Nucleon Decay Searches in Super-Kamiokande: Results and Prospects

Gabriel Santucci
2017 August 03
gabriel.santucci@stonybrook.edu

DPF Meeting

Does the Proton Decay?

- Proton stability is not guaranteed by any fundamental symmetry.

- Standard Model interactions share the same structure: gauge theories with unitary symmetry.

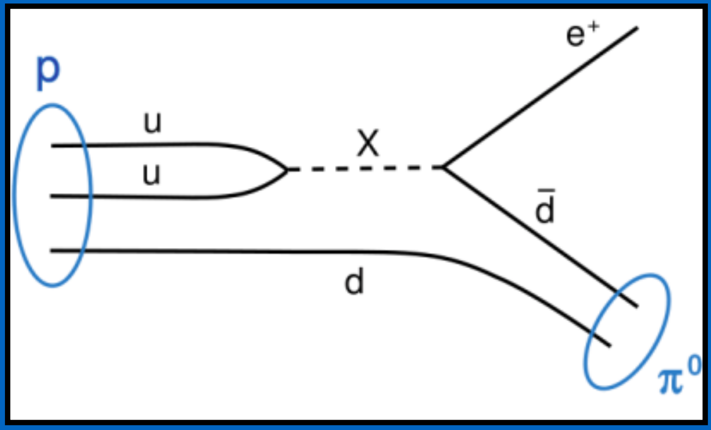
- Grand Unified Theories (GUTs) unifies the SM interactions at very high energies (GUT scale) - beyond the reach of accelerators.

- Most GUTs predict nucleon decay with a very long lifetime (> 10^{30} years).

- Thus, nucleon decay serves as a direct probe of GUTs. But very massive detectors are necessary for these searches.

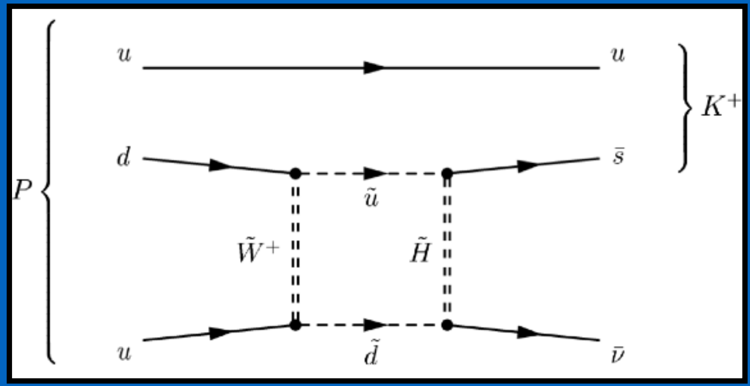
Benchmark Modes

$p \rightarrow e^{+} \pi^{0}$



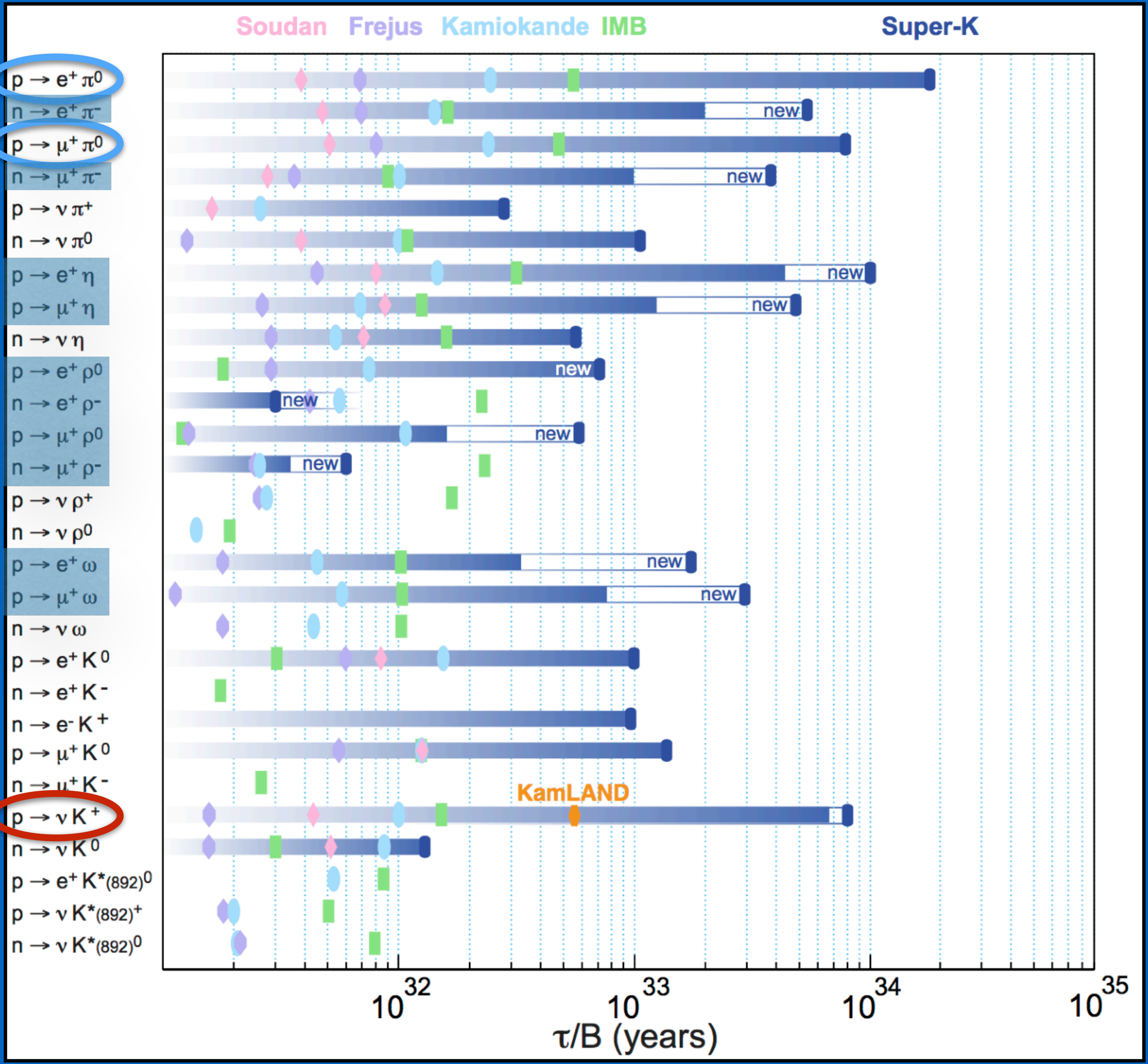
non-SUSY favored

$p \rightarrow \bar{\nu} K^{+}$



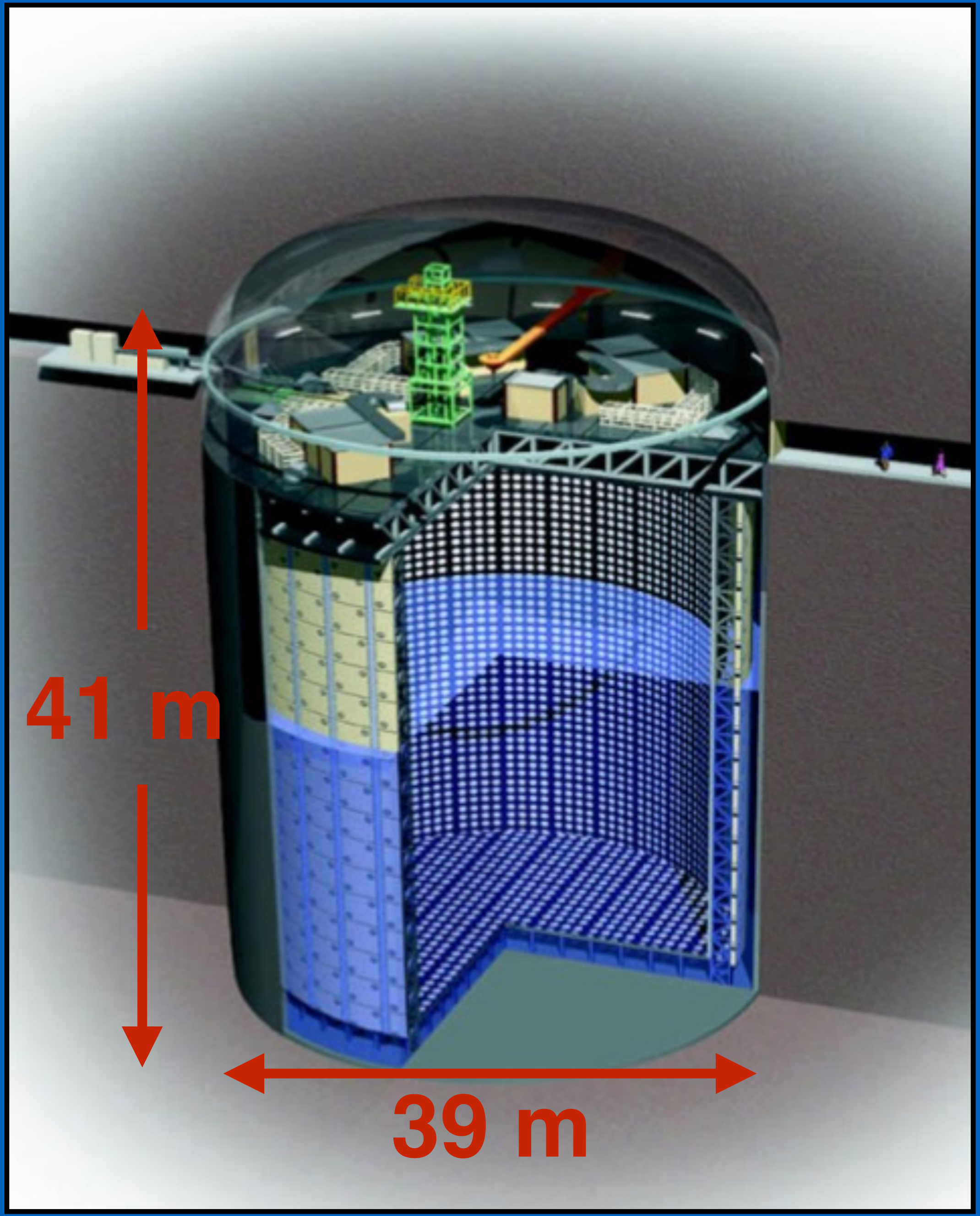
SUSY favored

Proton Decay Modes



- GUTs predict many nucleon decay (NDK) modes.
- Different experiments have searched for NDK in the 80's. But no evidence was found during these searches.
- Super-Kamiokande is the largest detector built to look for NDK and it has been taking data since 1996.

