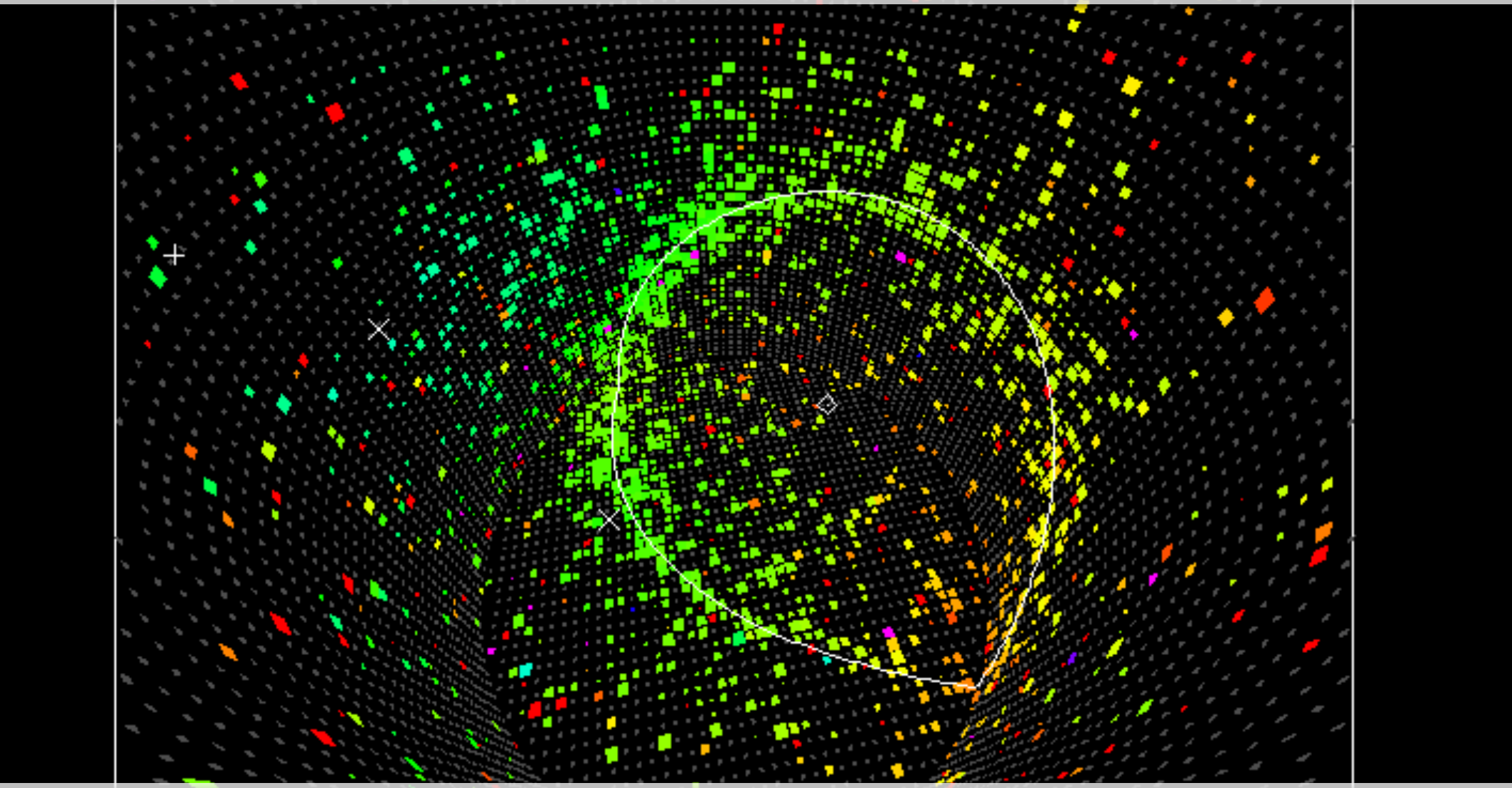
Atmospheric Neutrino and Proton Decay Results in Super-Kamiokande



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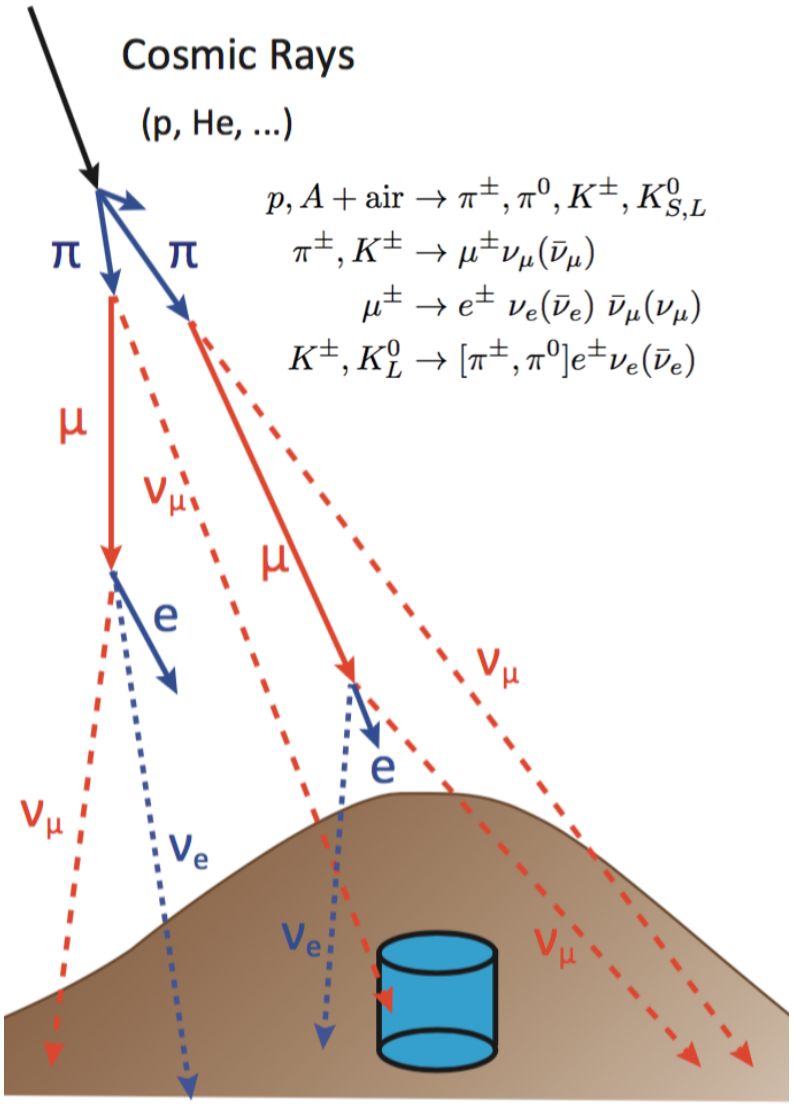
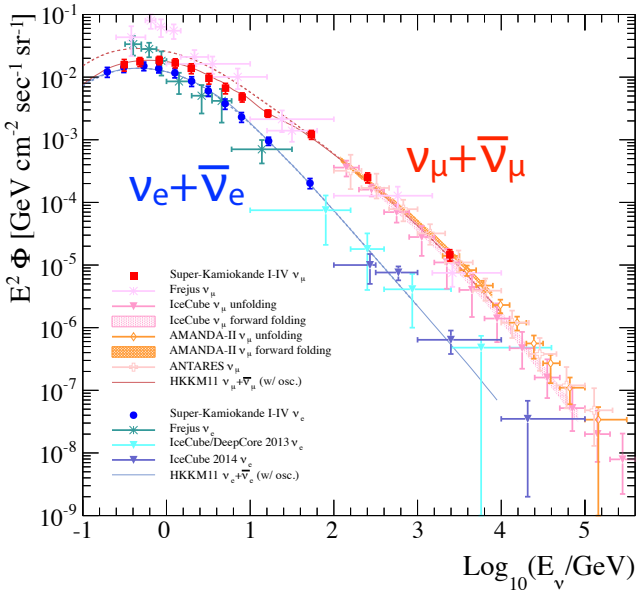
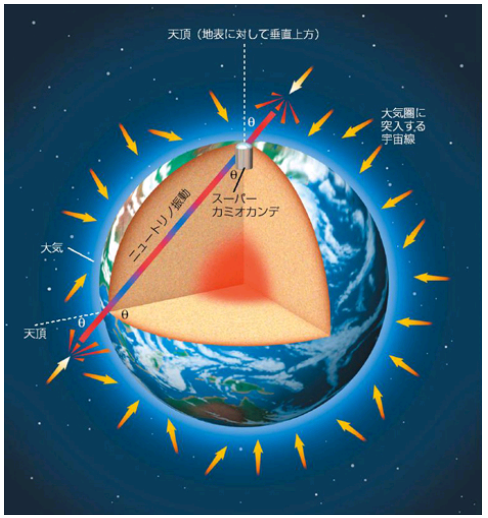
Atmospheric Neutrinos

