Results on Nucleon Decay Searches with **Super-K** and Prospects with **Hyper-K**

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Prospects of Neutrino Physics, April 9, 2019

Outline

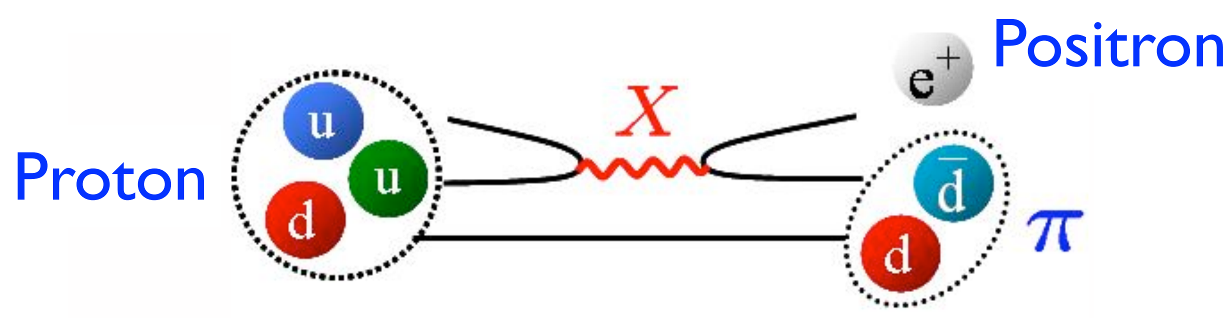
- Results of nucleon decay searches with **Super-K**
  - Mostly focuses on:
    - Two ‘flagship’ decay modes: $\mathbf{p \rightarrow e^{+}\pi^{0}}$ and $\mathbf{p \rightarrow \bar{\nu}K^{+}}$
    - The recent results for other decay modes

- Prospects on nucleon decay (NDK) searches with **Hyper-K**

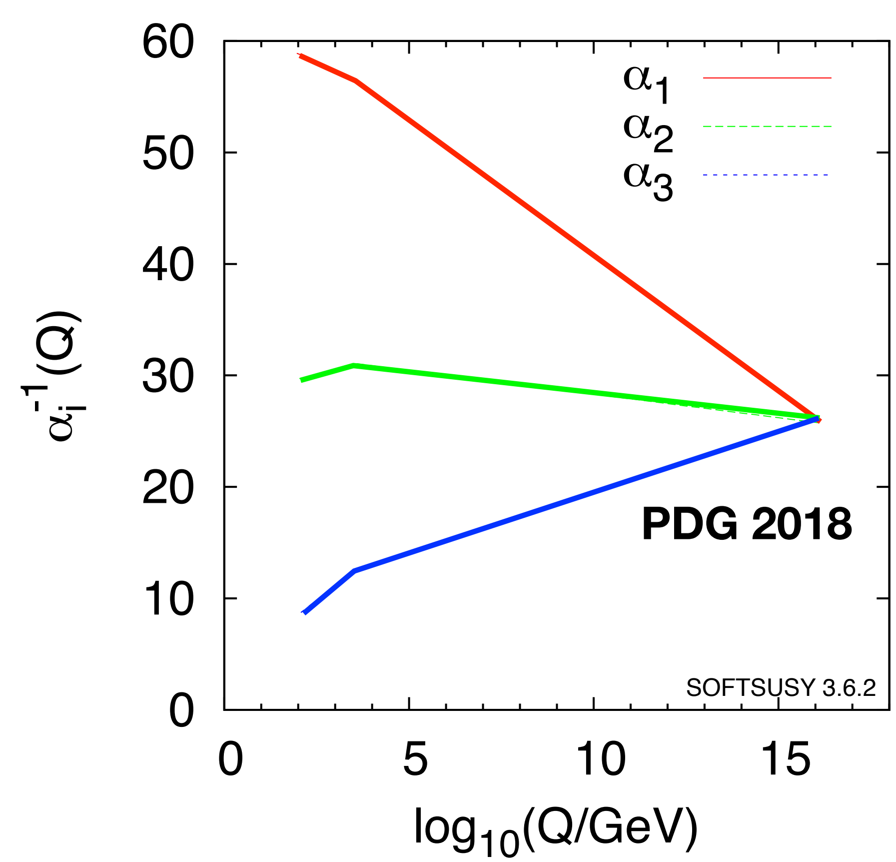
Nucleon Decay

- 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 an unique prove for GUT and physics in very high energy

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



Unification of running couplings



Nucleon Decay

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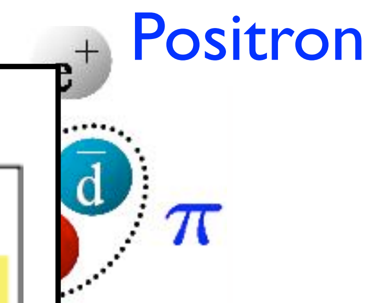
$p \to e^+\pi^0$ decay mode



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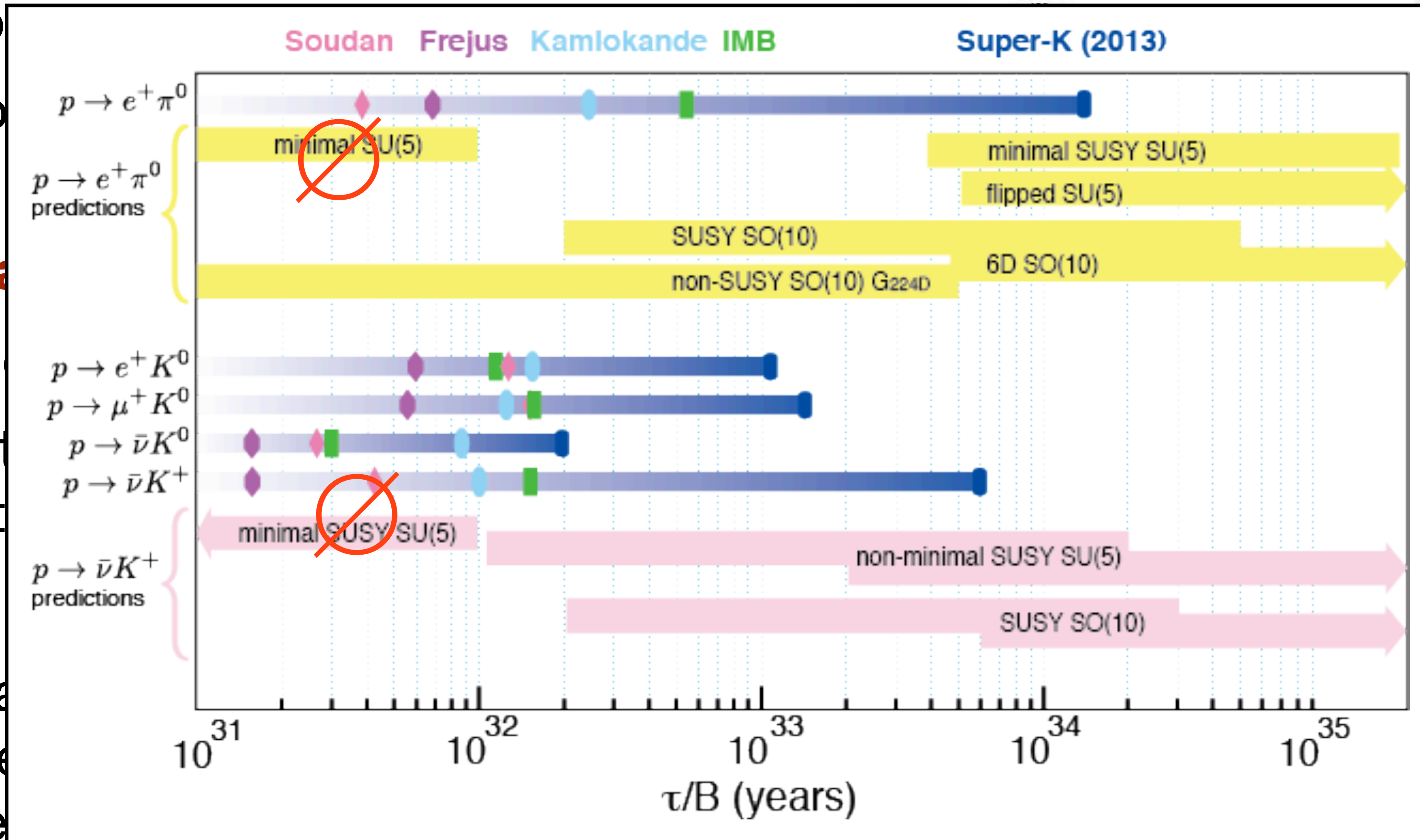
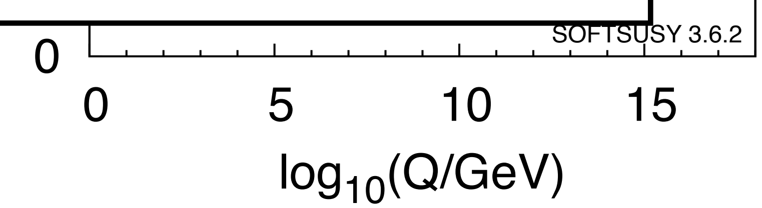
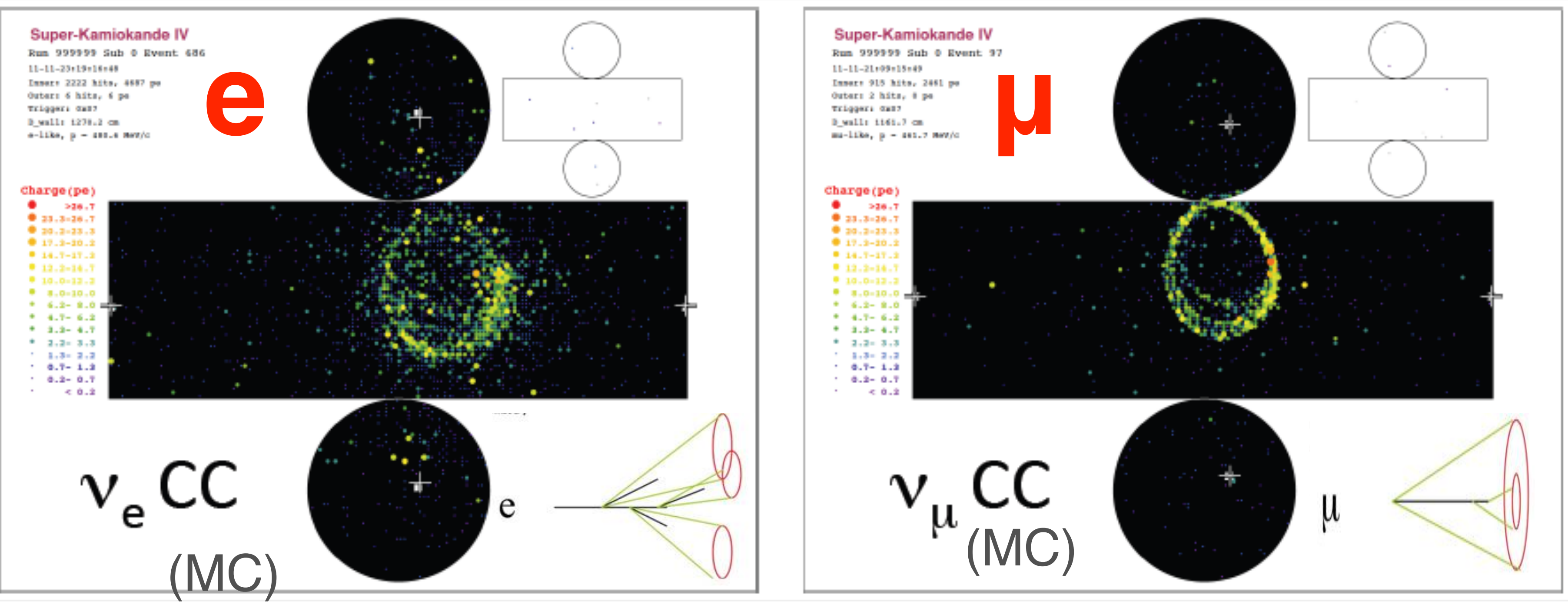


