Recent SK high-E results

S.Mine (UCI) for SK collaboration

Introduction

- nucleon decay searches:
  - motivation:
    - direct experimental test of Grand Unified Theories (GUTs)
    - $O(10^{16})$GeV is not reachable by accelerators, and so on..
  - several papers were published within a year
    - especially, many analysis improvements in $p \rightarrow \nu K^+$
    - several new searches for the first time by SK
- atmospheric neutrino oscillation analyses:
  - we have sensitivity to the mass hierarchy and CPV
  - we can study many things including exotic scenario test

(continued)

- SK has the world's best sensitivities in many analyses thanks to:
  - large fiducial volume
  - long stable detector operation
  - wide range of atmospheric ν energy and travel length

- SK detector is well calibrated* and stable:
  - momentum time variation: ~0.5% (SK-IV)
  - mis.-PID ($\mu \rightarrow e$) time variation: ~0.1% (SK-IV)

* Nucl. Instr. & Meth, A 737C (2014)

Recent published documents

- Calibration of the Super-Kamiokande Detector, The Super-Kamiokande Collaboration, Nucl. Instr. & Meth, A 737C (2014)

- Search for proton decay via p→νK+ using 260 kiloton·year data of Super-Kamiokande , The Super-Kamiokande Collaboration, Phys. Rev. D.90, 072005 (2014) ←this report
- Search for Nucleon Decay via n → νπ0 and p → νπ0 in Super-Kamiokande, The Super-Kamiokande Collaboration, Phys. Rev. Lett. 113, 121802 (2014) ←this report
- Search for Trilepton Nucleon Decay via p→e + νν and p→μ + νν in the Super-Kamiokande Experiment, The Super-Kamiokande Collaboration, Phys. Rev. Lett. 113, 101801 (2014) ←this report
- Search for Dinucleon Decay into Kaons in Super-Kamiokande , The Super-Kamiokande Collaboration, Phys. Rev. Lett. 112 (2014)

- Limits on Sterile Neutrino Mixing using Atmospheric Neutrinos in Super-Kamiokande, The Super-Kamiokande Collaboration, arXiv:1410.2008 ←this report
- Test of Lorentz Invariance with Atmospheric Neutrinos, The Super-Kamiokande Collaboration, arXiv:1410.4267

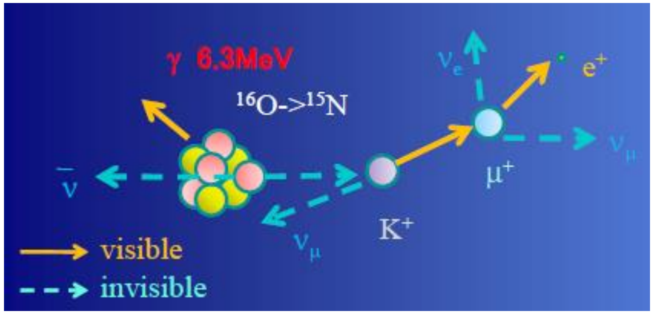
Nucleon decay searches

$p \rightarrow \nu K^+$ search

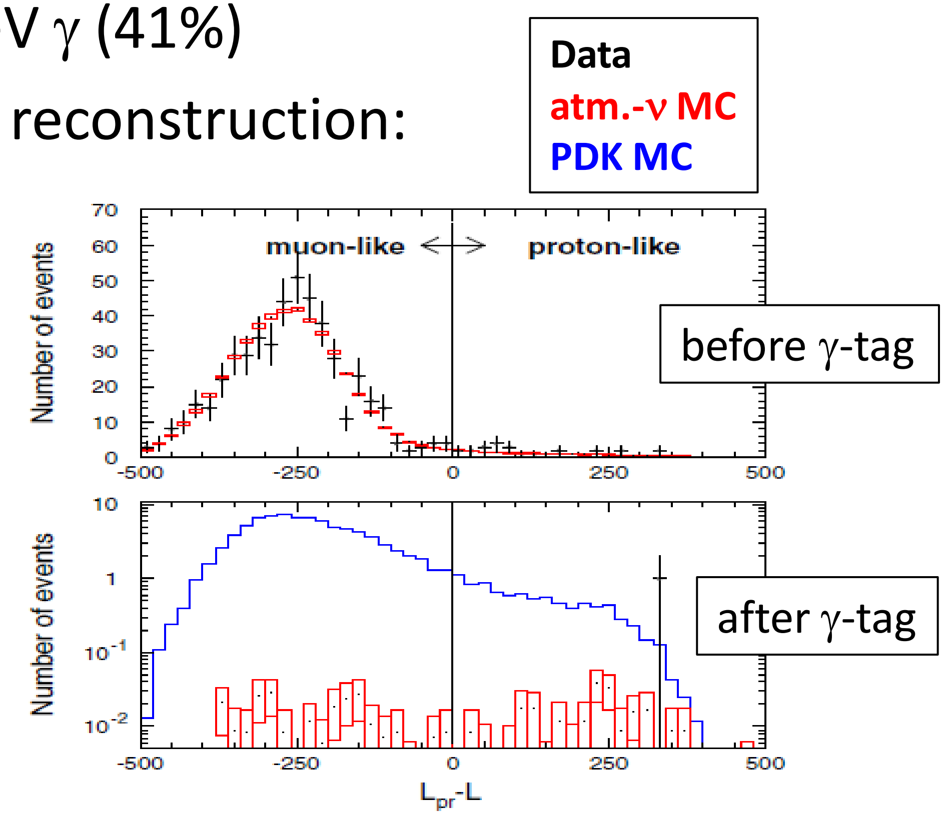
- dominant decay mode in supersymmetry(SUSY)-GUTs:
  - some models predict lifetime < ~10^{34} years → probed by this experimental search
- many improvements in the analysis and published in Phys. Rev. D.90, 072005 (2014)
- major improvements since our previous publication in 2005 using only SK-I data:
  - new data from SK-II to SK-IV → total exposure: 260kiloton·year used in this analysis
  - event reconstructions and selections
  - new readout electronics module in SK-IV → higher Michel electron tagging efficiency

