Proton decay and nnbar oscillations with SK(-Gd), DUNE, Hyper-K, and JUNO

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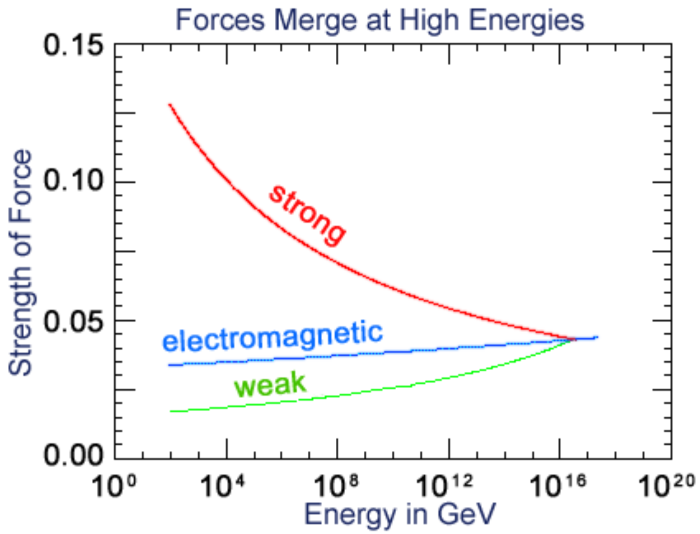
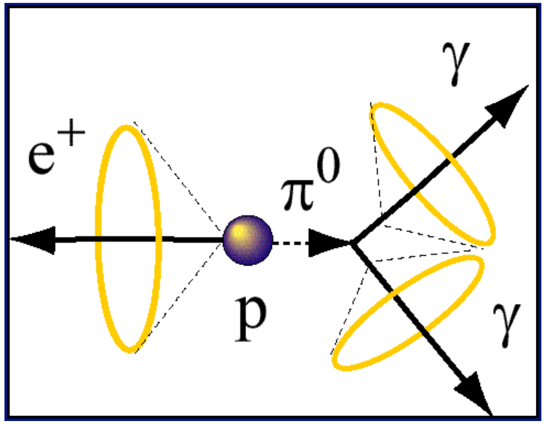
European Neutrino Town meeting @ CERN
22-24 October 2018

Motivation

- Proton decay observation would prove the Grand Unification of elementally particles.



- Neutrino mass/mixings/CPV and proton decays could be related to each other at very high energy physics (GUTs).

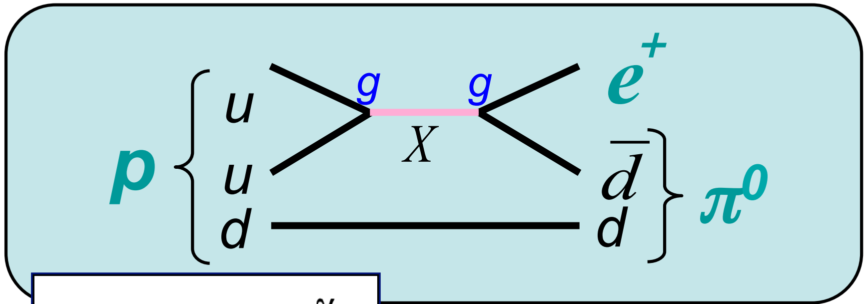


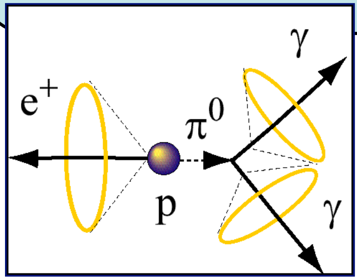
We are in an exciting era because large neutrino detectors (JUNO, DUNE, Hyper-K) are planned to start operation near future. They are also good proton decay detectors!

Various proton decay modes

- Two prominent decay modes

Mediated by gauge bosons

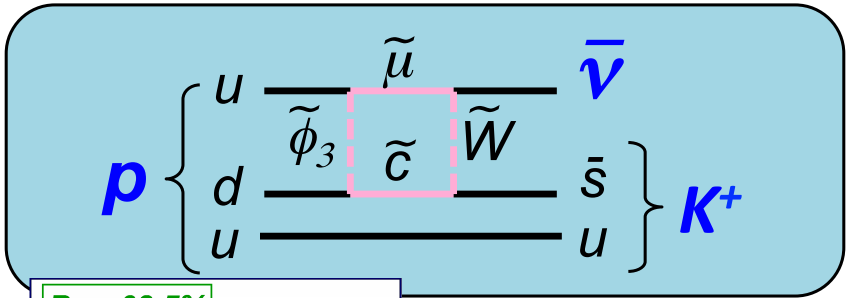


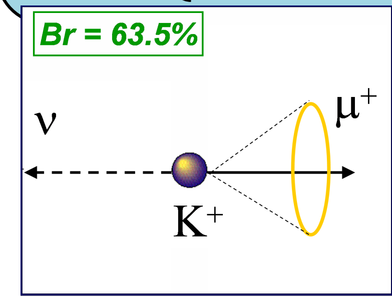


$p \rightarrow e^+\pi^0$

$$\Gamma(p \rightarrow e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY mediated





$p \rightarrow \nu K^+$

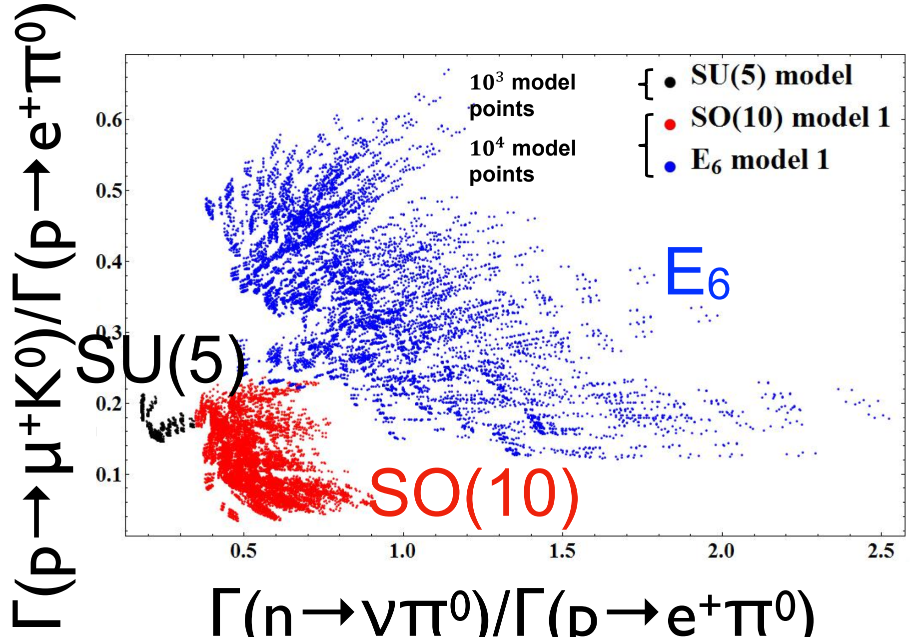
$$\Gamma(p \rightarrow \bar{\nu} K^+) \sim \frac{\tan^2 \beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

- Variety of predictions and no SUSY in LHC

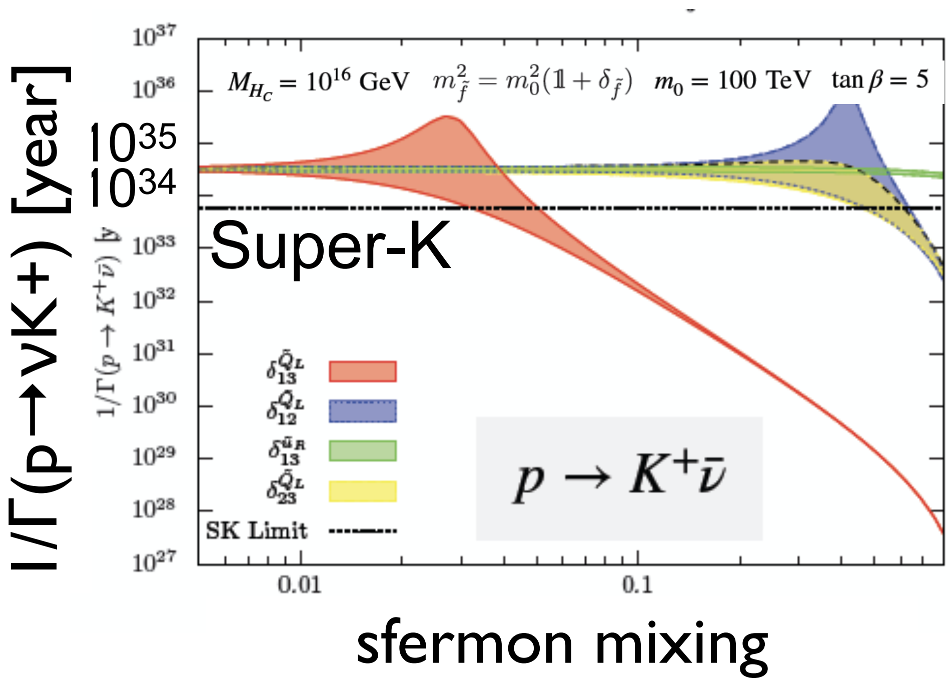
→ We need to experimentally pursue both and other decay modes

Strong cases

- We could identify details of unification picture, e.g. gauge group and other symmetries
  - $\Gamma(n \to \nu\pi^0)/\Gamma(p \to e^+\pi^0)$ depends on SU(5), SO(10), E_6 (Y. Muramatsu)

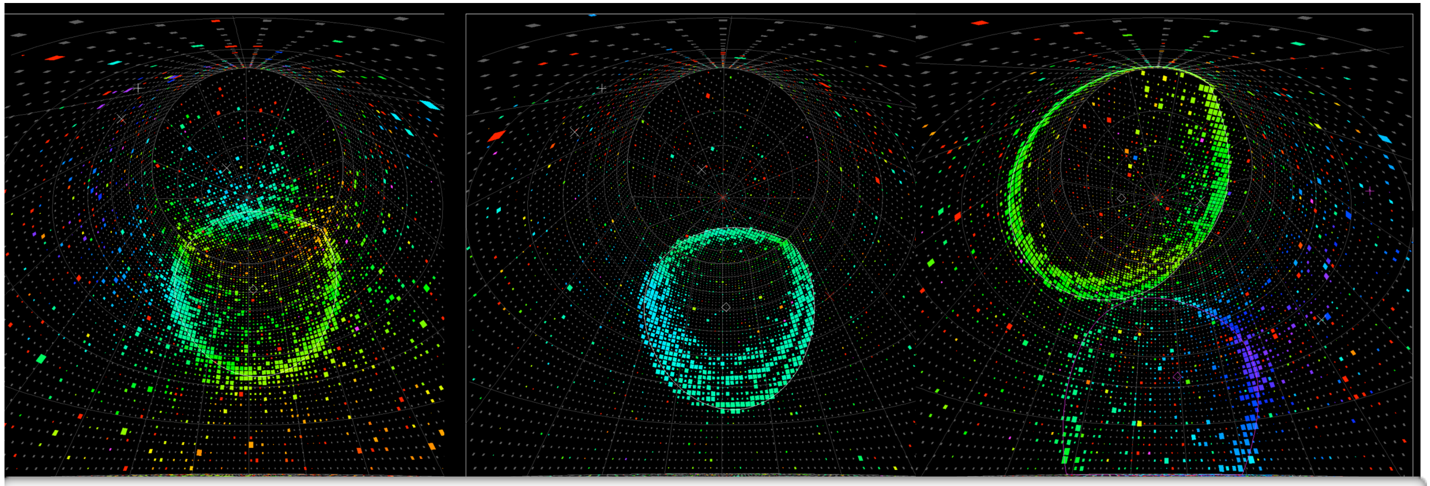


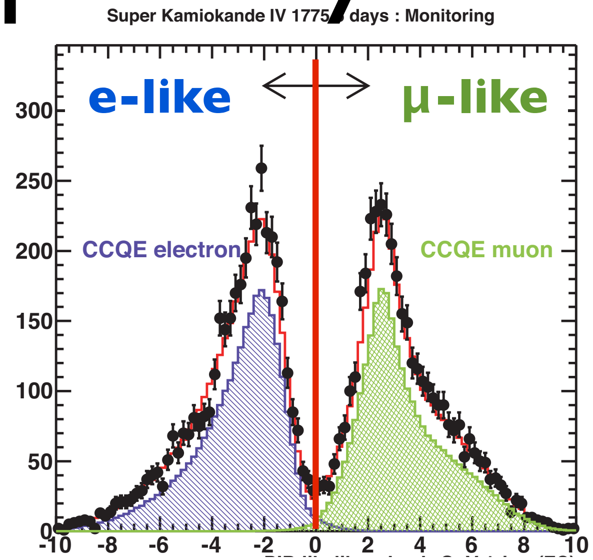
- P-decay Br. ratio could tell us flavor structure of SUSY particles.
  - Decay branches depends on the size of sfermion mixing. (N.Nagata and S.Shirai, JHEP 1403, 049 (2014))



