

April, 2 2025

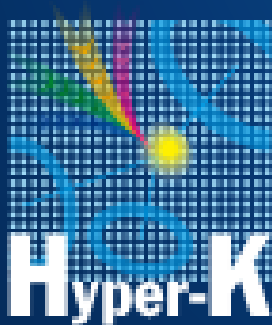
Search for proton decay

N. F. CALABRIA
(on behalf of the Hyper-Kamiokande Collaboration)
INFN and Politecnico di Bari

Neutrinos and Flavour: a stairway to New Physics

JENNIFER2 Project

INFN and University of Pisa
2-3 April 2025, Pisa, Italy



Outline

- Introduction
- State of the art in Super-Kamiokande
- Hyper-Kamiokande overview
- Proton decay in Hyper-Kamiokande
- Conclusions

Introduction

- Matter is very stable (age of the Universe $\sim 10^{10}$ years)
- Electrons must be stable due to the conservation of electric charge
- Neutrons decay if left outside of the nucleus

- What about protons?

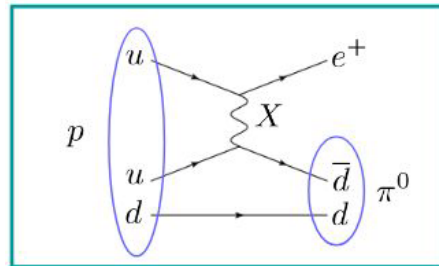
- Conservation of Baryon number introduced to explain matter stability [Weyl, 1929; Wigner, 1949]
Accidental global symmetry in the Standard Model, might be violated.

Proton decay is a valuable tool to probe physics Beyond the Standard Model (BSM)

Grand Unified Theories (GUTs)

- Unify SM gauge groups [Georgi, Glashow, 1974; Fritzsch, Minkowski, 1975]
- GUTs scale: 10^{14-16} GeV, well beyond collider energies.
- Lepton and baryon numbers are not conserved: protons can decay.

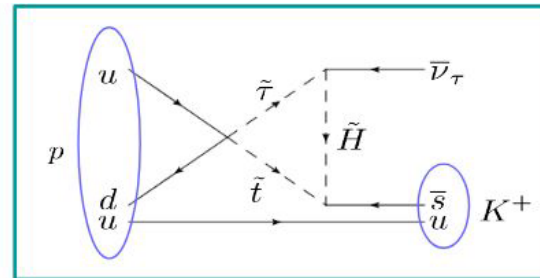
$$p \rightarrow e^+ \pi^0$$



SU(5)

$$\tau \sim 10^{30-40} \text{ years}$$

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



SUSY SU(5)

$$\tau \sim 10^{30-40} \text{ years}$$

Many models and predictions!

P S B Dev et al 2024 J. Phys. G: Nucl. Part. Phys. 51 033001

Many recent talks here:

<https://www.int.washington.edu/programs-and-workshops/25-91W>

SNSF-INT Joint Workshop: Baryon Number Violation:
From Nuclear Matrix Elements to BSM Physics
January 13-17, 2025

Institute for Nuclear Theory, University of Washington,
Seattle (USA)

How to search for proton decay

- Predicted proton lifetimes $> 10^{30}$ years
 - Age of the Universe: 10^{10} years
- Watch many (10^{30} or more!) protons for (relatively) short time
need many observable protons!
 - Large scale water Cherenkov detectors are a good choice:
 - Water is cheap and abundant
 - Water contains 10 protons per molecule, of which 2 are free (no nuclear momentum)
 - Water Cherenkov detectors are scalable

Super-Kamiokande: state of the art

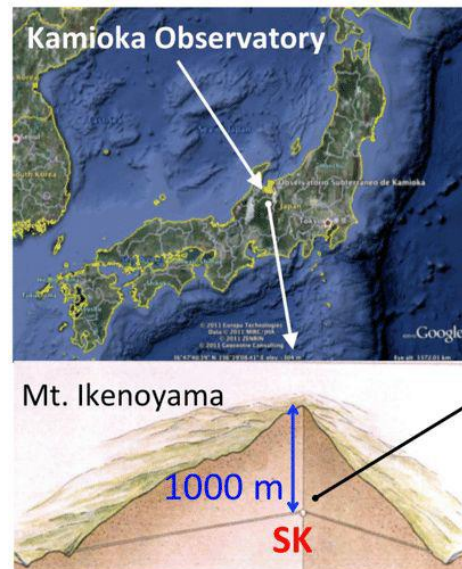
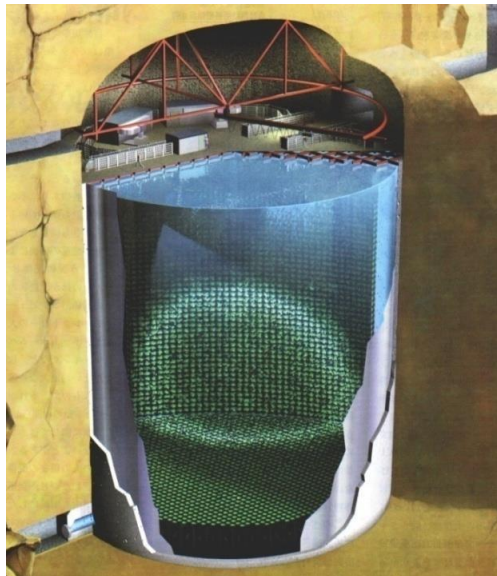
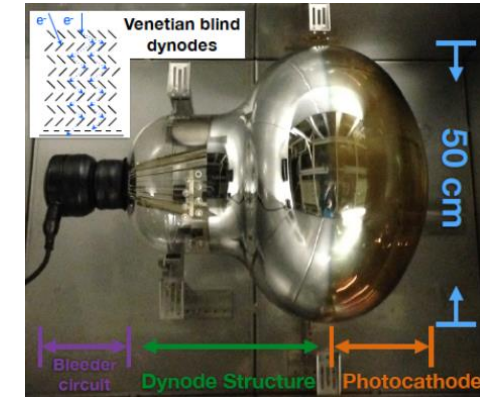
Location: Kamioka mine, Japan, ~1000 m underground below Mount Ikeno.

