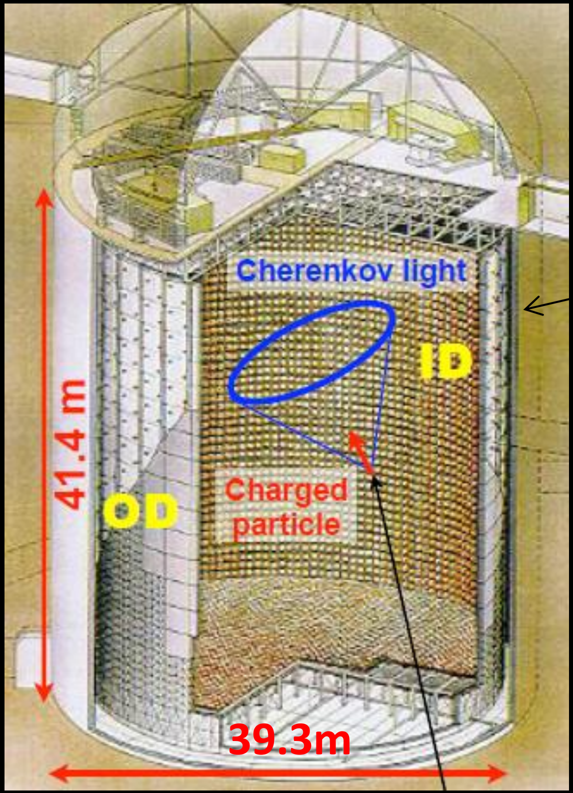
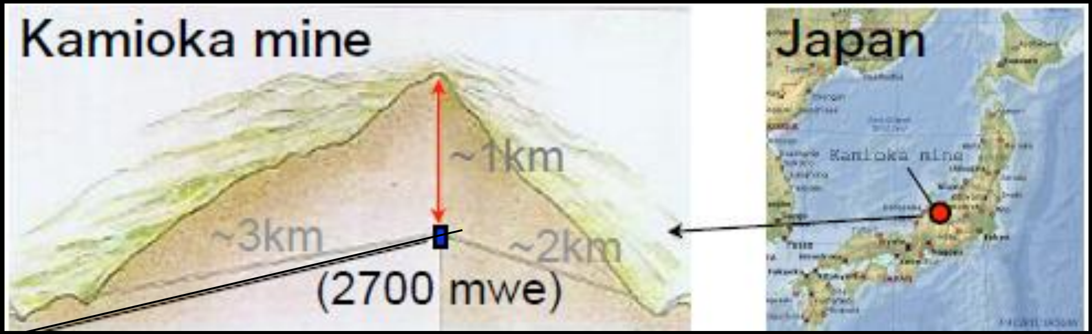
Atmospheric Neutrino and Proton Decay Studies in Super-Kamiokande

S.Mine(University of California, Irvine)
for SK collaboration

Super-Kamiokande(SK)





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

Phase		SK-I	SK-II	SK-III	SK-IV
Period	start end	1996 Apr. 2001 Jul.	2002 Oct. 2005 Oct.	2006 Jul. 2008 Sep.	2008 Sep. (running)
Number of PMTs	ID (photo-coverage)	11146 (40%)	5182 (19%)	11129 (40%)	11129 (40%)
	OD	1885			
Anti-implosion container		no	yes	yes	yes
OD segmentation		no	no	yes	yes
Front-end electronics		ATM (ID) OD QTC (OD)			QBEE

- SK total ~ 17 years

Recent published documents by SK

(within a year)

detector calibration:

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

nucleon decay searches:

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

atmospheric neutrino oscillation analyses:

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

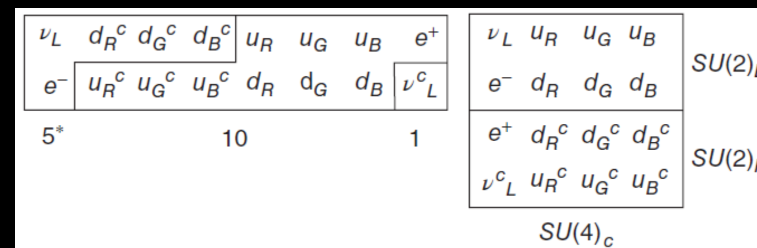
Nucleon Decay Searches

(atmospheric neutrinos as BKG)

Grand Unified Theory(GUT)

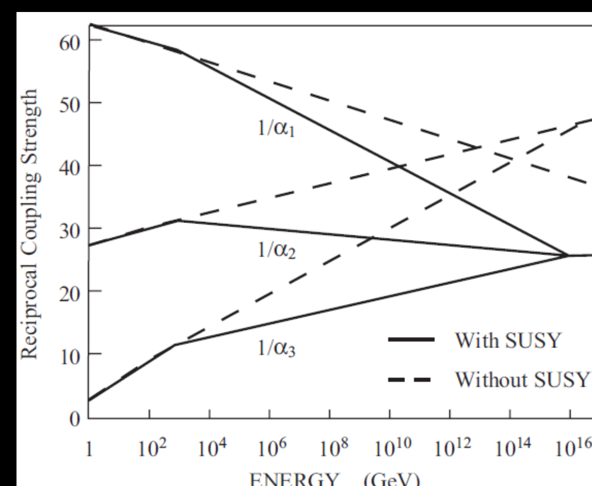
- single symmetry group G ⊃ $SU(3)_{color} \times SU(2)_L \times U(1)_Y$ → single coupling constant, quantization of electric charge, etc.

- popular models:
  - SO(10) GUT:



    - 15 fermions and $\nu_R(=\nu^C_L)$ in single representation, etc.
      - ν_R as partner in seesaw mechanism → ν_L mass light
  - supersymmetry(SUSY) GUT:
    - 3 coupling constants meet at ~10^{16}GeV, gravity, etc.

- GUT predicts instability of nucleon



Nucleon decay searches in SK

- SK has the world's best sensitivities on nucleon lifetime:
  - large fiducial volume (V)
    - 22.5kt → ~7.5×10^{33}protons
  - long stable detector operation since 1996 (T)
- lifetime limit $\propto \begin{cases} \varepsilon_{sig} / 2.3 \cdot VT \text{ (BKG free)} \\ \varepsilon_{sig} / \sqrt{\#BKG} \cdot \sqrt{VT} \text{ (BKG dominant)} \end{cases}$
  - important to increase signal efficiency and BKG rejection
- several new results published within a year
  - many analysis improvements in $p \rightarrow \nu K^+$
  - several new searches for the first time by SK

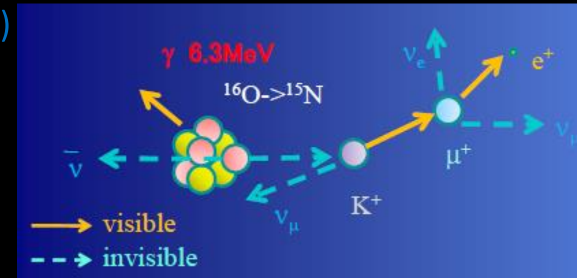
$p \to \nu K^+$ search

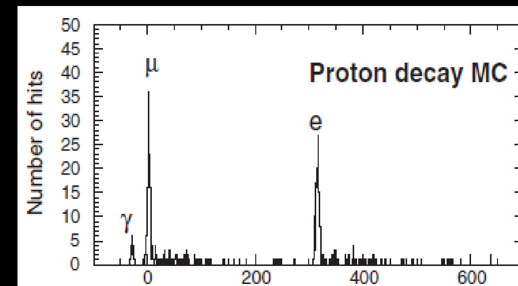
- dominant decay mode in SUSY GUTs
  - some models predict lifetime < ~10^{34} years → probed by this experimental search
- many improvements in the analysis and published in [Phys. Rev. D.90, 072005 (2014)]
  - highlighted with Synopsis by APS editor
- major improvements since SK publication in 2005 (SK-I data):
  - new data from SK-II to SK-IV → total: 260kt·year
  - event reconstructions and selections
  - new front-end electronics in SK-IV → higher Michel-e ε

