Search for proton decay into a single charged antilepton and a massless invisible particle using the full pure water data set of Super-Kamiokande

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Search for Proton Decay

☐ Why search for proton decay?

- Grand unified theories (GUTs) are motivated by charge quantization and unification of strong, weak, and electromagnetic interaction
- Unification at the energy order of 10^{15}-10^{16} GeV is beyond the current achievement of accelerators
- A direct transition between quarks and leptons predicted in GUTs is a unique way for the proof

☐ Examples of Proton decay channel

- Proton decay results from Super-Kamiokande (SK) in recent 10 years

Channels	$p \to l^+ + \pi^0$ Phys. Rev. D 102, 112011 (2020)	$p \to 3$ charged leptons Phys. Rev. D 101, 052011 (2020)	$p \to l^+ +$ meson (η, ρ^0, ω)	$p \to \mu^+ + K^0$ Phys. Rev. D 106, 072003 (2022)
Lifetime	$\sim 10^{34}$ years	$\sim 10^{34}$ years	$10^{32} \sim 10^{34}$ years	$\sim 10^{33}$ years
Model	Non-SUSY GUTs	Non-SUSY GUTs + lepton flavor symmetries	Non-SUSY GUTs Phys. Rev. D 96, 012003 (2017)	SUSY GUTs

Search for $p \to l^+ + X$

☐ Target proton decay

- $p \to e^+ + X$, $p \to \mu^+ + X$ $\quad$ X is an unknown massless neutral particle and cannot be detected
- New physics scenarios with light invisible particles
  Phys. Rev. D 110, L031701 (2024)
- X is allowed as anything with limited spin

☐ Previous results Phys. Rev. Lett. 115, 121803 (2015)

- Analyzed by SK collaboration with exposure: $273\ \mathrm{kton} \cdot \mathrm{years}$
  Data set collected in 1996-2012,
  SK I-III and part of SK IV phase included
- Technique: spectral fit method
- Lower lifetime limit of $p \to e^+ + X$: 7.9×10^{32} years
- Lower lifetime limit of $p \to \mu^+ + X$: 4.1×10^{32} years

☐ About this study

- Building upon previous results with its SK I-III phase data and MCs, extends the analysis to include additional exposure from SK IV-V
  SK I-V is referred as
  total pure water phase
- Total exposure: $401\ \mathrm{kton} \cdot \mathrm{years}$
- Complete systematic errors included

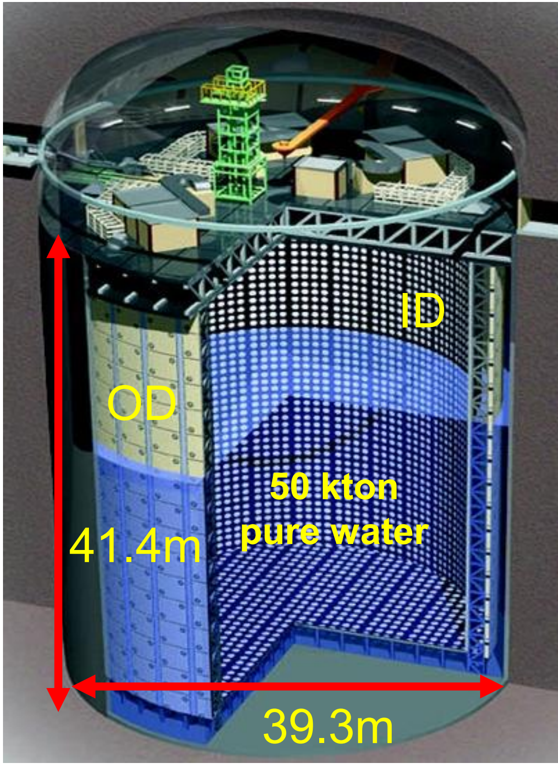
Super-Kamiokande (SK)

More details:
[doi:10.1142/9789819801107_0008](doi:10.1142/9789819801107_0008)

- **Location: 1000m underground in the Kamioka-mine, Japan**
- **Water-based detector (filled with 50 kton pure water)**
  - Water is the proton source for searches
  - Inner detector (ID): ~11000 20-inch PMTs
    Only half ID in SK II due to the accident
  - Outer detector (OD): 1885 8-inch PMTs

Total pure water phase in this study

Phase	Dates	Exposure (kton · years)
SK I	1996-2001	91.74
SK II	2002-2005	49.19
SK III	2006-2008	31.91
SK IV	2008-2018	199.86
SK V	2019-2020	28.40



SK upgraded and continued experiment with Gadolinium (Gd) dissolving in the water since 2020

Cherenkov Light Detection in SK

◻ Emission of Cherenkov light

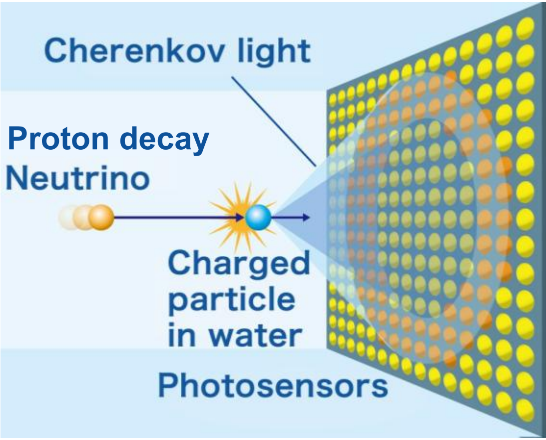
- Cherenkov light emitted by the interacted charged particle in the tank and is reconstructed as a ring of hit PMTs lined on the tank wall
- The energy, direction, interaction point, and type of the charged particles are determined by the information obtained from the PMTs