Ring-imaging water Cherenkov detectors
Super-K / SK-Gd / Hyper-K

Water Ch. detector for p-decays

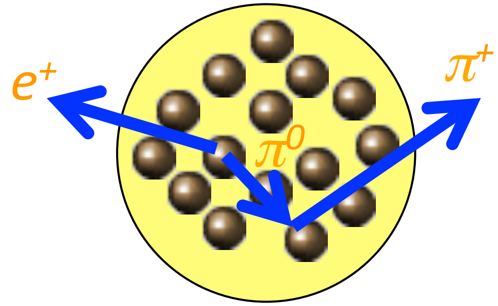




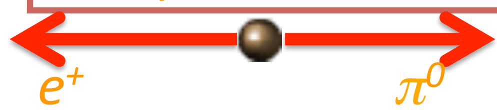
PID likelihood (atmν)

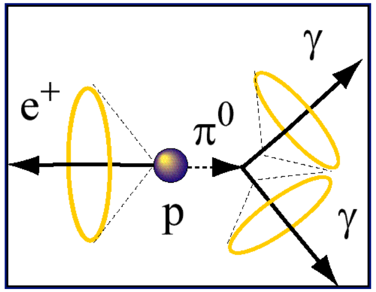
- **High mass is possible** (Super-K 22kton, Hyper-K 190kton ~ 8×Super-K)
  - **$p \to e^+\pi^0$, νK^+, and more** can be searched with high sensitivities
- **Excellent & well-proven performance**
  - Good ring-imaging capability at ~1GeV
  - Excellent particle ID (e or μ) capability > 99%
  - Energy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

$p \to e^+\pi^0$ in ^{16}O



Free proton $\to e^+\pi^0$

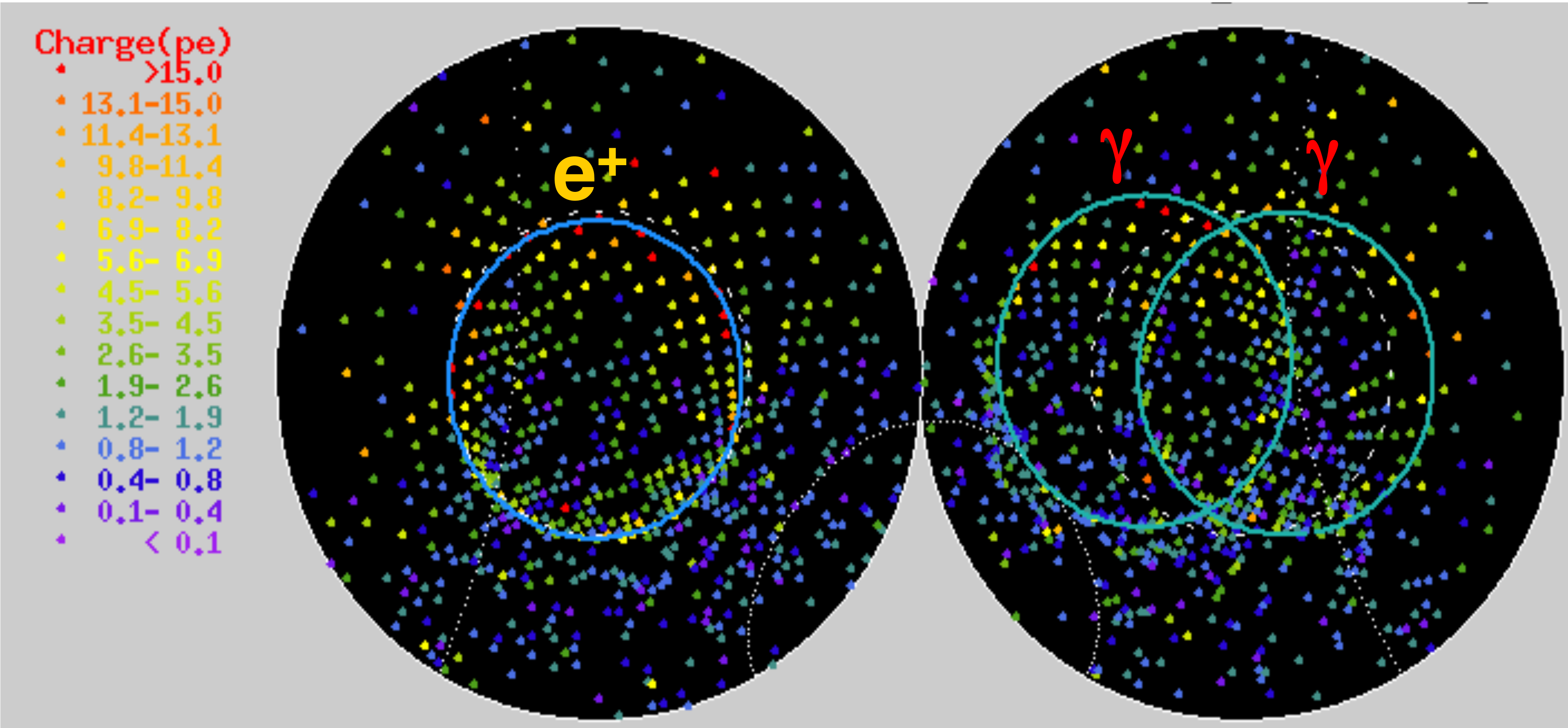




$p \rightarrow e^+ + \pi^0$ searches

Super-K cut

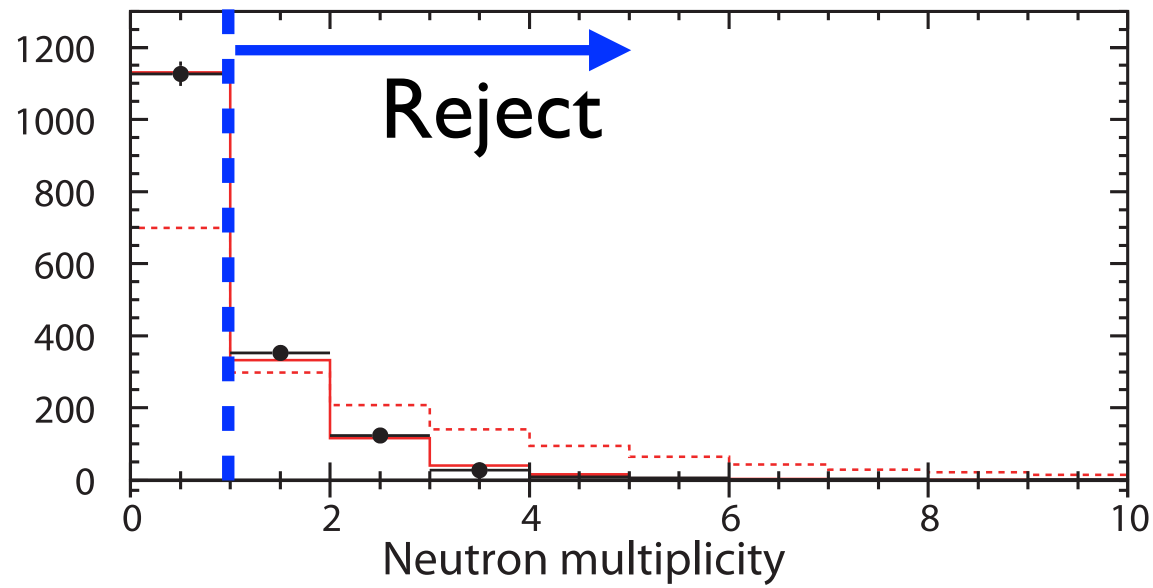
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050$ MeV/c^2
  $P_{total} < 250$ MeV/c



SK-II (half PMT) forward-backward display for $p \rightarrow e^+ + \pi^0$

BG reduction by neutron-tag & tighter P_{tot} cut

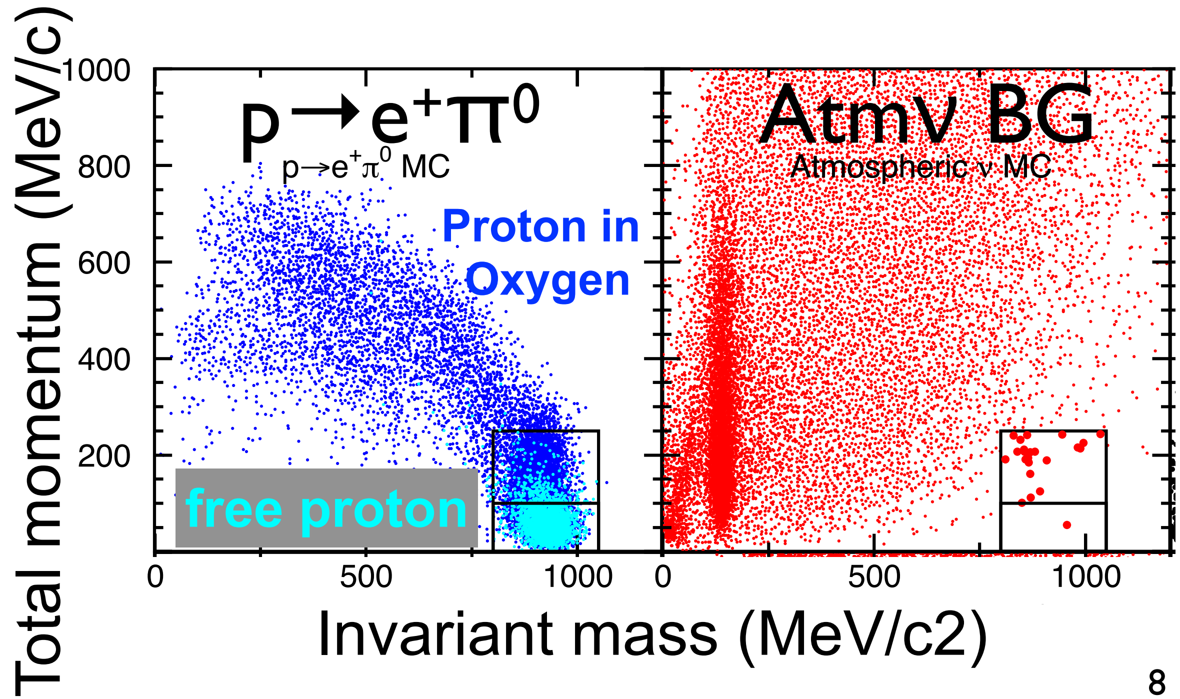
- Shiozawa@NNN00 workshop
- PRD95, 012004 (2017)