39 m x 42 m cylindric tank filled with 50 kton of ultrapure water:

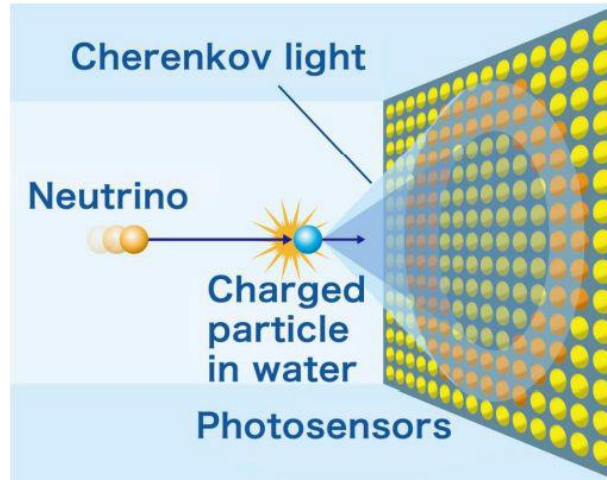
- **Inner Detector (ID):** 11k 50 cm Photomultiplier Tubes (PMTs) (40% coverage) facing inwards.
- **Outer Detector (OD):** 2k 20cm PMTs facing outwards

Some research topics in SK:

- **Proton decay**
- Neutrino oscillations (2015 Nobel Prize)
- Neutrino astrophysics

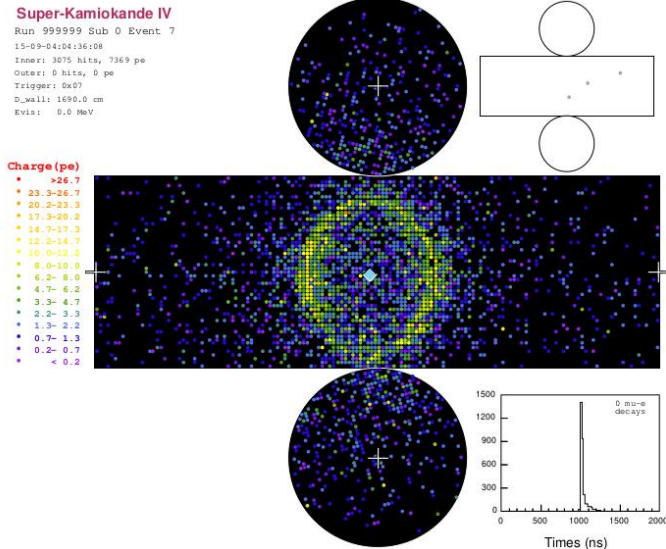


Events in Super-Kamiokande

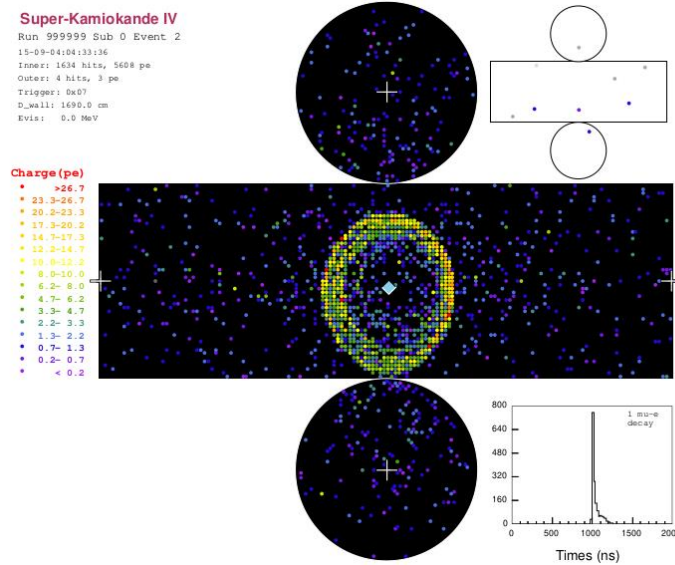


Monte Carlo simulated events

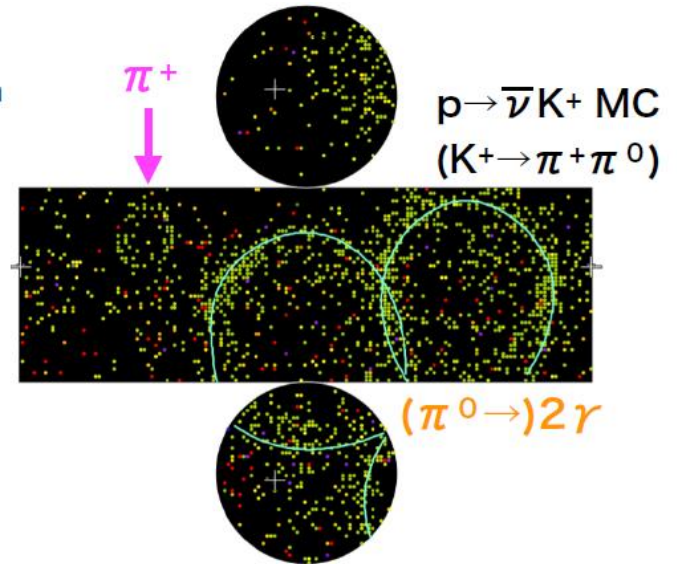
Showering (e-like)



Non showering (muon-like)



