Super-Kamiokande Results: Proton Decays and Atmospheric Neutrinos

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for the Super-Kamiokande collaboration

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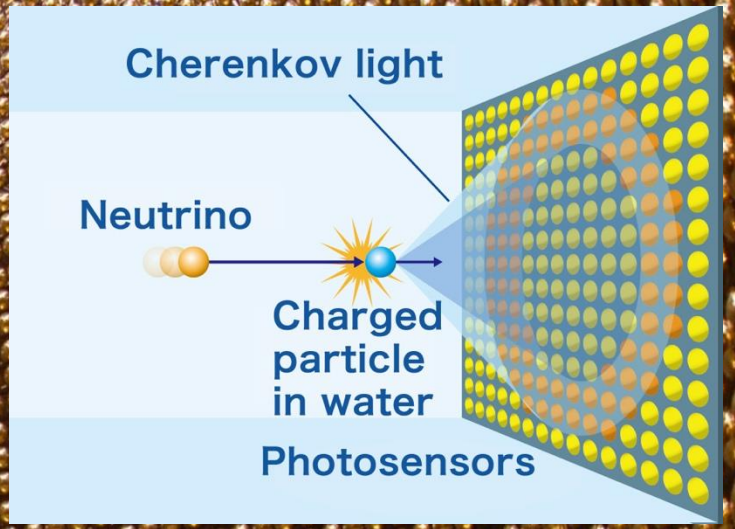
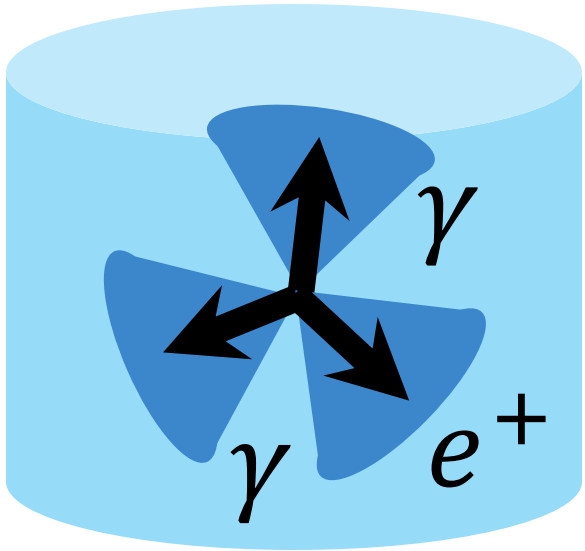
Super-Kamiokande

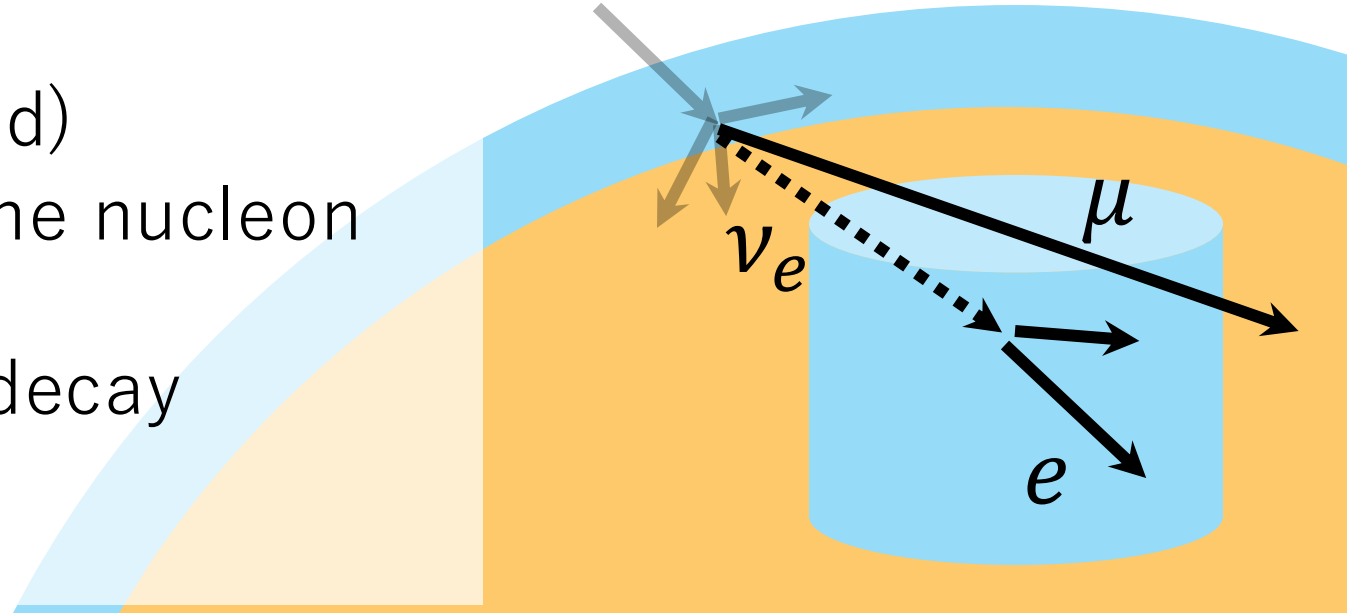
- Water Cherenkov detector located 1000m underground in Gifu Prefecture (1996~).
- Tank with 40m diameter and height containing 50 kton of ultrapure water.
  - From 2020, SK-Gd project has been started (Gd concentration).
- Detect Cherenkov light from charged particle in water by 11000 light sensor on the wall.



Nucleon decay search

- Nucleon decay (signal events)
  - Observe particles from the decay of nucleons in water
  - Observe ~10^{33} nucleons for ~10 years → explore the lifetime up to ~10^{34} years
- Cosmic ray muons (background)
- Atmospheric neutrino (background)
  - Large flux in the energy near the nucleon decay
  - Major background of nucleon decay
  - About 10 events/day in SK



