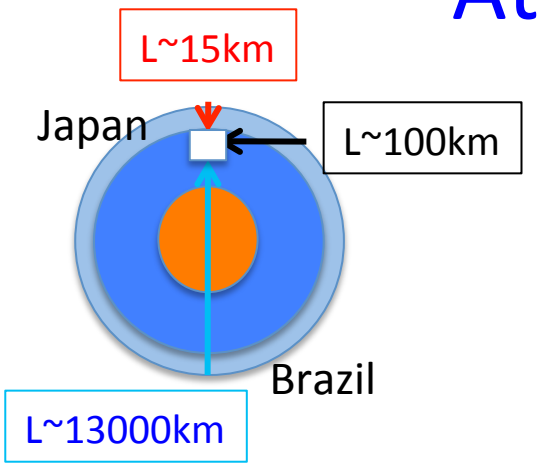
$$\rightarrow e^{\pm} + \boxed{\nu_{e}}(\bar{\nu}_{e}) + \boxed{\bar{\nu}_{\mu}}(\nu_{\mu})$$

- Several Flux predictions on the market:
- Simulation with external inputs
  - Primary CR fluxes, p+A cross sections,
  - π's production, Geo-magnetic field, ..
- Calculated fluxes are well tested (calibrated) by CR muons.

muon flux

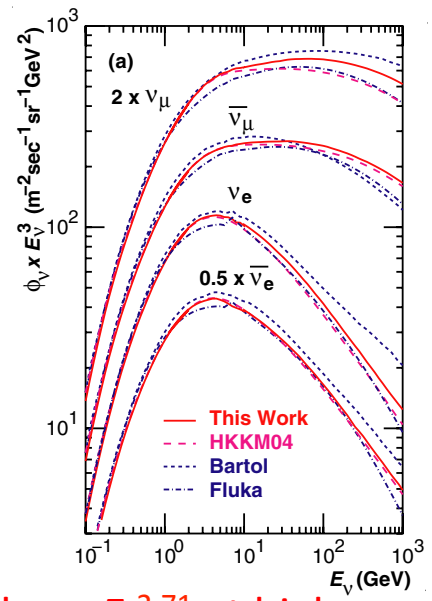


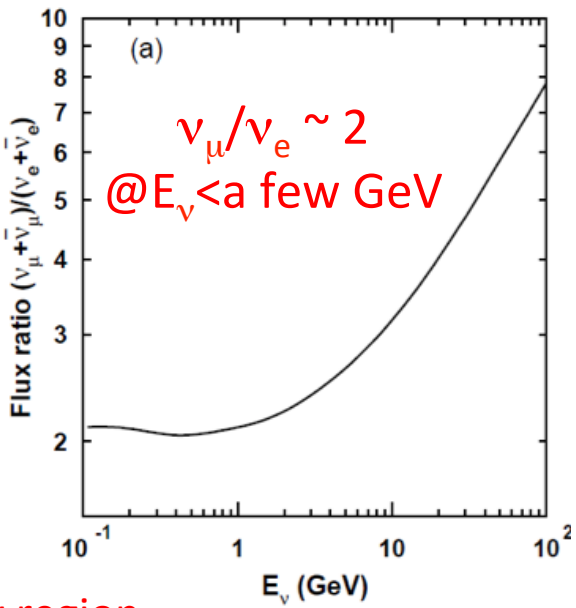
Atmospheric neutrinos

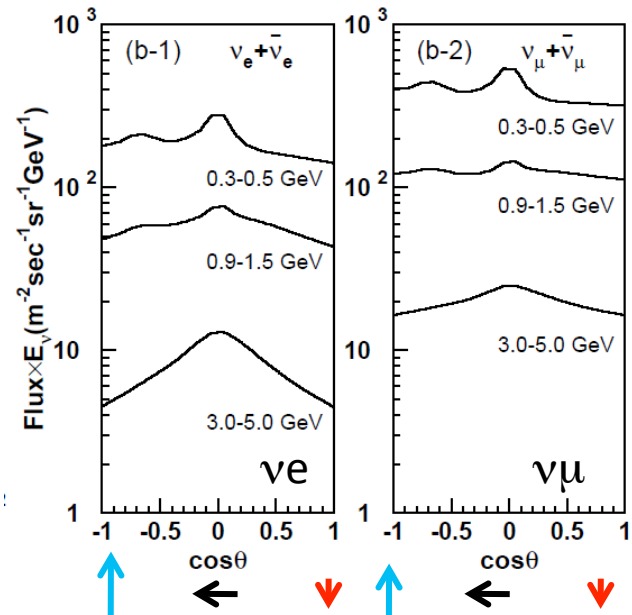


- Wide energy range
- Wide range of light length
- Passing through dense matter inside the Earth.
- Mixture of ν_μ, ν_e, (and their anti-neutrinos)
- Up/Down symmetric (> a few GeV)
- DC-like continuous beam, FREE.

→ Good opportunity to test ν oscillation physics.







Flux ~ $E^{-2.71}$ at high energy region

<10% uncertainty @1GeV region

Symmetric for E_ν > a few GeV

Neutrino flavor oscillation (PMNS matrix)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates

Atmospheric ν,
Accelerator ν experiments
(K2K, MINOS, T2K..)

$\theta_{23} \sim 45°$
$\Delta m^2_{23} \sim 2.5\times10^{-3}(eV^2)$

Reactor ν,
Accelerator ν,
Atm. ν

$\sin^2 2\theta_{13} \sim 0.1$

Solar ν,
Reactor ν

$\theta_{12} \sim 34°$
$\Delta m^2_{12} \sim 8\times10^{-5}(eV^2)$

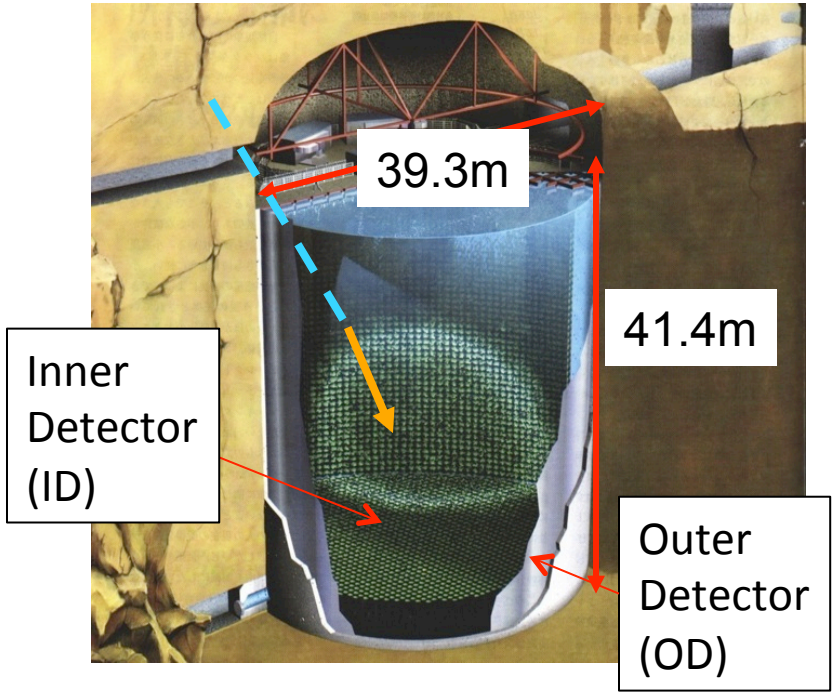
Mass eigenstates

$$P(\nu_\alpha \to \nu_\beta) =$$

$$\delta_{\alpha\beta} - 4 \cdot \sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \cdot \sin^2\left(\frac{\Delta m^2_{ij}}{4E} L\right) \pm 2 \cdot \sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \cdot \sin\left(2 \cdot \frac{\Delta m^2_{ij}}{4E} L\right)$$

- Three frequency driven by Δm^2_{ij}, amplitudes by mixing angles.
- Appearance ($\alpha \to \beta$) is a window to observe δ_{cp}.
- Mass hierarchy (sign of Δm^2_{ij}), phase of δ_{cp} is still open questions