(M.Miura)

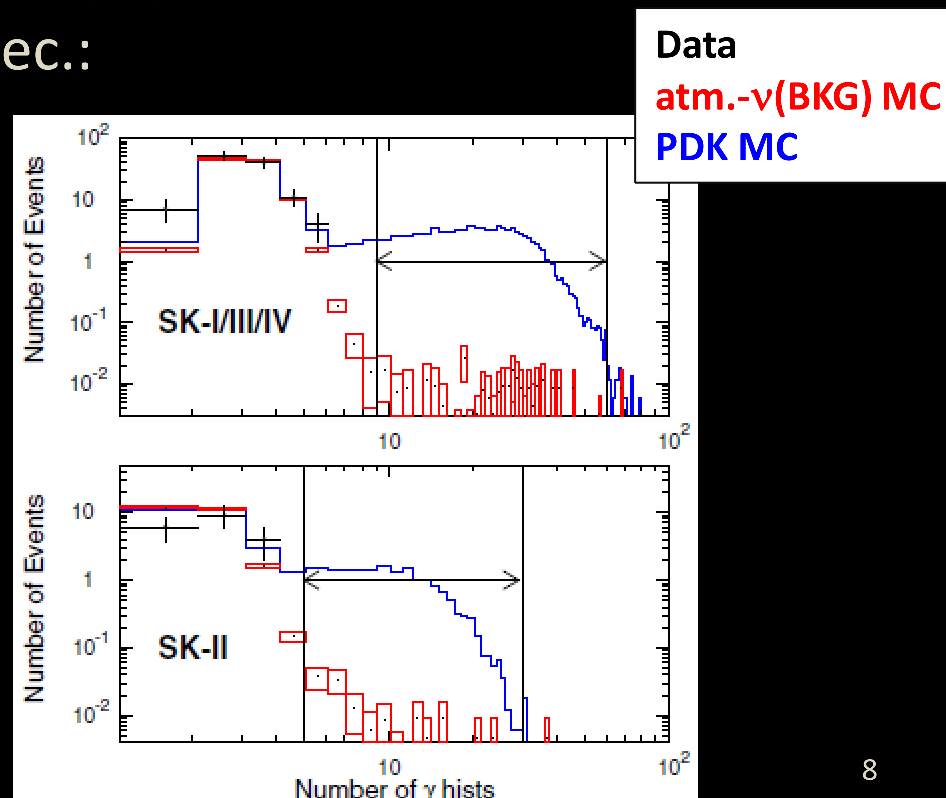
Prompt γ method:

($p \to \nu K^+$, $K^+ \to \mu\nu$ with prompt γ)



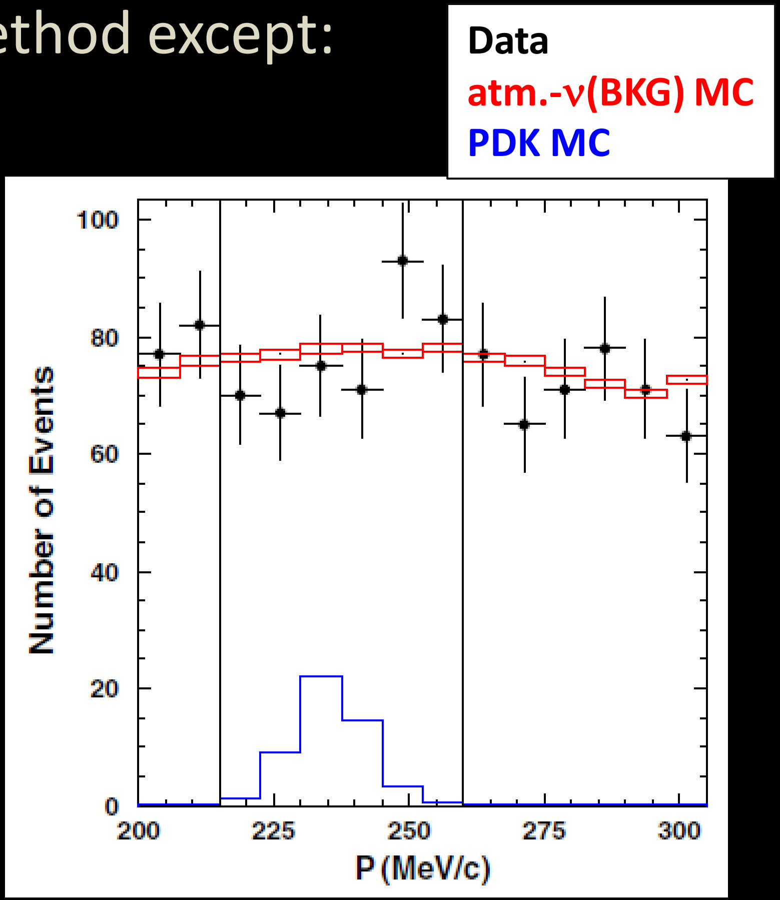


- SK cuts:
  - 1 μ-like with Michel-e, $215<P_\mu<260$MeV/c
  - proton ring rejection
  - $-8(4)<N_\gamma<60(30)$ for SK-I,III,IV(SK-II), $T_\mu - T_\gamma<75$ns
- major improvements in event rec.:
  - Michel-e
  - μ/p separation (new)
- for SK-I:
  - expected #BKG: 0.7→0.08
  - signal ε: 8.6%→7.9%
- no data candidate



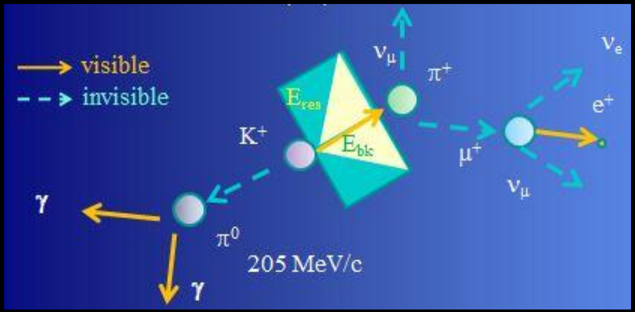
P_μ spectrum method:
($p \rightarrow \nu K^+$, $K^+ \rightarrow \mu\nu$)

- SK cuts same as the prompt γ method except:
  - relaxed momentum cut
  - no prompt γ hits
- no data excess in signal region