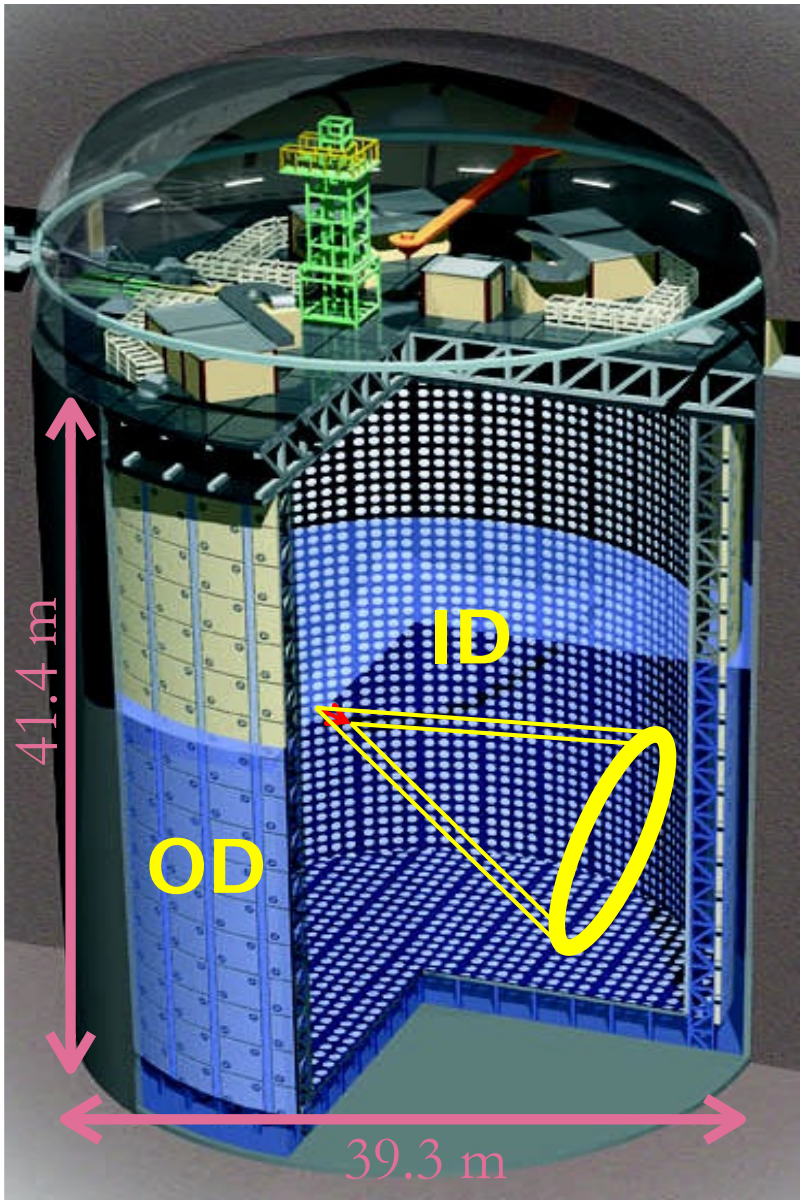






- Decay products of secondaries by cosmic ray interactions with atmosphere. ($\nu_\mu : \nu_e \sim 2 : 1$ at GeV energy)
- **Power-law like energy spectrum.** Affected by cutoff due to geomagnetic field below several GeV.
- Path length: distributed in **O(10)km ~ 13,000km** depending on zenith angle direction
- Neutrino oscillation driven by Δm^2_{32} below O(10) GeV

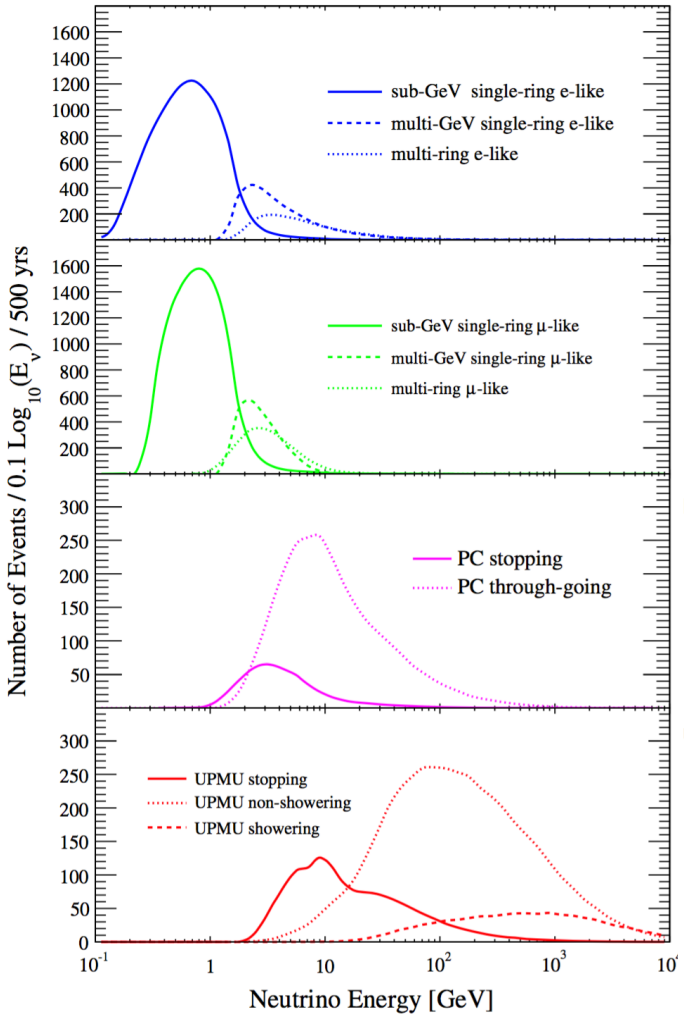
Super-Kamiokande Detector

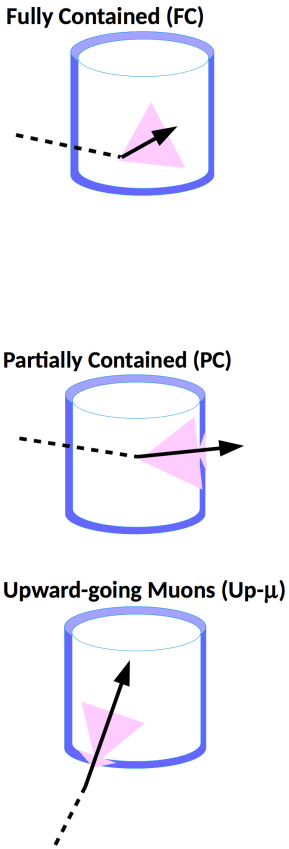


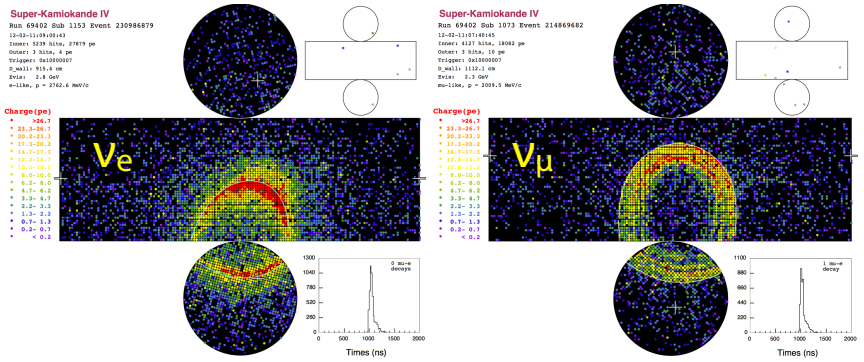
- Water Cherenkov imaging detector
- **1000 m underground** in Kamioka mine
- **50 kton volume** (fiducial 22.5 kton)
- **11129 20" PMTs** in inner detector (ID) for Cherenkov ring imaging
- 1885 8" PMTs for outer detector (OD)

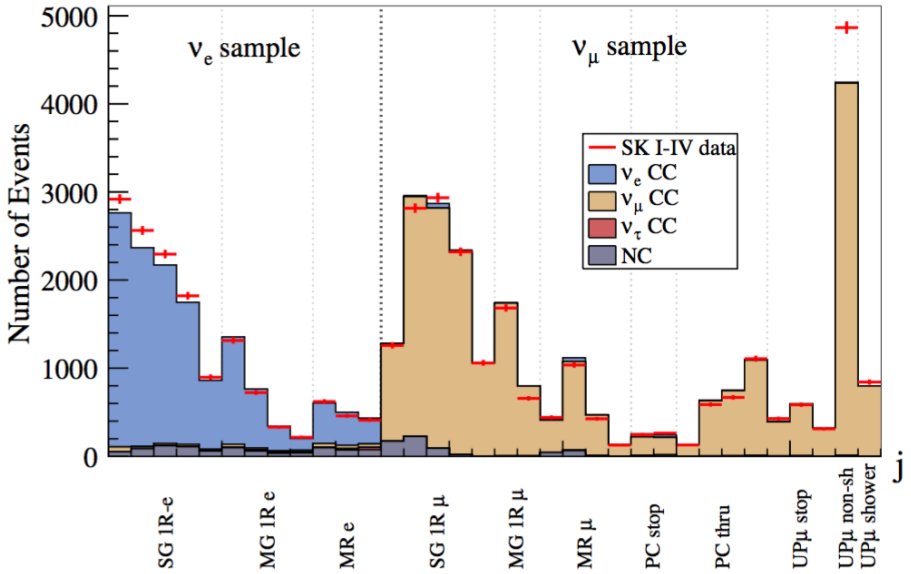
Phase	Period	# of PMTs
SK-I	1996.4 ~ 2001.7	11146 (40%)
SK-II	2002.10 ~ 2005.10	5182 (20%)
SK-III	2006.7 ~ 2008.8	11129 (40%)
SK-IV	2008.9 ~	

