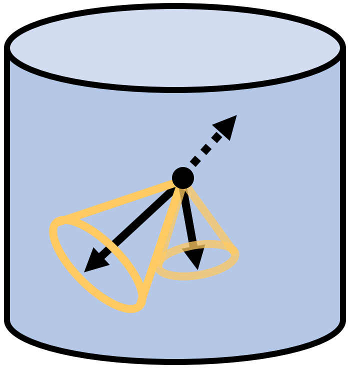

Search for neutron decay into an antineutrino and a neutral kaon in Super-Kamiokande

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for Super-Kamiokande Collaboration

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XICHANG SICHUAN, CHINA
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GUTs and nucleon decay

- **Grand Unified Theories (GUTs)**
  - Propose a unification of the weak, strong, and electromagnetic interactions at extremely high energies, typically the order of 10^{15}-10^{16} GeV, which is well beyond the energy currently achieved by accelerators.
    → **Predict** processes that violate baryon number conservation including **nucleon decay.**

- **Nucleon decay**
  - **Provides a critical experimental test for GUTs.**
  - Decay particles or lifetimes depend on the models.
    → Various decay modes have been searched for, but none have been discovered yet.
  - Super-Kamiokande monitors a large number of nucleons and searches for nucleon decay.

Super-Kamiokande detector

- 50 kton water Cherenkov detector
- Located 1,000 m underground in Kamioka mine, Japan.
- >11,000 PMTs are placed on the wall.

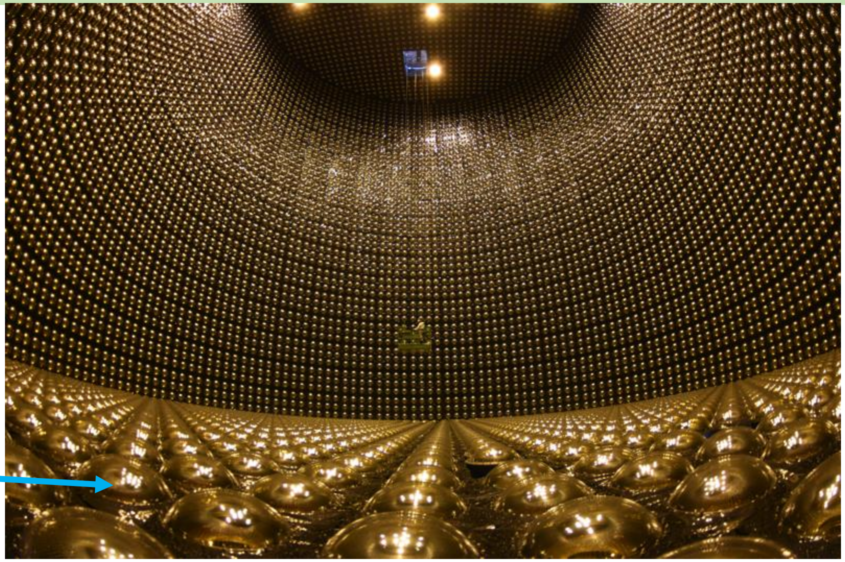
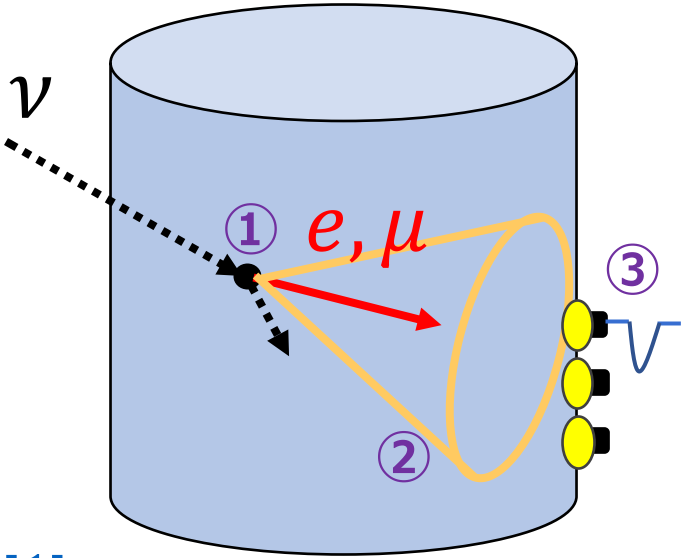


Photo-multiplier tube (PMT)

① Charged particles are generated by nucleon decay or neutrino interaction.

② They emit Cherenkov light.

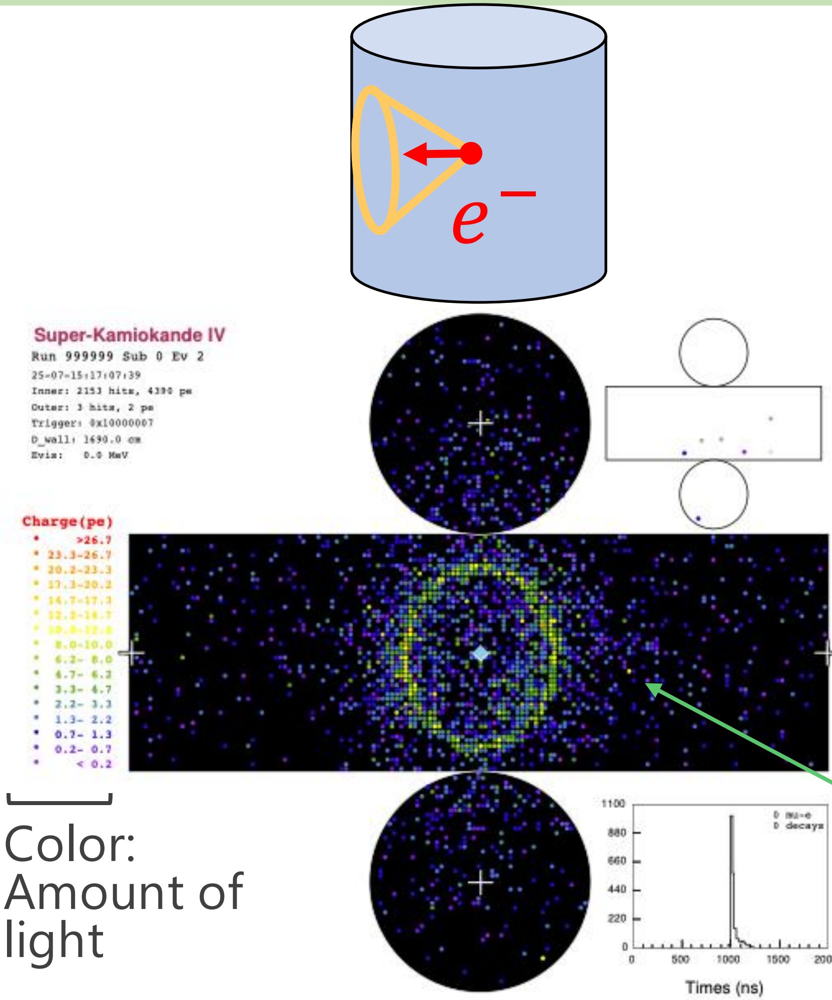
③ Cherenkov light is detected by PMTs.

