WIN2019

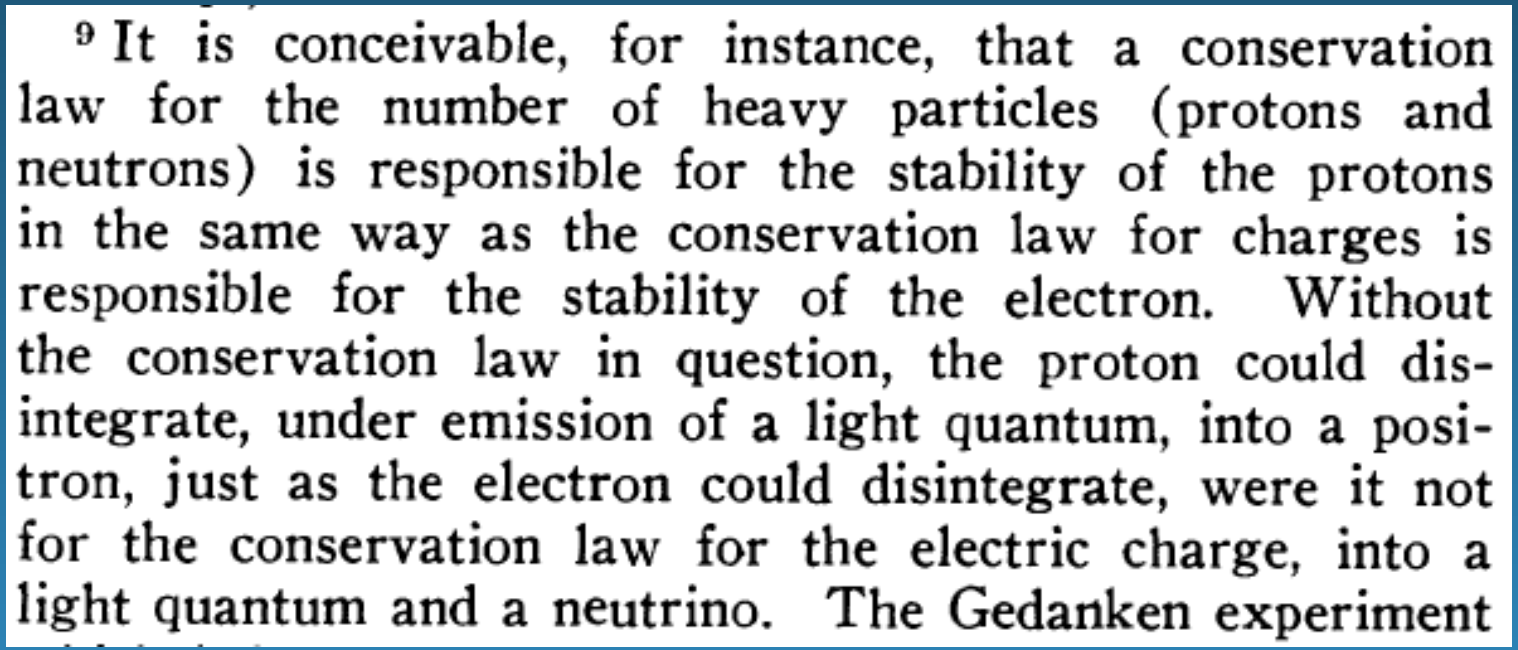
The 27th International Workshop on Weak Interactions and Neutrinos

FRANCESCA DI LODOVICO
QUEEN MARY UNIVERSITY OF LONDON

NEW FRONTIERS IN THE PROTON DECAY SEARCH

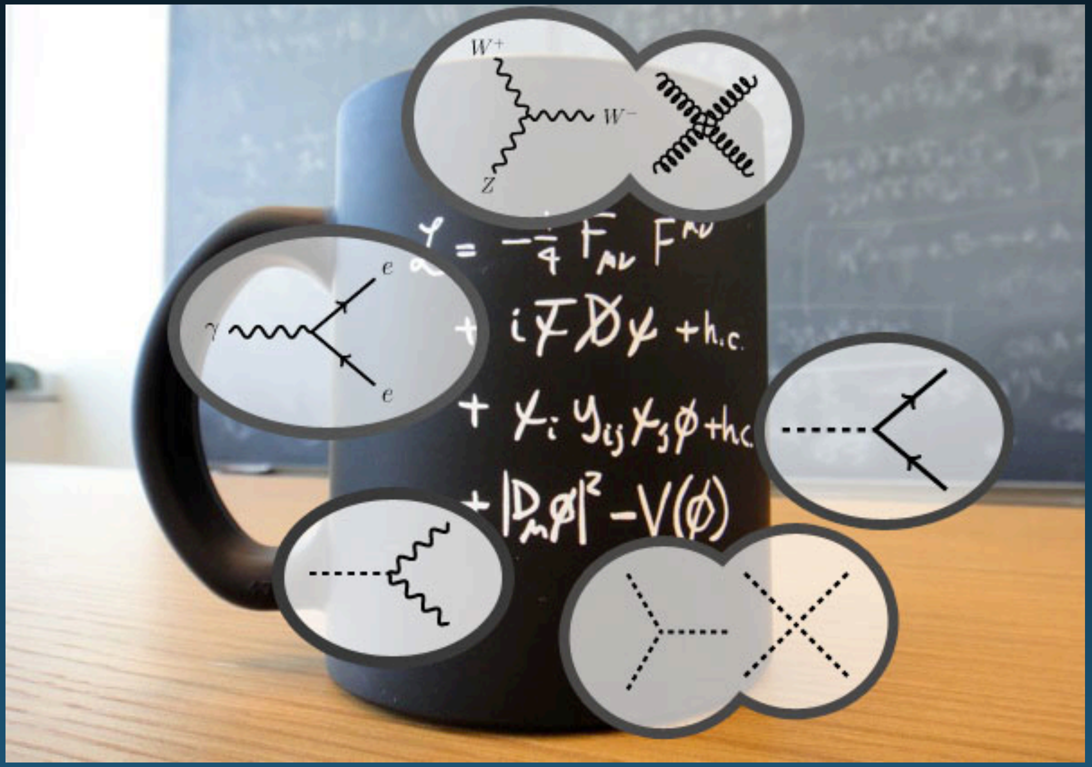
BARYON NUMBER

- Conservation of baryon number is observed in Nature, but no compelling reason for it
- Baryon number conservation formulated by: Weyl (1929), Stueckelberg (1938), Wigner (1949), Lee & Yang (1950) to explain stability of matter.



[9] It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino. The Gedanken experiment

Conserved in the Standard Model*



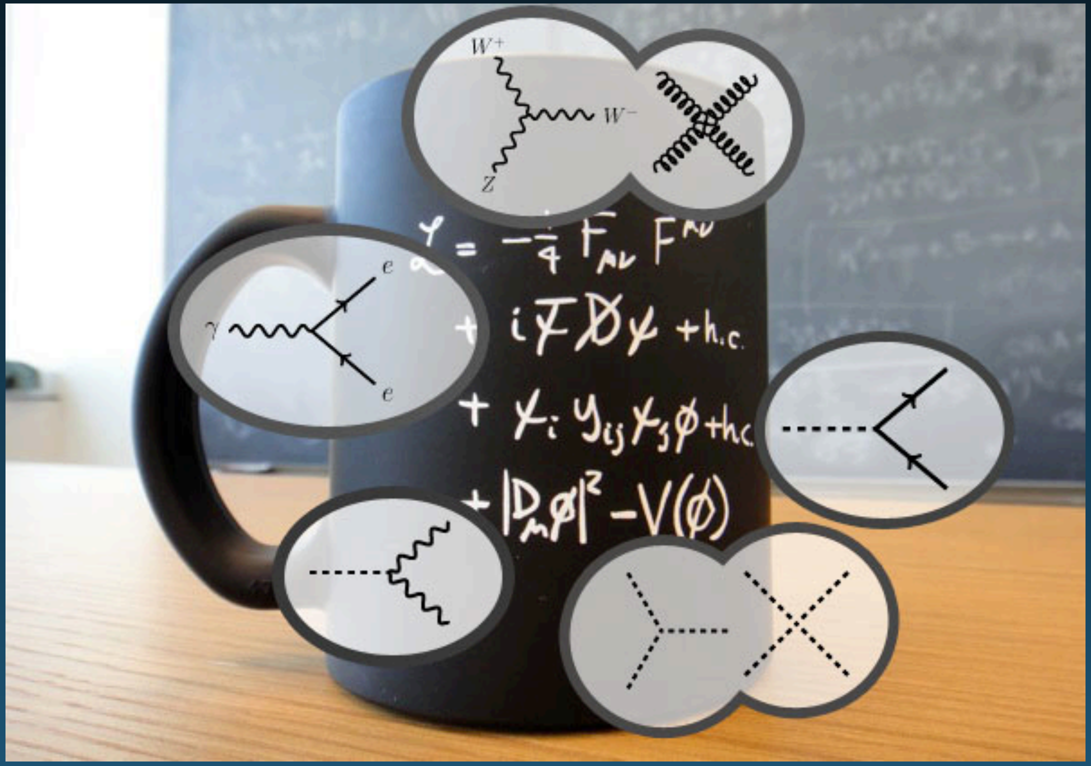
*imperfectly due to anomalies, but with irrelevantly long lifetimes

but the Standard Model is incomplete …

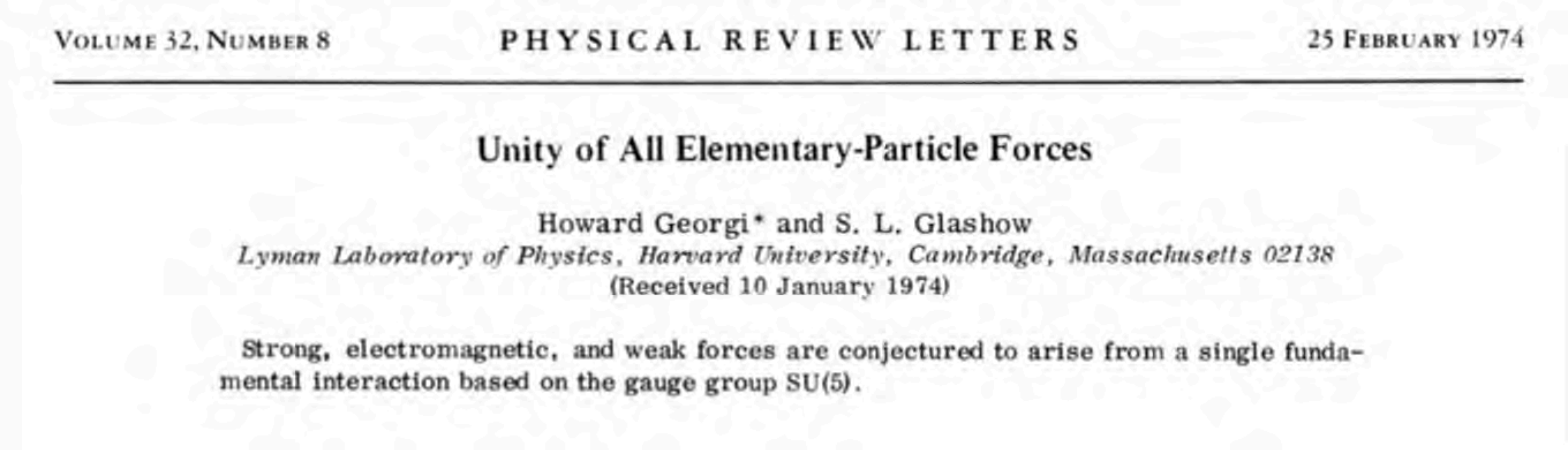
BARYON NUMBER VIOLATION

- Matter-antimatter asymmetry requires baryon number violation (BNV)
- **BNV**: anticipated for baryon asymmetry (Sakharov Condition #1)
- There are well-motivated theories, such as Grand Unified Theories (GUTs) that suggest proton decay may exist and be observable
  - Make specific predictions for decay modes, lifetimes, branching ratios
  - Unify strong, weak, and EM forces into a single underlying force at high energies
    - Standard Model's SU(3) x SU(2) x U(1) is embedded within a larger gauge group
    - Fundamental forces are low energy manifestations of a unified force
  - Can neatly explain many of the puzzling things observed in Nature that are not currently explained by the Standard Model
    - Quantization of electric charge
    - Quantum numbers of quarks and leptons
    - …

The Standard Model is incomplete



FIRST GRAND UNIFIED THEORY: SU(5)

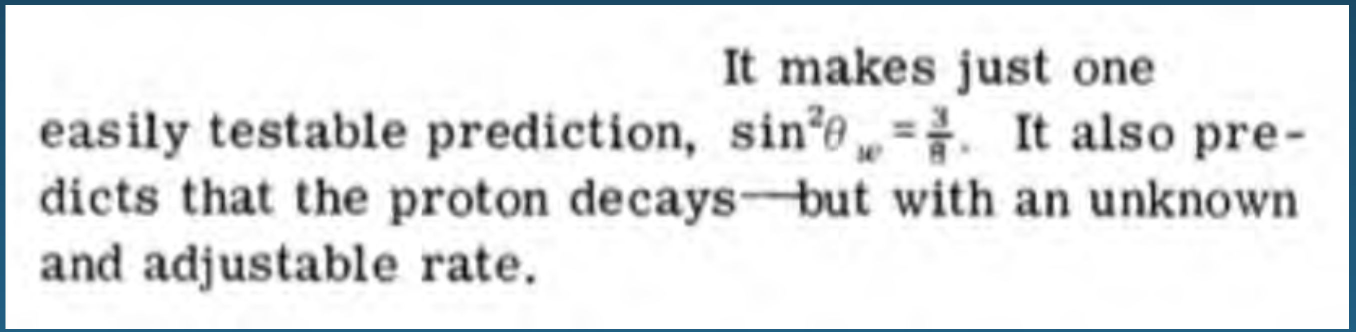


VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

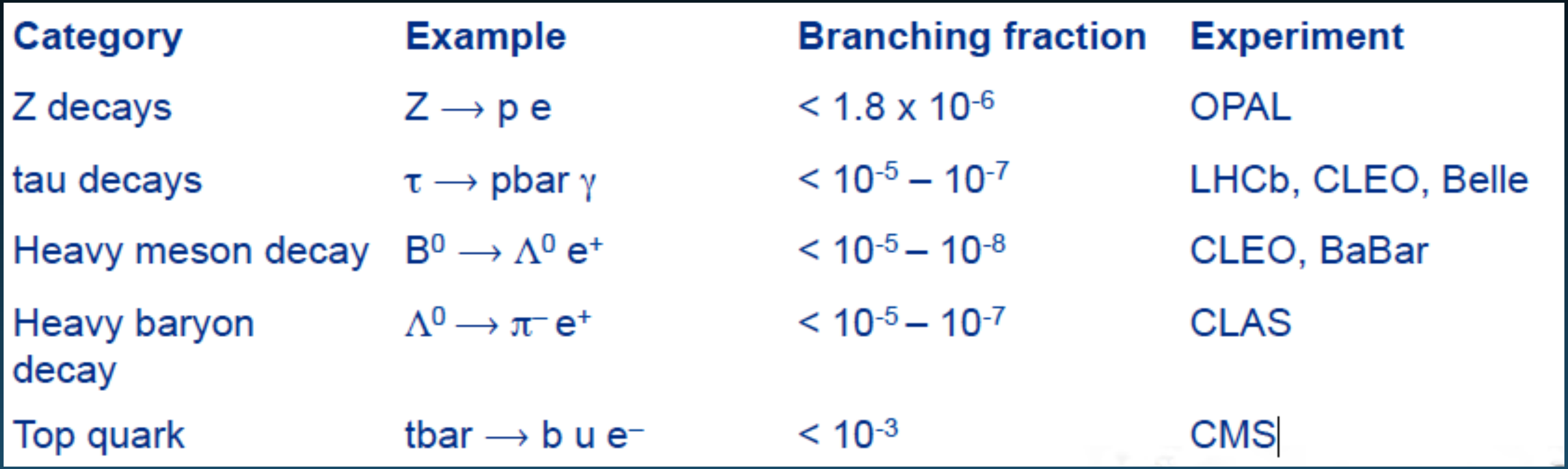
Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).



It makes just one easily testable prediction, $\sin^2\theta_w = \frac{3}{8}$. It also predicts that the proton decays—but with an unknown and adjustable rate.

- Had some nice consequences
  - (charge quantization, unified coupling,…)
- but clearly did not get everything right
  - (value of weak mixing angle, also predicted massless neutrinos and magnetic monopoles)

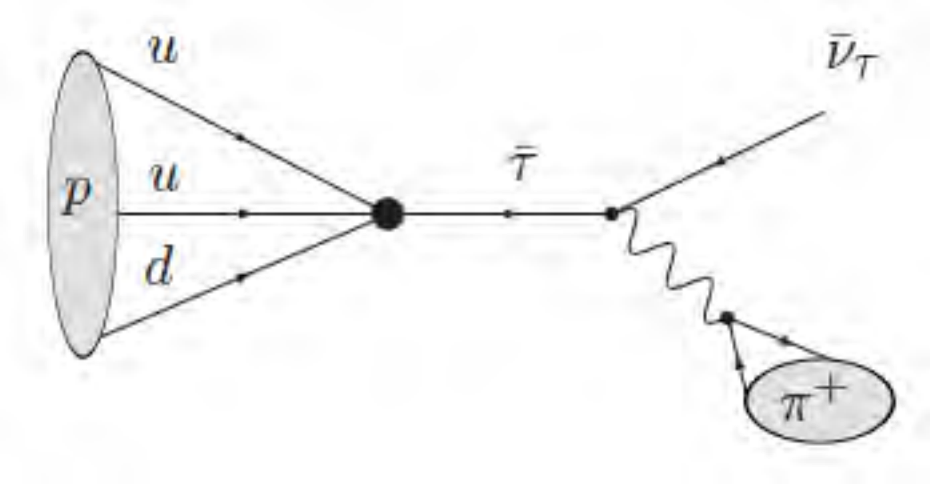
SOME BNV PROCESSES STUDIED WITH ACCELERATORS



Category	**Example**	**Branching fraction**	**Experiment**
Z decays	$Z \longrightarrow p\ e$	$< 1.8 \times 10^{-6}$	OPAL
tau decays	$\tau \longrightarrow \mathrm{pbar}\ \gamma$	$< 10^{-5} – 10^{-7}$	LHCb, CLEO, Belle
Heavy meson decay	$B^0 \longrightarrow \Lambda^0\ e^+$	$< 10^{-5} – 10^{-8}$	CLEO, BaBar
Heavy baryon decay	$\Lambda^0 \longrightarrow \pi^-\ e^+$	$< 10^{-5} – 10^{-7}$	CLAS
Top quark	$\mathrm{tbar} \longrightarrow b\ u\ e^-$	$< 10^{-3}$	CMS

Table fromE. Learn (BNV, 2017)

- Marciano (1995): some of these processes may be better constrained by nucleon decay.
- Nucleon decay is the most constraining



Hou, Nagashima, Soddu hep-ph/0509006

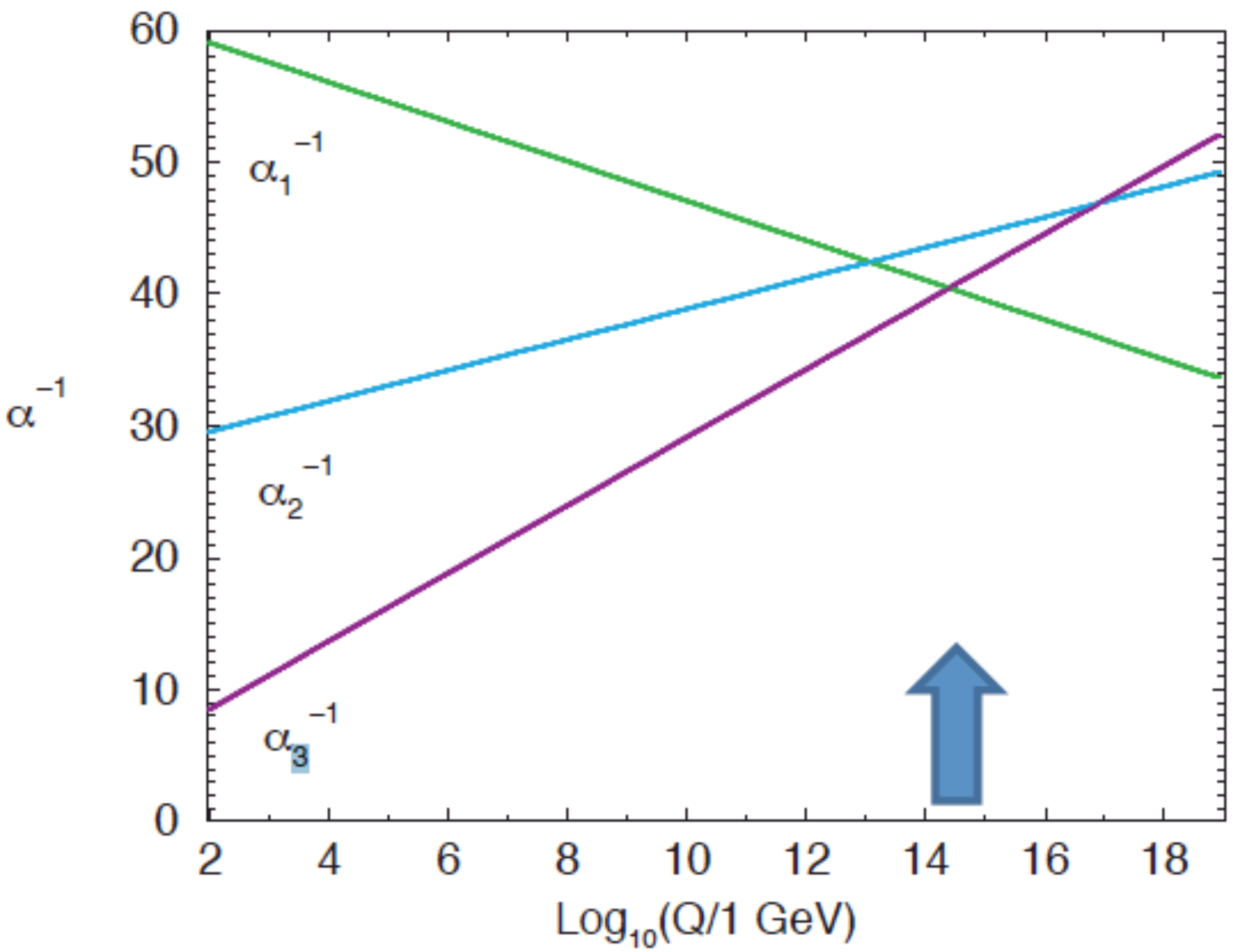
GRAND UNIFIED THEORIES

- Assume the Standard Model, SU(3)⊗SU(2)⊗U(1), is part of a larger symmetry group, e.g. SU(5):

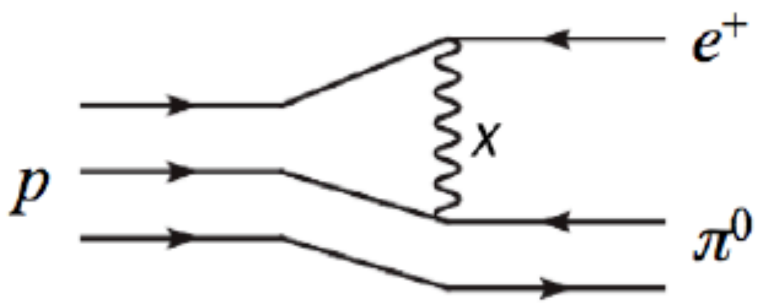
$$\bar{5} = \begin{pmatrix} \bar{d}_g \\ \bar{d}_r \\ \bar{d}_b \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 = \begin{pmatrix} 0 & \bar{u}_b & -\bar{u}_r & -u_g & -d_g \\ & 0 & \bar{u}_g & -u_r & d_r \\ & & 0 & -u_b & -d_b \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L \qquad 24 = \left(\begin{array}{ccc|cc} G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & \bar{X}_1 & \bar{Y}_1 \\ G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & \bar{X}_2 & \bar{Y}_2 \\ G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & \bar{X}_3 & \bar{Y}_3 \\ \hline X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{array}\right)$$

- Consequences:
  - Single (unified) coupling
  - Charge quantization: $Q_d = Q_e/3$, $Q_u = -2Q_d \Rightarrow Q_p = -Q_e$
  - **New gauge interactions (X, Y bosons) ⇒ proton decay**
  - Other predictions of SU(5): magnetic monopoles, value of weak mixing angle (poor), massless neutrinos (oops!)
  - There are other groups, e.g. SO(10) that accommodate massive neutrinos

CIRCUMSTANTIAL EVIDENCE



Gauge mediated



$$\tau = \frac{M_X^4}{\alpha\ m_p^2}$$

$\tau(e^+\pi^0) = 4.5\times10^{29\pm1.7}$ years (predicted)

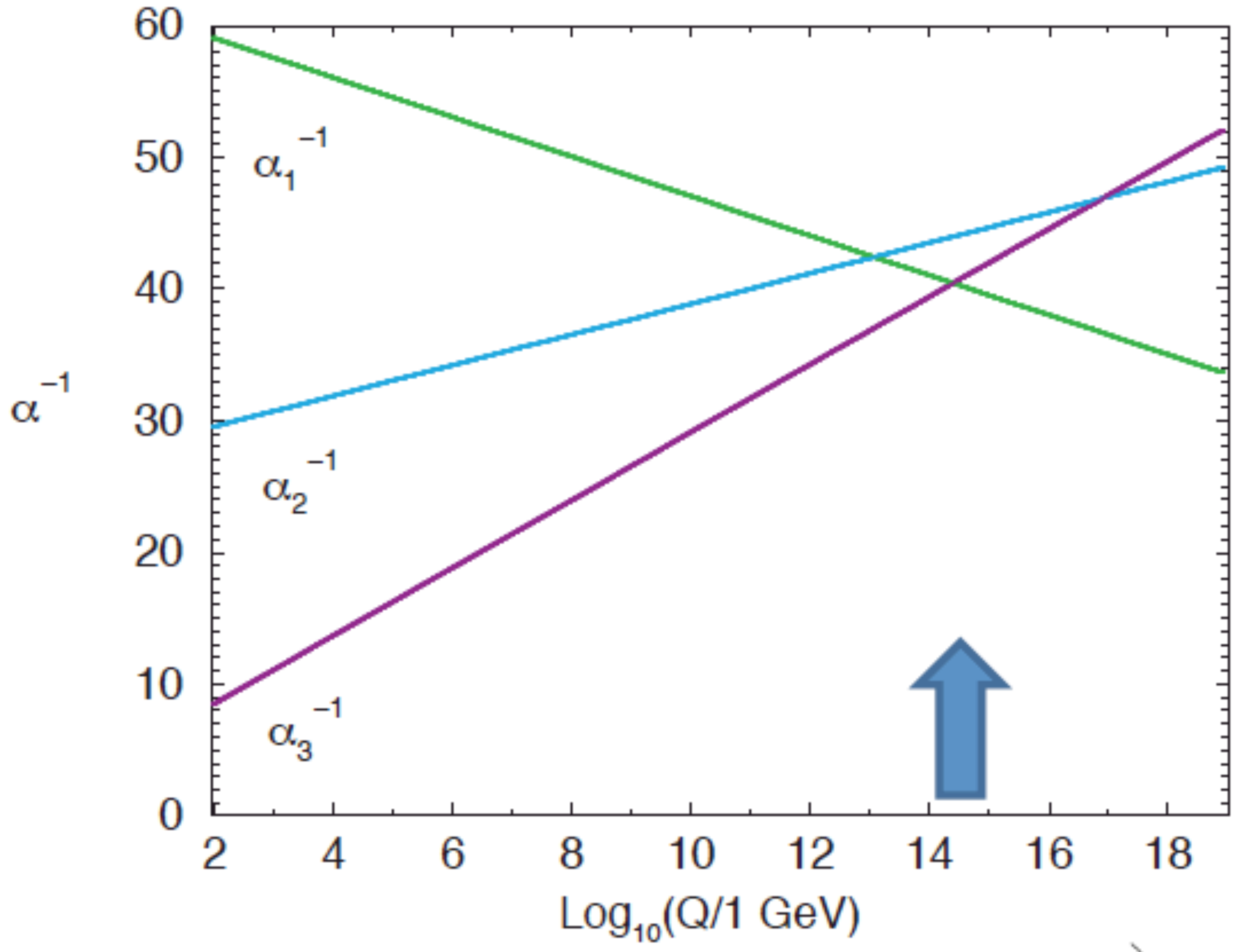
$\tau(e^+\pi^0) > 5.5\times10^{32}$ years (IMB/1990)

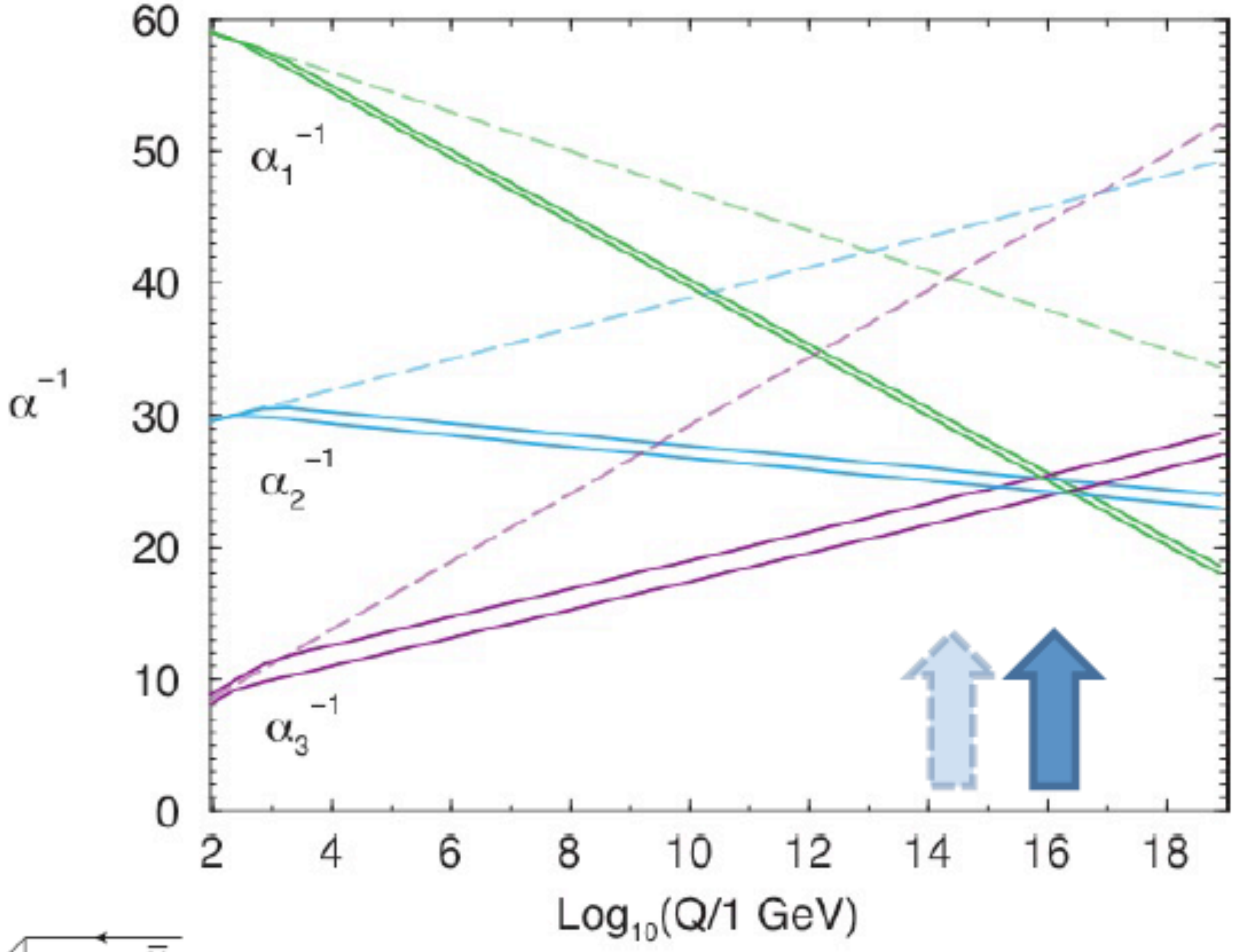
- Minimal SU(5) was ruled out long ago by Kamiokande and IMB measurements, but minimal SUSY SU(5) still viable and there are the kaon and other modes to search for.