The Super-Kamiokande Detector



Four Run Periods:

SK-I (96-01) SK-II (03-05)

SK-III (05-08) SK-IV (08-present)

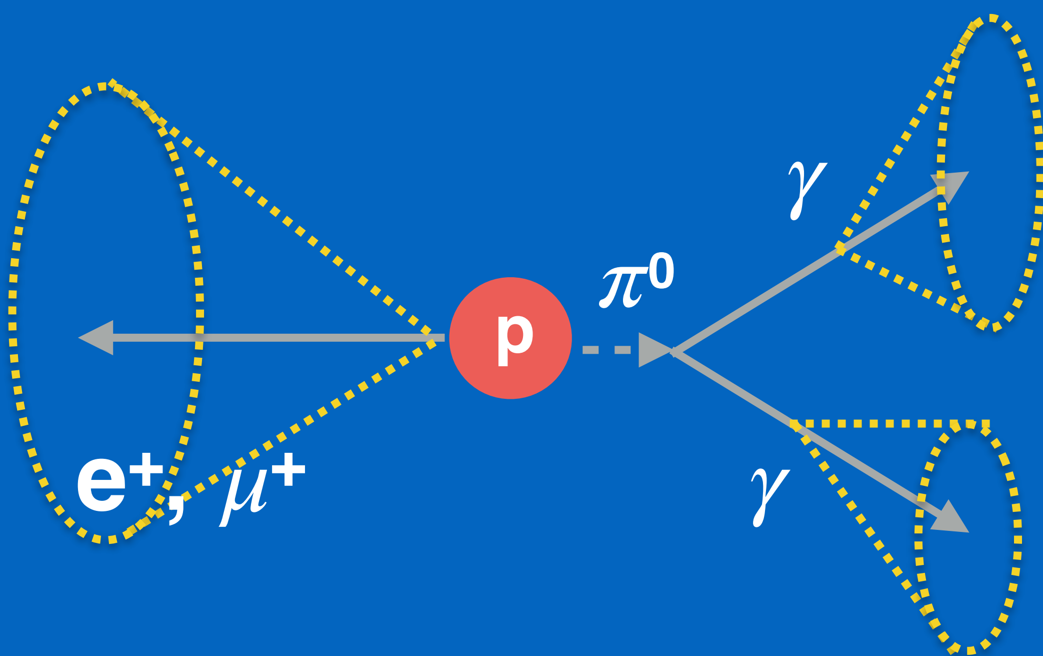
New front-end electronics

- Multipurpose 50 kton water Cherenkov detector (22.5 kton fiducial).
- Optically separated into:
  - Inner Detector: 11,146 20” PMTs
  - Outer Detector: 1,885 8” PMTs
- Excellent particle identification between showering (e-like) and non-showering (μ-like) rings.

SK 20” PMT

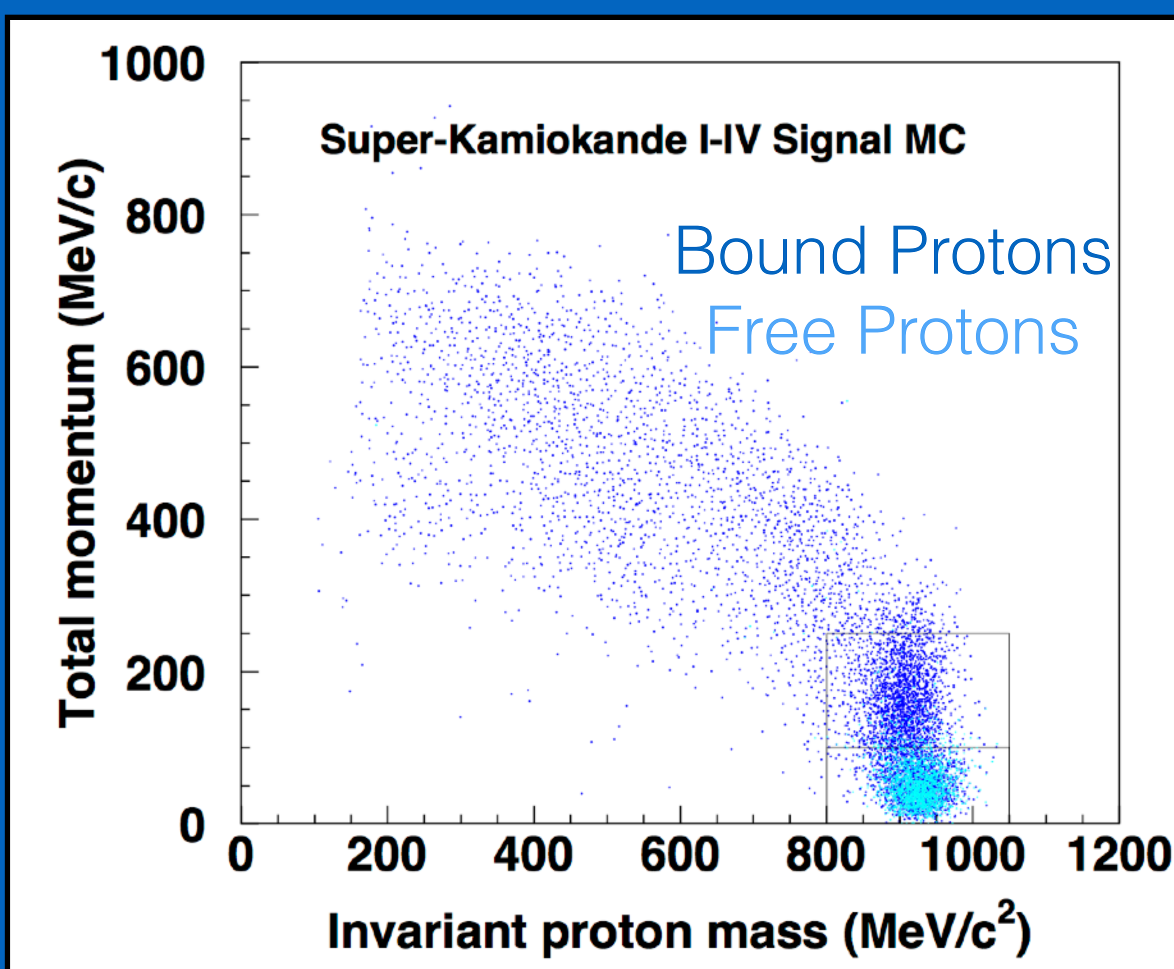
The modes: $p \to e^{+}\pi^{0}$ and $p \to \mu^{+}\pi^{0}$

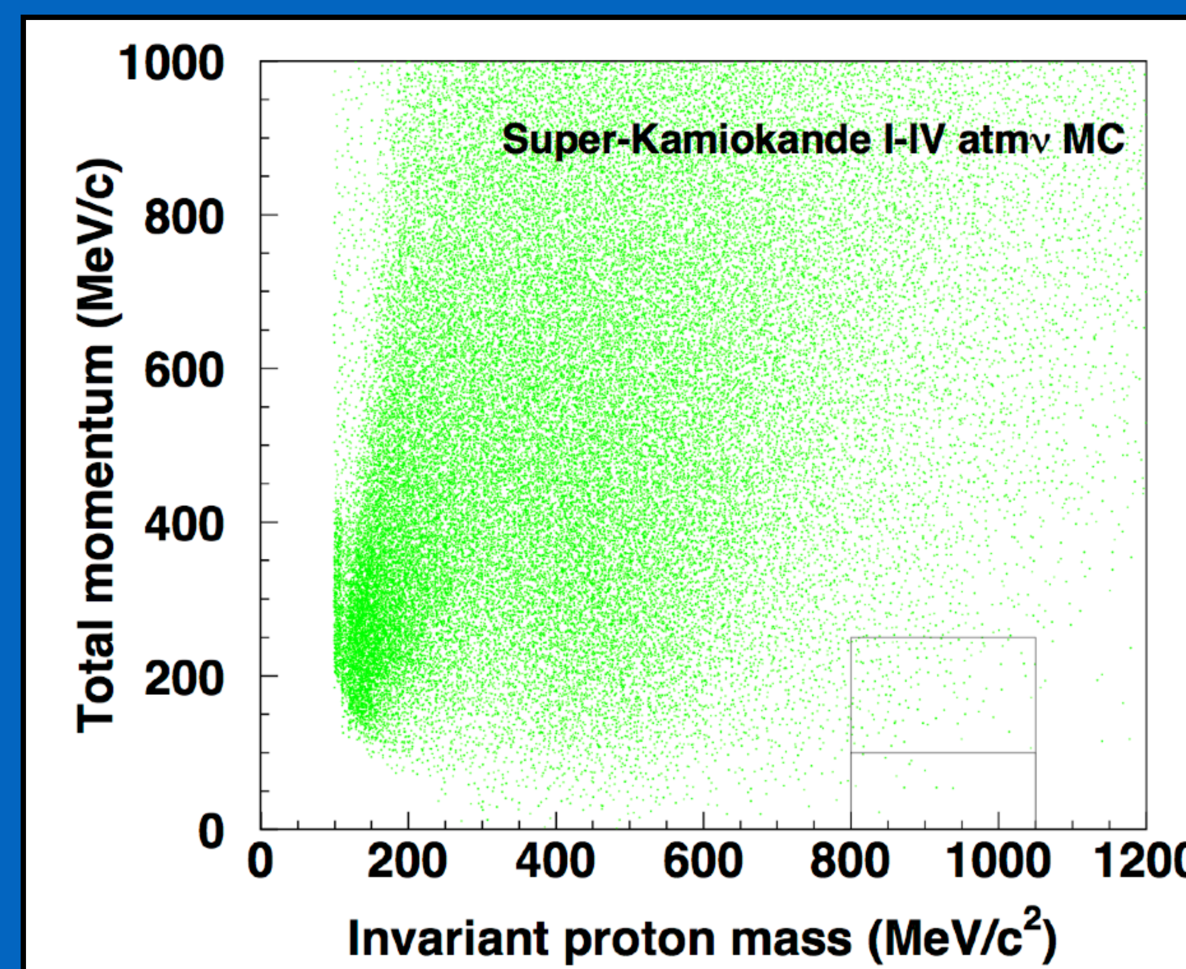
PRD 95, 12004 (2017)



