スーパーカミオカンデにおける最新結果（大気ニュートリノ、核子崩壊探索等）

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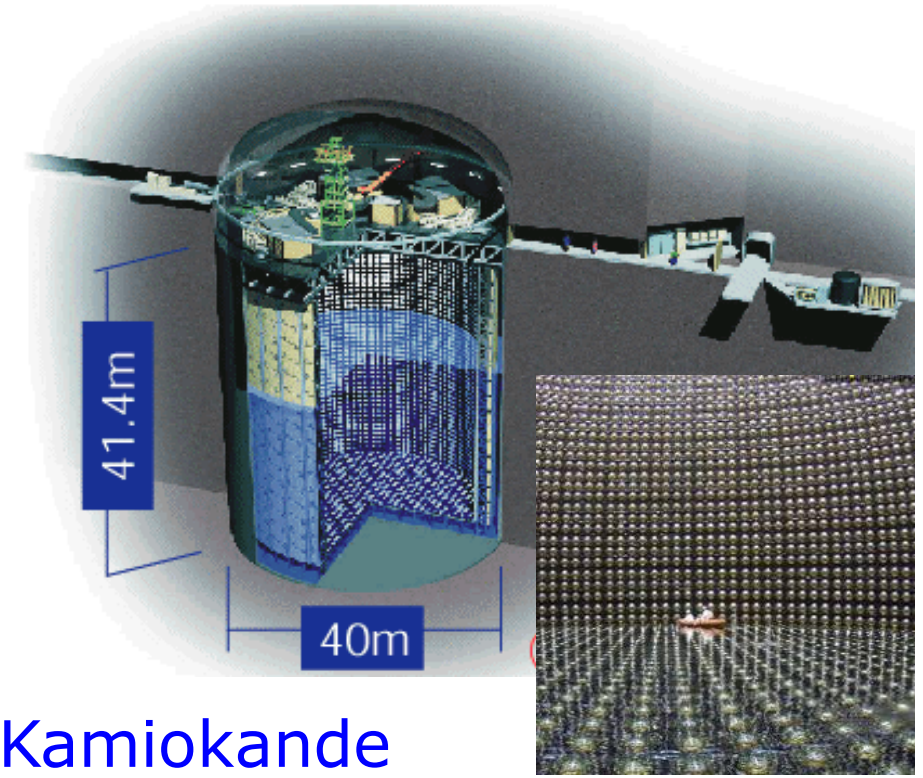
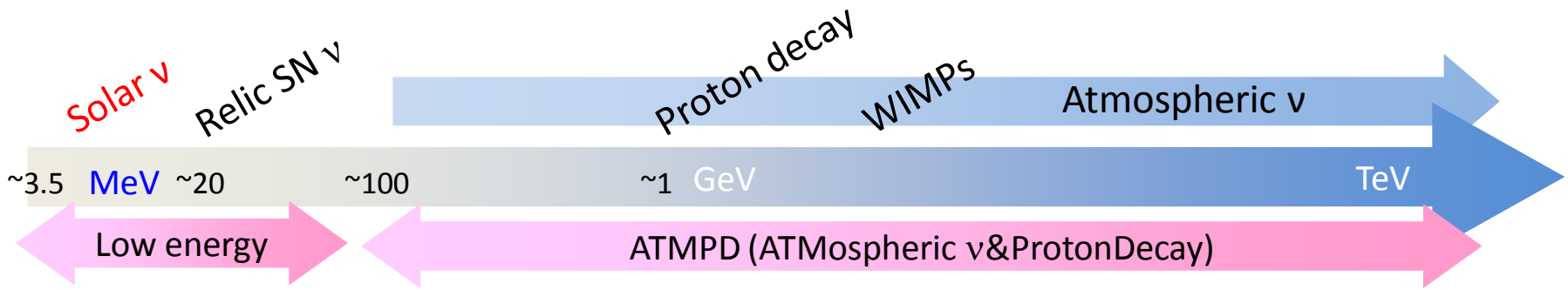
1. Introduction: Super-Kamiokande

- 50kton pure water Cherenkov detector
- 1km (2.7km w.e) underground in Kamioka
- 11129 50cm PMTs
  in Inner Detector
- 1885 20cm PMTs
  in Outer Detector



Physics targets of Super-Kamiokande



(Next speaker)