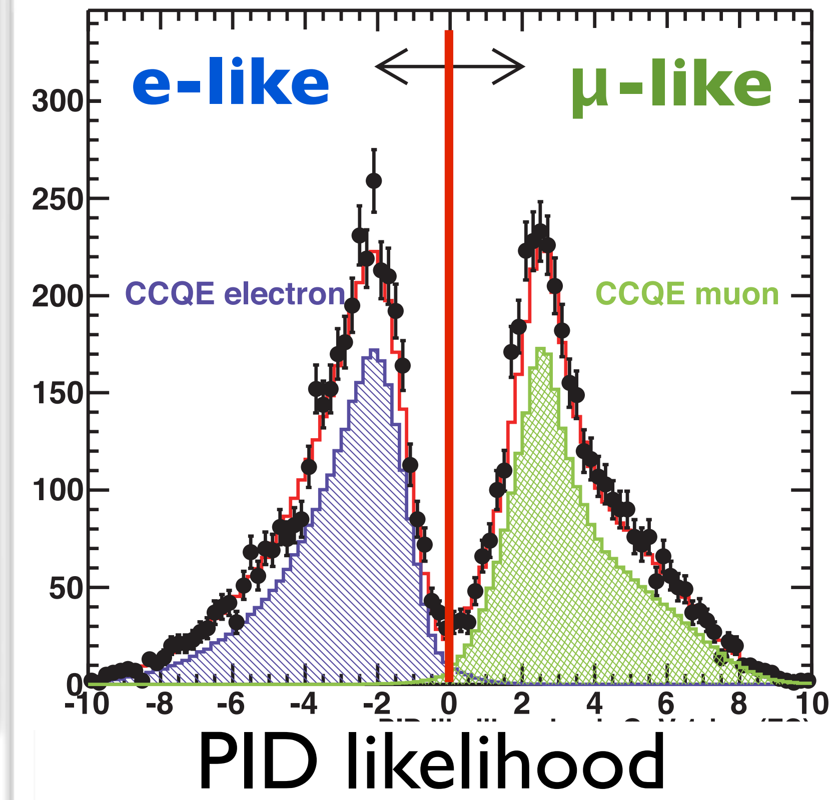


- Nucleon decay search an unique prove for GUT and physics in very high energy

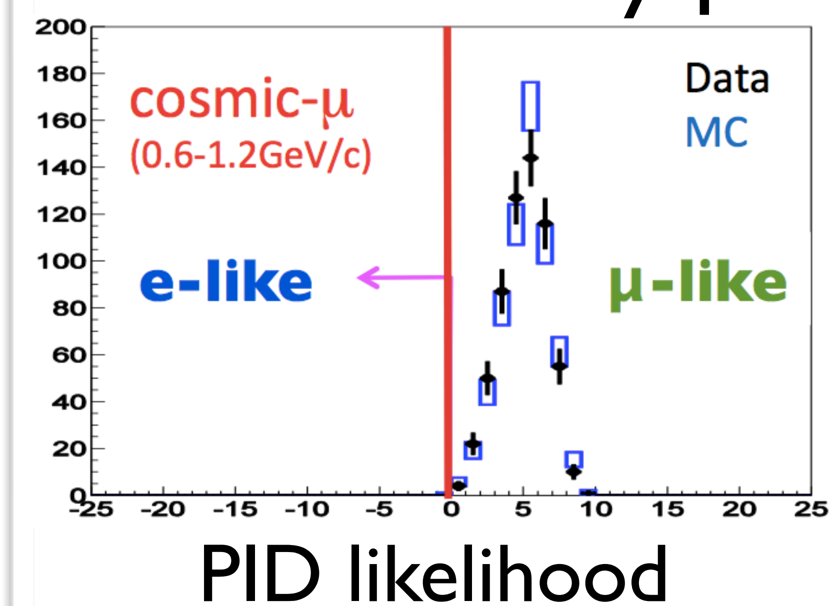
Super-Kamiokande



SK atmospheric ν



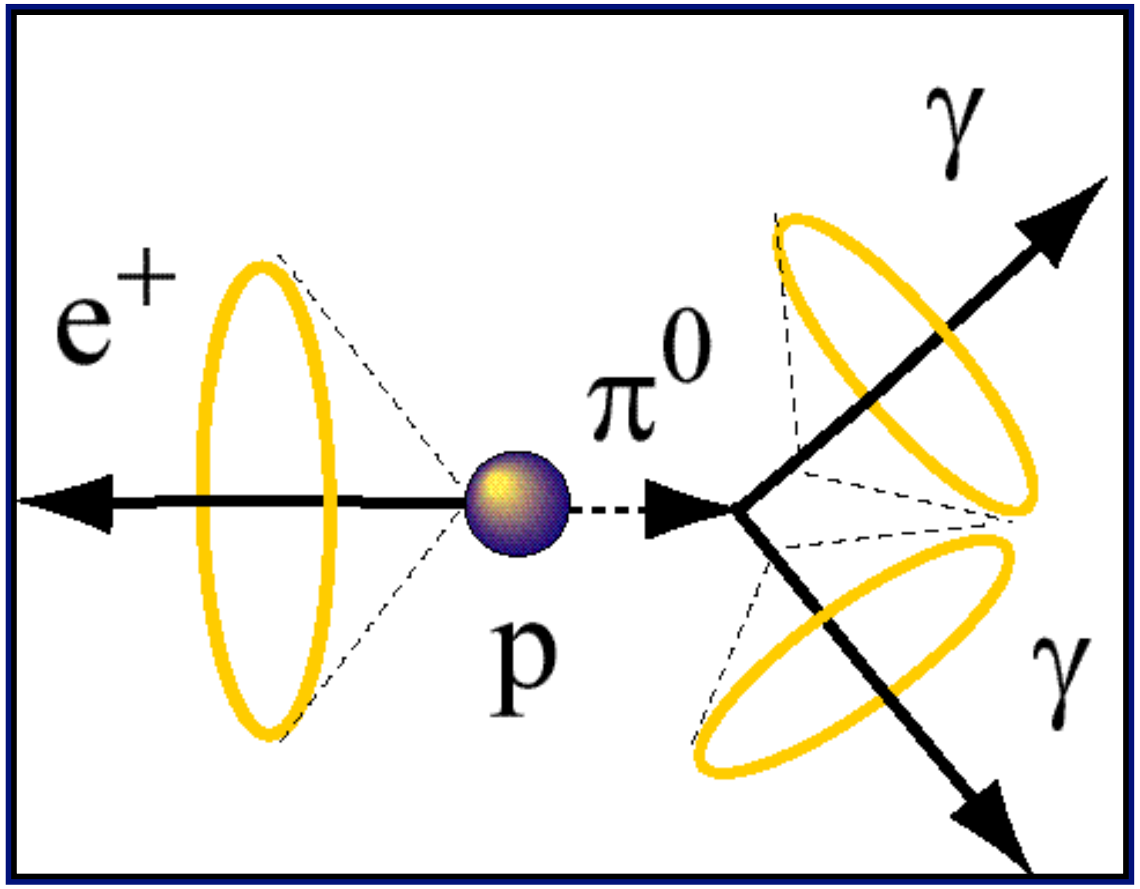
SK cosmic-ray μ

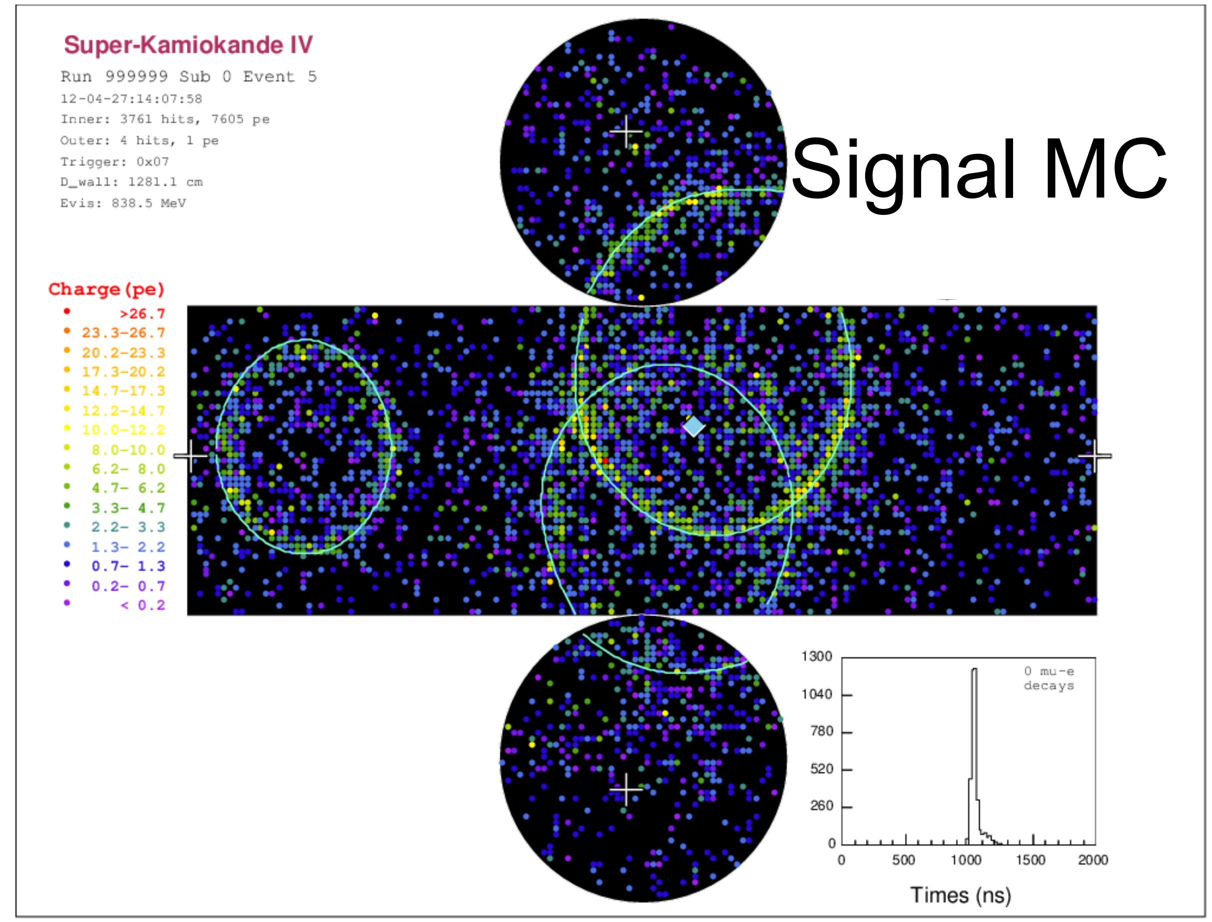


mis-PID:
Data: 0.00±0.16(stat.)%
MC : 0.10±0.10(stat.)%

- 42m (toll) x 39m (diameter) large water Č detector filled with 50kton ultra-pure water
  - Fiducial mass: 22.5kton (conventional)
- **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**
- **Good energy resolution: ~3% at ~1GeV**

Search for $p \rightarrow e^{+}\pi^{0}$



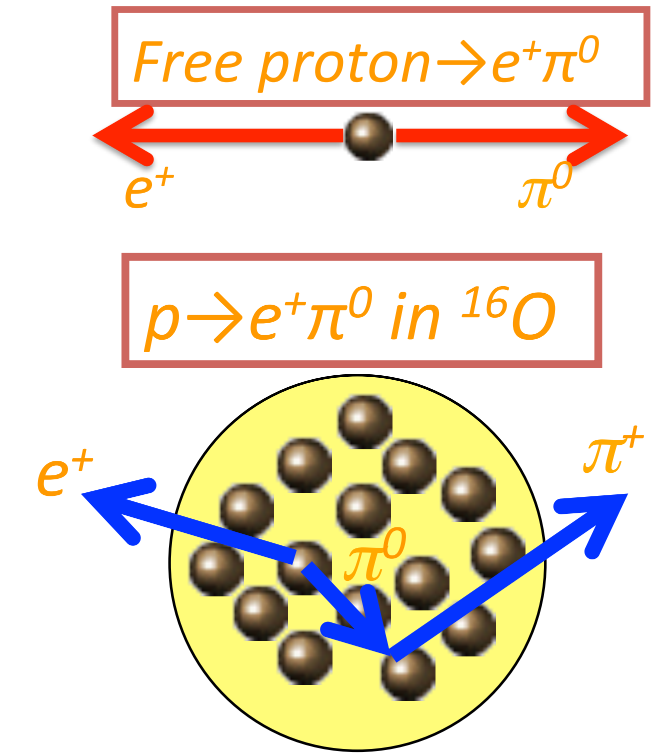


- **Positron and π^0 run back-to-back**
  - Momentum 459 MeV/c
- **All particles in the final stable are visible with Super-K**
  - **Able to reconstruct p mass and momentum**

- 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%

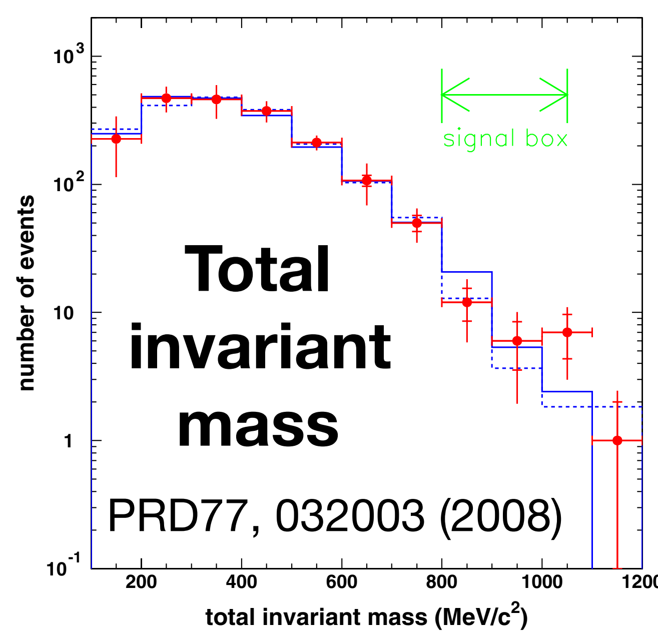
Signal & background

- **Signal**: $p \rightarrow e^+\pi^0$
  - 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. $p \rightarrow e^+\pi^0$ 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

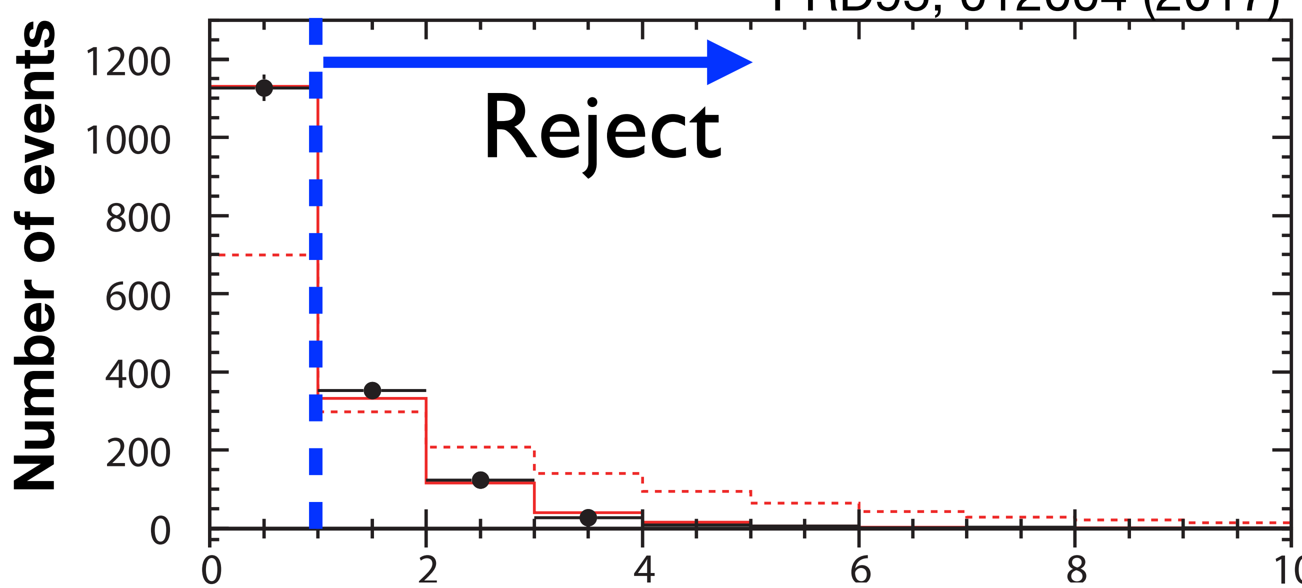
- **Background** for proton decay search
  - Atmospheric neutrino; CC-π production
  - **Background rate prediction confirmed with data from K2K-1KT Č detector**
  - **Background under control**



Background rejection (1)

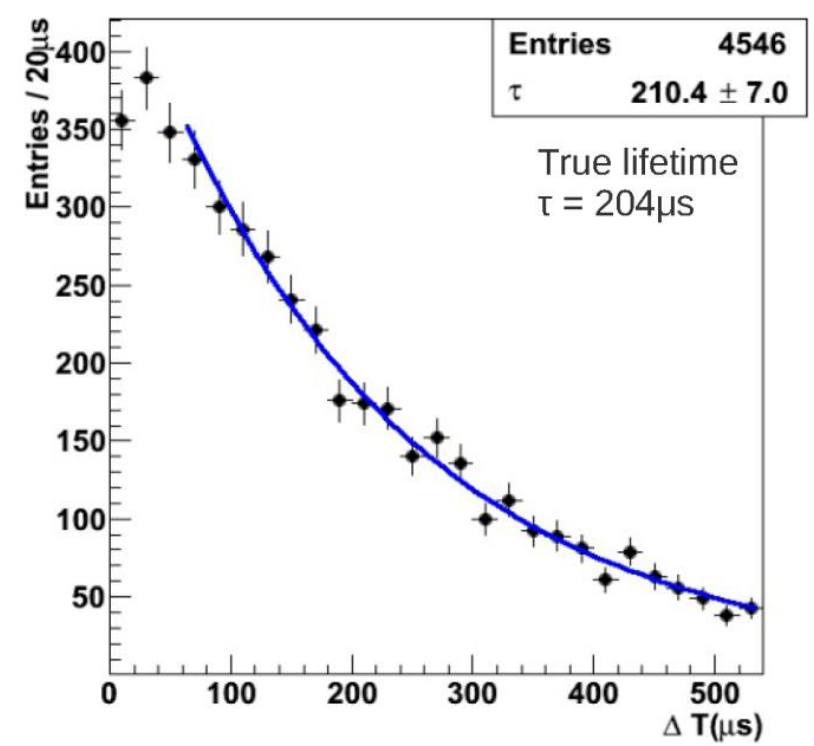
- Most of atm-ν bkg accompanied with neutrons, and n's captured by hydrogen (~200μs) & emit γ-ray
    - p+n→d+γ (2.2MeV)
- New electronics (dead-time free) installed SK-IV allows to identify the 2.2MeV γ-ray, 'neutron-tagging'
    - **Atm-ν bkg further reduced by ~50% with neutron-tagging technique**

PRD95, 012004 (2017)