Event Characteristics

- The l^+ and π^0 are back-to-back (459 MeV/c).
- $\pi^0 \to \gamma\gamma$: all final state particles are detectable.
- Able to reconstruct **proton mass** and **momentum**.
- Atmospheric neutrino interactions can mimic this type of signal.



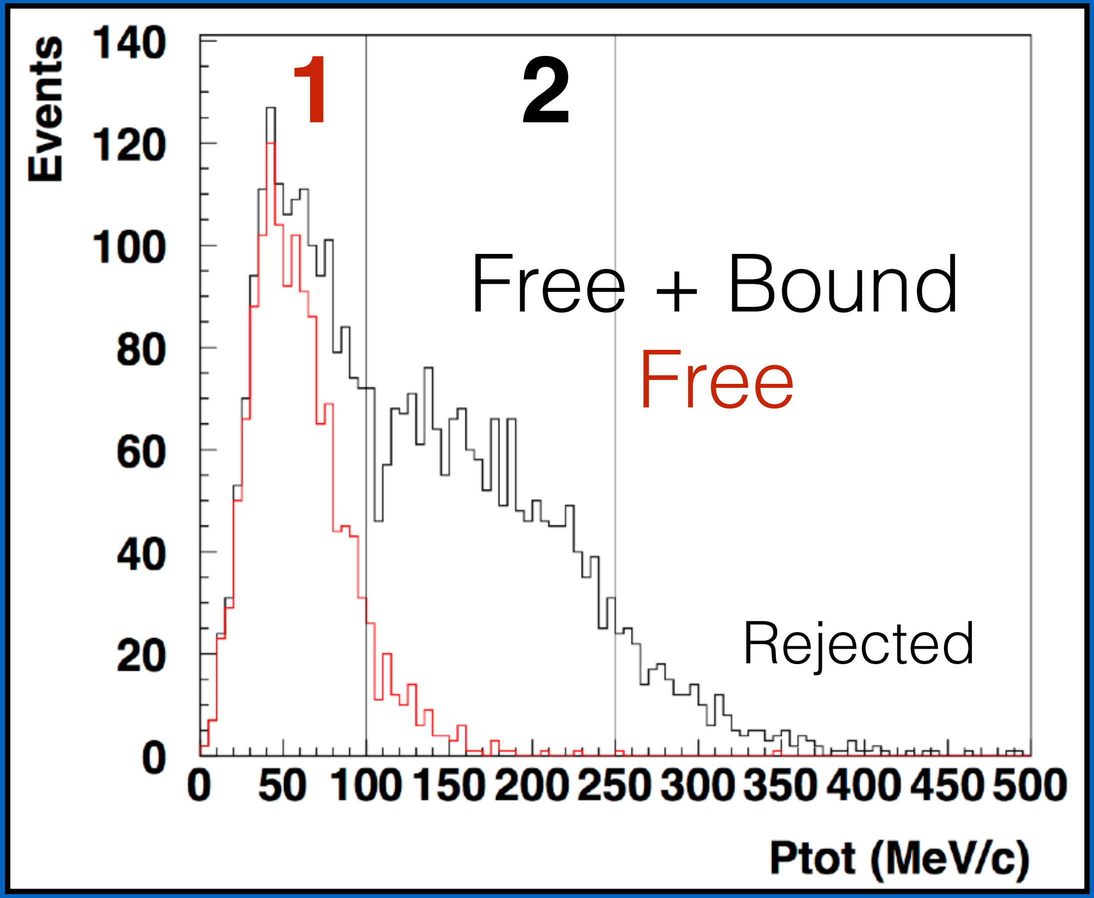


Analysis Improvements

PRD 95, 12004 (2017)

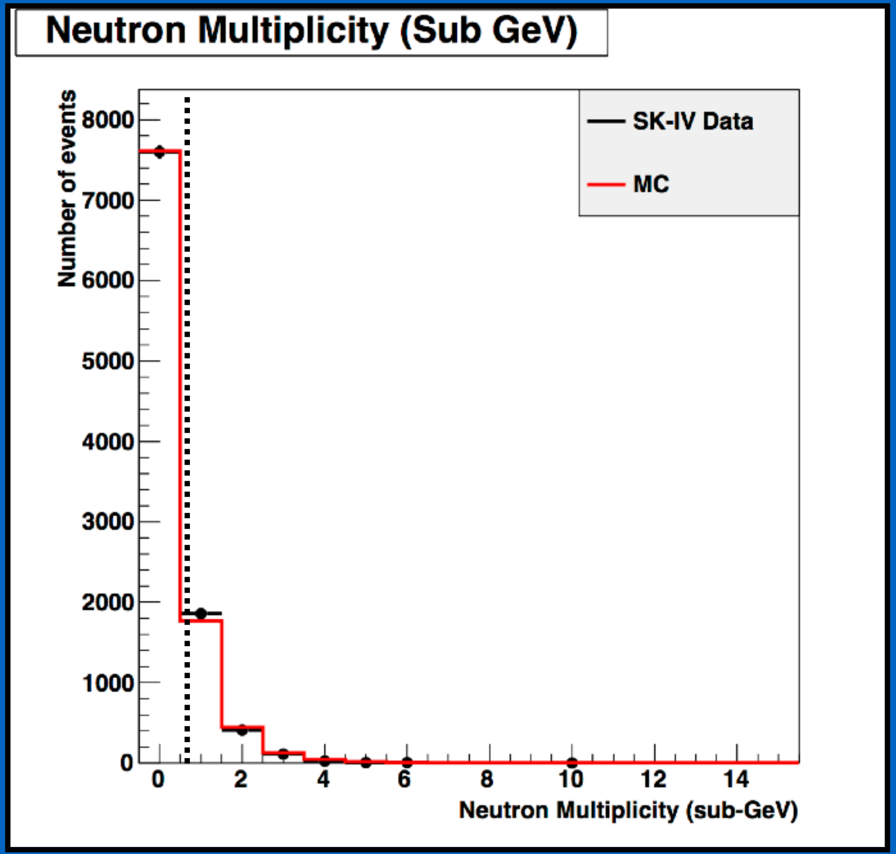
Two Box Analysis

- **Region 1:** P < 100 MeV/c.
  - Dominated by free protons.
  - No nuclear effects → Less Systematics.
- **Region 2:** 100 < P < 250 MeV/c.
  - Dominated by bound protons.



Neutron Capture (SK-IV only)

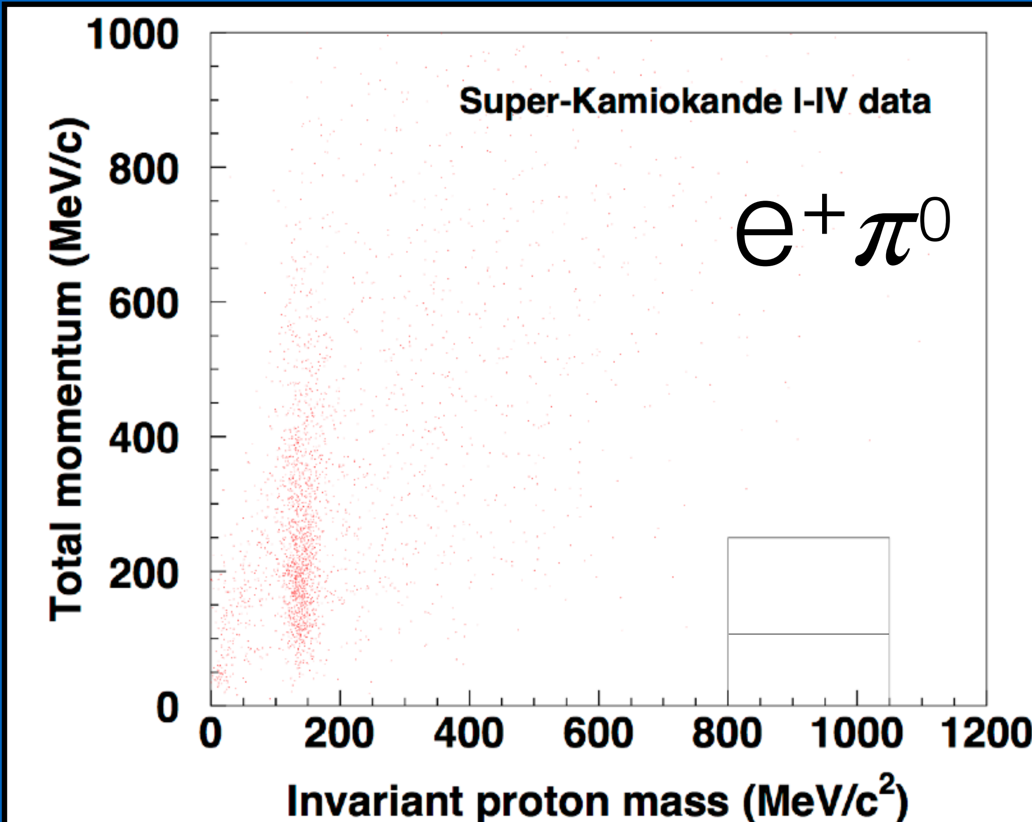
- Atm-ν interactions can produce neutrons in the final state.
- Neutron is captured by Hydrogen and a photon is emitted.
- Half of the remaining atm background can be removed using neutron tagging.

