Resent result from Super-Kamiokande and SK-Gd project

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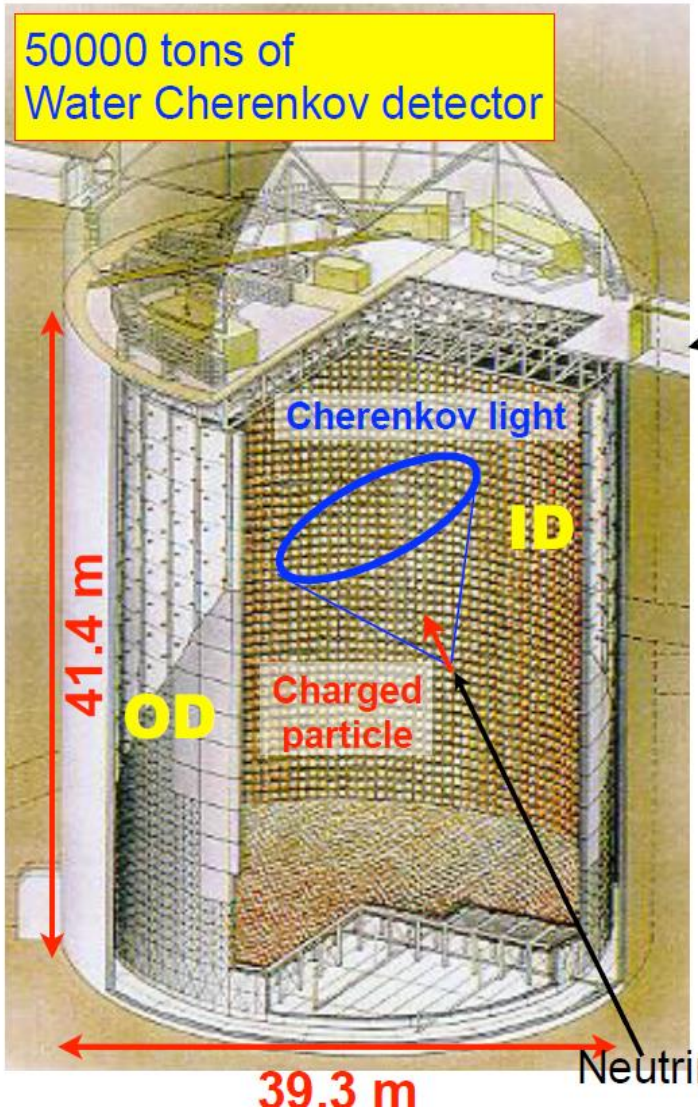
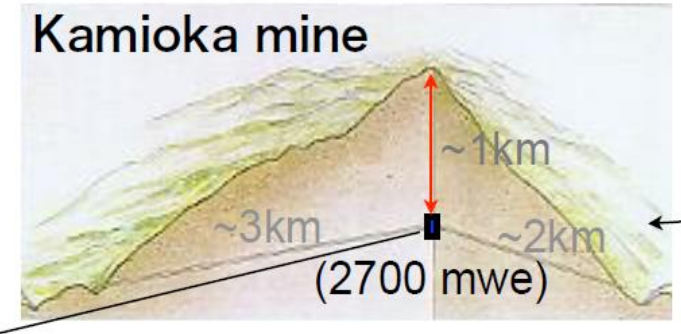
Super-Kamiokande





(For Solar neutrino analysis)

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	1669	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		**3.5**

(coverage) (Kinetic energy)

total **4504** days

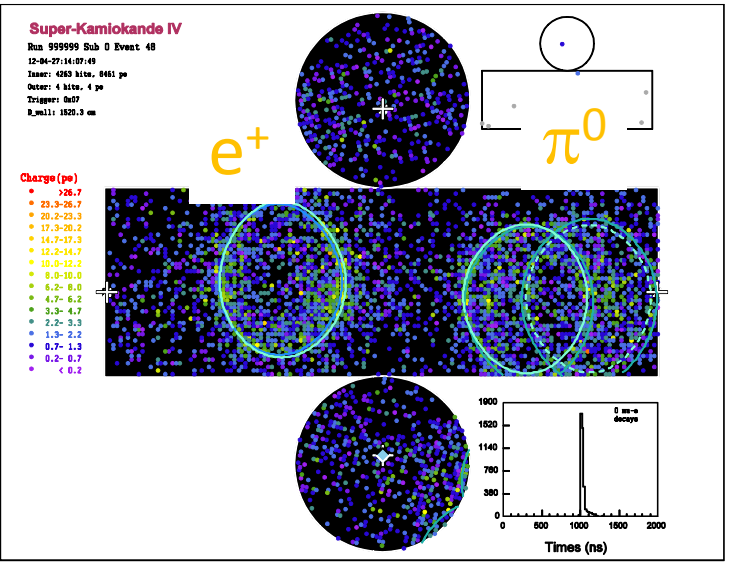
Proton decay searches in SK

- SK has the world's best sensitivities on proton lifetime:
  - large fiducial volume :22.5kt

    ~7.5×10^{33} protons and ~6×10^{33} neutrons
  - Long live time : close to 5000days
- Latest results:
  - $p \rightarrow e^+ \pi^0$ / $\mu^+ \pi^0$
  - $p \rightarrow \nu K^+$

Poster : Volodymyr Takhistov

$p \rightarrow e^+\pi^0 / \mu^+\pi^0$



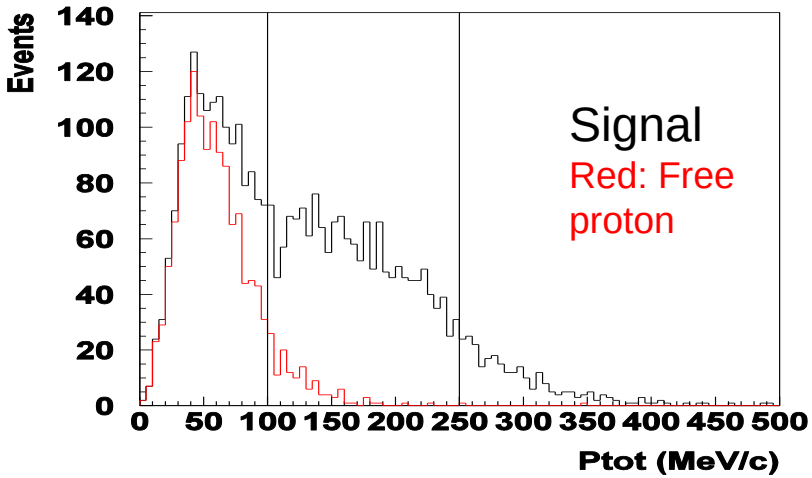
Event features;

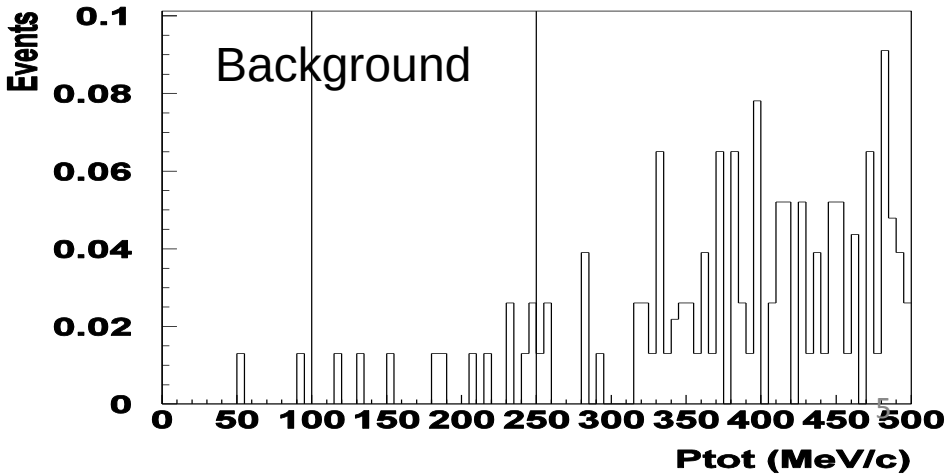
- e^+ / μ^+ and π^0 are back-to-back (459 MeV/c)
- $\pi^0 \rightarrow 2\ \gamma$s : all particles are visible.

➔Reconstruct proton mass and momentum.

- $850 < M_{tot} < 1050$ MeV/c^2 and $P_{tot} < 250$MeV/c are selected.
- Separate into two region to get better sensitivity.
  - Ptot<100 MeV/c:
    Free proton enriched. Almost BG free.
  - 100≤Ptot<250MeV/c:
    Bound proton enriched.

P_{tot} for $e^+\pi^0$





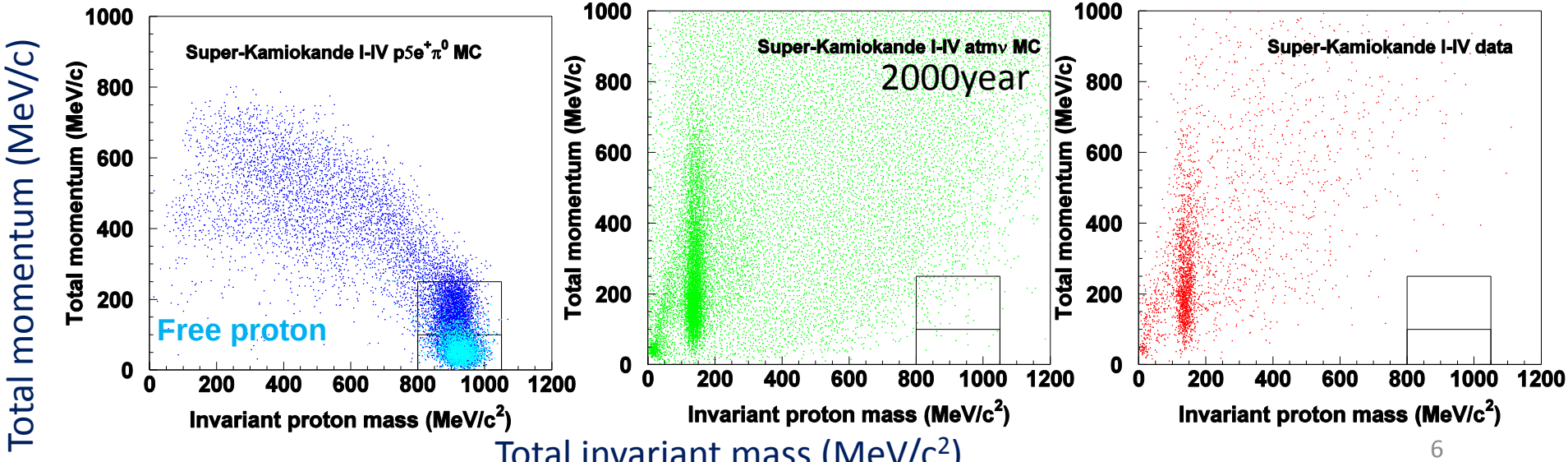
Results of $p \rightarrow e^+\pi^0$

- 306.3 kton·years (SKI-IV) (220kt·yrs in PRD 85, 112001 (2012))
- signal $\varepsilon(P_{tot}<250MeV/c)$: ~40%
- total(SKI-IV) expected #BKG$(P_{tot}<250MeV/c)$:0.6 events

  #BKG: confirmed with K2K ν beam data PRD 77,032003(2008)
- no data candidate

$$\tau/B_{p\rightarrow e\pi 0} > 1.67 \times 10^{34} \text{ years (90\% CL)}$$

Blue: Signal MC **Green: BG MC(ATMν)** **Red: Data**



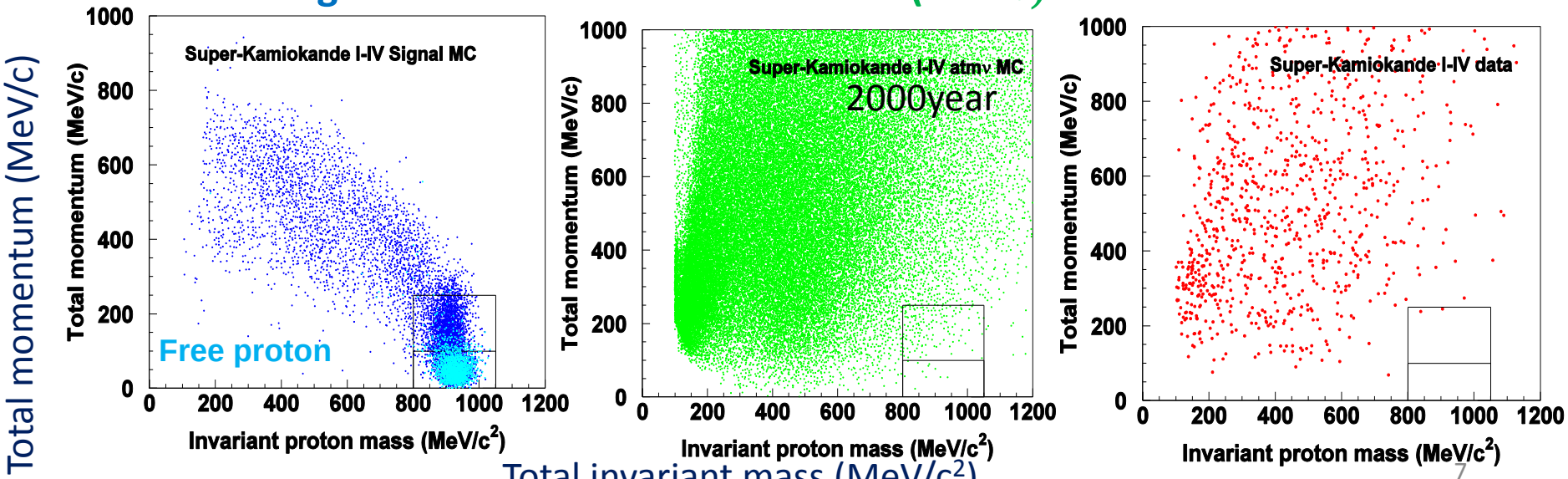
Results of $p \rightarrow \mu^+\pi^0$

(analysis proceeds as with $e^+\pi^0$ with additional requirement of 1 Michel-e)