  ✓ Energy: reconstructed by observed number of Cherenkov photons, counts of Cherenkov photons ∝ momentum of the particle

  ✓ Direction: determined by the cone shape of Cherenkov light

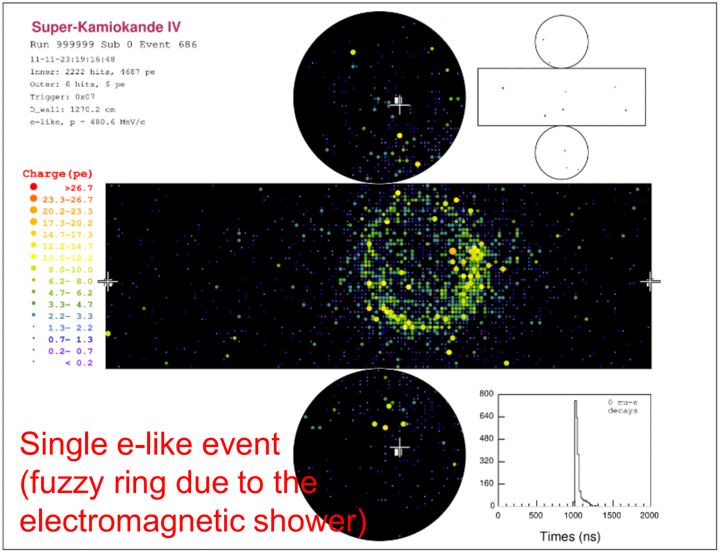
  ✓ Interaction point: determined by the photon arrival time information

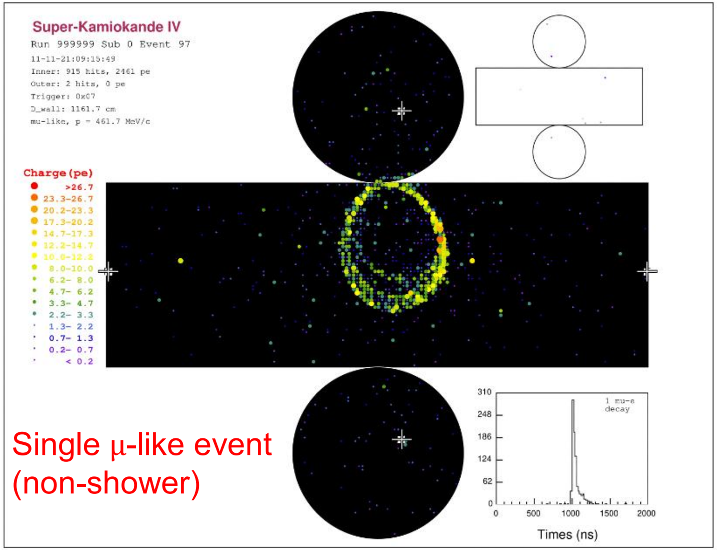
  ✓ Number of charged particles: counts of Cherenkov rings



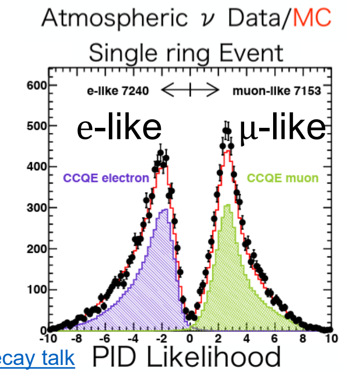
Ring Performance in SK

doi:10.1142/9789819801107_0008





- Good particle identification (PID) performance
  - ✓Shower ring ($e^{\pm}, \gamma$) and non-shower ring ($\mu^{\pm}, \pi^{\pm}$) can be identified by Cherenkov ring pattern
  - ✓Low mis-PID rate (~1% @ 1GeV for single ring)
- Good momentum resolution performance (~3% @ 1GeV for single ring)



Plot from proton decay talk @ NuPhys2019

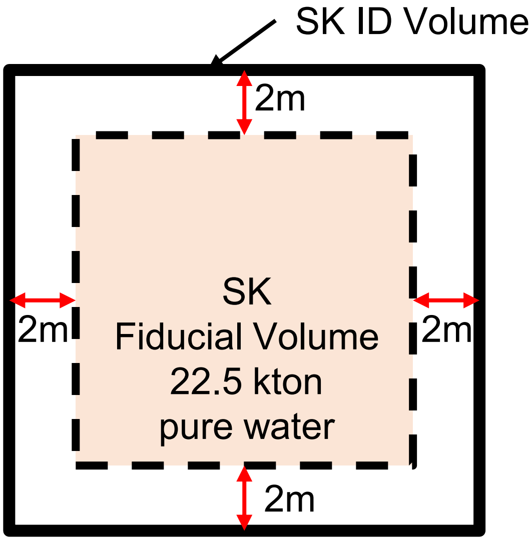
Event Selections

1. Fully Contained (FC), Fiducial Volume (FV) event
2. Single ring Sub-GeV ($E_{visible} < 1330$ MeV) event
3. Ring should be e-like for eX mode or μ-like for μX mode
4. No Michel electron for e-like event, 1 for μ-like event
5. Reconstructed Momentum cuts:

   100 < e-like event < 1000 MeV/c

   200 < μ-like event < 1000 MeV/c

By applying the event selections, around 80% background and collected data for $p \rightarrow e^+ + X$ and $p \rightarrow \mu^+ + X$ searches are subtracted in the FV region



Signal Detection Efficiency

Signal Efficiency [%]	$\mathbf{p \to e^+ + X}$	$\mathbf{p \to \mu^+ + X}$
SK I	92.7 ± 0.4	77.2 ± 0.7
SK II	95.1 ± 0.3	77.7 ± 0.7
SK III	94.4 ± 0.4	80.3 ± 0.6
SK IV	95.5 ± 0.1	95.6 ± 0.1
SK V	94.9 ± 0.1	95.2 ± 0.1

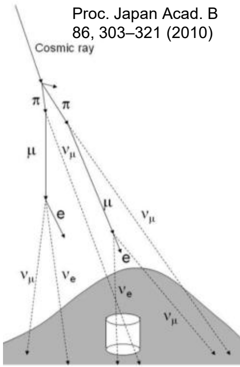
Upgrade of electronics before SK IV phase improves the Michel electron detection

Atmospheric Neutrino Background

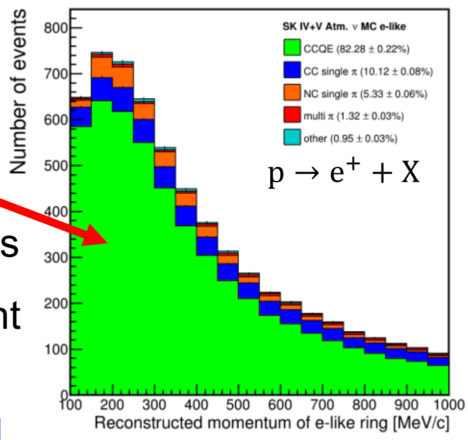
☐ The main background for proton decay searches

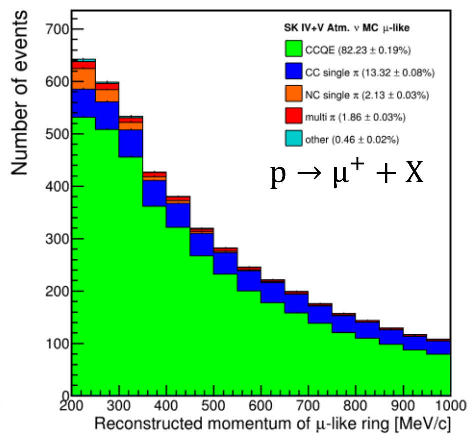
- Eventual production of cosmic rays interacting with the air molecule
- Neutrino interactions at SK: N, N': original and the outgoing nucleons
  l: outgoing charged lepton or neutrino
  - ✓CC/NC quasi-elastic (QE) scattering: $\nu + \mathrm{N} \rightarrow \mathrm{l} + \mathrm{N}'$
  - ✓CC/NC single-meson production: $\nu + \mathrm{N} \rightarrow \mathrm{l} + \mathrm{N}' + \mathrm{meson}$
  - ✓CC/NC coherent-pion production: $\nu + {}^{16}\mathrm{O} \rightarrow \mathrm{l} + {}^{16}\mathrm{O} + \pi^{\pm,0}$
  - ✓CC/NC deep inelastic scattering (DIS): $\nu + \mathrm{N} \rightarrow \mathrm{l} + \mathrm{N}' + \mathrm{hadrons}$

Proc. Japan Acad. B 86, 303–321 (2010)



- Dominant remaining background: CCQE
- CCQE systematic error is expected to be significant





Signals of $p \rightarrow e^+ + X$ and $p \rightarrow \mu^+ + X$

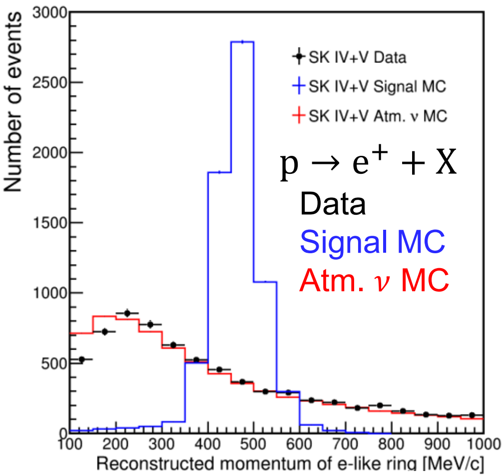
□ Source of protons comes from H_2O

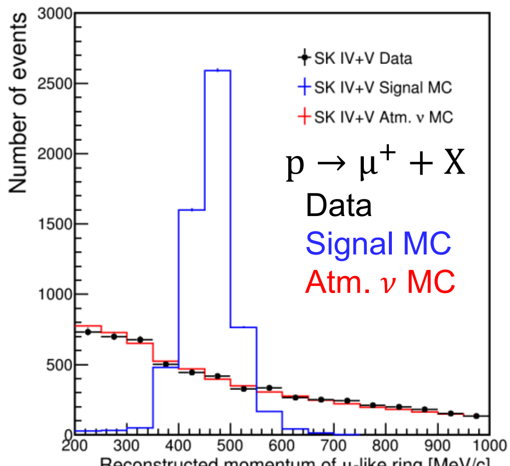
- 2 free protons from hydrogen: (initial mass of $938.27\,\mathrm{MeV/c^2}$ and 0 momentum)