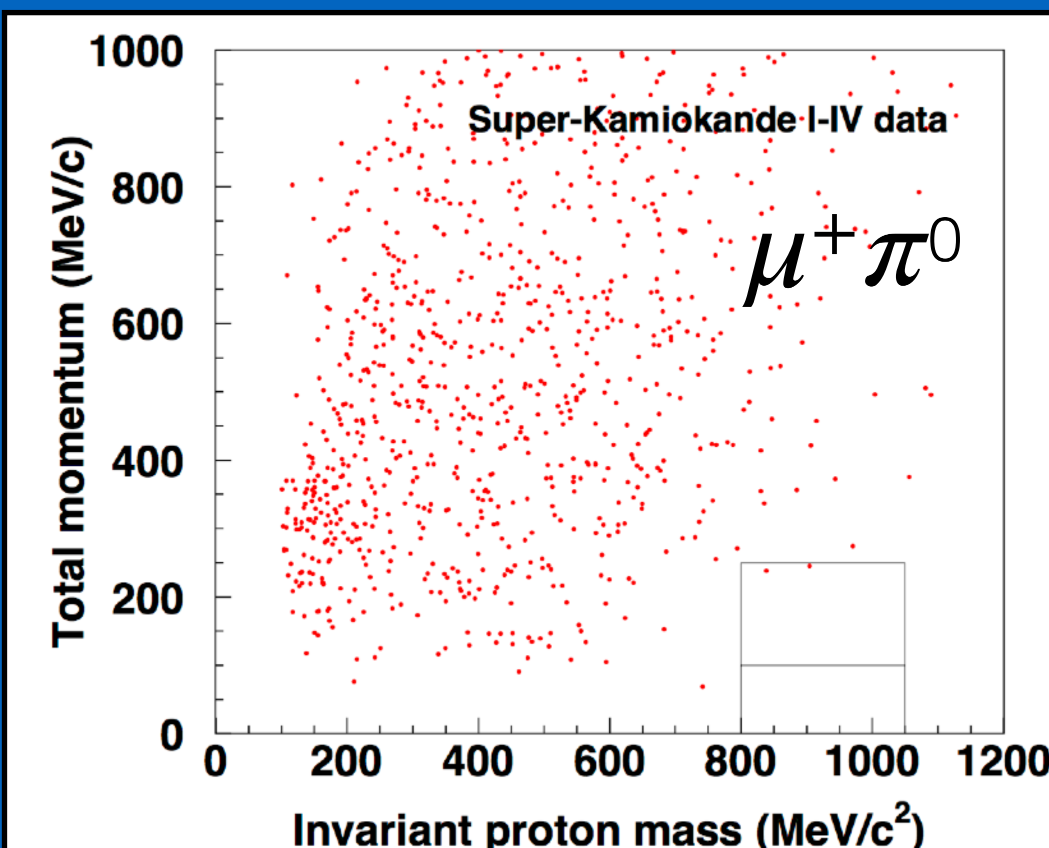


(2012) 220 kton · yrs data from SK I-II → (2017) 306 kton · yrs data from SK I-IV.

Results

PRD 95, 12004 (2017)





$e^+\pi^0$	Signal Efficiency	Expected Background	Observed Events
Low	18.7%	0.07	0
High	19.9%	0.54	0
Total	38.6%	0.61	0

$\mu^+\pi^0$	Signal Efficiency	Expected Background	Observed Events
Low	18.0%	0.05	0
High	16.7%	0.82	2
Total	34.7%	0.87	2

	Lifetime Limit at 90% CL with 306 kton · yrs exposure
$p \rightarrow e^+\pi^0$	$1.6 \cdot 10^{34}$ years
$p \rightarrow \mu^+\pi^0$	$7.7 \cdot 10^{33}$ years

Other N → l^+ + meson Searches

PRD 96, 012003 (2017)

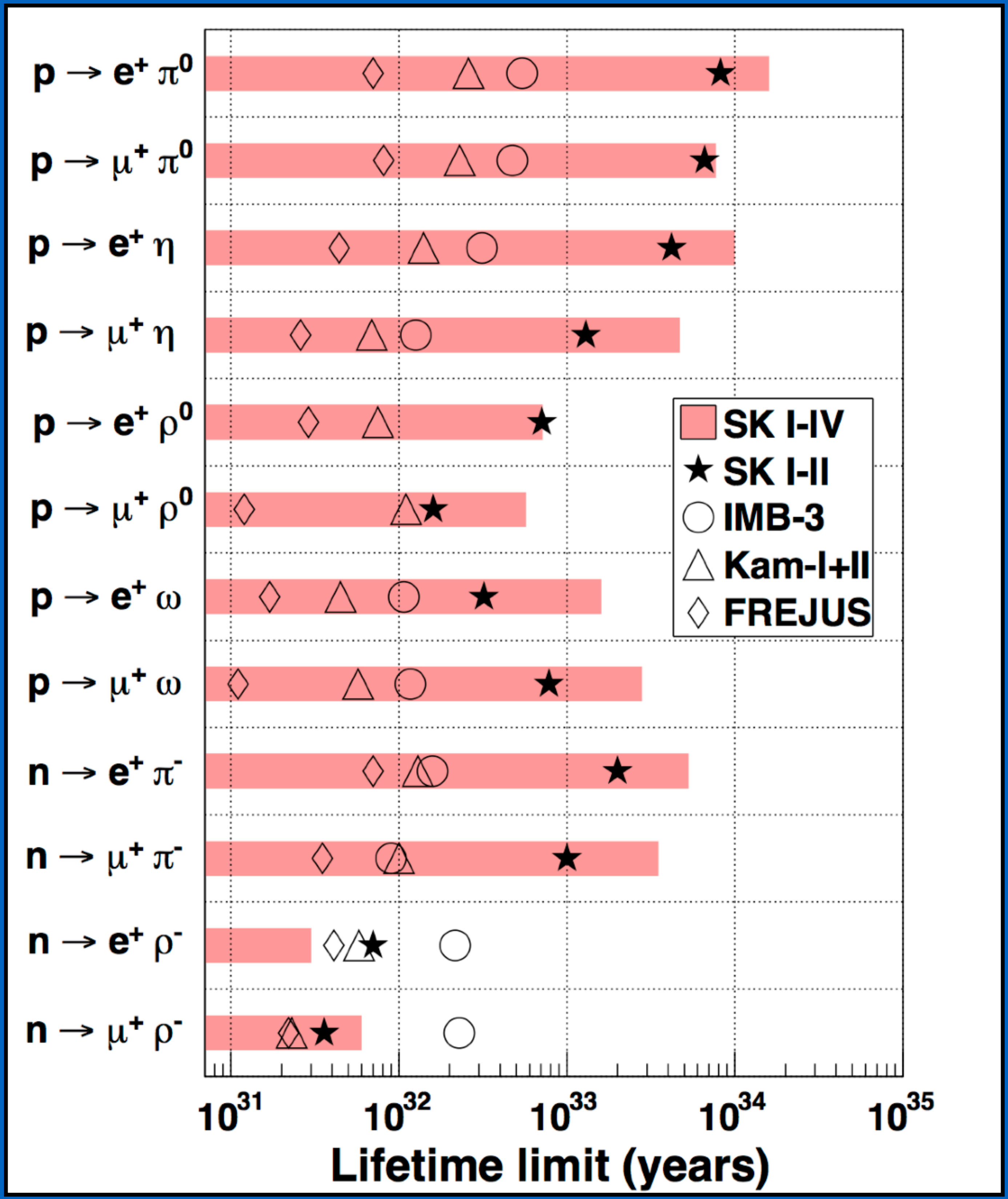
$$p \rightarrow (e^+, \mu^+) + (\eta, \rho^0, \omega)$$

$$n \rightarrow (e^+, \mu^+) + (\pi^-, \rho^-)$$

- Systematic search for several modes of anti-lepton + meson.
- Exposure has increased to 316 kton · year, 2.26 times more data since last result (2012).
- Similarly to $l^+\pi^0$, the analysis benefit from neutron tagging in SK-IV.
- 2-Box separation is introduced for $p \rightarrow l^+ \eta$, with $\eta \rightarrow \gamma\gamma$ only.

