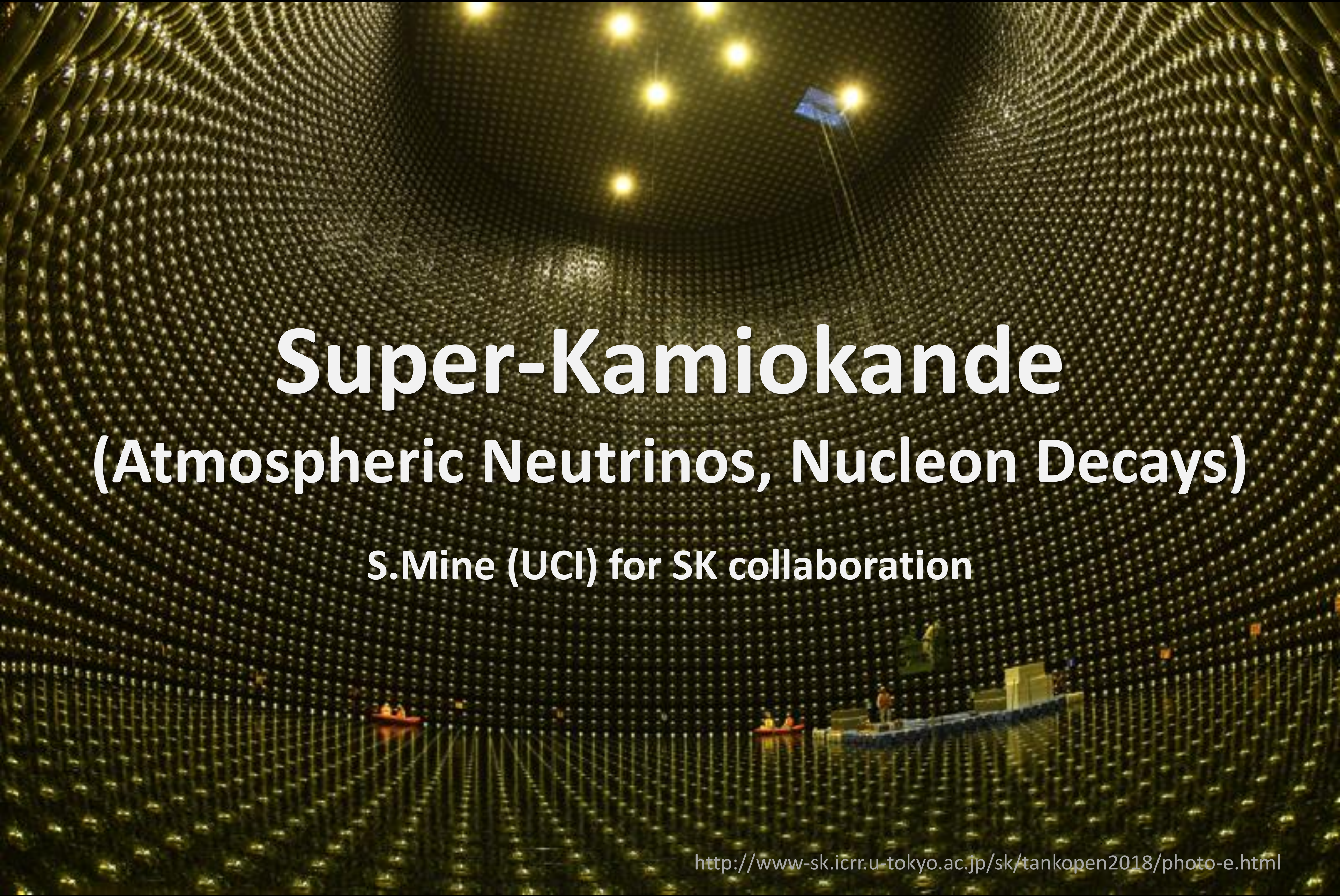
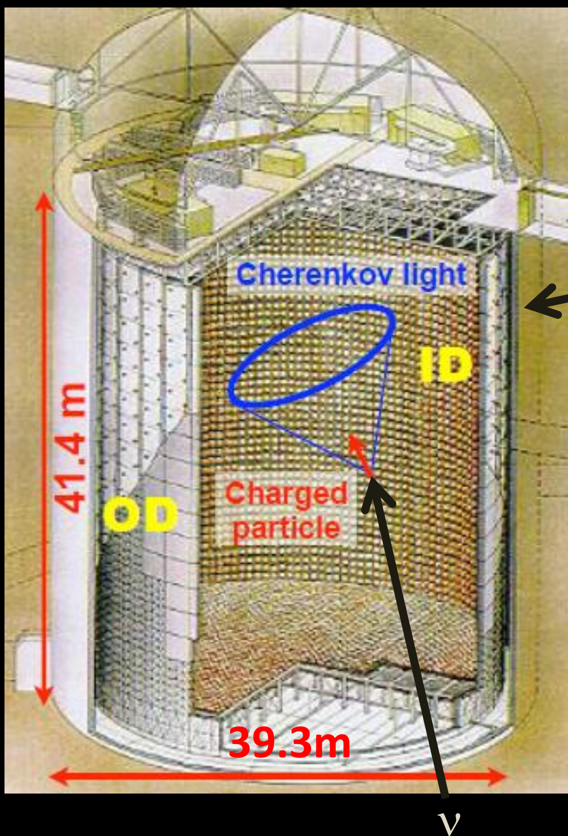
Super-Kamiokande
(Atmospheric Neutrinos, Nucleon Decays)

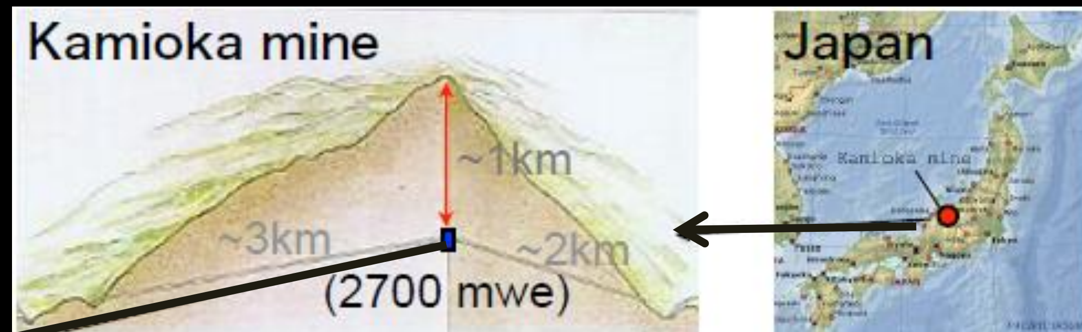
S.Mine (UCI) for SK collaboration



http://www-sk.icrr.u-tokyo.ac.jp/sk/tankopen2018/photo-e.html

Super-Kamiokande (SK)





NIM A 737C (2014)

Phase		SK-I	SK-II	SK-III	SK-IV
Period	start	1996 Apr.	2002 Oct.	2006 Jul.	2008 Sep.
	end	2001 Jul.	2005 Oct.	2008 Sep.	2018 May
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

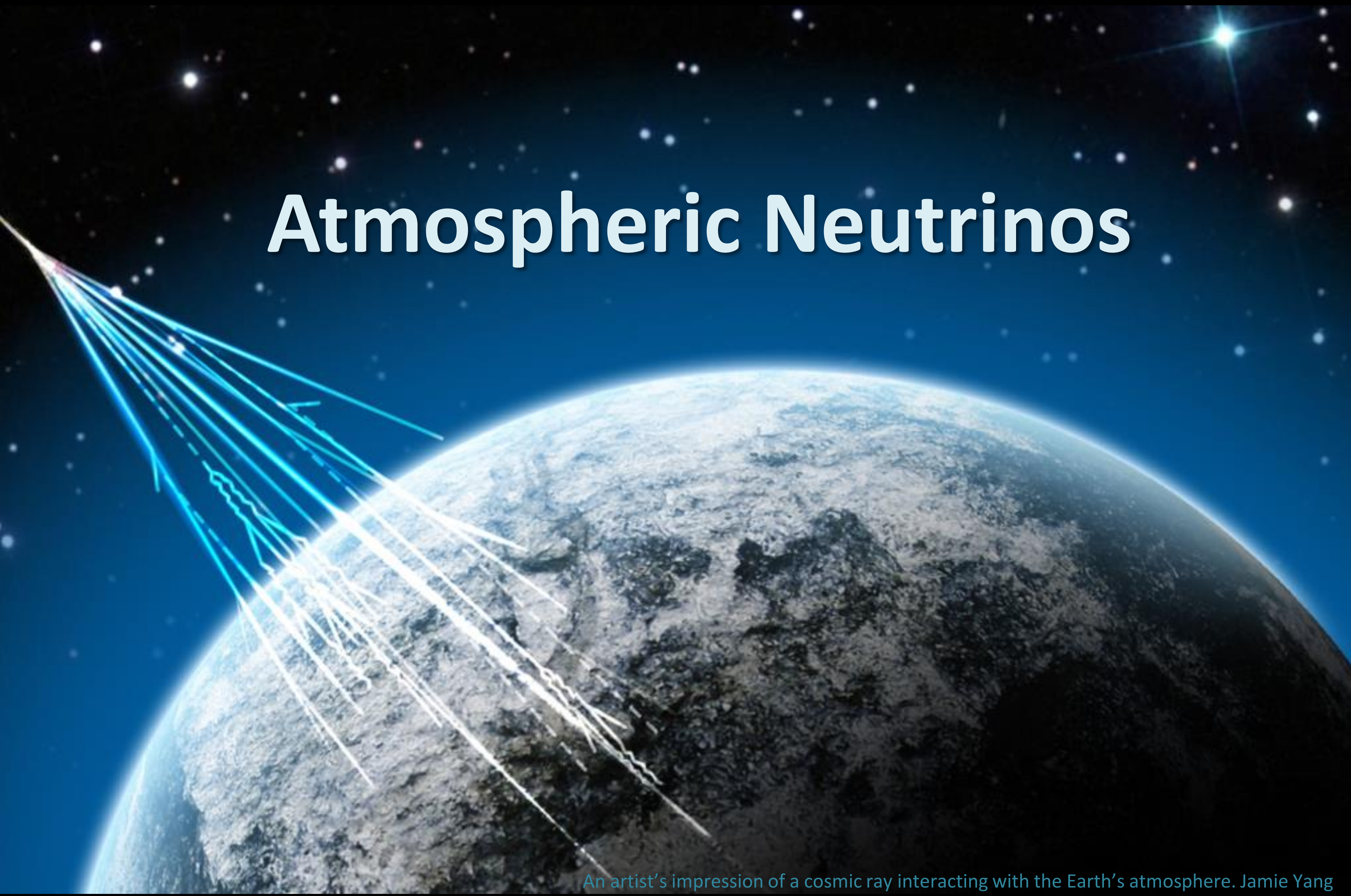
- SK total ~ 20 years

See Smy's talk for SK refurbishment work and SK-Gd

SK collaboration

- ~160 people
- ~40 institutes
- Japan, U.S., Korea, China, Poland, Spain, Canada, U.K., Italy, France

Atmospheric Neutrinos



An artist's impression of a cosmic ray interacting with the Earth's atmosphere. Jamie Yang

Neutrino oscillation

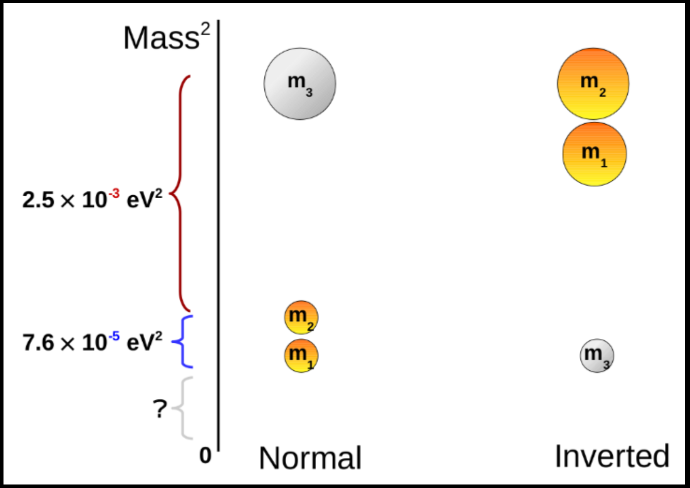
Three-neutrino mixing paradigm based on PMNS matrix

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- 3 mixing angles, 2 mass splittings, 1 CP violating phase

- Remain unknown parameters
  - CP violation phase
    - imbalance between matter and antimatter
  - Mass hierarchy
    - unification of forces
    - determine whether neutrino is Majorana

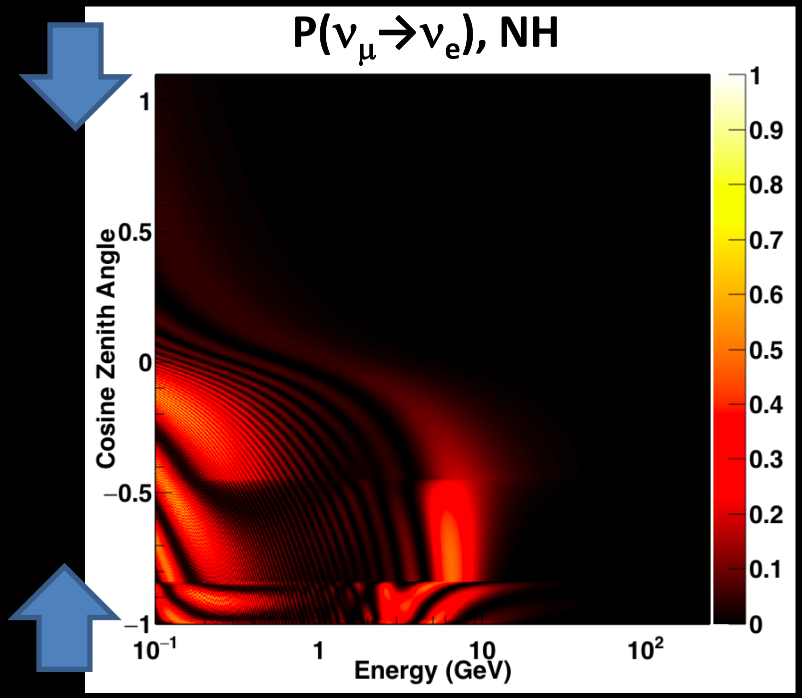
http://www.hyper-k.org/en/physics/phys-hierarchy.html



“NH” “IH”

Atmospheric ν oscillation analysis

- Sensitive to unknown parameters of PMNS formalism
  - presence of neutrinos and antineutrinos
  - effects of matter
  - wide variety of energies and pathlengths
- Measurement of mass hierarchy
  - upward-going excess of either ν_e (NH) or $\overline{\nu}_e$ (IH) by θ_{13}-induced matter effects between 2 and 10 GeV

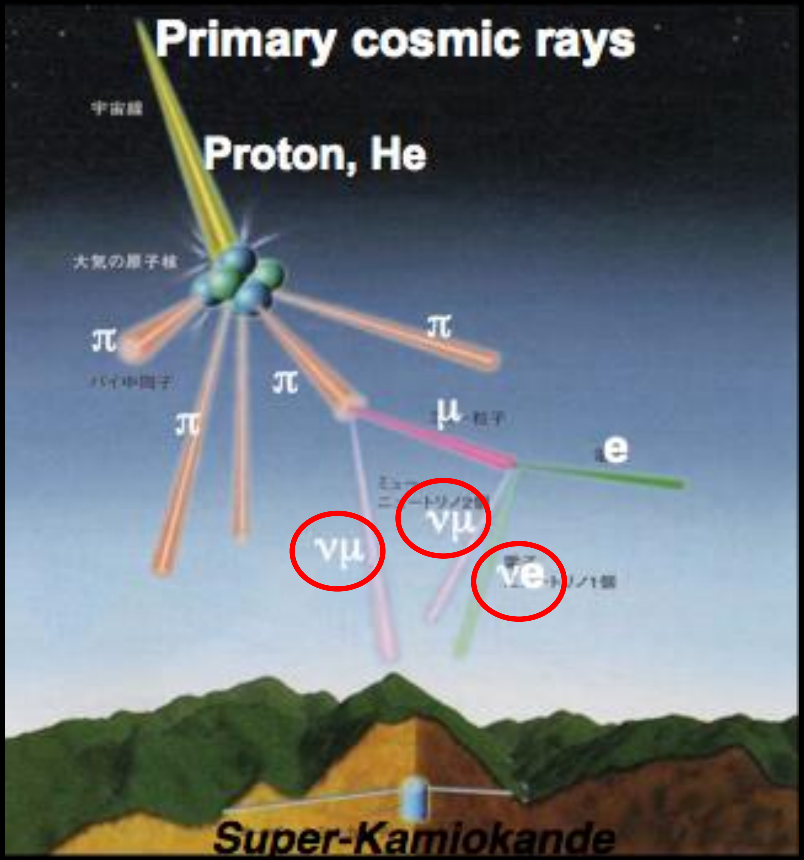


(for IH, matter effects appear in $\overline{\nu}$)

PRD 97, 072001 (2018)
PRD 98, 052006 (2018)

- This talk:
  - three-flavor ν oscillation analysis with external constraints
  - tau neutrino appearance

Atmospheric neutrinos

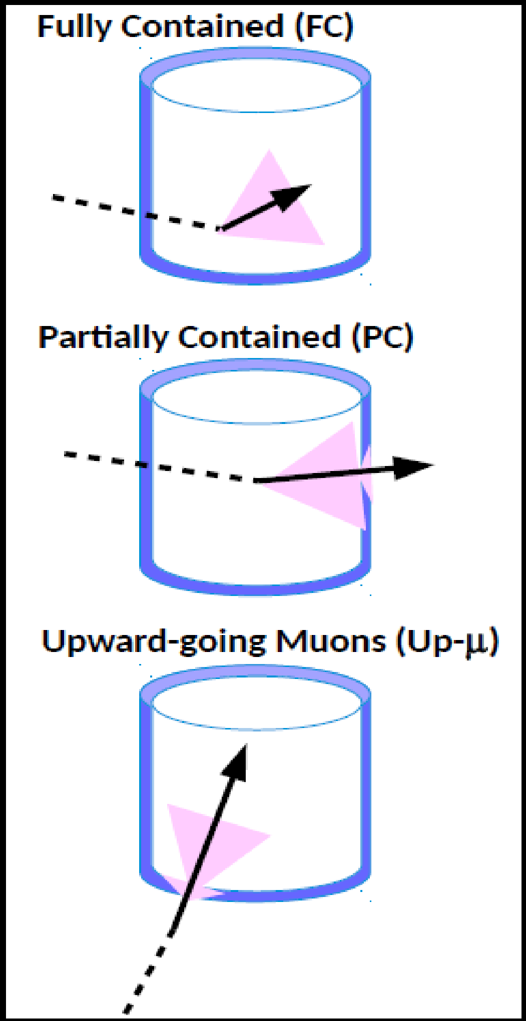


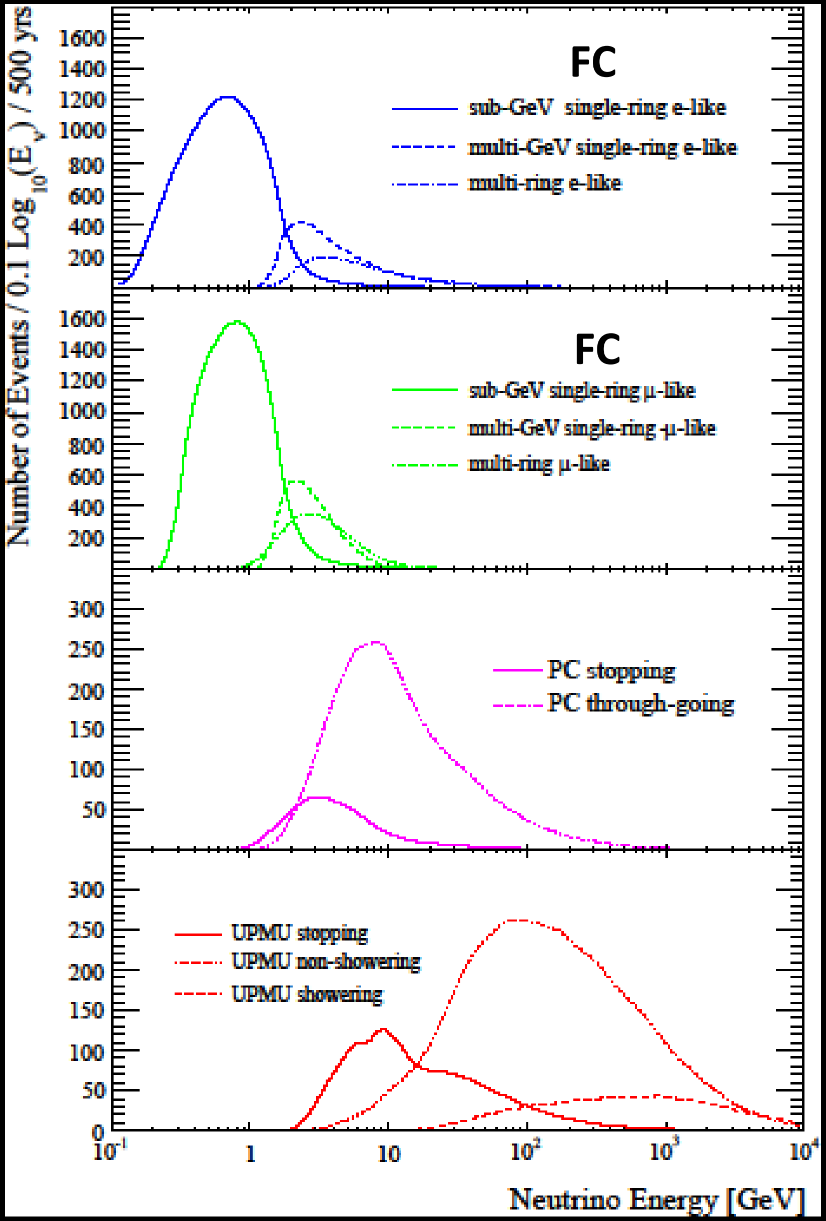
http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/atmos.html

