Search for Nucleon Decay with Hyper-K

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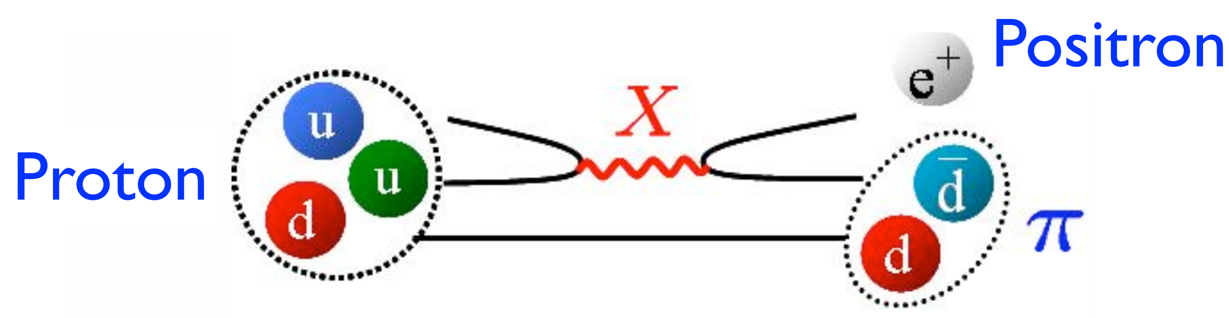
for Hyper-Kamiokande proto-collaboration

EPS-HEP 2019, July 11, 2019

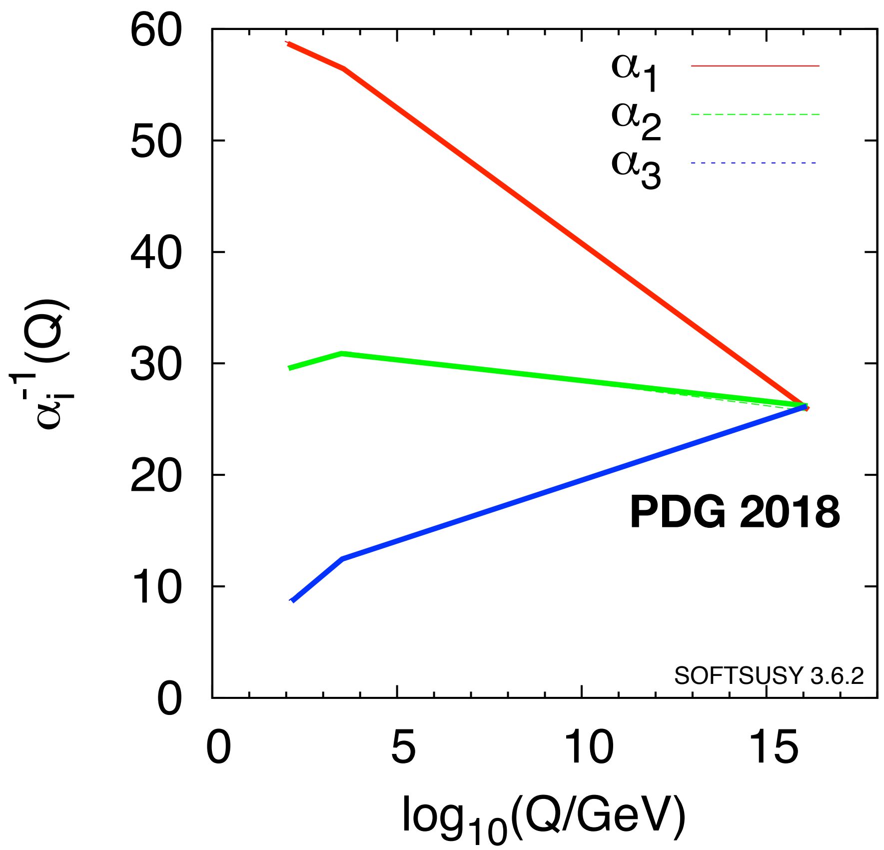
Nucleon Decay

- Nucleon decay can occur via a direct transition from quark into lepton
  - Forbidden in the Standard Model
  - **→ Clear evidence of beyond the standard model if it's observed**
- Grand Unified Theory (GUT)
  - Attempt to unify elementary particles (at $10^{15\text{-}16}$ GeV)
  - → Imply nucleon decay
  - Many GUT models and variety of predictions on nucleon lifetime, decay modes and branching ratio
- Nucleon decay search is an unique prove for GUT and physics in very high energy
- **Hyper-K aims to explore $\tau_p > 10^{35}$ yrs**

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



Unification of running couplings



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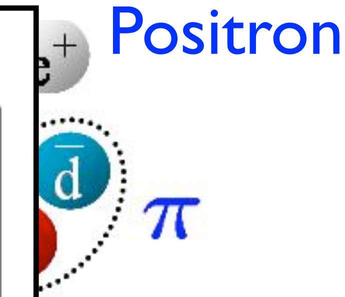

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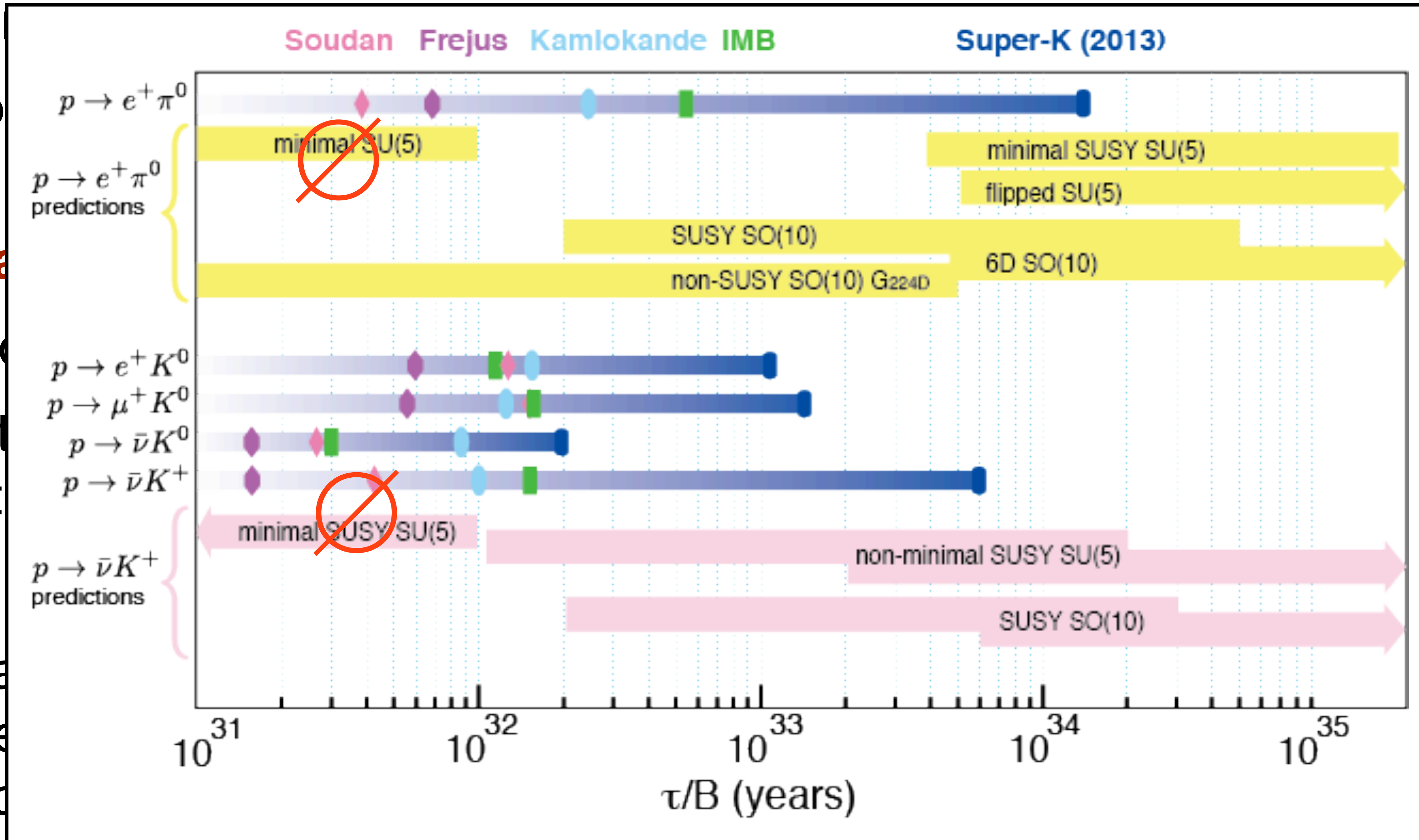

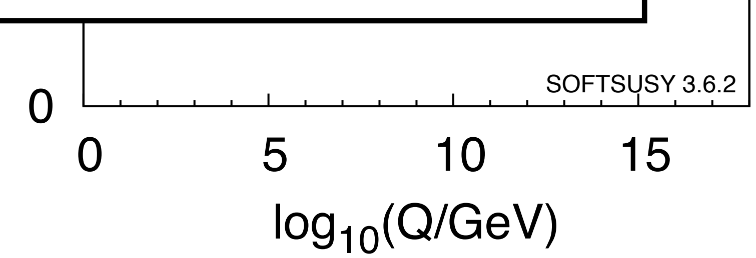

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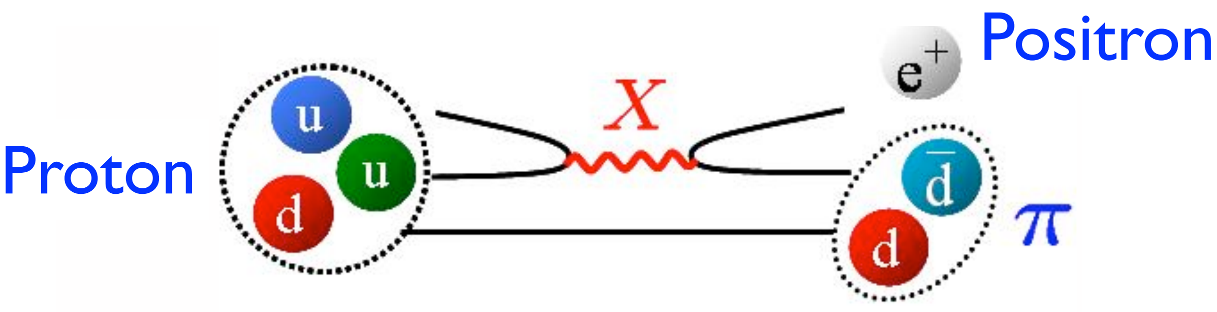