- 306.3 kton·yrs (SKI-IV) (220kt·yrs in PRD)
- signal $\varepsilon(P_{tot}<250\text{MeV/c})$: 30-40%
- total expected #BKG:
  - $P_{tot}<100$: ~0.05, $100 \leq P_{tot}<250$: ~0.82
- no significant data excess

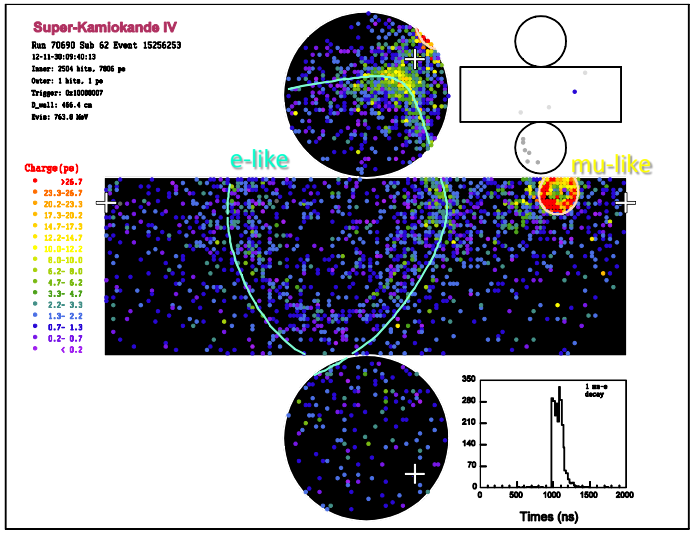
$$\tau/B_{p\rightarrow\mu\pi0} > 7.78 \times 10^{33} \text{ years (90\% CL)}$$

Blue: Signal MC **Green: BG MC(ATMν)** **Red: Data**



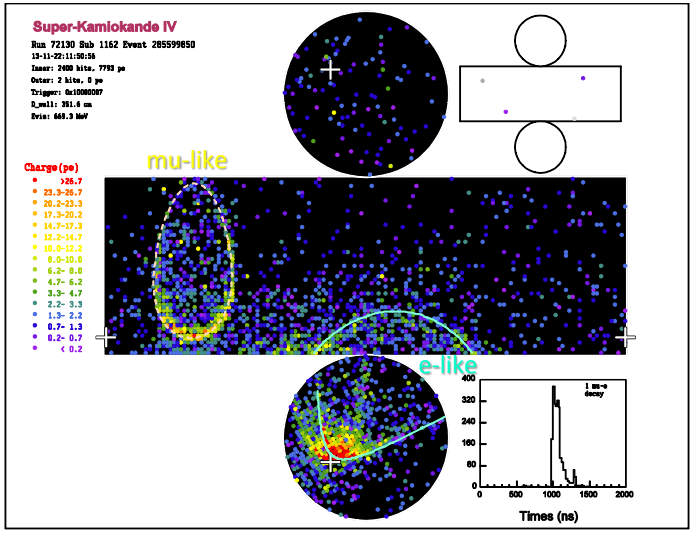
Details for the 2 candidate

Event #1



(M_p, P_{tot}) : (902.5, 248.0)MeV
Wall : 466.0cm
ring : 2
P_e: 374.9MeV/c
P_μ: 551.1MeV/c
$\theta_{e\text{-}mu}$: 157.9°

Event #2



(M_p, P_{tot}) : (832.4, 237.9)MeV
Wall : 351.6cm
ring : 2
P_e: 460.5MeV/c
P_μ: 391.3MeV/c
$\theta_{e\text{-}mu}$: 148.9°

(additional ring by manual fit → $M_{\pi 0}$: 406MeV/c^2. See supplement)

	P_{tot}<100MeV/c	100≤P_{tot}<250MeV/c
Total #BKG (SKI-IV)	~0.05	~0.82
Data(SKI-IV)	0	2

- Poisson prob. (≥2; 0.82): 19.9%

Result of $p \rightarrow \nu K^+$

Event features;

- K^+ is invisible, stops and 2 body decay .

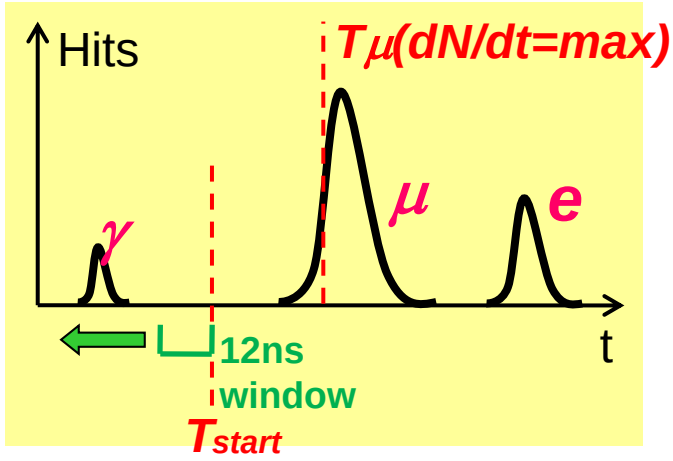
A) $K^+ \rightarrow \nu \mu^+$(236MeV/c) BR:65%

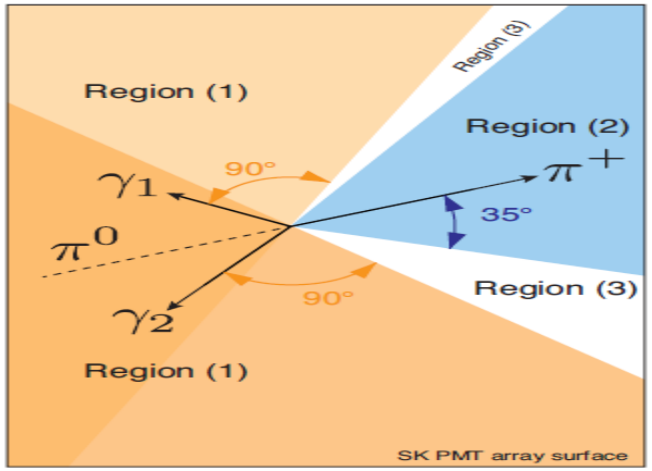
- Check $P\mu$ (monochromatic) distribution
- Proton in ^{16}O decays → De-excitation γ 6 MeV (Prob. 41%, not clear ring).

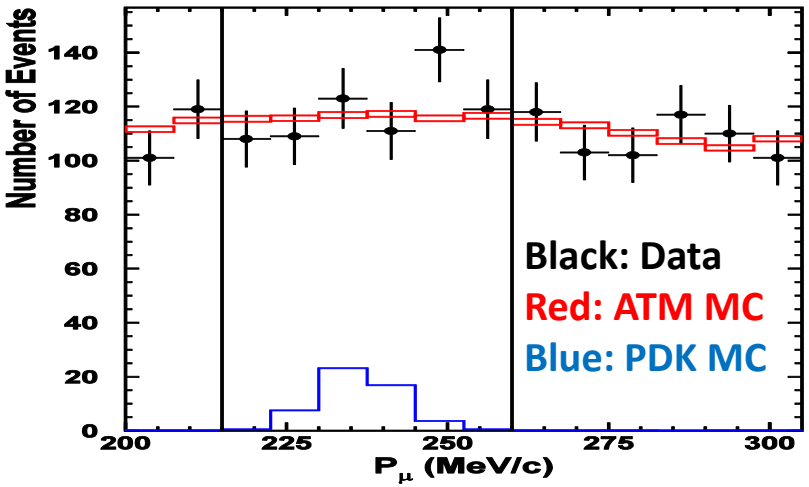
Tag γ to eliminate BKG.

B) $K^+ \rightarrow \pi^+ \pi^0$ (205MeV/c) BR:21%

- π^+ is not clear ring.
- Search π^0 with PMT hits in backward.







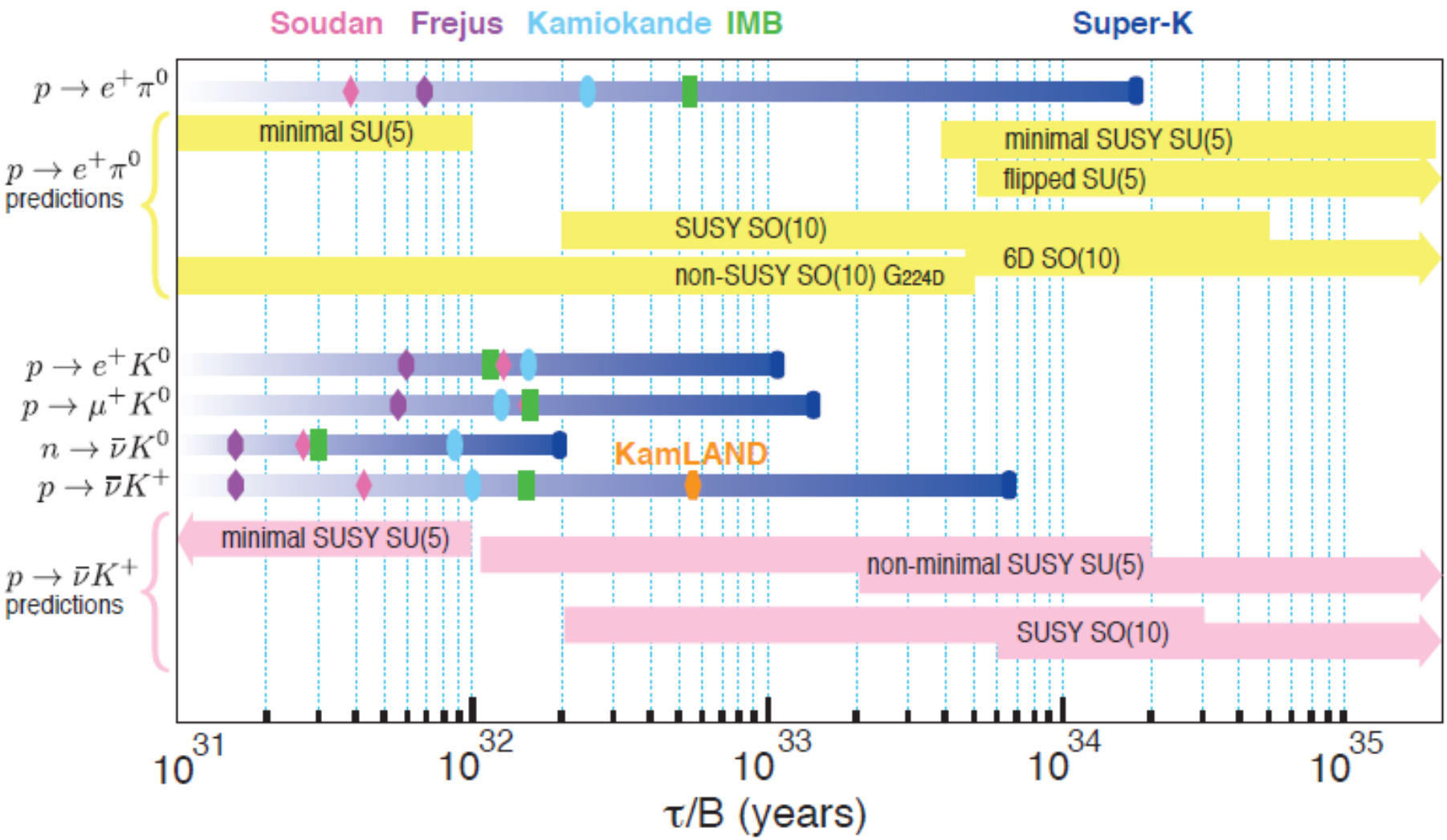
No candidates and no excess in P_μ.

$p \rightarrow \nu K^+$ Lifetime limit (90% CL) combining Method (A) and (B):

> 6.6×10^{33} yrs @306 kton·yr

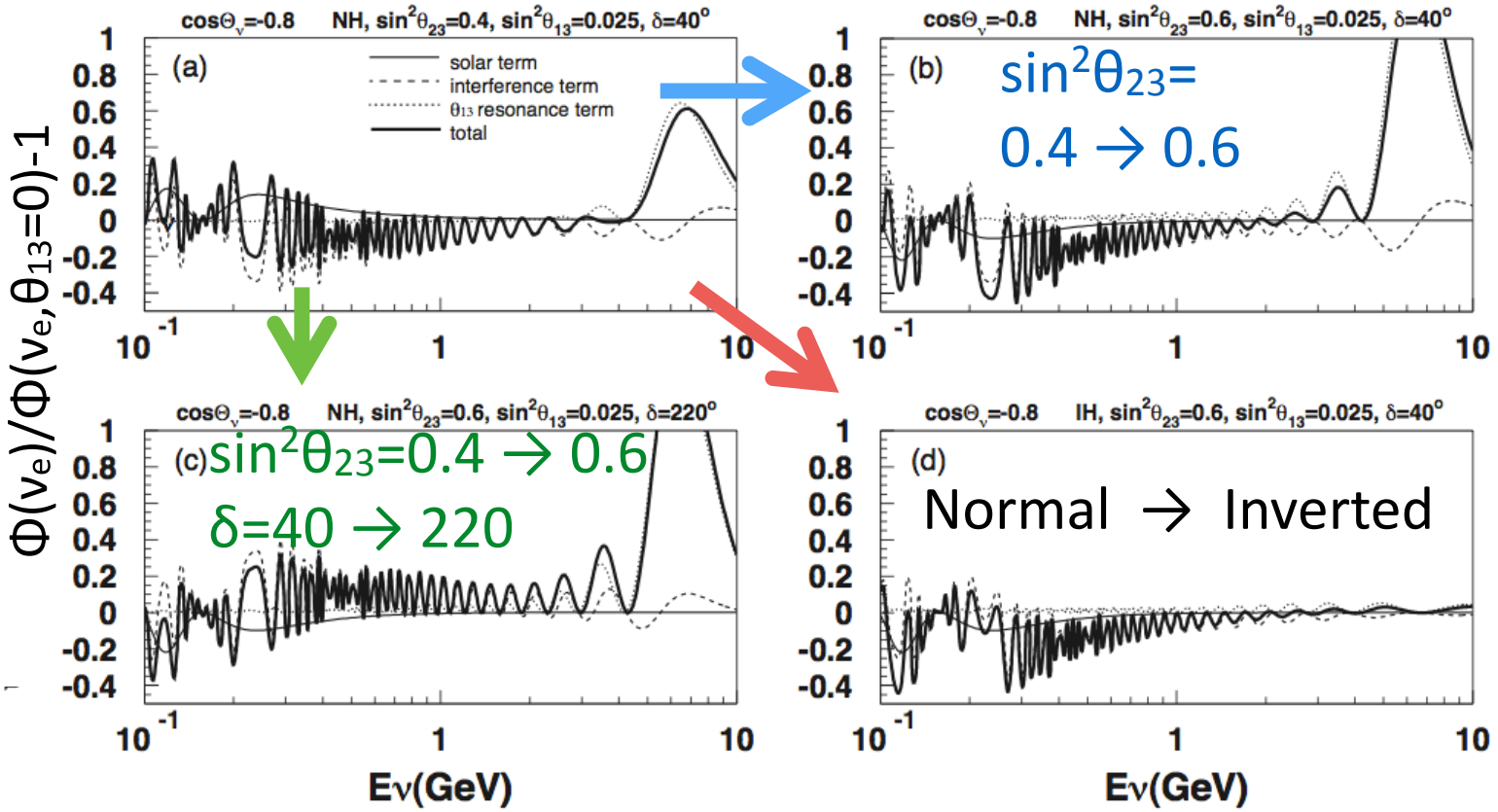
(260kt·yrs in **PRD 90, 072005 (2014)**)