Covered by this talk

2. Publications in this year (ATMPD)

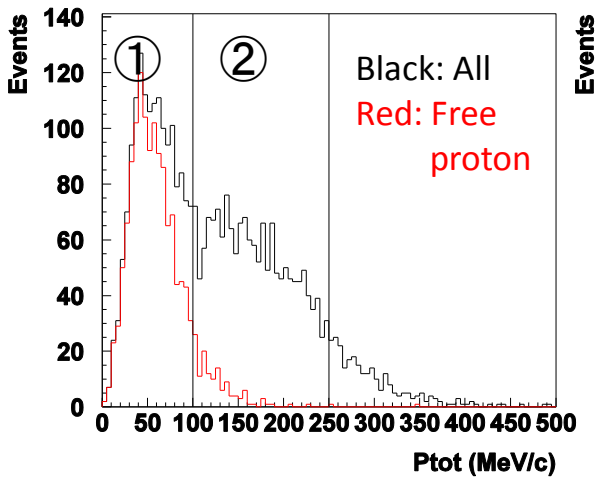
- Test of Lorentz invariance with atmospheric neutrinos: Phys. Rev. D 91, 052003 (2015)
- Limits on sterile neutrino mixing using atmospheric neutrinos in Super-Kamiokande: Phys. Rev. D91, 052019 (2015)
- Search for Neutrinos from Annihilation of Captured Low-Mass Dark Matter Particles in the Sun by Super-Kamiokande: Phys. Rev. Lett. 114, 141301 (2015)
- Search for n-nbar oscillation in Super-Kamiokande: Phys. Rev. D91, 072006 (2015)
- Search for dinucleon decay into pions at Super-Kamiokande: Phys. Rev. D91, 072009 (2015)
- Search for Nucleon and DiNucleon Decays with an Invisible Particle and a Charged Lepton in the Final State at the Super-Kamiokande Experiment: Phys. Rev. Lett. 115, 121803 (2015)

2 neutrino oscillation papers,
1 astrophysical paper,
3 nucleon decay papers.

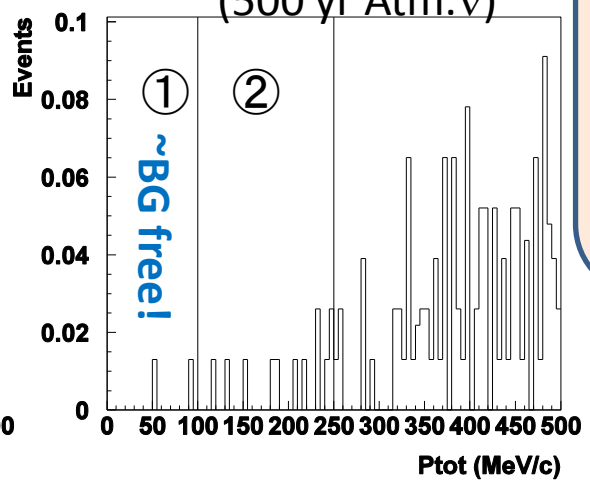
3. Nucleon decay analysis

- Update $p \rightarrow e^+\pi^0$, $\mu^+\pi^0$, and νK^+ by data until March, 2015 (total exposure: 306 kt･year).
- Neutron tagging is applied for SK4 analysis. Backgrounds are reduced by almost half (reported in the previous year).
- In $p \rightarrow e^+\pi^0$, $\mu^+\pi^0$, signal region is divided into two parts;
  - ① Ptot < 100 MeV/c: Free proton dominant, almost BG free!
  - ② 100<Ptot<250 MeV/c: Bound proton dominant.

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



BG MC (500 yr Atm.ν)



- Expected BG: 0.07 events
  Obs.in① ≥2 → 3σ
  ≥3 → 5σ
- BG increases very slowly: 0.003evts/year

Keep discovery potential!

