potential of Hyper-Kamiokande at some *non accelerator* physics and nucleon decay search programs

Luis Labarga, U. Autonoma Madrid

On behalf of

The Hyper-Kamiokande proto-Collaboration

- Hyper-Kamiokande: the next-generation
- Expectations for some DM searches
- Expectations for Nucleon Decay searches

ICHEP-2016

2016/08/06, Chicago, Illinois

MARIE CURIE ACTIONS

H2020-MSCA-RISE-2014-GA641540, SKPLUS

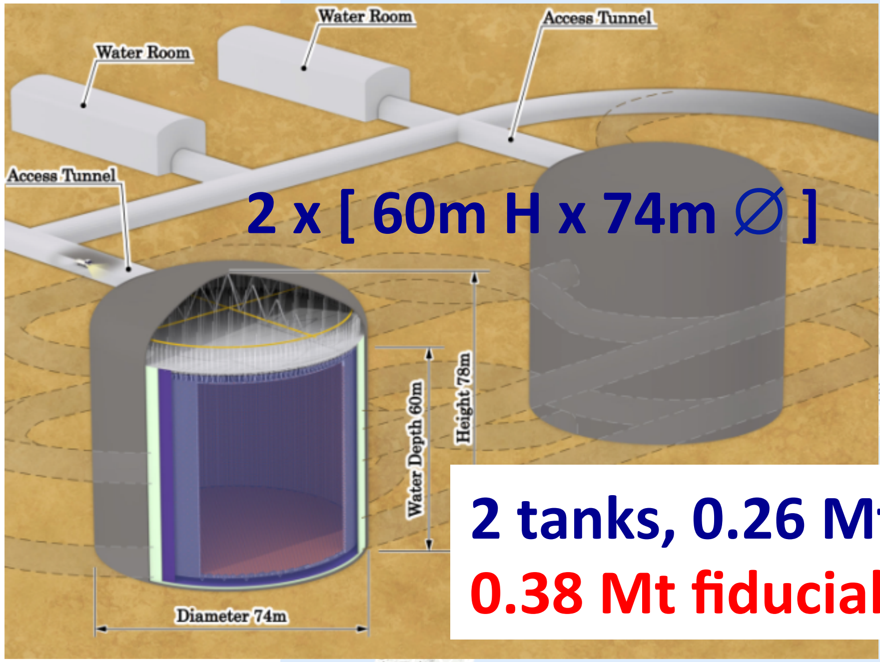
neutrino physics in Japan: **A most successful experimental program**

Kamiokande → Super-Kamiokande [K2K , T2K] →

- maximizes available resources → minimizes time, useless efforts …
- maximizes experience & know-how → minimizes risks, delays, failures

→ Hyper-Kamiokande [T2HK]

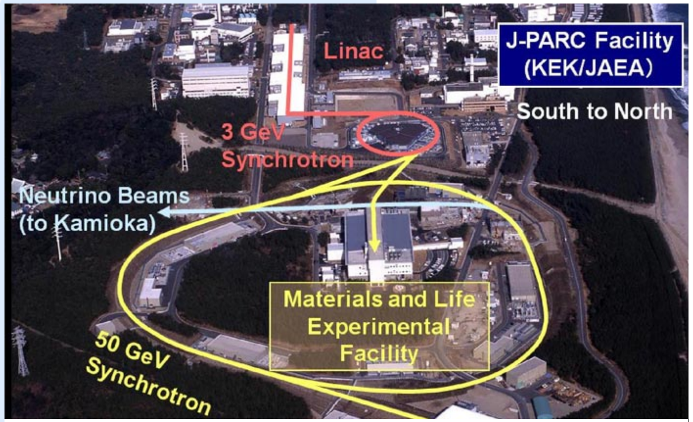
- uses Water-Cherenkov:
  - unique technique to achieve **huge amount of instrument matter**



2 x [60m H x 74m ∅]

2 tanks, 0.26 Mt each
0.38 Mt fiducial

295 Km



1.3 MW, 2.5° off-axis
narrow-band, ~600 MeV

- precise rec. of particle's energy, position, direction, type …

The key of HK: very large mass and excellent photosensitivity

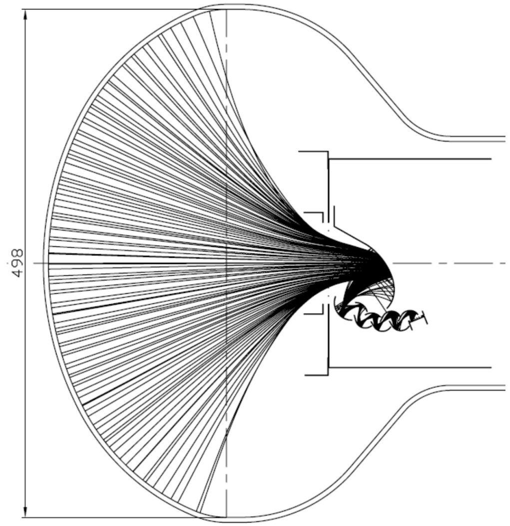
#638-talk **Y. Nishimura** *"New 50 cm Photo-Detectors for HK"*

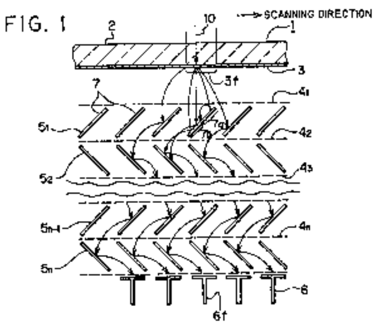
- current baseline: **high-QE Box&Line PMT** Hamamatsu R12860
    - R&D since 2011

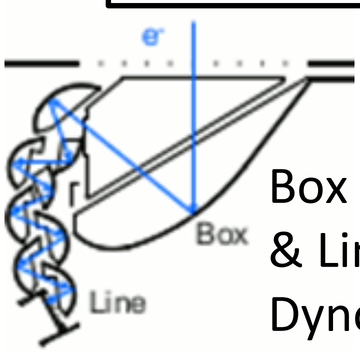
Super-K PMT

Venetian Blind

50 cm HQE Box&Line PMT



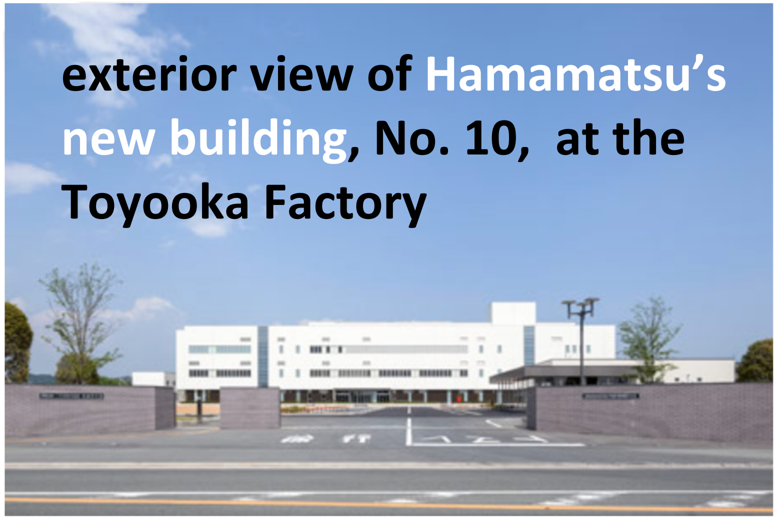




Box & Line Dynode

- also new bulb shape with higher pressure tolerance (> 100 m)
- now **ready** for mass production

- ≈ 80k 50 cm PMTs at inner detector



Exterior view of the new Building No. 10 at the Toyooka Factory

Kamiokande → Super-Kamiokande [K2K , T2K] →

the Hyper-Kamiokande [T2HK] experimental physics program

ν oscillation physics

- determination of **ν Mass Hierarchy** (atmospheric & beam)
- determination of θ_{23} octant (atm. & beam)
- measurement of **CP Violation** in leptonic sector (atm. & beam)
- reveal exotic scenarios

#1036-talk **M. Gonin** *"HK's neutrino oscillation physics sensitivity "*

Solar ν physics

- precision measurement of Δm^2_{21}
- measurement of energy spectrum **up-turn**
- discovery & measurement of **hep** neutrino

#635-poster **L. Labarga** *"Astrophysics Potential of HK"*

ν Astrophysics

- energy spectrum of **D**iffuse **S**upernova **N**eutrino **B**ackground
- galactic Supernova, high statistics, energy, time evolution …
- indirect **D**ark **M**atter search from GC, Sun, Earth

Grand Unification physics

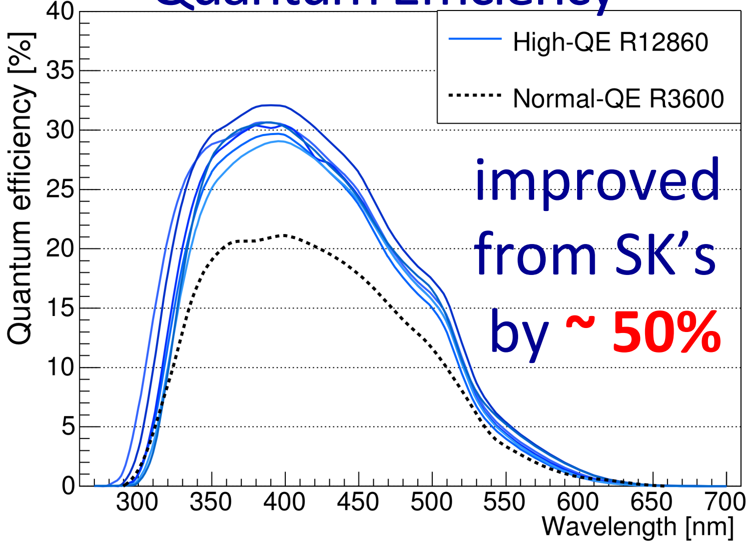
- $p \to e^+\pi^0$, $p \to \nu K^+$ & all visible modes
- reach 10^{35} sensitivity

---> *this talk*

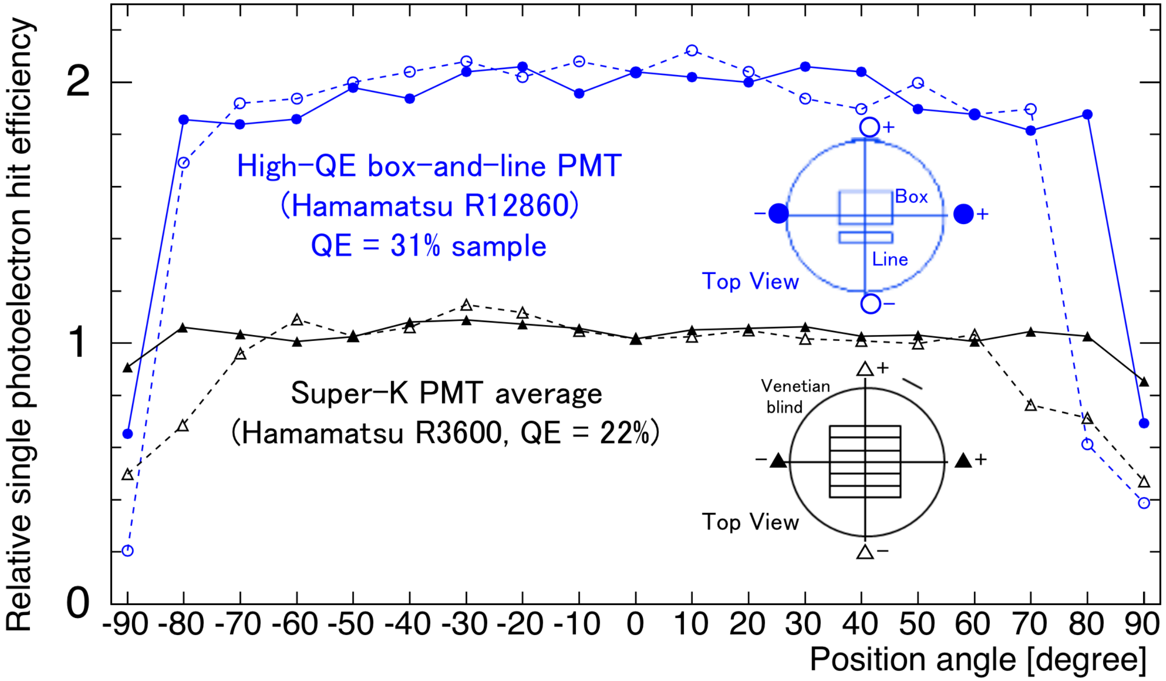
particularly relevant for the stuff of this talk:

main characteristics
high-QE Box&Line PMT
Hamamatsu R12860

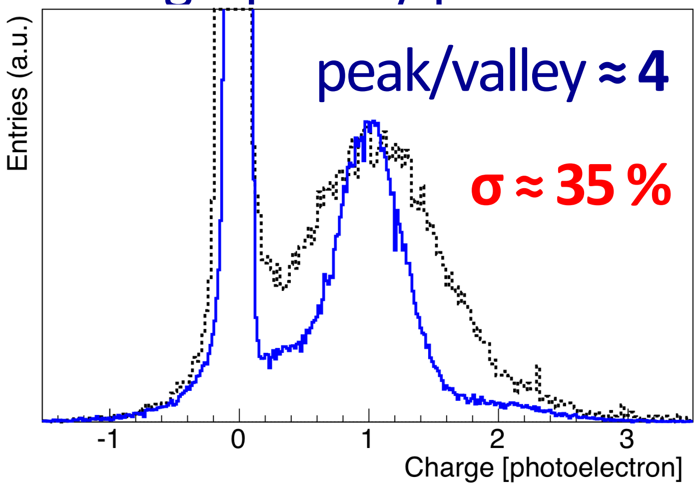
Quantum Efficiency



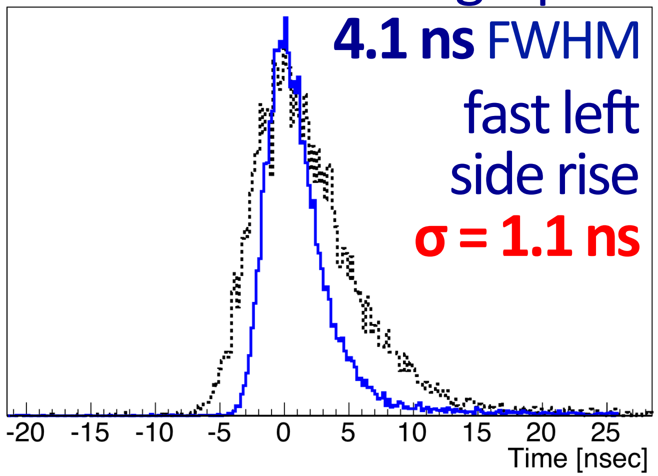
relative single photoelectron det. efficiency [Quantum, Collection, and Cut efficiencies]



single p.e. w/ pedestal



transit time for single p.e.

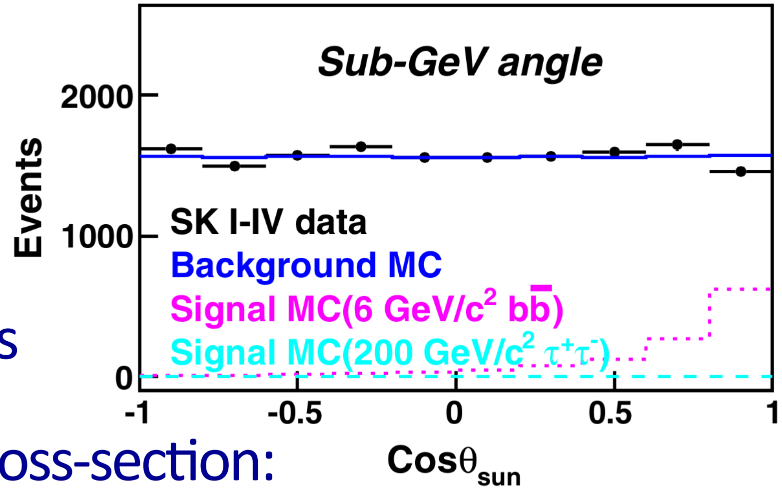


2 x better efficiency, timing resolution, charge resolutions →

- enhance solar ν_s ,
- signature n(p,d) γ
- p → ν K^+
- ....

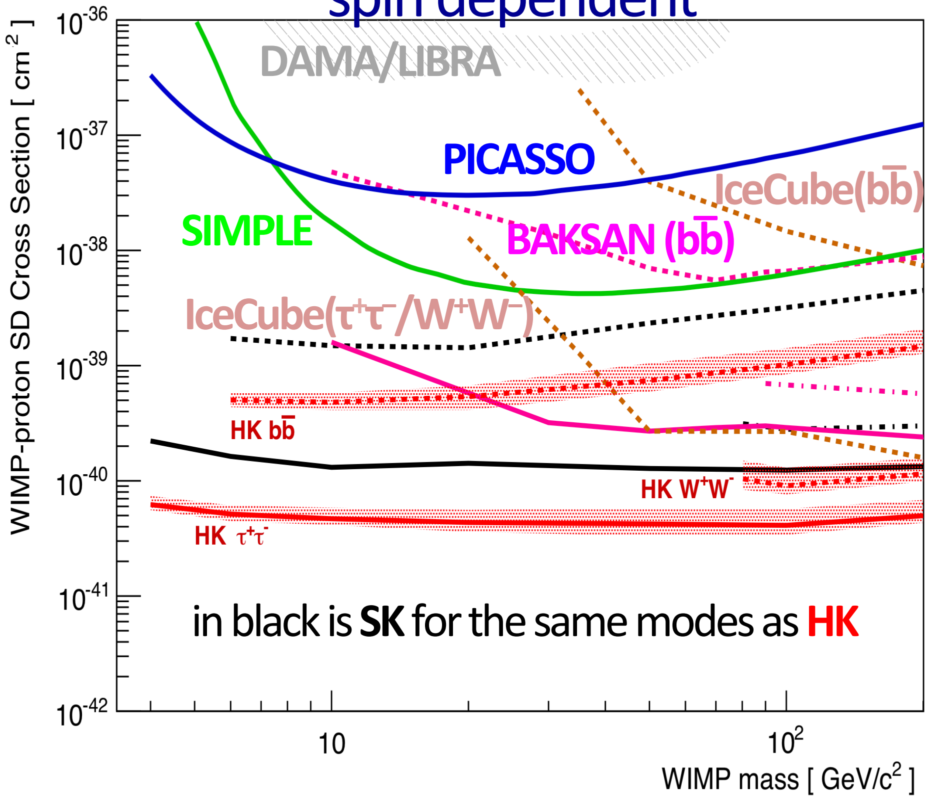
DM WIMP induced **ν, searches** at the **Sun**

- $\chi\chi \rightarrow \tau^+\tau^-, b\bar{b}, W^+W^- \rightarrow$ **ν** X
  search for **ν** "excess" from the sun
  use SK PRL 114, 141301 (2015) to illustrate →
- assume on WIMPs capture and annihilations

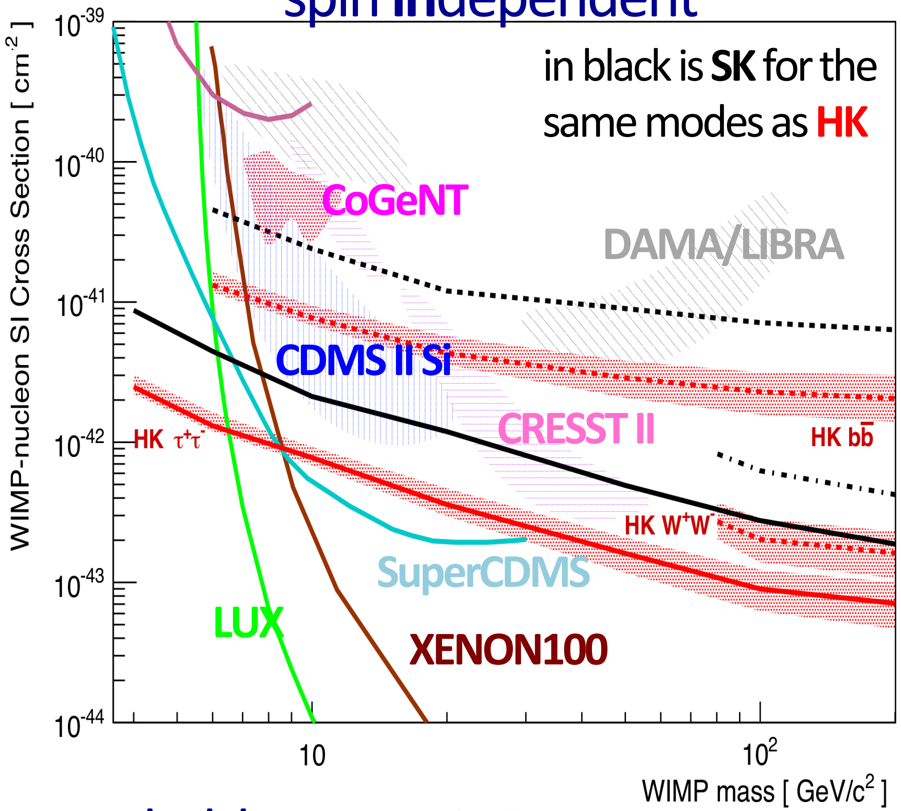


→ 90% CL limits on WIMP nucleon scattering cross-section:

spin dependent



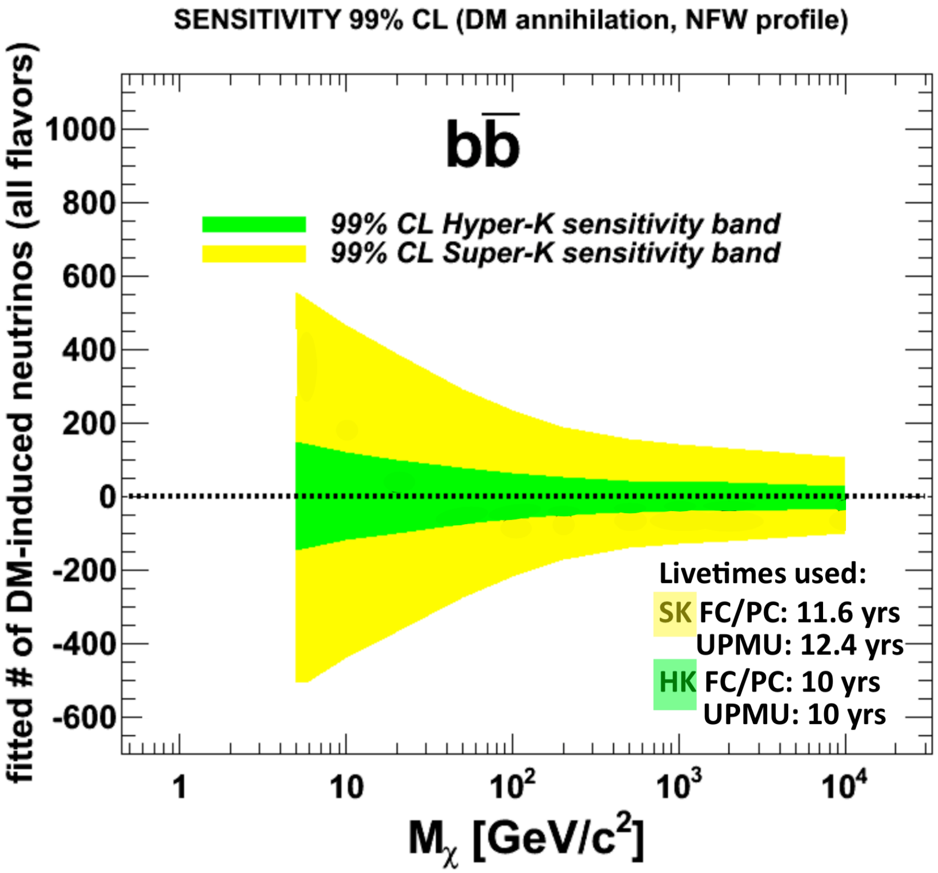
spin **in**dependent



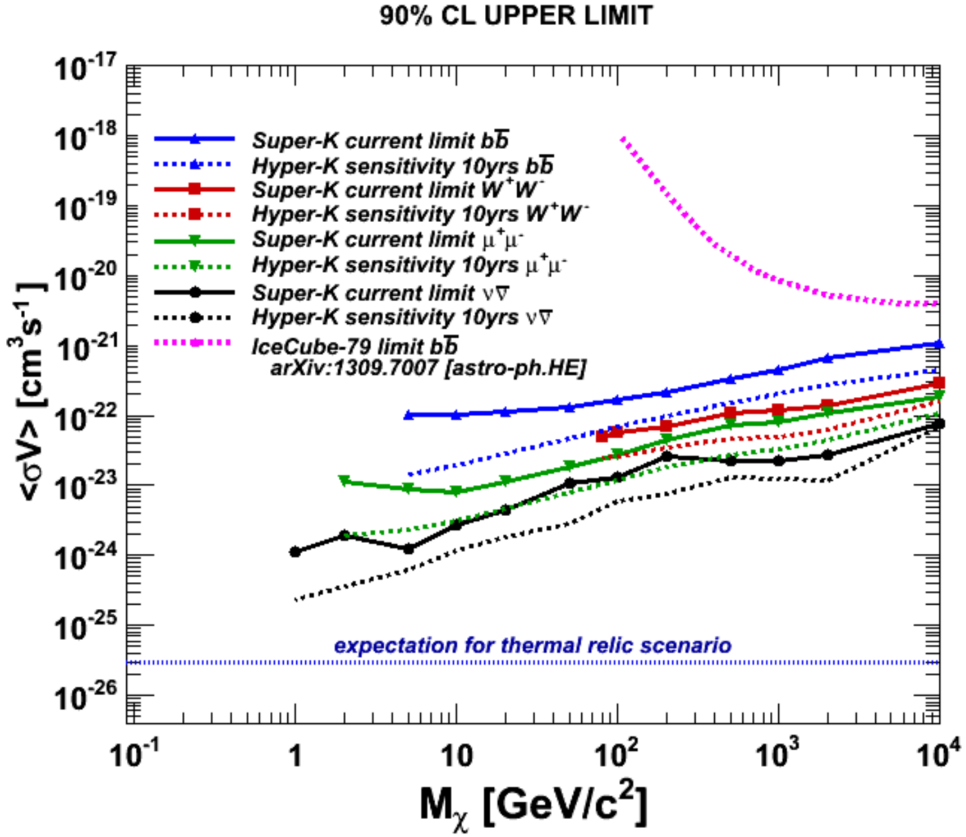
remarkable at < 10 GeV

DM WIMP-induced **ν**, **searches** at the **Galaxy**

DM induced ν event excess from $\chi\chi \rightarrow b\bar{b} \rightarrow \nu X$

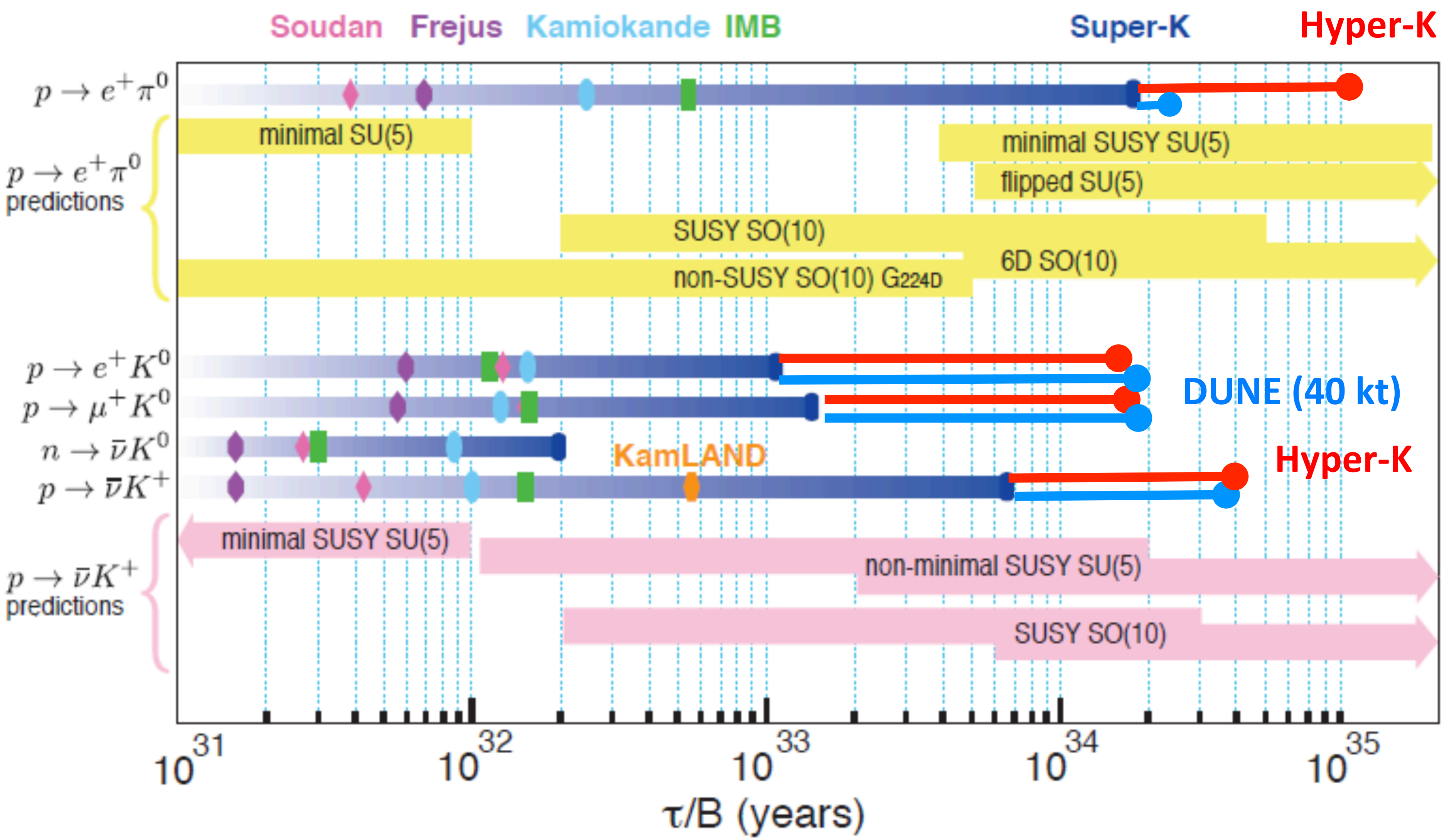


velocity averaged WIMP self-annihilation cross-section



an Hyper-Kamiokande primary goal: nucleon decay

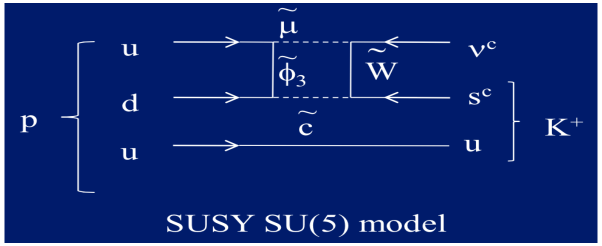
status & next generation expectations (10 y exposure), most important modes:



design emphasizes **p → e⁺π⁰**, **p → ν K⁺** while keeping sensitivity to many other

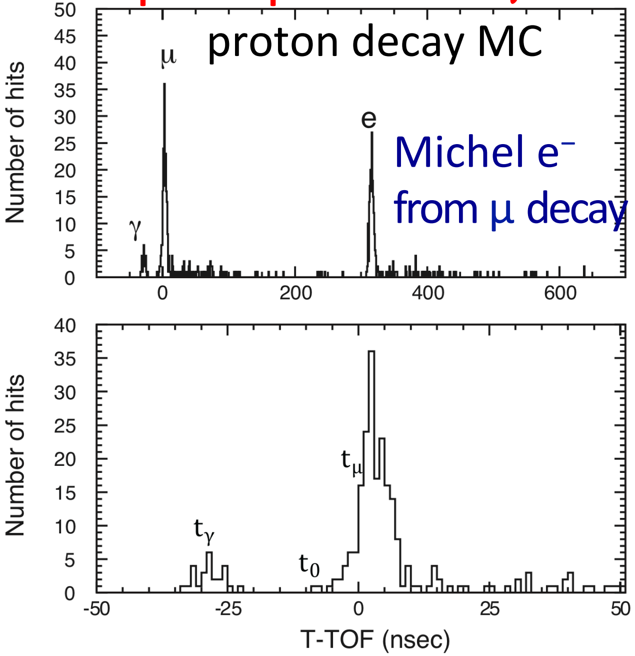
$p \rightarrow \bar{\nu} K^+$

- feature of super-symmetric GUTs

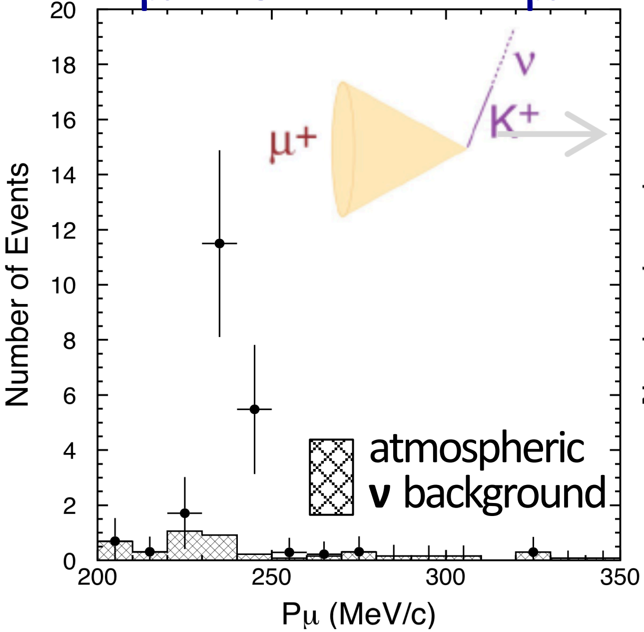


- rather interesting but difficult to reconstruct
- at decay $p(K^+)$= 340 MeV, K^+ ch-light threshold: 749 MeV → reconstruct K^+ from its decay products $K^+ \rightarrow \nu \mu^+$ *(64%)*, $K^+ \rightarrow \pi^+\pi^0$ *(21%)*
- 2-body decays → monochromatic particles: $p(\mu^+)$= 236 MeV, $p(\pi^+)= p(\pi^0)$= 205 MeV
- $\tau(K^+) \approx$ 12ns → possible to observe prompt 6 MeV γ from ^{16}O de-excitation

