Search for nucleon decay via $p \to \nu\pi^+$ and $n \to \nu\pi^0$ in 0.484 Mton·year of Super-Kamiokande data

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Nucleon Decay and Super-Kamiokande (SK)

Motivation

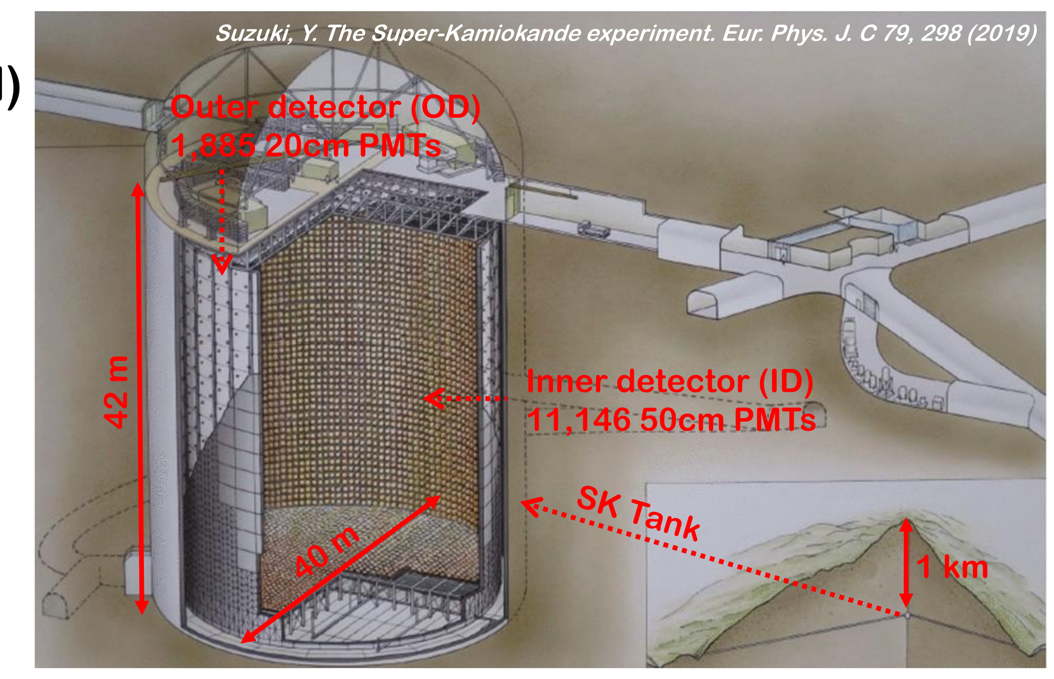
- A Grand Unified Theory (GUT) is proposed with extended gauge symmetry beyond the Standard Model (SM)
- Nucleon decay offer a direct probe for the viability of the GUTs with or without Supersymmetry (SUSY)
- The Super-Kamiokande (SK) water Cherenkov detector [1] is ideal for the nucleon decay searches
- GUT models which favor $p \to \nu\pi^+$ and $n \to \nu\pi^0$: SUSY flipped SU(5) [2-3] and a minimal SUSY SO(10) [4]

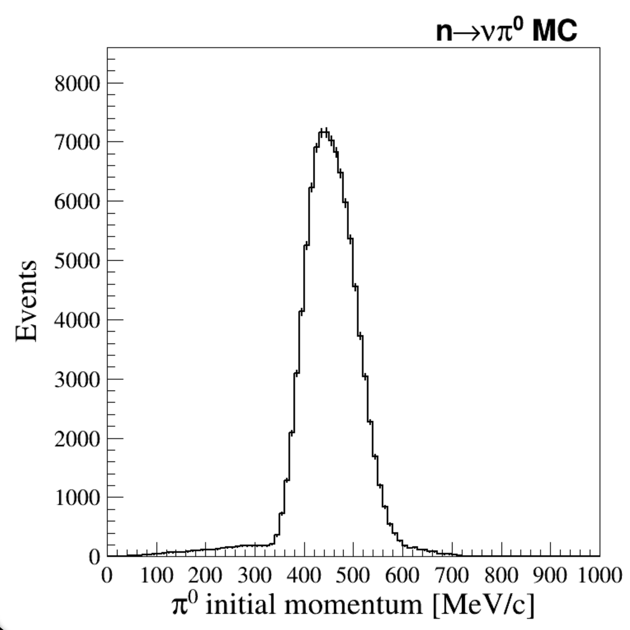
Improvements on previous analysis [5]