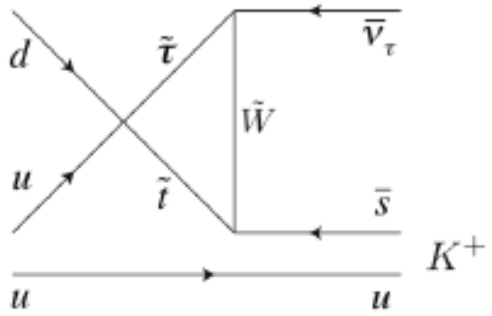
SUSY GUT

Unification scale pushed up ✔

$$\tau(e^+\pi^0) \approx 10^{35-38} \text{ years}$$





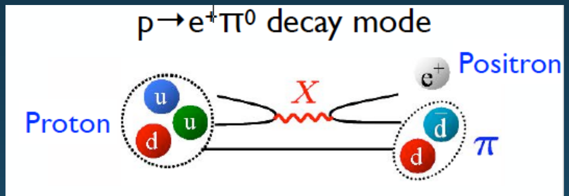


But new modes now present (D=5)

$$\tau(\bar{\nu}K^+) \approx 10^{29-35} \text{ years}$$

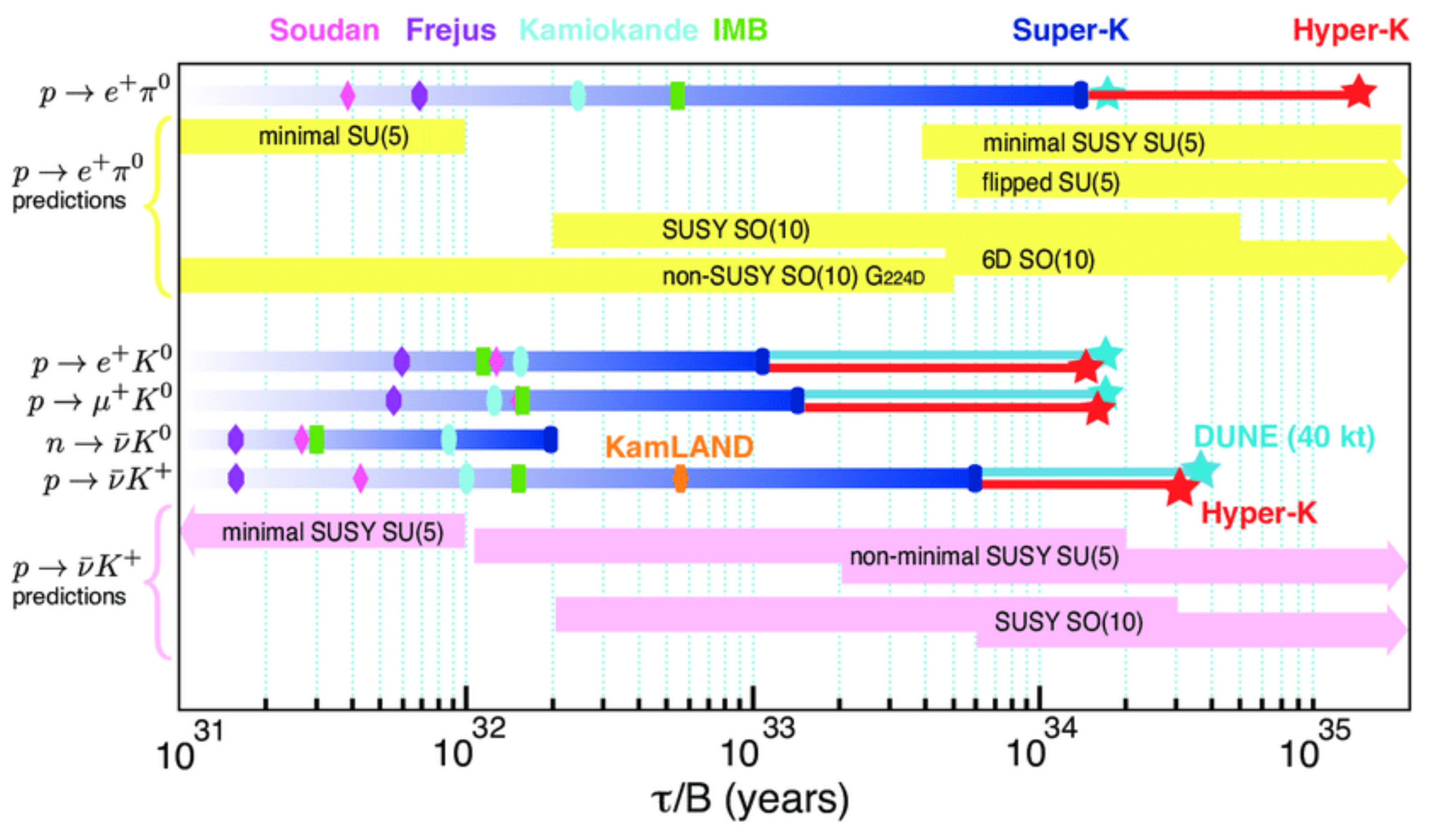
IN A NUTSHELL

- 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
- Various types of models exist
  - Supersymmetric & non-SUSY, different gauge groups (SU(5), SO(10), …)
- Lifetime predictions within those models are not precise
  - several orders of magnitude uncertainty
- Typically two proton decay modes are used as "benchmarks" for models:
  - $p \longrightarrow e^{+}\pi^{0}$(mediated by a new heavy gauge boson)
  - $p \longrightarrow \bar{\nu}K^{+}$ (supersymmetric dimension-5 operators)



- BUT, many other modes are also allowed, and since we don't know which model (if any) is correct, it is important to search for as many modes as possible
  - Beyond $e^{+}\pi^{0}$and $\bar{\nu}K^{+}$
    - ➡ Conserve B-L ($p \longrightarrow$ antilepton + meson)
    - ➡ Conserve B+L ($p \longrightarrow \mu^{-}\pi^{+}K^{+}$and many others)
    - ➡ $\Delta B = 2$ (neutron ⟷ anti-neutron oscillation, dinucleon decay)
    - ➡ 3-body decays ($p \longrightarrow e^{+}\nu\nu$)
    - ➡ Invisible decays ($n \longrightarrow \nu\nu\nu$)
    - ➡ …
- Even if no signal is seen, limits constrain the theories
- **Nucleon decay search an unique prove for GUT and physics in very high energy**

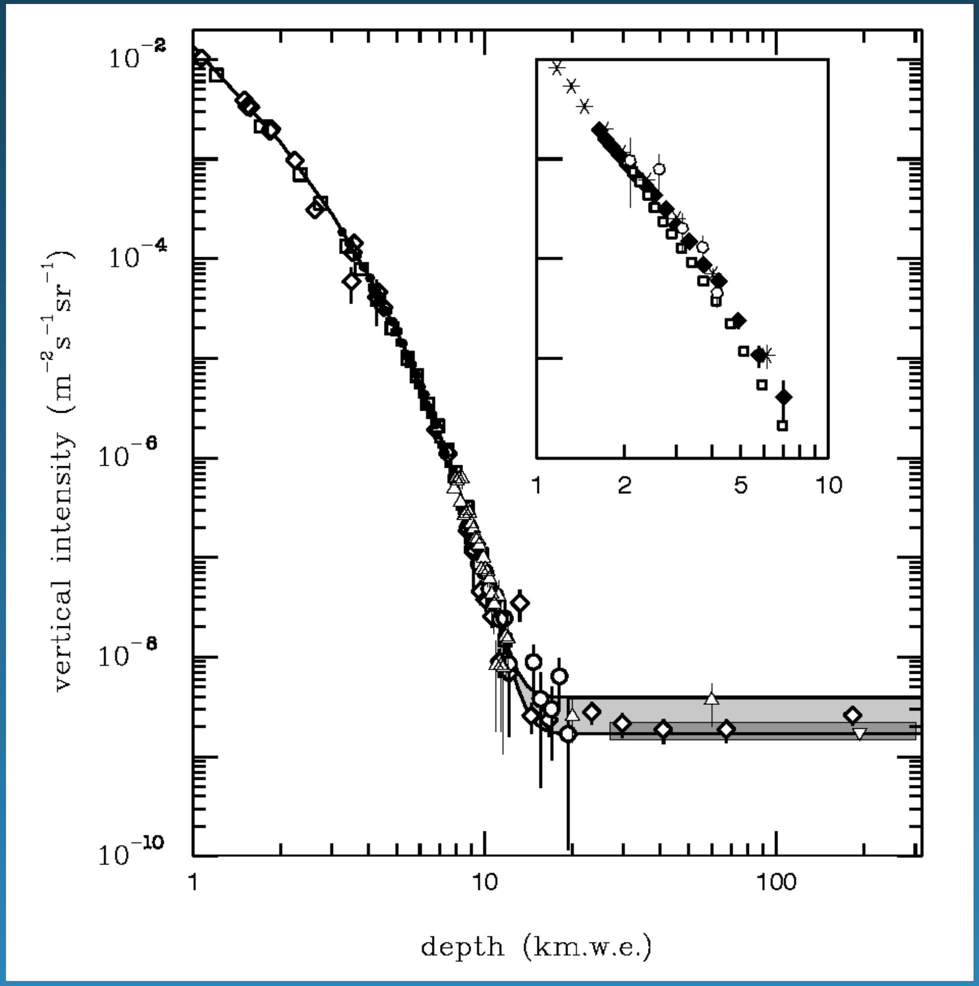
EXPERIMENTAL LIMITS CONSTRAIN THEORETICAL MODELS

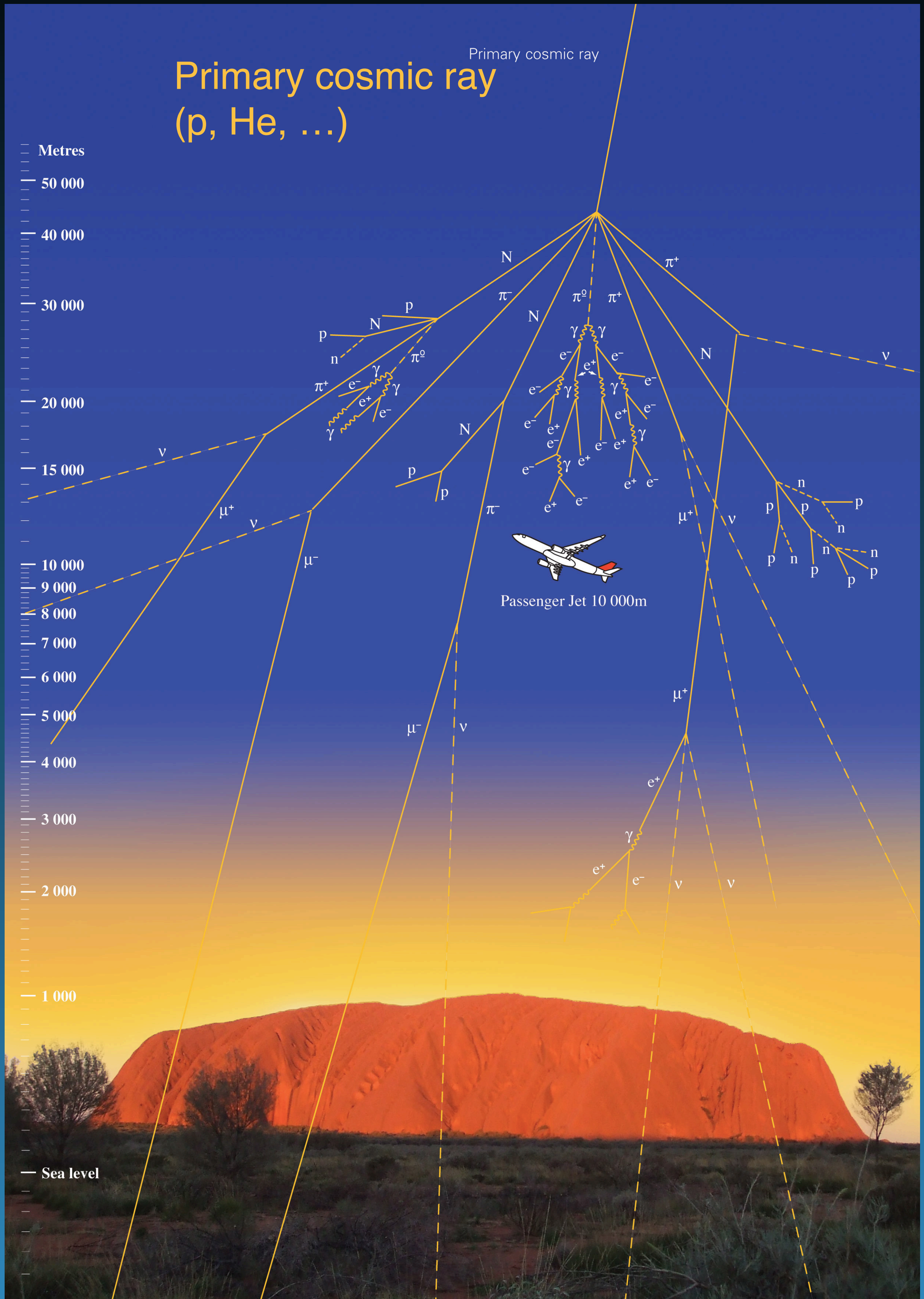


GUT AND NEUTRINO EXPERIMENTS

- Neutrino experiments are an ideal place to search for proton decay & other BNV
  - ➡ Underground to attenuate cosmic rays
  - ➡ Very big, to collect large statistics (neutrino interaction cross sections ~10^{-38} cm-^{2})

Neutrino-induced muons (from atmospheric neutrinos)



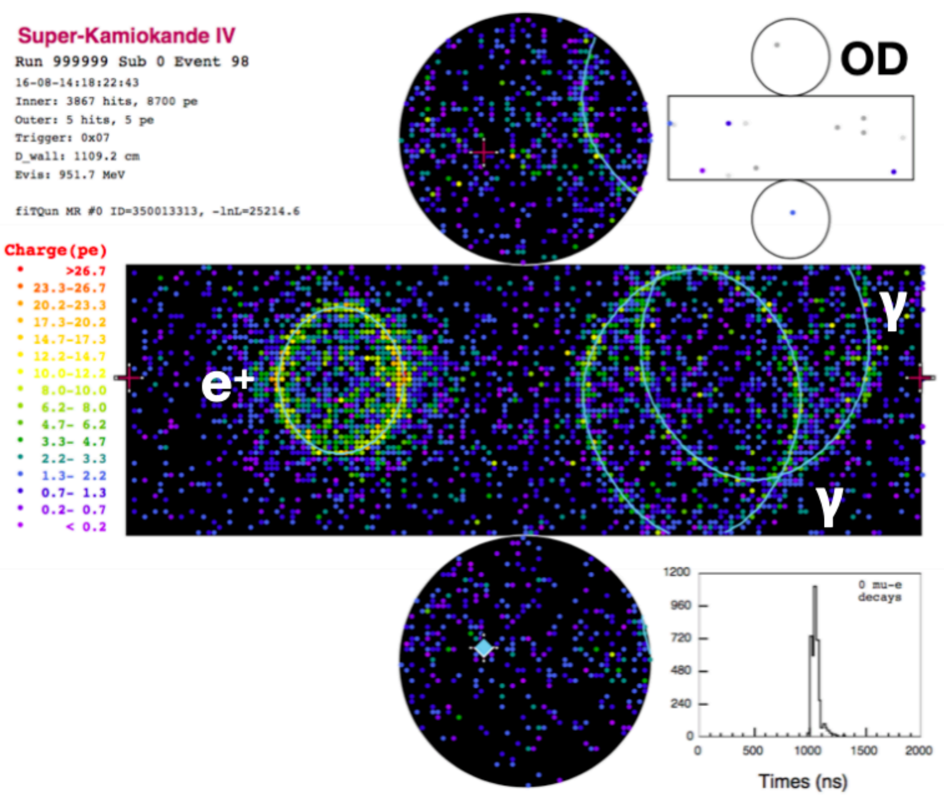


Primary cosmic ray (p, He, …)

BENCHMARK PROTON DECAY SIGNATURES

Water Cherenkov Detectors

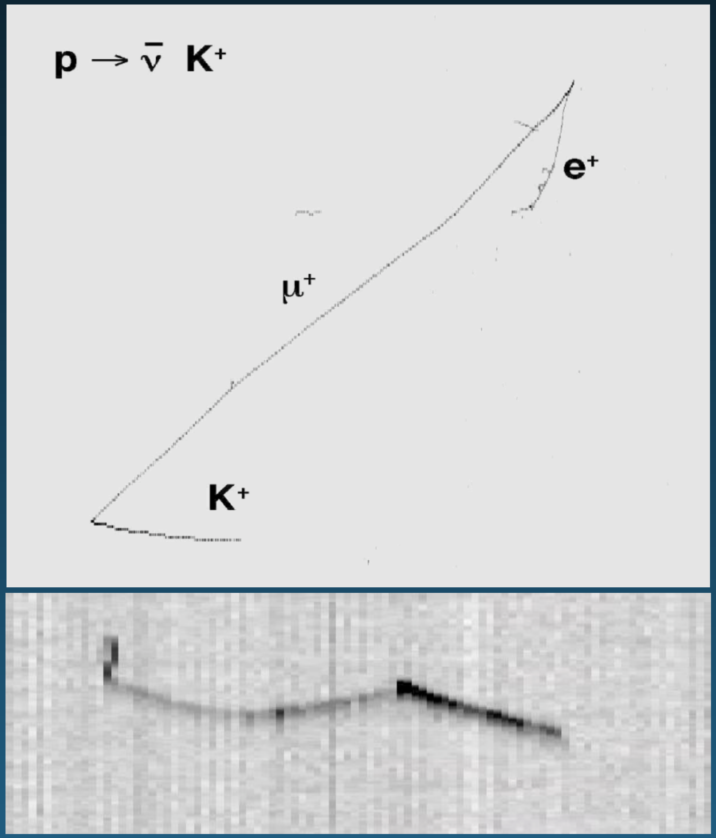
- Super-Kamiokande
- Hyper-Kamiokande



- Most massive – superior for $e^+\pi^0$
- Broad search capability
- Less kaons below Cherenkov threshold

Liquid Argon TPC

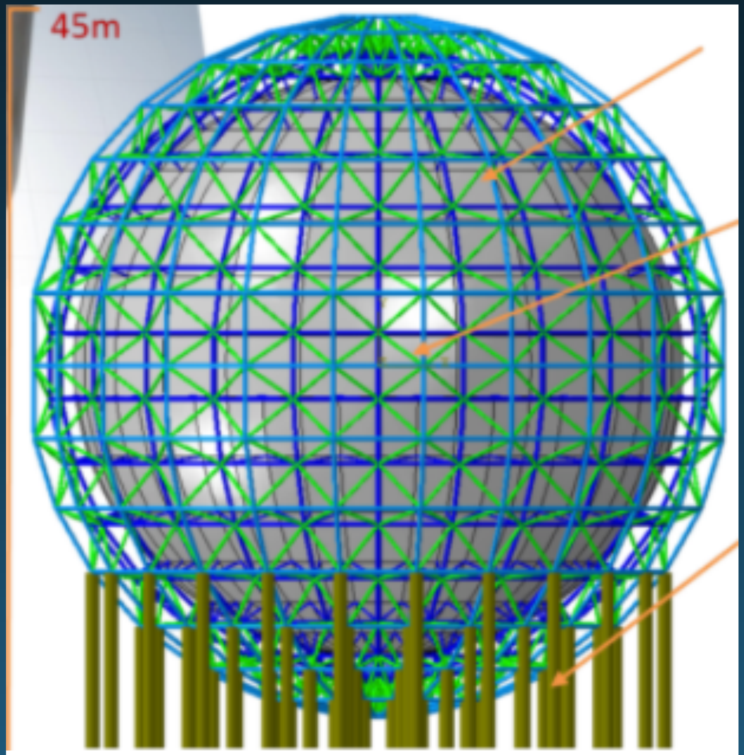
- DUNE

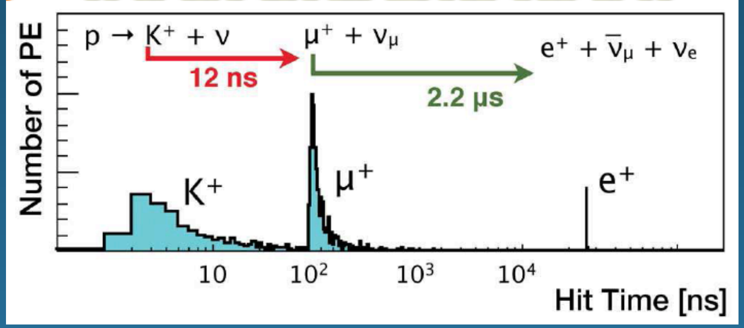


- Fine grained detail
- Visible kaon track
- Heavy nucleus, no free protons

Liquid Scintillator

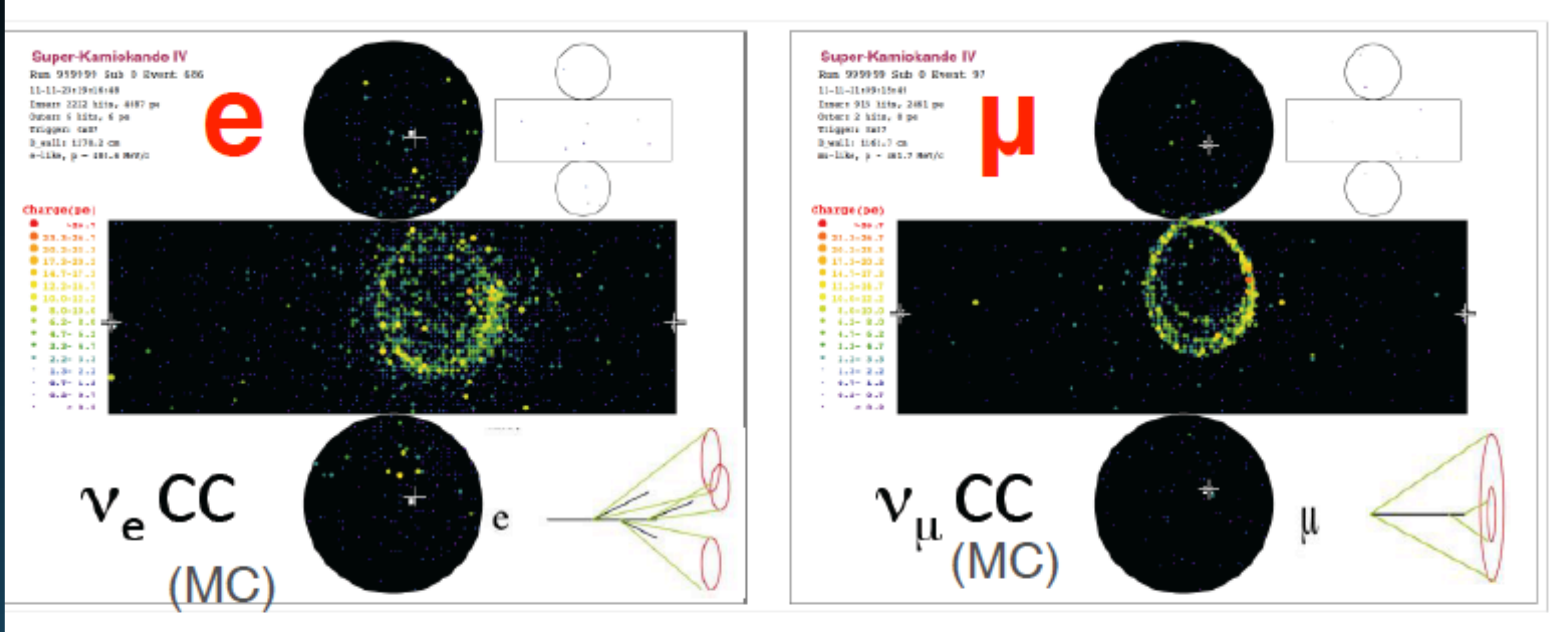
- KamLAND
- JUNO
- THEIA

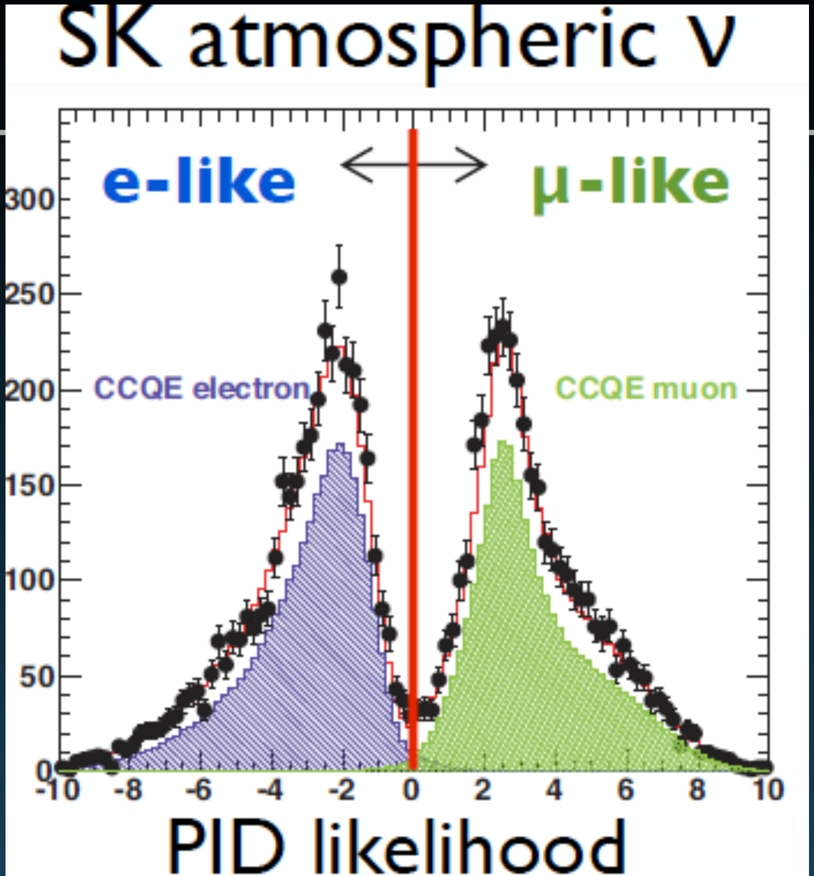




- Clean timing signature
- Specialize in charged kaon (also invisible mode)

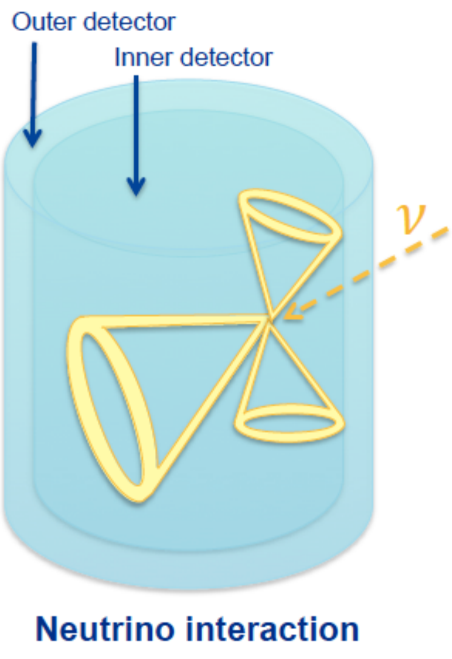
WATER CH. DETECTOR FOR P-DECAYS





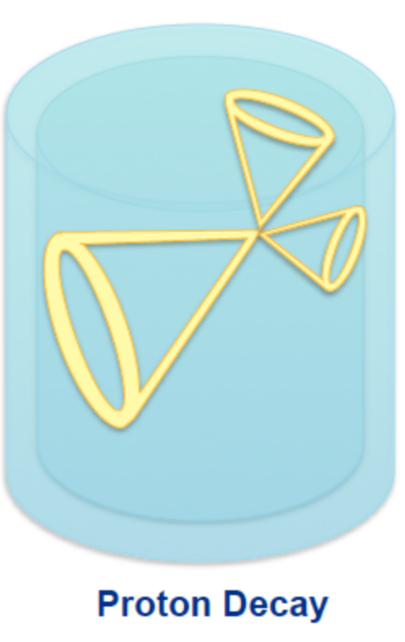
- High mass is possible (Super-K 22kton, Hyper-K 190kton ~ 8×Super-K)
  - $p \rightarrow e^+\pi^0$, $\bar{\nu}K^+$, and more can be searched with high sensitivities
- Excellent & well-proven performance
  - Good ring-imaging capability at ~1GeV
  - Excellent particle ID (e or μ) capability > 99%
  - Energy resolution for e and μ ~3%
- Free protons are available
  - No Fermi motion, nuclear effect
  - High efficiency & good S/N separation

NEUTRINOS VS. PROTON DECAY IN SUPER-K



Neutrino interaction

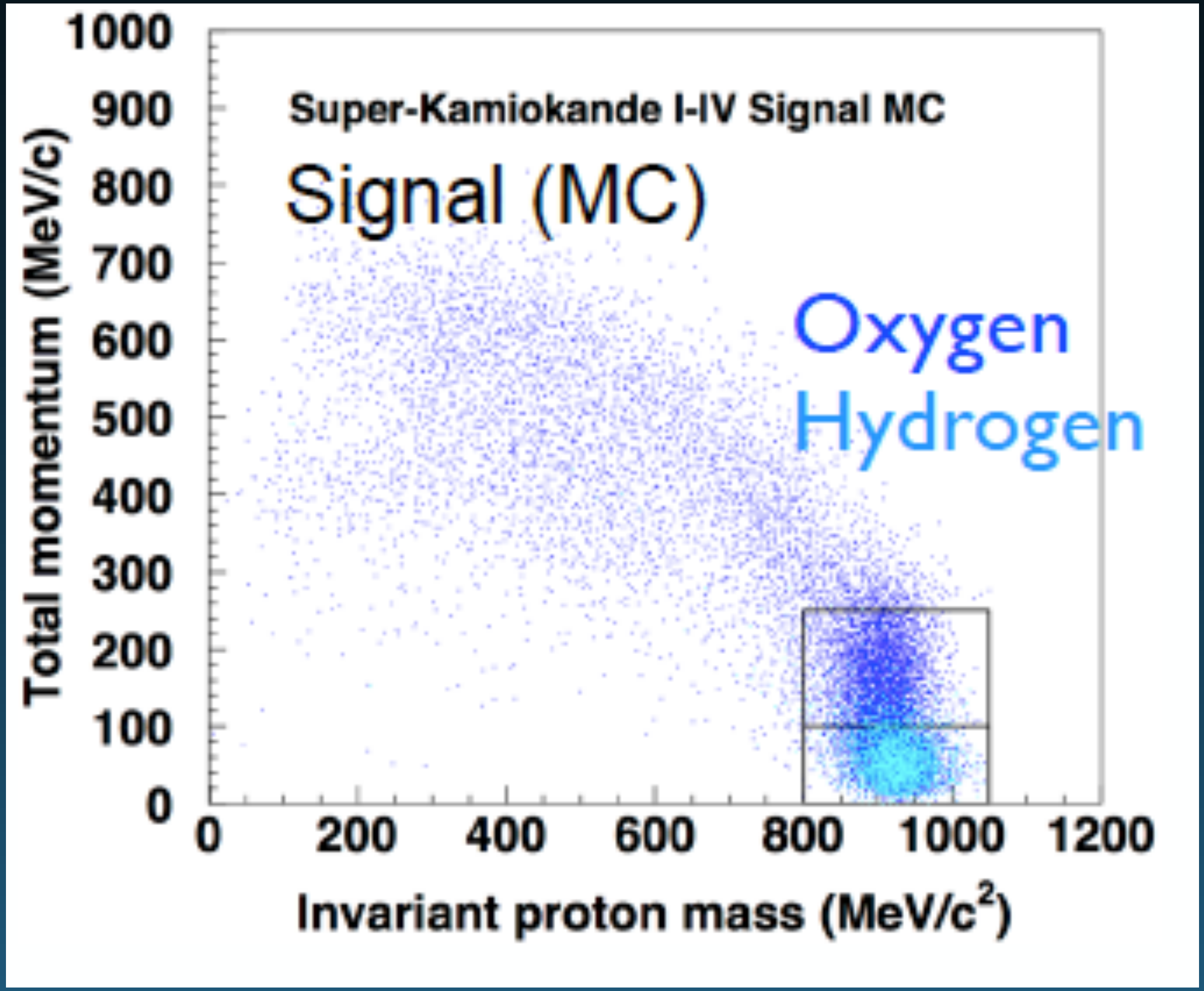
Neutrino Interaction	Proton Decay	Similar ?
Invisible neutrino enters and interact with proton or neutron of H_2O. Exiting particles make Cherenkov rings.	Proton or bound neutron of H_2O decays. Exiting particles make Cherenkov rings.	Yes
A very wide energy range, It goes from ~10's of MeVs to many TeVs	~1 GeV (mass of decaying proton or neutron)	Sometimes
A wide range of net momenta	Net momentum of outgoing particles should be near 0 (up to the Fermi momentum inside nucleus & correlations	Sometimes