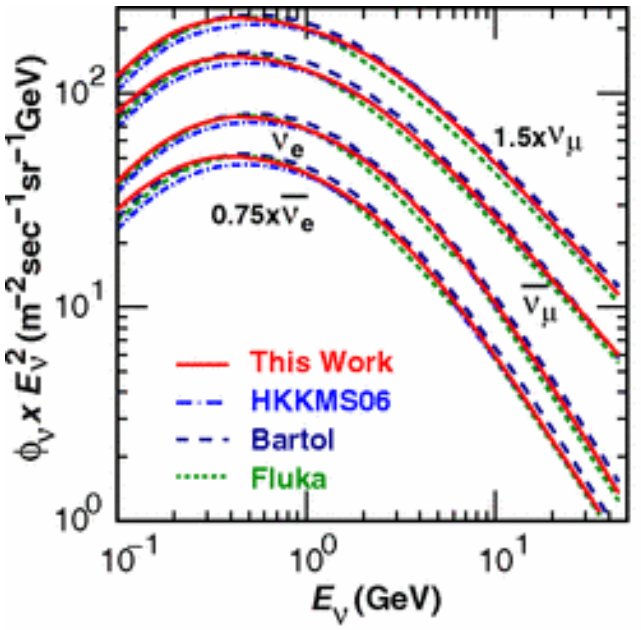


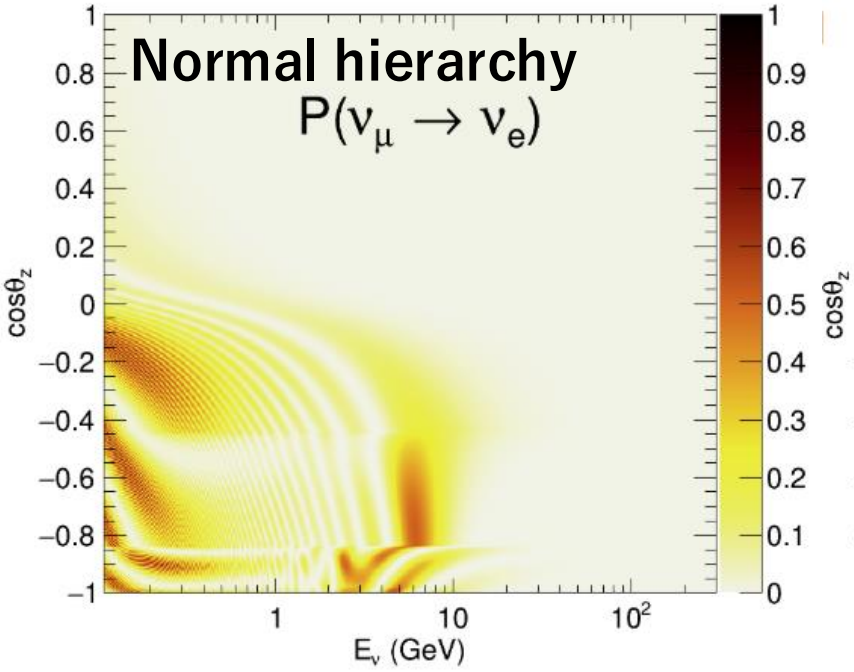
Atmospheric neutrino

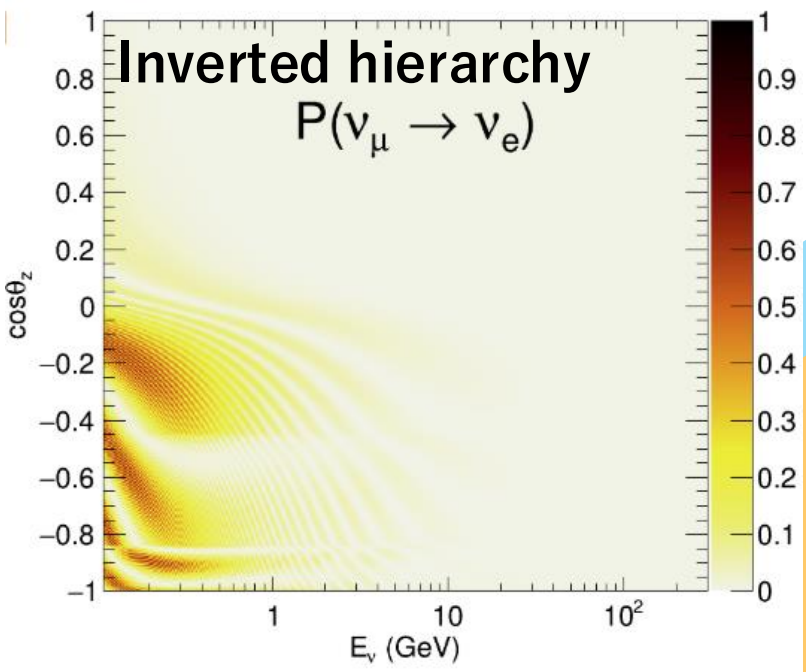
- Neutrinos are generated in the atmosphere.
- The energy is correlated with the cosmic ray.
  →Large flux around 1 GeV.
- Events are classified into several categories to make the effect of the oscillation apparent, and parameters are fitted.

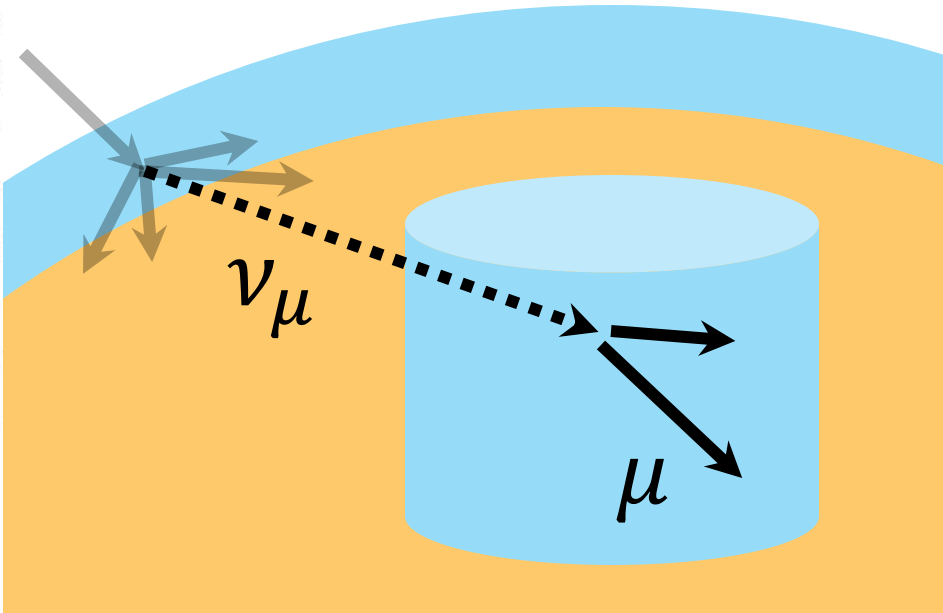
Neutrino flux simulation

M. Honda *et al.*, Phys. Rev. D **83,** 123001 (2011).









New results from Super-Kamiokande

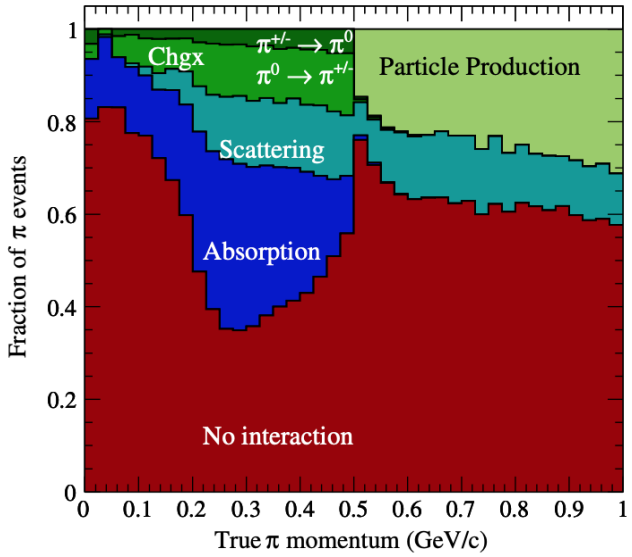
- Nucleon decay analysis
  - Published: $p \to l^+\eta$
  - $p \to \nu\pi^+$ and $n \to \nu\pi^0$
  - $n \to \nu K^0$
  - $p \to \mu^+ X$
  - $ppp \to e^+\pi^+\pi^+$

- Atmospheric neutrino oscillation analysis
  - Published: oscillation analysis with ntag and expanded FV in SK-I to V
  - Published: SK+T2K joint oscillation analysis

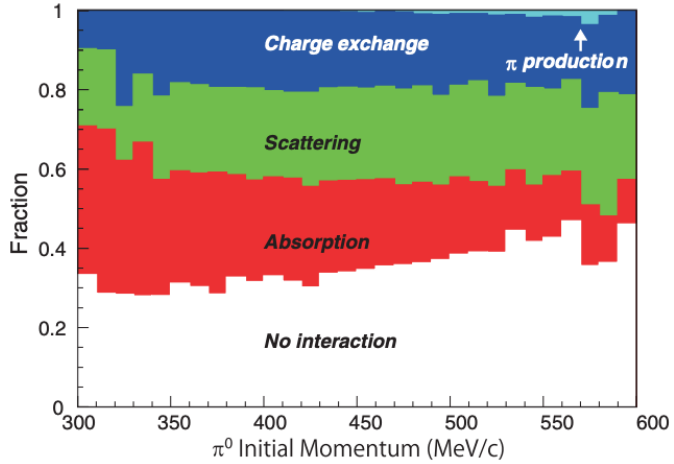
Search for $p \to \nu\pi^+$ and $n \to \nu\pi^0$

- Select events by using pion mass and momentum.
- Sensitivities with spectrum fit
- Expanded fiducial volume ($D_{\mathrm{wall}} > 2\mathrm{m} \to 1\mathrm{m}$)
- The last publication is PRL 113, 121802 (2014)
- Increased statistics:
  SK-I to III (172.8kton·yr)→SKI-V (484.9kton·yr)
- Updated physics model (π FSI)
  - Increased π^0 absorption (~30%)
- Estimation of systematic uncertainty, which was not taken into account in the previous analysis.
  - NC/CC ratio in ATM ν has impact on sensitivity.