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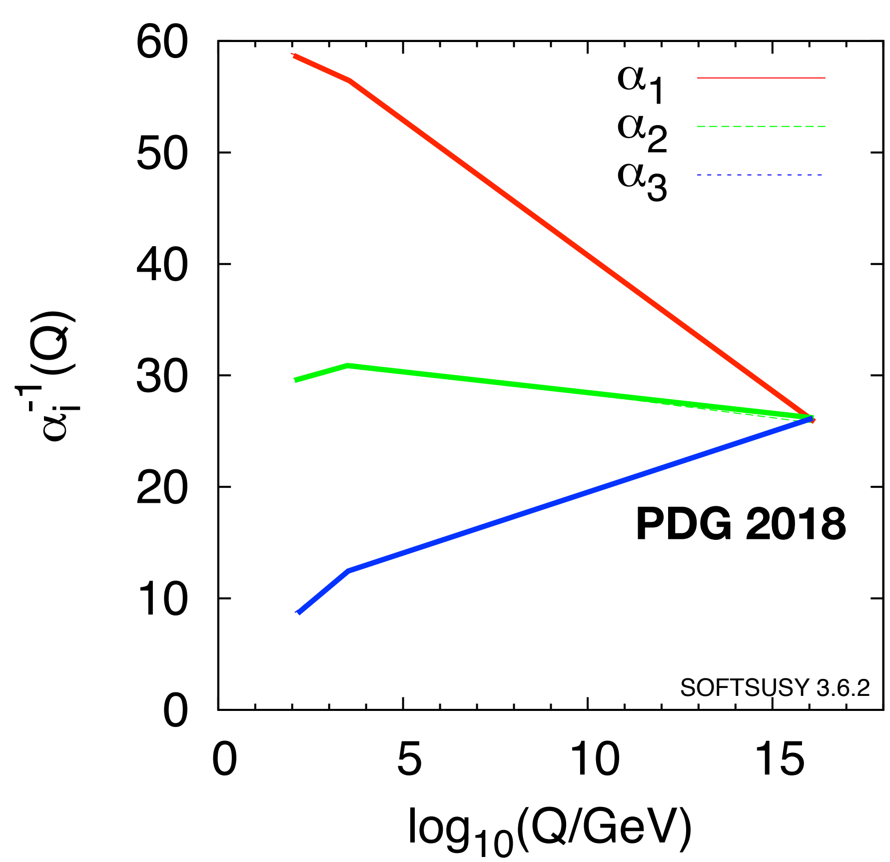
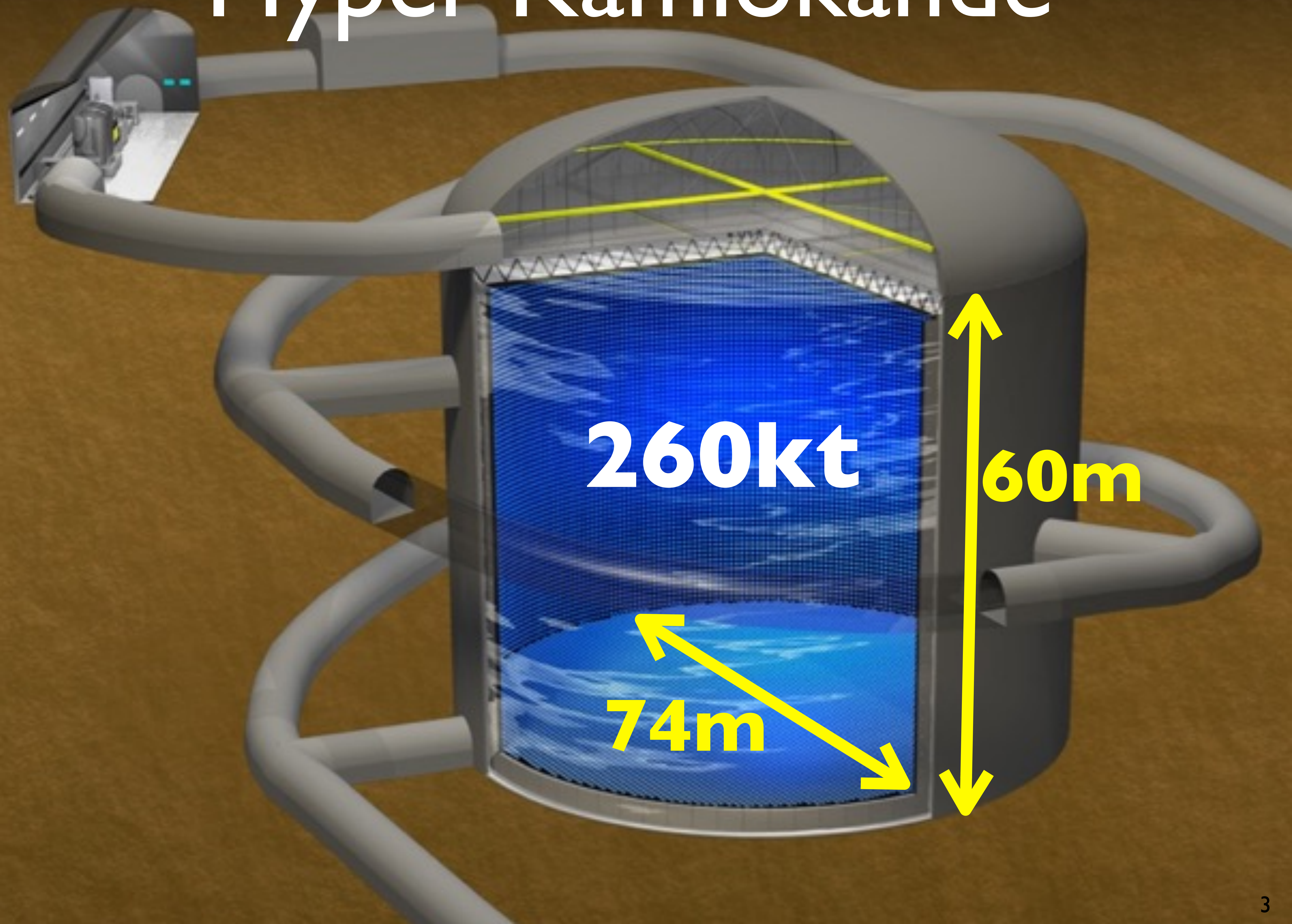
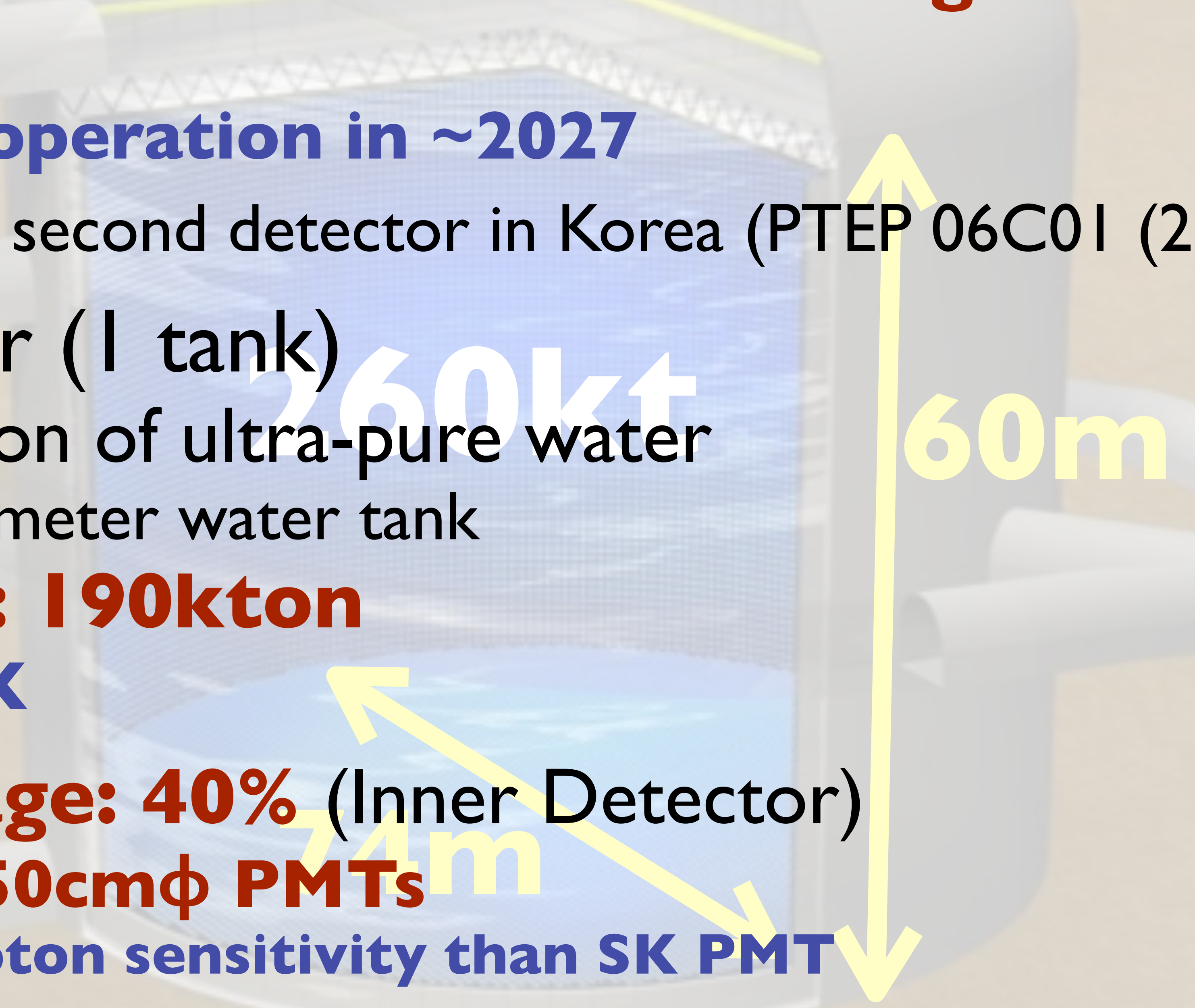


Hyper-Kamiokande



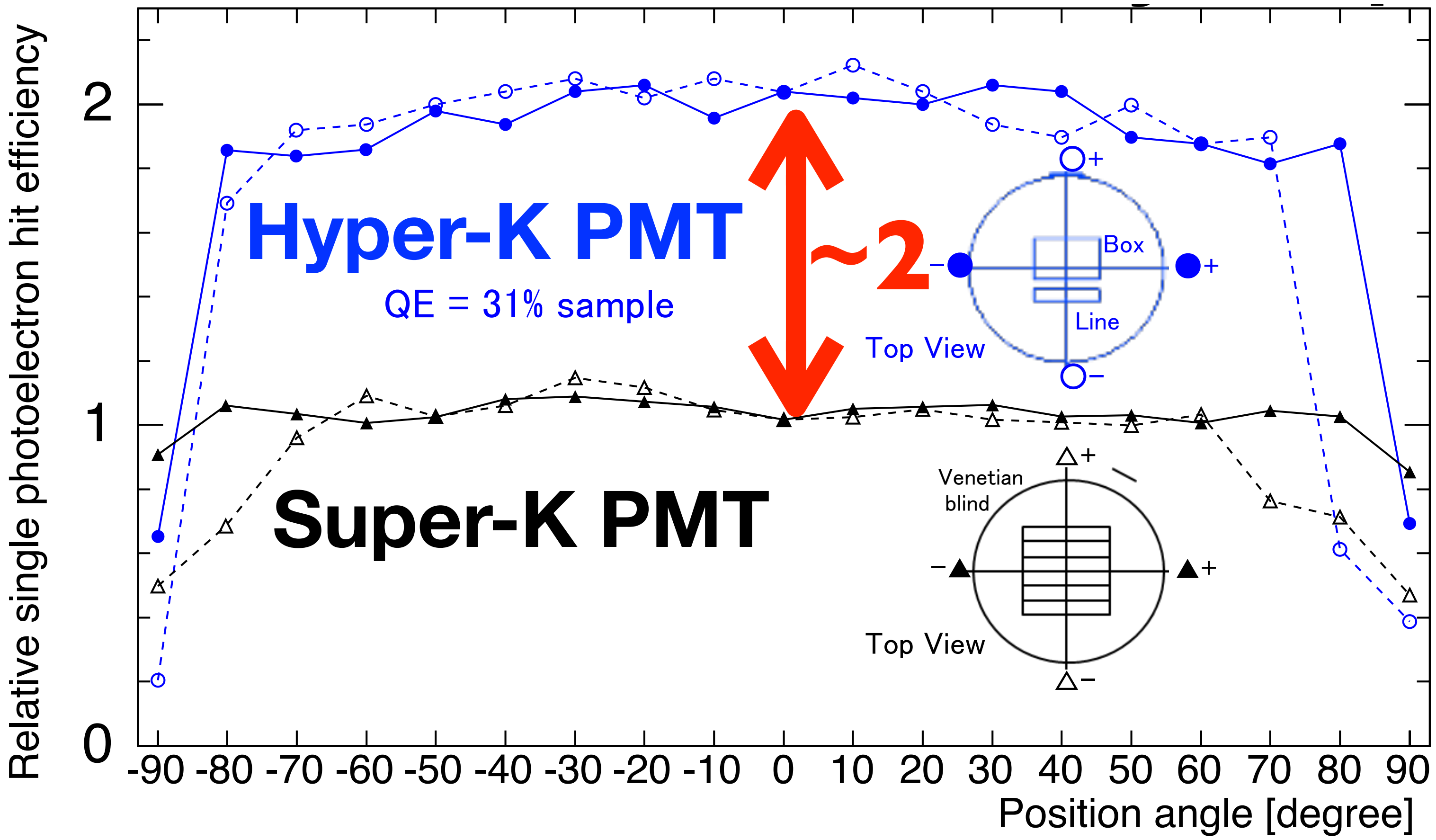
Hyper-Kamiokande

- **Next generation water Cherenkov detector**
  - Construct two detectors in stage
  - **Construction of the first detector begins in April 2020**
    - **Aim to start operation in ~2027**
    - An option of the second detector in Korea (PTEP 06C01 (2018))
- The first detector (1 tank)
  - Filled with 260kton of ultra-pure water
    - 60m tall x 74 diameter water tank
  - **Fiducial mass: 190kton**
    - **~10 x Super-K**
  - **Photo-coverage: 40%** (Inner Detector)
    - 40,000 of **new 50cmϕ PMTs**
      - **x2 higher photon sensitivity than SK PMT**
  - Hyper-K sensitivity shown in this talk assumes 1 tank

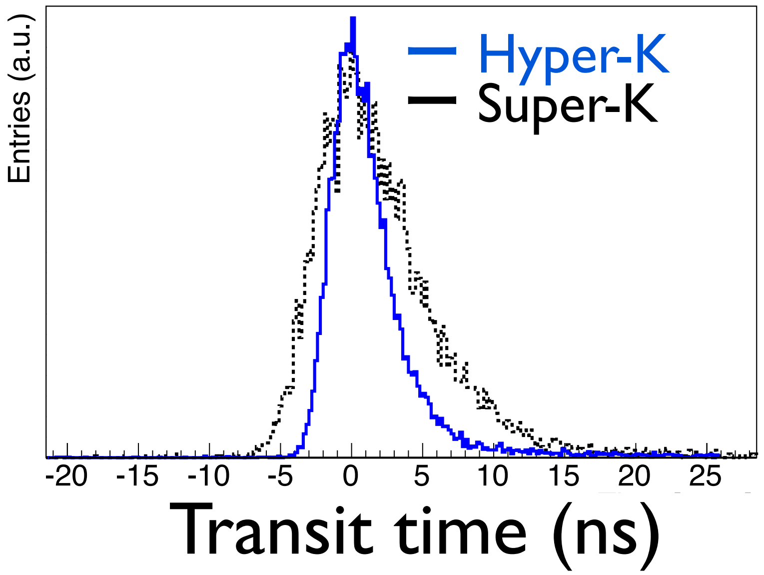


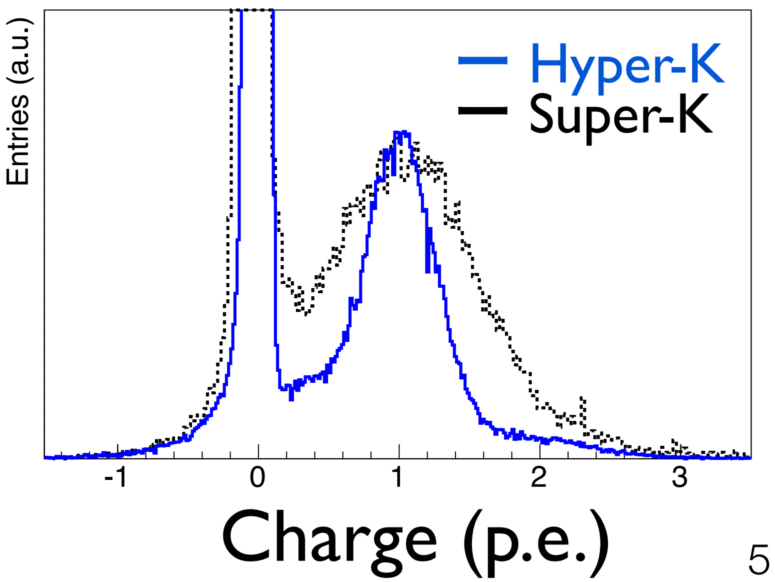
New 50cmΦ PMT for Hyper-K

Photo-detection efficiency (1 p.e.)