- Cosmic rays strike air nuclei and decay of hadrons gives νs
- νs travel length: 10-10,000km
- νs energy: 100MeV-10TeV
- Both νs and anti-νs

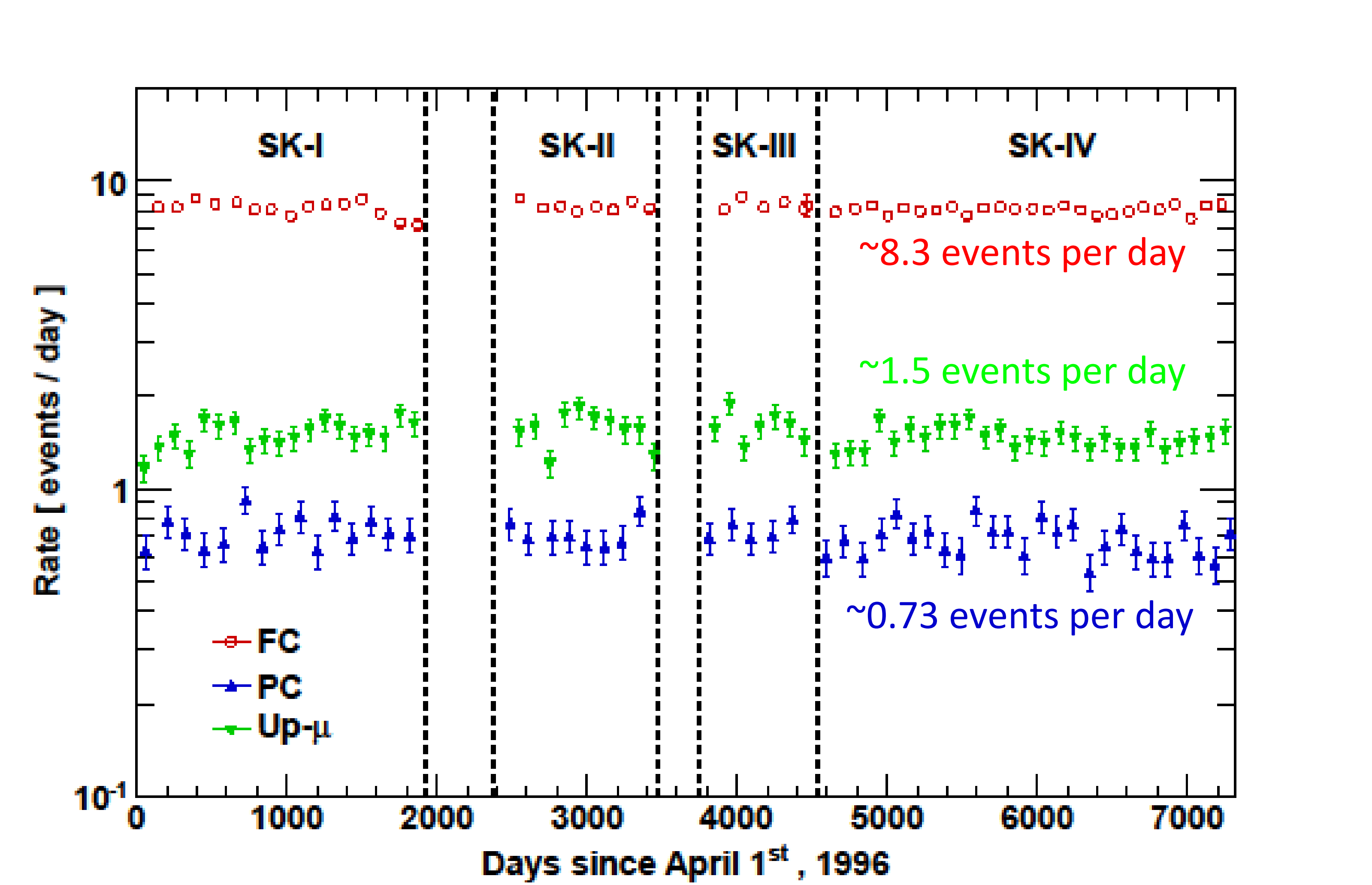
Excellent tool for broad studies of neutrino oscillations

Neutrino true-energy for each subsample





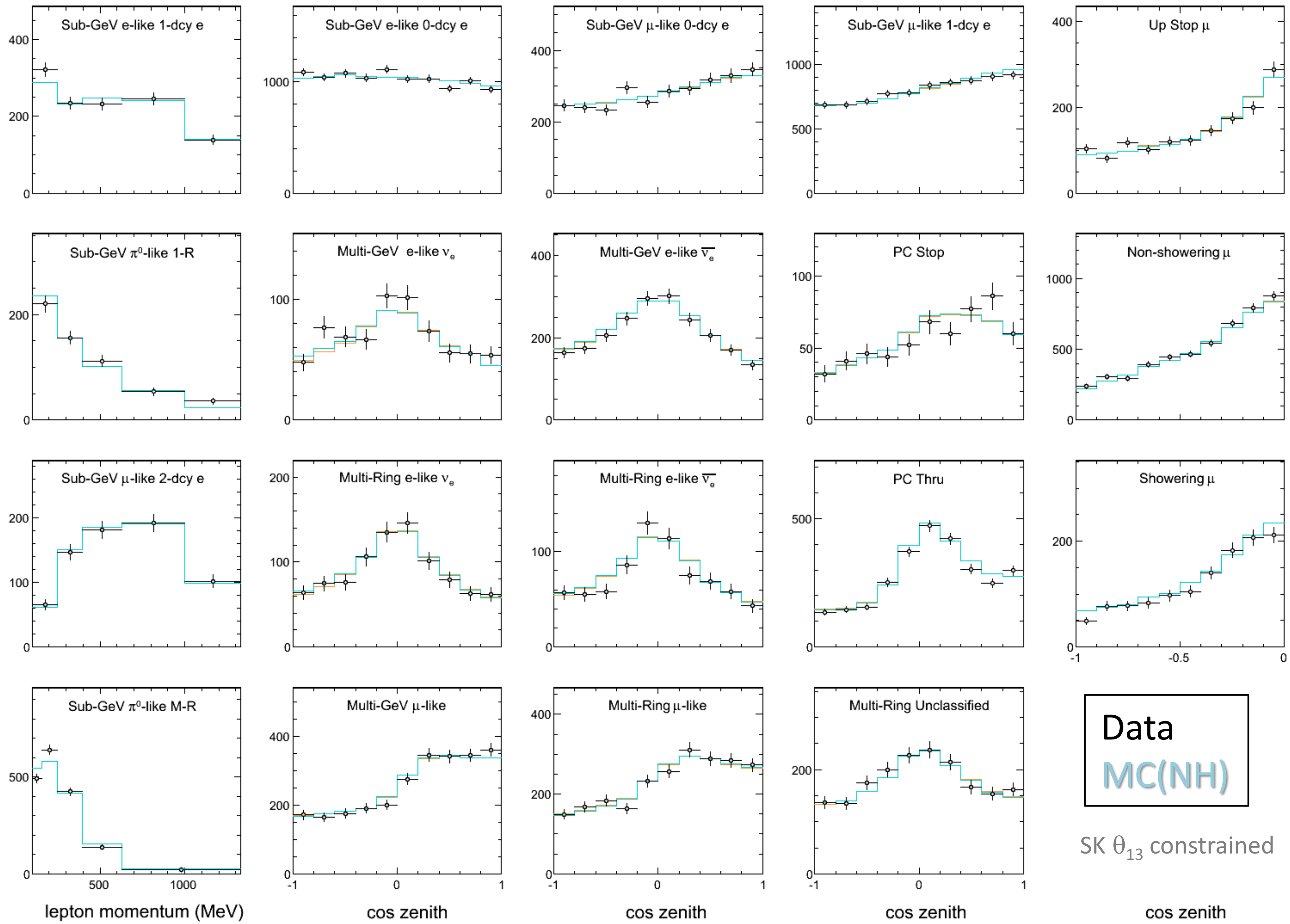
Atmospheric ν event rate



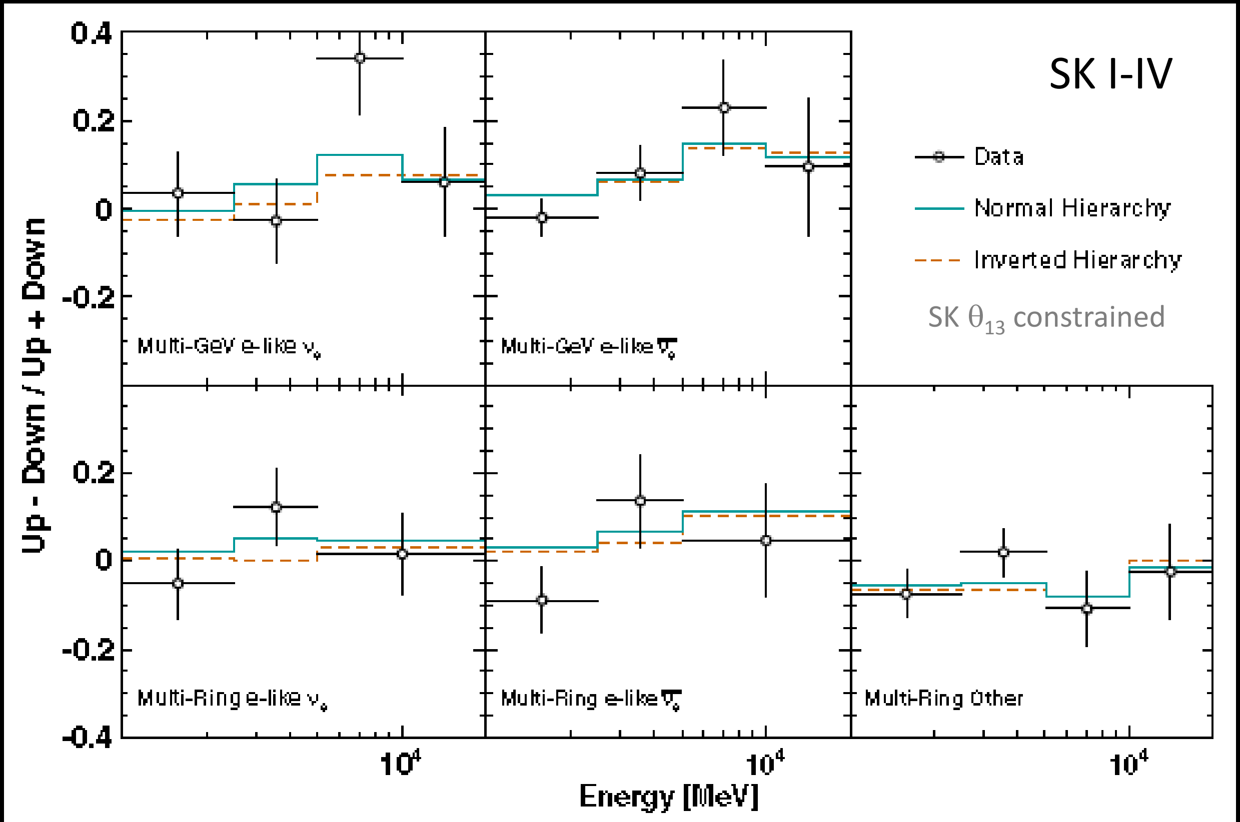
Zenith angle and momentum distributions

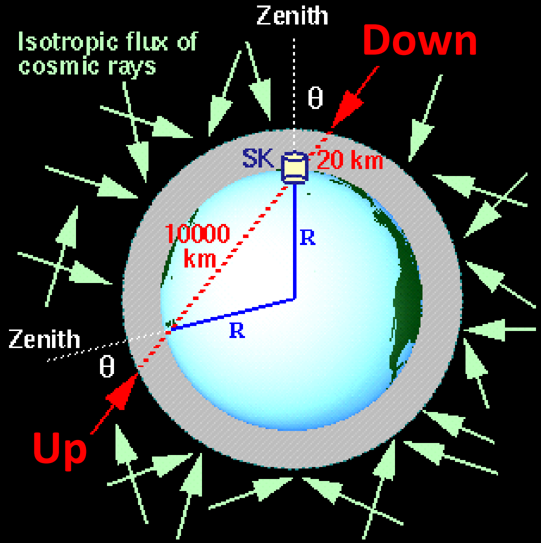
(19 analysis samples for 3-ν oscillation analysis)

SK I-IV



Up (cosθ<-0.4) to Down (cosθ>0.4) ratio

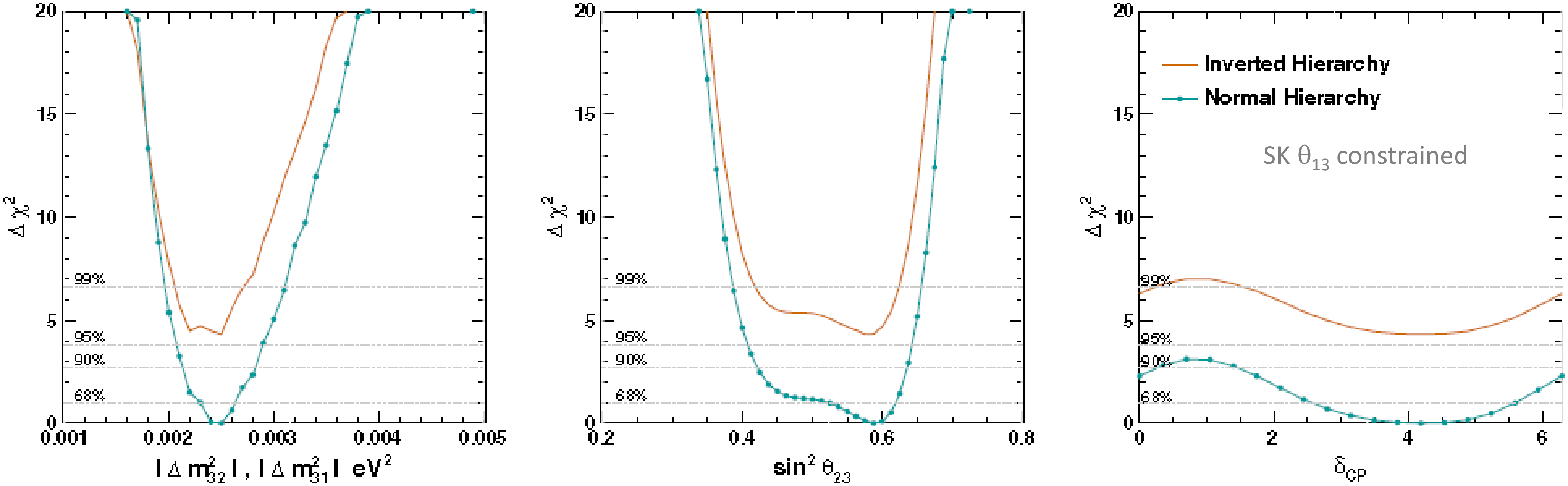




http://hep.bu.edu/~superk/atmnu/

Constraints on ν oscillation parameters

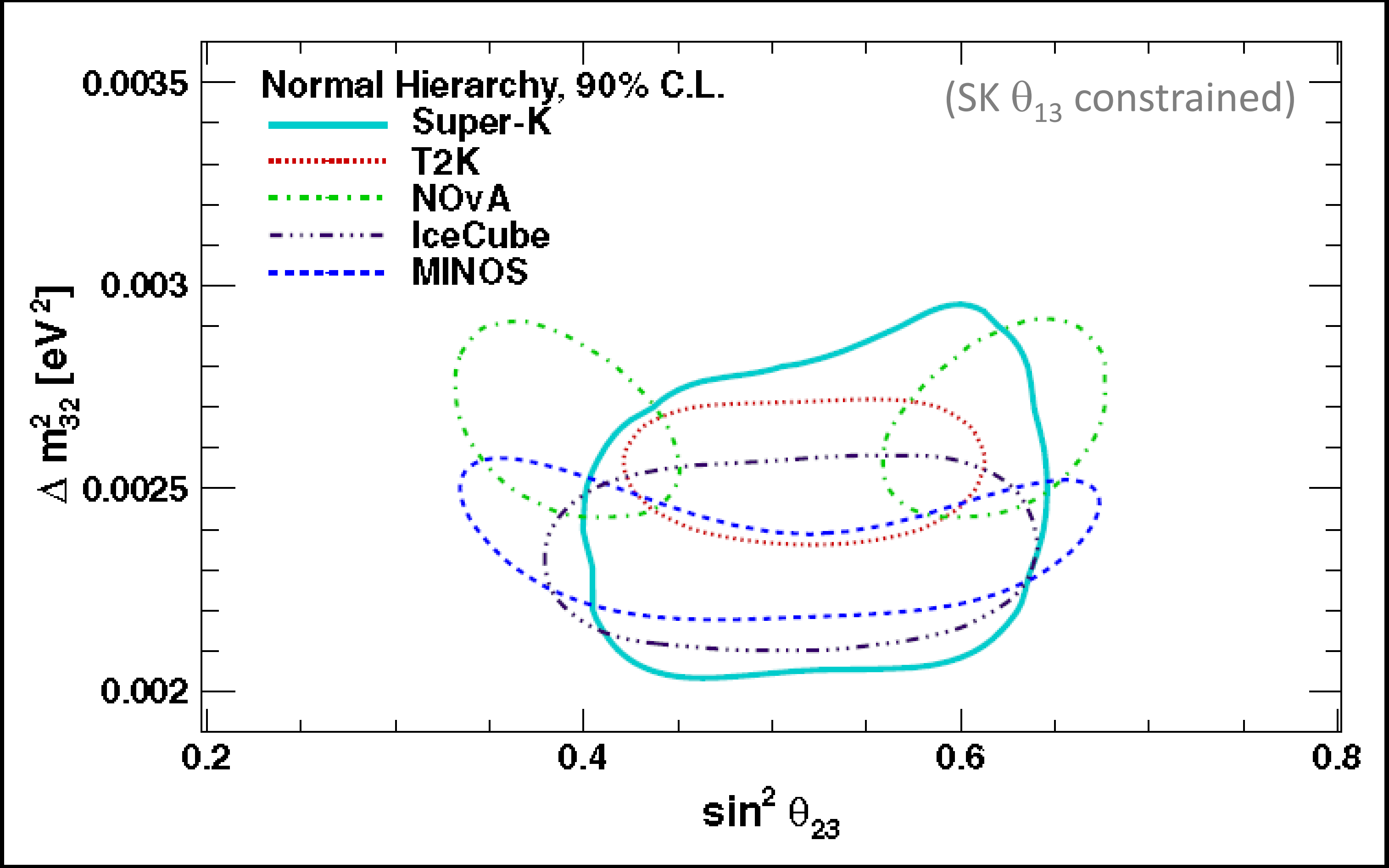
SK I-IV



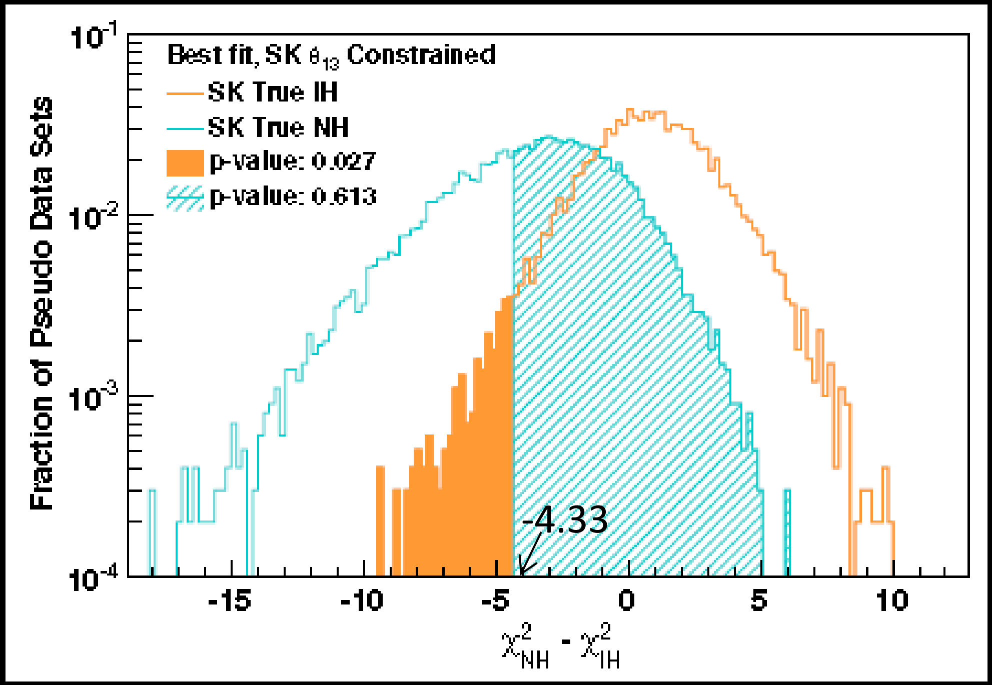
Fit	Hierarchy	χ^2	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32,31}\rvert$ [$\times 10^{-3}$ eV^2]	δ_{CP}
SK θ_{13} Free	NH	571.29	$0.018^{+0.029}_{-0.013}$	$0.587^{+0.036}_{-0.069}$	$2.50^{+0.13}_{-0.31}$	$4.18^{+1.45}_{-1.66}$
	IH	574.77	$0.008^{+0.017}_{-0.007}$	$0.551^{+0.044}_{-0.075}$	$2.20^{+0.33}_{-0.13}$	$3.84^{+2.38}_{-2.12}$
SK θ_{13} Constrained	NH	571.33	–	$0.588^{+0.031}_{-0.064}$	$2.50^{+0.13}_{-0.20}$	$4.18^{+1.41}_{-1.61}$
	IH	575.66	–	$0.575^{+0.036}_{-0.073}$	$2.50^{+0.08}_{-0.37}$	$4.18^{+1.52}_{-1.66}$
SK + T2K θ_{13} Constrained	NH	639.43	–	$0.550^{+0.039}_{-0.057}$	$2.50^{+0.05}_{-0.12}$	$4.88^{+0.81}_{-1.48}$
	IH	644.70	–	$0.550^{+0.035}_{-0.051}$	$2.40^{+0.13}_{-0.05}$	$4.54^{+1.05}_{-0.97}$