- SK-IV w/ new electronics can tag neutrons by n+p→d+2.2MeVγ
- Atmospheric neutrino BG is reduced by 40%

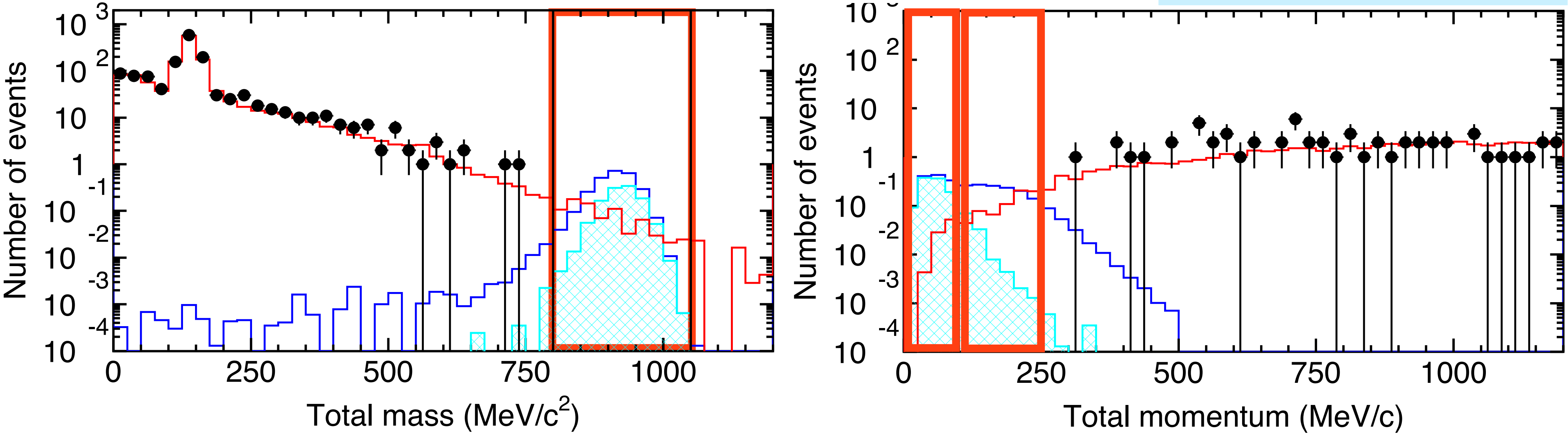
- Two regions of P_{tot} to enhance discovery reach
  - P_{tot} < 100MeV/c for free proton decays
  - P_{tot} < 250 MeV/c for ^{16}O

p_{tot}<100MeV/c		100<p_{tot}<250MeV/c	
Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
18.7	0.18	19.4	1.1



$p \rightarrow e^{+} + \pi^{0}$ in SK I-IV (306kt×yrs)

PRD95, 012004 (2017)



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

- detection efficiency = 40%
- atmospheric ν BG = 0.61 (0.05+0.55) events in 306kton×yr

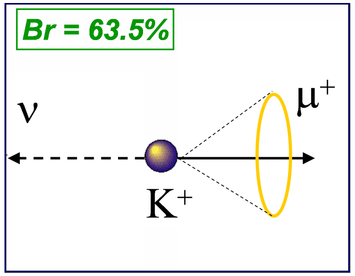
τ_{proton}/Br > 1.6 ×10^{34} years @ 90%C.L.

‣There is still discovery potential by keeping the low BG (especially for P_{tot} < 100MeV/c)

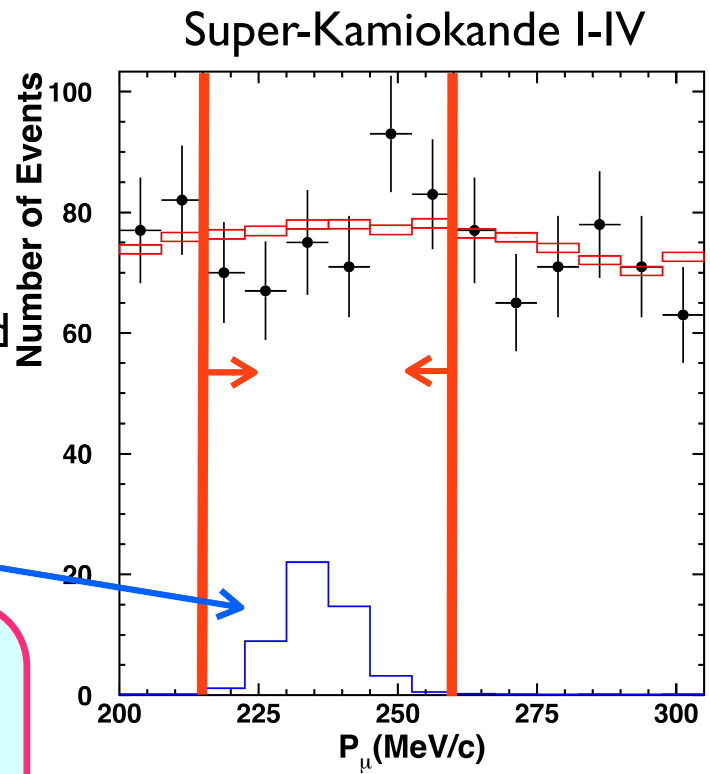
$p \rightarrow \nu + K^+$ searches in SK

PRD90, 072005 (2014)

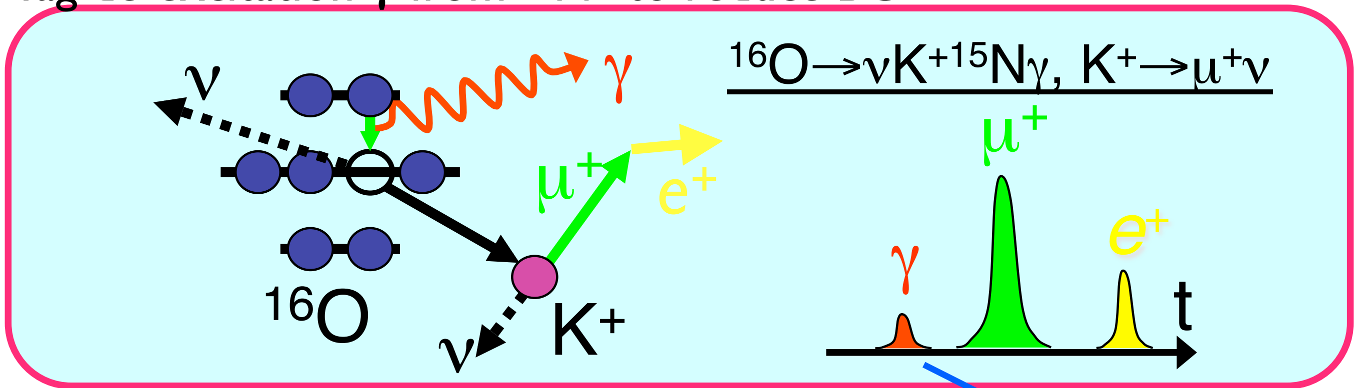
(I) $K^+ \rightarrow \mu^+\nu$, $\mu^+ \rightarrow e^+\nu\nu$



K+ is below Cherenkov threshold
→ 236MeV/c μ and muon decay electrons



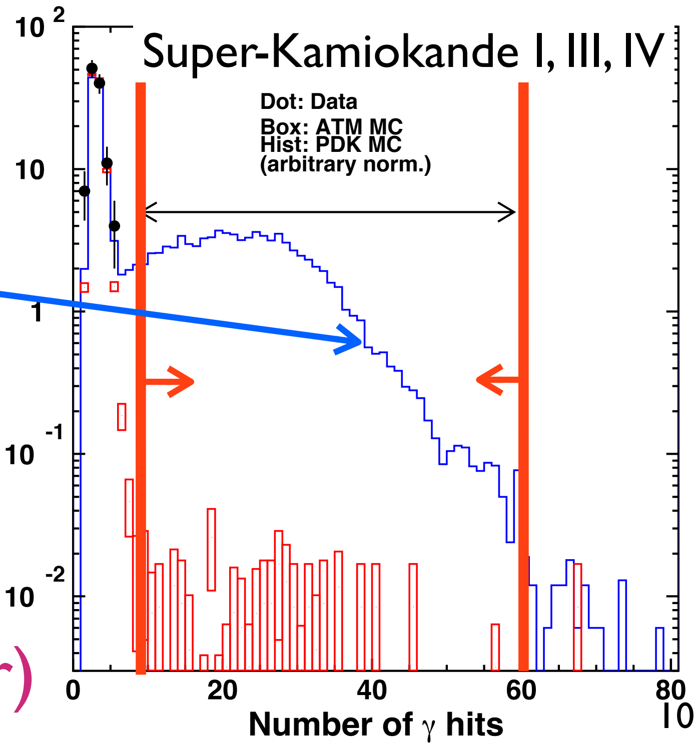
Tag de-excitation γ from $^{15}N^*$ to reduce BG



- signal efficiency = 9.1% (for SK-IV)
- Atmospheric neutrino BG 0.38/260ktyr

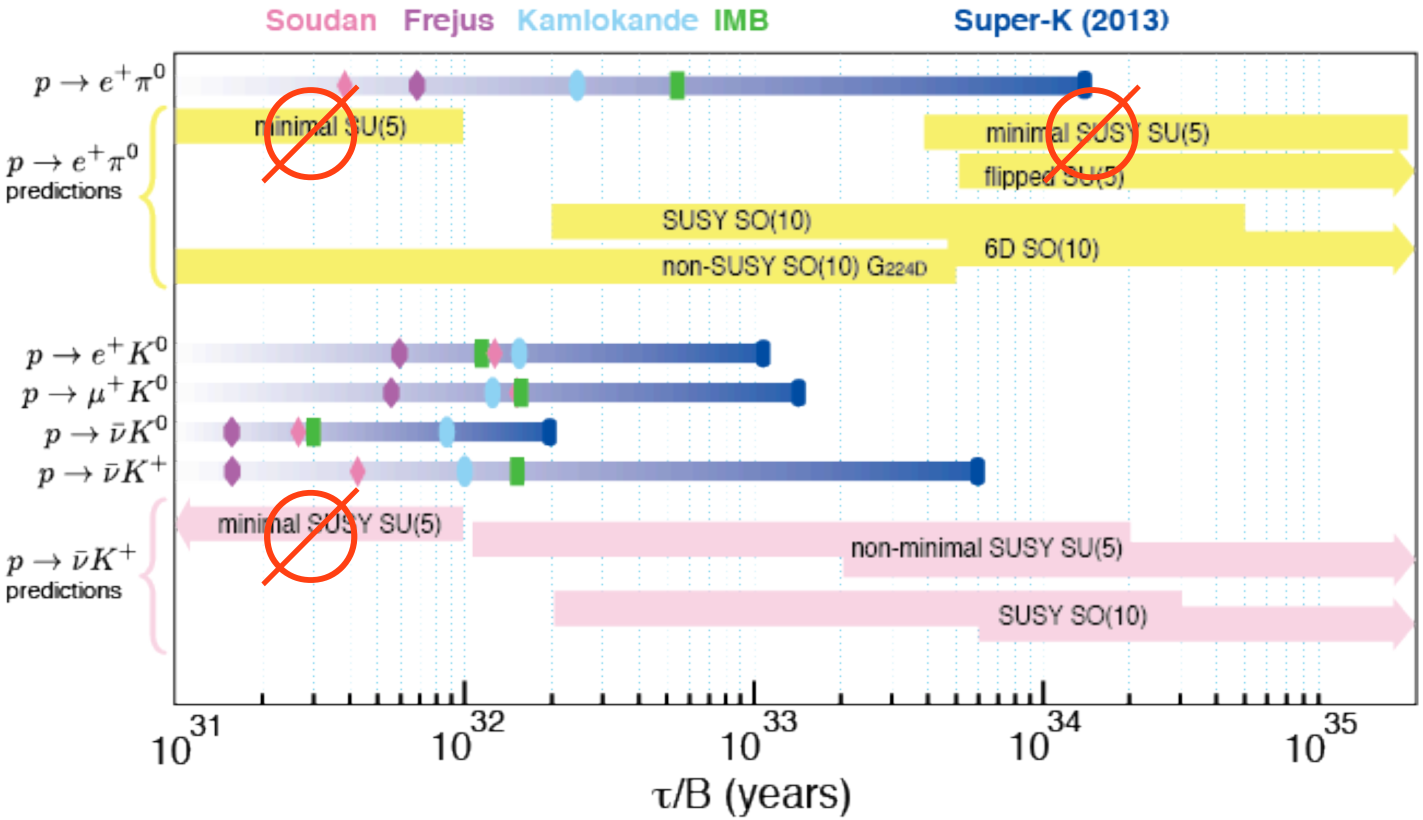
(II) $K^+ \rightarrow \pi^+\pi^0$

- signal efficiency = 10.0% (for SK-IV)
- Atmospheric neutrino BG 0.62/260ktyr



$\tau_{proton}/Br > 5.9 \times 10^{33}$ years @ 90%CL (260ktyr)