Prompt γ method

(M.Miura)

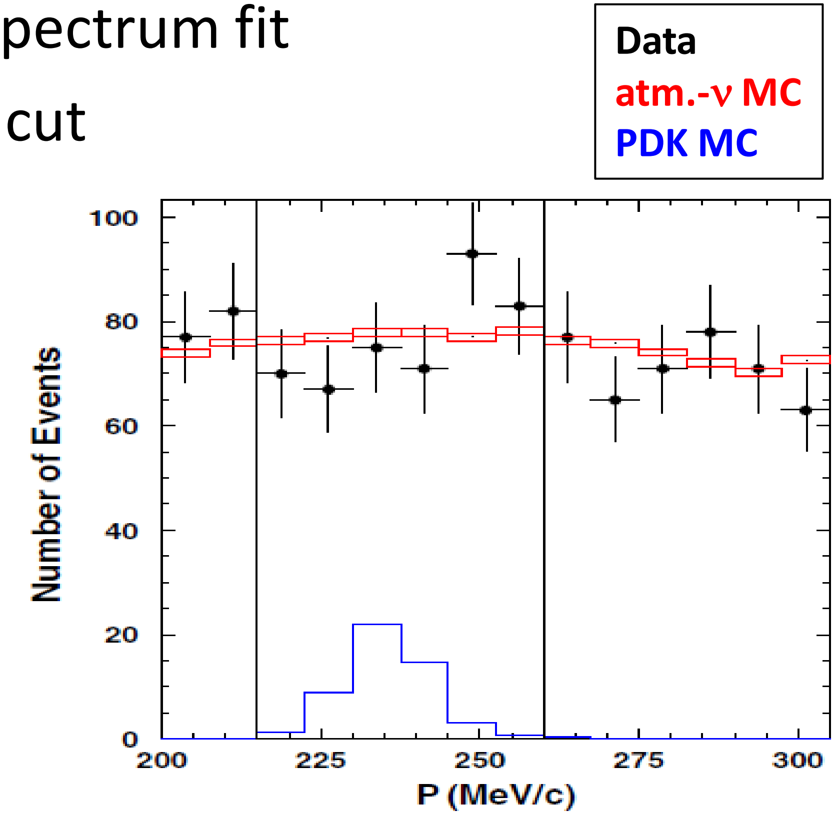


- $p \rightarrow \nu K^+$, $K^+ \rightarrow \mu\nu$ with prompt γ:
  - K^+ invisible
  - P_μ = 236MeV/c
  - excited nucleus emits 6MeV γ (41%)
- major improvements in event reconstruction:
  - Michel electron
  - muon/proton separation
- **for SK-I:**
  - **BKG: 0.7→0.08events**
  - **signal ε: 8%↘**



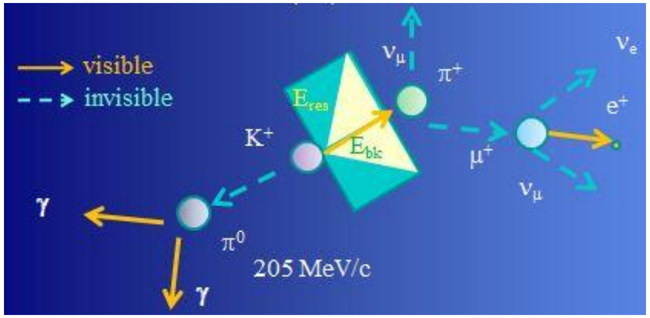
P_μ spec. method

- $p \rightarrow \nu K^+$, $K^+ \rightarrow \mu\nu$
- relaxed momentum cut for spectrum fit
- rejected events by prompt γ cut
- no excess in signal region



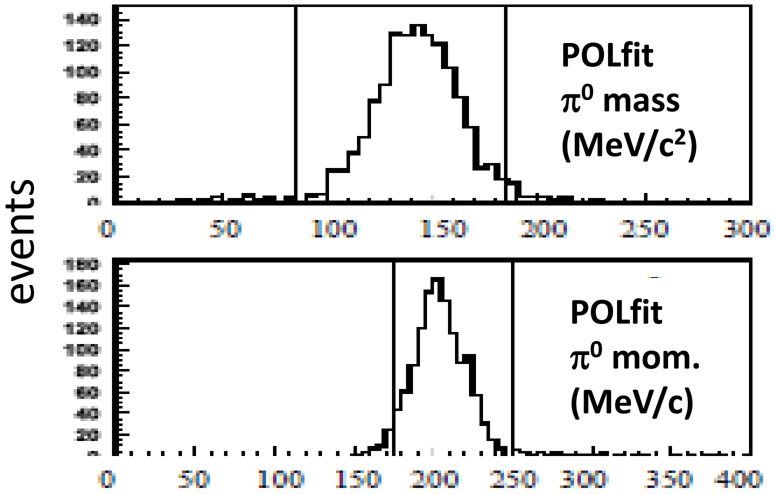
$\pi^+\pi^0$ method

(M.Miura)



- p→νK^+, $K^+ \to \pi^+\pi^0$:
  - π^+ and π^0 are back-to-back
  - P_π = 205MeV/c ,
    just above Cherenkov threshold for π^+
- major improvements in event reconstruction
  - single-ring π^0 fitter (POLfit)
  - charge profile for π^+
- **for SK-I:**
  - **BKG: 30%↘**
  - **signal ε: 30%↗**

single ring π^0 events



Result on p→νK⁺ search

TABLE V. Summary of the proton decay search with selection efficiencies and expected backgrounds for each detector period.

