Nucleon decay:
theory and experimental overview

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The full document is also uploaded.
All the references are included there.

Also, refer “Beyond the Standard Model (GUT)” by Natsumi Nagata at NNN22.

Grand Unified Theories (GUTs)

- Charge quantization
- Unification of forces
- Nucleon decay
- Representative GUTs

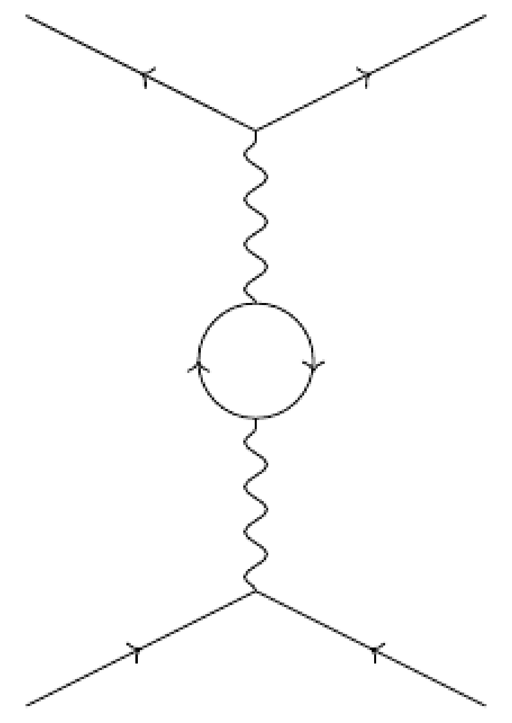
Charge quantization

- SM: the electric charge has no compelling reason to be quantized…
- $SU(5)$ GUT:
  - Electric charge generator Q must be traceless.
    - $Q = T_3 + \frac{Y}{2}$
  - Explains why the electric charges are quantized and why the absolute values of the electron and proton charges are the same.

- $SU(5)$: $\begin{pmatrix} \nu_e \\ e^- \\ \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \end{pmatrix}_L$
- $Q(\nu_e) + Q(e^-) + 3Q(\bar{d}) = 0$

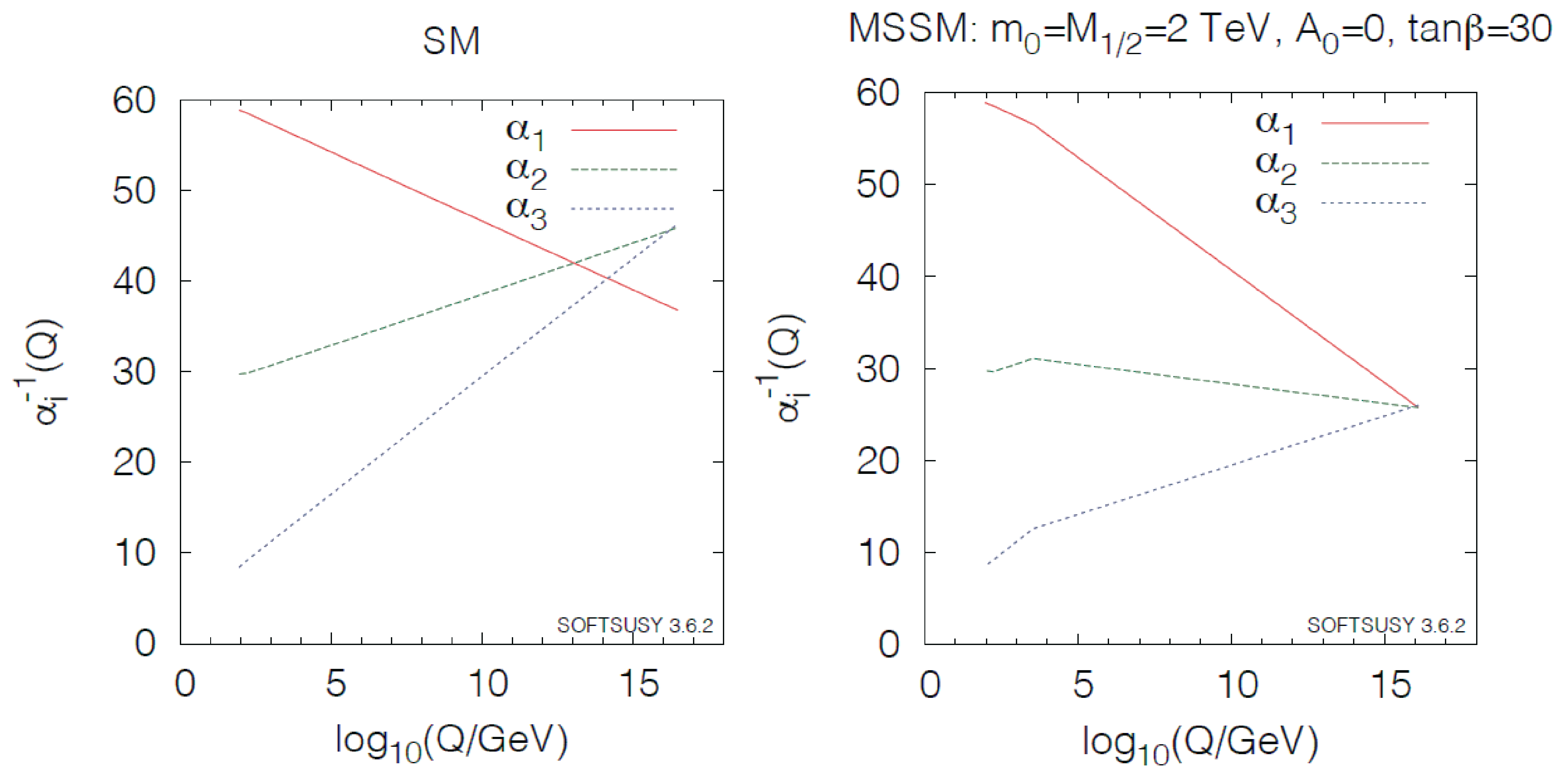
Unification of forces

- Running couplings:
  - $\frac{1}{\alpha_i(M^2)} = \frac{1}{\alpha_i(\mu^2)} + \frac{b_i}{4\pi} \ln \frac{M^2}{\mu^2}$
    - b_1, b_2, b_3: the $U(1)$, $SU(2)$, $SU(3)$ interactions
- The virtual diagrams cause the couplings to be a function of energy scale (M).
- Each GUT has some new particle loop and different b_i.
- Since the α_i vary differently depending on the energy scale, we can ask if they are equal at a certain mass.