Super-K Atmospheric Event Sample



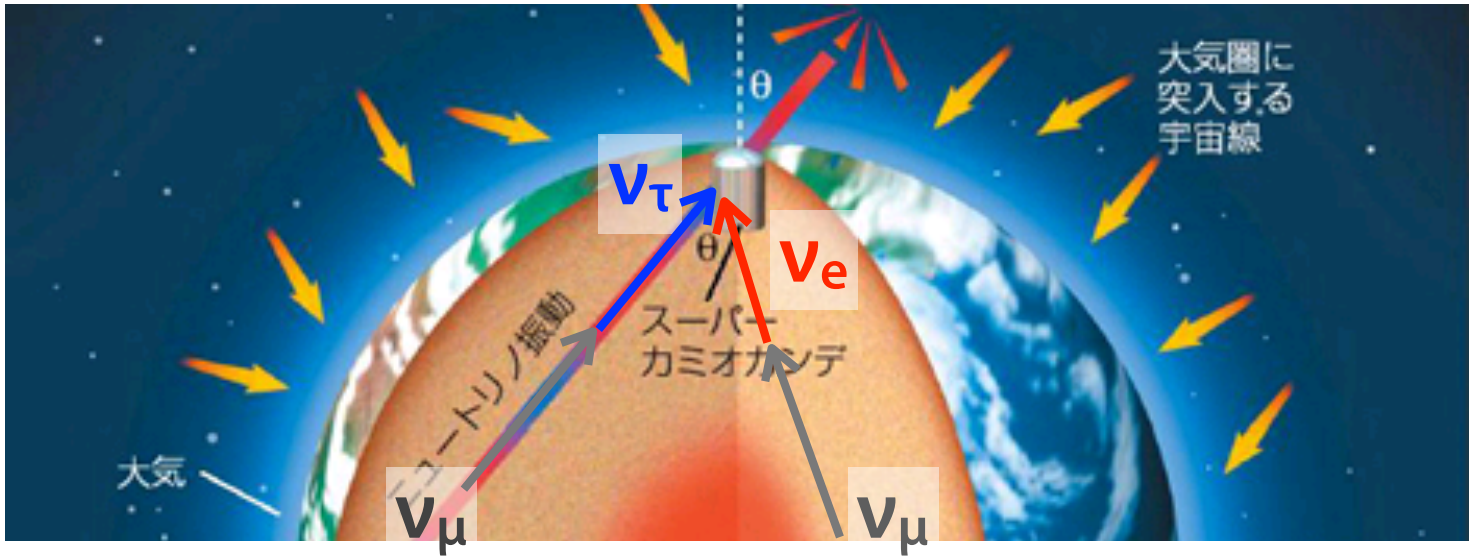




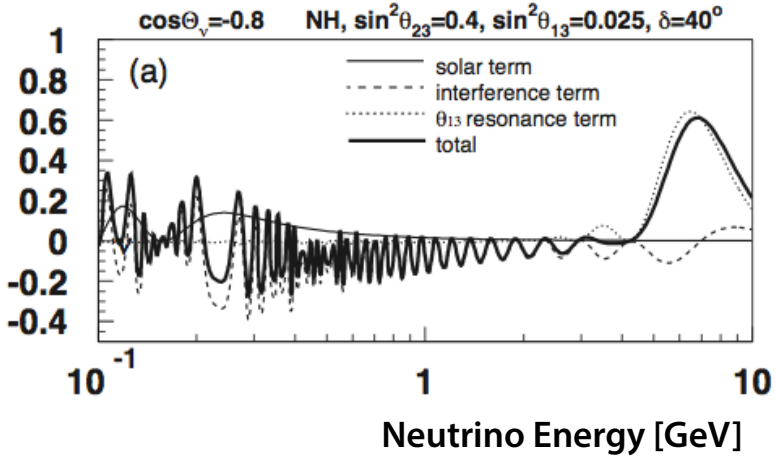


- Cover wide energy range **from 100 MeV up to 10 TeV** with three different event topologies
- High purity of ν_μ and ν_e CC sample with excellent particle ID performance

Atmospheric Oscillation Physics



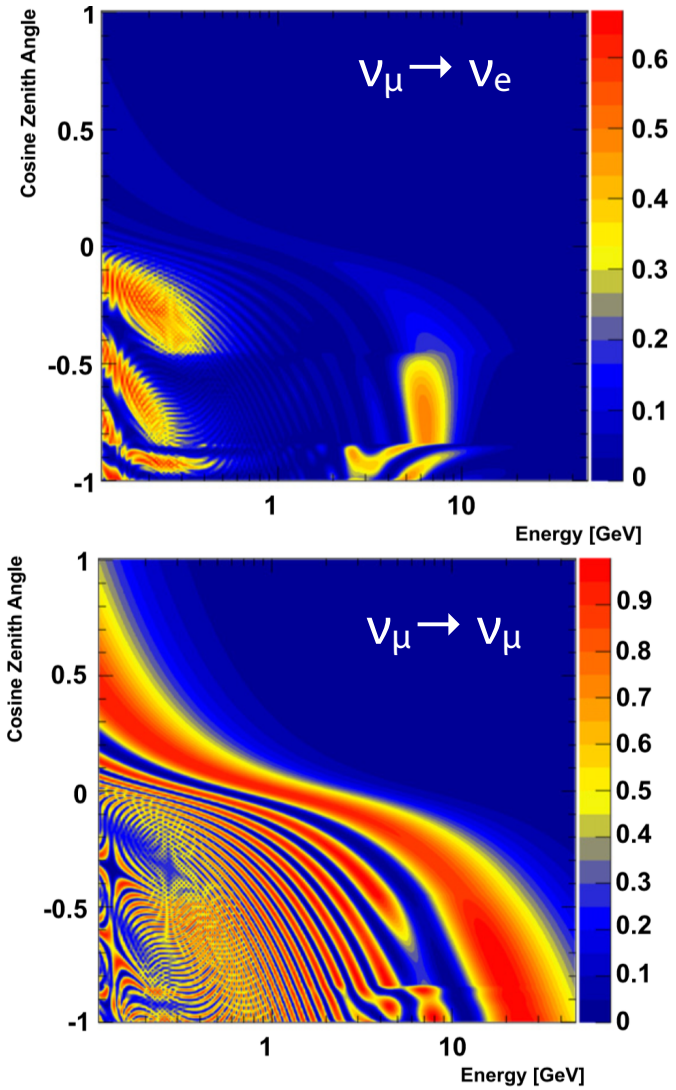
ν_e flux change due to sub-dominant oscillation:



- Many opportunities to test three flavor mixing:
  - ν_μ disappearance by ν_μ-> ν_τ (Δm^2_{32}, θ_{23})
  - Sub-dominant oscillation in ν_e sample: **mass hierarchy (sign of Δm^2_{32}), δ_{CP}, θ_{23} octant**
  - **ν_τ appearance**
- Exotic mode (sterile, NSI, ..)

Matter Effect and Mass Hierarchy

Normal hierarchy ($\Delta m^2_{32}>0$)



- Neutrino is affected by additional potential due to forward scattering with electrons (**matter effect**)

$$i\frac{d\nu(t)}{dt} = H_0\nu(t) \qquad H_0 \rightarrow H_0 + \frac{1}{2E}\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}$$

$$A = \pm 2\sqrt{2}G_F E_\nu n_e$$

- Effective mixing angle in matter:

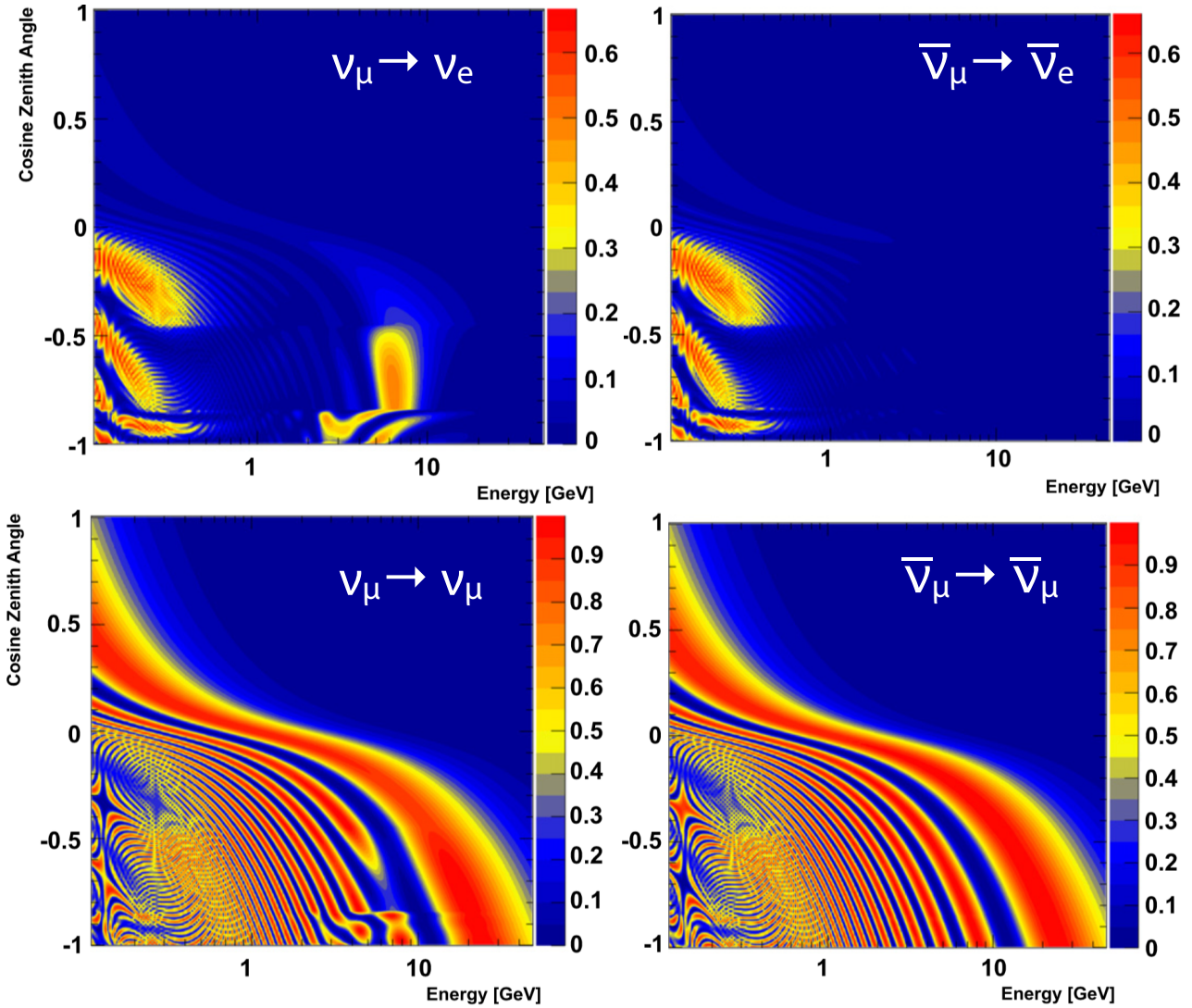
$$\sin 2\theta_{13}^M = \frac{\sin 2\theta_{13}}{\sqrt{\left(\frac{A}{\Delta m^2_{32}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}}$$

