Super-Kamiokande

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XVII International Workshop on Neutrino Telescope

March 14, 2017

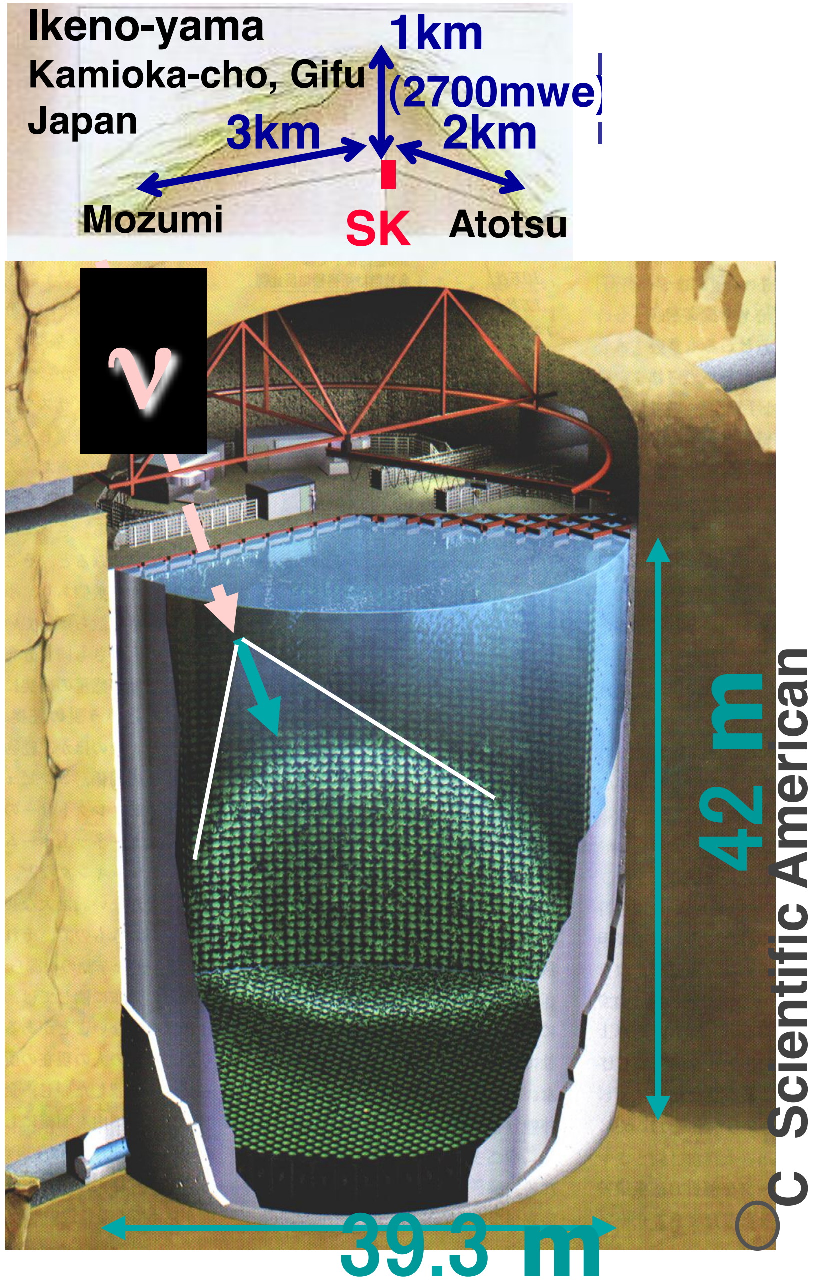
東京大学 THE UNIVERSITY OF TOKYO

ICRR Institute for Cosmic Ray Research University of Tokyo

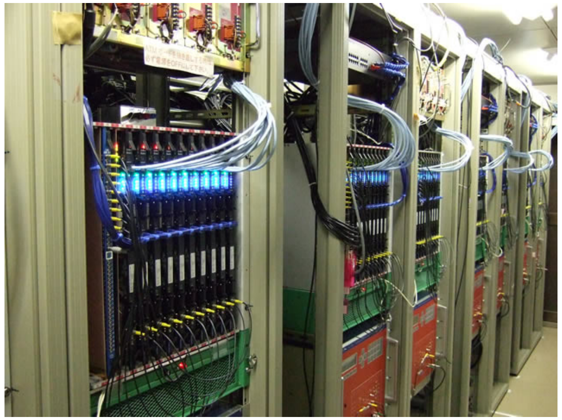
KAMIOKA OBSERVATORY

KAVLI IPMU

Super-K detector



- Ring-imaging water Cherenkov detector
  - Fiducial volume 22 kton (Total volume 50 kton)
  - Photon yield ~10p.e. / MeV
  - Atmospheric ν ~10 events/day
  - Solar ν ~15 events/day
  - Accelerator ν a few events/day (depends on the accelerator power)
  - always ready for Supernova ν and nucleon decays
- Observables
  - Direction of recoiled charged particles (leptons, pions, γ) by neutrinos
  - Particle spices (neutrino flavor)
  - Energy
  - Time



11,129 x 20inch PMTs (inner detector, ID)

3-flavor oscillation scheme

Flavor eigenstate — Mass eigenstate

$${}^t(\nu_e, \nu_\mu, \nu_\tau) = U^{MNS}_{\alpha i}\,{}^t(\nu_1, \nu_2, \nu_3)$$

U^{MNS}: Maki-Nakagawa-Sakata Matrix

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

Parameterized by 4 (mixing matrix) and 2 (difference of squared masses)

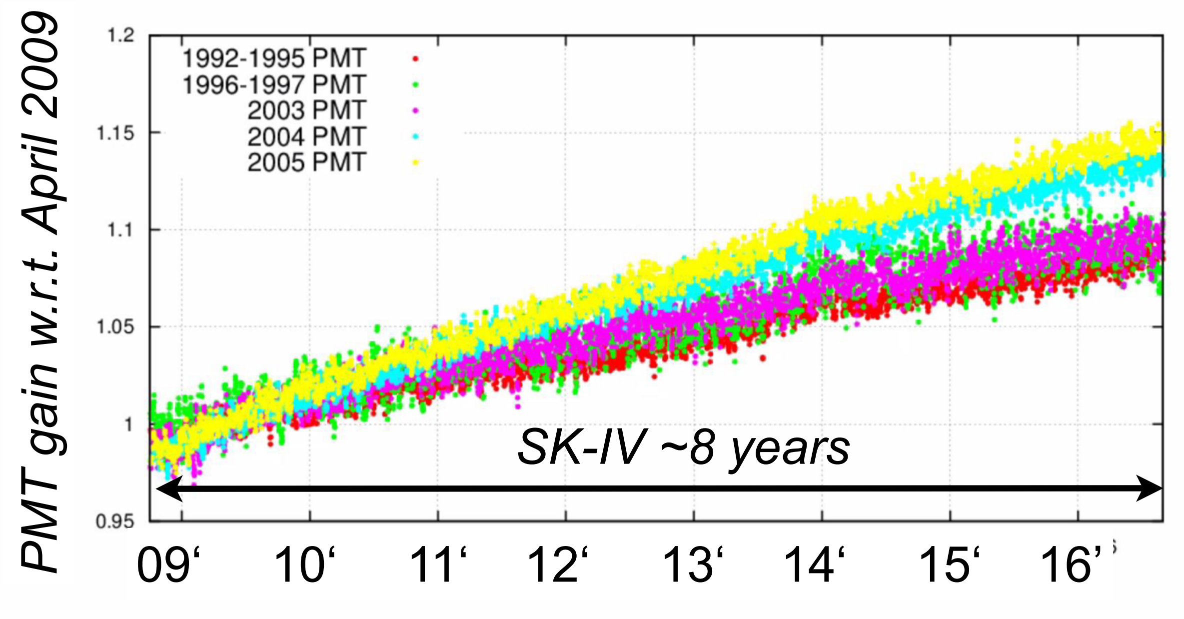
$\theta_{23}\sim45\pm5°$ $\lvert\Delta m^2_{32}\rvert=2.4\times10^{-3}\,eV^2$	$\theta_{12}\sim34\pm3°$ $\Delta m^2_{21}=+7.6\times10^{-5}\,eV^2$	$\theta_{13}\sim9°$	δ=unknown
Atmospheric ν, Accelerator ν	**Solar ν**, Reactor ν	Accelerator ν, Reactor ν, **Atm & Solar ν**	Accelerator ν, **Atmospheric ν**

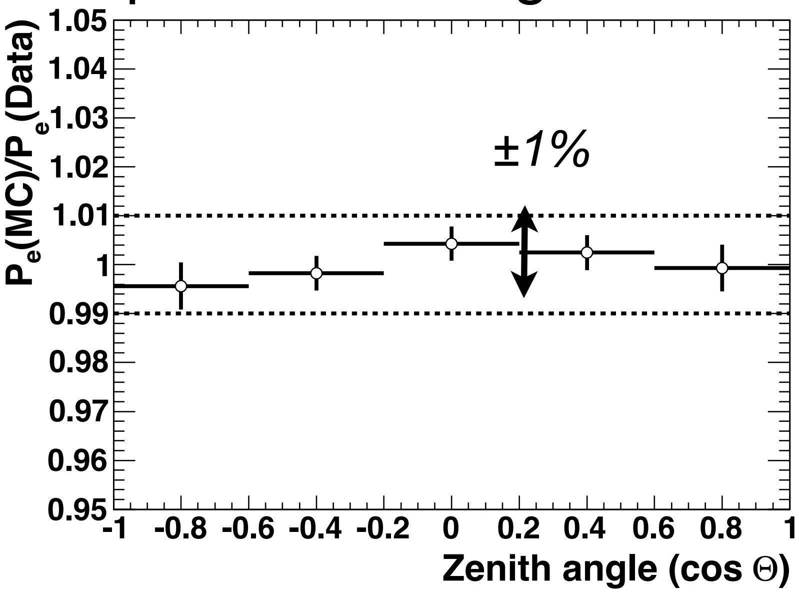
Mass hierarchy ($\Delta m^2_{32}=m^2_3-m^2_2>0$ or $\Delta m^2_{32}<0$) is also unknown:
Accelerator ν, **Atmospheric ν**, reactor ν

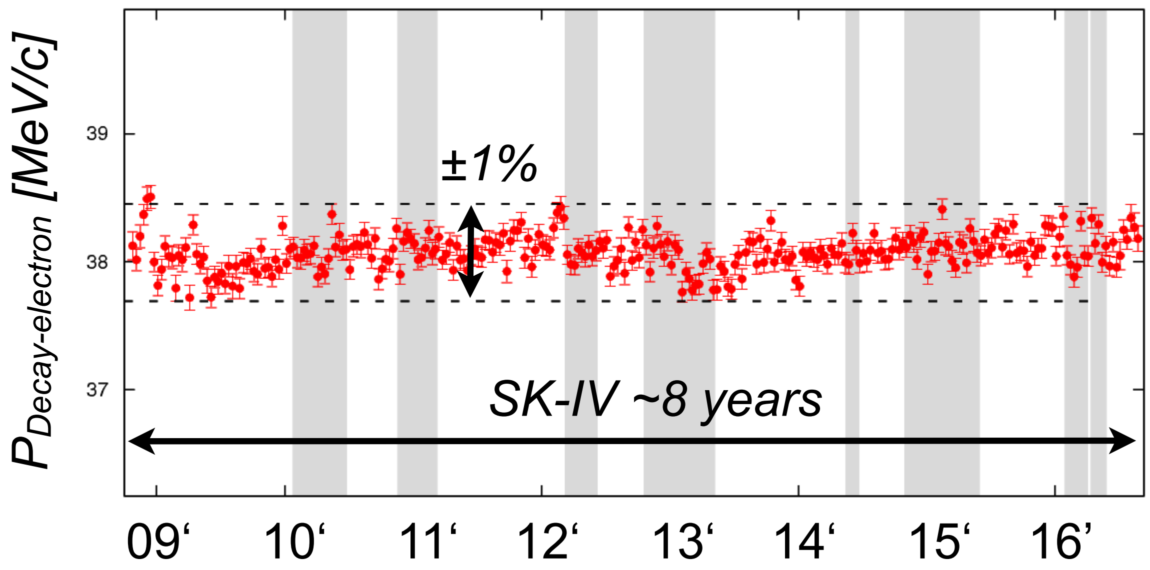
Solar&Atmospheric ν's played pioneering roles in the past and would also play important roles in future.