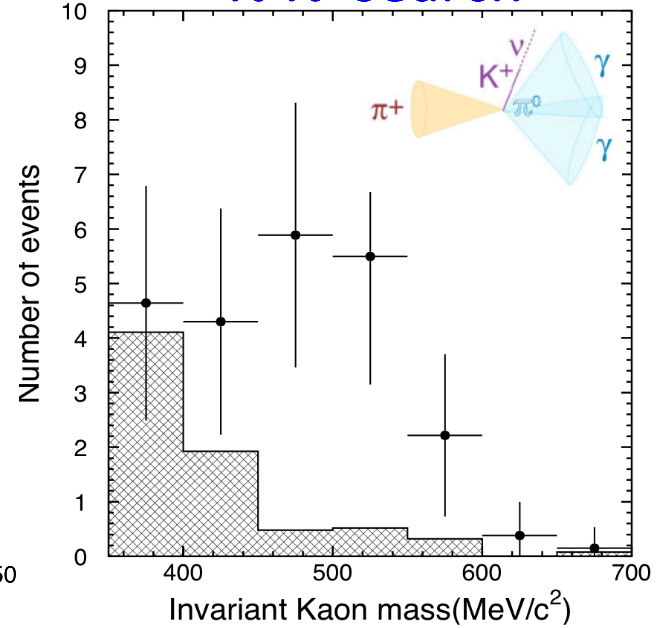
prompt 6 MeV γ



μ^+ from $K^+ \rightarrow \nu \mu^+$



$\pi^+\pi^0$ search

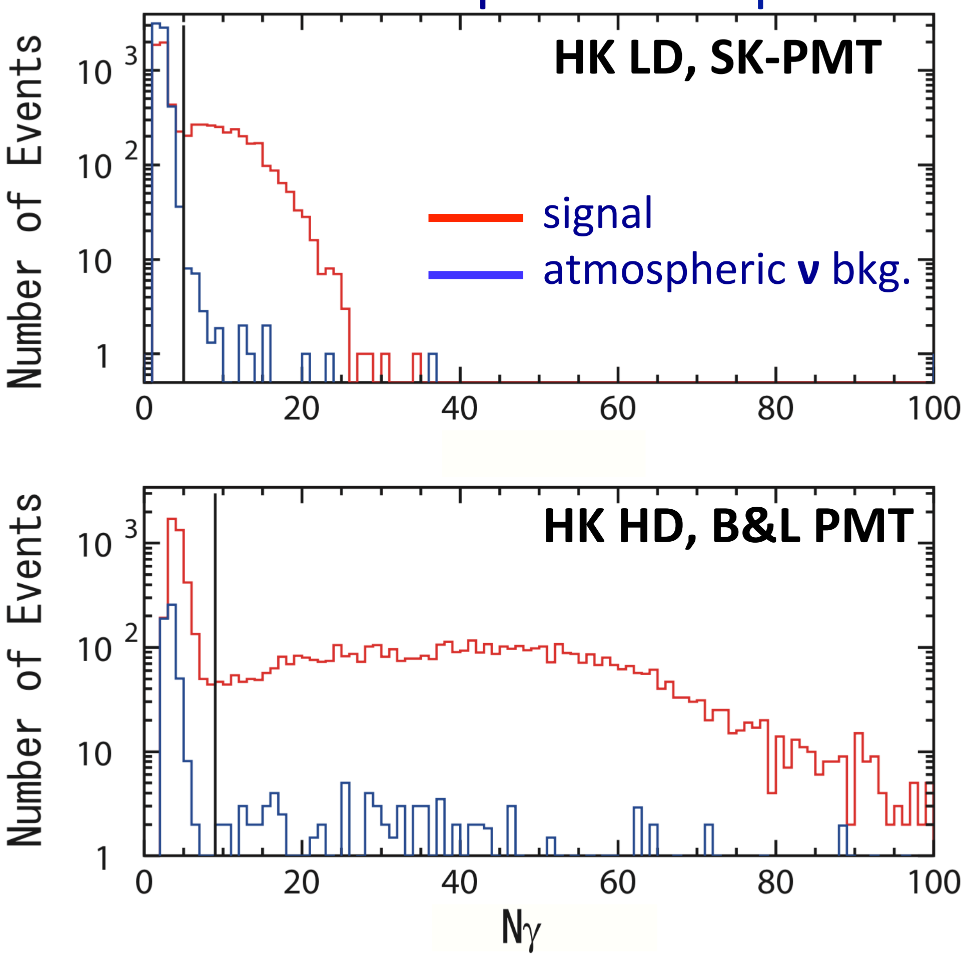


used τ_p= 6.6 • 10^{33} (SK limit), 10 years exposure

p → $\bar{\nu}$ K^+ benefits from increased photon yield and timing resolution

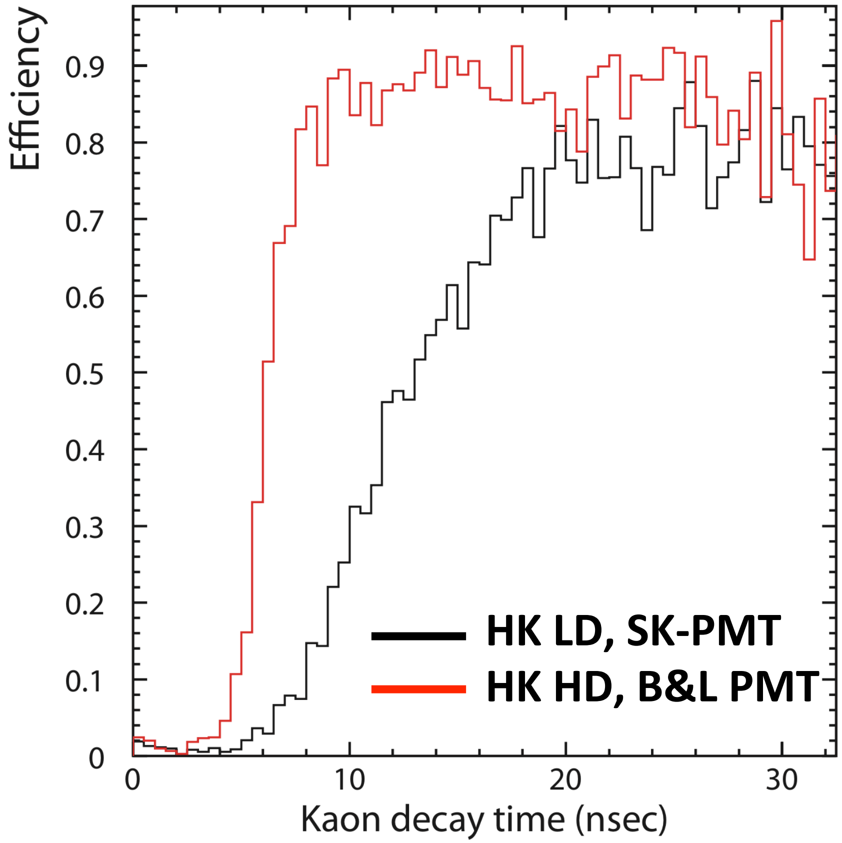
- search for the prompt 6 MeV γ from ^{16}O de-excitation:

number of hits within 12 ns wide time window prior to the μ^+



LD / HD : 20% / 40 % photo-coverage

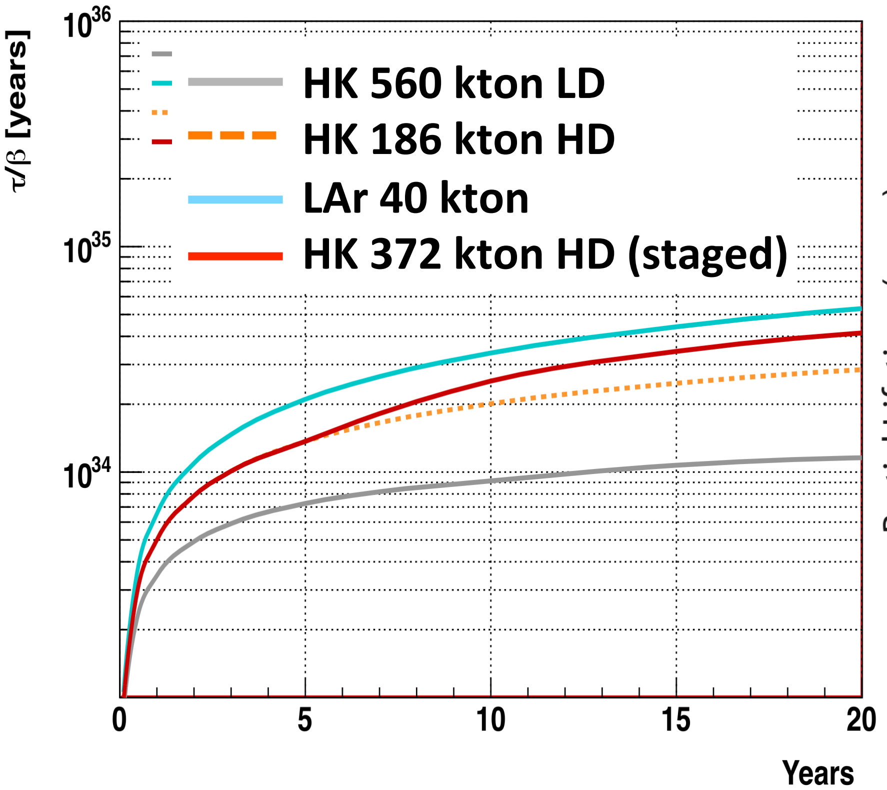
prompt-γ tagging efficiency as a function of the K^+ decay time



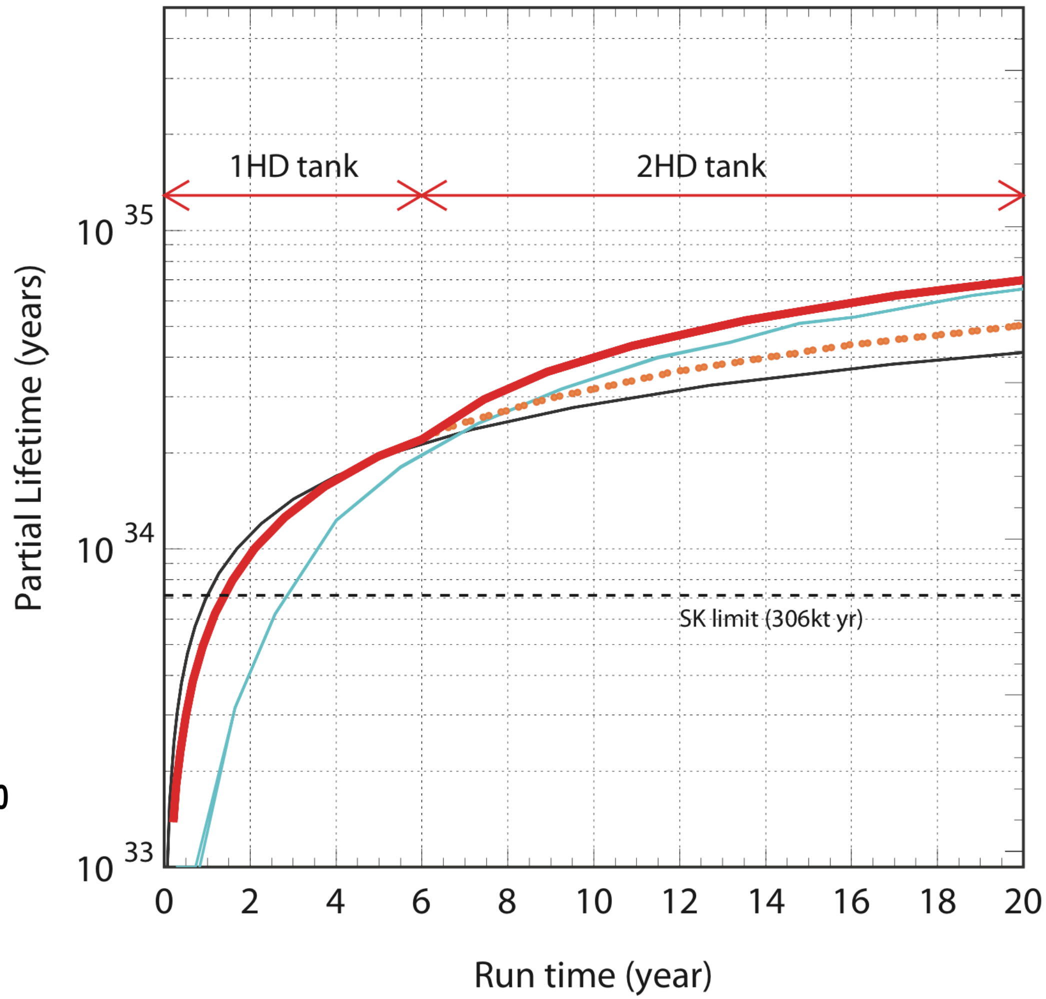
K^+ that decay earlier can be used in the analysis

$p \rightarrow \bar{\nu} K^+$

discovery potential (3 σ)



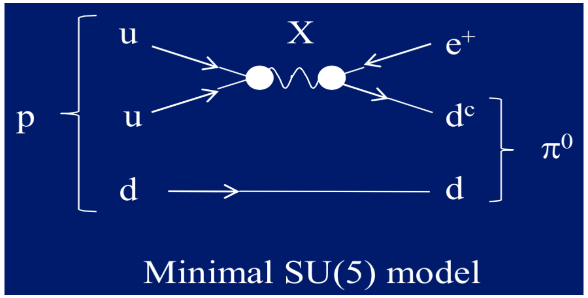
90% C.L. limits achievable
if no event is observed



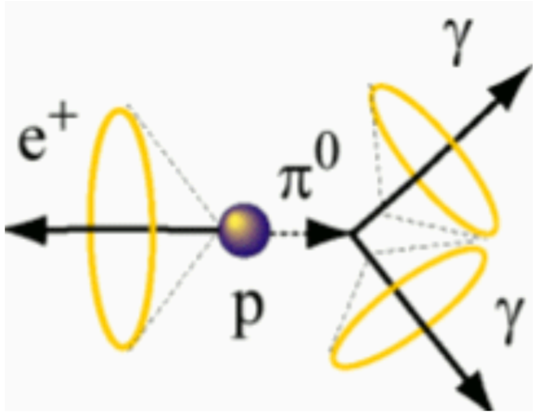
[Staging: 2nd tank comes into operation after 6 years]