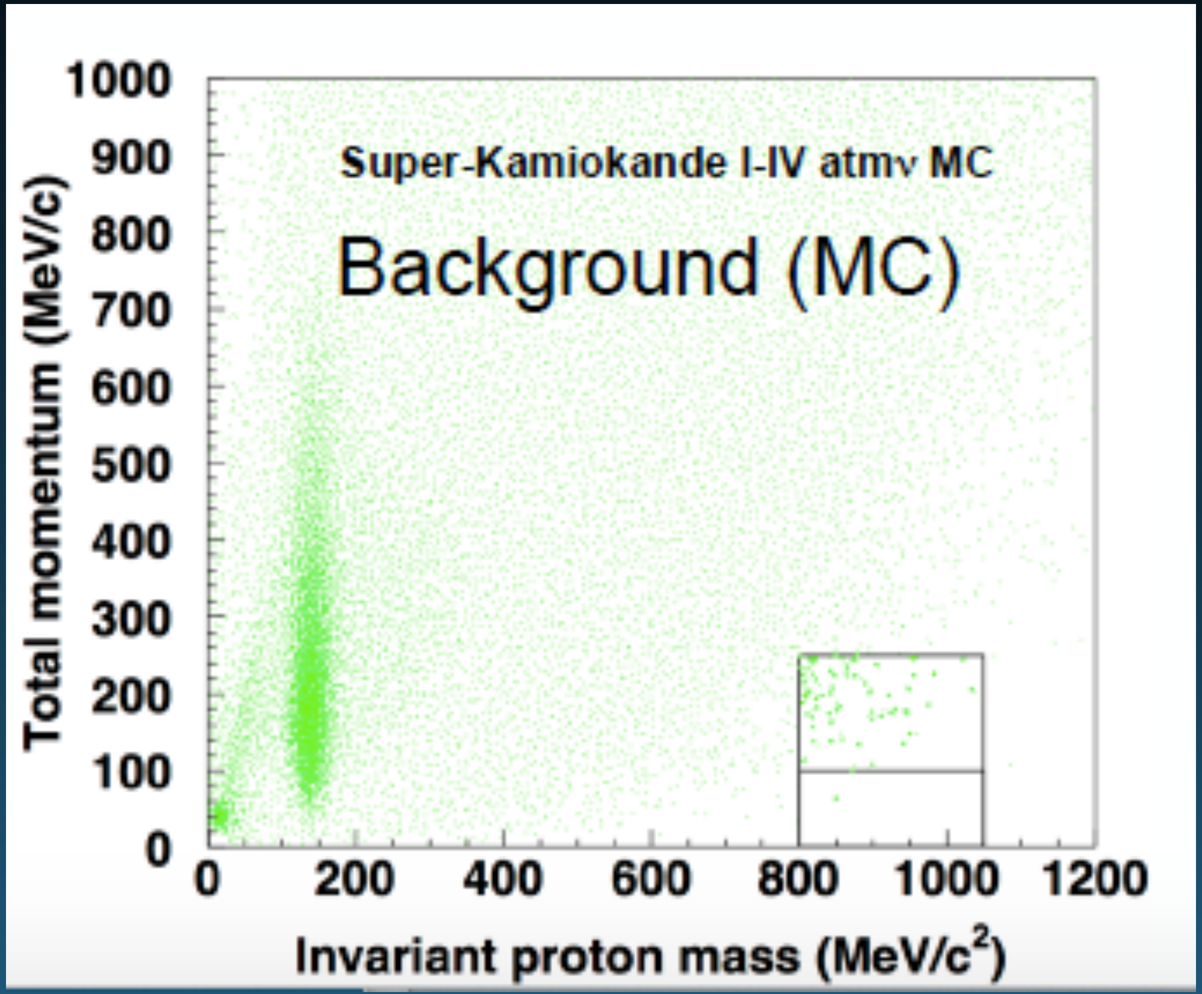


Proton Decay

SEARCH FOR P→$e^+\pi^0$ SELECTION

Super-K Data
(365 kt y)



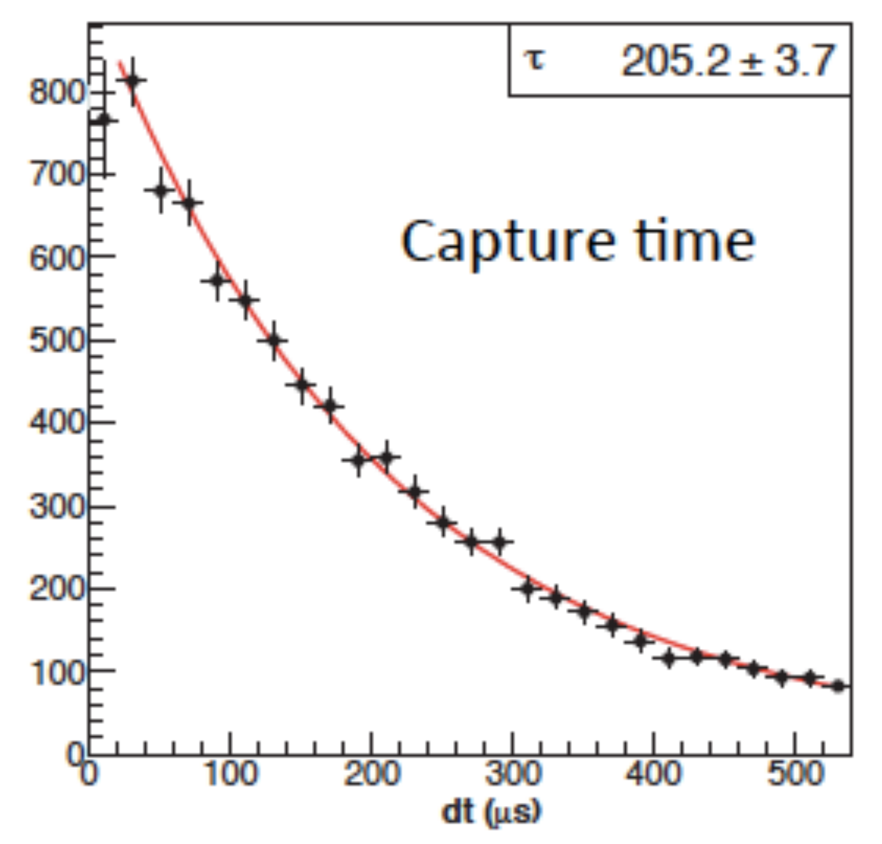


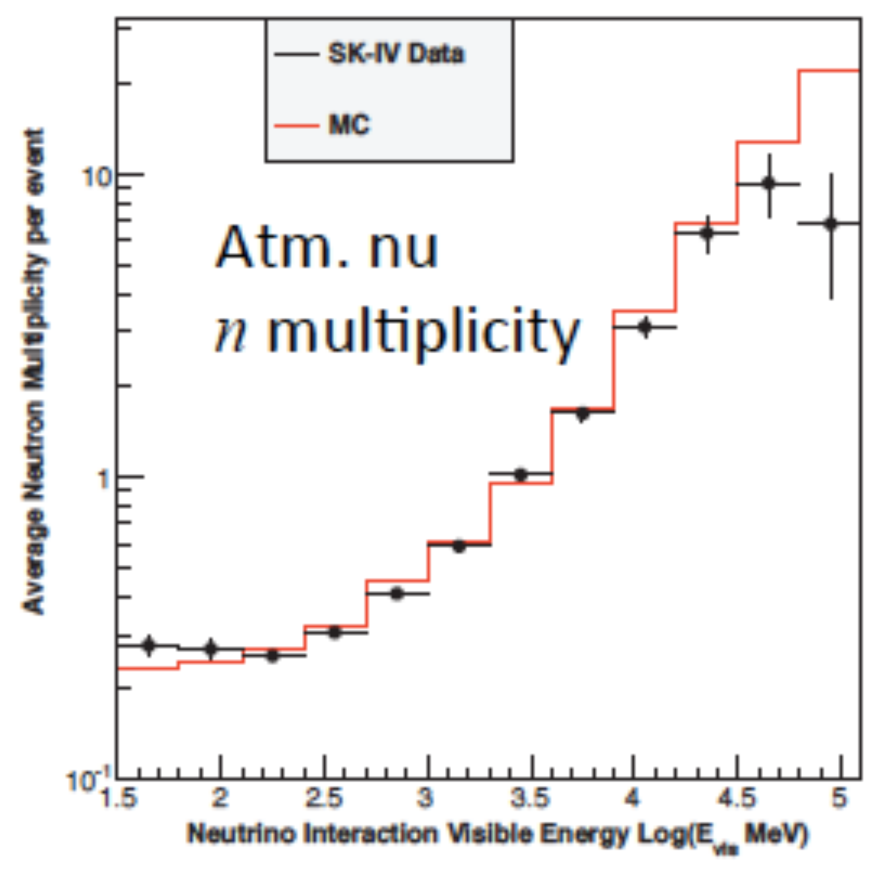
- Fully contained
- Fiducial volume
- 2 or 3 rings
- All rings are EM showers
- π^0 mass 85-185 MeV/c_2

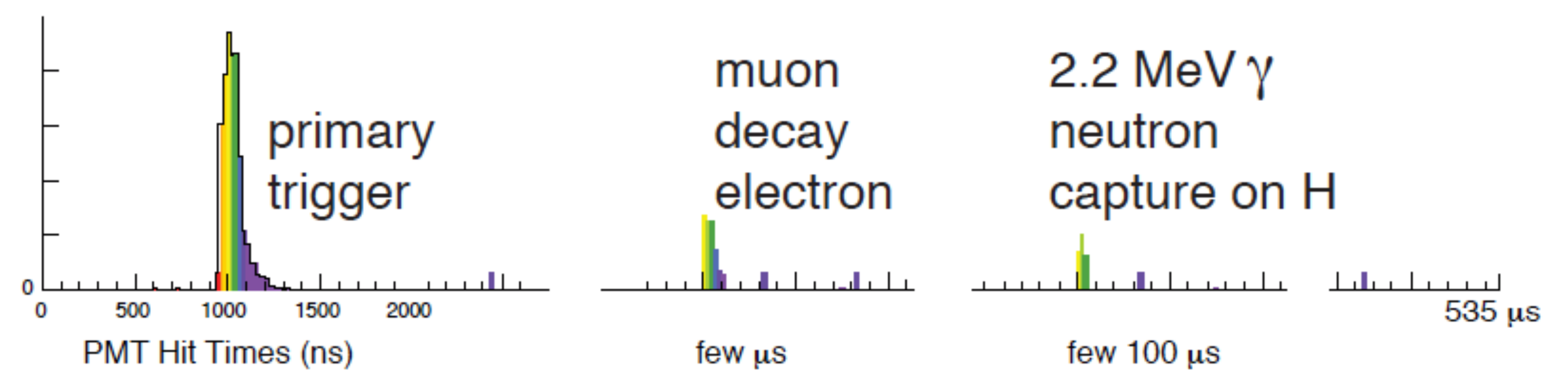
- No μ-decay electrons
- Mass range 800-1050 MeV/c_2
- Net momentum < 250 MeV/c
- SK-IV only: veto event if n-capture

BACKGROUND REJECTION (NEUTRON CAPTURE ON HYDROGEN)

- Background for proton decay search:
  - Atmospheric neutrino; CC-π production
  - Background rate prediction confirmed with data from K2K-1KT Č detector
  - Background under control
- **Atmospheric neutrino background is frequently accompanied by neutron production**
- Detection efficiency = 20.5% Can increase to ~90% with capture on Gd
- SK-Gd construction in 2018

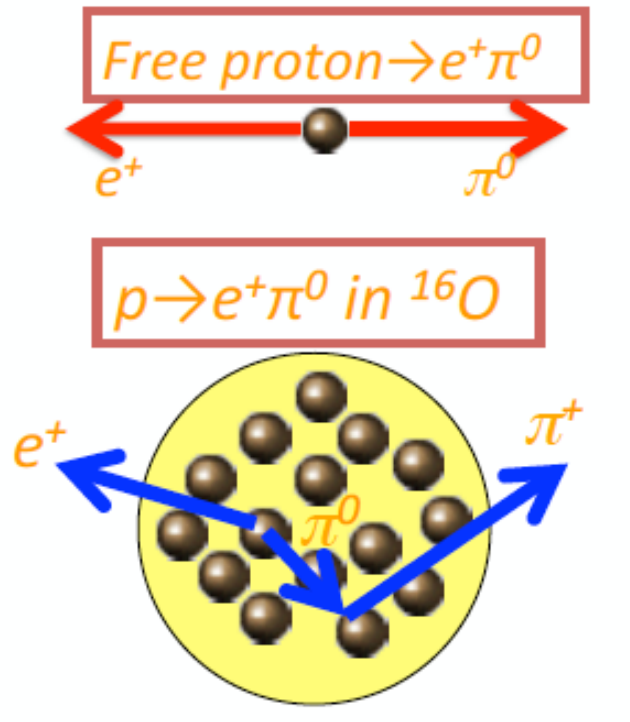




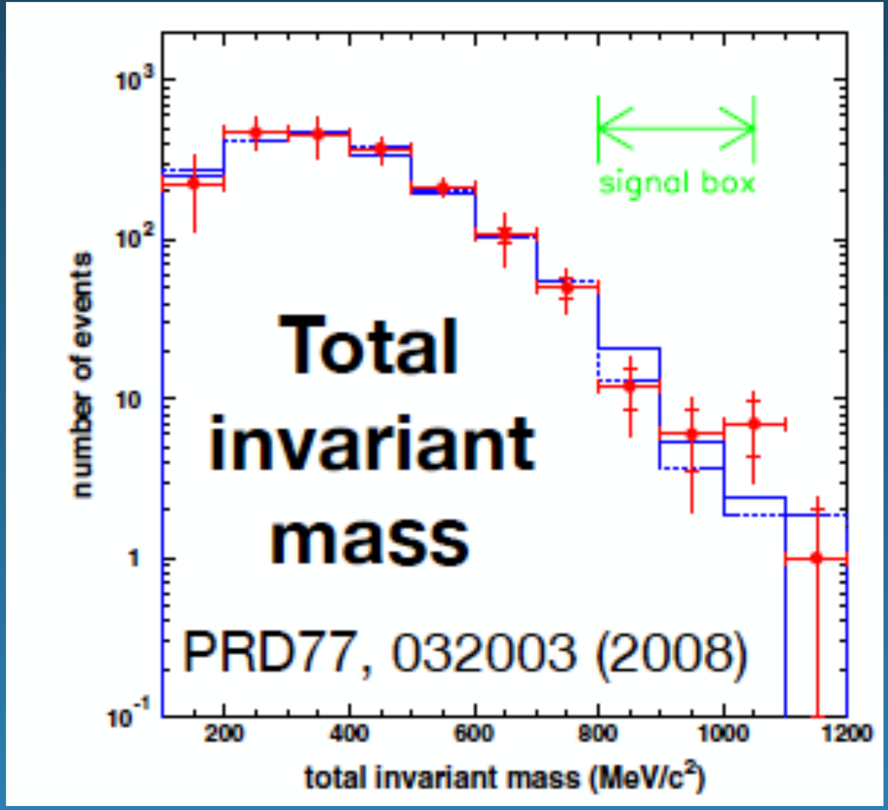


SIGNAL & BACKGROUND

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

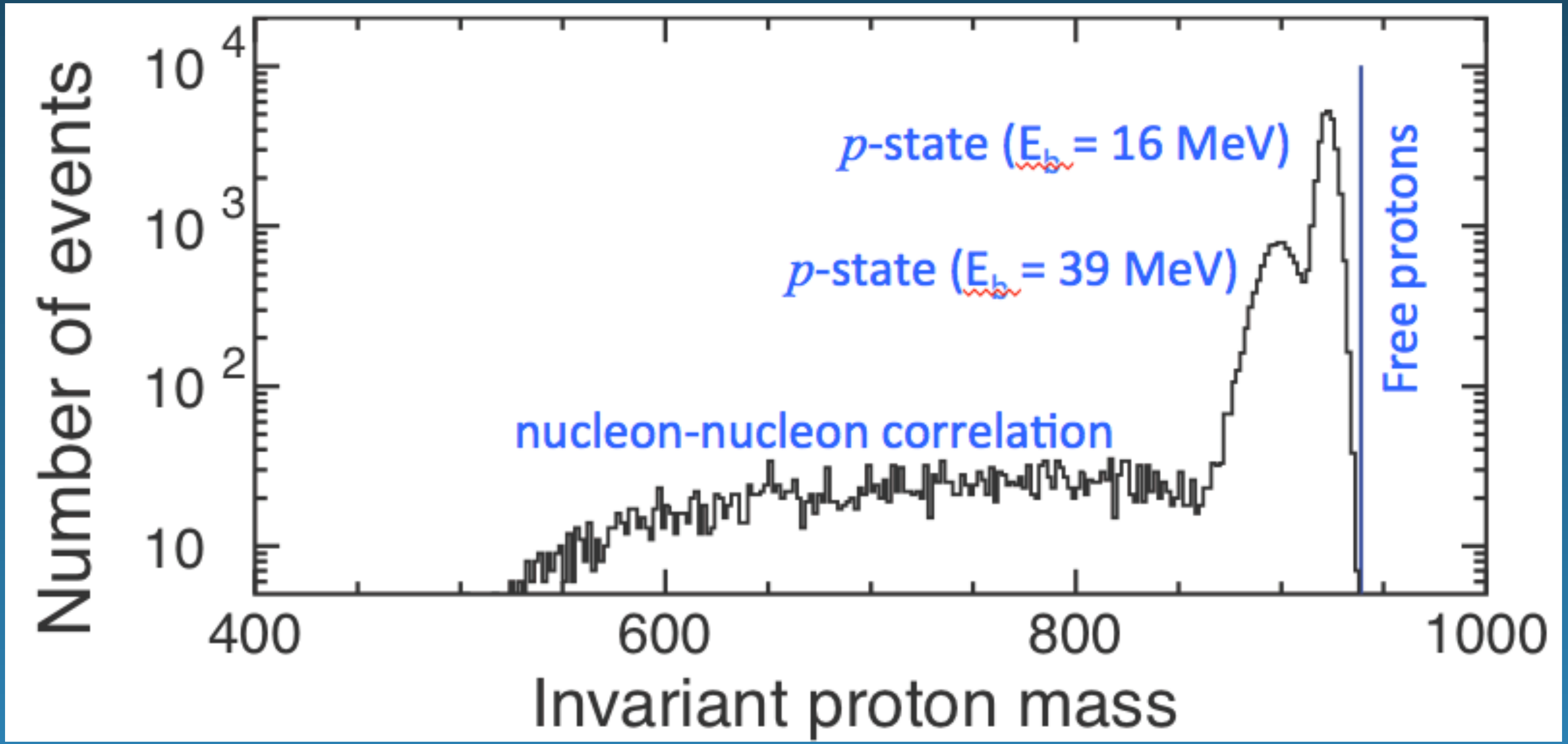


ex. π^0 from PDK interacts with nucleons in the target nucleus and loose original kinematics (ex. momentum) and/or modified charge



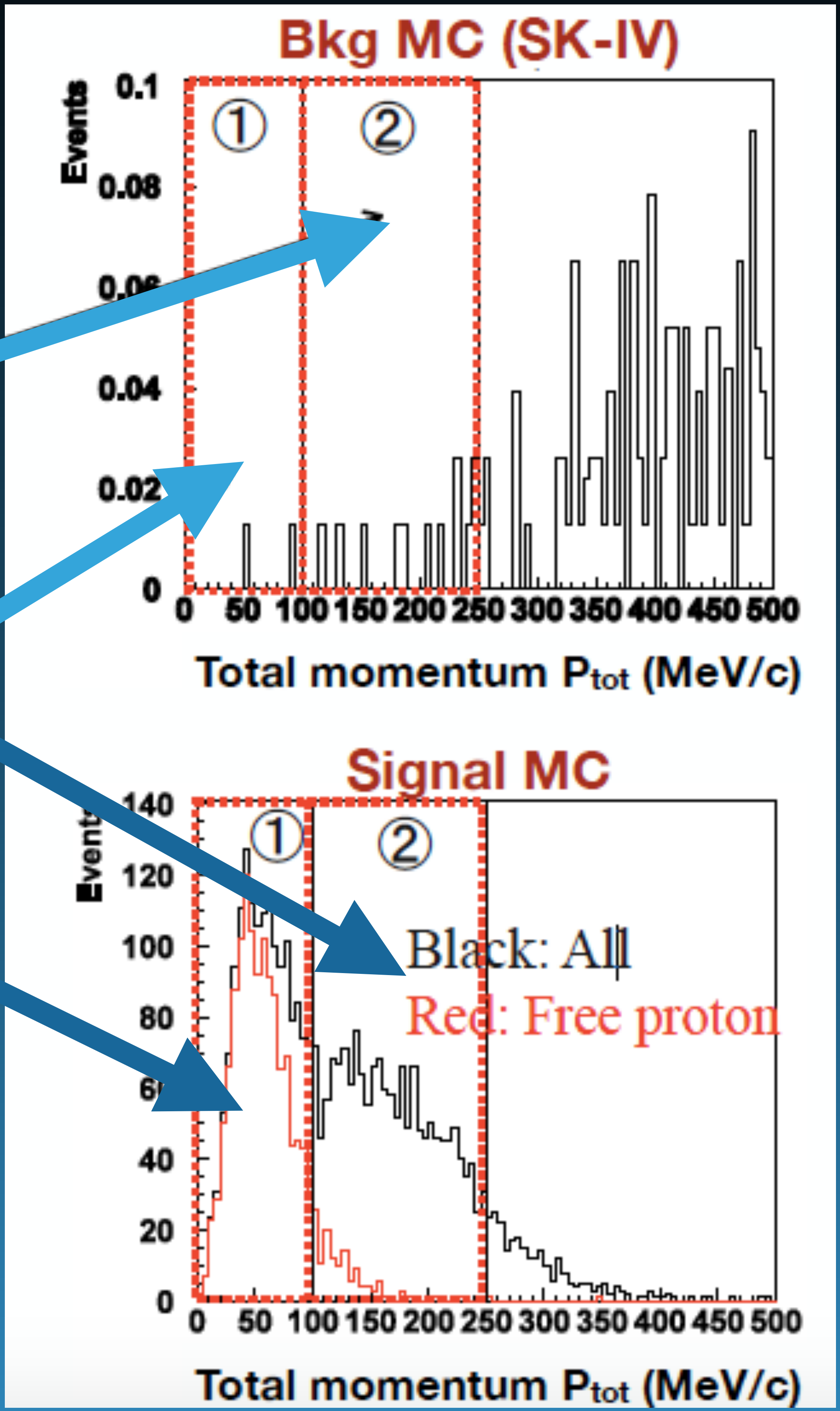
Total invariant mass

PRD77, 032003 (2008)

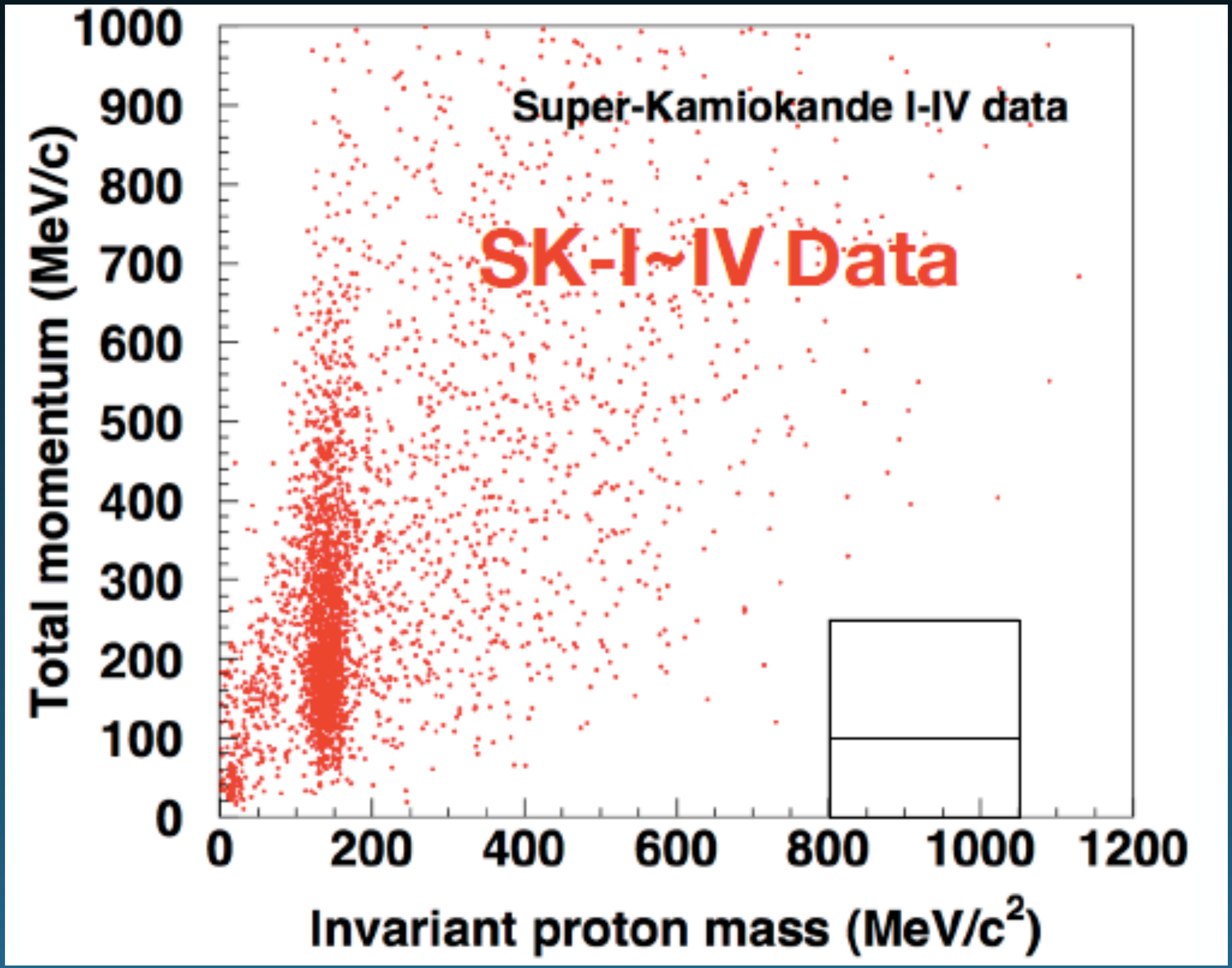


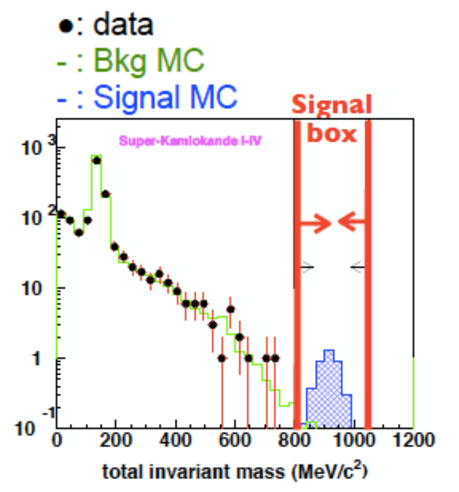
BACKGROUND REJECTION (TWO BOX STRATEGY)

- **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 compared to the upper P_{tot}
  - Free proton decay dominant
  - ➜ Accurate reconstruction of proton decay signature (less FSI) and lower background



P$\rightarrow e^{+}\pi^{0}$: SIGNAL & BACKGROUND



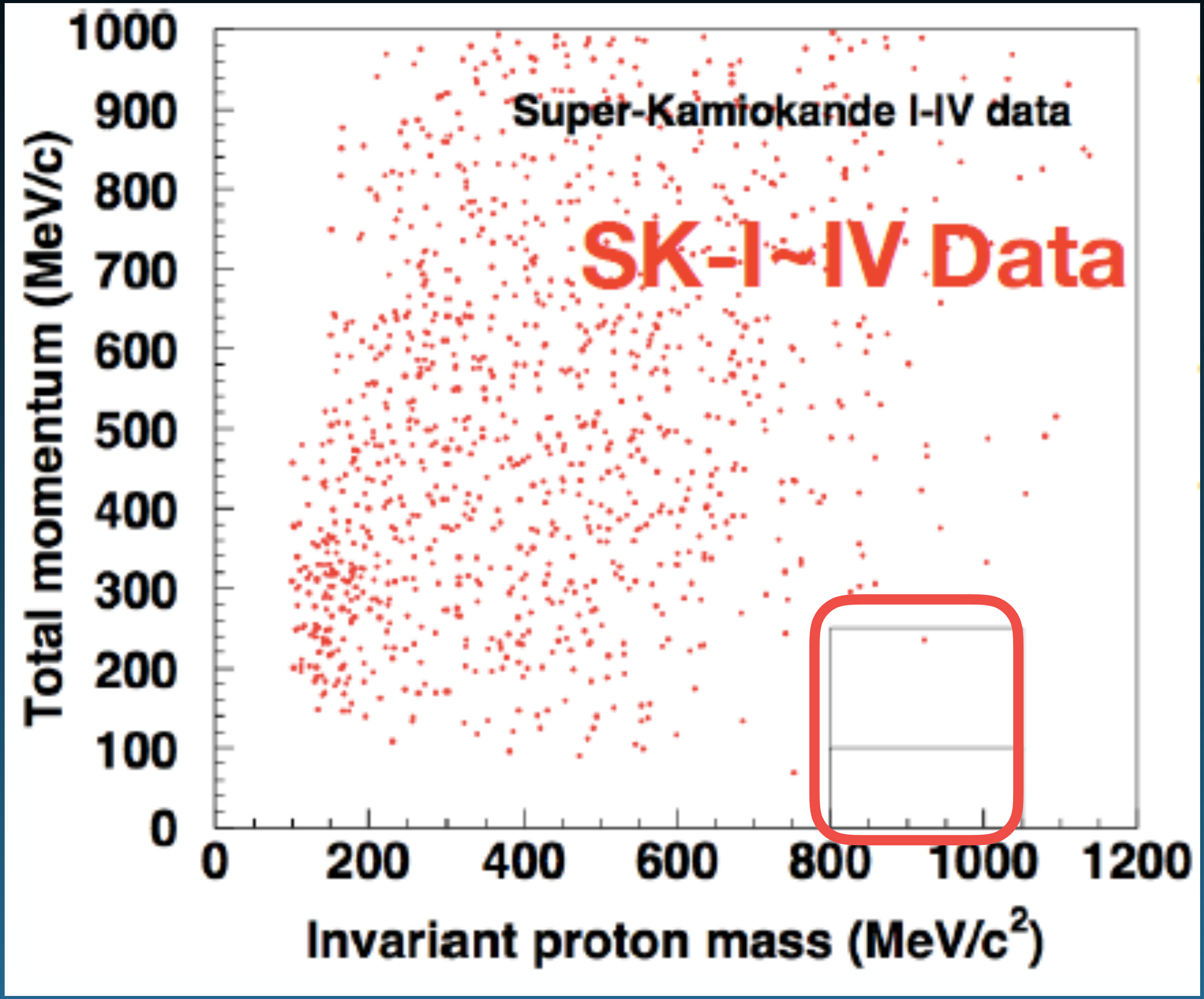


- Expected bkg contamination in signal region for entire SK period (SK-I~IV):
  - Lower P_{tot}: 0.07 events
  - Upper P_{tot}: 0.54 events
- Found no events in the signal box
- Lifetime limit at 90% C.L. with 365 kt·years (SK-I~IV) exposure:

τ/Br>2.0x10^{34} years [preliminary]

- Most stringent constraint

P→ $\mu^+\pi^0$: RESULTS

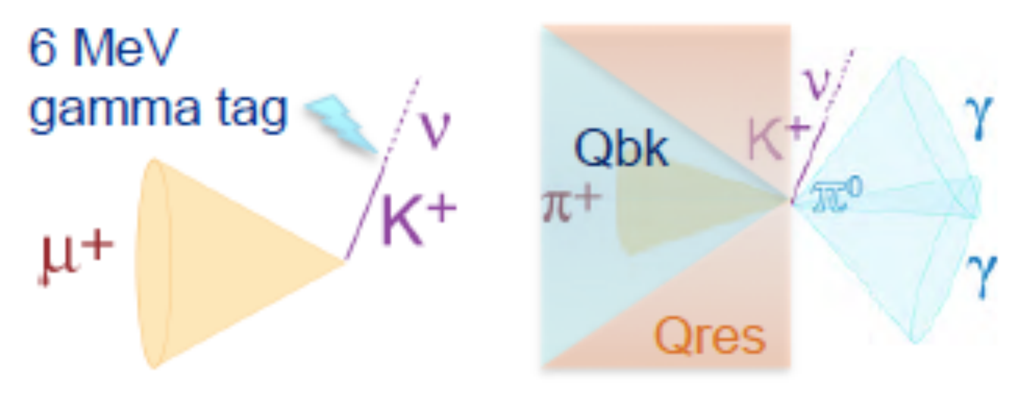


- Spirit of the event selection is similar to p→ $e^+\pi^0$ mode but requires 1 μ-like ring
- Expected bkg contamination in signal region for entire SK period (SK-I~IV):
  - Lower P_{tot}: 0.07 events
  - Upper P_{tot}: 0.65 events
- Found 1 evt in upper signal box
- It's not obvious data excess compared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

- Lifetime limit at 90% C.L. with 365 kt·years (SK-I~IV) exposure:

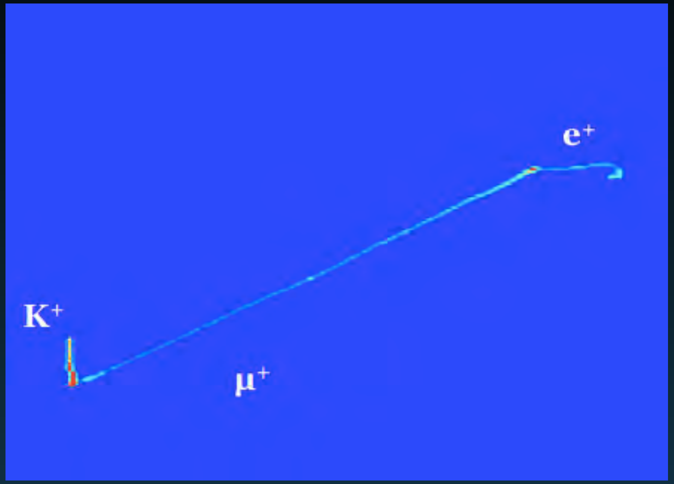
τ/Br>1.2x10^{34} years [preliminary]

P $\longrightarrow \bar{\nu}$ K SIGNATURES



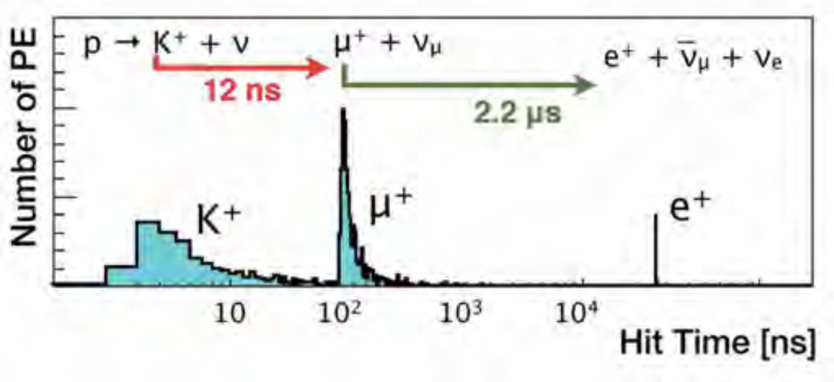
In Cherenkov detectors:

- Look for de-excitation gamma in time with non showering (muon) ring to identify events with leptonic decay mode of kaon (kaon ring, kaon momentum is 340 MeV/c, is below Cherenkov threshold of 749 MeV/c) [K^+ leptonic decay]
- Also perform search for hadronic decay mode of kaon, looking for π^+ ring in backward direction of 2 showering rings from π^0 decay [K^+ hadronic decay]



In LArTPC detectors:

- No detection threshold problem
- Use dE/dx to identify stopping kaon & decay products



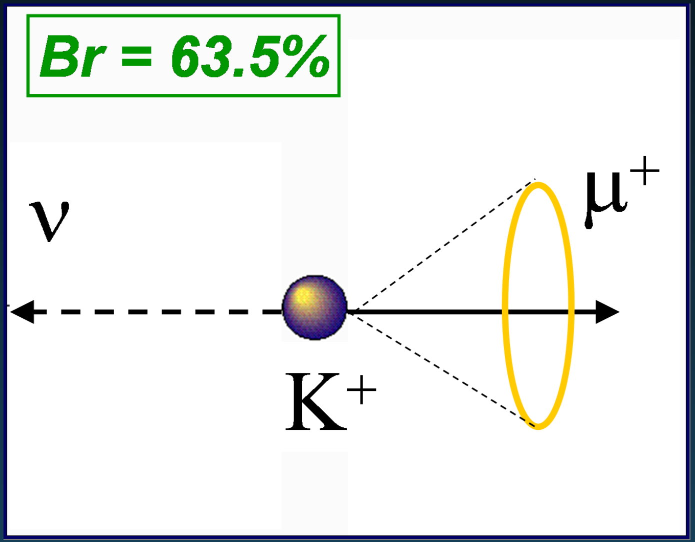
In scintillator detectors:

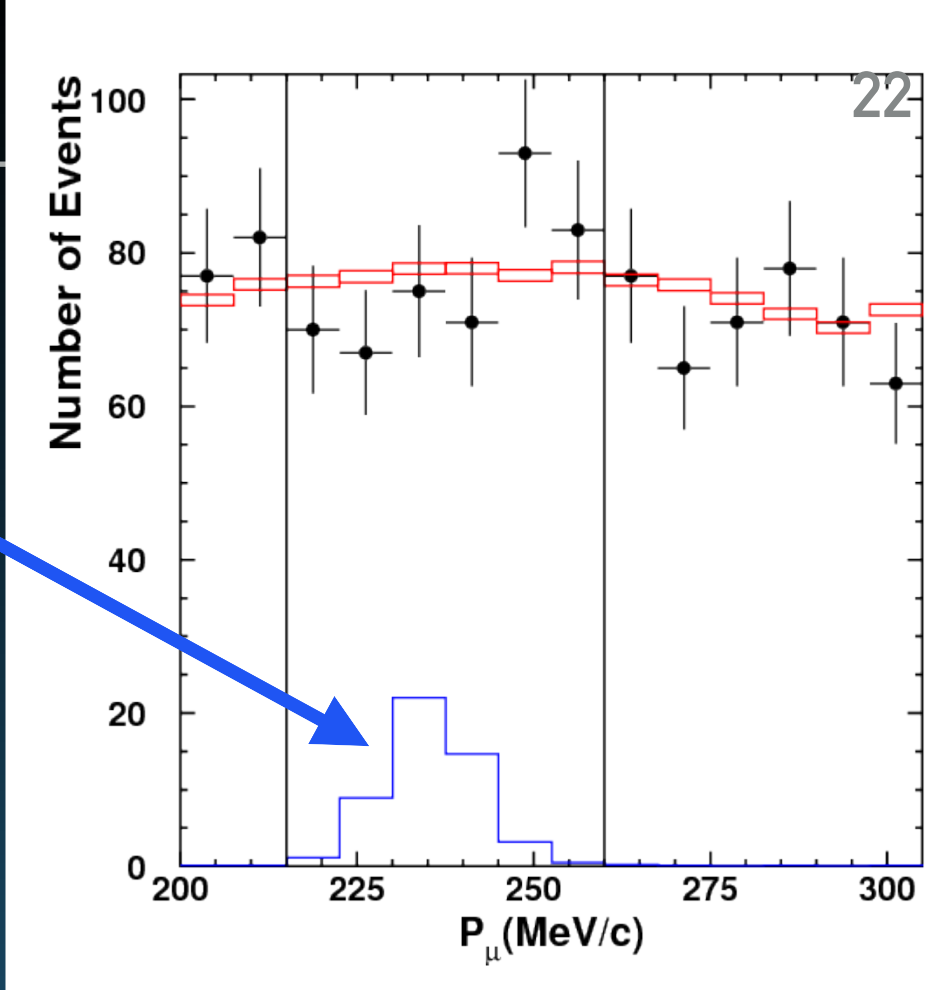
- Fast and precise timing capability allows detection of signals from each of the subsequent particles in the decay chain
- –Both the prompt and delayed signals have well defined energy spectra

powerful background rejection

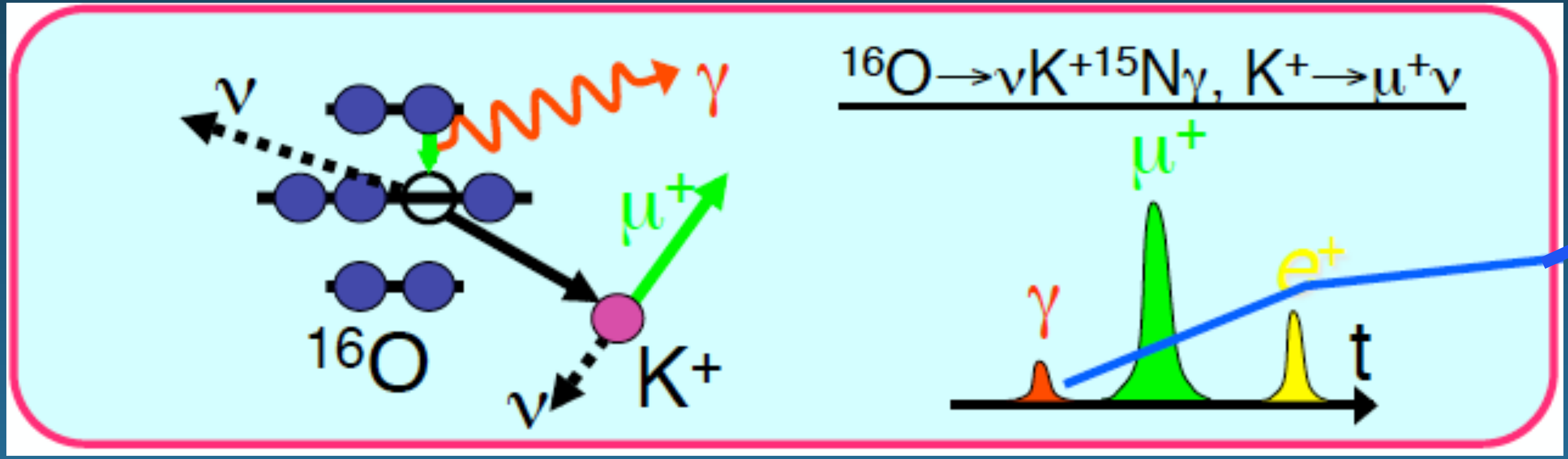
SEARCH FOR $P\rightarrow\bar{\nu}K^+$ [K^+ LEPTONIC DECAY]

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

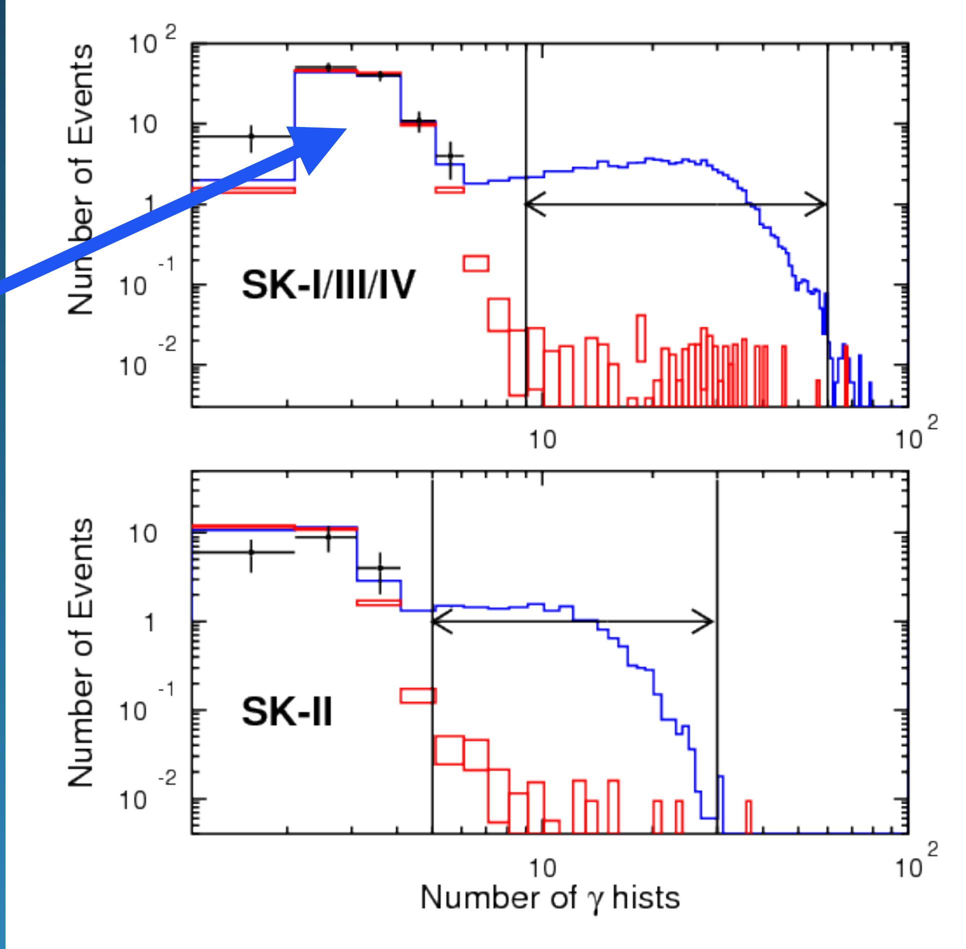




- De-excitation γ (6.3MeV) + μ decay



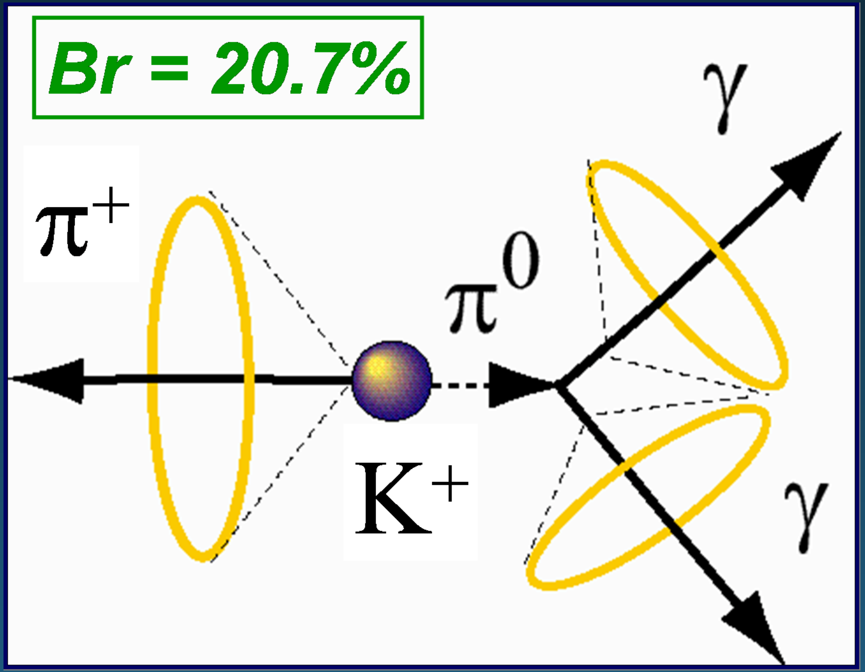
- Proton decays in ^{16}O → Excited nucleus (^{15}N*) emits 6.3 MeV γ-ray (~40% probability)
- ➜ γ, μ and Michel-e from μ-decay triple coincidence largely reduce the bkg contamination

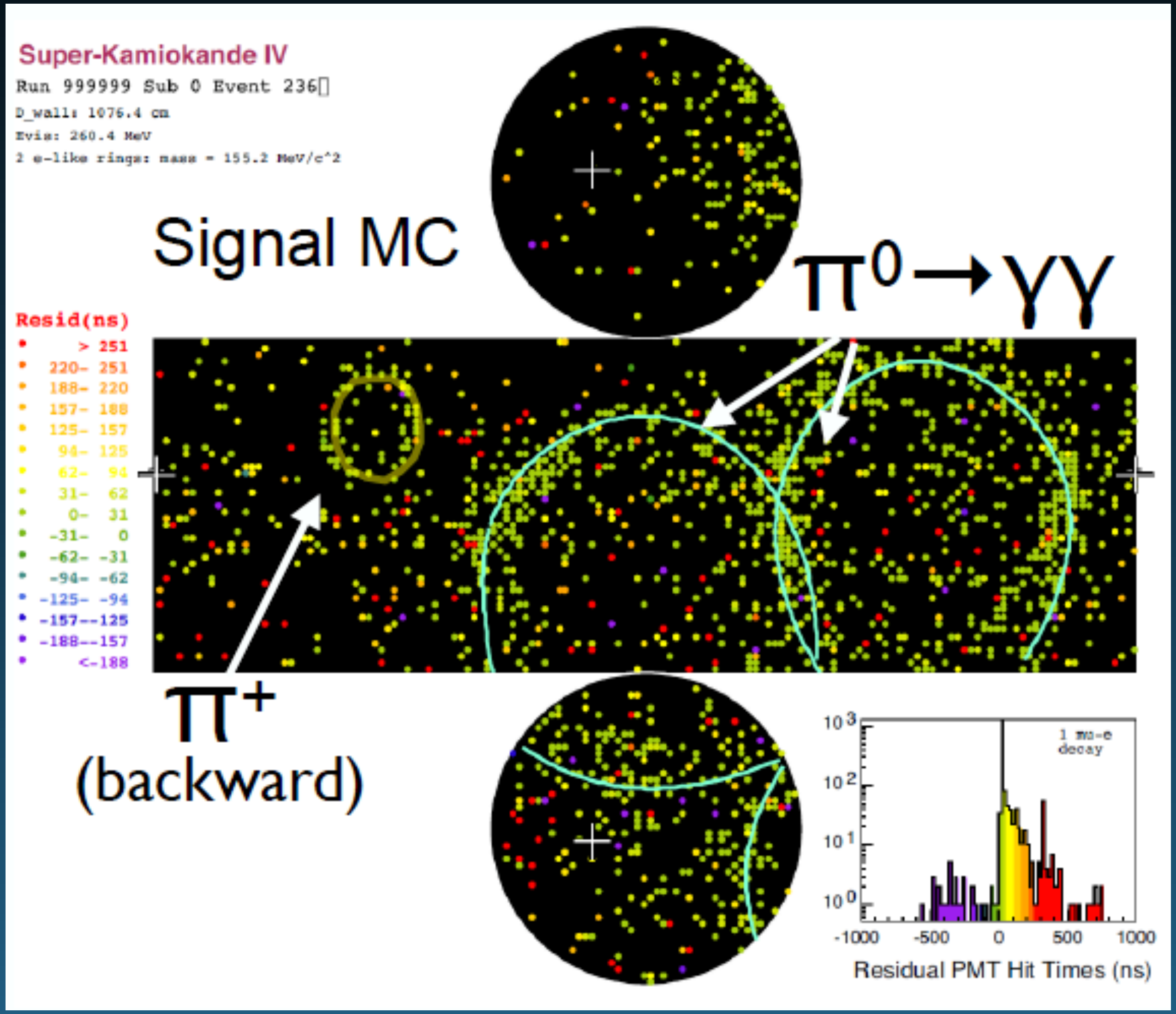


SEARCH FOR P$\rightarrow\bar{\nu}K^+$ [K^+ HADRONIC DECAY]

PRD90, 072005 (2014)

- $K^+\rightarrow\pi^+\pi^0$: π^+ and π^0 run back-to-back with 205 MeV/c (π^+ Č threshold 156MeV/c)





RESULTS

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

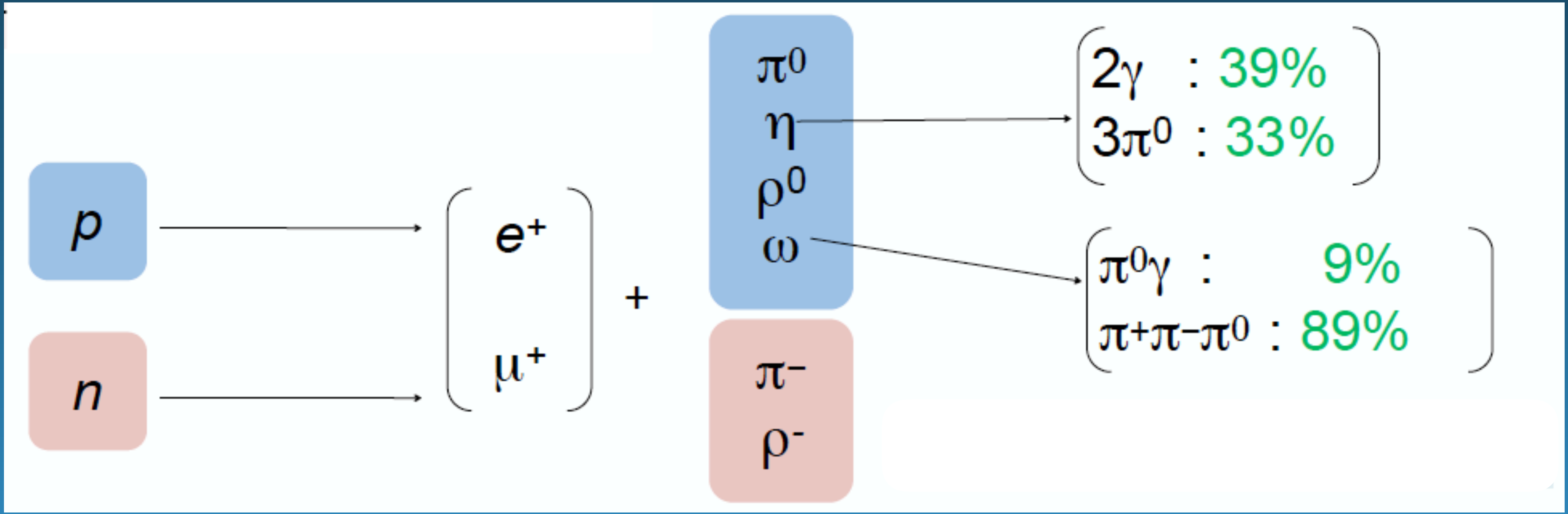
N→CHARGED LEPTON + MESON

[PRD96, 012003 (2017)]

Theoretical Predictions on Branching Ratio:

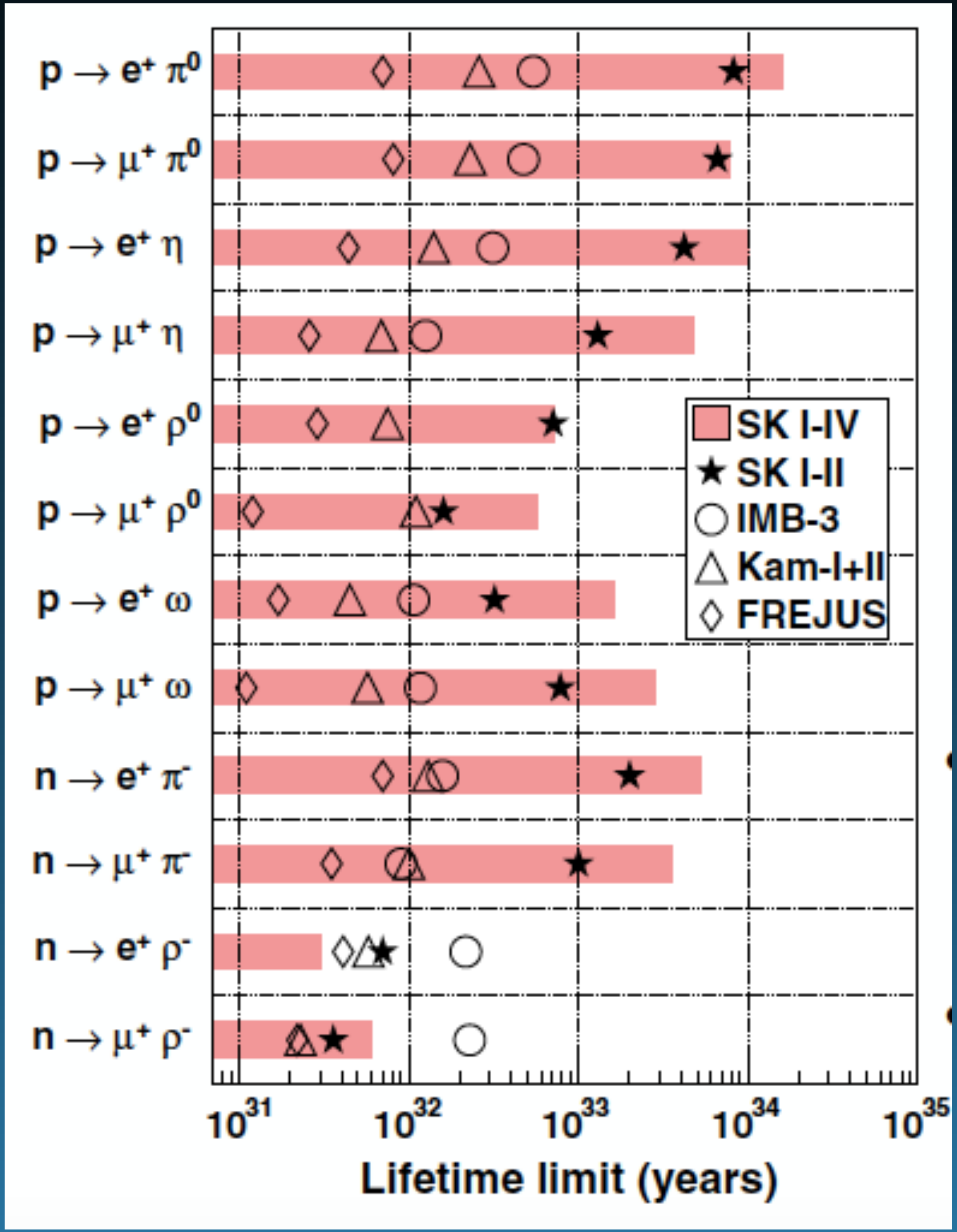
channels	Buccella et al. (1989)
$p \rightarrow e^+\pi^0$	30.0%
$p \rightarrow e^+\eta$	12.9%
$p \rightarrow e^+\rho^0$	1.8%
$p \rightarrow e^+\omega$	14.4%

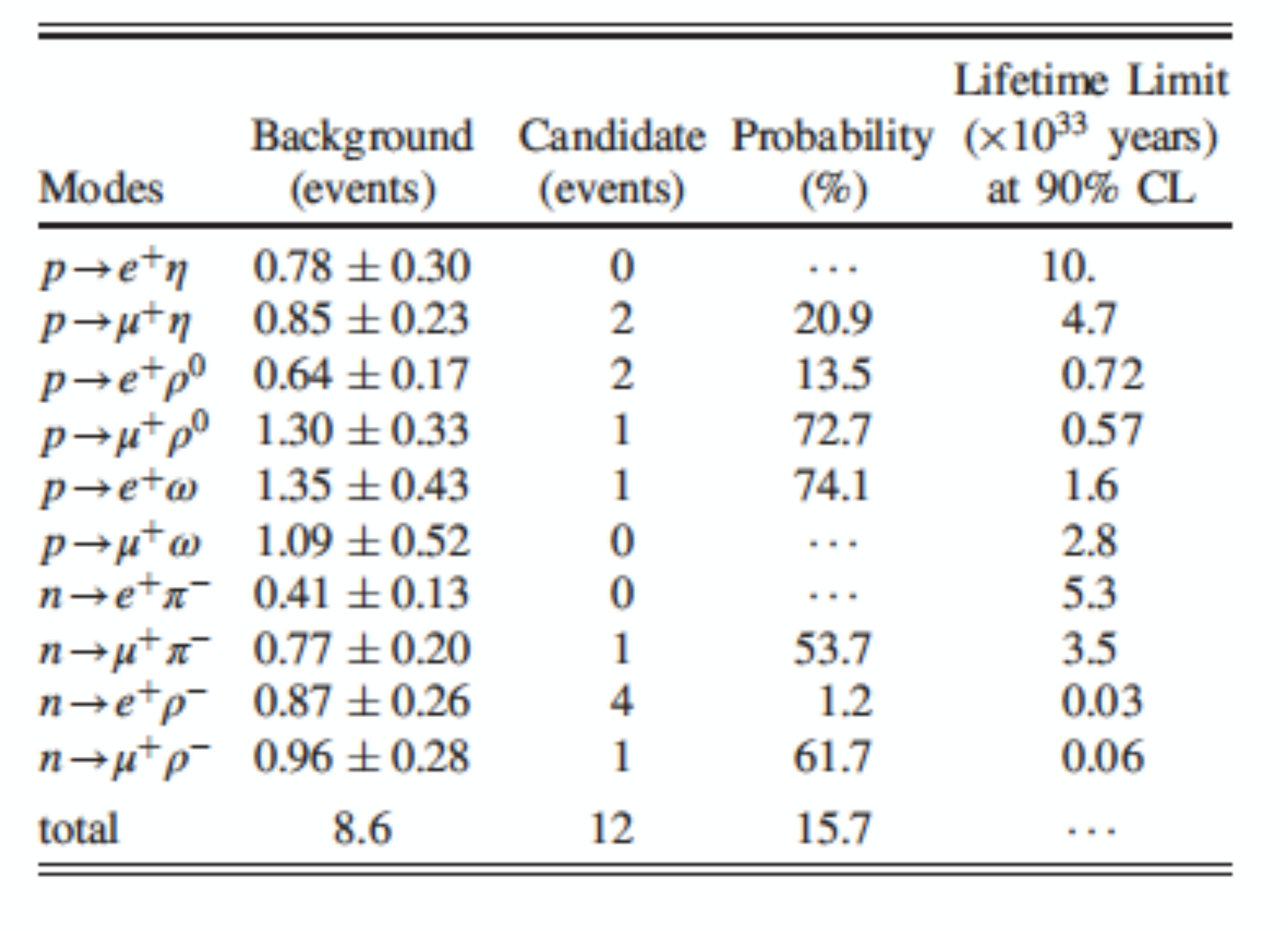
- Several decay modes consist of charged lepton and meson:
  - $[e^+/\mu^+] + [\eta, \rho, \omega, \ldots]$
- These decay mode can have a similar branching ratio to $p \rightarrow e^+/\mu^+ + \pi^0$
- Search for nucleon decay for many decay modes:



N→CHARGED LEPTON + MESON

[PRD96, 012003 (2017)]





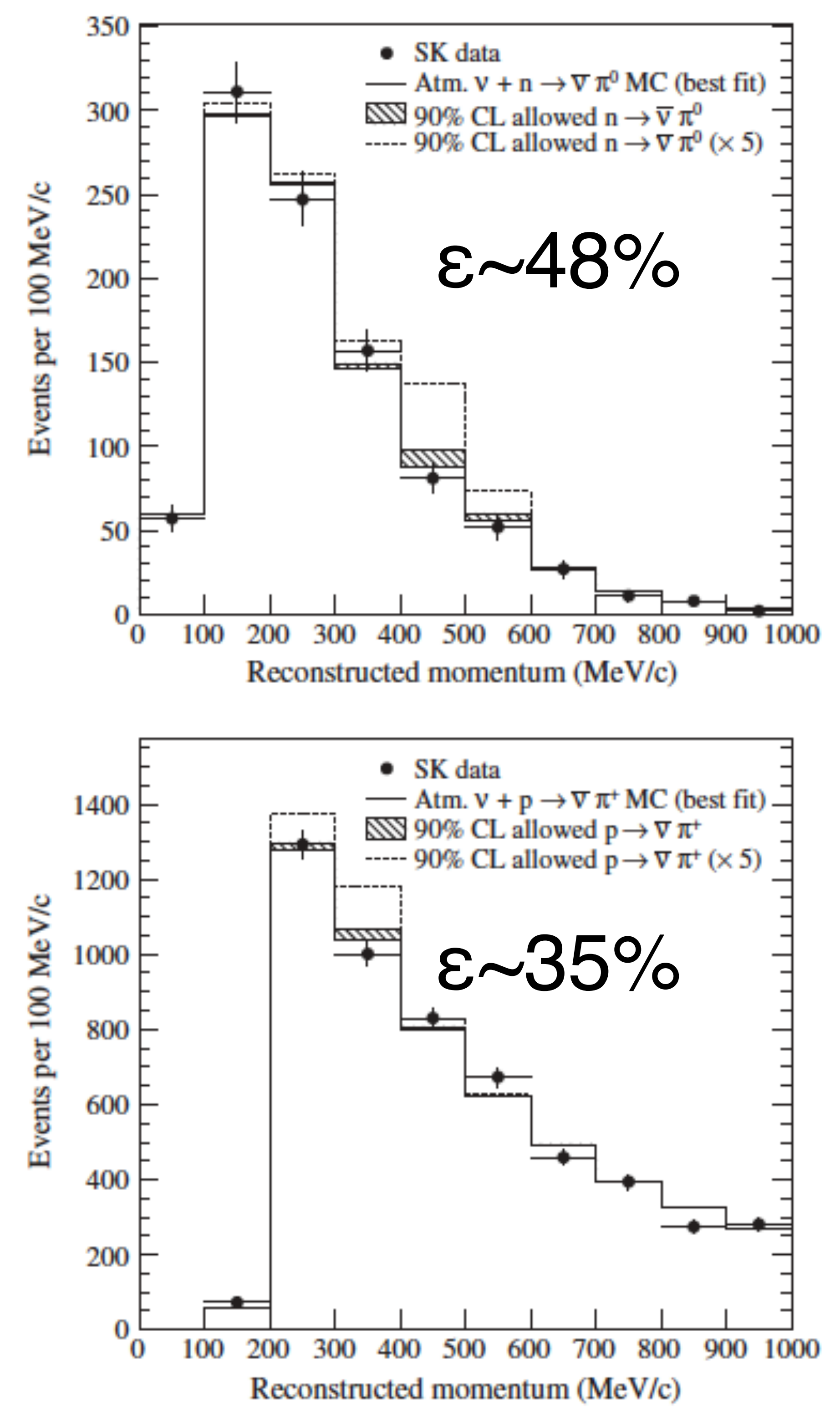
Modes	Background (events)	Candidate (events)	Probability (%)	Lifetime Limit ($\times 10^{33}$ years) at 90% CL
$p \to e^+ \eta$	0.78 ± 0.30	0	⋯	10.
$p \to \mu^+ \eta$	0.85 ± 0.23	2	20.9	4.7
$p \to e^+ \rho^0$	0.64 ± 0.17	2	13.5	0.72
$p \to \mu^+ \rho^0$	1.30 ± 0.33	1	72.7	0.57
$p \to e^+ \omega$	1.35 ± 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 SK 365 kt·year exposure (SK-I~IV)
- Lifetime limits reach to $\geq 10^{33}$ yrs for many of decay modes