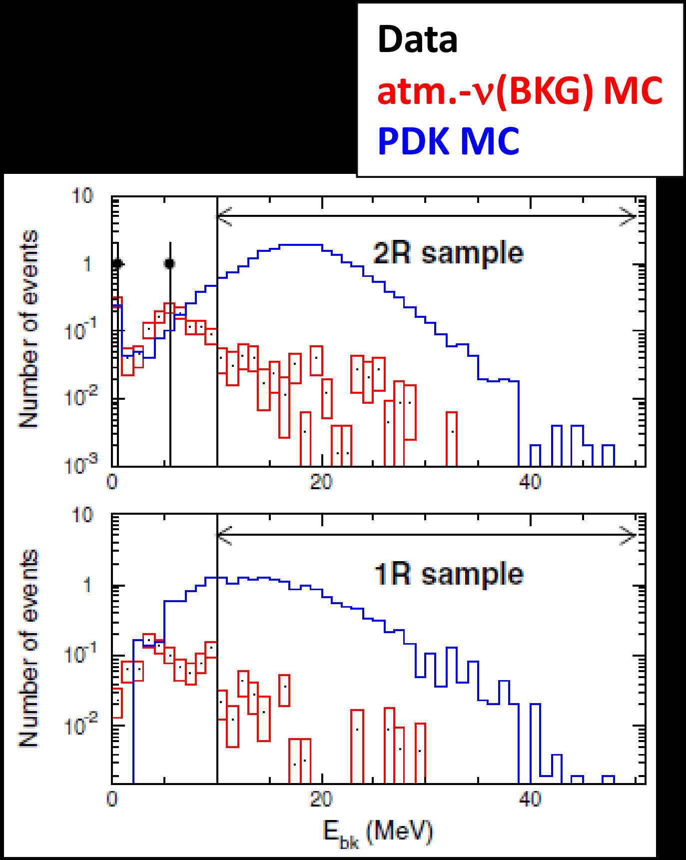
$\pi^+\pi^0$ method:

(M.Miura)



$(p \to \nu K^+, K^+ \to \pi^+\pi^0)$

- SK cuts:
  - 1 or 2 e-like rings with Michel-e
  - $85 < M_{\pi 0} < 185 MeV/c^2$, $175 < P_{\pi 0} < 250 MeV/c$
  - charge profile likelihood for π^+
  - $10 < E_{bk} < 50 MeV$ (E_{bk}: visible energy for π^+)
- major improvements in event rec.:
  - single-ring π^0 fitter (new)
  - π^+ charge profile
- for SK-I:
  - expected #BKG: 0.6→0.18
  - signal ε: 6.0%→7.8%
- no data candidate



Result on $p \to \nu K^+$ search

		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 (8.6%)	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 (0.7)	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 (6.0%)	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 (0.6)	0.17	0.09	0.18
	OBS	0	0	0	0

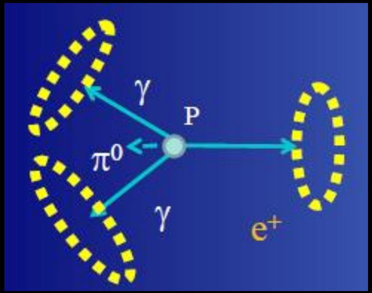
K. Kobayashi et al., Phys. Rev. D 72, 052007 (2005)

- total expected #BGK < 1 for prompt $\gamma/\pi^+\pi^0$ methods
- no data excess above BGK expectation

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

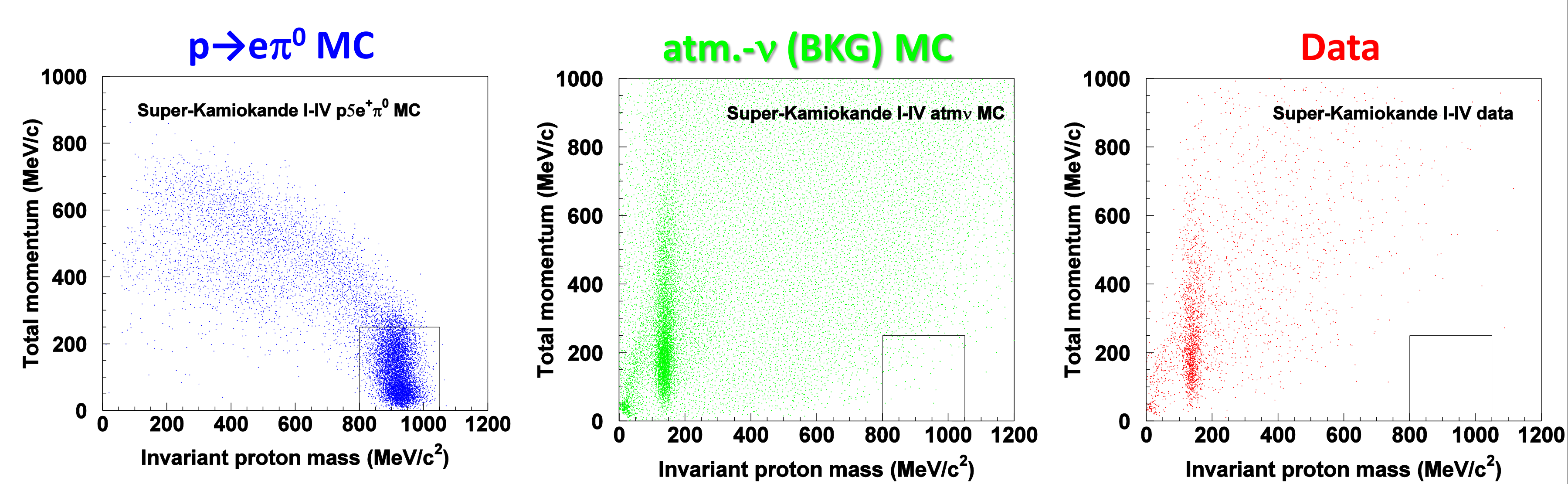
  - world's best limit
  - 2.5 times more stringent than previous result (2005)
  - constrains recent SUSY GUT models

$p \rightarrow e^+\pi^0$ search



(M.Miura)

- dominant decay mode in non-SUSY GUTs
- SK cuts:
  - 2 or 3 rings, all e-like, no Michel e, $85<M_{\pi 0}<185 MeV/c^2$(3-ring)
  - $800<M_p<1050 MeV/c^2$, $P_{tot}<250 MeV/c$



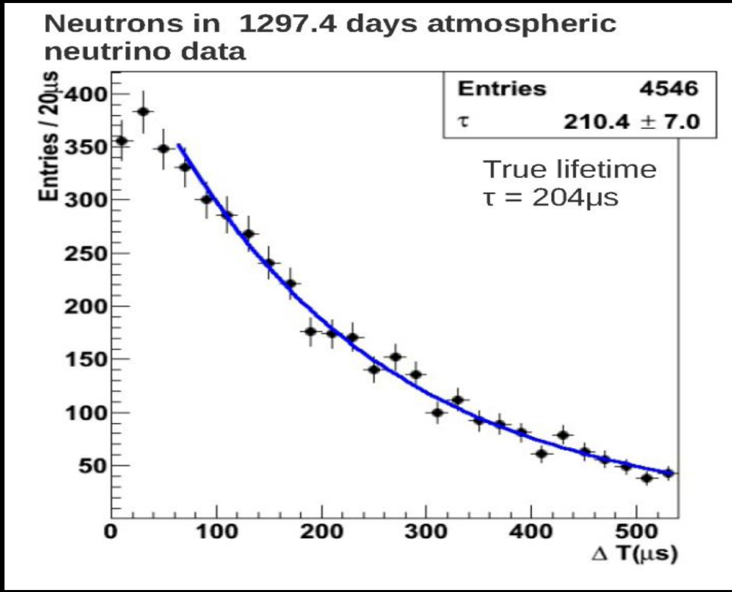
	Exp. (kt·yr) λ	Eff(%) ε	BKG b	Data n
SK1	91.7	39.2±0.7	0.27	0
SK2	49.2	38.5±0.7	0.15	0
SK3	31.9	40.1±0.7	0.07	0
SK4	87.3	39.5±0.7	0.22	0
Total	260.1		0.71	0