Experimental limits and models

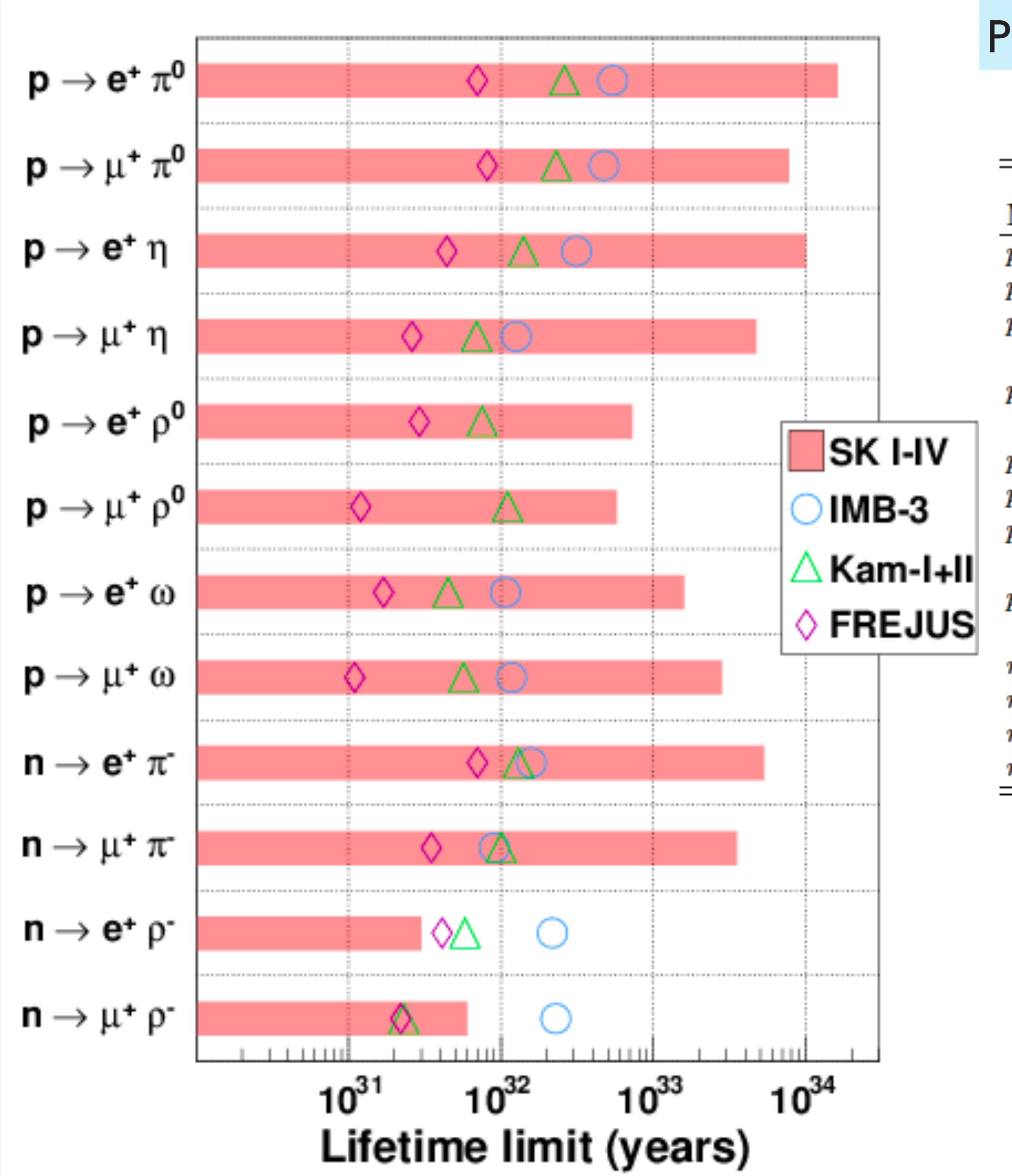


- **Super-K provides world stringent limits**
  - $\tau(p \rightarrow e^+\pi^0) > 1.6\times10^{34}$ years (90%C.L.)
  - $\tau(p \rightarrow \nu K^+) > 5.9\times10^{33}$ years (90%C.L.)
  - **already constrain the construction of many GUT models**

PRD 95, 012004 (2017)
PRD 90, 072005 (2014)

- **Many models predict $\tau = O(10^{34\text{-}35})$ years**
  - **Discovery could be around corner!**

charged-lepton + meson decay



PRD 96, 012003 (2017)

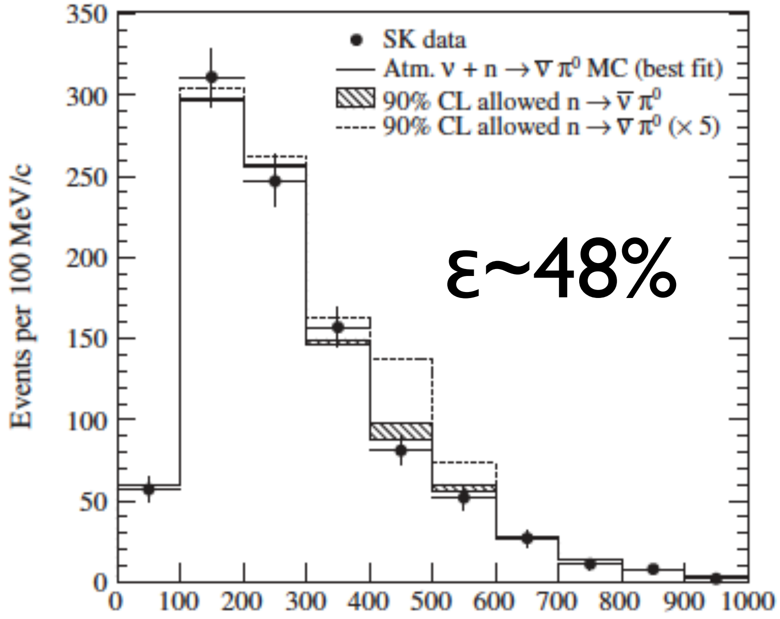
Modes		Eff.(%) SK-I	SK-II	BG (SK-I+II) NEUT	(NUANCE)	Candidates SK-I+II
$p \to e^+\pi^0$		44.6	43.5	0.31	(0.27)	0
$p \to \mu^+\pi^0$		35.5	34.7	0.34	(0.27)	0
$p \to e^+\eta$	(2γ)	18.8	18.2	0.28	(0.29)	0
	$(3\pi^0)$	8.1	7.6	0.16	(0.32)	0
$p \to \mu^+\eta$	(2γ)	12.4	11.7	0.04	(0.04)	0
	$(3\pi^0)$	6.1	5.4	0.45	(0.44)	2
$p \to e^+\rho^0$		4.9	4.2	0.35	(0.34)	0
$p \to \mu^+\rho^0$		1.8	1.5	0.42	(0.46)	1
$p \to e^+\omega$	$(\pi^0\gamma)$	2.4	2.2	0.14	(0.29)	0
	(3π)	2.5	2.3	0.39	(0.30)	1
$p \to \mu^+\omega$	$(\pi^0\gamma)$	2.8	2.8	0.31	(0.37)	0
	(3π)	2.7	2.4	0.17	(0.05)	0
$n \to e^+\pi^-$		19.4	19.3	0.27	(0.37)	0
$n \to \mu^+\pi^-$		16.7	15.6	0.43	(0.44)	1
$n \to e^+\rho^-$		1.8	1.6	0.38	(0.44)	1
$n \to \mu^+\rho^-$		1.1	0.94	0.29	(0.69)	0

- No evidence is found in Super-K

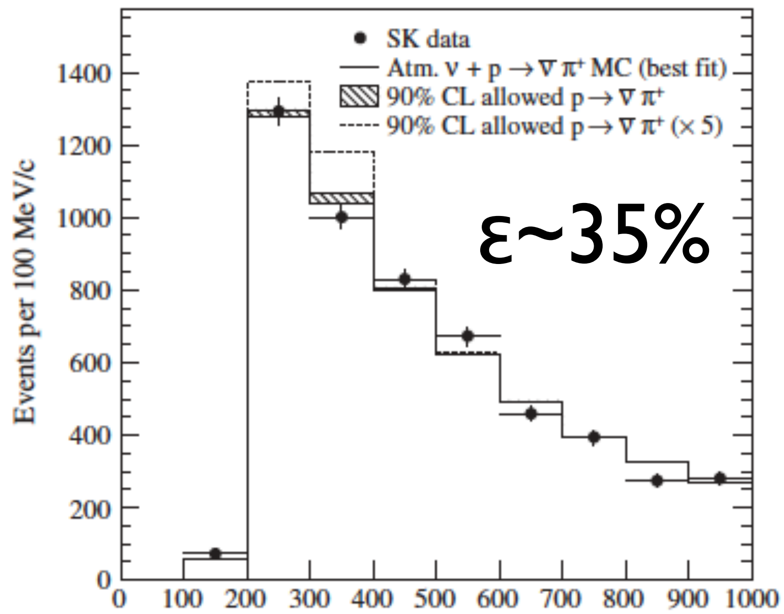
PRL 113, 121802 (2014)

Searches for $n \rightarrow \nu\pi^0$ and $p \rightarrow \nu\pi^+$

- Motivated by minimal SUSY SO(10) (e.g. PLB587, 105 (2004).)