- With addition of SK IV-V data to SK I-III, the detector livetime has increased by 132% to 17.8 years
- The fiducial volume (FV) of SK is enlarged by 21% using an improved analysis techniques [6]
- Additional systematic uncertainties have been newly implemented (atmospheric ν flux and interactions)
- Physics models for pion production and its nuclear interactions (FSI) are updated with external data [6-7]

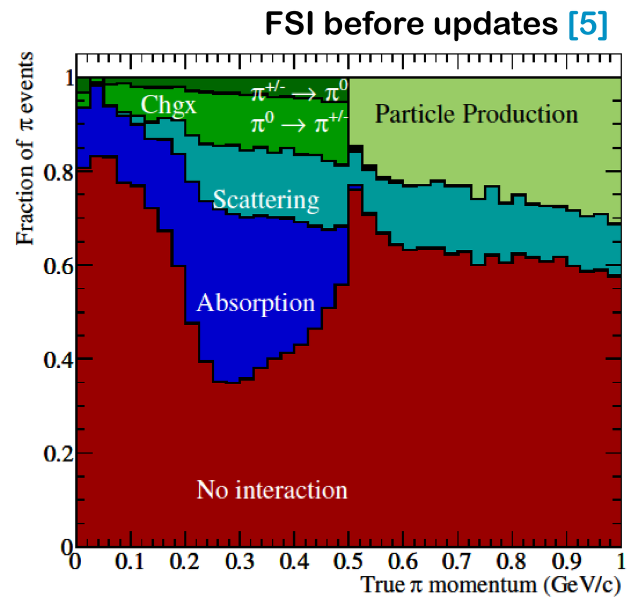
→ Signal efficiency is decreased by increased pion absorption in (300,600) MeV/c region

Suzuki, Y. The Super-Kamiokande experiment. Eur. Phys. J. C 79, 298 (2019)

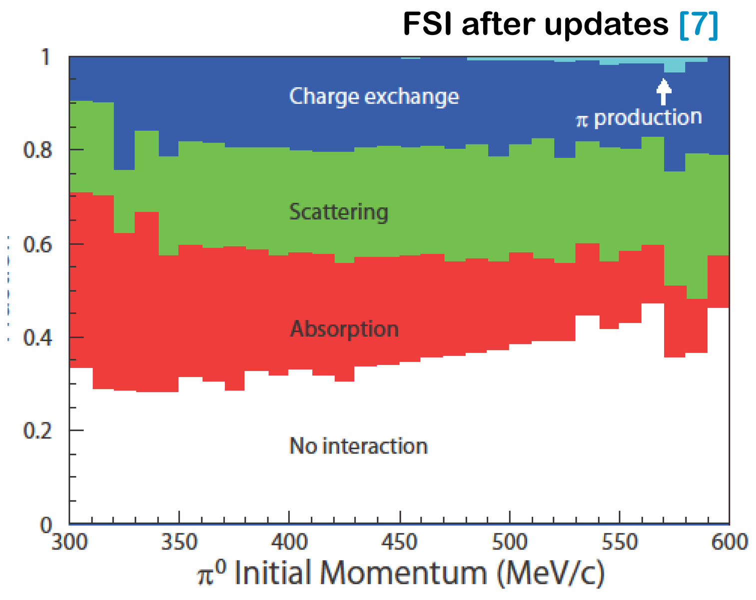




FSI before updates [5]



FSI after updates [7]



Detector phase	SK-I	SK-II	SK-III	SK-IV	SK-V
Live days	1489	799	518	3244	461
Photo-coverage [%]	40	19	40	40	40
Electronics [8]	ATM	ATM	ATM	QBEE	QBEE