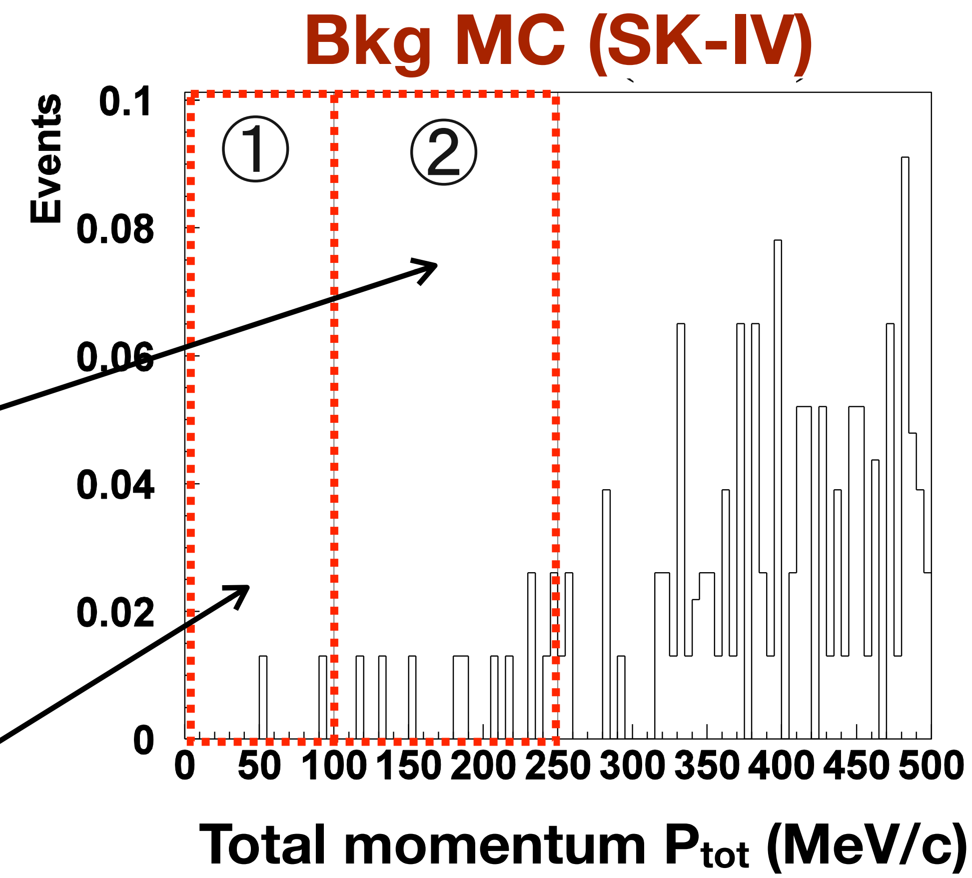
# of tagged neutrons
(neutron multiplicity)

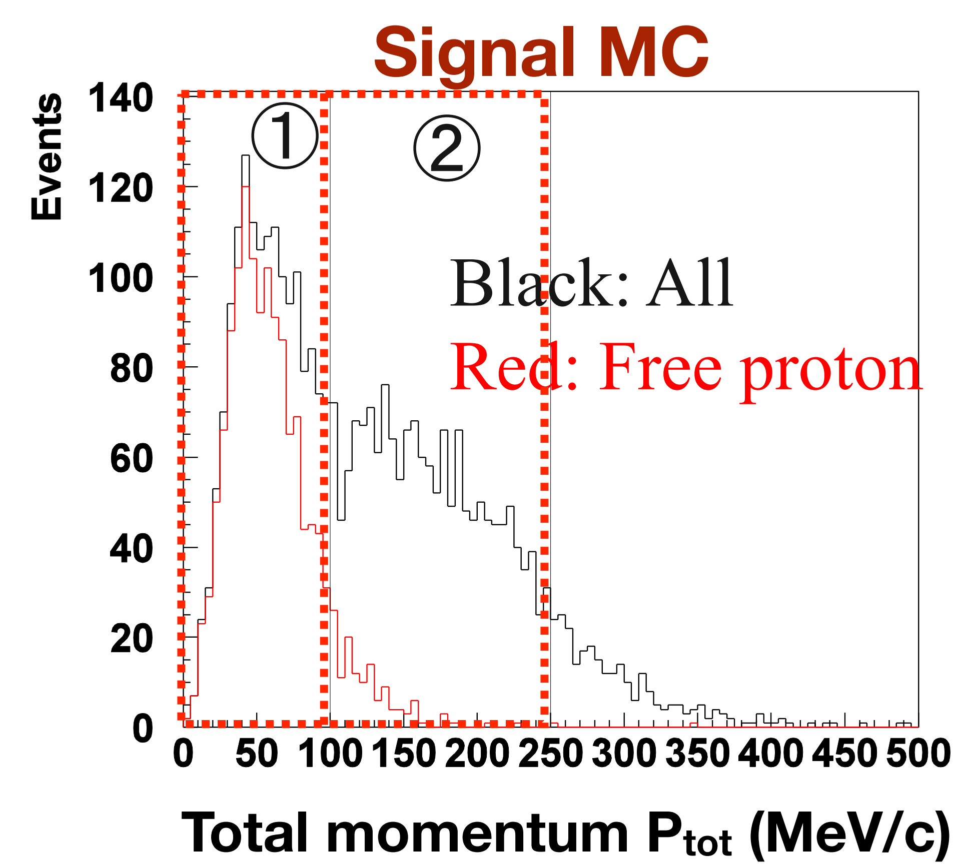
Time difference from prompt signal



Background rejection (2)

- Divide the signal box into two with P_{tot} to enhance the discovery potential
  - **Upper P_{tot}** (100~250 MeV/c)
    - Atm-ν background tail
    - Proton decay in ^{16}O dominant
  - **Lower P_{tot}** (<100 MeV/c)
    - **~1/10 smaller bkg compered to the upper P_{tot}**
    - Free proton decay dominant





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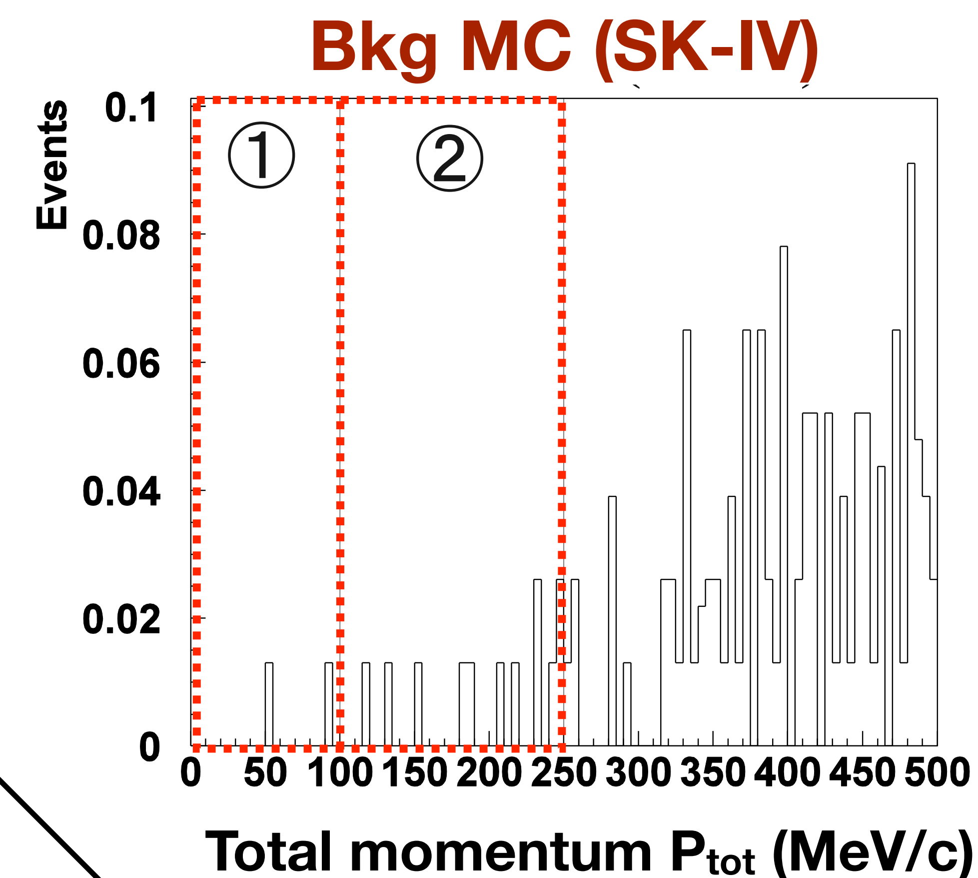
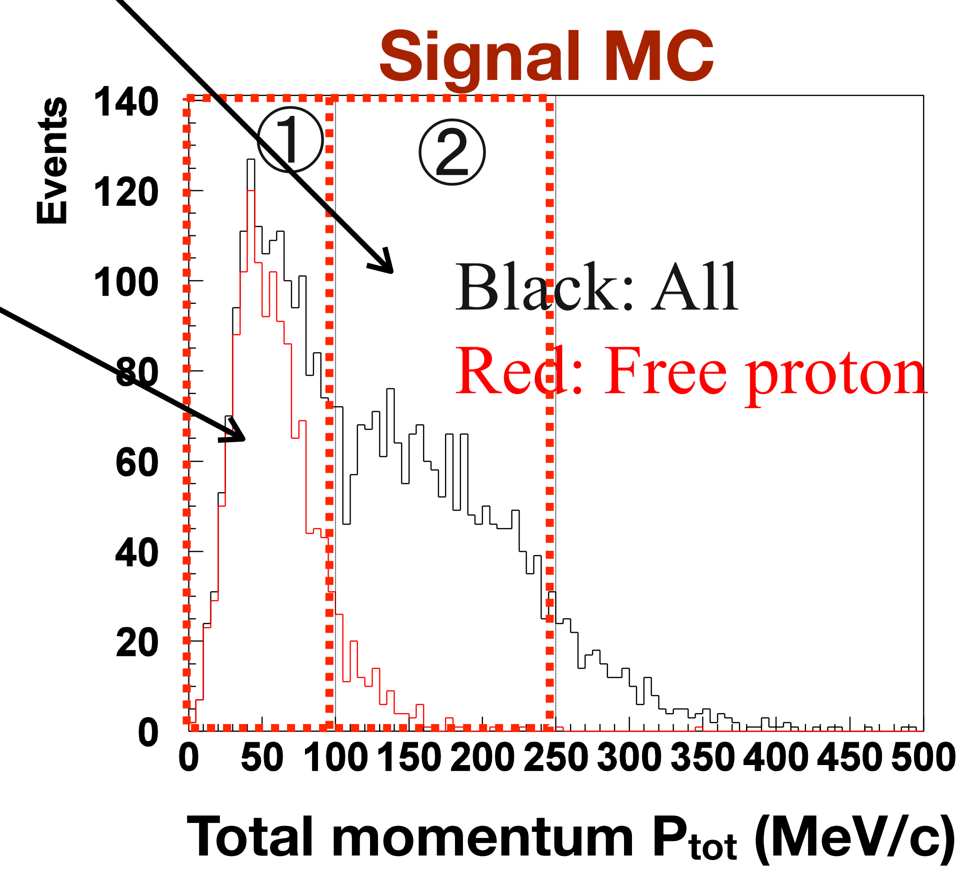
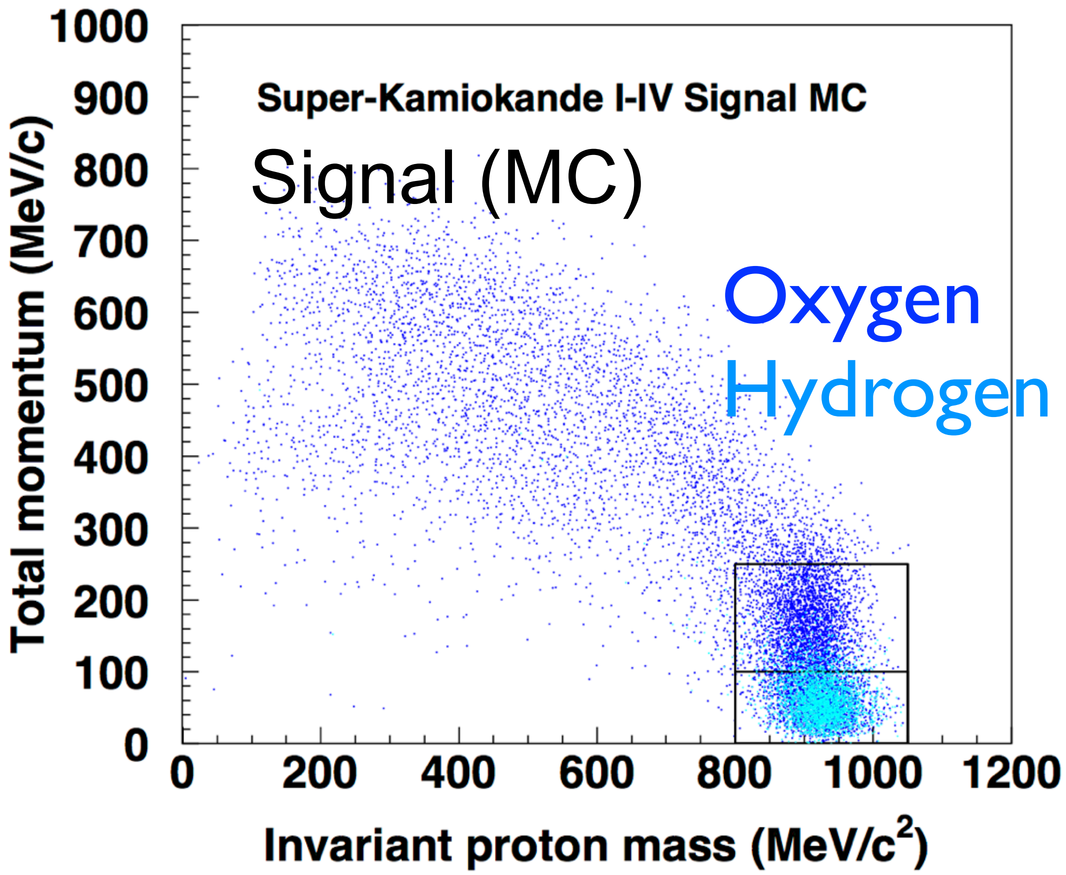
    - Proton decay in ^{16}O dominant
  - **Lower P_{tot}** (<100 MeV/c)
    - **~1/10 smaller bkg compered to the upper P_{tot}**
    - Free proton decay dominant
    - ➜ Accurate reconstruction of PDK signature (less FSI) and lower background