π^0 momentum (MeV/c)



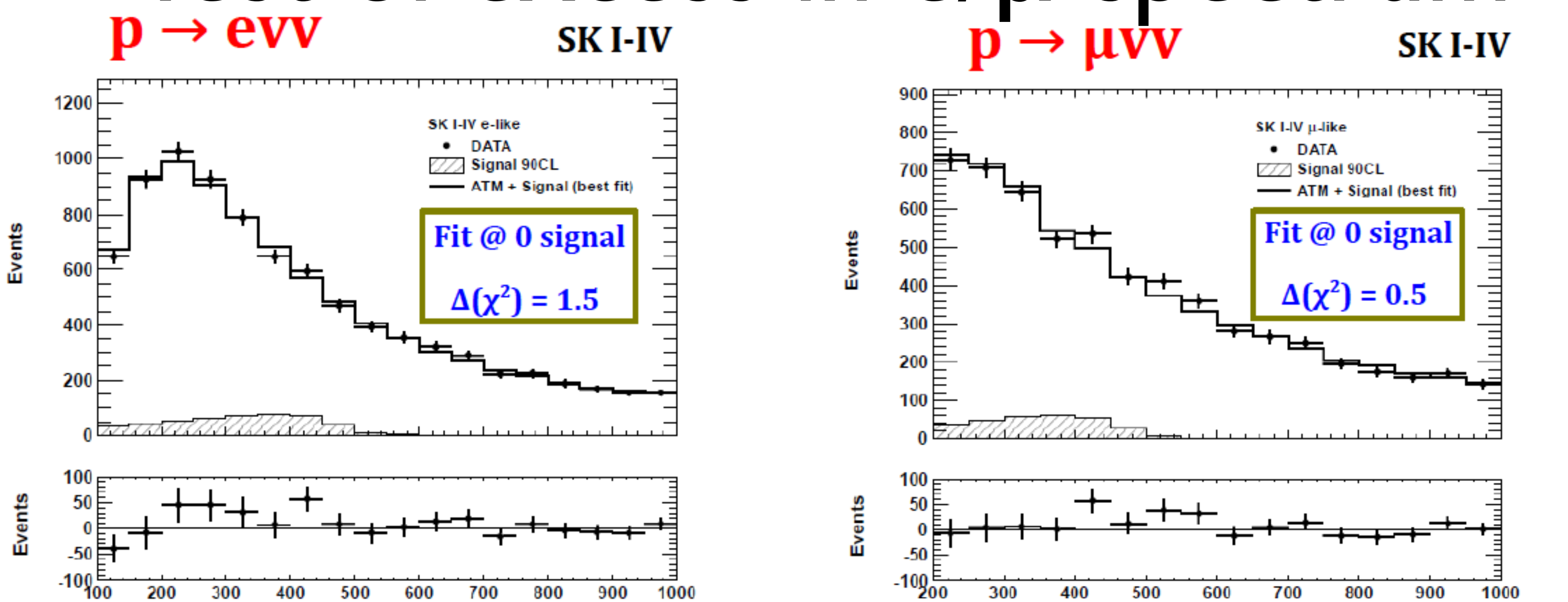
π^+ momentum (MeV/c)

$p \rightarrow \nu\pi^0$
- detection efficiency = 49%(SK-I), 44%(SK-II), 49%(SK-III)
- $\tau_p > 1.1 \times 10^{33}$ years @ 90%C.L.

$p \rightarrow \nu\pi^+$
- detection efficiency = 35%(SK-I), 35%(SK-II), 36%(SK-III)
- $\tau_p > 3.9 \times 10^{32}$ years @ 90%C.L.

almost ruled out the prediction by PLB587, 105 (2004):
- $\tau_{p\rightarrow\nu\pi0} = 2\tau_{p\rightarrow\nu\pi+} < 5.7 - 13 \times 10^{32}$ years @ 90%C.L.

Test of excess in e/μ spectrum



electron momentum (MeV/*c*)   muon momentum (MeV/*c*)

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

PRL113,101801(2014)

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

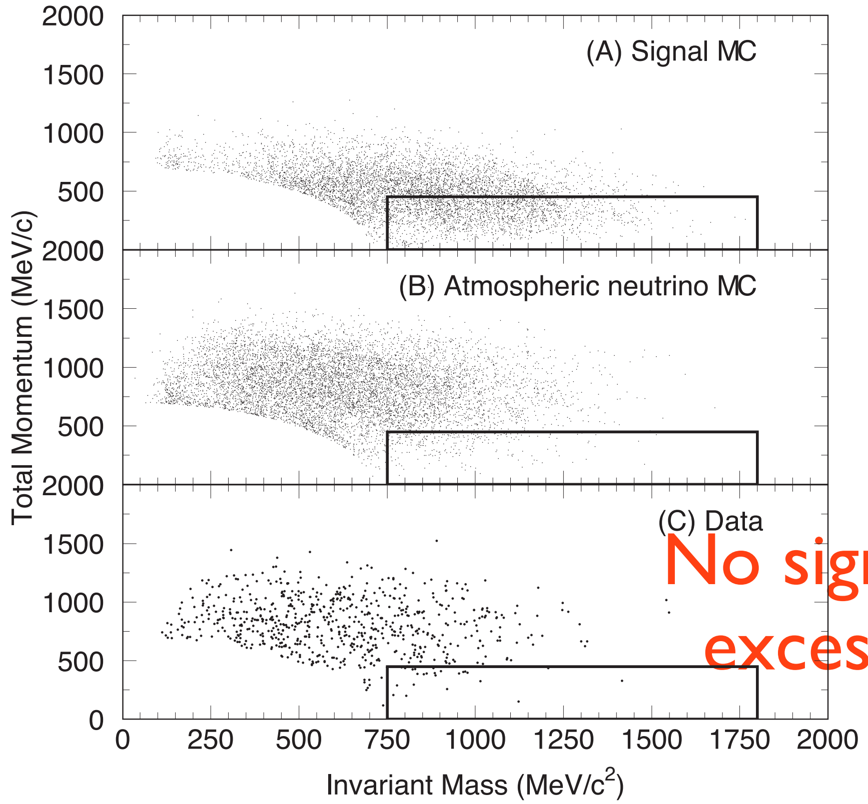
Preliminary

ΔB=2: n-n̄ 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

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



No signal excess

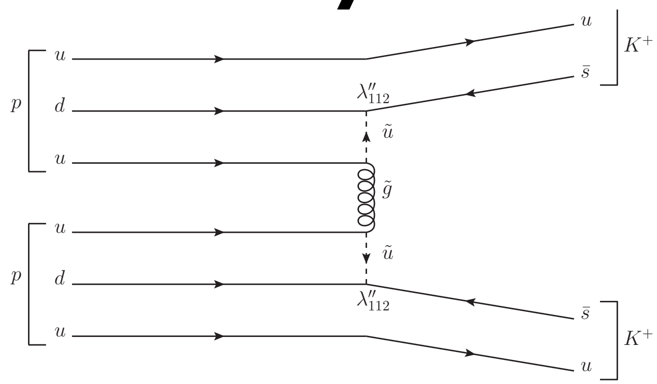
n-nbar oscillation in ^{16}O
- detection efficiency = 12.1%
- atmospheric ν BG = 24.1 events in 92kton×years (Super-K-I)
- observed signal = 24 events
- $T_{n\text{-}nbar}(^{16}O) > 1.9 \times 10^{32}$ years @ 90%C.L.
  → $\tau_{n\text{-}nbar}(\text{free}) > 2.7\times10^{8}$ sec

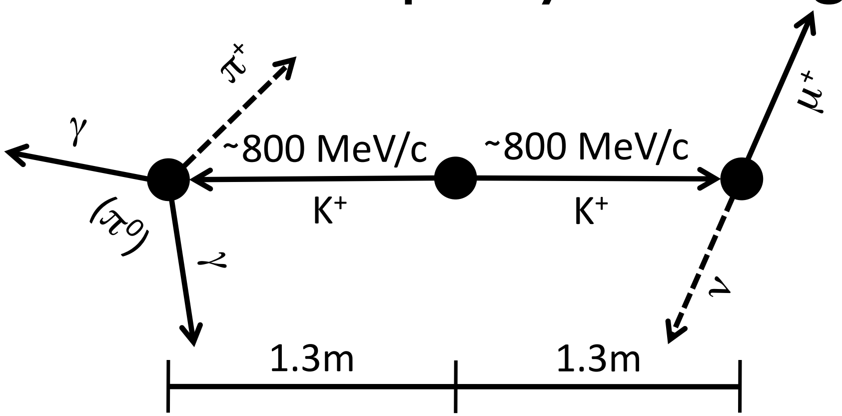
Machine learning analysis is also performed.

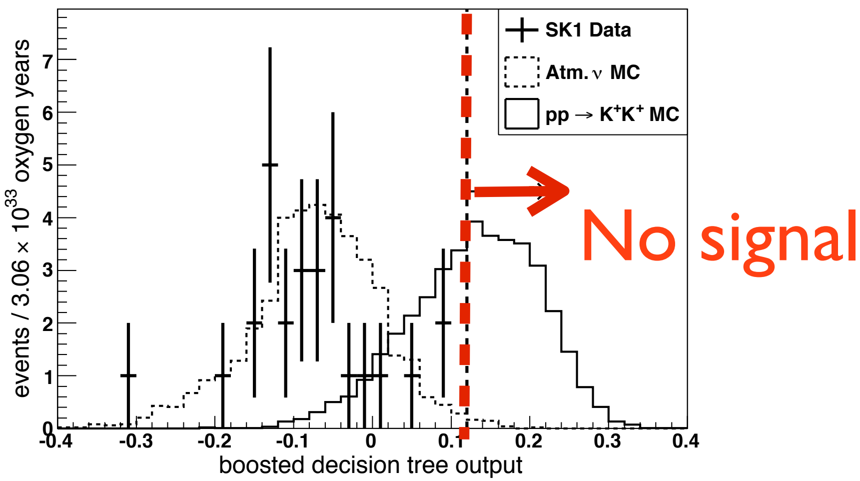
PRL112,131803(2014)

ΔB=2: Dinucleon decays

- $^{16}O(pp) \rightarrow {}^{14}CK^{+}K^{+}$
  - Boosted Decision Tree (BDT) by using vertex separation, K+ momentum etc.
- sensitive to R-parity-violating λ_{112}''







$^{16}O(pp) \rightarrow {}^{14}CK^{+}K^{+}$

- detection efficiency = 12.6%±3.2%
- atmospheric ν BG = 0.28±0.19 events in 92kton×years (Super-K-I)
- $\tau(^{16}O(pp) \rightarrow {}^{14}CK^{+}K^{+}) > 1.7 \times 10^{32}$ years @ 90%C.L.
  $\rightarrow \lambda_{112}'' < 7.8 \times 10^{-9}$

We also searched for $pp \rightarrow \pi^{+}\pi^{+}$, $pn \rightarrow \pi^{+}\pi^{0}$, $n \rightarrow \pi^{0}\pi^{0}$

Super-K: next phase

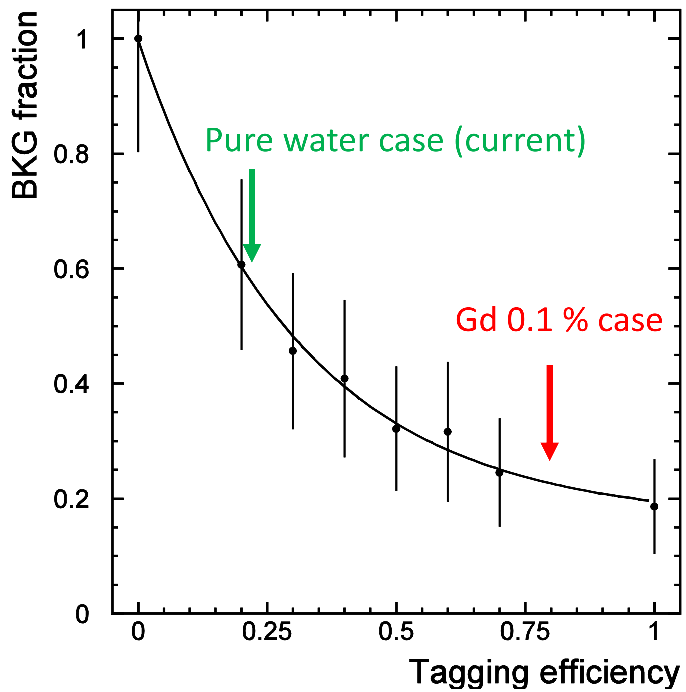
- 2018: Tank refurbishment work to be ready for loading Gadolinium

- 2020(TBD): Neutron capture 50% (0.01%w Gd) →202X: 90% (0.1%w Gd)
- Discovery of supernova relic neutrinos ($\overline{\nu}_e$) by coincidence of e^+ + γs

Beacom and Vagins PRL93:171101(2004)