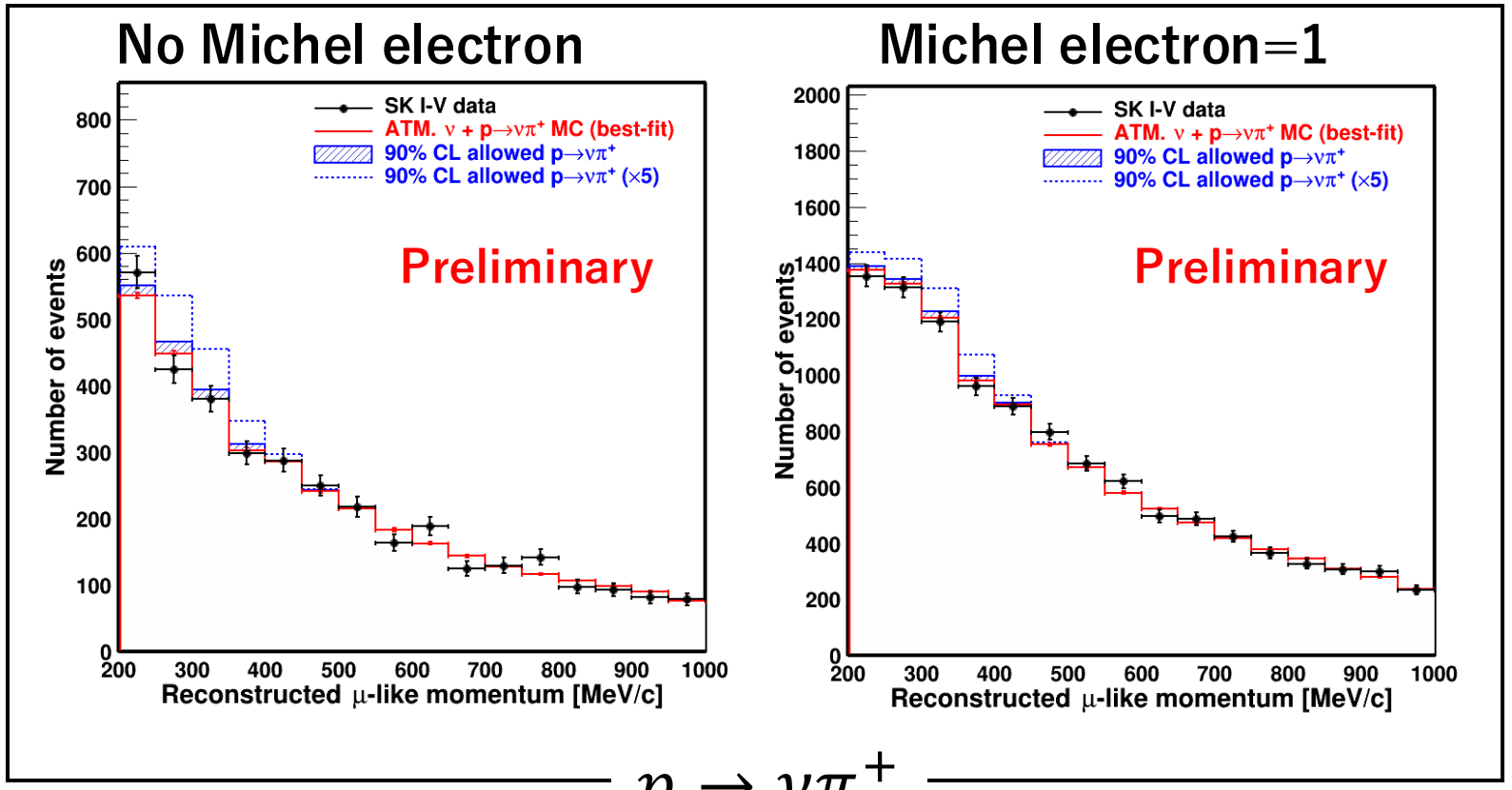
PRL 113 121802 (2014)



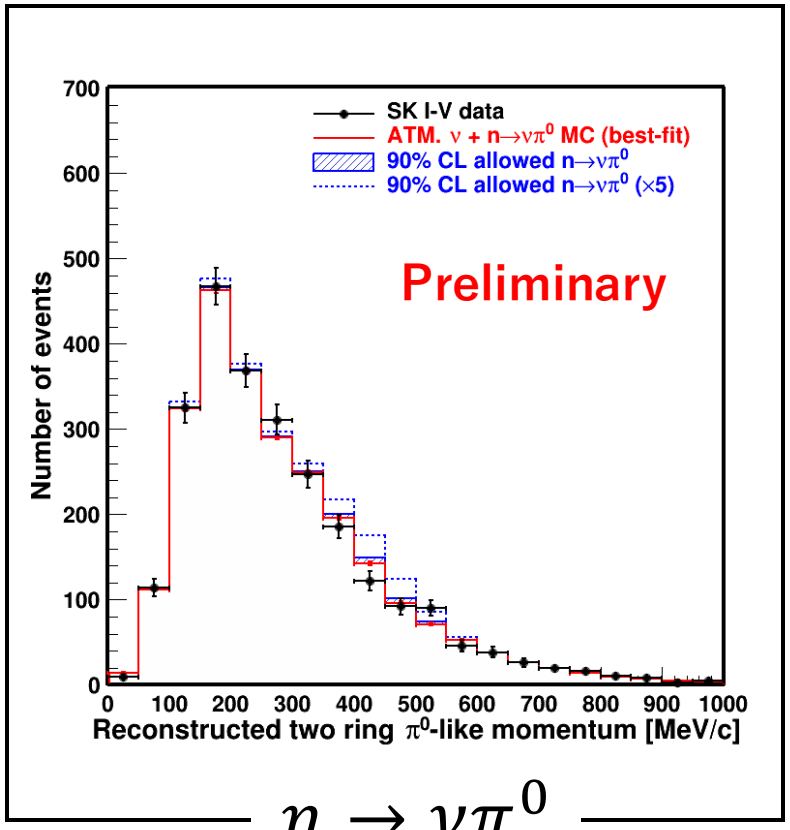
PRD 95 012004 (2017)



Search for $p \to \nu\pi^+$ and $n \to \nu\pi^0$



$p \to \nu\pi^+$



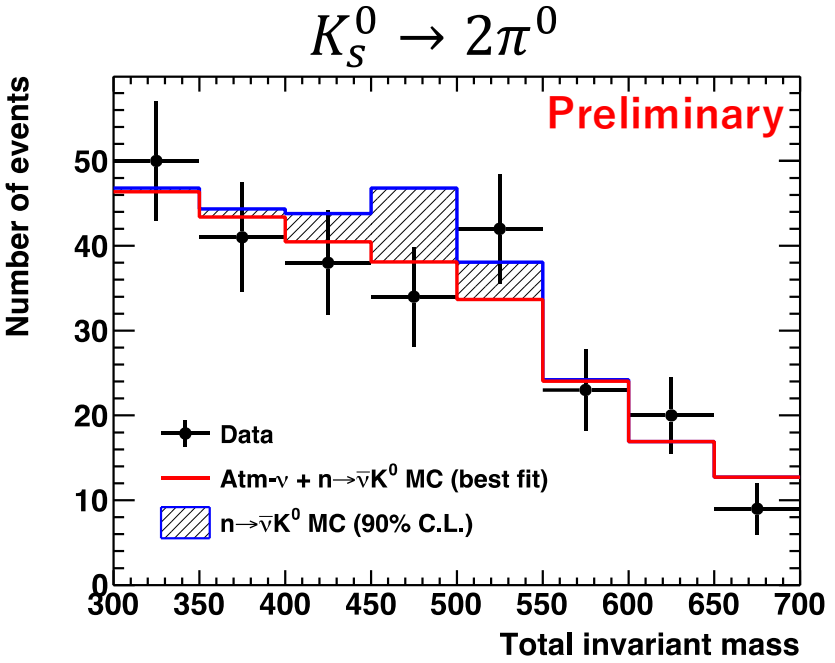
$n \to \nu\pi^0$

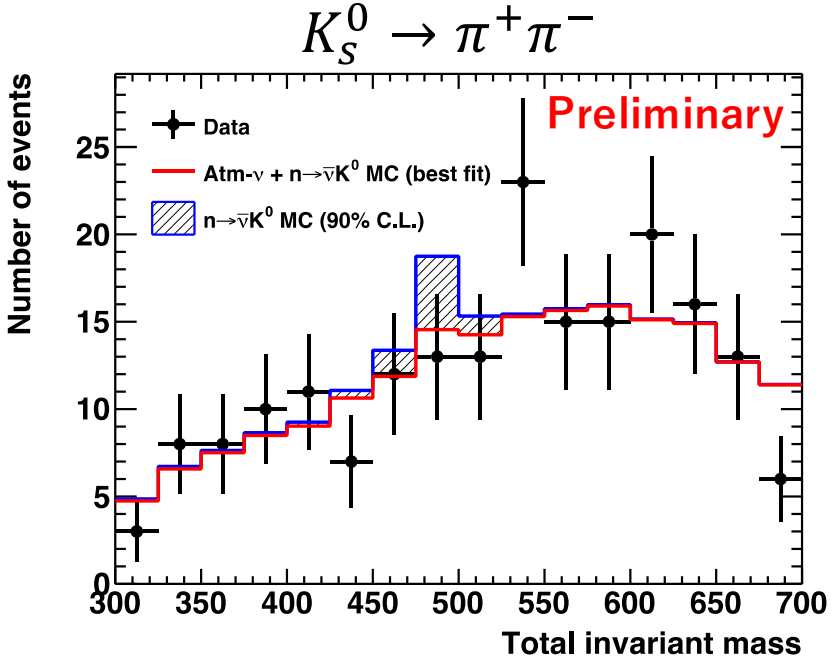
Lifetime limit at 90% CL

- $p \to \nu\pi^+$: $> 3.5 \times 10^{32}$ years (paper in 2014: 3.9×10^{32} years)
- $n \to \nu\pi^0$: $> 1.4 \times 10^{33}$ years (paper in 2014: 1.1×10^{33} years)