Stable operation and det. response

- Very stable operation
  - <1% Downtime
- Energy scale uniformity and stability w/ RMS <0.4% by correcting
  - time-dependent light attenuation length in water
  - time-dependent, production-period-dependent PMT gain







20th anniversary

Symposium and Celebration (June 6, 2016)

http://www-sk.icrr.u-tokyo.ac.jp/sk/news/2016/06/sk20th-0617-e.html

Symposium: 240 participants

Theoretical importance of the SK results by A. Smirnov

Celebration: 313 participants

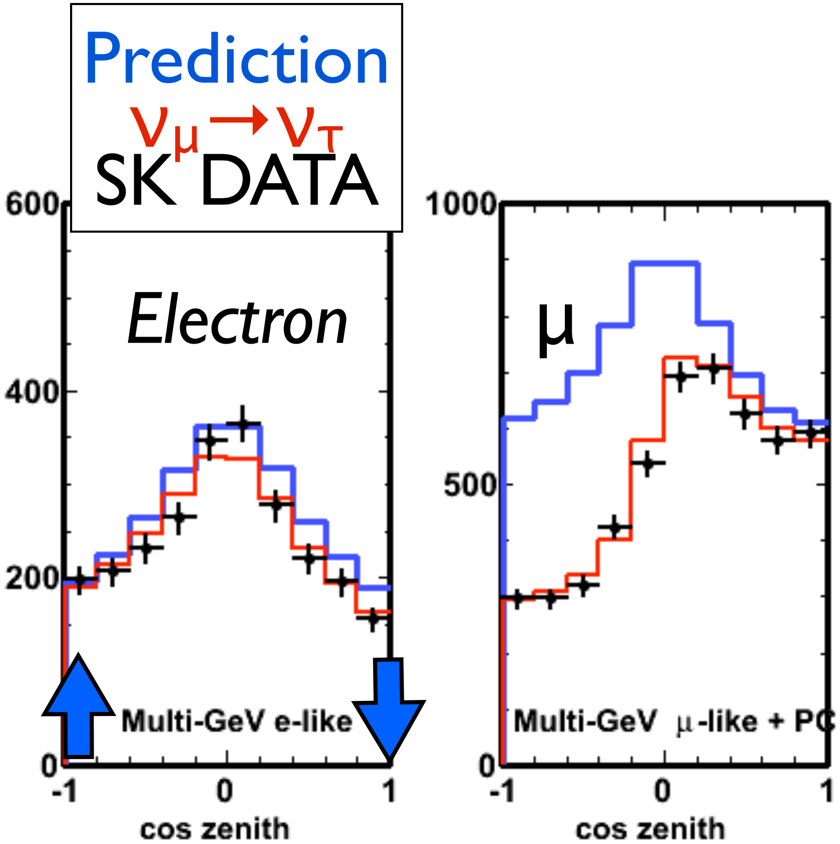
- Reviewed past scientific achievements but...
- Many problems remains
  - unknown parameters (δ, mass hierarchy, θ_{23} octant), Solar Day/Night, spectrum, Supernova ν, proton decays, WIMP...
- Discussed future prospects:

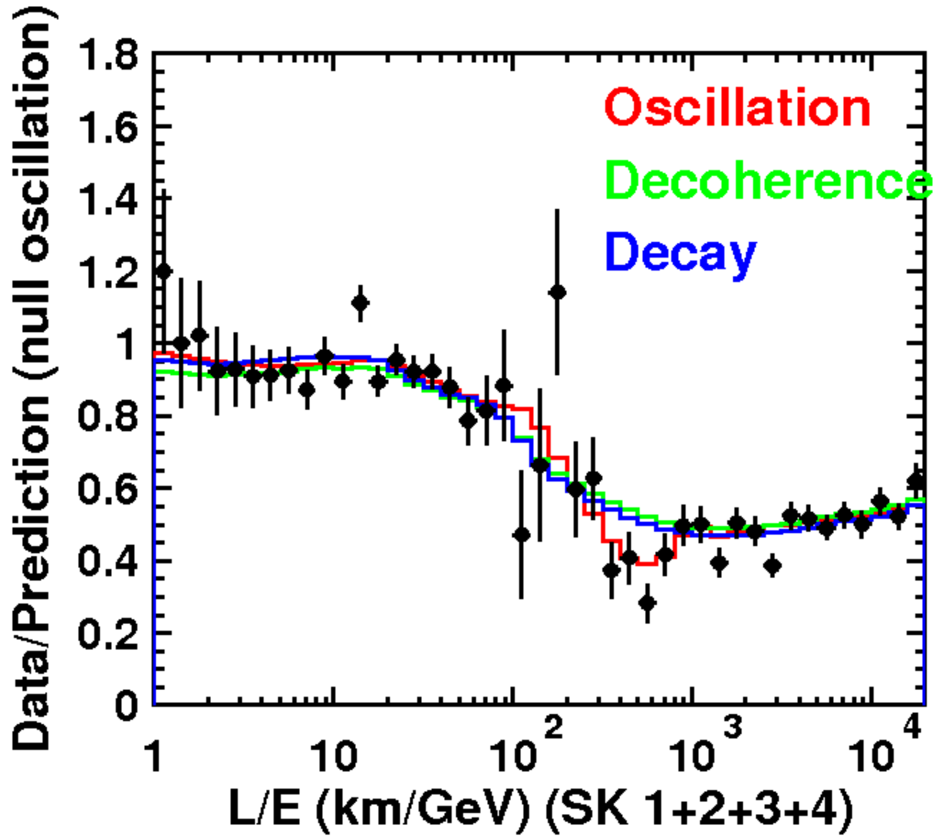
  Gadolinium loading and Hyper-Kamiokande

Contents

- Atmospheric neutrinos
- Solar neutrinos
- SK-Gd
- Proton decays

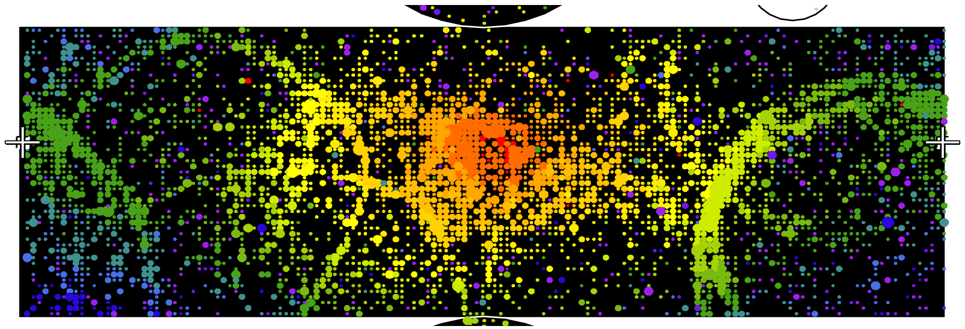
Studies of atmospheric ν





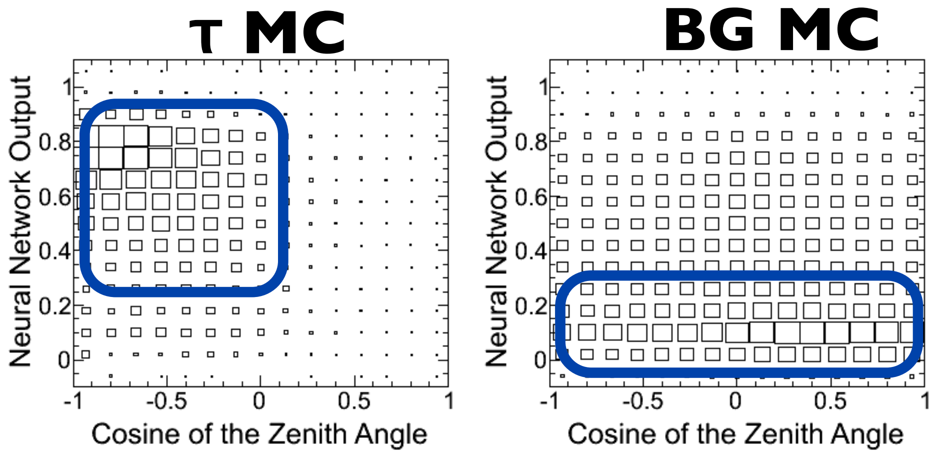
- Dominant effect is ν_μ disappearance **(discovered in 1998)**
- Oscillatory signature **(evidence in 2004)**
- ν_τ appearance **(established in 2013)**
- Full three flavor analysis
  - Studies on ν_e and ν_μ flux change to extract information on mass hierarchy, δ_{CP}, θ_{23} octant
- Test of various non-standard scenarios

Evidence for τ neutrino appearance



τ: Event-by-event ID is difficult

Define neural network to enhance hadronic decays of τ

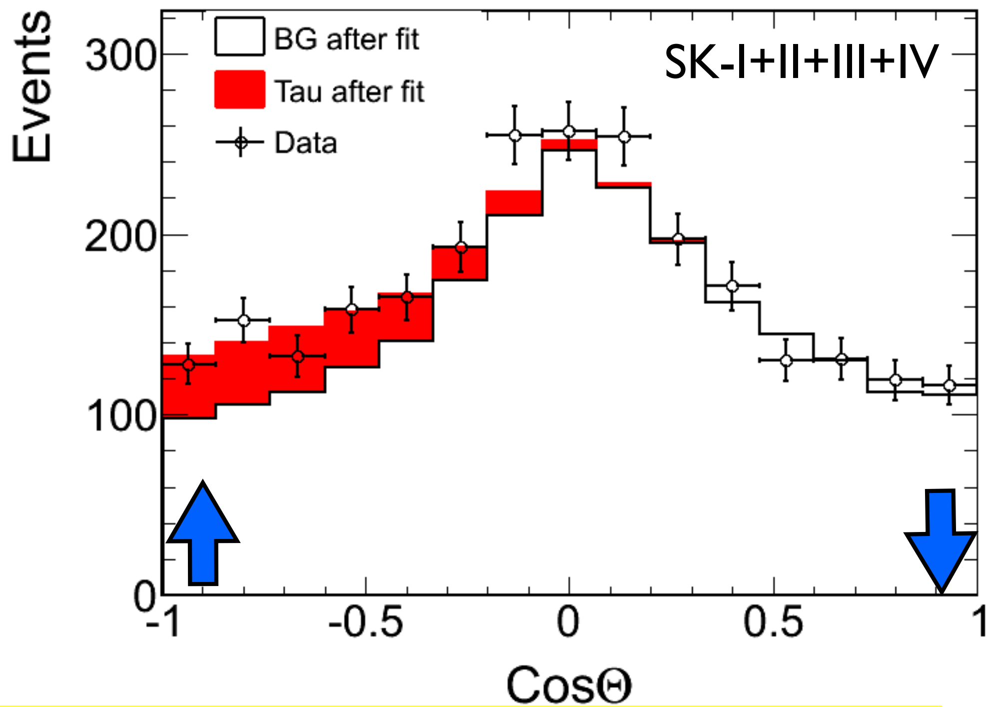


Update from PRL 110, 181802 (2013)

2D unbinned fit

$N_\tau^{DATA}/N_\tau^{exp} = 1.47 \pm 0.32$(stat+syst.)