  Simple 2-body decay, daughter particles take $\sim m_p/2$ of energy

- 8 bound protons from oxygen:

  Kinematics of Fermi momentum, binding energy, and correlated decay





MCs are normalized by data area

Spectral fit is applied by taking into account the shape different between MCs

Spectral Fit (χ^2 minimization fit)

$$\chi^2 = 2\sum_{i=1}^{nbins}\left(N_i^{exp} + N_i^{obs}\left[\ln\frac{N_i^{obs}}{N_i^{exp}} - 1\right]\right) + \sum_{j=1}^{N_{syserr}}\left(\frac{\epsilon_j}{\sigma_j}\right)^2$$

$$N_i^{exp} = \left[\alpha N_i^{bkg} + \beta N_i^{sig}\right]\left(1 + \sum_{j=1}^{N_{syserr}} f_i^j \frac{\epsilon_j}{\sigma_j}\right)$$

- ✓ N_i^{obs}, N_i^{sig}, N_i^{bkg}, N_i^{exp} are the numbers of observed data (“fake data” for sensitivity calculation) , signal MC, background MC and total MC (signal and background) in each reconstructed momentum bin i.
- ✓ j labels systematic errors, while f_i^j, σ_j, ϵ_j correspond to the fractional change, the 1σ error uncertainty and the fit error parameter.
- ✓ α and β are fitting parameters and χ^2 minimization is carried out over each (α, β) point according to $\partial\chi^2/\partial\epsilon_j = 0$

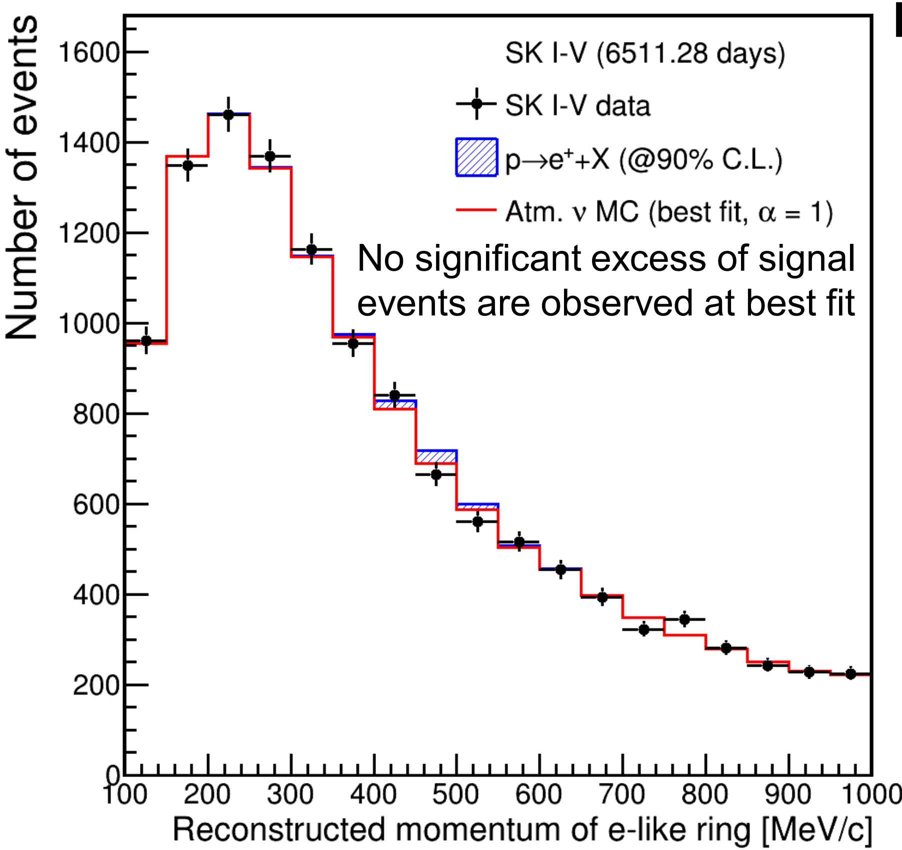
Systematics Performance of $p \rightarrow l^+ + X$

SK IV phase

Systematic uncertainty		Sensitivity $[10^{33}$ years]	
		$p \rightarrow e^+ + X$	$p \rightarrow \mu^+ + X$
Without systematic uncertainties		1.02	1.01
With all systematic uncertainties		0.92	0.93
Neutrino flux		0.99	1.01
Neutrino oscillation		1.02	1.01
Neutrino interaction	**CCQE scattering**	**0.96**	**0.94**
	Single π production	1.00	1.00
	DIS scattering	1.02	1.01
Final State Interaction (FSI)		0.97	1.00
Detector and reconstruction (FCFV, ring, PID, Michel electron, etc.)		1.00	0.99
Physical model for proton decay (Fermi momentum and correlated decay)		1.00	1.00

The sensitivity is greatly affected by the uncertainty of CCQE model, which is the main background interaction for $p \rightarrow e^+ + X$ and $p \rightarrow \mu^+ + X$

Spectral fit result of $p \to e^+ + X$



☐ Lifetime limit @ 90% C.L. (τ_{90})

- $\tau_{90} = \dfrac{\sum_i \lambda_i \times \epsilon_i \times N_{proton}}{N_{90}}$

λ: exposure (kton·year), ϵ: Signal eff.