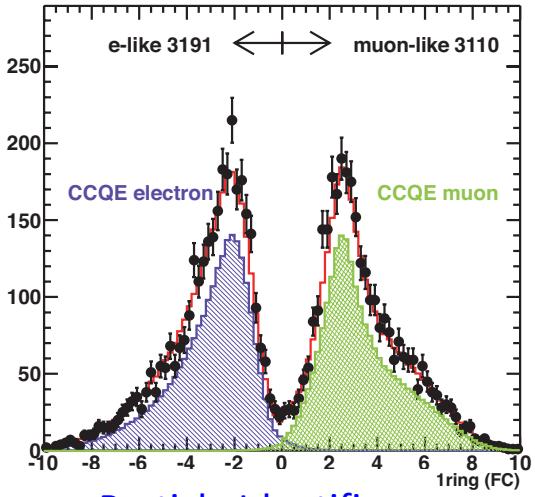
Super-Kamiokande



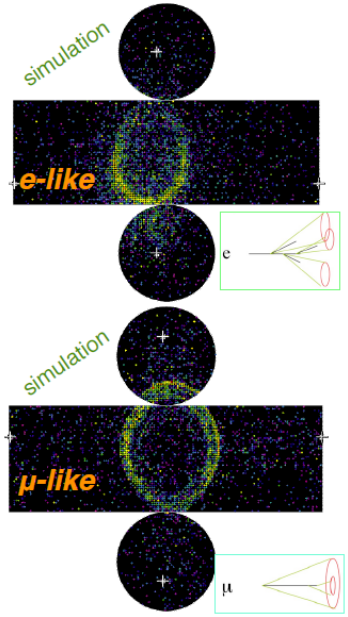
- 4π acceptance, very efficient π^0/e separation.
- High Particle ID (μ/e) power (~99% at 600MeV/c)
- Up/Down Symmetric response
- Cylindrically symmetric response
- Good energy reconstruction (~3% @ 1GeV)

- Ring-imaging Water Cherenkov Detector, @1000m underground, Kamioka, Japan
- Multi-Purpose experiment
  (Atm.ν, WIMP, Proton decay, solar-ν, T2K,..)
- 22.5kton Fiducial Volume.

atmospheric neutrinos



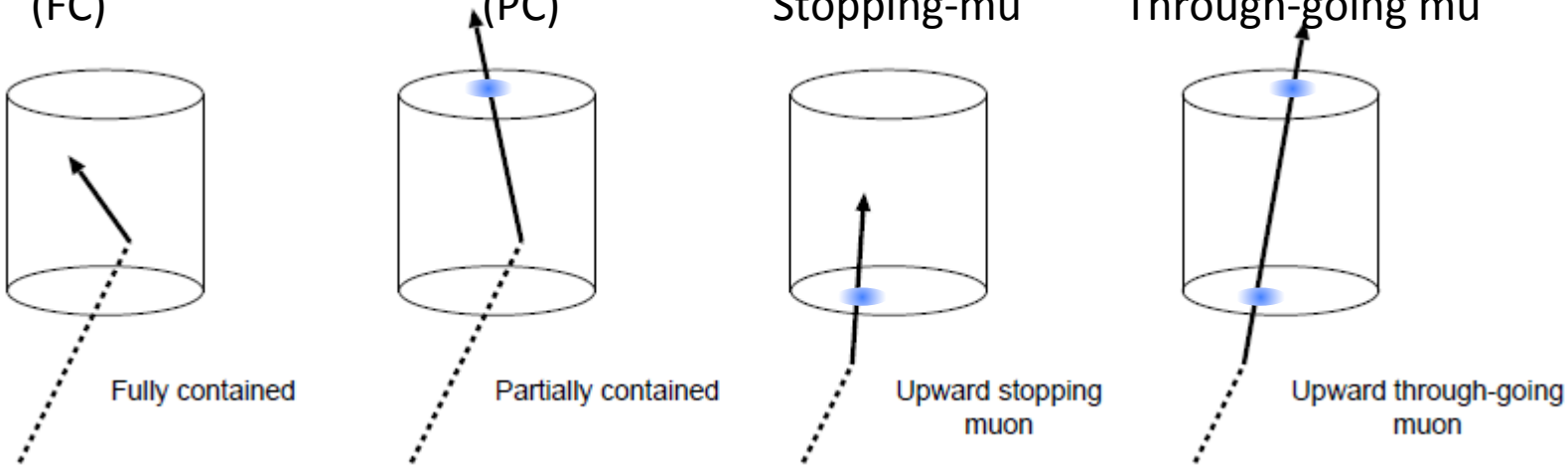
Particle Identifier



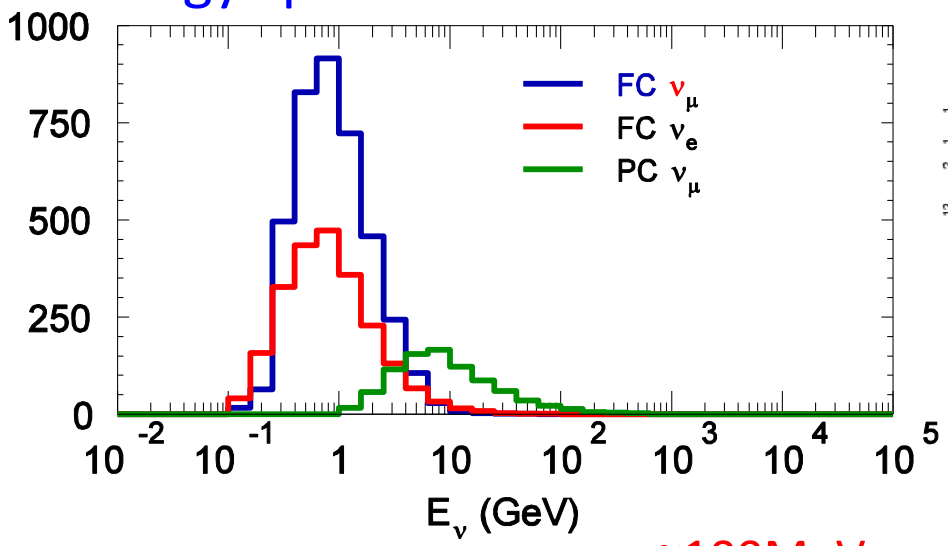
Four periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III(2005-2008) SK-IV(2008-Present) → total 4972days

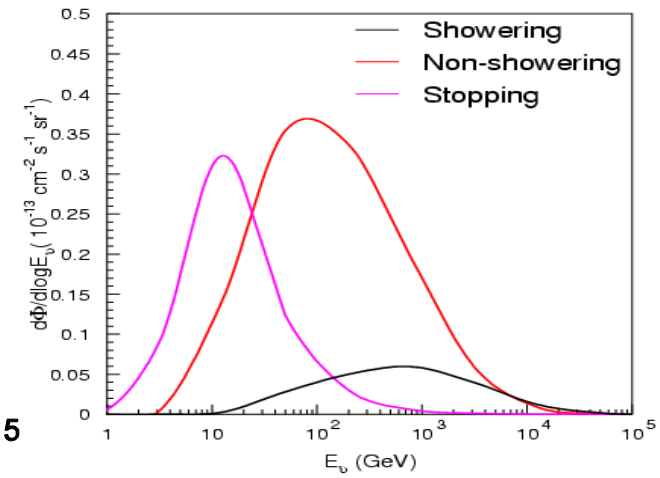
Event Topologies of Super-K events

Fully Contained (FC) | Partially Contained (PC) | Upward Stopping-mu | Upward Through-going mu