Hyper-K PMT
(R12860 "Box & line PMT")

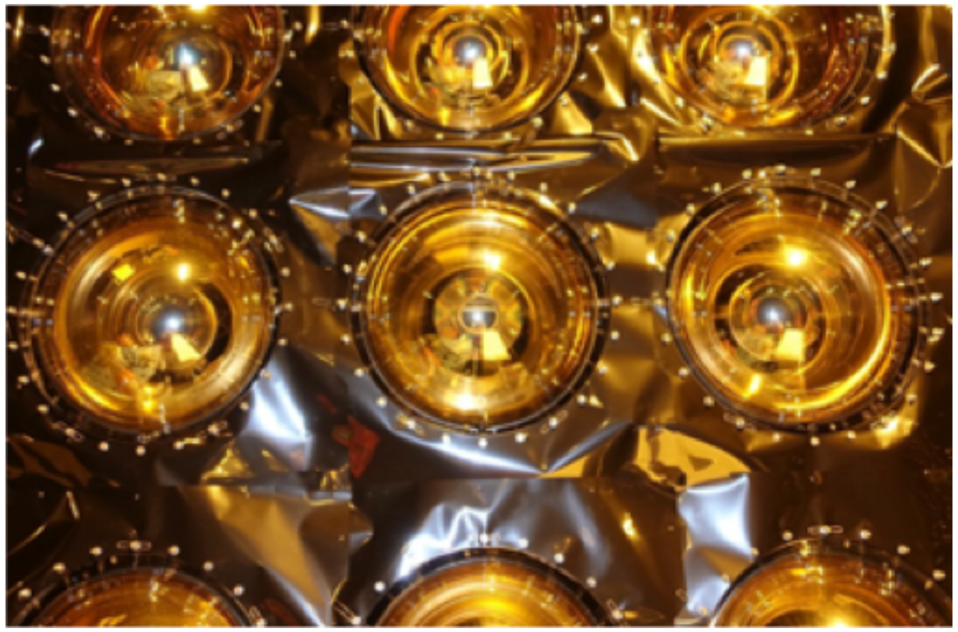




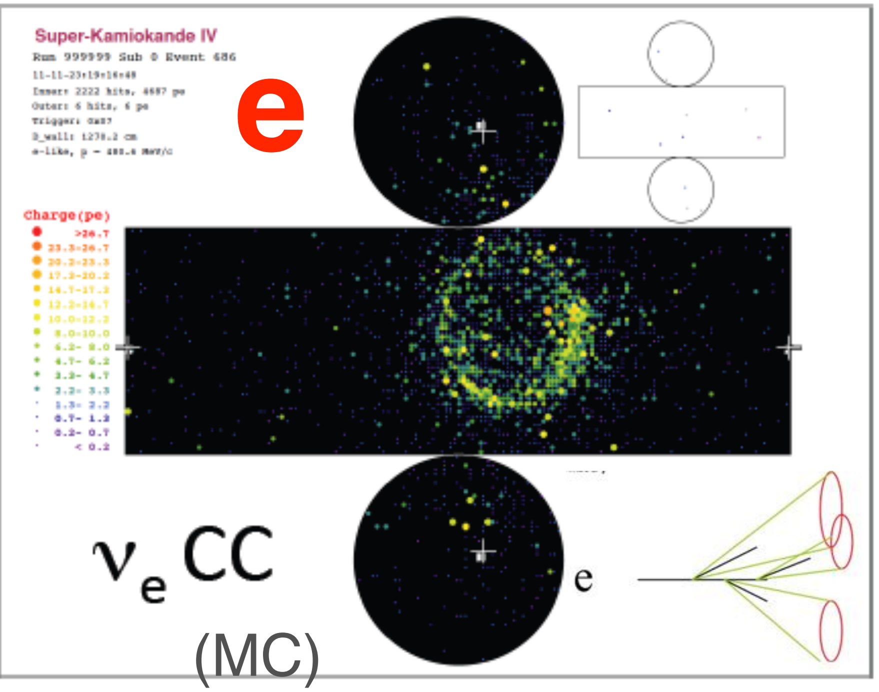
- **Twice better photo-detection efficiency than Super-K PMT (R3600)**
- **Timing resolution (T.T.S.): 1.1ns**
  - cf. Super-K PMT: 2.1ns
- New PMTs enhances Hyper-K physics sensitivity (ex. nucleon decay search)

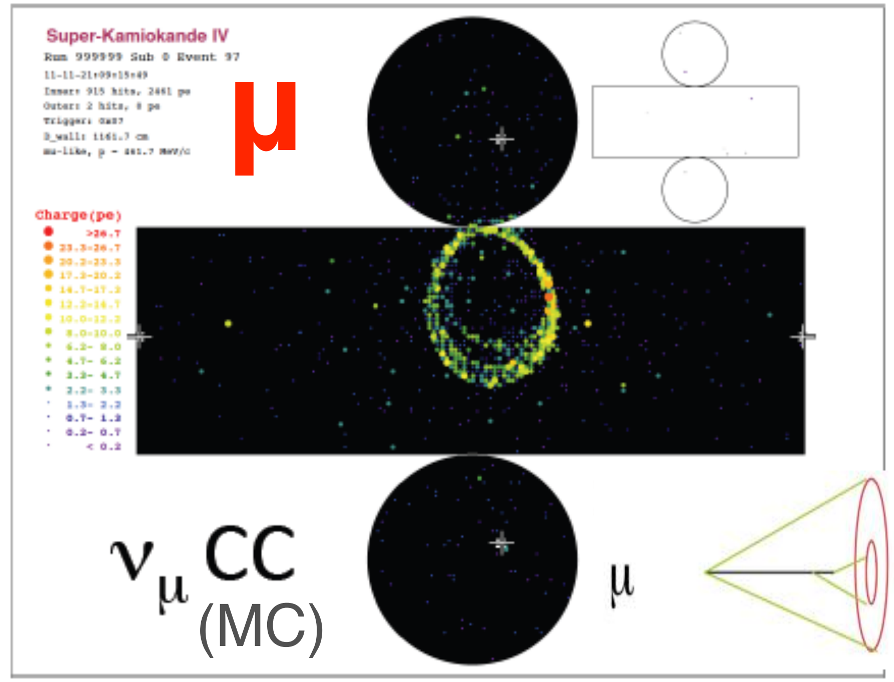
HK PMTs installed in Super-K

- Super-K refurbishment in 2018 towards Gd loading
- **More than 100 of Hyper-K PMTs have been installed in Super-K during the refurbishment work in 2018**
- Confirmed their performances: photo-detection efficiency, etc
  - cf. **Dark rate ~6kHz**