Unification of forces

(PDG)



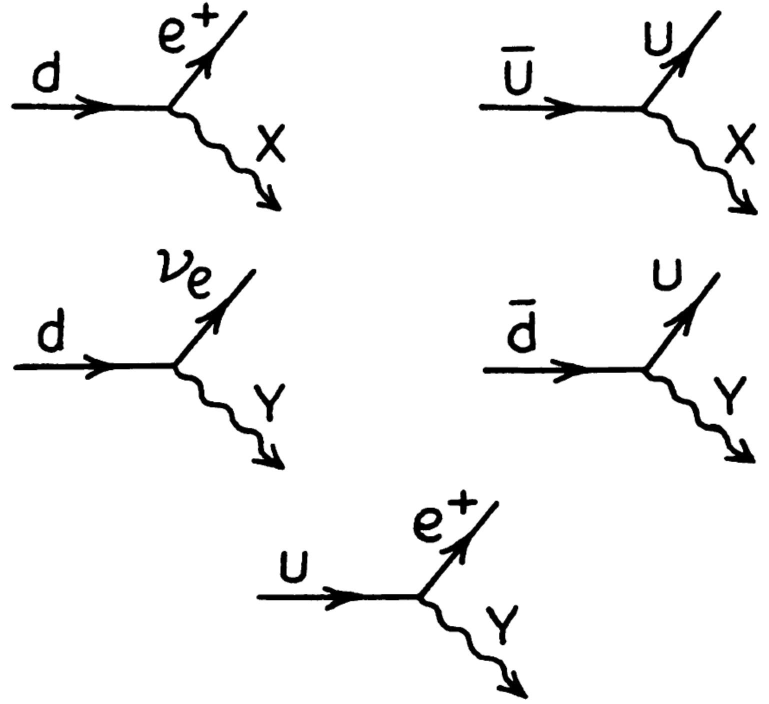
Unification of forces

$$\frac{\alpha_i^{-1}(\mu) - \alpha_j^{-1}(\mu)}{\alpha_j^{-1}(\mu) - \alpha_k^{-1}(\mu)} = \frac{b_i - b_j}{b_j - b_k}$$

- LHS:
  - LEP data at M_Z: 1.37 ± 0.07
- RHS:
  - SM: 1.90
  - SUSY $SU(5)$: 1.4

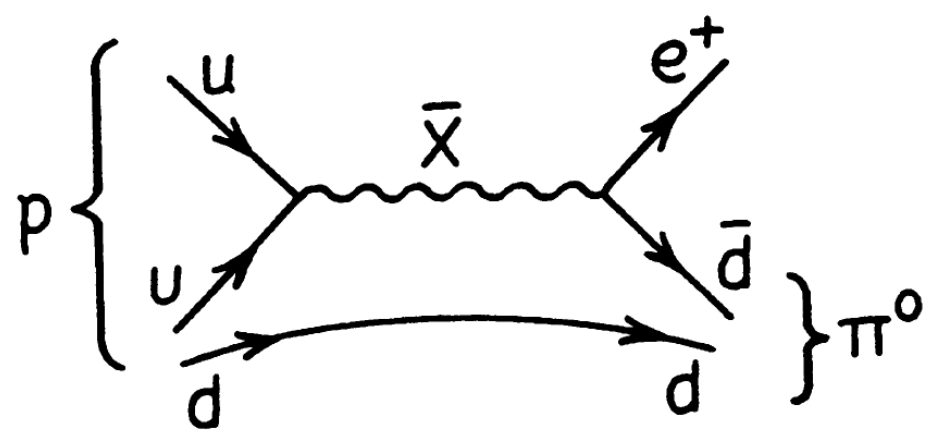
Nucleon decay

- $SU(5)$ GUT:
  - The gauge bosons have $\mathbf{5} \times \overline{\mathbf{5}} = \mathbf{1} + \mathbf{24}$: $(1,1) + (3,1) + (1,1) + (1,8) + (2,\overline{3}) + (\overline{2},3)$
  - New gauge bosons $(Y\ X)$: $SU(2)$ doublet of color triplets and their antiparticles



Nucleon decay

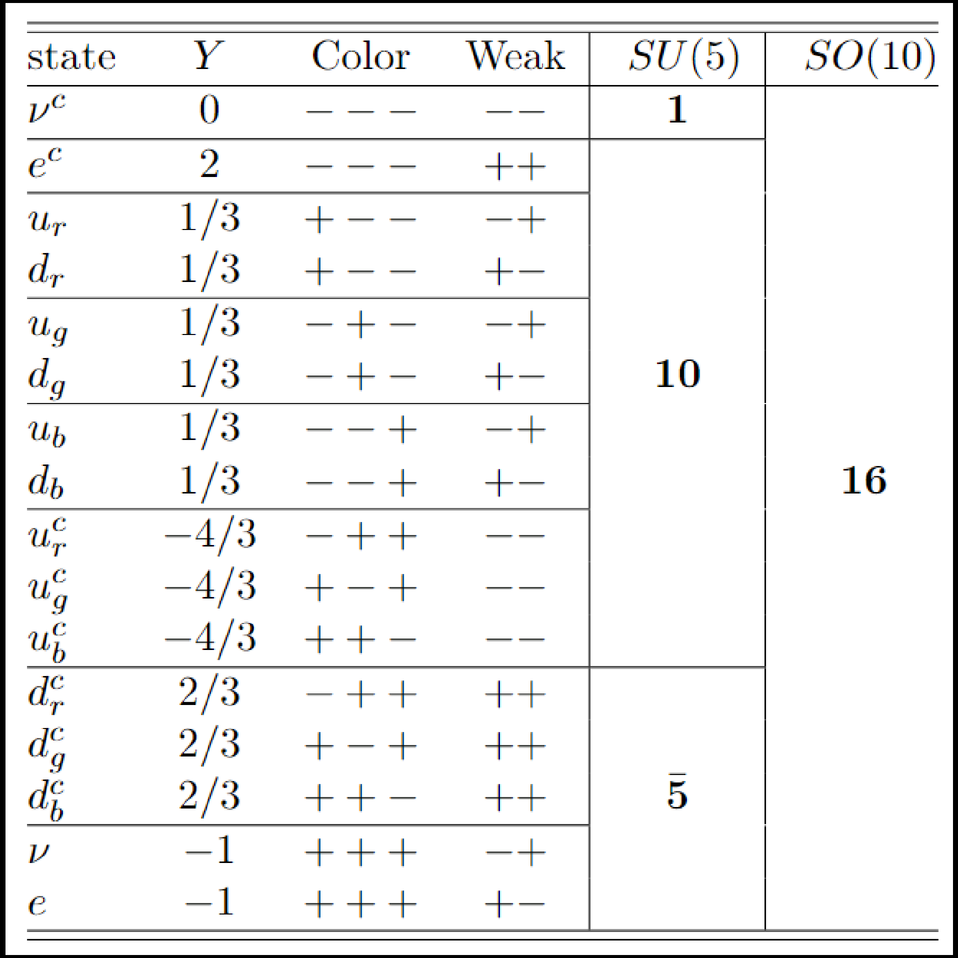
- The $p \rightarrow e^{+}\pi^{0}$ is the dominant decay mode predicted by many GUTs (not allowed in the SM).
- M_X is on the order of the grand unification scale:
  - $\Gamma_{p\rightarrow e^{+}\pi^{0}} \approx \frac{{g_5}^4 {m_p}^5}{{M_{unif}}^4}$
- $\tau_p = 1/\Gamma_p \sim 10^{31}$ years for $M_{unif} = 5 \times 10^{15}$ GeV
  - Consistent with our perception of protons as stable
- Most GUTs predict baryon number violation (BNV), which is one necessary condition for the matter dominance in the universe.