- $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.33$ (SK θ_{13} constrained; $\sin^2\theta_{13}=0.0219$)
- Publicly available information to model T2K (6.6×10^{20} pot ν beam)

Comparison with other experiments



Interpretation with Toy MC



$$CL_s = \frac{p_0(IH)}{1 - p_0(NH)}$$

- $p_0(IH)$ ($p_0(NH)$): p-value for $\Delta\chi^2$ < (>) -4.33
- At 90% C.L .bounds on θ_{23} and δ_{CP} and best fit

	$p_0(IH)$			CL_s		
Fit	Lower 90% C.L.	Best Fit	Upper 90% C.L.	Lower 90% C.L.	Best Fit	Upper 90% C.L.
SK θ_{13} Constrained	0.012	0.027	0.020	0.181	0.070	0.033
SK + T2K θ_{13} Constrained	0.004	0.023	0.024	0.081	0.075	0.056

- IH disfavored by 81.9-96.7% for SK θ_{13} constrained
- IH disfavored by 91.9-94.5% for SK θ_{13} constrained +T2K

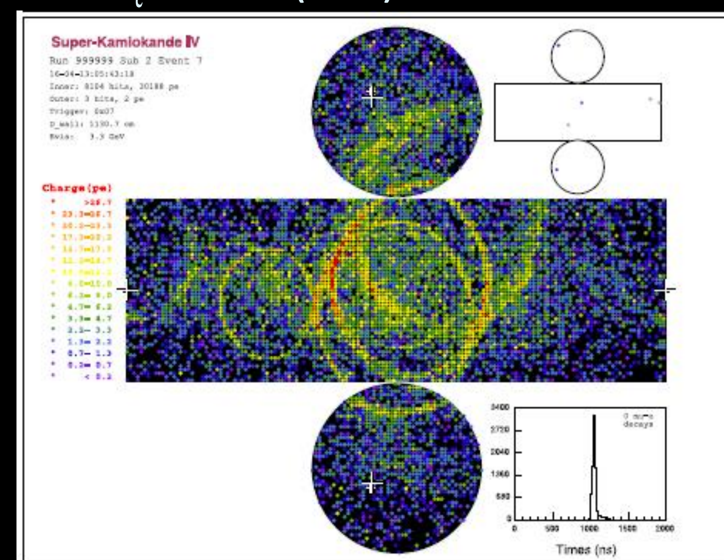
Measurement of atm.-ν_τ appearance

- Direct detection of ν_τs for confirmation of three-flavor oscillations
- Energy threshold for CC ν_τ int.: 3.5GeV
- Not possible to directly detect τs due to short life time
- Difficult to distinguish multi-ring BKG events (multi-π/DIS) from τ signal
- Multivariate method to statistically identify CC ν_τ events. Inputs:
  - visible energy
  - # Michel electrons
  - etc.

τ decay modes

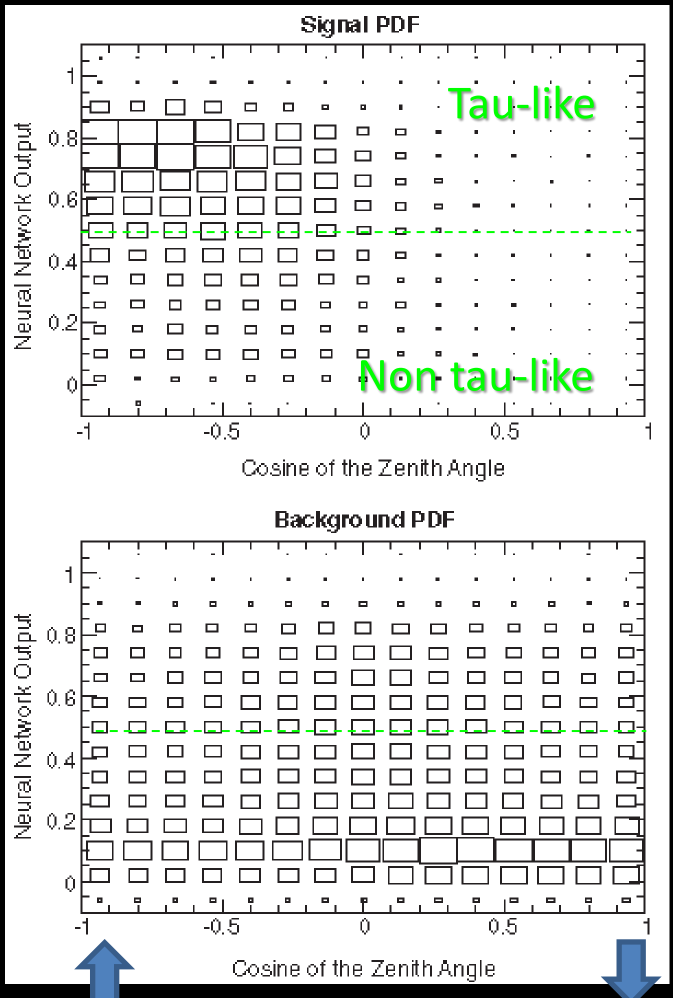
Decay mode	Branching ratio (%)
$e^-\bar{\nu}_e\nu_\tau$	17.83
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.41
$\pi^-\nu_\tau$	10.83
$\pi^-\pi^0\nu_\tau$	25.52
$3\pi\nu_\tau$	18.29
others	10.12

CC ν_τ event (MC)



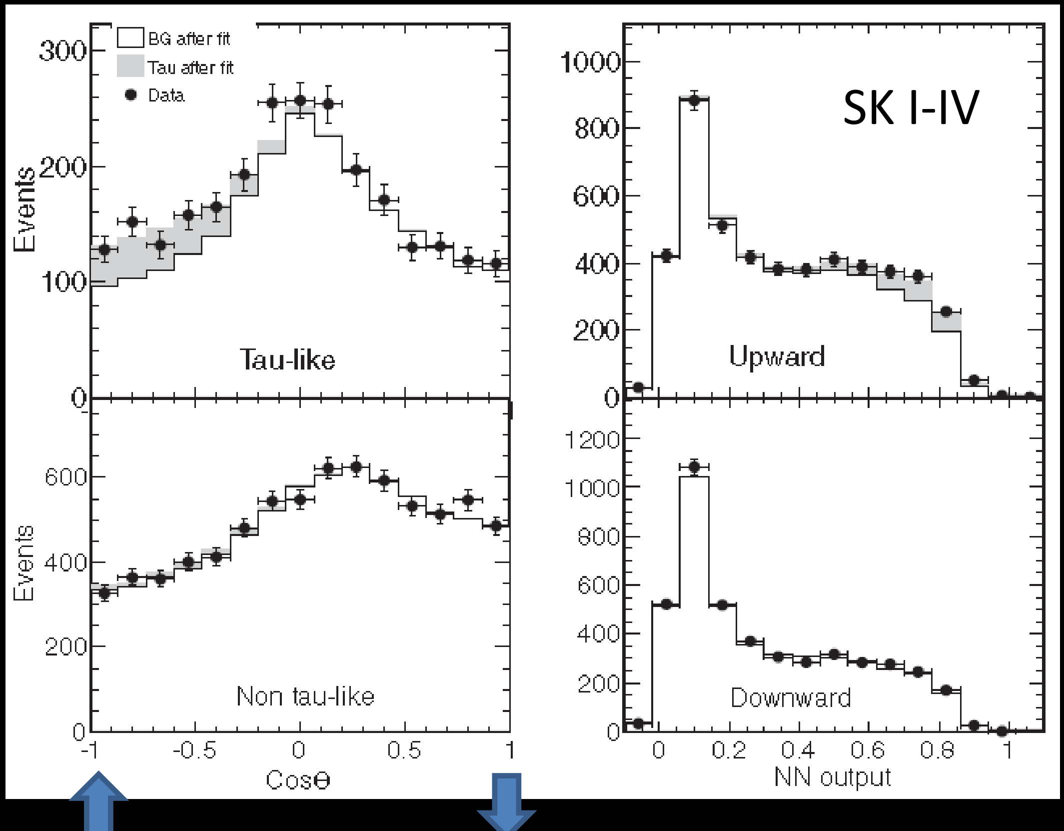
$$\text{Data} = \text{PDF}_{\text{BG}} + \alpha \times \text{PDF}_{\text{tau}} + \sum \epsilon_i \times \text{PDF}_i$$

(NH case shown)



α = 1.47±0.32(stat.+syst.)

- 4.6σ of rejection hypothesis of no τ appearance

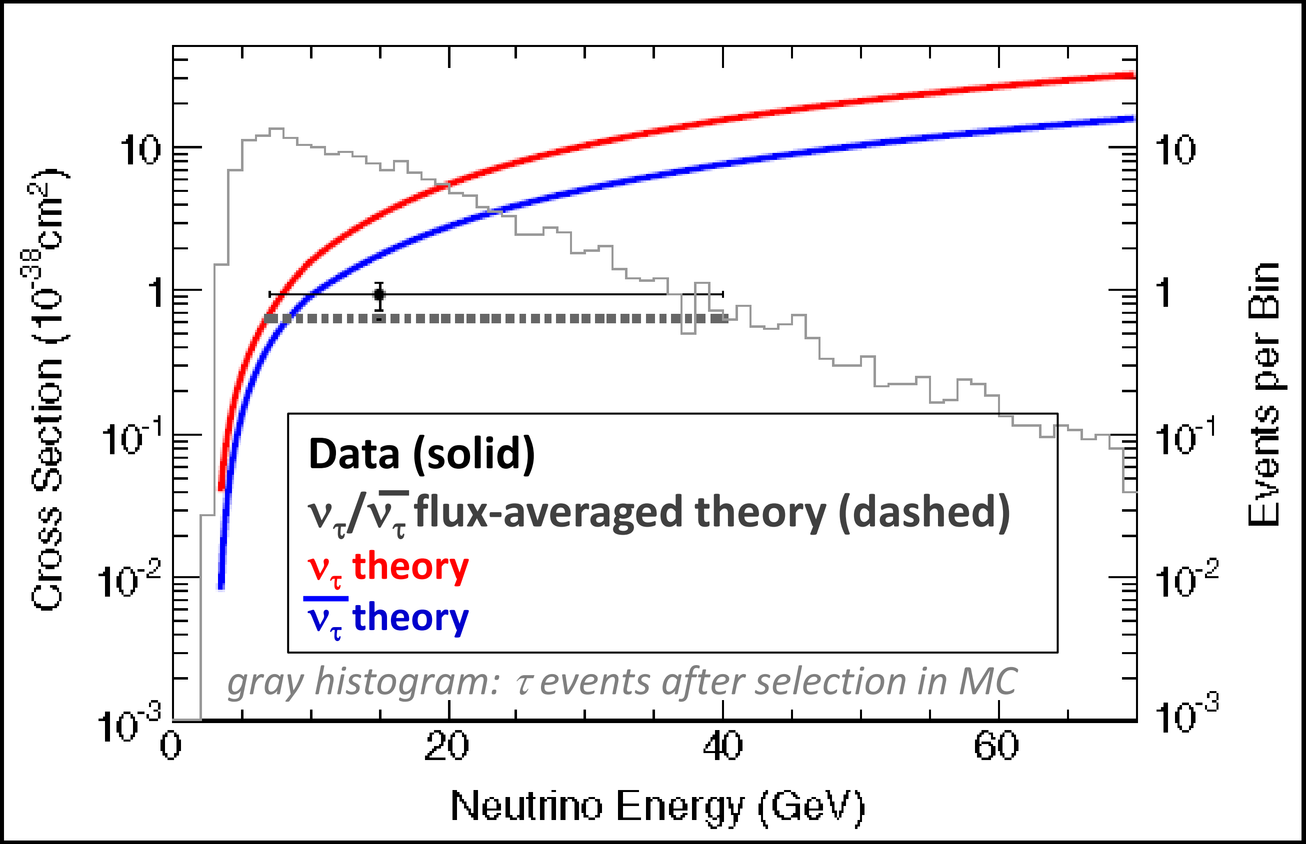


- *Constraining τ background would improve mass hierarchy measurement (on-going)*

Measured fluxed averaged CC ν_τ cross section

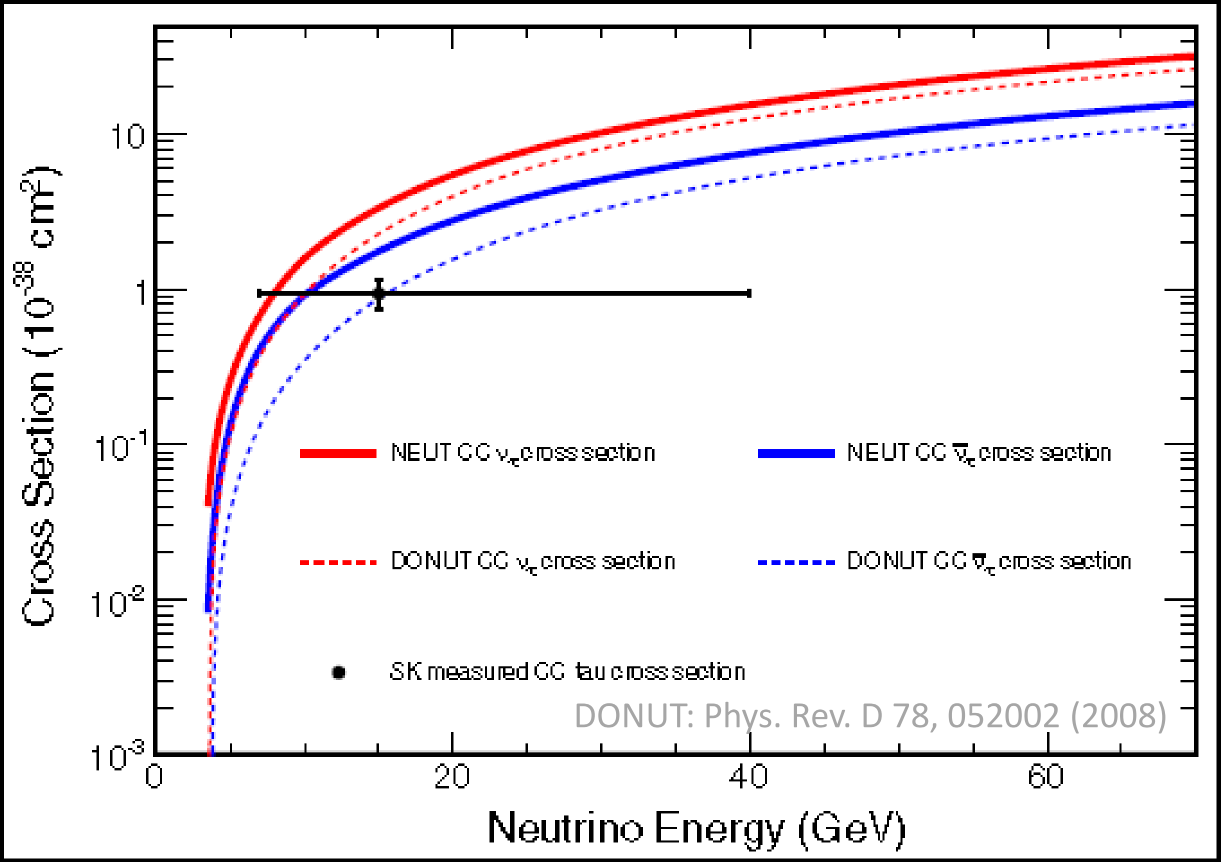
$\sigma_{measured} = (1.47 \pm 0.32) \times \langle\sigma_{theory}\rangle$

- $\langle\sigma_{theory}\rangle$ (NEUT) = $0.64 \times 10^{-38}cm^2$ at 3.5-70GeV



- $(0.94 \pm 0.20) \times 10^{-38}cm^2$ for ν energy at 3.5-70GeV
  - consistent with theory at 1.5σ

Comparison with DONUT



- Consistent with DONUT result
  - assuming DIS CC ν_τ cross section had a linear dependence on ν energy

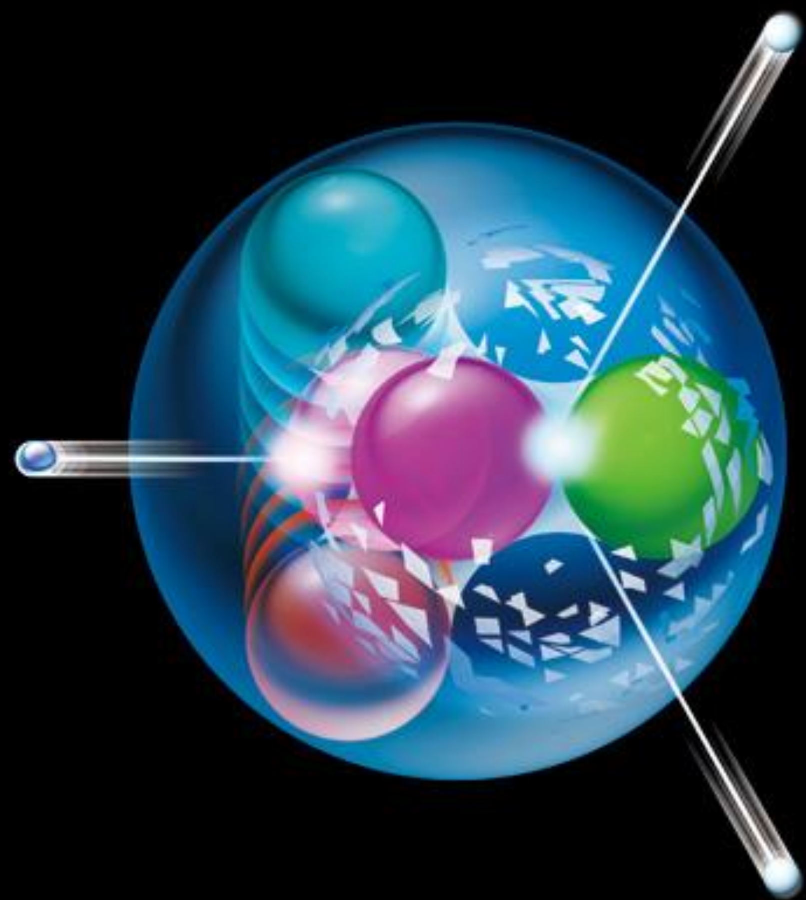
Summary (Atm.-ν)

PRD 97, 072001 (2018)
PRD 98, 052006 (2018)

- $\sin^2\theta_{23} = 0.588^{+0.031}_{-0.064}$, $\Delta m^2_{32} = 2.50^{+0.13}_{-0.20}$,
  $\delta_{CP} = 4.18^{+1.41}_{-1.61}$ (NH, SK θ_{13} const.)
- Inverted mass hierarchy disfavored between:
  - 81.9-96.7% (SK θ_{13} const.), 91.9-94.5% (SK θ_{13} const. + T2K)
- Tau neutrino appearance: significance of signal 4.6σ
  - CC ν_τ cross section: $(0.94\pm0.20)\times10^{-38}\text{cm}^2$ at 3.5-70GeV

- Prospect to improve sensitivities such as neutron tagging, $\nu_\mu/\bar{\nu}_\mu$ separation, updated constraints from T2K, etc.