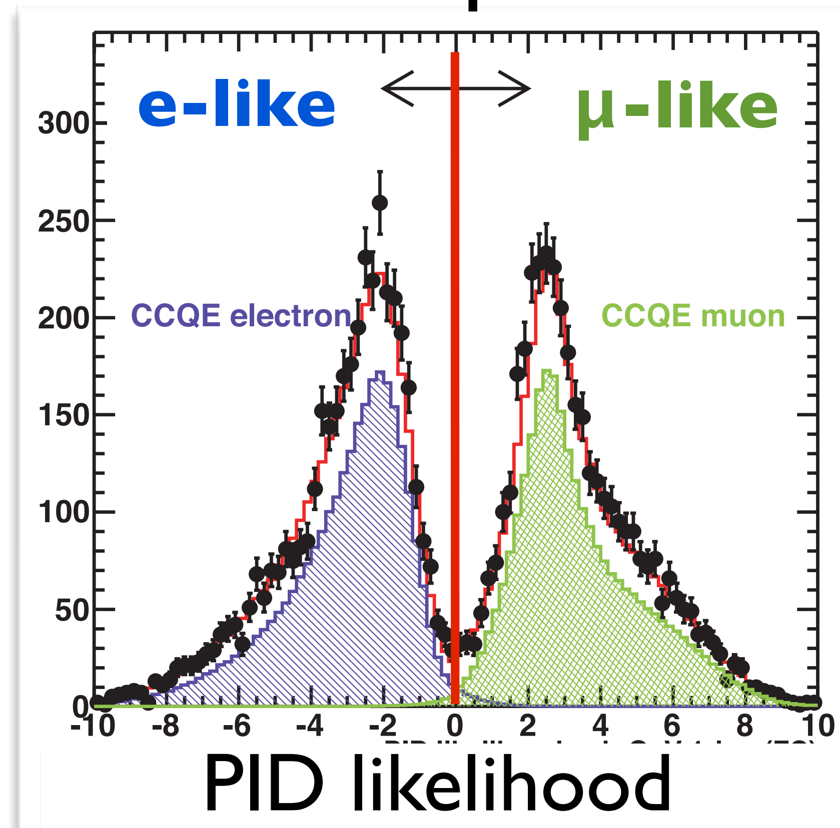


Water Cherenkov Detector



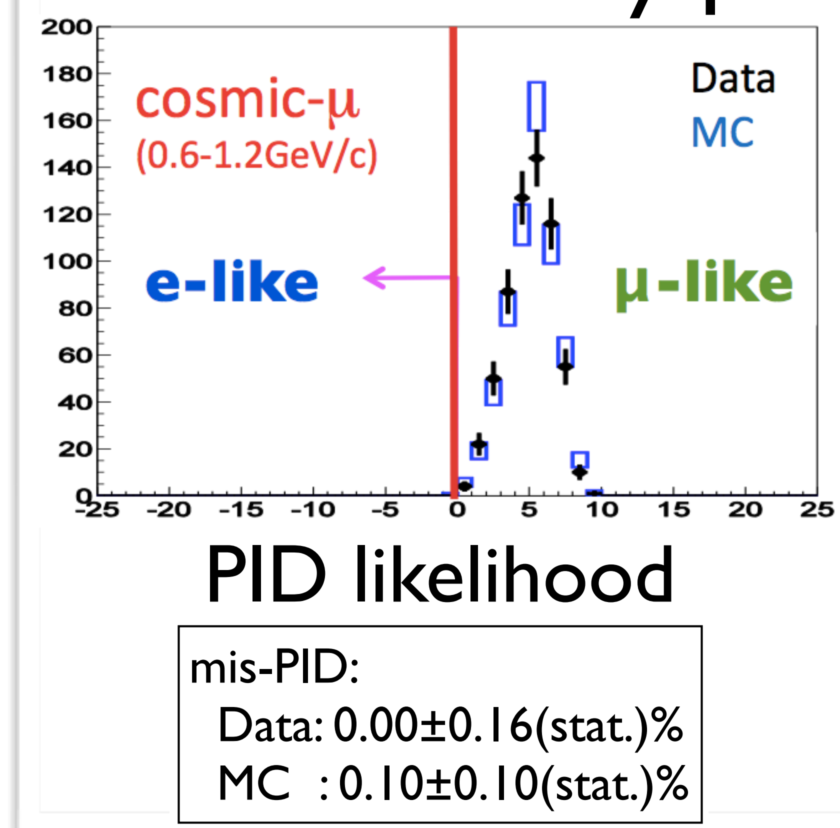


SK atmospheric ν

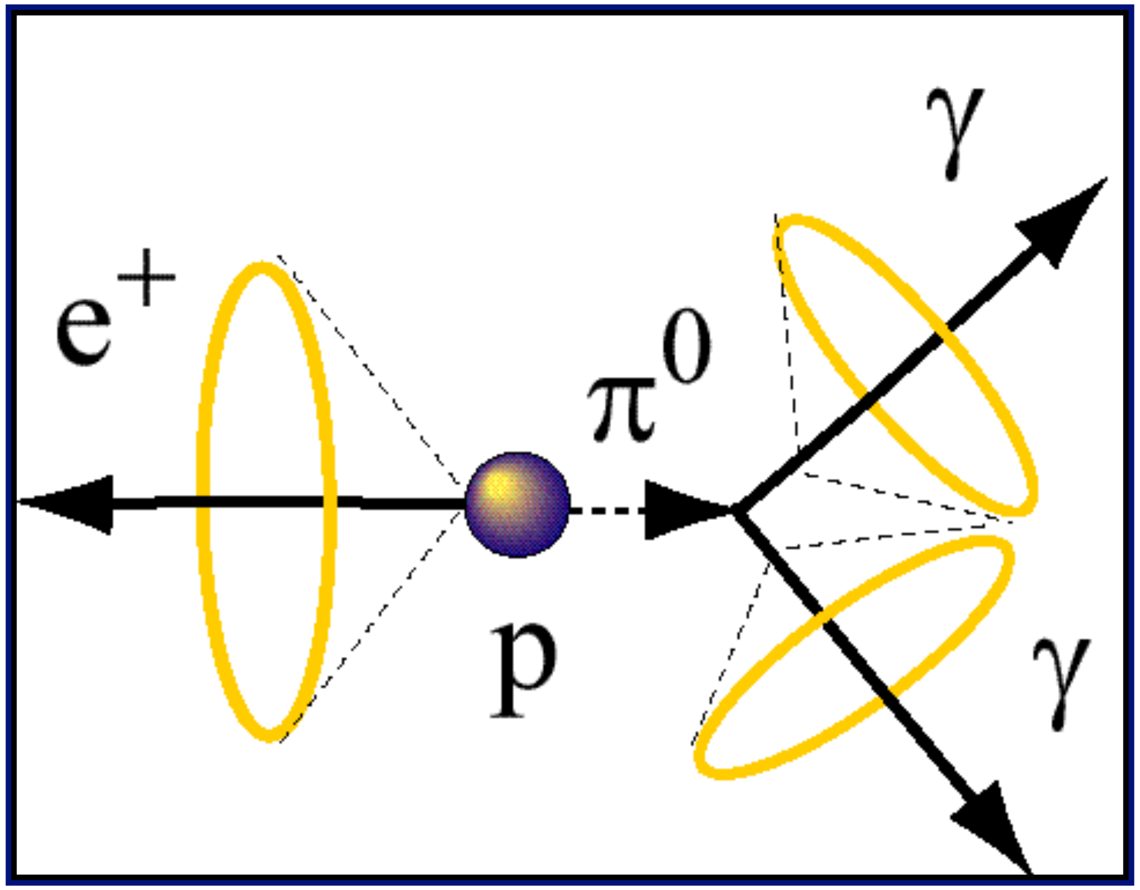


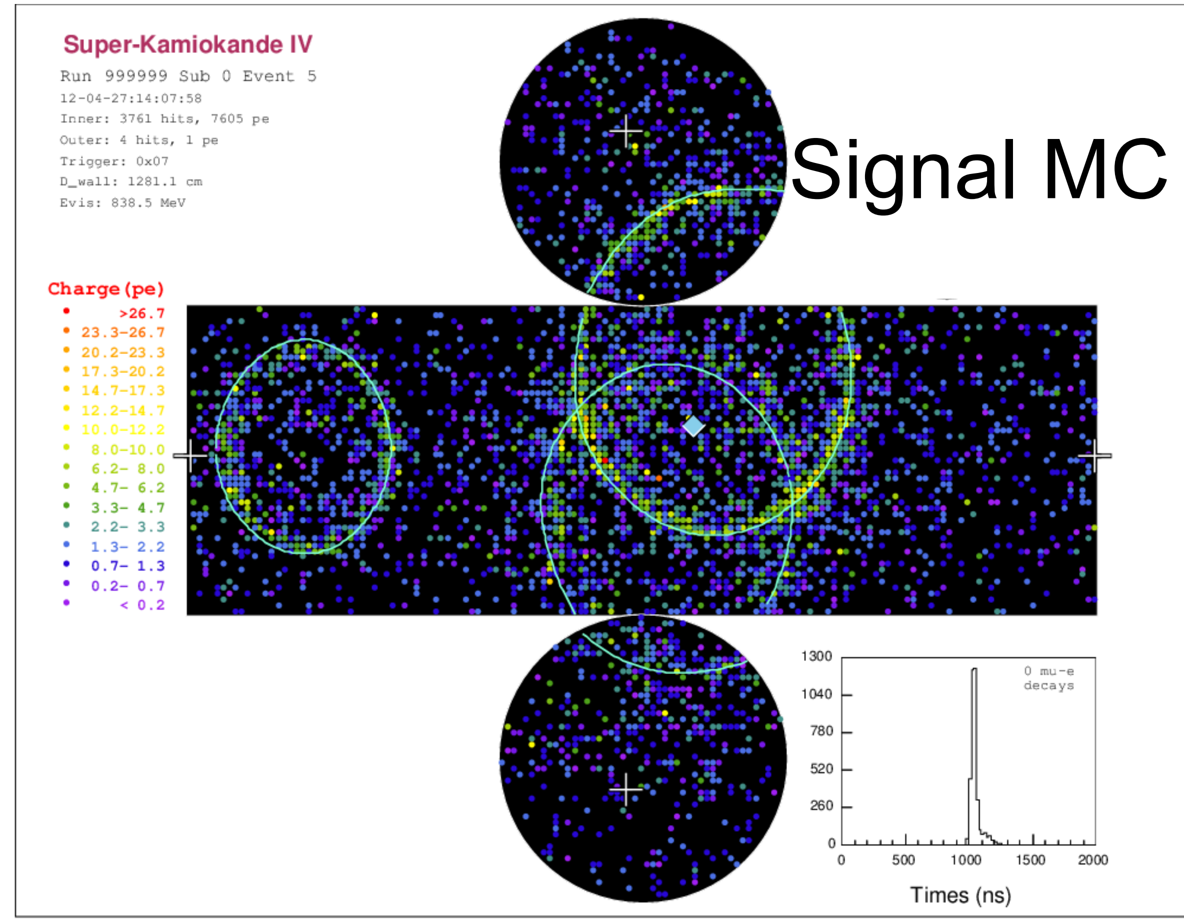
- **Water Č ring imaging detector**
- **Excellent particle identification (μ and e)**
  - Separate EM-shower type (e-like) and muon type (μ-like) with Č ring pattern
  - **Mis-PID rate below 1% at ~1GeV (Super-K)**
- **Good energy resolution: ~3% at ~1GeV (Super-K)**

SK cosmic-ray μ



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





- **Positron and π^0 run back-to-back**
  - Momentum 459 MeV/c
- **All particles in the final state are visible with Water Č detector**
  - **Able to reconstruct p mass and momentum**

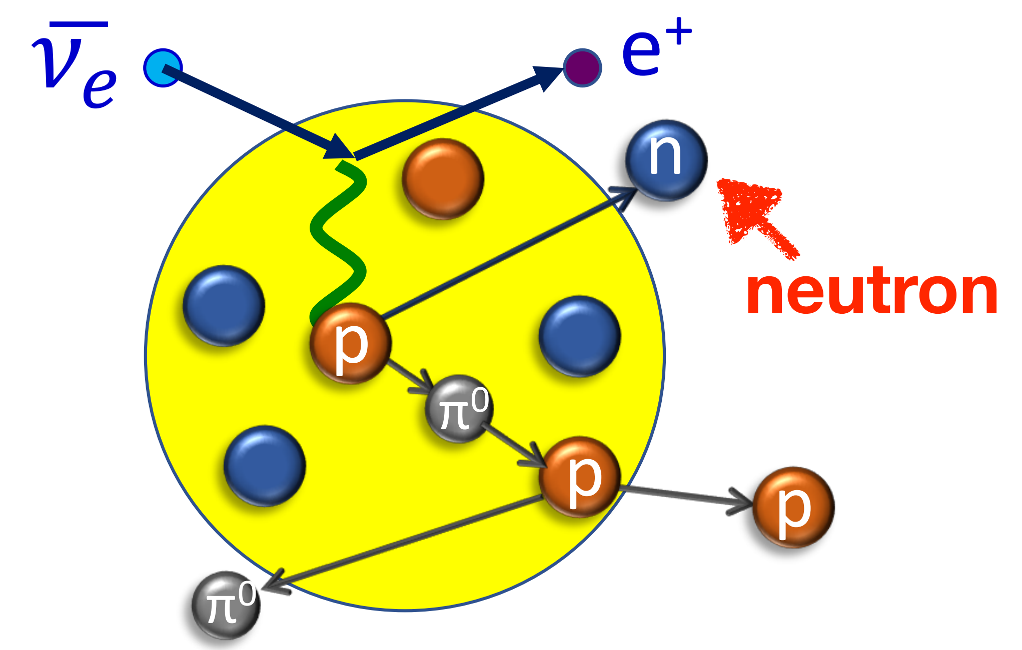
- Event selection:
  - All particles are fully contained in FV
  - 2 or 3 rings (two of them from π0)
  - All particles are e-like, w/o Michel-e
  - $85 < M_{\pi 0} < 185$ MeV/c^2
  - $800 < M_p < 1050$ MeV/c^2
  - $100 < P_{tot} < 250$ or $P_{tot} < 100$MeV/c
  - Neutron-tagging (SK-IV)
    - Further reduce bkg by ~50%

Background rejection

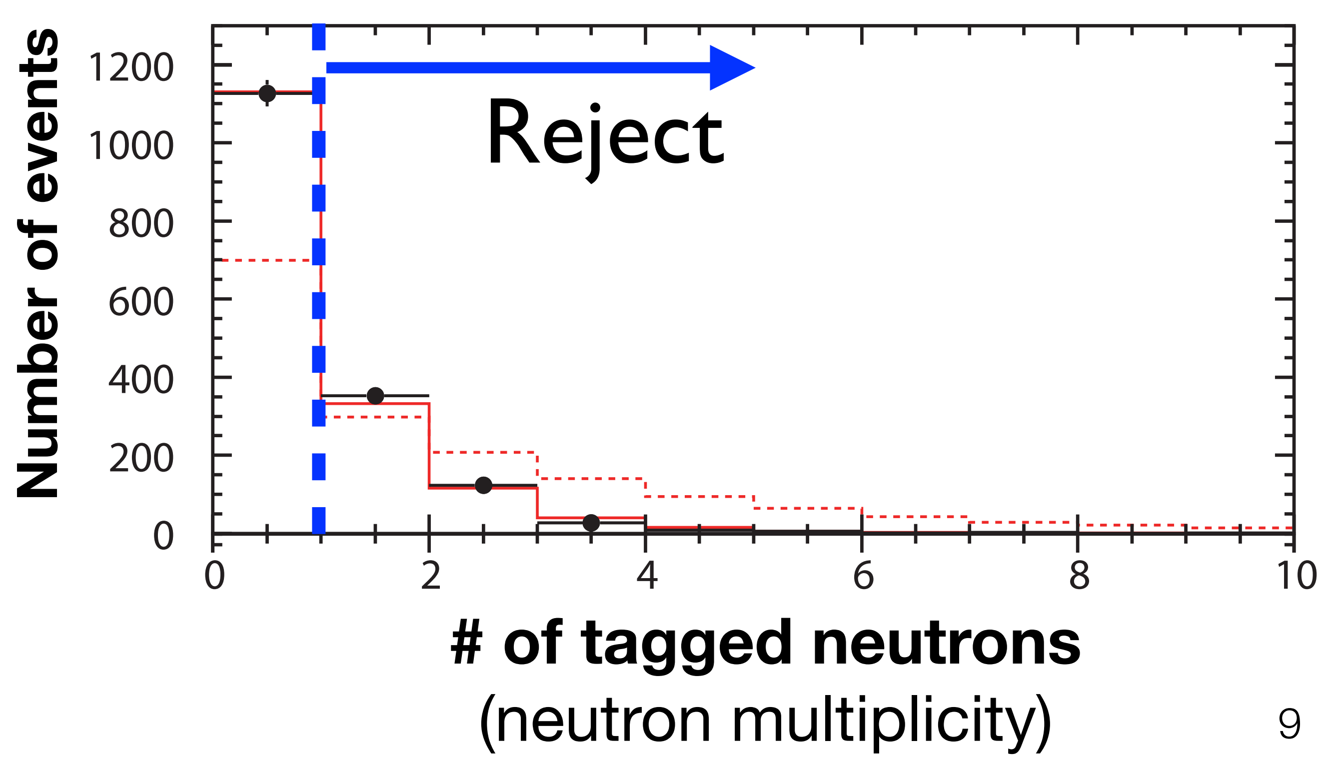
- Background for nucleon decay search is atmospheric neutrino: CC-π production
- **Most of atm-ν bkg accompanied with neutrons**, and n's captured by hydrogen (~200μs) & emit γ-ray
  - **p+n→d+γ (2.2MeV)**
- By identifying 2.2MeV γ-ray, "neutron tagging", atmospheric neutrino bkg can be largely eliminated
  - **ex. Super-K (SK-IV) neutron tagging efficiency: ~20% → reduces bkg by ~50%**
- Hyper-K can further improve neutron-tagging efficiency with new Hyper-K PMT

Atmospheric ν background

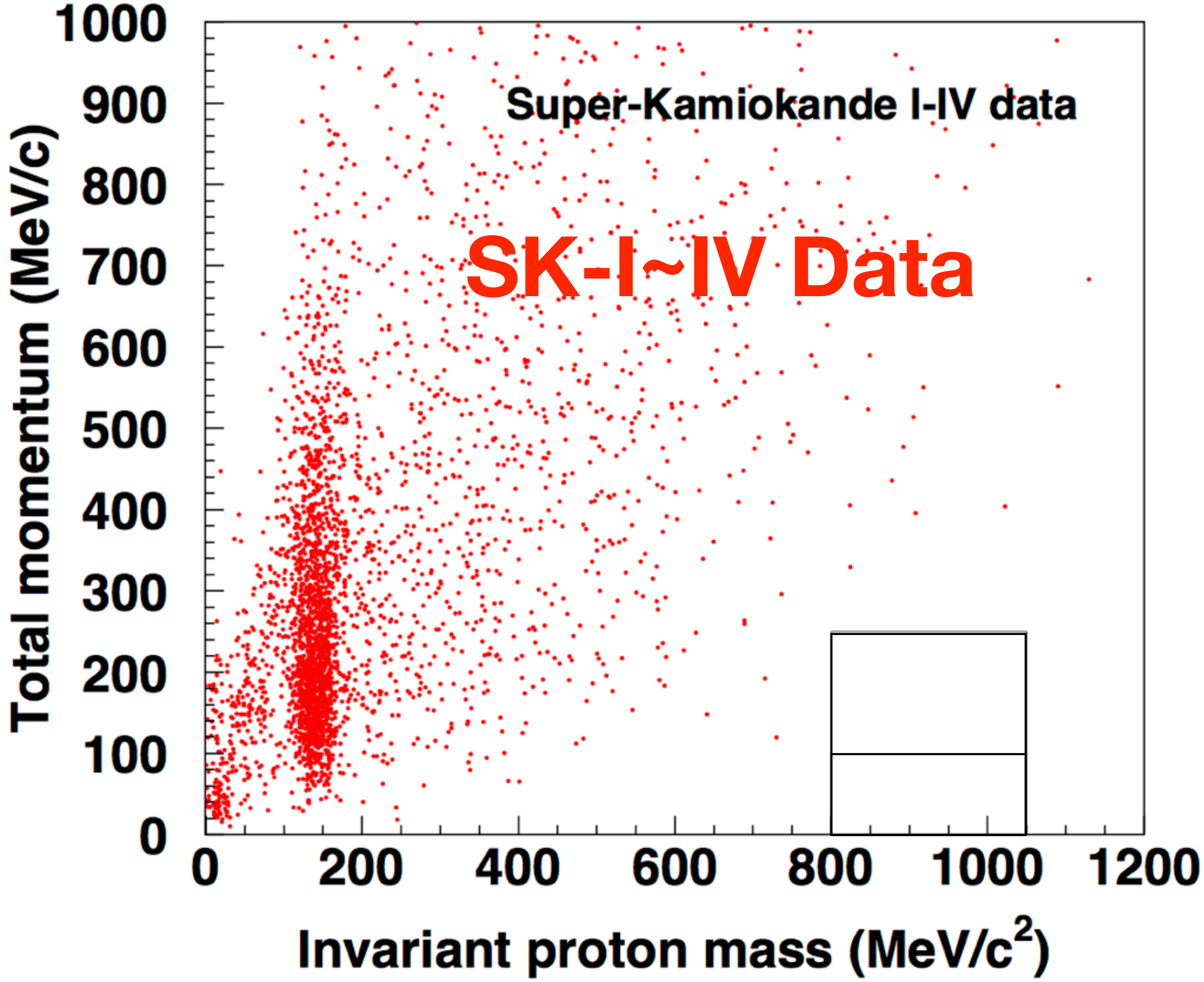
$\bar{\nu}_e + p \rightarrow e^+ + \pi^0 + n$ (for example)