Representative GUTs

- The minimal SU(5) has already been ruled out experimentally.
- SO(10):
  - 16-dimentional spinor representation accommodates all SM fermions together with an extra singlet, potentially providing the ν_R.
  - It is possible to have the three couplings meet and to reproduce the observed nucleon decay rate limit.
- SUSY:
  - There are additional sources for BNV dimension-five operator.
  - The dominant decay mode: $p \rightarrow \bar{\nu}K^{+}$

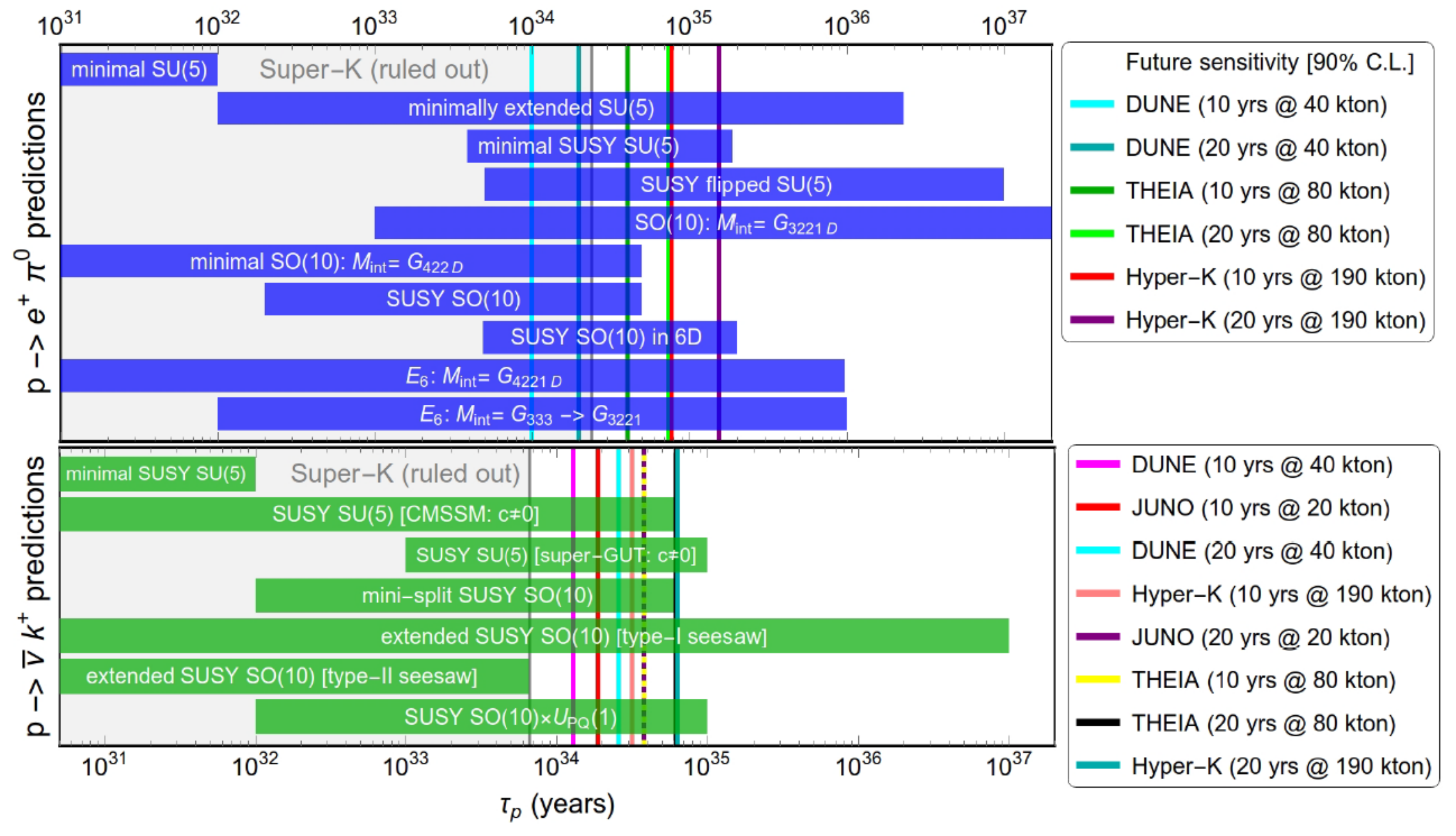
(PDG)



state	Y	Color	Weak	$SU(5)$	$SO(10)$
ν^c	0	$- - -$	$- -$	**1**	**16**
e^c	2	$- - -$	$+ +$	**10**	
u_r	$1/3$	$+ - -$	$- +$		
d_r	$1/3$	$+ - -$	$+ -$		
u_g	$1/3$	$- + -$	$- +$		
d_g	$1/3$	$- + -$	$+ -$		
u_b	$1/3$	$- - +$	$- +$		
d_b	$1/3$	$- - +$	$+ -$		
u_r^c	$-4/3$	$- + +$	$- -$		
u_g^c	$-4/3$	$+ - +$	$- -$		
u_b^c	$-4/3$	$+ + -$	$- -$		
d_r^c	$2/3$	$- + +$	$+ +$	$\bar{\mathbf{5}}$	
d_g^c	$2/3$	$+ - +$	$+ +$		
d_b^c	$2/3$	$+ + -$	$+ +$		
ν	-1	$+ + +$	$- +$		
e	-1	$+ + +$	$+ -$		

Theoretical predictions of proton lifetime

arXiv:2203.08771v2



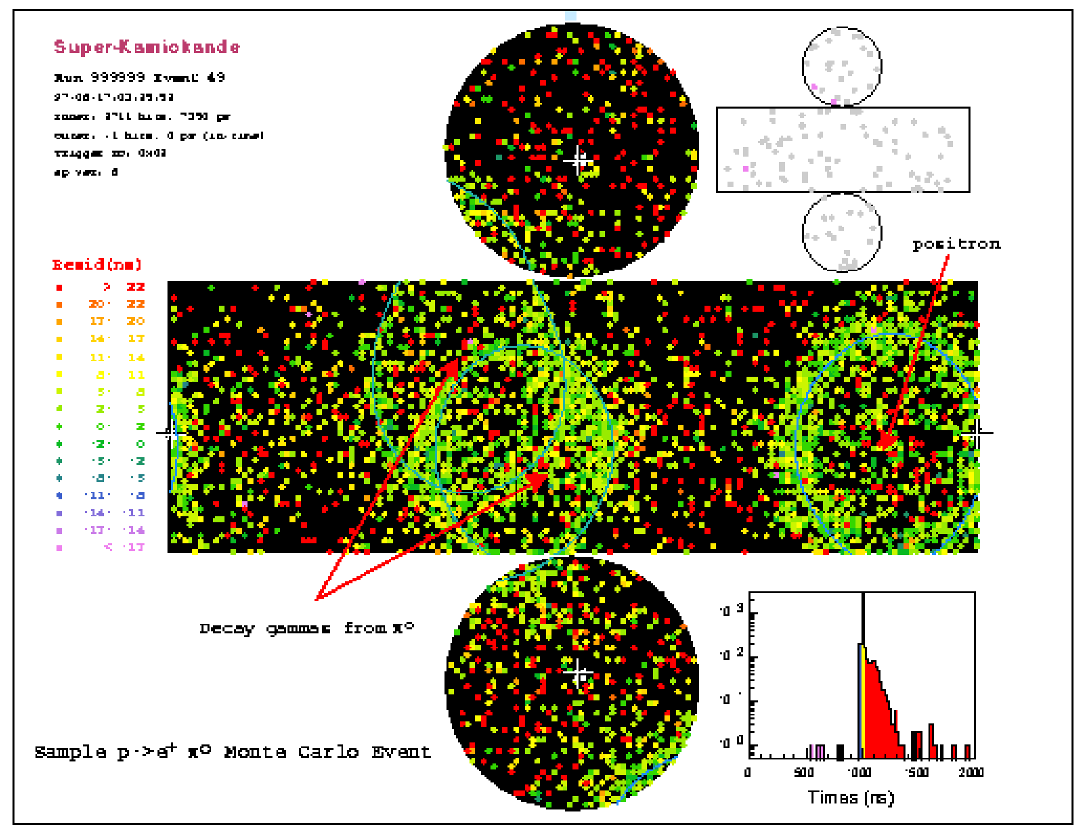
Also, refer “Experimental Studies of the Grand Unification” by Ed Kearns at SSI 2022.