Search for $n \to \bar{\nu} K^0$

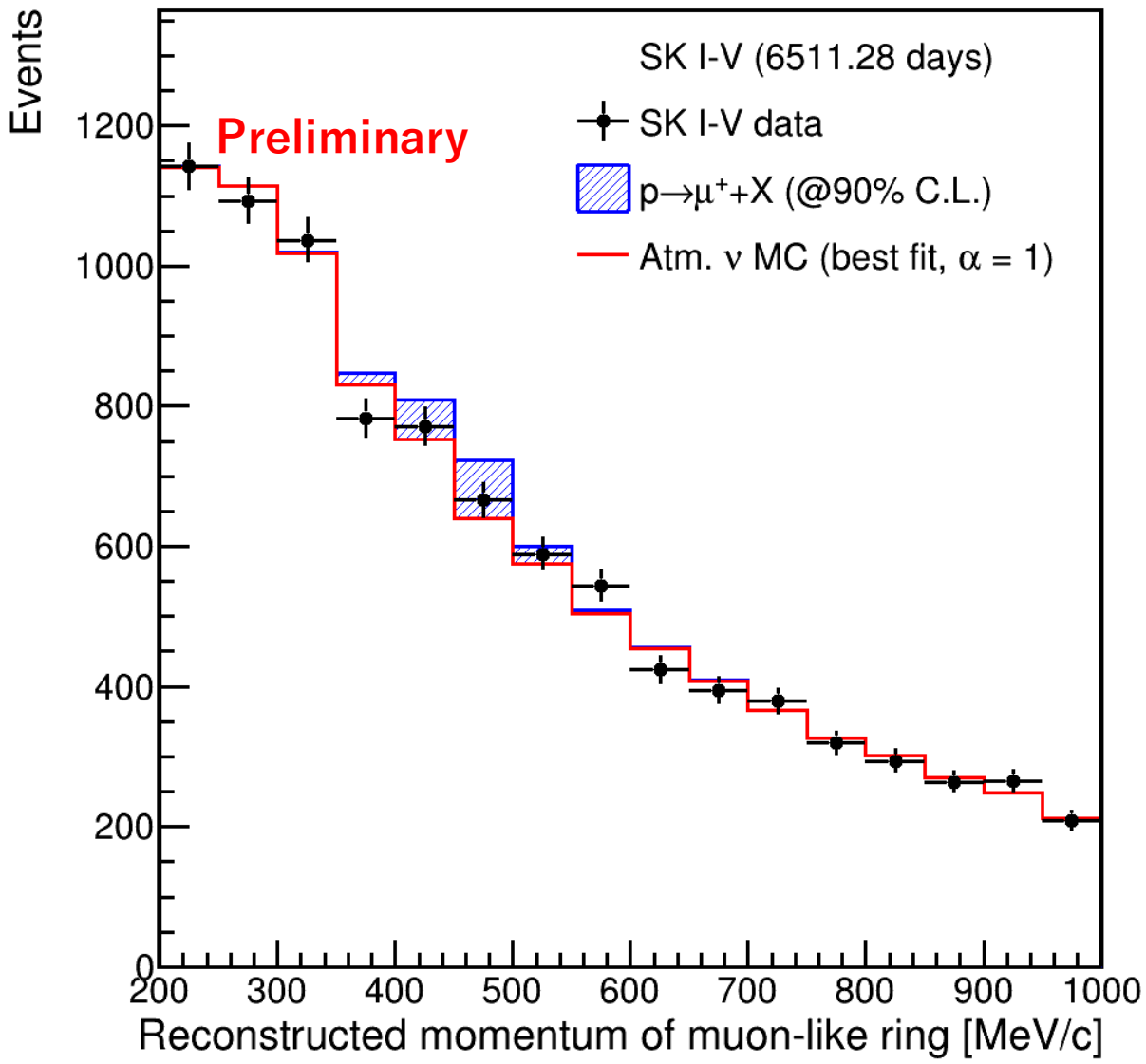
- Select events by using K_S^0 invariant mass
  - Major K_L^0 decay mode is $K_L^0 \to \pi^{\pm} l^{\mp} \nu_l$.
    →cannot reconstruct invariant mass
- The box cut analysis in the last publication (PRD 72 052007 (2005)) but larger BG
  → Use spectrum fit for this analysis
- Increased statistics:
  SK-I (1489 days) → SK-I to V (6511 days)
- Improved π^+ reconstruction
- Lifetime limit $> 7.8 \times 10^{32}$ years
  (updated from 1.3×10^{32} years)





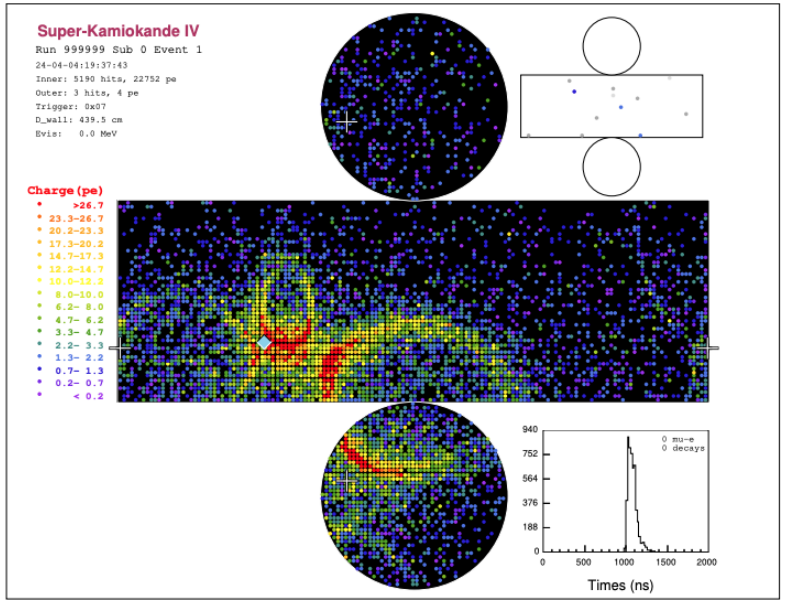
Search for $p \to \mu^+ X$

- X is a massless, neutral and invisible particle.
- Sensitivities with spectrum fit
- The last publication:
  PRL 115 121803 (2015)
- Increased statistics:
  SK-I to partial IV (4438 days)
  → SK-I to V (6511 days)
- Lifetime limit is 6.1×10^{32} years
  (updated from 4.1×10^{32} years)

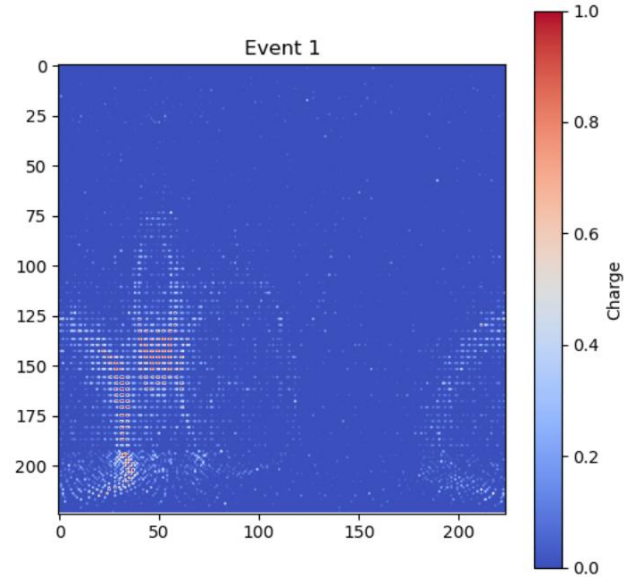


Search for $ppp \rightarrow e^+\pi^+\pi^+$

- High energy pions make many secondaries due to hadronic interaction and make reconstruction complicated.
- Image classification based on CNN (MoblileNet v3) using Mercator projection
- Preselection cuts:
  - Events in the fiducial volume
  - 500 < visible energy < 2800 MeV
  - Number of rings = 3 or 4
  - Michel electron count = 1 or 2