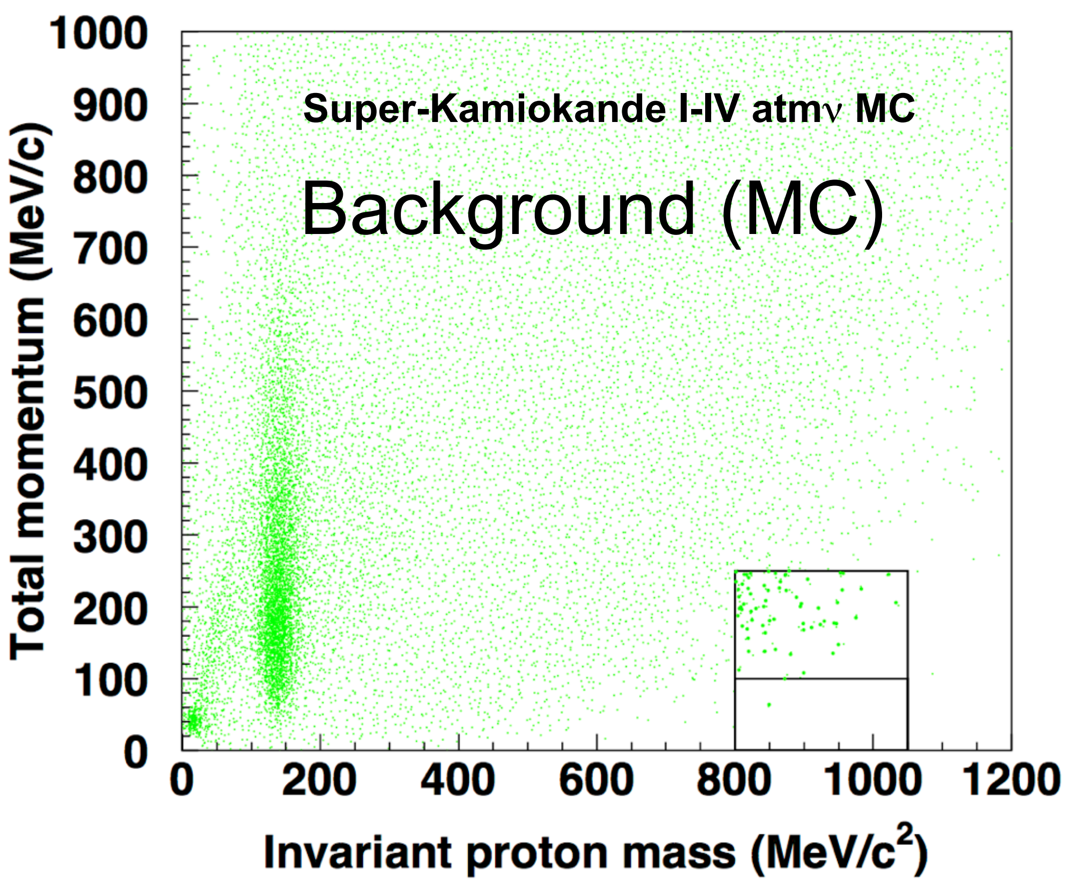




$p \rightarrow e^+\pi^0$: Signal & Bkg

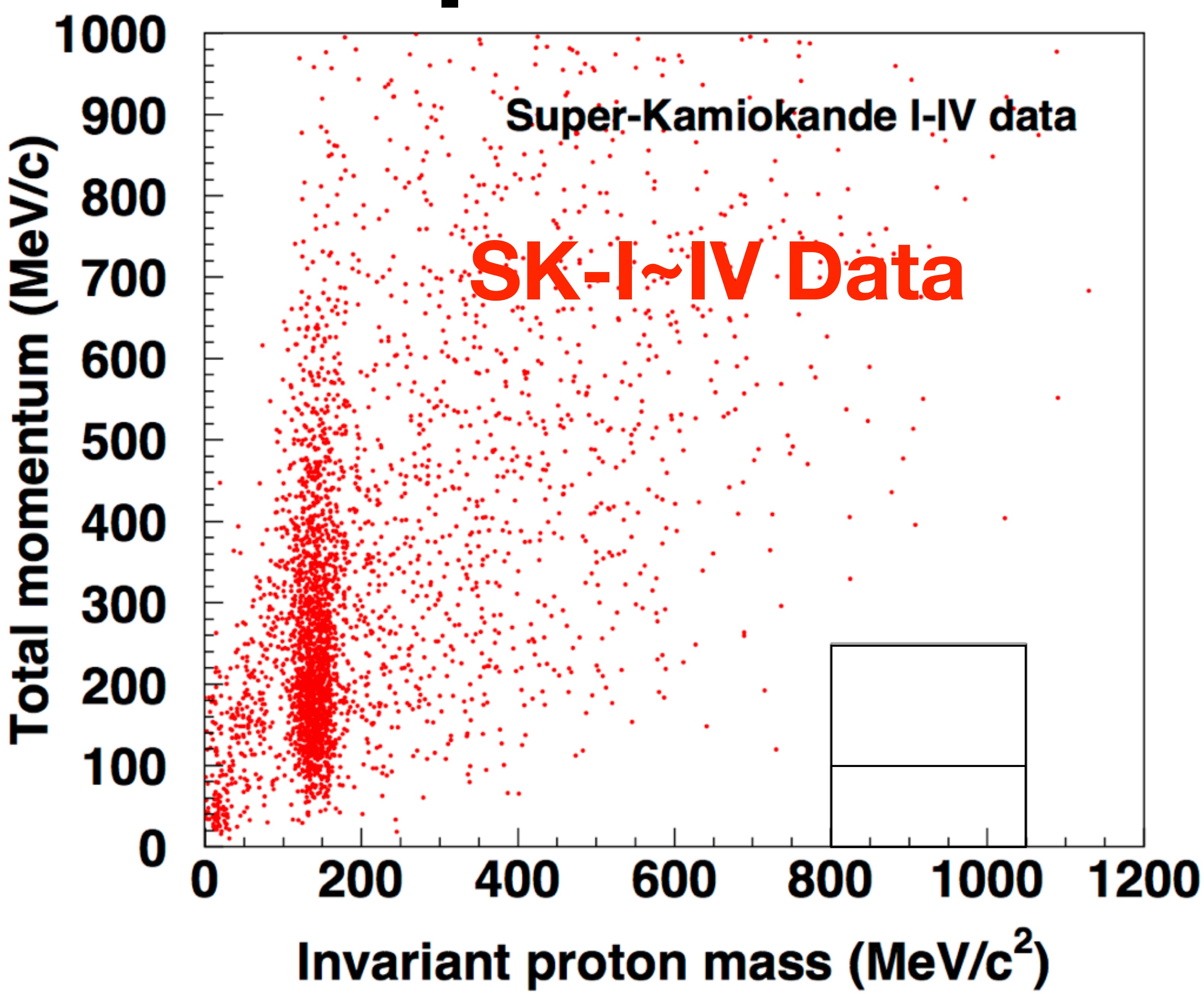


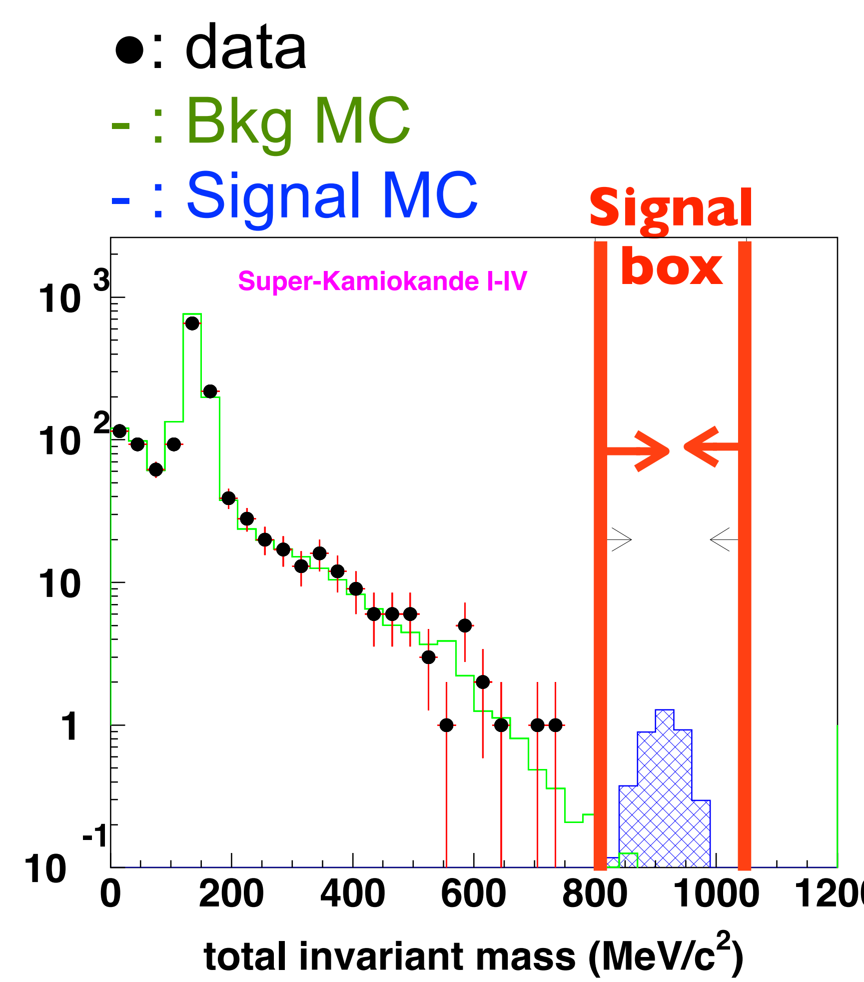
- **Signal selection efficiency: ~40%**
  - cf. ~80% for free proton decay



- **Expected bkg** contamination in signal region for entire SK period (SK-I~IV):
  - **Lower P_{tot}: 0.05 events**
  - **Upper P_{tot}: 0.58 events**

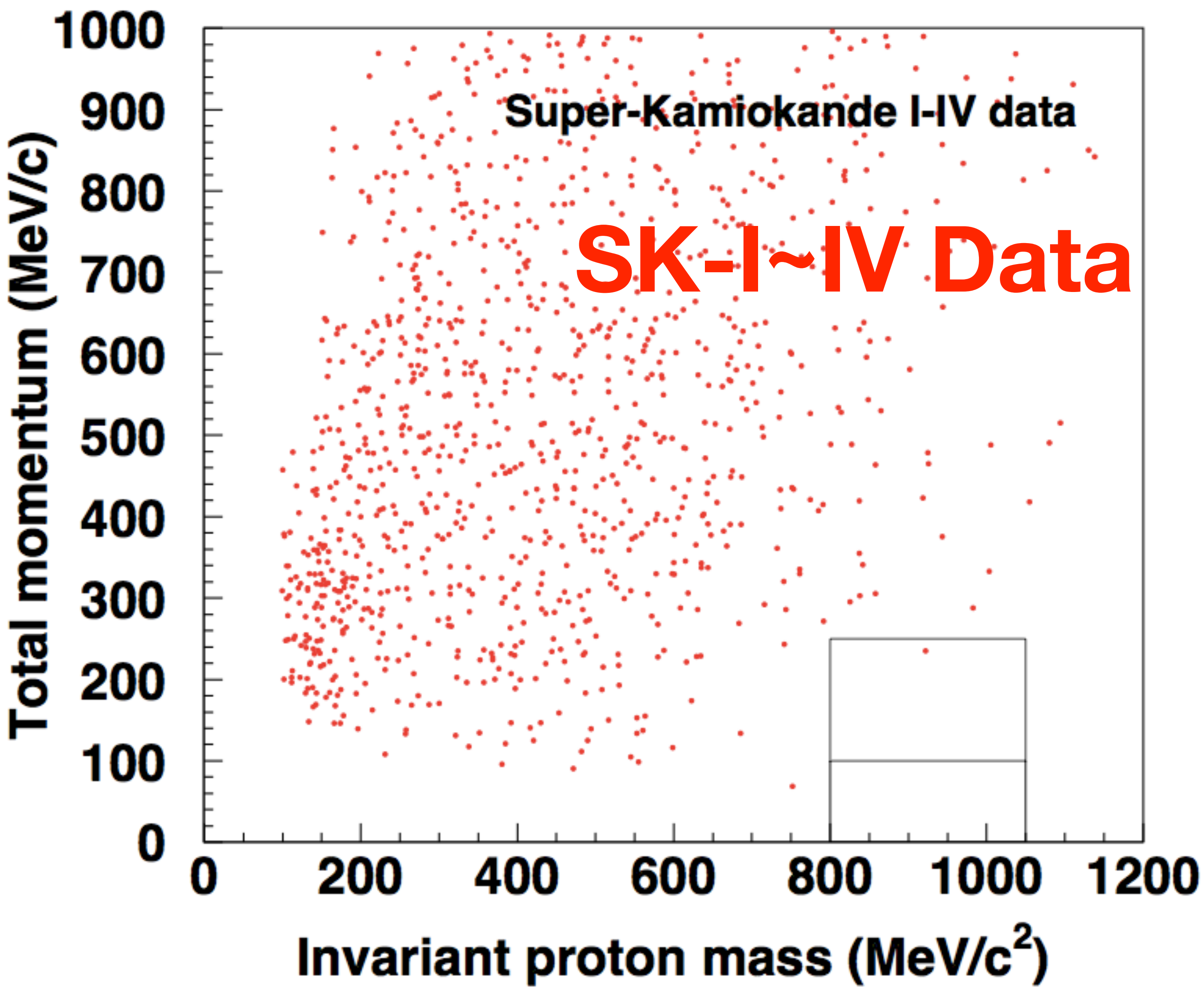
$p \to e^+\pi^0$: Results





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

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



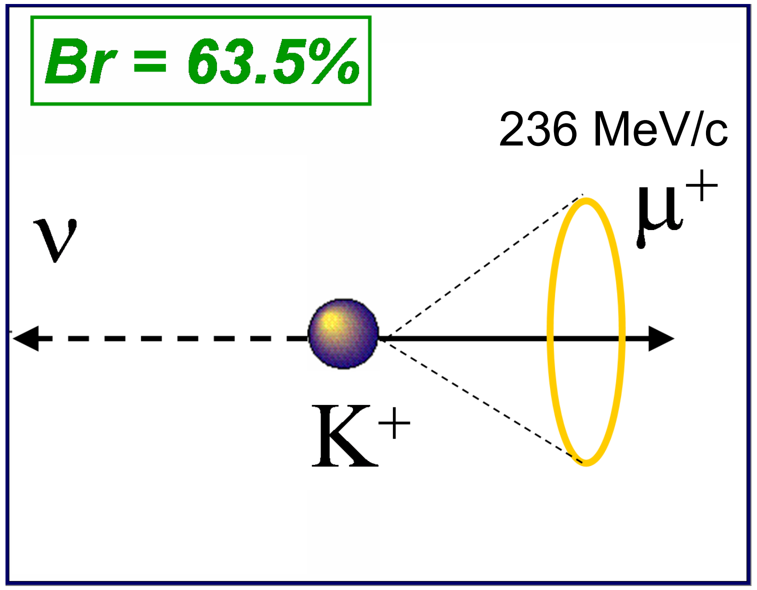
- Spirit of the event selection is similar to $p \rightarrow e^+\pi^0$ mode but requires 1 μ-like ring
- Signal selection eff: ~40%
- Expected bkg contamination for entire SK observation period (SK-I~IV):
  - Lower P_{tot}: 0.07 events
  - Upper P_{tot}: 0.65 events
- Found 1 evt in upper signal box
  - It's not obvious data excess compared to expected bkg
  - See PRD95, 012004 (2017)

- Lifetime limit at 90% C.L. with 365 kt·years (SK-I~IV) exposure
  τ/Br>1.2×10^{34} years [preliminary]

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

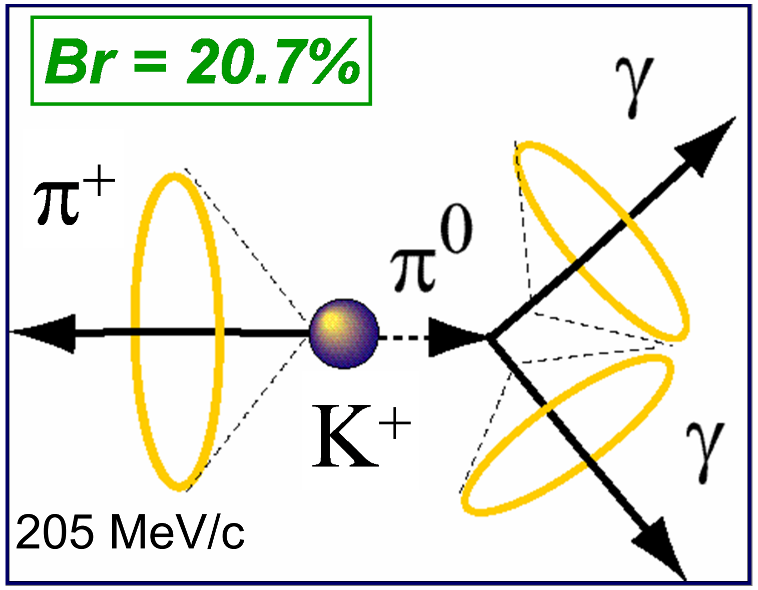
- K^+ has momentum of 340 MeV/c
  - Below Cherenkov threshold (749 MeV/c)
- **Identify K^+ by finding its decay products**

$K^+ \to \mu^+ \nu_\mu$
(K+ **leptonic** decay)