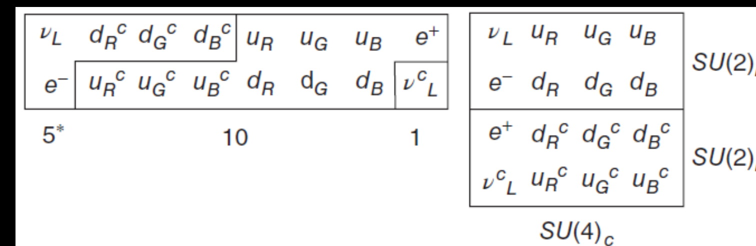
Nucleon Decays

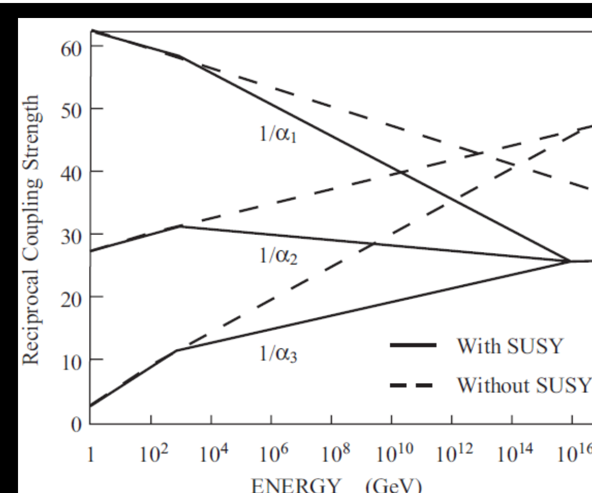


“What is Proton Decay?” https://www.youtube.com/watch?v=7NMs0Vnwd1Q

Grand Unified Theory (GUT)

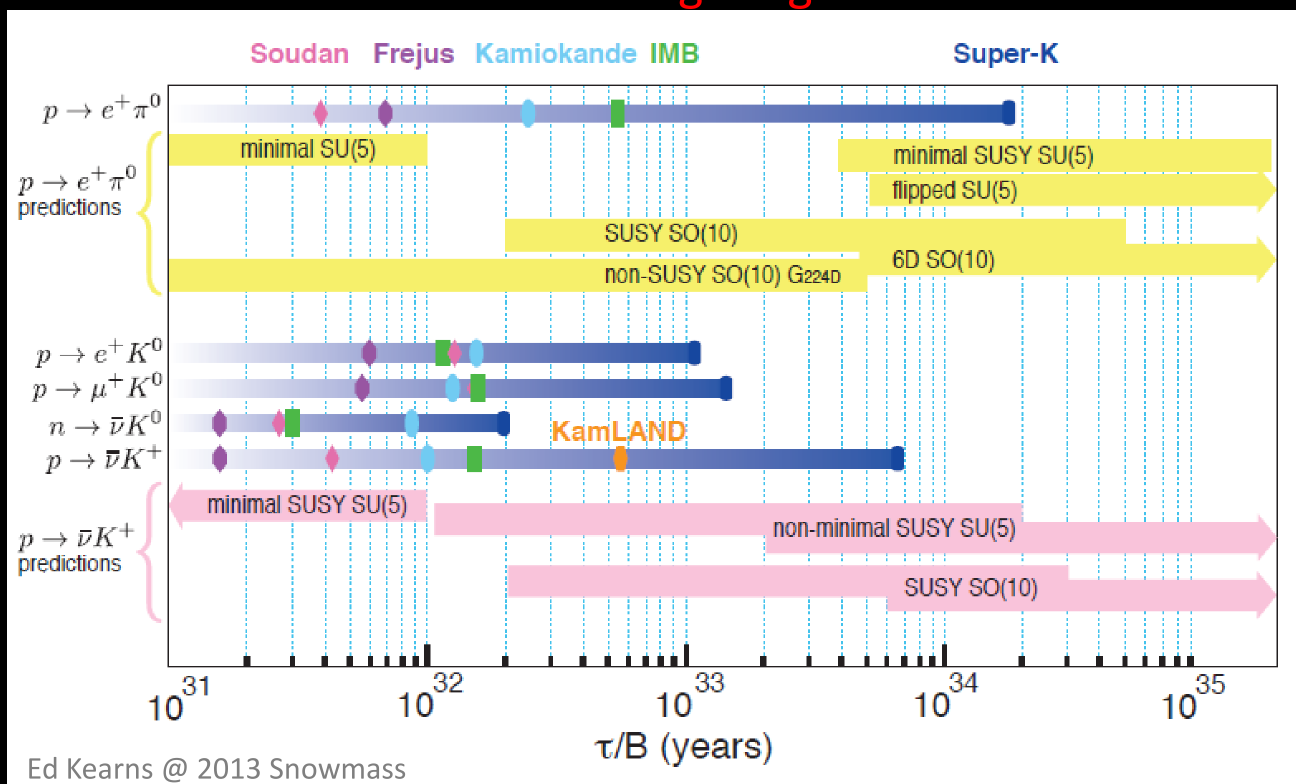
- Single symmetry group G ⊃ $SU(3)_{color} \times SU(2)_L \times U(1)_Y$
  - Single coupling constant, quantization of electric charge, etc.
- Numerous GUTs exist. Examples
  - SO(10) GUT
    - 15 fermions and ν_R in single rep.
  - Supersymmetry(SUSY) GUT
    - 3 coupling constants meet at ~10^{16}GeV





- GUTs predict instability of nucleon
  - Two benchmark decay modes
    - $p \rightarrow e^+\pi^0$(non-SUSY), $p \rightarrow \nu K^+$(SUSY)
  - Some models predict lifetime < 10^{34} years, can be probed by SK
  - Baryon asymmetry of the Universe

- Numerous GUTs…
  - Δ(B-L) = 0
  - Δ(B-L) = -2
  - dinucleon decay, etc.
- Lifetime prediction uncertainty: $10^{2\text{-}3}$
- Should experimentally test various GUTs
  - current searches in interesting ranges



Nucleon decay searches in SK

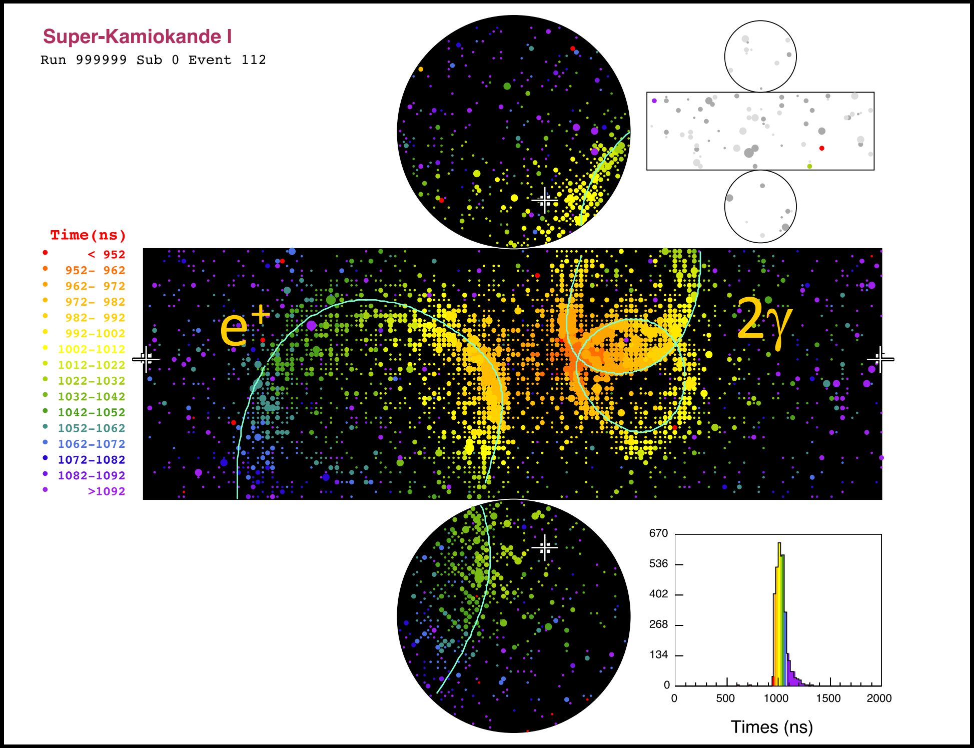
(unique way to directly probe GUTs)

- The world's best sensitivities on nucleon lifetime
  - large fiducial volume (V)
    - 22.5kt water: ~7.5/~6 $\times 10^{33}$ protons/neutrons (~0.8 $\times 10^{33}$ oxygen nuclei)
  - excellent detector performance (ε_{sig}, #BKG) NIM A 433 (1999)
  - long stable detector operation from 1996 to 2018 (T)
- Lifetime sensitivity $\propto \begin{cases} (\varepsilon_{sig} / 2.3) \cdot VT \text{ (BKG free)} \\ (\varepsilon_{sig} / \sqrt{\#BKG}) \cdot \sqrt{VT} \text{ (BKG dominant)} \end{cases}$
  - important to increase signal efficiency and BKG rejection
- This talk: the latest results on
  - $p \to e^+\pi^0$, $p \to \nu K^+$
  - other nucleon decay to charged antilepton + meson
  - dinucleon and nucleon decay to two-body final states with no Hadrons

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

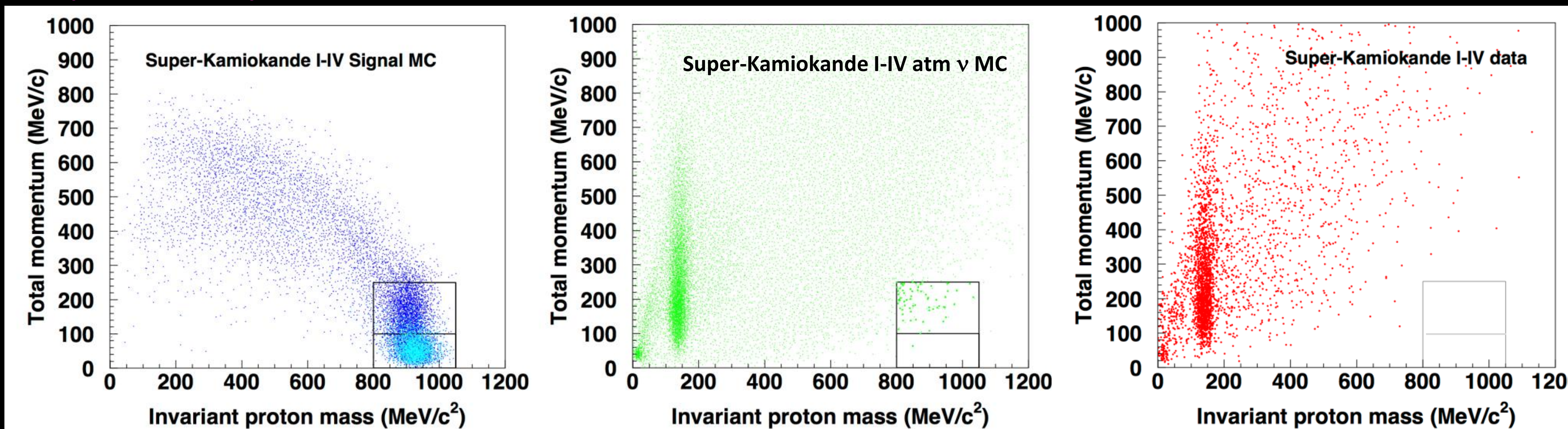
- Event selections
  - fully contained
  - fiducial volume
  - 2 or 3 rings
  - all e-like (PID)
  - no Michel electrons
  - $85 < M_{\pi 0} < 185 MeV/c^2$(3-ring)
  - $800 < M_{tot} < 1050 MeV/c^2$
  - $P_{tot} < 100 MeV/c$,
    $100 \leq P_{tot} < 250 MeV/c$
  - no neutrons (SK-IV only)

$p \rightarrow e^+\pi^0 (\pi^0 \rightarrow 2\gamma)$ MC



$p \to e^+\pi^0$ search result

SK preliminary



$p \to e^+\pi^0$	Eff. (%)	BKG	OBS
Low P_{tot}	18.7	0.05	0
High P_{tot}	19.9	0.58	0
Total	38.6	0.63	0

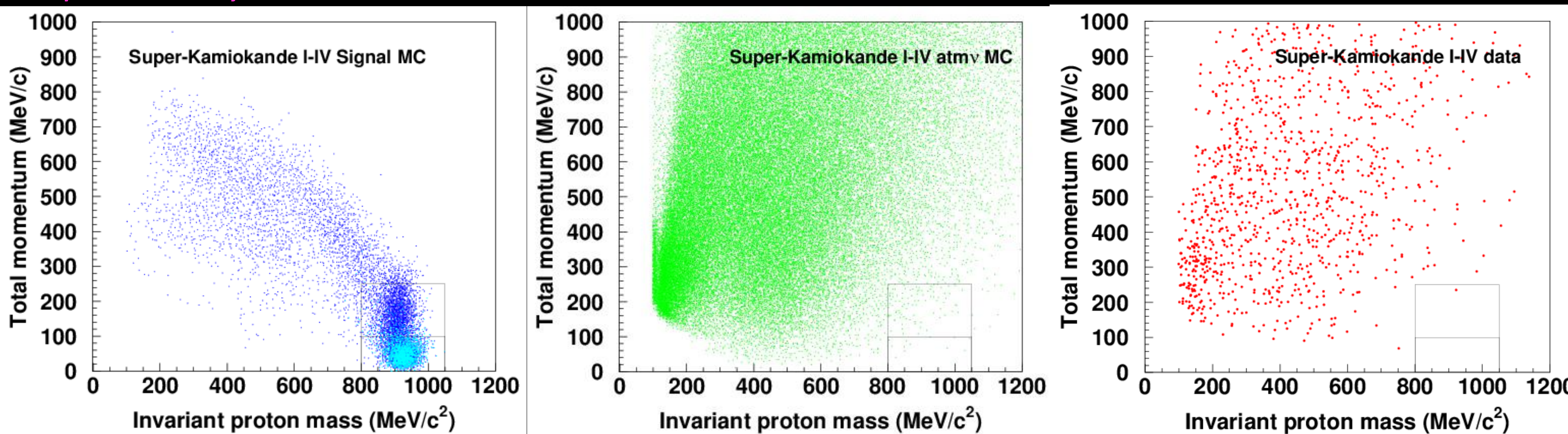
- Total expected #BKG (SK I-IV) < 1:
  - confirmed with K2K ν beam data; PRD 77, 032003 (2008)
- No data candidate (SK I-IV 0.37 Mt·yrs)
  - $\tau/B_{p \to e\pi} > 2.0 \times 10^{34}$ years (90% CL)

PRD 95, 012004 (2017) *(0.31 Mt·yrs)*

$p \to \mu^+\pi^0$ search result

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

SK preliminary



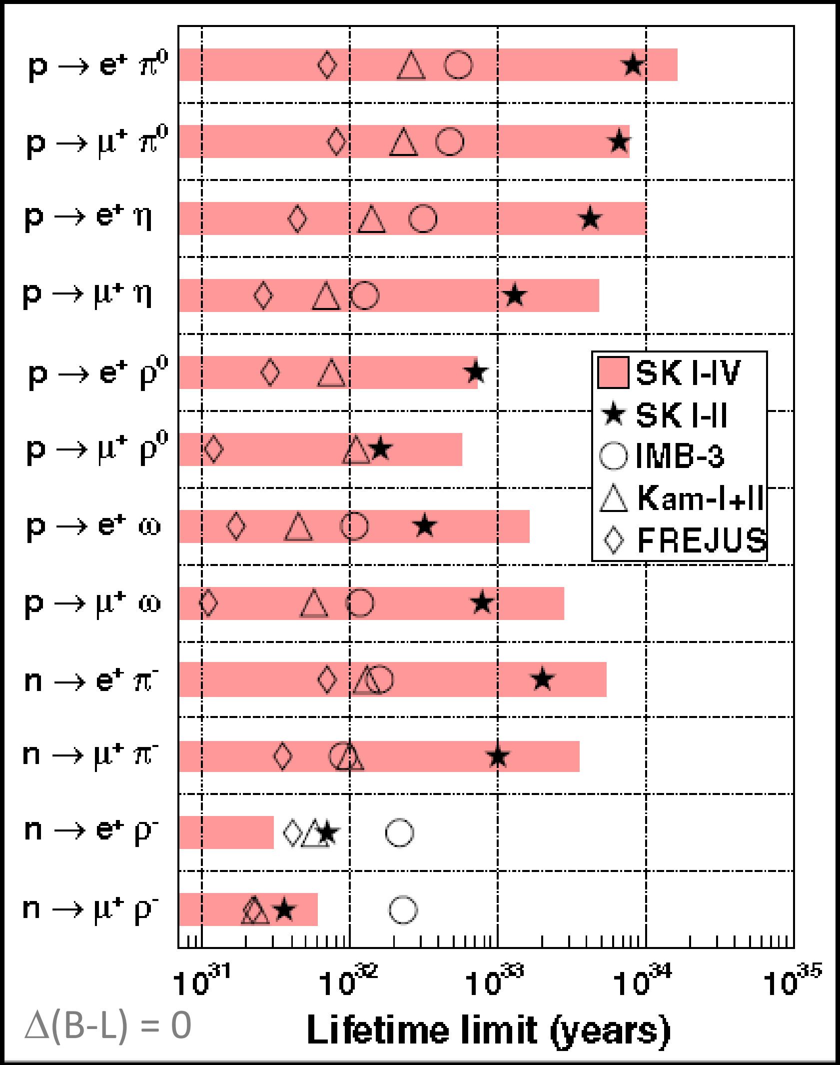
$p \to \mu^+\pi^0$	Eff.(%)	BKG	OBS
Low P_{tot}	18.0	0.07	0
High P_{tot}	16.7	0.65	1
Total	34.7	0.72	1

- No significant data excess (0.37Mt·yrs):
  - $\tau/B_{p\to\mu\pi} > 1.2 \times 10^{34}$ years (90% CL)

PRD 95, 012004 (2017) *(0.31 Mt·yrs)*

Summary of antilepton + meson searches

$\Delta(B\text{-}L) = 0$



PRD 96, 012003 (2017) *(~0.31Mt·yrs)*

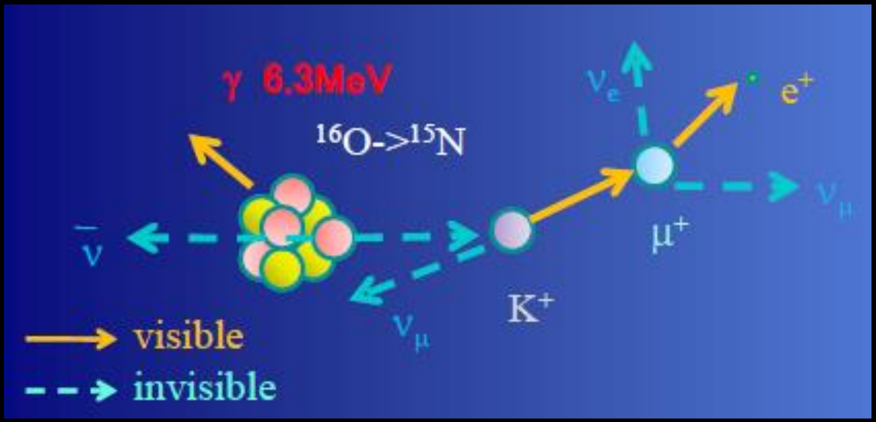
- Depending on GUT models, different decay modes can dominate
- Searching in multiple decay modes enhances chance to observe any nucleon decay
- Observing nucleon decay from nonstandard channel might hint at some exotic scenario

- No significant data excess
- Most SK results better than other exp. by 1-2 orders of magnitude
  - lower for $n \rightarrow (e^+,\mu^+)\rho^-$ mainly due to lower ε, syst. errors on ε, data cand. > #BKG