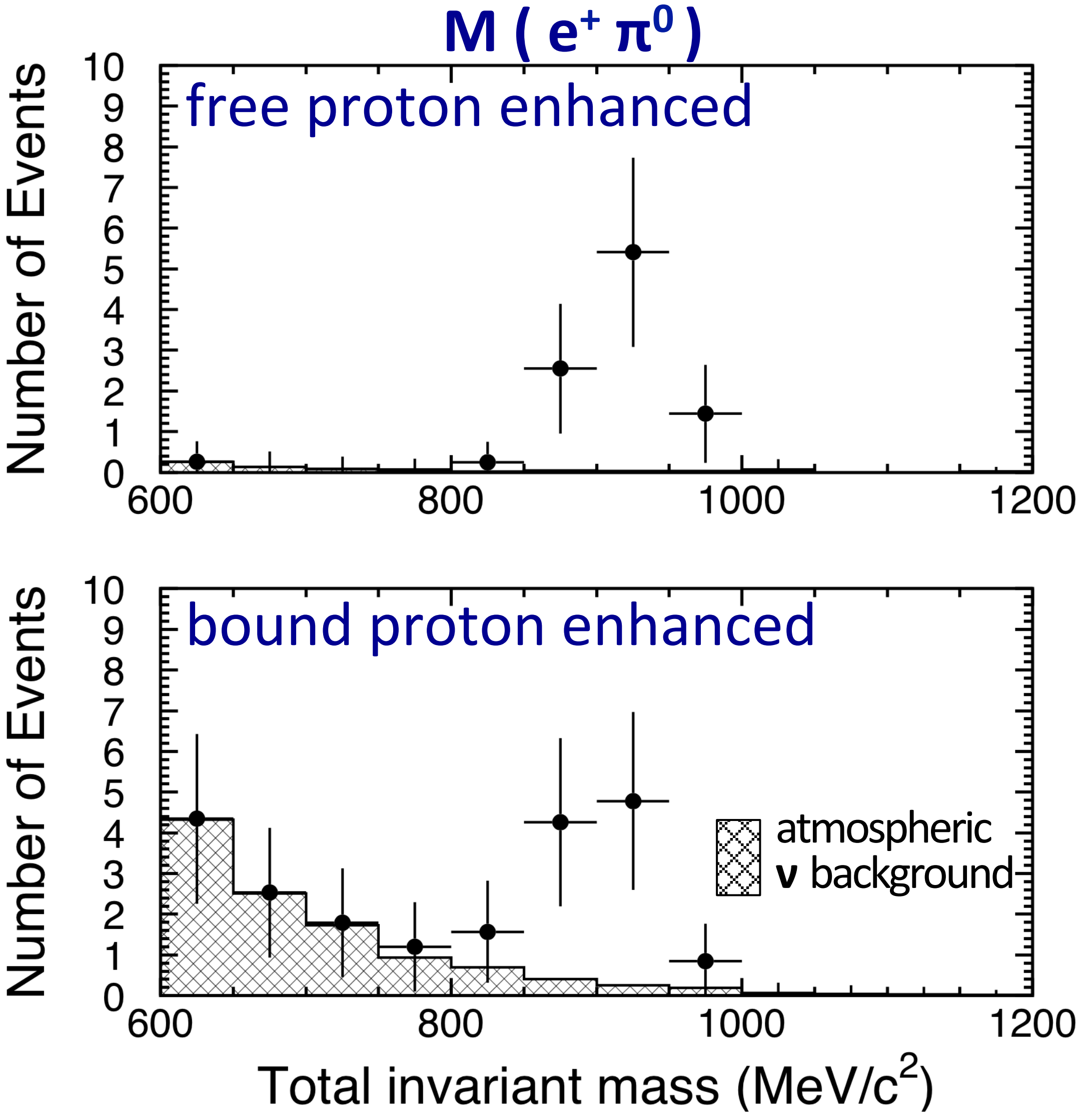
LAr discovery potential computed using numbers from DUNE CDR 2015:
signal efficiency: 97%, background: 1 event Mton/year, no systematic errors

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



- favored by non supersymmetric GUTs
- nearly model independent reaction



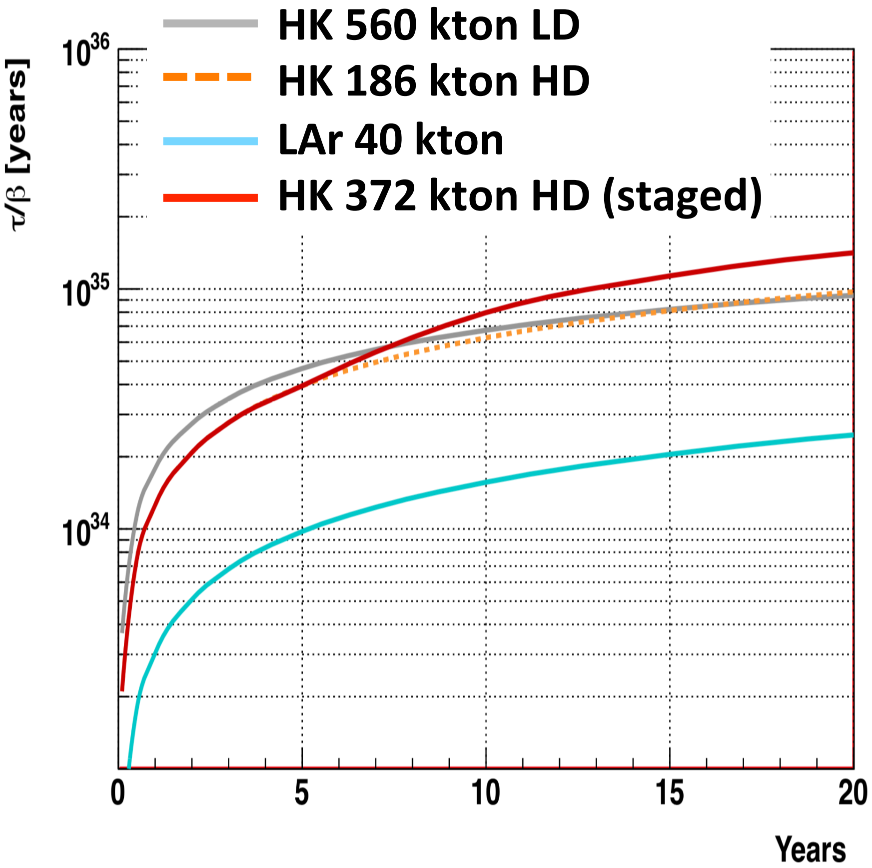


- back-to-back e^+, π^0 (459 MeV)
- e^+, π^0 ($\to \gamma\ \gamma$) are detected
- final state fully reconstructed in Water Cherenkov detectors

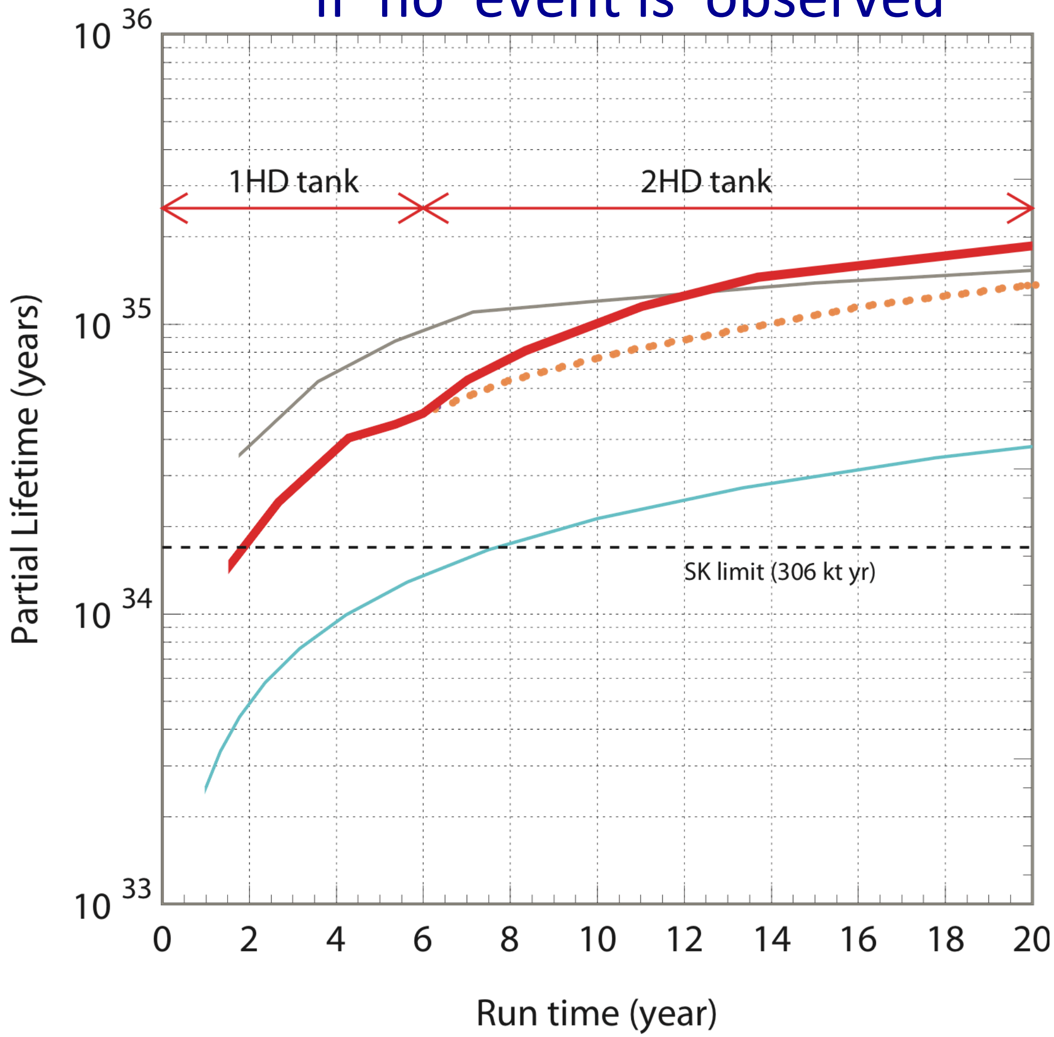
used $\tau_p = 1.7 \cdot 10^{34}$ (SK limit), 10 years exposure

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

discovery potential (3 σ)



90% C.L. limits achievable if no event is observed

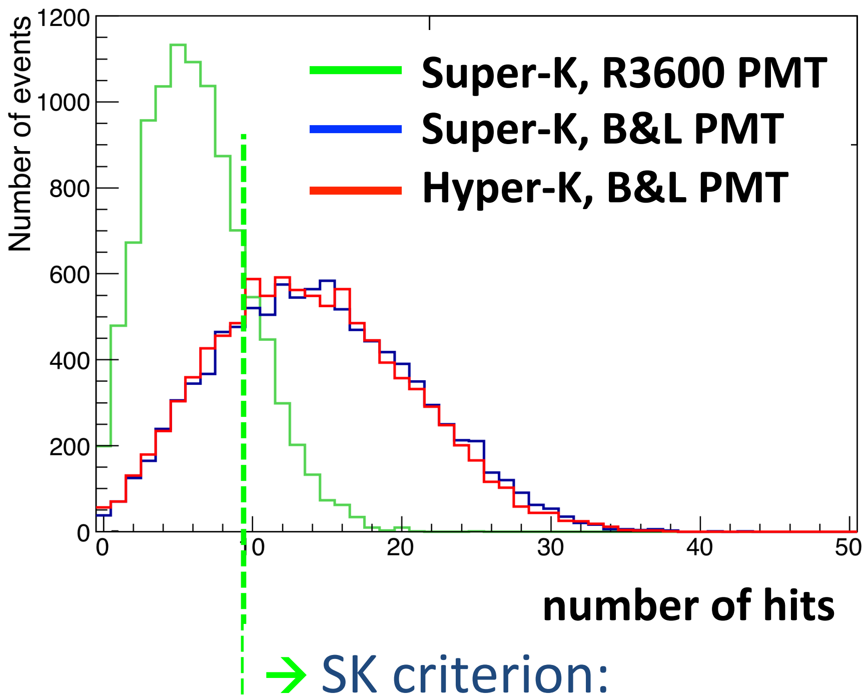


[Staging: 2nd tank comes into operation after 6 years]

LAr discovery potential computed using numbers from DUNE CDR 2015:
signal efficiency: 97%, background: 1 event Mton/year, no systematic errors