- At resonance region in multi-GeV:

$$A \sim \Delta m^2_{32}\cos 2\theta_{13} \quad \rightarrow \quad \theta_{13}^M \gg \theta_{13}$$

Matter Effect and Mass Hierarchy

Normal hierarchy ($\Delta m^2_{32}>0$)



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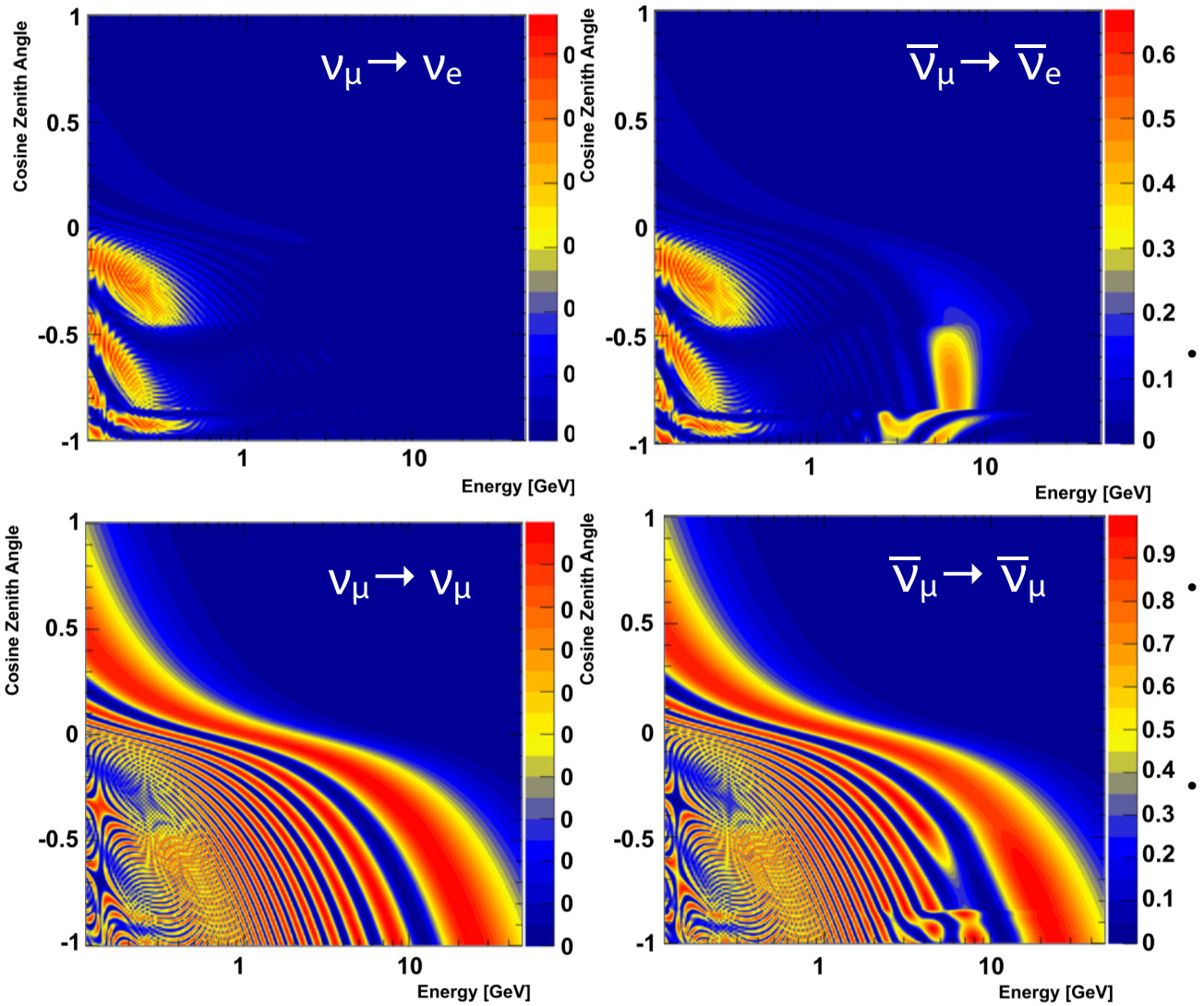
- At resonance region in multi-GeV:

$$A \sim \Delta m^2_{32}\cos 2\theta_{13} \quad \rightarrow \quad \theta_{13}^M \gg \theta_{13}$$

- Presence of resonance depends:
  - **ν / $\bar{\nu}$ (A→ -A)**

Matter Effect and Mass Hierarchy

Inverted hierarchy ($\Delta m^2_{32}<0$)



- Neutrino is affected by additional potential due to forward scattering with electrons (**matter effect**)

$$i\frac{d\nu(t)}{dt} = H_0\nu(t) \qquad H_0 \rightarrow H_0 + \frac{1}{2E}\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}$$

$$A = \pm 2\sqrt{2}G_F E_\nu n_e$$

- Effective mixing angle in matter:

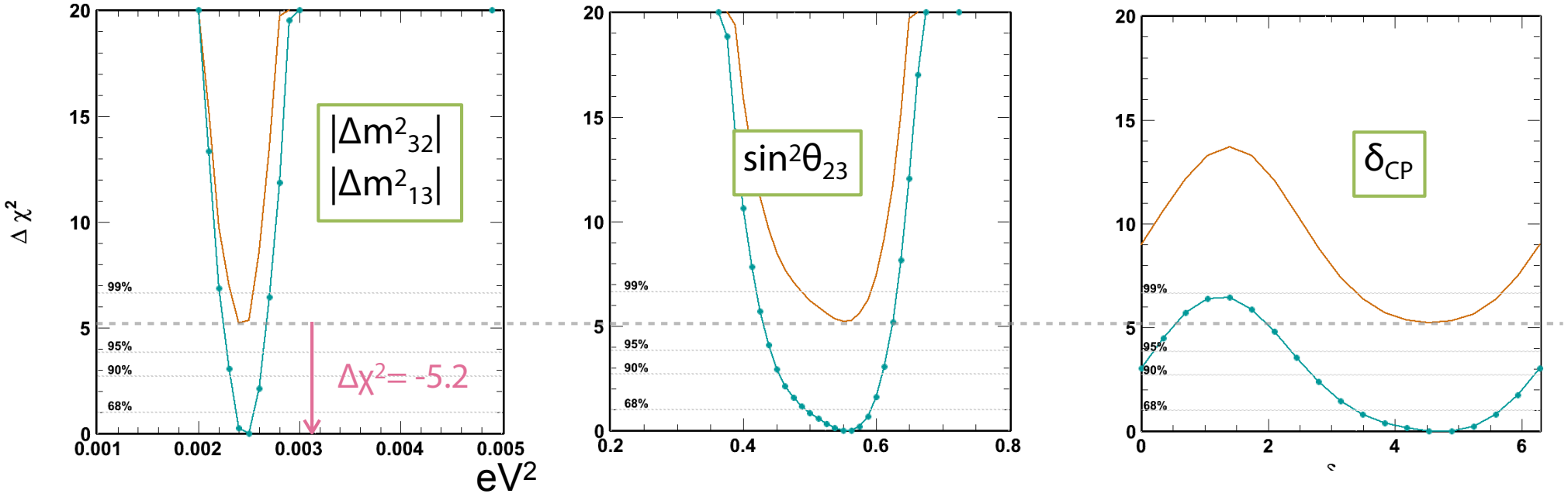
$$\sin 2\theta_{13}^M = \frac{\sin 2\theta_{13}}{\sqrt{\left(\frac{A}{\Delta m^2_{32}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}}$$