Benchmark searches and theoretical predictions



- Current searches are in interesting ranges

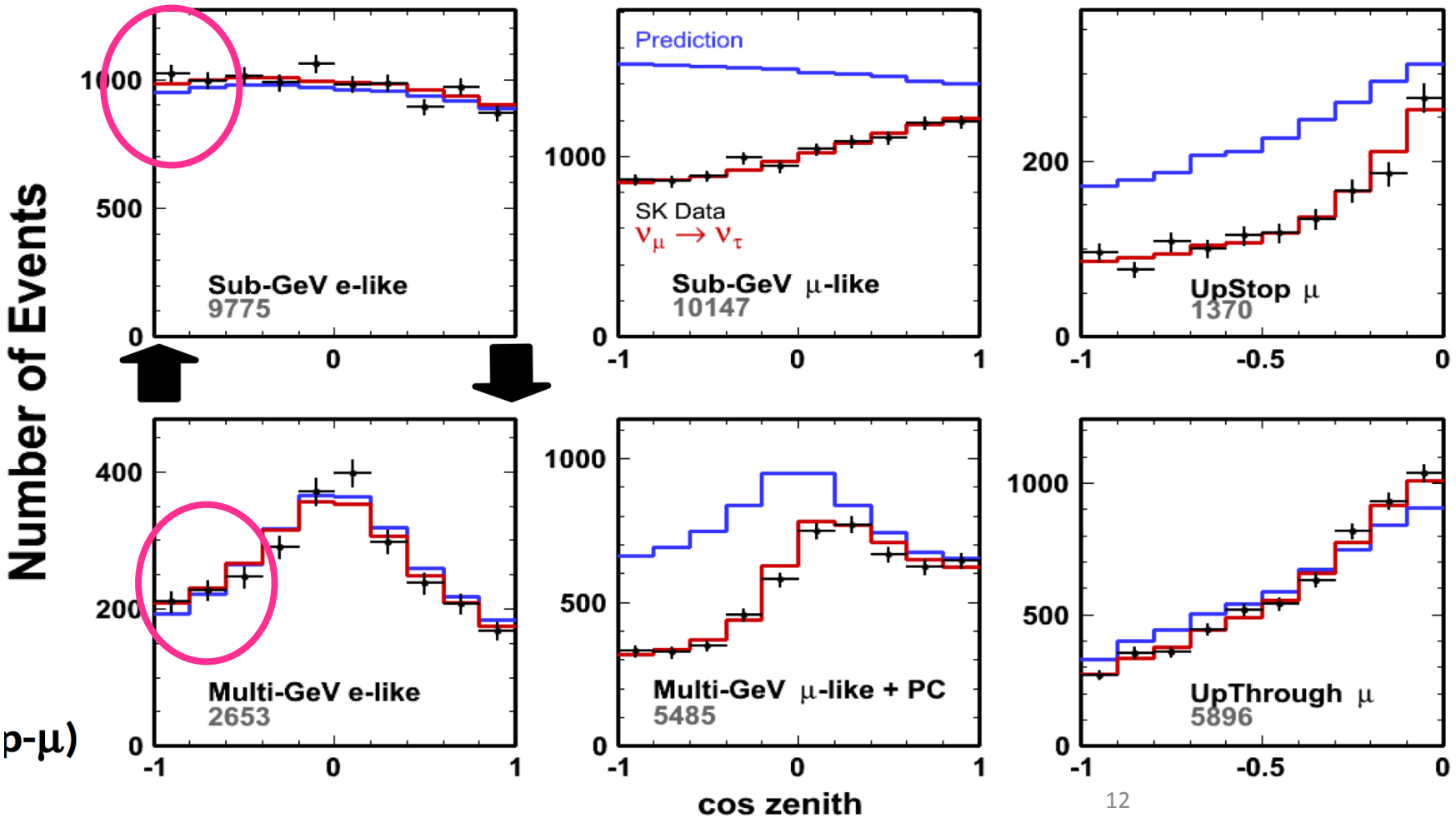
Oscillation analysis updates:
$\nu_\mu \rightarrow \nu_e$ effect in atmospheric ν



- Multi-GeV: resonant-like peak due to matter effect in Earth
  - appear in ether ν or $\bar{\nu}$, and depends on mass hierarchy
  - θ_{23} octant changes size of resonance peak
- sub-GeV : flux normalization changes by CP phase δ_{CP}

Super-K atmospheric sample

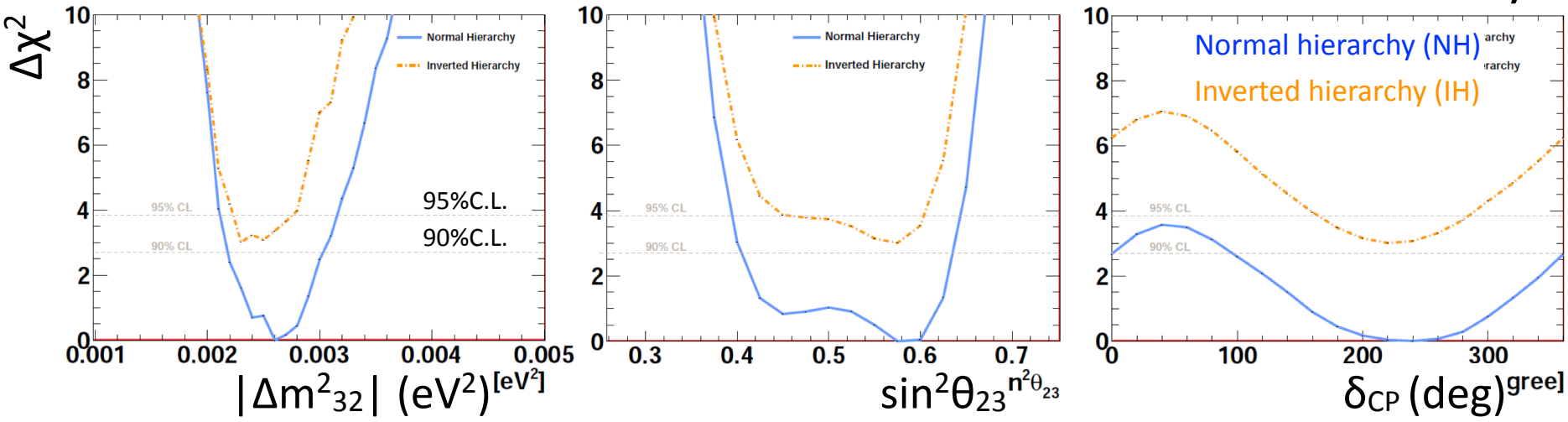
- $\nu_\mu \rightarrow \nu_\tau$ is dominant, but sensitive to other osc. parameters
- Interested in upward $\nu_\mu \rightarrow \nu_e$ containing sub-dominant effect



Oscillation fit result

- χ^2 scan for δ_{CP}, θ_{23}, Δm^2_{32}, MH. (θ_{13} is fixed for reactor).
- Super-K data favored normal hierarchy,
  but not significant (χ^2_{NH}-χ^2_{IH}= -3.0)

Preliminary

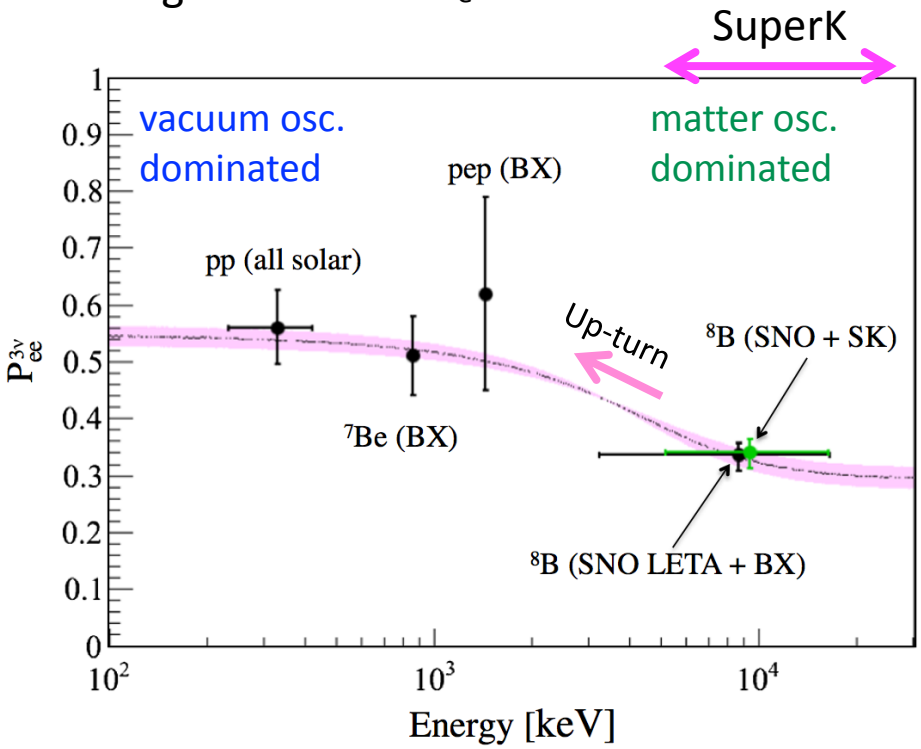


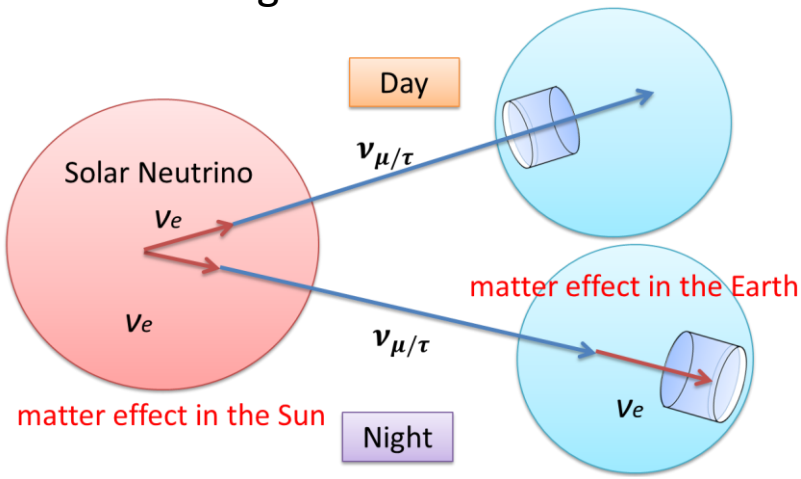
Fit (517dof)	χ^2	$\sin^2\theta_{13}$ (fix)	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{32}
Normal	582.4	0.0238	240	0.575	2.6×10^{-3}
Inverted	585.4	0.0238	220	0.575	2.3×10^{-3}

Physics motivation of solar neutrino

1. large statistics and long time observation of solar neutrinos
   Obtain information inside of Sun.
2. Spectrum distortion (no yet observed) Poster : Muhammad Elnimr
   - "Up-turn" by MSW oscillation is expected around 3MeV
3. Day / Night flux asymmetry

Regeneration of ν_e in Earth's matter effect will enhance night flux

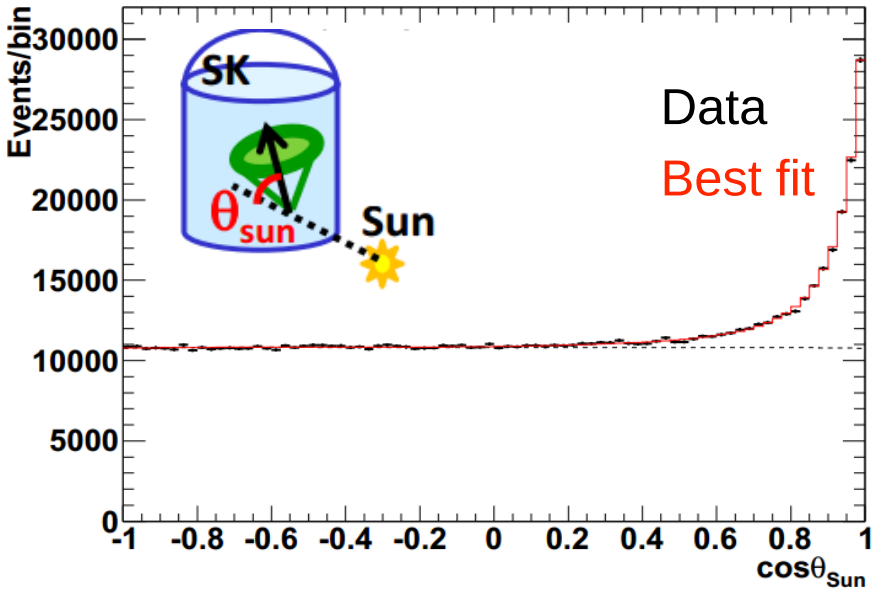




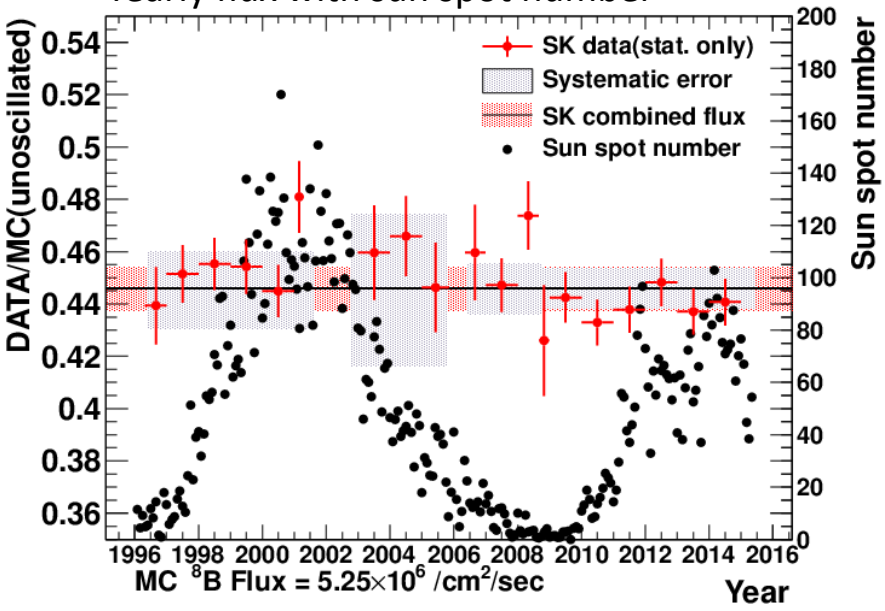
$$A_{DN} = \frac{\Psi_{day} - \Psi_{night}}{(\Psi_{day} + \Psi_{night})/2}$$