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

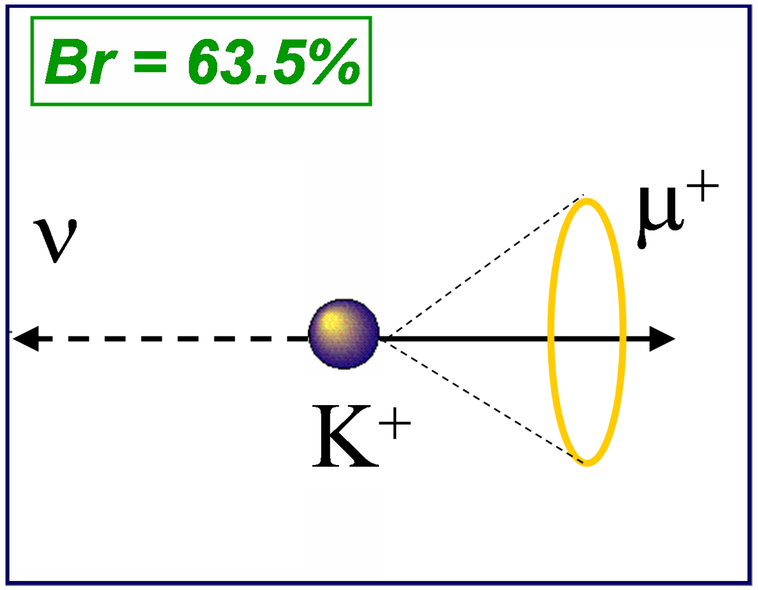
$K^+ \to \pi^+ \pi^0$
(K+ **hadronic** decay)



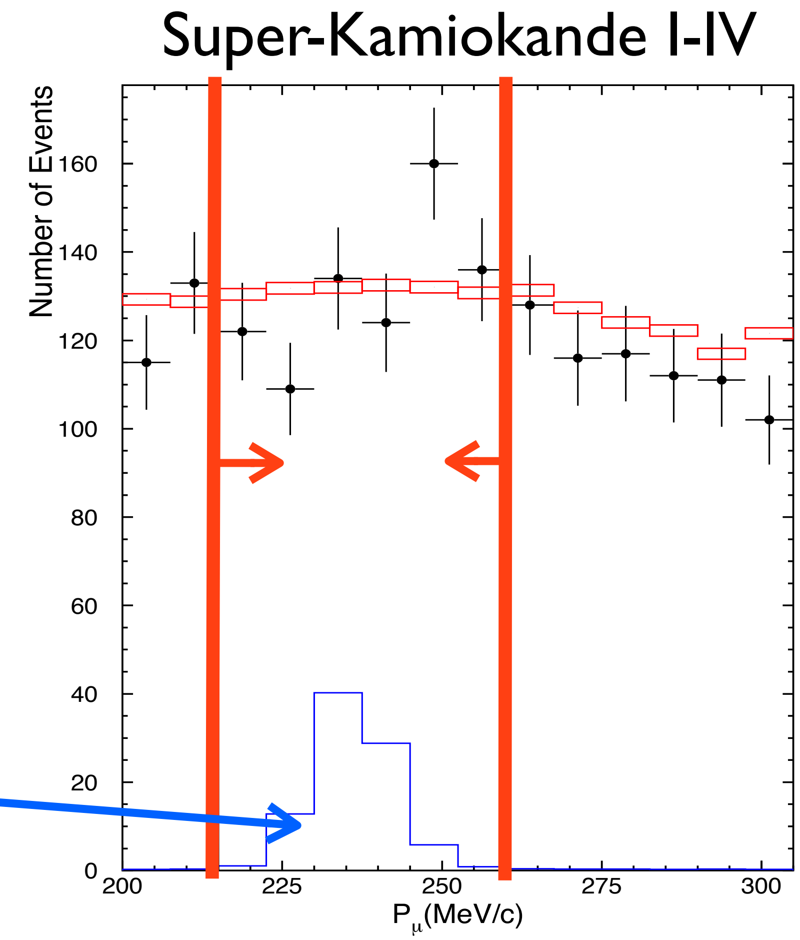
Search Method
- π^+ and two γ from π^0 decay
  (π+ Č threshold 156MeV/c)

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

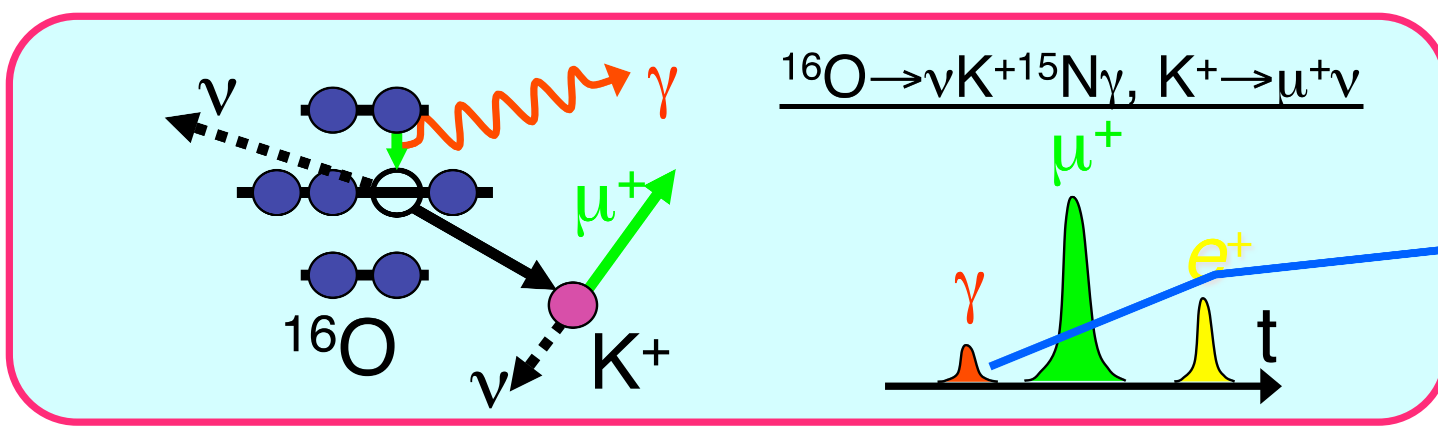
【K+ leptonic decay】

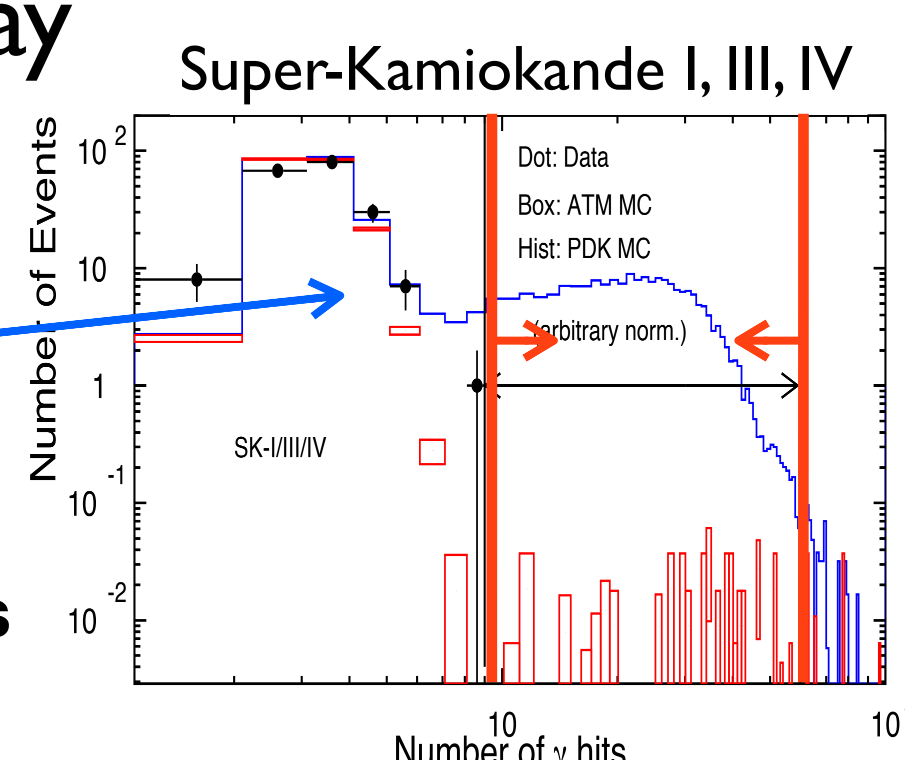


(a) Search for mono-energetic (236MeV/c) μ



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

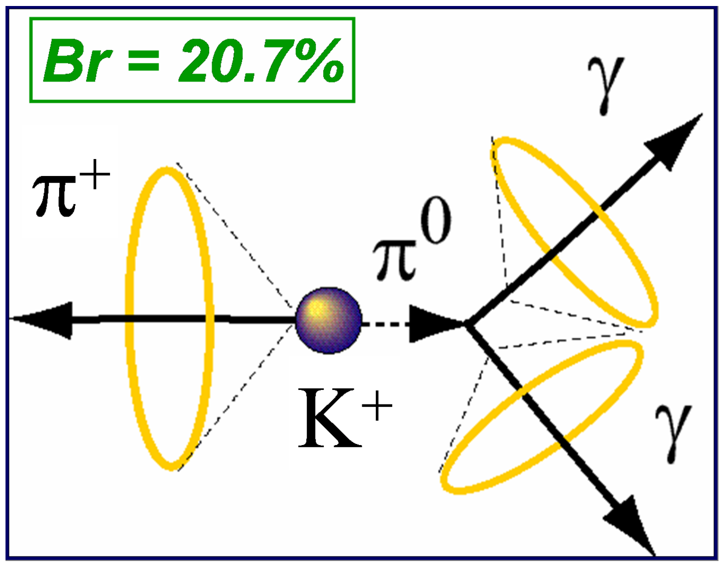


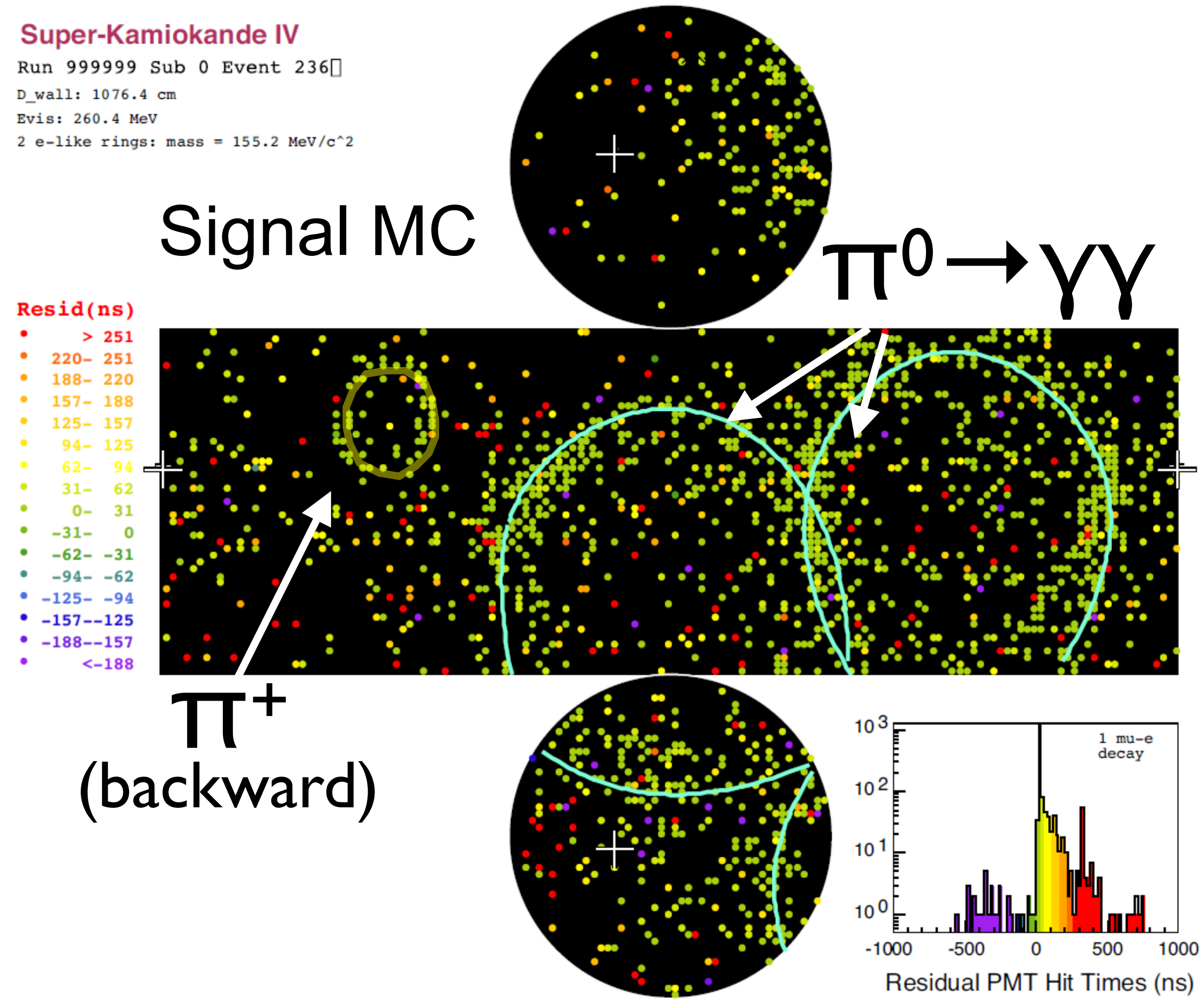


Proton decays in ^{16}O → Excited nucleus ($^{15}N^*$) emits 6.3 MeV γ-ray (~40% probability)
➜ γ, μ and Michel-e from μ-decay triple coincidence largely reduce the bkg contamination

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

【K+ hadronic decay】





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

- **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)

N→charged lepton + meson

[PRD96, 012003 (2017)]

Theoretical prediction on branching ratio

channels	Buccella et al. (1989)
p→$e^+\pi^0$	30.0%
p→$e^+\eta$	12.9%
p→$e^+\rho^0$	1.8%
p→$e^+\omega$	14.4%

- Several decay modes consist of charged lepton and meson:
  - [e^+ / μ^+] + [η, ρ, ω, …]
- These decay mode can have a similar branching ratio to p→$e^+/\mu^+\pi^0$
- Search for nucleon decay for 10 decay modes:

p → (e^+, μ^+) + (π^0, η, ρ^0, ω)

n → (e^+, μ^+) + (π^-, ρ^-)

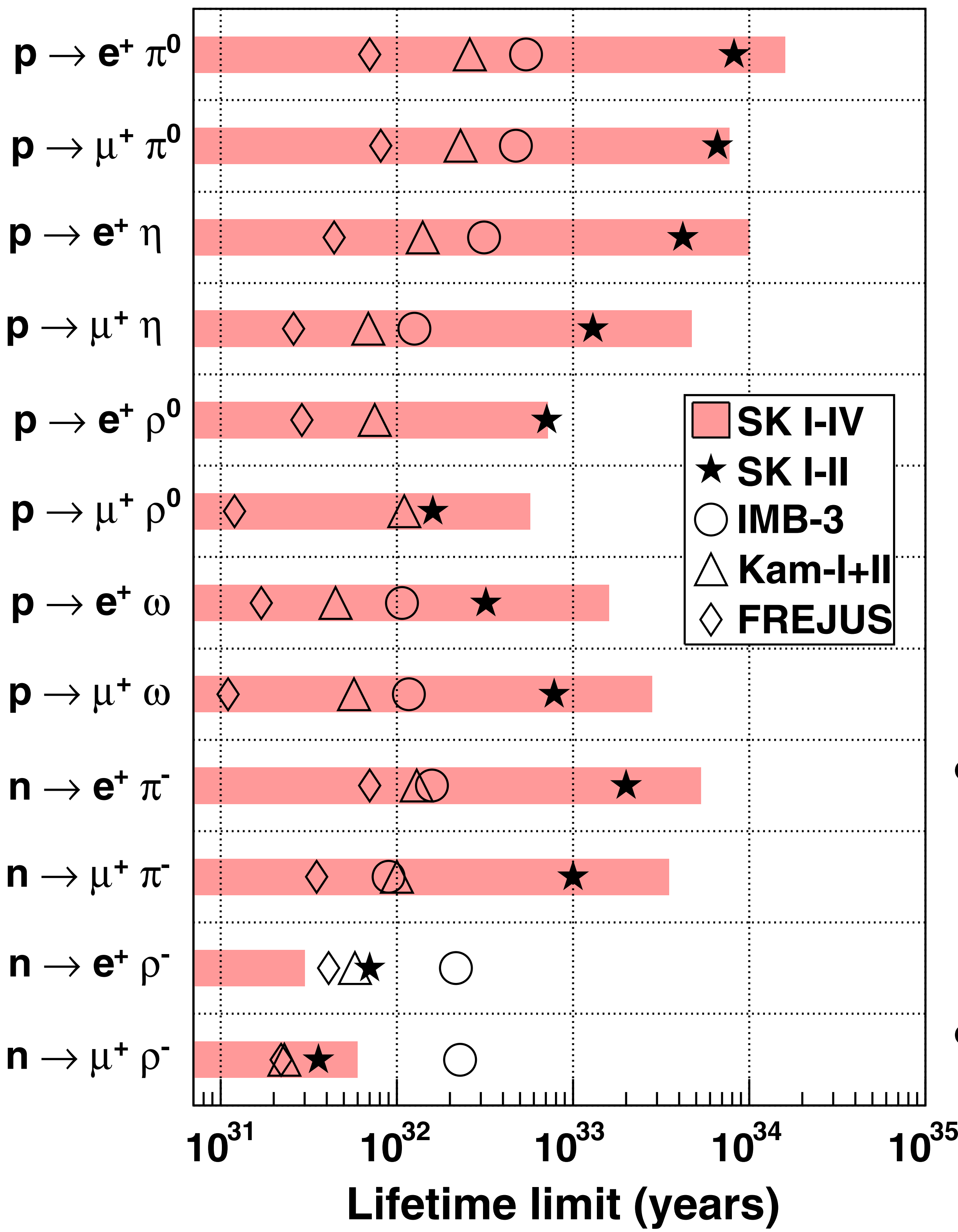
η → (2γ : 39%, $3\pi^0$: 33%)