Experiments

- Principle and method
- Experimental check of atmospheric neutrino background
- Recent results from SK
- Future experiments

Principle and method

A typical $p \to e^+\pi^0$ event simulated in SK



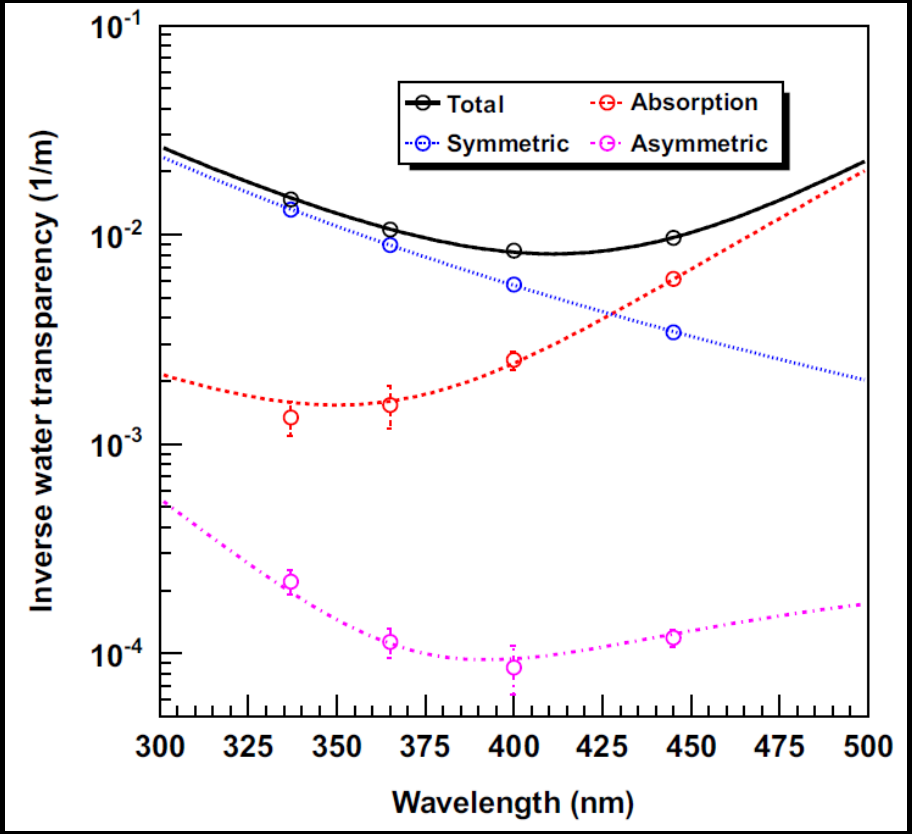
http://hep.bu.edu/~superk/pdk.html

- Super-Kamiokande (SK):
  - 39 m × 42 m vertical cylindrical tank
  - A conventional fiducial volume (the distance from the reconstructed vertex to the nearest ID wall > 2 m) contains approximately 7.5×10^{33} protons and 6.0×10^{33} neutrons.

Principle and method

- The combination of water with PMTs is beneficial for achieving a large effective volume.
- The light transmittance is highest at around 400 nm, matching the maximum quantum efficiency of the photocathode of the SK PMTs.
- At this wavelength the water transparency is ~100 m.

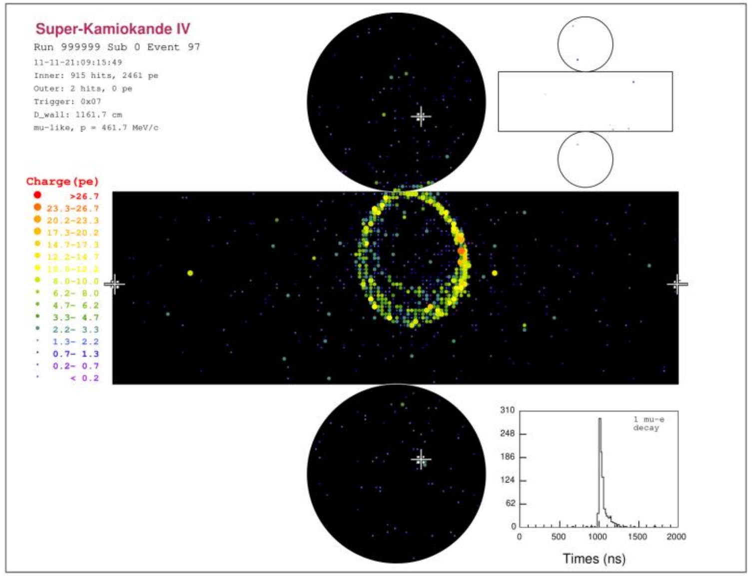
Nucl. Instrum. Methods Phys. Res. A 737, 253 (2014)



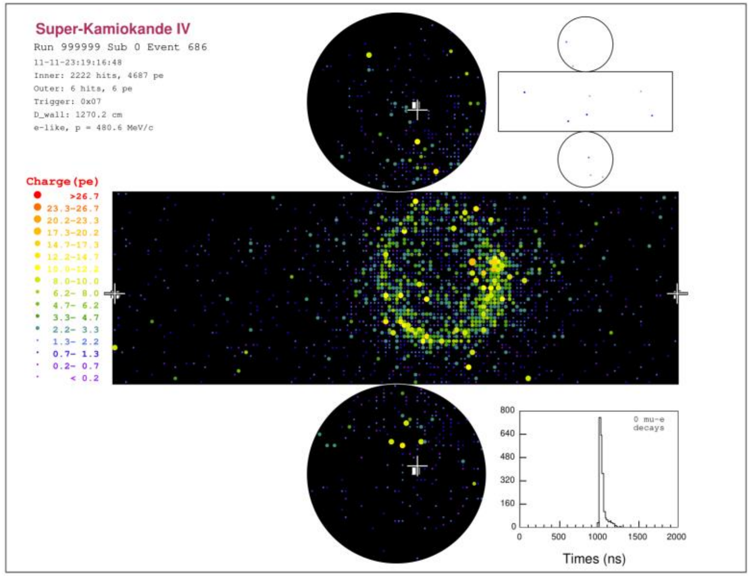
Principle and method

- Muon are basically single particles and make sharp rings.
- Electrons, positrons, and gamma ray photons initiate electromagnetic showers and the nearly parallel electrons and positrons in the shower combine to make a fuzzy ring. Coulomb scattering of the electron also contributes to the fuzziness of the ring.
- The excellent PID performance was experimentally confirmed using a 1-kiloton (KT) water Cherenkov detector with electron and muon beams from the 12 GeV proton synchrotron at KEK.

(Figure courtesy: Kamioka Observatory, ICRR, The University of Tokyo.)