Multi-ring

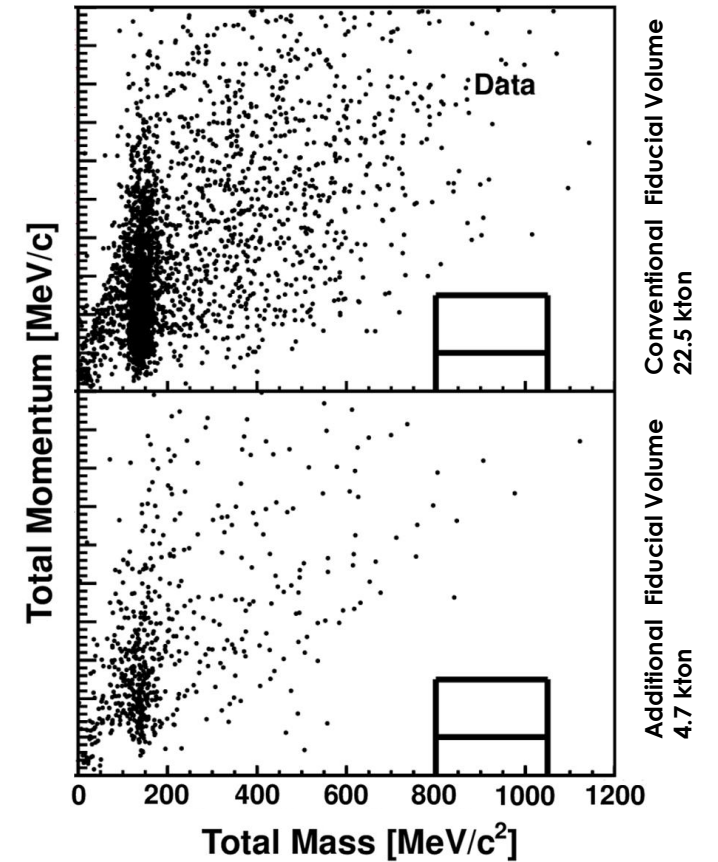
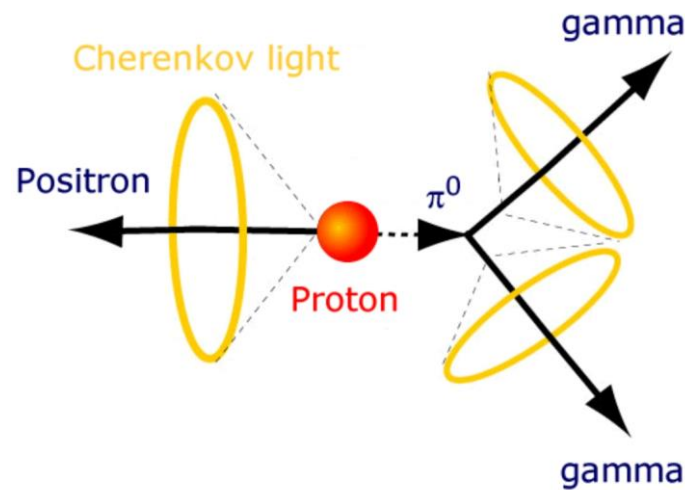
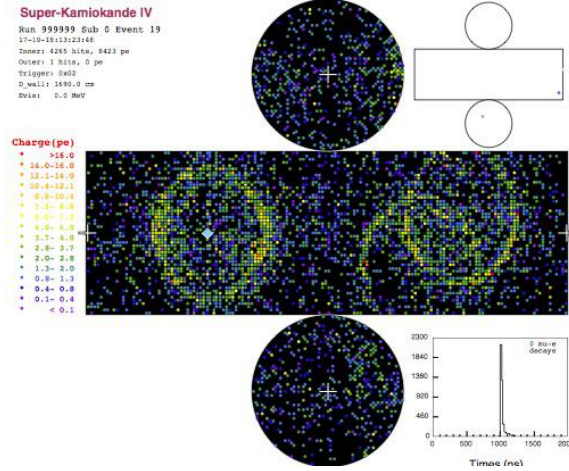


Event reconstruction

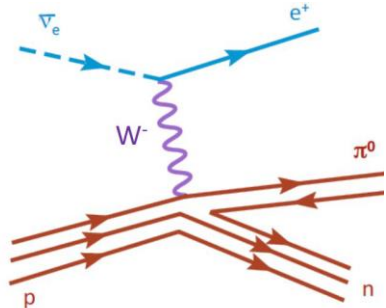
	APfit	fiTQun
Type of fit	Sequential fits	Single log-likelihood function minimization $L(\mathbf{x}) = \prod_j^{\text{unhit}} P_j(\text{unhit} \mathbf{x}) \prod_i^{\text{hit}} [1 - P_i(\text{unhit} \mathbf{x})] f_q(q_i \mathbf{x}) f_t(t_i \mathbf{x})$
Used by	Super-Kamiokande	T2K, MiniBooNE, Super-Kamiokande, Hyper-Kamiokande
Max # rings	5	6
PID	e^\pm, μ^\pm	e^\pm, μ^\pm, π^\pm

- fiTQun is part of the official reconstruction software suite for Hyper-Kamiokande.
- Machine Learning algorithms for Hyper-Kamiokande are under development and study.

$p \rightarrow e^+ \pi^0$ in Super-Kamiokande



Final state: three rings visible, all three showering.
Signal from both free (hydrogen) and bound (oxygen) protons.
Nuclear effects are an unavoidable source of inefficiency.



Typical background from atmospheric ν interaction

Neutron tagging algorithm (~20% efficiency) applied to reduce background

Exposure: 450 kton*year

	Conventional FV	Additional FV
Signal efficiency	39.8%	25.8%
Expected background	0.49 events	0.10 events

Total Exp. Bkg
1.3 ev / Mton * yr

No candidates: lower limit on proton partial lifetime set at

$\tau > 2.4 \times 10^{34}$ years

$p \rightarrow \bar{\nu} K^+$ in Super-Kamiokande

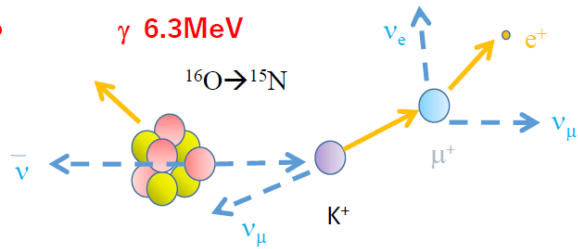
K^+ Cherenkov threshold in water is 560 MeV/c
most of K^+ can't emit a ring

Most of K^+ produced stop in water (~89%)

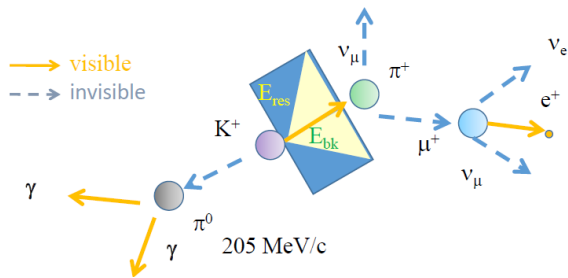
Look for K^+ decays:

- $K^+ \rightarrow \nu \mu^+$: 64%
($P = 236 \text{ MeV/c}$ if decay at rest)

γ emission
prob. 40%

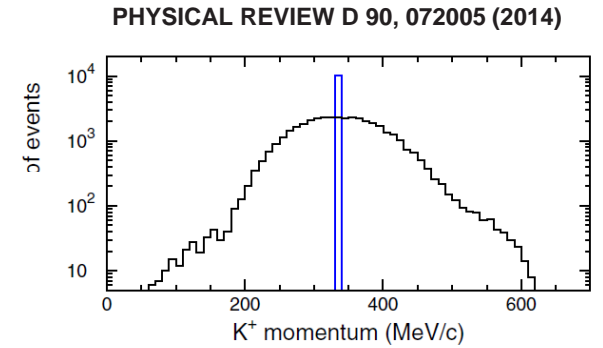
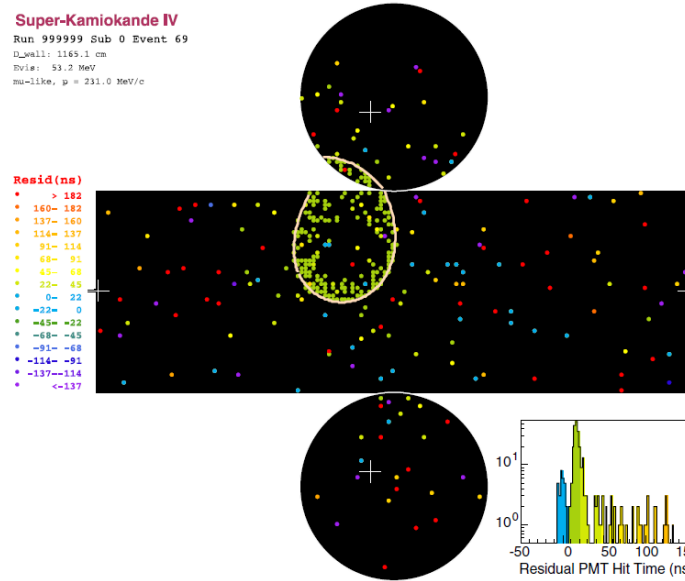