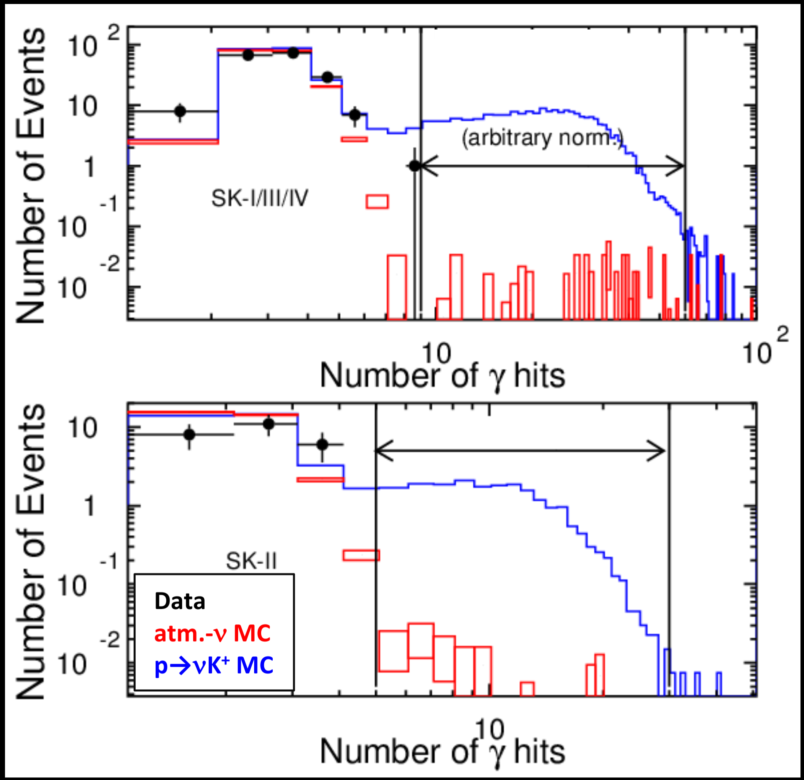
$p \rightarrow \nu K^+$ search

(prompt γ method)

- Event selections:
  - fully contained
  - fiducial volume
  - 1 μ-like (PID)
  - 1 Michel-e
  - $215 < P_\mu < 260$MeV/c
  - proton ring rejection
  - $8(4) < N_\gamma < 60(30)$ for SK-I,III,IV(SK-II)
  - $T_\gamma - T_\mu < 75$ns
  - no neutrons (SK-IV only)
- No data candidate

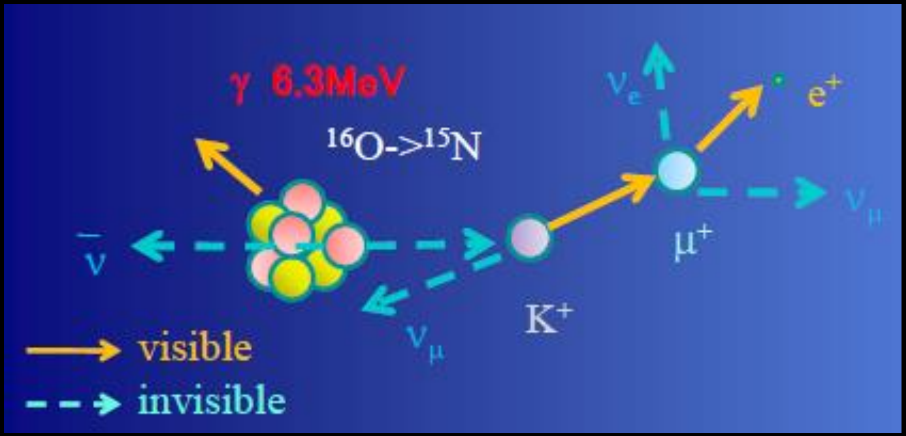


SK preliminary



$p \rightarrow \nu K^+$ search

(P_μ spec. method)

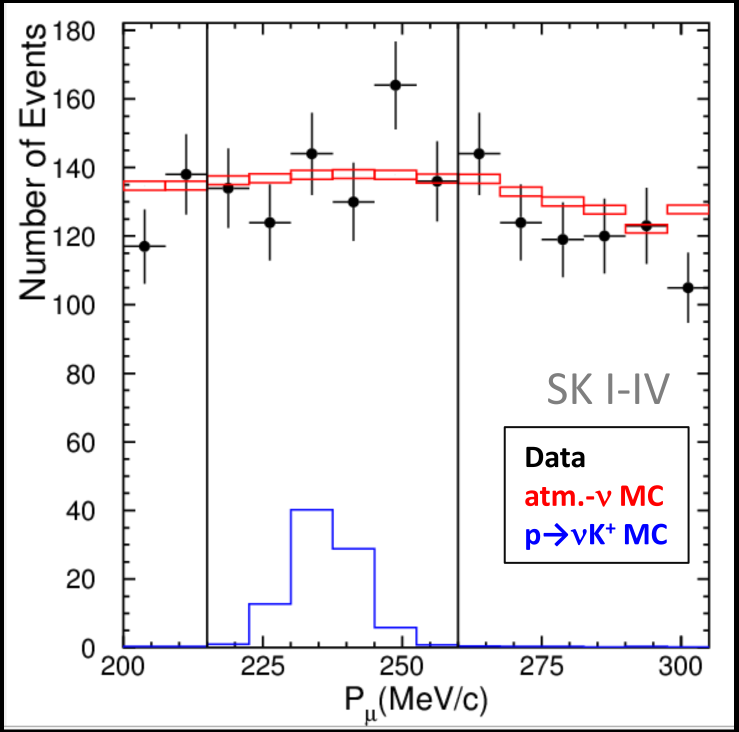


- Event selections:

  same as γ meth. except

  - no prompt γ hits
  - relaxed P_μ cut
- No data excess

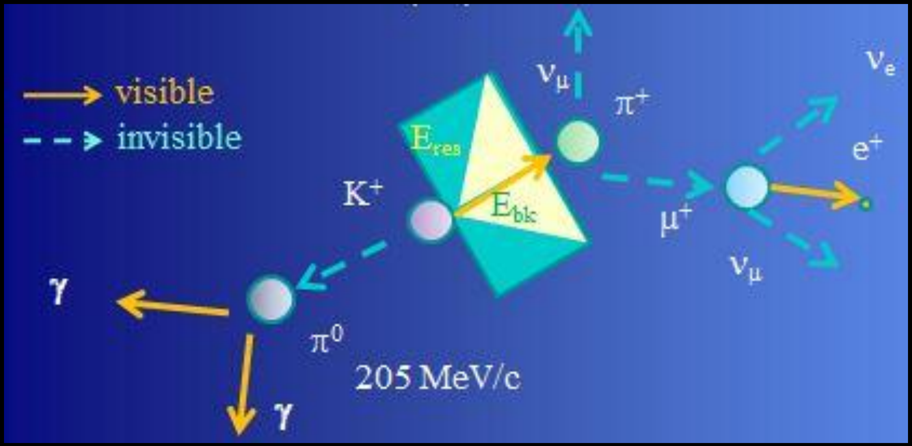
SK preliminary

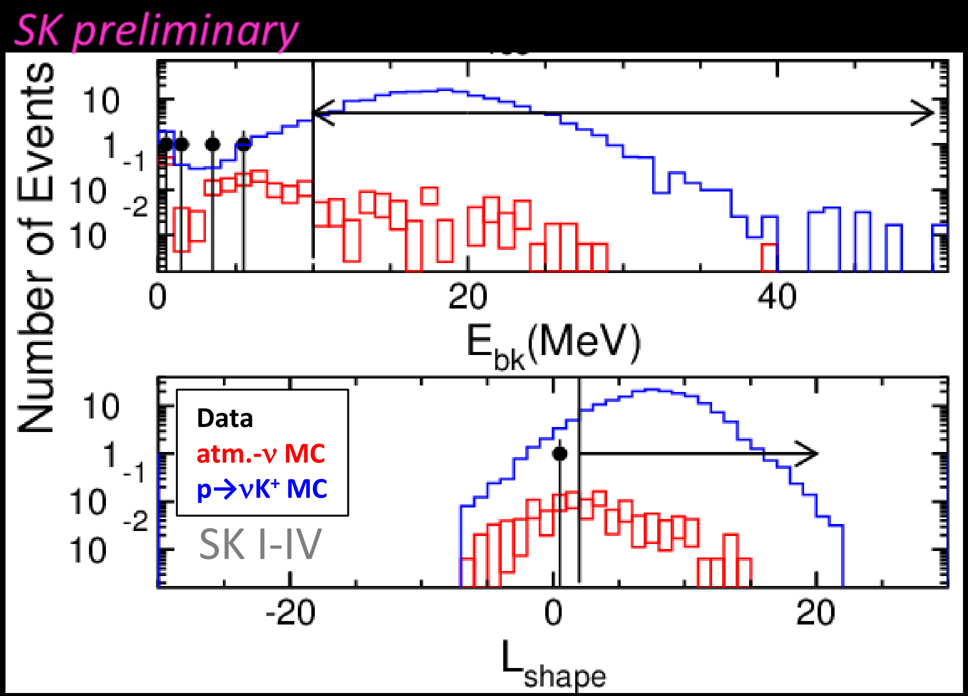


$p \rightarrow \nu K^+$ search

($\pi^+\pi^0$ method)

- Event selections:
  - fully contained
  - fiducial volume
  - 1 or 2 e-like rings (PID)
  - 1 Michel-e
  - $85 < M_{\pi 0} < 185 MeV/c^2$, $175 < P_{\pi 0} < 250 MeV/c$
  - charge profile likelihood for π^+
  - $10 < E_{bk} < 50 MeV$
  - no neutrons (SK-IV only)
- No data candidate





$p \to \nu K^+$ search result

SK preliminary

exposure (megaton·years): 0.09, 0.05, 0.03, 0.19

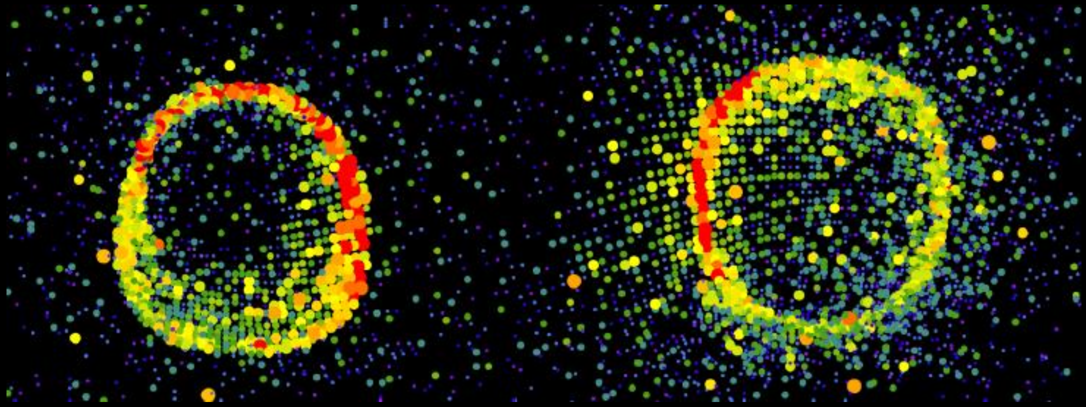
	SK1			SK2			SK3			SK4		
	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)
Pr.γ	7.9 ±0.1	0.078	0	6.5± 0.1	0.082	0	7.5 ±0.1	0.018	0	9.4 ±0.1	0.12	0
$\pi^+\pi^0$	7.8 ±0.1	0.21	0	6.5± 0.1	0.19	0	8.3± 0.1	0.07	0	9.6 ±0.1	0.14	0

- No data candidate (SK I-IV 0.37 Mt·yrs)
  - $\tau/B_{p\to\nu K+} > 8.2 \times 10^{33}$ years (90% CL)

Dinucleon and nucleon decay to two-body final states with no Hadrons

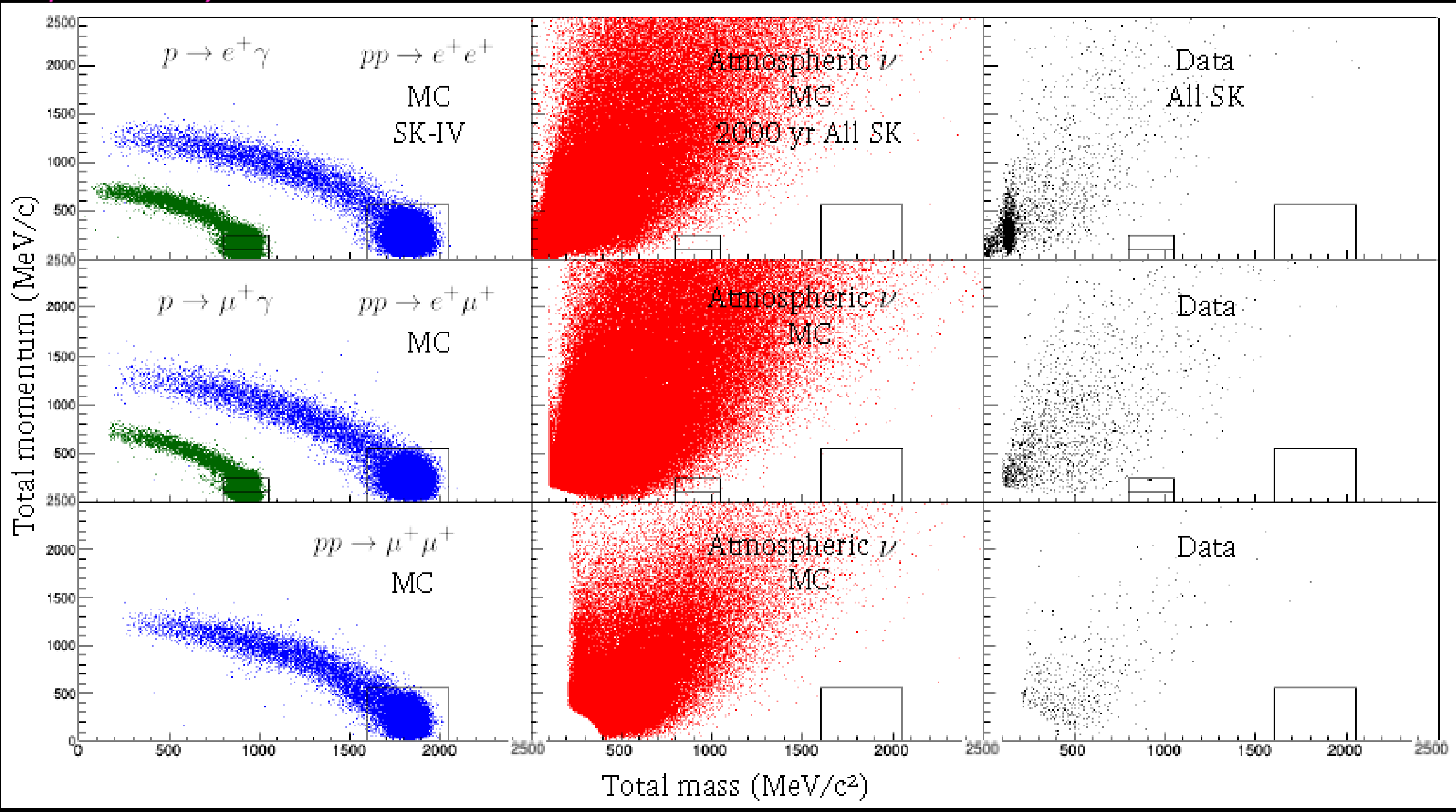
(paper in preparation)

- Dinucleon decay search:
  - "NN→ee": $pp \rightarrow e^+e^+$, $nn \rightarrow e^+e^-$, $nn \rightarrow \gamma\gamma$
  - "NN→eμ": $pp \rightarrow e^+\mu^-$, $nn \rightarrow e^+\mu^-$, $nn \rightarrow e^-\mu^+$
  - "NN→μμ": $pp \rightarrow \mu^+\mu^+$, $nn \rightarrow \mu^+\mu^-$
    - 5/8 modes: $\Delta(B-L) = -2$
- Proton decay search: $p \rightarrow e^+\gamma$, $p \rightarrow \mu^+\gamma$



$pp \rightarrow e^+\mu^+$ (MC)

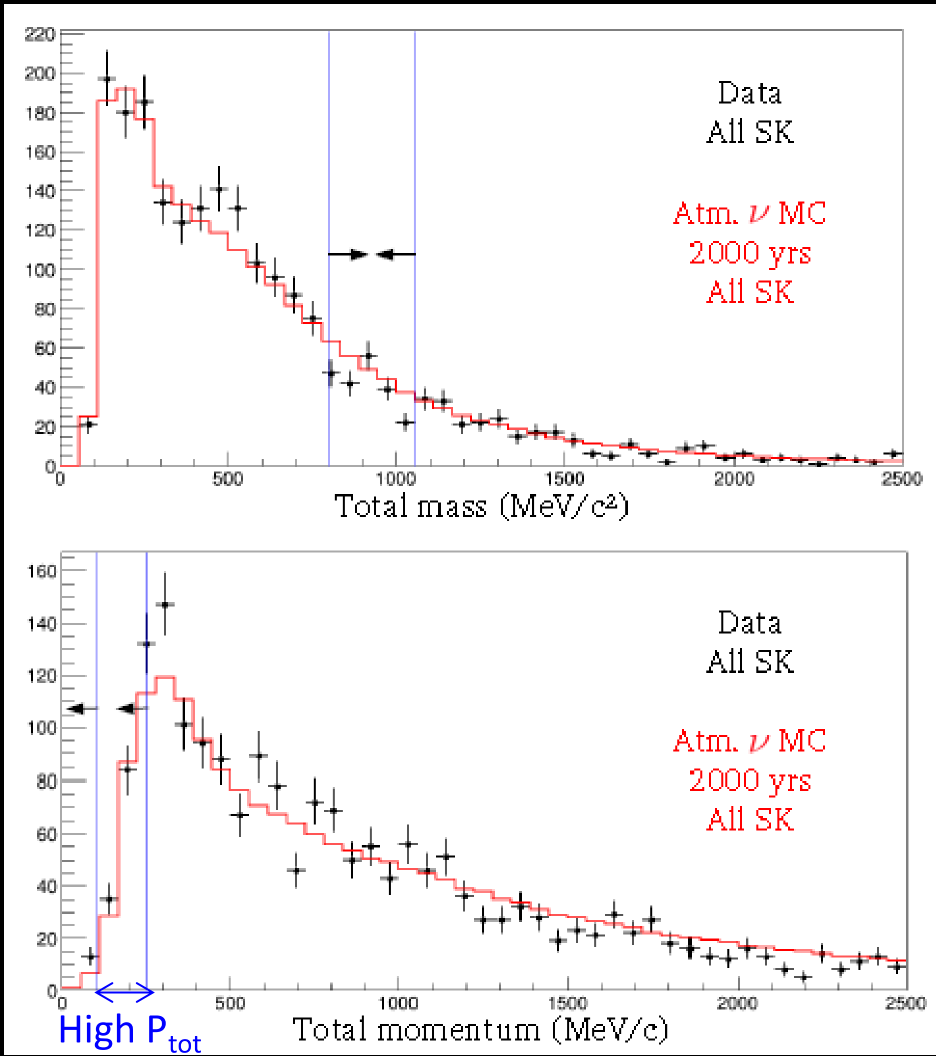
SK preliminary



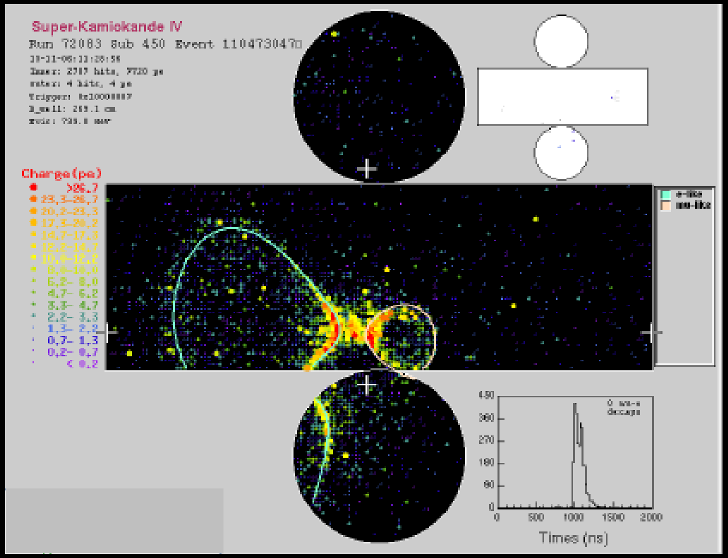
- No data candidates for 8 dinucleon decay modes and $p \to e^+\gamma$
- 2 candidates (High P_{tot}) for $p \to \mu^+\gamma$

p→$\mu^+\gamma$ search

SK preliminary



- 2 candidates in High P_{tot}
  - one candidate also found in p→$\mu\pi^0$
  - the other candidate with 0 Michel-e:
    (may be ν_en→e⁻p, p: identified as μ)



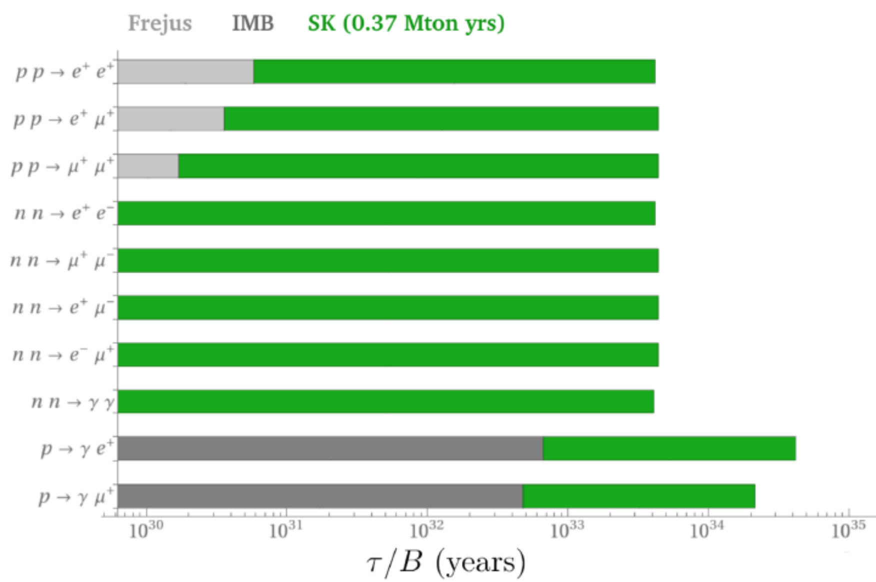
- # expected BKG: 0.23±0.14±0.07
  - Poisson Prob.(≥2, 0.23): 2.3%