N_{90} : # of proton decay counts @ 90% C.L.

N_{proton}: proton numbers in the tank ($3.34 \times 10^{32} \mathrm{kton}^{-1}$)

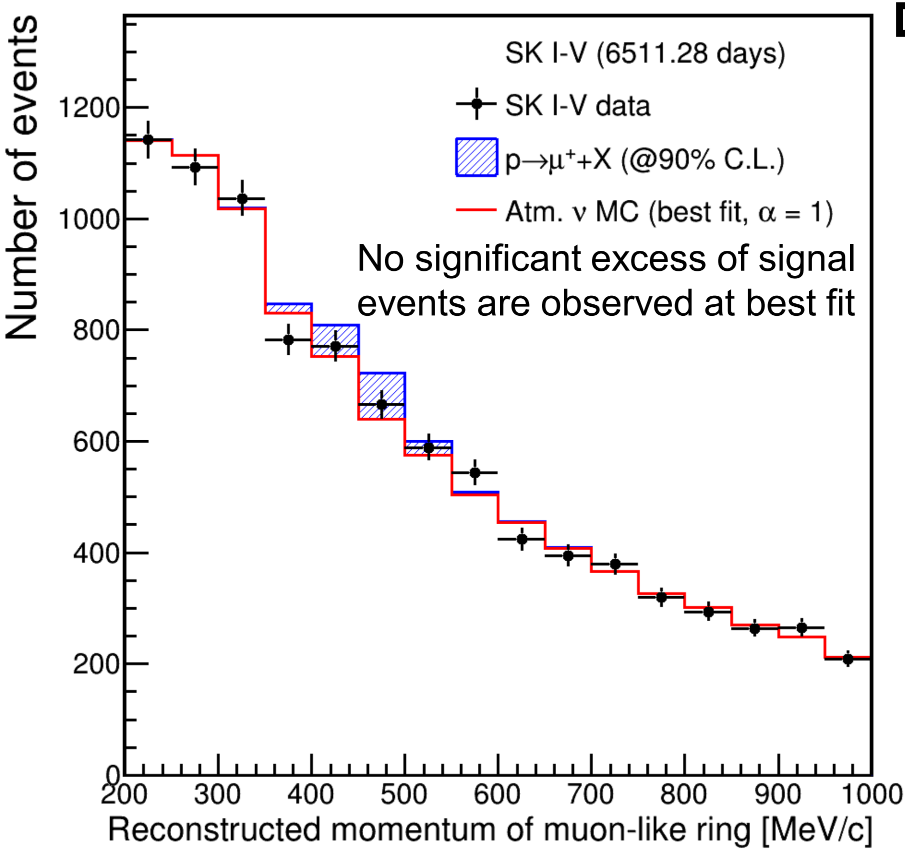
- τ_{90} of $p \to e^+ + X$:

  1.72×10^{33} years

  ($N_{90} = 73$)

- Lifetime limit is doubly improved by comparing to the previous result (0.79×10^{33} years)

Spectral fit result of $\mathrm{p} \rightarrow \mu^{+} + \mathrm{X}$



☐ Lifetime limit @ 90% C.L. (τ_{90})

- $\tau_{90} = \dfrac{\sum_i \lambda_i \times \epsilon_i \times N_{proton}}{N_{90}}$
- τ_{90} of $\mathrm{p} \rightarrow \mu^{+} + \mathrm{X}$:

  $\mathbf{0.61 \times 10^{33}}$ **years**

  $(N_{90} = 190)$

- Lifetime limit is 50% improved by comparing to the previous result (0.41×10^{33} years)

Summary

- Super-Kamiokande devotes it energies to search for proton decay and has set most stringent limits on plenty channels

- The search for $\mathrm{p} \rightarrow \mathrm{e}^{+} + \mathrm{X}$ and $\mathrm{p} \rightarrow \mu^{+} + \mathrm{X}$ are updated with the SK total pure water phase ($273\mathrm{kton} \cdot \mathrm{years}$ to $401\mathrm{kton} \cdot \mathrm{years}$)

- Lower lifetime limit**:**
  - No significant signal events beyond the expected ATM. ν BG events for $\mathrm{p} \rightarrow \mathrm{e}^{+} + \mathrm{X}$ and $\mathrm{p} \rightarrow \mu^{+} + \mathrm{X}$

  - New stringent lifetime limits, $\mathbf{1.72 \times 10^{33}}$ **years** ($\mathrm{p} \rightarrow \mathrm{e}^{+} + \mathrm{X}$) and $\mathbf{0.61 \times 10^{33}}$ **years** ($\mathrm{p} \rightarrow \mu^{+} + \mathrm{X}$), are set with a factor about 2 and 1.5 improvement, respectively

  - More overview and prospect decay channels in link SK and keeping an eye on the SK-Gd phase and future Hyper-Kamiokande

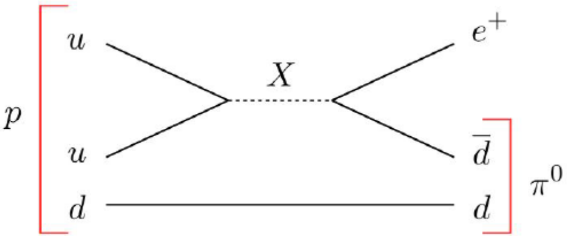
“

BACKUP SLIDES

Grand unified theories (GUTs)