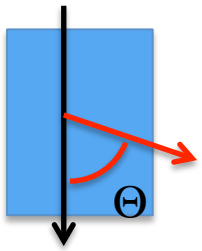
- Energy spectrum of neutrinos



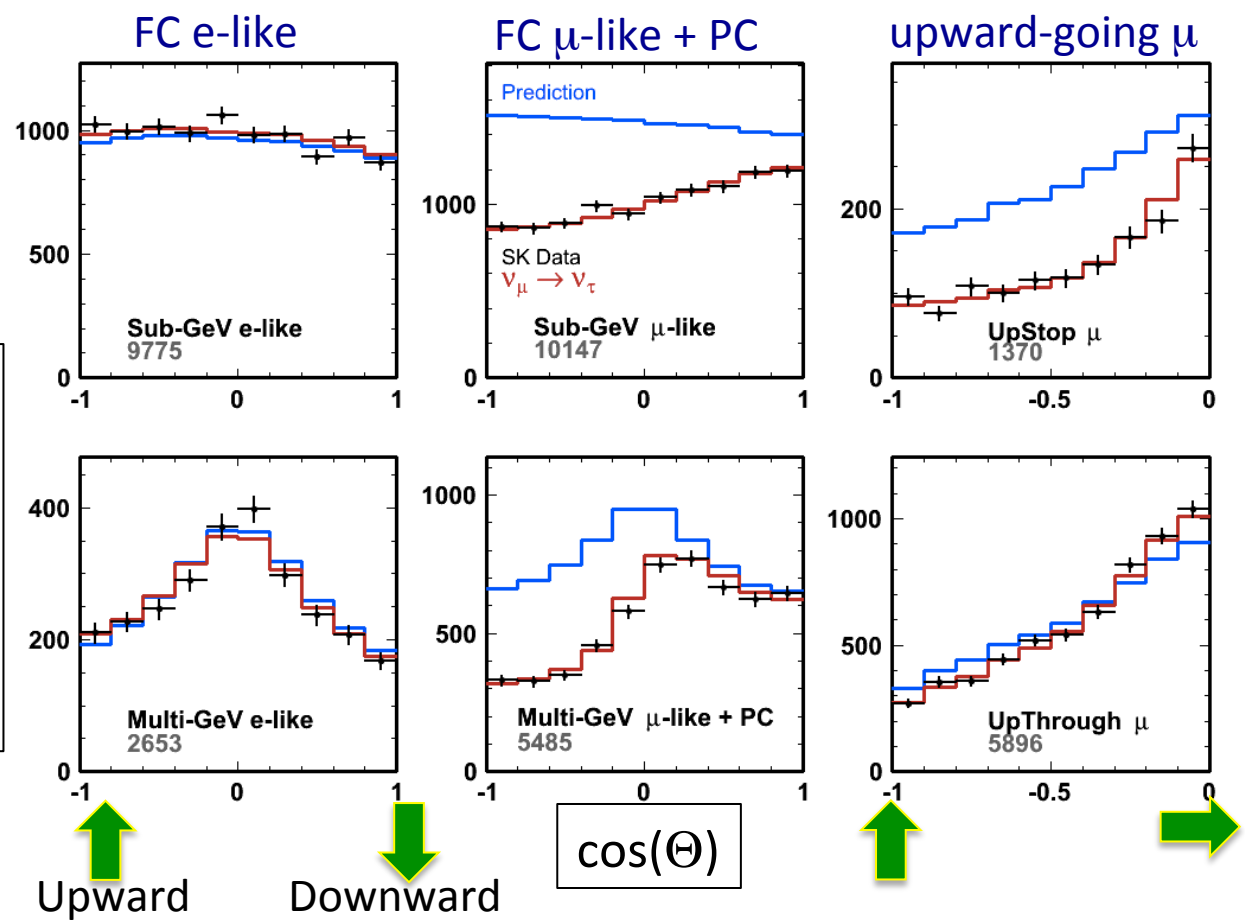


~100MeV – over TeV neutrinos

Super-K 1+2+3+4 data (4972days)

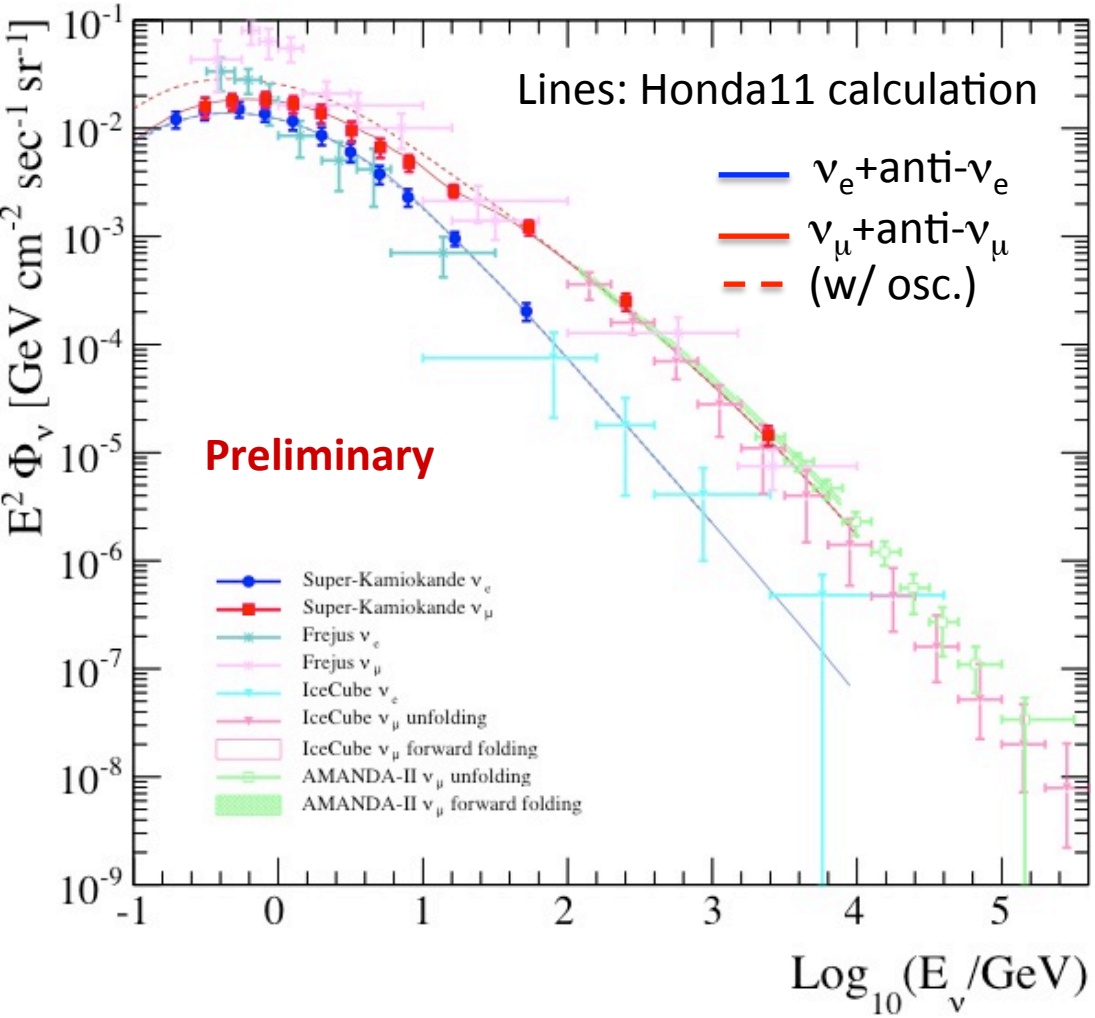


Totally 19 Sub-divided samples.
They further binned by
- zenith angle
- energy (momentum)
- SK period



- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillation, ν_e oscillation is sub-dominant effect.
- In ν oscillation analyses, calculate χ^2 between (Data vs MCs) for given ν oscillation parameters.
- In calculation, fit MC expectation by modifying within the estimated systematic errors (~150 systematic errors from SK detector, flux, σ int.).

Atmospheric neutrino flux measurement in Super-K

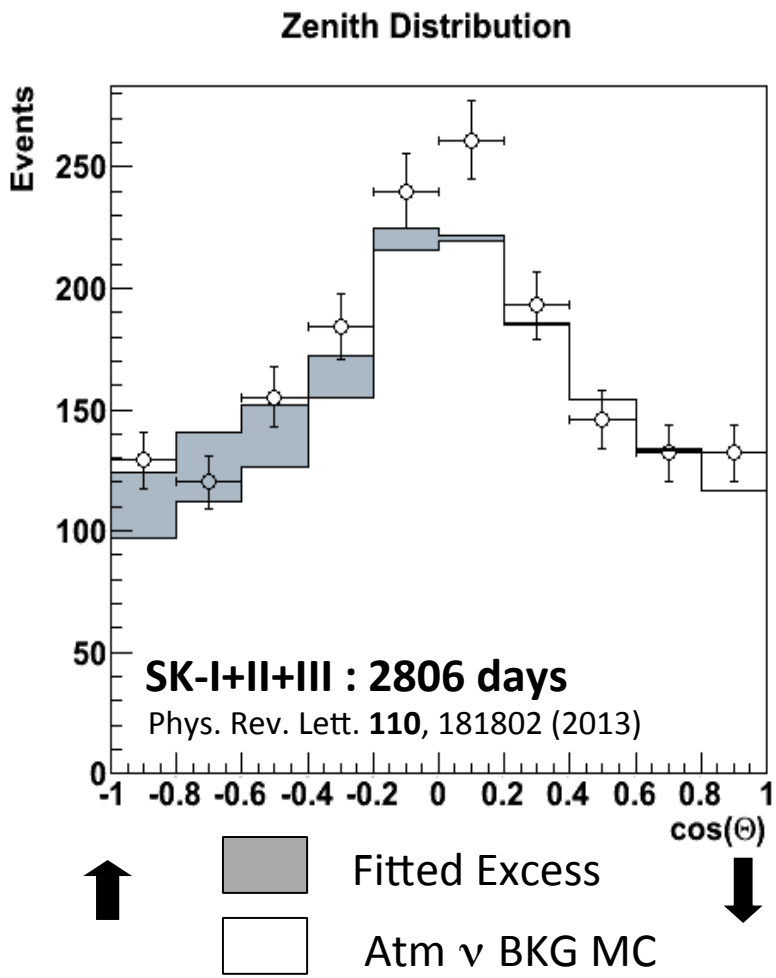


- Using the observed Super-K atmospheric neutrino events, neutrino fluxes (ν_μ+anti-ν_μ, ν_e +anti-ν_e) are measured.
- An Unfolding method with Bayesian theory is employed: No bias, mathematically robust.
- Systematic errors are assigned (from SK detector, ν-interaction, ν- oscillation parameters.)
- Especially, low energy region Super-K gives good measurement.