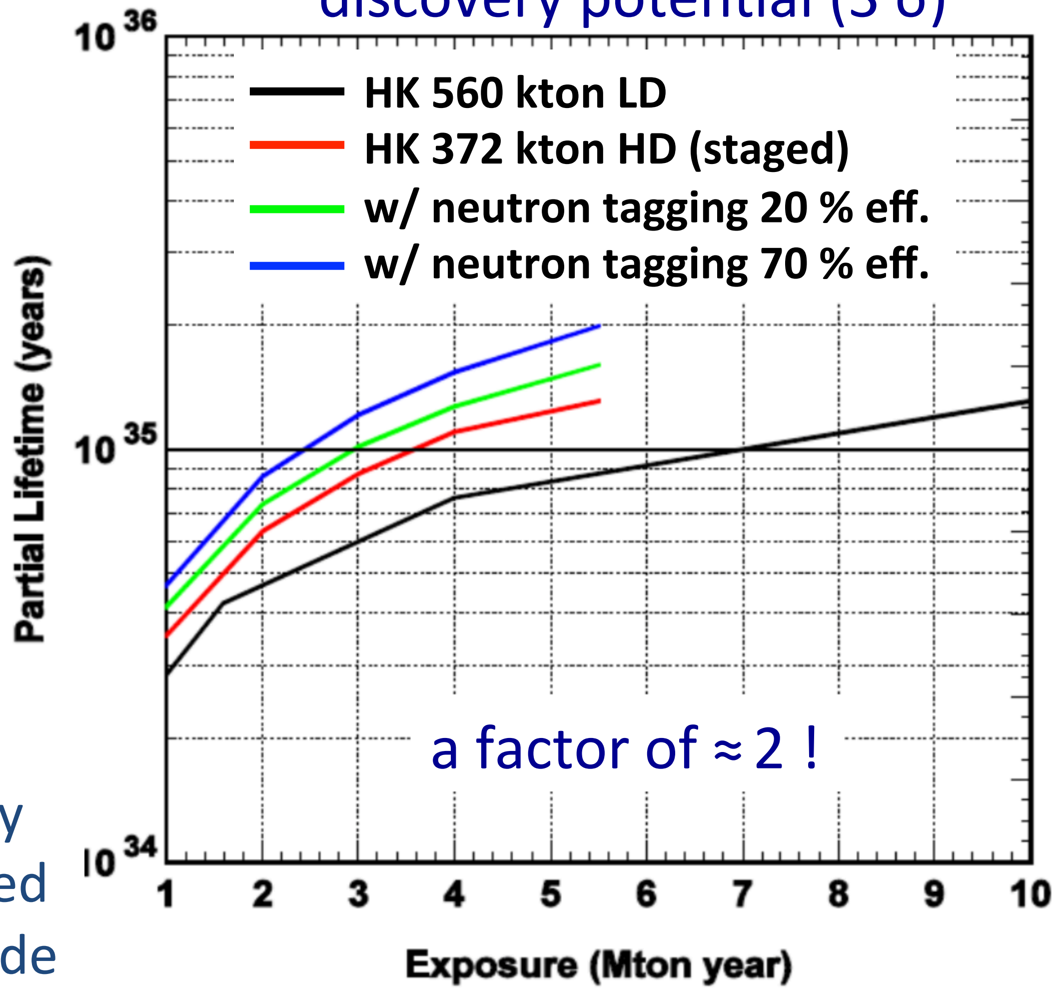
p → $e^+\pi^0$ some of the benefits from increased photon yield

- neutron tagging (veto):
  - p decay: **no** neutrons // atmospheric ν background: **yes** neutrons
  - neutrons at (pure) water: 2.2 MeV γ from n (p, d) γ



→ SK criterion:
≈ 18% tagging efficiency
→ much better expected
for Hyper-Kamiokande

discovery potential (3 σ)



other modes

90% C.L. limits achievable if no event is observed

[exposure: 5.6 Mton•year, detector: HK 560 kton LD]

| B - L | conserving

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\pi^0$	1.2×10^{35}	1.4×10^{34}
$p \to \overline{\nu}K^+$	2.8×10^{34}	0.7×10^{34}
$p \to \mu^+\pi^0$	9.0×10^{34}	1.1×10^{34}
$p \to e^+\eta^0$	5.0×10^{34}	0.42×10^{34}
$p \to \mu^+\eta^0$	3.0×10^{34}	0.13×10^{34}
$p \to e^+\rho^0$	1.0×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.37×10^{34}	0.02×10^{34}
$p \to e^+\omega^0$	0.84×10^{34}	0.03×10^{34}
$p \to \mu^+\omega^0$	0.88×10^{34}	0.08×10^{34}
$n \to e^+\pi^-$	3.8×10^{34}	0.20×10^{34}
$n \to \mu^+\pi^-$	2.9×10^{34}	0.10×10^{34}

SK, PRD85, 112001 (2012)

|Δ (B – L)|= 2, |Δ B|= 2

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\nu\nu$	$10.2\ \times10^{32}$	$1.7\ \times10^{32}$
$p \to \mu^+\nu\nu$	$10.7\ \times10^{32}$	$2.2\ \times10^{32}$
$p \to e{+}X$	$31.1\ \times10^{32}$	$7.9\ \times10^{32}$
$p \to \mu^+X$	$33.8\ \times10^{32}$	$4.1\ \times10^{32}$
$n \to \nu\gamma$	$23.4\ \times10^{32}$	$5.5\ \times10^{32}$
$np \to e^+\nu$	$6.2\ \times10^{32}$	$2.6\ \times10^{32}$
$np \to \mu^+\nu$	$4.2\ \times10^{32}$	$2.0\ \times10^{32}$
$np \to \tau^+\nu$	$6.0\ \times10^{32}$	$3.0\ \times10^{32}$

SK, PRL113, 101801 (2014)

SK, PRL115, 121803 (2015)

→ basically 1 order of magnitude for most of the modes

Summary / Conclusions / Outlook

- Hyper-Kamiokande: the very-high mass, high precision, high beam power, highly reliable next generation M-ton neutrino and nucleon decay experiment
- The photo-sensor is now ready for mass production. It features a 2x better efficiency, time and charge resolutions.
- Unique sensitivity to medium mass DM WIMPS at the Galaxy and Sun

- Nucleon decay: partial lifetimes limits (90% C.L., 10 y exposure) of $1.1 \cdot 10^{35}$ years for $p \rightarrow e^+\pi^0$, $4 \cdot 10^{34}$ years for $p \rightarrow \nu K^+$ and basically one order of magnitude improvement for many other nodes

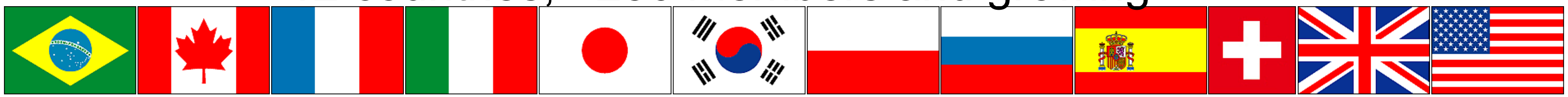
Thus,
if you want to explore GUTs experimentally in the next decades you'd better work (within your field) for Hyper-Kamiokande

Thank you !

Additional

Inaugural Symposium of the HK proto-collaboration@Kashiwa, Jan-2015

12 countries, ~250 members and growing



- Proto-collaboration formed.
- International steering group
- International conveners
- International chair for international board of representative (IBR)
- International Advisory Committee (HKAC)

KEK-IPNS and UTokyo-ICRR signed a MoU for cooperation on the Hyper-Kamiokande project.

MEMORANDUM OF UNDERSTANDING

of the cooperation in the Hyper-Kamiokande project

January 31, 2015

THE INSTITUTE FOR COSMIC RAY RESEARCH OF THE UNIVERSITY OF TOKYO and THE INSTITUTE OF PARTICLE AND NUCLEAR STUDIES OF THE HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION have reached agreement regarding cooperation in promoting the advanced nucleon decay and neutrino experiment program, Hyper-Kamiokande, by understanding that the program would make significant progress in a wide range of fields in physics and astronomy. It is also agreed to review and develop the program in its comprehensive aspects including promoting organization and budget measures.

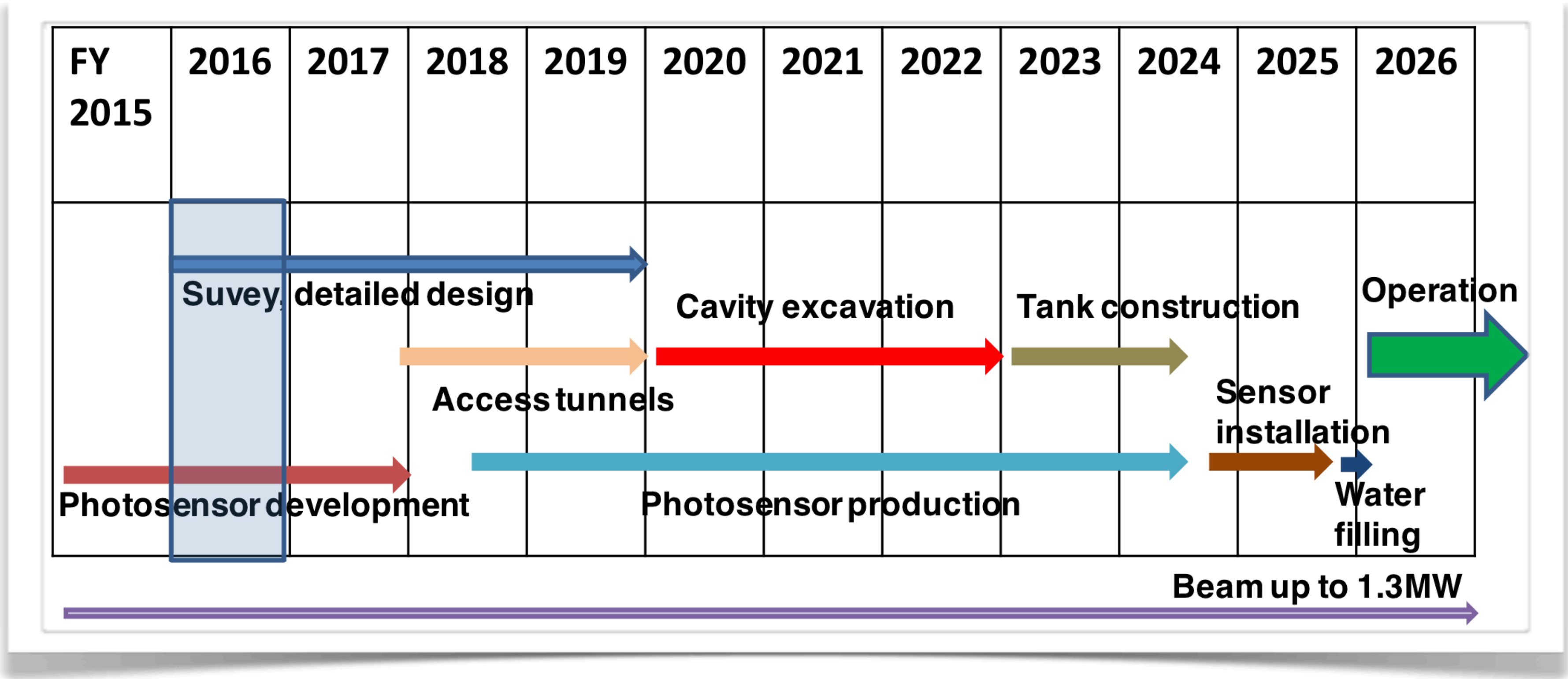
This agreement is effective for two years from January 31, 2015 and is able to be updated upon the discussion between the two organizations.

Prof. Takaaki KAJITA
Director
Institute for Cosmic Ray Research,
The University of Tokyo

Prof. Masanori YAMAUCHI
Director
Institute of Particle and Nuclear Studies,
High Energy Accelerator
Research Organization

F. Di Luduvico @ NEUTRINO 2016

The Hyper-Kamiokande Timeline



- 2018 - 2025 HK construction.
- 2026 onwards CPV study, Atmospherics ν, Solar ν, Supernova ν, Proton decay searches, …
- The 2nd identical tank starts operation 6yrs after the first one.

Box&Line PMT Hamamatsu R12860HQE

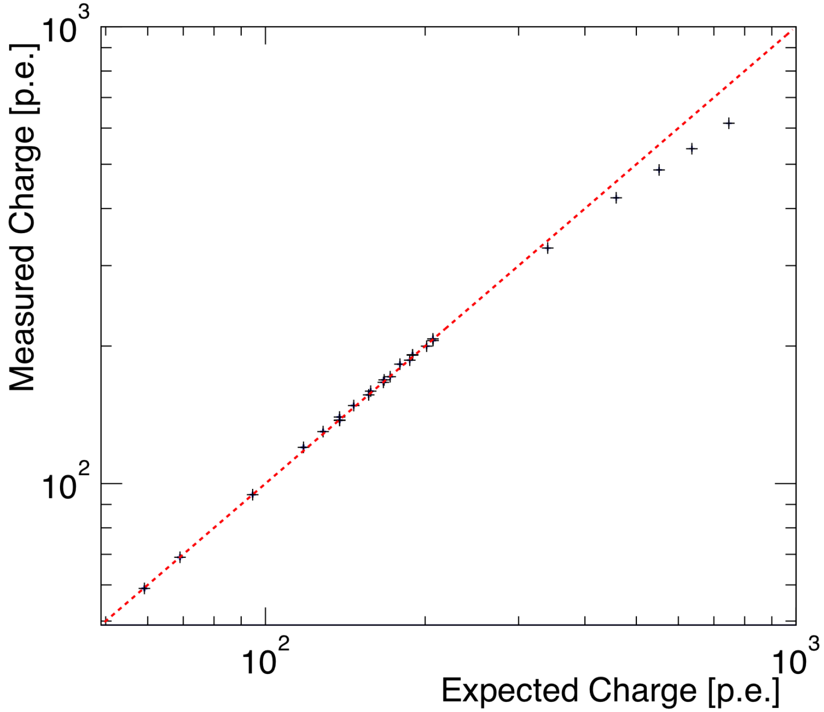


FIG. 62. Output linearity of the HQE B&L PMT in charge, where a dotted line shows an ideal linear response. It is derived by measurements of a coincident emission by two light sources compared with an expectation by sum of individual detections.