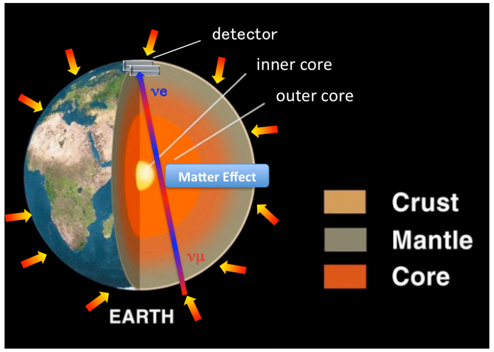
4.6 σ significance for zero τ



Atm. ν anomaly has been concluded by $\nu_\mu \rightarrow \nu_\tau$ observation

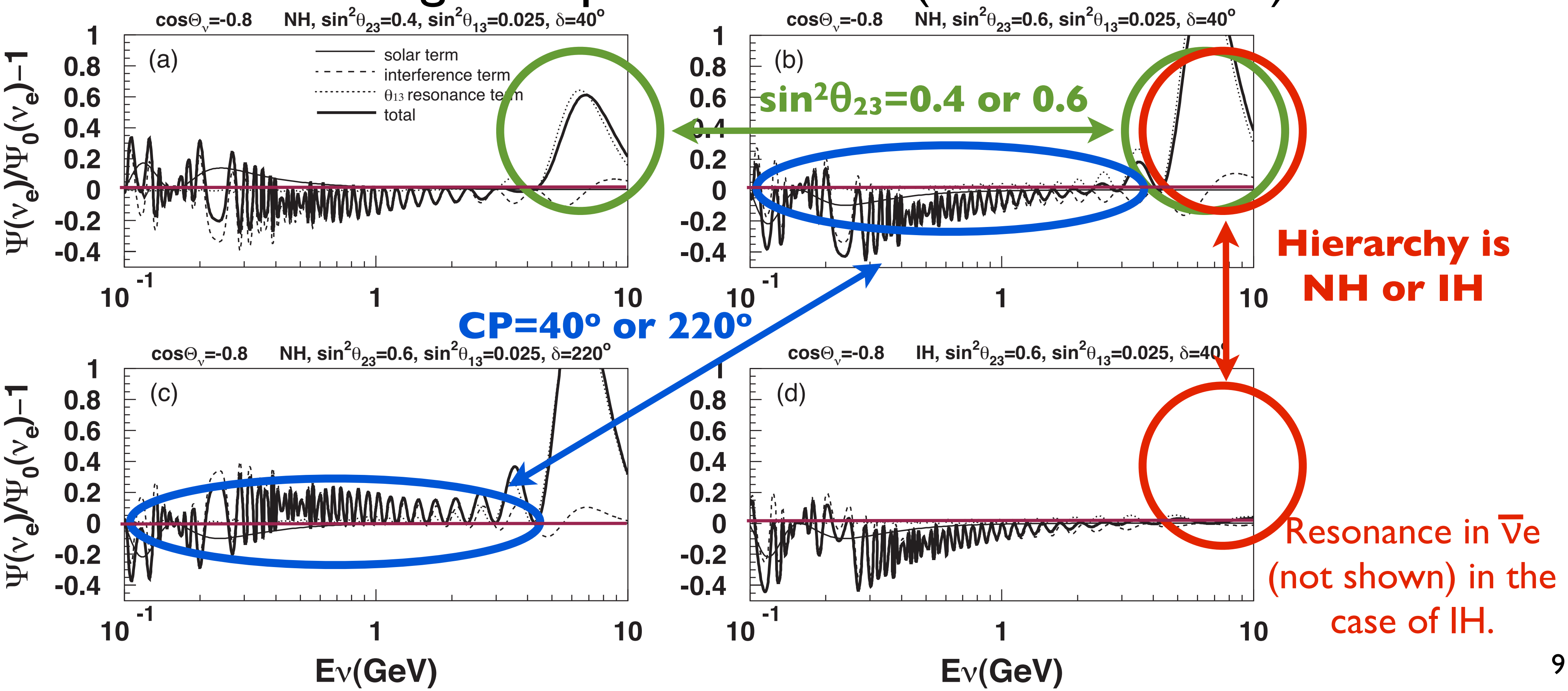
Ongoing study to extract ν_τ CC crosssection.

3-flavor oscillation study



Through the matter effect in the Earth, we study on
- Mass hierarchy : resonance in multi-GeV νe or $\bar{\nu}$e
- CP δ : interference btw two Δm^2 driven oscill.
- θ_{23} octant : magnitude of the resonance

"Fractional change of upward ν_e flux ($\cos\Theta_{zenith}$=-0.8)"



ν_e-like and anti-ν_e-like sample

$\nu_e + N \rightarrow e^- + X$

$\bar{\nu}_e + N \rightarrow e^+ + X$

- ν_e CC produce more positive π^+ than ν_e-bar
  - because of negative lepton (e^-)
  - more muon decays
- More energy transfer to hadronic system
  - more pions and muon decays
  - lower charged lepton energy

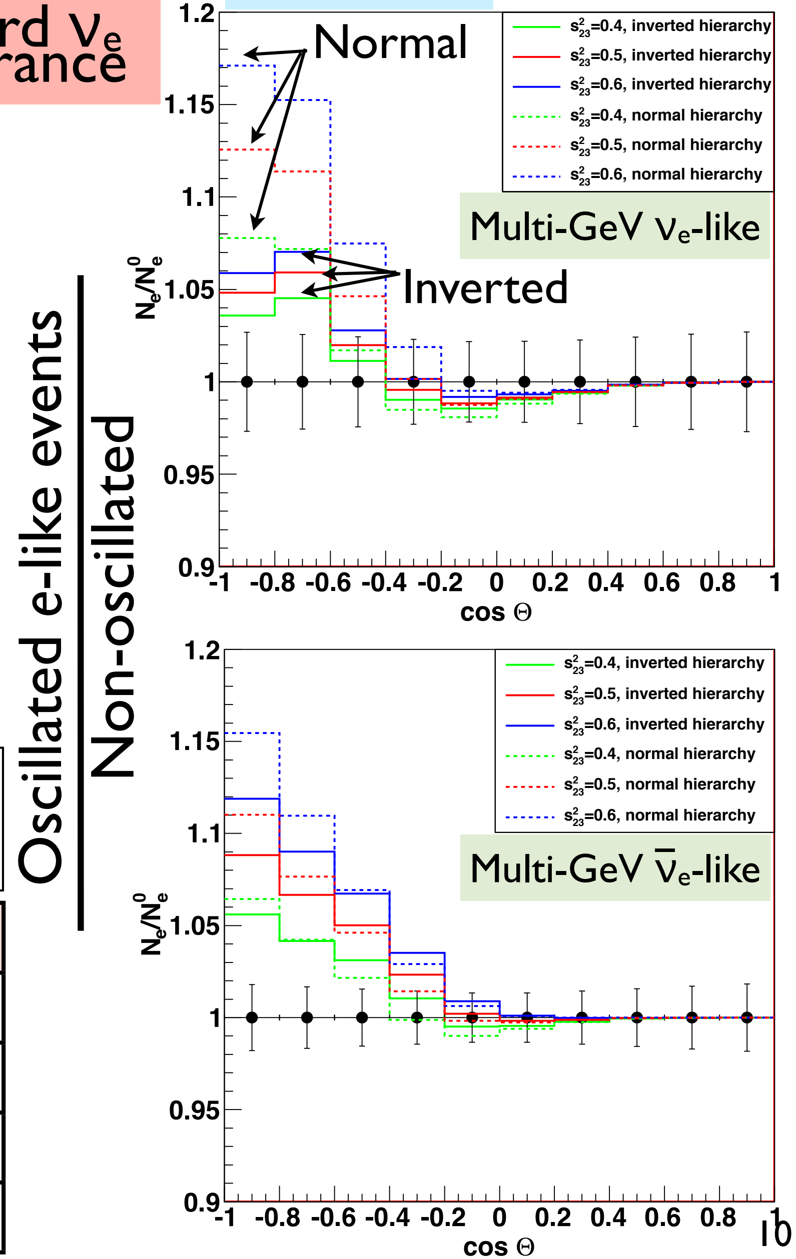
Define likelihood to make enhanced samples

- Multi-GeV (1-ring) νe
- Multi-GeV (1-ring) νe-bar
- Multi-GeV Multi-ring νe
- Multi-GeV Multi-ring νe-bar

	νe CC	anti-νe CC	others	Total
1R νe-like	62%	9%	29%	100%
1R $\bar{\nu}$e-like	55%	37%	8%	100%
MR νe-like	56%	10%	34%	100%
MR $\bar{\nu}$e-like	53%	27%	20%	100%

Upward ν_e appearance

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



Oscillation fit to SK Atmν data

1. $\sin^2\theta_{13} = 0.0219$(PDG14), additional scale factor α for Earth's matter effect
2. $\sin^2\theta_{13} = 0.0219$(PDG14)
3. MH sensitivity enhanced w/ T2K constraint