- At resonance region in multi-GeV:

$$A \sim \Delta m^2_{32}\cos 2\theta_{13} \quad \rightarrow \quad \theta_{13}^M \gg \theta_{13}$$

- Presence of resonance depends:
  - **ν / $\bar{\nu}$ (A→ -A)**
  - **Mass hierarchy ($\Delta m^2_{32} \rightarrow -\Delta m^2_{32}$)**

Three Flavor Fit (w/ reactor and T2K constraints)



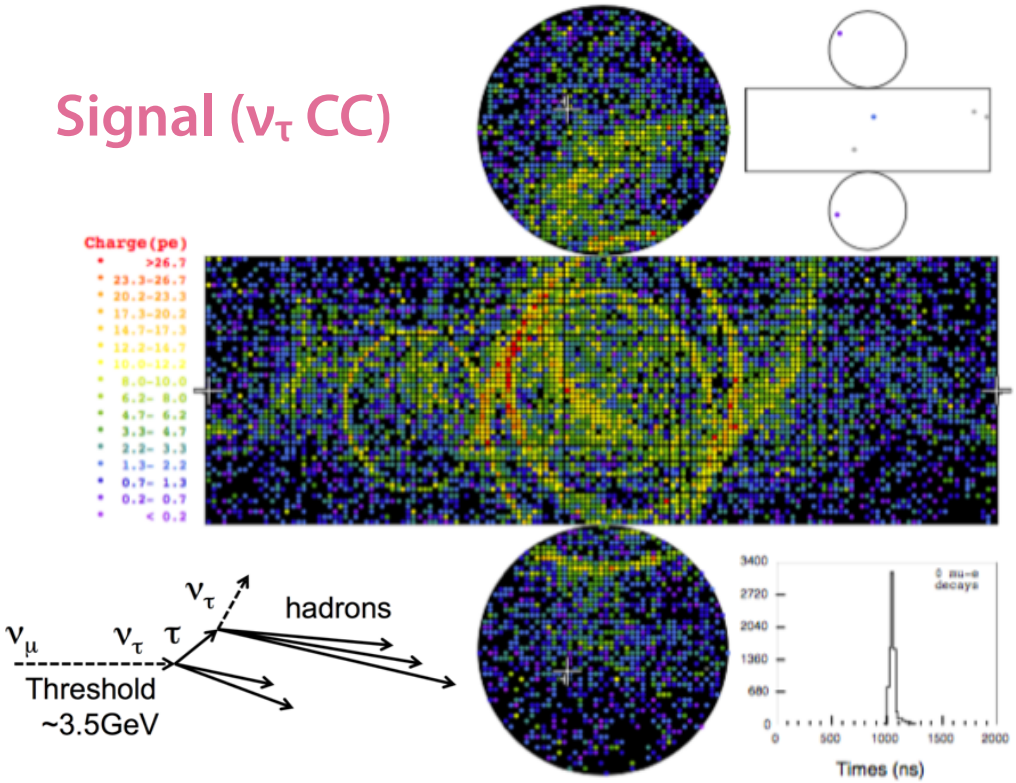
- Perform full parameter fit with additional constraints from reactor (θ_{13}) and T2K public data (Δm^2_{32} and θ_{23})
- Best-fit at NH, $\delta_{CP} \sim 3\pi/2$, $\sin^2\theta_{23}=0.55$
- **Normal hierarchy is slightly preferred** ($\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$)
- p-value of Inverted hypothesis is 0.024 and 0.001 for $\sin^2\theta_{23}=0.6$ and 0.4, respectively

Best-fit parameters:

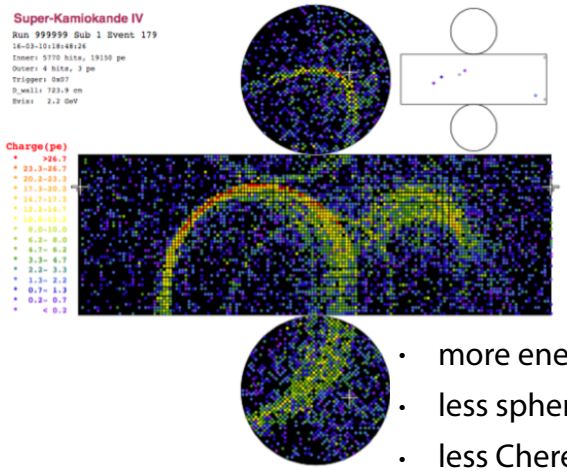
	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ (eV²)
Inverted	4.538	0.55	2.5×10^{-3}
Normal	4.887	0.55	2.4×10^{-3}

Tau Appearance Analysis

Signal (ν_τ CC)

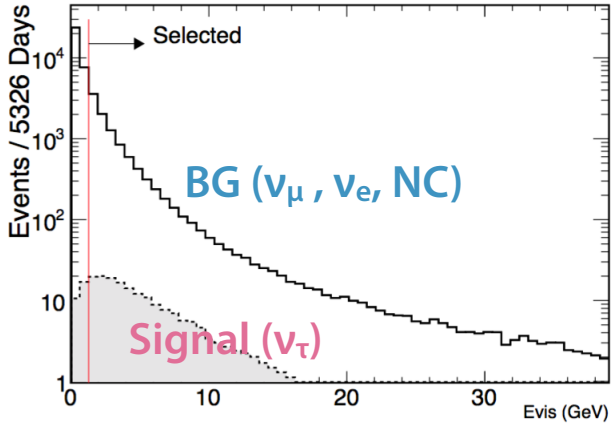


Background (ν_μ CC)

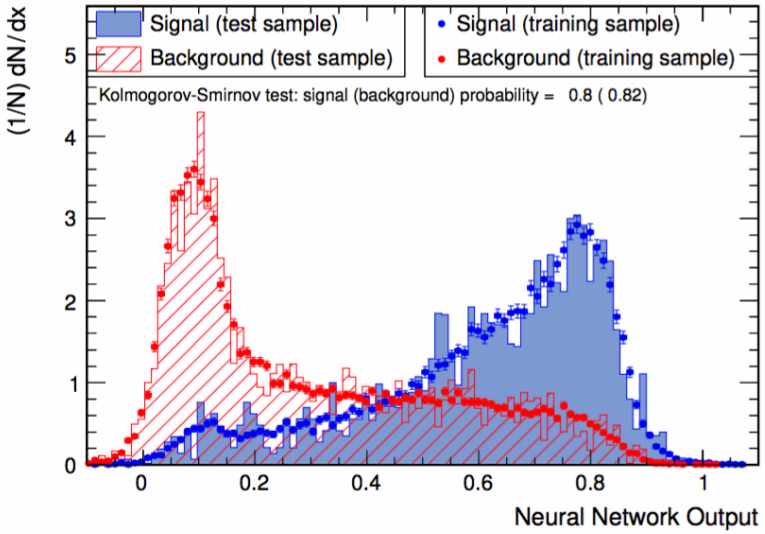


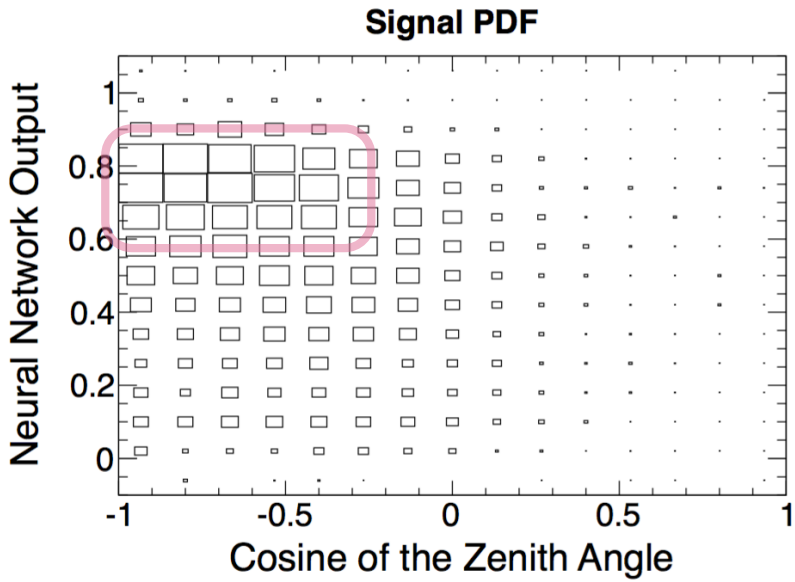
- more energy in 1st ring
- less sphericity
- less Cherenkov rings
- less mu-e decays
- …

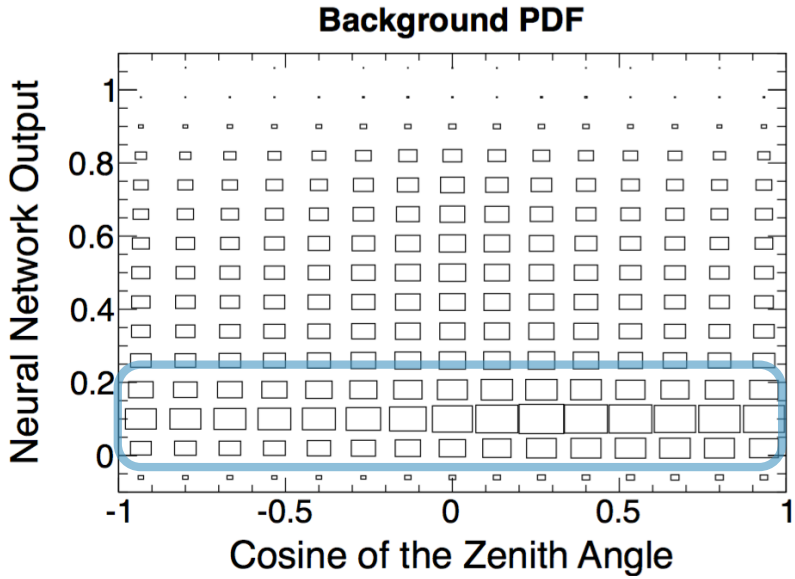
- Detection of tau appearance induced by $\nu_\mu \rightarrow \nu_\tau$ is critical for verifying three-flavor mixing scheme
- Detection is challenging: **low signal rate** (~1 event / kton year) with **huge backgrounds**
- Search for **hadronic modes of tau decay** (branching ratio: 65%)