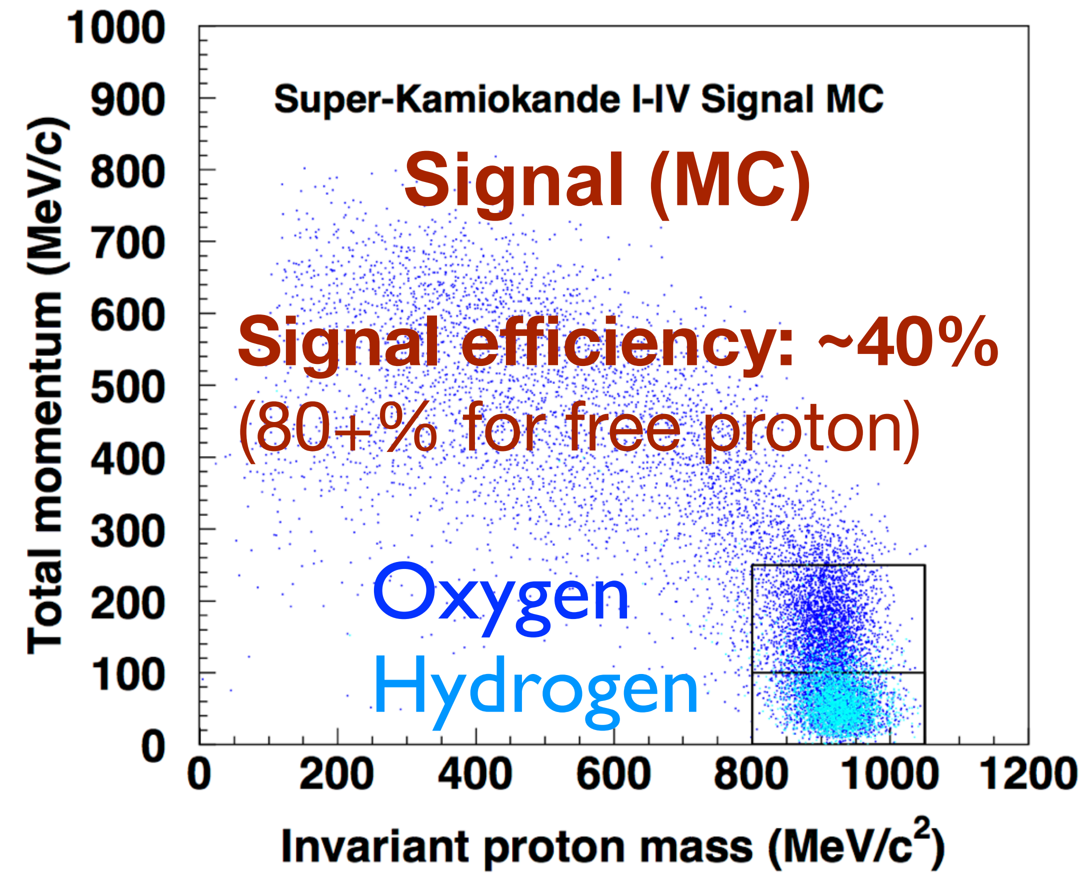


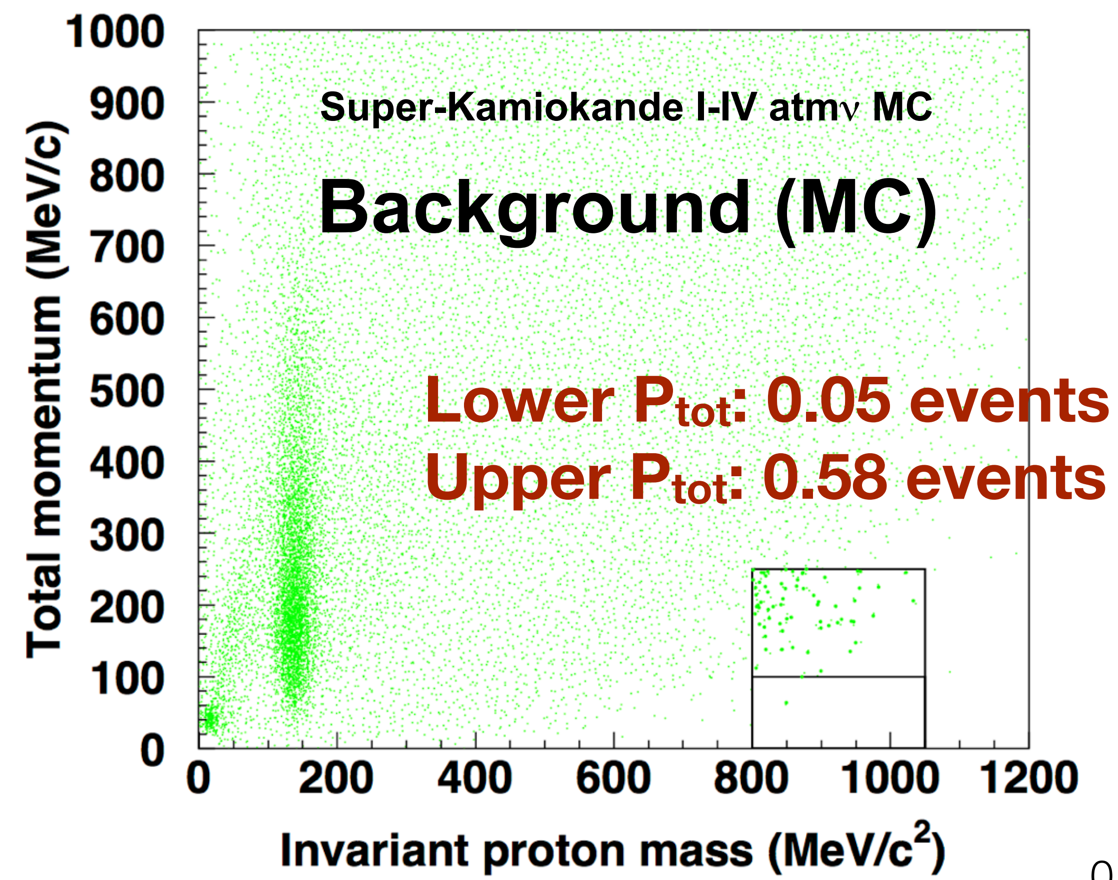
Super-K: PRD95, 012004 (2017)



$p \to e^+\pi^0$: Super-K results







- Found no event in the signal box
- Lifetime limit at 90% C.L.
  - **$\tau/Br > 2.0 \times 10^{34}$ years**
    with 365 kton·yrs (SK-I~IV)

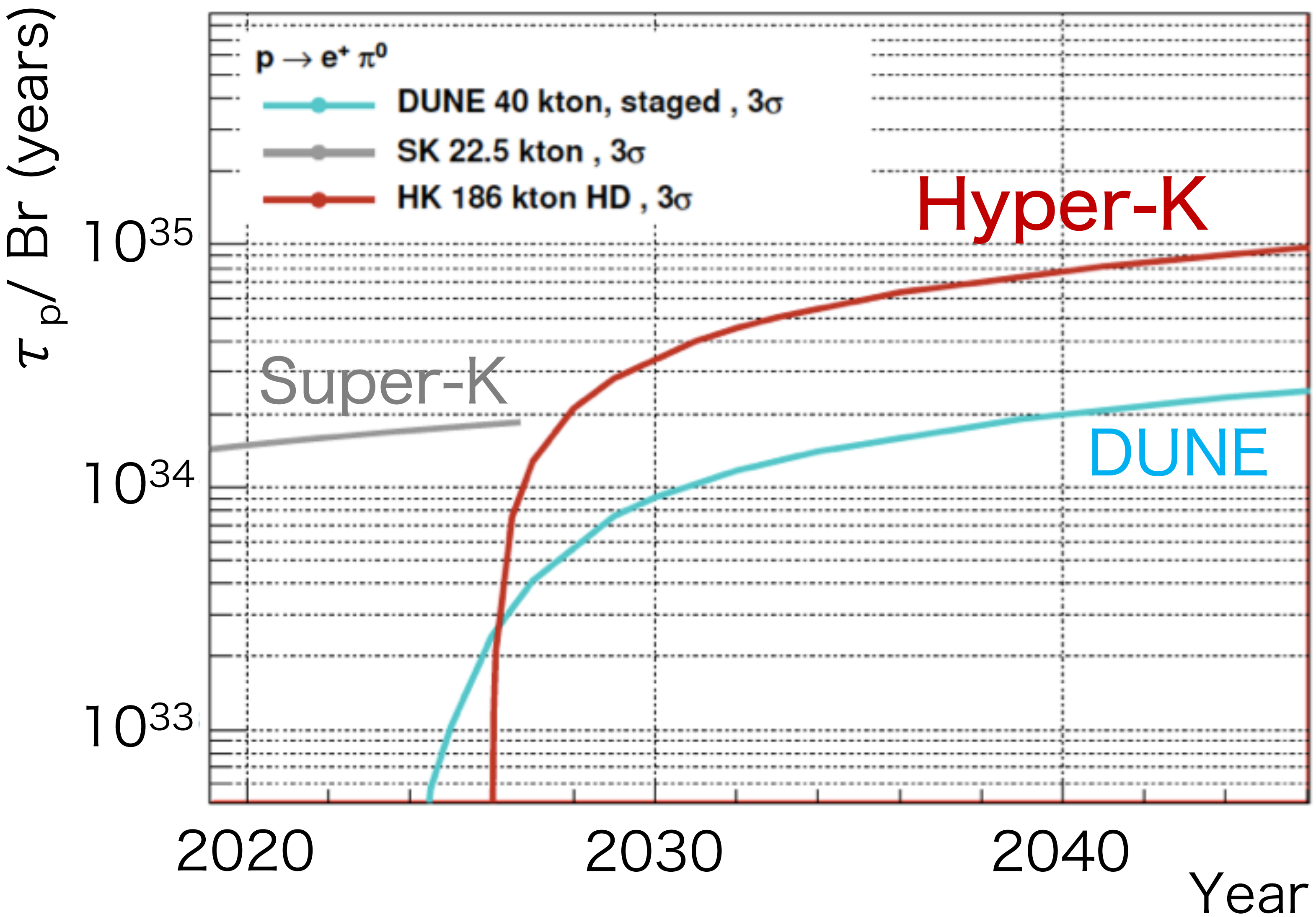
$p \to e^+\pi^0$ search w/ Hyper-K

- **Hyper-K PMTs have twice better photo-detection efficiency**
- **'Neutron tagging' efficiency reaches ~70%** (cf. SK efficiency ~20%)

$p \to e^+\pi^0$	$0 < P_{tot}$ (MeV/c) < 100		$100 < P_{tot}$ (MeV/c) < 250	
	Signal efficiency	# of bkg (/Mton·year)	Signal efficiency	# of bkg (/Mton·year)
SK-IV	19%	0.2	19%	1.1
Hyper-K	19%	0.06	19%	0.6

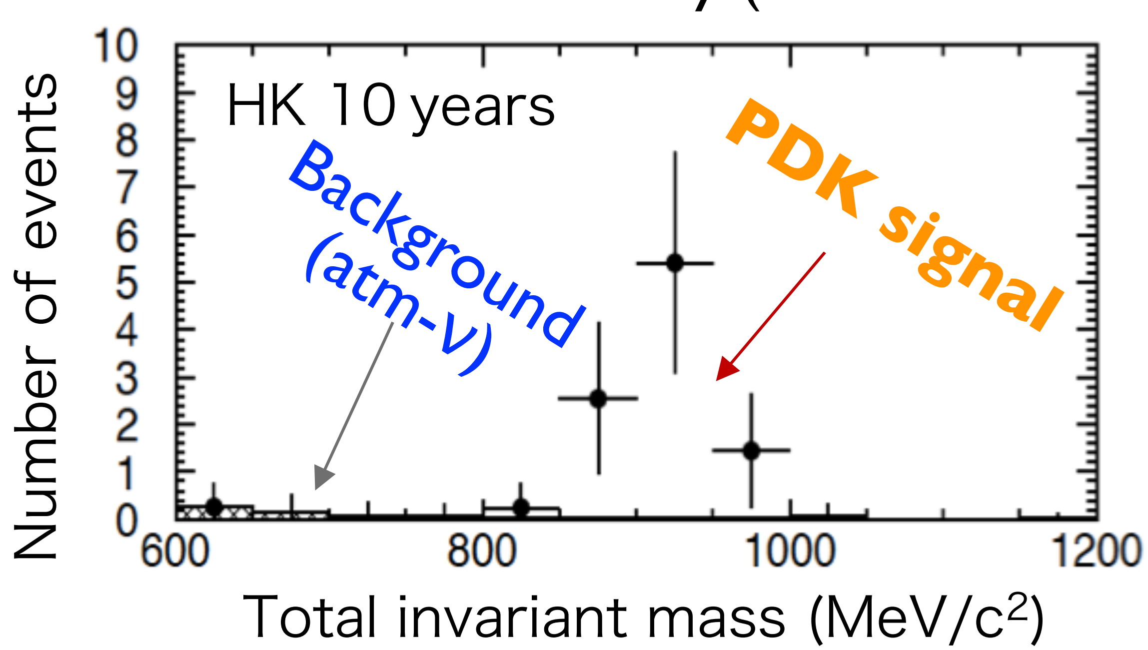
- # of background events in Hyper-K further reduced with the improved neutron tagging efficiency thanks to new PMTs

$p \to e^+\pi^0$ search w/ Hyper-K



3σ discovery sensitivity

Assume $\tau/Br = 1.7 \times 10^{34}$y (SK 90%CL limit)



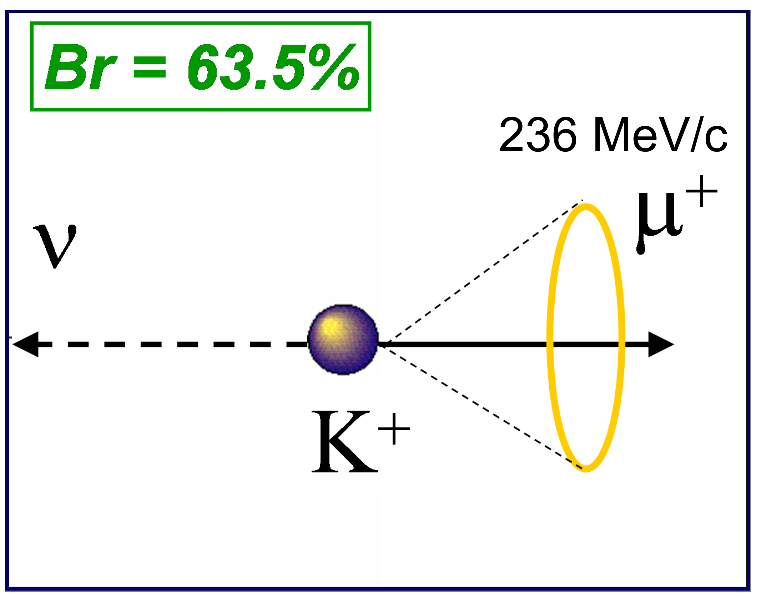
- **Hyper-K reaches to 10^{35} yrs with 3σ discovery sensitivity**
- **~9σ discovery potential if the lifetime at the current SK limit ($\tau_p/Br = 1.7 \times 10^{34}$yrs)**

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

- K^+ has momentum of 340 MeV/c
  - Below Cherenkov threshold (749 MeV/c)
- **Identify K^+ by finding its decay products**