$N \rightarrow l^{+}$ + meson Results

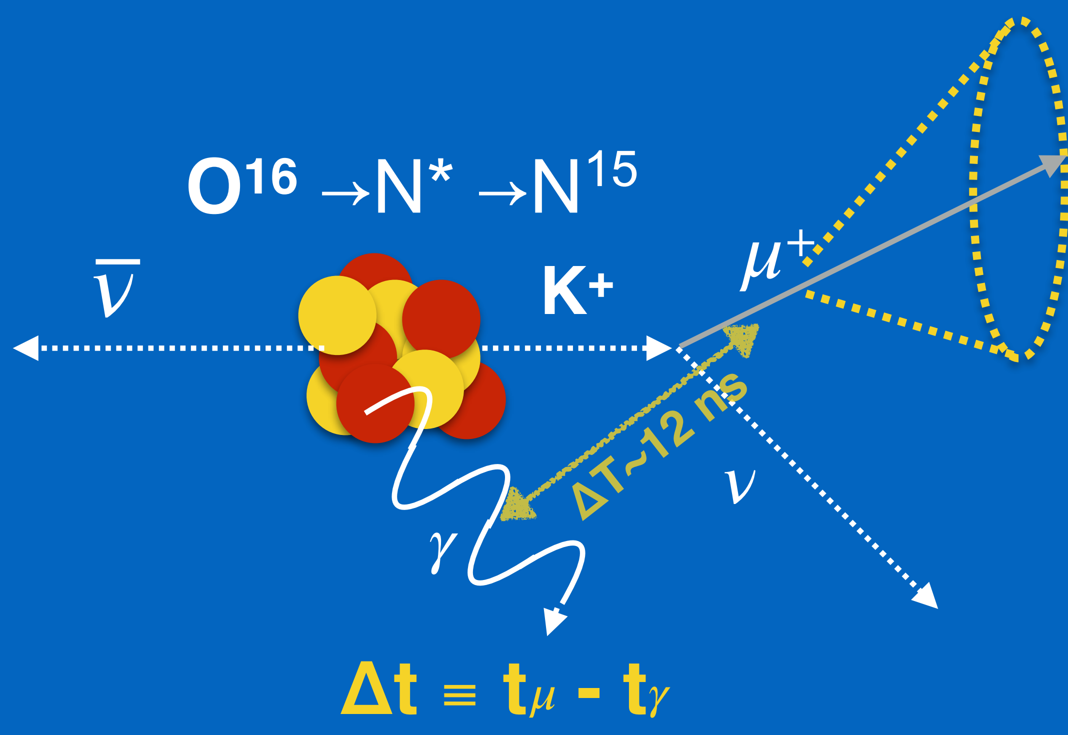
PRD 96, 012003 (2017)



- Most channels have increased by a factor of 2 or 3 since the previous publication (SK-I and II).
- Some events have been observed, but in all cases the observation was consistent with expected background.

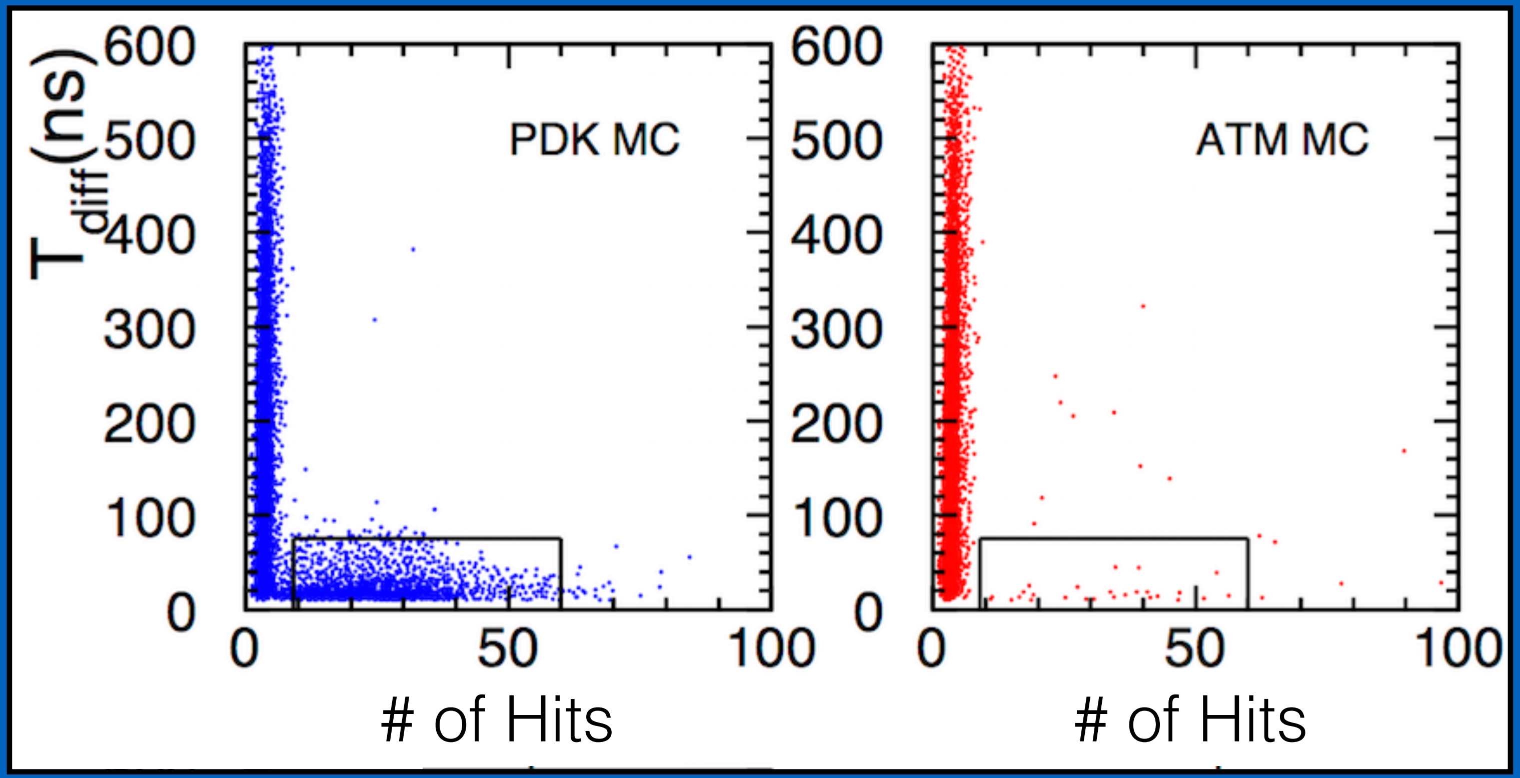
$p \to \bar{\nu} K^+$: Prompt-γ and Monochromatic Excess Searches

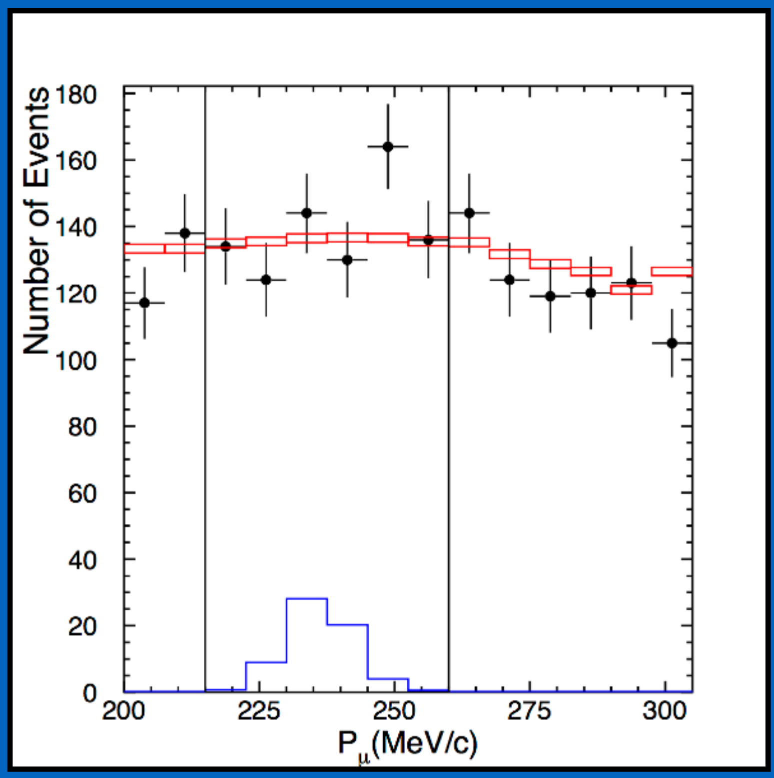
PRD 90, 072005 (2014)



Event Characteristics

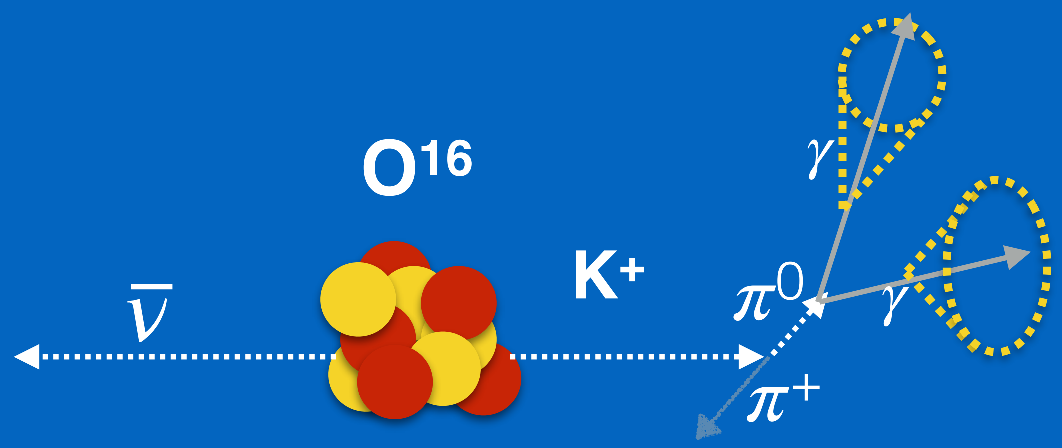
- Neutrino and Kaon are invisible.
- Dominant Kaon decay mode: mono-chromatic μ with ~236 MeV/c.
- Nuclear de-excitation: ~6 MeV γ.
- Coincidence measurement of low-E γ and a mono-energetic μ.
- If γ not found: look for excess of monochromatic μ in the spectra (statistically independent search).