Tau Signal Discrimination



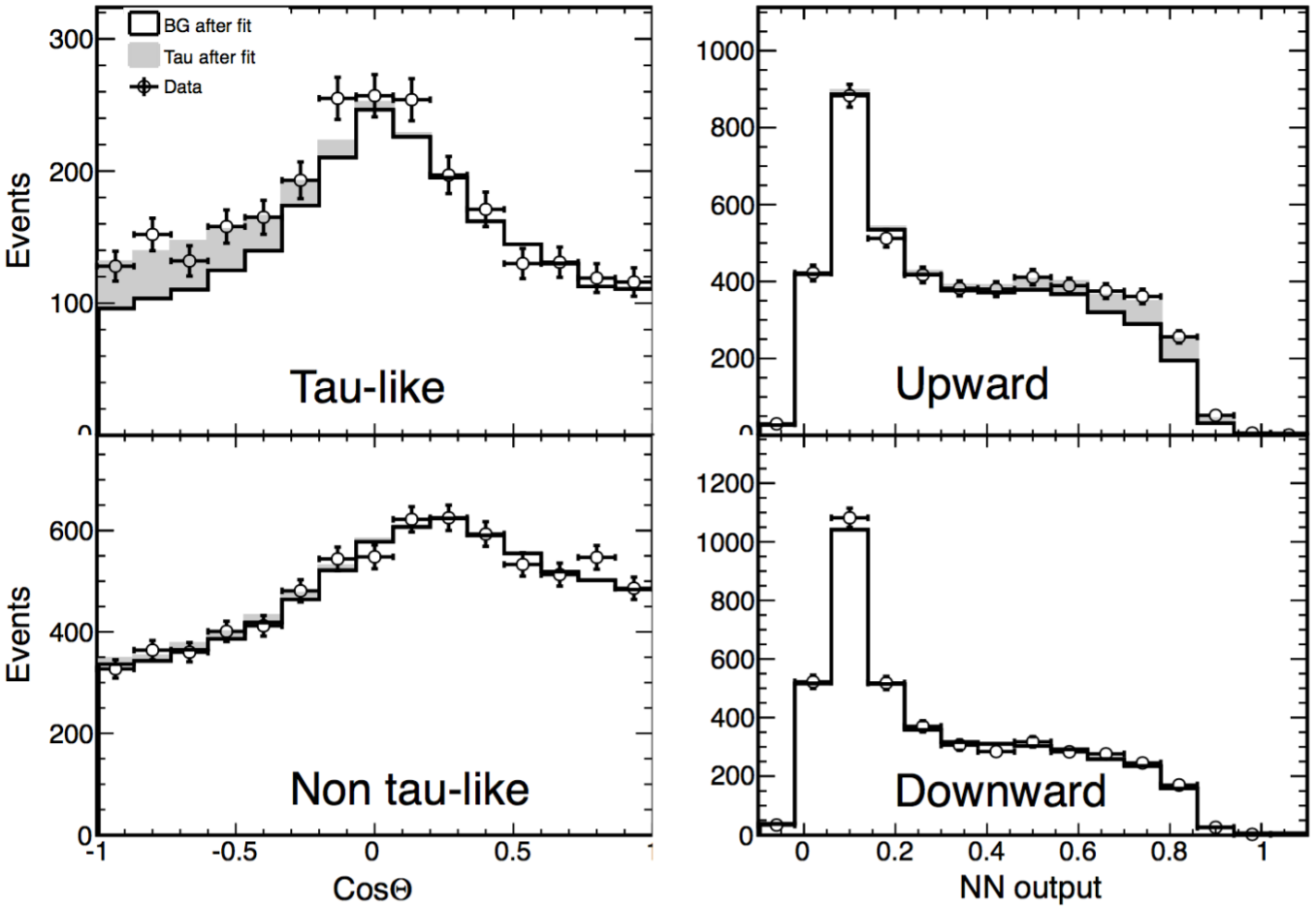




- Employ **neural network (NN)** technique to discriminate tau signal from background
  - Signal eff. 76%, 26% of background remains by NN>0.5 cut
- Tau events have higher NN output and enhanced in **upward direction**
- Perform 2-dim. fit with signal scale parameter:

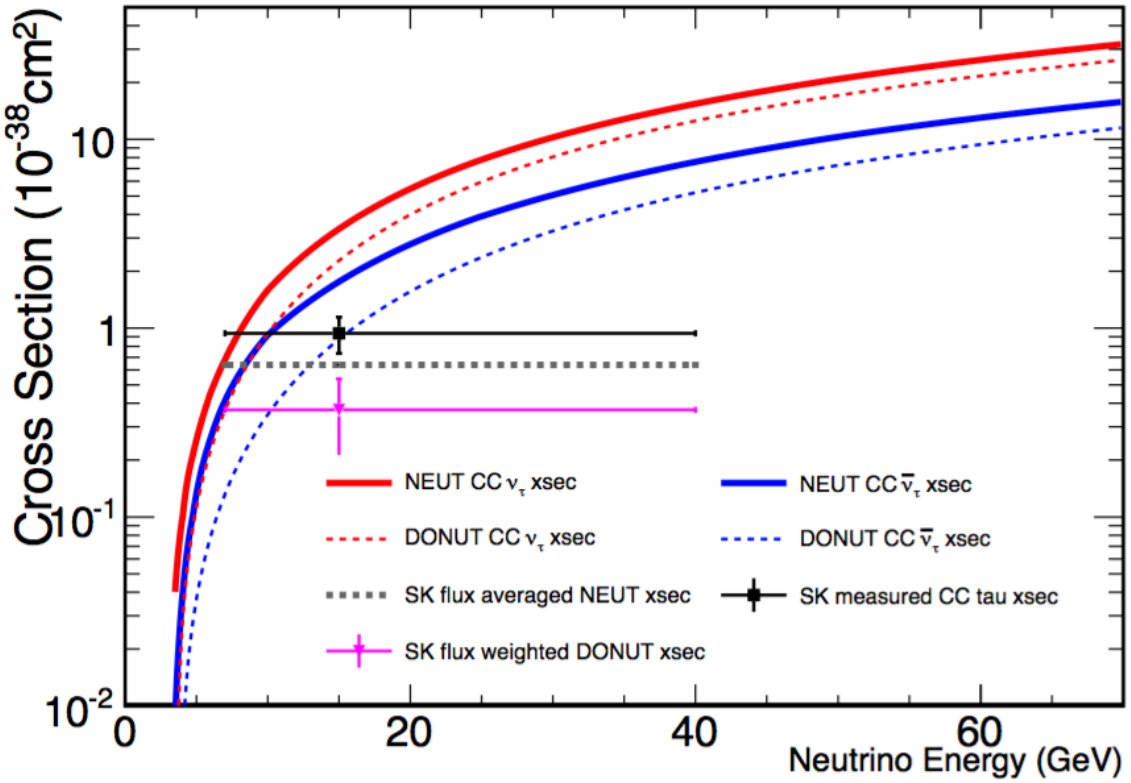
$$Data = PDF_{BG} + \alpha \times PDF_{tau} + \sum \epsilon_i \times PDF_i$$

Tau Appearance Result



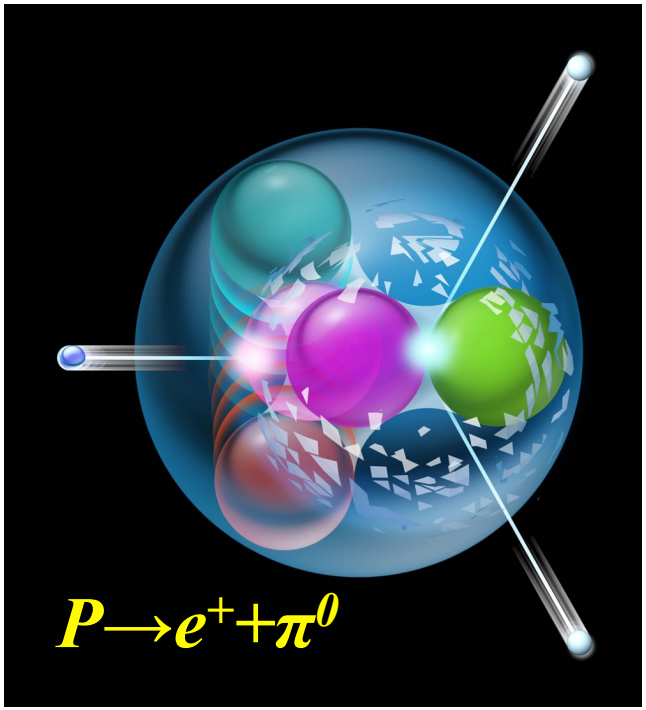
- Data: **SK-I~IV 5,326 days**
- Fitted tau normalization:
  α = **1.47 ± 0.32** (stat+syst)
  - Observed events:
    338.1 ± 72.7 events
    (exp'd: 224.5)
- Excluding no tau appearance hypothesis with **4.6 σ**
  (exp'd 3.3σ)
- Still dominated by statistical uncertainty