Results of analysis of ν oscillation

Evidence for ν_τ Appearance at Super-K

Phys. Rev. Lett. **110**, 181802 (2013)



- Search for events consistent with hadronic decay of τ leptons.
  - Multi-ring e-like events, mostly DIS interactions
- Event selection performed by neural network
  - Total efficiency ~60%
- Negligible primary ν_τ flux so ν_τ must be oscillation-induced.

$\beta = 0$: no ν_τ

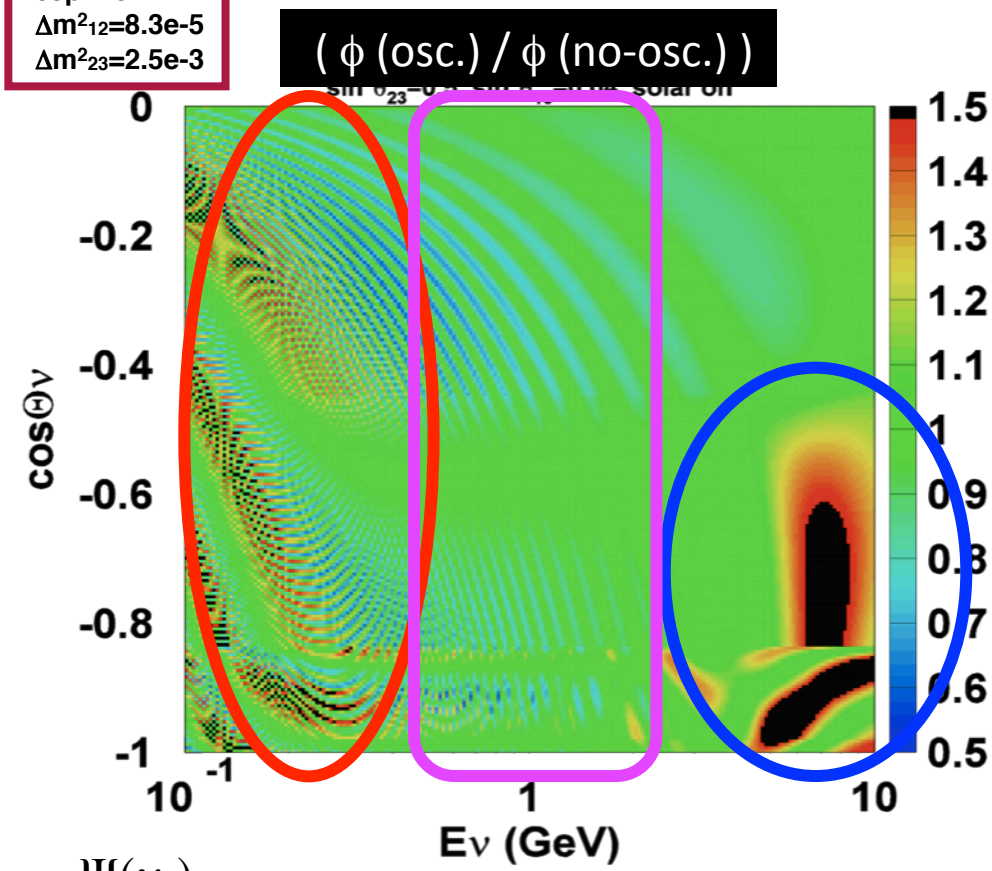
$$Data = \alpha(\gamma) \times bkg + \beta(\gamma) \times signal$$

Background	DIS (γ)	Signal
0.94 ± 0.02	1.10 ± 0.05	**1.42 ± 0.35**

This corresponds to
180.1 ±44.3 (stat) +17.8-15.2 (sys) events, a
3.8 σ excess (Expected 2.7 σ significance)

Neutrino oscillation in atmospheric ν

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.4$
$s^2\theta_{13}=0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e\text{-}5$
$\Delta m^2_{23}=2.5e\text{-}3$



- ν_e flux distortion is a key to access to mass hierarchy, CP phase.

- Resonance term → sensitive to mass hierarchy
- "Solar term" → sensitive to $\sin^2\theta_{23}$ octant degeneracy
- Interference term → CP violation phase

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2(r \cdot c_{23}^2 - 1)$$

"Solar Term"

$$- r \cdot \tilde{s}_{13} \cdot \tilde{c}_{13}^2 \cdot \sin 2\vartheta_{23} (\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$

Interference

$$+ 2\tilde{s}_{13}^2 (r \cdot s_{23}^2 - 1)$$

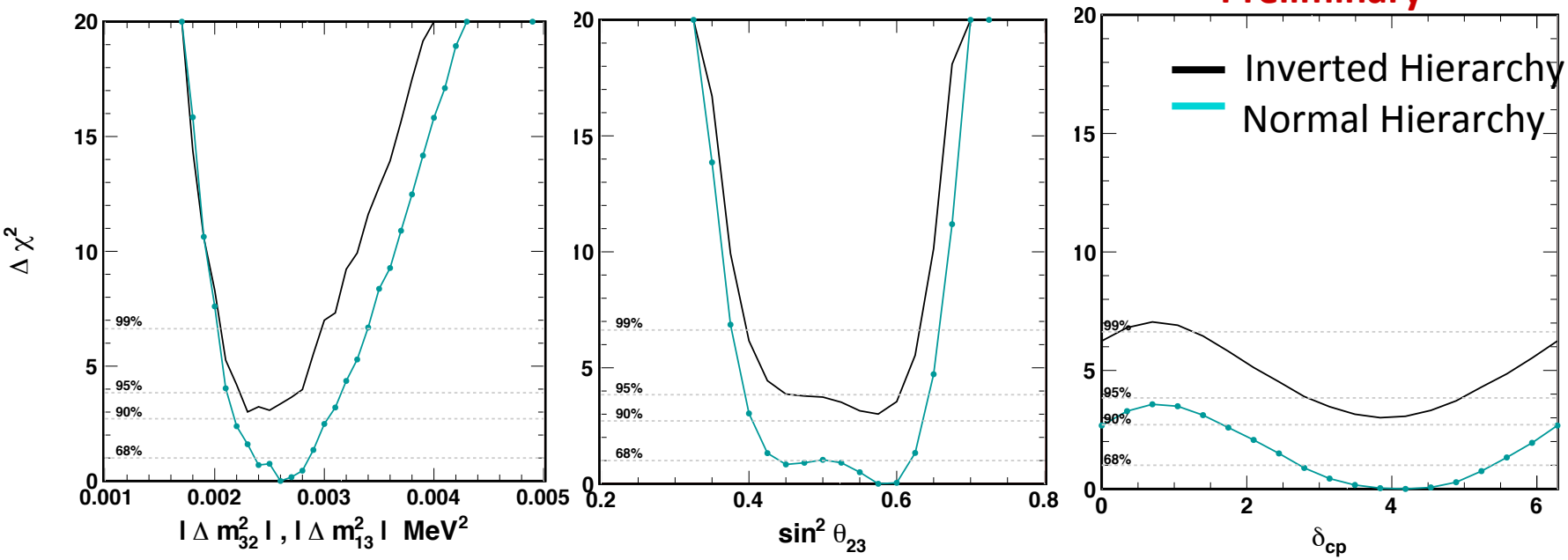
Resonance

P2: Osc. prob. driven by 12 sector
r: ν_μ/ν_e flux ratio
R2, I2: osc. prob driven by 12sector

Three flavor n oscillation analysis (θ_{13} **Fixed** , NH or IH)