μ MC
(~500 MeV/c)

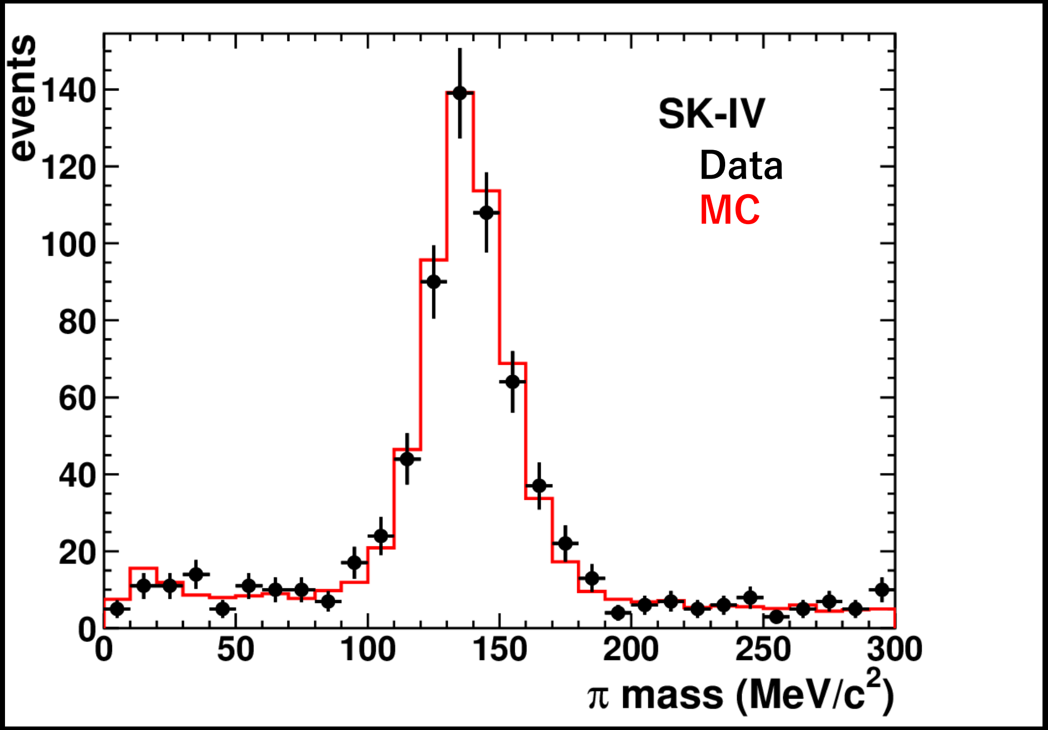


e MC
(~500 MeV/c)

Principle and method

- When multiple Cherenkov rings are observed, the direction, the particle type, and momentum are obtained for each ring, as in the case of the single ring event.
  - π^0 mass: The difference between the data and simulation peaks is used to estimate the absolute energy scale uncertainty.
- By assuming a type of nucleon decay, measurements of each charged particle and energetic photon in the final state can be used to reconstruct the original nucleon mass and so on.

Phys. Rev. D 96, 012003 (2017)



Principle and method

See T. Wester's talk on status of SK.

NIM A 501, 418 (2003)
NIM A 737, 253 (2014)
NIM A 1027, 166248 (2022)

Detector phase (years)	Live time [days]	Exposure [kt–years] conventional FV / expanded FV		ID PMT photo-coverage [%]	ID PMT cover	ID readout elec. modules	Gd-loading	Gd-n capture efficiency [%]
I (1996–2001)	~1489	~92	~111	~40		ATM		N/A
II (2002–2005)	~799	~49	~59	~20	✓	ATM		N/A
III (2006–2008)	~518	~32	~39	~40	✓	ATM		N/A
IV (2008–2018)	~3244	~200	~241	~40	✓	QBEE		N/A
V (2019–2020)	~461	~28	~34	~40	✓	QBEE		N/A
VI (2020–2022)	~564	~35	~42	~40	✓	QBEE	✓	~50
VII (2022–)	on-going	on-going	on-going	~40	✓	QBEE	✓	~75

"conventional/expanded FV": the distance from the reconstructed vertex to the nearest ID wall > 2/1 m.

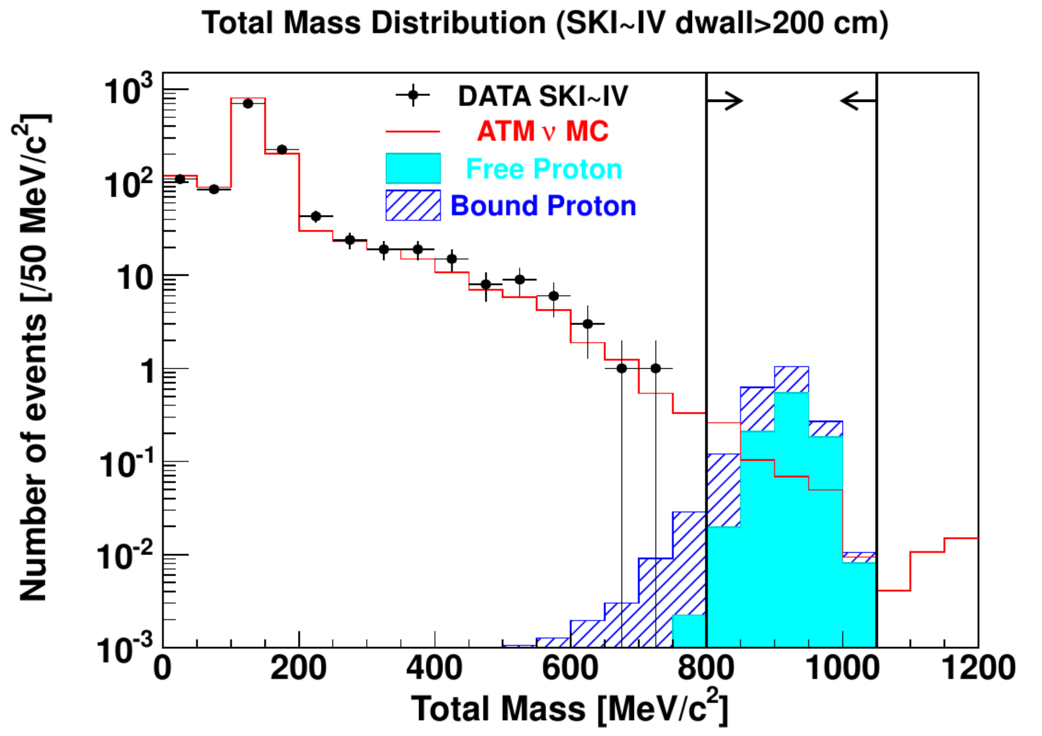
Principle and method

- Lifetime sensitivity ∝
  - $\begin{cases} \varepsilon \cdot VT & \text{(background-free)} \\ \left(\varepsilon/\sqrt{N_{bkg}}\right) \cdot \sqrt{VT} & \text{(background-dominant)} \end{cases}$
- The detector must have high detection efficiency to nucleon decay signal events.
- It is necessary to efficiently reduce the atmospheric neutrino background events.
- It is important to reduce systematic errors in the detection efficiency and the expected number of the background events.