Dinucleon decay and p→l⁺γ search result

SK preliminary

Decay mode		Efficiency (%) SK-I	SK-II	SK-III	SK-IV	Background (Events/livetime) SK-I	SK-II	SK-III	SK-IV
$p \to e^+\gamma$	High P_{tot}	51.0 ± 0.2	49.5 ± 0.2	50.8 ± 0.2	50.6 ± 0.2	0.01 ± 0.01	0.02 ± 0.02	< 0.01	0.07 ± 0.07
	Low P_{tot}	27.6 ± 0.1	26.1 ± 0.1	27.6 ± 0.1	27.5 ± 0.1	0.02 ± 0.02	0.01 ± 0.01	0.01 ± 0.01	0.04 ± 0.04
$p \to \mu^+\gamma$	High P_{tot}	50.2 ± 0.2	49.7 ± 0.2	51.0 ± 0.2	48.1 ± 0.2	0.22 ± 0.14	0.14 ± 0.11	0.07 ± 0.07	0.23 ± 0.14
	Low P_{tot}	29.1 ± 0.1	28.3 ± 0.1	29.0 ± 0.1	29.4 ± 0.1	0.02 ± 0.02	0.01 ± 0.01	< 0.01	0.02 ± 0.02
$NN \to ee$		80.9 ± 0.1	77.2 ± 0.1	79.5 ± 0.1	78.6 ± 0.1	0.01 ± 0.01	< 0.01	< 0.01	0.01 ± 0.01
$NN \to e\mu$		84.1 ± 0.1	83.7 ± 0.1	83.4 ± 0.1	81.7 ± 0.1	0.01 ± 0.01	< 0.01	< 0.01	0.01 ± 0.01
$NN \to \mu\mu$		86.3 ± 0.1	85.9 ± 0.1	86.0 ± 0.1	82.8 ± 0.1	0.01 ± 0.01	< 0.01	< 0.01	0.01 ± 0.01

Decay mode	Lifetime limit per oxygen nucleus ($\times 10^{33}$ years)	per nucleon ($\times 10^{34}$ years)
$pp \to e^+e^+$	4.2	—
$nn \to e^+e^-$	4.2	—
$nn \to \gamma\gamma$	4.1	—
$pp \to e^+\mu^+$	4.4	—
$nn \to e^+\mu^-$	4.4	—
$nn \to e^-\mu^+$	4.4	—
$pp \to \mu^+\mu^+$	4.4	—
$nn \to \mu^+\mu^-$	4.4	—
$p \to e^+\gamma$	—	4.1
$p \to \mu^+\gamma$	—	2.1



- No significant data excess (0.37Mt·yrs)
- Improved current world limits by more than 1 order of magnitude *(paper in preparation)*

Summary (Nucleon Decays)

- **Testing baryon number violation is an essential and high priority objective of particle physics**
- **Nucleon decay searches in Super-Kamiokande**
  - **No evidence so far: Most stringent lifetime limits in the world**
  - **Keep discovery potential and increasing statistics**
  - **Prospect of sensitivity improvements by expanding FV, sophisticated reconstruction algorithm, etc.**
  - **Searching new modes**

PRD 95, 012004 (2017)
PRD 96, 012003 (2017)
more in supplement

Tomorrow morning:
- SK refurbishment work and SK-Gd (solar & supernova) by Michael Smy
- Hyper-Kamiokande (HK) by Adrian

Supplement

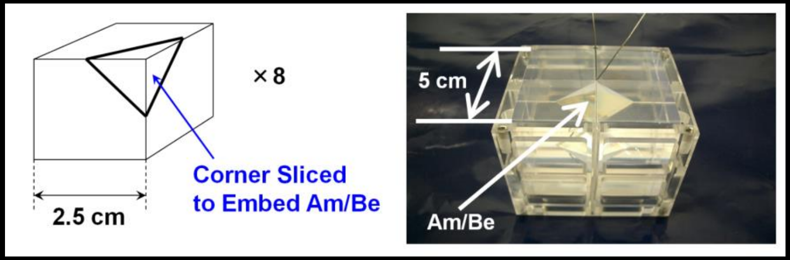
Neutron tag in SK-IV

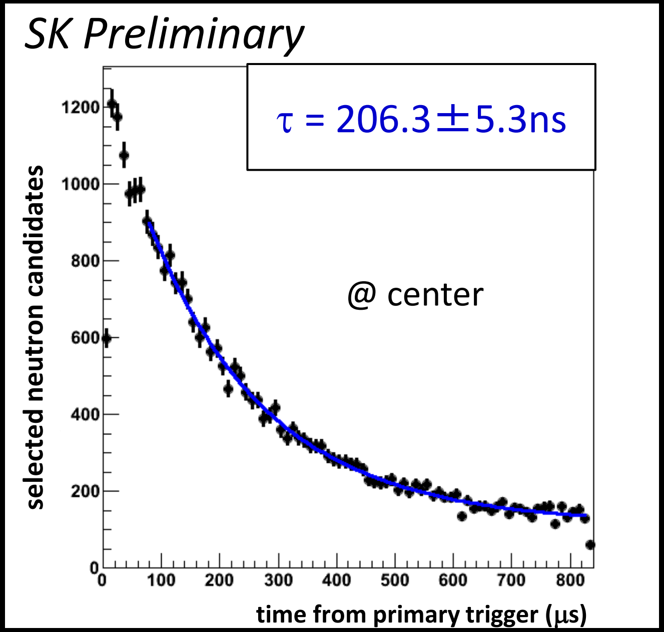
(Paper in preparation)

$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^{*} + n$$
$$ {}^{12}\mathrm{C}^{*} \rightarrow {}^{12}\mathrm{C} + \gamma \ (4.43\ \mathrm{MeV})$$
or
$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n$$

- Atm.-ν interactions frequently accompanied by n production
- $n + p \rightarrow d + \gamma(2.2\mathrm{MeV})$
- γ hit search enabled by QBEE
  - signal ε: 20.5% *(~80% with Gd)*
- Already implemented in nucleon decay searches

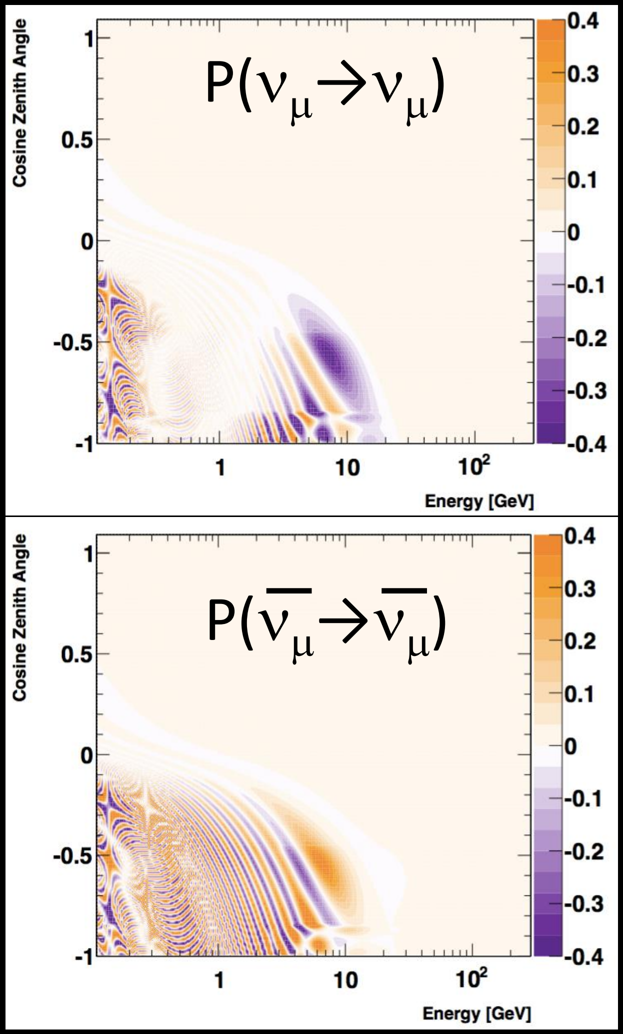
  ex.) ~50% BKG rejection for $p \rightarrow e\pi^0$ search
- Studies on-going to improve sensitivities on ν oscillation analyses with n-tag



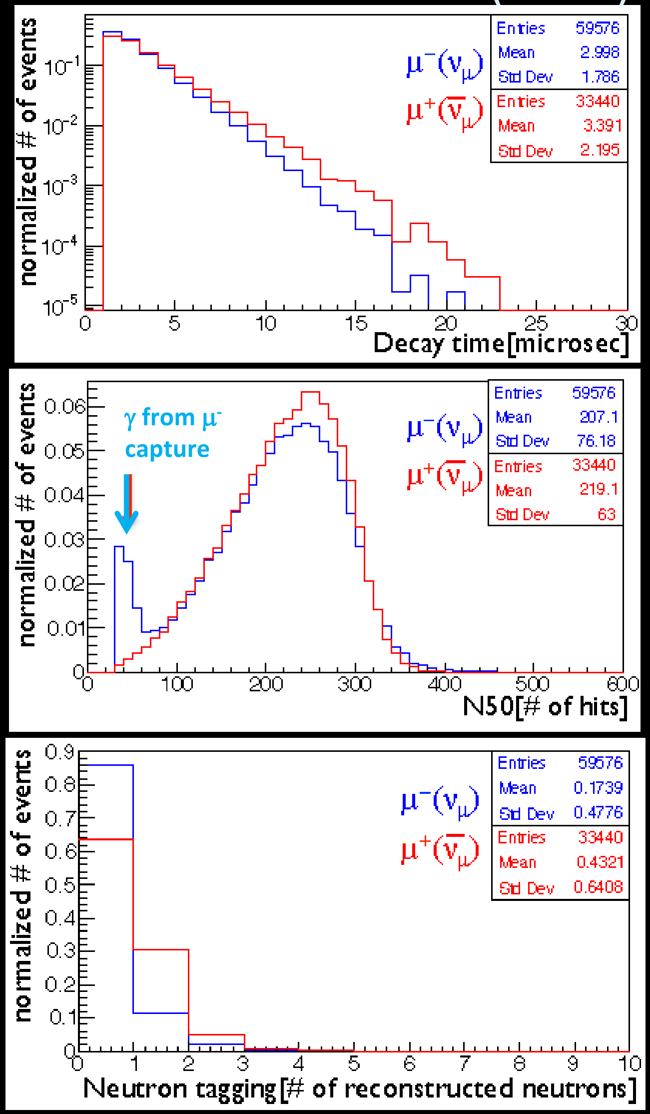


$\nu_\mu/\overline{\nu}_\mu$ separation
(on-going study)

NH - IH



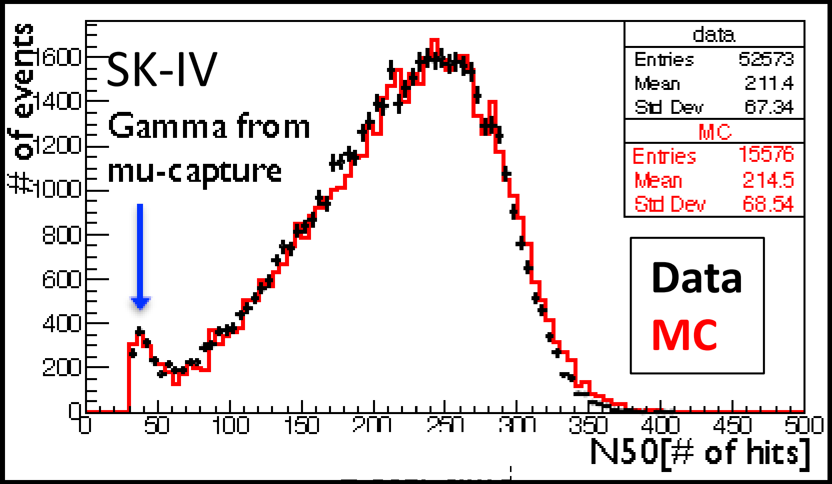
Atm.-ν MC (SK-IV)



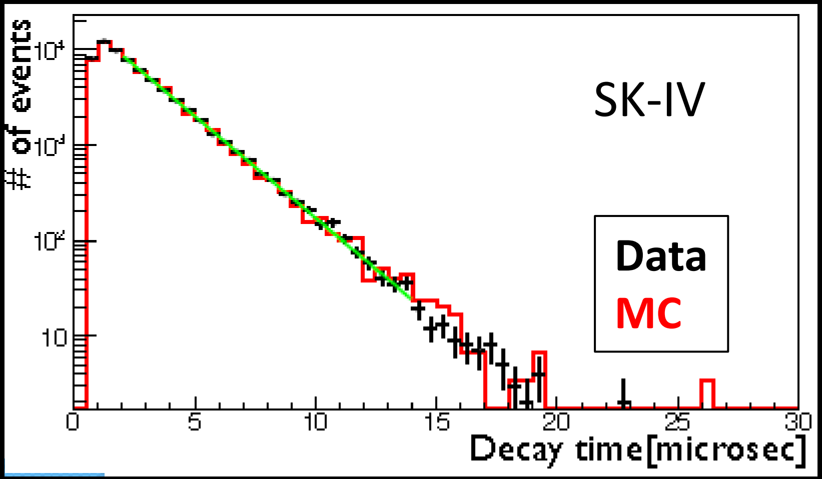
(N50: #hits in 50ns sliding window)

Michel electrons from cosmic ray muons

SK Preliminary



(N50: #hits in 50ns sliding window)



$\tau = \begin{cases} 2.057 \pm 0.009\mu s \text{ (Data)} \\ 2.042 \pm 0.009\mu s \text{ (MC)} \end{cases}$

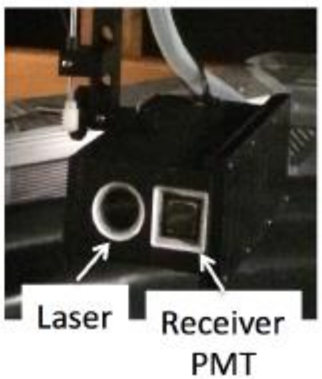
(μ^+/μ^- = 1.37 @ Kamioka)

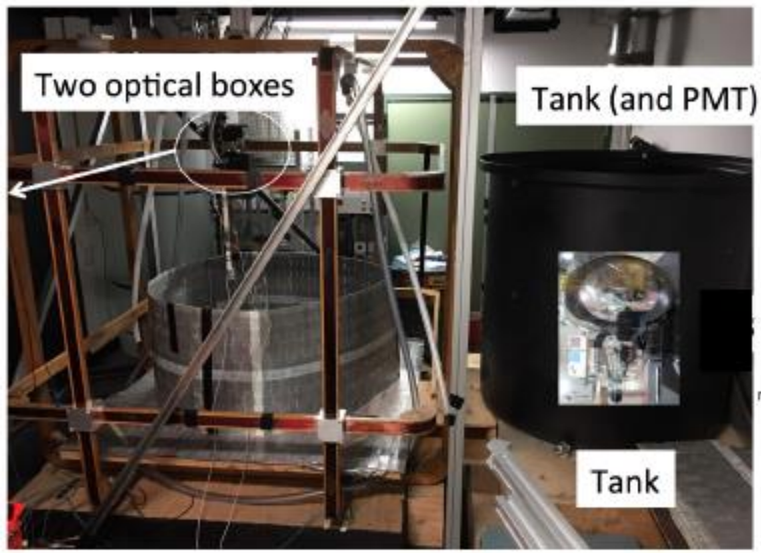
A.Konaka (TRIUMF)@ HK meeting (Mar. 2018)

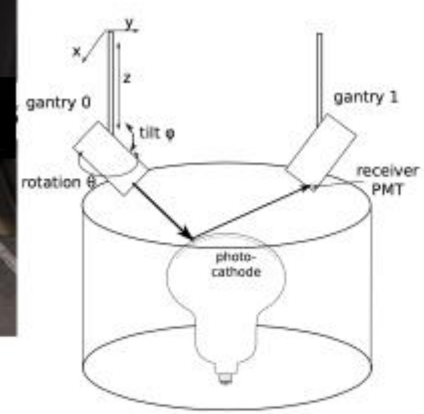
TRIUMF

PTF setup

- Robotic arms with laser and PMT
  - laser light with polarization
  - monitor PMT
  - magnetometer
- Magnetic shielding
  - compensation coil, Giron shield







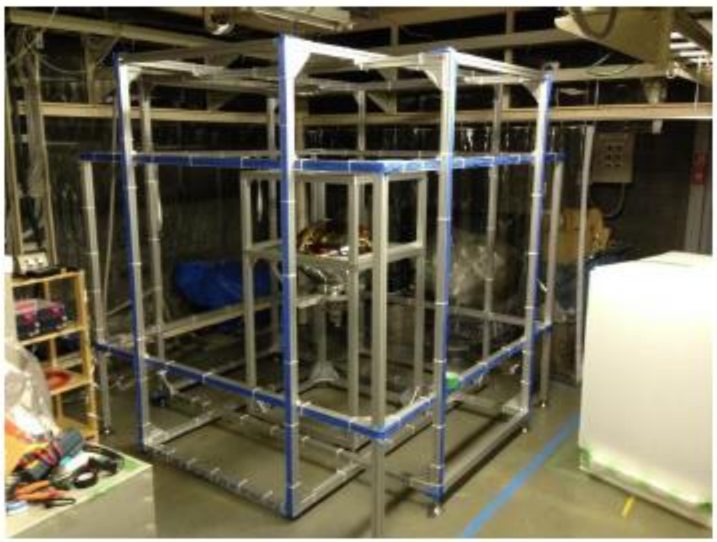
- ID: 20% increase if we can expand FV to dwall>1m

C.Bronner (ICRR) @ HK meeting (Sep. 2018)

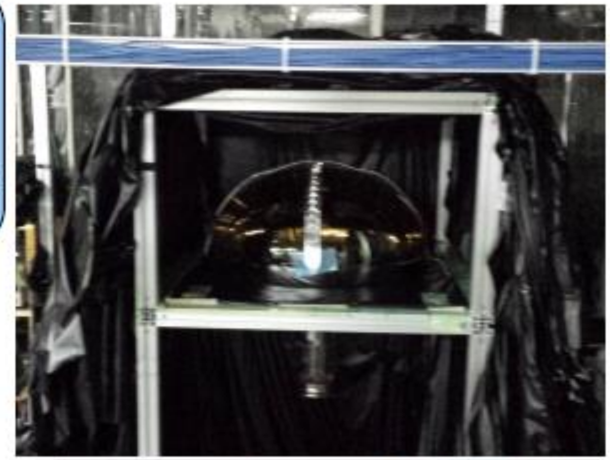
Introduction

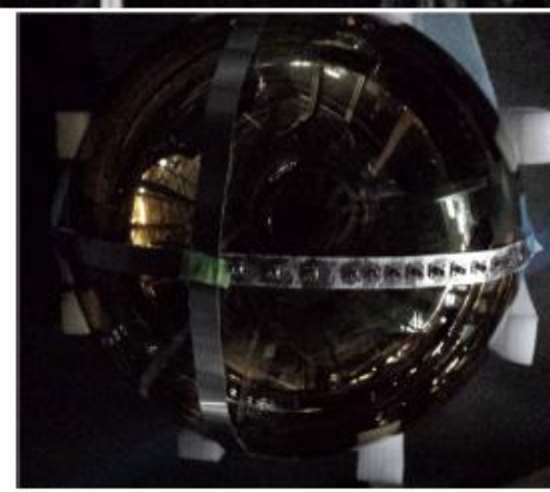
@Kamioka

- Setup developed by C-H Zhao, Takenaka-san and Rika
- Allows to measure PMT response for different values of the magnetic field and light arriving at different positions on the PMT