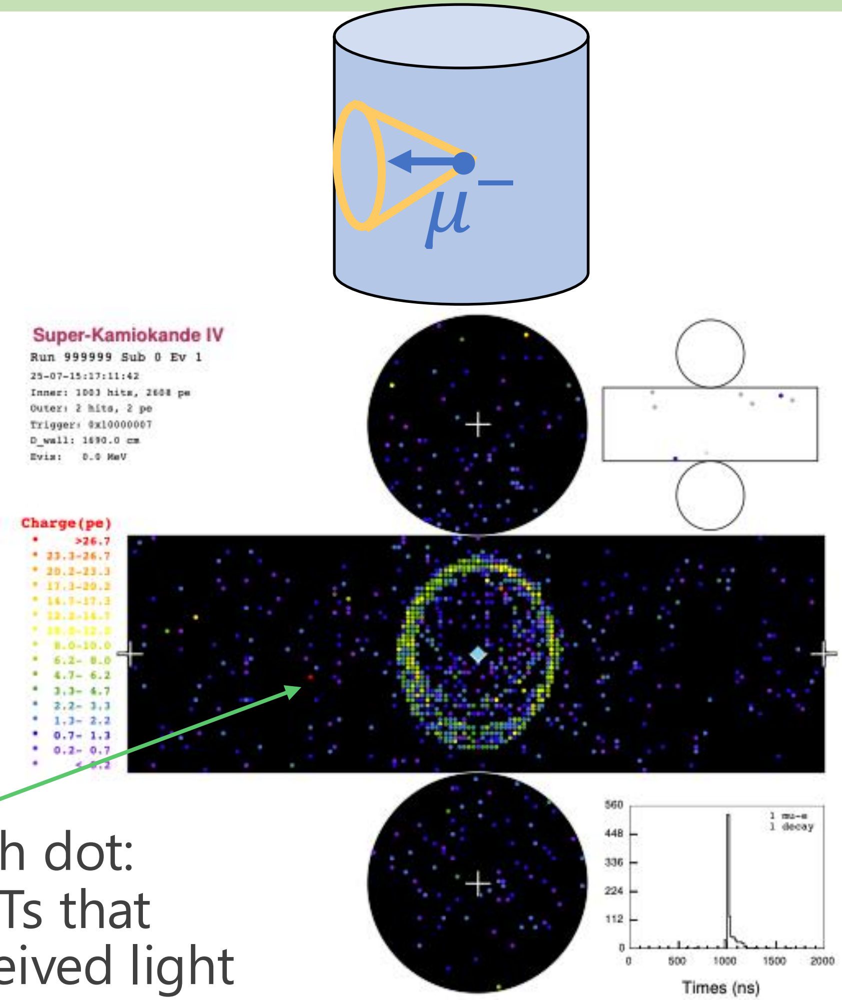


More details of the detector can be found in [1].

[1] S. Mine, Instrumentation and Technics in High Energy Physics, edited by D. Lincoln, pp.251-290 (2024).

Particle identification by the shape of Cherenkov ring





Color: Amount of light

Each dot: PMTs that received light

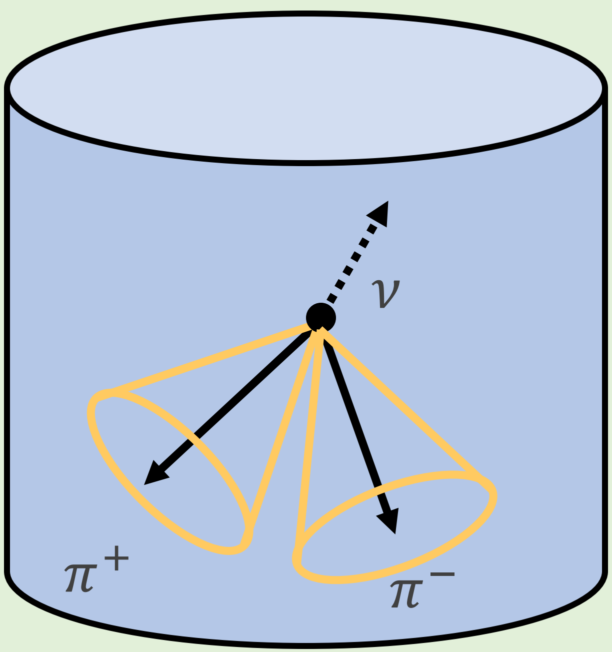
Electron: diffuse ring
→ shower type (e, γ)