[1] S. Mine, The Super-Kamiokande and Other Detectors: A Case Study of Large Volume Cherenkov Neutrino Detectors, World Scientific, Instrument and Techniques in High Energy Physics, 251 (2025)
[2] J. Ellis et al., Aspects of the flipped unification of strong, weak and electromagnetic interactions, Nucl. Phys. B 311, 1 (1988)
[3] J. Ellis et al., Proton decay: flipped vs. unflipped su(5), JHEP 2020 (2020)
[4] H. Goh et al., Proton decay in a minimal SUSY SO(10) model for neutrino mixings, Phys. Lett. B 587, 105 (2004)
[5] K. Abe et al., Search for Nucleon Decay via $n \to \bar{\nu}\pi^0$ and $p \to \bar{\nu}\pi^+$ in Super-Kamiokande, Phys. Rev. Lett. 113, 121802 (2014)
[6] A. Takenaka et al. Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an enlarged fiducial volume in Super-Kamiokande I-IV, Phys. Rev. D 102, 112011 (2020)
[7] K. Abe et al., Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ in 0.31 megaton·years exposure of the Super-Kamiokande water Cherenkov detector, Phys. Rev. D 95, 012004 (2017)
[8] H. Nishino et al., High-speed charge-to-time converter ASIC for the Super-Kamiokande detector, NIM-A 610, 710 (2009)

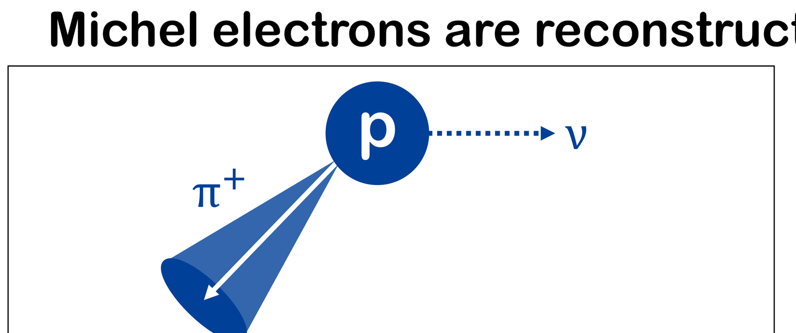
Event Selection

Events fully contained in the fiducial volume (FCFV)

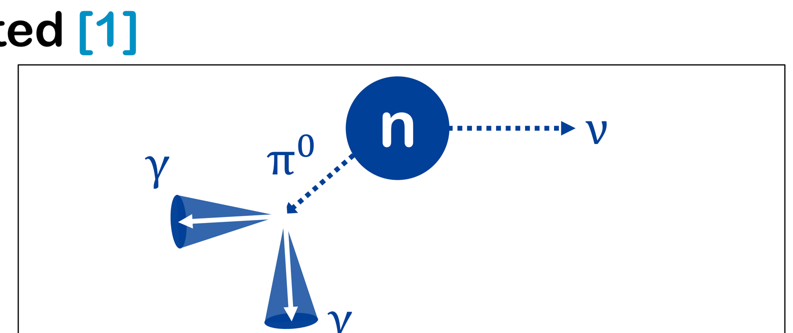
- Eliminate background events in raw data which are caused by cosmic ray muons, low-energy radioactivity, and flashing PMTs
- FV = region inside the ID located at least 1m away from the walls
- Events are required to be reconstructed within the FV, to exhibit sufficient visible energy deposit, and to show no activity in the OD

Event reconstruction

- Physics quantities such as vertex position, the number of Cherenkov rings, momentum, particle type, and the number of Michel electrons are reconstructed [1]



One non-showering ring with
(1) 0-decay e (π^+ absorption in water)
(2) 1-decay e ($\pi^+ \to \mu^+\nu$)



Two showering rings with
0-decay e and
Mass $M_{\mathrm{tot}} \in (85, 185)\,\mathrm{MeV}/c^2$