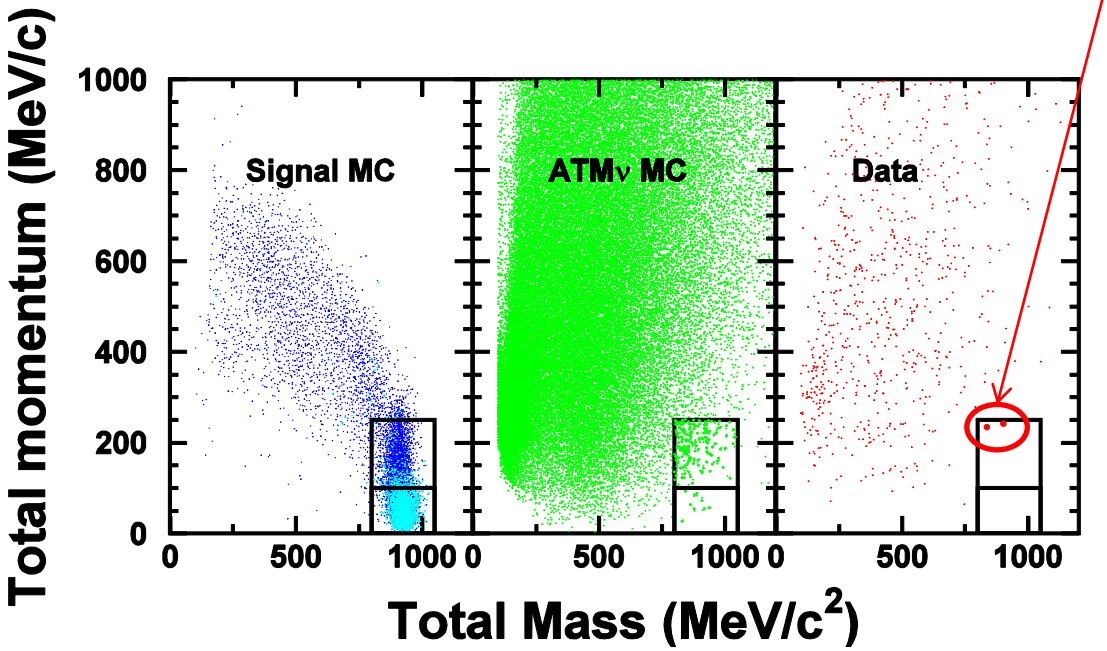
Results with 306kt·year exposure

$p \rightarrow e^+\pi^0$	0~100MeV/c	100~250MeV/c	Total
Observed	0	0	0
BKG	0.07	0.54	0.61

$p \rightarrow \mu^+\pi^0$	0~100MeV/c	100~250MeV/c	Total
Observed	0	2	2
BKG	0.05	0.82 (SK4:0.23)	0.87

2 events remained in $p \rightarrow \mu\pi^0$!

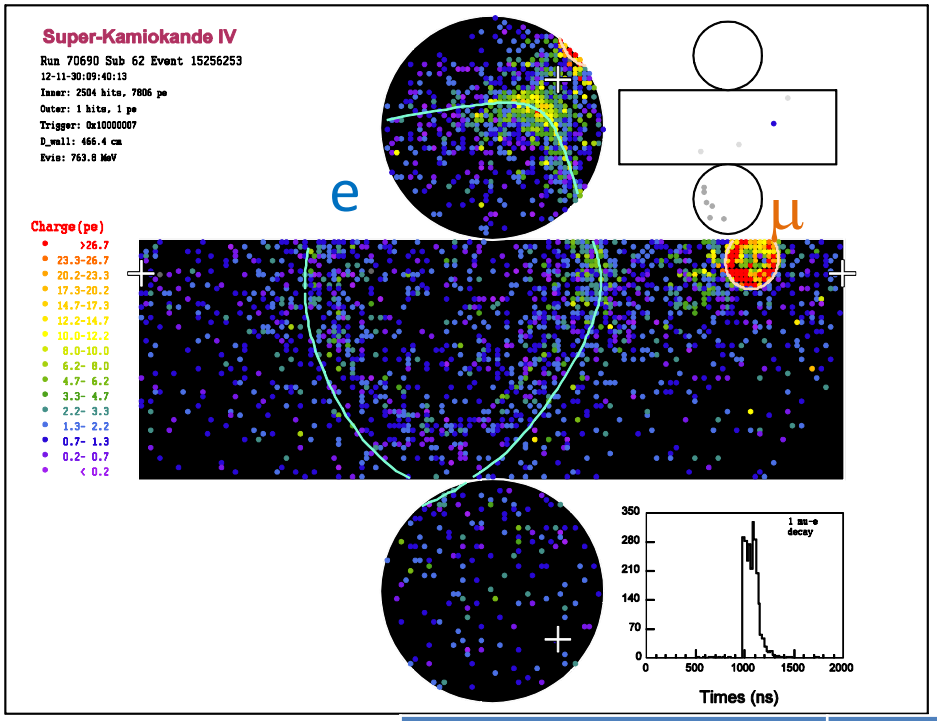
Both events are
- in SK4 period,
- near by boarder (P_{tot}~ 250 MeV/c),
- 2 ring (e-like+μ-like)



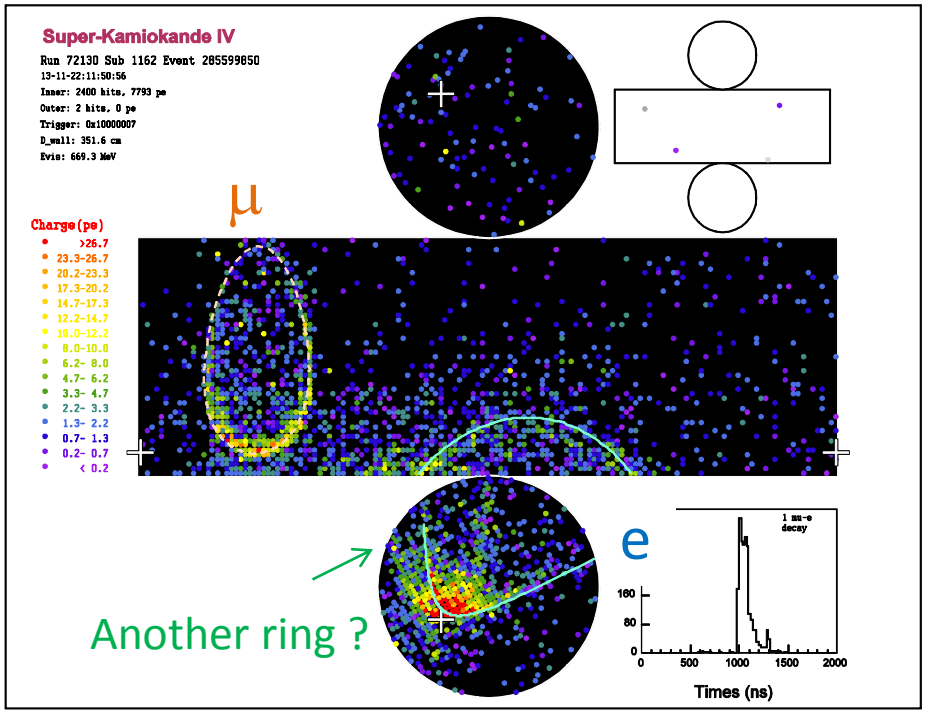
Probability assuming BG;
Poisson(≥2,0.82)=20%
(SK4 only: 2.3 %)