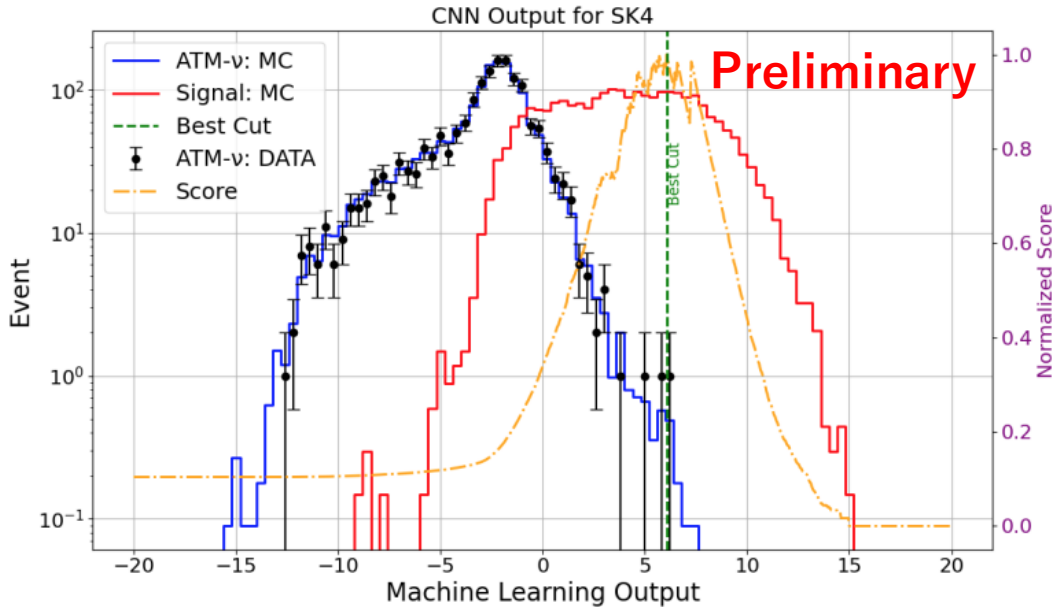


Event display (simulation)



Mercator projection

Search for $ppp \rightarrow e^+\pi^+\pi^+$



$$\text{Score} = \frac{\text{true positive rate}}{\sqrt{\text{true positive rate} + \text{true negative rate}}}$$

SK Period Comparison Table

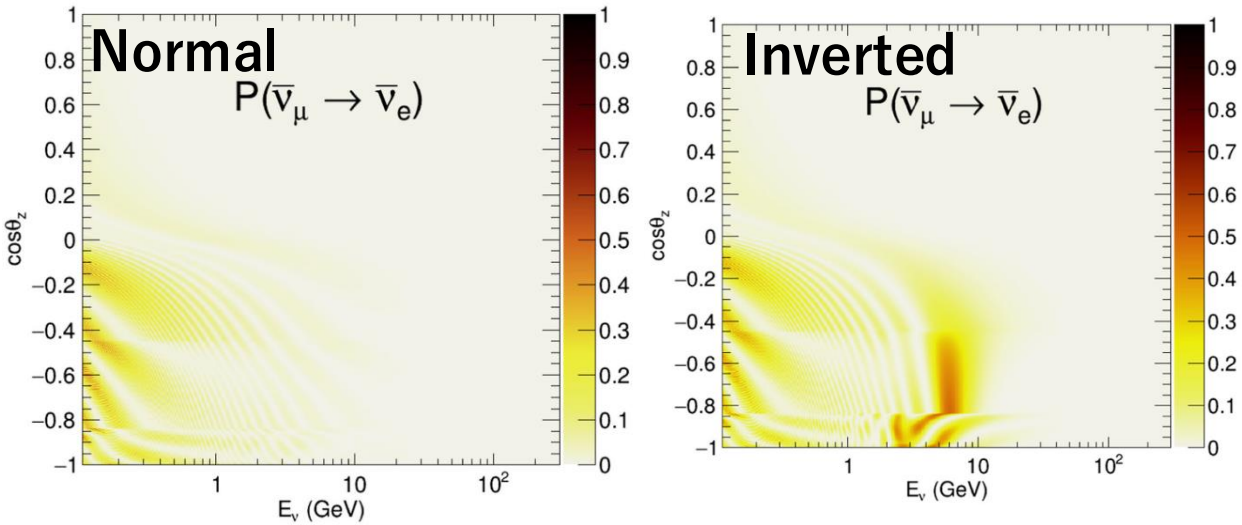
SK	Efficiencies [%]	Background Events	Cand. Count
SK1	FC Eff: 95.30 ± 1.50 Pre Eff: 81.35 ± 1.31 ML Eff: 25.91 ± 0.64	FC: 11595.76 ± 9.50 Pre: 524.72 ± 1.98 ML: 0.41 ± 0.06	0
SK2	FC Eff: 94.75 ± 1.51 Pre Eff: 80.85 ± 1.32 ML Eff: 22.80 ± 0.63	FC: 6366.20 ± 3.00 Pre: 189.15 ± 0.65 ML: 0.19 ± 0.02	0
SK3	FC Eff: 94.30 ± 1.51 Pre Eff: 80.35 ± 1.32 ML Eff: 25.67 ± 0.63	FC: 4229.20 ± 3.00 Pre: 129.05 ± 0.65 ML: 0.13 ± 0.02	0
SK4	FC Eff: 94.49 ± 1.49 Pre Eff: 81.31 ± 1.31 ML Eff: 25.75 ± 0.64	FC: 24973.11 ± 20.45 Pre: 1207.34 ± 4.43 ML: 0.92 ± 0.09	1
SK5	FC Eff: 95.23 ± 1.50 Pre Eff: 81.23 ± 1.30 ML Eff: 25.90 ± 0.64	FC: 3568.76 ± 2.94 Pre: 170.64 ± 0.63 ML: 0.12 ± 0.01	0

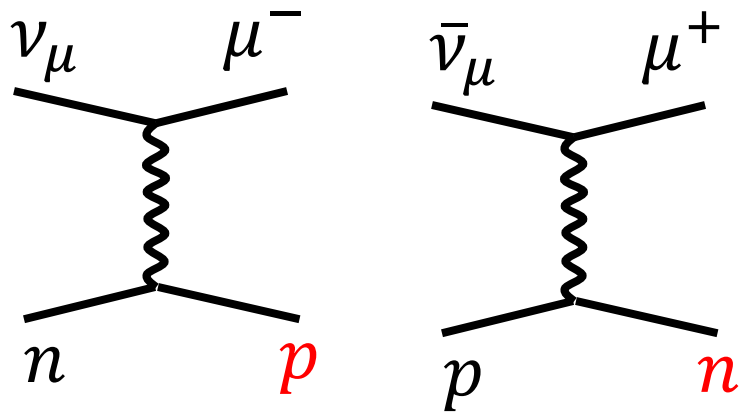
- Lifetime limit: $> 4.2 \times 10^{32}$ years
- Reference: $>1.2 \times 10^{26}$ years (GERDA, EPJC 83 778 (2023))

published paper, PRD 109, 072014 (2024)

Atmospheric neutrino oscillation analysis w/ ntag and expanded FV in SK-I to V

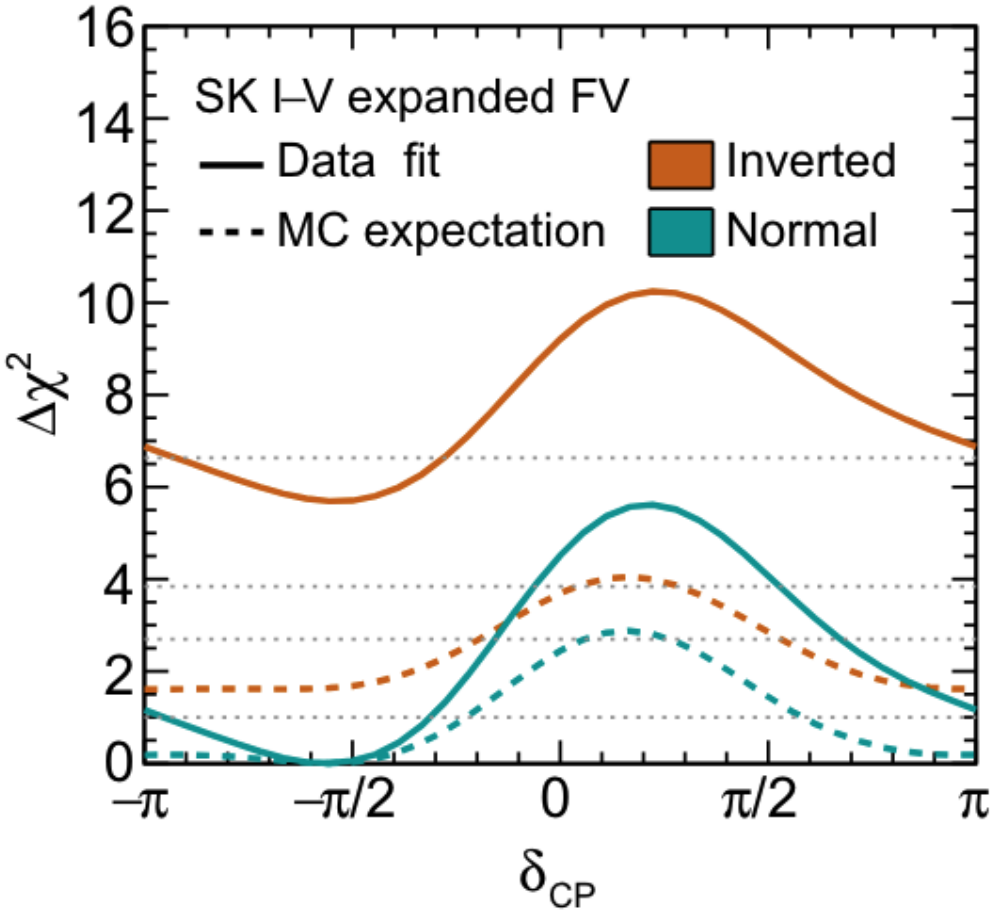
- Including the last SK phase with pure water (SK-I to V).
- Neutron tagging (H capture).
  - Resonance appears in $\bar{\nu}$ with IO (opposite to neutrino mode).
    $\rightarrow \nu/\bar{\nu}$ separation contribute to MO.
- New multi-ring selection
- Expanded fiducial volume ($D_{\mathrm{wall}} > 2\mathrm{m} \rightarrow 1\mathrm{m}$)