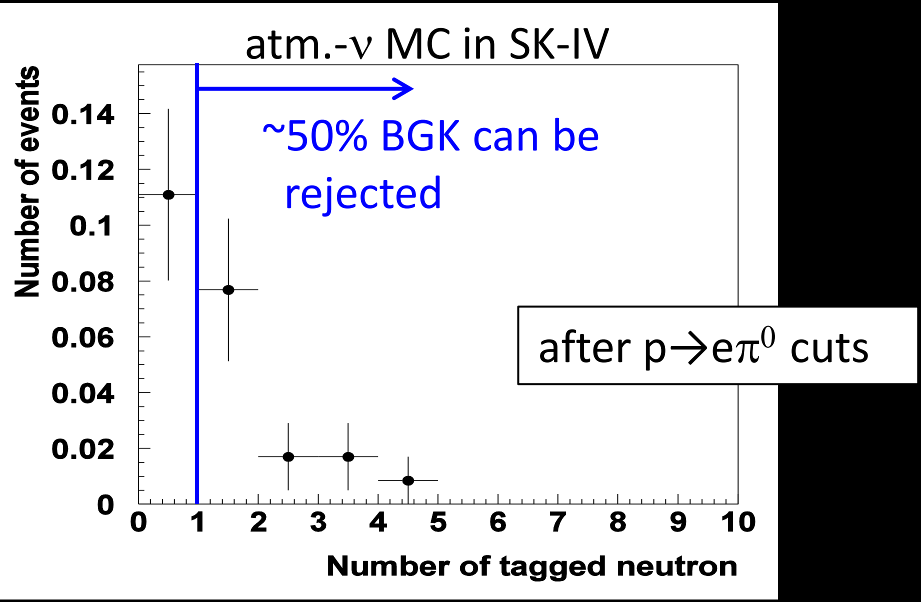
- signal ε~40% , total expected #BKG~0.7
- no data candidate

$\tau/B_{p\rightarrow e\pi 0} > 1.4 \times 10^{34}$ years (90% CL)
(world's best limit)

- major on-going improvements :
  - neutron tag in SK-IV
    - n + p → d + γ(2.2MeV)
  - sophisticated event reconstruction algorithm (see Suda-san's talk)
  - reduction of systematic errors (FSI, Fermi momentum, rec.,,,), etc.

ex.) neutrino tag performance

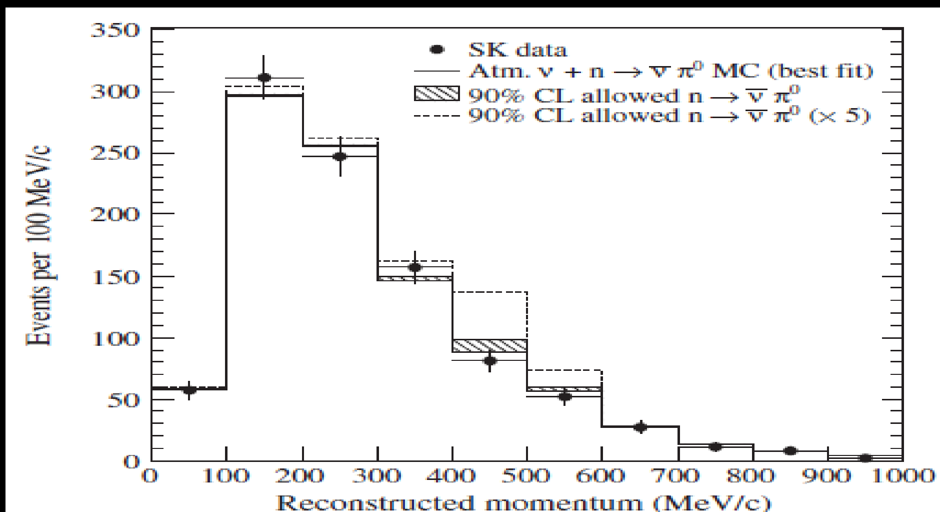


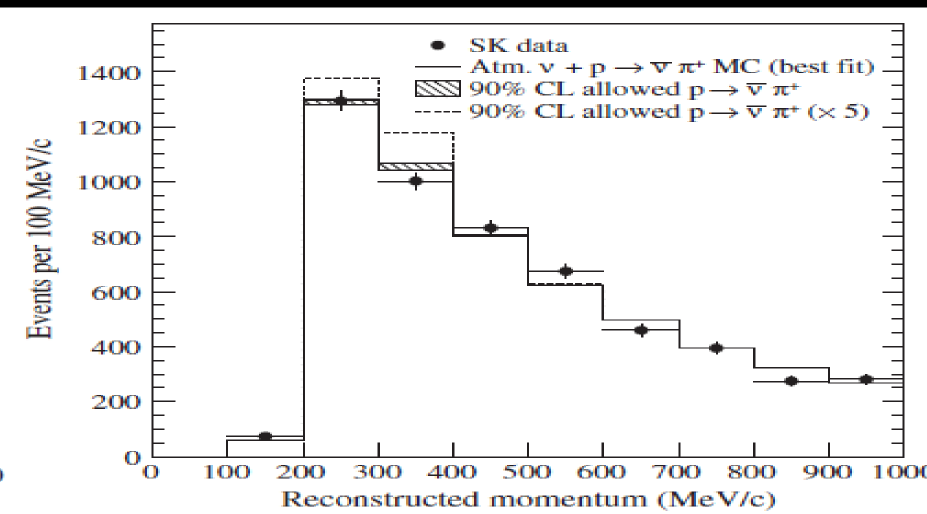


$n \rightarrow \overline{\nu}\pi^0$ and $p \rightarrow \overline{\nu}\pi^+$ searches

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

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





no excess in signal region:

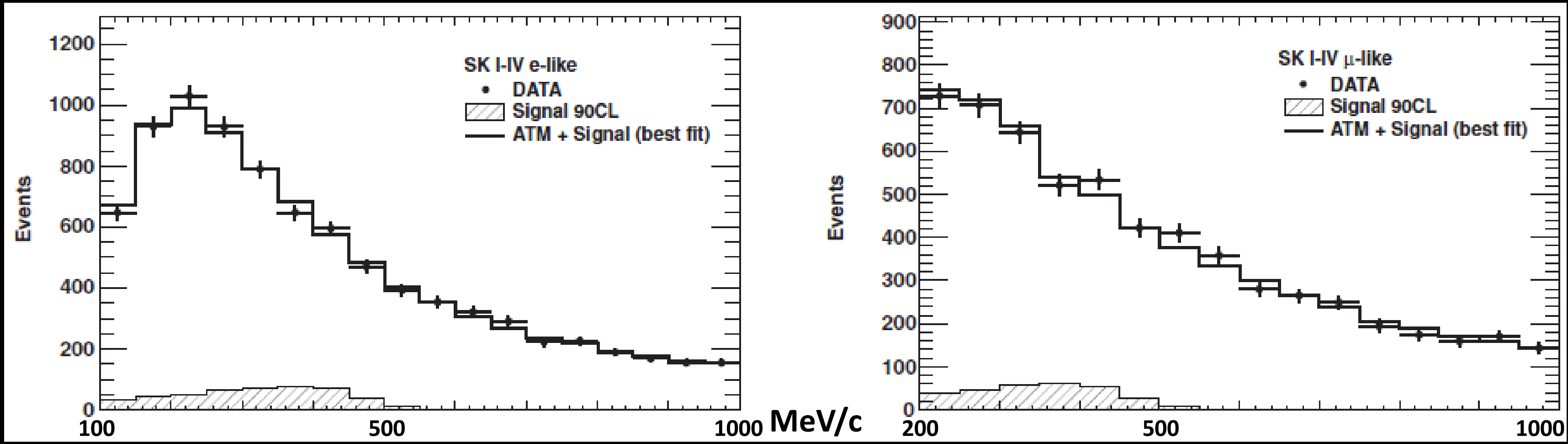
$\tau/B_{n\rightarrow\nu\pi 0} > 1.1 \times 10^{33}$ and $\tau/B_{p\rightarrow\nu\pi+} > 3.9 \times 10^{32}$ years (90% CL)