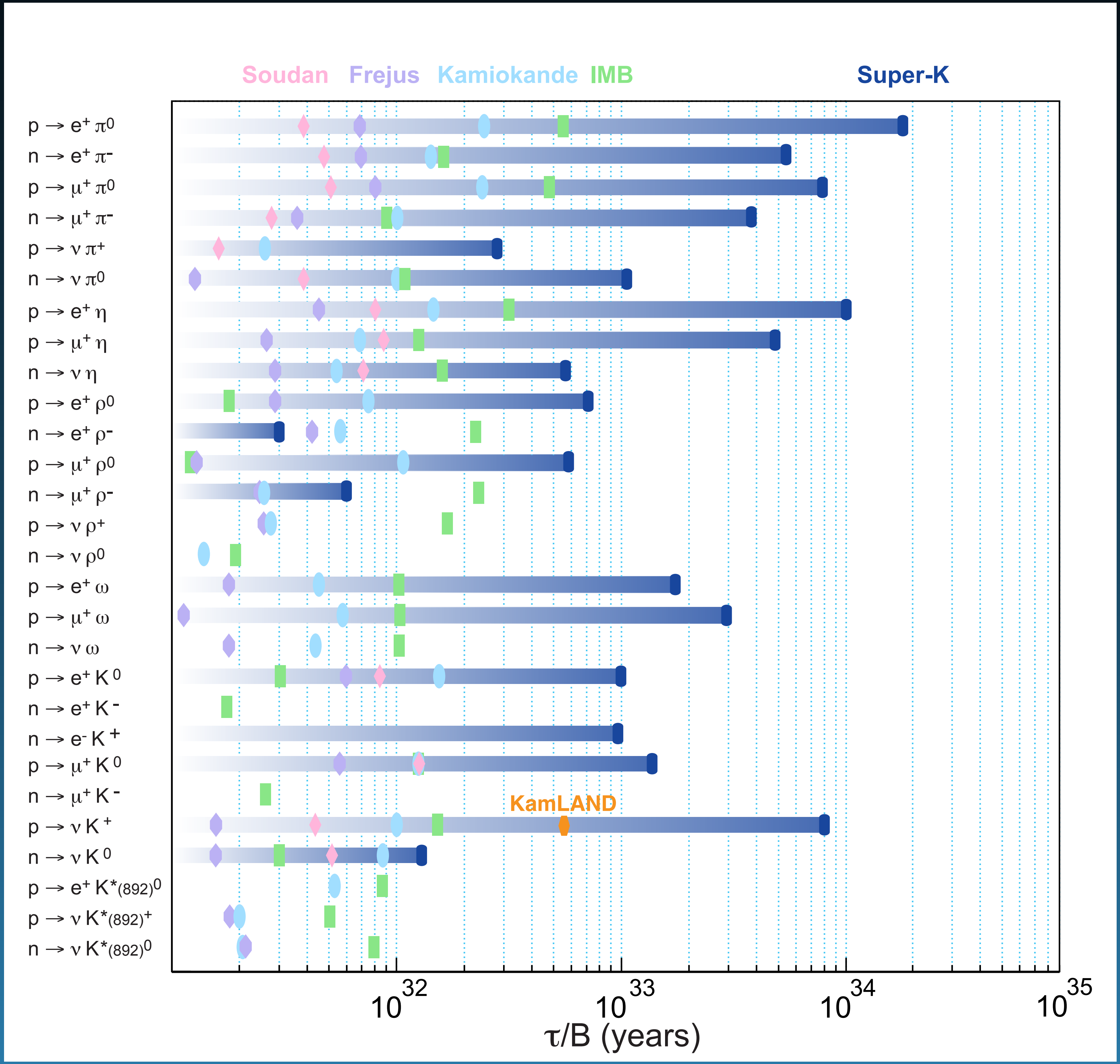
SEARCHES FOR N$\rightarrow\nu\pi^0$ AND P$\rightarrow\nu\pi^+$

[PRL 113, 121802 (2014)]

- Motivated by minimal SUSY SO(10) (e.g. PLB587, 105 (2004).)
- n$\rightarrow\nu\pi^0$
  - detection efficiency = 49%(SK-I), 44%(SK-II), 49%(SK-III)
  - $\tau_{p\rightarrow\nu\pi 0}$ > 1.1 x 10^{33} years @ 90%C.L.
- p$\rightarrow\nu\pi^+$
  - detection efficiency = 35%(SK-I), 35%(SK-II), 36%(SK-III)
  - $\tau_{p\rightarrow\nu\pi+}$> 3.9 x$10^{32}$years @ 90%C.L.
- almost ruled out the prediction by PLB587, 105 (2004):
  - $\tau_{p\rightarrow\nu\pi 0}=2\tau_{p\rightarrow\nu\pi+}$<5.7 – 13 x 10^{32}years @ 90%C.L.



CURRENT LIMITS



E. Kearns

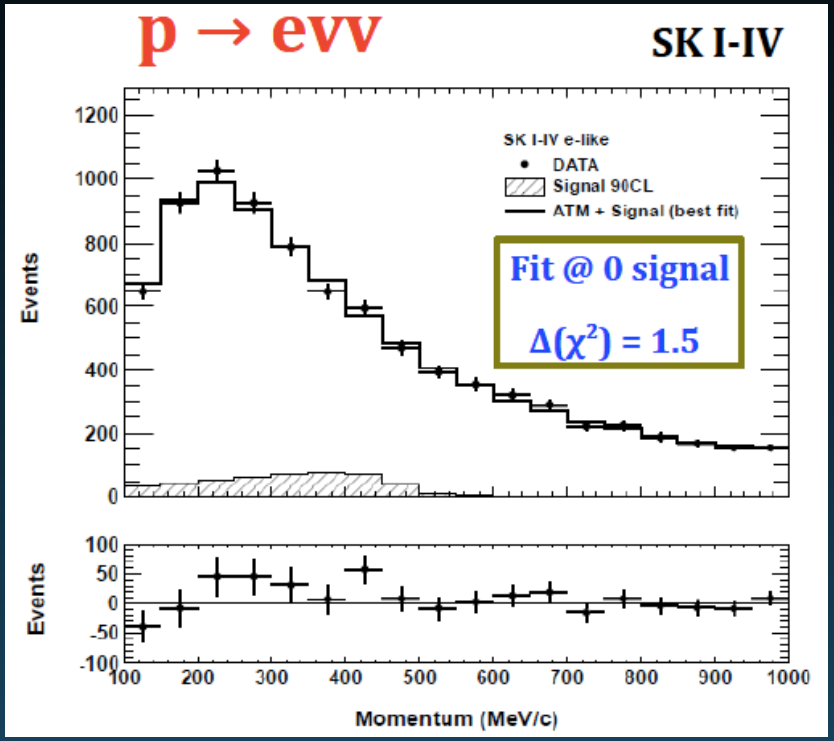
Lepton+ meson

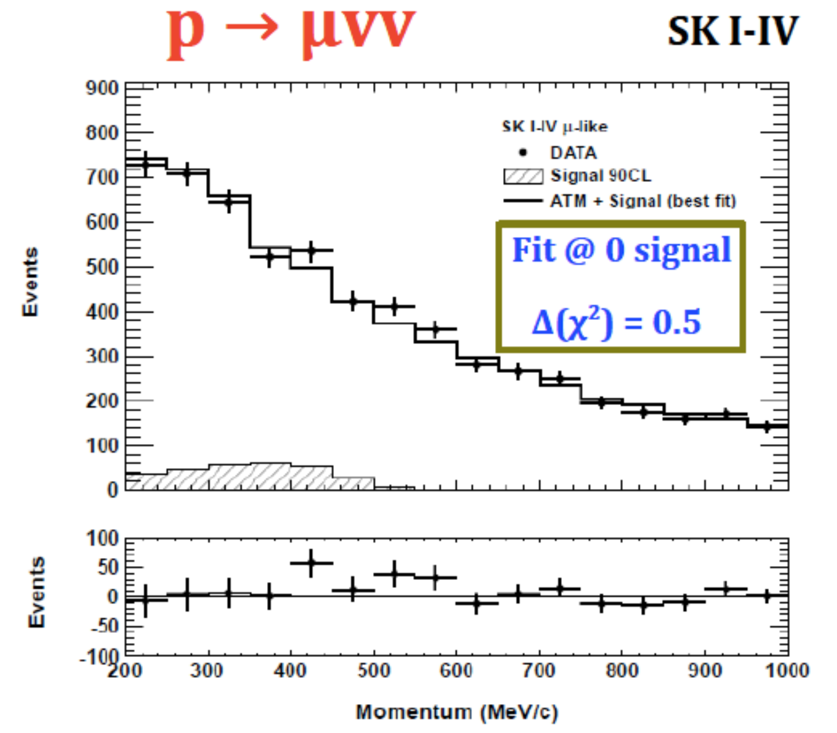
Conserves (B-L)

Non-strange mesons

Strange mesons

TEST OF EXCESS IN e/μ SPECTRUM





[PRL113,101801(2014)]

Mode	SK I-IV Sensitivity (years)	SK I-IV Limit (years)	PDG Limit (years)
$p \to e^+\nu\nu$	$2.7 \cdot 10^{32}$	$1.7 \cdot 10^{32}$	$1.7 \cdot 10^{31}$
$p \to \mu^+\nu\nu$	$2.5 \cdot 10^{32}$	$2.2 \cdot 10^{32}$	$2.1 \cdot 10^{31}$

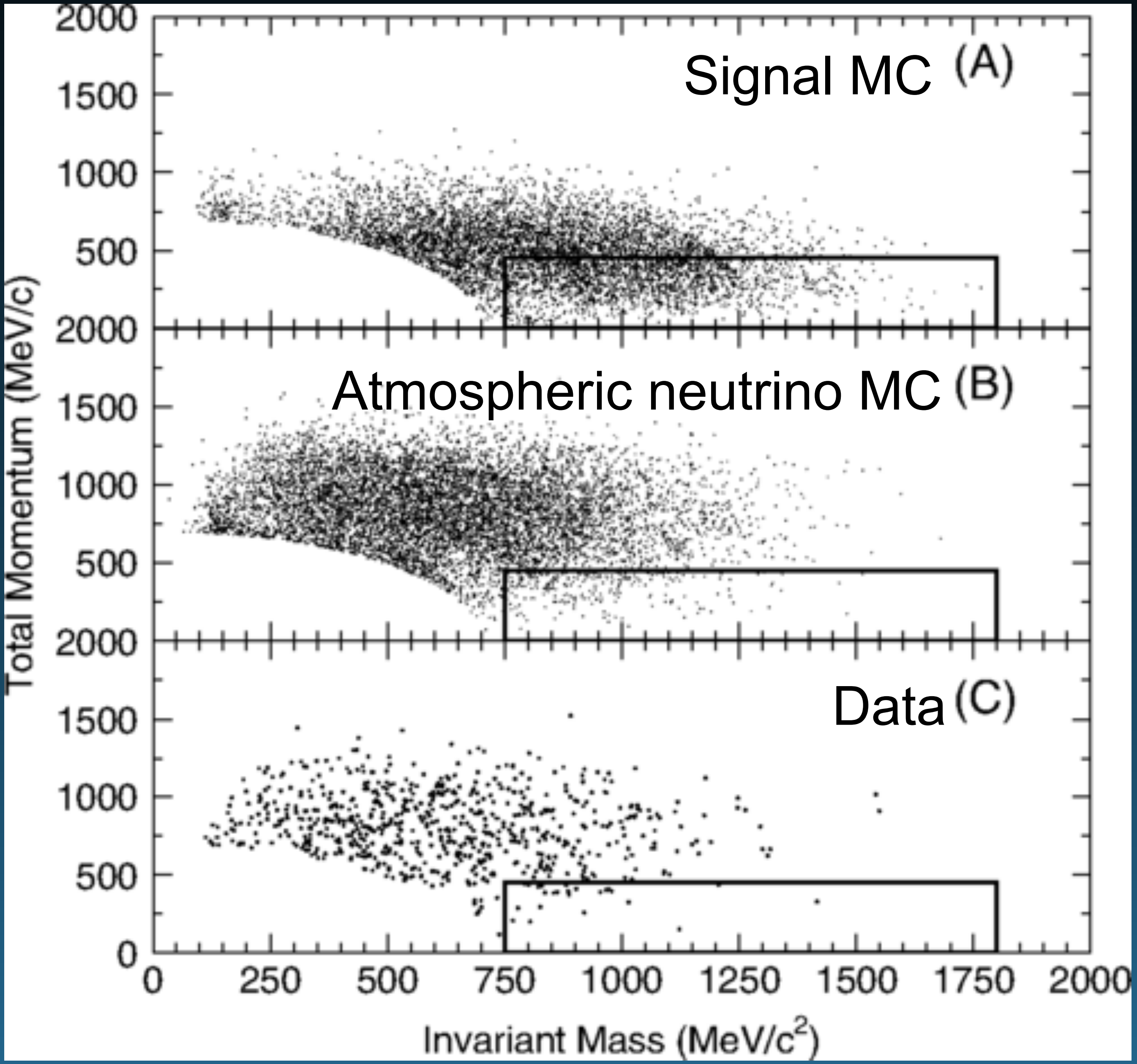
Mode	SK I-IV Sensitivity (years)	SK I-IV Limit (years)	PDG Limit (years)
$p \to e^+X$	$7.9 \cdot 10^{32}$	$7.9 \cdot 10^{32}$	–
$p \to \mu^+X$	$7.7 \cdot 10^{32}$	$4.1 \cdot 10^{32}$	–
$n \to \nu\gamma$	$5.8 \cdot 10^{32}$	$5.5 \cdot 10^{32}$	$2.8 \cdot 10^{31}$
$np \to e^+\nu$	$9.9 \cdot 10^{31}$	$2.6 \cdot 10^{32}$	$2.8 \cdot 10^{30}$
$np \to \mu^+\nu$	$1.1 \cdot 10^{32}$	$2.2 \cdot 10^{32}$	$1.6 \cdot 10^{30}$
$np \to \tau^+\nu$	$1.1 \cdot 10^{31}$	$2.9 \cdot 10^{31}$	–

ΔB=2: N-$\overline{\text{N}}$ OSCILLATION

[PRD91,072006(2015)]

- ΔB=Δ(B-L)=2, might be relevant for the matter asymmetry in the Universe.
- Look for multiple pions from nbar+nucleon annihilation

- n-$\overline{\text{n}}$ oscillation in ^{16}O
  - detection efficiency = 12.1%
  - atmospheric ν BG = 24.1 events in 92kton x years (Super-K-I)
  - observed signal = 24 events
  - τ(^{16}O) > 1.9 x10^{32} years @ 90%C.L.
  - →τ(free)>2.7x10^{8}sec

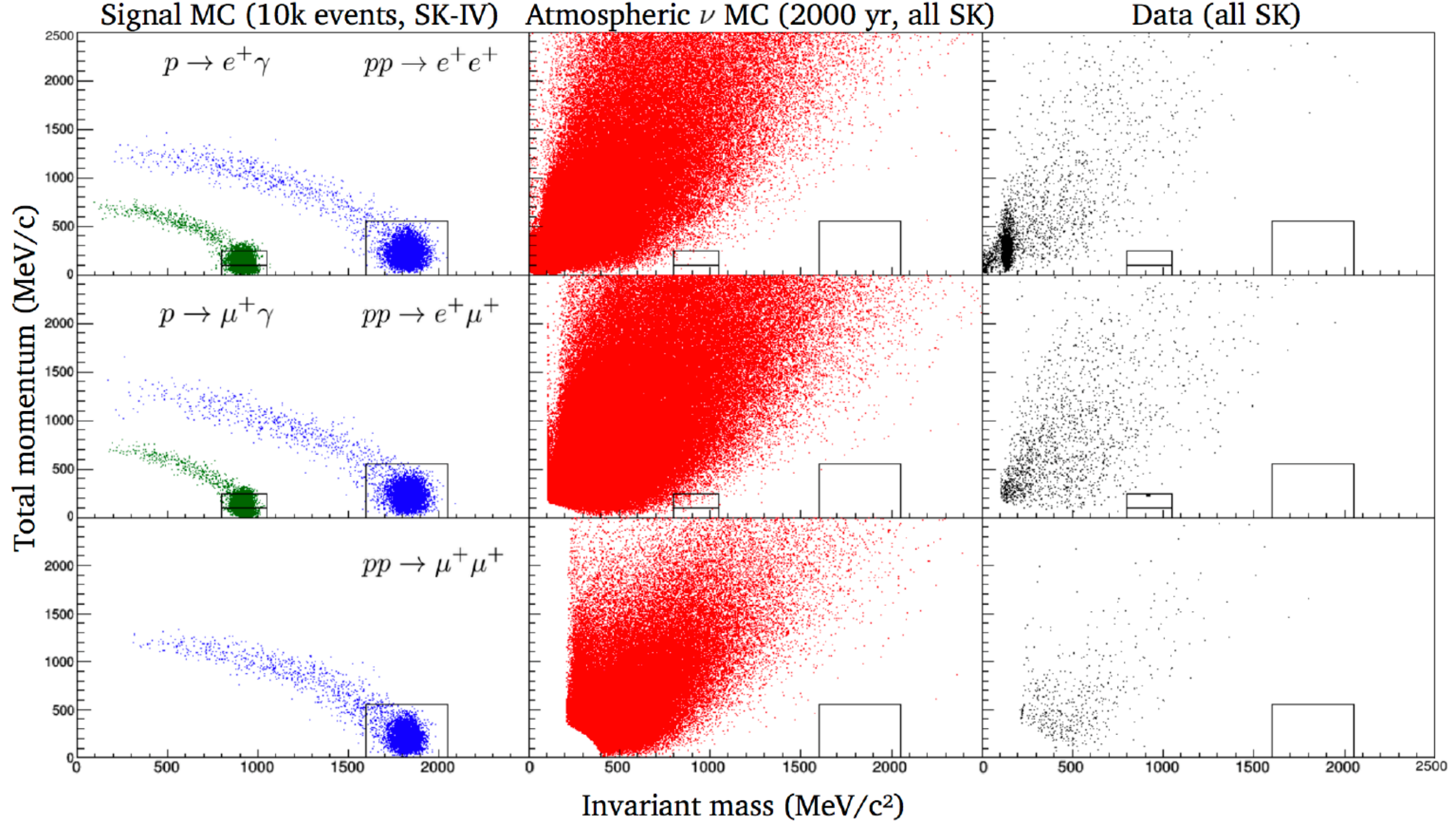


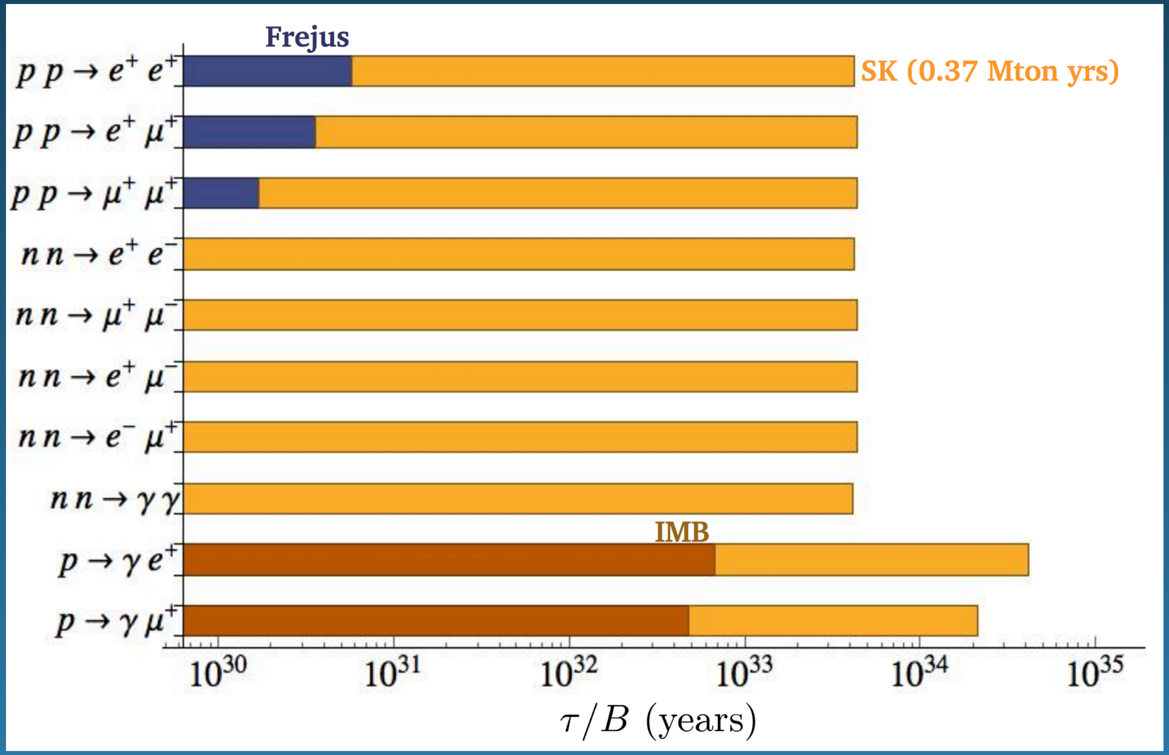
- ≧2 Cherenkov rings
- 700<Visible Energy<1300 MeV/c^2
- 750<M_{tot}<1800 MeV/c^2
- P_{tot}<450 MeV/c

SEARCH FOR DI-NUCLEON DECAY

[arXiv:1811.12430]

- Search for di-nucleon decay with only leptons or γ's in final state
  - $pp \rightarrow e^+e^+$, $nn \rightarrow e^+e^-$, $nn \rightarrow \gamma\gamma$, $pp \rightarrow e^+\mu^+$, $nn \rightarrow e^\pm\mu^\mp$, $pp \rightarrow \mu^+\mu^+$, $nn \rightarrow \mu^+\mu^-$, and $p \rightarrow e^+\gamma$, $\mu^+\gamma$
- 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 order of magnitudes from previous limits





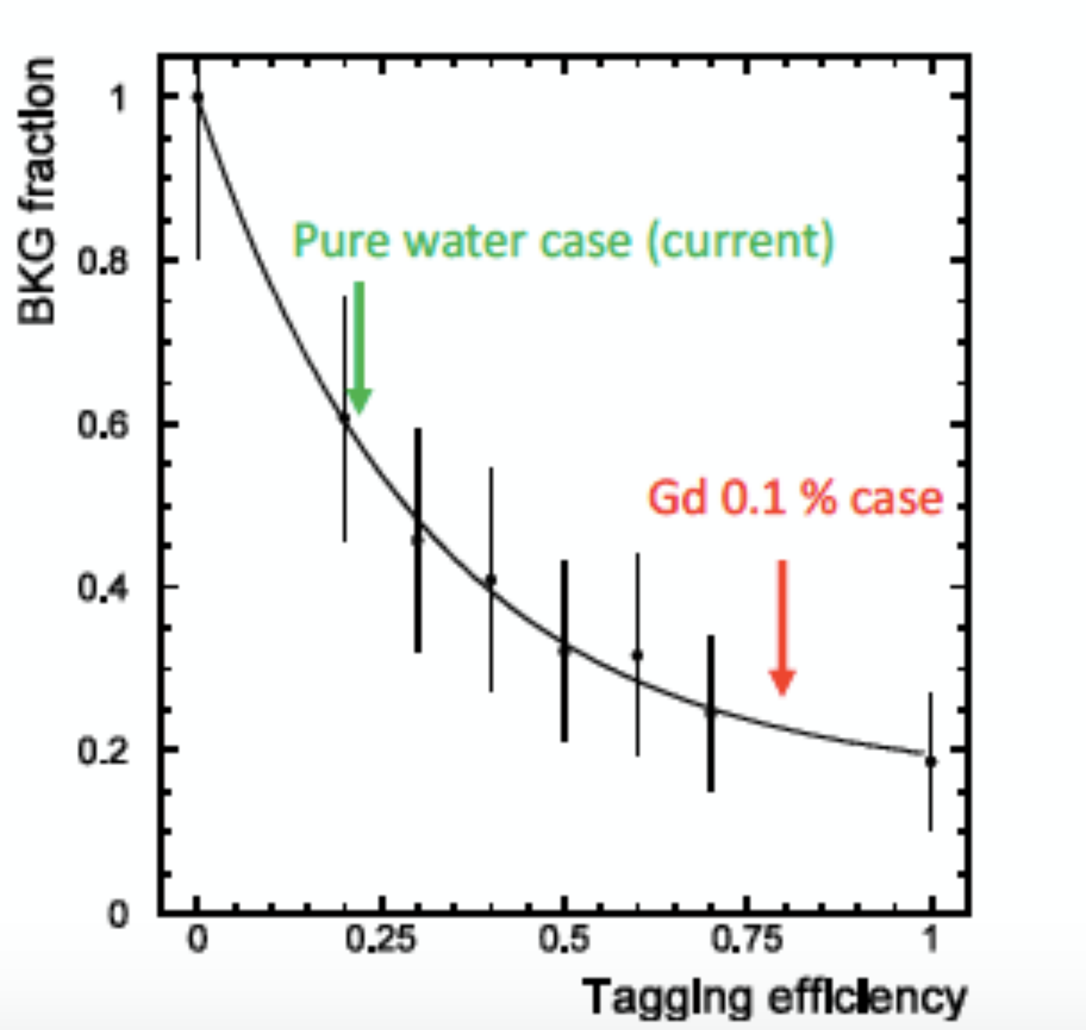
SUPER-KAMIOKANDE NEAR FUTURE

- 2018: Tank refurbishment work to be ready for loading Gadolinium
- 2020(TBD): Neutron capture 50% (0.01%with Gd) → 202X: 90% (0.1% with Gd)
- Discovery of supernova relic neutrinos (anti-***nue***) by coincidence of $e^+ + \gamma s$

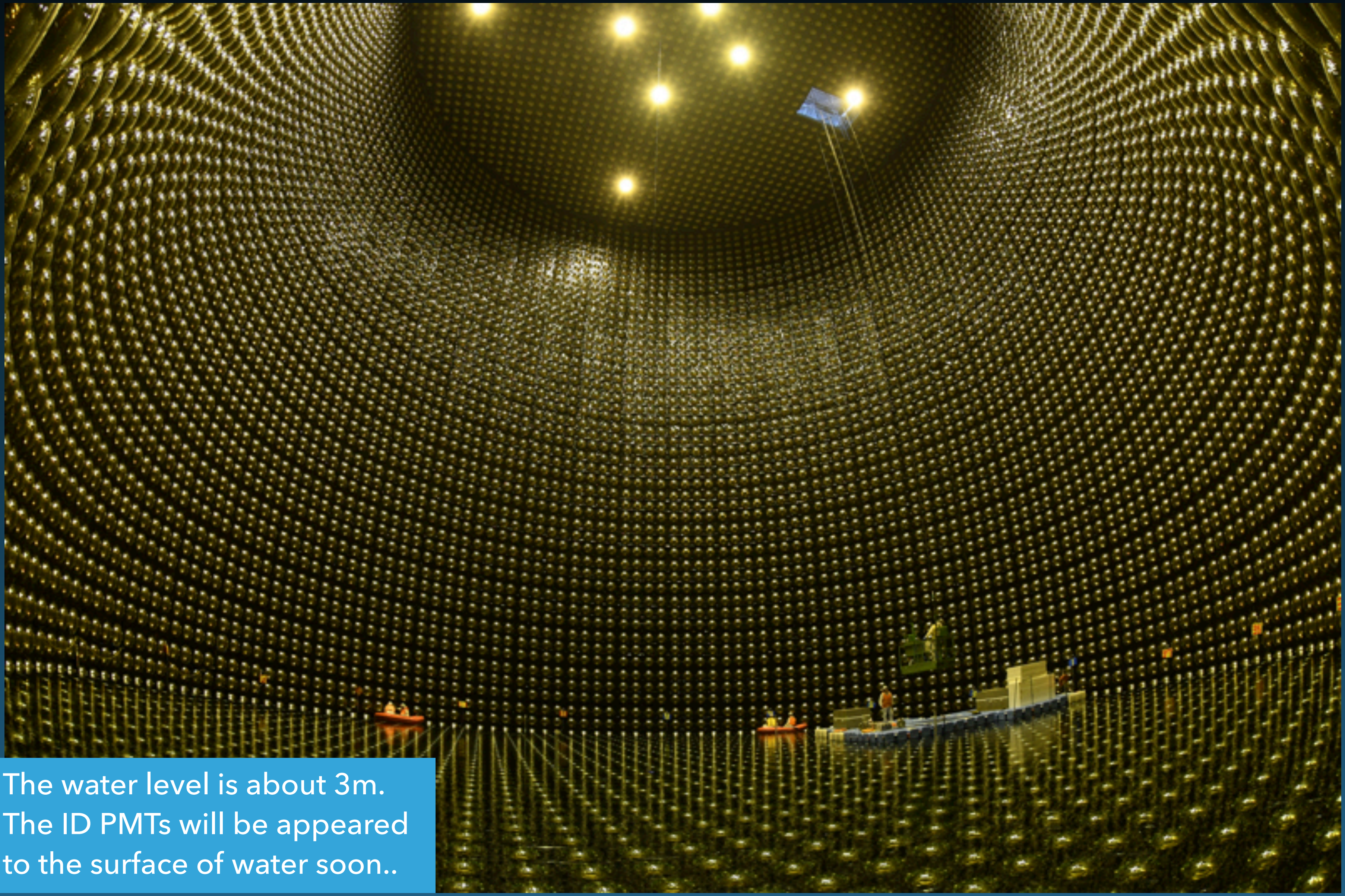
For proton decay searches

- Further BG rate reduction by a factor of 2 for $p \rightarrow e^+ \pi^0$
- Better (cleaner) searches can be performed.
- It provides opportunity to study neutron production by beam/ atmospheric neutrinos for future proton decay search program.

Beacom and Vagins PRL93:171101(2004)



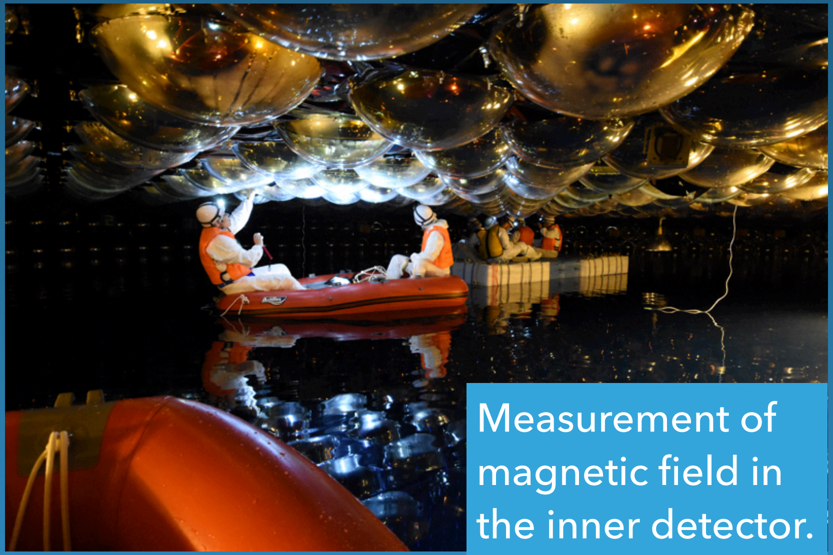
SK-GD REFURBISHMENT (SUMMER 2018)



The water level is about 3m.
The ID PMTs will be appeared to the surface of water soon..

Replacement work of inner detector PMTs.