published paper, PRD 109, 072014 (2024)

Atmospheric neutrino oscillation analysis w/ ntag and expanded FV in SK-I to V

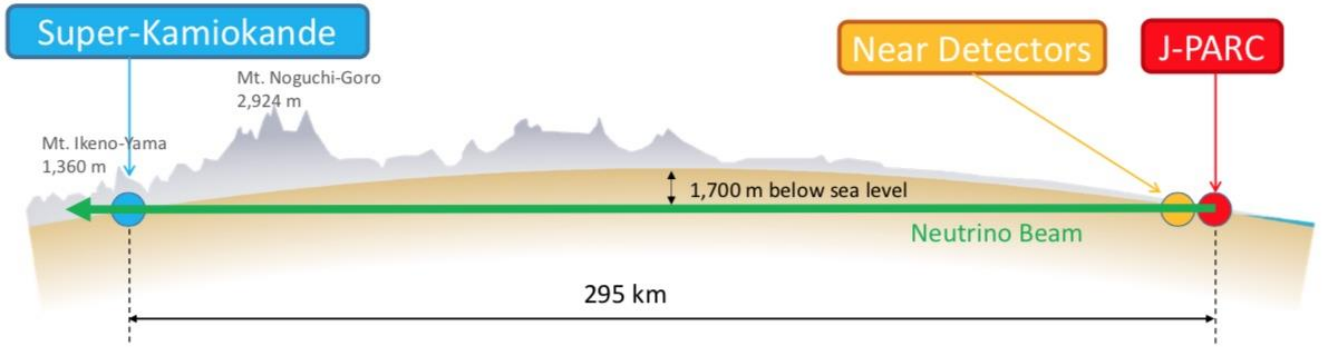


- Result with constraint $\sin^2\theta_{13} = 0.0220 \pm 0.0007$ (PTEP 2022 083C01 (2022))
- Best fits:
  - $\delta_{CP} \sim -\pi/2$
  - $\Delta\chi^2_{I.O.-N.O.} \sim 5.69$
  - $\Delta m^2_{32} \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$
  - $\sin^2\theta_{23} \sim 0.45$
- Rejection of the inverted mass ordering is about 92.3%.

published paper, PRL 134, 011801 (2025)

SK+T2K joint oscillation analysis

- T2K is sensitive to Dirac CP.
  - SK is the far detector of the long baseline.



- Atmospheric neutrino analysis is sensitive to mass ordering.
- Dirac CP phase and mass hierarchy degenerate on $\nu_e/\bar{\nu}_e$.
  →Joint fit among SK and T2K give better constraints.

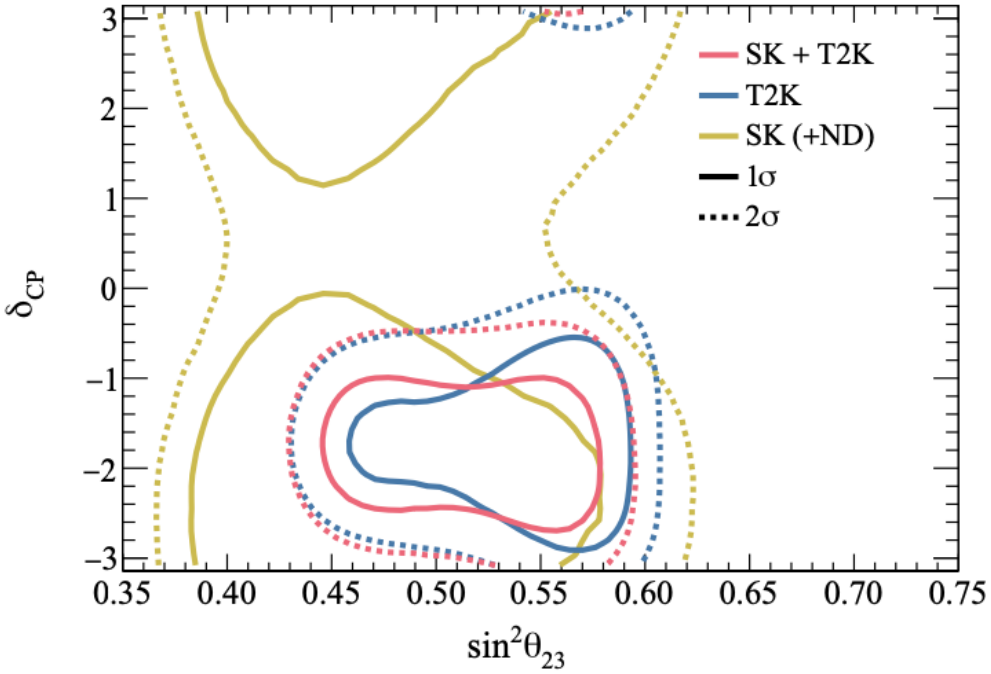
Atmospheric　　Reactor

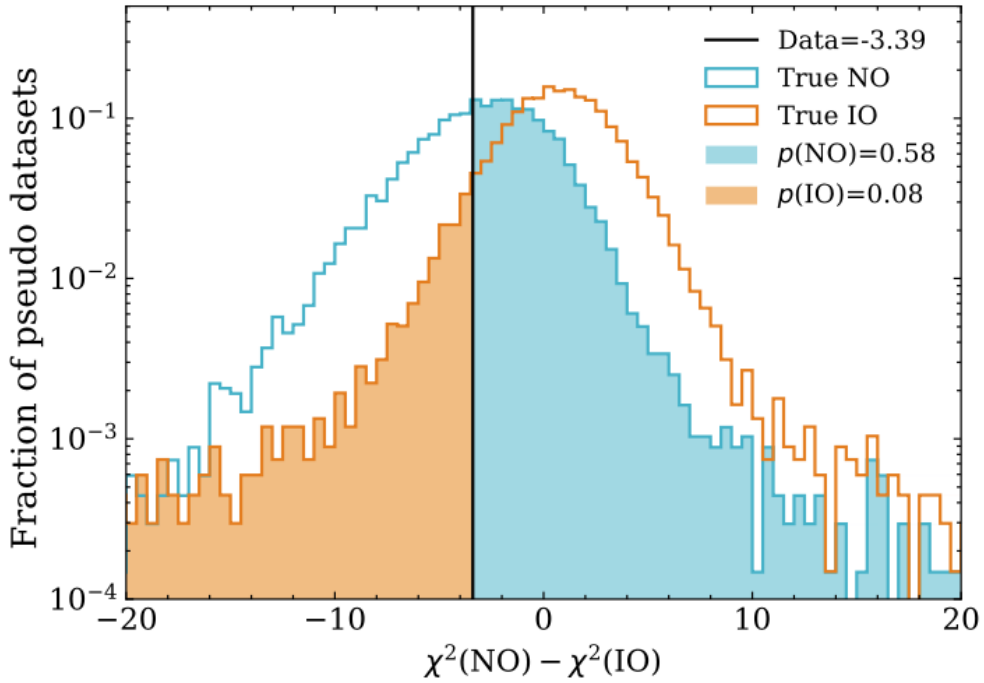
$$U_{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Accelerator　　Solar

published paper, PRL 134, 011801 (2025)

SK+T2K joint oscillation analysis





- Atmospheric ν sample: SK-I to IV (3244.4 days)
- 1.9 σ exclusion of CP conservation
- 1.2 σ exclusion of the inverted mass ordering.