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

$p \to e\nu\nu$ and $p \to \mu\nu\nu$ searches

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

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



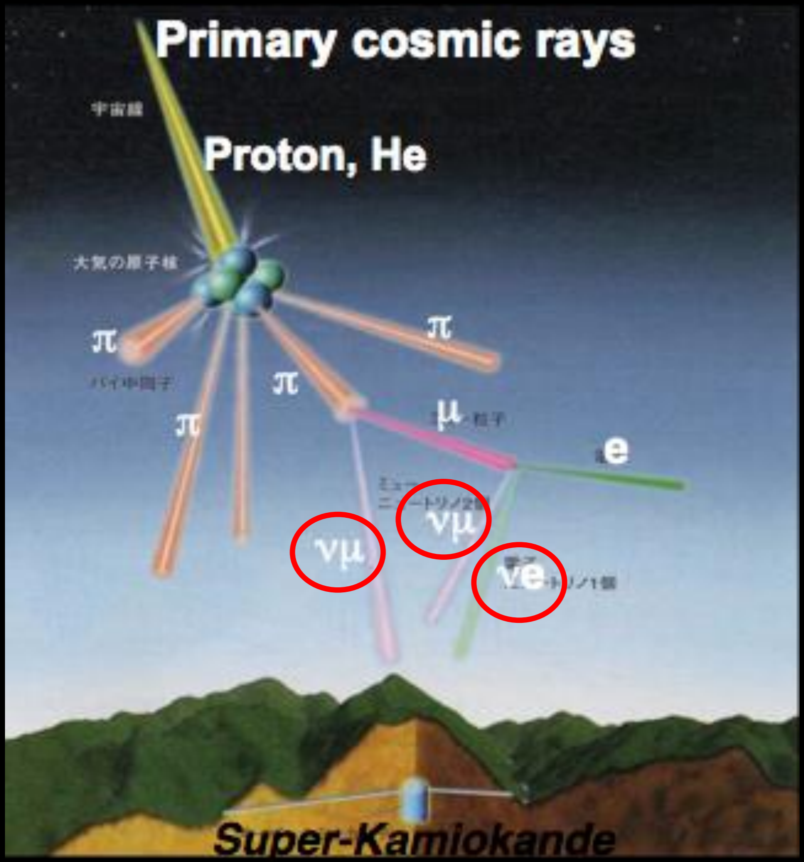
no significant excess in signal region:

$$\tau/B_{p\to e\nu\nu} > 1.7 \times 10^{32} \text{ and } \tau/B_{p\to\mu\nu\nu} > 2.2 \times 10^{32} \text{ years (90\% CL)}$$

- world's best limit
- an order of magnitude improvement over previous results
- provide strong constraints to the models

Atmospheric ν Oscillation Analyses

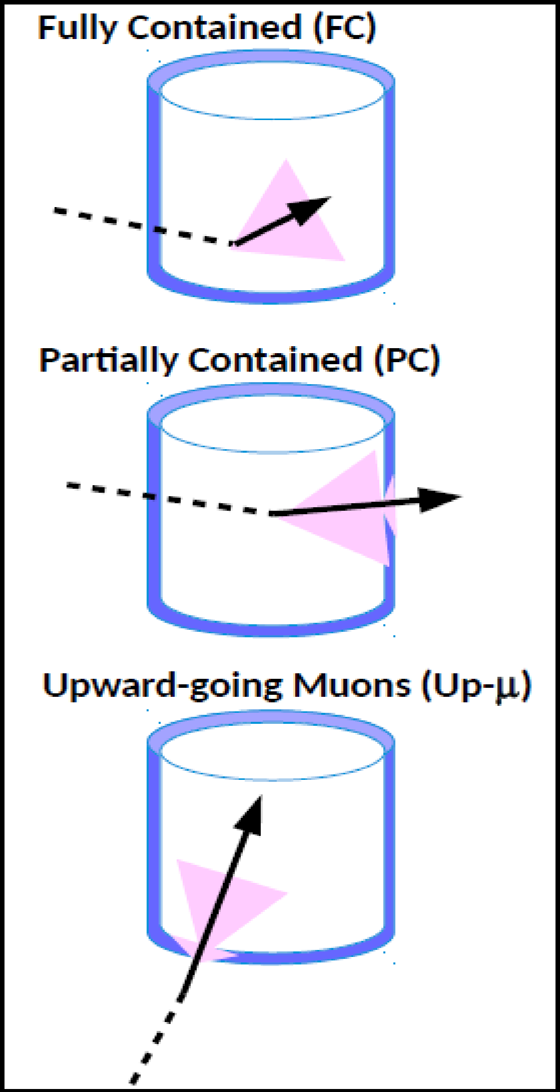
Atmospheric neutrinos

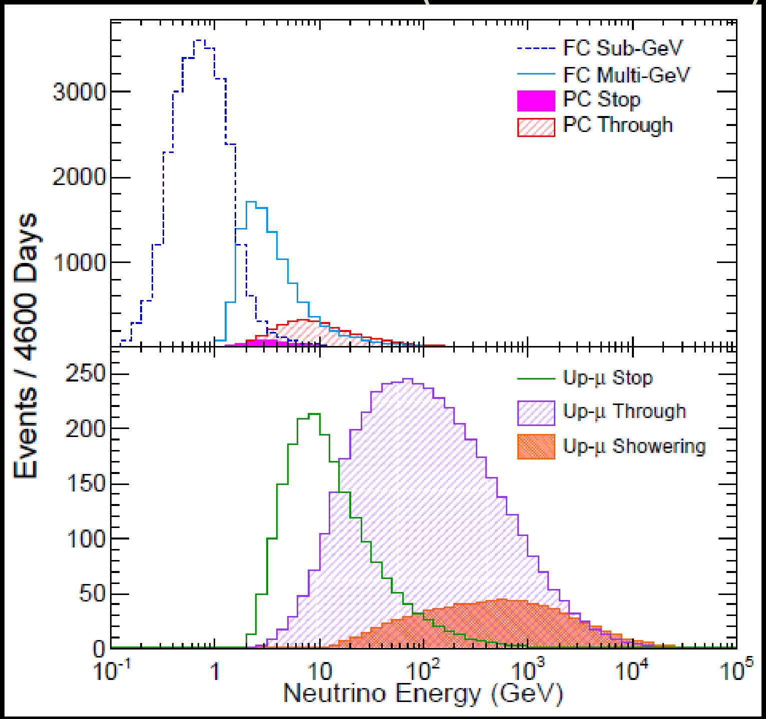


- cosmic rays strike air nuclei and decay of hadrons gives νs
- #νs > 40,000 in SK
- νs travel length: ~10-10,000km
- νs energy: ~0.1-10^4GeV
- both νs and $\overline{\nu}$s
  - ~30% for $\overline{\nu}$s in final samples
- background for nucleon decay searches