Observed events

1st event



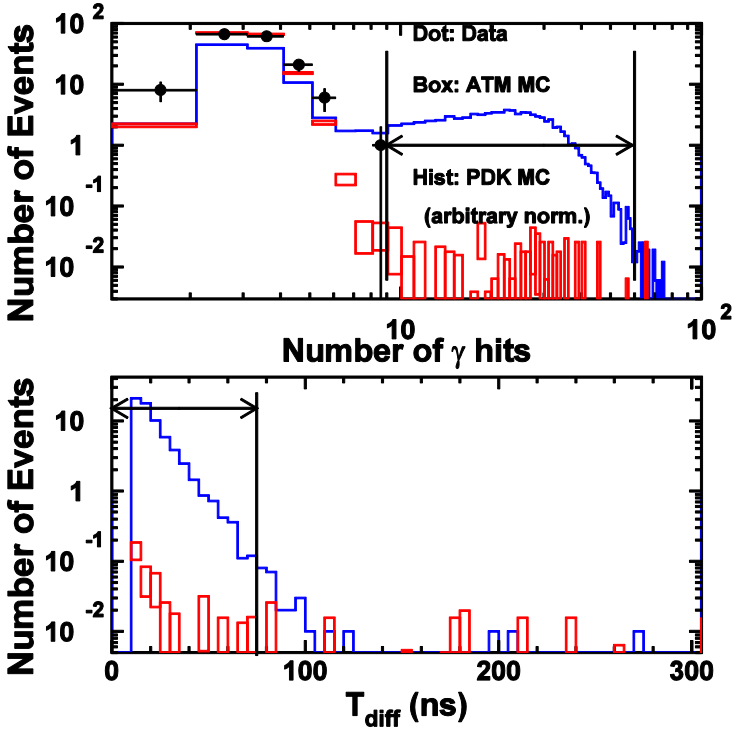
2nd event



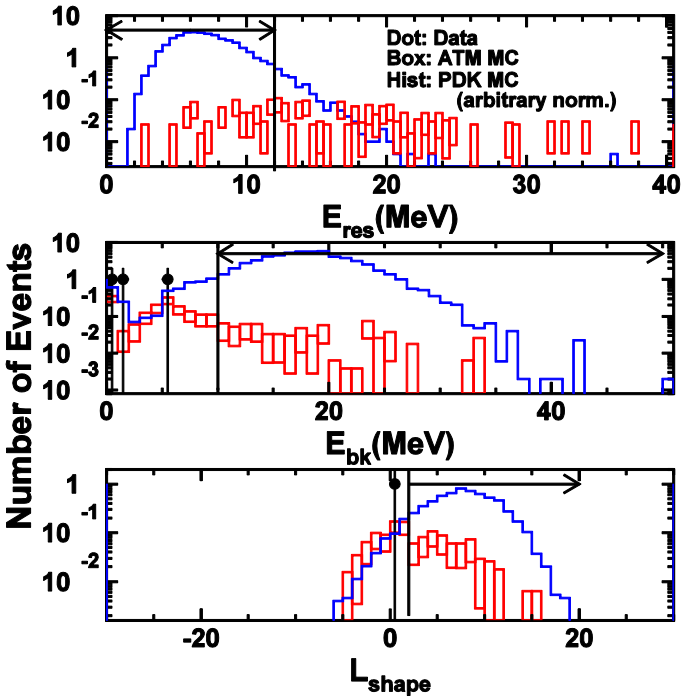
	1st event	2nd event
Mtot (MeV/c^2)	902.5	832.4
Ptot (MeV/c)	248.0	237.9
Pe (MeV/c)	374.9	460.5
Pμ(MeV/c)	551.1	391.3
Opening ang (deg)	157.9	148.9