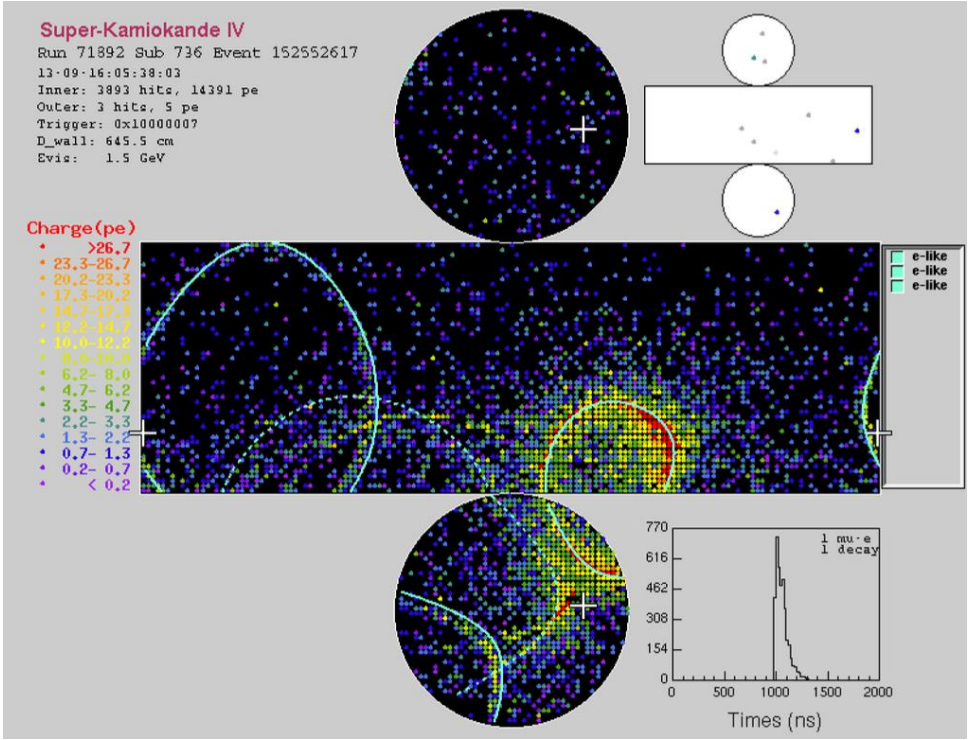
Summary

- Published paper:
  - Search for $p \to l^+\eta$
  - Oscillation analysis with neutron tagging and expanded FV in SK-I to V
  - Joint oscillation analysis (SK+T2K)
- Various proton decay modes were searched utilizing spectrum fitting.
  - $p \to \nu\pi^+$: 3.5×10^{32} years
  - $n \to \nu\pi^0$: 1.4×10^{33} years
  - $n \to \bar{\nu}K^0$: 7.8×10^{32} years
  - $p \to \mu^+X$: 6.1×10^{32} years
- $ppp \to e^+\pi^+\pi^+$ was also searched using CNN for the complex hit patterns by high energy pions.
  - Lifetime limit at 90% CL: 4.2×10^{32} years

Backup

Final sample in $ppp \rightarrow e^+\pi^+\pi^+$ analysis

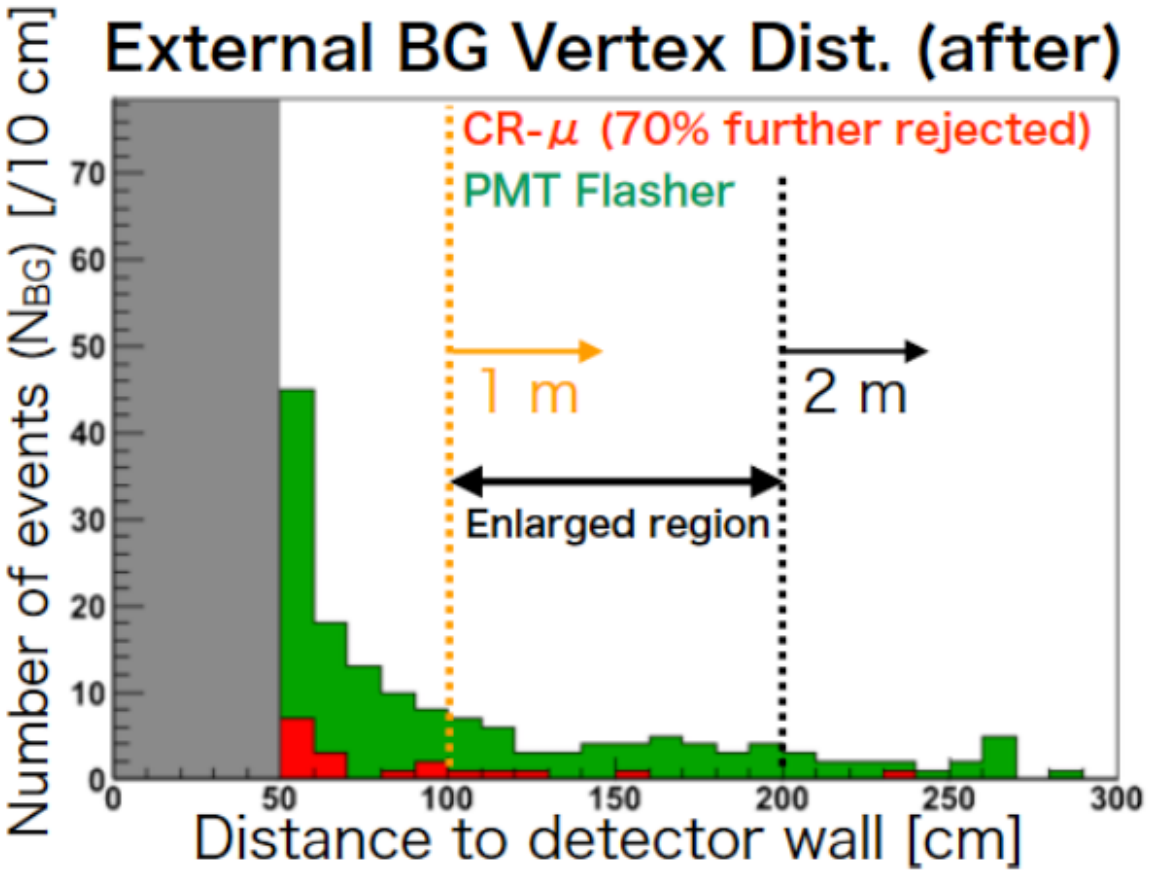
- One event in the final sample (SK-IV) with 29.8% Poisson probability
- Three electron-like
- One Michel electron
- Total invariant mass 1.289GeV
- Total momentum 889 MeV
- CNN prediction value=6.20 (>6.12)

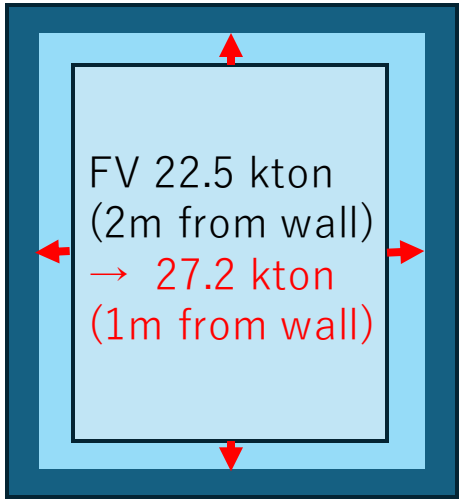


- Images processed by a model combining CNN and attention.
- Convolutional layers extract features; attention identifies feature relationships.
- Enables the model to recognize inter-feature connections gradually.