Event selection		Signal efficiency [%]				
		SK-I	SK-II	SK-III	SK-IV	SK-V
$p \to \nu\pi^+$	0-decay-e	14.5±0.1	14.2±0.1	14.5±0.1	11.6±0.1	11.7±0.1
	1-decay-e	15.9±0.1	15.3±0.1	15.9±0.1	18.1±0.2	18.1±0.2
$n \to \nu\pi^0$		32.2±0.2	30.1±0.2	31.9±0.2	32.6±0.2	32.9±0.2

Spectrum Analysis

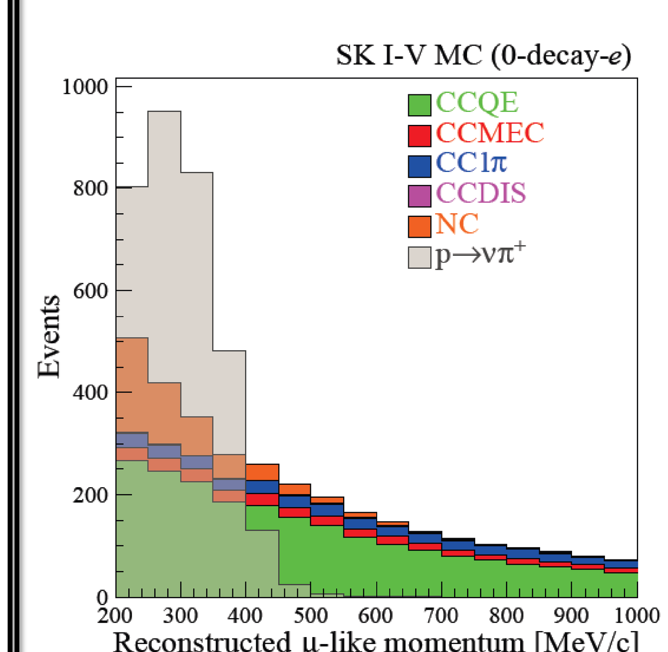
Search for signal bump above the data spectrum

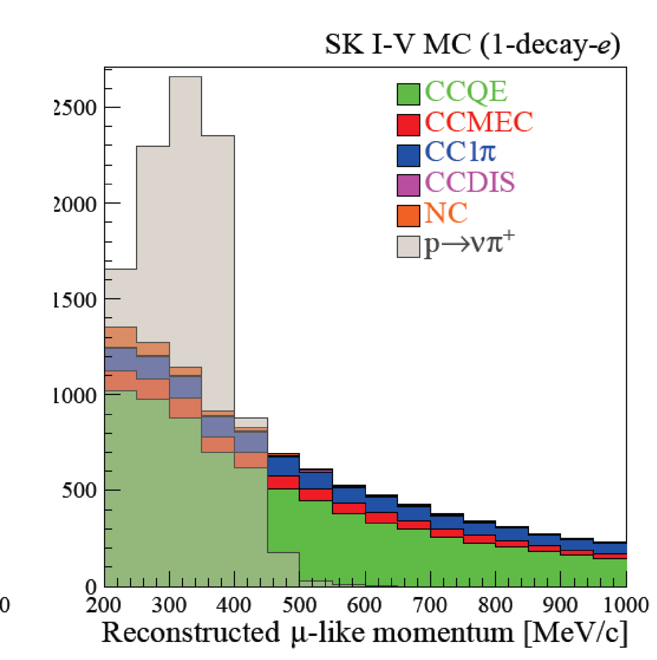
- χ^2 is based on the Poisson probability and quadratic penalty terms