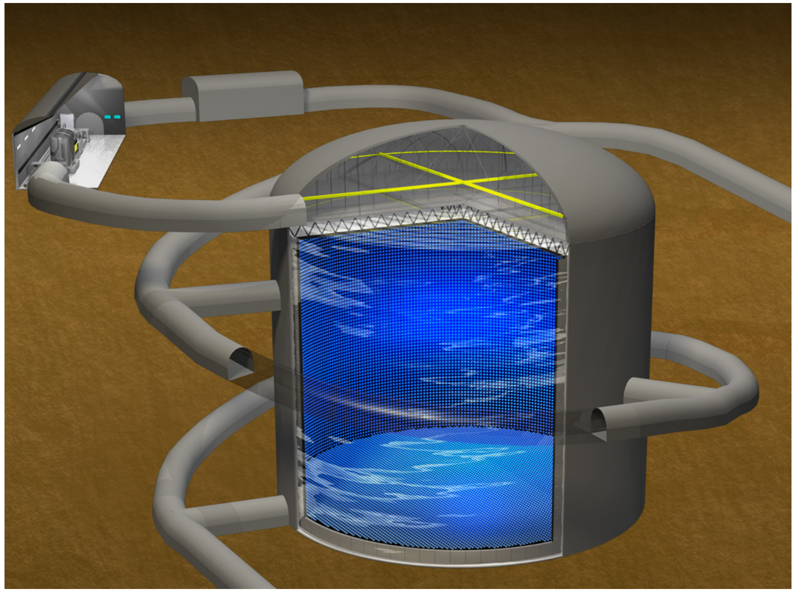
For proton decay searches

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



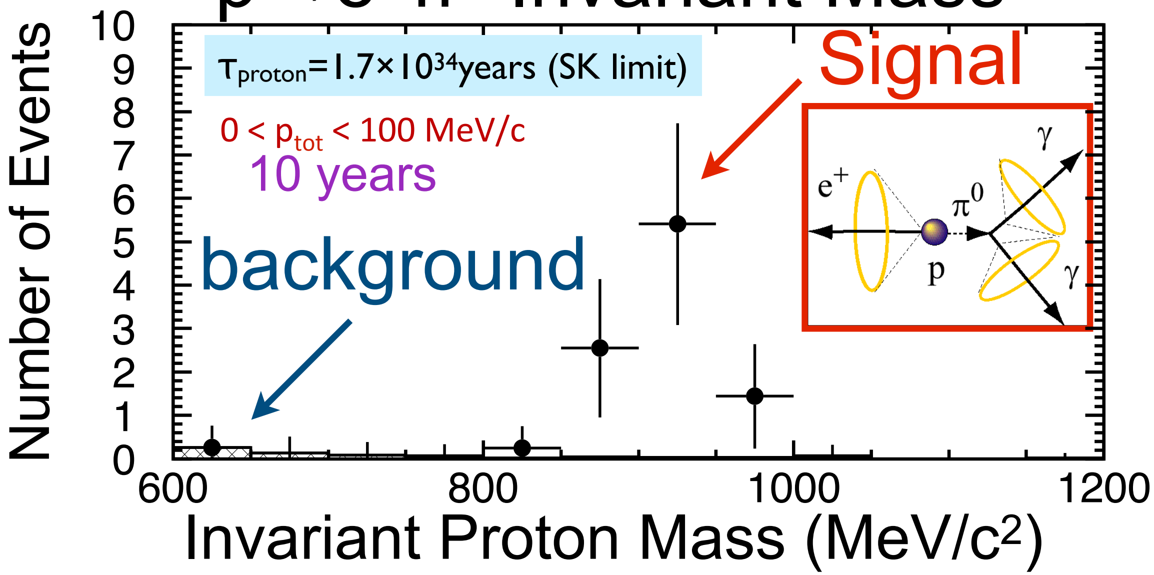
Hyper-K: big step forward

arXiv:1805.04163



- Start operation in ~2027 with higher mass (190kton, 8×Super-K)
- BG free search possible: 0.01 BG/year for p_{tot}<100 MeV/c
- Invariant proton mass would be a compelling evidence
- Reach to 10^{35} yrs

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

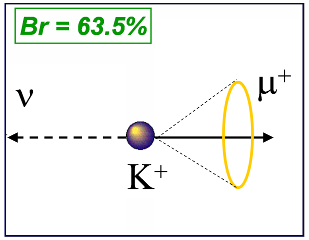


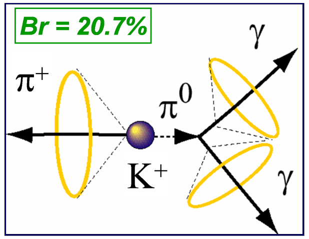
	p_{tot}<100MeV/c		100<p_{tot}<250 MeV/c	
	Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
HK	18.7	0.06	19.4	0.62

$p \rightarrow \nu K^+$ discovery in Hyper-K

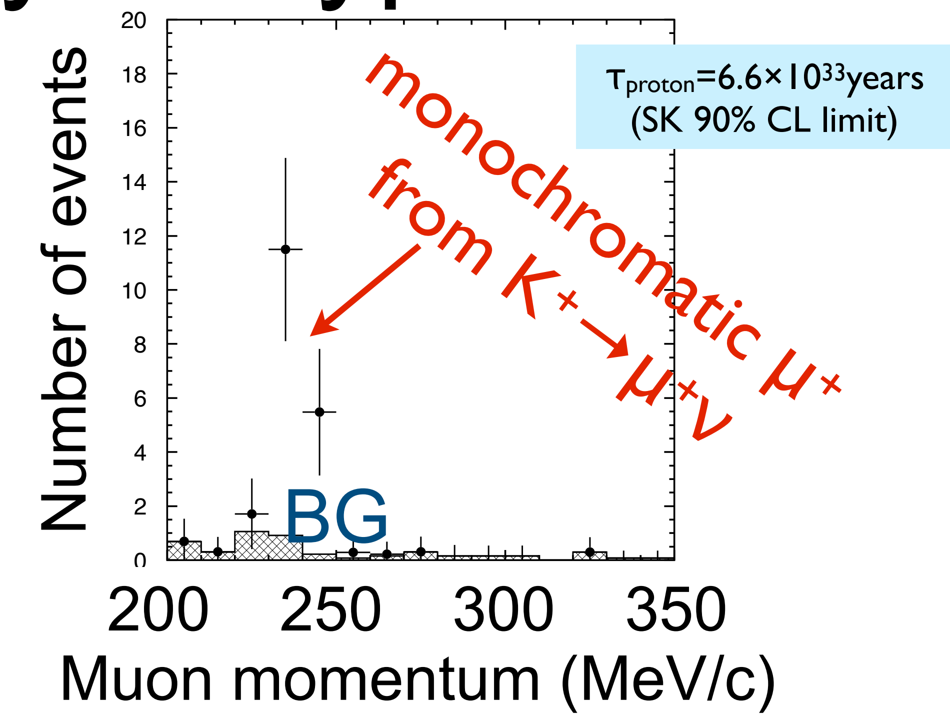
arXiv:1805.04163

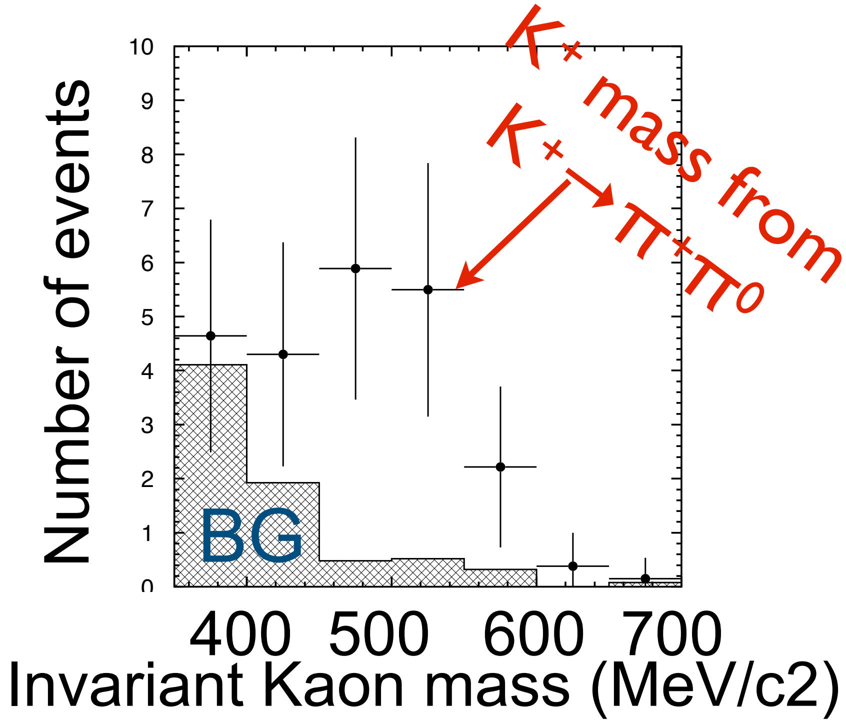
- K+ is invisible so signal signature are:
  - 236 MeV/c muon
  - $\pi^+\pi^0$
- Discovery reach to 3×10^{34} years





	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



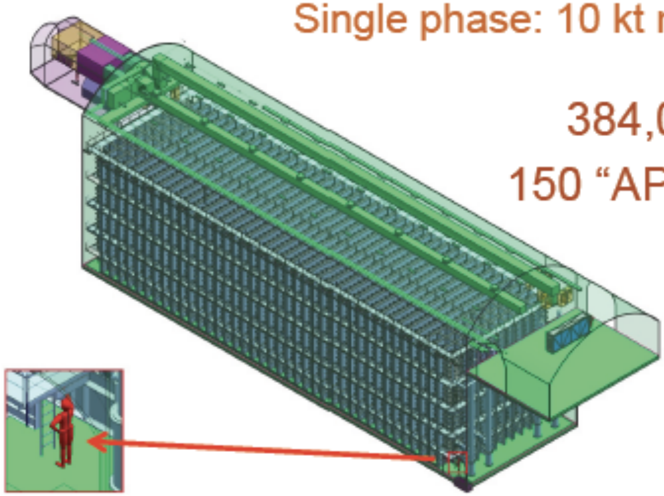


Liquid Argon TPC
DUNE

DUNE: Liquid Argon TPC

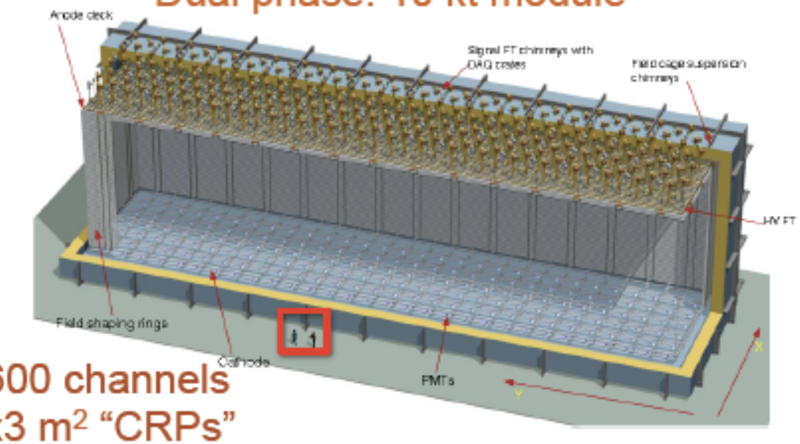
- 4 10-kiloton liquid Argon TPC modules
- Starting data taking before 2026