- $K^+ \rightarrow \pi^+ \pi^0$: 21%
($P = 205 \text{ MeV/c}$ if decay at rest)



Super-Kamiokande IV
Run 999999 Sub 0 Event 69
D_wall: 1165.1 cm
E_vis: 53.2 MeV
mu-Like, $p = 231.0 \text{ MeV/c}$

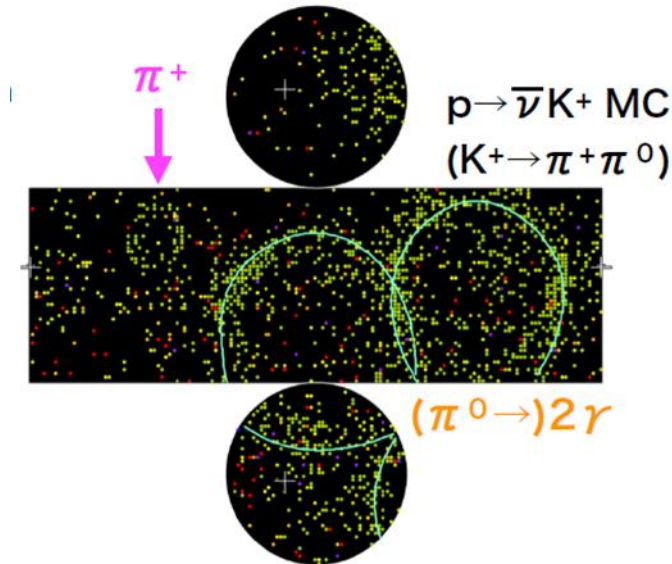
Resid (ns)
• > 182
• 160-182
• 137-160
• 114-137
• 91-114
• 68-91
• 45-68
• 22-45
• 0-22
• -22-0
• -45-22
• -68-45
• -91-68
• -114-91
• -137-114
• < -137



2 possible methods for $K^+ \rightarrow \nu \mu^+$ search:

- Prompt γ
- Spectrum fit

Dominant background:
 $\nu p \rightarrow \nu \Lambda K^+, \Lambda \rightarrow p \pi^-$



Dominant background:
 $\nu \mu \text{ CC } 1\pi$

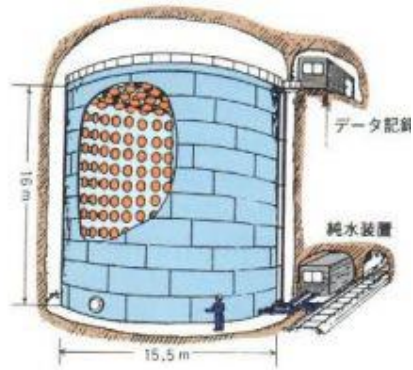
Three methods combined
over 260 kton*year
exposure:

$$\tau > 5.9 \times 10^{33} \text{ years}$$

The future: Hyper-Kamiokande (Hyper-K, HK)