☐ Extension of the Standard Model

- Strong, weak and electromagnetic forces are unified
- Leptons are able to interact with quarks
  - ⇒ Baryon number violation is allowed
  - ⇒ Proton decay is predicted



☐ Minimal SU(5)

- The simplest GUT model
- SU(5) group contains SU(3), SU(2) and U(1) gauge groups
- $p \rightarrow e^{+} + \pi^{0}$ is predicted
- The minimal SU(5) model is ruled out by the experiment results

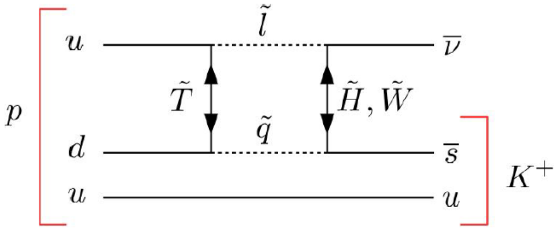
Grand unified theories (GUTs)

◻ SO(10)

- SU(3)×SU(2)×U(1) is included
- Intermediate symmetries such as SU(5)×U(1) in its breaking process to SM
- Predict $p \to e^+ + \pi^0$, $p \to \mu^+ + \pi^0$, $p \to \bar{\nu} + \pi^+$ and $p \to \mu^+ + K^0$

◻ Supersymmetric GUTs

- Supersymmetry (SUSY) framework is added to GUTs
- Contributions from the SUSY make the energy scale of the GUTs higher and extend the lifetime of proton decay
- $p \to \bar{\nu} + K^+$ is predicted



Latest proton decay search in SK

Decay channel	Lifetime limit (years)	Reference
$p \to e^+ + \pi^0$	2.4×10^{34}	Phys. Rev. D 102, 112011 (2020)
$p \to \mu^+ + \pi^0$	1.6×10^{34}	Phys. Rev. D 102, 112011 (2020)
$p \to \bar{\nu} + K^+$	8.2×10^{33}	Phys. Rev. D 90, 072005 (2014)
$p \to \bar{\nu} + \pi^+$	3.9×10^{32}	Phys. Rev. Lett. 115, 121802 (2014)
$p \to \mu^+ + K^0$	3.6×10^{33}	Phys. Rev. D 106, 072003 (2022)
$p \to e^+ + e^+ + e^-$	3.4×10^{34}	Phys. Rev. D 101, 052011 (2020)
$p \to \mu^+ + e^+ + e^-$	2.3×10^{34}	Phys. Rev. D 101, 052011 (2020)
$p \to \mu^- + e^+ + e^+$	1.9×10^{34}	Phys. Rev. D 101, 052011 (2020)
$p \to e^+ + \mu^+ + \mu^-$	9.2×10^{33}	Phys. Rev. D 101, 052011 (2020)
$p \to e^- + \mu^+ + \mu^+$	1.1×10^{34}	Phys. Rev. D 101, 052011 (2020)
$p \to \mu^+ + \mu^+ + \mu^-$	1.0×10^{34}	Phys. Rev. D 101, 052011 (2020)