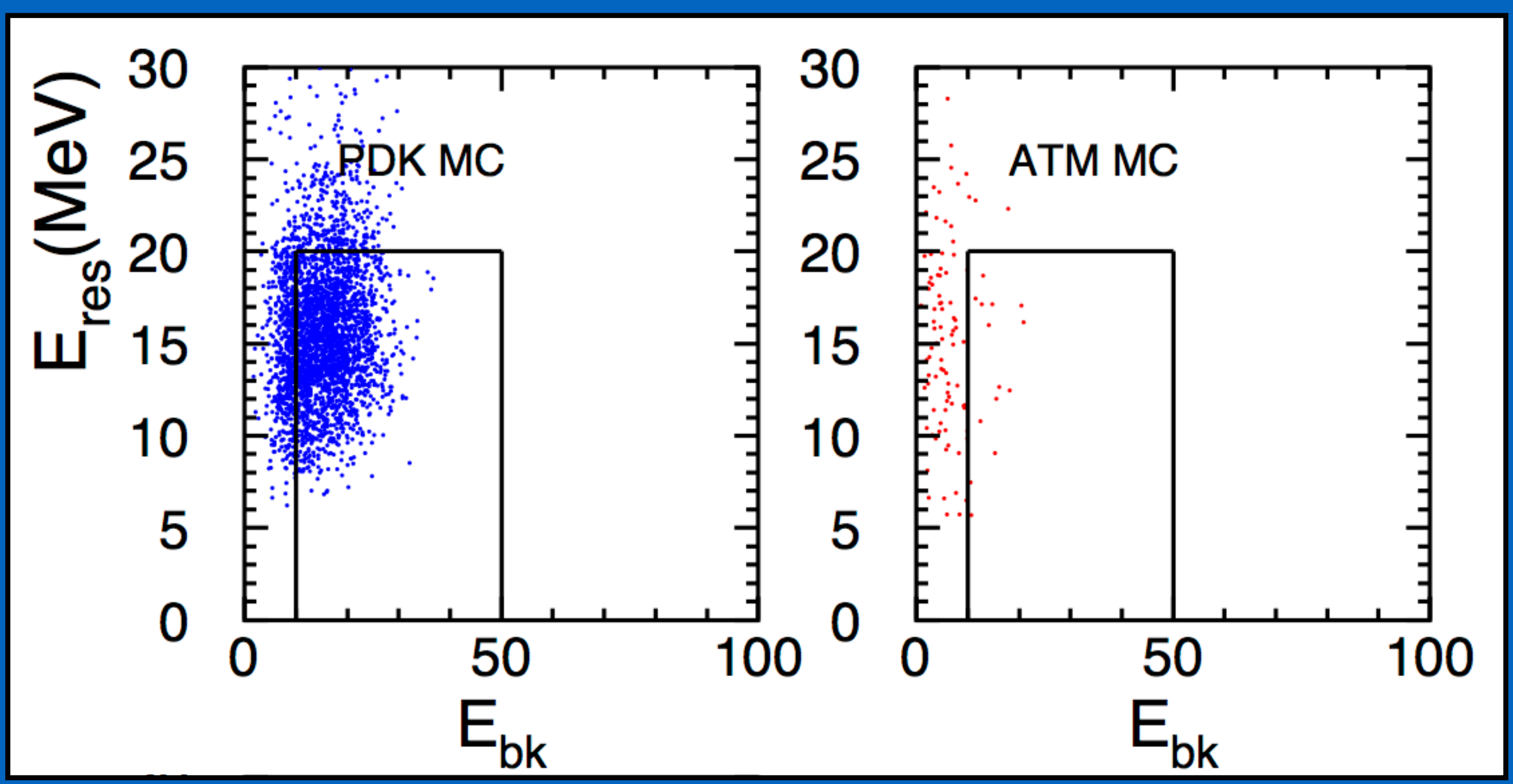
$p \rightarrow \bar{\nu} K^+$ Hadronic Decay

PRD 90, 072005 (2014)



Kaon Hadronic Decay

- Kaon decays to $\pi^+\pi^0$.
- Mono-chromatic π^0 (205 MeV/c) and faint π^+.
- E_{bk}: energy in the backward region defined by the π^0 direction.
- E_{res}: residual hits close to the π^+ direction.

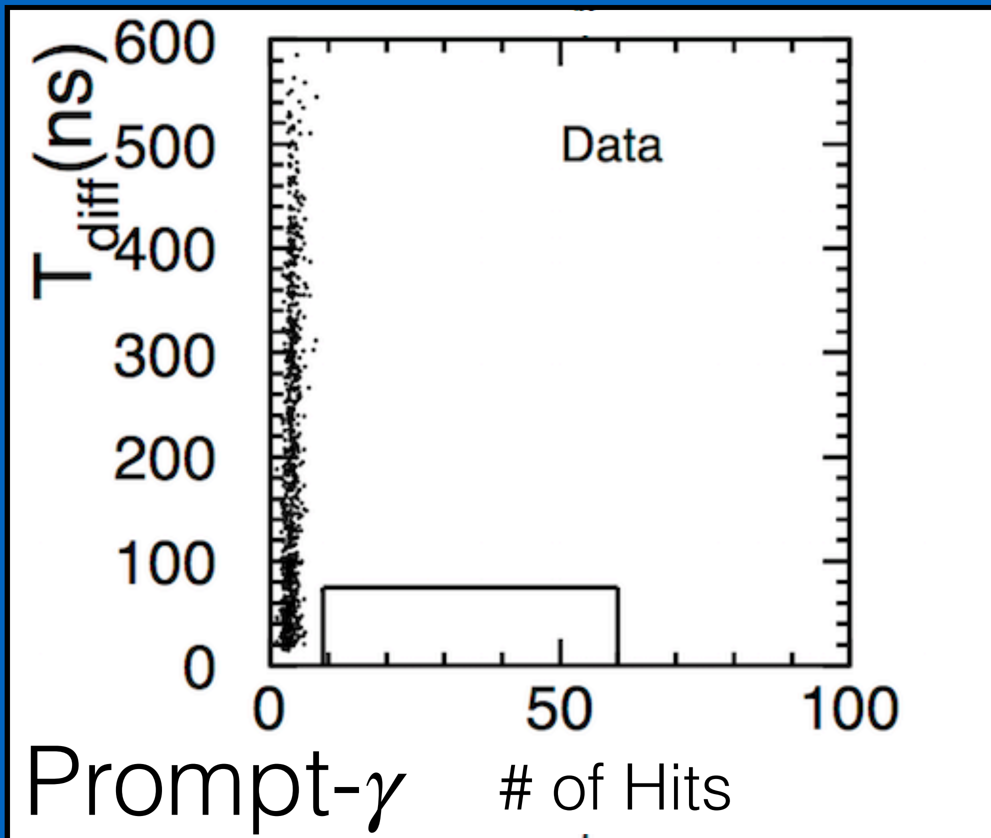


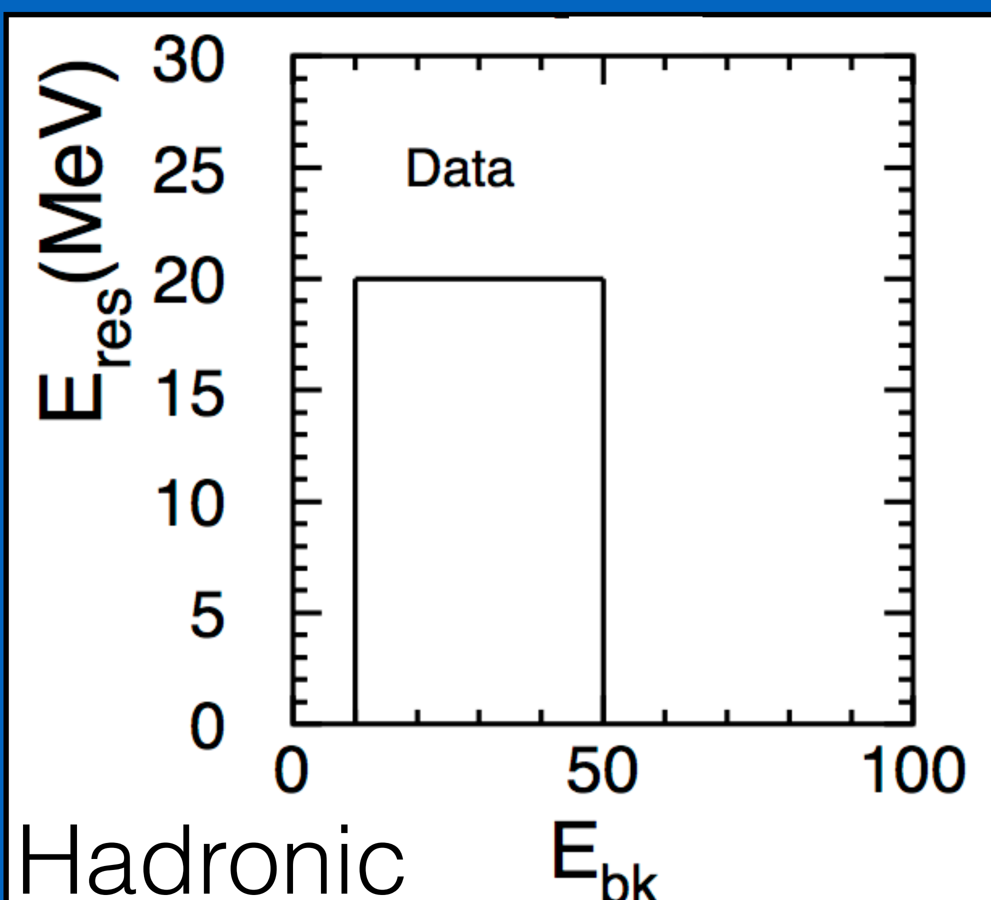
Event Selection

- 1 or 2 rings consistent with 205 MeV/c π^0.
- E_{bk} consistent with faint π^+.
- Low residual activity in the detector (E_{res}).