Kamiokande



3 kton

1983 - 1996

Supernova SN1987A neutrinos



Super-Kamiokande

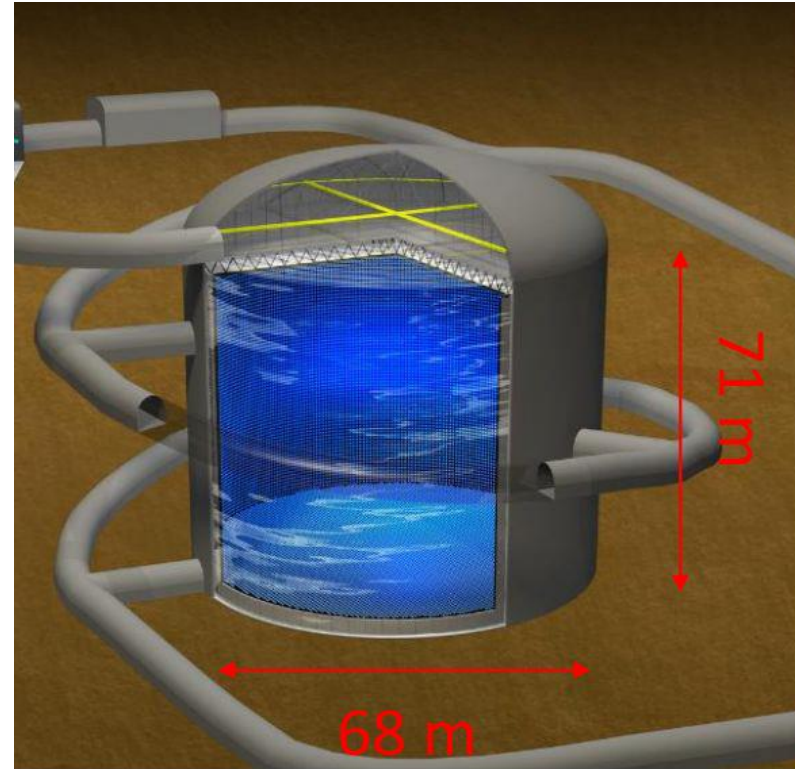


50 kton

1996 - Present

Neutrino oscillations

Hyper-Kamiokande

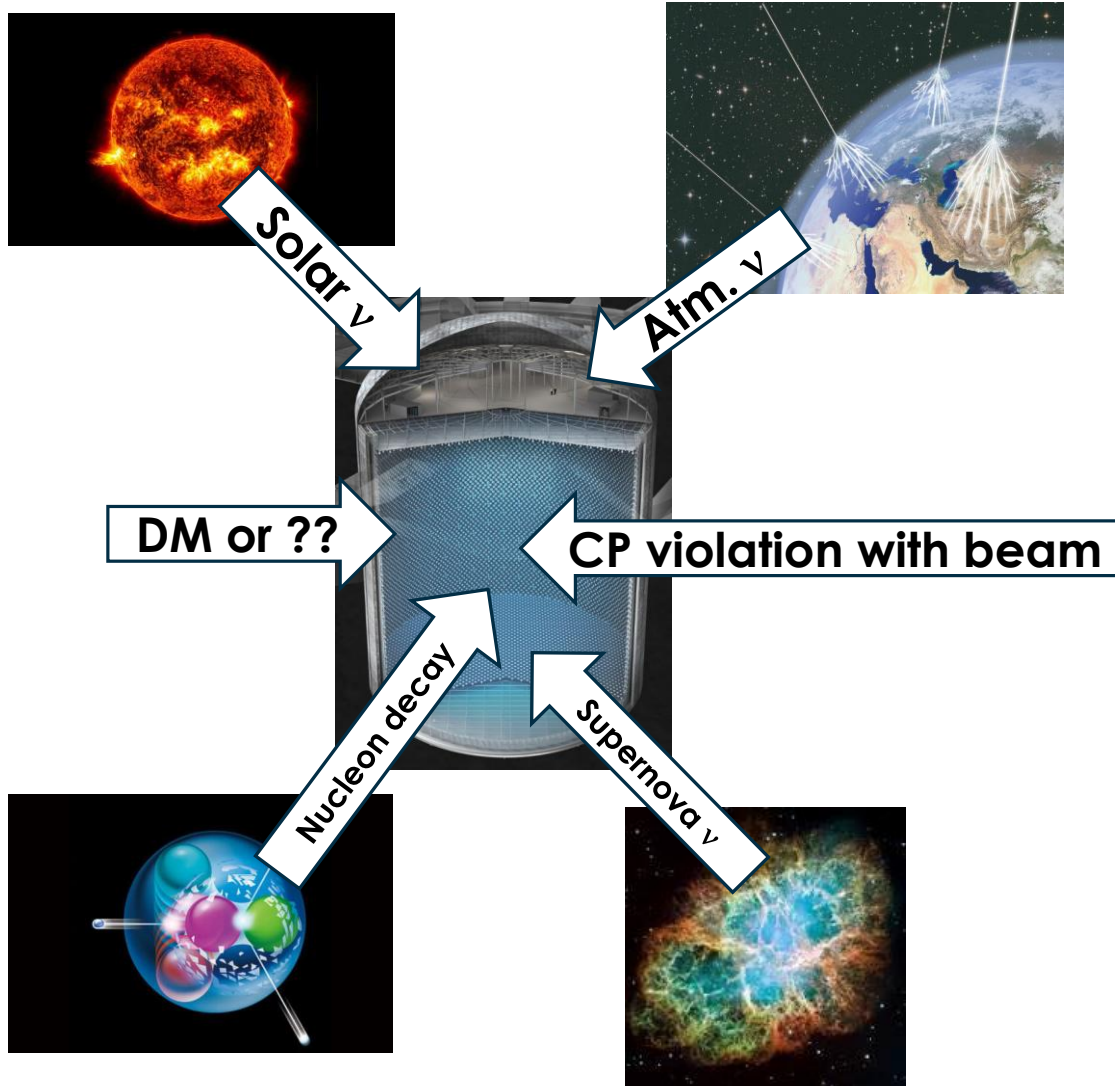


260 kton

2027 - ...

Proton decay? + much more...

Hyper-K is a multipurpose experiment



Very broad physics program,
many opportunities for discovery!

2020 – Construction started
2027 – Operation start



2 Main hosts:

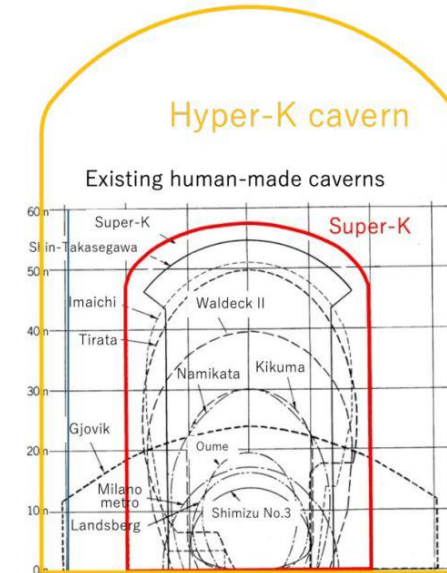
- U-Tokyo for HK detector
- KEK J-PARC for beam/near detectors

Hyper-K Overview

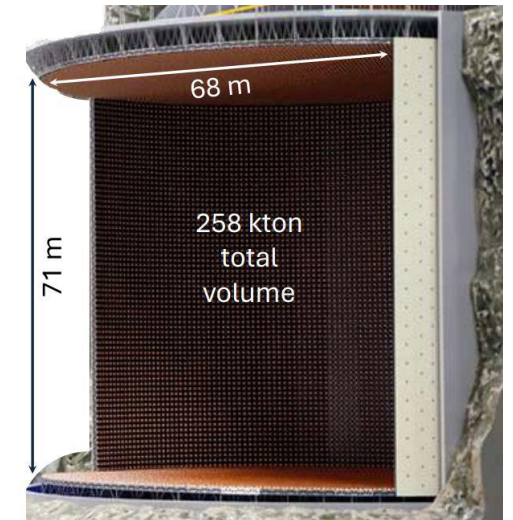
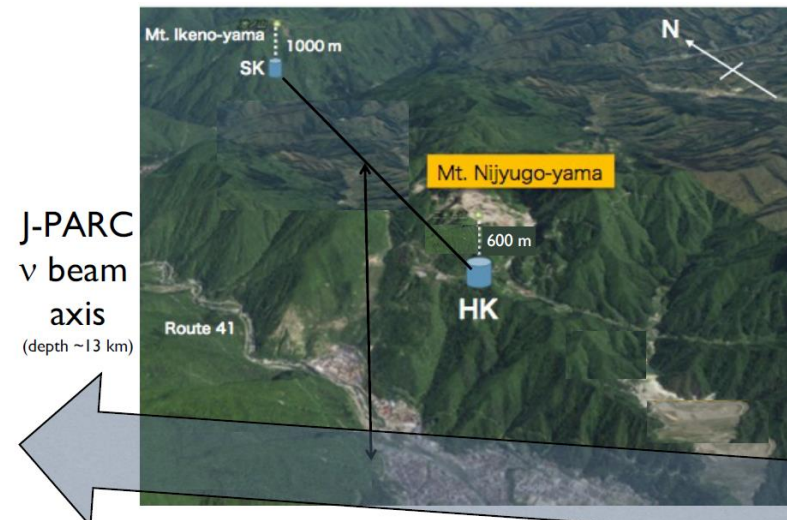
Hosted in the world's largest human-made cavern

Excavation is in progress:

- Access tunnel: done
- Dome: done
- Cavern: in progress



	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% ($\times 2$ efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton



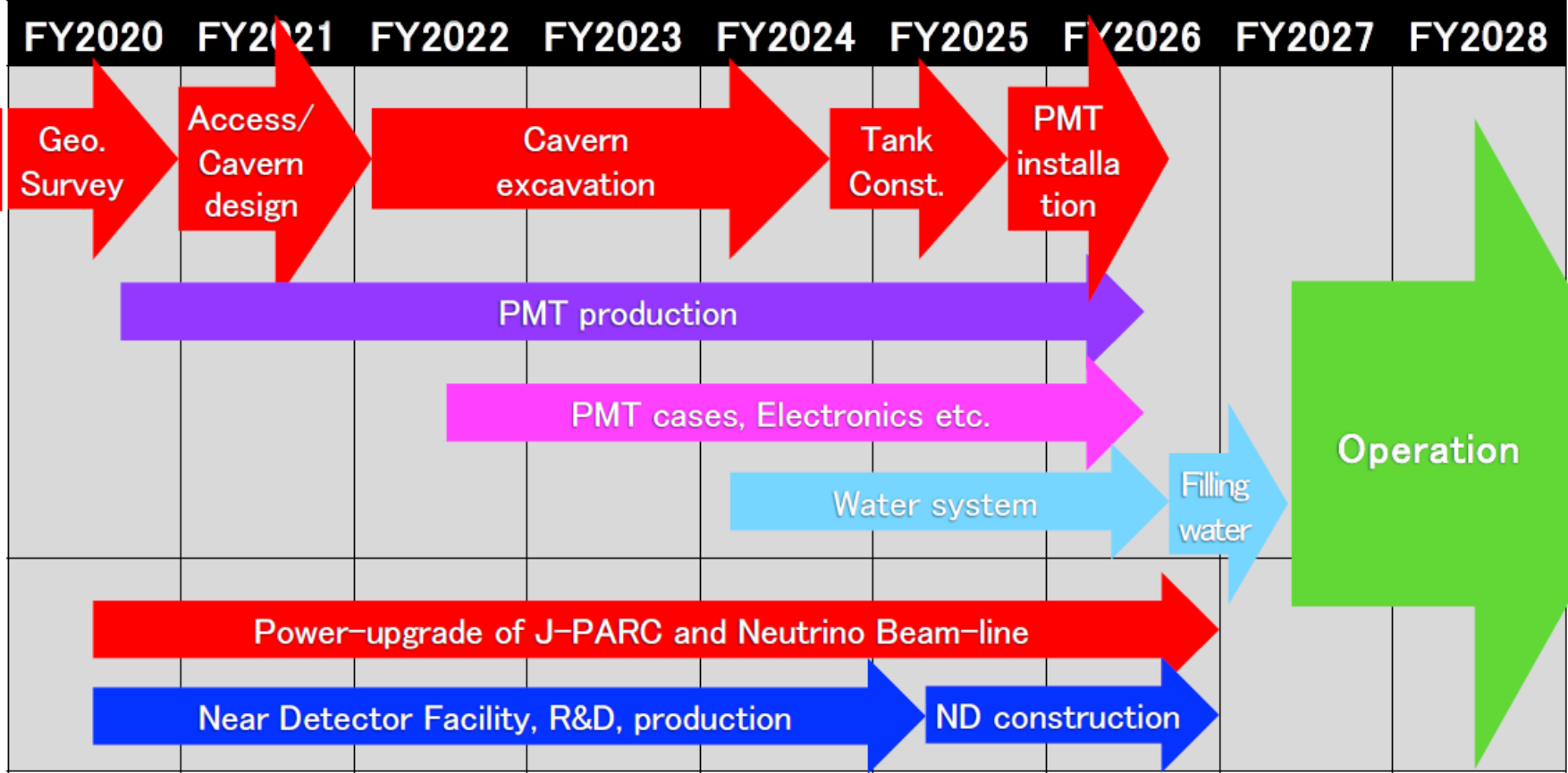
Hyper-K Overview



HK dome completed – Oct. 3, 2023

Hyper-K Status Schedule

Aiming at operation start in 2027



Cavern Tank, installation

Photosensors

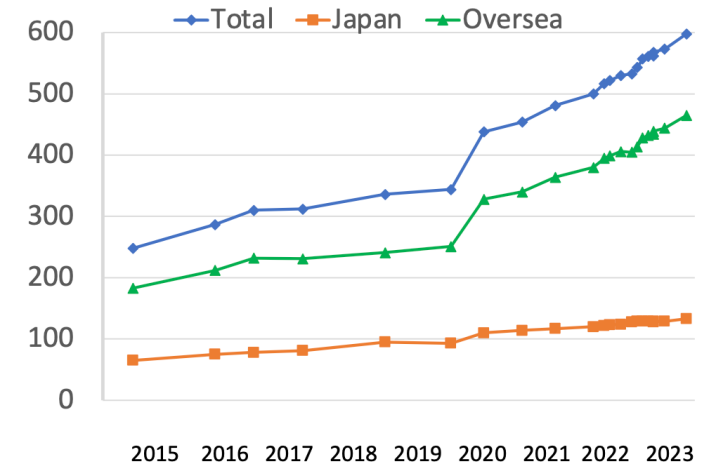
Near detectors, Intermediate Water Cherenkov Detector (IWCD)

Hyper-K Collaboration

22 countries, 104 institutes, 583 members as of April 1, 2024



NUMBER OF COLLABORATORS

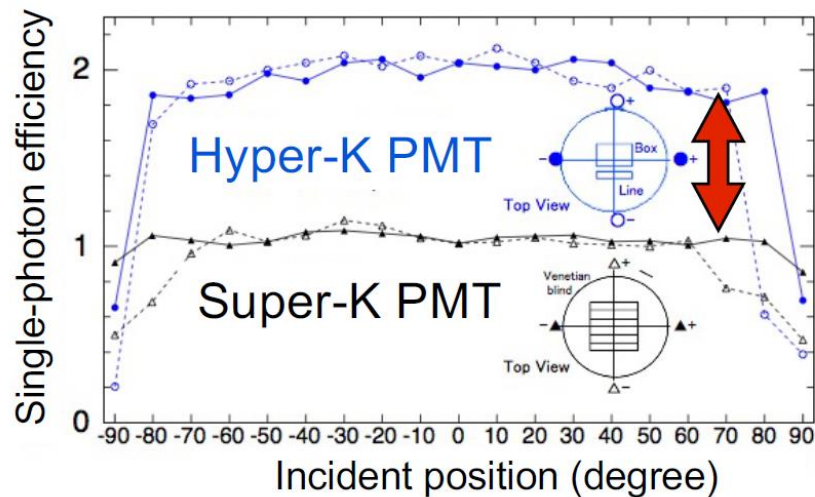


Hyper-K Collaboration Meeting,
October 2024, Toyama.