		SK-I	SK-II	SK-III	SK-IV
Exp.(kton · yrs)		91.7	49.2	31.9	87.3
Prompt γ	Eff.(%)	7.9 ± 0.1	6.3 ± 0.1	7.7 ± 0.1	9.1 ± 0.1
	BKG/Mt · yr	0.8 ± 0.2	2.8 ± 0.5	0.8 ± 0.3	1.5 ± 0.3
	BKG	0.08	0.14	0.03	0.13
	OBS	0	0	0	0
P_μ spec.	Eff.(%)	33.9 ± 0.3	30.6 ± 0.3	32.6 ± 0.3	37.6 ± 0.3
	BKG/Mt · yr	2107 ± 39	1916 ± 35	2163 ± 40	2556 ± 47
	BKG	193	94.3	69.0	223.1
	OBS	177	78	85	226
$\pi^+\pi^0$	Eff.(%)	7.8 ± 0.1	6.7 ± 0.1	7.9 ± 0.1	10.0 ± 0.1
	BKG/Mt · yr	2.0 ± 0.4	3.4 ± 0.6	2.3 ± 0.4	2.0 ± 0.3
	BKG	0.18	0.17	0.09	0.18
	OBS	0	0	0	0

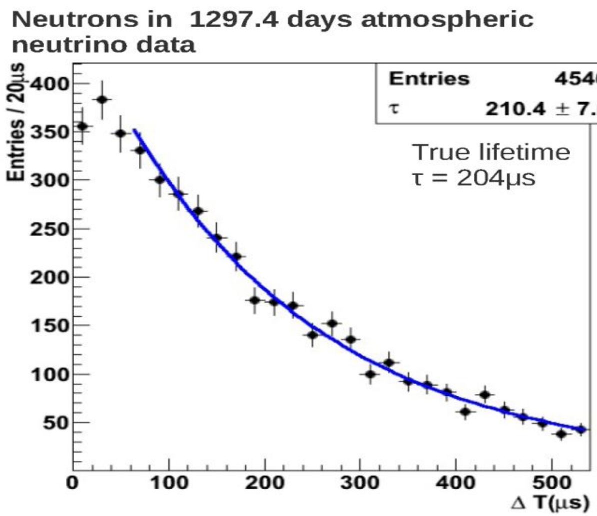
no excess above BGK expectation → combined lifetime limit:

$$\tau/B_{p\rightarrow\nu K+} > 5.9 \times 10^{33} \text{ years (90\% CL)}$$

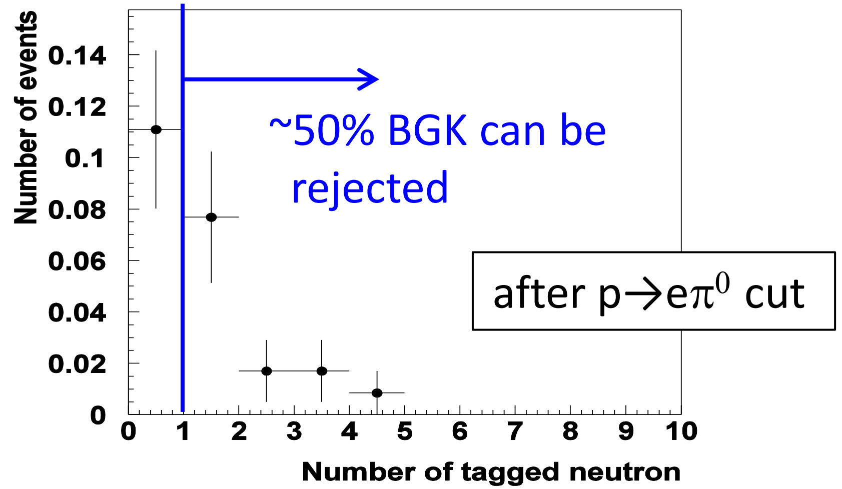
- 2.5 times more stringent than our previous result
- constrains recent SUSY GUT models

p→eπ^0 search

- dominant decay mode in non-SUSY GUTs
- no update of lifetime limit result (>1.4 × 10^{34} years at 90%CL)
- major on-going improvements :
  - neutron tagging in SK-IV (n+p→d+γ(2.2MeV), τ=204μs)
  - sophisticated event reconstruction algorithm
  - reduction of systematic errors