Super-K atm.ν

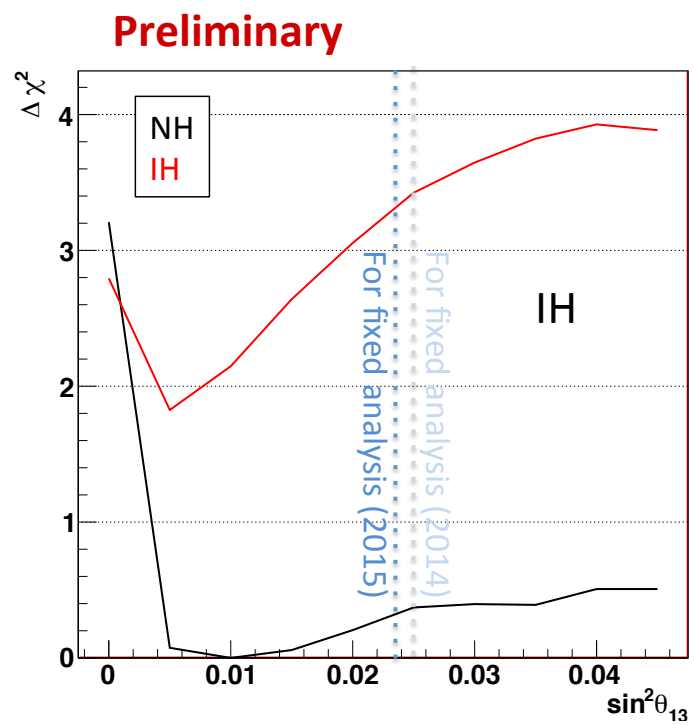
Preliminary

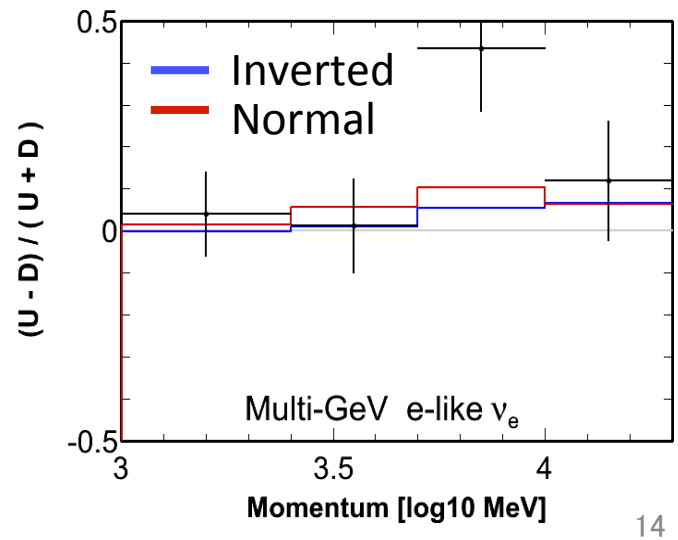


Fit (517 d.o.f.)	$\chi 2$	δ_{cp}	θ_{23}	Δm_{23} ($x10^{-3}$)
Normal Hierarchy	582.4	4.19	0.575	2.6
Inverted Hierarchy	585.4	3.84	0.575	2.3

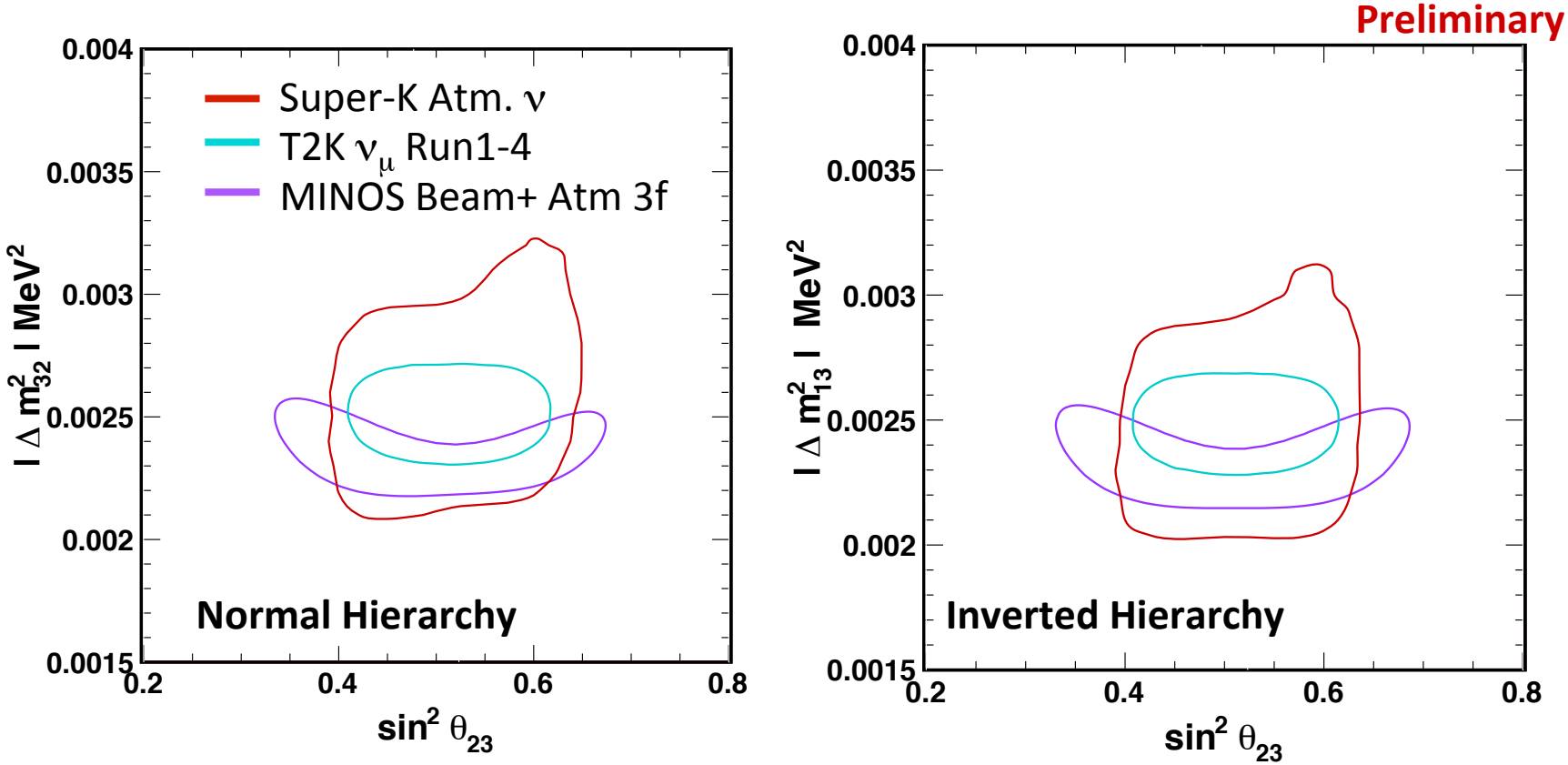
- θ_{13} fixed to PDG average, but its uncertainty is included as a systematic error.
- Offset in these curves shows the difference in the hierarchies.

- **Normal** hierarchy favored at:
  - $\chi^2_{NH} - \chi^2_{IH}$ = **-3.0 (-0.9 at 2014)**
    - Additional data
    - Bug fix (small effect)
  - Still Not a significant preference
- Driven by excess of upward-going e-like events.
  - consistent with the effects of θ_{13}
  - Primarily in SK-IV data
  - Fit for θ_{13} now weakly favors $\theta_{13} > 0$
- Rejection of $\delta_{cp} \sim 60^o$ driven by excess in Sub-GeV electron events
  - Constraint is consistent with sensitivity





Allowed region on ($\sin^2\theta_{23}$, Δm^2_{32} or Δm^2_{13})



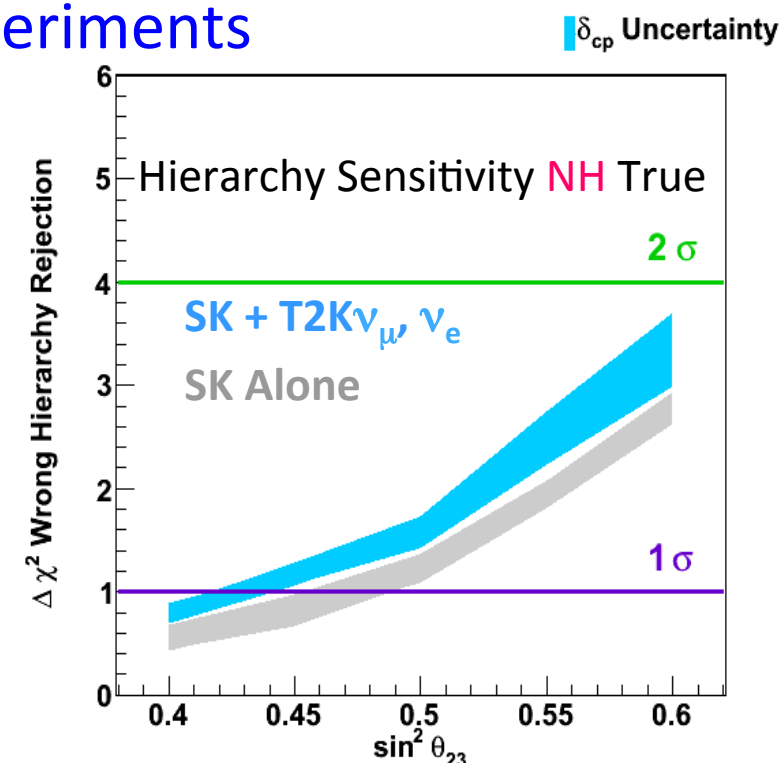
- Consistent with long-baseline measurements.
- Atmospheric neutrinos allow wider parameter space,

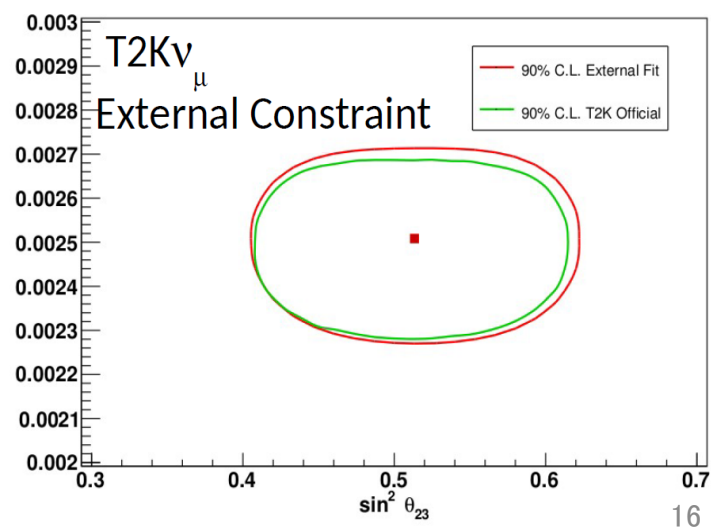
External Constraint from other Experiments

- Adding external data set to atmospheric neutrinos improve the sensitivity to the mass hierarchy: Sensitivity depends on values of Δm^2 and $\sin^2\theta_{23}$.