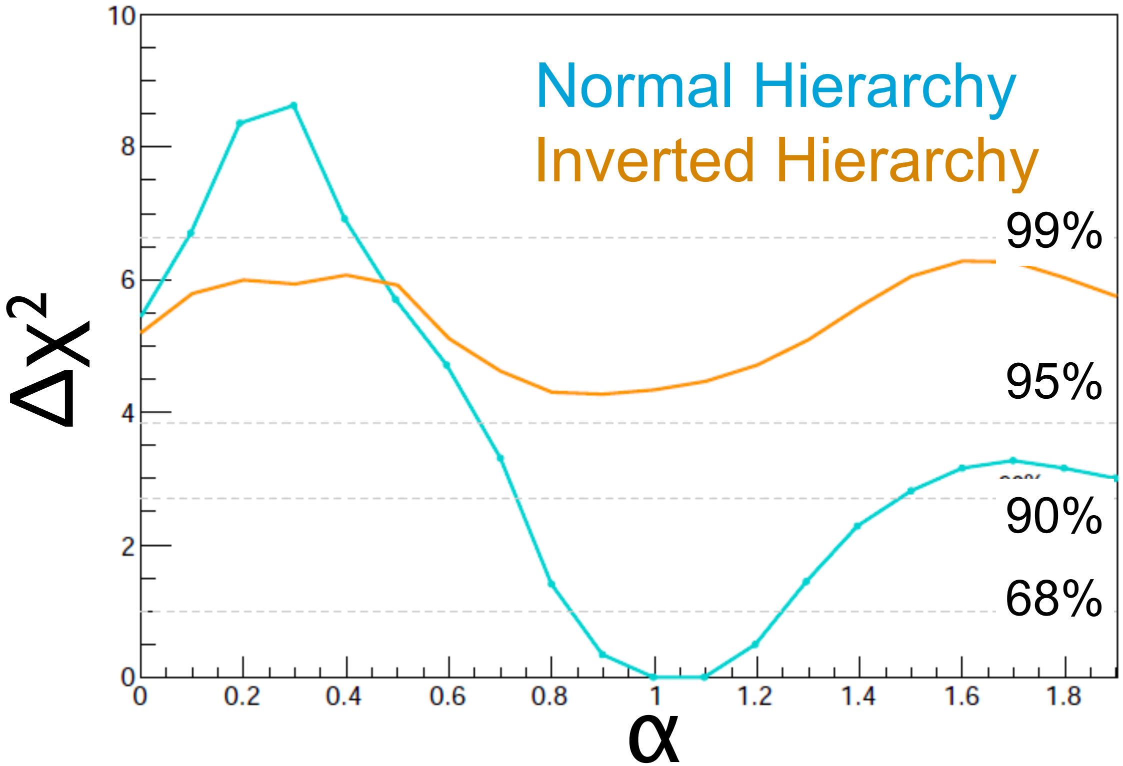
Parameter	Value
Δm^2_{21}	$7.53 \pm 0.18 \times 10^{-5}$ eV^2 (fix)
$\sin^2\theta_{12}$	0.304 ± 0.014 (fix)
Δm^2_{32}	free
$\sin^2\theta_{23}$	free
$\sin^2\theta_{13}$	0.0219 ± 0.0012 (fix)
δ_{CP}	free
Mass Hierarchy	free

Matter effect fit

$$H_{\mathrm{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} \alpha a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U$$

α: scale factor

a=sqrt(2) G_f N_e

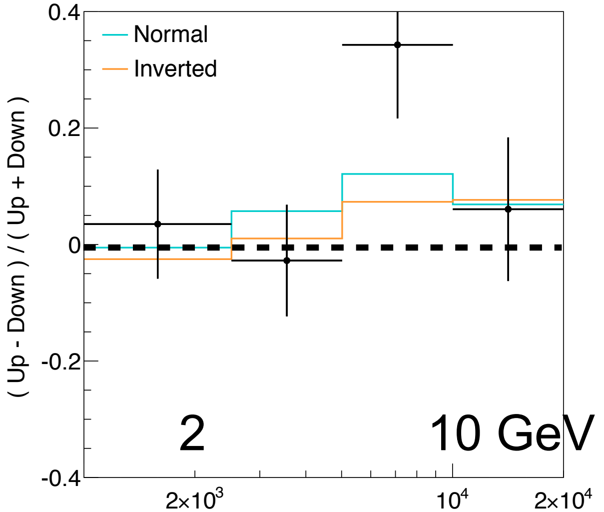


- Best fit α=1 for NH, consistent w/ standard matter effect
- $\Delta\chi^2$=5.2 for α=0, Data disfavors zero matter-effect by >2σ

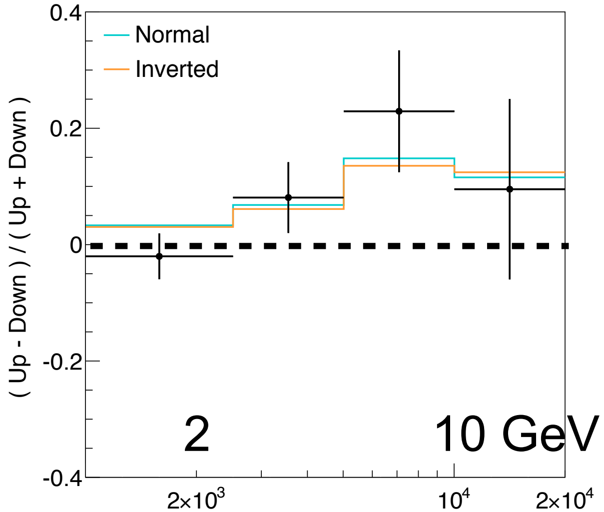
electron's Up/Down ratio

Up(cosΘ<-0.4) to Down(cosΘ>0.4) event ratio for multi-GeV electrons

Multi-GeV ν_e-like



Multi-GeV $\overline{\nu}_e$-like

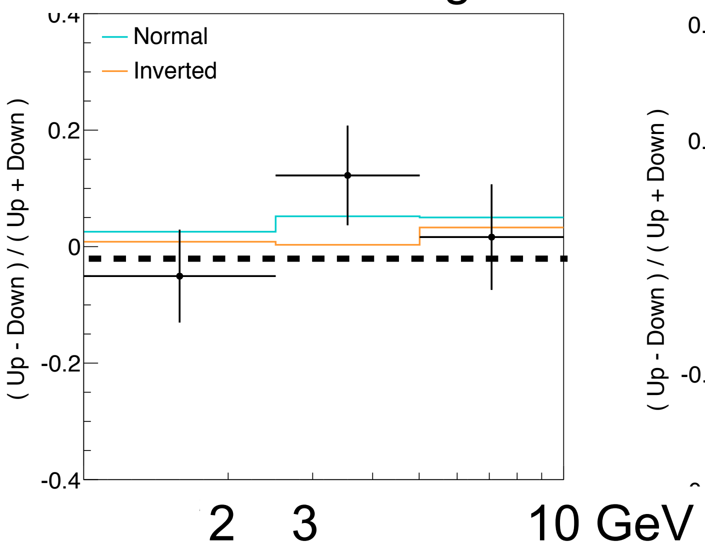


Normal Hierarchy

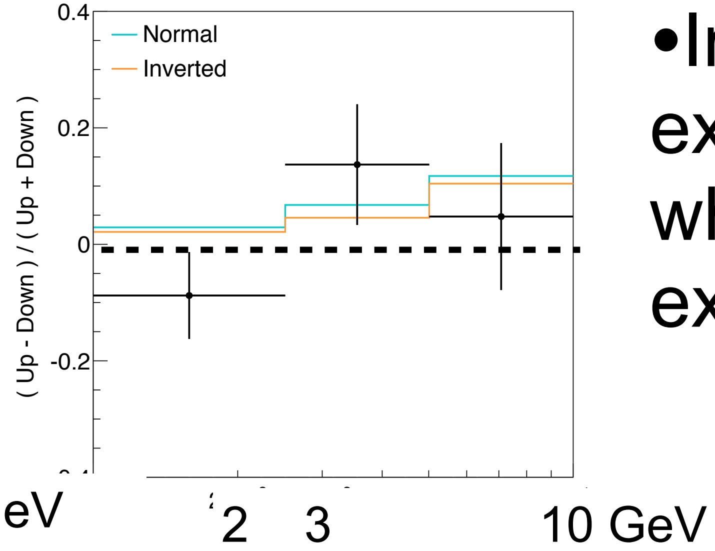
Inverted Hierarchy

- Some data points favors matter-effect

Multi-GeV Mulri-ring ν_e-like

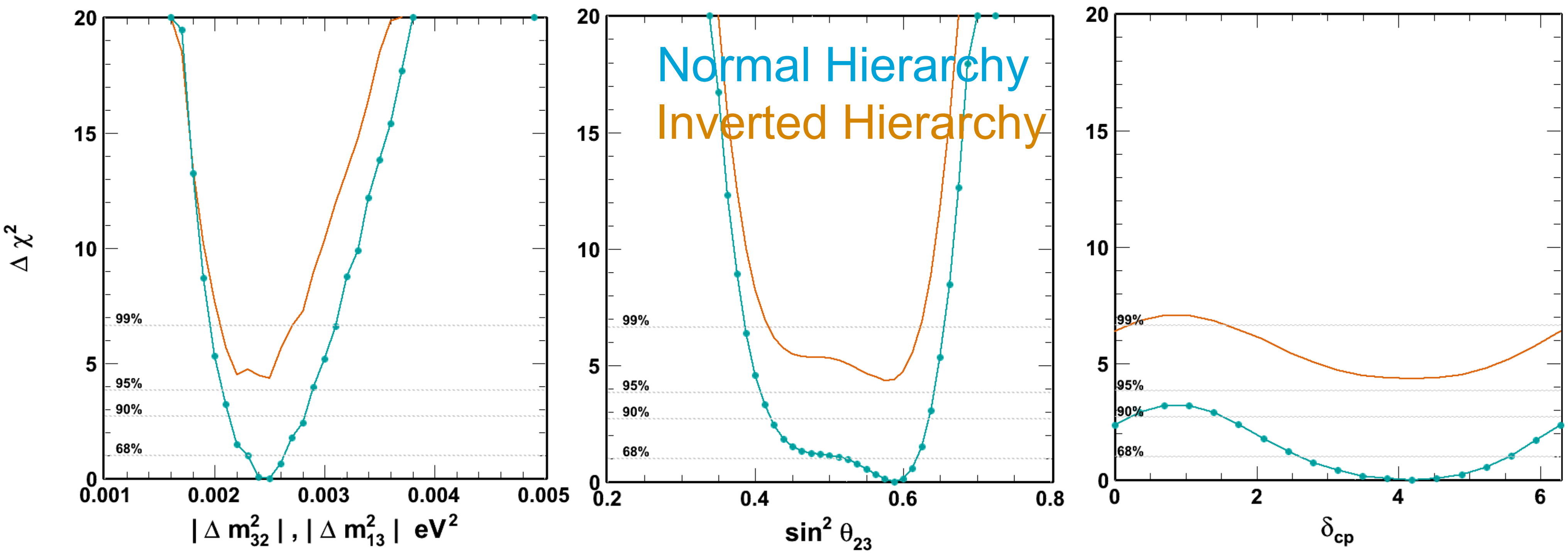


Multi-GeV Mulri-ring $\overline{\nu}_e$-like



- Indication of excess at ~5GeV where resonance is expected to occur

Atmν data fit w/ fixed θ_{13}



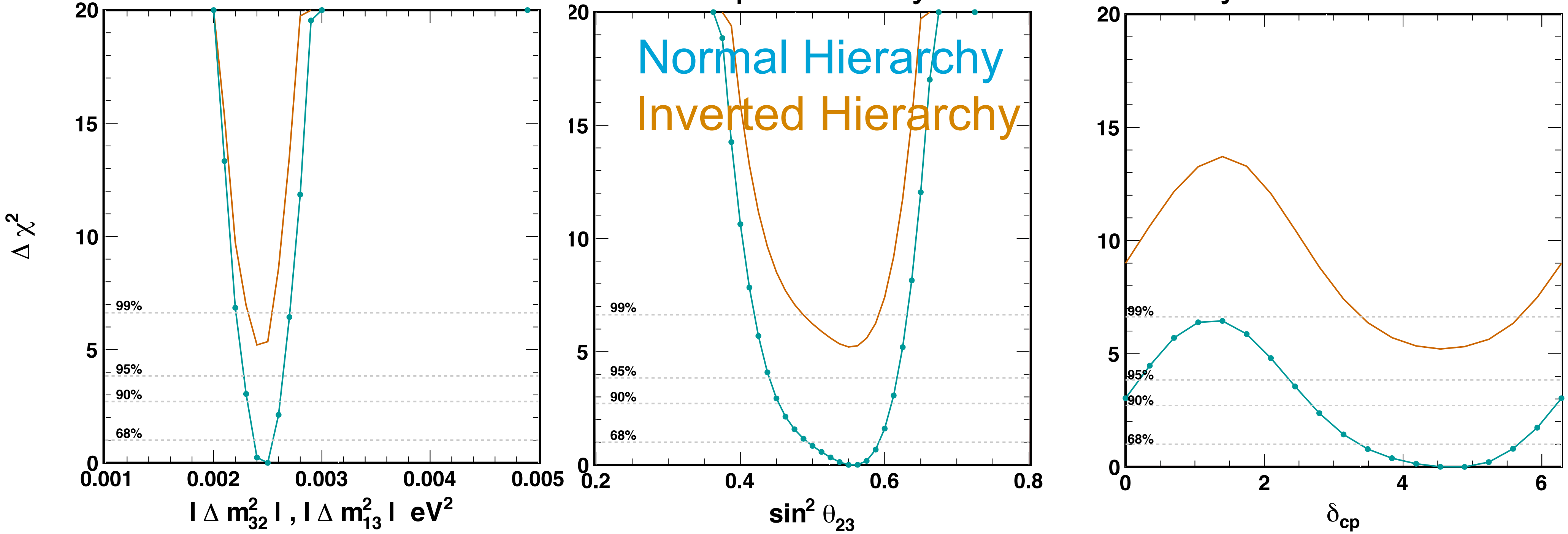
Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$eV^2
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5×10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5×10^{-3}