Input	Operator	exp size	#out	SE	NL	s
$224^2 \times 3$	conv2d	-	16	-	HS	2
$112^2 \times 16$	bneck, 3x3	16	16	-	RE	1
$112^2 \times 16$	bneck, 3x3	64	24	-	RE	2
$56^2 \times 24$	bneck, 3x3	72	24	-	RE	1
$56^2 \times 24$	bneck, 5x5	72	40	-	RE	2
$28^2 \times 40$	bneck, 5x5	120	40	✓	RE	1
$28^2 \times 40$	bneck, 5x5	120	40	✓	RE	1
$28^2 \times 40$	bneck, 3x3	240	80	-	HS	2
$14^2 \times 80$	bneck, 3x3	200	80	-	HS	1
$14^2 \times 80$	bneck, 3x3	184	80	-	HS	1
$14^2 \times 80$	bneck, 3x3	184	80	-	HS	1
$14^2 \times 80$	bneck, 3x3	480	112	✓	HS	1
$14^2 \times 112$	bneck, 3x3	672	112	✓	HS	1
$14^2 \times 112$	bneck, 5x5	672	160	✓	HS	2
$7^2 \times 160$	bneck, 5x5	960	160	✓	HS	1
$7^2 \times 160$	bneck, 5x5	960	160	✓	HS	1
$7^2 \times 160$	conv2d, 1x1	-	960	-	HS	1
$7^2 \times 960$	pool, 7x7	-	-	-	-	-
$1^2 \times 960$	conv2d 1x1, NBN	-	1280	-	HS	1
$1^2 \times 1280$	conv2d 1x1, NBN	-	k	-	-	-

Table: MobileNet V3 Architecture

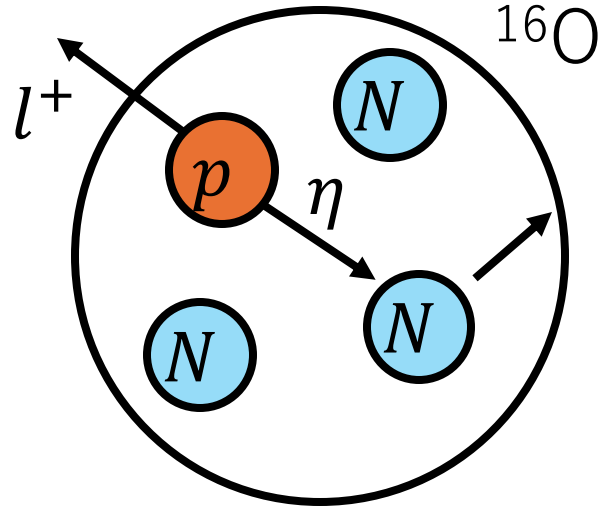

External BG Vertex Dist. (after)
CR-μ (70% further rejected)
PMT Flasher
1 m
2 m
Enlarged region
Number of events (NBG) [/10 cm]
Distance to detector wall [cm]
0
10
20
30
40
50
60
70
0
50
100
150
200
250
300

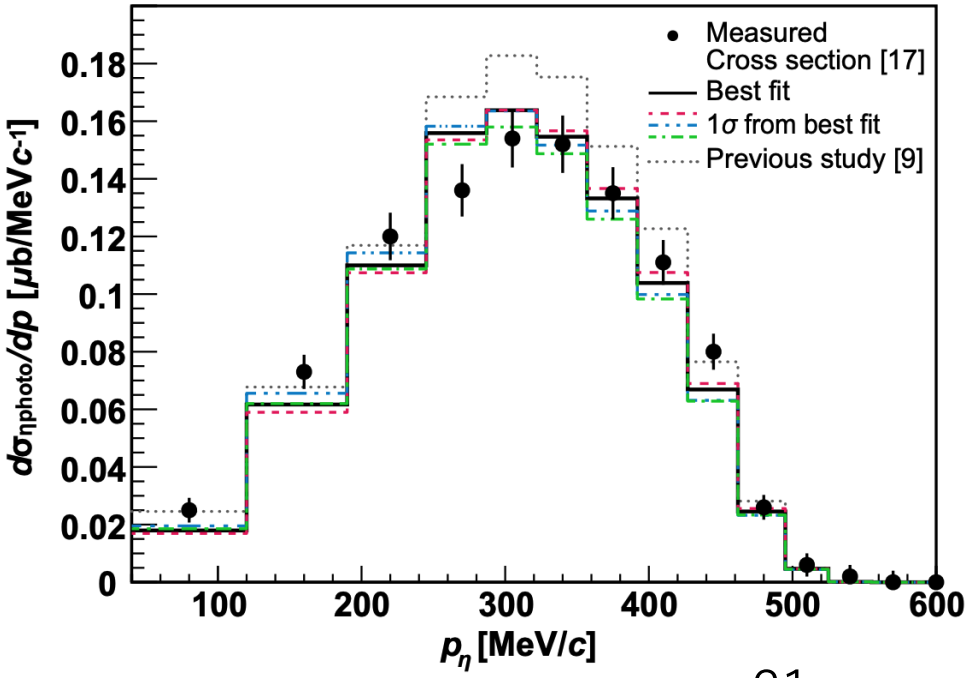

FV 22.5 kton
(2m from wall)
→ 27.2 kton
(1m from wall)

published paper, PRD 110, 112011 (2024)

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

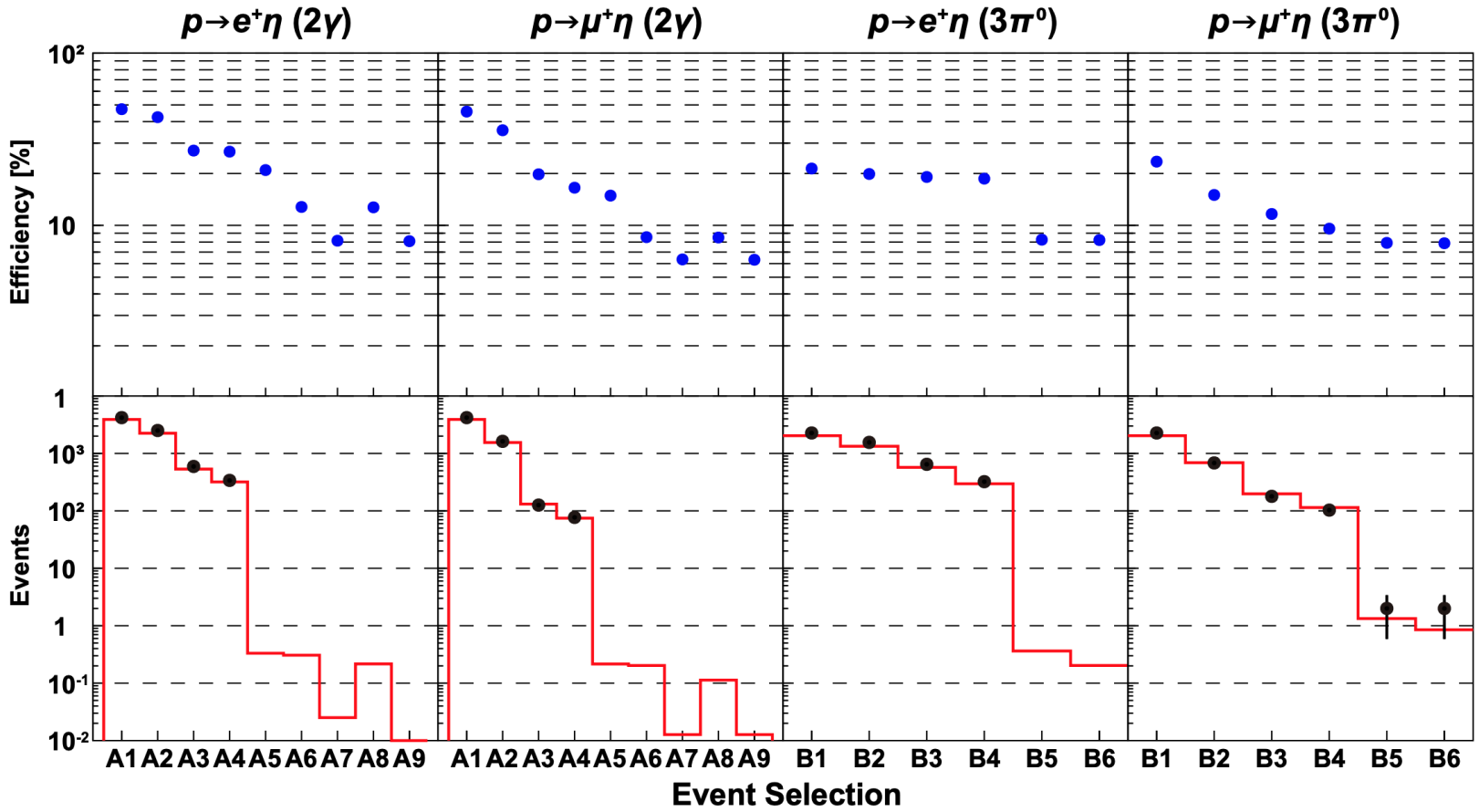
- The last publication:
  PRD 96 012003 (2017)
- Increased statistics:
  SK-I to partial IV (5145 days)
  → SK-I to IV (6050 days)
- Updated physics model
  (ηN cross section)
  - Reduced uncertainty to
    signal efficiency ~30% → ~10%





published paper, PRD 110, 112011 (2024)

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



Lifetime limit

- $e^+\eta$: $> 14.0 \times 10^{33}$ years (updated from 10×10^{33} years)
- $\mu^+\eta$: $> 7.3 \times 10^{33}$ years (updated from 4.7×10^{33} years)

Atmospheric neutrino oscillation analysis w/ ntag and expanded FV in SK-I to V