- Fit the T2K ν_μ and ν_e data sets with SK
  - Same detector, generator and reconstruction: systematic error correlations incorporated easily
  - Fit is based on **publicly available** T2K information and results
  - Simulate T2K using SK tools: make a mimic T2K data.
    - (not a joint result of the T2K and SK collaborations)

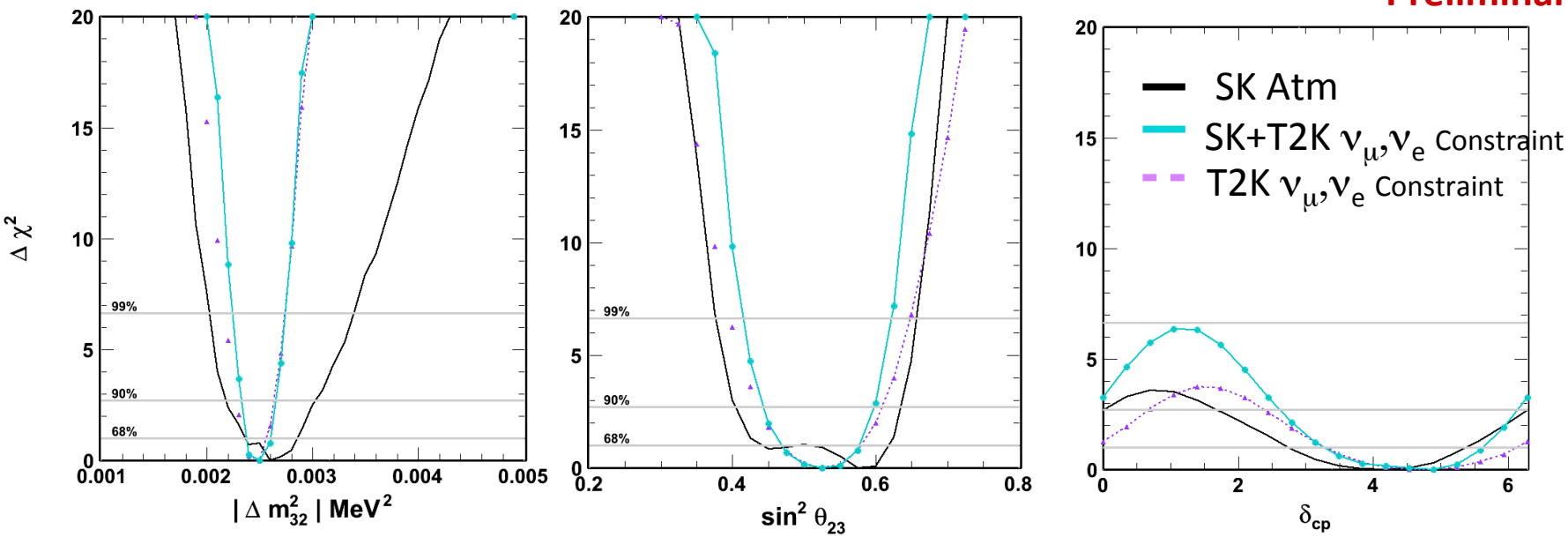
MINOS constraint is similarly important but harder to model accurately (so far...)





θ_{13} Fixed SK + T2K ν_μ, ν_e , Normal Hierarchy

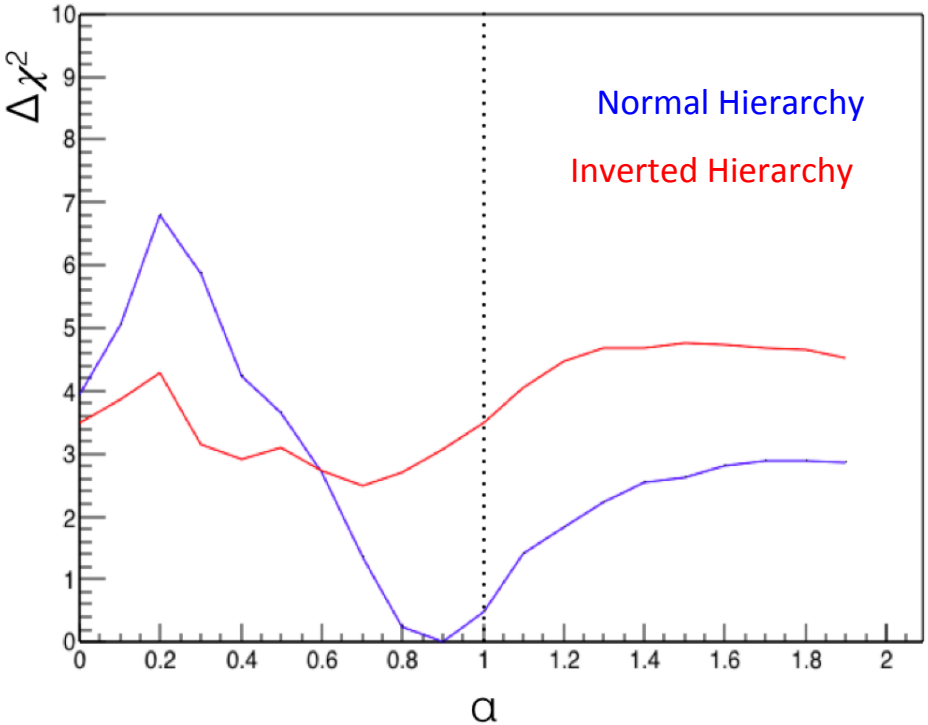
Preliminary



Fit (517 dof)	$\chi2$	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK + T2K (NH)	651.53	4.887	0.525	2.5
SK + T2K (IH)	654.73	4.189	0.550	2.4

- $\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (-3.0 SK only)
- **CP** Conservation ($\sin\delta_{cp} = 0$) allowed at (at least) 90% C.L. for both hierarchies

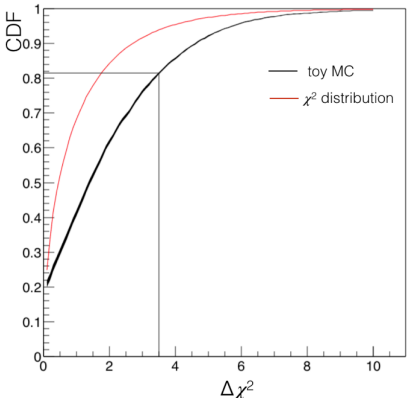
Test of Matter effect



- Atmospheric neutrino data in SK prefer the matter effect hypothesis or not?
- Introduce a phenomenological scaling factor α to electron potential:

$$H = UMU^{\dagger} + \alpha \cdot V_e$$

and carried out 3-flavor ν oscillation analysis.



- Best fit is at α = 0.9 for NH.
- $\Delta\chi^2$ = 3.5 (vacuum), 0.5(α=1.0)
- Based on Toy MC, vacuum case (α=0) excluded at 82% confidence. Weakly prefer existence of matter effect.