- Mass hierarchy: $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$ (-3.1 expected)
- Under IH hypothesis, the probability to obtain -4.3 or less is 3.1% ($\sin^2\theta_{23}$=0.6) and 0.7%($\sin^2\theta_{23}$=0.4).
- Under NH hypothesis, it is as large as 45% ($\sin^2\theta_{23}$=0.6)

Atmν data fit w/ T2K

Publicly available T2K data is used as an external constraints

T2K's constraints on θ_{23} and Δm^2_{32} help sensitivity to mass hierarchy



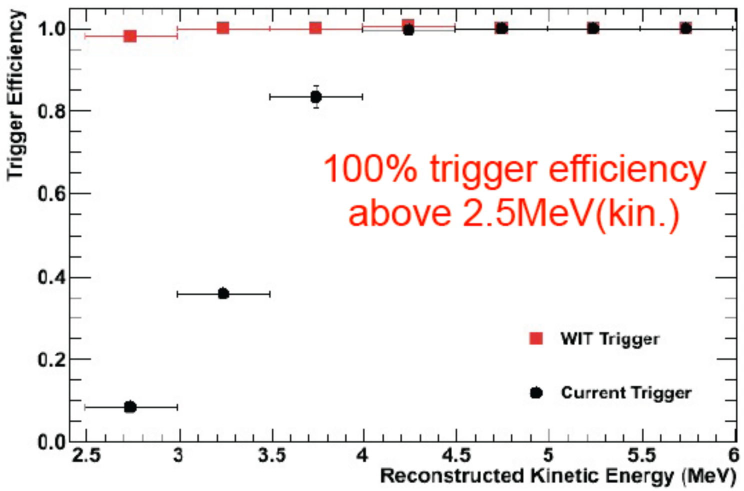
Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

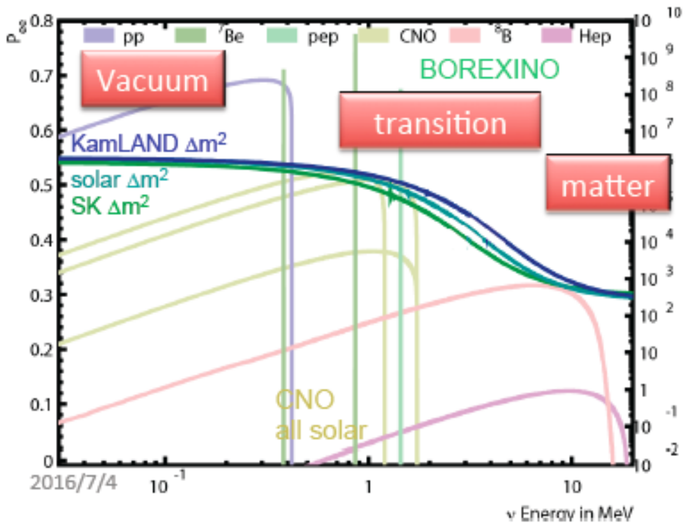
- SK+T2K: $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$ (-3.8 exp'd for SK best point, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain -5.2 or less is 2.4% ($\sin^2\theta_{23}$=0.6) and 0.1%($\sin^2\theta_{23}$=0.4).
- Under NH hypothesis, it is 43% ($\sin^2\theta_{23}$=0.6)

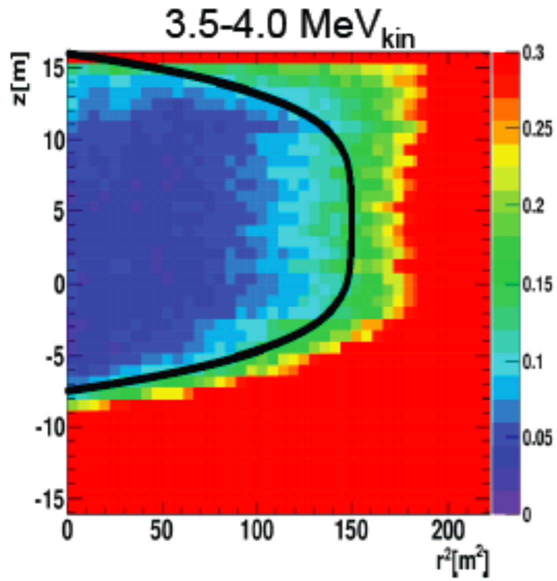
Paper in preparation

Solar Neutrinos

- Remaining issues: precision measurements of day/night and spectrum upturn
  - They will be compelling evidence of solar ν oscillations
  - Precision measurement of ν_e's θ_{12} and Δm^2_{21} necessary to address the 2σ tension between Solar and KamLAND
- Recent Activities
  - Reduce Radon BG in water
  - Effort to lowering trigger threshold
    - eff. @Ekin = 3.5-4.0MeV 84%→99%