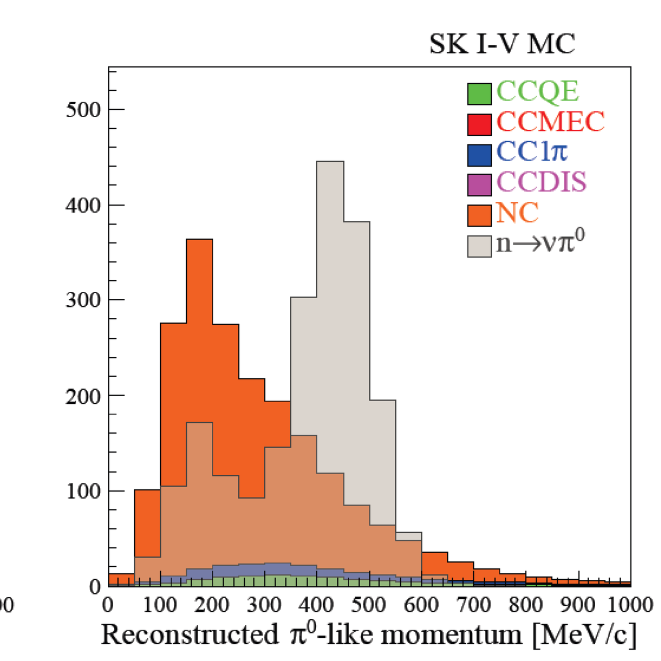
$$\chi^2 = 2 \times \sum_i^{\mathrm{nbins}} \left(E_i + O_i \times \left[\ln\frac{O_i}{E_i} - 1\right]\right) + \sum_j^{\mathrm{nsys}} \left(\frac{\epsilon_j}{\sigma_j}\right)^2$$

$$E_i = \left[E_i^{\mathrm{bkg}} + \beta \times E_i^{\mathrm{sig}}\right] \times \left(1 + \sum_j^{\mathrm{nsys}} f_{ij}\epsilon_j\right)$$

E_i: Expected events
O_i: Observed events
σ_j: Size of the systematic error
f_{ij}: Fractional change by error
ϵ_j: Nuisance parameter for fitted error
β: Signal normalization parameter







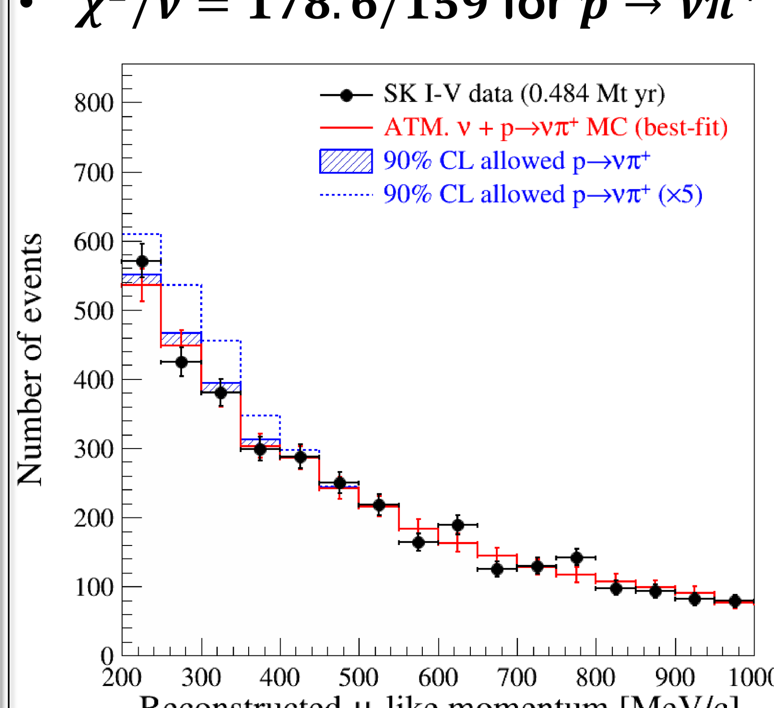
Sensitivity with respect to the null-hypothesis