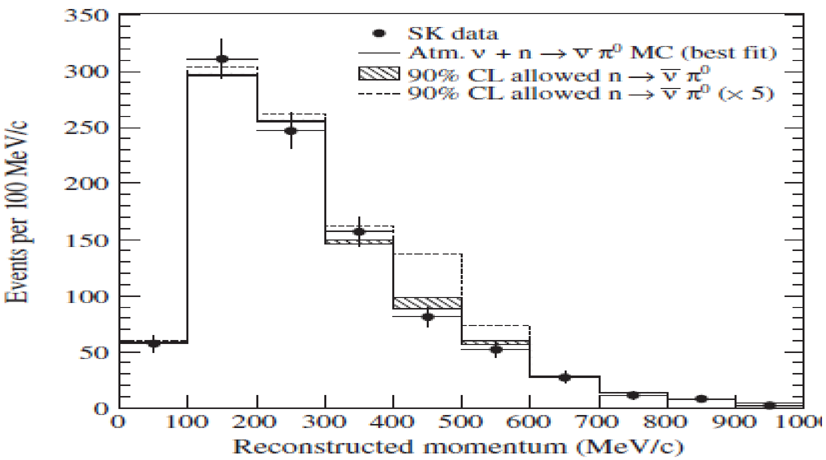
atm.-ν MC in SK-IV

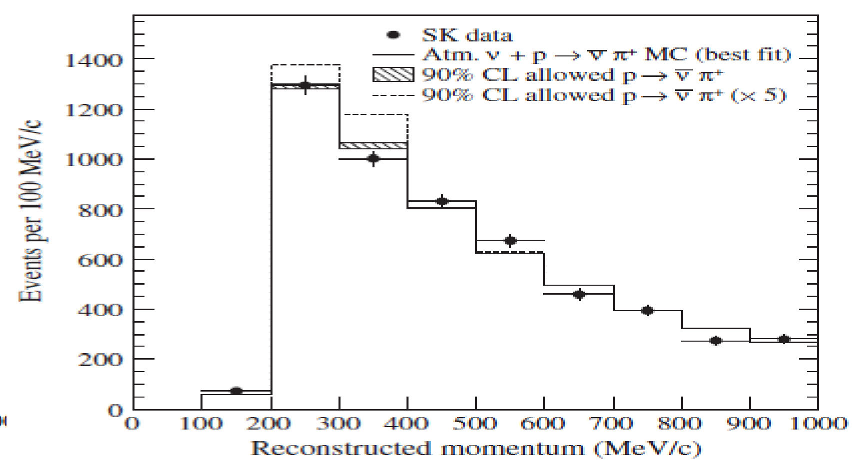


$n \to \bar{\nu}\pi^0$ and $p \to \bar{\nu}\pi^+$ searches

Phys. Rev. Lett. 113, 121802 (2014)

- minimal SUSY SO(10) model with a **126** Higgs field predicts $\tau(n \to \bar{\nu}\pi^0) = 2\tau(p \to \bar{\nu}\pi^+) \leq 5.7\text{-}13 \times 10^{32}$ years
- data from SK-I to SK-III → total exposure: 172.8kiloton·year





no excess in signal region:

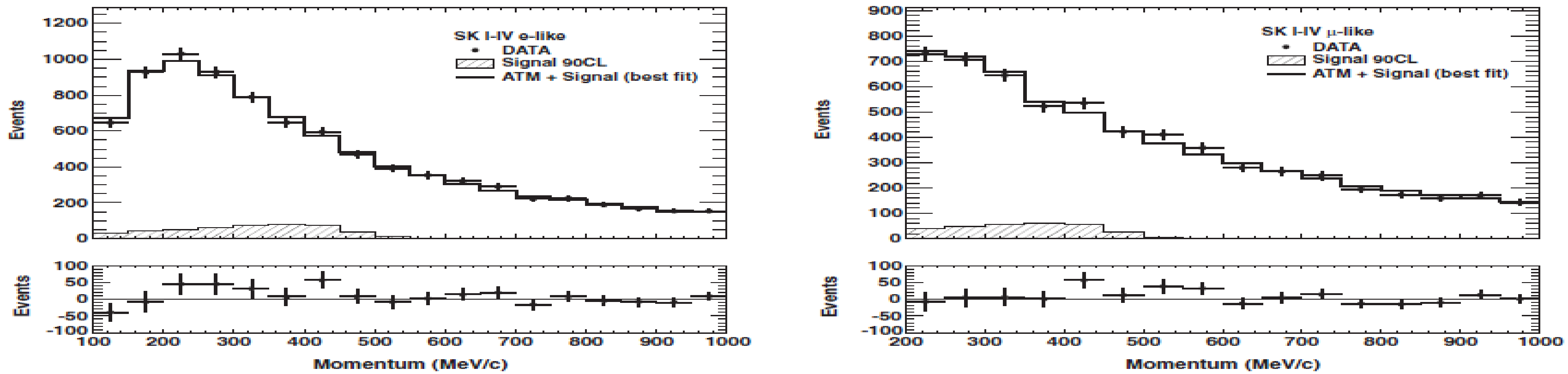
$\tau/B_{n \to \nu\pi 0} > 1.1 \times 10^{33}$ and $\tau/B_{p \to \nu\pi +} > 3.9 \times 10^{32}$ years (90% CL)

- model's allowed ranges are nearly ruled out
- an order of magnitude improvement over previously published limits

p→ eνν and p→μνν searches

Phys. Rev. Lett. 113, 101801 (2014)

- some SO(10) models embedded in Pati-Salam's left-right symmetric model predict lifetimes around 10^{30}-10^{33} years
- $|\Delta(B\text{-}L)| = 2$, unusual for standard decay channels
- data from SK-I to SK-IV → total exposure: 273.4kiloton·year



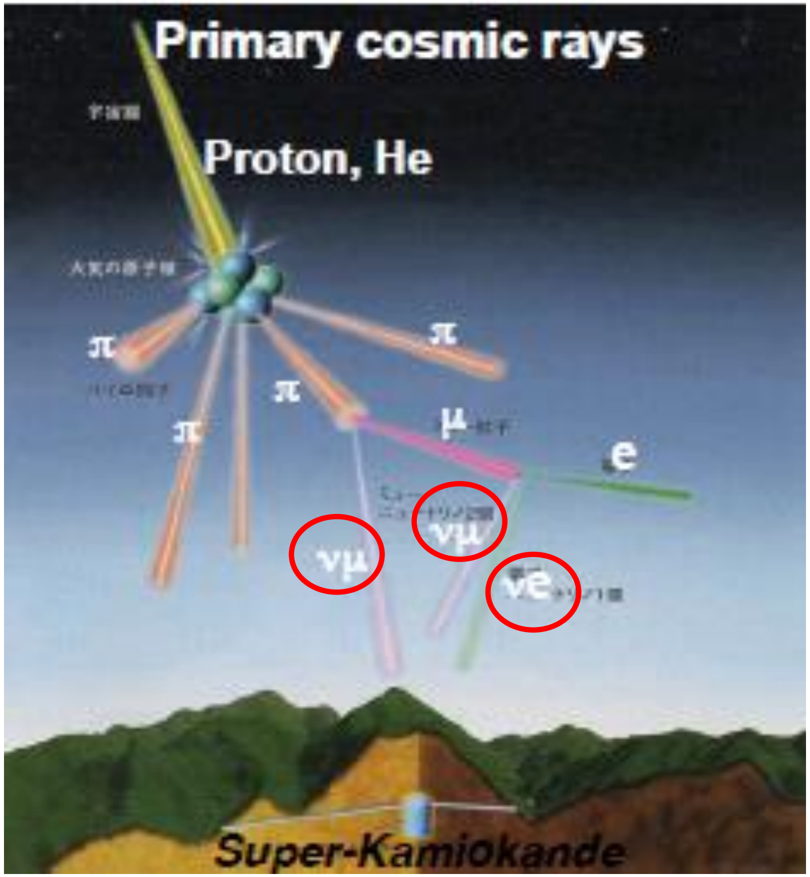
no significant excess in signal region:

$\tau/B_{p\to e\nu\nu} > 1.7\times10^{32}$ and $\tau/B_{p\to\mu\nu\nu} > 2.2\times10^{32}$ years (90% CL)

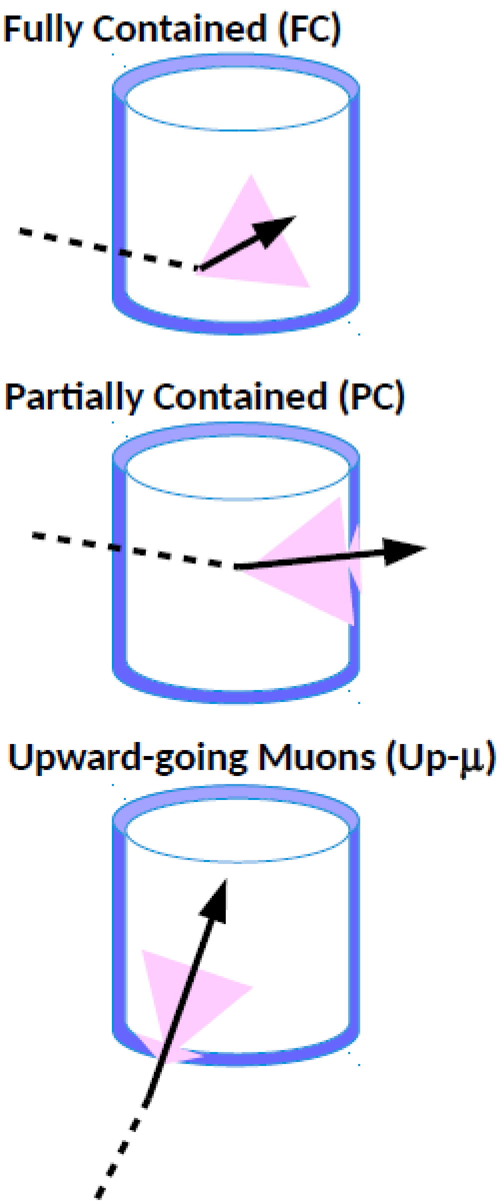
- an order of magnitude improvement over previous results
- provide strong constraints to the models

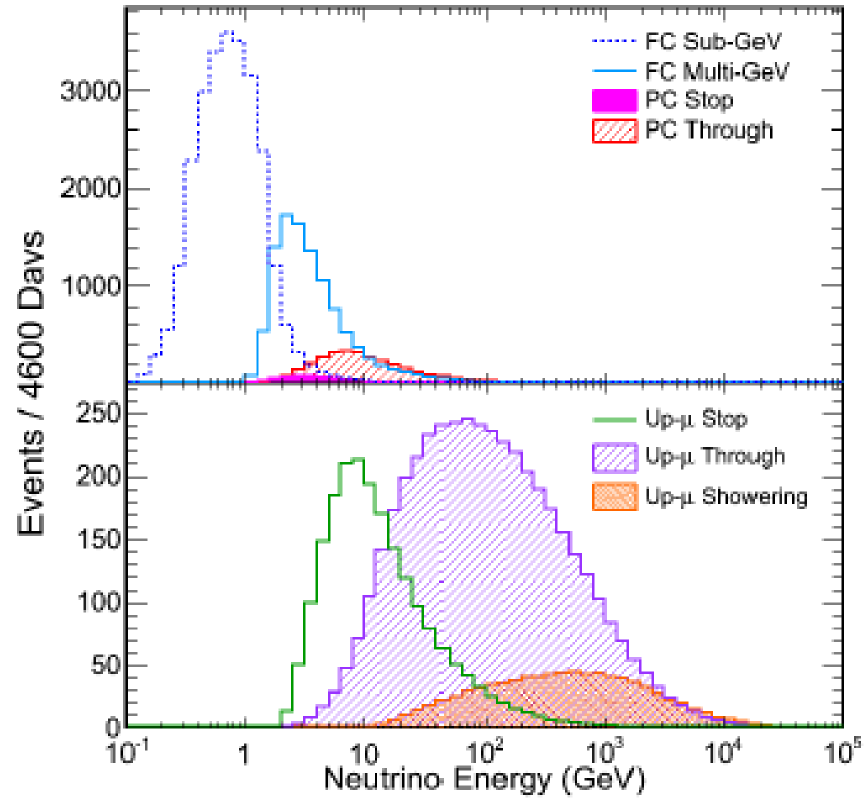
Atm.-ν oscillation analyses

Atmospheric neutrinos



- cosmic rays strike air nuclei and decay of hadrons gives νs
- #ν events > 40,000 in SK
- νs travel length: ~10-10,000km
- νs energy: ~0.1-10^4GeV
- both νs and $\bar{\nu}$s
  - ~30% for $\bar{\nu}$s in final samples
- background for nucleon decay searches