Muon: sharp-edged ring
→ non-shower type $(\mu, \pi^{\pm}, p)$

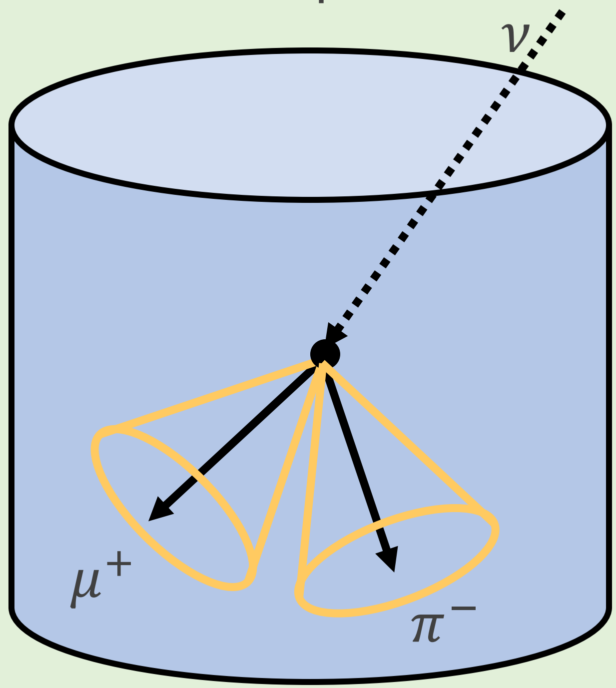
Shower or non-shower type can be distinguished by the difference in ring shape

Nucleon decay search in Super-K

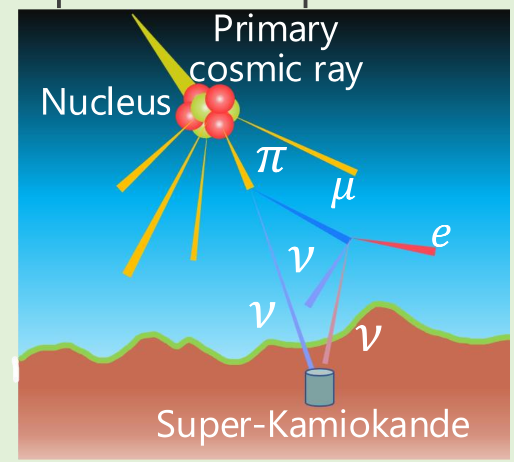
Nucleon decay (signal)



Atmospheric neutrino (background)



Atm. neutrino production process



Cherenkov ring produced by $\mu, \pi^{\pm}$: sharp edge (non-shower type)

- Charged particles produced by the decay of protons or a bound neutron in oxygen nuclei are detected.
- By monitoring a large number of nucleons ($\sim 10^{33}$), Super-K is sensitive to nucleon decay with extremely long lifetime ($> 10^{32}$ years).
- Background events are atmospheric neutrino interactions.

Recent nucleon decay searches in Super-K

- Although $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$ are predicted as major decay modes by GUTs, it is important to search for other decay modes to test various GUT models.

Decay mode	Exposure [kton·years]	Lifetime limit [years]	Analysis method	Reference
$p \to e^+\pi^0$	450	2.4×10^{34}	Box cut	PRD **102**, 112011 (2020)
$p \to \mu^+\pi^0$		1.6×10^{34}		
$p \to \nu\pi^+$	484	3.5×10^{32}	Spectrum fit	In preparation, preliminary
$n \to \nu\pi^0$		1.4×10^{33}		
$p \to e^+\eta$	373	1.4×10^{34}	Box cut	PRD **110**, 112011 (2024)
$p \to \mu^+\eta$		7.3×10^{33}		
$p \to e^+e^+e^-$	373	3.4×10^{34}	Box cut	PRD **101**, 052001 (2020)
$p \to \mu^+e^+e^-$		2.3×10^{34}		
$p \to \mu^-e^+e^+$		1.9×10^{34}		
$p \to e^+\mu^+\mu^-$		9.2×10^{33}		
$p \to e^-\mu^+\mu^+$		1.1×10^{34}		
$p \to \mu^+\mu^+\mu^-$		1.0×10^{34}		

Recent nucleon decay searches in Super-K

- Various approaches are employed in recent analyses to search for nucleon decay modes in which nucleon invariant mass cannot be reconstructed.
- More details of some decay modes can be found in [2][3].

[2] S. Mine, NNN23 (2024). [3] S. Miki, NNN24 (2024).

Decay mode	Exposure [kton·years]	Lifetime limit [years]	Analysis method	Reference
$p \to e^+\pi^0\pi^0$	401	7.2×10^{33}	Box cut	In preparation, preliminary
$p \to \mu^+\pi^0\pi^0$		4.5×10^{33}		
$p \to e^+X$ *	401	1.72×10^{33}	Spectrum fit	In preparation, preliminary
$p \to \mu^+X$ *		0.61×10^{33}		
$p \to \bar{\nu}K^+$	365	8.2×10^{33}	Box cut	Presentation at BLV 2019
$p \to \mu^+K^0$	373	3.6×10^{33}	Box cut	PRD **106**, 072003 (2022)
$n \to \bar{\nu}K^0$	401	7.8×10^{32}	Spectrum fit	arxiv:2506.14406, preliminary
${}^{16}\mathrm{O}(ppp) \to {}^{13}\mathrm{C}(\pi^+\pi^+e^+)$	401	4.2×10^{32}	Machine learning (CNN)	In preparation, preliminary
$n \to \bar{n}$	373	3.6×10^{32}	Multivariate analysis (MVA)	PRD **103**, 012008 (2021)

*X is an unknown massless neutral particle and cannot be detected

Target neutron decay in this study

- **Target neutron decay mode: $n \rightarrow \bar{\nu} K^0$**
  - Predicted by SUSY models
  - Charged particles from K^0 decay are detected.

- **Previous research**: K. Kobayashi *et al.*, Phys. Rev. D **72** 052007 (2005).
  - Analyzed about 4 years of the data since the start of Super-K observation (referred to as SK-I period)
  - Set lower lifetime limit as $\tau/B(n \rightarrow \bar{\nu} K^0) > 1.3 \times 10^{32}$ years at 90% C.L.

- **Updates in this study**: arxiv:2506.14406
  - Expand the observation period to cover the entire pure water phase (1996-2020, about 18 years, ×4.4 exposure)
  - Improve the reconstruction of charged pion
  - Improve the event selection
    - Previous study: Determined the signal region from reconstructed K^0 invariant mass and momentum (box cut)
    - This study: Perform spectrum fit (likelihood analysis) on the invariant mass distribution.