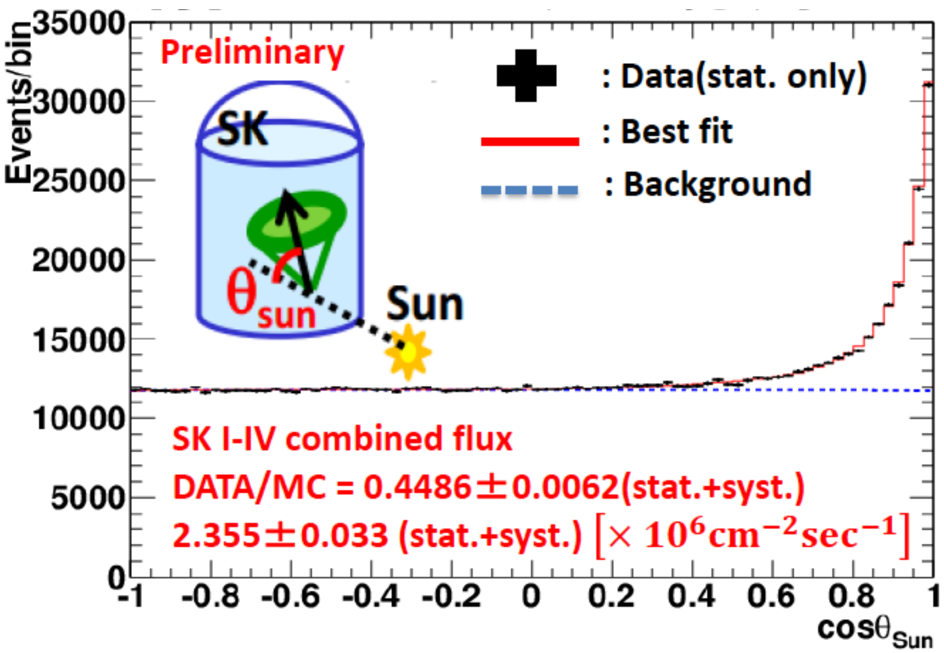


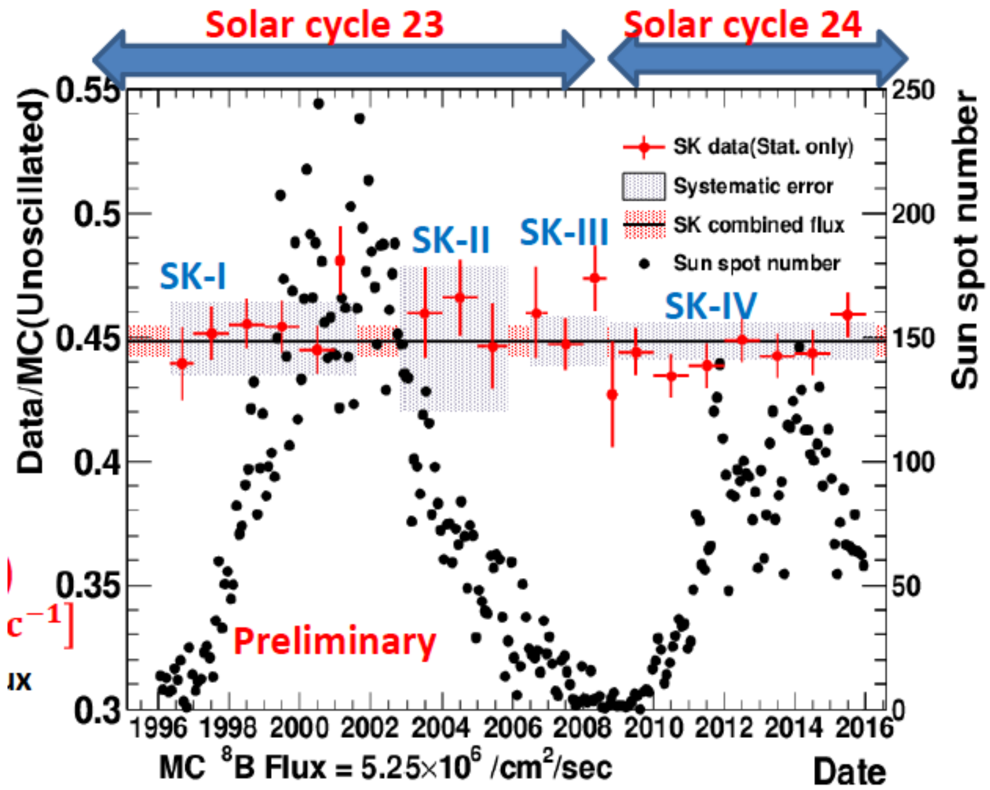




Flux measurement updates

All SK I-IV, 5200 days



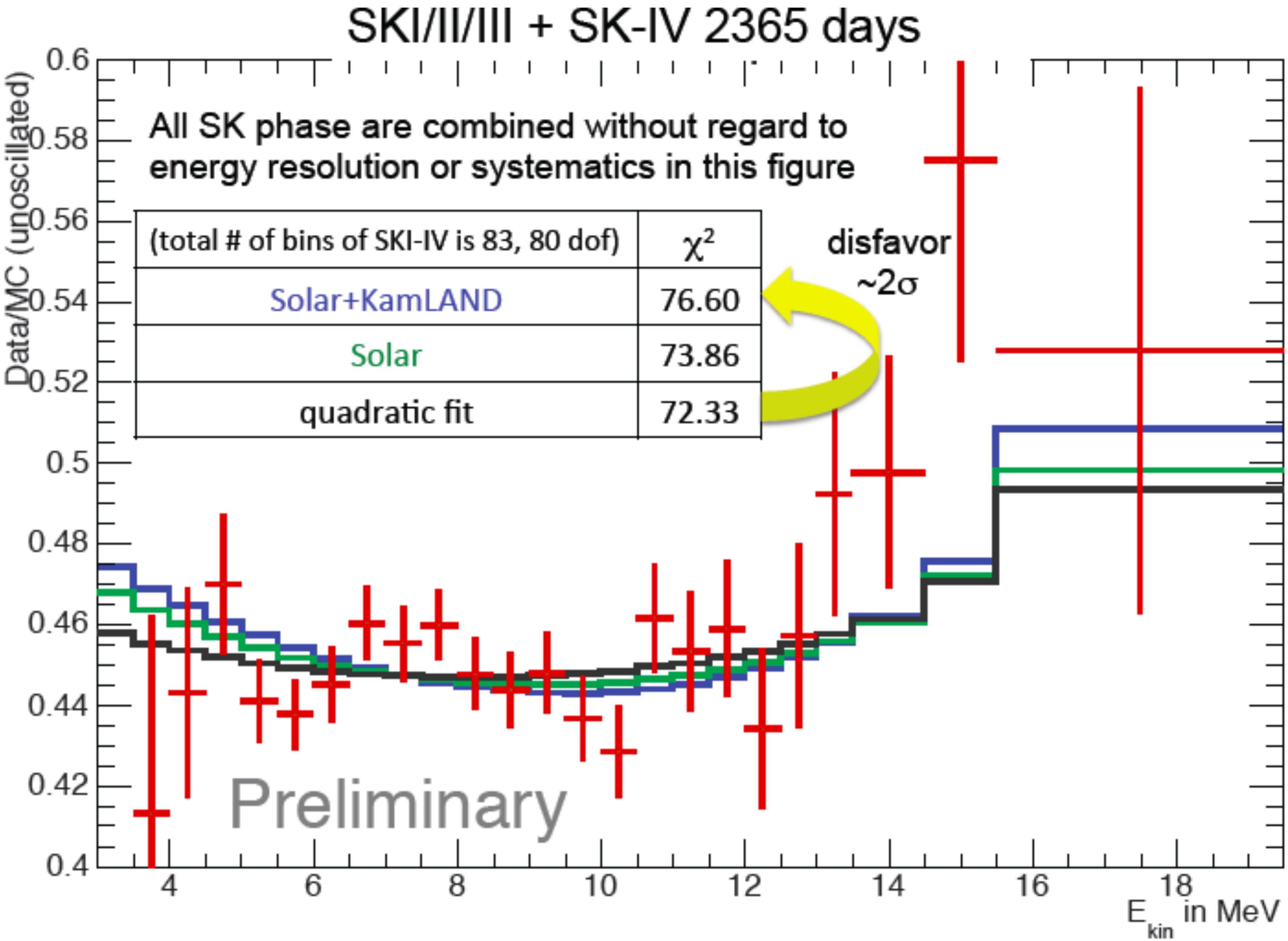


- 84k signal for 5200 days
- Data/MC = 0.4486 ± 0.0062(stat+syst)
- φ = 2.355 ± 0.033 (stat+syst) [10^6 $cm^{-2}s^{-1}$]

- χ^2 for flat = 15.52/19d.o.f.
- p-value = 68.9%

Data is consistent with a constant flux emission by Sun

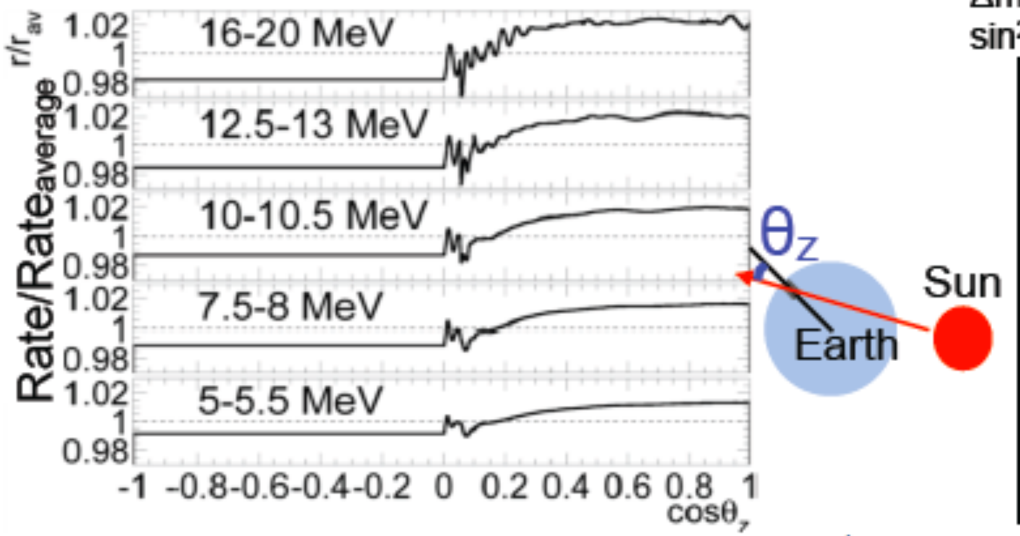
Spectrum



(total # of bins of SKI-IV is 83, 80 dof)	χ^2
Solar+KamLAND	76.60
Solar	73.86
quadratic fit	72.33

Day/Night aymmetry

Assuming the expected time variation as a function of $\cos\theta_z$ like below, amplitude of A_{DN} was fitted.



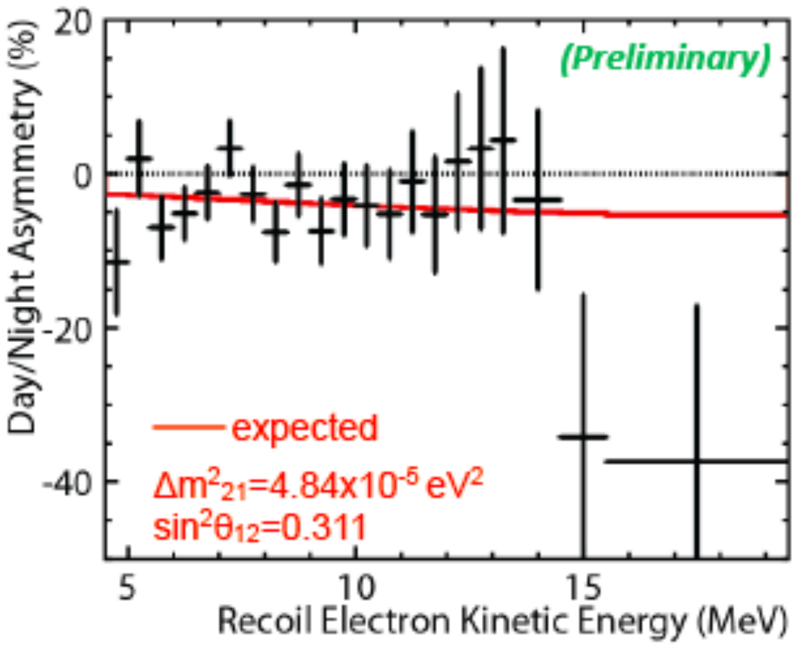
For solar global parameter: $A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$

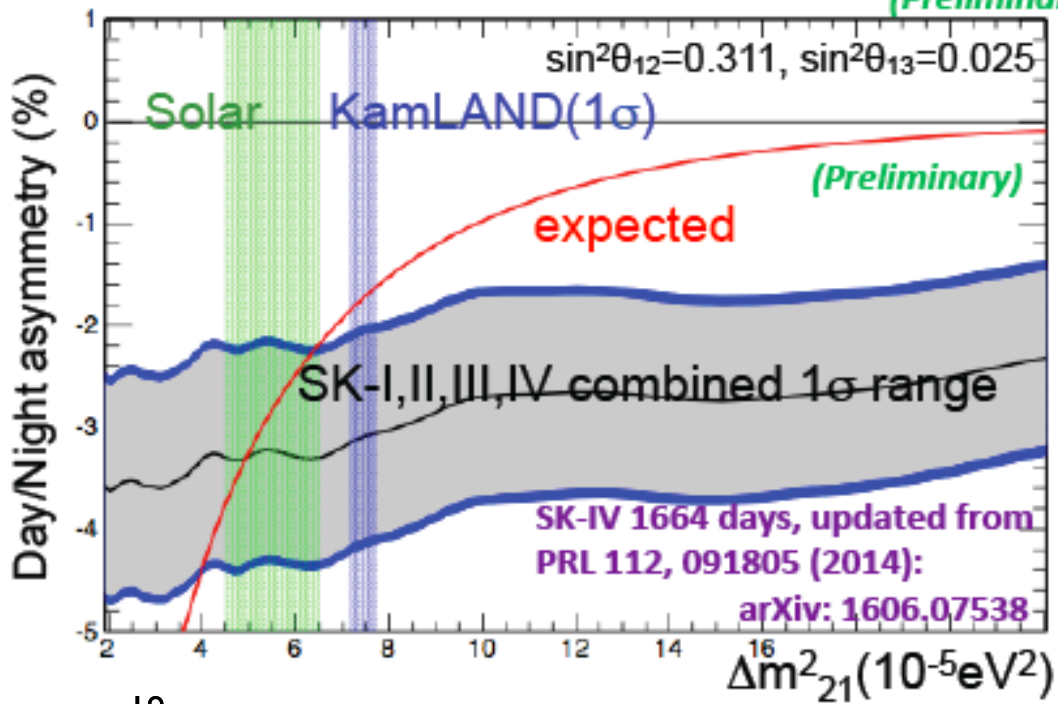
$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2

$\sin^2\theta_{12}=0.311$

	A^{fit}_{DN}
SK-I	-2.0±1.8±1.0%
SK-II	-4.4±3.8±1.0%
SK-III	-4.2±2.7±0.7%
SK-IV	-3.6±1.6±0.6%
combined	-3.3±1.0±0.5%
non-zero significance	3.0σ

(Preliminary)