$K^+ \rightarrow \mu^+ \nu_\mu$

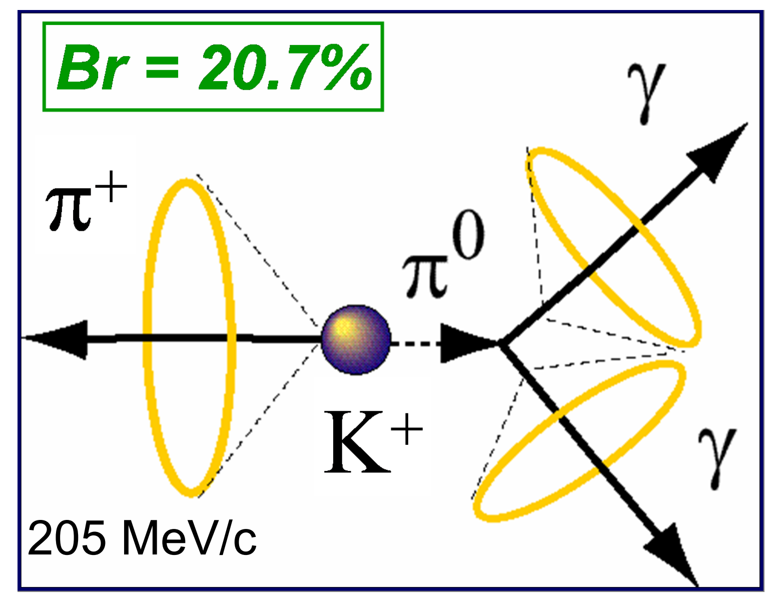
(K+ **leptonic** decay)



Search Methods
- Nuclear de-exitation γ, μ, and decay e+
- Monochromatic μ from K+ decay

$K^+ \rightarrow \pi^+ \pi^0$

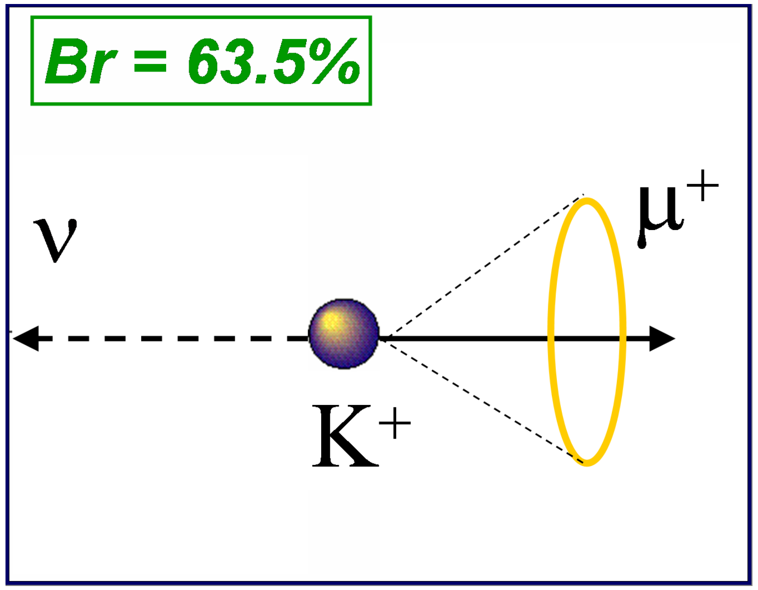
(K+ **hadronic** decay)



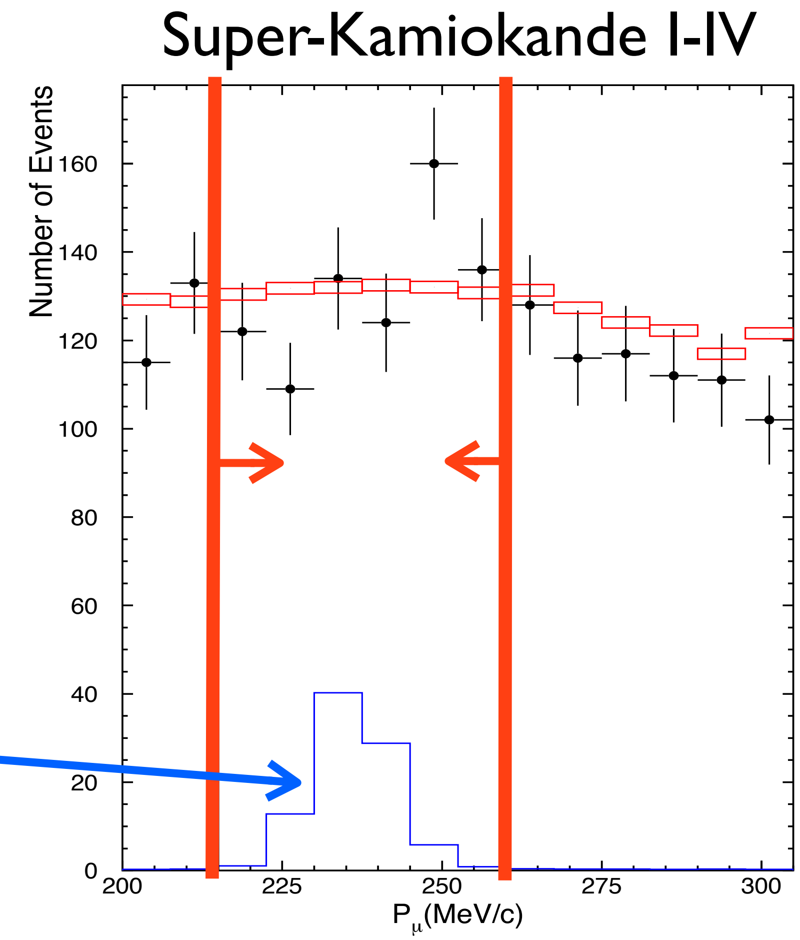
Search Method
- π^+ and two γ from π^0 decay
  (π+ Č threshold 156MeV/c)

$p \to \bar{\nu} K^+$: Super-K

【K^+ leptonic decay】

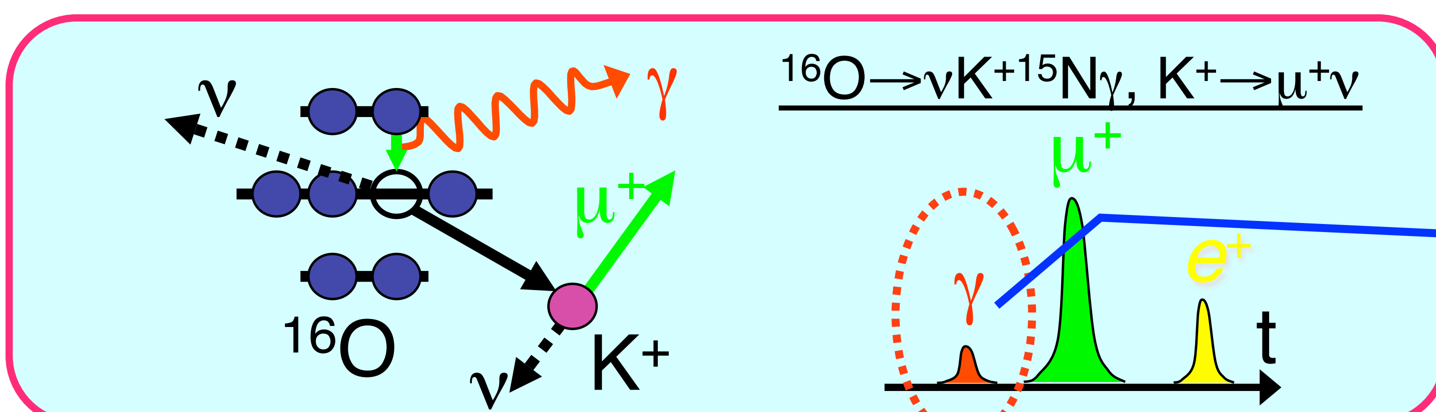


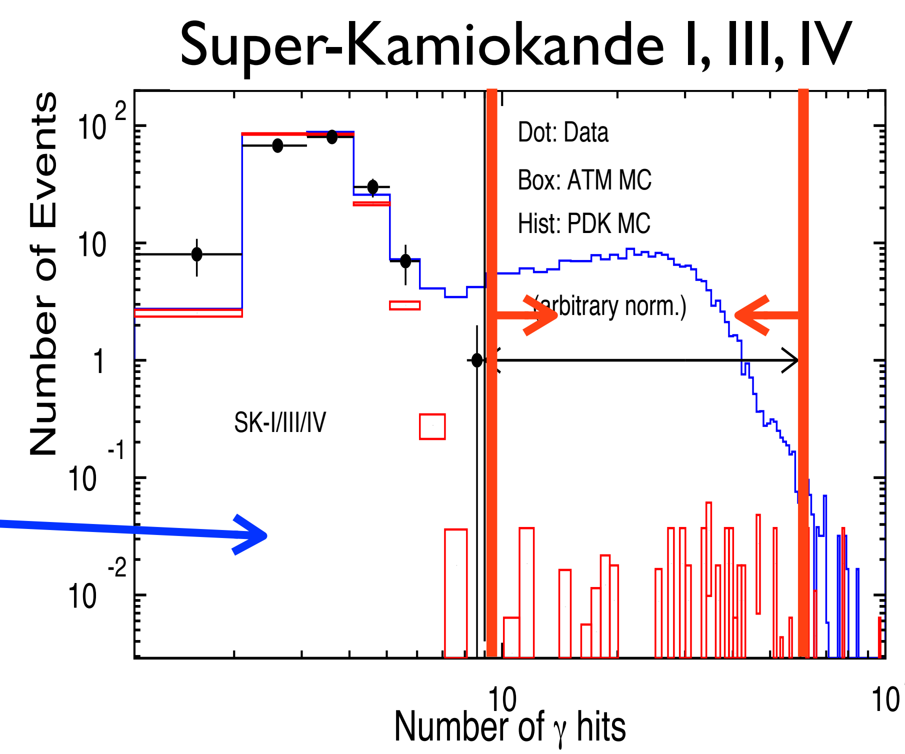
(1) Search for mono-energetic μ (236MeV/c)



(2) De-excitation γ (6.3MeV) + μ decay

Proton decays in ^{16}O → Excited nucleus ($^{15}N^*$) emits **6.3 MeV γ-ray** (~40% probability)



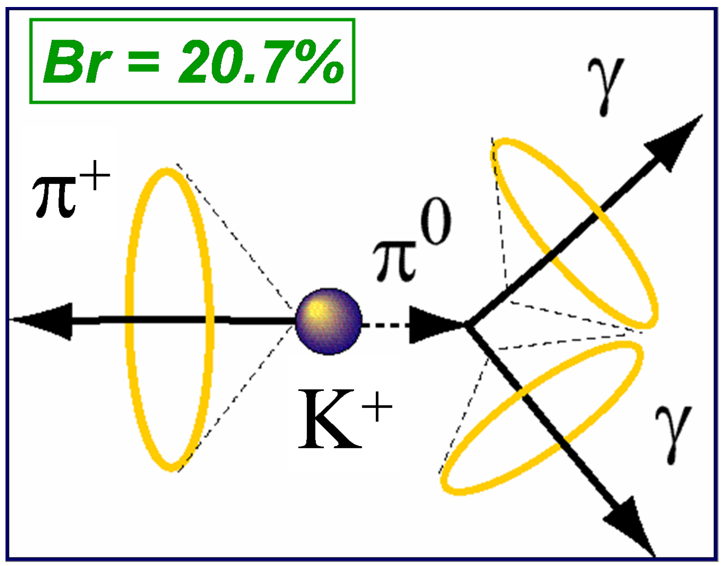


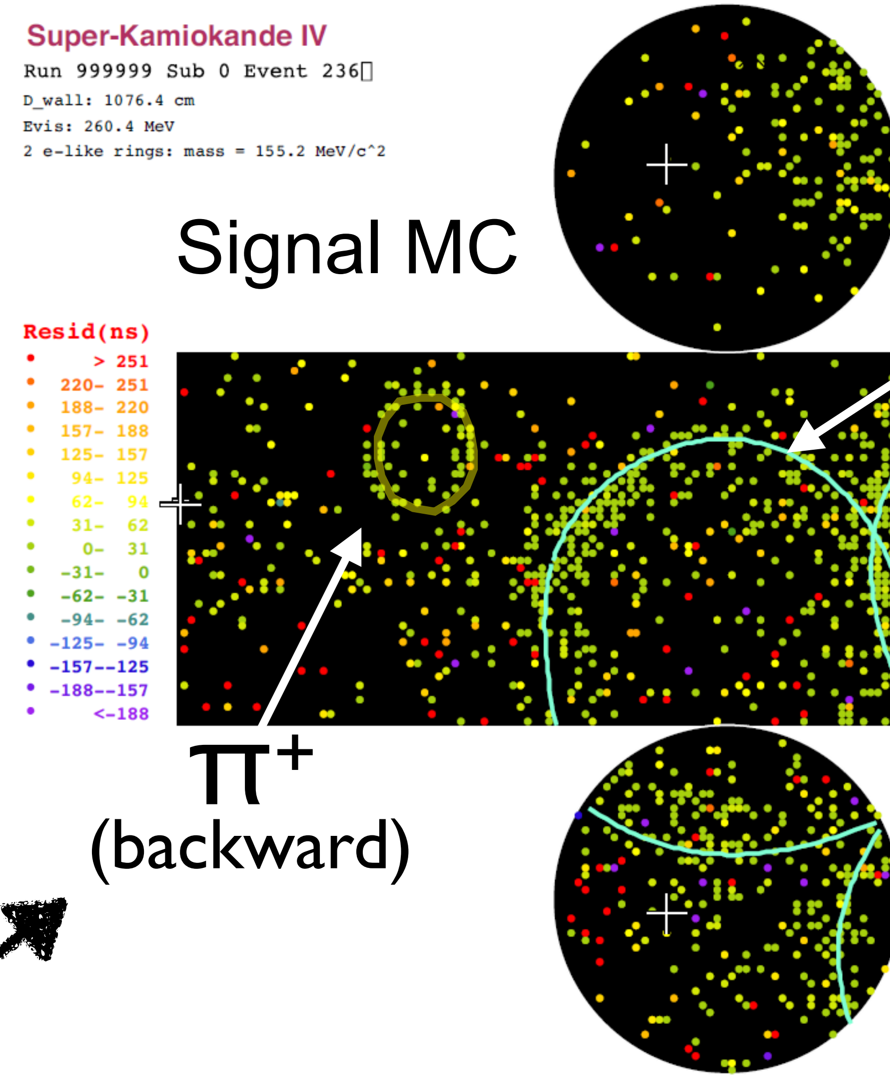
➔ γ, μ and Michel-e from μ-decay triple coincidence largely reduce background