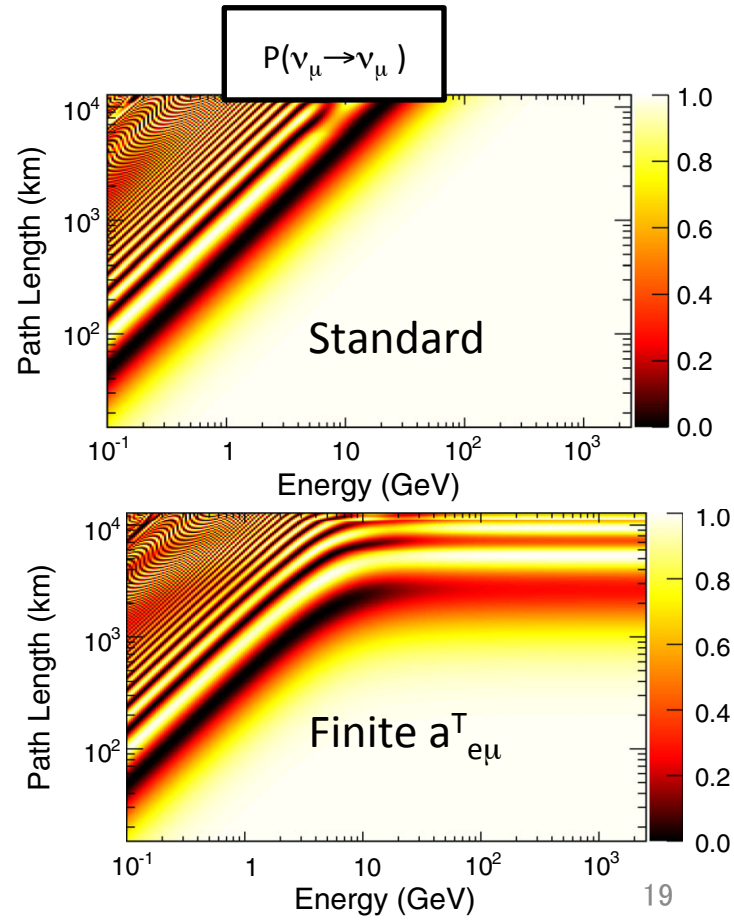
Tests of Lorentz Invariance

PHY. REV.D 91, 052003 (2015)

- Non-standard terms from Lorentz invariance violating (LIV) effect is tested.

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger \pm \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \pm \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - E \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$

- In addition to Standard L/E dependence, L or L・E dependences are introduced.
- Spacially isotropic case is tested (sensitive to sidereal effects as well...)



Results

Most Stringent limit, (O(3)~O(7) improved

Re(a^T)			Im(a^T)		
eμ	eτ	μτ	eμ	eτ	μτ
2×10^{-23}	4×10^{-23}	8×10^{-24}	2×10^{-23}	2×10^{-23}	4×10^{-24}

Re(c^{TT})			Im(c^{TT})		
eμ	eτ	μτ	eμ	eτ	μτ
4×10^{-26}	2×10^{-24}	2×10^{-26}	4×10^{-26}	2×10^{-24}	2×10^{-26}

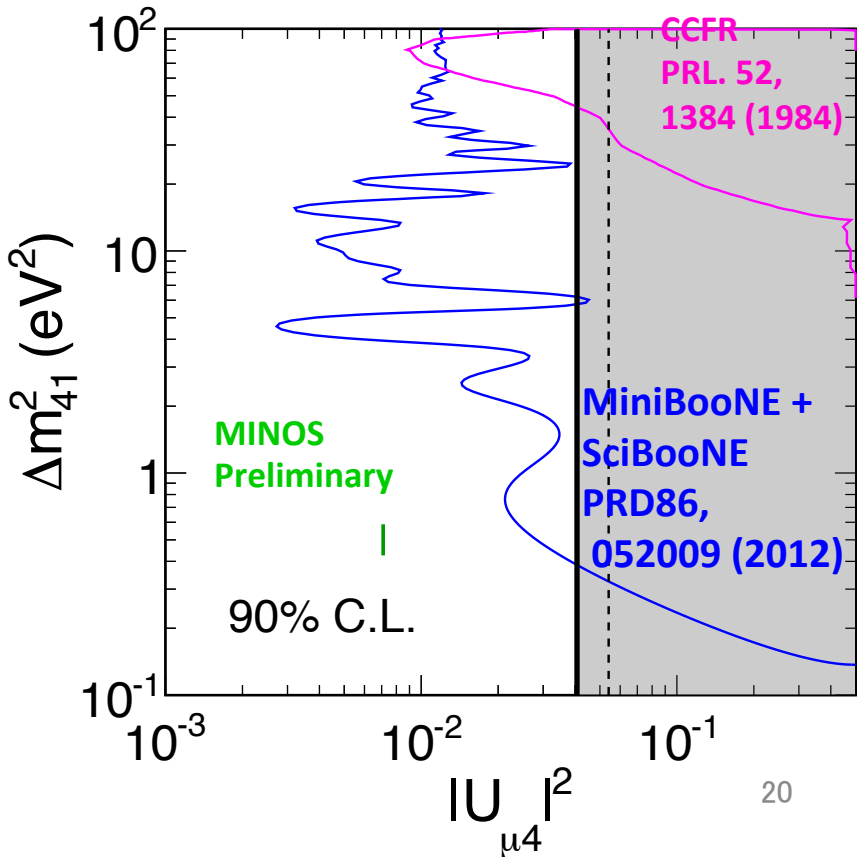
Sterile Neutrino Oscillations in Atmospheric Neutrinos

PHYS. REV.D 91, 052019 (2015)

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

PMNS Sterile

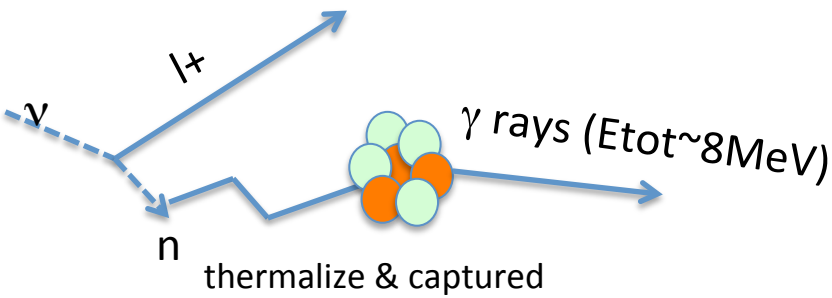
- (Standard neutrinos + sterile neutrinos) is tested for large Δm^2_{41} region (>0.01eV^2) .
- Two cases are investigated
  - U_{e4} is assumed to be 0.
  - No matter effect from NC potent on sterile neutrinos.
- Turning off sterile matter effects while preserving standard three-flavor oscillations provides a pure measurement of $|U_{\mu 4}|^2$
- As with similar experiments, no strong sterile-driven ν_μ disappearance
- $|U_{\mu 4}|^2 < 0.041$ at 90% C.L.



Super-K-Gd project

=Water Cherenkov detector with Gd dissolved water as neutron absorber

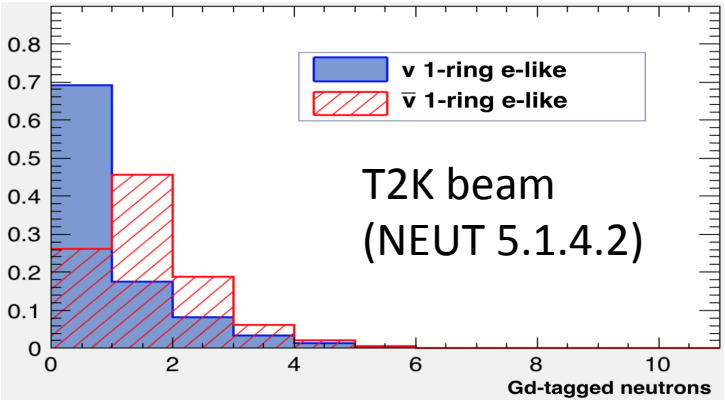
- High efficient neutron tagging using 0.2% $Gd_2(SO_4)_3$ dissolved water.
- Delayed coincidence of γ-ray signal from thermal neutron capture on Gd.



Physics targets:

- Supernova relic neutrino (SRN)
- Reduce proton decay background
- Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)

and more..



- 5yr evaluation experiment (EGADS) tests water quality, materials, basic techniques,..
- On June 27, 2015, the Super-Kamiokande collaboration approved the Super-K-Gd project.
- Actual schedule including refurbishment of the tank, Gd loading time will be determined soon taking into account the T2K schedule.

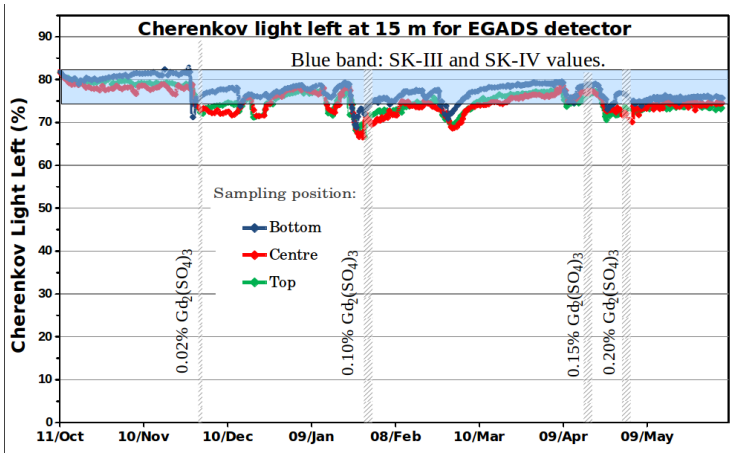
Summary

- Presented new result with 4972 days SK data
  - 3-flavor neutrino oscillation
    - $\chi^2_{NH} - \chi^2_{IH}$ = **-3.0** (**-3.2** with T2K external)
    - Weakly favor Normal hierarchy, but not significant.
    - Weakly favor non-zero θ_{13}
- Test matter effect
  - No matter effect is weakly disfavored by 86% C.L.
- 3.8σ evidence of ν_τ appearance
- Non-standard ν oscillation
  - No indication of Lorentz invariance violation.
  - No indication of sterlie neutrino oscillation .
- Neutrino flux measurement via Super-K data
- Super-K next project
  - Super-Kamiokande approved SK-Gd project

Supplements

After ~5yr Technical Evaluation experiment (EGADS) , we proved that basic techinique is

☑Gd water transparency must be similar to SK water
☑Effect of Gd to detector materials
☑Effect of Gd water quality to physics analysis
☑How to stop leak of SK detector
(But still exploring improved methods)
☐Reduction of radioactive backgrounds in Gd powder
(only affects Lowe analysis)
☑ : done, ☐ : under study



"Mini" Super-K : same materials used

Measured Water quality → MC study for Physics

- On June 27, 2015, the Super-Kamiokande collaboration approved the Super-K-Gd project.
- Actual schedule including refurbishment of the tank, Gd loading time will be determined soon taking into account the T2K schedule.