- The $p \rightarrow e^{+}\pi^{0}$ event selections:
  - FCFV
  - 2 or 3 rings
  - All e-likes
  - $800 \leq M_{tot} \leq 1{,}050$ MeV/c^2
  - $P_{tot} \leq 250$ MeV/c
  - No tagged Michel electrons
  - No tagged neutrons (from SK-IV)

Principle and method

Phys. Rev. D 102, 112011 (2020)

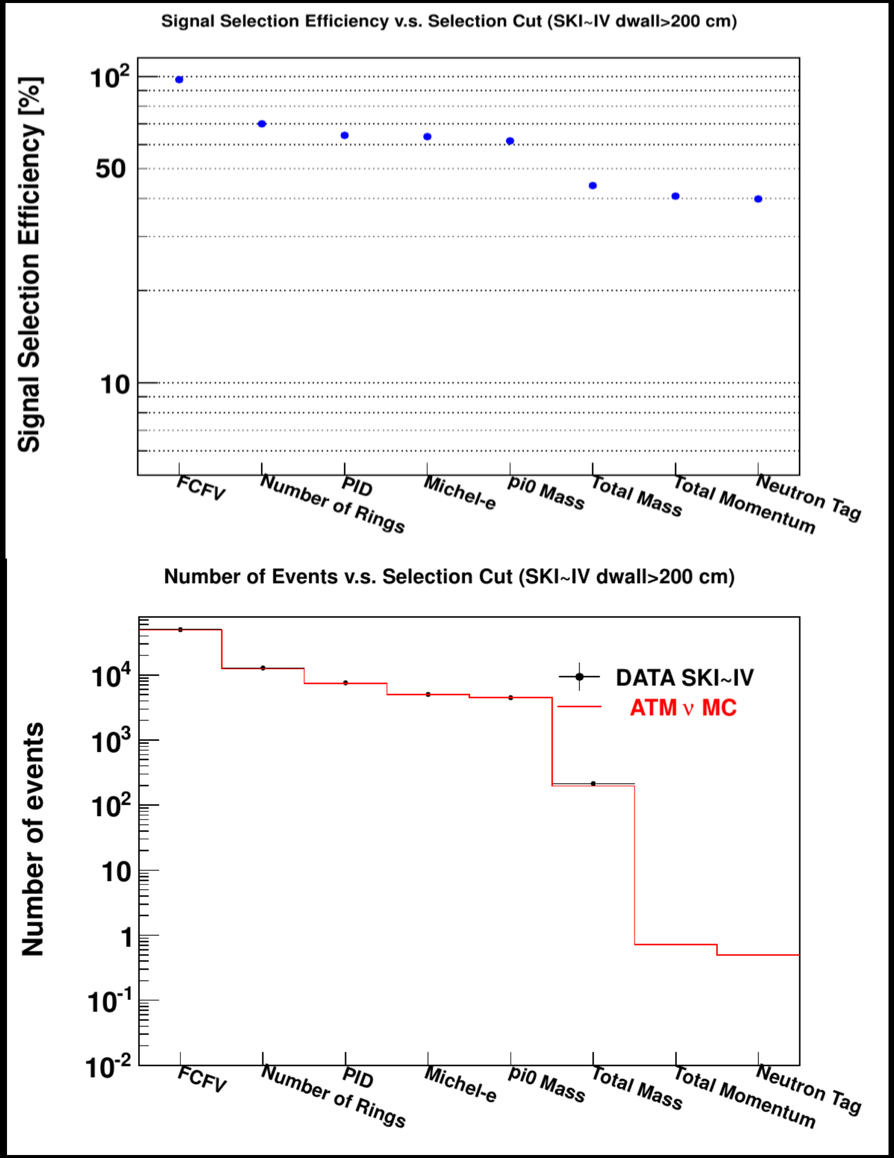


- Free protons are well reconstructed around the expected proton mass.
  - The kinematics of bound proton decays suffer pion scattering or correlated decay.
- The data distribution is well reproduced by atmospheric neutrino background MC.
- There are no data events in the signal region…

Principle and method

- The total signal selection efficiency and expected number of background events are ~40% and ~0.5 events, respectively.
- Suppressing the number of expected background events to 1 or less is one criterion for optimizing event reconstruction and event selections.

Phys. Rev. D 102, 112011 (2020)



Signal Selection Efficiency v.s. Selection Cut (SKI~IV dwall>200 cm)

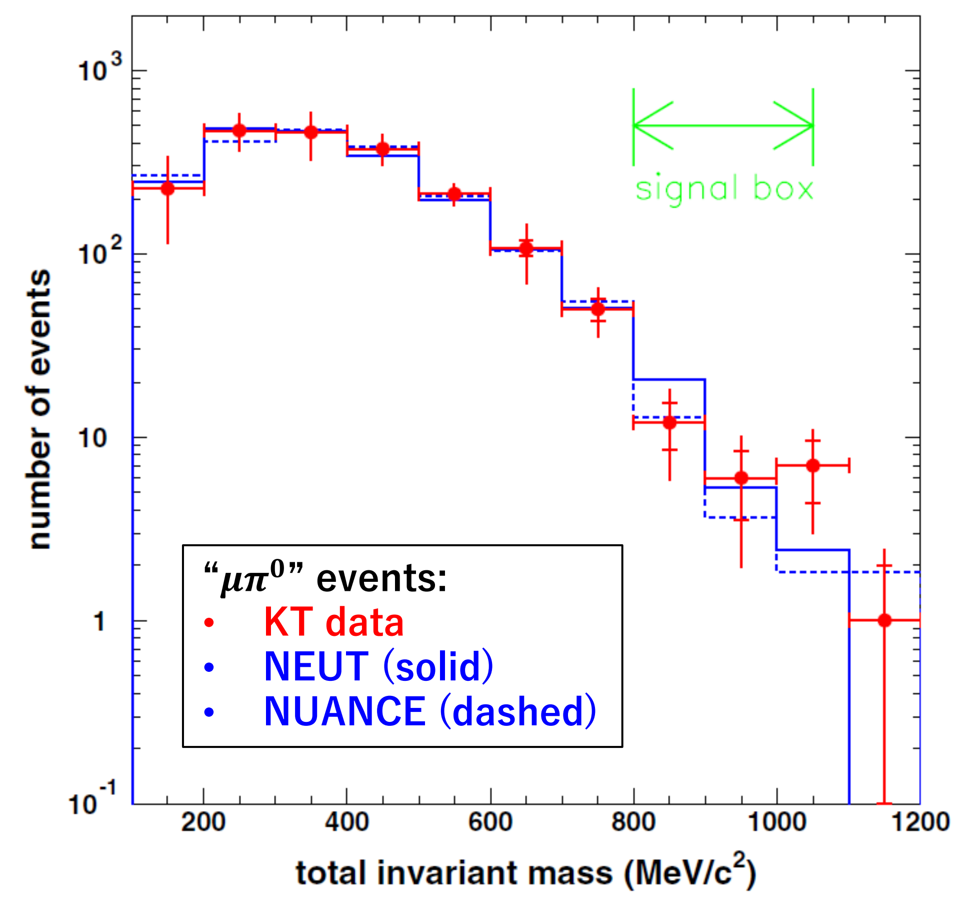
Number of Events v.s. Selection Cut (SKI~IV dwall>200 cm)

See Y. Hayato's talk on neutrino-nucleus interactions.

Experimental check of atmospheric neutrino background

- CC interaction of atmospheric ν_e with only an electron and single π^0 in the final state are the dominant source of the background to $p \rightarrow e^+\pi^0$ search.
- It is essential to experimentally check the neutrino interactions and the interactions of generated particles in oxygen nuclei and in water, which are used in atmospheric neutrino background simulations.
- The K2K KT detector accumulated data equivalent to atmospheric ν exposures of 15.9 and 4.5 Mt-years for the CC and NC background events.
- The measured event rate of the $p \rightarrow e^+\pi^0$ background: $1.63^{+0.42}_{-0.33}(\mathrm{stat})^{+0.45}_{-0.51}(\mathrm{syst})$ /Mt-yrs ($E_\nu < 3$ GeV)
  - In the SK's search, the expected atmospheric ν background rate estimated with MC is ~1.84 /Mt-yrs.
- Further reduction of the background events, such as improved neutron tagging, is crucial to make a clean discovery of proton decay.