The gondola lift in the inner detector

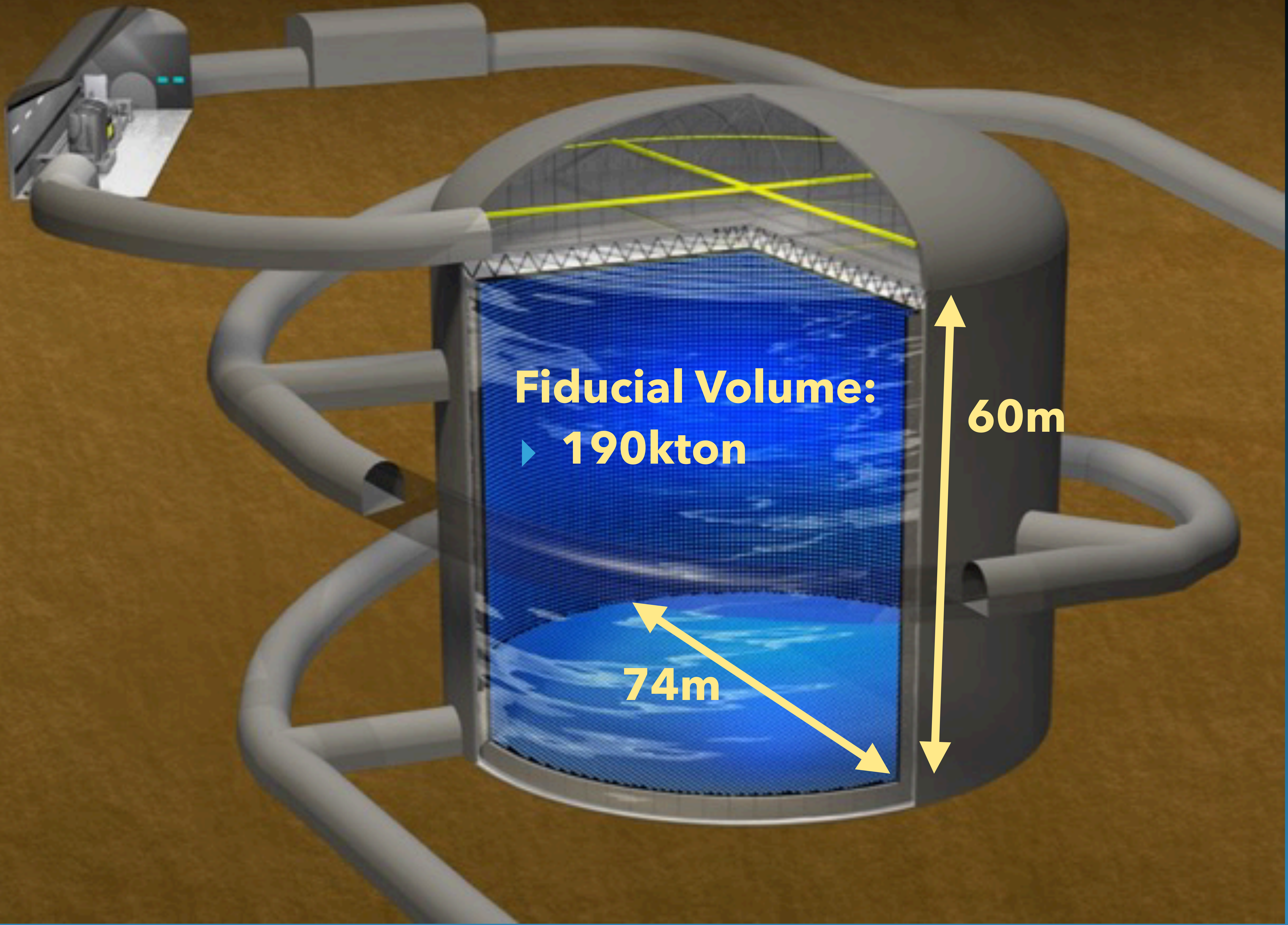


Measurement of magnetic field in the inner detector.

Works in the outer detector. The outer detector is about 2m wide..

All the water of the tank is drained

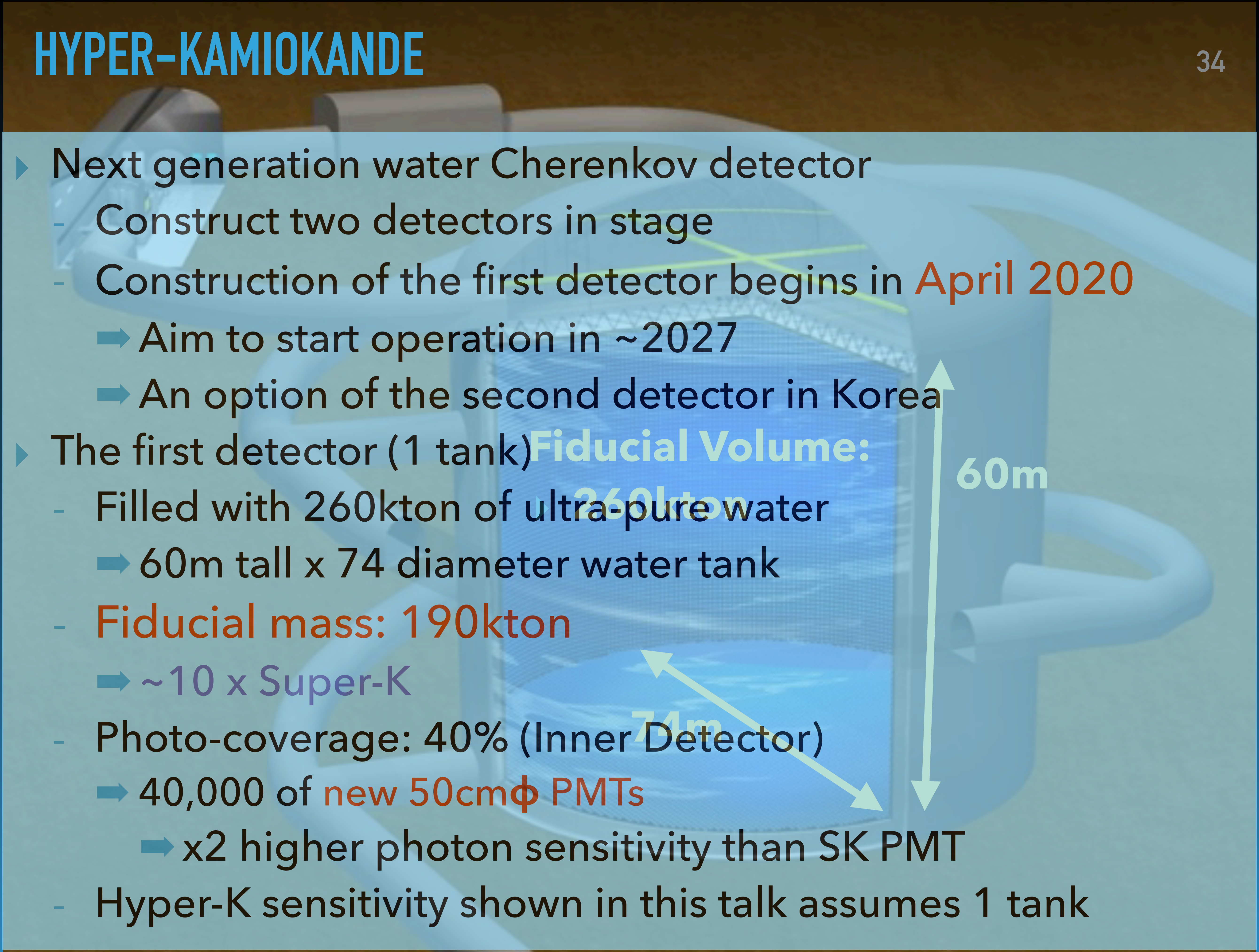
HYPER-KAMIOKANDE



Fiducial Volume:

- 190kton

HYPER-KAMIOKANDE

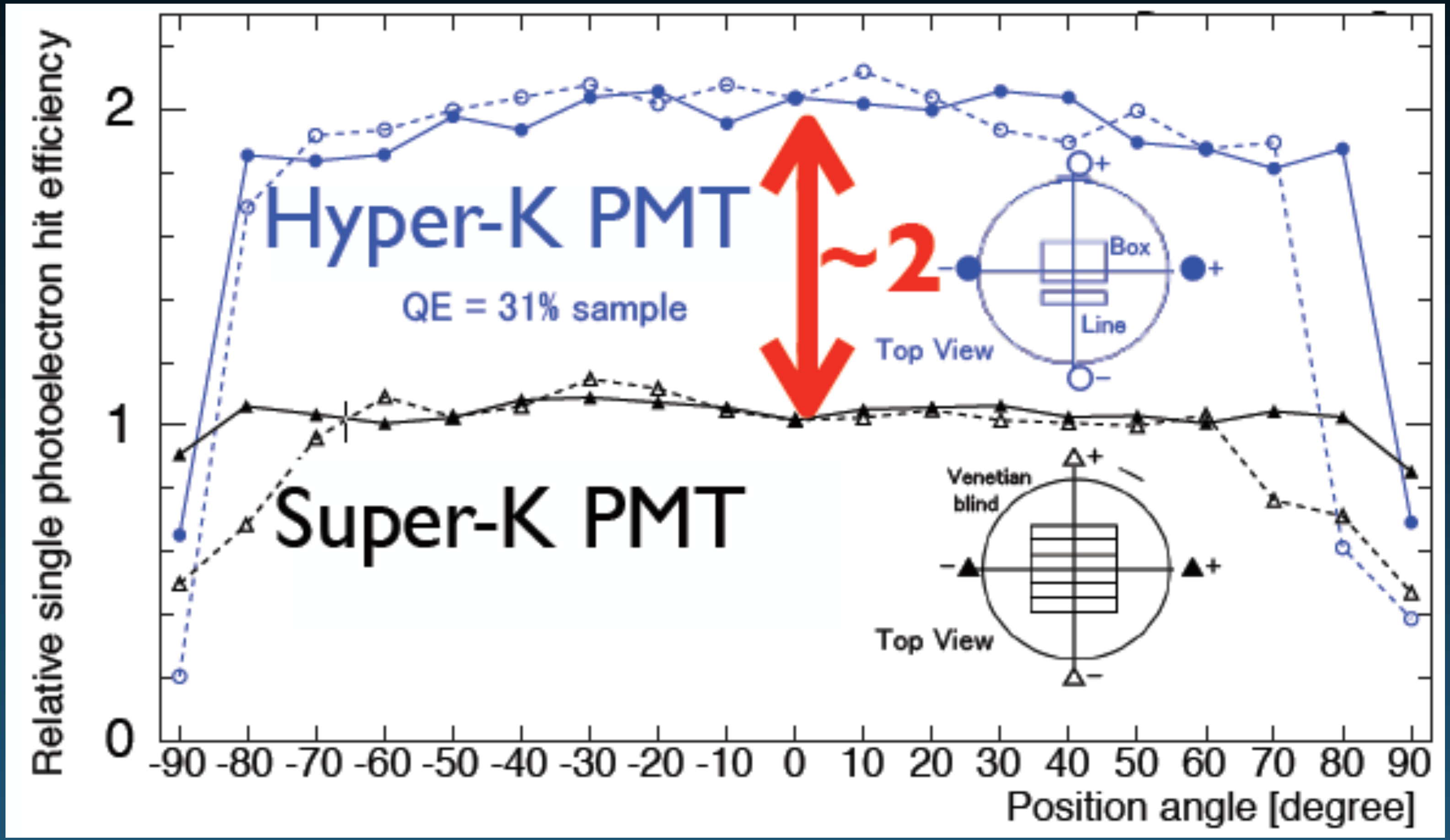


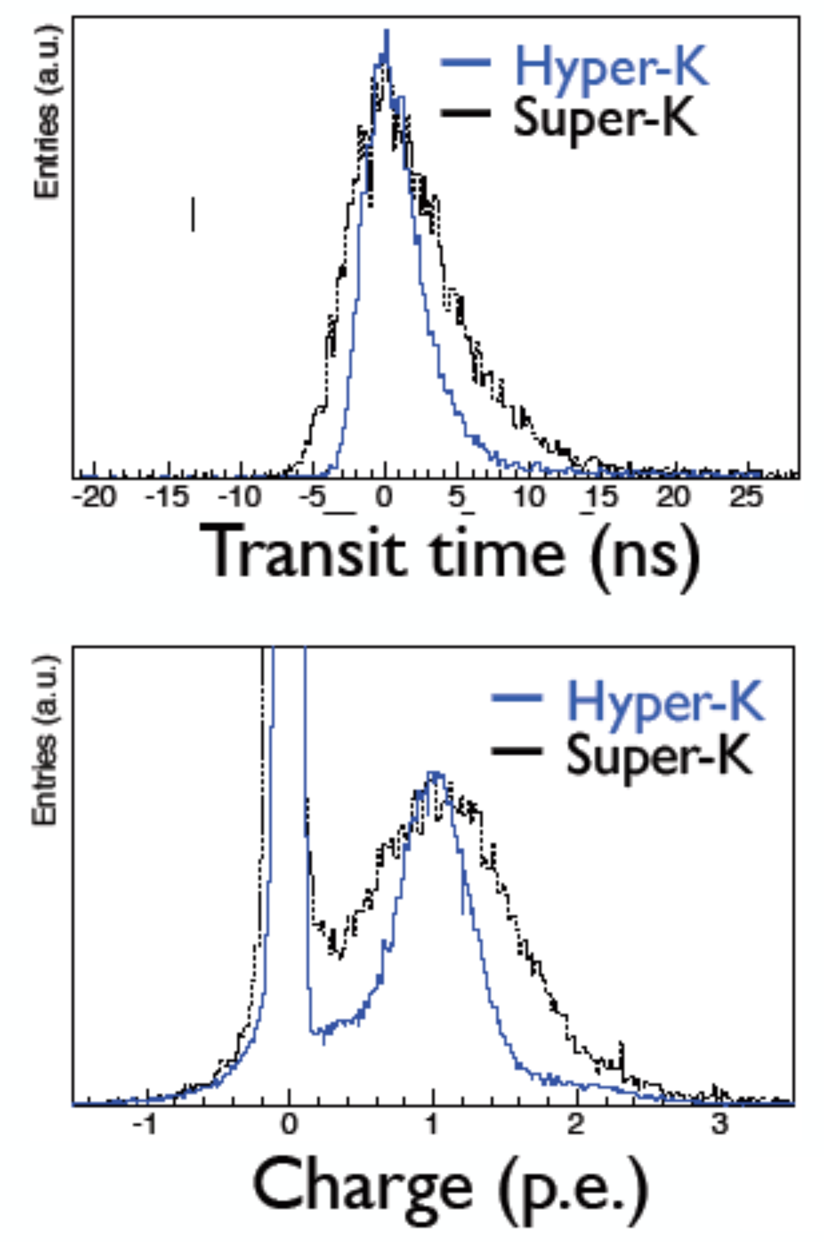
- Next generation water Cherenkov detector
  - Construct two detectors in stage
  - Construction of the first detector begins in April 2020
    - ➡ Aim to start operation in ~2027
    - ➡ An option of the second detector in Korea
- The first detector (1 tank)
  - Filled with 260kton of ultra-pure water
    - ➡ 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

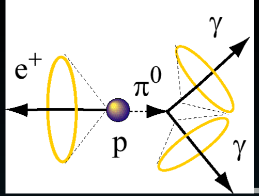
Box&Line dynode PMT

Photo-detection Efficiency (1P.E.)





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

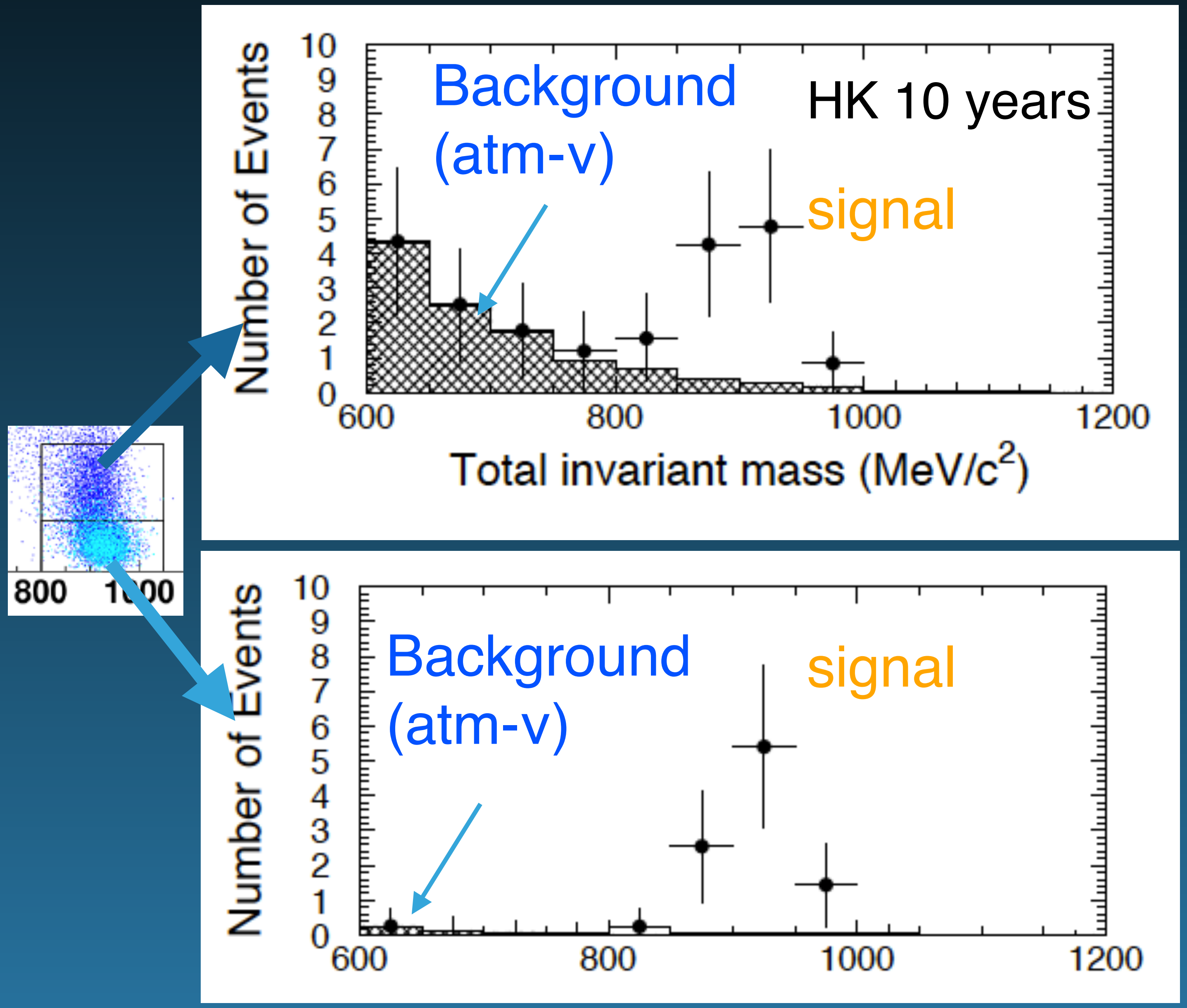


HYPER-K: P→$e^+\pi^0$

[arXiv:1805.04163]

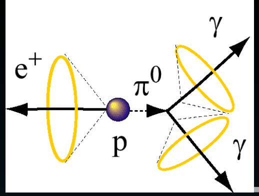
$e+$

Assume τ/Br=1.7x10^{34}y (SK 90%CL limit)

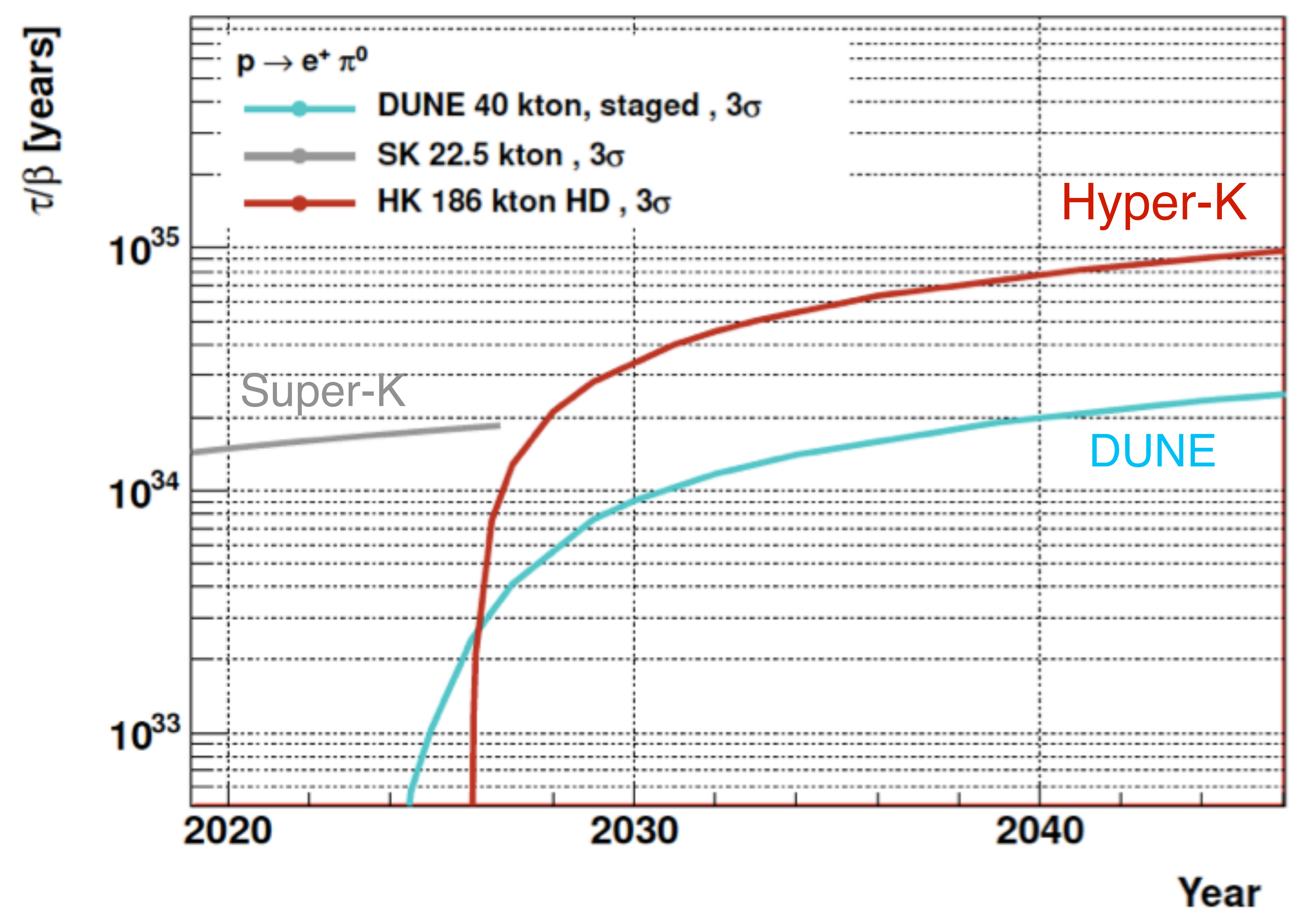


- “Background free” search thanks to the new photo-sensors (ex. n-tag eff: ~20% at SK → ~70% at HK) (0.06 bkg events / Mt·year)
- ~9σ discovery potential if nucleon lifetime at the current SK limit (τ/Br=1.7x10^{34}yrs)

	p_{tot}<100MeV/c		100<p_{tot}<250 MeV/c	
	Sig. ε(%)	Bkg (/ Mtyr)	Sig. ε(%)	Bkg (/ Mtyr)
HK	18.7	0.06	19.4	0.62

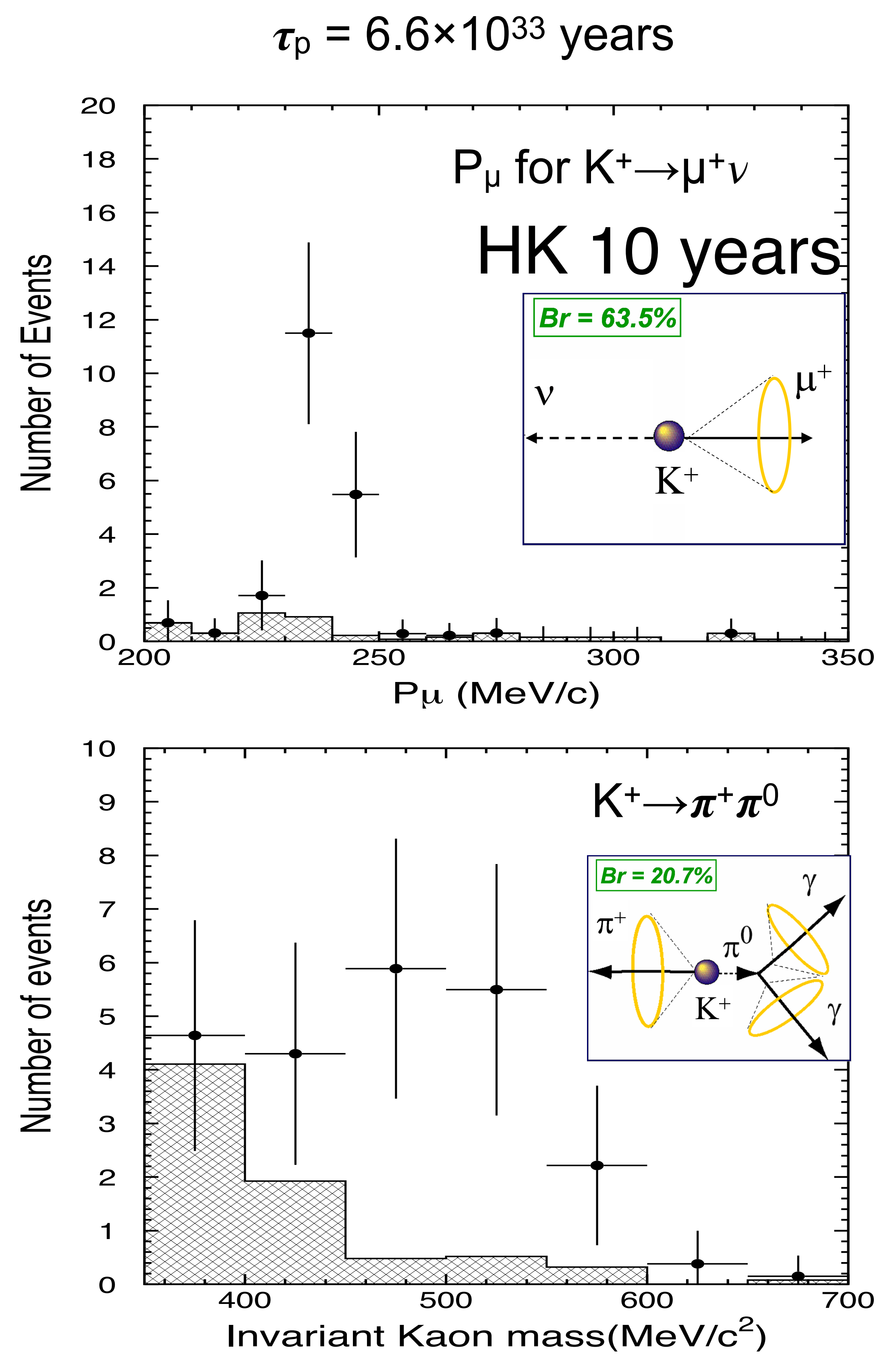


HYPER-K: P→$e^+\pi^0$



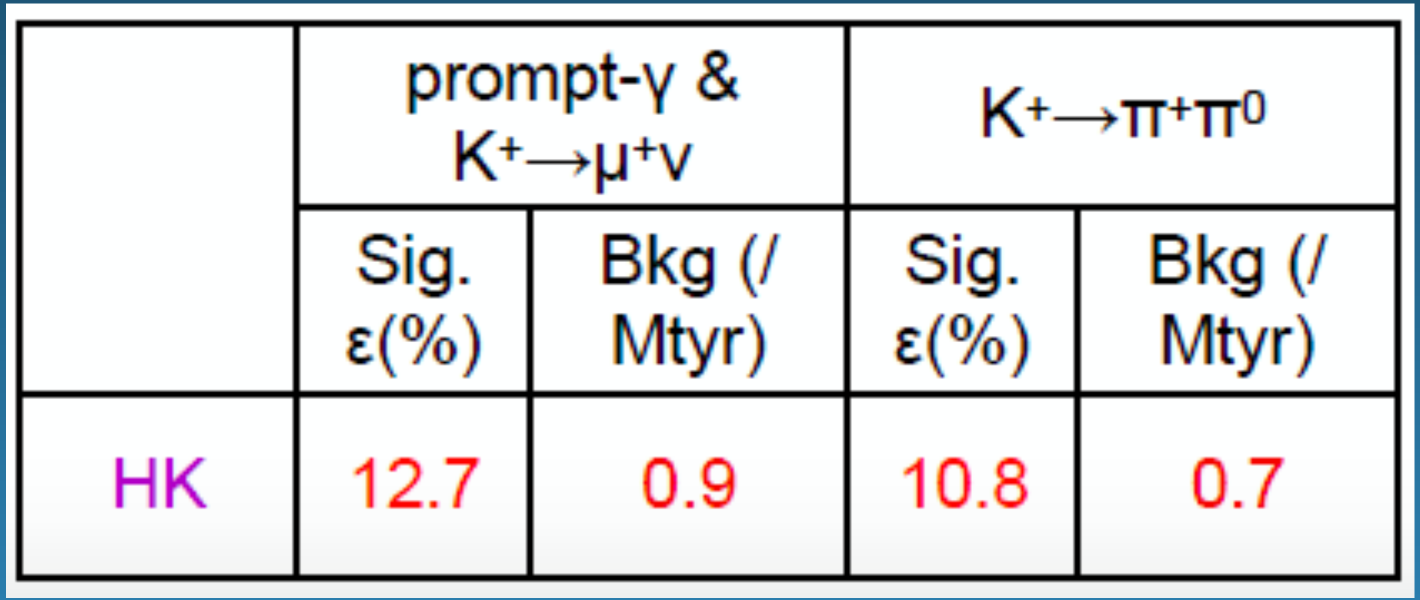
Hyper-K reaches to 10^{35} yrs with 3σ discovery sensitivity

HYPER-K: $P \rightarrow \bar{\nu} + K^+$



$\tau_p = 6.6\times10^{33}$ years

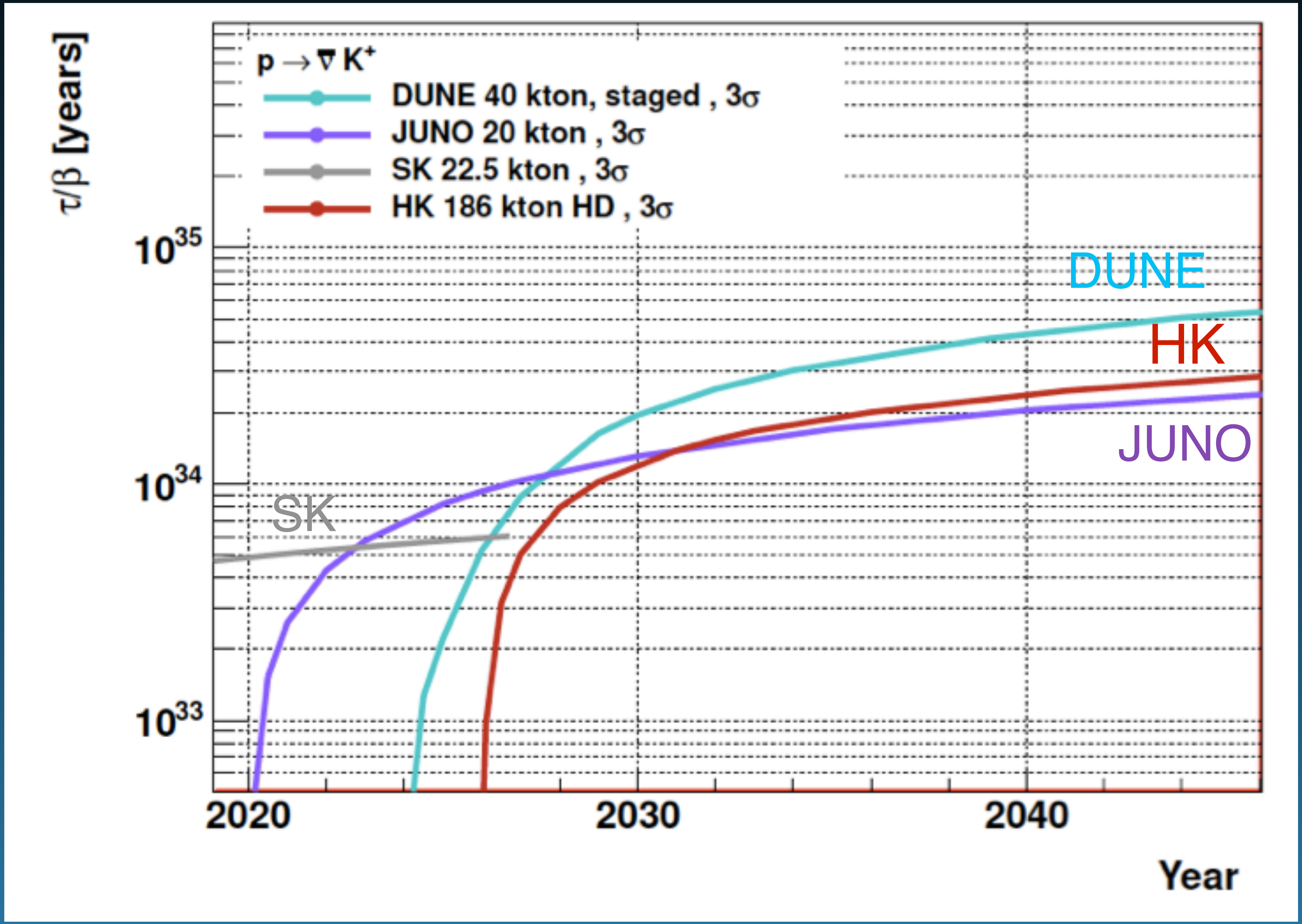
- $K^+ \rightarrow \mu^+ \nu$ (Br: 64%):
  - 236MeV/c μ^+
    - ➡ de-excitation γ from $^{15}O^*$ (6MeV γ)
- $K^+ \rightarrow \pi^+ \pi^0$ (Br: 21%):
  - 205MeV/c π^0 & π^+



	prompt-γ & $K^+ \rightarrow \mu^+\nu$		$K^+ \rightarrow \pi^+\pi^0$	
	Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
HK	12.7	0.9	10.8	0.7