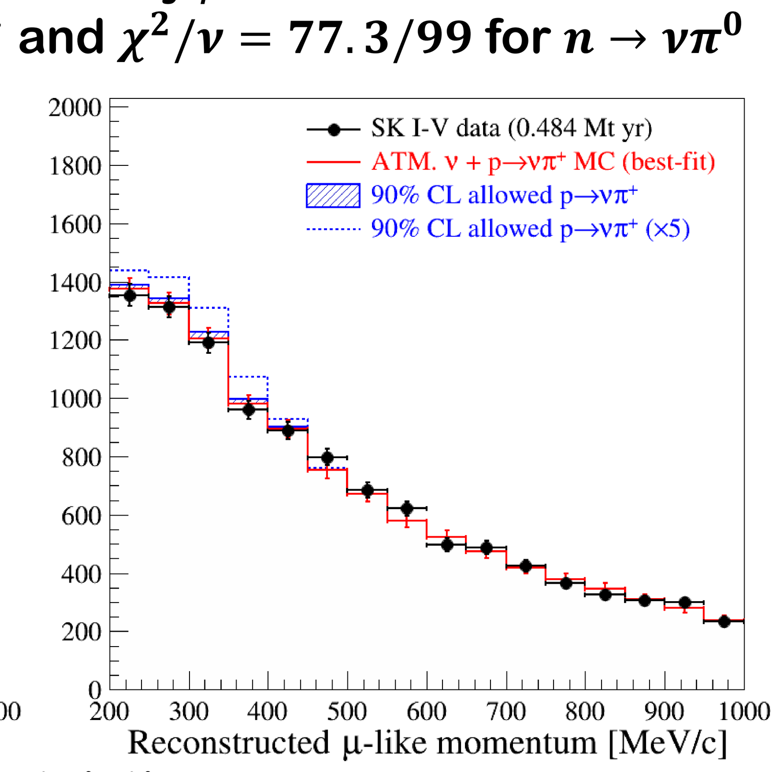
- Updated FSI model reduced it by 16% for $p \to \nu\pi^+$ and 32% for $n \to \nu\pi^0$
- Adding the SK IV-V to the SK I-III data increased it by 60% for both modes
- Enlarging the FV increased it by 10% for $p \to \nu\pi^+$ and 5% for $n \to \nu\pi^0$
- Systematic uncertainties reduced it by 65% for $p \to \nu\pi^+$ and 40% for $n \to \nu\pi^0$