Phys. Rev. D 77, 032003 (2008)



Recent results from SK

- Although the $p \rightarrow e^{+}\pi^{0}$ decay mode is predicted to be dominant in many GUTs, a variety of other decay modes are possible, each with a sizable branching ratio.
- The diversity in those predictions suggests that in order to make a discovery and to subsequently constrain nucleon decay models, it is critical to probe as many nucleon decay modes as possible.
- SK is sensitive to many decay modes beyond the two benchmark decays.
- So far, no nucleon decay signals have been observed that significantly exceed the expected number of background events…

References: See the full document.

Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]	Reference	Comments
$p \to e^+\pi^0$	I–IV	450	2.4×10^{34}	[20]	Expanded FV
$p \to \mu^+\pi^0$	I–IV	450	1.6×10^{34}	[20]	Expanded FV
$p \to \bar{\nu}\pi^+$	I–III	173	3.9×10^{32}	[21]	
$n \to \bar{\nu}\pi^0$	I–III	173	1.1×10^{33}	[21]	
$p \to e^+\eta$	I–IV	373	1.4×10^{34}	In prep.	
$p \to \mu^+\eta$	I–IV	373	7.3×10^{33}	In prep.	
$p \to e^+\rho^0$	I–IV	316	7.2×10^{32}	[22]	A part of SK IV data
$p \to \mu^+\rho^0$	I–IV	316	5.7×10^{32}	[22]	A part of SK IV data
$p \to e^+\omega$	I–IV	316	1.6×10^{33}	[22]	A part of SK IV data
$p \to \mu^+\omega$	I–IV	316	2.8×10^{33}	[22]	A part of SK IV data
$n \to e^+\pi^-$	I–IV	316	5.3×10^{33}	[22]	A part of SK IV data
$n \to \mu^+\pi^-$	I–IV	316	3.5×10^{33}	[22]	A part of SK IV data
$n \to e^+\rho^-$	I–IV	316	3.0×10^{31}	[22]	A part of SK IV data
$n \to \mu^+\rho^-$	I–IV	316	6.0×10^{31}	[22]	A part of SK IV data

See S. J. Woong's poster on $p \to l^+\pi^0\pi^0$ *and other latest searches at SK.*

Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]	Reference	Comments
$p \to e^+\pi^0\pi^0$	I–V	401	7.2×10^{33}	In prep.	
$p \to \mu^+\pi^0\pi^0$	I–V	401	4.5×10^{33}	In prep.	
$p \to e^+e^+e^-$	I–IV	373	3.4×10^{34}	[23]	
$p \to \mu^+e^+e^-$	I–IV	373	2.3×10^{34}	[23]	
$p \to \mu^-e^+e^+$	I–IV	373	1.9×10^{34}	[23]	
$p \to e^+\mu^+\mu^-$	I–IV	373	9.2×10^{33}	[23]	
$p \to e^-\mu^+\mu^+$	I–IV	373	1.1×10^{34}	[23]	
$p \to \mu^+\mu^+\mu^-$	I–IV	373	1.0×10^{34}	[23]	

Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]	Reference	Comments
$p \rightarrow e^{+}\nu\nu$	I–IV	273	1.7×10^{32}	[24]	A part of SK IV data
$p \rightarrow \mu^{+}\nu\nu$	I–IV	273	2.2×10^{32}	[24]	A part of SK IV data
$p \rightarrow e^{+}X$	I–IV	273	7.9×10^{32}	[25]	A part of SK IV data
$p \rightarrow \mu^{+}X$	I–IV	273	4.1×10^{32}	[25]	A part of SK IV data
$n \rightarrow \nu\gamma$	I–IV	273	5.5×10^{32}	[25]	A part of SK IV data

X is an invisible, massless particle.

Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]	Reference	Comments
$p \rightarrow \nu K^{+}$	I–IV	365	8.2×10^{33}	[26]	A part of SK IV data
$p \rightarrow \mu^{+} K^{0}$	I–IV	373	3.6×10^{33}	[27]	
$p \rightarrow e^{+} K^{0}$	I	92	1.3×10^{33}	[28]	
$p \rightarrow \mu^{+} K^{0}$	I	92	1.0×10^{33}	[28]	

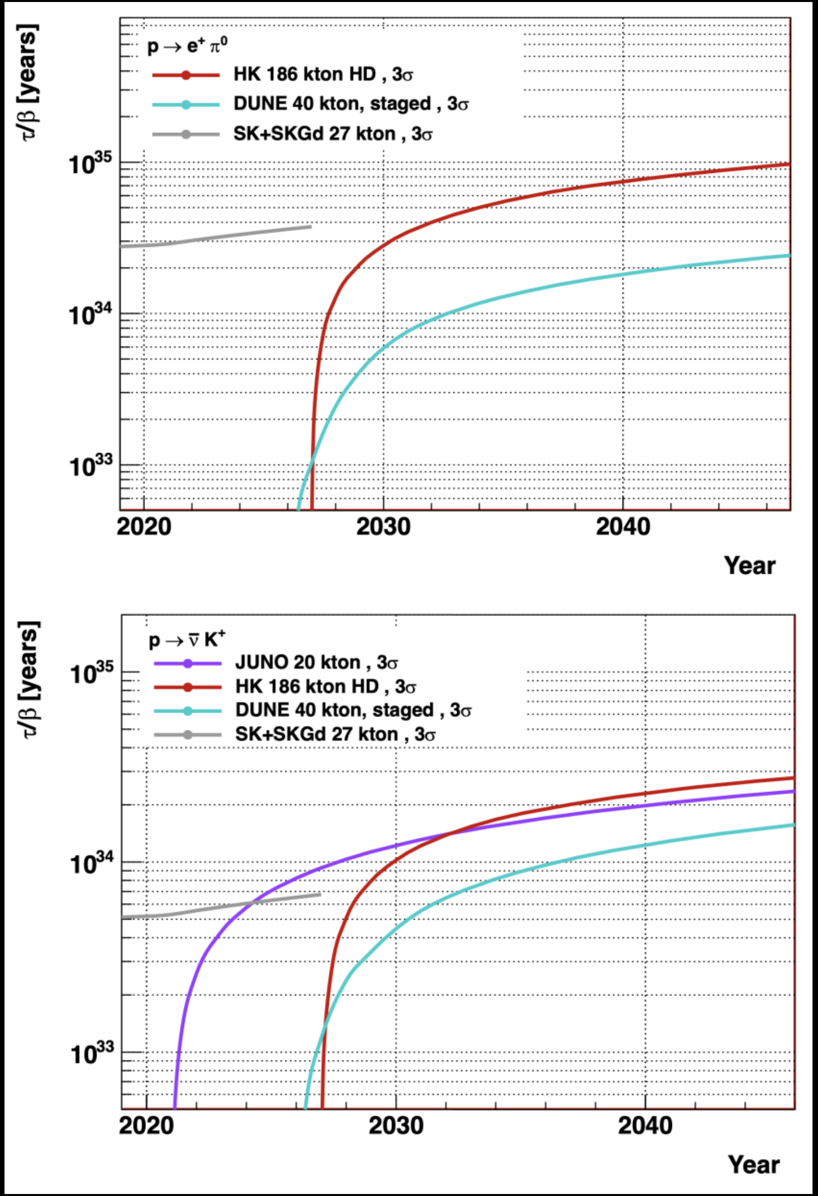
Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]	Reference	Comments
$pp \rightarrow e^+e^+$	I–IV	373	4.2×10^{33}	[29]	
$nn \rightarrow e^+e^-$	I–IV	373	4.2×10^{33}	[29]	
$nn \rightarrow \gamma\gamma$	I–IV	373	4.1×10^{33}	[29]	
$pp \rightarrow e^+\mu^+$	I–IV	373	4.4×10^{33}	[29]	
$nn \rightarrow e^+\mu^-$	I–IV	373	4.4×10^{33}	[29]	
$nn \rightarrow e^-\mu^+$	I–IV	373	4.4×10^{33}	[29]	
$pp \rightarrow \mu^+\mu^+$	I–IV	373	4.4×10^{33}	[29]	
$nn \rightarrow \mu^+\mu^-$	I–IV	373	4.4×10^{33}	[29]	
$pp \rightarrow \pi^+\pi^+$	I–IV	282	7.2×10^{31}	[30]	A part of SK IV data
$pn \rightarrow \pi^+\pi^0$	I–IV	282	1.7×10^{32}	[30]	A part of SK IV data
$nn \rightarrow \pi^0\pi^0$	I–IV	282	4.0×10^{32}	[30]	A part of SK IV data
$np \rightarrow e^+\nu$	I–IV	273	2.6×10^{32}	[25]	A part of SK IV data
$np \rightarrow \mu^+\nu$	I–IV	273	2.2×10^{32}	[25]	A part of SK IV data
$np \rightarrow \tau^+\nu$	I–IV	273	2.9×10^{31}	[25]	A part of SK IV data
$pp \rightarrow K^+K^+$	I	92	1.7×10^{32}	[31]	
$n \rightarrow \bar{n}$	I–IV	373	3.6×10^{32}	[32]	