HYPER-K: $P \rightarrow \bar{\nu} + K^+$

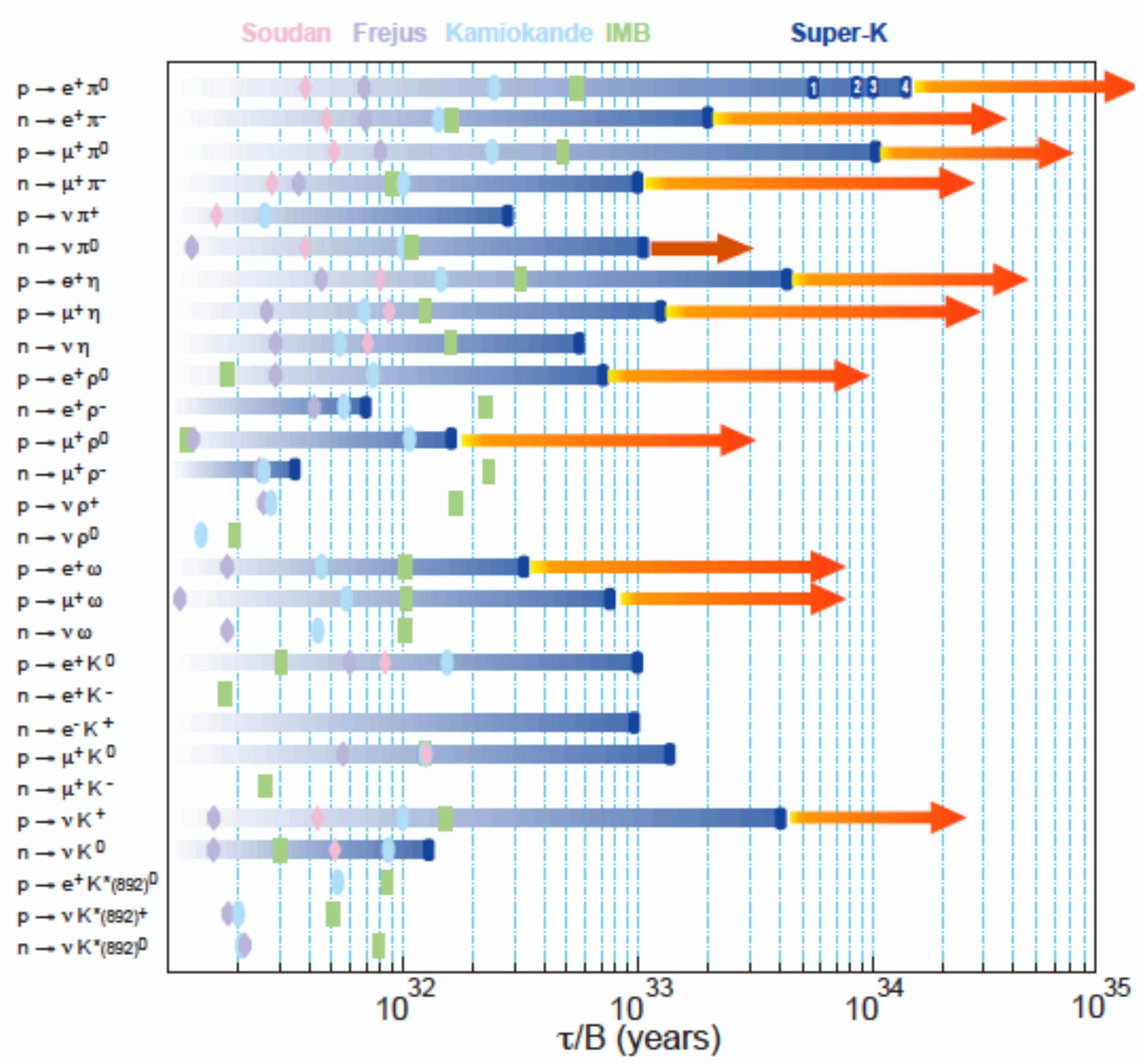
3σ discovery sensitivity

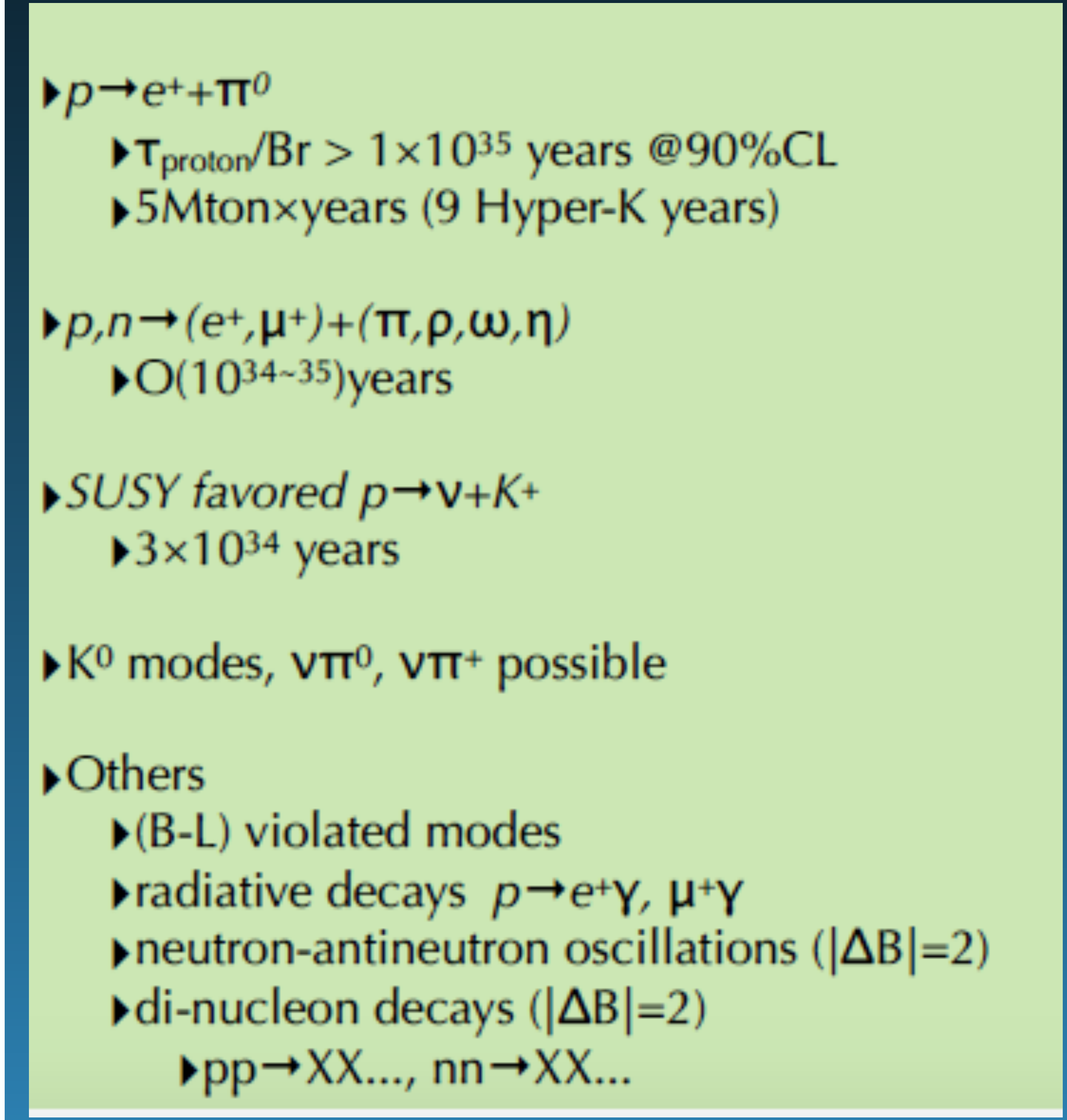


- HK 3σ discovery potential reaches 3x10^{34} years

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**

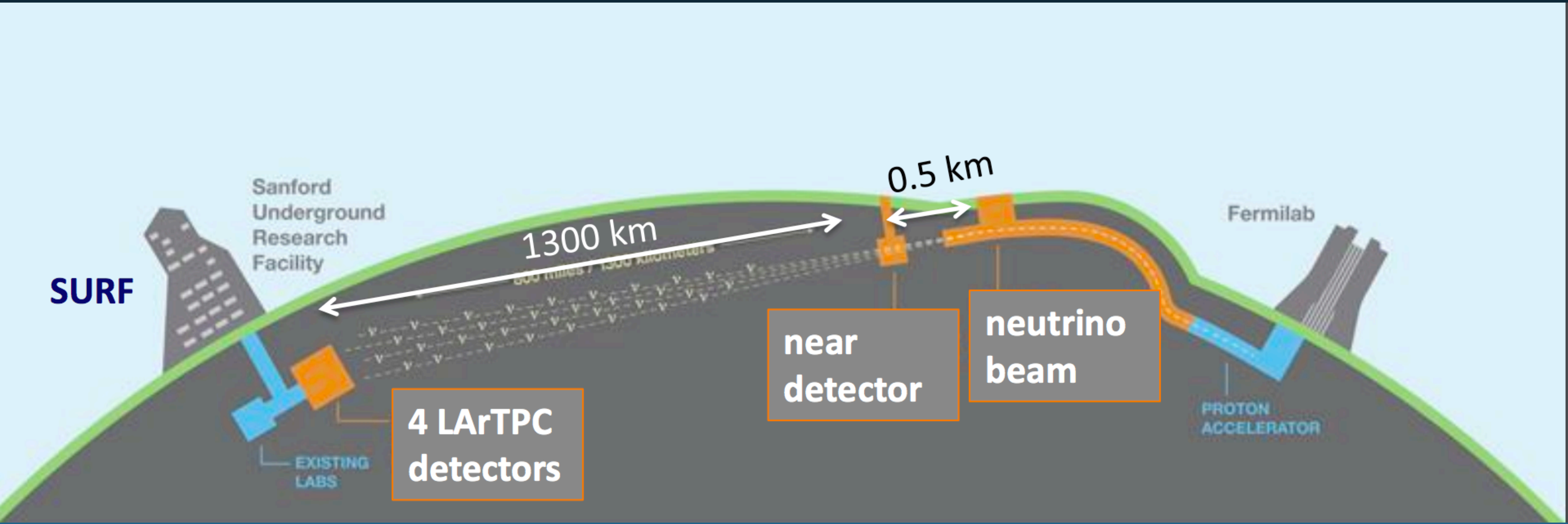




- $p \rightarrow e^+ + \pi^0$
  - $\tau_{proton}/Br > 1\times10^{35}$ years @90%CL
  - 5Mton×years (9 Hyper-K years)
- $p,n \rightarrow (e^+,\mu^+) + (\pi,\rho,\omega,\eta)$
  - $O(10^{34\sim35})$years
- SUSY favored $p \rightarrow \nu + K^+$
  - 3×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- 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→XX..., nn→XX...

DUNE

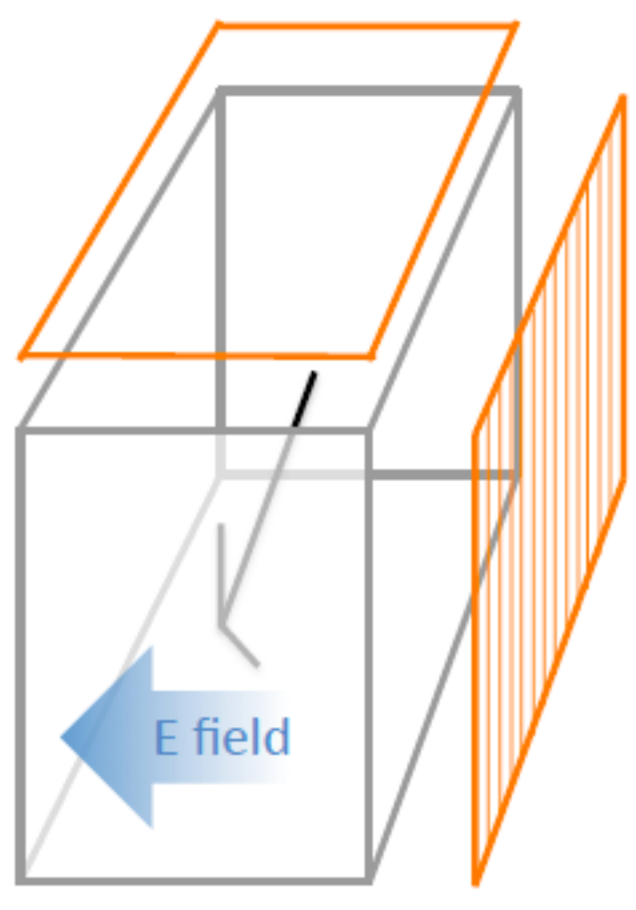
- DUNE will employ a large-mass liquid argon time projection chamber (LArTPC) detector, deep underground in a low cosmogenic background environment

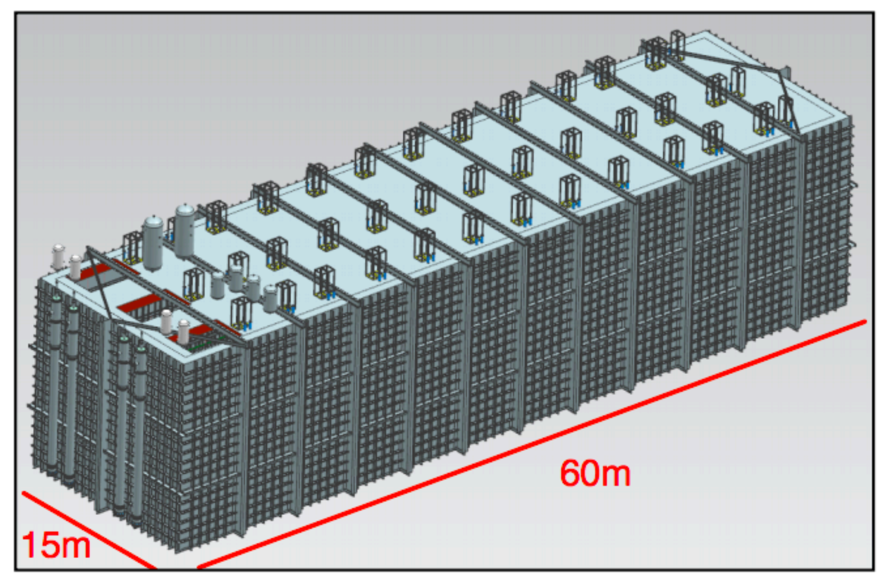


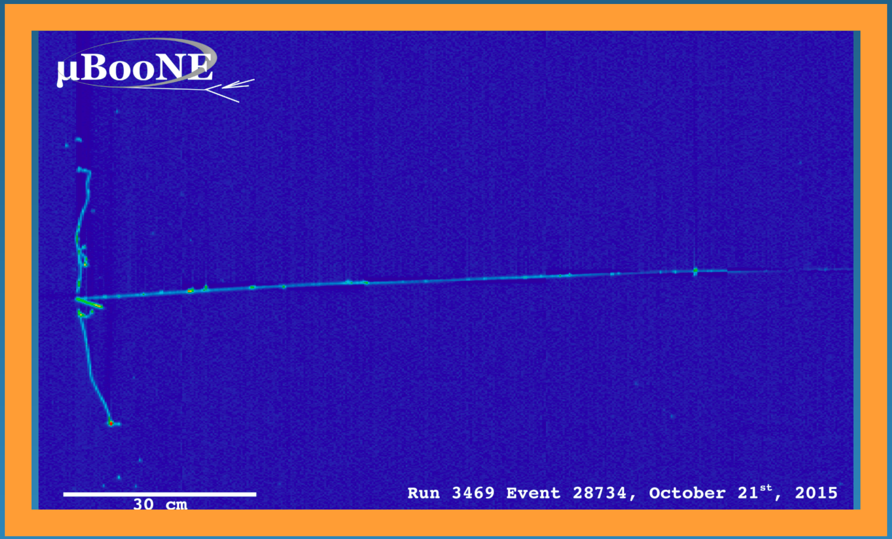
- Each LArTPC sub-detector: 10kton fiducial mass; 4850ft (1.5km) underground. Staged detector construction: first sub-detector operational in 2024; subsequent ones 1/year.

DUNE: AN IONIIZATION 3D IMAGING DEVICE

- Example for DUNE “single-phase” design: Each 10kton sub-detector consists of 300 LArTPC “cells”:



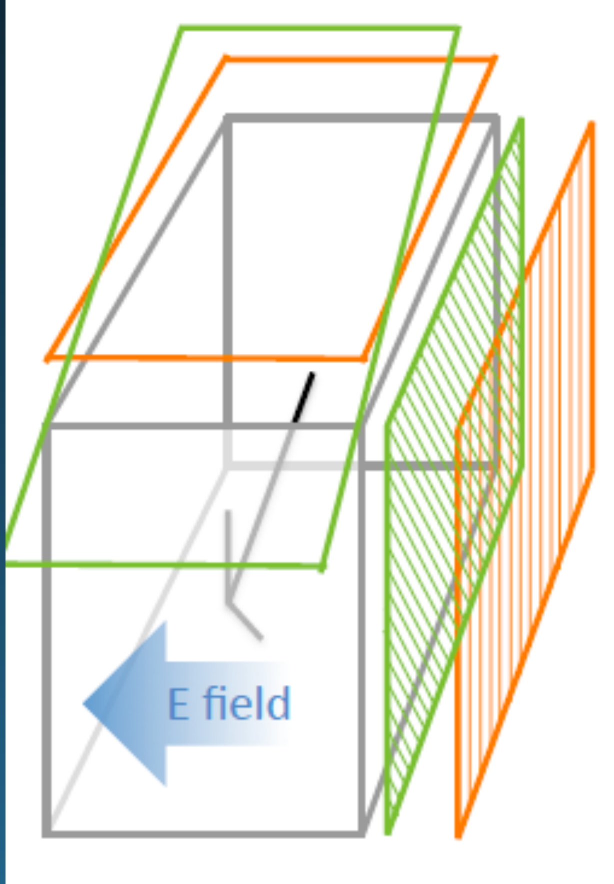


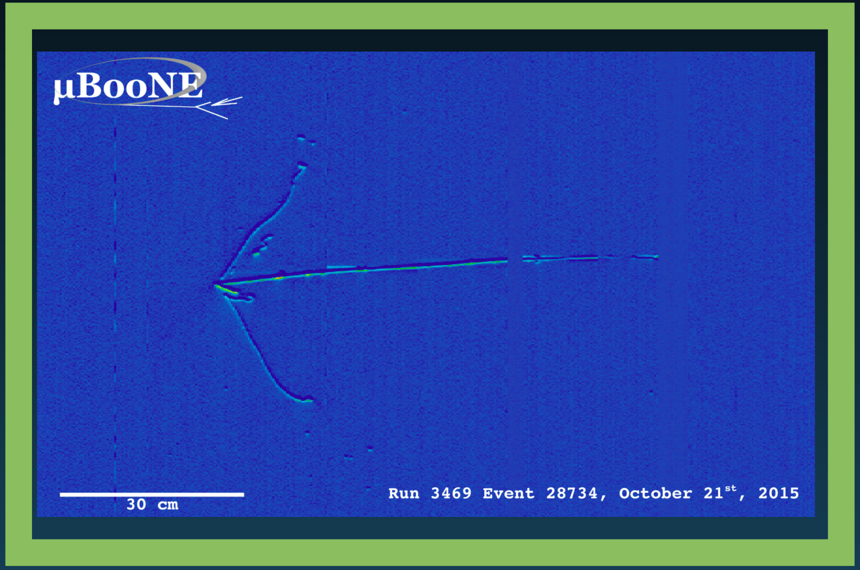


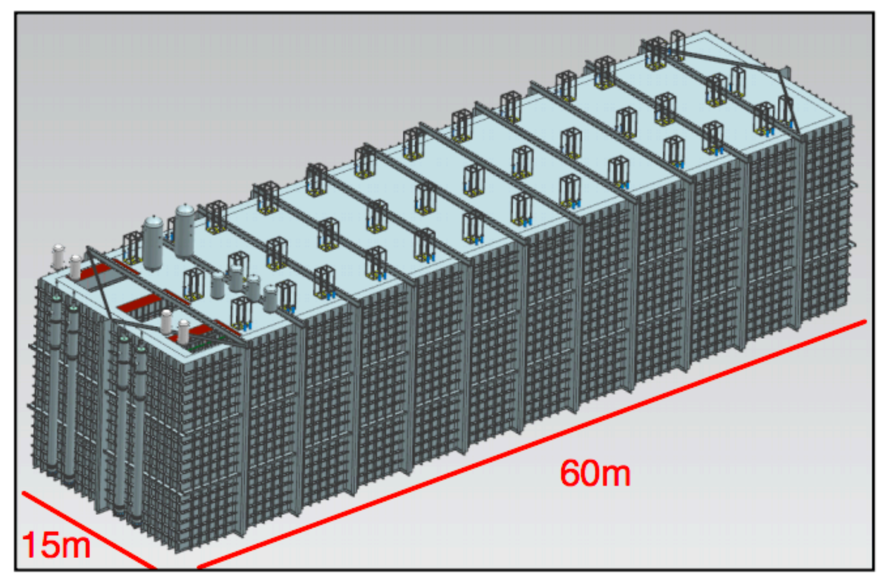
- Local ionization dE/dx recorded with sub-mm spatial resolution; can resolve minimum-ionizing particles (MIPs) to few overlapping protons based on local ionization energy deposition.

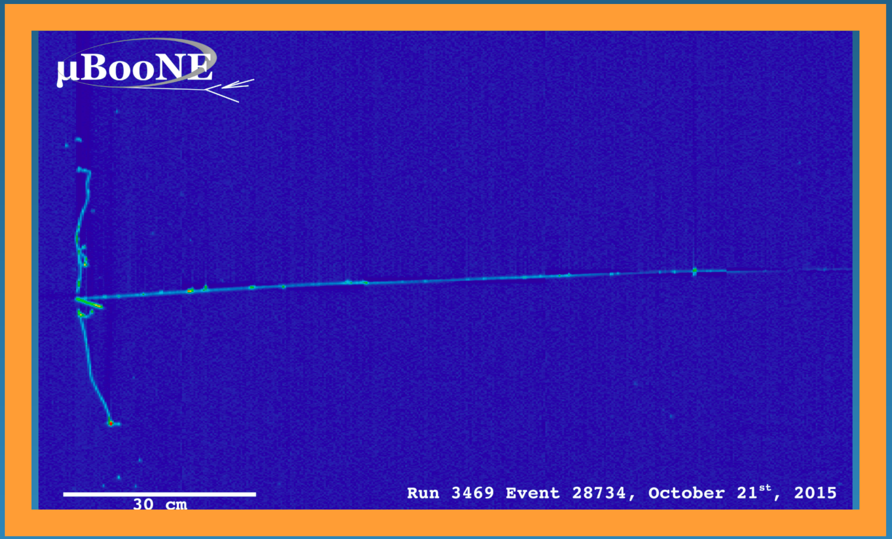
DUNE: AN IONIIZATION 3D IMAGING DEVICE

- Example for DUNE "single-phase" design: Each 10kton sub-detector consists of 300 LArTPC "cells":





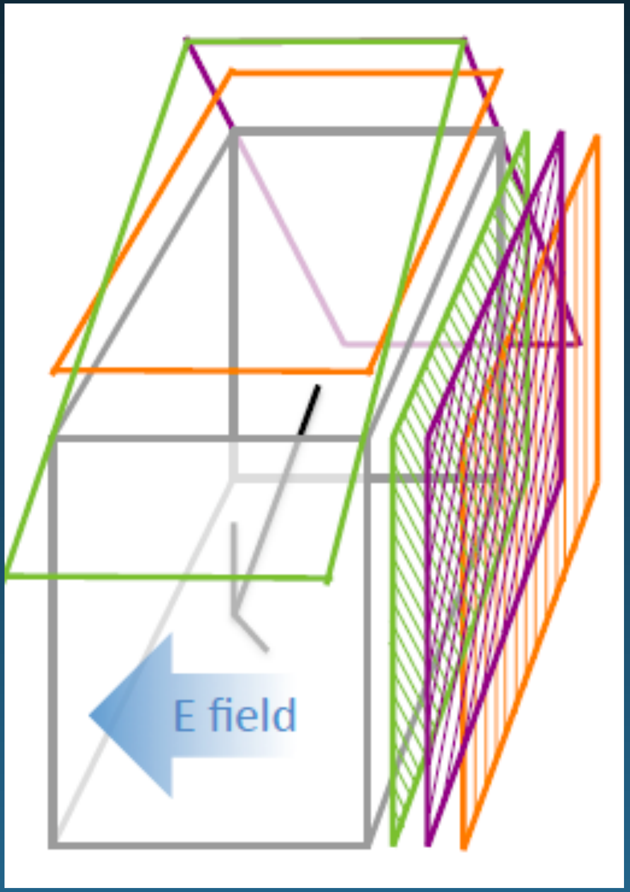


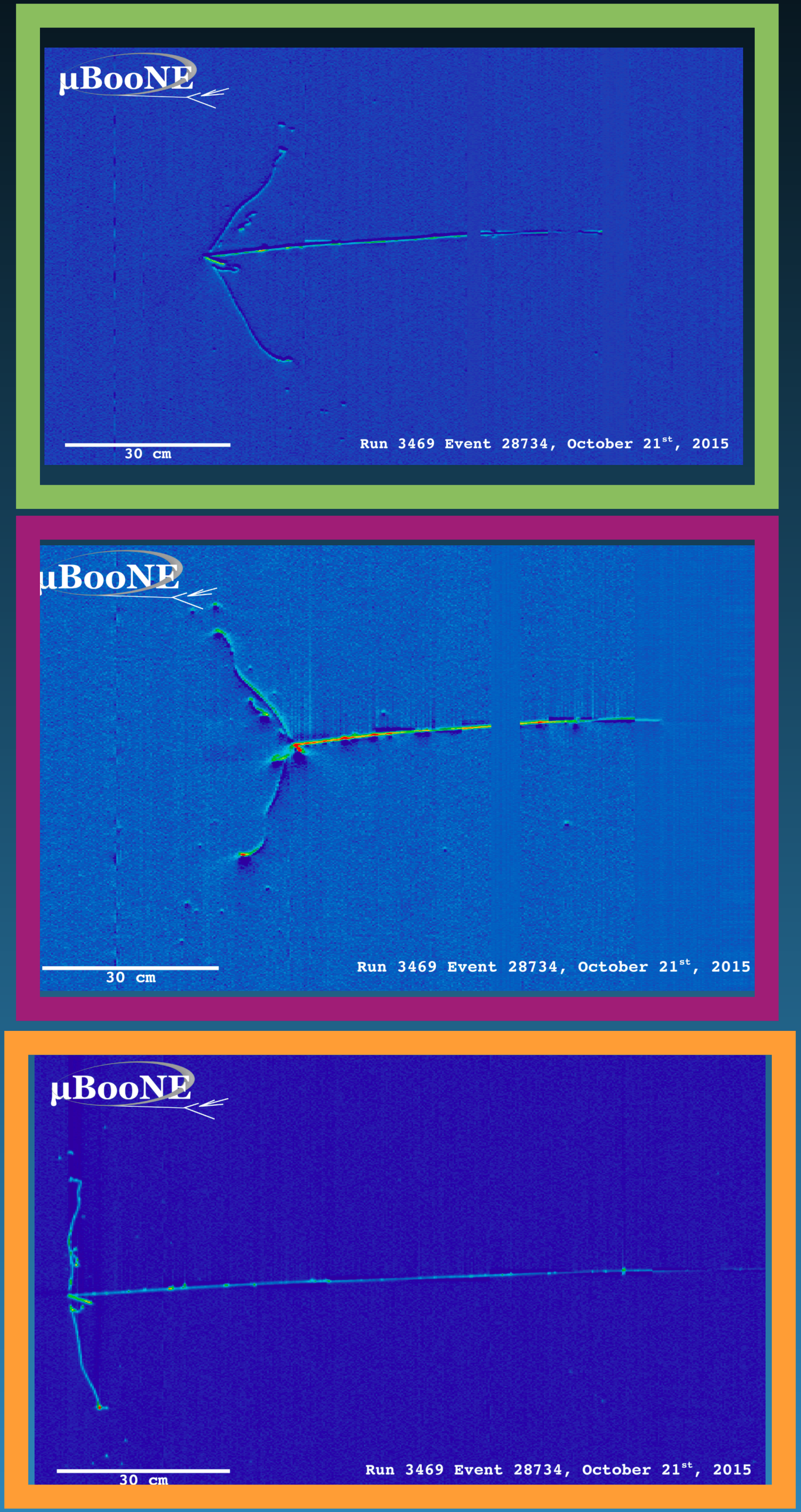


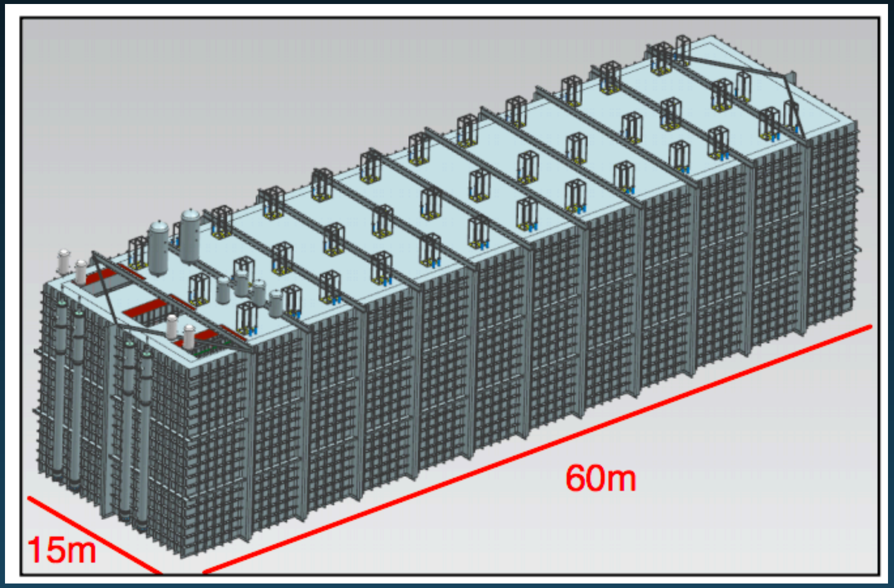
- Local ionization dE/dx recorded with sub-mm spatial resolution; can resolve minimum-ionizing particles (MIPs) to few overlapping protons based on local ionization energy deposition.

DUNE: AN IONIIZATION 3D IMAGING DEVICE

- Example for DUNE “single-phase” design: Each 10kton sub-detector consists of 300 LArTPC “cells”:





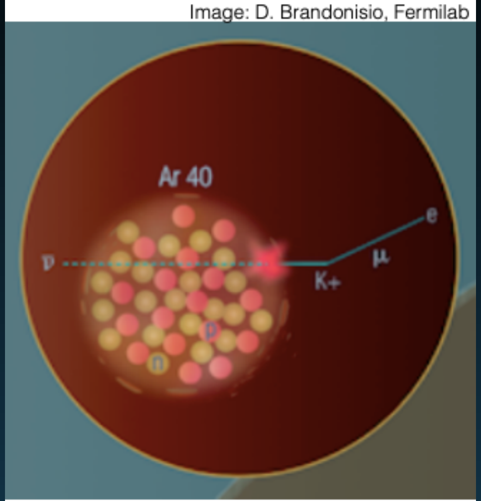


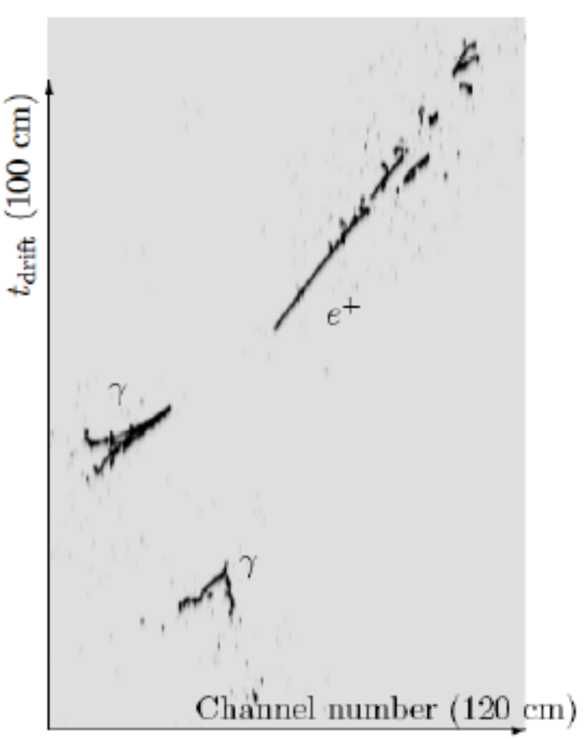
- Local ionization dE/dx recorded with sub-mm spatial resolution; can resolve minimum-ionizing particles (MIPs) to few overlapping protons based on local ionization energy deposition.