K^0 decay modes to search for

- For the $n \to \bar{\nu} K^0$ mode, particles from K^0 decay are detected.
- There are various decay modes for K_S^0 ($\tau = 90$ ps) and K_L^0 ($\tau = 51$ ns), which have different lifetimes.
  - $K_S^0 \to \pi^+\pi^-$ (BR: 69.2%), $2\pi^0$(30.7%)
  - $K_L^0 \to \pi^\pm l^+ \nu$ (67.6%), $3\pi^0$(19.5%), $\pi^+\pi^-\pi^0$ (12.5%)

Proportion of each decay mode in detector simulation

$K_S^0 \to \pi^+\pi^-$	$K_S^0 \to 2\pi^0$	$K_L^0 \to \pi^\pm l^\mp \nu$	$K_L^0 \to 3\pi^0$	$K_L^0 \to \pi^+\pi^-\pi^0$	Others (charge exchange, etc)
41.7±0.2%	18.5±0.1%	8.3±0.1%	2.8±0.1%	1.73±0.05%	27.0±0.2%

Target decay modes ($K_S^0 \to \pi^+\pi^-$, $K_S^0 \to 2\pi^0$)

$K_L^0 \to \pi^\pm l^\mp \nu$: **Neutrino carries away energy → Cannot construct K^0 invariant mass**

$K_L^0 \to 3\pi^0$: Small statistics and included $K_S^0 \to 2\pi^0$ selection

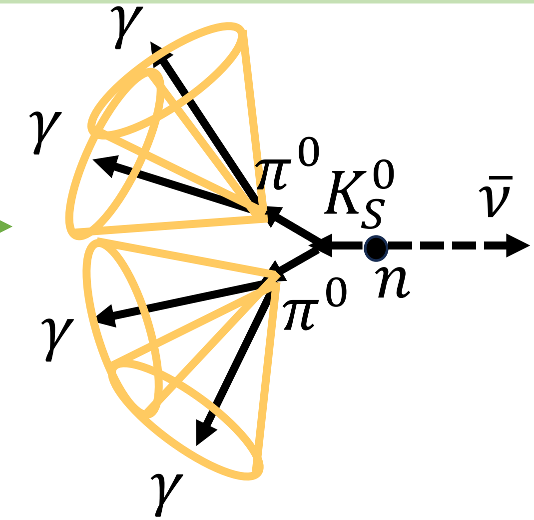
$K_L^0 \to \pi^+\pi^-\pi^0$: Small statistics

Others: K_L^0 decays into K^+ and other particles via scattering in water

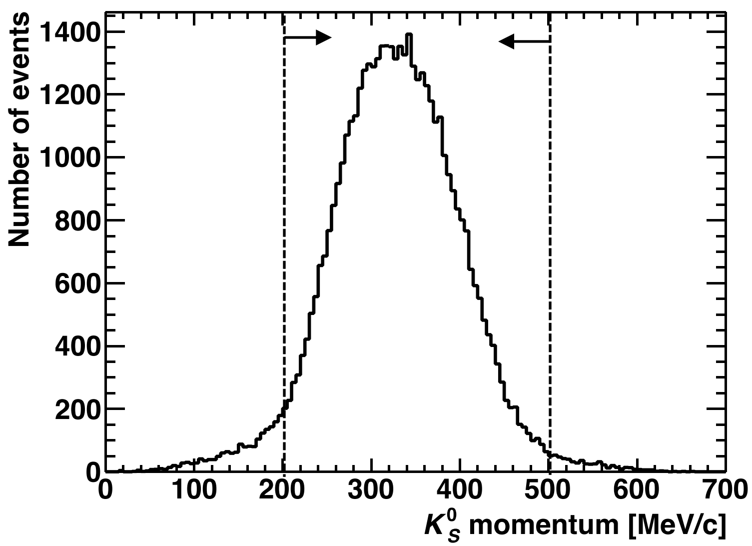
Only K_S^0 decay events are searched for, same as the previous study.

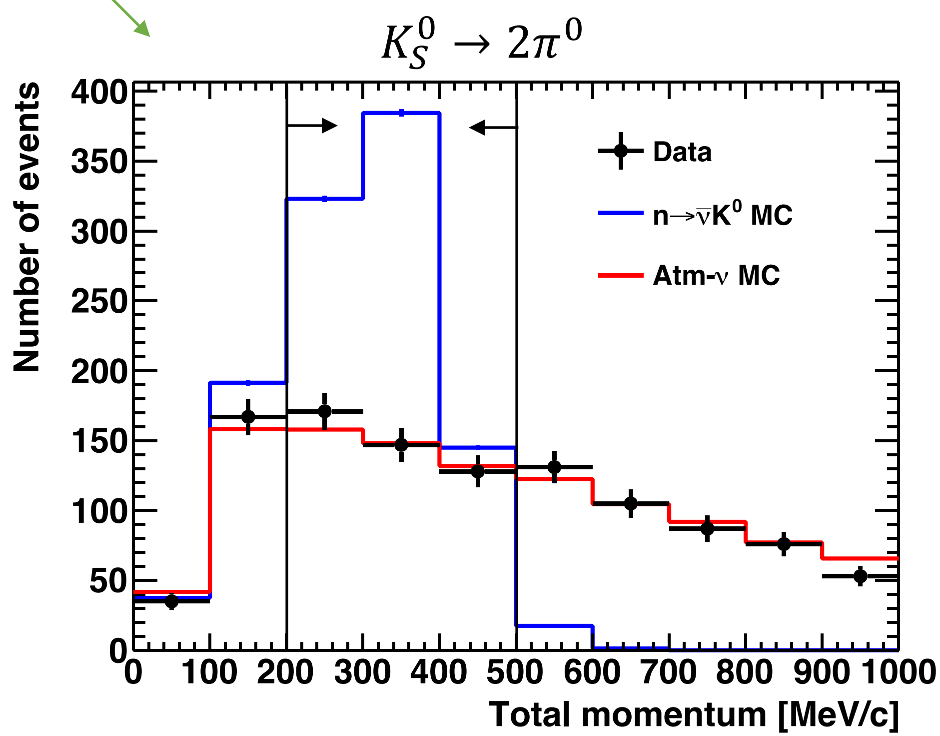
Signal event selection for $K_S^0 \to 2\pi^0$

- **Main selection criteria**
  - The number of rings should be 3 or 4.
    - All ring should be showering due to $\pi^0 \to 2\gamma$.
  - The reconstructed K^0 momentum should be $200 < P_{K^0} < 500$ MeV/c.