ω → ($\pi^0\gamma$: 9%, $\pi^+\pi^-\pi^0$: 89%)

10 decay modes

N→charged lepton + meson

[PRD96, 012003 (2017)]



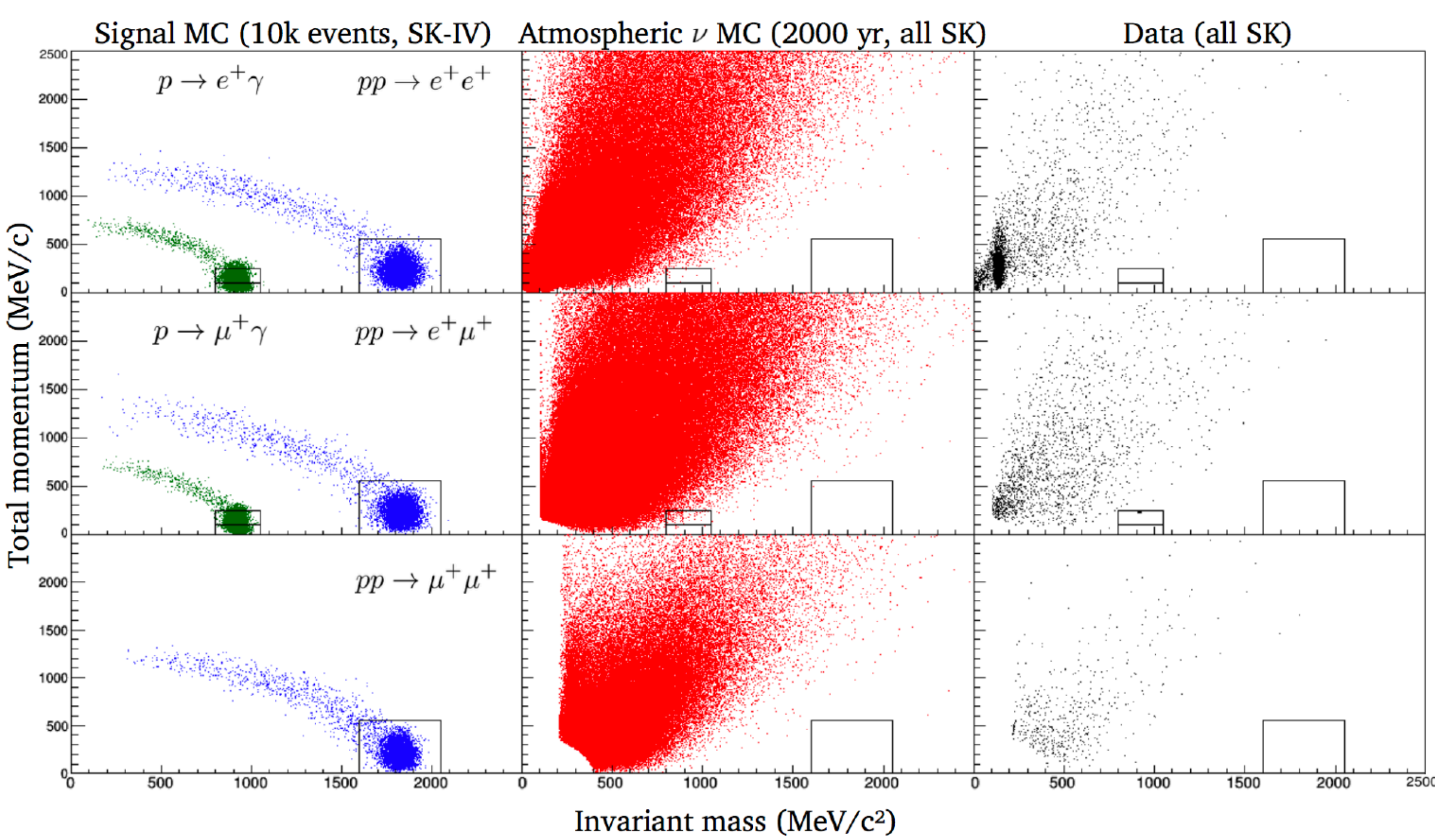
Modes	Background (events)	Candidate (events)	Probability (%)	Lifetime Limit ($\times 10^{33}$ years) at 90% CL
$p \to e^+\eta$	0.78 ± 0.30	0	...	10.
$p \to \mu^+\eta$	0.85 ± 0.23	2	20.9	4.7
$p \to e^+\rho^0$	0.64 ± 0.17	2	13.5	0.72
$p \to \mu^+\rho^0$	1.30 ± 0.33	1	72.7	0.57
$p \to e^+\omega$	1.35 ± 0.43	1	74.1	1.6
$p \to \mu^+\omega$	1.09 ± 0.52	0	...	2.8
$n \to e^+\pi^-$	0.41 ± 0.13	0	...	5.3
$n \to \mu^+\pi^-$	0.77 ± 0.20	1	53.7	3.5
$n \to e^+\rho^-$	0.87 ± 0.26	4	1.2	0.03
$n \to \mu^+\rho^-$	0.96 ± 0.28	1	61.7	0.06
total	8.6	12	15.7	...

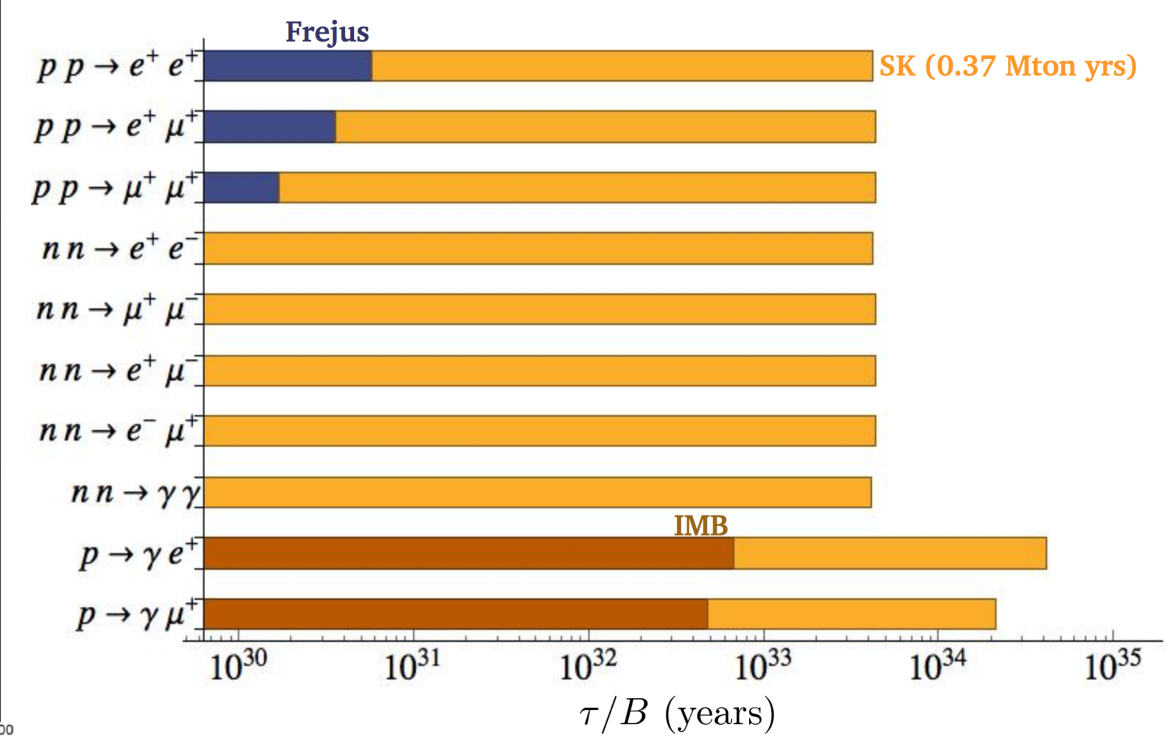
- **No obvious data excess** with Super-K 365 kt·year exposure (SK-I~IV)
- **Lifetime limits reach to ≥10^{33} yrs** for many of decay modes

Search for di-nucleon decay

[arXiv:1811.12430]

- Search for di-nucleon decay with only leptons or γ's in final state
  - $pp \to e^+e^+$, $nn \to e^+e^-$, $nn \to \gamma\gamma$, $pp \to e^+\mu^+$, $nn \to e^\pm\mu^\mp$, $pp \to \mu^+\mu^+$, $nn \to \mu^+\mu^-$, and $p \to e^+\gamma$, $\mu^+\gamma$
- 5 out of 8 di-nucleon decay modes are $\Delta(B-L)=-2$
- Experimentally very clean (low bkg) and high signal efficiency: ~80%
- **No evidence of nucleon decay**
- Lifetime limits improved by <u>order of magnitudes</u> from previous limits