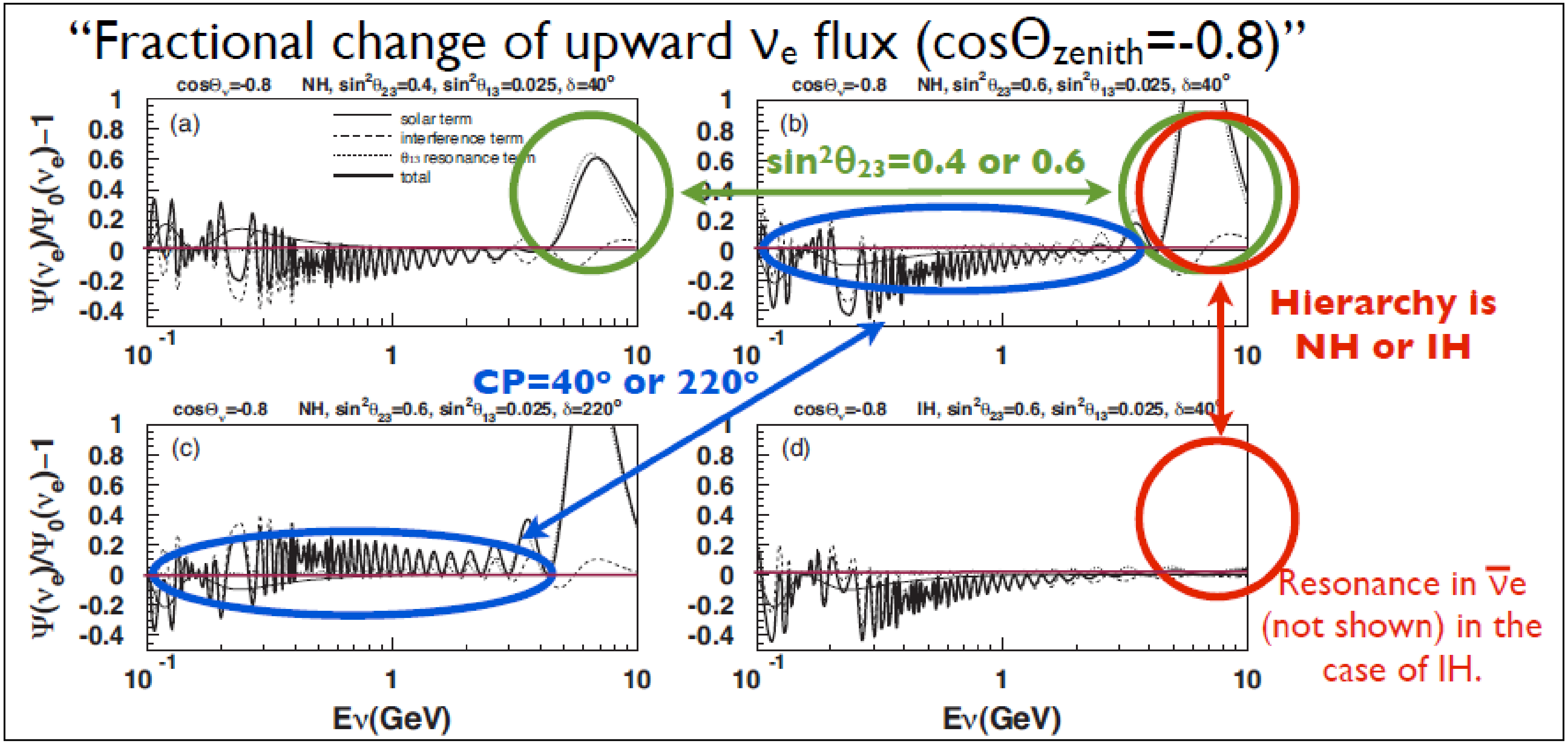


average energies:

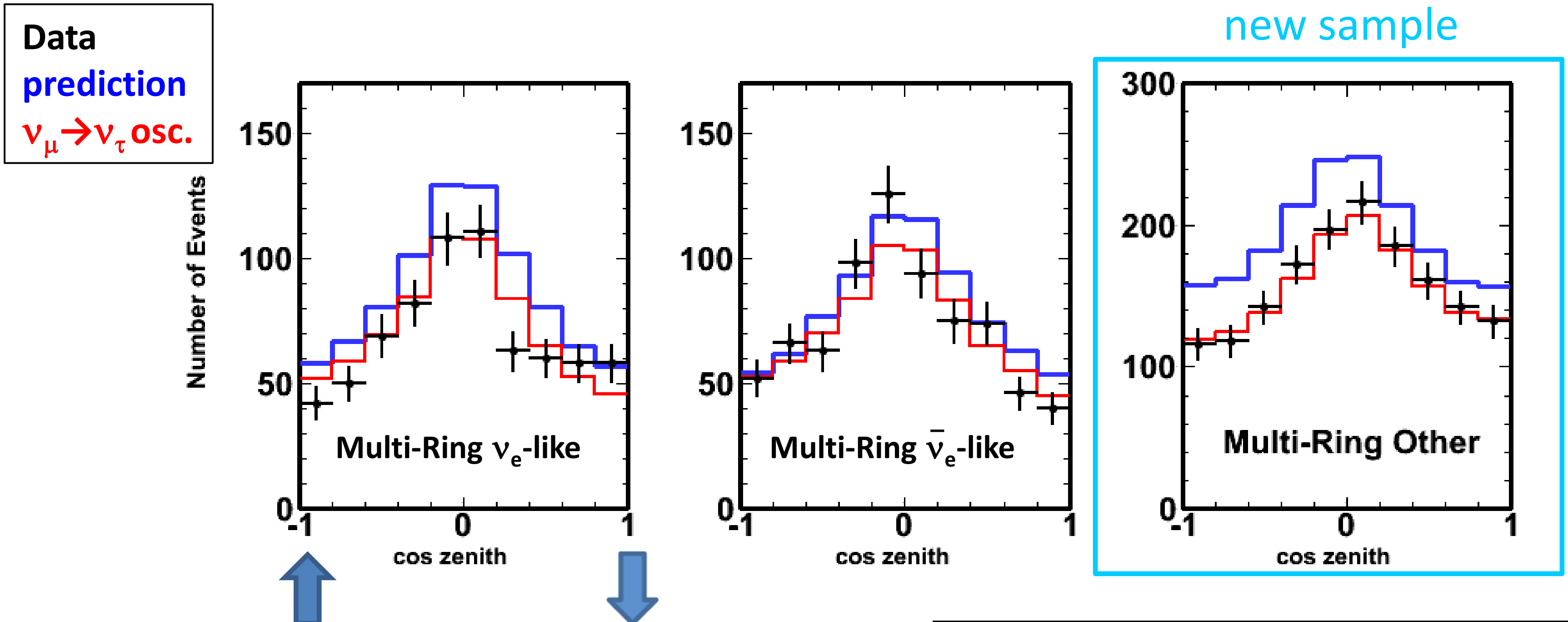
- FC: ~1GeV
- PC: ~10GeV
- UpMu: ~100GeV