Used it to study 20” candidate PMTs



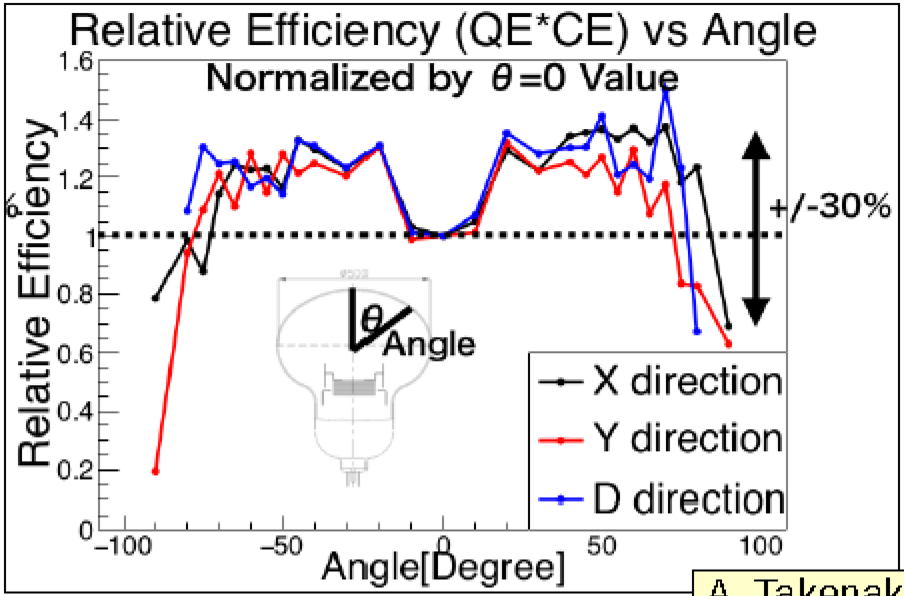


C.Bronner (ICRR) @ HK meeting (Sep. 2018)

Motivations
PMT non-uniformity

@Kamioka

Performance of SK PMTs was found to vary with arrival position of photon



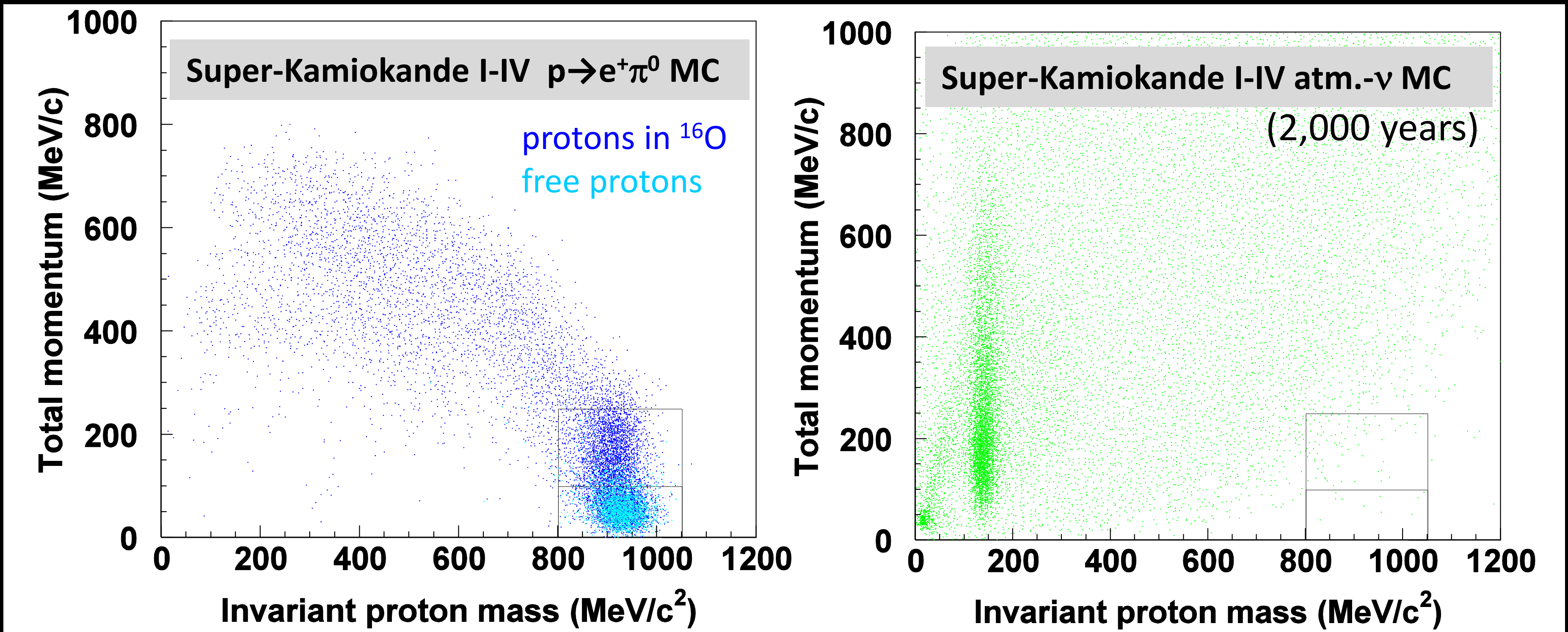
A. Takenaka

- This could have an impact for events close to wall
- Also in case of asymmetry, will increase importance of PMT orientation

P_{tot} separation into 2 regions

P_{tot}<100MeV/c, 100≤P_{tot}<250MeV/c

(after p→eπ^0 selections without (M_{tot}, P_{tot}) cut)



- Total(SK I-IV) expected #BKG(P_{tot}<100, 100≤P_{tot}<250): (~0.05, ~0.5)
- P_{tot}<100MeV/c: smaller syst. error on ε and almost BKG free
  → 3σ discovery reach in lifetime: ~13%(~21%) higher at ~0.3(1)Mt·yr

PRD 95, 012004 (2017)

$p \rightarrow (e^+, \mu^+)\pi^0$ searches

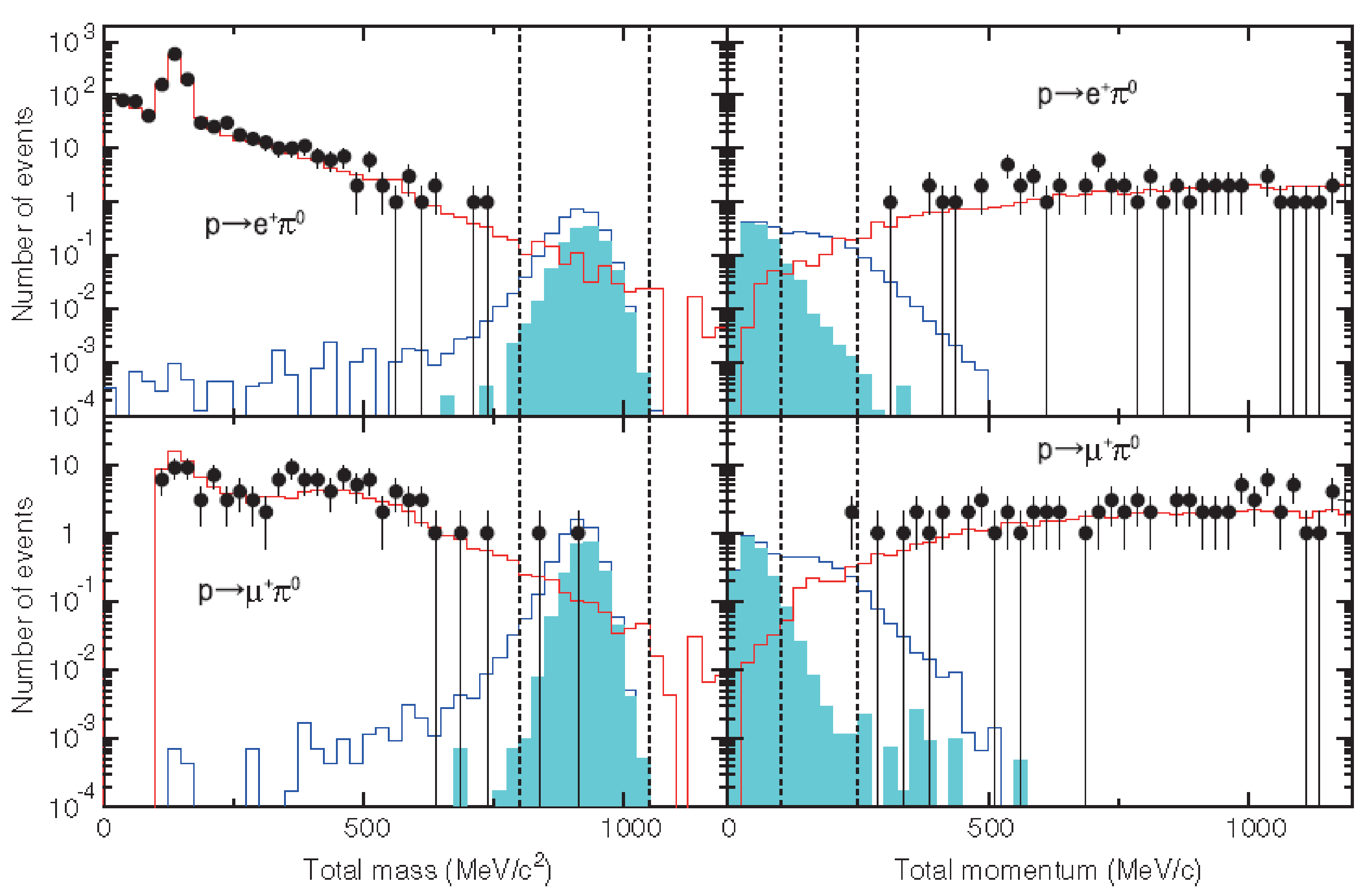


FIG. 4. Distributions of reconstructed invariant mass (left) and total momentum (right) for $p \rightarrow e^+\pi^0$ in the top panels and for $p \rightarrow \mu^+\pi^0$ in the bottom panels, after all selection cuts except cuts on the plotted variable. The dark blue histograms correspond to 90% confidence level allowed signal and the histograms filled by light blue show the portion contributed by free proton decay. The red histograms show atmospheric ν MC, and the dots are data with 0.306 Mton · years exposure. Vertical dashed lines indicate the signal regions. The peak around 150 MeV/c^2 in the total mass distribution of atmospheric ν and data in the left top panel arises from π^0 decays.

PRD 95, 012004 (2017)

$p \rightarrow (e^+, \mu^+)\pi^0$ searches

		SK-I	SK-II	SK-III	SK-IV
Exp.	kt · yrs	91.7	49.2	31.9	133.5
$p \to e^+\pi^0$					
Low P_{tot}	Eff.(%)	18.8 ± 1.9	18.3 ± 1.9	19.6 ± 2.0	18.7 ± 1.9
	BKG	$0.03^{+0.03}_{0.02}$	<0.01	<0.01	$0.02^{+0.03}_{0.02}$
	(/Mt · yr)	$0.36^{+0.30}_{0.20}$	$0.26^{+0.27}_{0.17}$	$0.09^{+0.21}_{0.08}$	$0.18^{+0.25}_{0.13}$
	OBS	0	0	0	0
High P_{tot}	Eff.(%)	20.4 ± 3.6	20.2 ± 3.6	20.5 ± 3.6	19.4 ± 3.4
	BKG	0.22 ± 0.08	0.12 ± 0.04	0.06 ± 0.02	0.15 ± 0.06
	(/Mt · yr)	2.4 ± 0.8	2.5 ± 0.9	1.8 ± 0.7	1.1 ± 0.3
	OBS	0	0	0	0
$p \to \mu^+\pi^0$					
Low P_{tot}	Eff.(%)	16.4 ± 1.5	16.0 ± 1.5	16.4 ± 1.5	20.1 ± 1.9
	BKG	$0.03^{+0.02}_{0.02}$	<0.01	<0.01	$0.01^{+0.02}_{0.01}$
	(/Mt · yr)	$0.31^{+0.26}_{0.17}$	$0.10^{+0.13}_{0.07}$	$0.22^{+0.22}_{0.14}$	$0.09^{+0.21}_{0.08}$
	OBS	0	0	0	0
High P_{tot}	Eff.(%)	15.3 ± 2.8	15.3 ± 2.8	16.5 ± 3.0	18.2 ± 3.3
	BKG	0.33 ± 0.10	0.14 ± 0.05	0.12 ± 0.04	0.23 ± 0.08
	(/Mt · yr)	3.6 ± 1.1	2.9 ± 0.9	3.7 ± 1.2	1.7 ± 0.6
	OBS	0	0	0	2

PRD 95, 012004 (2017)

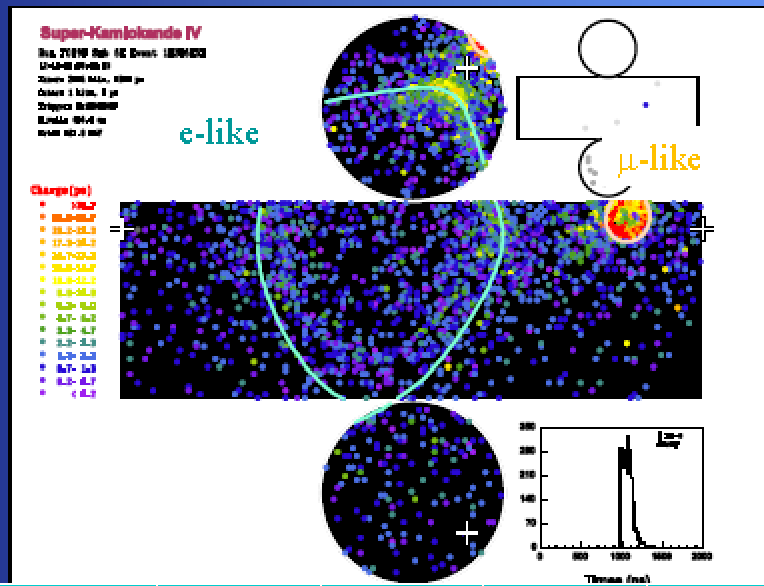
$p \rightarrow (e^+, \mu^+)\pi^0$ searches

		$p \to e^+\pi^0$		$p \to \mu^+\pi^0$	
		low P_{tot}	high P_{tot}	low P_{tot}	high P_{tot}
Efficiency					
	π-FSI	2.8	10.6	2.9	12.1
	Correlated decay	1.9	9.1	1.7	9.0
	Fermi momentum	8.5	9.3	8.0	9.6
	Reconstruction	4.6	5.6	3.7	3.3
	Total	10.2	17.7	9.4	18.2
Background					
	Flux	7.0	6.9	7.0	7.0
	Cross section	14.5	10.4	8.4	7.8
	π-FSI	15.4	15.4	14.2	14.4
	Reconstruction	21.7	21.7	21.7	21.7
	(neutron tag)	10	10	10	10
	Total (I/II/III)	31.2	29.4	28.1	28.1
	(IV)	32.7	31.1	29.9	29.8
Exposure		1.0	1.0	1.0	1.0

$p \to \mu^+\pi^0$ data candidate

M.Miura (ICRR) at TMEX2018

Observed events (2-ring events)



TotMass (MeV/c^2)	TotMom. (MeV/c)	Pe (MeV/c)	Pμ (MeV/c)	Ang. (deg.)
903	248	375	551	158

Note1: Cut: Ptot <250MeV/c, they were really close to boundary.
Note2: The 2nd event in the paper went out from signal box with updated gain correction.

28

PRD 95, 012004 (2017)

(OLD) $p \rightarrow \mu^+\pi^0$ 2nd data candidate

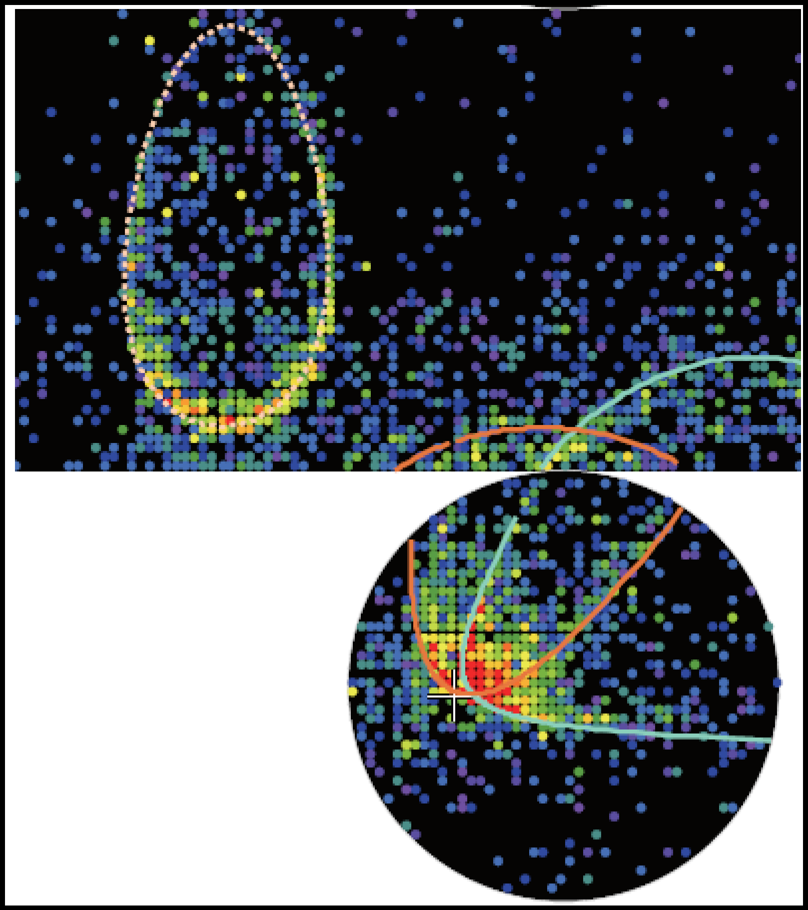


FIG. 5. Event display of the second candidate event, zoomed to the region of the rings. The blue solid line and the tan dashed line show the reconstructed e-like and μ-like rings, respectively. The dark orange solid line shows an additional e-like ring that was identified in the initial ring counting process, but it is rejected by the ring correction because it is too close in angle to the other e-like ring (blue line). As a result, this event is judged as a two-ring event.

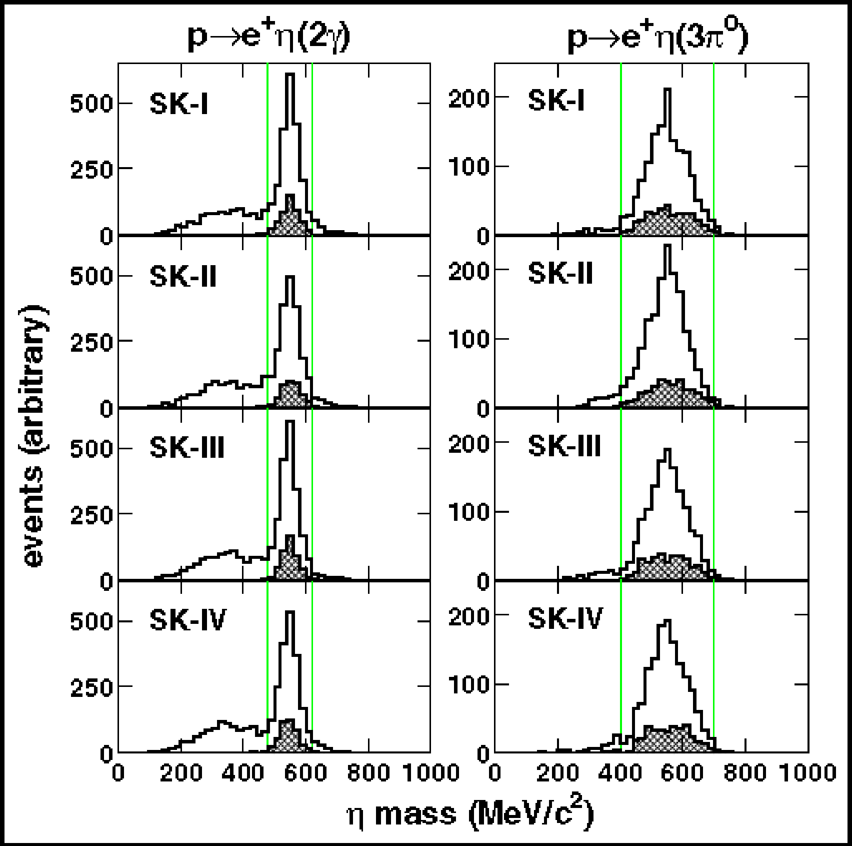
[1]This event is judged as a 3-ring event, but leaves the signal box if we use updated PMT gain correction, introduced in 2016, which depends on PMT production year.

Other charged antilepton + meson searches

- $p \to (e^+, \mu^+) + (\eta^0, \rho^0, \omega^0)$, $n \to (e^+, \mu^+) + (\pi^-, \rho^-)$
- SK I-IV data (316kton·year)
- Several analysis improvements from previous results using SK-I,II data (PRD 85, 112001(2012))
  - 2.26 times data
  - P_{tot} separation in $p \to (e^+, \mu^+)\eta^0$, $\eta^0 \to 2\gamma$
  - n-tag in SK-IV
  - systematic error estimations
  - etc.