Tau Neutrino Cross Section

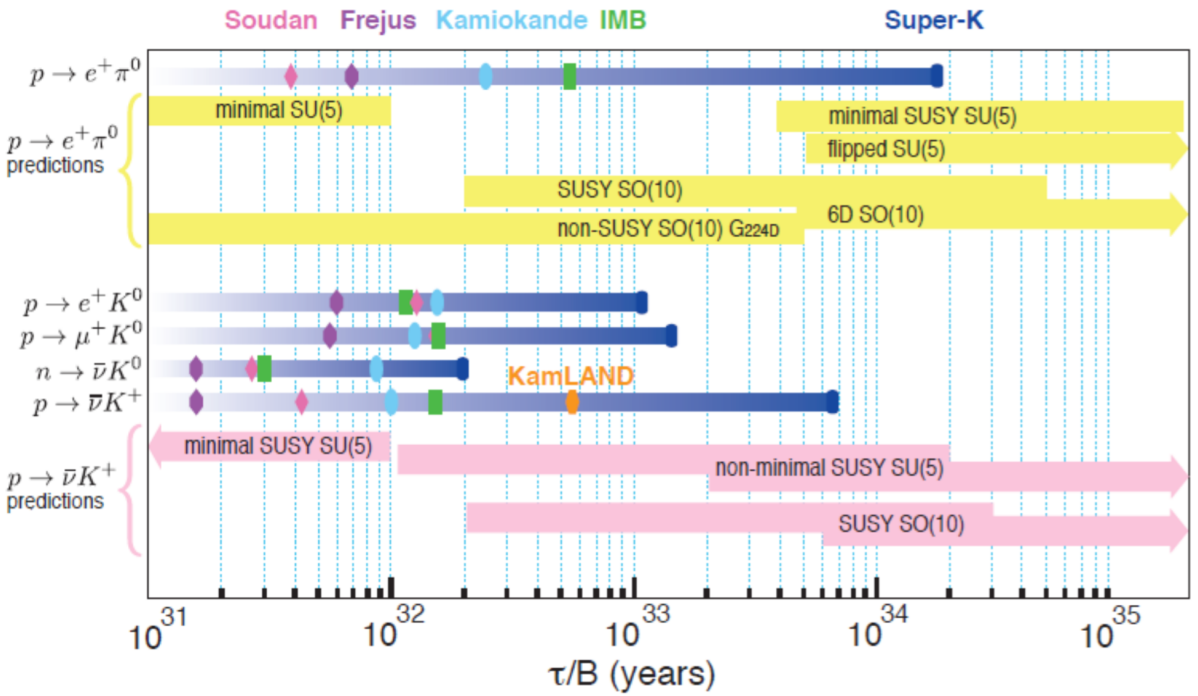


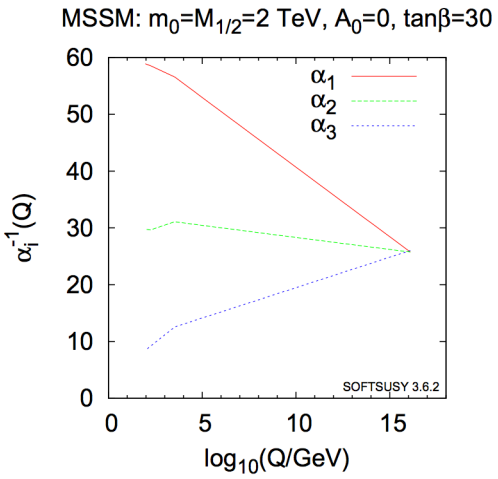
- Large sample of CC ν_τ sample offers the opportunity to **measure CC ν_τ cross section**
- Sensitive energy: 3.5 ~ 70 GeV
- Flux averaged cross section (x10^{-38}cm^2):
  measured: 0.94 ± 0.20
  theory: 0.64
- **Consistent with SM prediction** within 1.5 sigma
- Larger than scaled σ measured by DONUT at 111 GeV

Proton Decay



Ed Kearns (Snowmass 2013)





- Proton decay is predicted by **GUTs (Grand Unified Theory)**
  - Provide the method for baryon asymmetry Universe
  - Open direct path to "Beyond SM" if detected
- **Many GUT predictions** — SU(5), SO(10), SUSY GUT
- Major decay modes: **$P \to e^+ + \pi^0$, $P \to \bar{\nu} + K^+$**

Proton Decay Measurement in Super-K

- World leading experiment in proton decay
  large mass, high efficiency, various modes
- Categories:
  - decay to anti-lepton + meson
  - **decay to $\bar{\nu}$ + K (Updated)**
  - others (di-nucleon decay, n-$\bar{n}$, ..)

(S. Mine, NNN16)

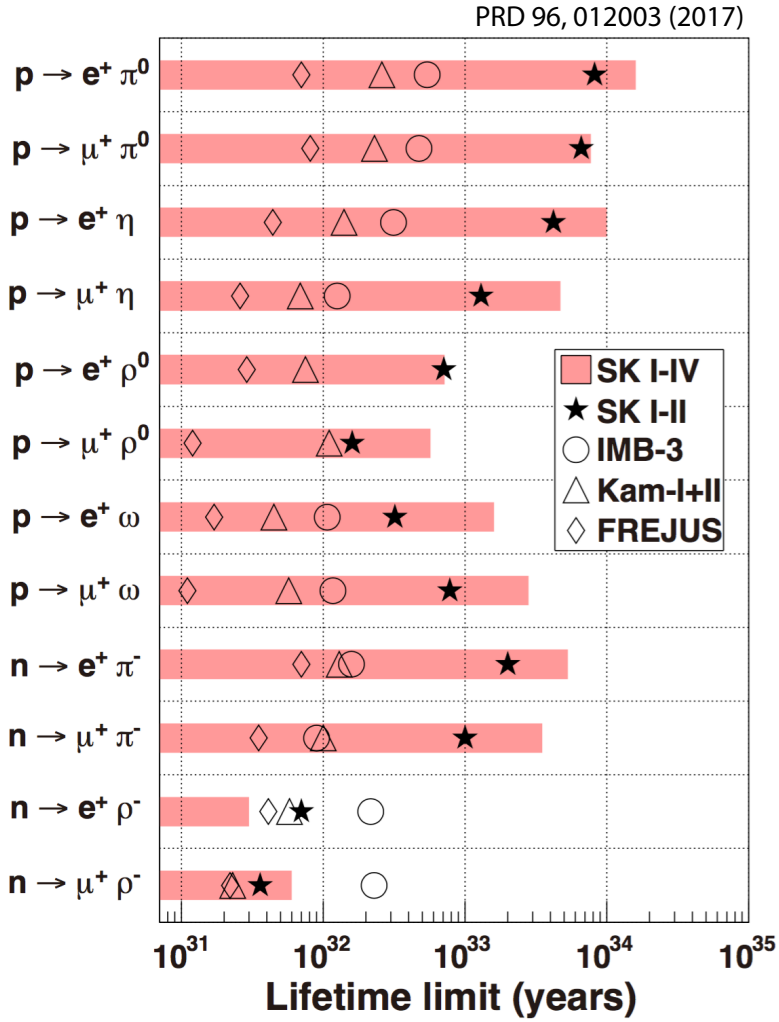
Recent nucleon decay and n-$\bar{n}$ results in SK

Decay mode	$\|\Delta(B-L)\|$	Lifetime lower limit at 90% CL (years)	Paper	
$p\to e^+\pi^0$	0	1.6×10^{34}	arXiv:1610.03597 (submitted to PRD)	(*)
$p\to\nu K^+$	0($\bar{\nu}$), 2(ν)	6.6×10^{33}	PRD 90, 072005 (2014)	
$p\to\mu^+\pi^0$	0	7.7×10^{33}	arXiv:1610.03597 (submitted to PRD)	(*)
$p\to(e^+,\mu^+)(\eta,\rho,\omega)$, $n\to(e^+,\mu^+)(\pi,\rho)$	0	$(0.03\text{-}10)\times10^{33}$	will submit to PRD	(**)
$p\to\mu^+K^0$	0	1.6×10^{33}	PRD 86, 012006 (2012)	
$\bar{n}\to\nu\pi^0$, $\bar{p}\to\nu\pi^+$	0	1.1×10^{33}, 3.9×10^{32}	PRL 113, 121802 (2014)	
$p\to(e^+,\mu^+)\nu\nu$	0($\bar{\nu}\nu$), 2($\nu\nu$,$\bar{\nu}\bar{\nu}$)	$1.7/2.2\times10^{32}$	PRL 113, 101801 (2014)	
$p\to(e^+,\mu^+)X$	?	$7.9/4.1\times10^{32}$	PRL 115, 121803 (2015)	
$n\to\nu\gamma$	0($\bar{\nu}$), 2(ν)	5.5×10^{32}	PRL 115, 121803 (2015)	
$pp\to K^+K^+$	2	1.7×10^{32}	PRL 112, 131803 (2014)	
$pp\to\pi^+\pi^+$, $pn\to\pi^+\pi^0$, $nn\to\pi^0\pi^0$	2	7.2×10^{31}, $1,7\times10^{32}$, 4.0×10^{32}	PRD 91, 072009 (2015)	
$np\to(e^+,\mu^+,\tau^+)\nu$	0($\bar{\nu}$), 2(ν)	$(0.22\text{-}5.5)\times10^{32}$	PRL 115, 121803 (2015)	
n-$\bar{n}$ oscillation	2	1.9×10^{32}	PRD 91, 072006 (2015)	