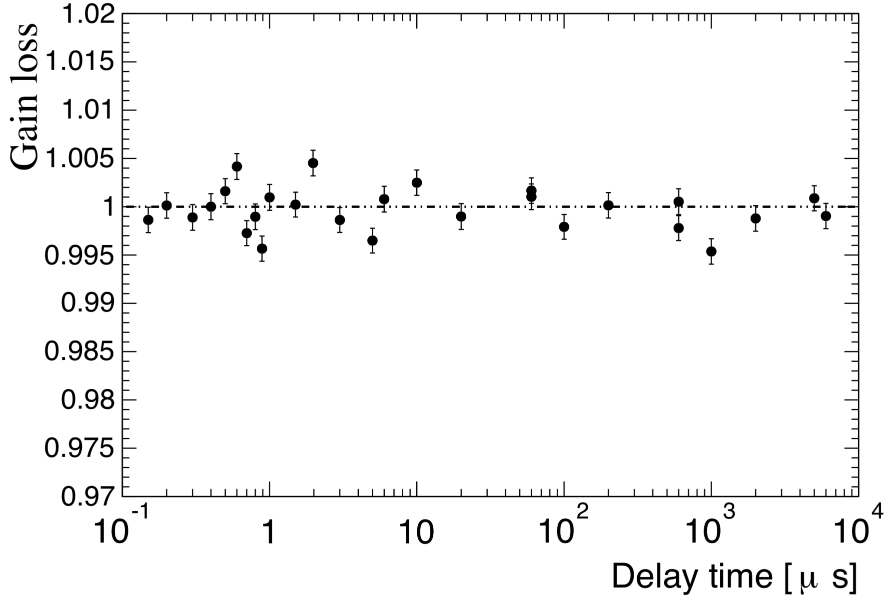


FIG. 63. Gain stability of a delayed pulse after a primary pulse, compared with no primary pulse. The charge set is about 150 PEs at 10^7 gain for both primary and delayed pulses in various delayed time.

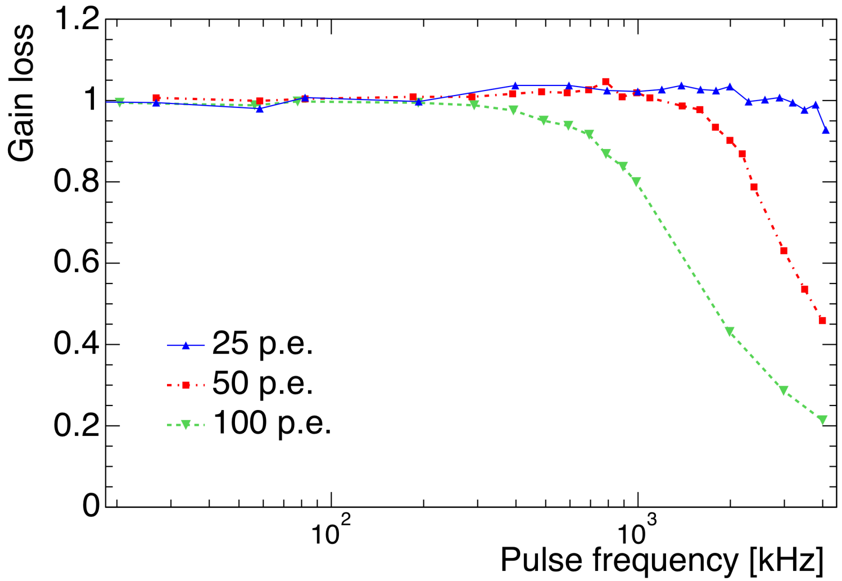


FIG. 64. A measured gain stability as a function of the pulse rate in three light intensities of 25, 50 and 100 photoelectrons, relative to outputs at 100 Hz. Each charge is calculated using the baseline just before the pulse.

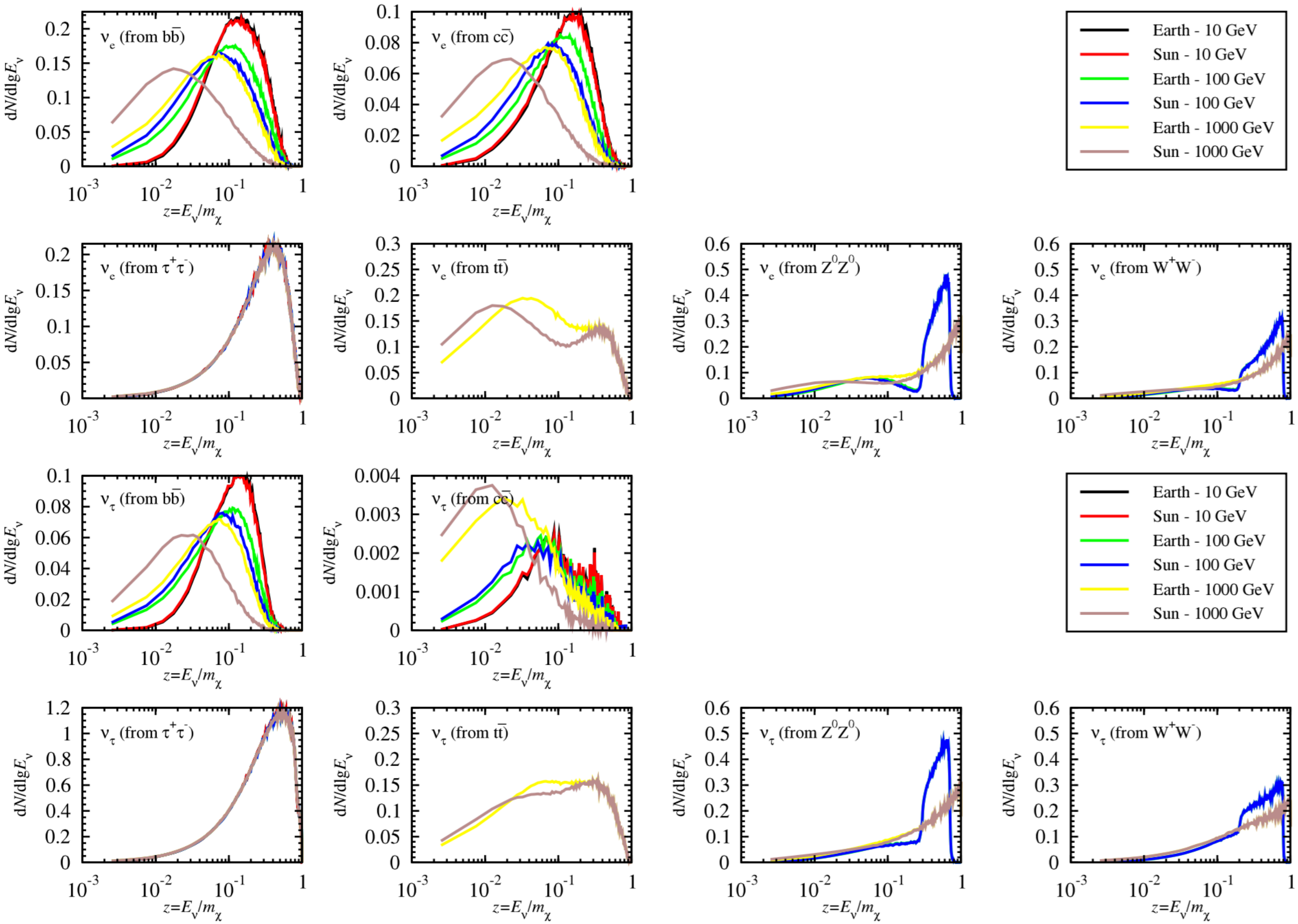
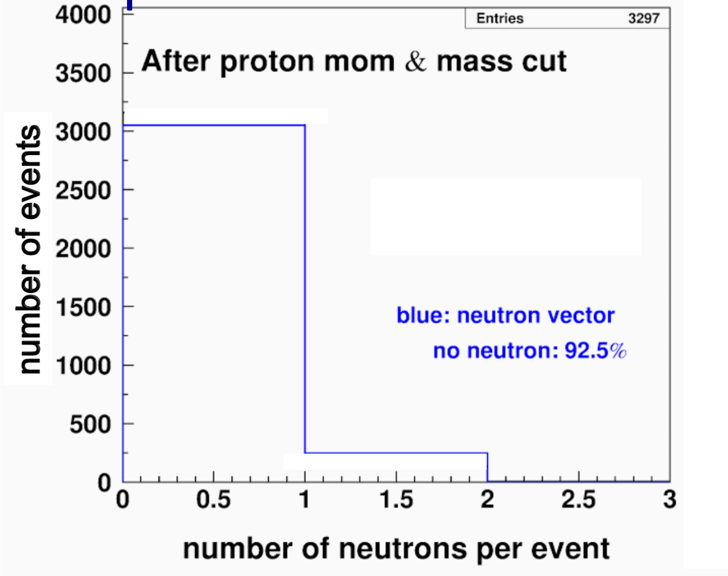


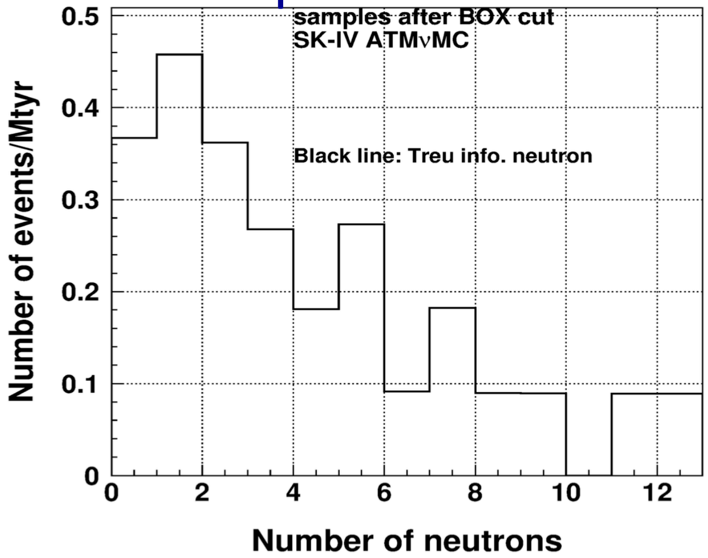
Figure 1. The neutrino yields for electron and tau neutrinos as functions of $z = E_\nu/m_\chi$ for six different WIMP annihilation channels at production in the center of the Sun and the Earth. Note that the muon neutrino yields are the same as the electron neutrino yields and are therefore not shown separately.