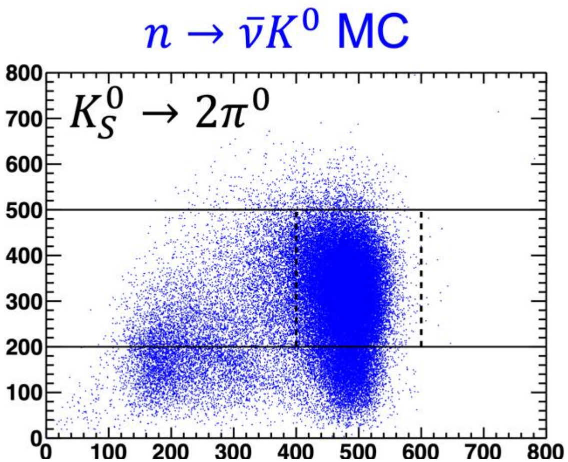
True K_S^0 momentum just after leaving the oxygen nucleus



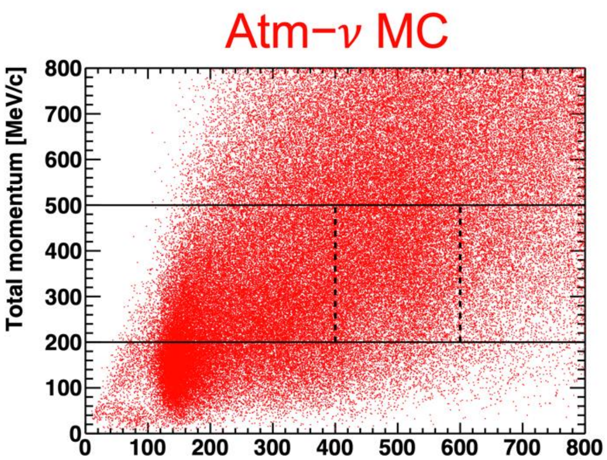


Final samples for $K_S^0 \to 2\pi^0$

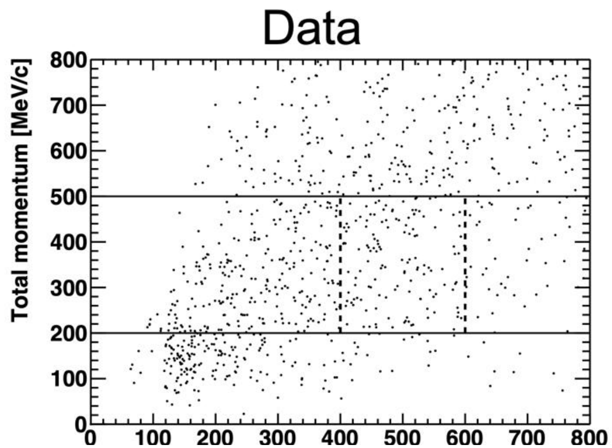
K^0 momentum [MeV/c]



K^0 invariant mass [MeV/c^2]



K^0 invariant mass [MeV/c^2]

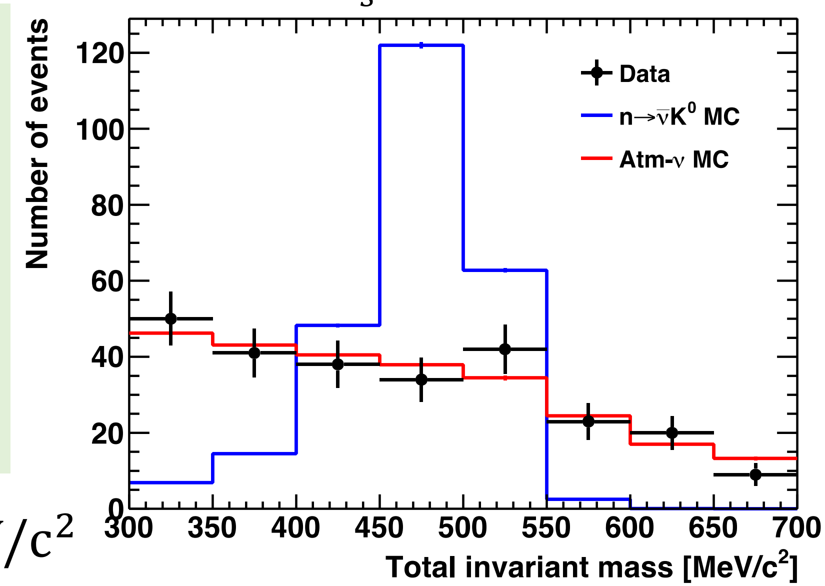


K^0 invariant mass [MeV/c^2]

Vertical dashed line: signal region used in the previous analysis

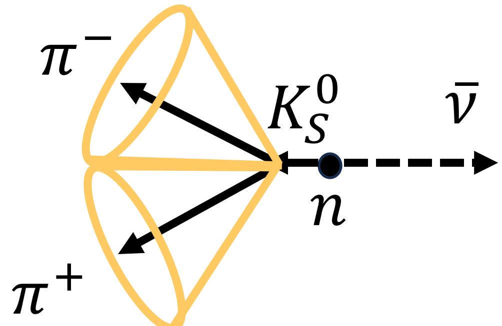
- Many events remain in the signal region (right top, as expected).
  → Instead of cutting off events based on a threshold, perform spectrum fitting to K^0 invariant mass distribution (discussed later)

$K_S^0 \to 2\pi^0$



$m_{K^0} = 497.6\ \mathrm{MeV/c^2}$

Signal event selection for $K_S^0 \to \pi^+\pi^-$



- **Main selection criteria**
  - The number of rings should be 2.
    - All rings should be non-showering due to $\pi^\pm$.
  - Cut off at K^0 momentum threshold