$p \rightarrow \nu K^+$: No candidates

$K^+ \rightarrow \nu\mu$ with nuclear γ



$K^+ \rightarrow \pi^+\pi^0$



Updated lower limit of proton lifetime

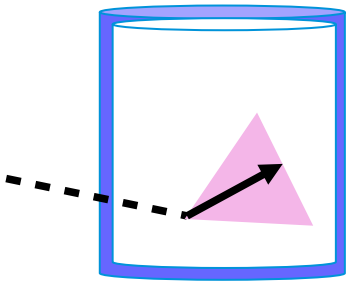
$p \rightarrow e^+\pi^0$: $> 1.7 \times 10^{34}$ years

$p \rightarrow \mu^+\pi^0$: $> 7.8 \times 10^{33}$ years

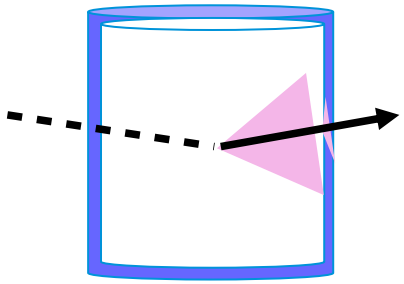
$p \rightarrow \nu K^+$: $> 6.6 \times 10^{33}$ years

4. Neutrino oscillation analysis

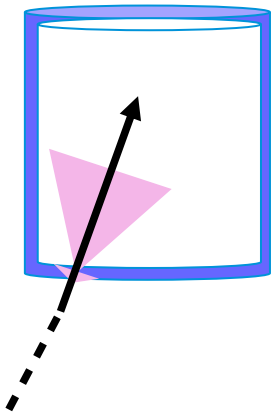
Fully Contained (FC)
~1GeV



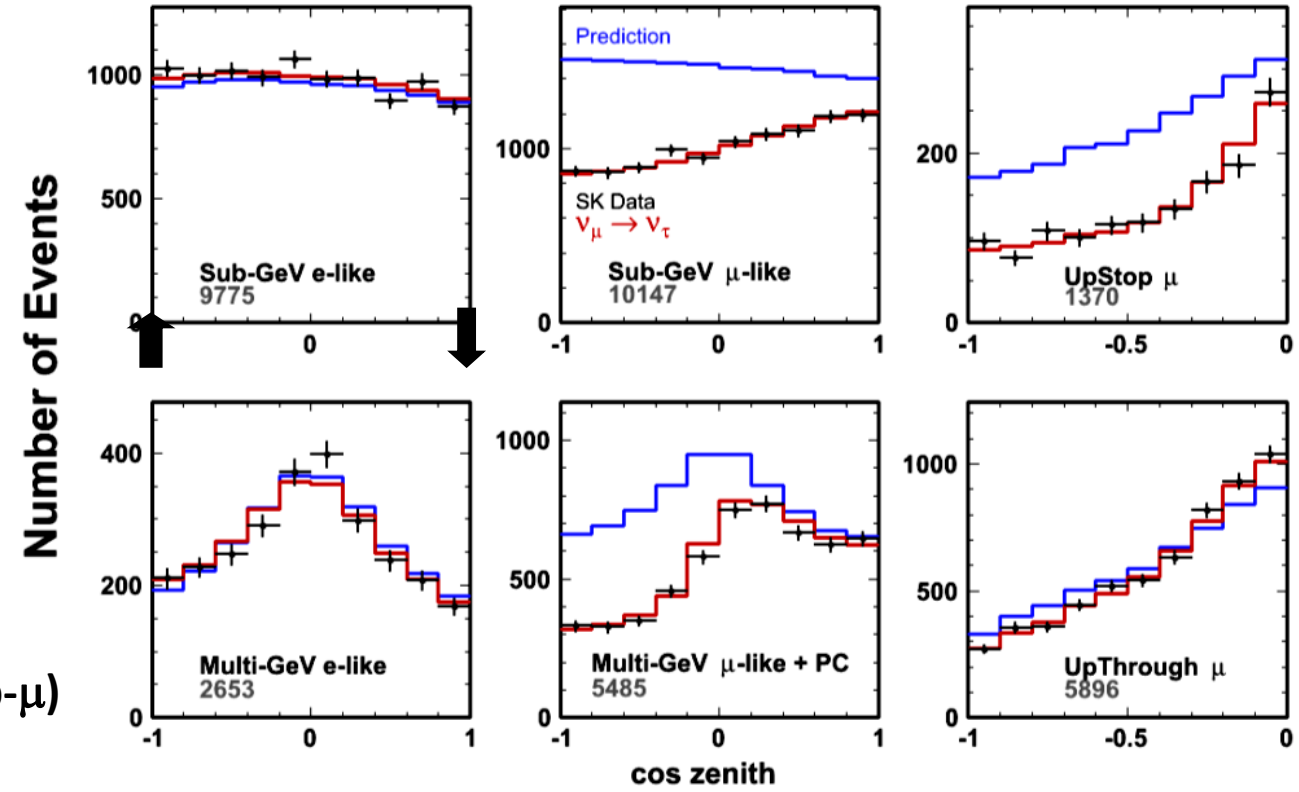
Partially Contained (PC)
~10GeV



Upward-going Muons (Up-μ)
~ 100GeV



Zenith angle distribution of each sample



- In total 19 analysis samples
  (classified by ν flavors, event topologies, energies, …)
- *Fit to the data in bins of* ***$\cos\theta_{zenith}$ and momentum***
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in sub-dominant contributions.