Preliminary

Results of solar neutrino observation

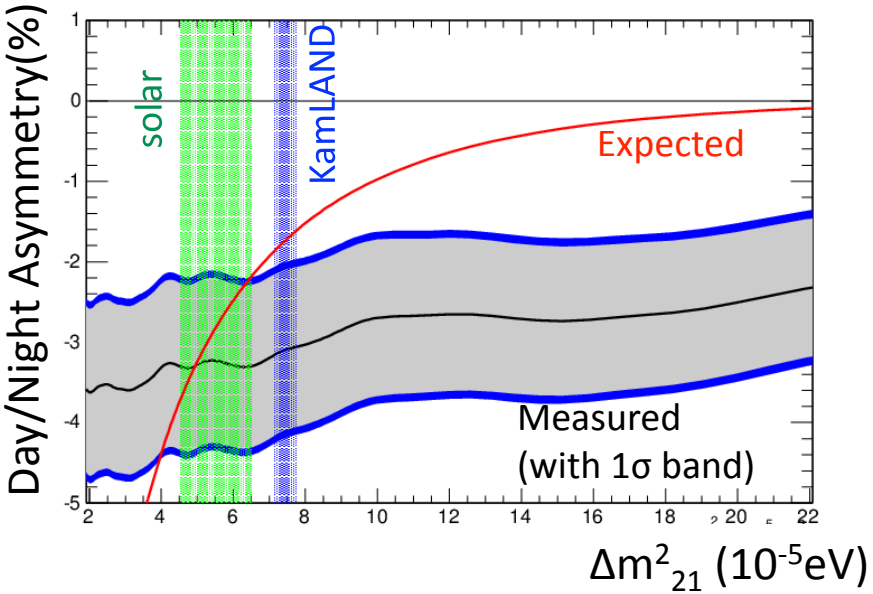


Yearly flux with sun spot number



- ~77 k solar events in SK I-IV

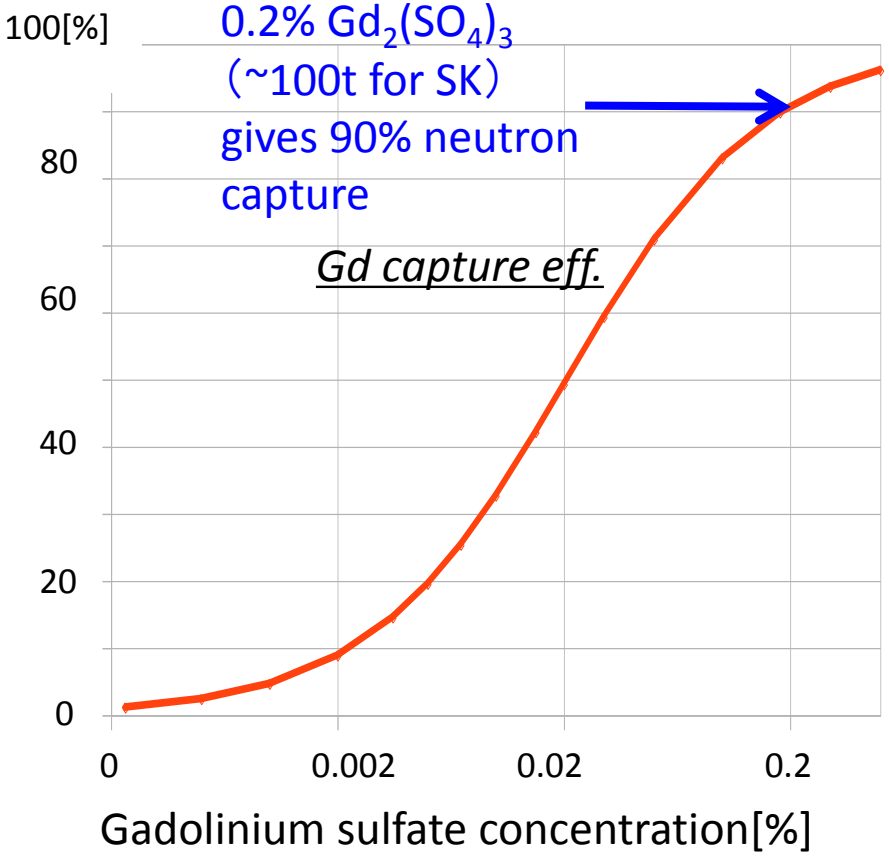
  Data/MC = 0.4459 ± 0.0084(stat.+syst.)
- No correlation seen with sun spot number (p-value=0.786)
- ~3σ difference in day and night
  - First direct indication of matter effect in Earth



Super K-Gd

Beacom and Vagins PRL93,171101 (2004)

- Gd has large cross section for thermal neutron (48.89kb)
- Neutron captured Gd emits 3-4 γ ray in total 8 MeV
- **We can tag $\bar{\nu}_e$ by using the delayed coincidence technique.**



Physics targets:

(1) Supernova relic neutrino (SRN)

(2) Improve pointing accuracy for galactic supernova

(3) Precursor of nearby supernova by Si-burning neutrinos

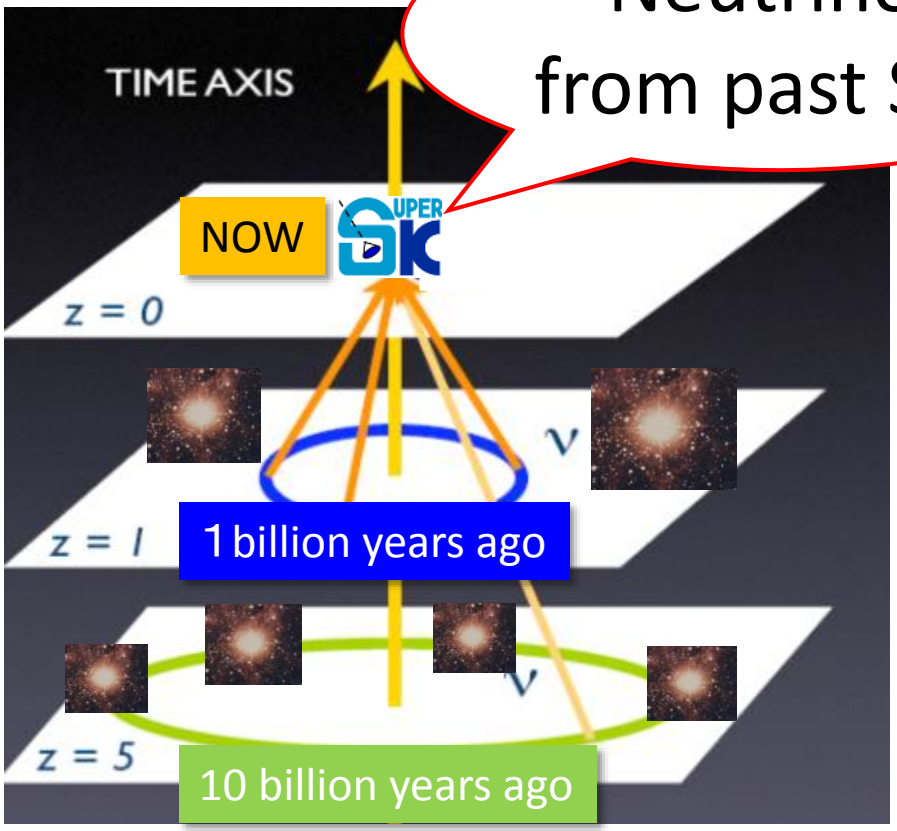
(4) Reduce proton decay background

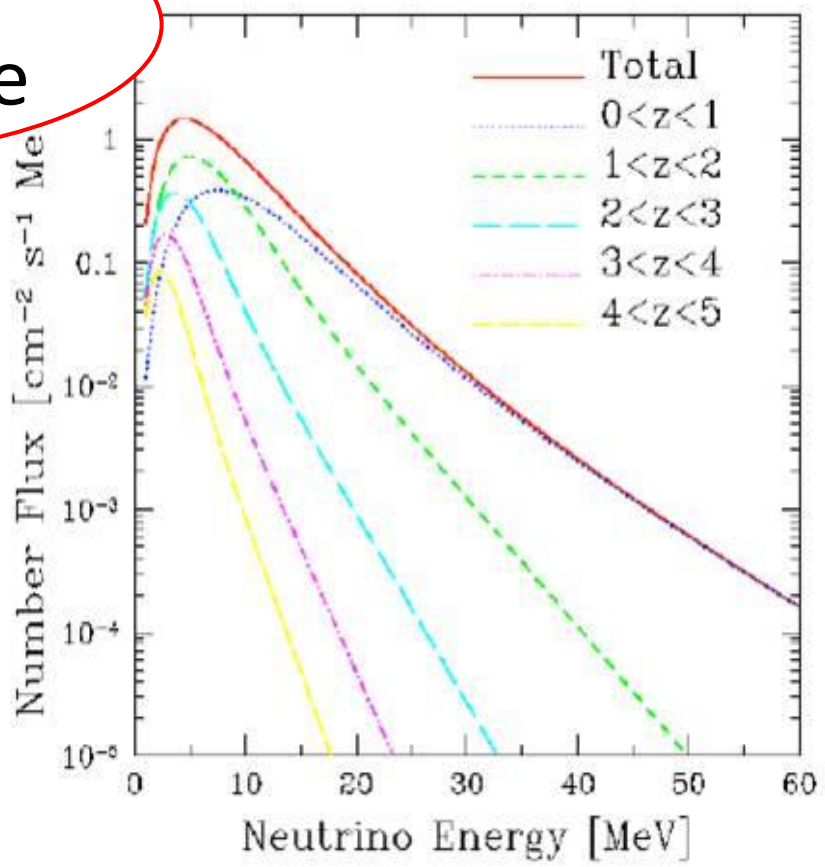
(5) Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)

(6) Reactor neutrinos

Supernova Relic Neutrino (SRN)

10^{10} stellar/galaxy ×10^{10} galaxy ×0.3%(become SNe) ~$O(10^{17})$SNe





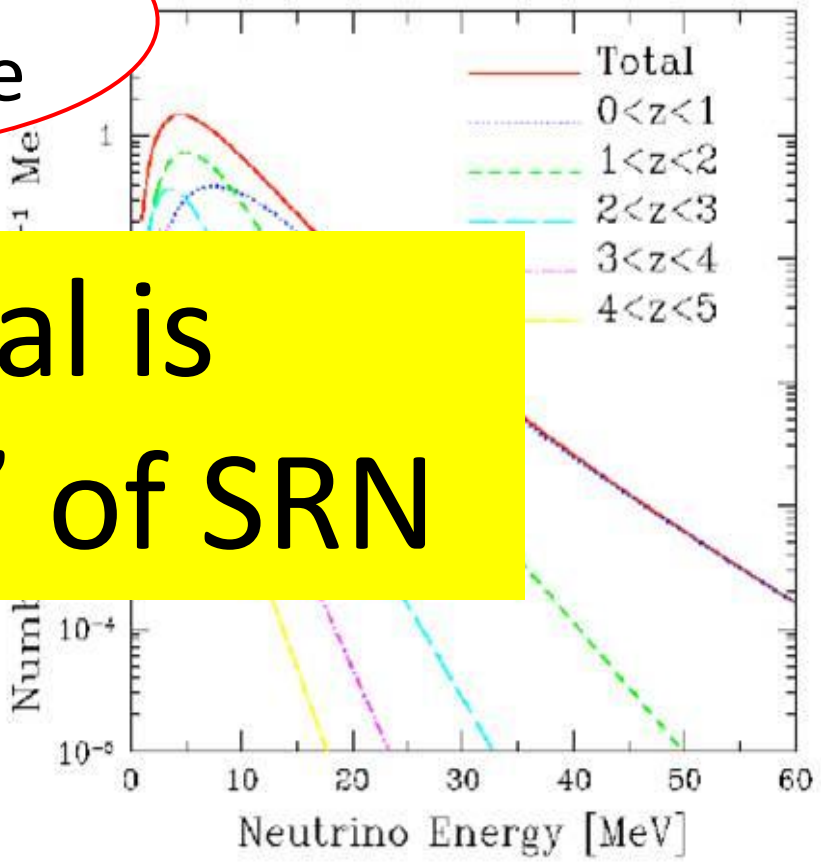
S.Ando, Astrophys.J. 607, 20(2004)

Theoretical flux prediction : 0.3~1.5 /cm2/s (17.3MeV threshold)

Supernova Relic Neutrino (SRN)