$p \to e^+\eta^0$ search

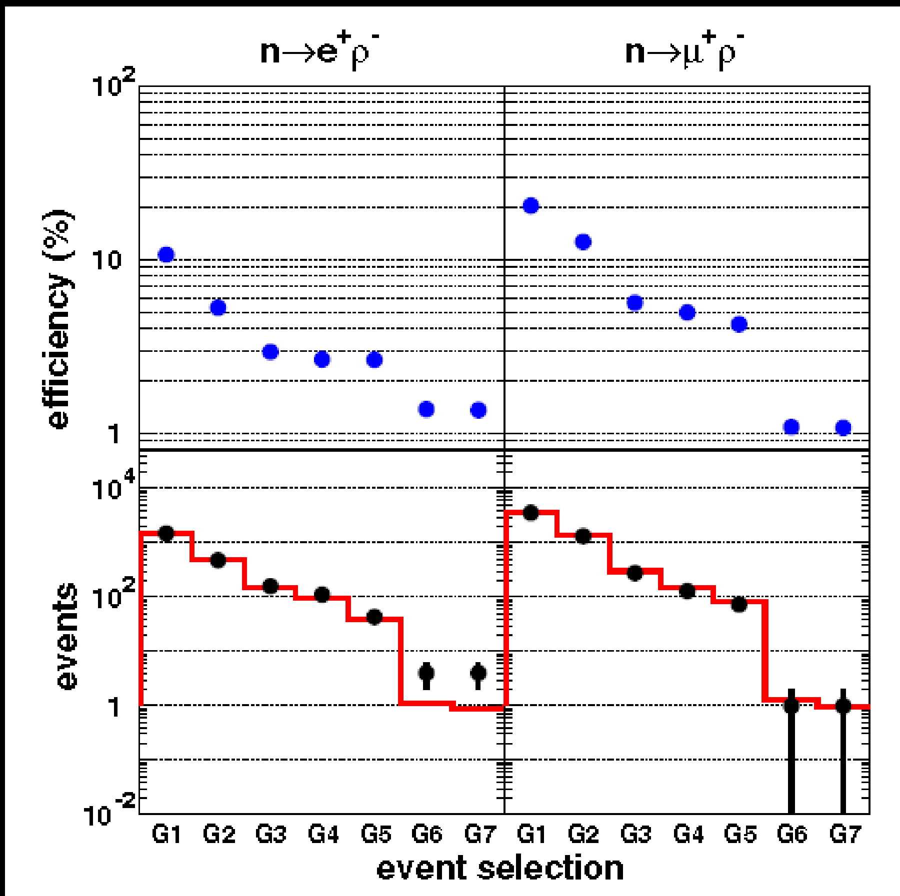
$\eta^0 \to 2\gamma$ search　　$\eta^0 \to 3\pi^0$ search



$p \to e^+\eta^0$ MC: open(hatch) for all(free) protons

NDK MC
Atm.ν MC
SK I-IV Data

n→(e⁺,μ⁺)ρ⁻ search



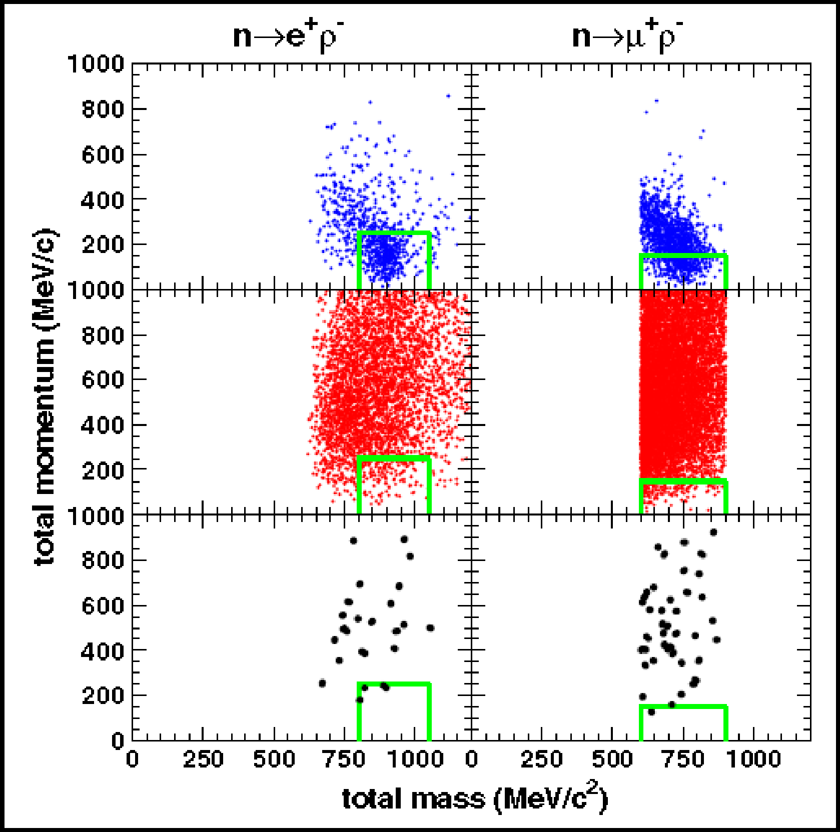
The ρ^- meson has a mass of 770 MeV/c^2 and a width of 150 MeV, immediately decaying into $\pi^-\pi^0$ with a branching ratio of nearly 100%.

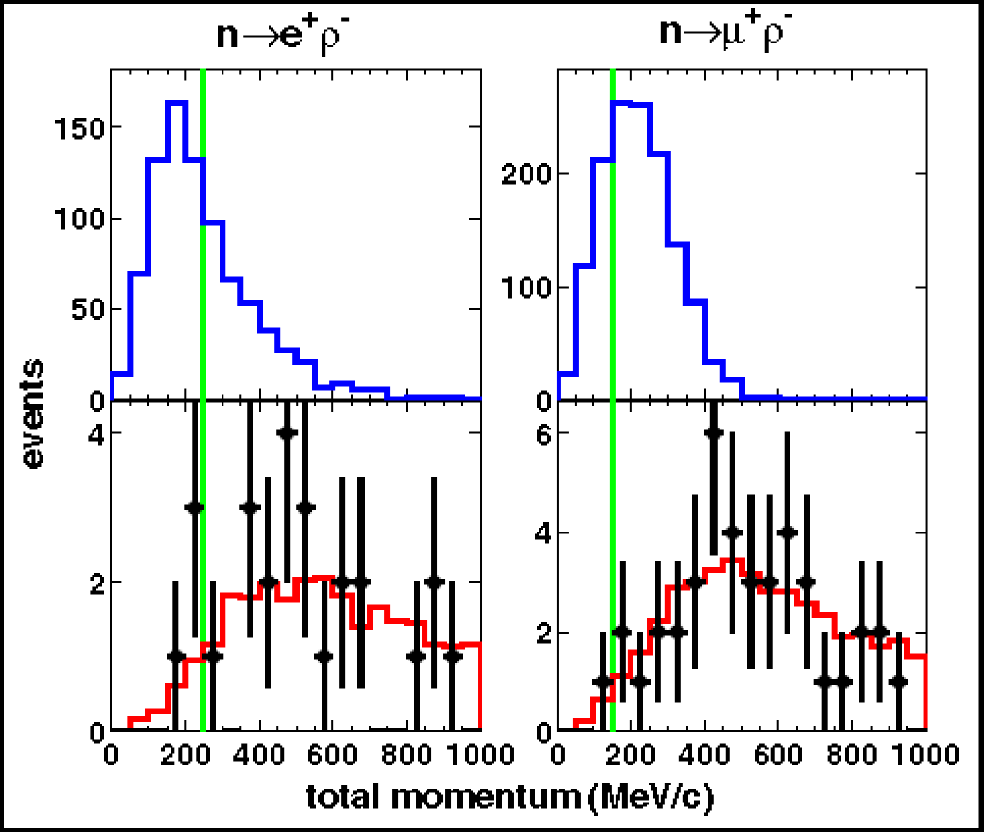
The following event selection is used for this search:

(G1) the number of Cherenkov rings is four for $n \to e^+\rho^-$ and three for $n \to \mu^+\rho^-$,
(G2) one of the rings is a nonshower ring,
(G3) the ρ^- mass is between 600 and 900 MeV/c^2,
(G4) the π^0 mass is between 85 and 185 MeV/c^2,
(G5) the number of Michel electrons is 0 for $n \to e^+\rho^-$ and 1 for $n \to \mu^+\rho^-$,
(G6) the total momentum is less than 250 MeV/c for $n \to e^+\rho^-$ and less than 150 MeV/c for $n \to \mu^+\rho^-$; the total invariant mass is between 800 and 1050 MeV/c^2 for $n \to e^+\rho^-$,
(G7) the number of neutrons is 0 in SK-IV.

NDK MC
Atm.ν MC
SK I-IV Data

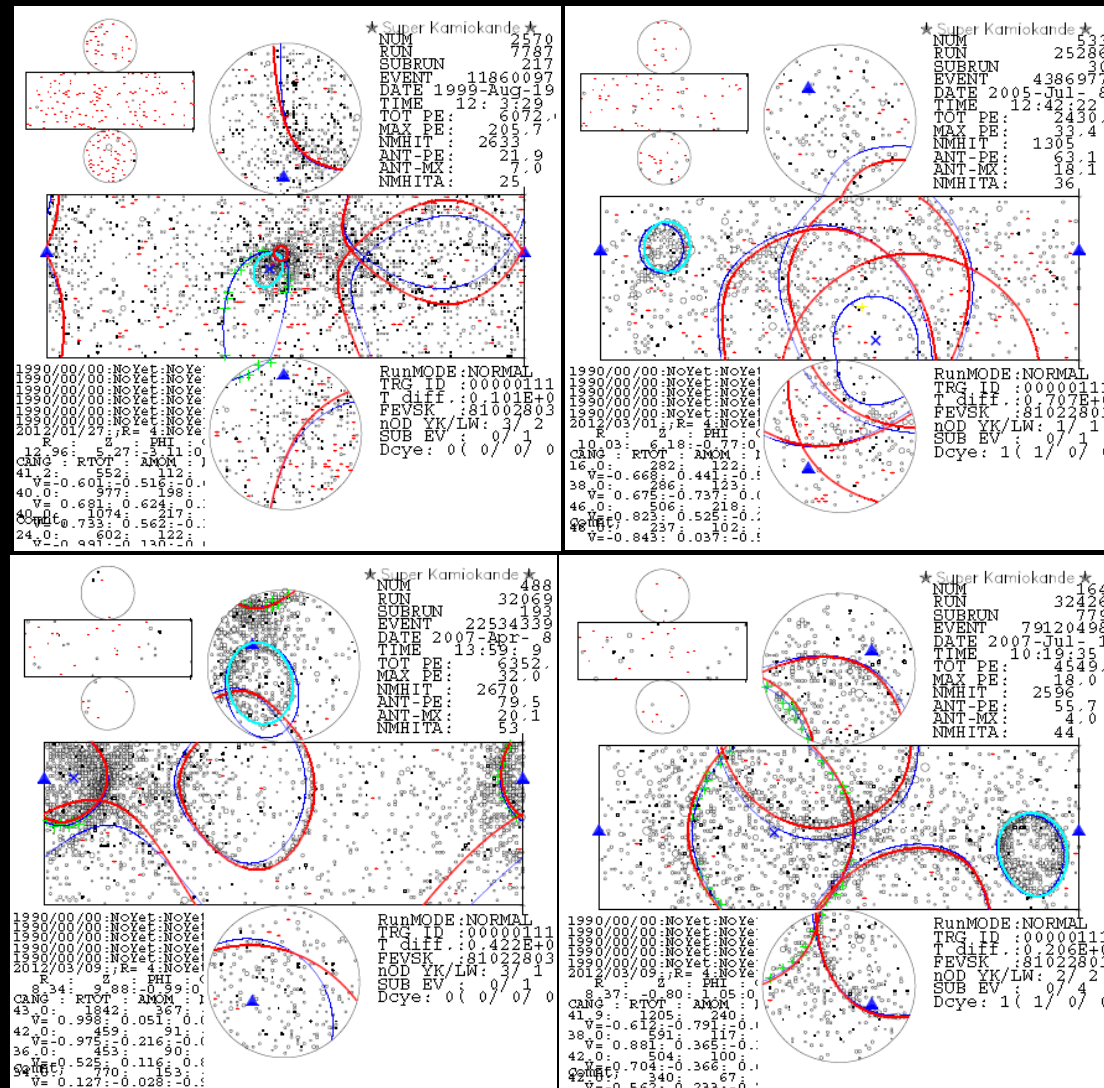
$n \to (e^+, \mu^+)\rho^-$ search





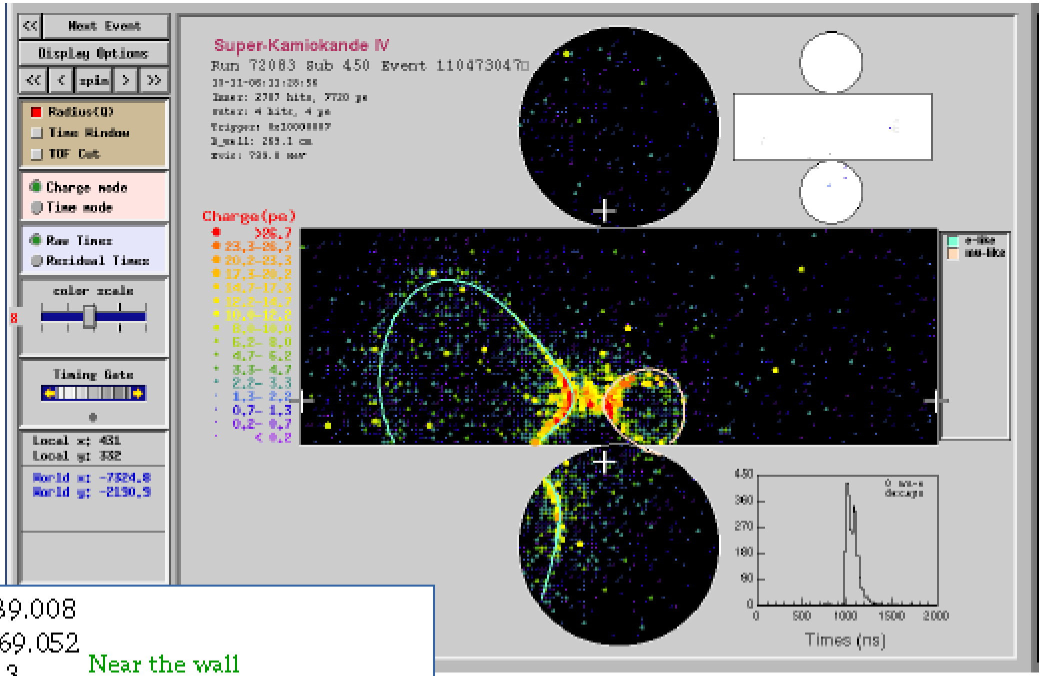
- All selections applied except (M_{tot},P_{tot}) cut

Data candidates in n→$e^+\rho^-$ search



SK preliminary

$p \to \mu^+ \gamma$ candidate #2



evis = 739.008
wall = 269.052 Near the wall
nhitac = 3
nring = 2
likelihoodprm = -157.829
likelihoodprm1 = 2.09317
ndecaye = 0 low mu-like likehood.
Minv = 913.601
Ptot = 229.676
Cos(ang b/w rings) = -0.948724

Run = 72083
Subrun = 450
Date = 11/6/2013

24

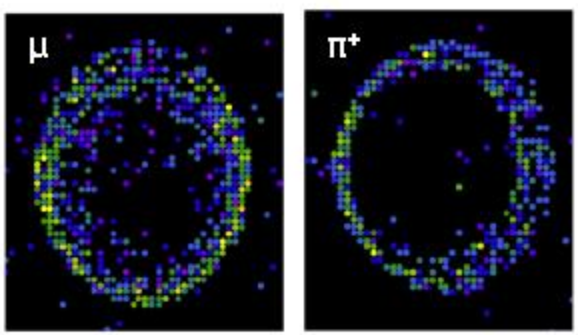
Recent nucleon decay and n-$\bar{n}$ results in SK

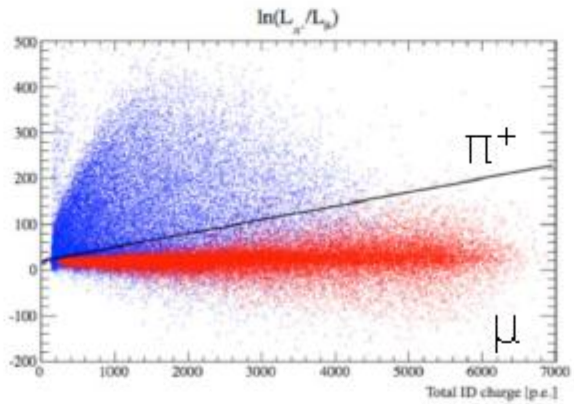
Decay mode	Paper
$p \to e^+\pi^0$	PRD 95, 012004 (2017)
$p \to \nu K^+$	PRD 90, 072005 (2014)
$p \to \mu^+\pi^0$	PRD 95, 012004 (2017)
$p \to (e^+,\mu^+)(\eta,\rho,\omega)$, $n \to (e^+,\mu^+)(\pi,\rho)$	PRD 96, 012003 (2017)
$p \to \mu^+K^0$	PRD 86, 012006 (2012)
$n \to \nu\pi^0$, $p \to \nu\pi^+$	PRL 113, 121802 (2014)
$p \to (e^+,\mu^+)\nu\nu$	PRL 113, 101801 (2014)
$p \to (e^+,\mu^+)X$	PRL 115, 121803 (2015)
$n \to \nu\gamma$	PRL 115, 121803 (2015)
$pp \to K^+K^+$	PRL 112, 131803 (2014)
$pp \to \pi^+\pi^+$, $pn \to \pi^+\pi^0$, $nn \to \pi^0\pi^0$	PRD 91, 072009 (2015)
$np \to (e^+,\mu^+,\tau^+)\nu$	PRL 115, 121803 (2015)
n-$\bar{n}$ oscillation	PRD 91, 072006 (2015)

Charged pions

(fiTQun)

- Single-ring π^+ difficult to distinguish from μ
- However π^+ are more likely to hard-scatter
- Look for kinked π^+ track with one or two rings
  - "Upstream" ring is thinner
  - "Downstream" ring is fainter or invisible
- New PID handle at Super-K.





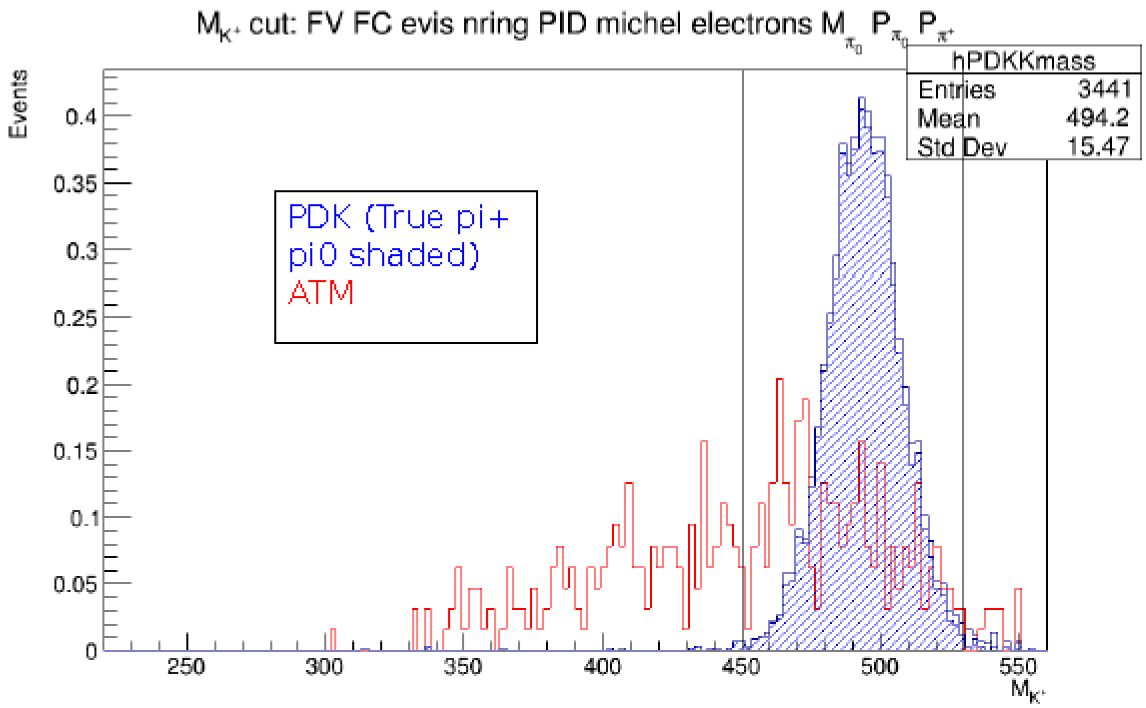
- Detail in Doctor thesis at UBC in 2018 by Sophie Berkman

https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0365713

Nicola Fulvio Calabria (Bari), Gabriel Santucci (SUNY), Thomas Mueller (LLR)

(fiTQun)

Kaon Mass PDK vs ATM MC normalized



20

Hybrid $\pi^+\pi^0$ sample (on-going)

Nicola Fulvio Calabria (Bari), Gabriel Santucci (SUNY), Thomas Mueller (LLR)