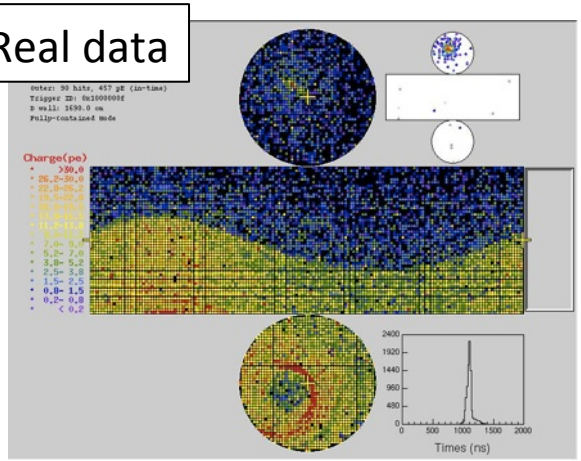
Official statement from Super-K collaboration

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water.

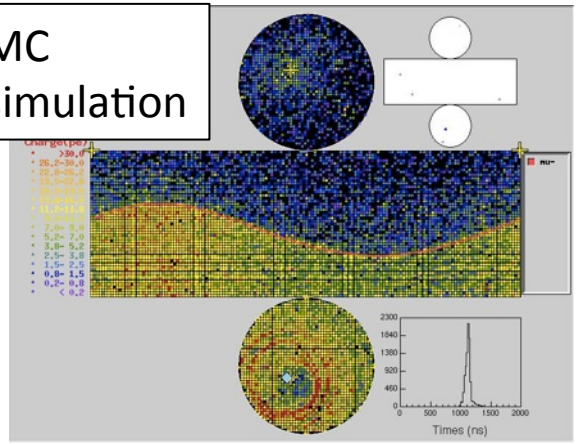
The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.

Calibration of the detector

Real data



MC simulation

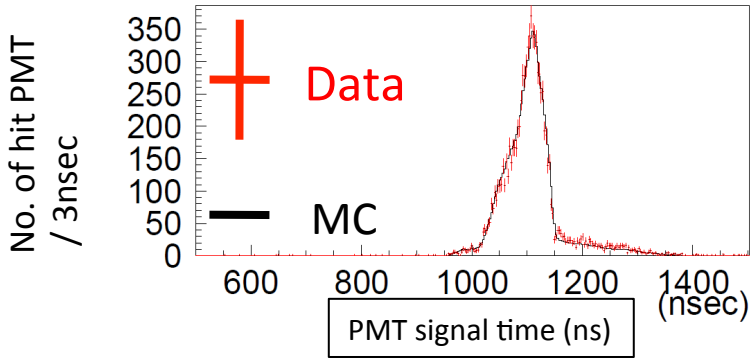


Detailed Calibration works has been done intensively with in-situ & ex-situ sources: (pulse laser, CRμ, electron LINAC, ..)

- Timing response of PMTs
- Gain of PMTs
- Water transparency measurement
- Detector Uniformity …

Well test the event reconstruction performance

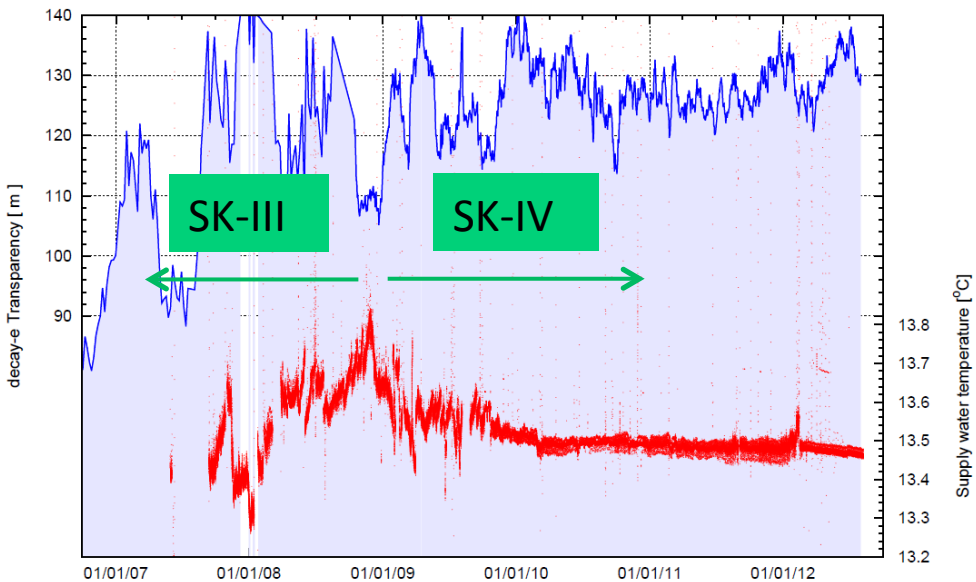
- Vertex, direction
- Particle identification
- Energy reconstruction, …

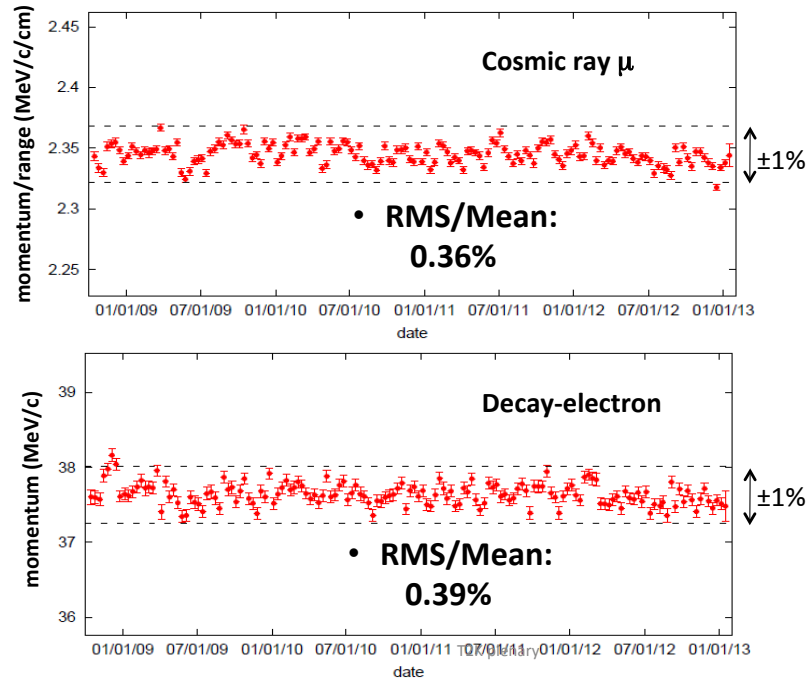
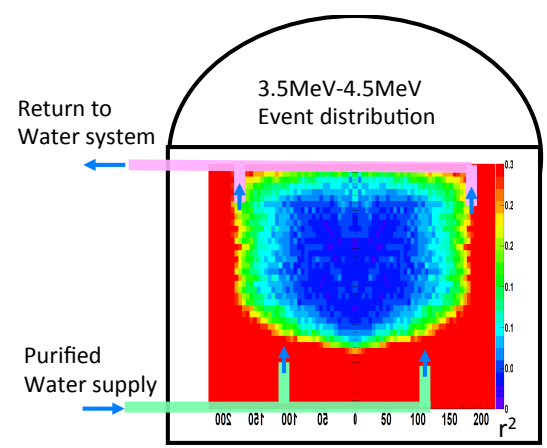


Full Monte Carlo (MC) simulation has been developed based on measurements of fundamental parameters & available models.

Stability

Key issue is a water quality.





- Keep water quality by continuous purification of the water.
- Carefully control the flow inside Super-K
- Water transparency is continuously monitored and taken into account in event reconstruction.
- 1% level stability of energy estimation.