⇨ Spectrum fit to K^0 invariant mass

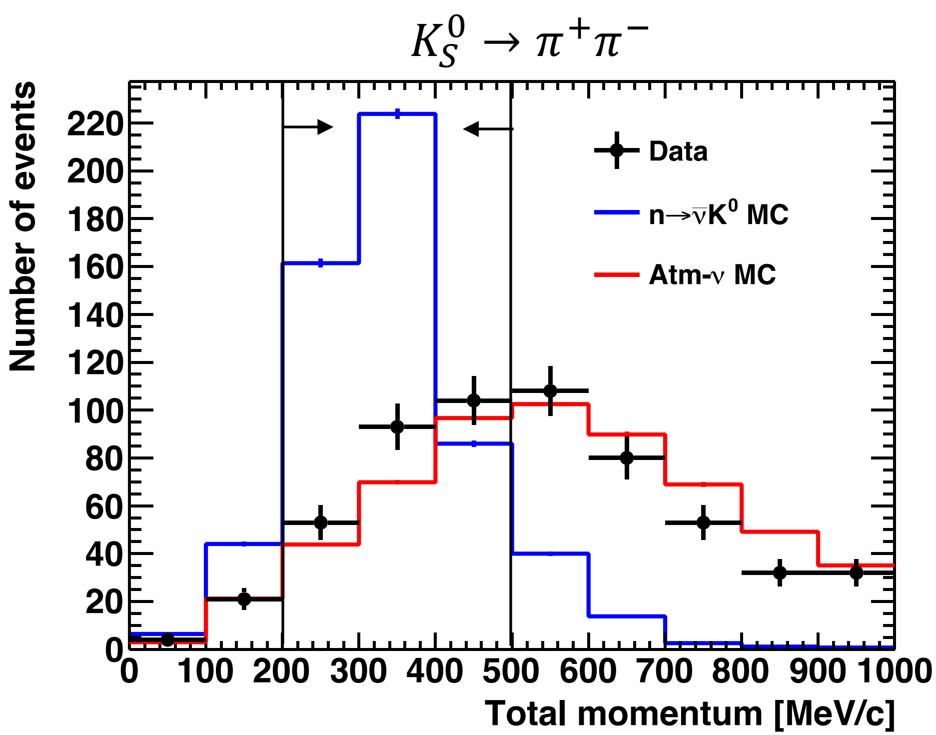
Calculated from $\pi^\pm$ momentum (and direction + mass)

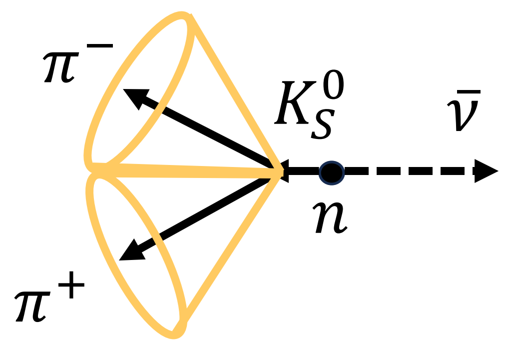
⇒ **The performance of $\pi^\pm$ momentum reconstruction is important.**

It has been improved in this study (details are in backup).

Event selection for $K_S^0 \to \pi^+\pi^-$

- **Main selection criteria**
  - The number of Cherenkov rings should be 2.
    - All rings should be non-showering due to $\pi^{\pm}$.
  - **The K^0 momentum should be $200 < P_{K^0} < 500$ MeV/c.**