Atmospheric neutrino event topologies

(arXiv:1410.2008)





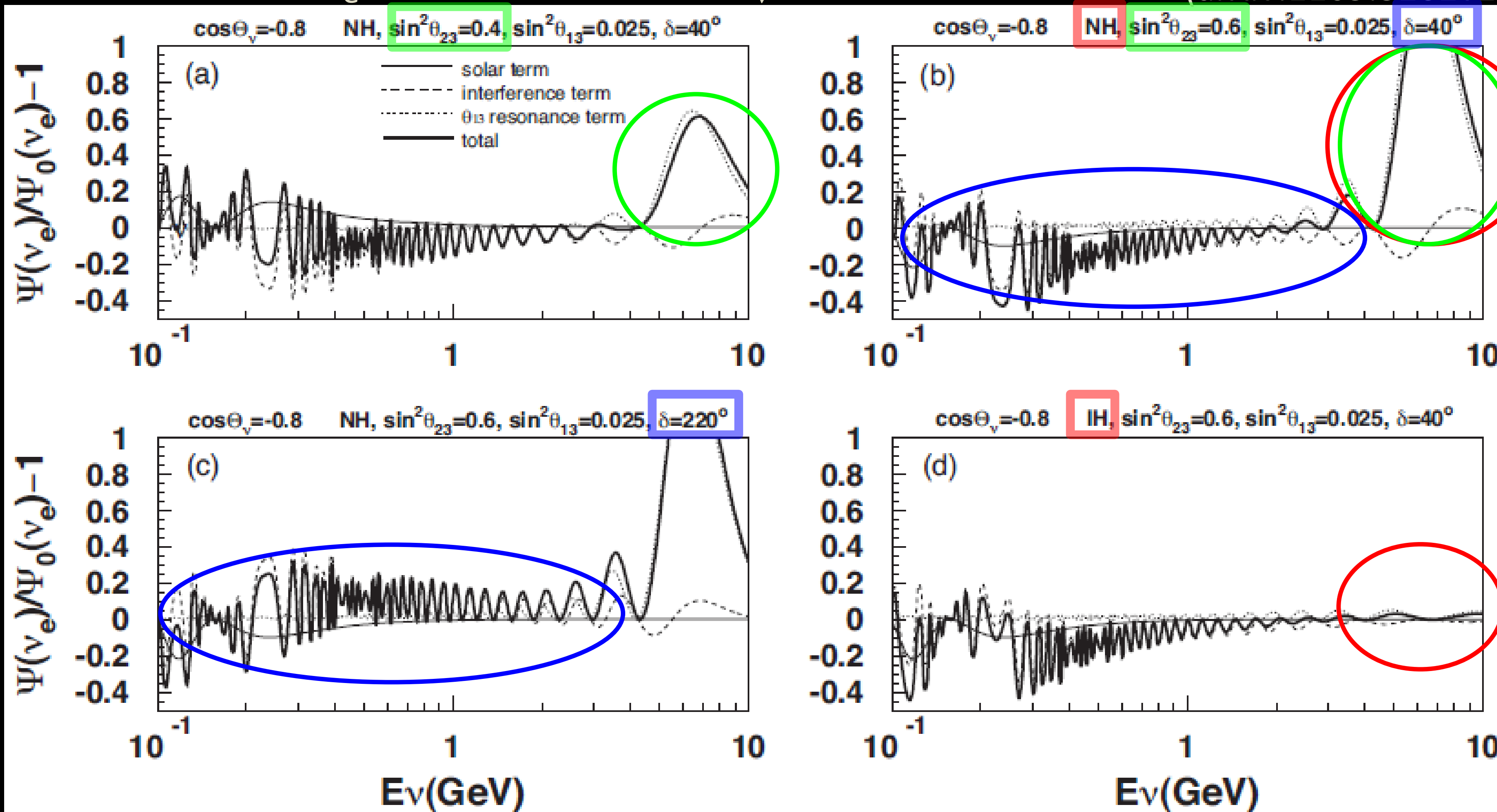
average energies:

- FC: ~1GeV
- PC: ~10GeV
- Up-μ: ~100GeV

Oscillation probabilities in three flavor mixing scheme

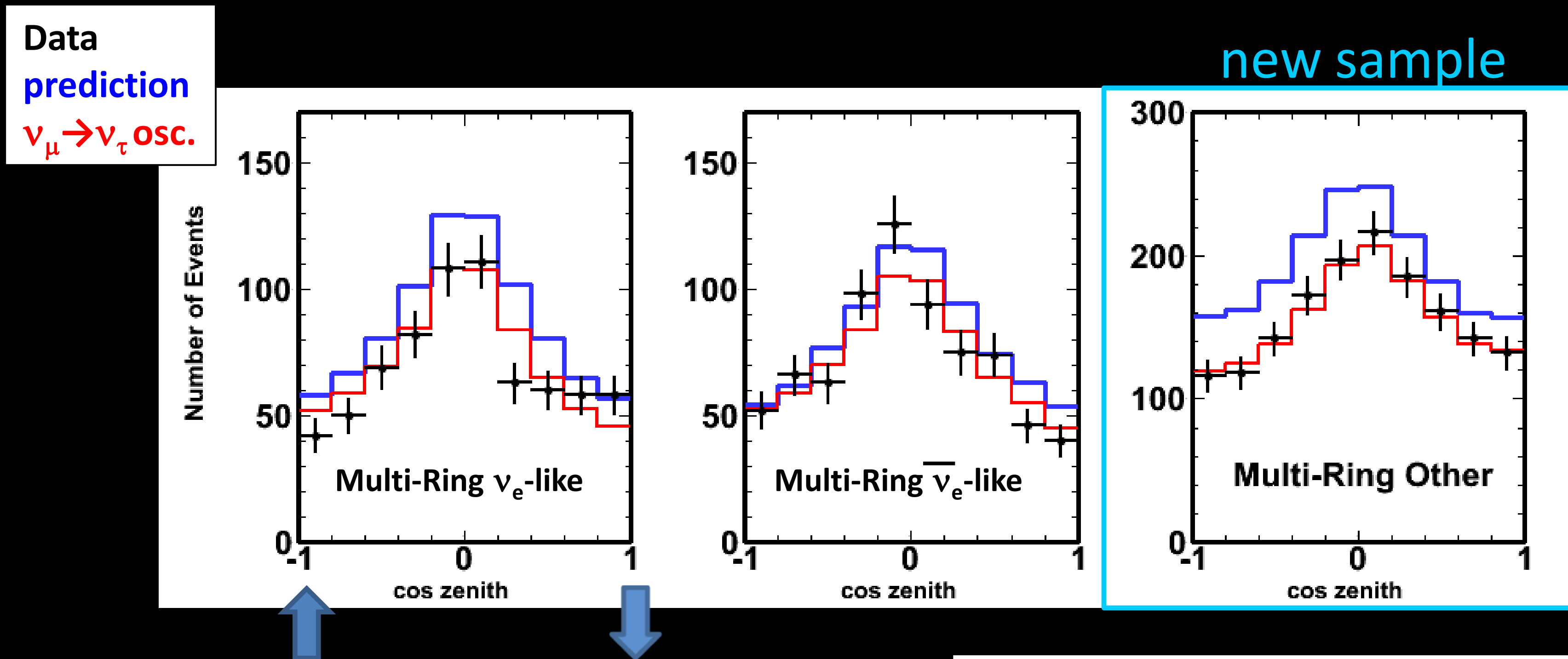
upward-going ν_es with zenith $\cos\Theta_\nu$ = -0.8:

(arXiv:1109.3262v1)



- we have sensitivity to mass hierarchy, θ_{23} octant, and CPV

Updates to three flavor oscillation analyses

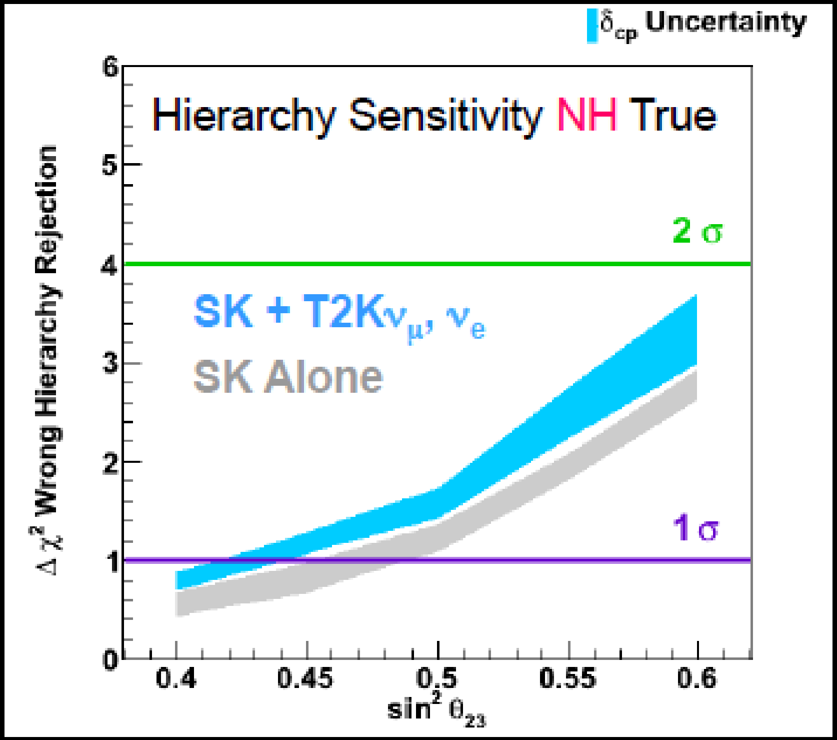


- "Multi-Ring Other": events which fail multi-ring e-like CC purification likelihood
- improved systematic errors
- 282.2kt·year

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%

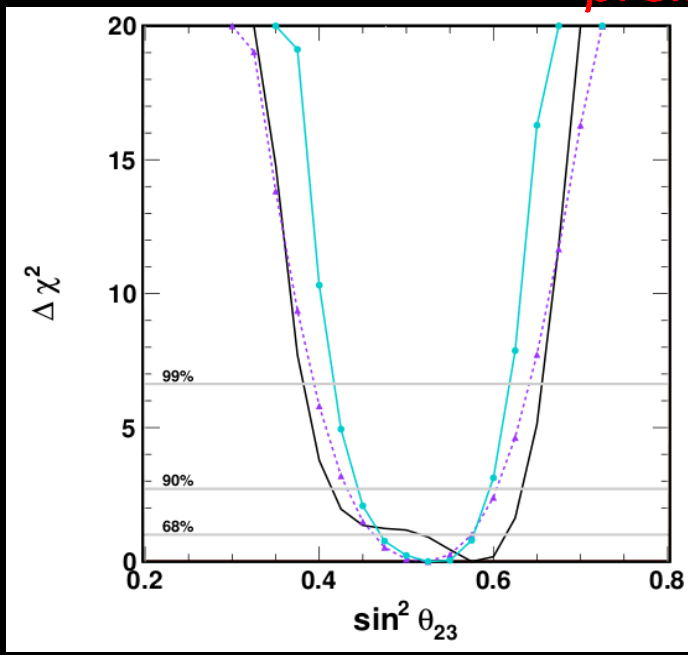
External constraints with T2K

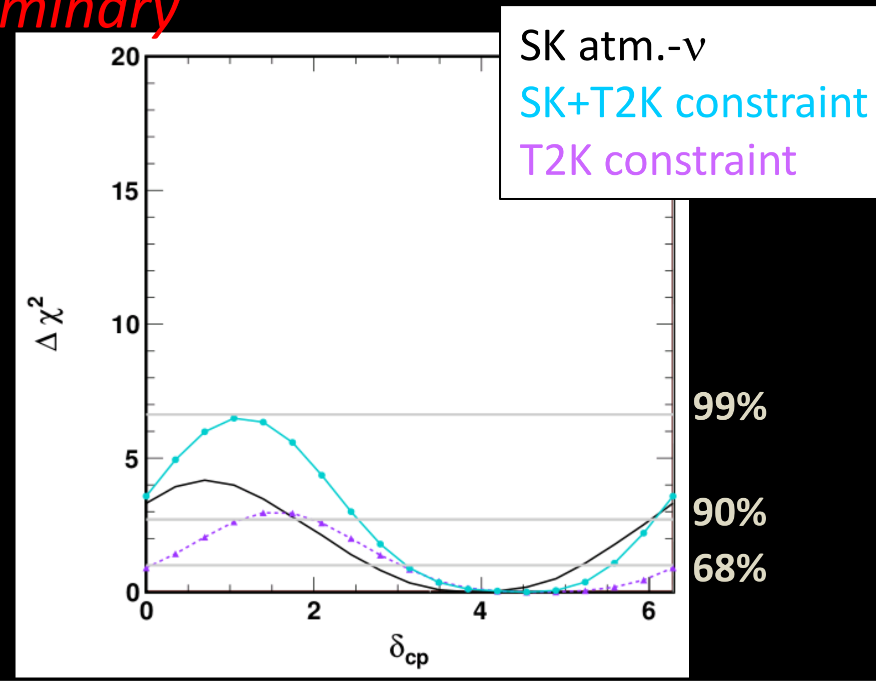


- T2K constraints on θ_{23} and Δm^2_{32} enhance mass hierarchy discrimination
- using a common SK detector, systematic errors handled in consistent way

Results with T2K constraints

preliminary





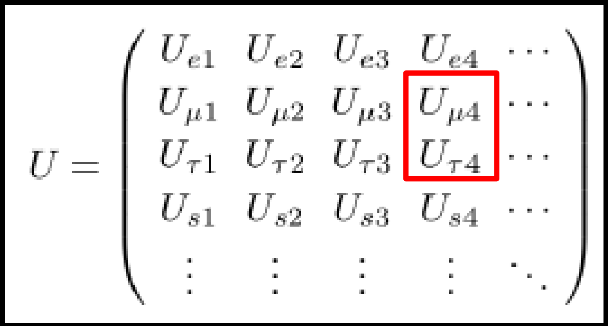
Fit (543 dof)	$\chi2$	θ_{13} (fixed)	δ_{cp}	θ_{23}	Δm_{23} ($x10^{-3}$)
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