$p \to \bar{\nu} K^+$ Results

PRD 90, 072005 (2014)





	Signal Efficiency	Expected Background	Observed Events
prompt-γ	9.4%	0.11	0
$\pi^+\pi^0$	9.6%	0.13	0

	Lifetime Limit at 90% CL with 349 kton · yrs exposure
Update	$8.0 \cdot 10^{33}$ years

2017 Updates

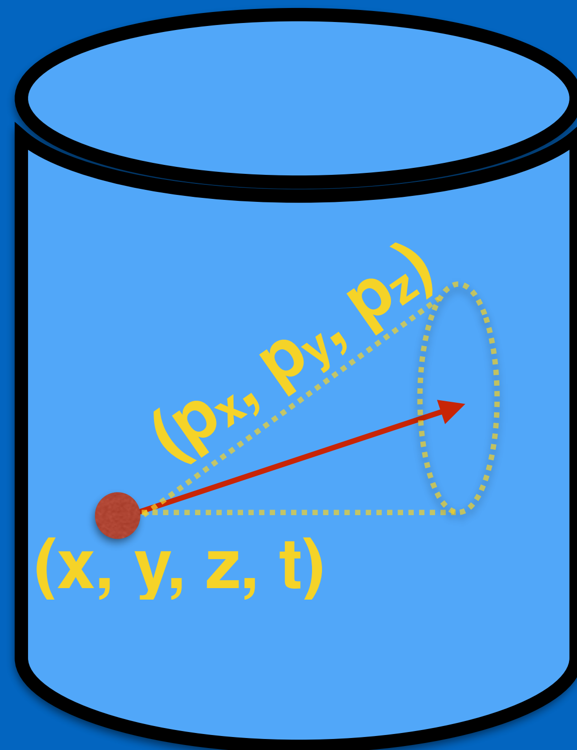
- 260 → 349 kton · yrs exposure.
- Neutron tagging in SK-IV.
- No candidate events were observed in either search methods.

Reconstruction with fiTQun

- FiTQun is a new **maximum likelihood** event reconstruction algorithm in SK.

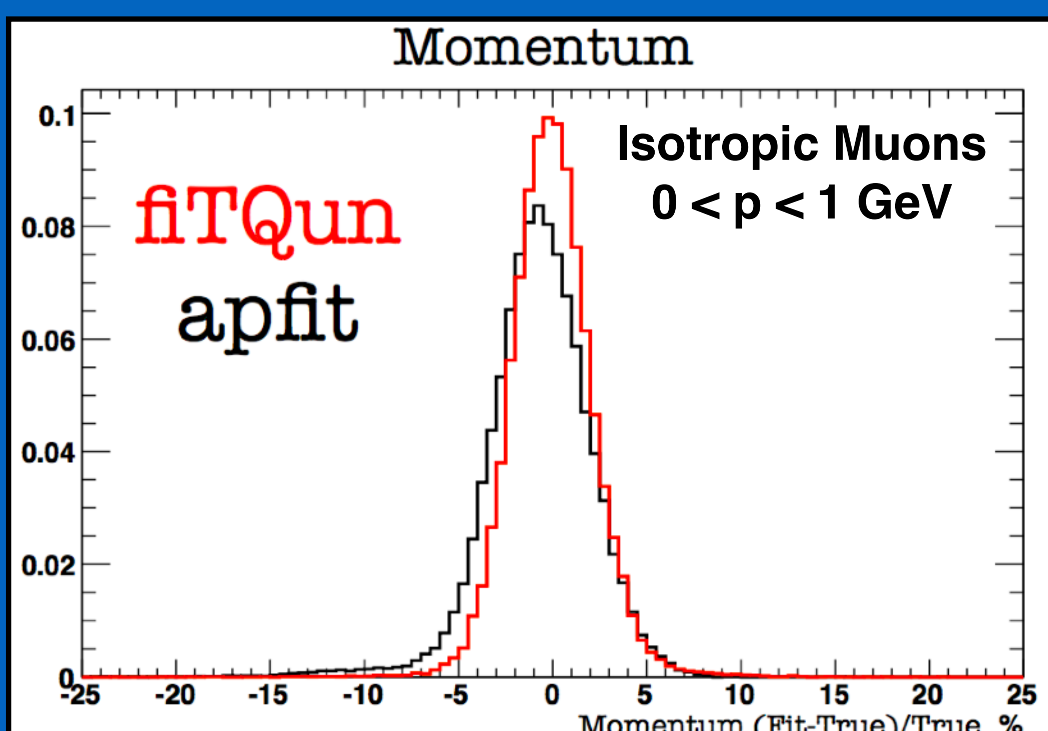
  Based on MiniBooNE (NIM A608, 206 - 2009)

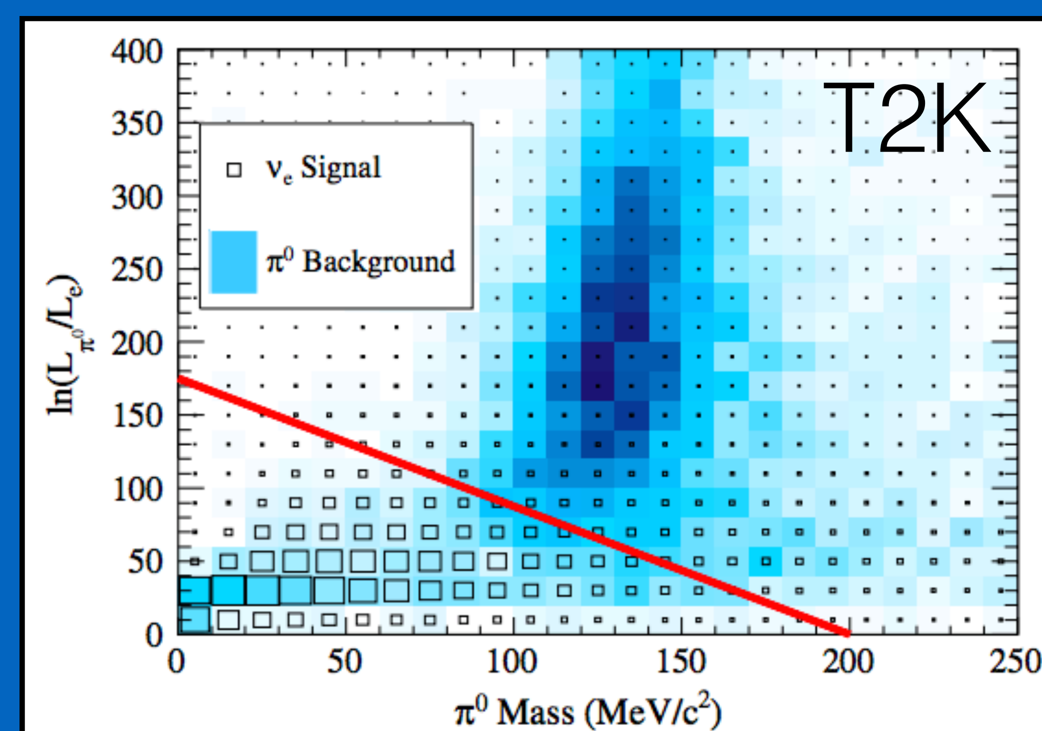
  Official T2K result (PRL 112, 061802 - 2014)



- A single track can be specified by a particle type (PID) plus 7 kinematic variables ($\mathbf{X}$):
  - Position (x, y, z, t)
  - Momentum (p)
  - Direction (θ, ϕ)

- For a given set $\mathbf{X}$, **charge and time** PDF's are produced for each PMT in SK.
- A likelihood is calculated for the event hypothesis.
- Event hypothesis are chosen by **comparing best-fit likelihoods**.