(*) published in PRD 95, 012004 (2017)
(**) published in PRD 96, 012003 (2017)

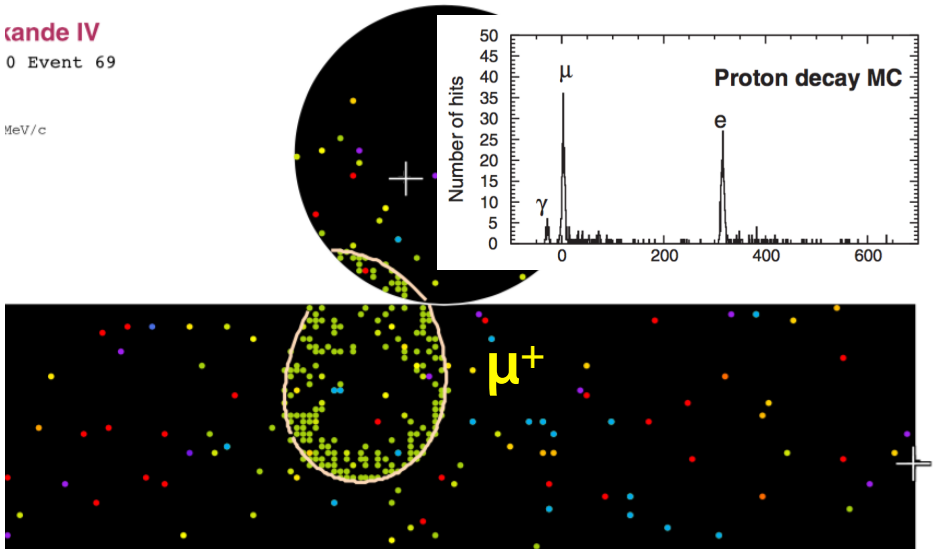
Limits on decay modes of anti-lepton + meson

PRD 96, 012003 (2017)

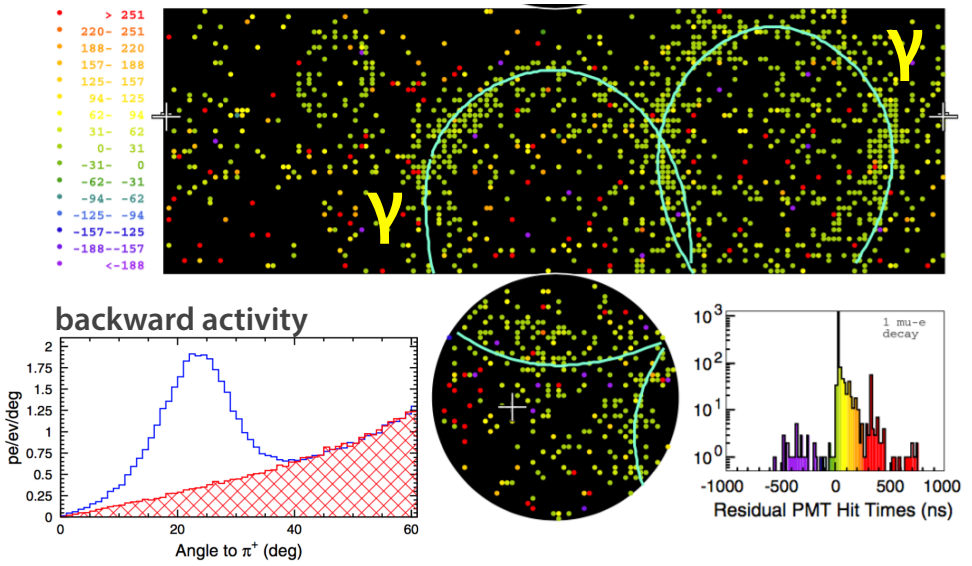


Search for $P \rightarrow \overline{\nu} + K^+$ Decay

(A) $K^+ \rightarrow \nu_\mu + \mu^+$ (BR: 64%)



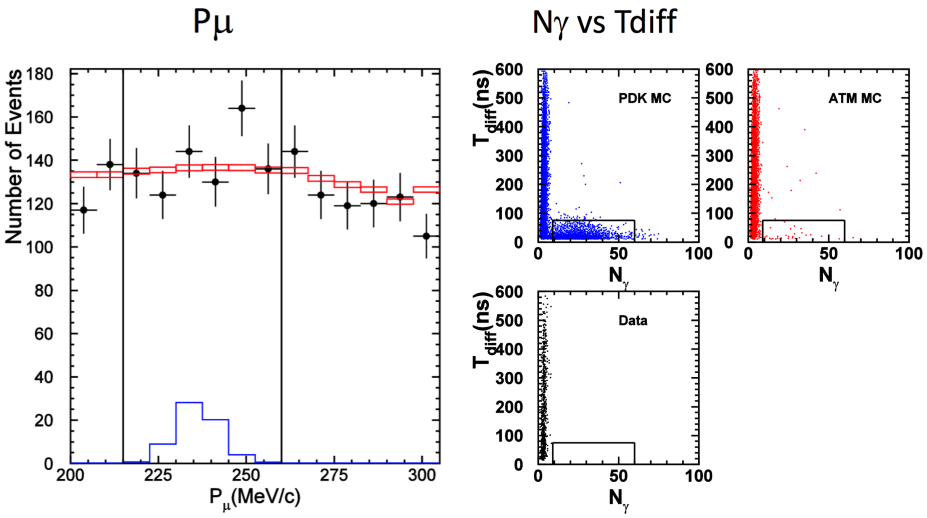
(B) $K^+ \rightarrow \pi^0 + \pi^+$ (BR: 21%)



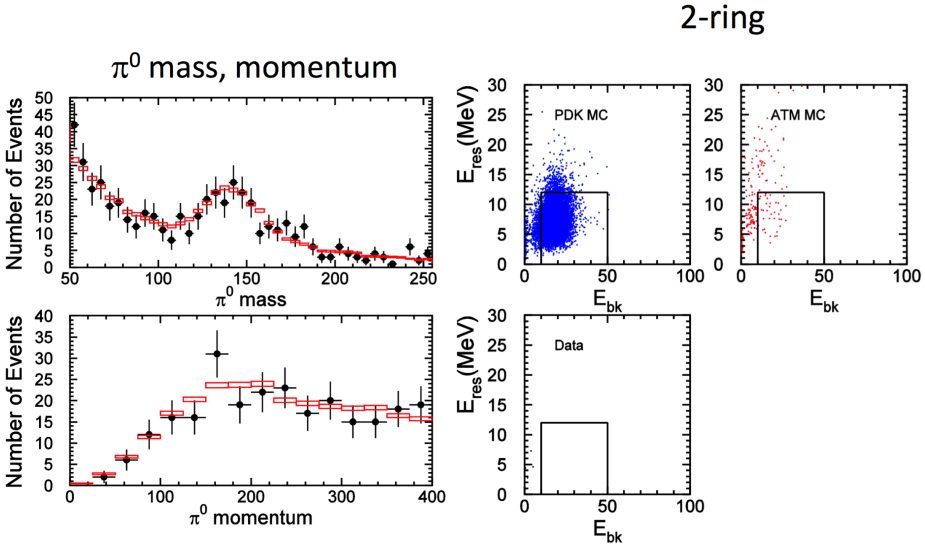
- **Single mono-energetic muon** (Pμ=236MeV/c) from K^+ decay with following μ-e decay
- Require **prompt 6 MeV gamma** from excited oxygen nuclei
- Search for **$\pi^0 \rightarrow 2\gamma$ decay** ($P\pi^0$=205MeV/c) event with **faint π^+ activity** in backward direction

Search for $P \rightarrow \overline{\nu} + K^+$ Decay

(A) $K^+ \rightarrow \nu_\mu + \mu^+$



(B) $K^+ \rightarrow \pi^0 + \pi^+$



	SK1			SK2			SK3			SK4		
	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)
Pr.γ	7.9 ±0.1	0.078	0	6.5 ±0.1	0.082	0	7.5 ±0.1	0.018	0	9.4 ±0.1	0.112	0
$\pi^+\pi^0$	7.8 ±0.1	0.21	0	6.5 ±0.1	0.19	0	8.3 ±0.1	0.07	0	9.6 ±0.1	0.13	0

- **No candidate events** are observed for both modes in 349 kton·year exposure
- Lifetime limit: **>8.0 x 10^{33} years** (90% C.L.)

Summary

Atmospheric Neutrino:

- Various features of atmospheric neutrinos allow us to test **three flavor mixing scheme**.
- **Resonance oscillation by matter effect** in multi-GeV is sensitive to mass hierarchy. According to oscillation fit to data with reactor and T2K constraints, **normal hierarchy is slightly preferred**.
- Tau appearance has **improved to 4.6 sigma**. Measured larger ν_τ cross section than prediction though still **consistent with theory**.

Proton Decay:

- Unique method to probe GUT theory. Super-K has been contributing to explore the possibility of this new "beyond SM" physics.
- The analysis of **$p \rightarrow \bar{\nu} + K^+$ has been updated**. There were no candidate events observed from the searches of two K^+ decay modes. Lower lifetime limit has been **improved to 8.0×10^{33} yrs**.

END