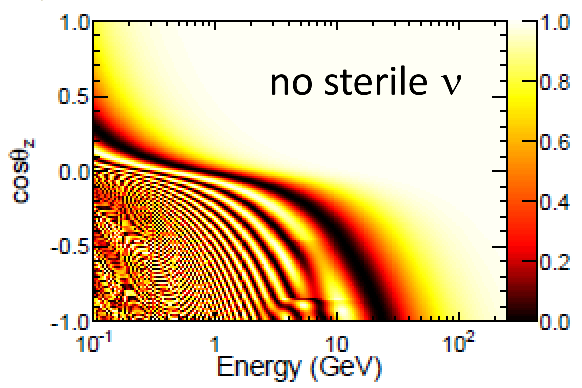
- θ_{23}: 2nd octant slightly favored
- δ_{CP}: preference near $3\pi/2$, CP conservation ($\sin\delta_{CP}$= 0) allowed at 90% CL
- $\chi^2_{IH} - \chi^2_{NH}$ = 1.2 (0.9 SK only), NH slightly favored

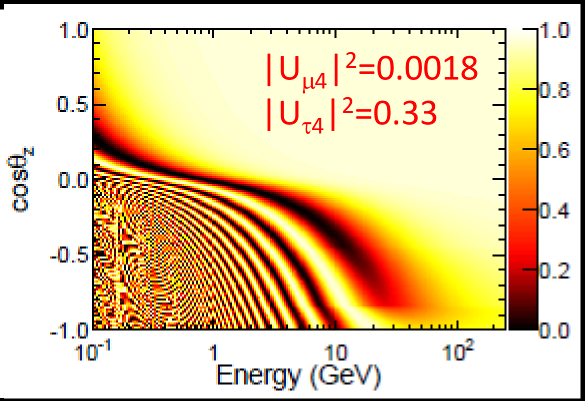
Sterile neutrino oscillations

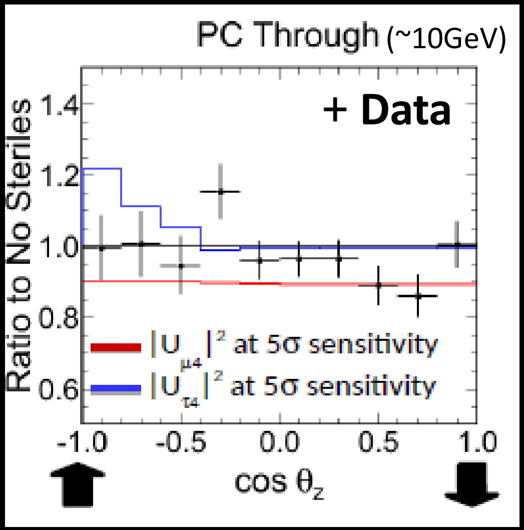
arXiv:1410.2008

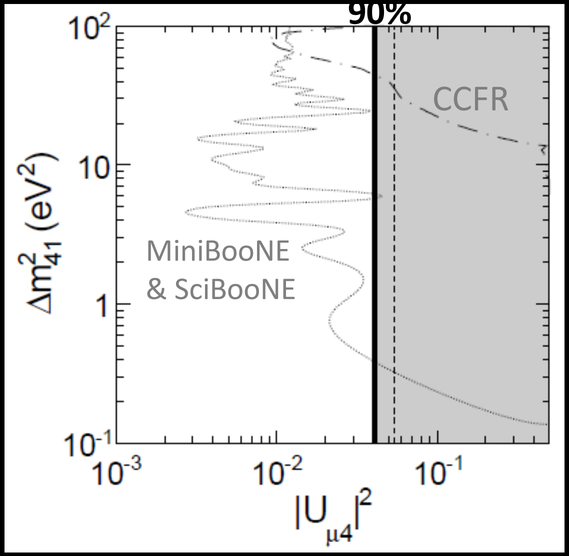
ν_μ survival prob.:











- no evidence of sterile oscillations (4,438days ~ 274kt·year)
- $|U_{\mu 4}|^2<0.041$ and $|U_{\tau 4}|^2<0.18$ for $\Delta m^2>0.8\text{eV}^2$ (90% CL)

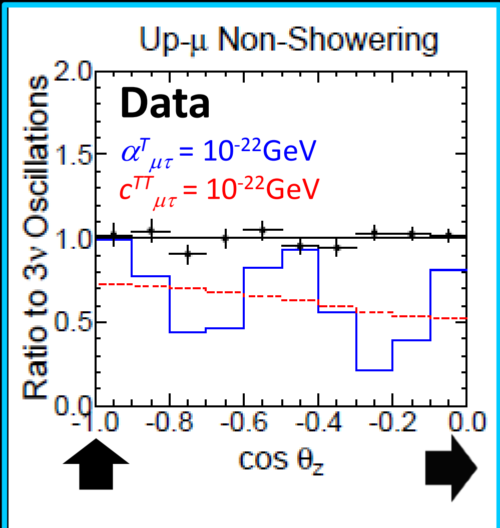
Test of Lorentz invariance

arXiv:1410.4267

$$H = UMU^{\dagger} + V_e + H_{LV},$$

$$H_{LV} = \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - E \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$

Coefficient	Unit	d	CPT	Oscillation Effect
Isotropic				
$a^T_{\alpha\beta}$	GeV	3	odd	$\propto L$
$c^{TT}_{\alpha\beta}$	-	4	even	$\propto LE$



	LV Parameter	95% Upper Limit	Best Fit	No LV $\Delta\chi^2$	Previous Limit
$e\mu$	$\mathrm{Re}\,(a^T)$	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [51]
	$\mathrm{Im}\,(a^T)$	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	$\mathrm{Re}\,(c^{TT})$	1.1×10^{-26}	1.0×10^{-28}	0.0	9.6×10^{-20} [51]
	$\mathrm{Im}\,(c^{TT})$	1.1×10^{-26}	1.0×10^{-28}		
$e\tau$	$\mathrm{Re}\,(a^T)$	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV [52]
	$\mathrm{Im}\,(a^T)$	2.8×10^{-23} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}\,(c^{TT})$	1.2×10^{-24}	1.0×10^{-28}	0.3	1.3×10^{-17} [52]
	$\mathrm{Im}\,(c^{TT})$	1.4×10^{-24}	4.6×10^{-25}		
$\mu\tau$	$\mathrm{Re}\,(a^T)$	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	–
	$\mathrm{Im}\,(a^T)$	5.1×10^{-24} GeV	1.0×10^{-28} GeV		
	$\mathrm{Re}\,(c^{TT})$	5.8×10^{-27}	1.0×10^{-28}	0.1	–
	$\mathrm{Im}\,(c^{TT})$	5.6×10^{-27}	1.0×10^{-27}		

- no evidence of Lorentz violation observed (4,438days ~ 274kt·year)
- set limits for the first time in neutrino μτ sector of SME
- improved existing limits by up to 7 orders of magnitude

Summary

- Nucleon decay searches:
  - no evidence so far → most stringent lifetime limits in the world
  - keep discovery potential and increase statistics
- Atmospheric neutrino oscillation 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 → stringent limits on relevant parameters
- Prospect of sensitivity improvements by sophisticated reconstruction algorithm, reducing systematic errors, etc.