Oscillation probabilities

(M.Shiozawa at ICHEP2014)



Updates to three flavor oscillation analyses

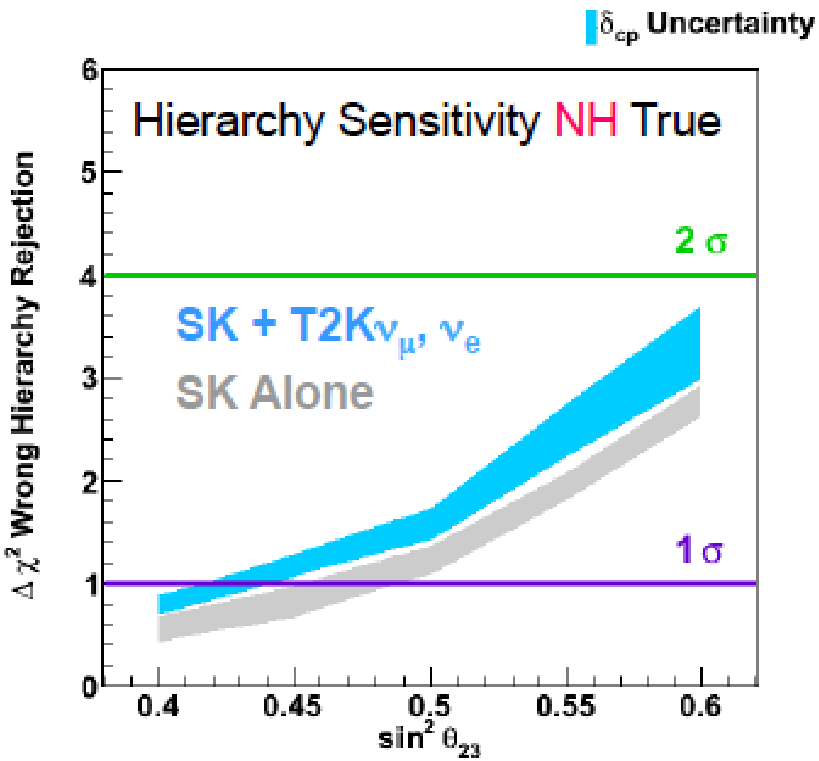


- "multi-ring other": events which fail multi-ring e-like CC purification likelihood
- improved systematic errors
- 282.2kiloton·year

Multi-Ring e-like Sample Purities

Purity	CC ν_e	CC ν_μ	CC ν_τ	NC
ν-like	72.2%	8.3%	3.2%	16.1%
$\bar{\nu}$-like	75.0%	6.5%	2.8%	15.6%
other	30.9%	33.4%	5.1%	30.5%