Neutrino oscillation studies using atmospheric ν

High statistics atmospheric neutrino data : FC ~48k ev (98': 4353ev)

~ Possibility in observing small distortion in ν_e

- Matter effect ~ from mass hierarchy

  Possible ν_e enhancement in several GeV passed through the earth core

- Solar term ~ from θ_{23} octant degeneracy

  Possible ν_e enhancement in sub-GeV

- Interference

  CP phase could be studied.

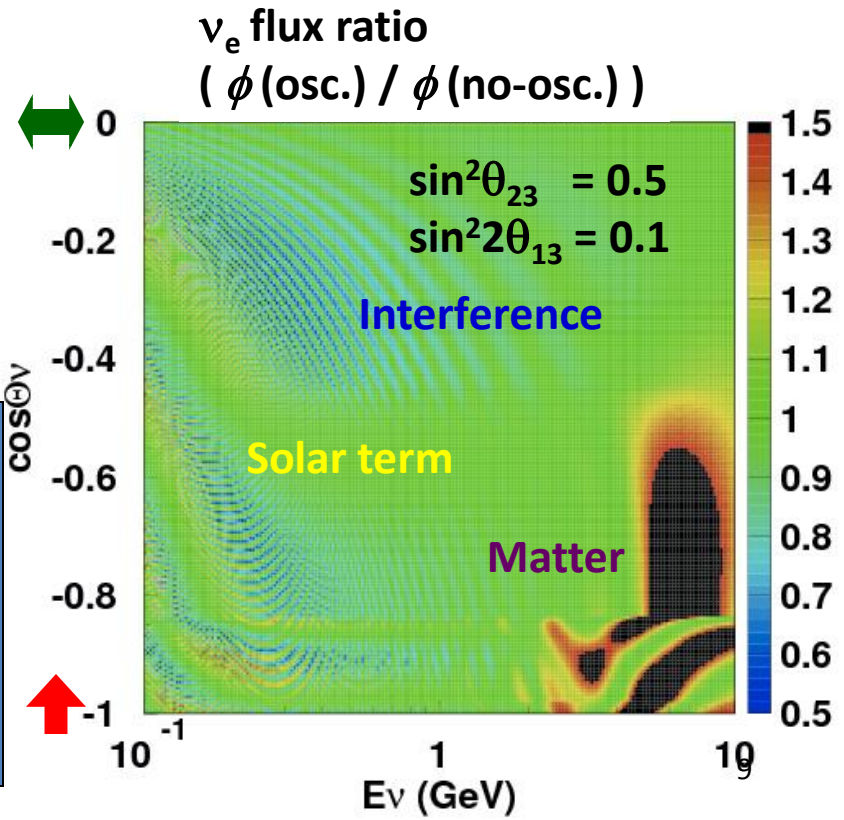
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m^2_{12}) + \Delta_3(\theta_{13}, \Delta m^2_{12}, \delta)$$