LARGE LIQUID ARGON TPC DETECTOR

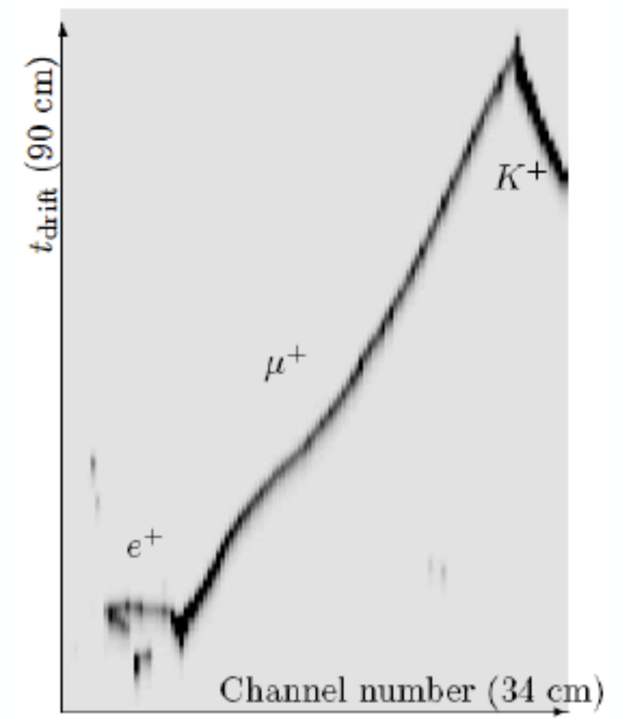
[JHEP0704(2007)041; arXiv:1512.06148]

Image: D. Brandonisio, Fermilab

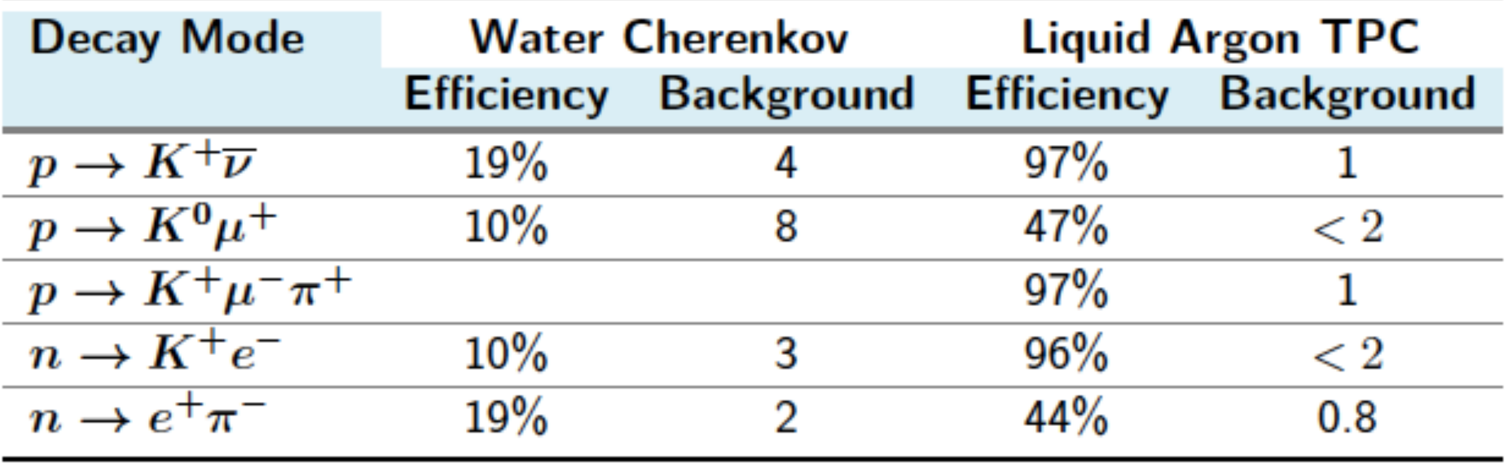




$p \rightarrow e^+ + \pi^0$
- efficiency = 45%, 1BG/Mtyr



$p \rightarrow \nu + K^+$
- efficiency = 97%, 1BG/Mtyr

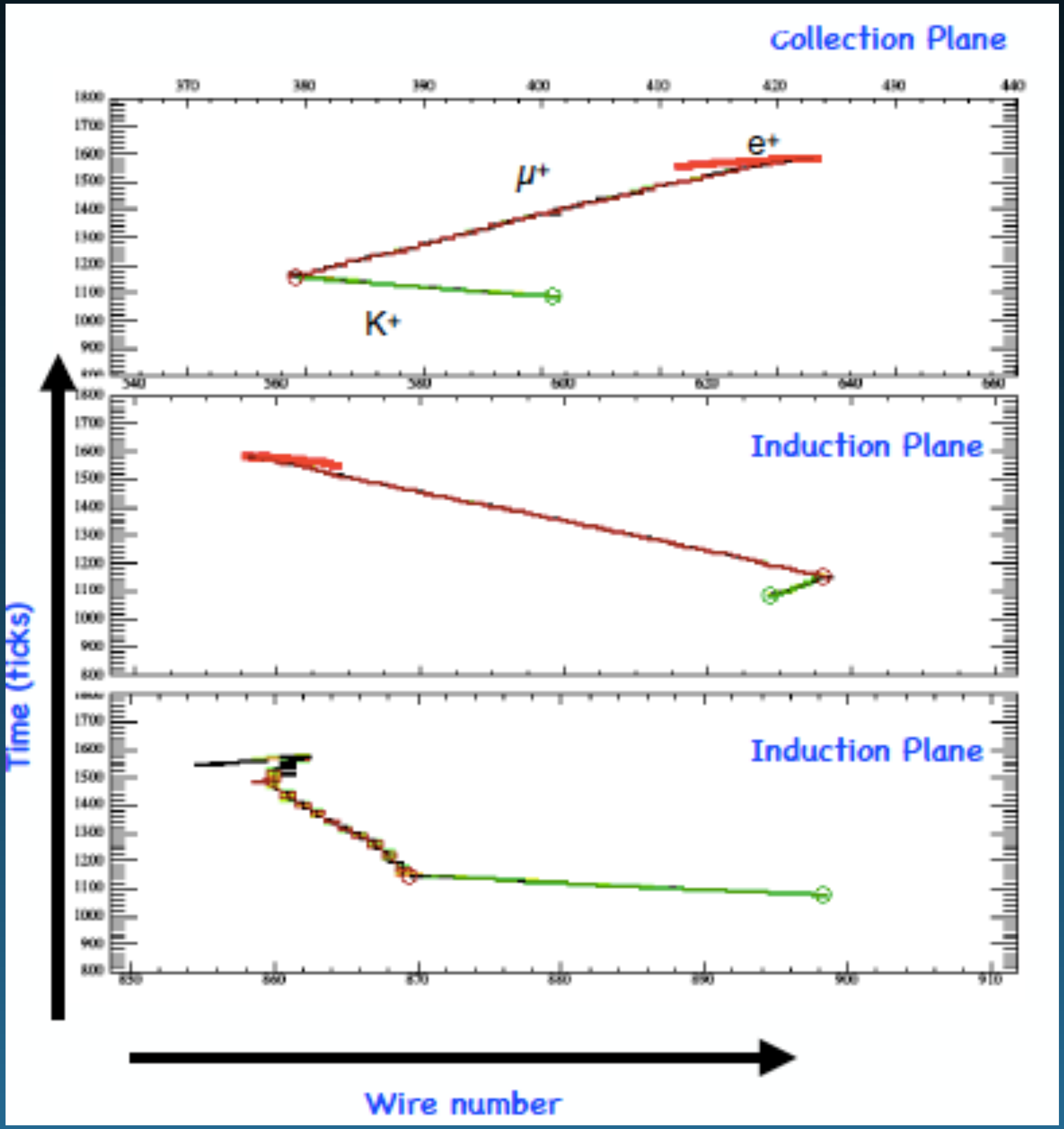


Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+ \overline{\nu}$	19%	4	97%	1
$p \to K^0 \mu^+$	10%	8	47%	< 2
$p \to K^+ \mu^- \pi^+$			97%	1
$n \to K^+ e^-$	10%	3	96%	< 2
$n \to e^+ \pi^-$	19%	2	44%	0.8

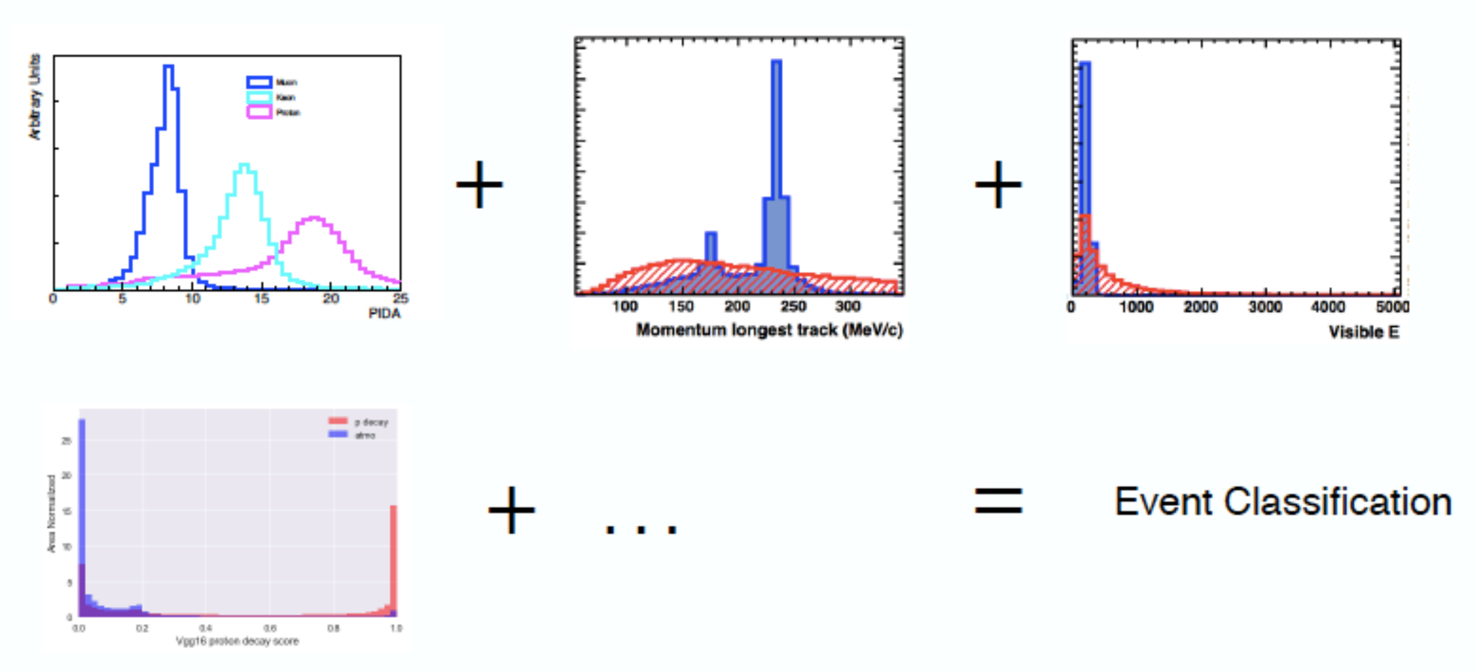
- K^+ track by higher ionization density with high efficiency.
- Single-event discovery could be possible.
- Clean search for neutron-antineutron oscillation (ΔB=2) and other modes for which significant BG for water Cherenkov detectors
- Simulation and automatic reconstruction under development

NUCLEON DECAY SIGNATURES IN DUNE

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

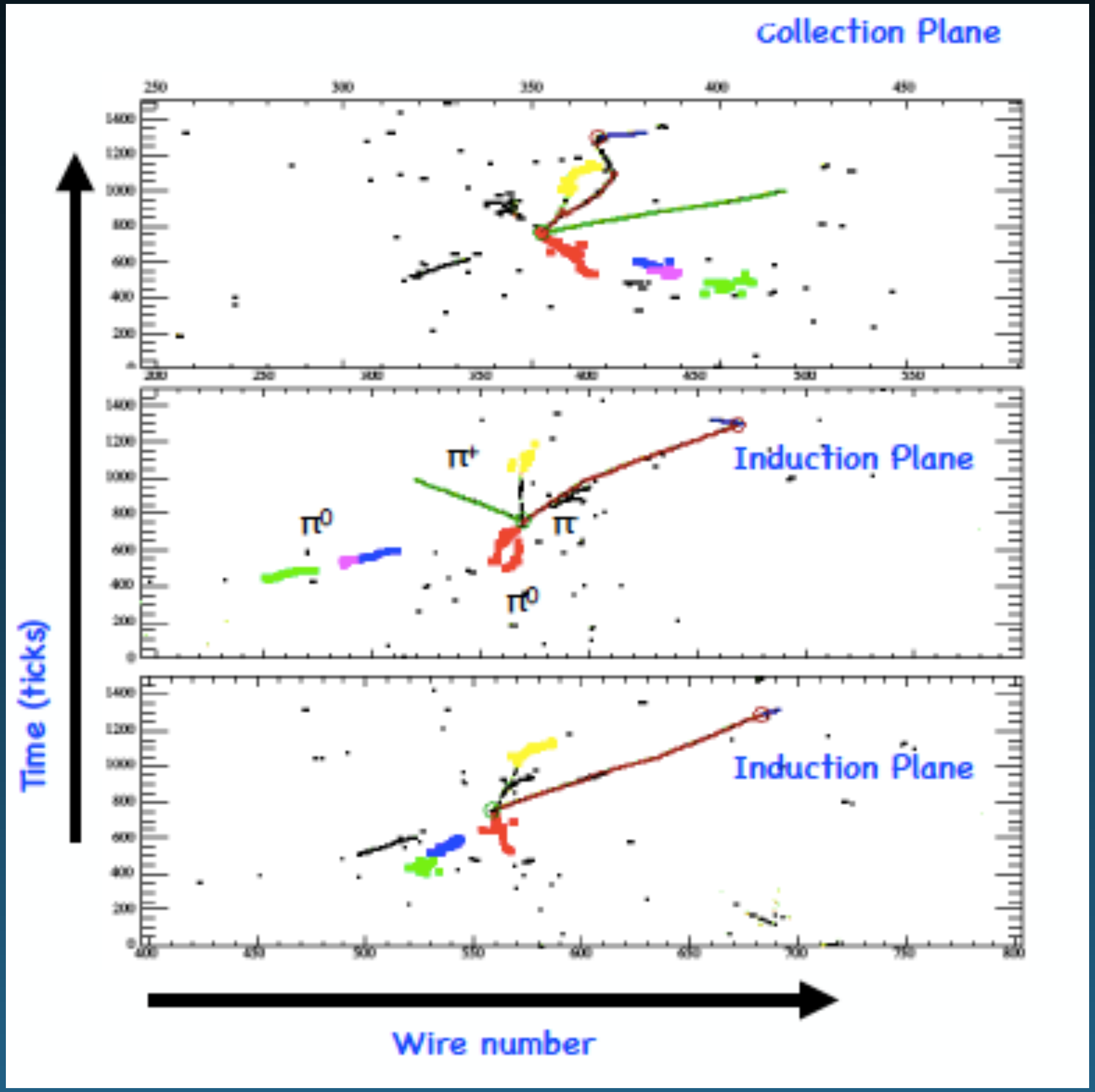


- Particle ID via dE/dx
- Multi-variable Analysis (Boosted Decision Tree) for nucleon decay signatures

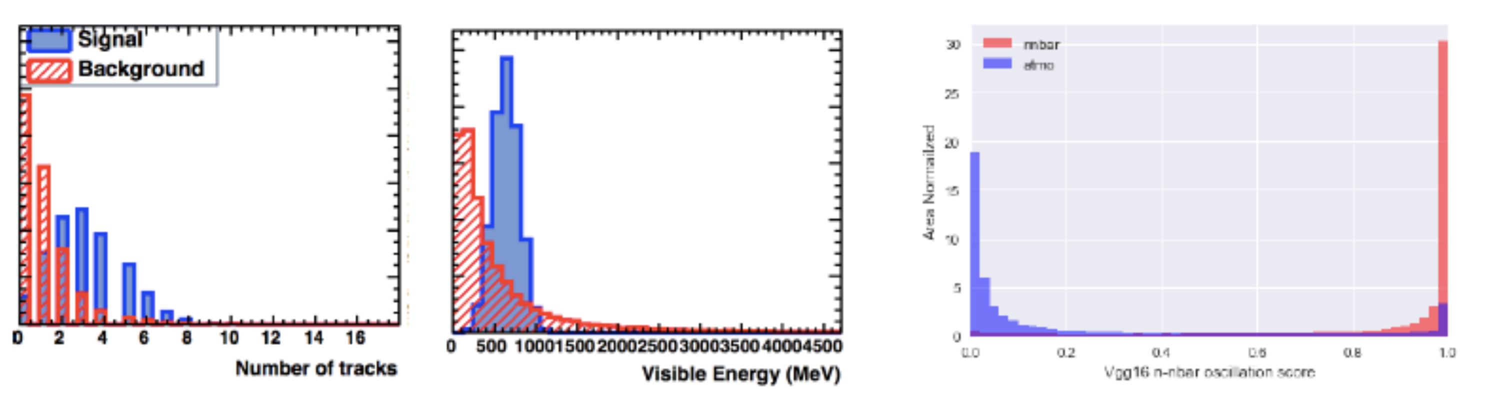


A. Higuera, CoS SURF 2019

N-$\bar{N}$ SIGNATURES IN DUNE



- Image Classification
- Standard reconstruction
  - track & vertex multiplicity
  - PID
  - visible energy …
- Multi-variable Analysis (Boosted Decision Tree)



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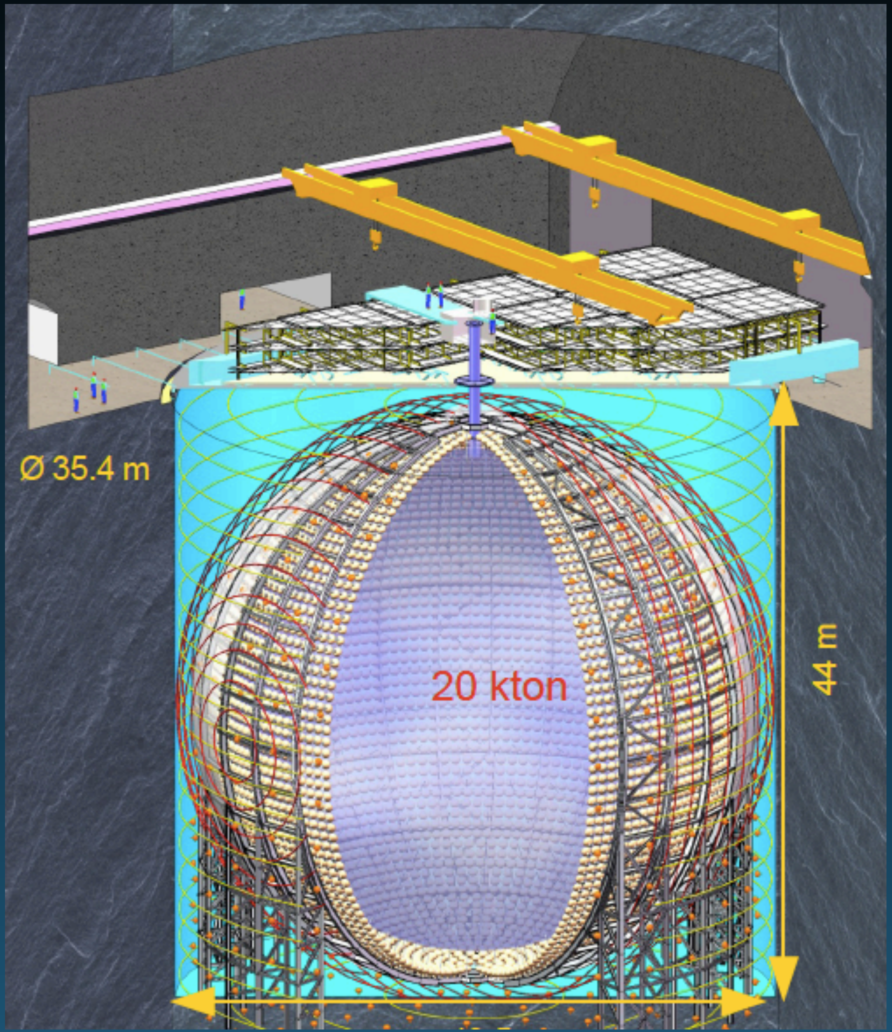
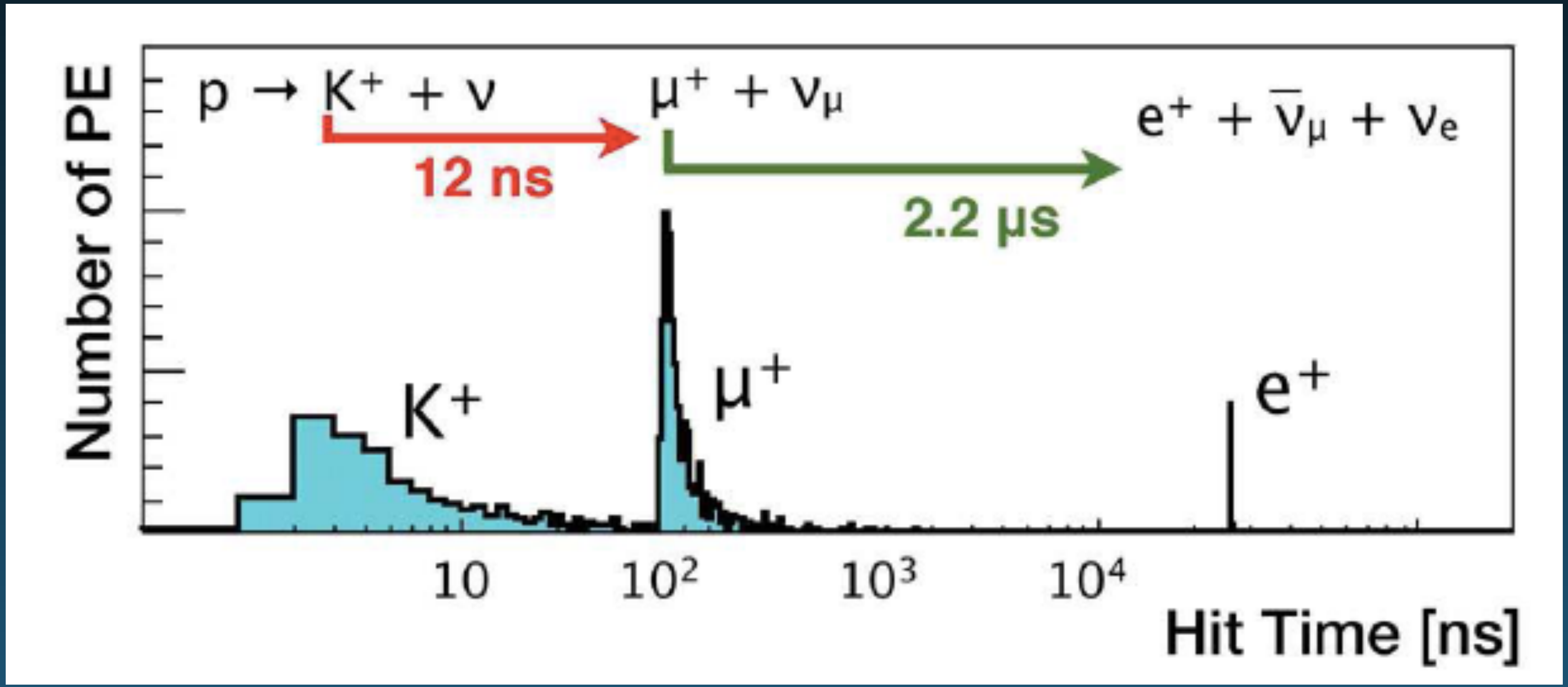
$P \to \bar{\nu} + K^+$ IN JUNO

[arXiv:1507.05613]



- 20 kiloton liquid scintillator
- Starting data taking in 2021



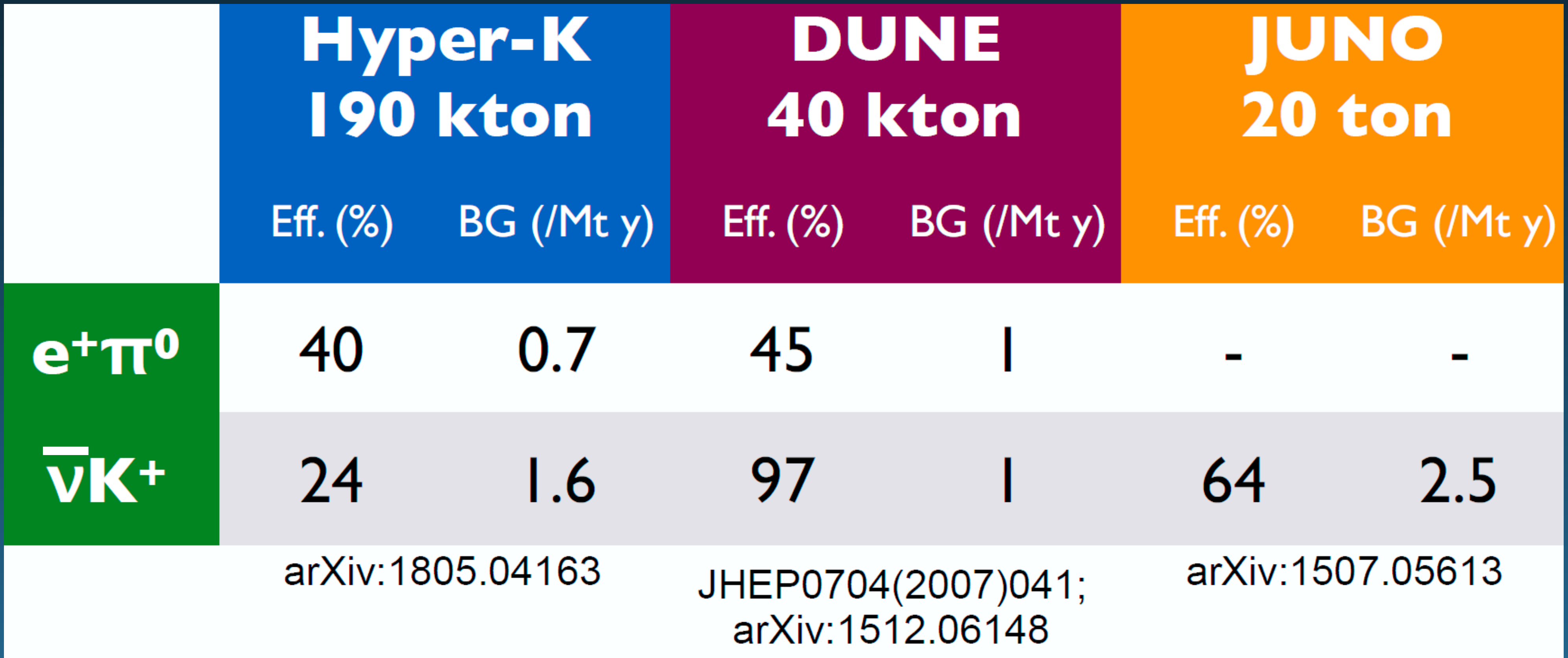
- Triple coincidence of $K^+ \to \mu^+ \to e^+$ with well-defined time constant of (12nsec, 2.2μsec) and particle energies
- Signal efficiency = 64% (pulse shape cut+energy cut+decay positron cut)
- Estimated backgrounds = 0.5 evt./ 10 years
- $\tau/\mathrm{Br}(p \to \bar{\nu} K^+) = 1.9 \times 10^{34}$ years assuming zero candidates

SUMMARY

We are in an exciting era because large neutrino detectors (JUNO, DUNE, Hyper-K) are planned to start operation near future. They are also good proton decay detectors!

2

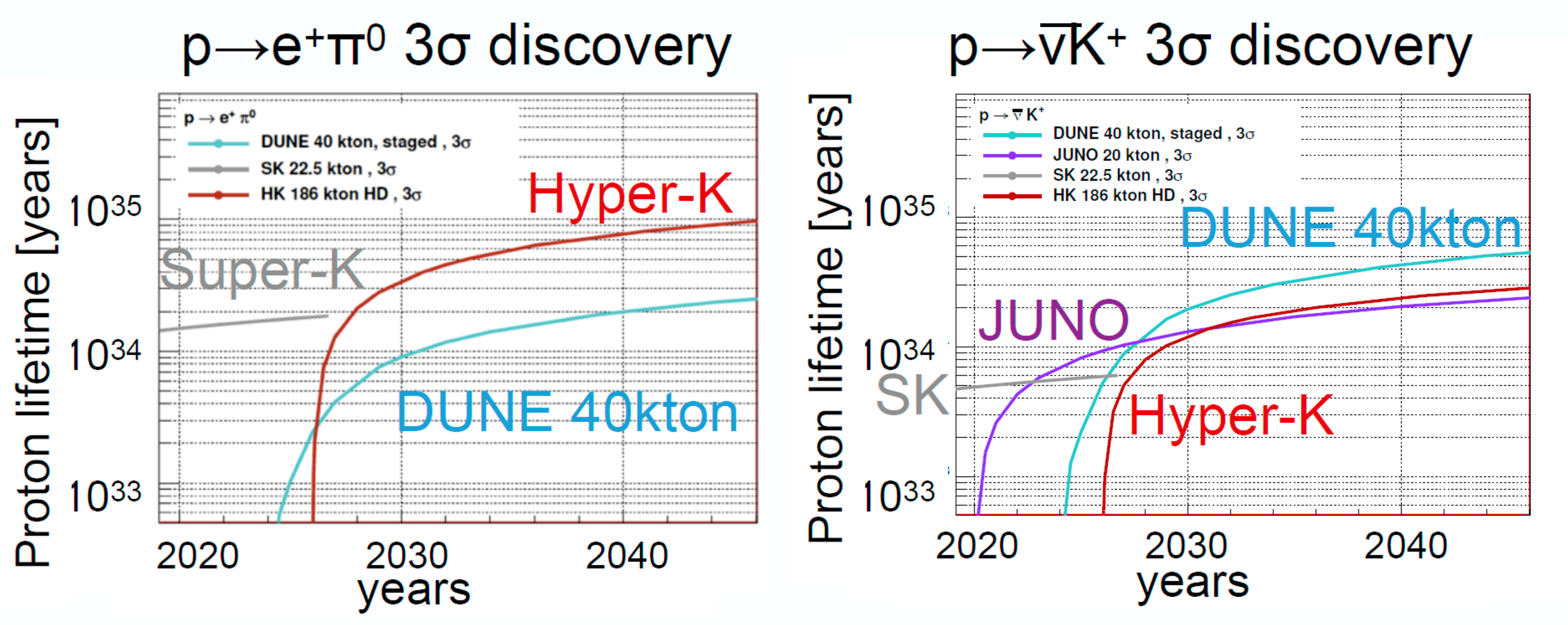
SENSITIVITIES OF FUTURE EXPERIMENTS



	Hyper-K 190 kton		**DUNE 40 kton**		**JUNO 20 ton**	
	Eff. (%)	BG (/Mt y)	Eff. (%)	BG (/Mt y)	Eff. (%)	BG (/Mt y)
$e^+\pi^0$	40	0.7	45	1	-	-
$\bar{\nu}K^+$	24	1.6	97	1	64	2.5
	arXiv:1805.04163		JHEP0704(2007)041; arXiv:1512.06148		arXiv:1507.05613	

- For modes with Kaons, DUNE and JUNO can benefit from K identification and expected to have better S/N than water.
- For modes of "charged lepton plus mesons" like p→$e^+\pi^0$, Hyper-K sensitivities are better by high mass.

PROTON LIFETIME SENSITIVITIES



(Lines for DUNE and JUNO experiment have been generated based on numbers in the literature.)

3σ discovery potential will reach:

- 1×10^{35} years for $p \rightarrow e^{+}\pi^{0}$
- 5×10^{34} years for $p \rightarrow \bar{\nu} K^{+}$