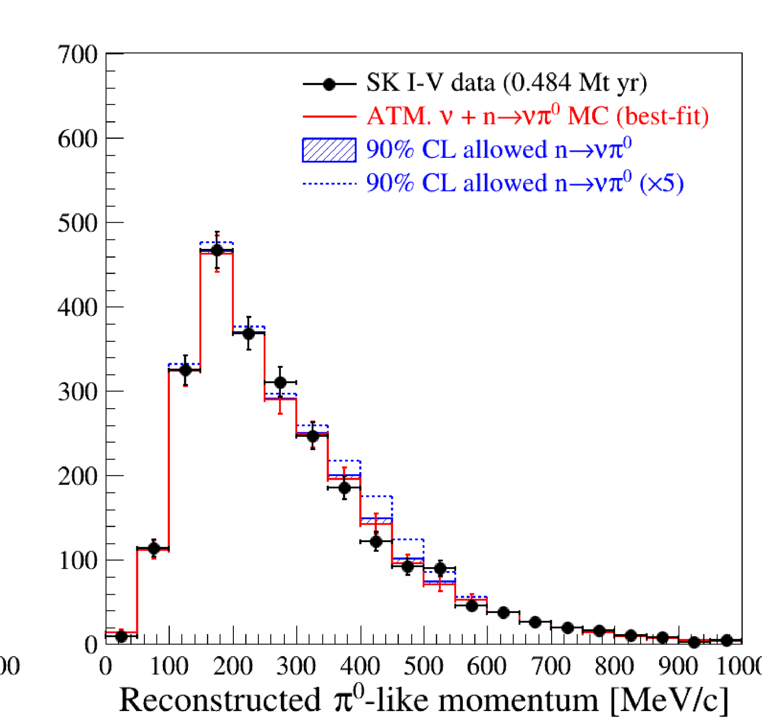
Search Results

Best-fit

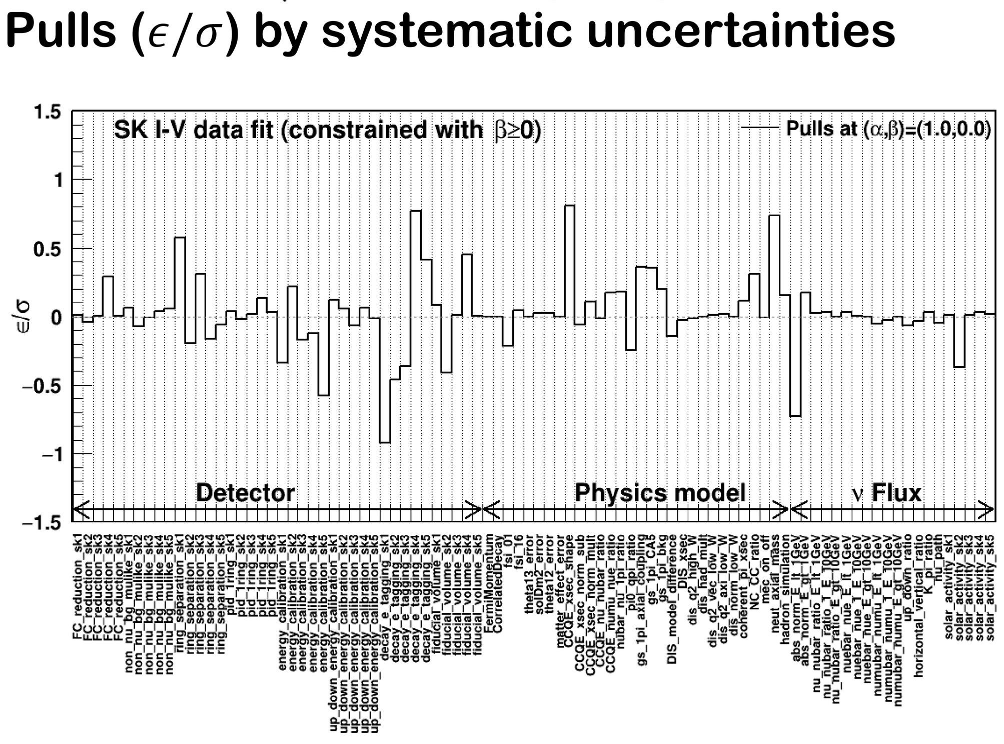
- Best-fit gives $\beta = 0$ with constraint by $\beta \geq 0$ for both modes
- $\chi^2/\nu = 178.6/159$ for $p \to \nu\pi^+$ and $\chi^2/\nu = 77.3/99$ for $n \to \nu\pi^0$