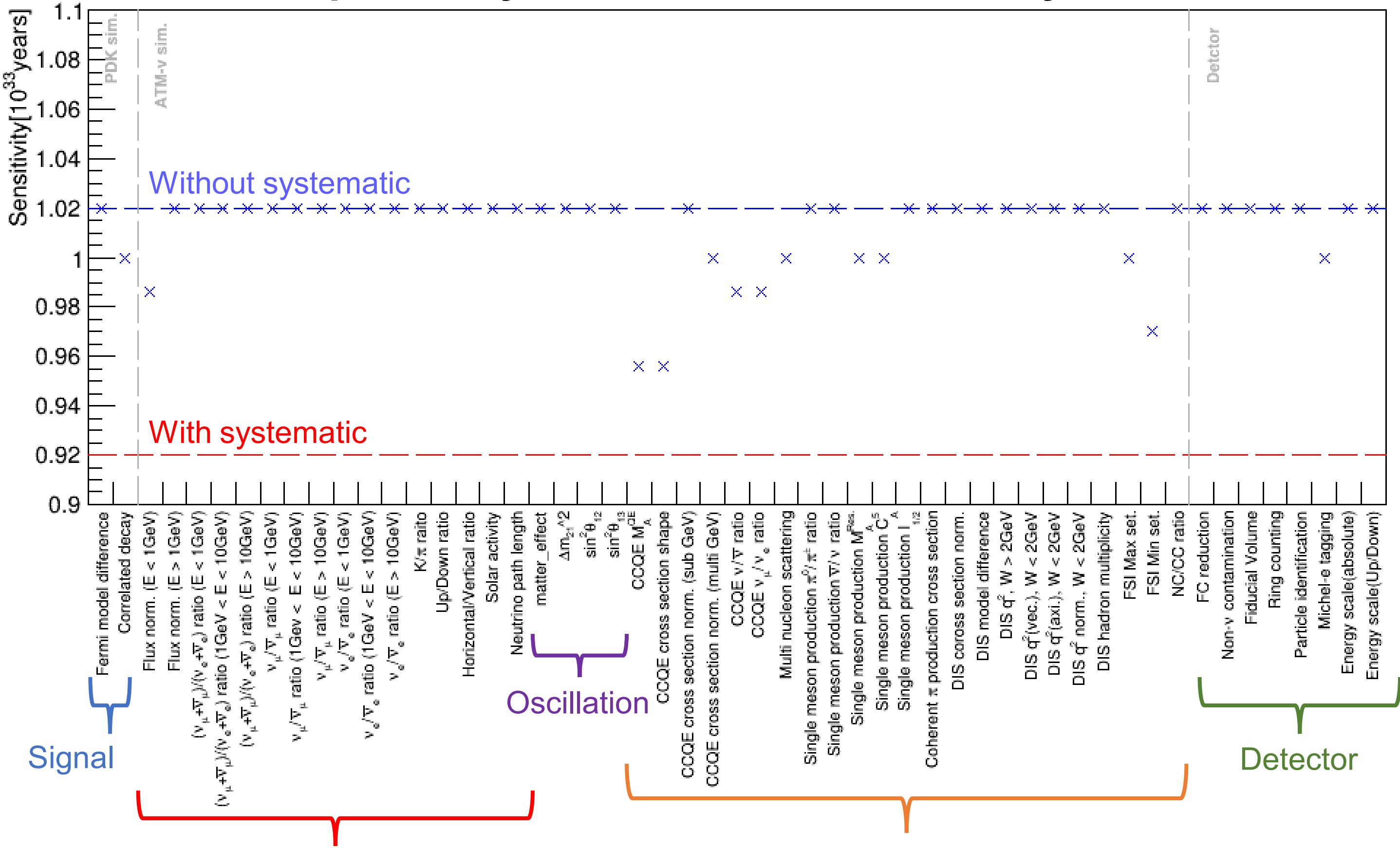
Latest proton decay search in SK

summay of nucleon decay

Decay channel	Lifetime limit (years)	Reference
$p \rightarrow e^+ + \eta$	1.0×10^{34}	Phys. Rev. D 96, 012003 (2017)
$p \rightarrow \mu^+ + \eta$	4.7×10^{33}	Phys. Rev. D 96, 012003 (2017)
$p \rightarrow e^+ + \rho^0$	7.2×10^{32}	Phys. Rev. D 96, 012003 (2017)
$p \rightarrow \mu^+ + \rho^0$	5.7×10^{32}	Phys. Rev. D 96, 012003 (2017)
$p \rightarrow e^+ + \omega$	1.6×10^{33}	Phys. Rev. D 96, 012003 (2017)
$p \rightarrow \mu^+ + \omega$	2.8×10^{33}	Phys. Rev. D 96, 012003 (2017)
$p \rightarrow e^+ + \nu + \nu$	1.7×10^{32}	Phys. Rev. Lett. 117, 101801 (2014)
$p \rightarrow \mu^+ + \nu + \nu$	2.2×10^{32}	Phys. Rev. Lett. 117, 101801 (2014)
$p \rightarrow e^+ + K^0$	1.3×10^{33}	Phys. Rev. D 72, 052007 (2005)
$p \rightarrow e^+ + X$	7.9×10^{32}	Phys. Rev. Lett. 115, 121803 (2015)
$p \rightarrow \mu^+ + X$	4.1×10^{32}	Phys. Rev. Lett. 115, 121803 (2015)

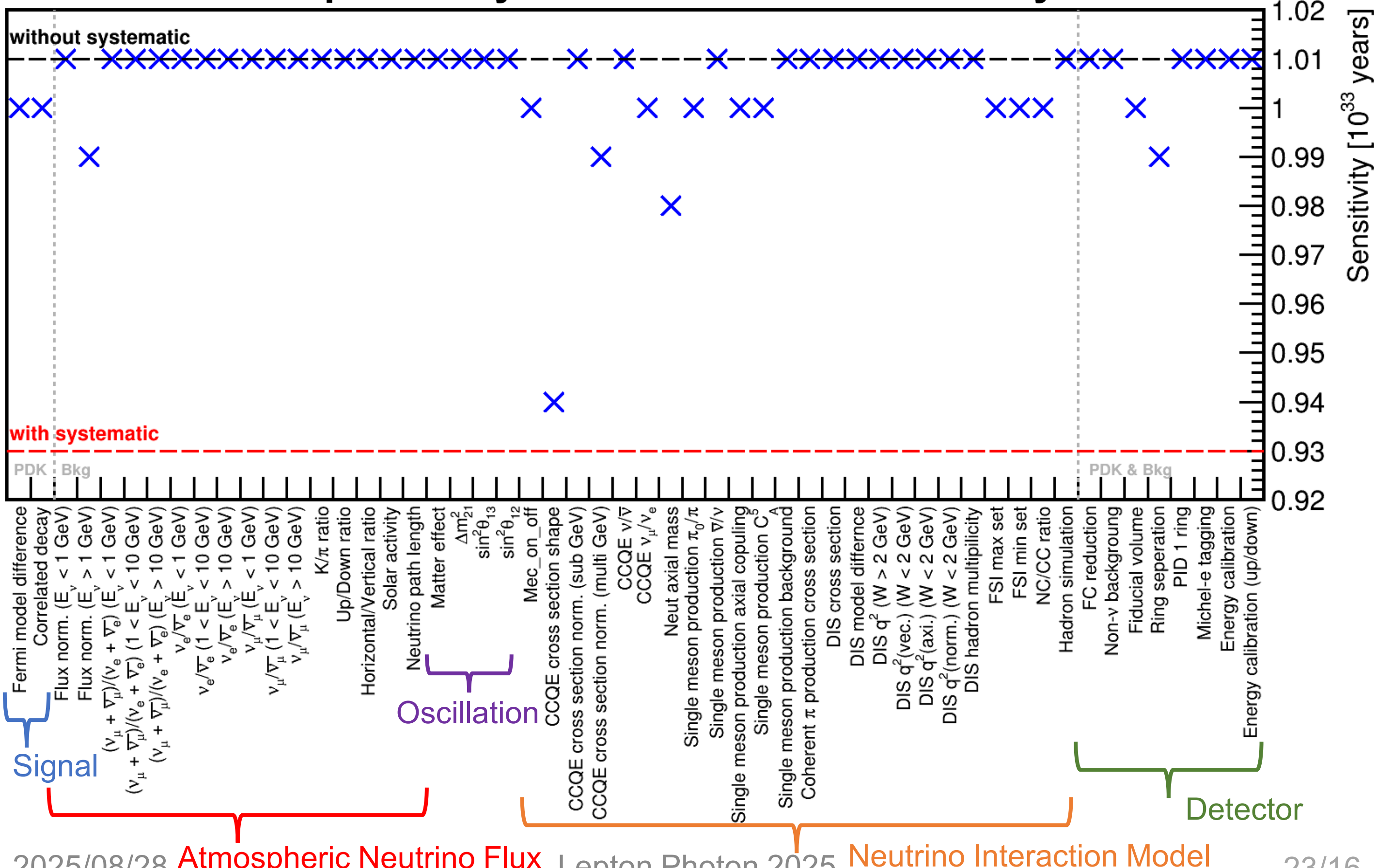
Systematics Performance of $p \to e^+ + X$