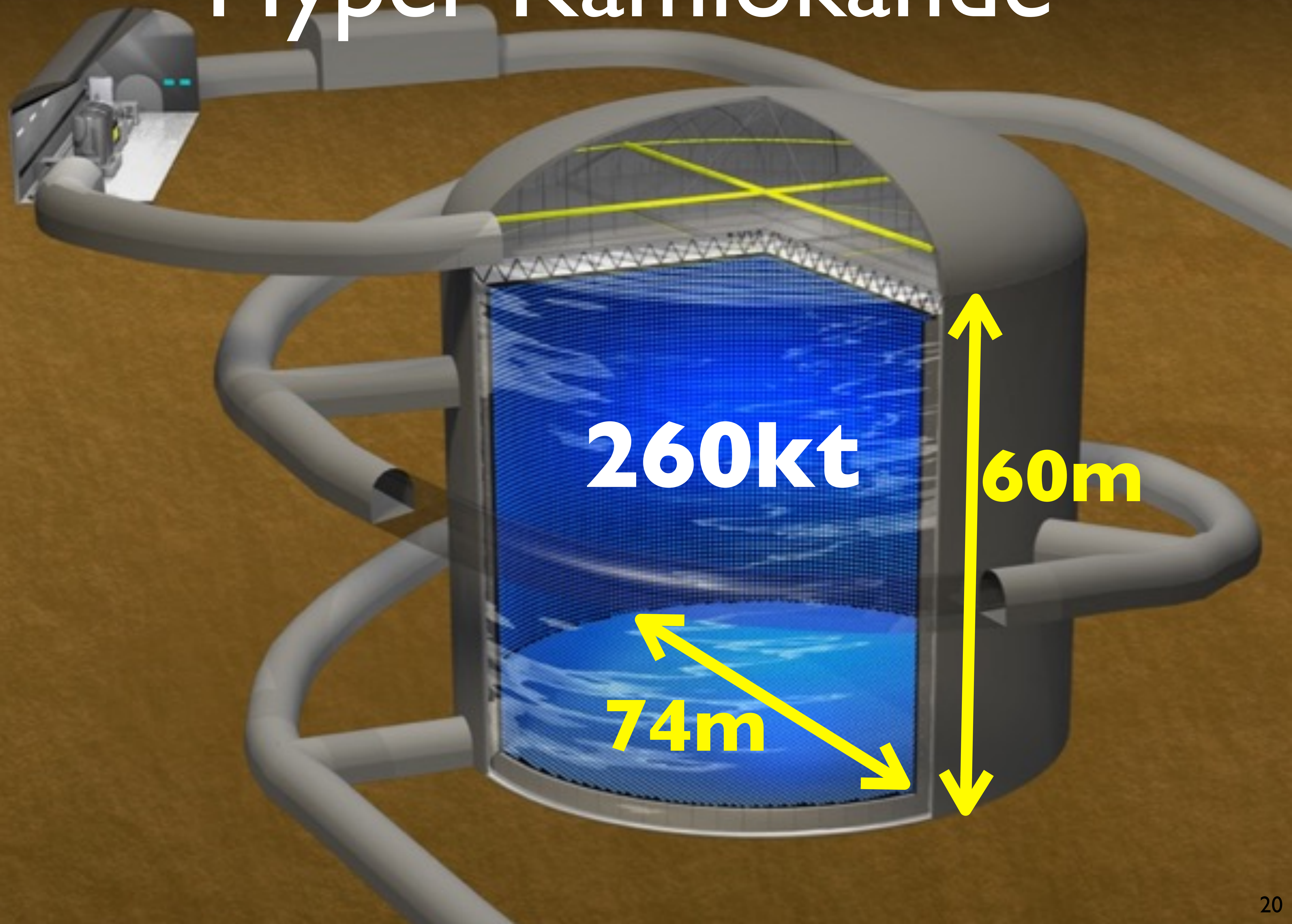




SK: near future

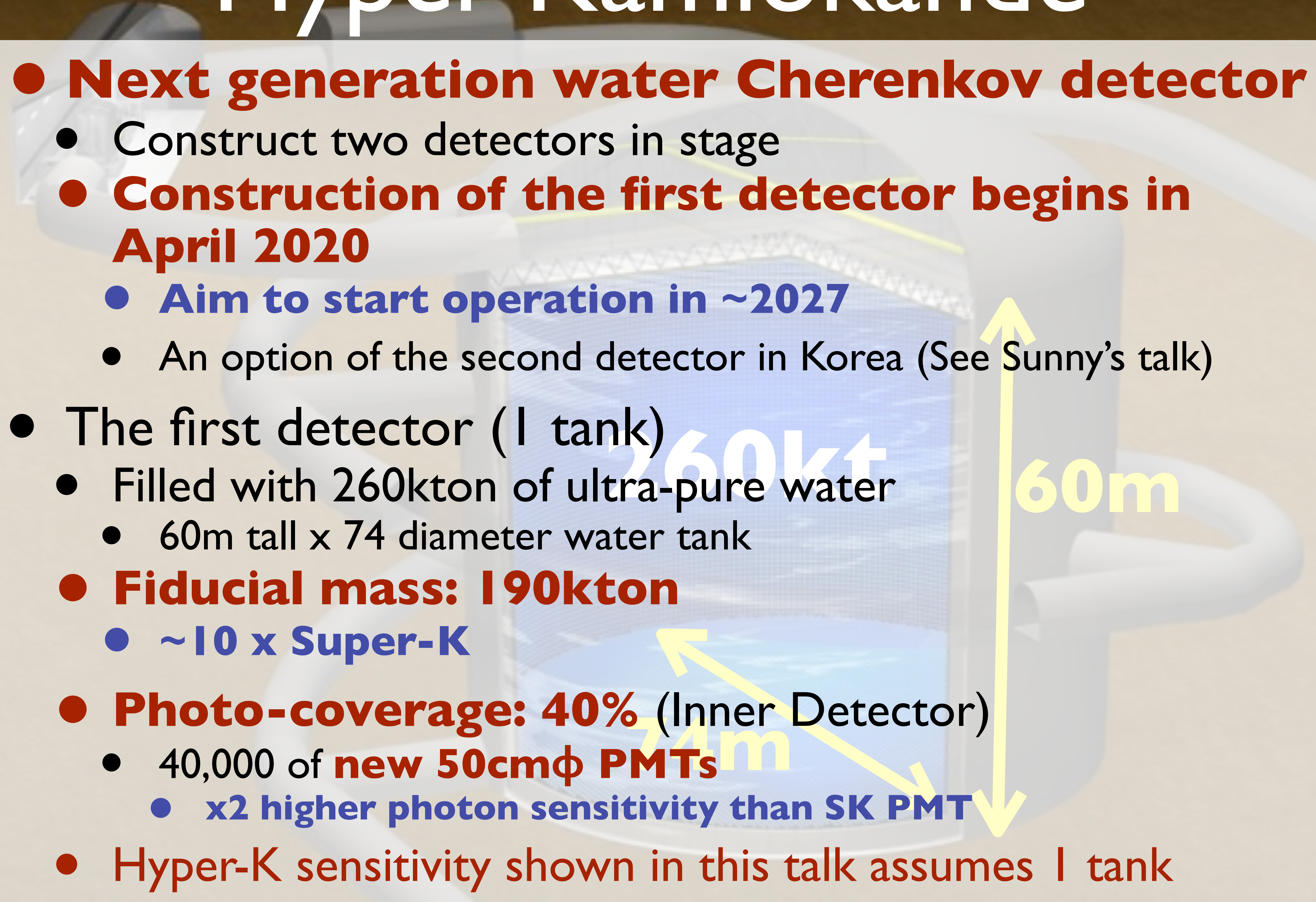
- SK tank refurbishment completed and ready for Gd loading: **SK → SK-Gd**
  - Neutron capture: ~50% w/ 0.01% of Gd
    → ~90% w/ 0.1% of Gd
- Nucleon decay search with SK-Gd:
  - **Further reduction bkg rate by ~50% for $p \to e^+\pi^0$**
- **In parallel, several studies to improve NDK searches on-going:**
  - Enlarge fiducial mass (+20%), improve event reconstruction algorithm, improve hydrogen n-tag, use of machine learning, …
- New results from Super-K in near future

Hyper-Kamiokande



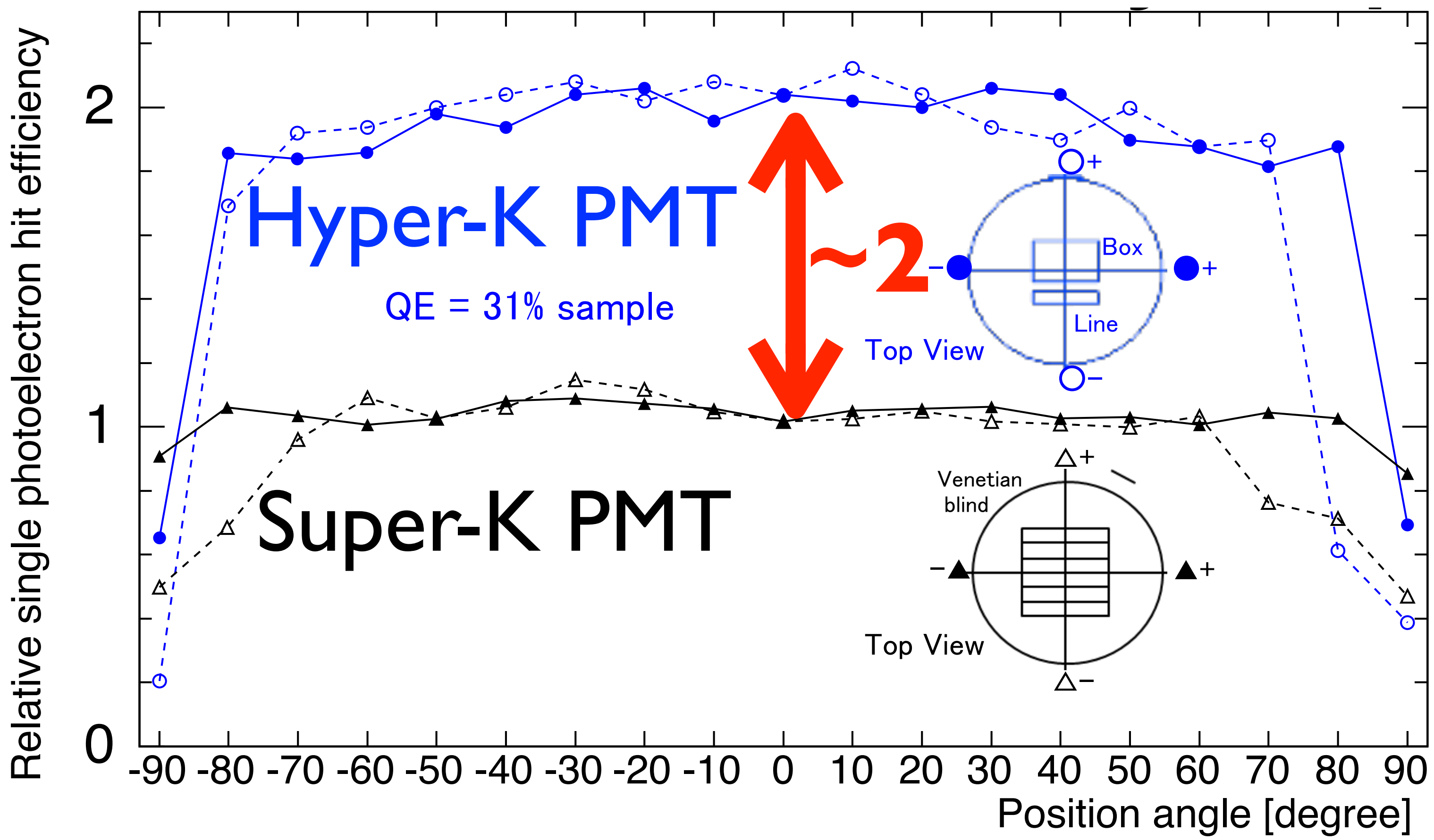
Hyper-Kamiokande

- **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 (See Sunny's talk)
- 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

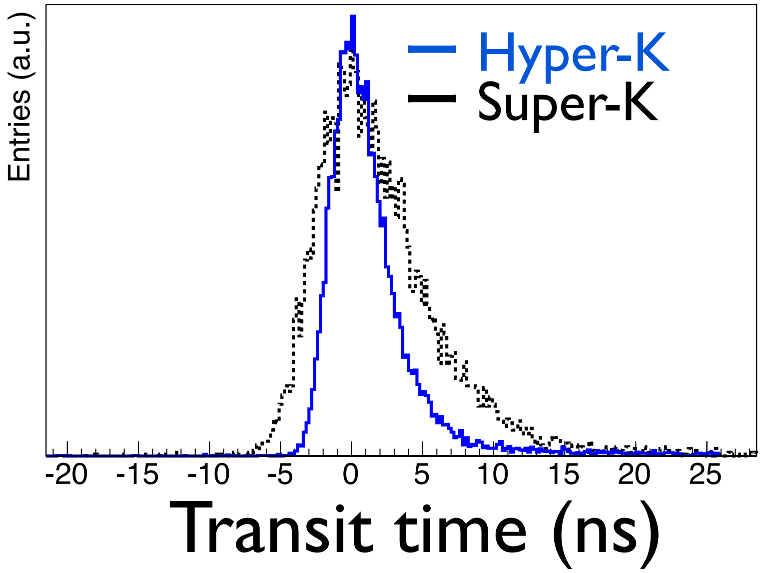


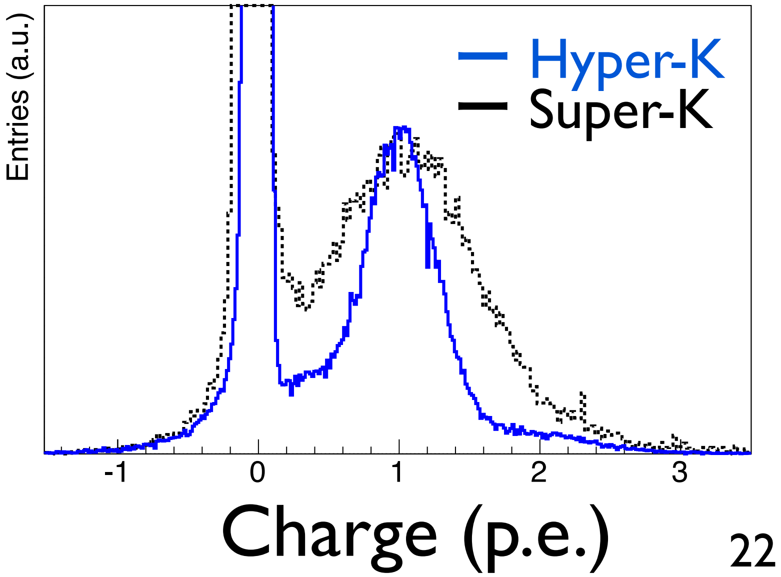
New 50cmΦ PMT for Hyper-K

Photo-detection efficiency (1p.e.)



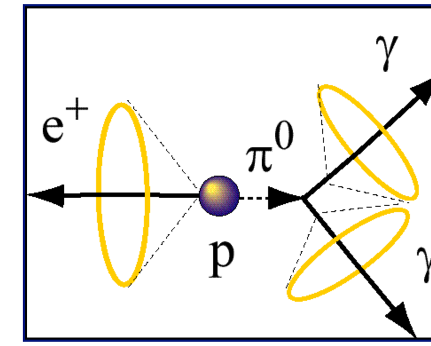
Box & line dynode PMT



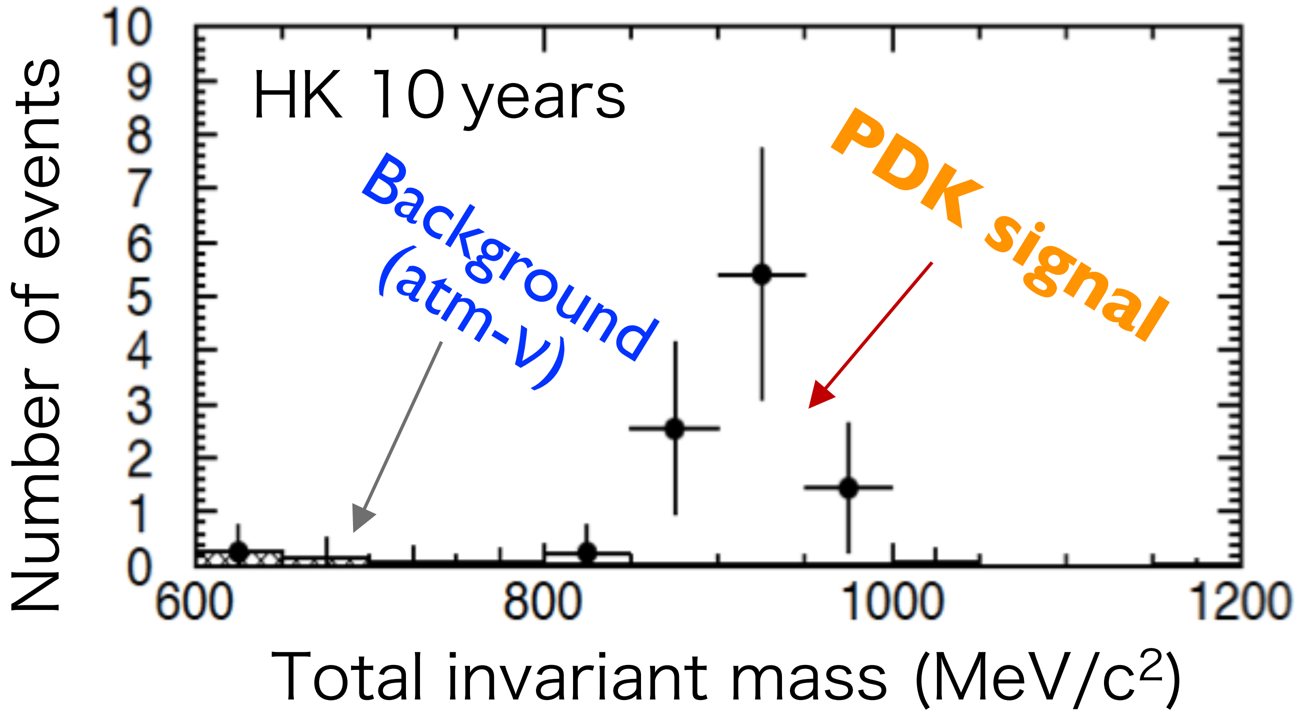


- Twice better photo-detection efficiency than SK PMTs
- Timing resolution (TTS): 1.1ns
  - cf. SK PMT: 2.1ns

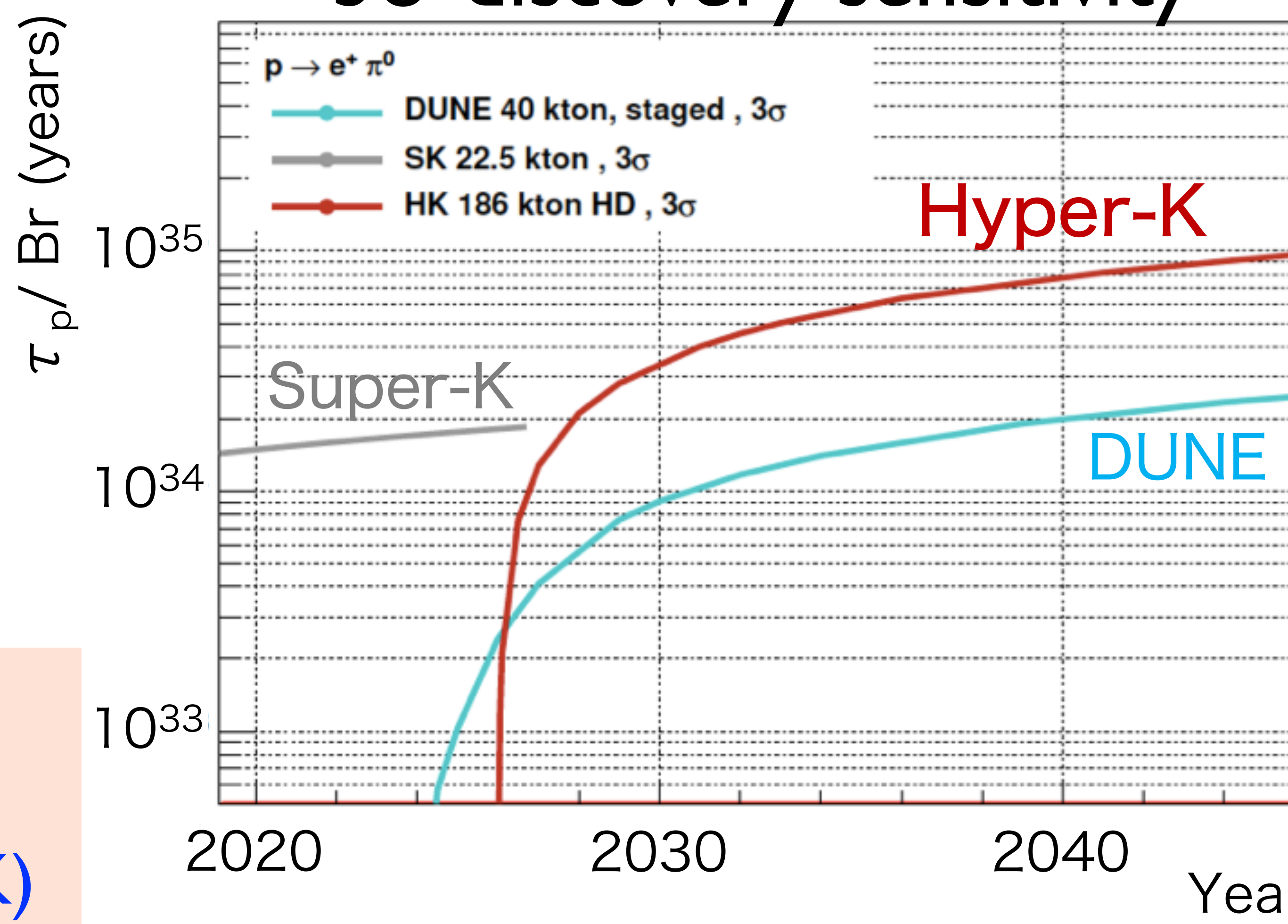
Hyper-K: $p \rightarrow e^+\pi^0$



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



3σ discovery sensitivity



"Background free" NDK search
thanks to the new photo-sensors
(ex. n-tag eff: ~20% at SK → ~70% at HK)