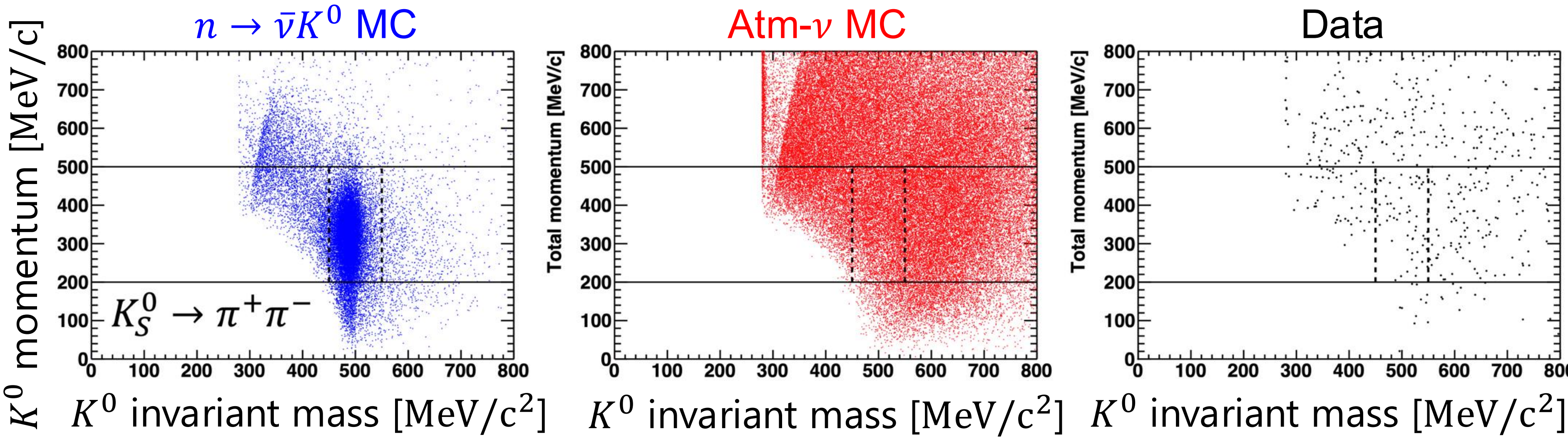


Data

Neutron decay MC

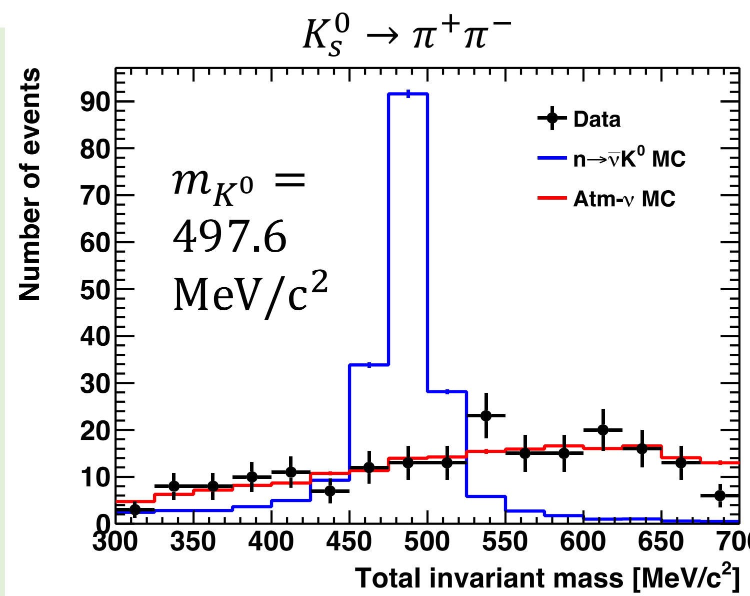
Atmospheric neutrino MC

Final samples for $K_S^0 \to \pi^+\pi^-$



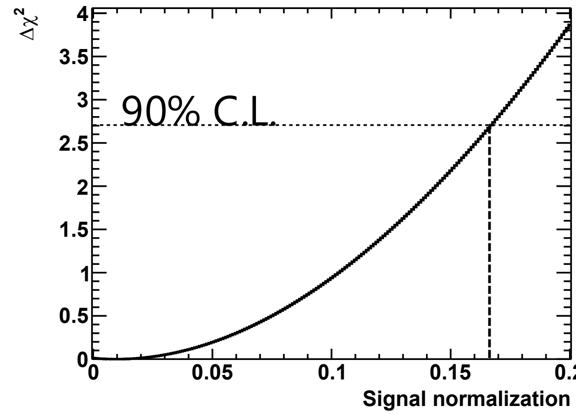
Vertical dashed line: signal region used in the previous analysis

- Many events remain in the signal region.
  → Perform **spectrum fit**
- **Spectrum fit:**
  - Signal and BG MC are compared with data.
  - Systematic uncertainties in signal and BG MC are accounted in the fit.
  - Two K_S^0 decay modes are simultaneously fitted.



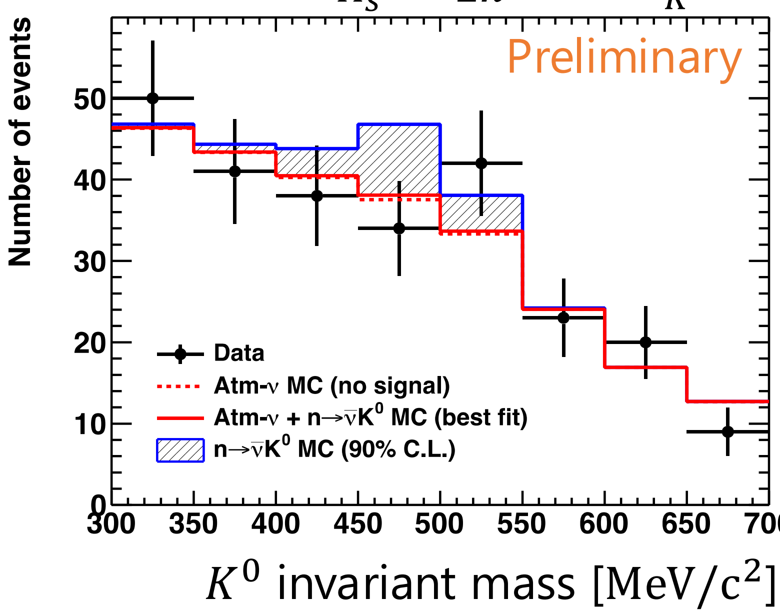
Fitting to K^0 invariant mass distribution

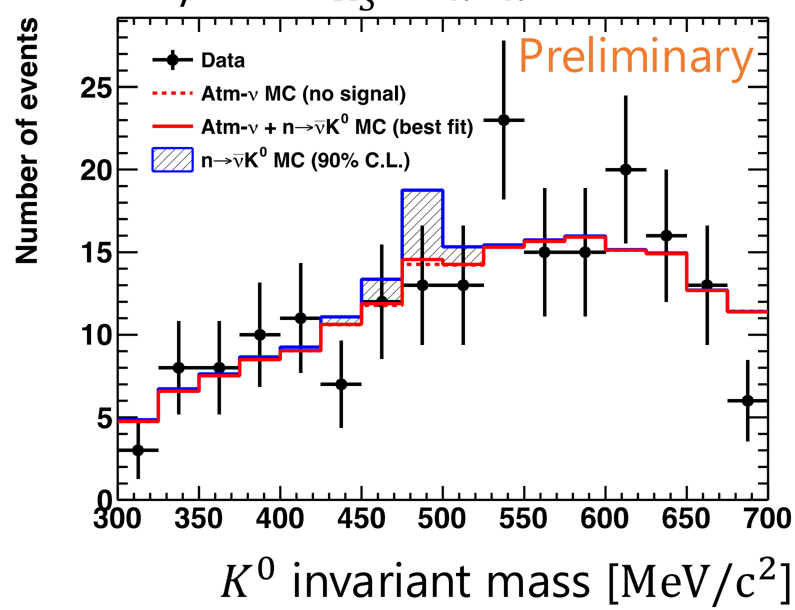
- After fitting, there is no significant excess of neutron decay signals over the background.
  - Best fit: $\chi^2/N_{\mathrm{dof}} = 117.4/119$



Upper limit of $n \rightarrow \bar{\nu} K^0$ decay is obtained by the fit (90% C.L. upper limit is shown by blue lines).

$K_S^0 \rightarrow 2\pi^0$ $m_{K^0} = 497.6\ \mathrm{MeV/c^2}$ $K_S^0 \rightarrow \pi^+\pi^-$





Impact of systematic uncertainties on sensitivity

Systematic uncertainties		Sensitivity [$\times 10^{33}$ years]
No systematic uncertainties are considered		**1.07**
All systematic uncertainties are considered		**0.85**
Neutrino flux and neutrino oscillation	Flux	0.96
	Oscillation	1.07
Neutrino interaction	Quasi-elastic scat.	1.06
	Single pion production	**0.91**
	Deep inelastic scat.	0.95
Reconstruction (ring, particle ID, Michel-e, etc)		1.03
Final State Interaction (FSI) and Secondary Interaction (SI)	K^0 FSI, SI	1.07
	π FSI+SI	**0.92**
Physical model for neutron decay (correlated decay and Fermi momentum)		1.07
Energy scale	Electron momentum	1.06
	$\pi^{\pm}$ momentum	1.03

- The sensitivity is greatly affected by the uncertainty of
  - model of single pion production, which is the main background interaction
  - model of pion scattering within the nucleus (FSI) and in water (SI)

Limits on neutron decay lifetime

- As no significant neutron decay was observed against atmospheric neutrino, a lower limit on the lifetime of a bound neutron was set.