⬅ Matter effect

⬅ Solar term

⬅ Interference

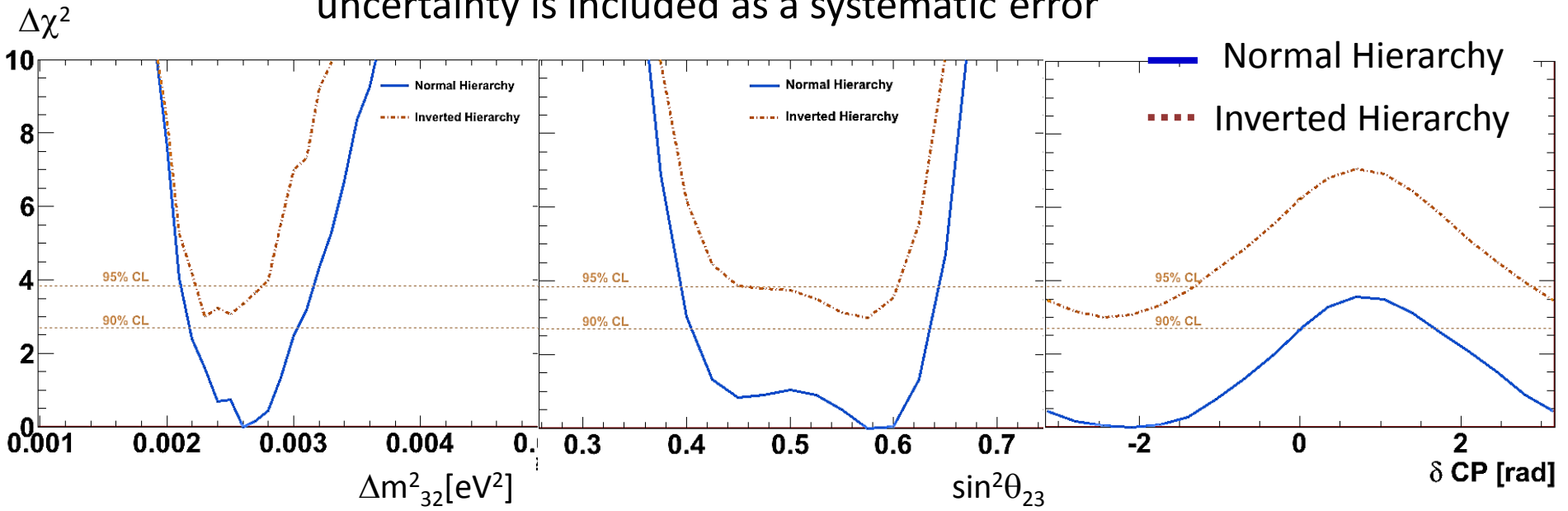


Neutrino oscillation studies using atmospheric ν

θ_{13} **Fixed** Analysis (NH+IH) SK Only

θ_{13} fixed to PDG2014 value ($\sin^2 2\theta_{13}$ =0.093 ±0.08)
uncertainty is included as a systematic error

Preliminary



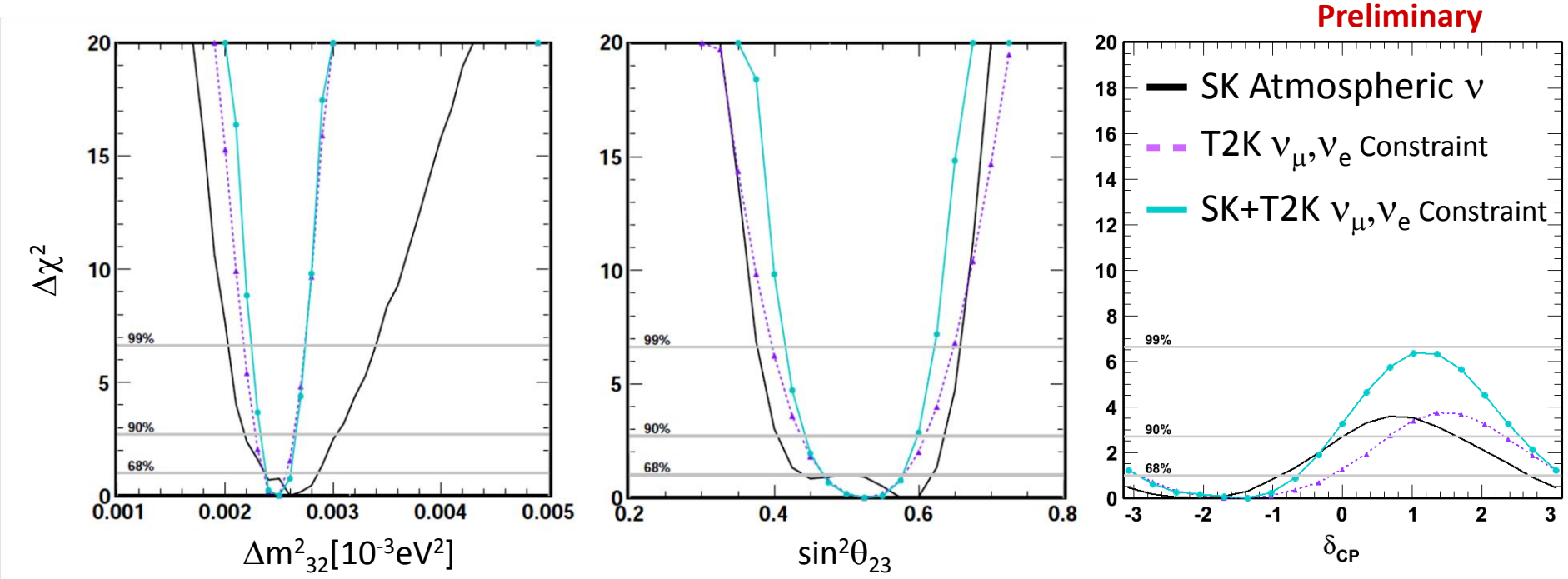
Fit (517 dof)	χ2	δ_{cp} (rad)	$\sin^2\theta_{23}$	$\Delta m^2_{32/23}$ (x10^{-3}eV^2)
SK (NH)	**582.4**	-2.09 (-0.67π)	0.575	2.6
SK (IH)	**585.4**	-2.44 (-0.78π)	0.575	2.3

Offsets in these curves show the absolute χ^2 diff. in the hierarchies.