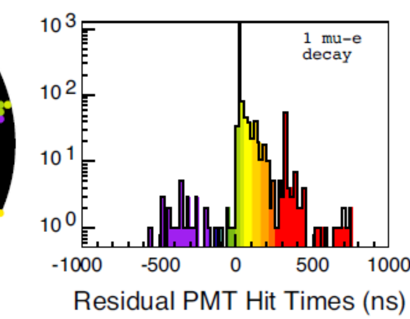
$p \to \bar{\nu} K^+$: Super-K

【K+ hadronic decay】

$K^+ \to \pi^+ \pi^0$: π^+ and π^0 run back-to-back with 205 MeV/c







Identify backward going π^+ (barely above Č threshold)

- **Found no evidence of $p \to \bar{\nu} K^+$**
- Lifetime limit combining all three search methods:
  $\tau/Br > 8.2 \times 10^{33}$ years [preliminary]
  - at 90% C.L. with 365 kt·years (SK-I~IV)

$p \to \bar{\nu} K^+$ search w/ Hyper-K

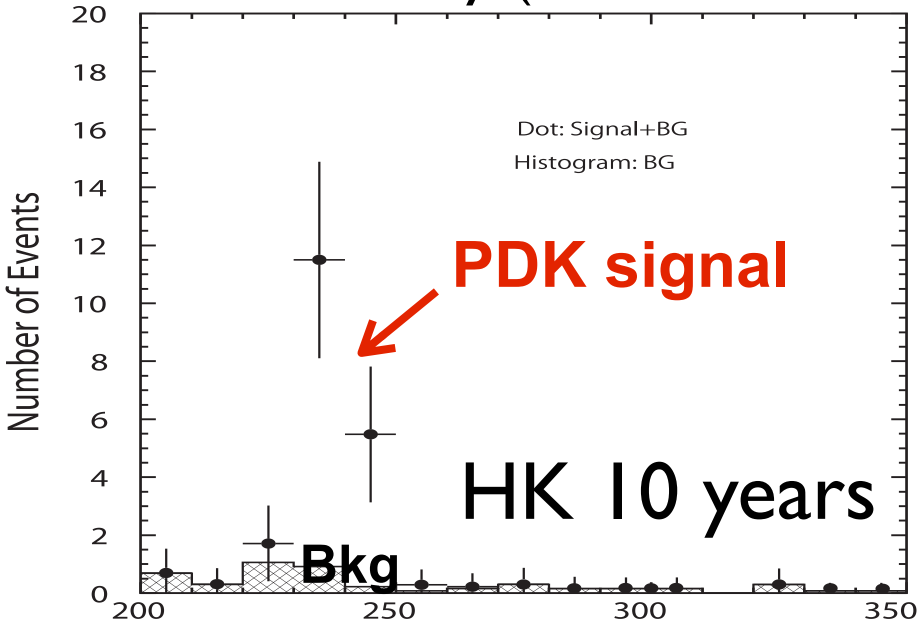
- **Hyper-K PMTs have twice better photo-detection efficiency**
- Improve signal selection efficiency
  - Prompt gamma-ray, π^+ identification

$p \to \bar{\nu} K^+$	$K^+ \to \mu^+ \nu_\mu$ w/ prompt γ		$K^+ \to \pi^+ \pi^0$	
	Signal efficiency	# of bkg (/Mton·year)	Signal efficiency	# of bkg (/Mton·year)
SK-IV	8.5%	1.1	9%	0.9
Hyper-K	13%	0.9	11%	0.7

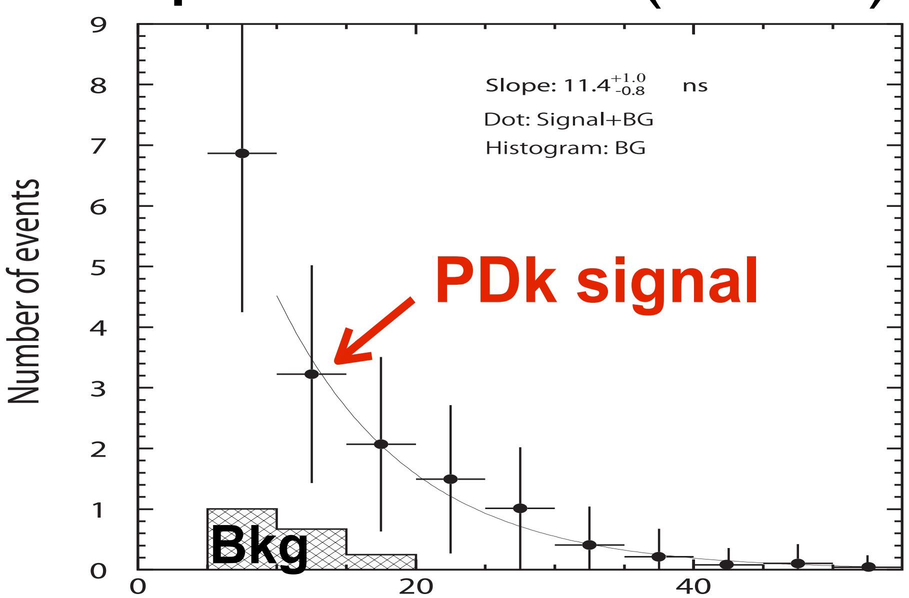
- Signal efficiencies are improved thanks to new PMTs

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

$\tau/Br = 6.6 \times 10^{33}$y (SK 90%CL limit)

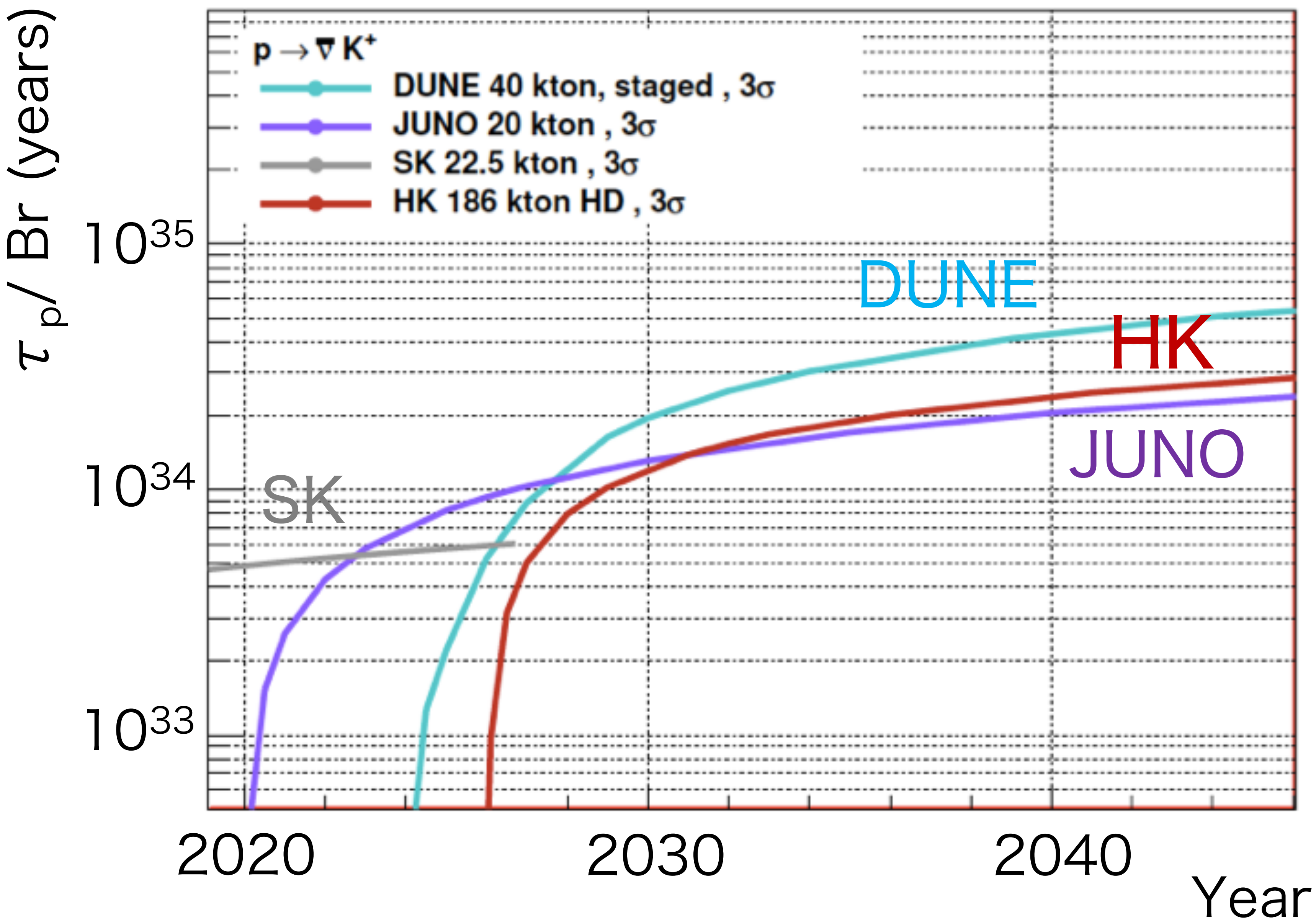


μ Momentum (MeV/c)



K^+ decay time (nsec)

3σ discovery sensitivity

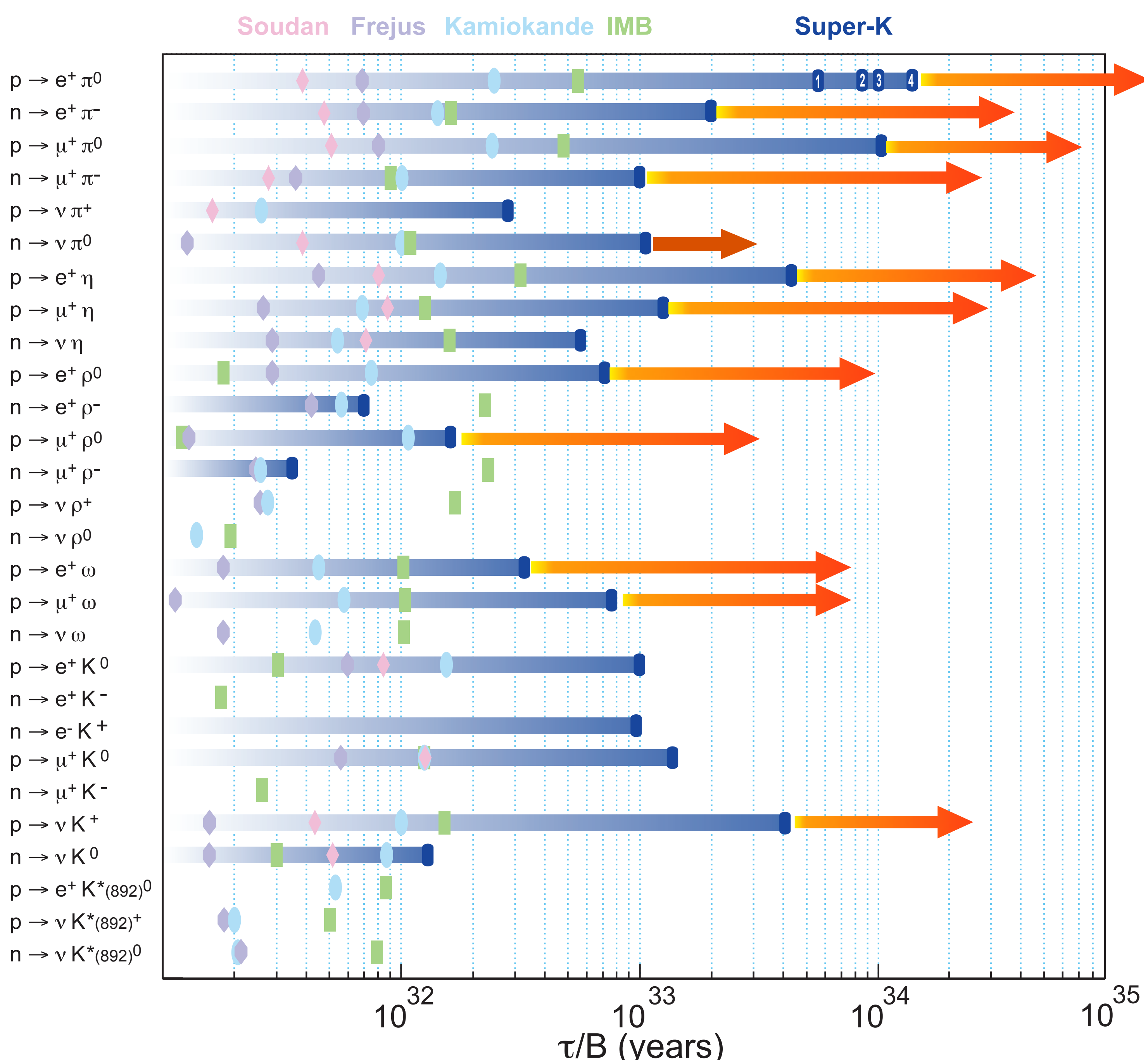


- $K^+ \rightarrow \mu + \nu$ (Br: 64%): 236MeV/c μ^+
  - de-excitation γ from $^{15}O^*$ (6MeV γ)
- $K^+ \rightarrow \pi^+ \pi^0$ (Br: 21%): 205MeV/c π^0 & π^+

- HK 3σ discovery potential reaches 3×10^{34} years

Hyper-K sensitivities

- **Improvements in many decay modes by a factor ~10**
  - Open for many decay modes
- **Hyper-K has a large potential for discovery**



- $p \rightarrow e^+ + \pi^0$
  - $\tau_{proton}/Br > 1\times10^{35}$ years @90%CL
  - 5Mton×years (9 Hyper-K years)
- $p,n \rightarrow (e^+,\mu^+)+(\pi,\rho,\omega,\eta)$
  - $O(10^{34\sim35})$years
- *SUSY favored* $p \rightarrow \nu + K^+$
  - 3×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- Others
  - (B-L) violated modes
  - radiative decays $p \rightarrow e^+\gamma$, $\mu^+\gamma$
  - neutron-antineutron oscillations ($|\Delta B|=2$)
  - di-nucleon decays ($|\Delta B|=2$)
    - $pp \rightarrow XX...$, $nn \rightarrow XX...$

Reports on Physics Sensitivity

arXiv:1109.3262 Letter of Intent

Letter of Intent:

The Hyper-Kamiokande Experiment

— Detector Design and Physics Potential —

(Hyper-Kamiokande working group)