10^{10} stellar/galaxy ×10^{10} galaxy ×0.3%(become SNe) ~$O(10^{17})$SNe

First goal is
"discovery" of SRN

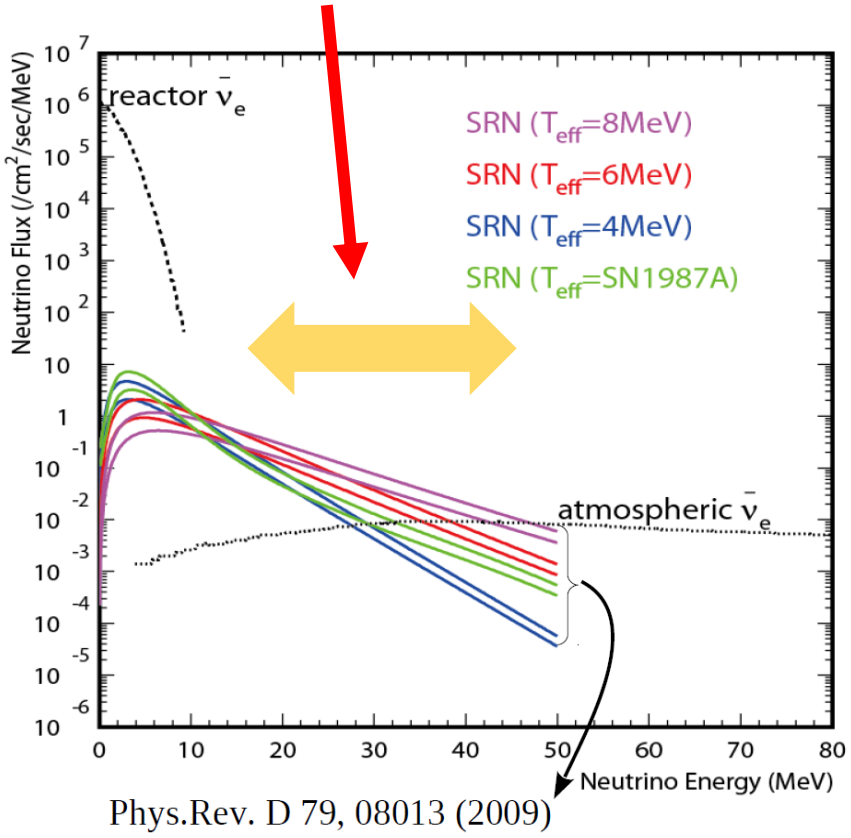


S.Ando, Astrophys.J. 607, 20(2004)

Theoretical flux prediction : 0.3~1.5 /cm2/s (17.3MeV threshold)

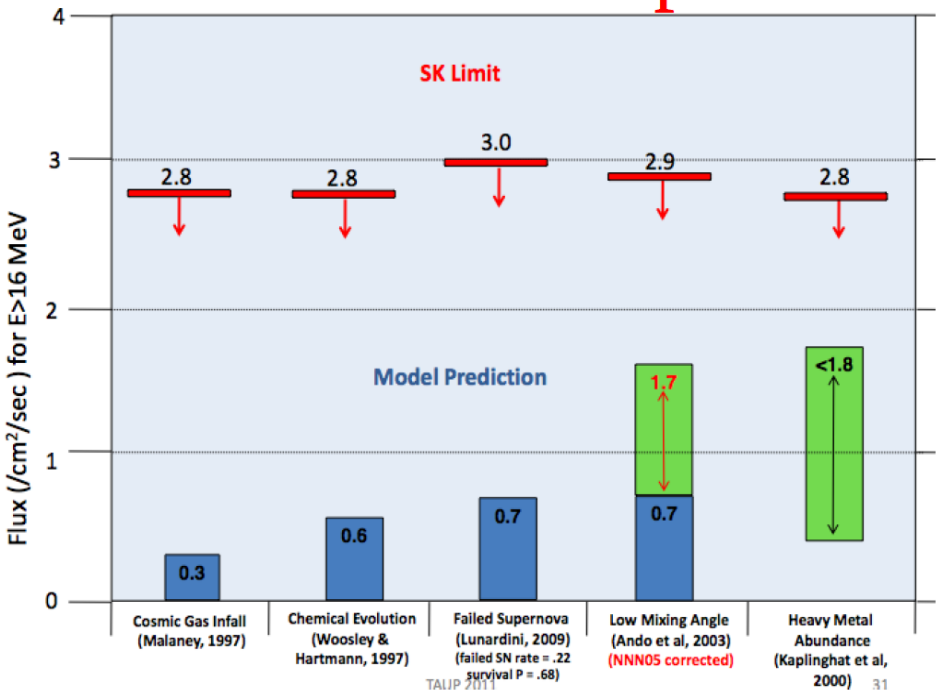
Search for SRN at Super-K

Search window for SRN at SK : From ~10MeV to ~30MeV



Phys.Rev. D 79, 08013 (2009)

Flux limit at Super-K



Phys. Rev. D 85, 052007 (2012)

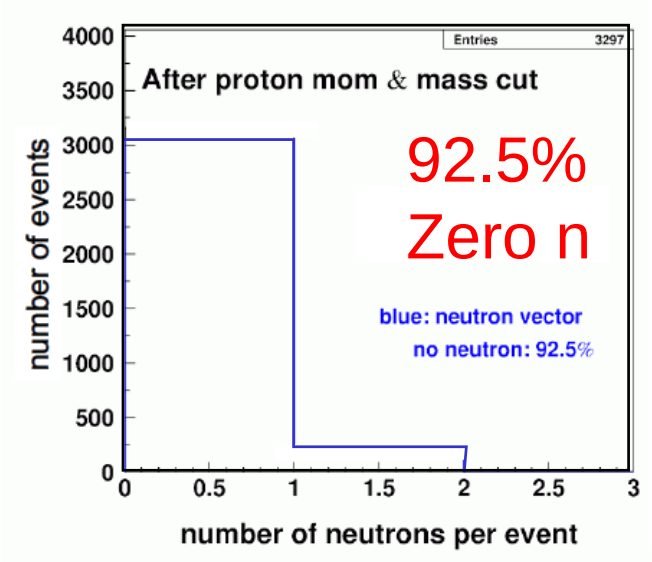
Now SRN search is limited by BG.

We need BG reduction by the neutron tagging!

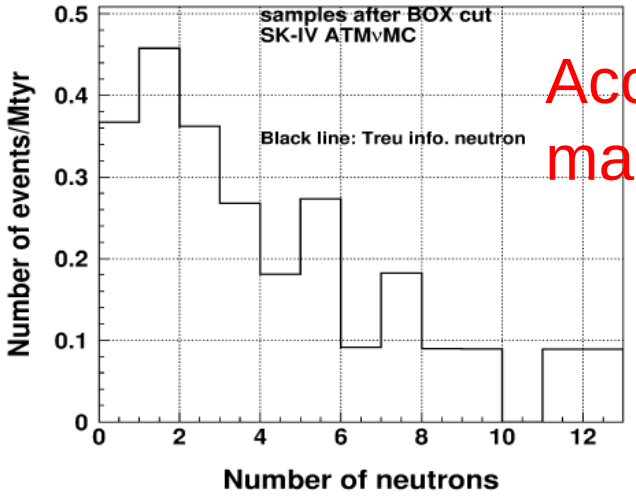
Improvement for Proton decay

Neutron multiplicity for

P→$e^+\pi^0$ MC



Atmospheric ν BG



Accompany many n

<u>If one proton decay event is observed at Super-K after 10 years</u>

Current background level: 0.58 events/10 years

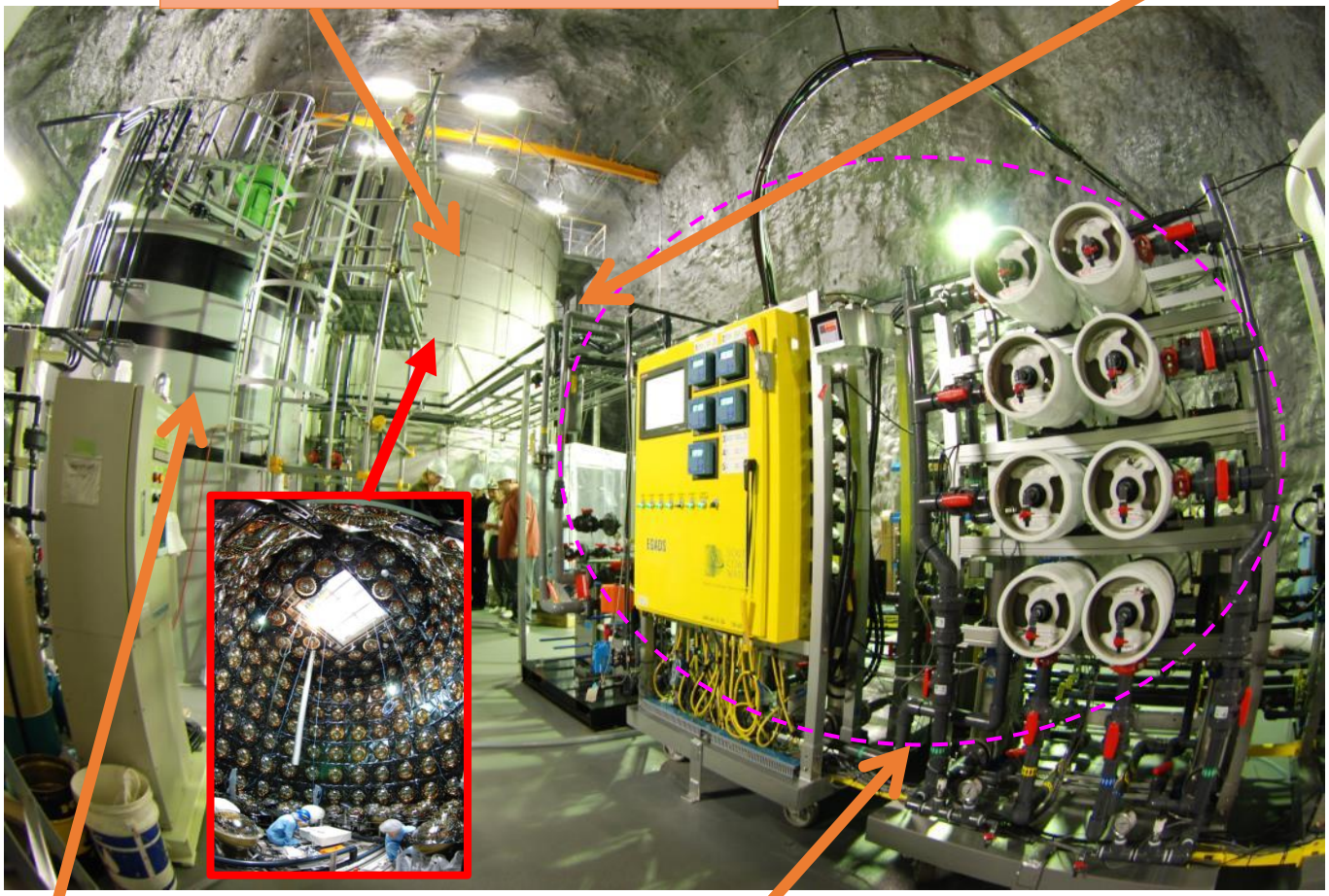
Background with neutron anti-tag: 0.098 events/10 years

Background probability will be decreased from 44%(w/o n) to 9%(w/ n).

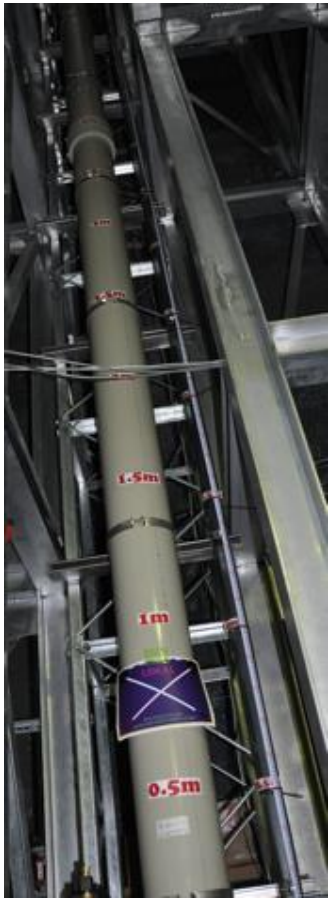
EGADS

Evaluating Gadolinium's Action on Detector Systems

200 m^3 tank with 240 PMTs



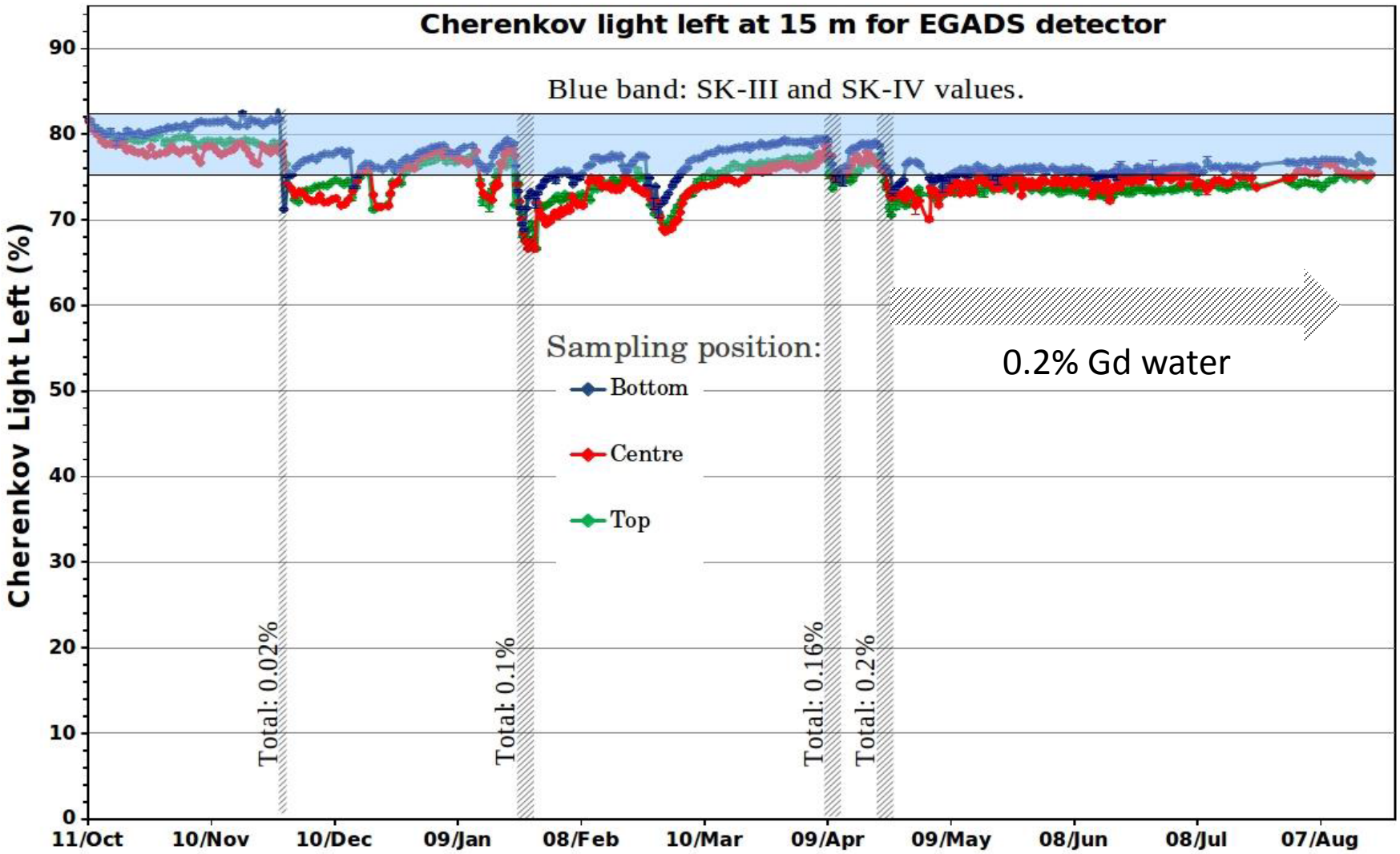
Transparency measurement (UDEAL)