- Lower lifetime limit at 90% C.L.
  - **This study: $\boldsymbol{\tau > 7.8 \times 10^{32}}$ years (401 kton·years exposure)**
  - Previous study: $\tau > 1.3 \times 10^{32}$ years (92 kton·years exposure)

  → The results improves the previous limit by a factor of six, making it the most stringent constraint on the $n \to \bar{\nu} K^0$ decay mode to date.

Summary

- Nucleon decay provides a critical experimental test for GUTs.
- Super-K is searching for various nucleon decay modes [2][3].

[2] S. Mine, NNN23 (2024). [3] S. Miki, NNN24 (2024).

- **We searched for the neutron decay via $\boldsymbol{n \rightarrow \bar{\nu} K^0}$** using 4.4 times larger data set from the Super-Kamiokande and by the improved analysis method
  - **No significant signal events were found.**
  - Spectrum fit to the K^0 invariant mass distribution yielded a lower limit on the decay lifetime of $\boldsymbol{7.8 \times 10^{32}}$ **years** at 90% C.L., which is six times better than the previous search.

Backup

Signal selection of $\boldsymbol{n \rightarrow \bar{\nu} K^0}$ search

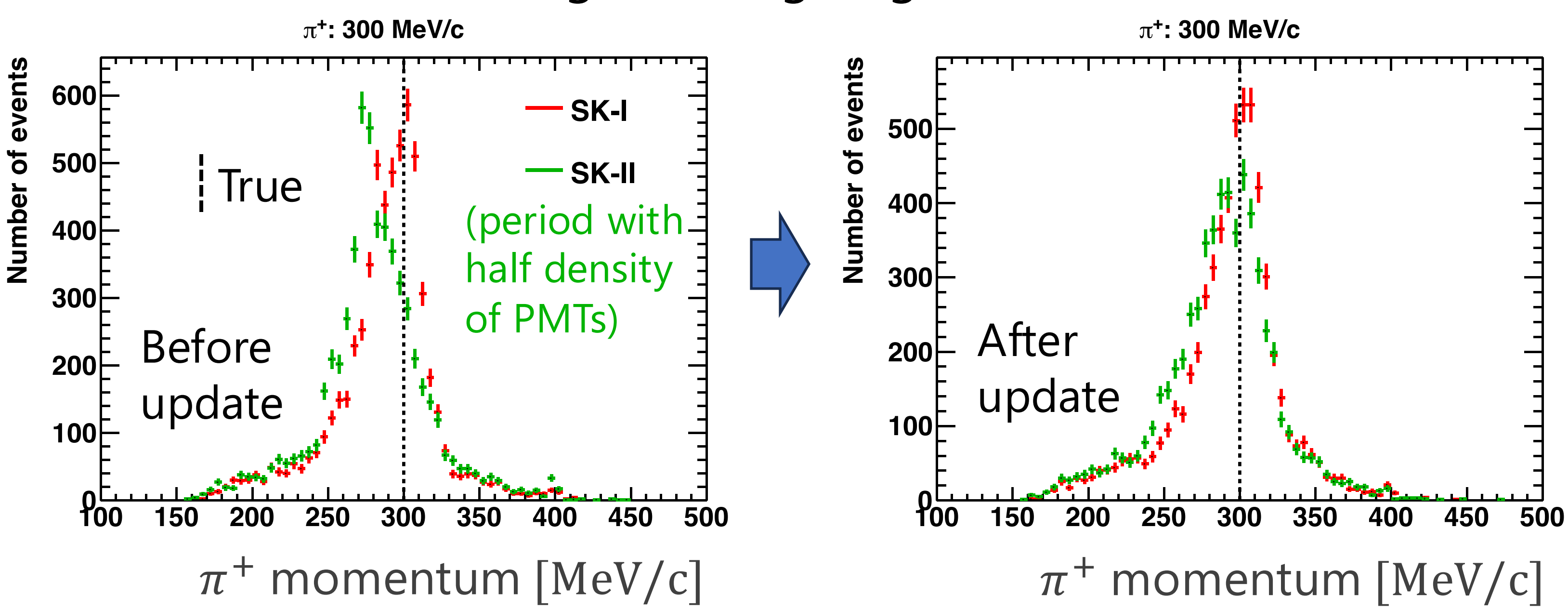
Two selections for K_S^0 decay modes

	$K_S^0 \rightarrow 2\pi^0$	$K_S^0 \rightarrow \pi^+\pi^-$
#1	Fully Contained (FC), Fiducial Volume (FC)	
#2	$N_{\text{ring}} = 3 \text{ or } 4$	$N_{\text{ring}} = 2$
#3	$N_{\mu-\text{like ring}} = 0$ (3 or 4 e-like rings)	$N_{\mu-\text{like ring}} = 2$
#4	$N_{\text{Michel}-e} = 0$	$N_{\text{Michel}-e} = 0 \text{ or } 1$
#5	$200 \text{ MeV} < p_{K^0} < 500 \text{ MeV}$	
#6	**$300 < W_{K^0} < 700 \text{ GeV}$ → invariant mass fit**	

Improvement of $\pi^{\pm}$ momentum reconstruction

- **Method for momentum reconstruction**
  - e, μ: Estimate from the correlation between momentum and collected charge
  - $\pi^{\pm}$: Momentum is reconstructed by the combination of collected charge and the opening angle of Cherenkov rings

Simulation generating single-momentum π^{+}



- By refining the estimation of the photoelectron distribution, better accounting for the effects of $\pi^{\pm}$ hadronic scattering, the accuracy of opening angle reconstruction has been improved.