Hyper-K as a Nucleon Decay Discovery Experiment

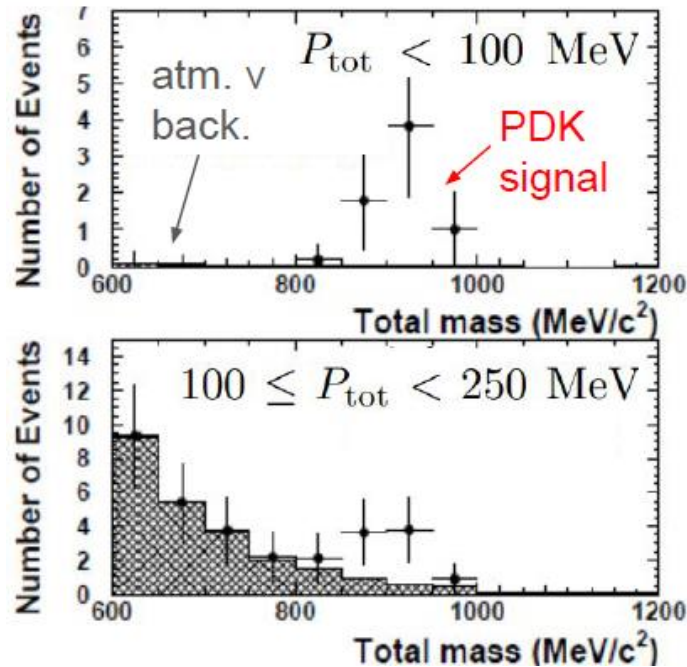
- Fiducial Mass ~ 8 times SK: 186 kton (HK) vs. 22.5 kton (SK)
- Upgraded photosensors (50 cm Box & Line PMTs)
 - 2x detection efficiency
 - 2x timing resolution
 - 2x pressure tolerance

Expected ~1 order of magnitude sensitivity gain for proton decay search.
Start probing lifetimes ~ 10^{35} years



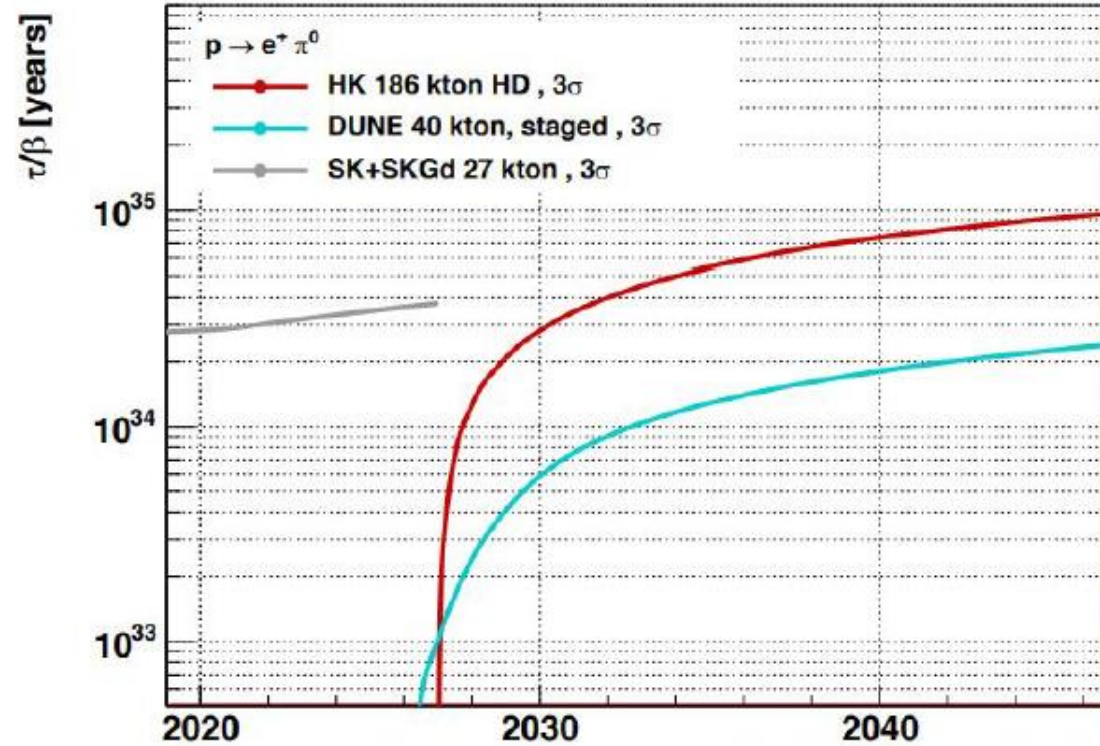
$p \rightarrow e^+ \pi^0$ in Hyper-K

Assuming 10 years of HK exposure and lifetime limit \sim SK (1.7×10^{34} years)