15m^3 tank to dissolve Gd

Gd water circulation system (purify water with Gd)

Transparency of Gd water with PMTs

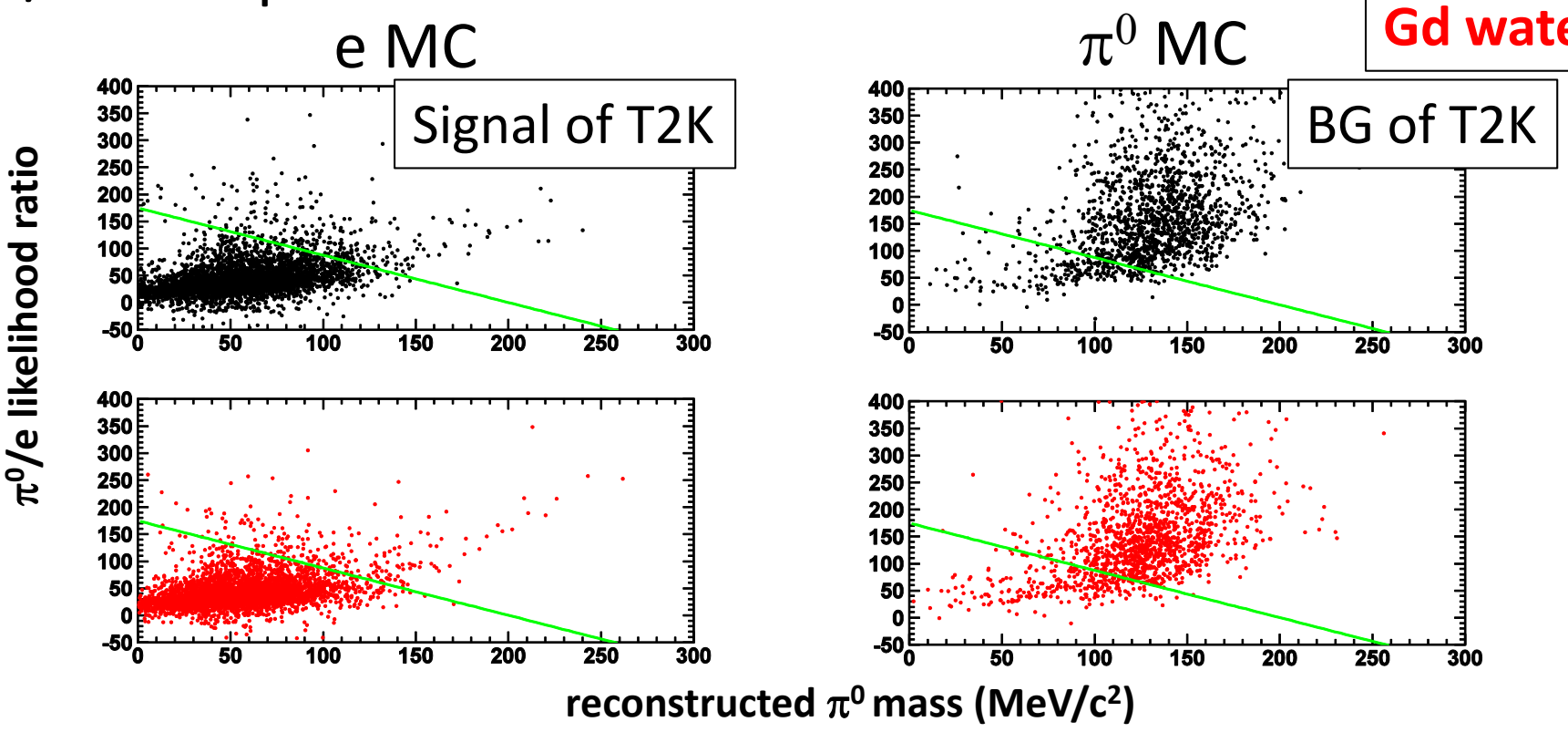


Poster : Ryosuke Akutsu

The light left at 15 m in the 200m^3 tank was ~75% for 0.2% $Gd_2(SO_4)_3$, which corresponds to ~92% of SK-IV pure water average.

e/π^0 separation (ex. 500MeV/c)

pure
Gd water



e MC, det. ε(%)

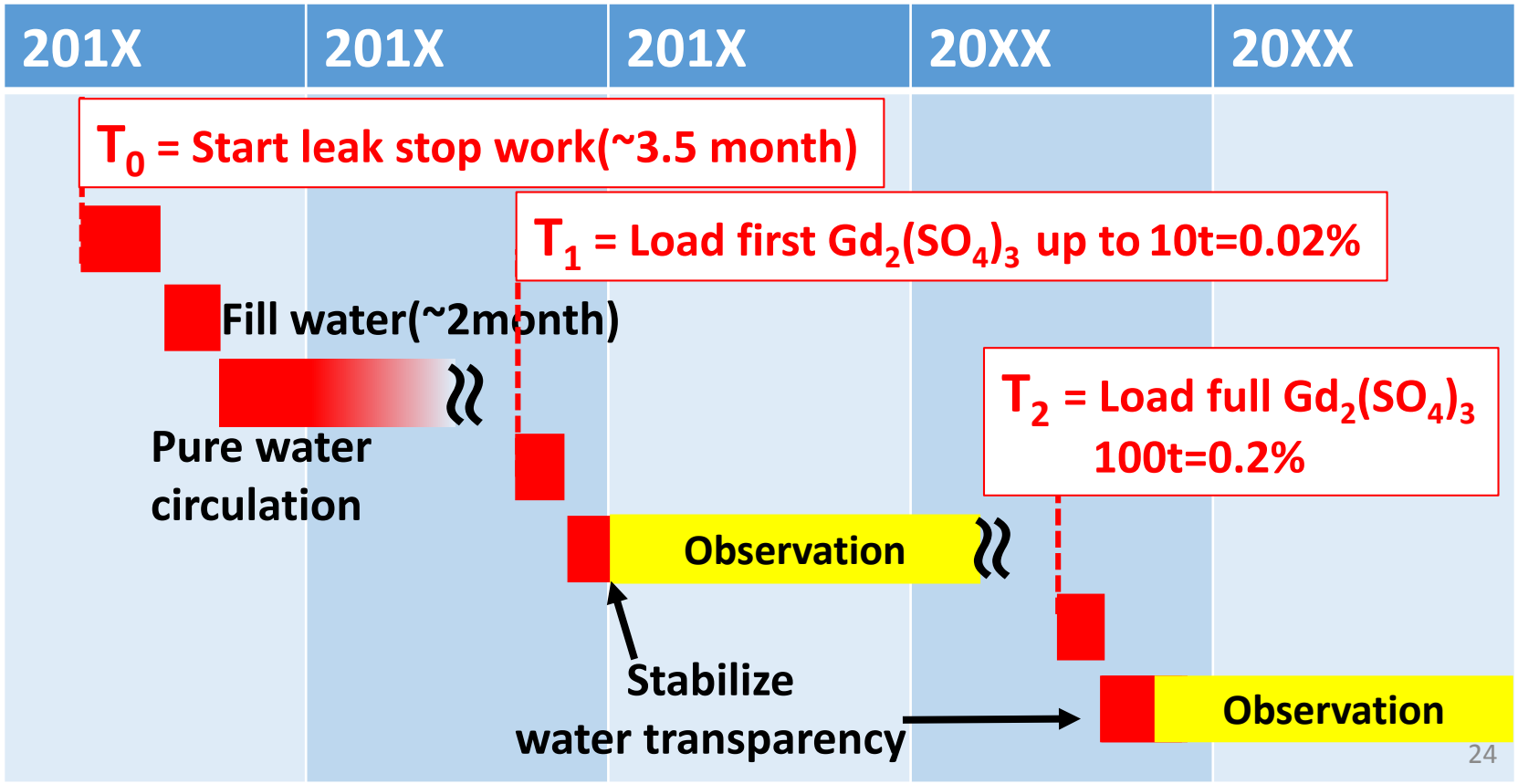
true (MeV/c)	pure	Gd water
250	92.9±2.1	91.9±2.1
500	89.3±2.0	88.4±2.0
1000	75.7±1.8	77.7±1.8

π^0 MC, remain ε(%)

true (MeV/c)	pure	Gd water
250	1.7±0.2	1.9±0.2
500	4.7±0.3	6.1±0.4
1000	15.8±0.7	16.7±0.7

Timeline of SK-Gd

- On June 27, 2015, the Super-Kamiokande collaboration approved the SK-Gd project.
- T0, T1, and T2 will be determined with T2K collaboration.



Summary

- Latest result from Super-K
  - Proton decay
    - No evidence so far.
    - longest lifetime limt: $\tau/B_{p\rightarrow e\pi 0} > 1.67 \times 10^{34}$ years (90% CL)
  - Atmospheric neutrinos:
    - there is ~1 σ preference in normal hierarchy ($\chi^2_{NH}-\chi^2_{IH}= -3.0$)
    - indicate $\delta_{CP} \sim -\pi/2$, but still CP conservation allowed
  - Solar neutrinos:
    - 3σ difference of day-night solar neutrino flux.
    - No correlation between Sun spot and solar neutrino flux
- SK-Gd
  - Aim to detect SNR using neutron capture by adding Gd
  - SK-Gd project approved by collaboration
  - Schedule will be determined with T2K

Summary of recent nucleon decay results in SK

Decay mode	$\|\Delta(B-L)\|$	Lifetime lower limit at 90% CL (years)	Paper (previous result)
$p \to e^+\pi^0$	0	(*) 1.67×10^{34}	(PRD 85, 112001 (2012))
$p \to \nu K^+$	0(ν), 2(ν)	6.61×10^{33}	(PRD 90, 072005 (2014))
$p \to \mu^+\pi^0$	0	(*) 7.78×10^{33}	(PRD 85, 112001 (2012))
$p \to e^+/\mu^+(\eta,\rho,\omega)$	0	$(0.04\text{-}4.2) \times 10^{33}$	PRD 85, 112001 (2012)
$p \to \mu^+K^0$	0	1.6×10^{33}	PRD 86, 012006 (2012)
$n \to \bar{\nu}\pi^0$, $p \to \bar{\nu}\pi^+$	0	1.1×10^{33}, 3.9×10^{32}	PRL 113, 121802 (2014)
$p \to e^+/\mu^+\nu\nu$	0($\nu\nu$), 2($\nu\nu$,$\nu\nu$)	$1.7/2.2 \times 10^{32}$	PRL 113, 101801 (2014)
$p \to e^+/\mu^+X$	?	$7.9/4.1 \times 10^{32}$	arXiv:1508.05530, accepted by PRL
$n \to \nu\gamma$	0(ν), 2(ν)	5.5×10^{32}	arXiv:1508.05530, accepted by PRL
$pp \to K^+K^+$	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	7.22×10^{31}, $1{,}70 \times 10^{32}$, 4.04×10^{32}	PRD 91, 072009 (2015)
$np \to (e^+,\mu^+,\tau^+)\nu$	0(ν), 2(ν)	$(0.22\text{-}5.5) \times 10^{32}$	arXiv:1508.05530, accepted by PRL
n-$\bar{n}$ oscillation	2	1.9×10^{32}	PRD 91, 072006 (2015)

(* will be published soon)

$p \rightarrow \mu^+ \pi^0$

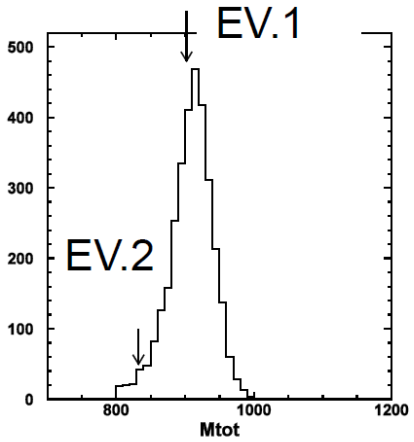
		SK-I	SK-II	SK-III	SK-IV
Exp.(kton·yrs)		91.7	49.2	31.9	133.5
$p \rightarrow \mu^+ \pi^0$					
(Free)	Eff.(%)	16.4±0.8	16.0±0.8	16.4±1.0	20.1±1.0
(P_{tot}<100)	BKG	0.04±0.01	<0.01	<0.01	0.01±0.01
	OBS	0	0	0	0
(Bound)	Eff.(%)	15.3±2.5	15.3±2.6	16.5±0.8	18.2±1.1
(100≤P_{tot}<250)	BKG	0.33±0.09	0.14±0.04	0.12±0.03	0.23±0.07
	OBS	0	0	0	2