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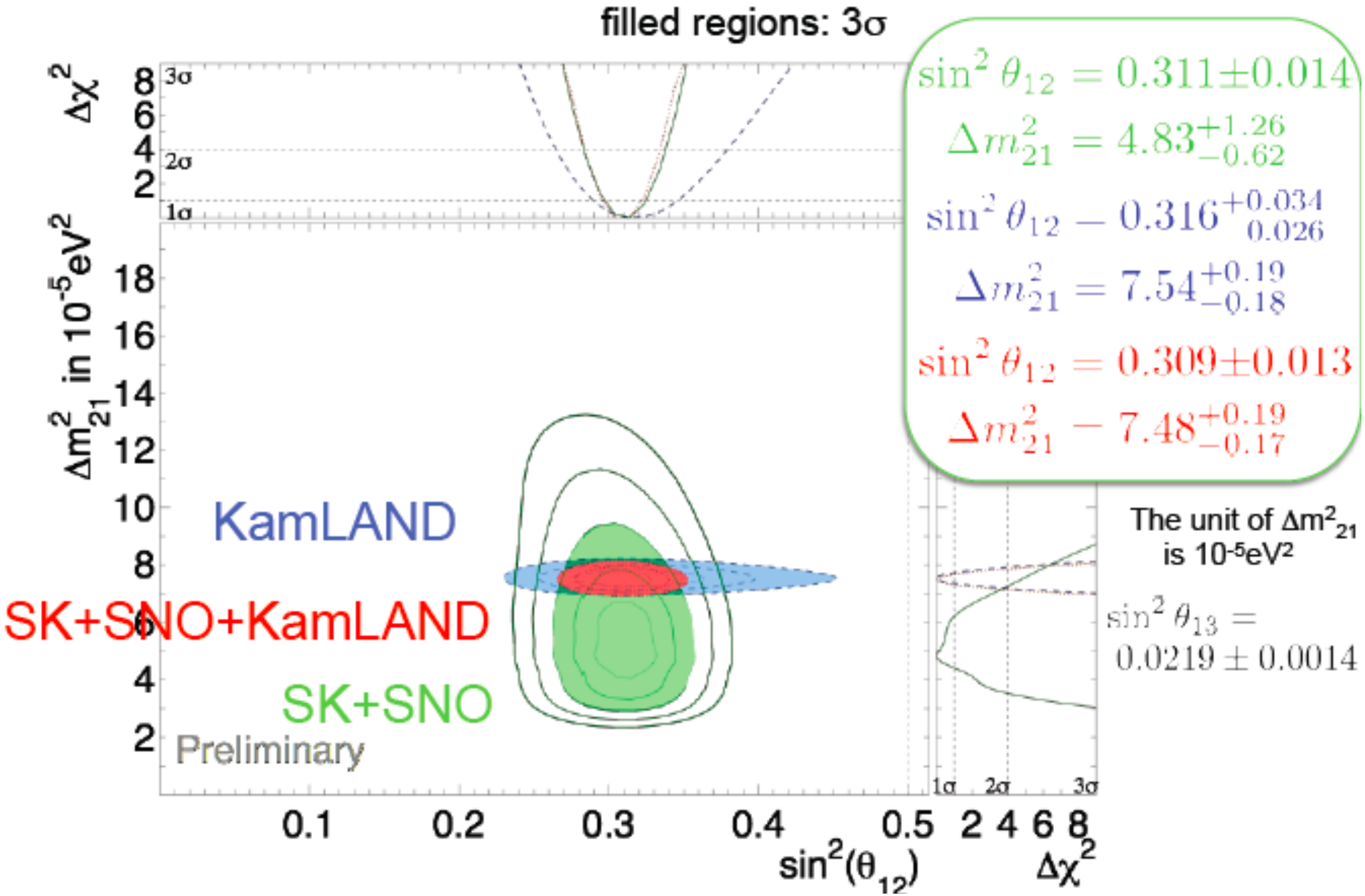
Super-K+SNO vs KamLAND

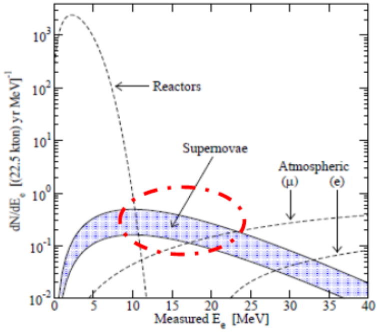


SK spectrum and D/N favor lower Δm^2_{21} that causes ~2σ tension w/ KamLAND. More data is needed to conclude.

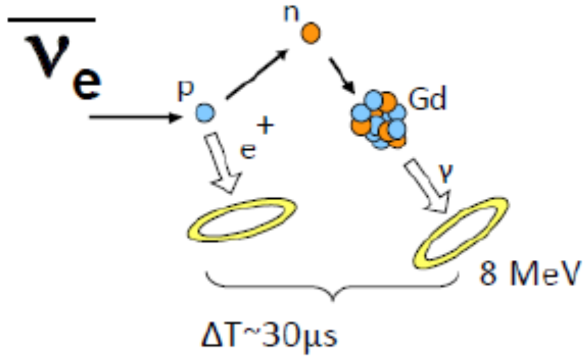
SK-Gd

- Discovery of relic SN neutrinos is expected by O(1) sensitivity improvement
- 0.1% Gd loading to tag $\overline{\nu}e+p\rightarrow e+n$, $Gd+n\rightarrow Gd+\gamma s$

- R&D in test tank and water system construction going on
- Start SK-Gd in a few yrs

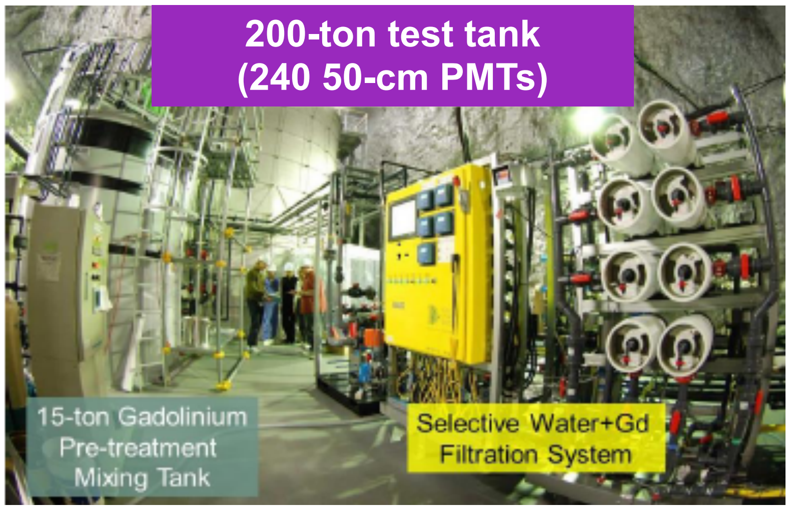


Phys. Rev. Lett. 93 (2014) 171101.



Model Tν	10-16MeV Eve/10yrs	16-28MeV Eve/10yrs	Total (10-28MeV)	Significance 2 energy bin
8 MeV	11.3	19.9	31.2	5.3σ
6 MeV	11.3	13.5	24.8	4.3σ
4 MeV	7.7	4.8	12.5	2.5σ
1987a	5.1	6.8	11.9	2.1σ
BG	10	24	34	---

Model: Phys. Rev. D 79 (2009) 083013.



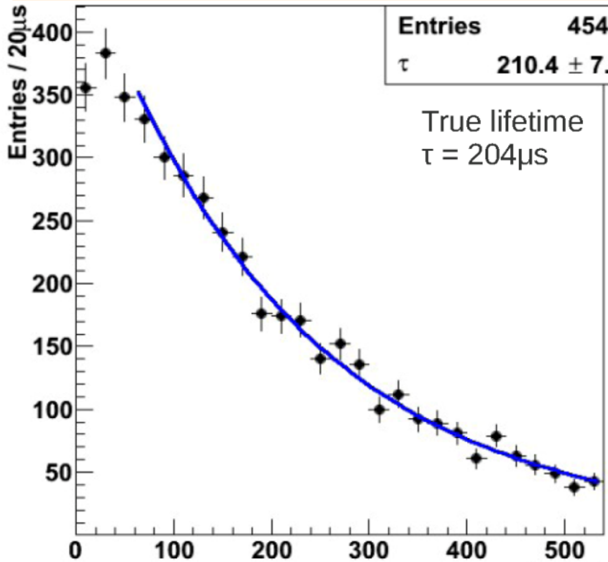
PDecay-BG reduction by neutrons

Beacom and Vagins PRL93:171101(2004)

- We expect that neutrino events are often accompanied with neutrons ($\text{e.g.}\ \overline{\nu}_e + p \rightarrow e^+ + \pi^0 + n$, recoiled protons kick neutrons in water etc.)
- neutron emission probability in proton decay is expected to be small.

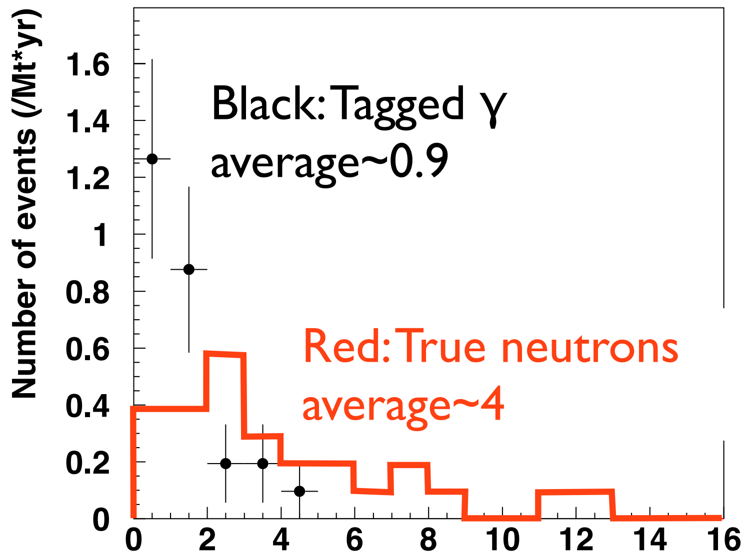
Since SK-IV we have started recording faint signature of neutrons;
$n + p \rightarrow d + \gamma$ (2.2MeV, $\tau \sim 200\mu$sec)
by new high speed pipelined electronics. BG reduction by ~2

SK-IV 1297days atmν Data



Tagged γ's Timing (μsec)