◻ Individual impact of systematics on the sensitivity



Systematics Performance of $p \to \mu^+ + X$

□ Individual impact of systematics on the sensitivity



Neutrino Flux Related Systematic Errors

Error sources are identical with the atmospheric neutrino oscillation analysis, Phys. Rev. D 109, 072014 (2024). Details can be checked here

Systematic errors		1σ
Solar activity	SK I	0.2
	SK II	0.5
	SK III	0.2
	SK IV	0.07
	SK V	0.2

Systematic errors		1σ
Flux normalization	$E_\nu < 1GeV$	0.25
	$E_\nu > 1GeV$	0.15
$\frac{(\nu_\mu + \overline{\nu_\mu})}{(\nu_e + \overline{\nu_e})}$	$E_\nu < 1GeV$	0.02
	$1 < E_\nu < 10GeV$	0.03
	$E_\nu > 10GeV$	0.05
$\frac{\overline{\nu_e}}{\nu_e}$	$E_\nu < 1GeV$	0.05
	$1 < E_\nu < 10GeV$	0.05
	$E_\nu > 10GeV$	0.08
$\frac{\overline{\nu_\mu}}{\nu_\mu}$	$E_\nu < 1GeV$	0.02
	$1 < E_\nu < 10GeV$	0.06
	$E_\nu > 10GeV$	0.06
up/down ratio		0.01
horizontal/vertical ratio		0.01
K/π ratio		0.1
Neutrino path length		0.1

Oscillation Related Systematic Errors

Systematic errors	1σ
Matter effect	0.068
$\sin^2(\theta_{13})$	0.0007
$\sin^2(\theta_{12})$	0.013
Δm^2_{21}	1.8×10^{-6}

Neutrino Interaction Related Systematic Errors

Error sources are identical with the atmospheric neutrino oscillation analysis, [Phys. Rev. D 109, 072014 (2024)](). Details can be checked [here]()

Systematic errors	1σ
Coherent π production	1
NC/CC ratio	0.2
Hadron simulation	0.1
FSI parameter 1	0.1
FSI parameter 2	0.1
Axial mass	0.1
Meson charge current	0.1

Systematic errors		1σ
CCQE	cross section	0.1
	cross section (sub-GeV)	0.1
	cross section (multi-GeV)	0.1
	$\bar{\nu}/\nu$	0.1
	ν_μ/ν_e	0.1
DIS	model difference	0.1
	cross section	0.1
	Q^2(high W)	0.1
	Q^2(low W)	0.1
	Q^2(vector)	0.1
	Q^2(axial)	0.1
	Hadron multiplicity	0.1
Single π production	π_0/π	0.4
	$\bar{\nu}/\nu$	0.1
	Axial coupling	0.1
	CA5	0.1
	background	0.1

Signal Related Systematic Errors

Systematic errors	1σ
Fermi model	0.1
Correlated decay	1

Detector Related Systematic Errors

1σ uncertainty of Systematic error	FC reduction	Non-ν background	Ring separation	PID 1 ring
SK I	0.002	0.01	0.1	0.01
SK II	0.002	0.01	0.1	0.01
SK III	0.008	0.01	0.1	0.01
SK IV	0.017	0.01	0.1	0.01
SK V	0.017	0.01	0.1	0.01

1σ uncertainty of Systematic error	Energy calibration	Energy calibration (up/down)	Michel-e tagging	Fiducial volume
SK I	0.033	0.006	0.1	0.02
SK II	0.02	0.011	0.1	0.02
SK III	0.024	0.006	0.1	0.02
SK IV	0.021	0.005	0.1	0.02
SK V	0.018	0.0069	0.1	0.02