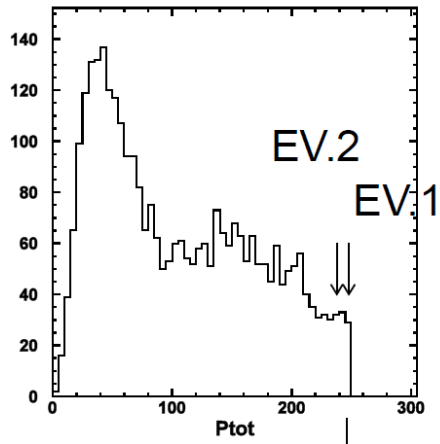
Signal ? Background ? (1)

M_{tot}

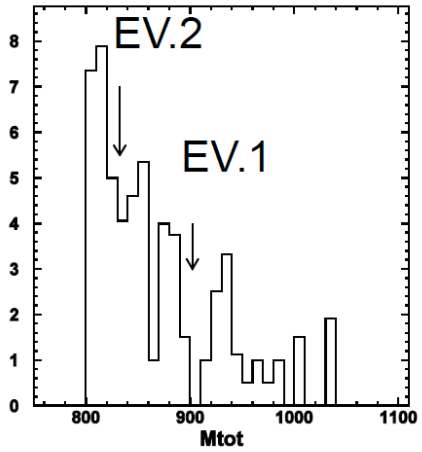
P_{tot}

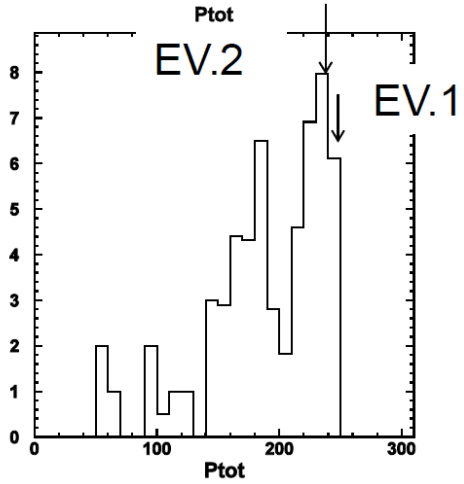
Signal MC





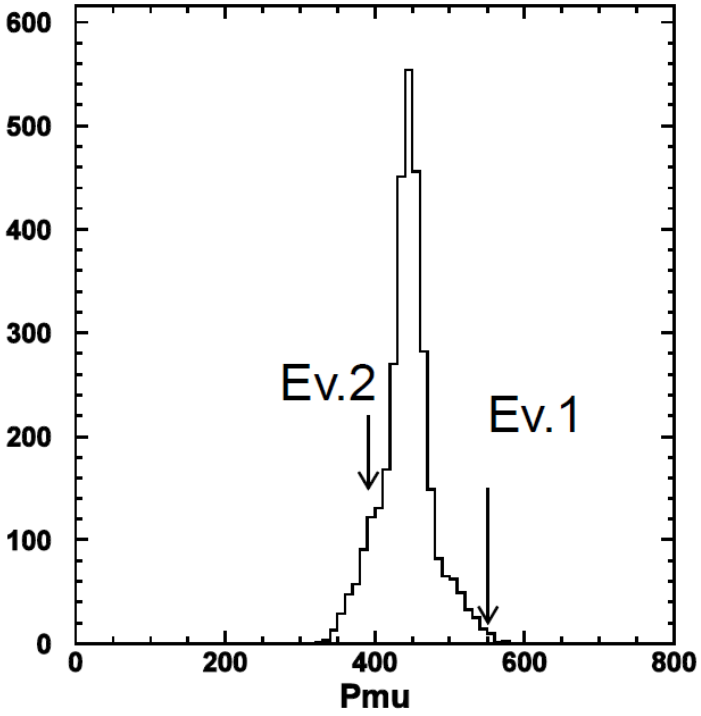
BKG MC (merge SK1-SK4)



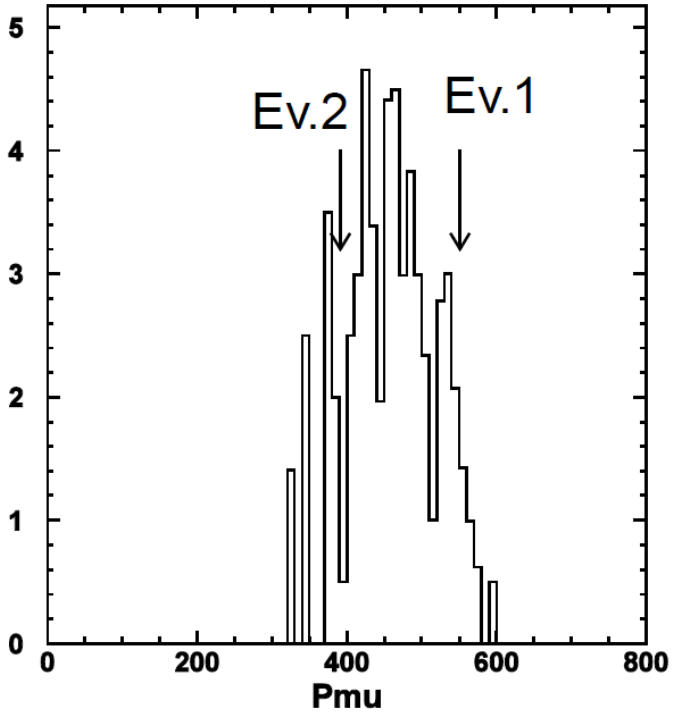


Pμ after all cut cuts+2R cut

Signal MC



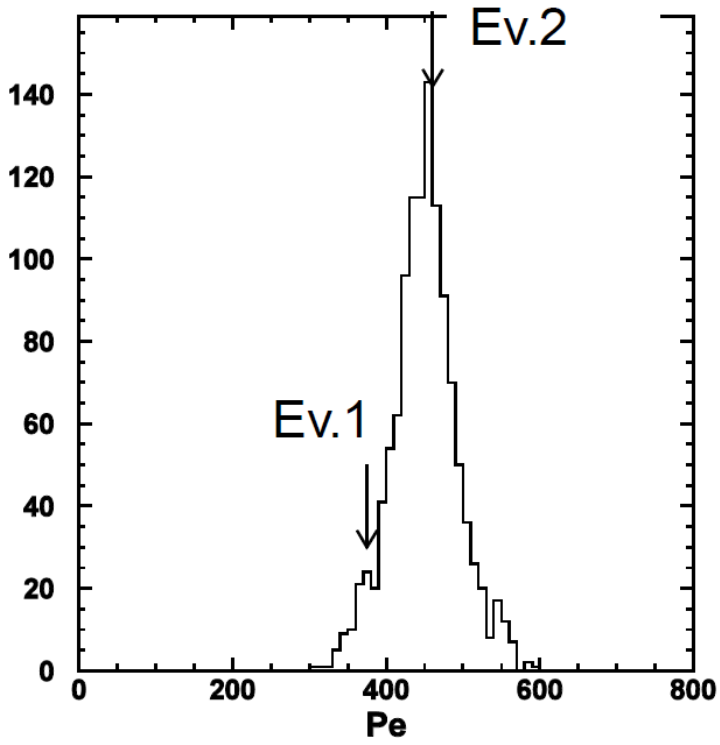
BKG MC



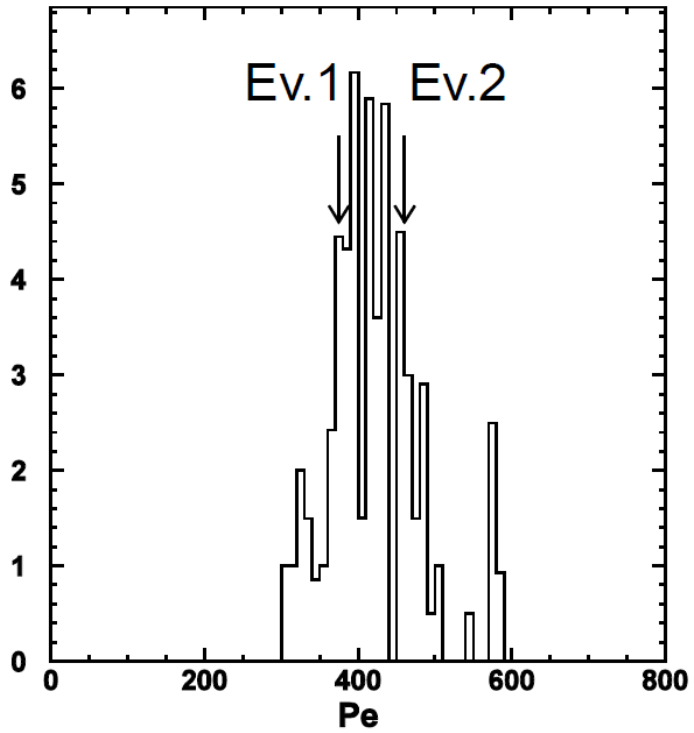
Pμ of Ev.1 is too large…

Pe after all cuts+2R cut

Signal MC

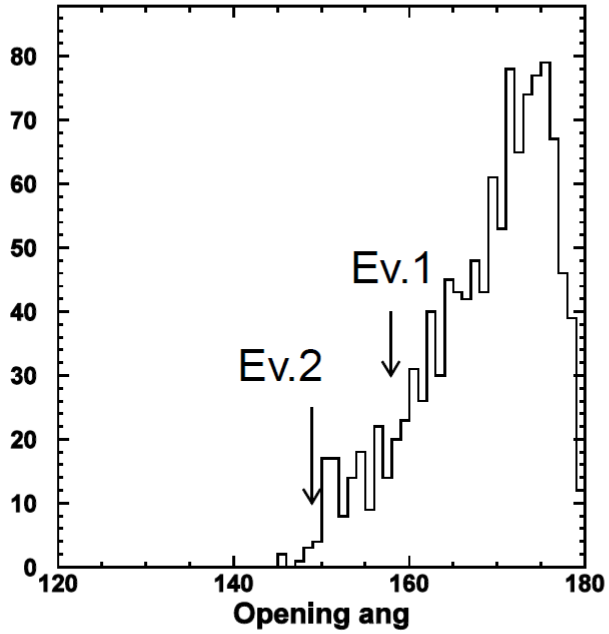


BKG MC

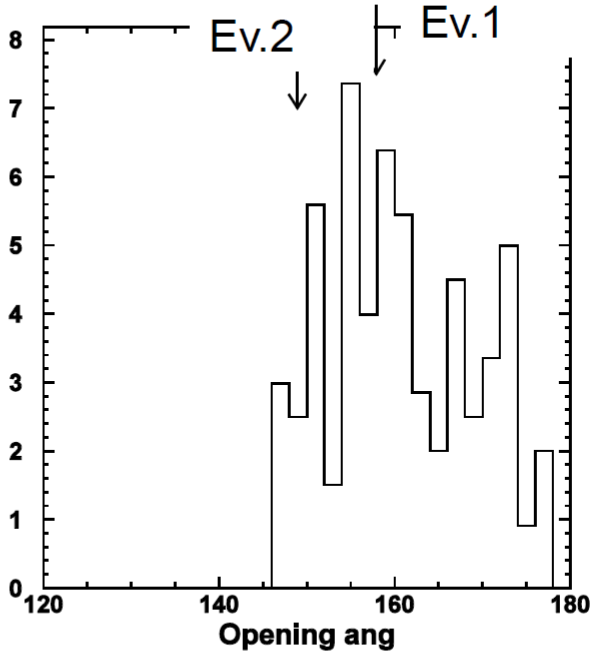


Opening angle after all cuts + 2R cut)

Signal MC



BKG MC



θ of Ev.2 is too small…

Unfortunately, both events look like BKG:
Ev.1: too large Pμ
Ev2: Too small θ

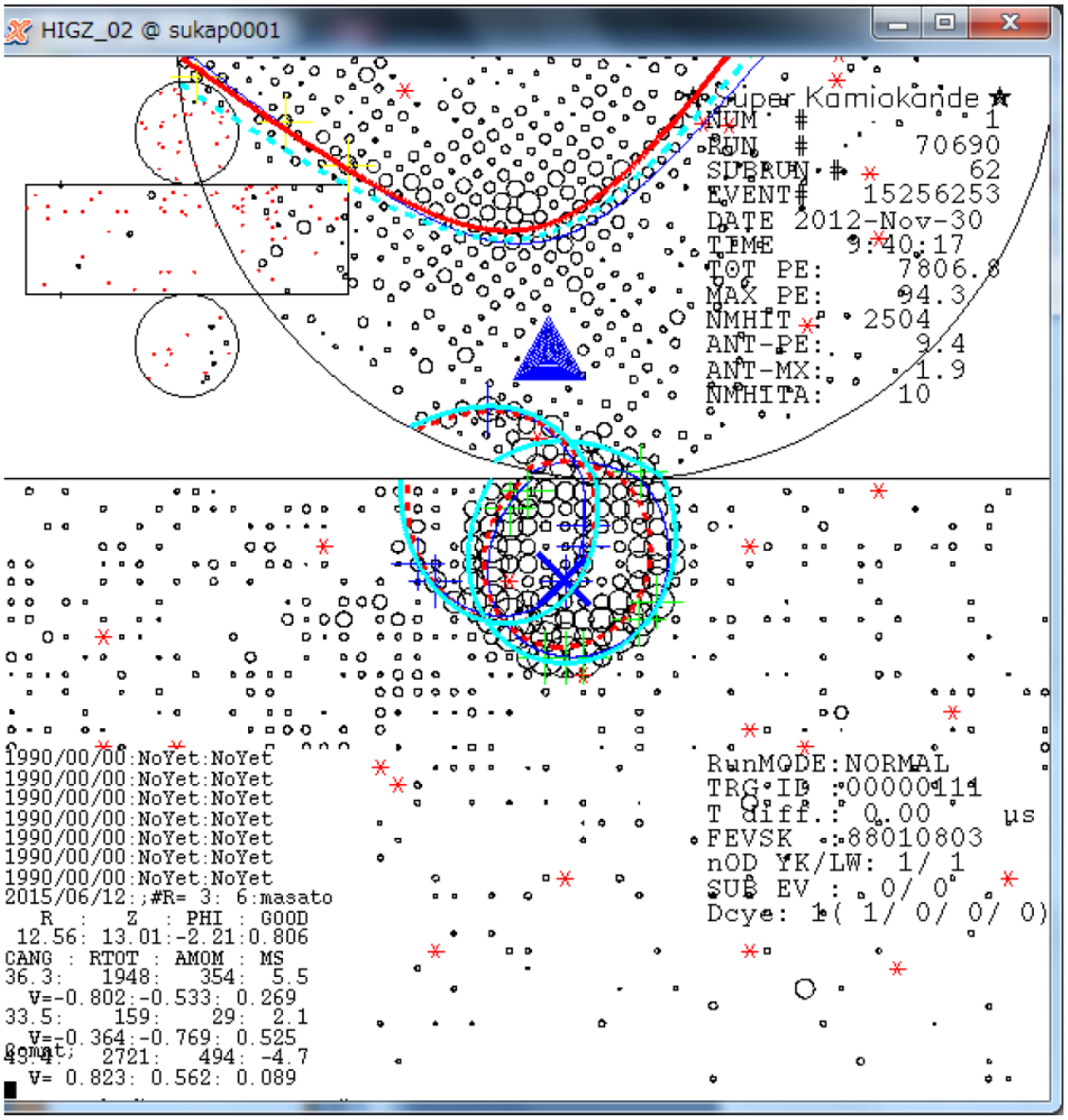
Q. Is it consistent with expected background in each period ?