arXiv:1805.04163
arXiv:2002.03005
arXiv:1508.07166

Future experiments

See K. Hiraide's talk on status of HK.

- Hyper-Kamiokande (HK):
  - Will use a 187 kiloton water target, about 8 times that of SK.
  - Expected to begin operations in 2027 and to improve on nucleon decay searches at SK by an order of magnitude or more.
  - Improved 50 cm PMTs: Twice the photon detection efficiency of the sensors used in SK. Also, about half the timing resolution for single photoelectron signals.
  - Notably, atmospheric neutrino backgrounds can be reduced by 30% relative to SK's achievement.



Future experiments

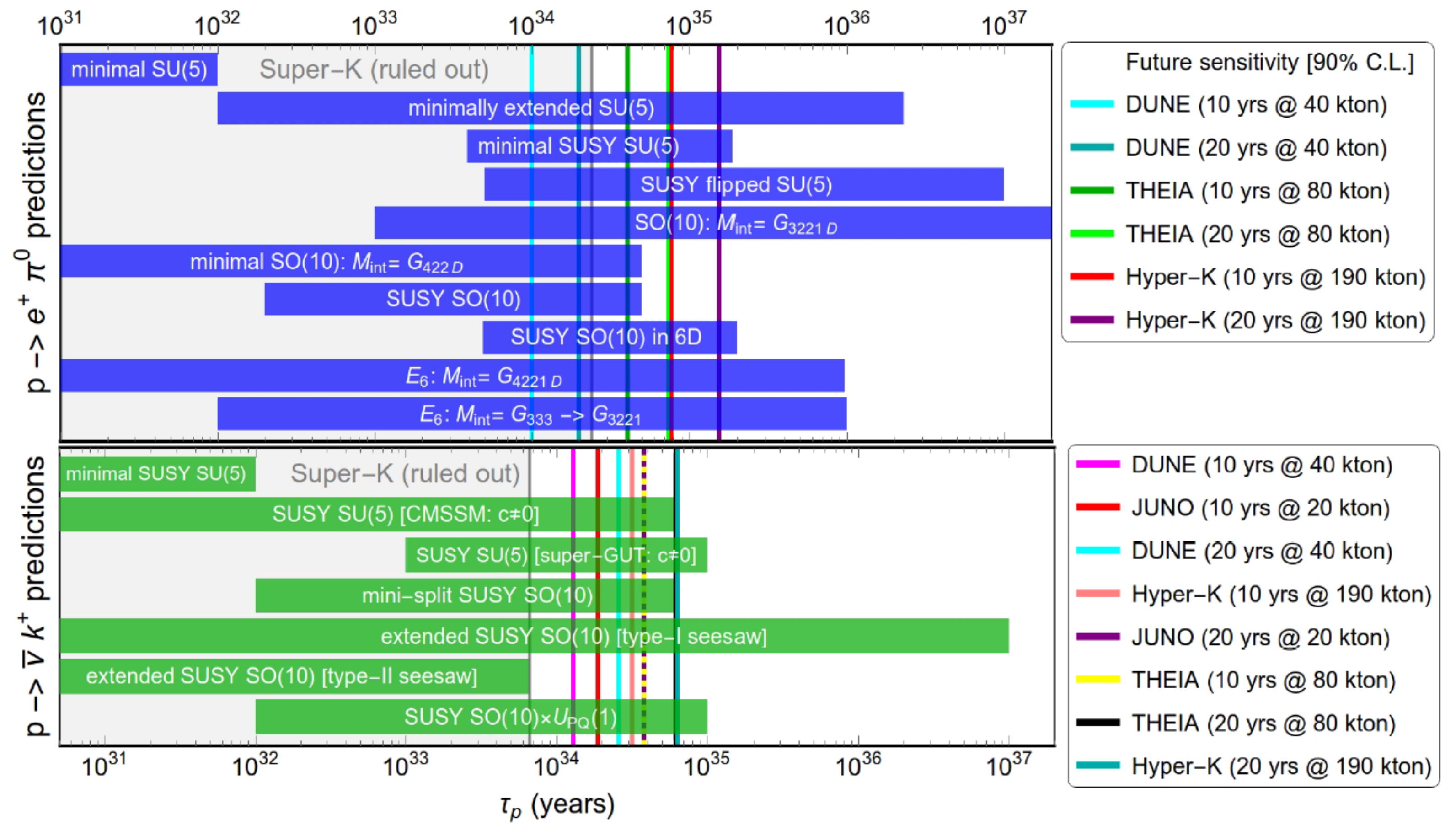
arXiv:2203.08771v2

Experiment	Detector technology	Fiducial volume [kiloton]
HK	Water Cherenkov	~190
DUNE	Liquid argon TPC	~40
JUNO	Liquid scintillator	~20
THEIA	Water-based liquid scintillator	~100

See M. Tenti's and M. Grassi's talks on status of DUNE and JUNO.

The sensitivity of the future experiments

arXiv:2203.08771v2



Summary

See the full document for details!

- Testing BNV is an essential and high priority objective of particle physics. The discovery of BNV will be an unambiguous signal of new physics, and therefore, it is important to search for as many BNV channels as possible.
- Nucleon decay searches at SK are on-going:
  - We have not yet found any evidence and continue to provide the most stringent limits.
  - We have prospects of sensitivity improvements by expanding FV, sophisticated event recontraction algorithms, and other improvements.
  - We are also searching for new decay modes.
- Future experiments will be conducted using different detector technologies. Confirmation of the observation of the BNV signal using them would provide powerful evidence of physics beyond the SM of particle physics.