→ neutron veto

p → $e^+ \pi^0$ MC



Atmospheric ν MC



background probability reduced from 44% to 9%

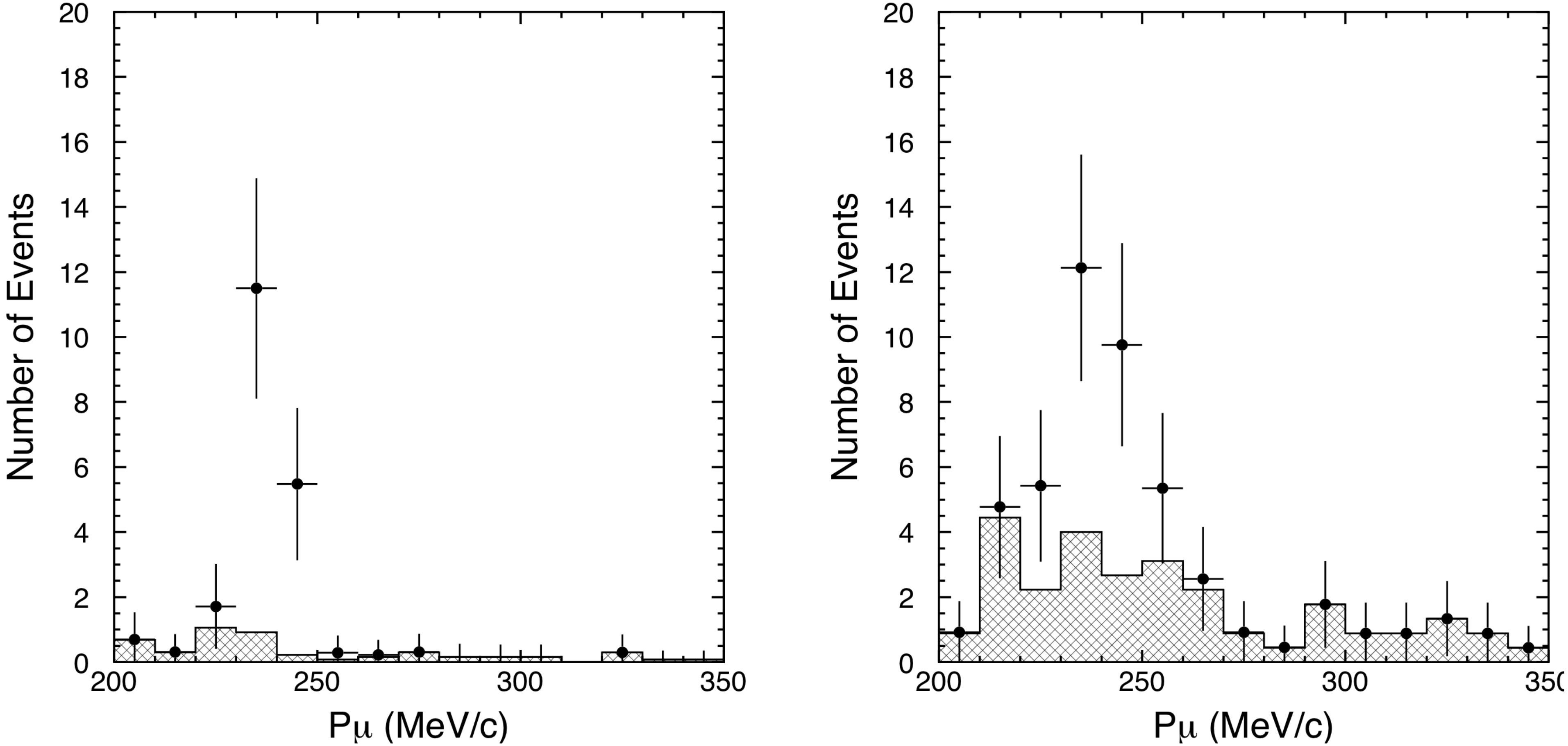


FIG. 143. Reconstructed muon momentum distributions for muons found in the prompt γ search for $p \rightarrow \bar{\nu} K^+$. The hatched histograms show the atmospheric neutrino background and the solid crosses denote the sum of the background and proton decay signal. Here the proton lifetime is assumed to be, 6.6×10^{33} years, just beyond current Super-K limits. The plots on the left and right show the expectation for the 1TankHD and 3TankLD designs, respectively, after a 10 year run. In the latter a second tank is assumed to come online six years after the start of the experiment.

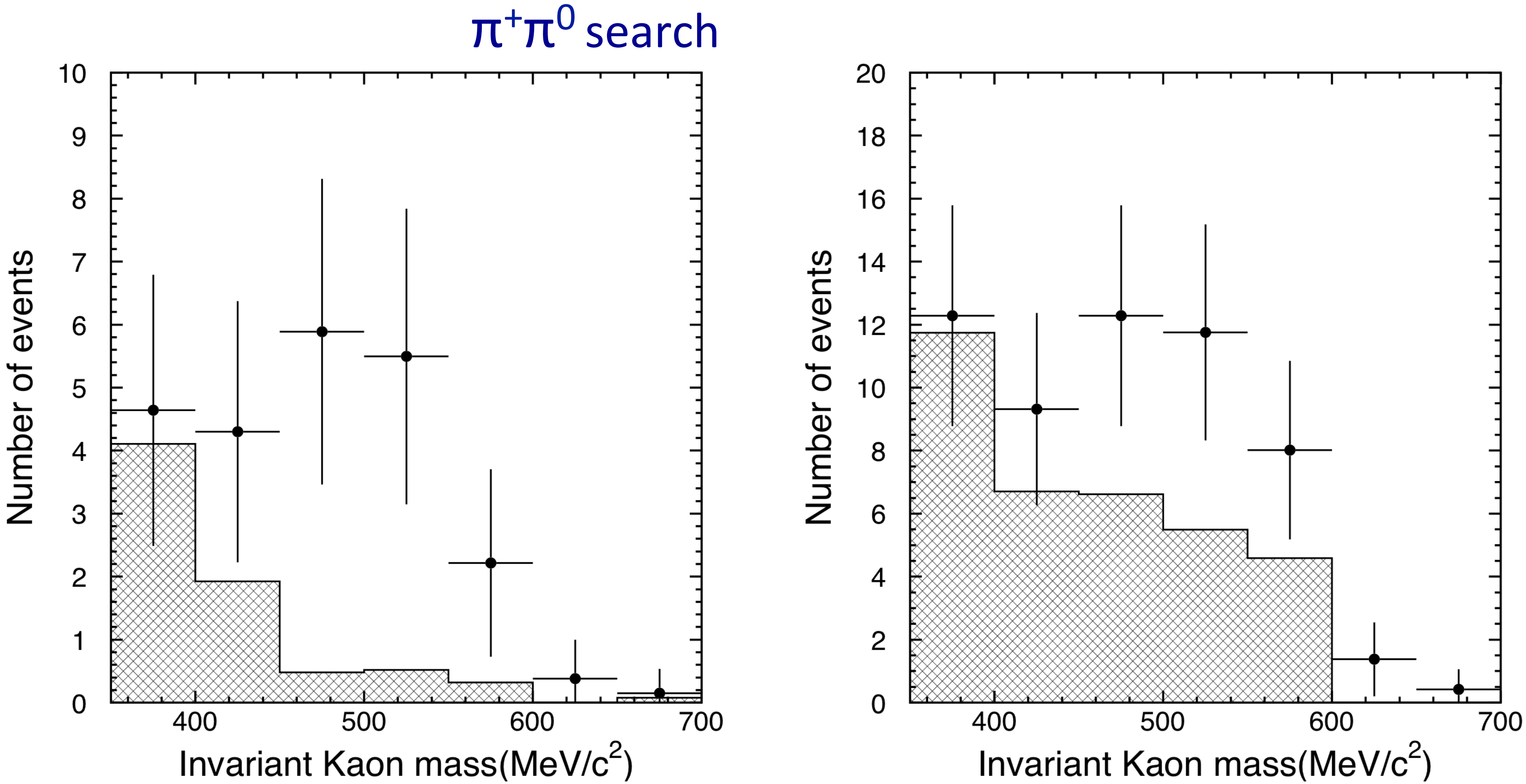


FIG. 144. Reconstructed kaon mass based on the reconstructed final in the $p \rightarrow \bar{\nu} K^+$ modes $\pi^+\pi^0$ search . The hatched histograms show the atmospheric neutrino background and the solid crosses denote the sum of the background and proton decay signal. Here the proton lifetime is assumed to be, 6.6×10^{33} years, just beyond current Super-K limits and all cuts except for the cut on visible energy opposite the π^0 candidate have been applied. The plots on the left and right show the expectation for the 1TankHD and 3TankLD designs, respectively, after a 10 year run. In the latter a second tank is assumed to come online six years after the start of the experiment.

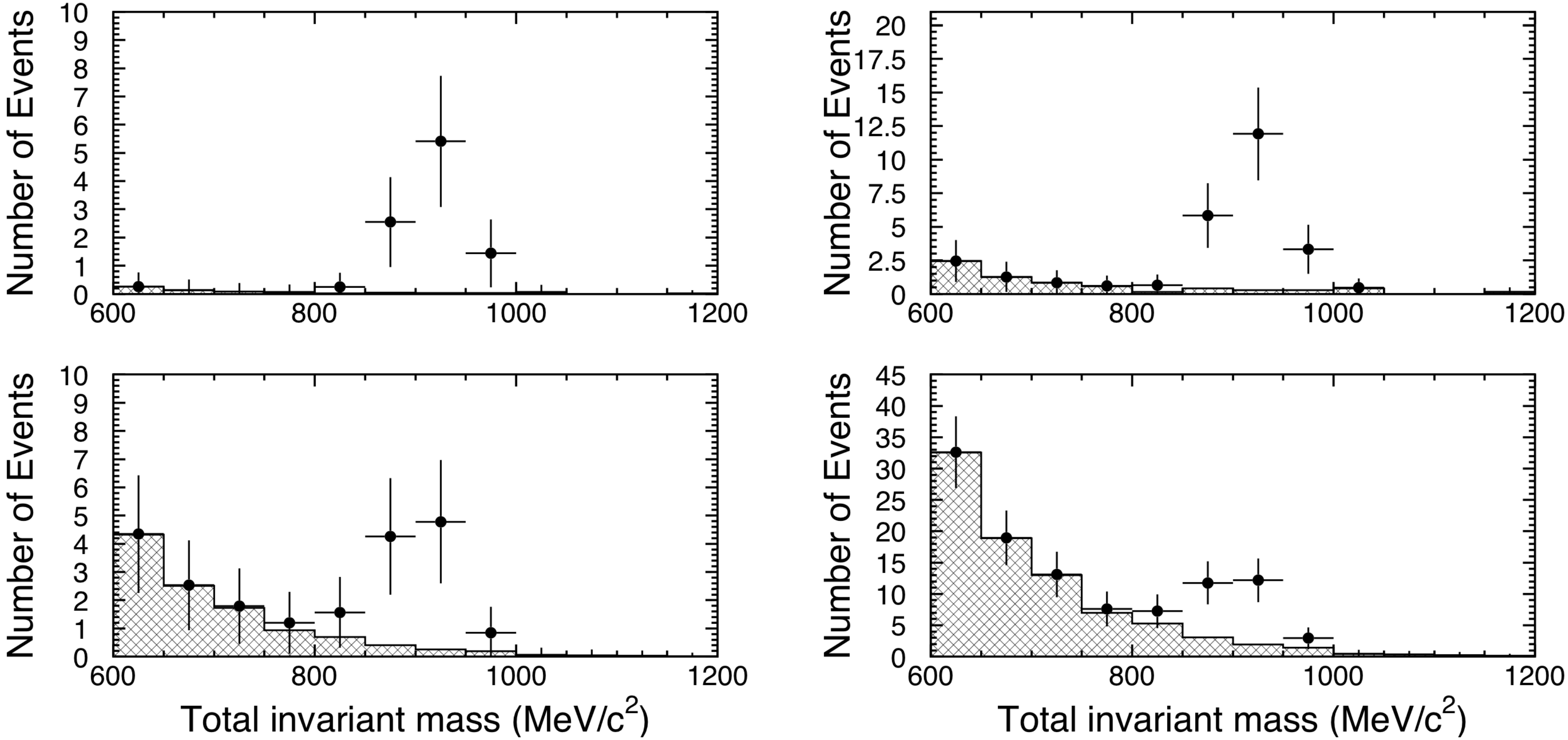


FIG. 138. Reconstructed invariant mass distribution of events passing all steps of the $p \rightarrow e^+\pi^0$ event selection except the invariant mass cut. The hatched histograms show the atmospheric neutrino background and the solid crosses denote the sum of the background and proton decay signal. Here the proton lifetime is assumed to be, 1.7×10^{34} years, just beyond current Super-K limits. The plots on the left and right show the expectation for the 1TankHD and 3TankLD designs, respectively, after a 10 year run. For the former an additional tank is assumed to come online six years after the start of the experiment. In each configuration the free (bound) proton enhanced bin appears in the upper (lower) panel of each figure.

Design	$0 < p_{tot} < 100$MeV/c				$100 < p_{tot} < 250$MeV/c			
	ϵ_{sig} [%]	σ_{ϵ} [%]	Bkg [/Mton·yr]	σ_{Bkg} [%]	ϵ_{sig} [%]	σ_{ϵ} [%]	Bkg [/Mton·yr]	σ_{Bkg} [%]
1TankHD	18.7	6.5	0.06	32.8	19.4	14.9	0.62	31.9
3TankLD	18.8	5.3	0.27	29.0	20.4	15.2	2.17	31.3

TABLE XXXVIII. Signal efficiency and background rates as well as estimated systematic uncertainties for the analysis $p \to e^+\pi^0$ at Hyper-K.

Design	Prompt γ				$\pi^+\pi^0$				p_μ Spectrum		
	ϵ_{sig} [%]	σ_{ϵ} [%]	Bkg	σ_{Bkg} [%]	ϵ_{sig} [%]	σ_{ϵ} [%]	Bkg	σ_{Bkg} [%]	ϵ_{sig} [%]	Bkg	σ_{fit} [%]
1TankHD	12.7	19.0	0.9	27.0	10.8	10.0	0.7	31.0	31.0	1916.0	8.0
3TankLD	7.4	19.0	2.7	25.0	6.7	10.0	3.4	29.0	31.0	1916.0	8.0

TABLE XXXIX. Signal efficiency and background rates as well as estimated systematic uncertainties for the analysis $p \to \bar{\nu}K^+$ at Hyper-K. Background rates are listed as events per Mton·yr.