	SK1	SK2	SK3	SK4
BKG	0.36	0.15	0.12	0.24
Obs	0	0	0	2
Prob	69.8%	86.1%	88.7%	2.3%

One event until the first event: 35.8 %
One event between the 1st and 2nd event: 3.8%

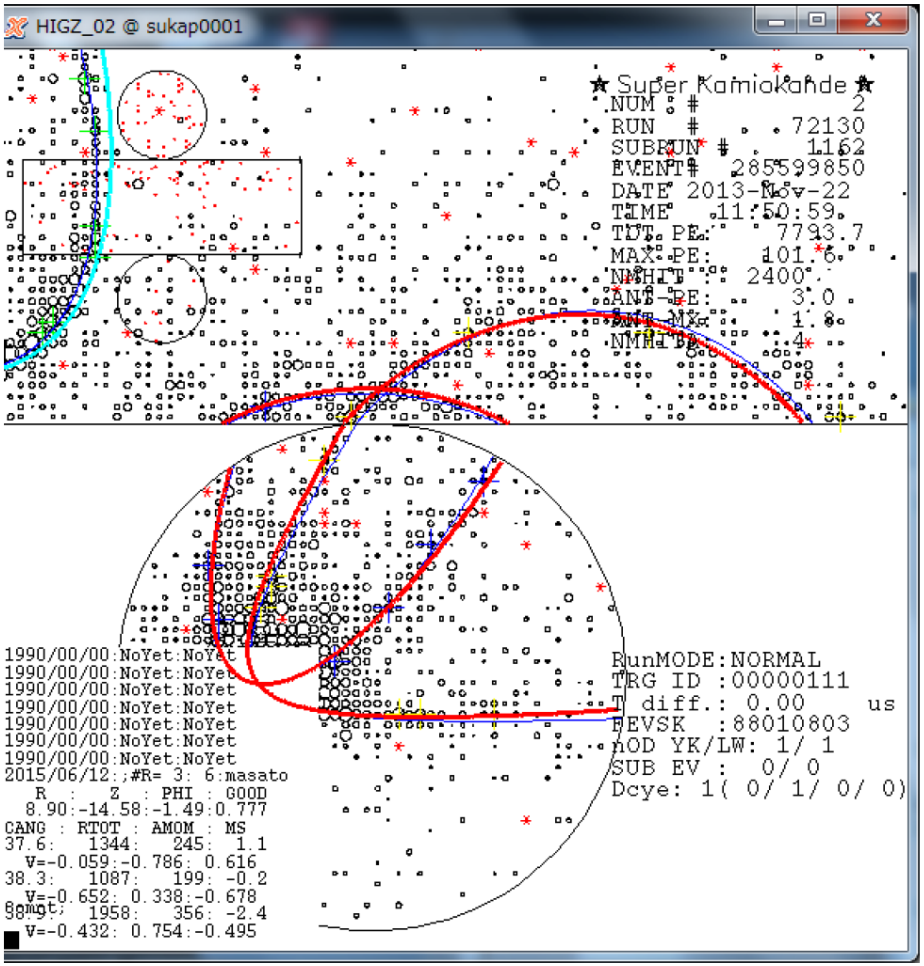
A. It could be happened.

Hand-fit for Ev.1



Take 3 rings
μ: 468 MeV/c
μ: 273 MeV/c
e: 408 MeV/c
Ptot: 413 MeV/c
Mtot: 1107 MeV

Hand-fit for Ev.2



Take 3 rings

μ: 418 MeV/c

e: 159 MeV/c

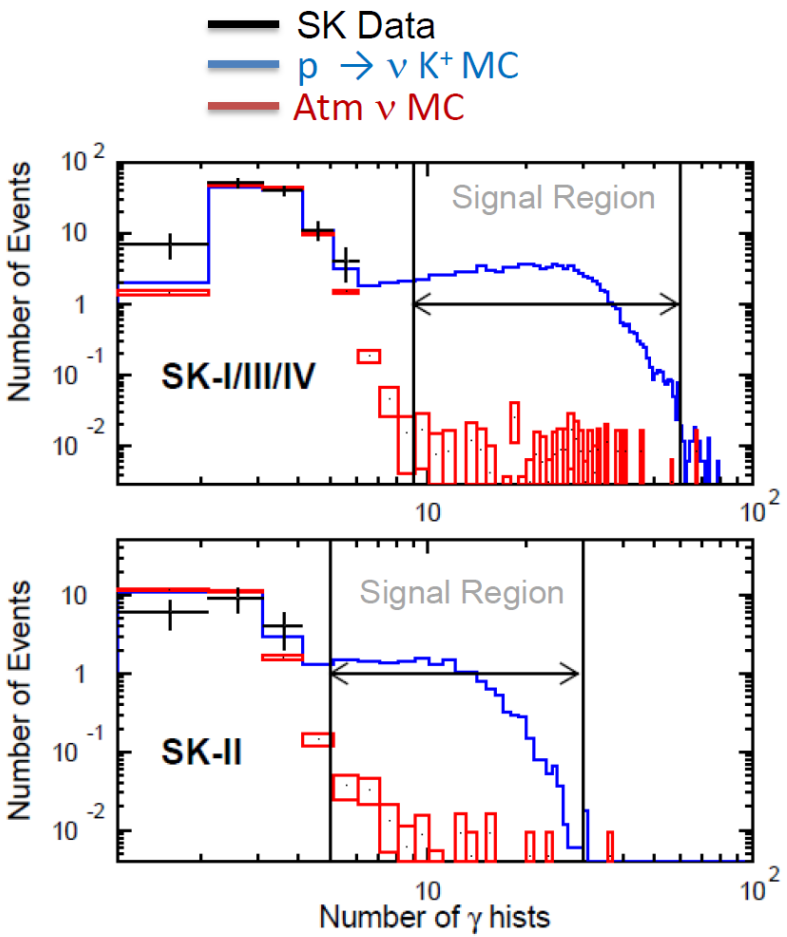
e: 338 MeV/c

Ptot: 294 MeV/c

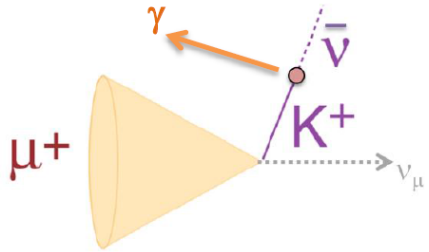
Mtot: 880 MeV

→ Mγγ=406 MeV

$p \rightarrow \nu K^+ \rightarrow \mu^+ \nu_\mu$: Method 1) Nuclear deexitation γ, μ, and decay e^+ Results



Number of hits in γ-tagged cluster
($t_\mu - t_\gamma < 75$ ns)



	Effic (%)	BKG	Data
SK-I	7.9 ± 0.1	0.08	0
SK-II	6.3 ± 0.1	0.14	0
SK-III	7.7 ± 0.1	0.03	0
SK-IV	9.1 ± 0.1	0.13	0

Backgrounds from:

$48\% : \nu p \rightarrow \nu K^+ \Lambda + \gamma, \Lambda \rightarrow p\pi^-$ (invis)

$25\% : \nu_\mu n \rightarrow \mu p + \gamma$

No observed candidates

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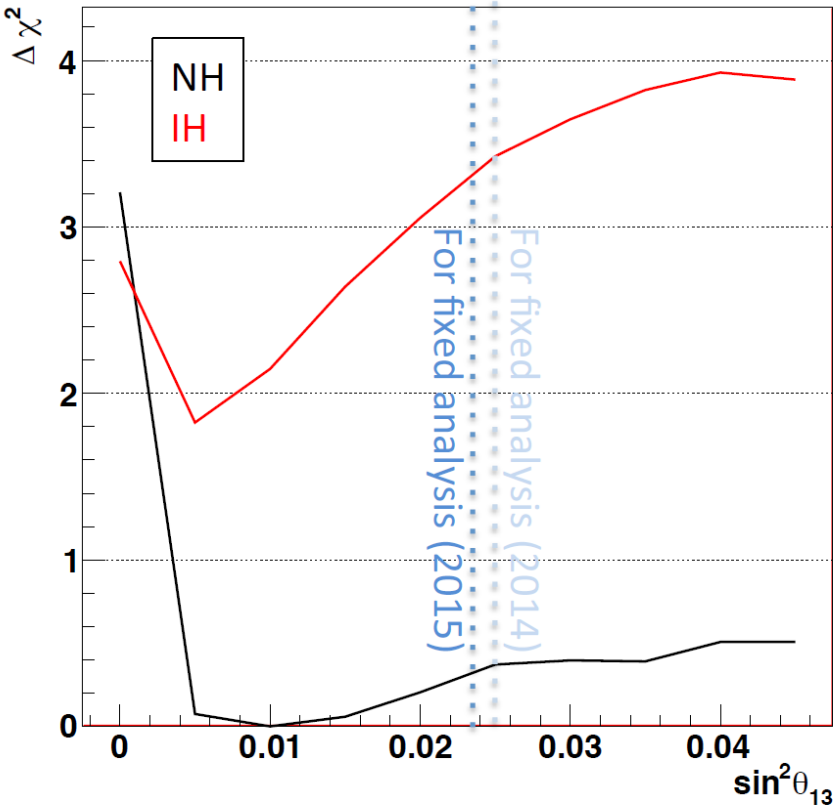
Update of SK analysis (θ_{13} is free)



Best Fit (DOF 518)

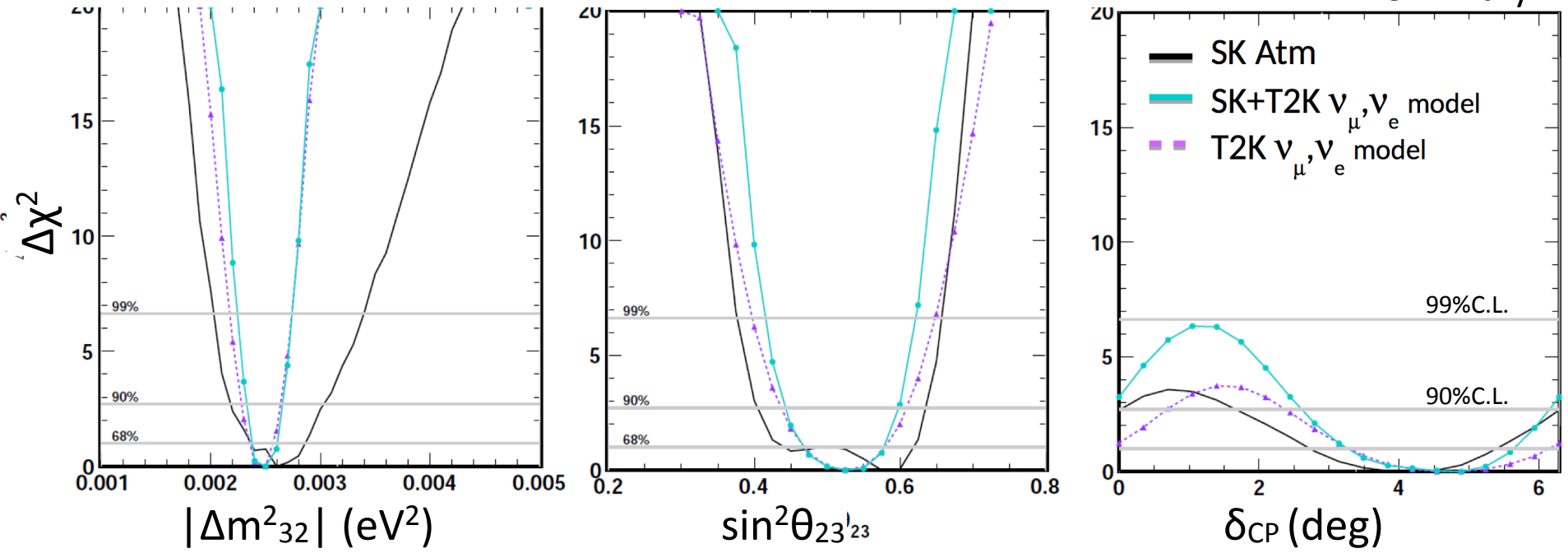
	NH	IH
χ^2	582.0	583.9
δCP	240	220
$\sin^2\theta_{23}$	0.575	0.55
Δm^2_{23}	0.0026	0.0023
$\sin^2\theta_{13}$	**0.01**	**0.005**

- Best fits of $\sin^2\theta_{13}$ are different from $\sin^2\theta_{13}$-fixed analysis value.
- The effect from the change of θ_{13} is very small.

Fit with T2K published data (NH)

- Introduce constraint from modeled T2K data(6.57e20POT) for better sensitivity
- $\chi^2_{NH}-\chi^2_{IH}$= -3.2 (SK only : -3.0)
- SK and T2K favors δ_{CP}~$-\pi/2$, but CP conservation ($\sin\delta_{CP}=0$) allowed

Preliminary



Fit (585dof)	χ^2	$\sin^2\theta_{13}$ (fix)	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{32}
Normal	651.5	0.0238	280	0.525	2.5×10^{-3}
Inverted	654.7	0.0238	240	0.550	2.4×10^{-3}