Prog. Theor. Exp. Phys. 053C02 (2015)

PTEP

Prog. Theor. Exp. Phys. **2015**, 053C02 (35 pages)
DOI: 10.1093/ptep/ptv061

Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande

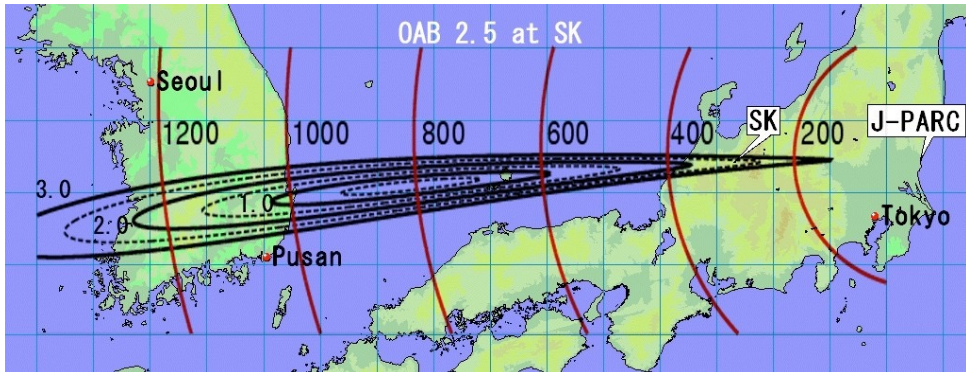
Prog. Theor. Exp. Phys. 063C01 (2018)

optional 2nd tank in Korea under investigation

Physics Potentials with the Second Hyper-Kamiokande Detector in Korea

(Hyper-Kamiokande Proto-Collaboration)

Having two detectors at different baselines improves sensitivity to CP violation, neutrino mass ordering



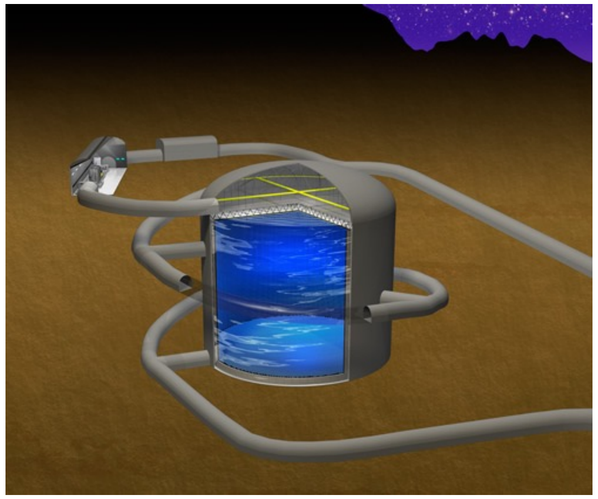
arXiv:1805.04163

Hyper-Kamiokande

Design Report
(Dated: May 9, 2018)

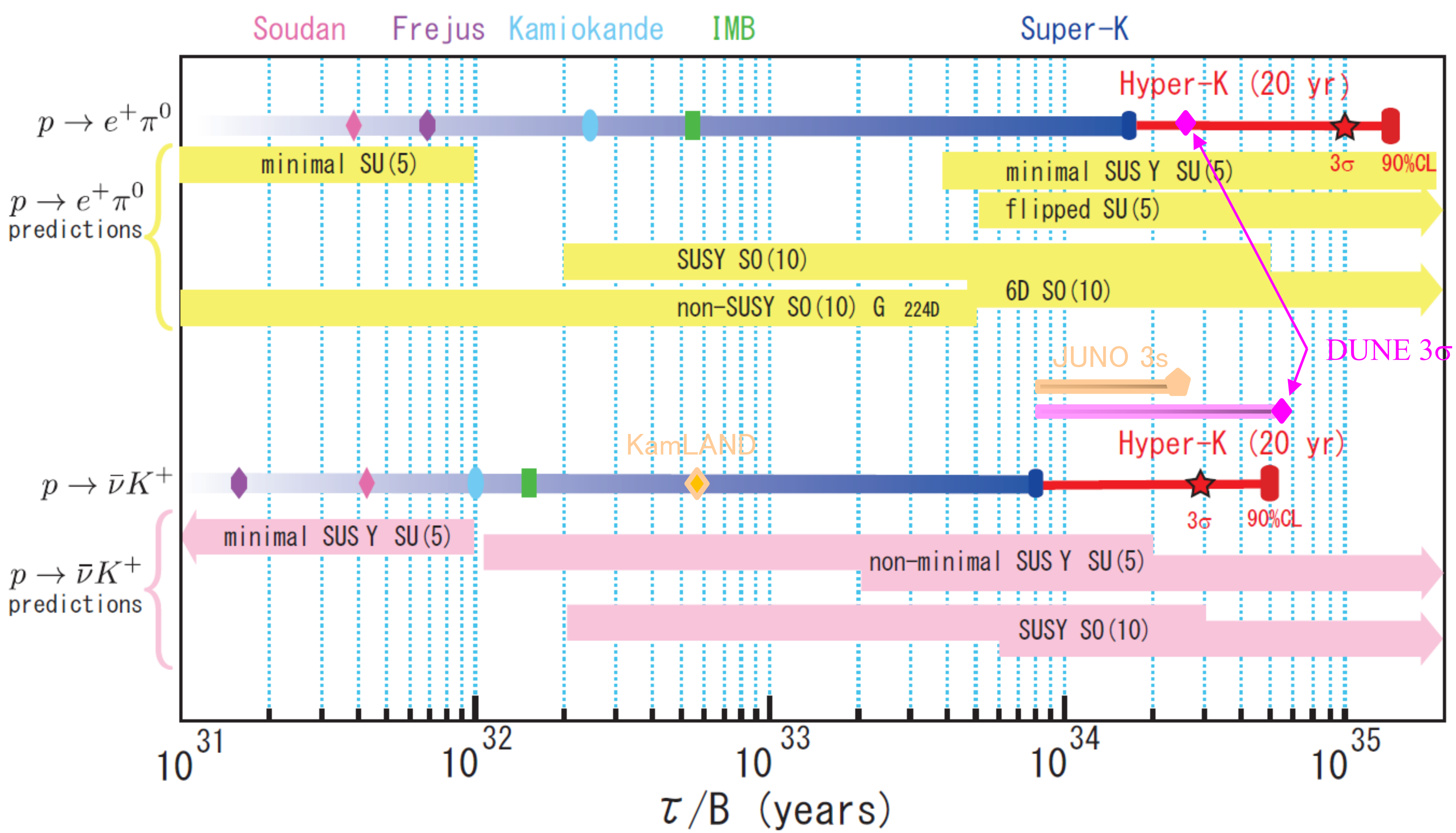
(Hyper-Kamiokande proto-collaboration)

Maximizing physics sensitivities with optimized tank design



Summary

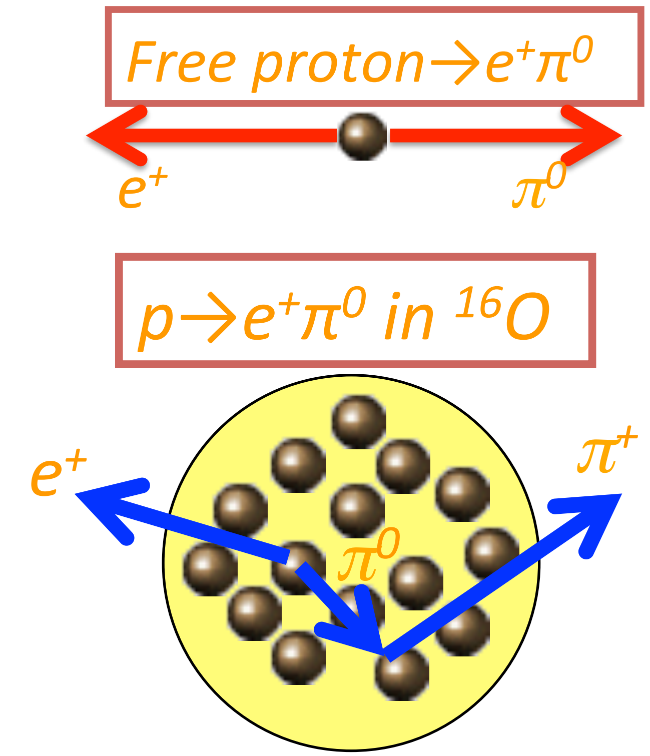
- **Hyper-K will be only experiment which can explore $\tau_p > 10^{35}$ yrs**
  - Large discovery potential with many decay modes
- **Hyper-K detector construction begins in April 2020** and aim to start the operation in 2027



Back up

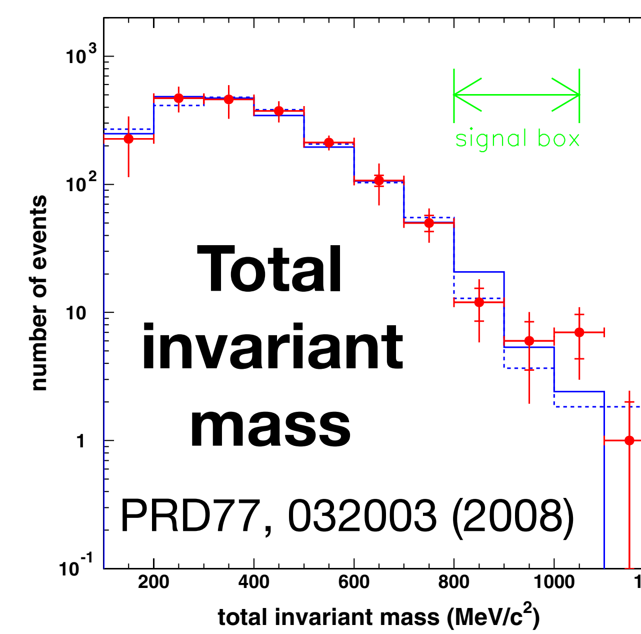
Signal & background

- **Signal**: $p \to e^+\pi^0$
  - One of major causes of signal efficiency loss is due to **final state interaction (FSI) in the target nucleus of π** from proton decay
  - **An advantage of water Č detector is to have 'free proton' target**
    - cf. SK $p \to e^+\pi^0$ signal selection efficiency: in oxygen: ~40%, in hydrogen: 80+% (SK-IV)

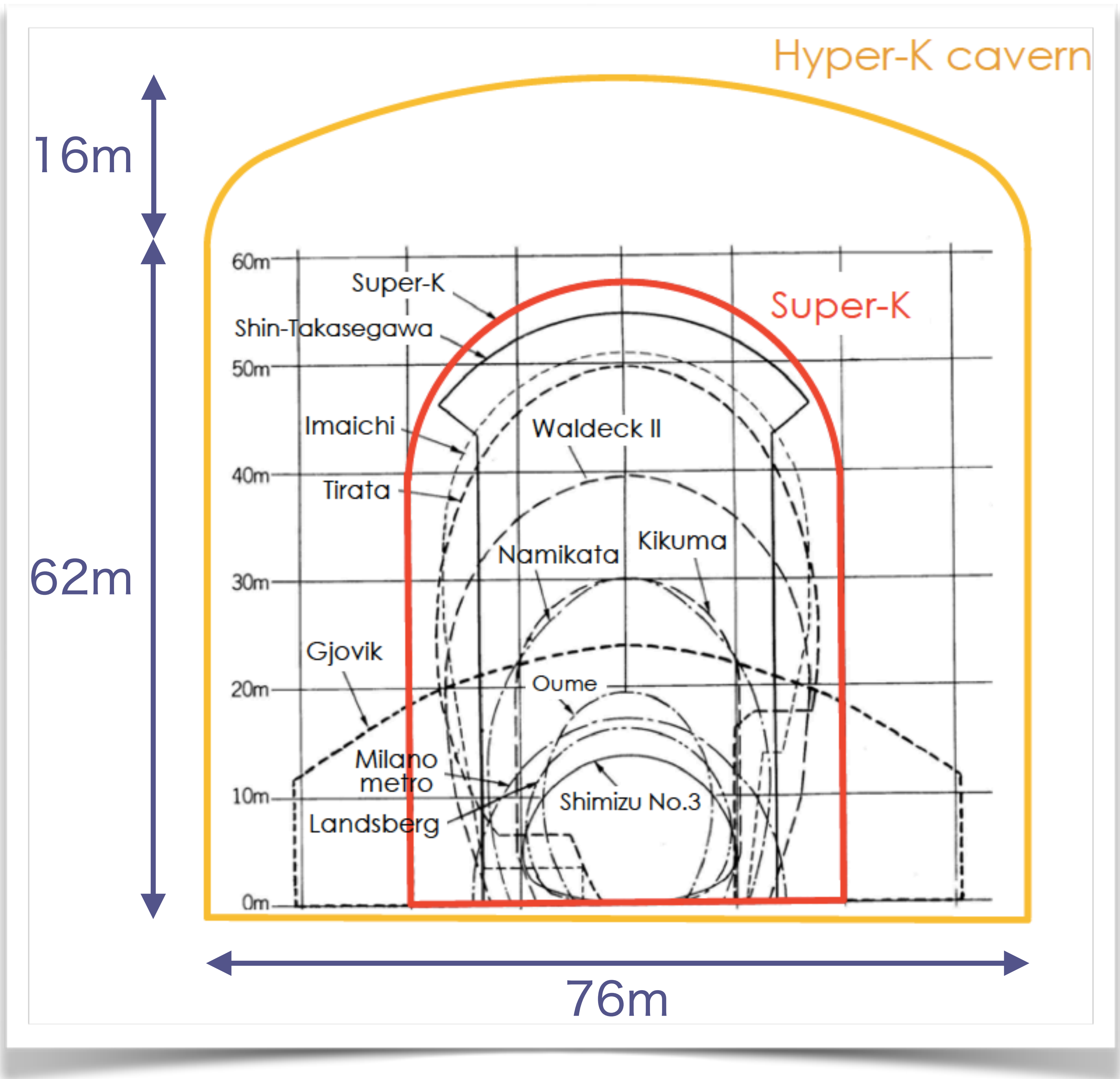


ex. π^0 from PDK interacts with nucleons in the target nucleus and loose original kinematics (ex. momentum) and/or modified charge

- **Background** for proton decay search
  - Atmospheric neutrino; CC-π production
  - **Background rate prediction confirmed with data from K2K-1KT Č detector**
  - **Background is under control**



Hyper-Kamiokande cavern



- **Hyper-K cavern will be the world largest underground cavern**