Single phase: 10 kt module



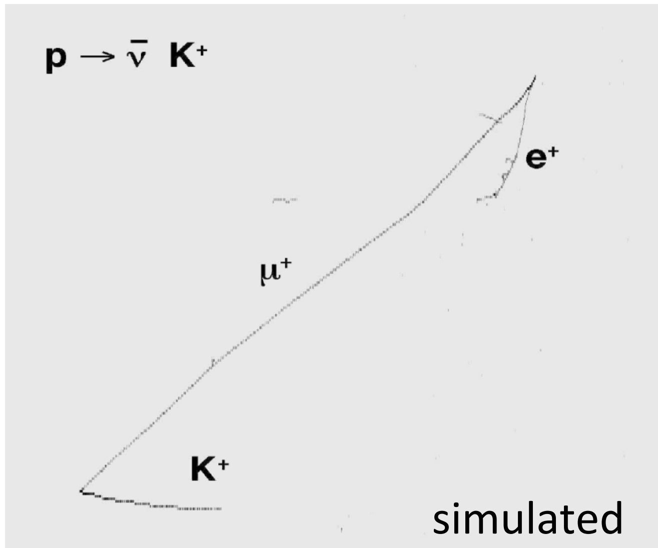
384,000 readout wires
150 “APAs” (2.3 m x 6 m)
12 m high
15.5 m wide
58 m long

Dual phase: 10 kt module



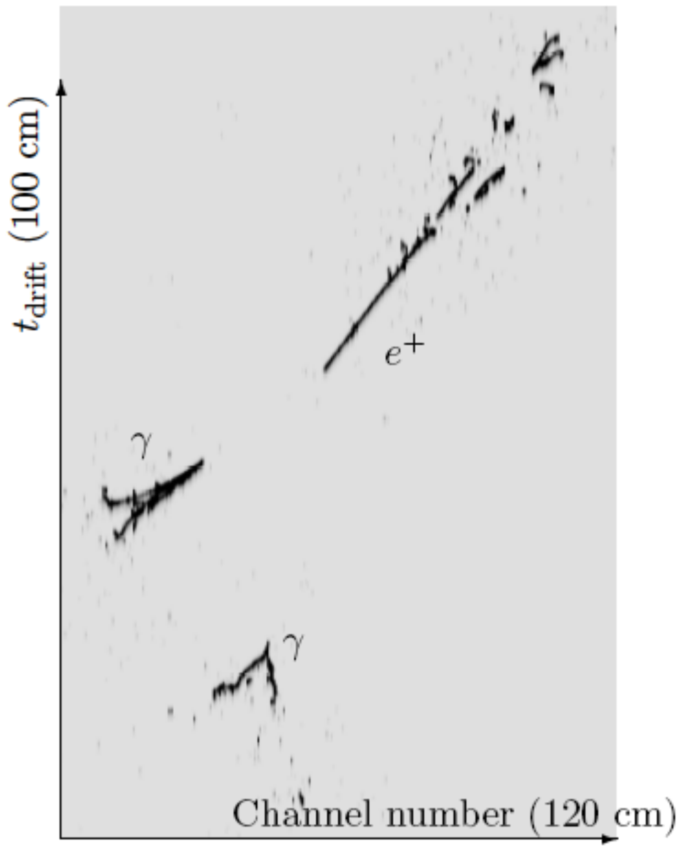
153,600 channels
80 3x3 m^2 “CRPs”
(Charge Readout Planes)

- LArTPC could identify the K^+ track by higher ionization density with high efficiency.
  - Single-event discovery could be possible.
- In addition, potential clean search for neutron-antineutron oscillation ($\Delta B=2$) and other modes for which significant BG for water Cherenkov detectors

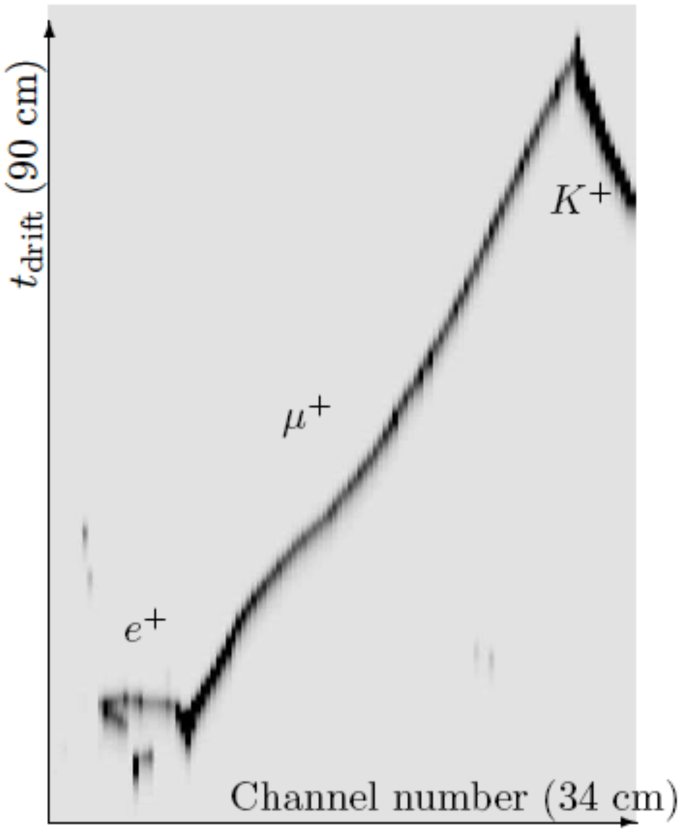


Large Liq. Argon TPC detector

JHEP0704(2007)041; arXiv:1512.06148



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



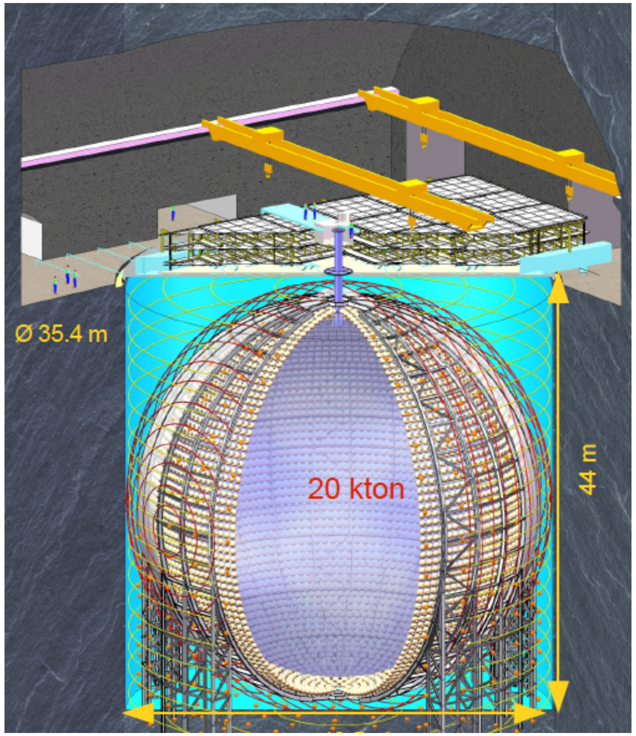
$p \rightarrow \nu + K^+$
- efficiency = 97%, 1BG/Mtyr

Full detector simulation and automatic reconstruction under development

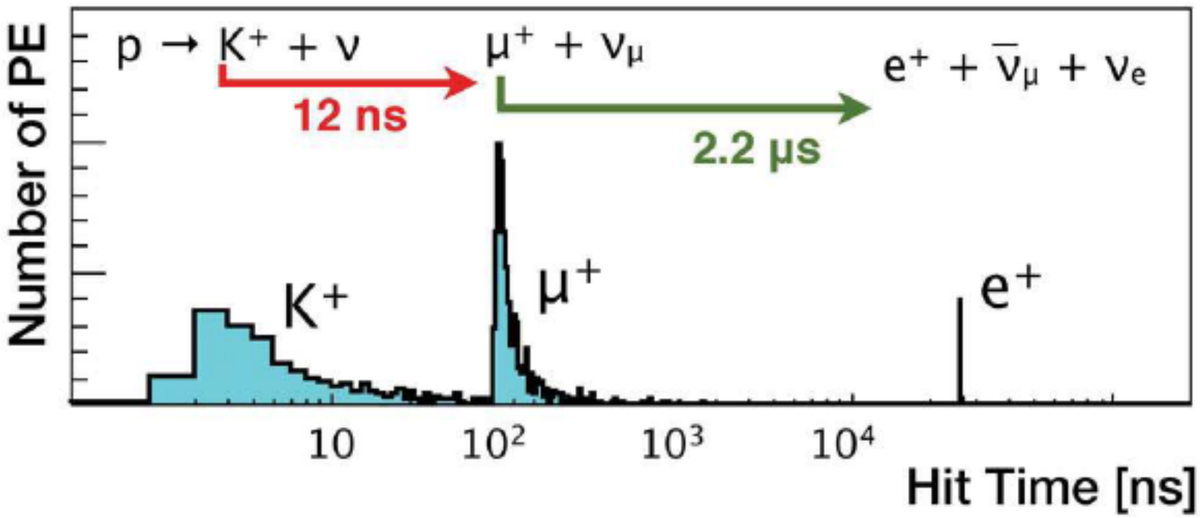
Liquid scintillator detector JUNO

p→νK⁺ in JUNO

arXiv:1507.05613



- 20 kiloton liquid scintillator
- Starting data taking in 2021



- Triple coincidence of K+→μ+→e+ w/ 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
- $\tau_{proton}/Br(p\to\nu K^+)=1.9\times10^{34}$ years assuming zero candidates

Summary

Comparison

	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	-	-
νK^+	24	1.6	97	1	64	2.5