Normal hierarchy is favored at $\chi^2_{NH} - \chi^2_{IH}$ = -3.0 (not significant still.)

Neutrino oscillation studies using atmospheric ν

θ_{13} **Fixed** SK + T2K ν_μ, ν_e (External Constraint) Normal Hierarchy



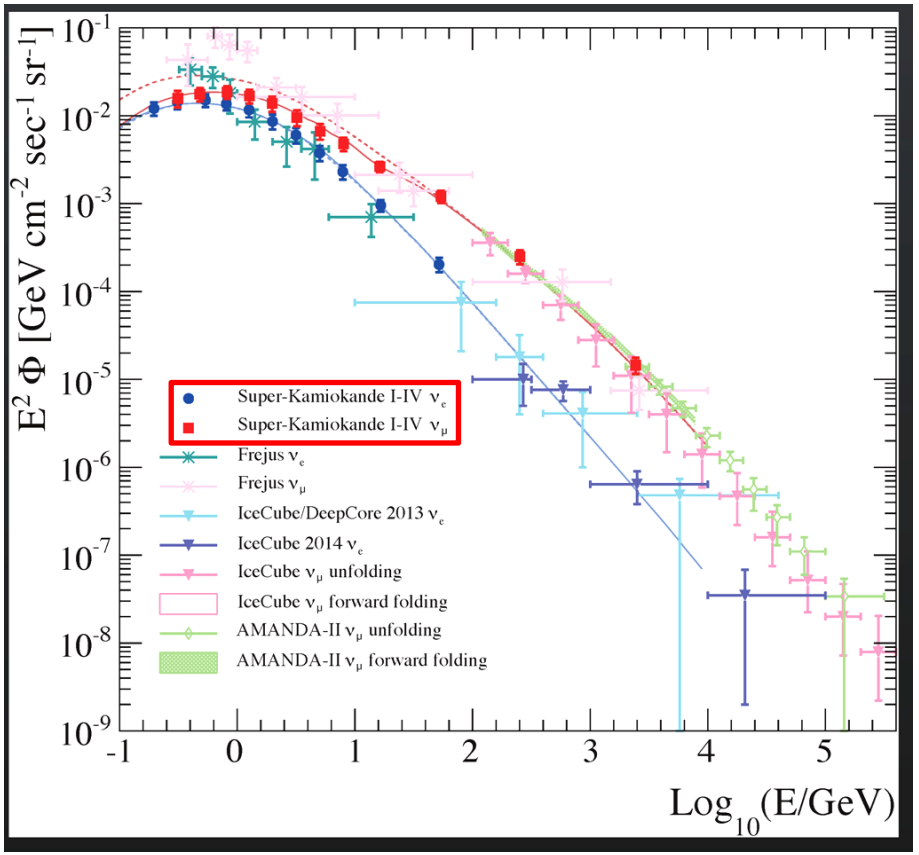
Fit (543 dof)	χ2	θ_{13}	δ_{cp}	θ_{23}	$\Delta m^2_{32/23}$ (x10^{-3}eV^2)
SK + T2K (NH)	651.5	0.0238	-1.39	0.525	2.5
SK + T2K (IH)	654.7	0.0238	-2.09	0.550	2.4

$\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (-3.0 SK only)

$\sin\delta_{cp}$ = 0 is still allowed at (at least) 90% C.L. for both hierarchies.

5. Atmospheric ν flux measurement

- Our measurement can be translated to ν flux via detector response matrix estimated by MC.
- Our data provide improved precision, extending up to 100 GeV for ν_e and 10 TeV for ν_μ.
- First data below 320 MeV.
- Overlap with km^3 detectors.
- Consistent with HKKM11, Bartol, and Fluka Models.



Paper has been submitted (http://arxiv.org/abs/1510.08127).

6. Summary

- 6 papers related to ATMPD have been published in 2015.
- Updated major proton decay modes.
  - 2 box analysis introduced to $p \rightarrow e\pi^0, \mu\pi^0$ to keep high sensitivity and discovery potential even for longer exposure.
  - $p \rightarrow e\pi^0$: 0 event observed, > 1.7×10^{34} years
  - $p \rightarrow \mu\pi^0$: 2 events observed, > 7.8×10^{33} years
  - $p \rightarrow \nu K^+$: 0 event observed, > 6.6×10^{33} years
- Atmospheric ν data favors Normal hierarchy slightly ($\chi^2_{NH} - \chi^2_{IH} = -3.0$, SK only).
- SK provides precise data points of ν flux. Consistent with existing models.