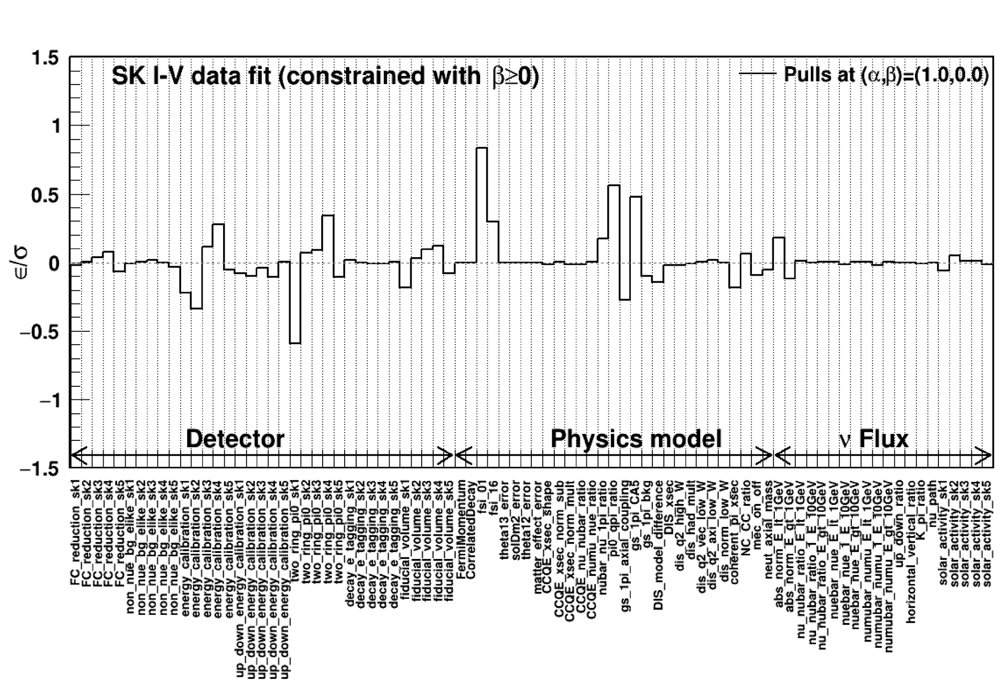






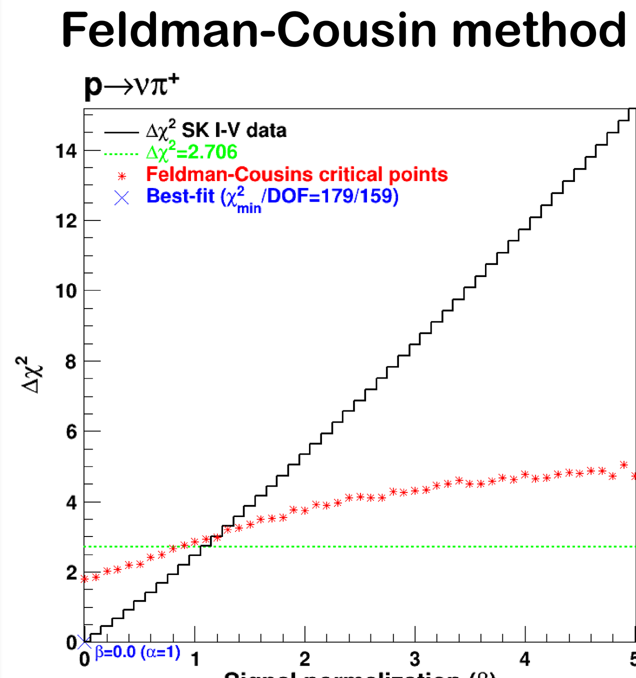
- Pulls (ϵ/σ) by systematic uncertainties

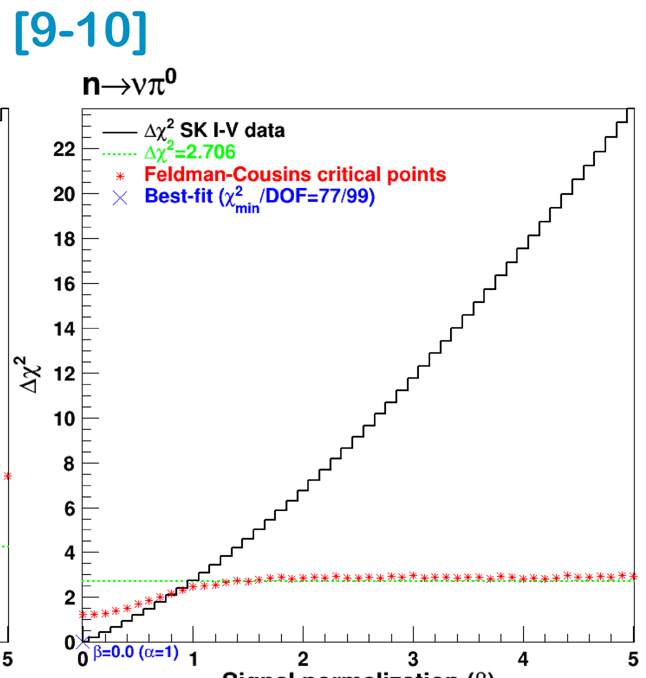




Nucleon decay partial lifetime limits

- $\Delta\chi^2$ contour over $\beta \geq 0$ (physical region)
- Critical values for 90% C.L. are estimated by the Feldman-Cousin method [9-10]





Signal Events Allowed at 90% C.L.

$p \to \nu\pi^+$	136.7
$n \to \nu\pi^0$	30.3

Partial lifetime at 90% C.L. [year]

$p \to \nu\pi^+$	3.5×10^{32}
$n \to \nu\pi^0$	1.4×10^{33}

[9] G. Feldman et al., Unified approach to the classical statistical analysis of small signals, Phys. Rev. D 57, 3873 (1998)
[10] M. A. Acero et al., Monte Carlo method for constructing confidence intervals with unconstrained and constrained nuisance parameters in the NOvA experiment, JINST 20 T02001 (2025)