$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

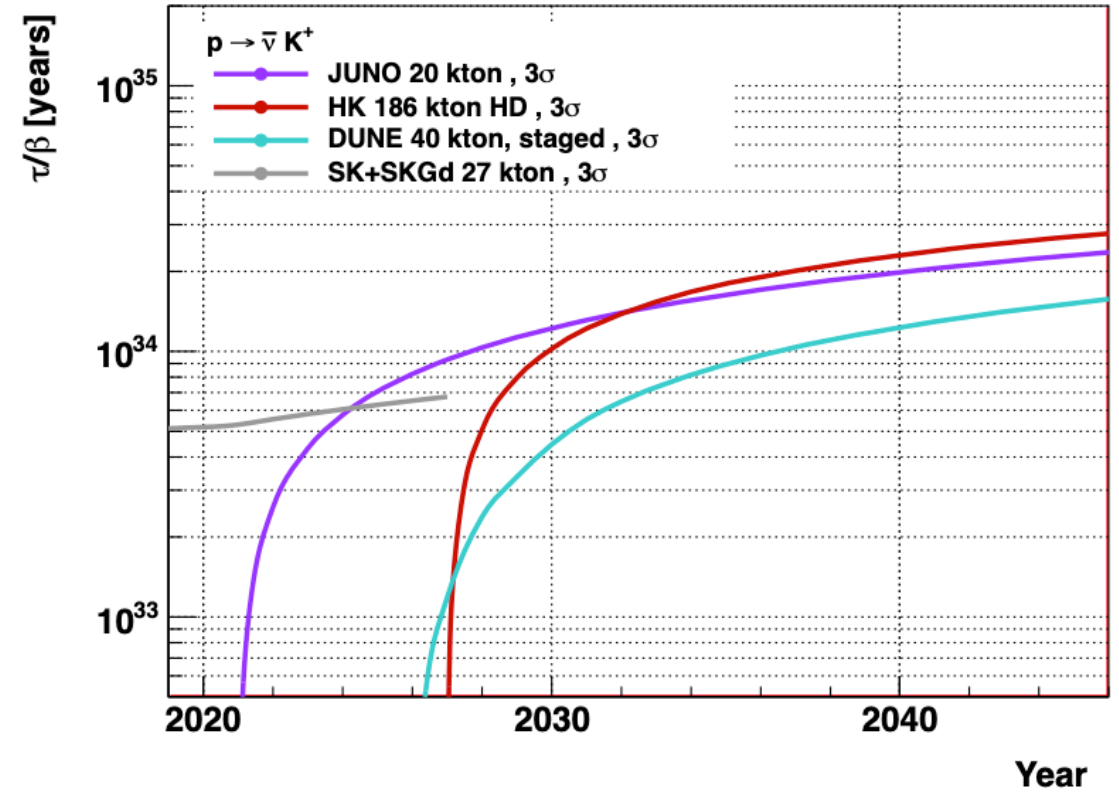
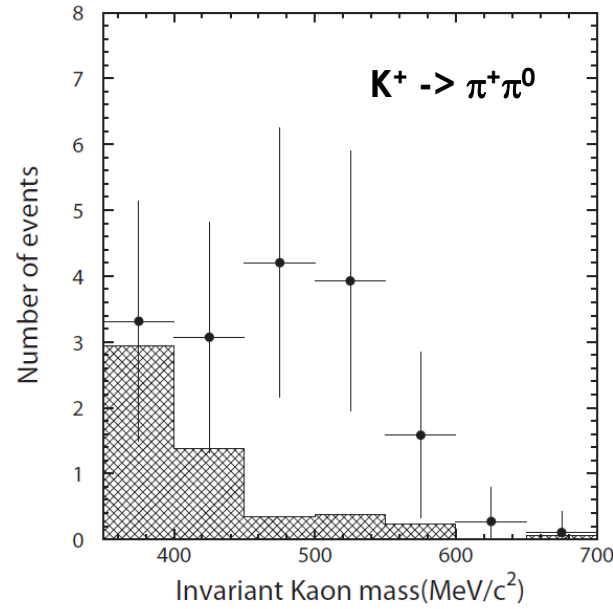
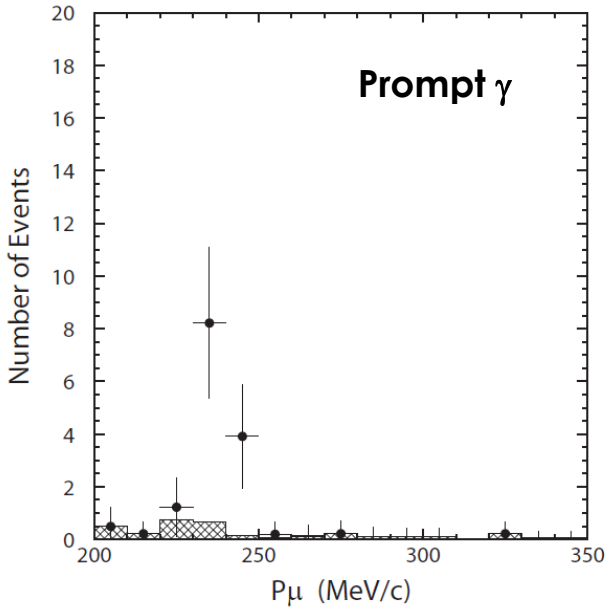
Probe $\tau \sim 10^{35}$ years



HK background is \sim 50% of SK

$p \rightarrow \bar{\nu} K^+$ in Hyper-K

10 years HK exposure assuming $\tau = 6.6 \times 10^{33}$ years



Prompt γ		$\pi^+ \pi^0$		p_μ Spectrum		
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	σ_{fit} [%]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2	31.0	1916.0	8.0

Other channels

Hyper-K TDR, Nov 2018, arXiv:1805.04163

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \rightarrow e^+ \pi^0$	7.8×10^{34}	1.6×10^{34}
$p \rightarrow \bar{\nu} K^+$	3.2×10^{34}	0.7×10^{34}
$p \rightarrow \mu^+ \pi^0$	7.7×10^{34}	0.77×10^{34}
$p \rightarrow e^+ \eta^0$	4.3×10^{34}	1.0×10^{34}
$p \rightarrow \mu^+ \eta^0$	4.9×10^{34}	0.47×10^{34}
$p \rightarrow e^+ \rho^0$	0.63×10^{34}	0.07×10^{34}
$p \rightarrow \mu^+ \rho^0$	0.22×10^{34}	0.06×10^{34}
$p \rightarrow e^+ \omega^0$	0.86×10^{34}	0.16×10^{34}
$p \rightarrow \mu^+ \omega^0$	1.3×10^{34}	0.28×10^{34}
$n \rightarrow e^+ \pi^-$	2.0×10^{34}	0.53×10^{34}
$n \rightarrow \mu^+ \pi^-$	1.8×10^{34}	0.35×10^{34}

10 years of HK exposure

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \rightarrow e^+ \nu \nu$	10.2×10^{32}	1.7×10^{32}
$p \rightarrow \mu^+ \nu \nu$	10.7×10^{32}	2.2×10^{32}
$p \rightarrow e + X$	31.1×10^{32}	7.9×10^{32}
$p \rightarrow \mu^+ X$	33.8×10^{32}	4.1×10^{32}
$n \rightarrow \nu \gamma$	23.4×10^{32}	5.5×10^{32}
$np \rightarrow e^+ \nu$	6.2×10^{32}	2.6×10^{32}
$np \rightarrow \mu^+ \nu$	4.2×10^{32}	2.0×10^{32}
$np \rightarrow \tau^+ \nu$	6.0×10^{32}	3.0×10^{32}

30 years of HK exposure

Also neutron – antineutron oscillation analysis possible:
 Searched in SK with 90 kton*year
 exposure. $\tau > 2.7 \times 10^8$ s
 [PHYSICAL REVIEW D 91, 072006 (2015)]

Summary

- Proton decay is a valuable probe to test Physics Beyond the Standard Model
- Hyper-K will play a central role in exploring the future of particle physics
- Hyper-K will bring proton decay searches to proton lifetimes $\sim 10^{35}$ years
- Many exciting challenges and discoveries ahead: data taking is expected to start in 2027!

THANK YOU FOR YOUR ATTENTION!