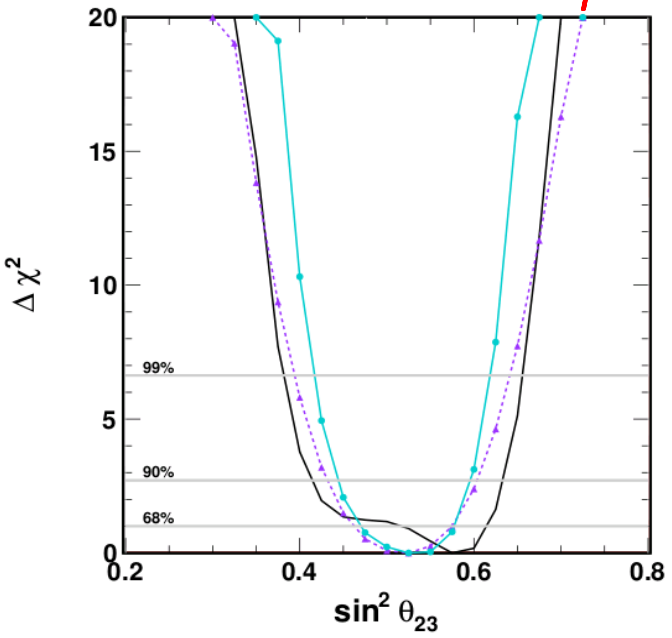
External constraints with T2K

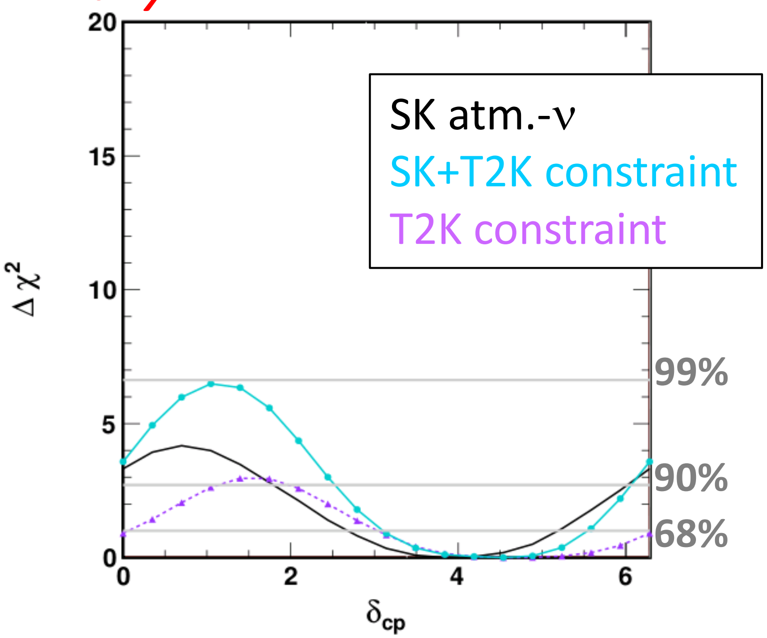


- T2K constraints on θ_{23} and Δm^2_{32} enhance mass hierarchy discrimination
- using a common SK detector, systematic errors are handled in consistent way

Results with T2K constraints

preliminary





Fit (543 dof)	$\chi2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

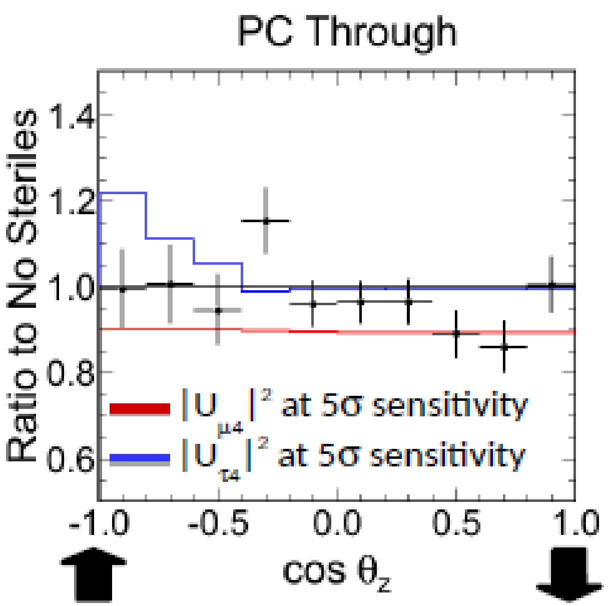
- θ_{23}: 2nd octant slightly favored
- δ_{CP}: preference near $3\pi/2$, CP conservation ($\sin\delta_{CP}$= 0) allowed at 90% CL
- $\chi^2_{IH} - \chi^2_{NH}$ = 1.2 (0.9 SK only), NH slightly favored

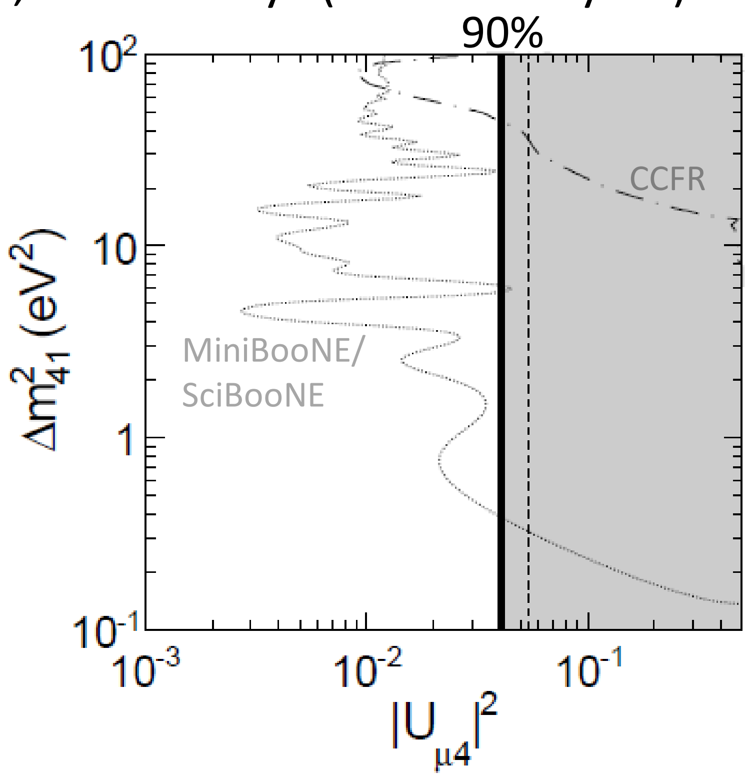
Sterile neutrino oscillations

arXiv:1410.2008

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

- sterile ν searches at SK are independent from sterile Δm^2 and #sterile ν
- 4,438 live-days (~274kilton·year)





- no evidence of sterile oscillations
- $|U_{\mu 4}|^2<0.041$ and $|U_{\tau 4}|^2<0.18$ for $\Delta m^2>0.8\text{eV}^2$ (90% CL)

Summary

- nucleon decay searches:
  - no evidence of nucleon decay so far → most stringent lifetime limits in the world
- atmospheric neutrino analyses:
  - three-flavor analysis:
    - mass hierarchy: ~1σ preference for NH
    - θ_{23} octant: 2nd octant slightly favored
    - δ_{CP}: preference near $3\pi/2$. CP conservation allowed
  - no indication of non-standard models such as sterile ν → stringent limits on relevant parameters
- prospect of sensitivity improvements by neutrino tagging, sophisticated reconstruction algorithm, reducing systematic errors, and so on.