arXiv:1805.04163

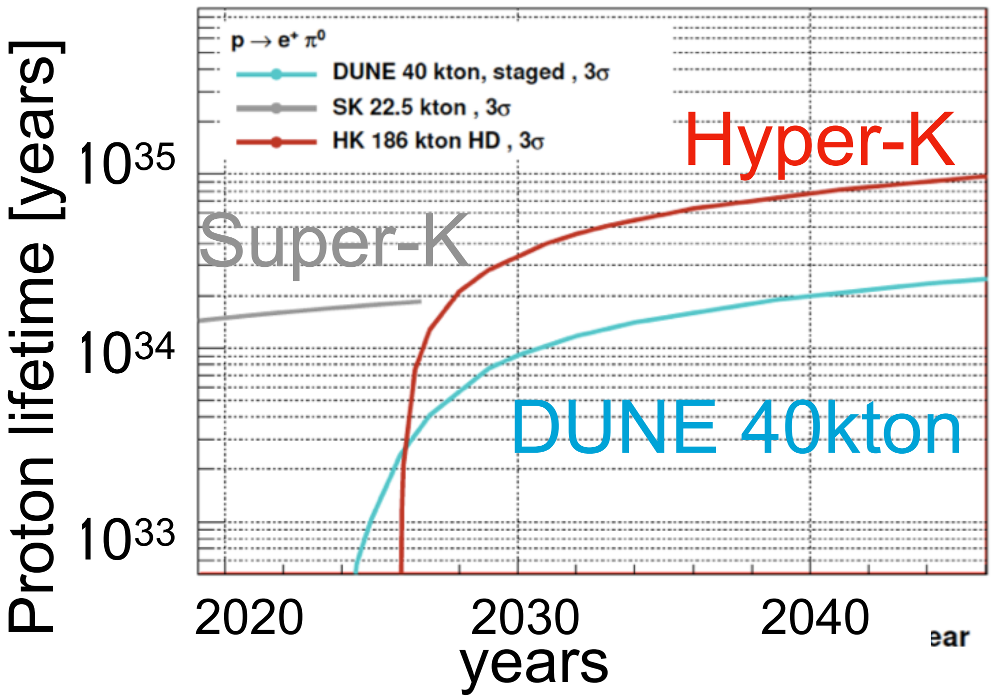
JHEP0704(2007)041; arXiv:1512.06148

arXiv:1507.05613

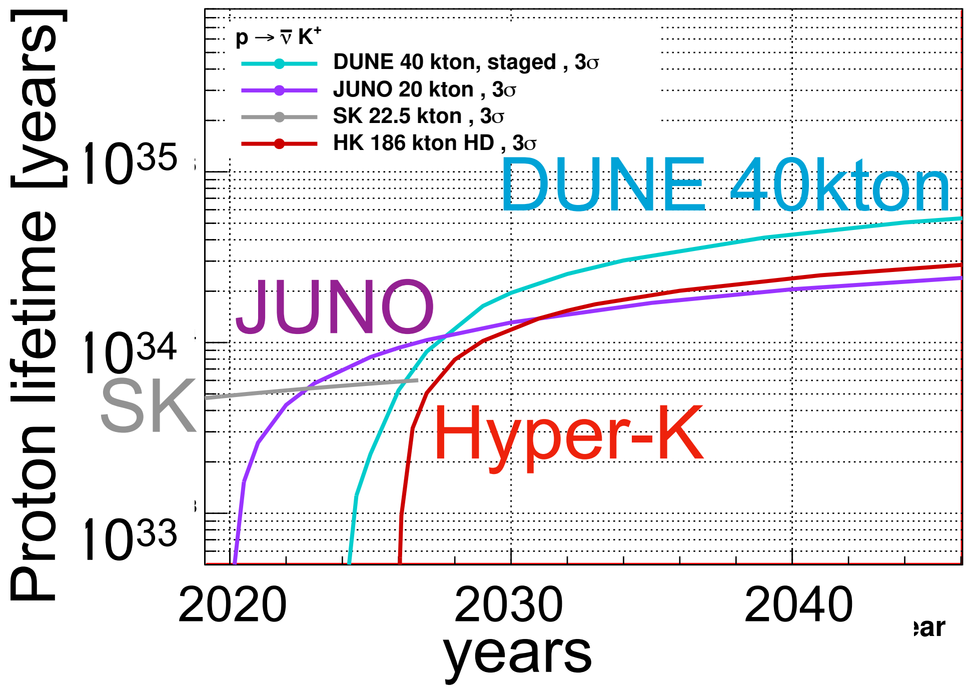
- For modes with Kaons,
  DUNE and JUNO can benefit from K identification and expected to have better S/N than water.
- For modes of "charged lepton plus mesons" like $p \rightarrow e^+\pi^0$, Hyper-K sensitivities are better by high mass.

Proton lifetime sensitivities

$p \rightarrow e^+\pi^0$ 3σ discovery



$p \rightarrow \nu K^+$ 3σ discovery



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

3σ discovery potential will reach to

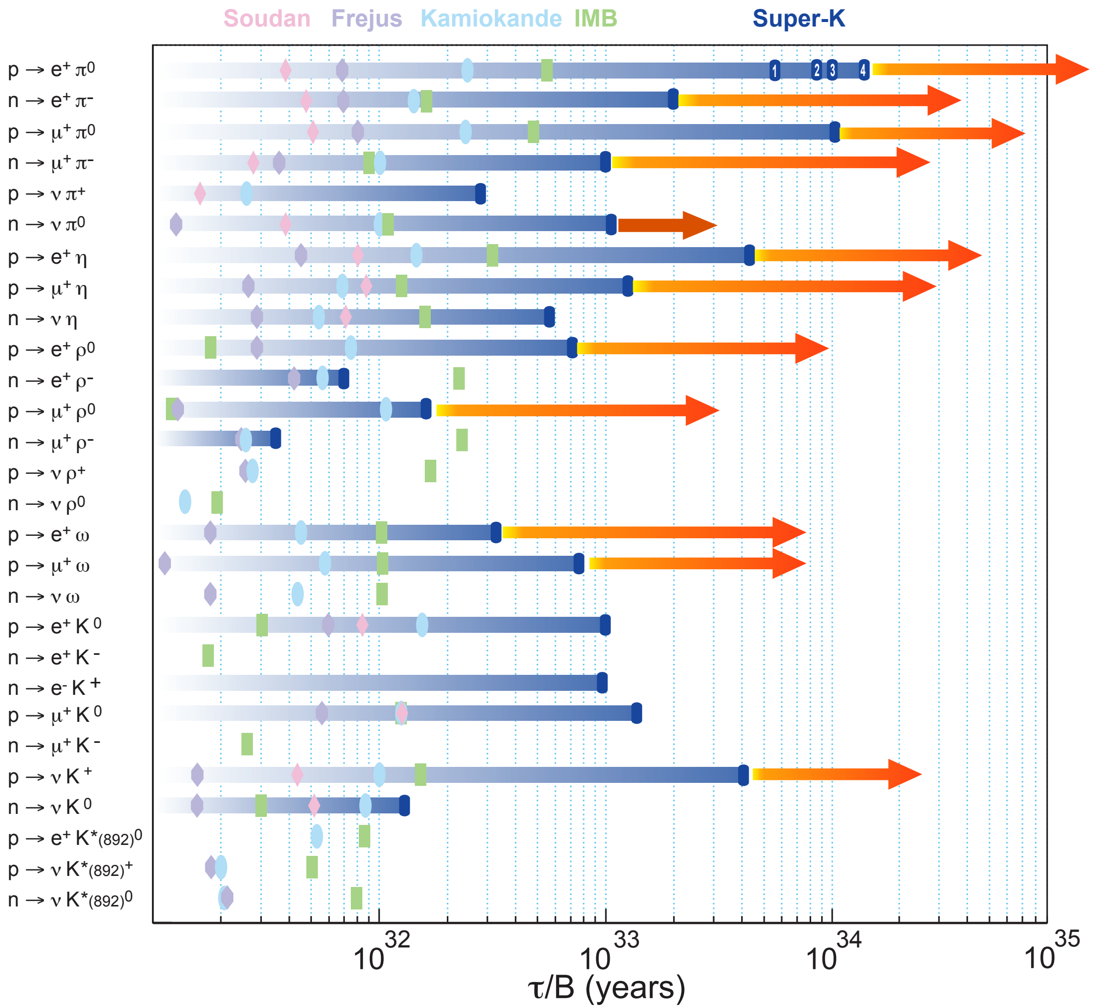
- 1×10^{35} years for $p \rightarrow e^+\pi^0$
- 5×10^{34} years for $p \rightarrow \nu K^+$

Hyper-K's sensitivities

Improvements in many modes by a factor ~10

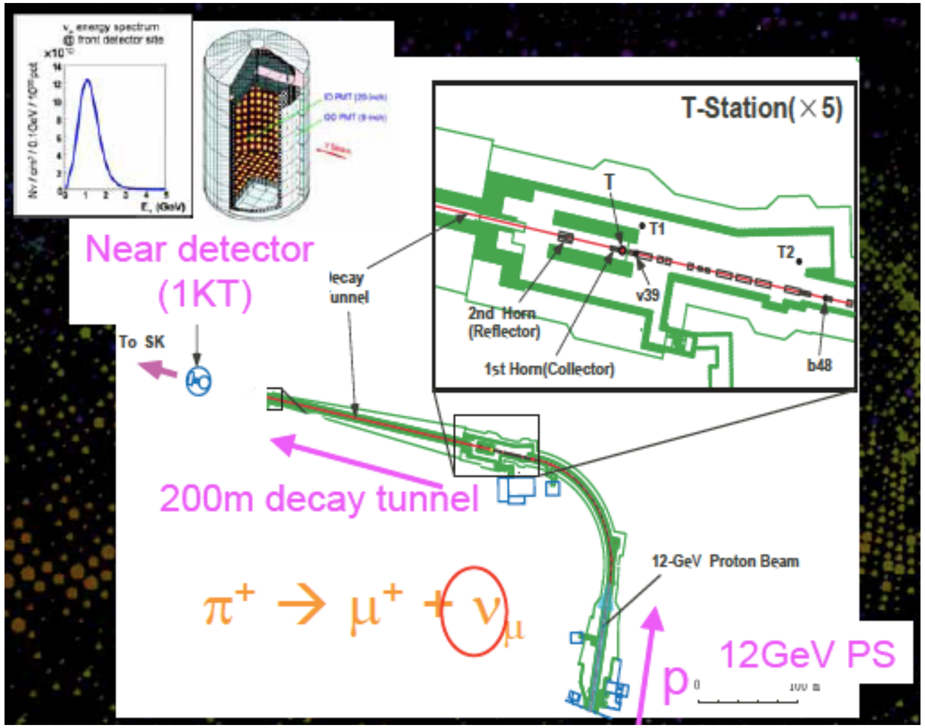
Open for many decay modes including $p \to e^+\pi^0$, $p \to \nu K^+$

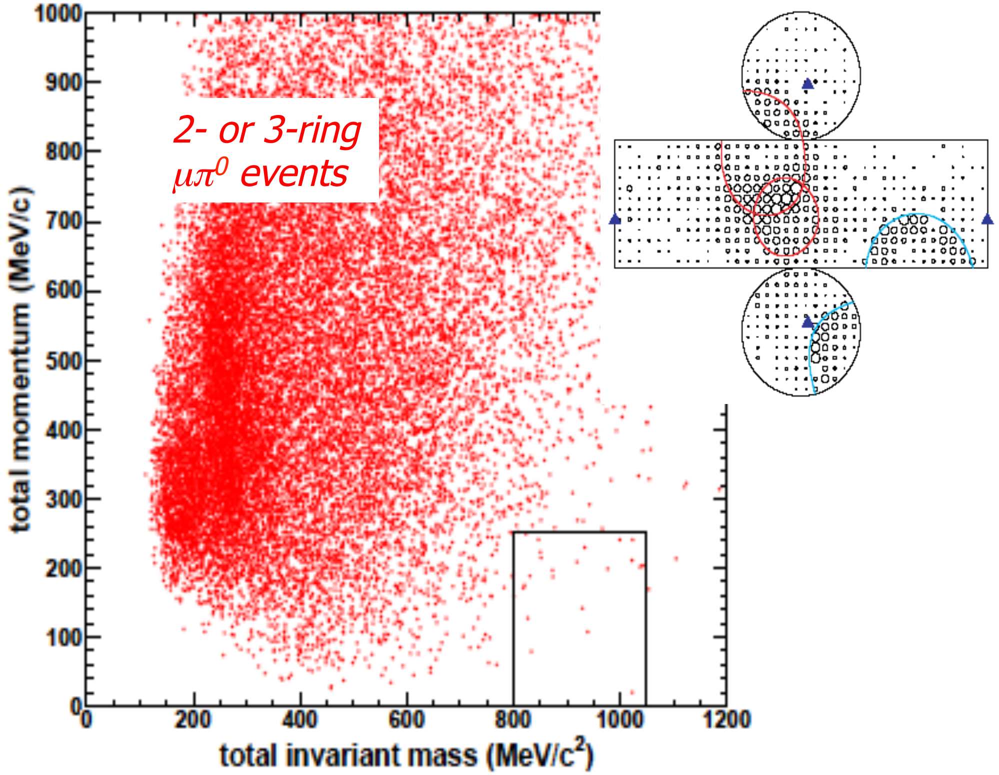
Good chance for discovery!



- *p*→e⁺+π⁰
  - τ_{proton}/Br > 1×10³⁵ years @90%CL
  - 5Mton×years (9 Hyper-K years)
- *p,n*→*(e⁺,μ⁺)+(π,ρ,ω,η)*
  - O($10^{34\sim35}$)years
- *SUSY favored p*→ν+*K⁺*
  - 3×10³⁴ years
- K⁰ modes, νπ⁰, νπ⁺ possible
- Others
  - (B-L) violated modes
  - radiative decays *p*→*e⁺*γ, μ⁺γ
  - neutron-antineutron oscillations (|ΔB|=2)
  - di-nucleon decays (|ΔB|=2)
    - pp→XX..., nn→XX...

BG measurement by K2K beam





$\mu\pi^0$ converted to $e\pi^0$ assuming lepton universality

K2K ($p \rightarrow e^+ + \pi^0$ BG by $E\nu$<3GeV)
1.63 +0.42/-0.33(stat.) +0.45/-0.51 (sys.) events/Mton-years

consistent ⇕

NEUT+SK simulation, $E\nu$<3GeV
1.8 +/- 0.3(stat.) events/Mton-years