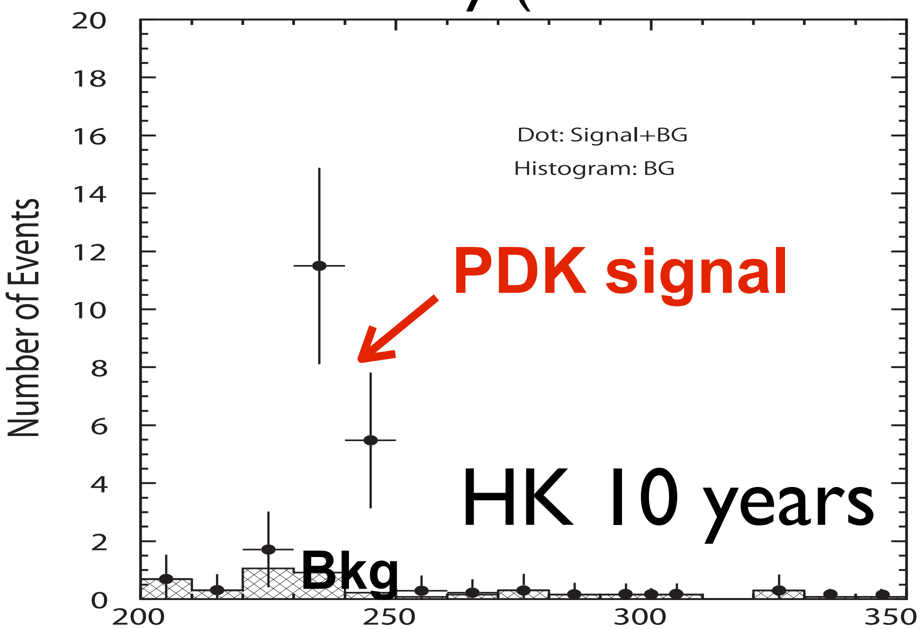
(0.06 bkg events / Mt·year)

~9σ discovery potential if nucleon lifetime at the current SK limit
($\tau_p/Br = 1.7 \times 10^{34}$yrs)

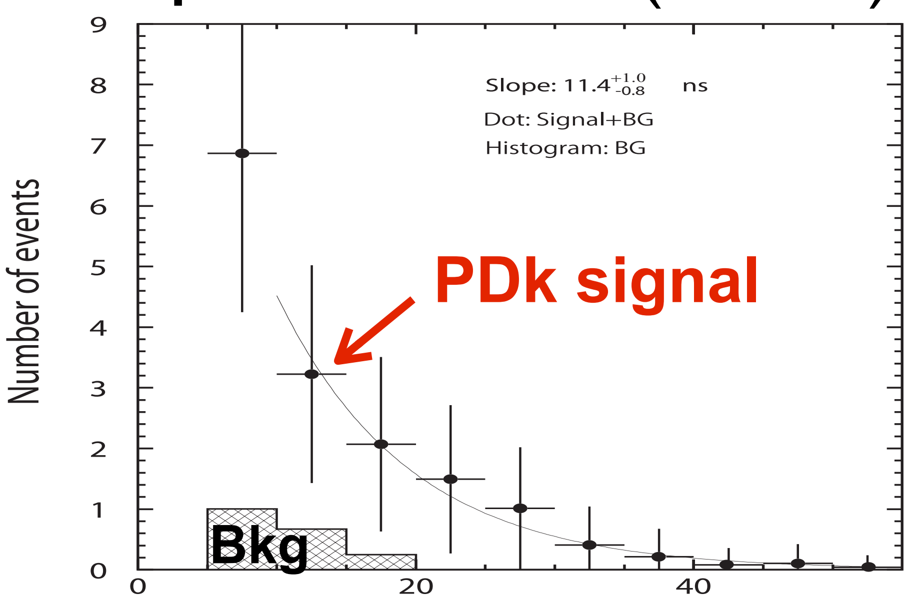
- **Hyper-K reaches to 10^{35} yrs with 3σ discovery sensitivity**

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

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

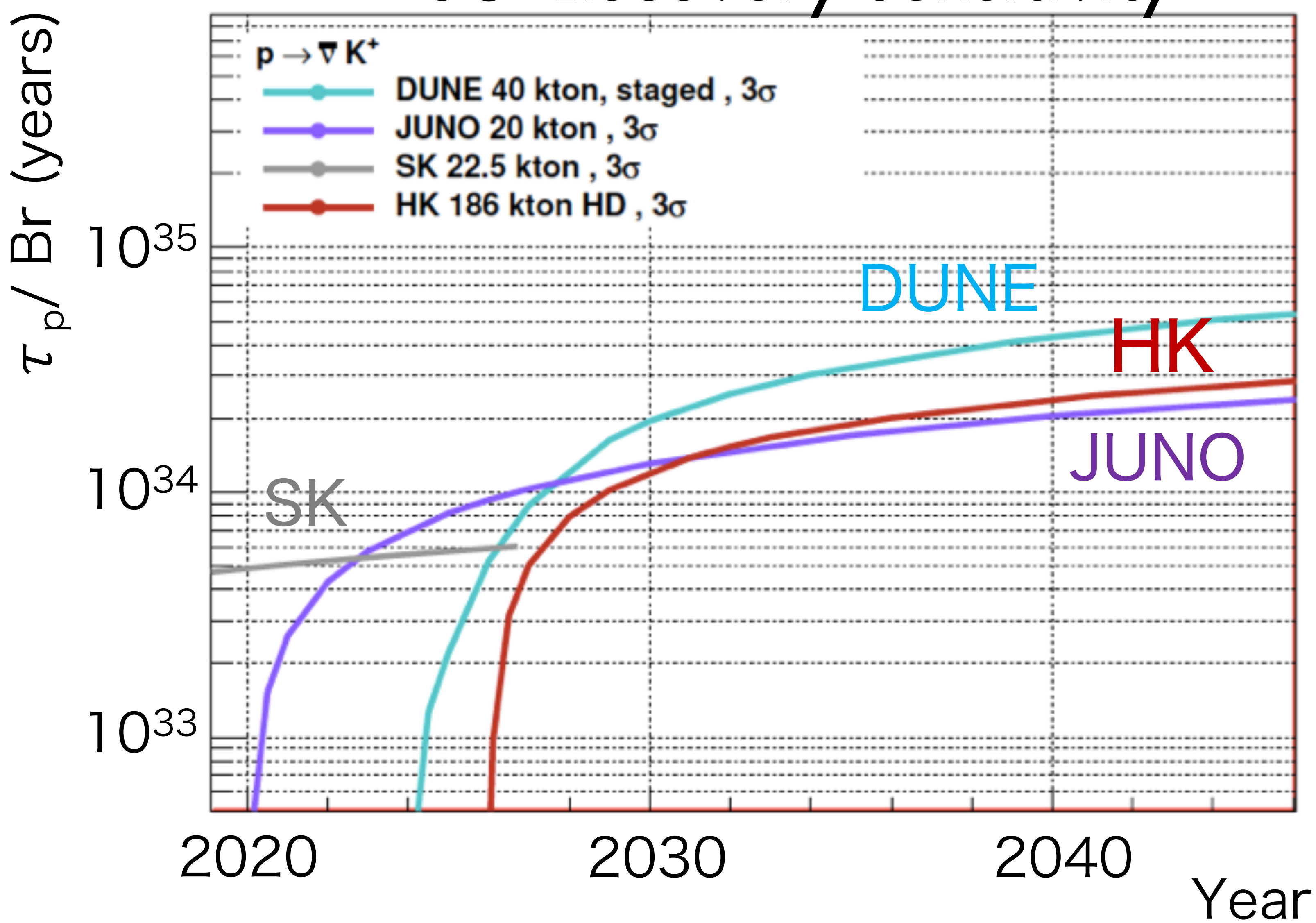


μ Momentum (MeV/c)



K^+ decay time (nsec)

3σ discovery sensitivity

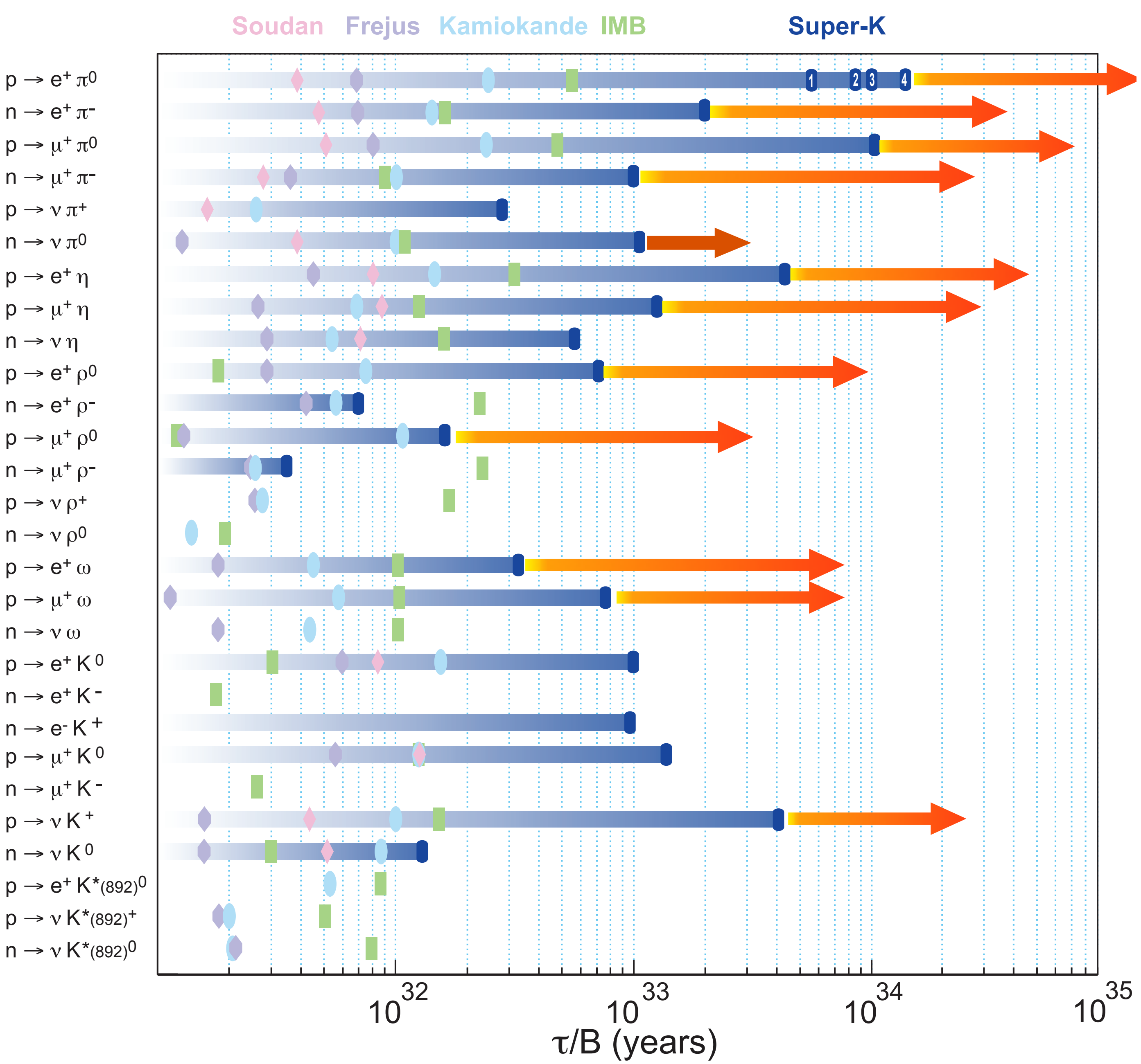


- HK 3σ discovery potential reaches 3×10^{34} years

- $K^+ \rightarrow \mu + \nu$ (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^+

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→XX..., nn→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

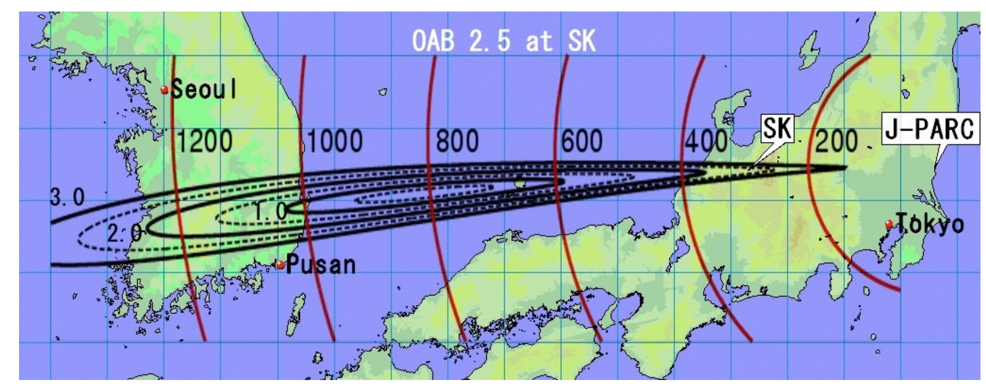
Prog. Theor. Exp. Phys. 063C01 (2018)

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



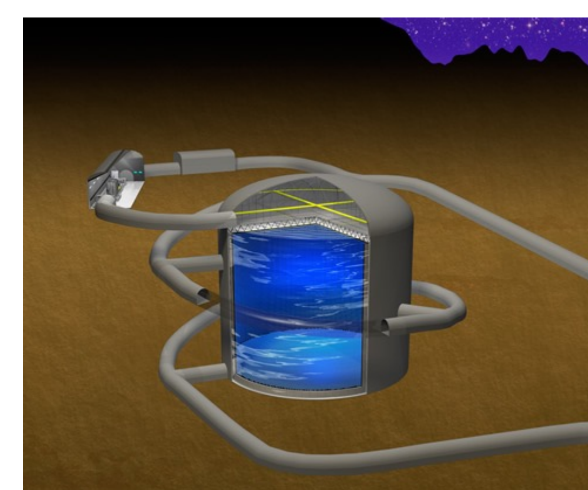
arXiv:1805.04163

Hyper-Kamiokande

Design Report
(Dated: May 9, 2018)

(Hyper-Kamiokande proto-collaboration)

Maximizing physics sensitivities with optimized tank design



Summary

- **Super-K**
  - So far, no evidence of nucleon decay…
  - **Most stringent lifetime limits for almost all decay modes**
  - Studies to improve NDK search with Super-K on-going:
    - Enlarge fiducial mass (+20%), improve event reconstruction algorithm, improved n-tag, …
  - **SK-Gd**
    - Further reduce atm-ν bkg by Gd neutron-tagging

- **Hyper-K**
  - **Realize ‘background free’ NDK search**
  - **3σ discovery potential reaches to 10^{35} years for $p \rightarrow e^{+}\pi^{0}$ (10^{34} yrs for $p \rightarrow \bar{\nu}K^{+}$)**
  - Improvements for many decay modes by a factor ~10
  - **Detector construction begins in April 2020**