$p \rightarrow e^+ \pi^0$ BG Monte Carlo



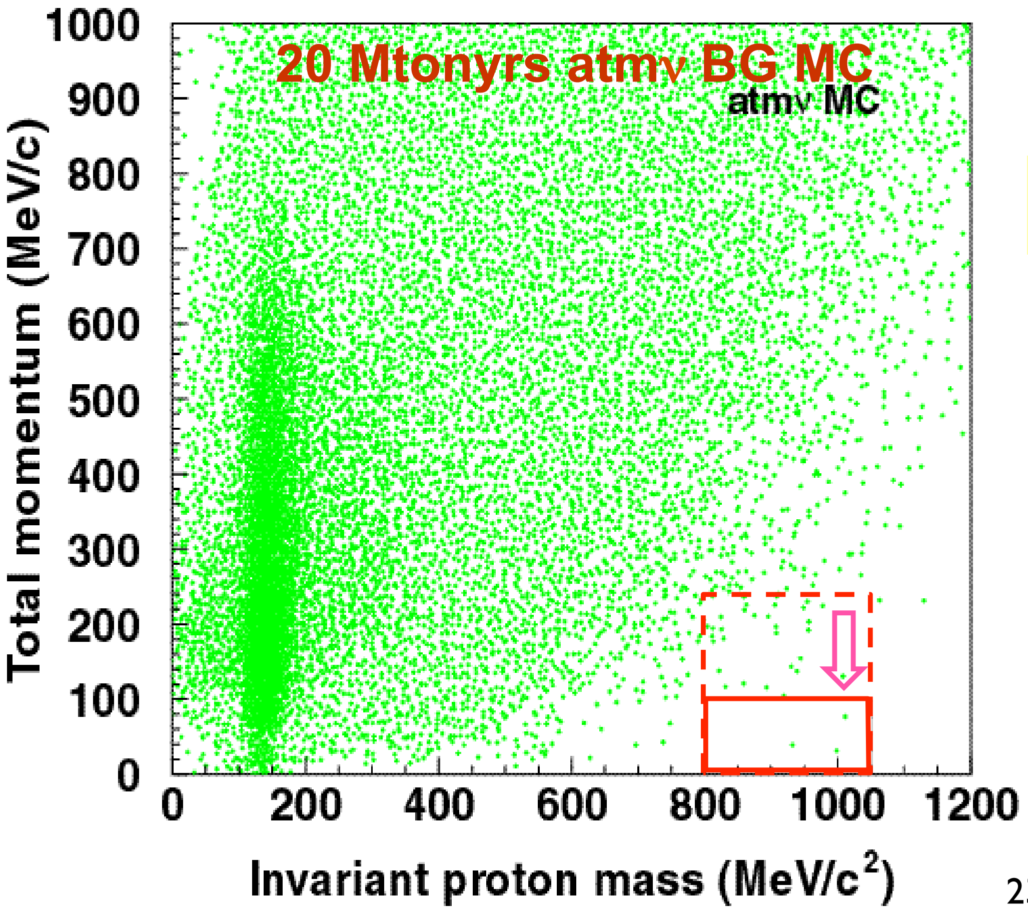
Number of neutrons or γ's

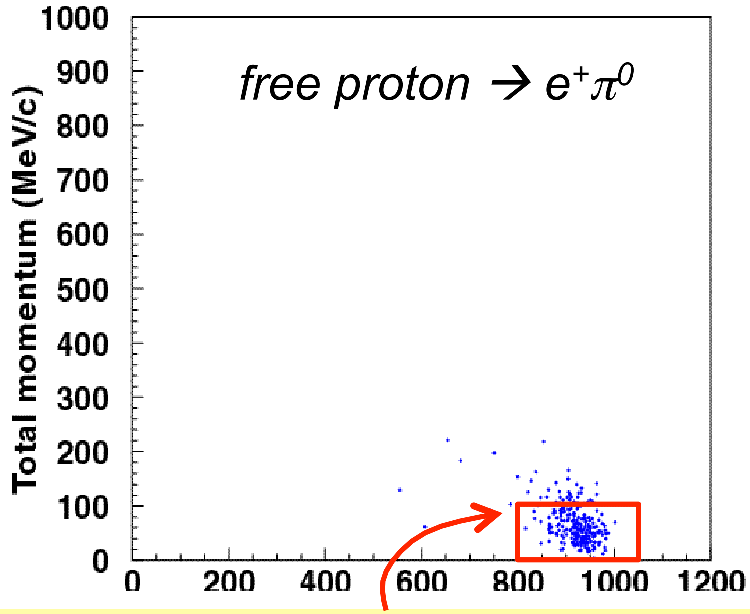
Potential BG reduction by tighter cut

Shiozawa, talk@NNN00-Fermilab

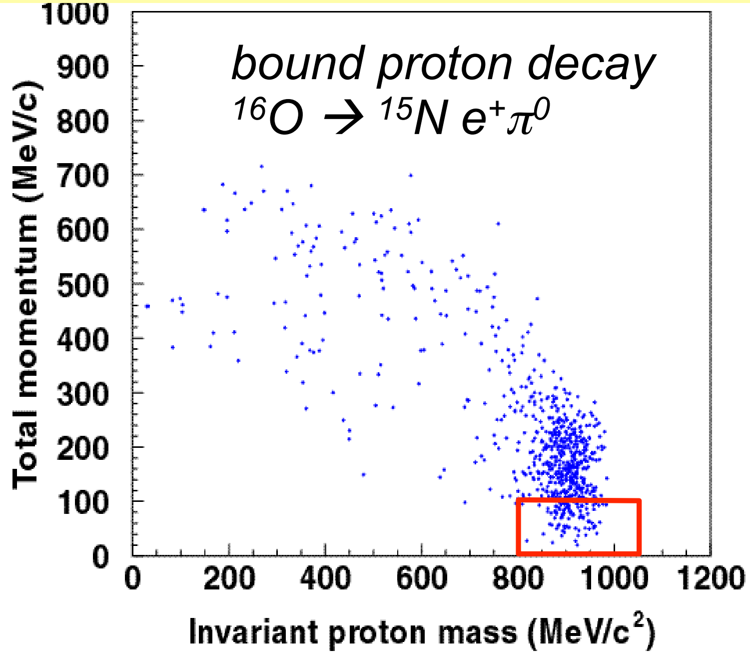
- Ptot < 250 MeV/c (SK cut)
  BG=**2.2** ev/Mtonyrs, eff.=**44%**

  BG reduction by ~15
- Ptot < 100 MeV/c (tighter cut)
  BG=**0.15**ev/Mtonyrs, eff.=**17.4%**





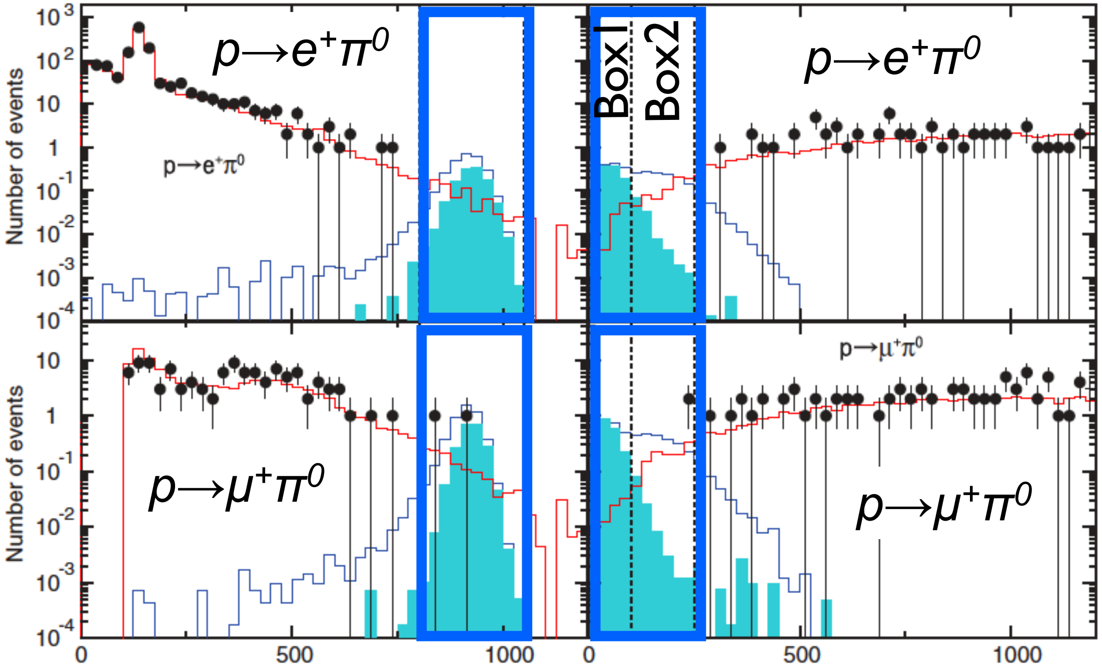
main target is *free proton decays*



Proton decays into lepton+meson

signal MC(free proton)
BG MC

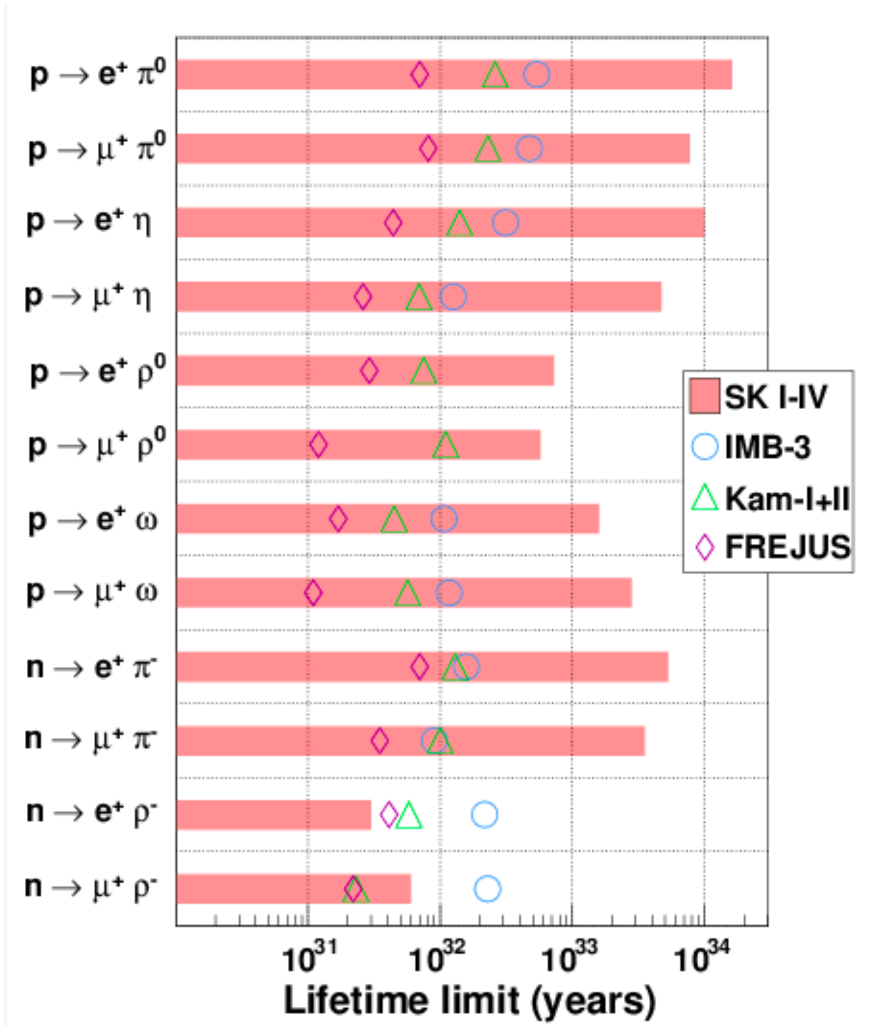
PRD 95, 012004 (2017)



Total mass (MeV/c2)   Total mom (MeV/c)

- $p \to e^+\pi^0$
  - 0 candidates (40% eff. & 0.61BG)
  - τ_p/Br > 1.6 x 10^{34} yrs
- $p \to \mu^+\pi^0$
  - 2 candidates (40% eff. & 0.87BG), one is rejected after energy re-calibration
  - τ_p/Br > 7.7 x 10^{33} yrs

paper under preparation



Summary

- **Atmospheric neutrino**
  - τ appearance (4.6σ) concluded the atmν anomaly
  - Data consistent w/ Earth's matter effect (>2σ)
  - Mass hierarchy: preference to Normal hierarchy
    SK+T2K: $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$
    Under IH hypothesis, the probability to obtain -5.2 or less is 2.4% ($\sin^2\theta_{23}$=0.6) and 0.1%($\sin^2\theta_{23}$=0.4).

- **Solar neutrinos**
  - SK spectrum and D/N favor lower Δm^2_{21} that causes ~2σ tension w/ KamLAND.

- **SK-Gd**
  - Discovery is within the reach. Start in a few years.

- **Proton decays**
  - Continuous efforts to reduce BG and keep BG-free regions.