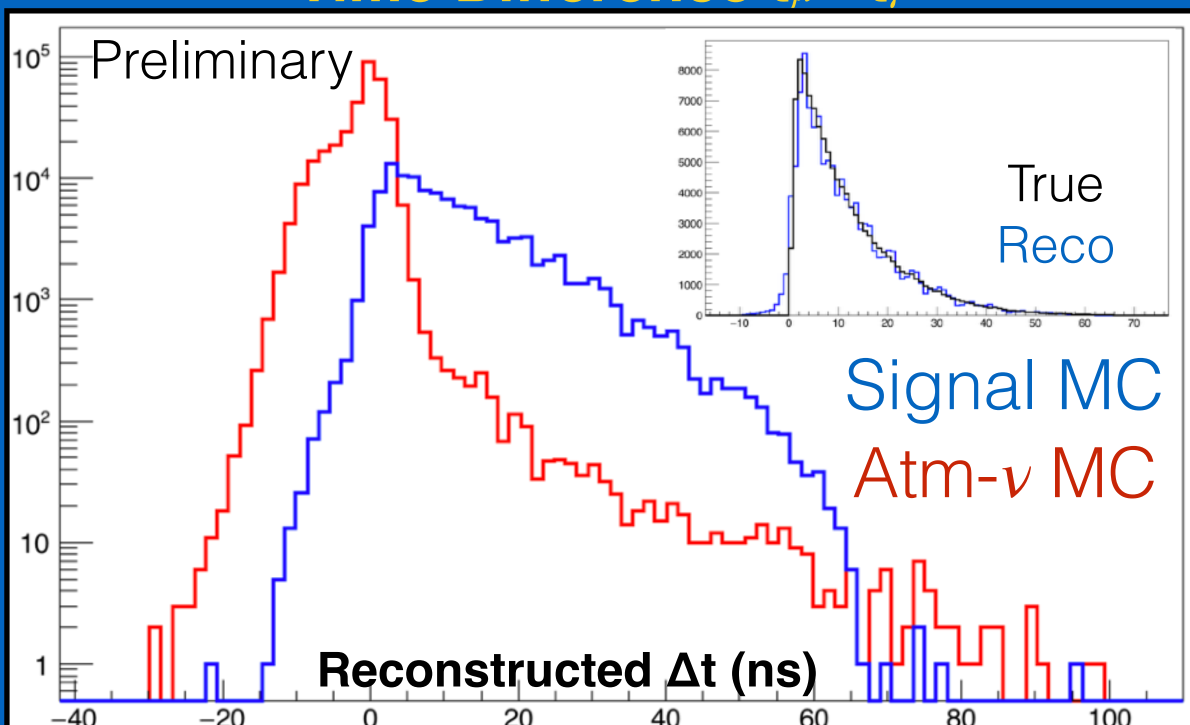




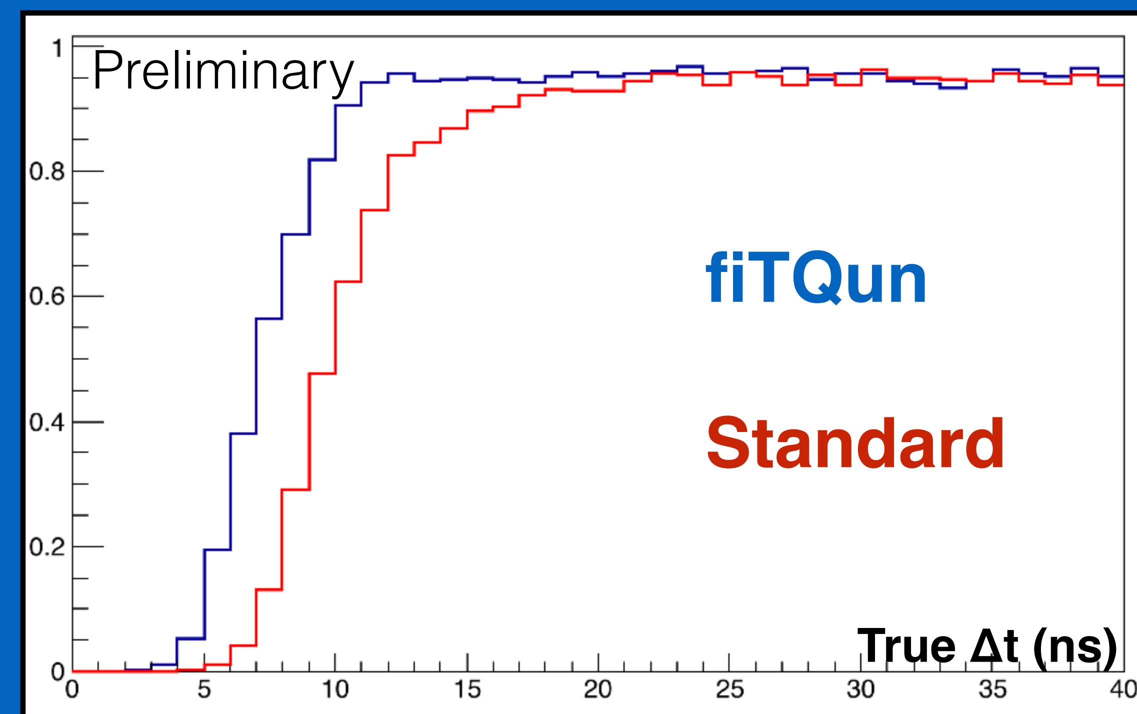
$p \rightarrow \bar{\nu} K^+$: Prompt-$\gamma$ Search with fiTQun

- **Event hypothesis: simultaneously fit for μ-like ring + 6 MeV γ.**
- **FiTQun can reconstruct the γ energy and time.**
- **Lower Δt reconstruction is achieved by comparing with CCQE hypothesis.**

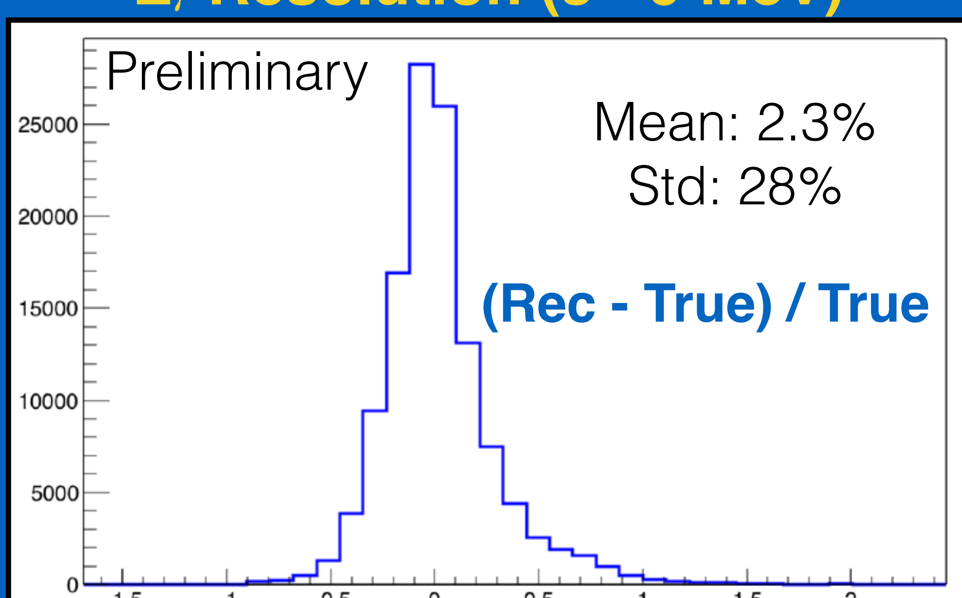
Time Difference t_μ - t_γ



γ - Tagging Efficiency



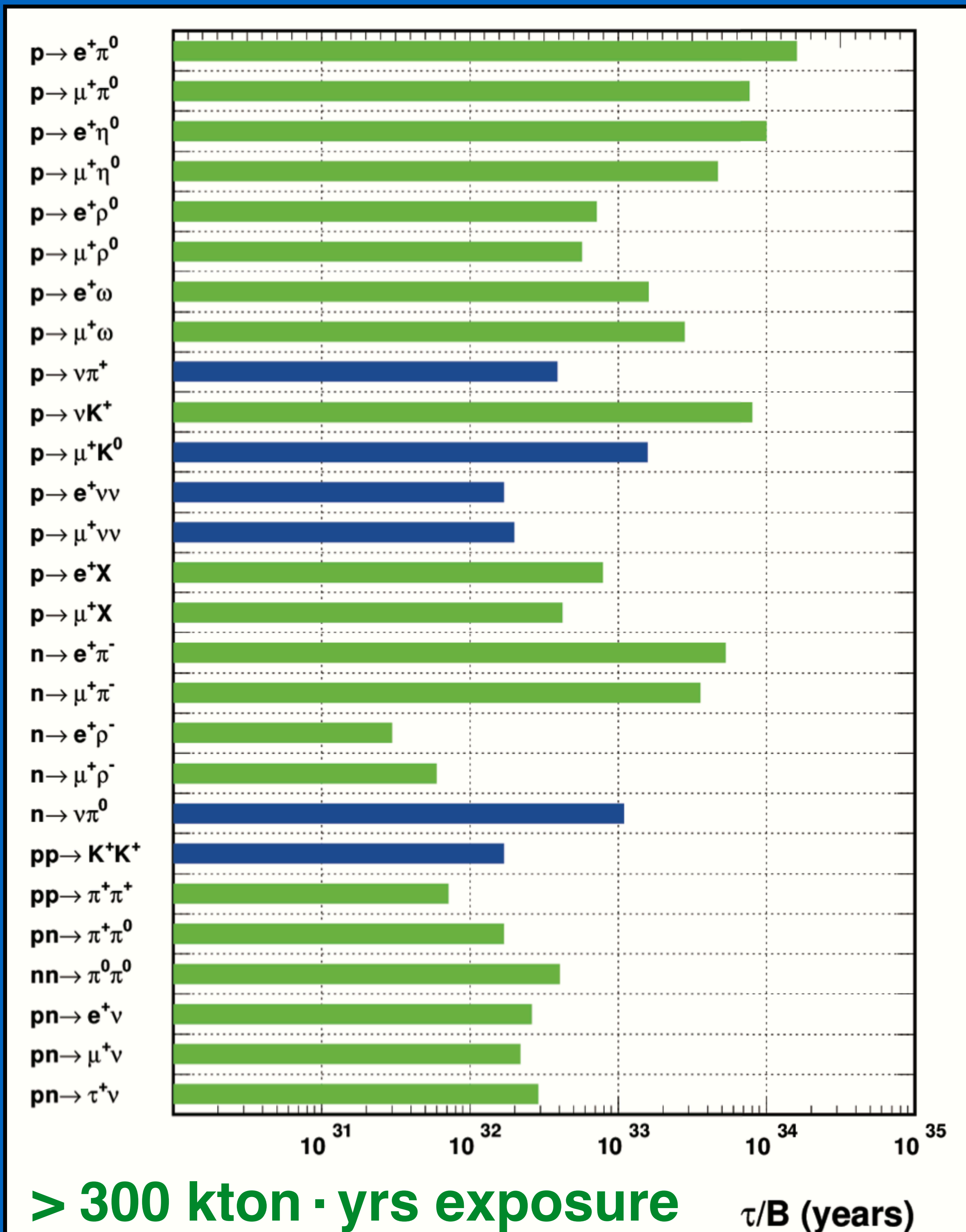
E_γ Resolution (3 - 9 MeV)



Preliminary Results

- **Similar performance for high Δt values.**
- **Significant improvement for low Δt.**
- **Efficiency gain: 9.4% → 13.9% .**
- **Similar expected background.**

Summary and Prospects



- Super-Kamiokande can search for many different NDK modes.
- Most modes have been updated to more than 300 kton · yrs exposure.
- Observed candidates are consistent with expected background.
- New search methods are being developed.
- Preliminary results indicate significant improvements on efficiency (~50%).

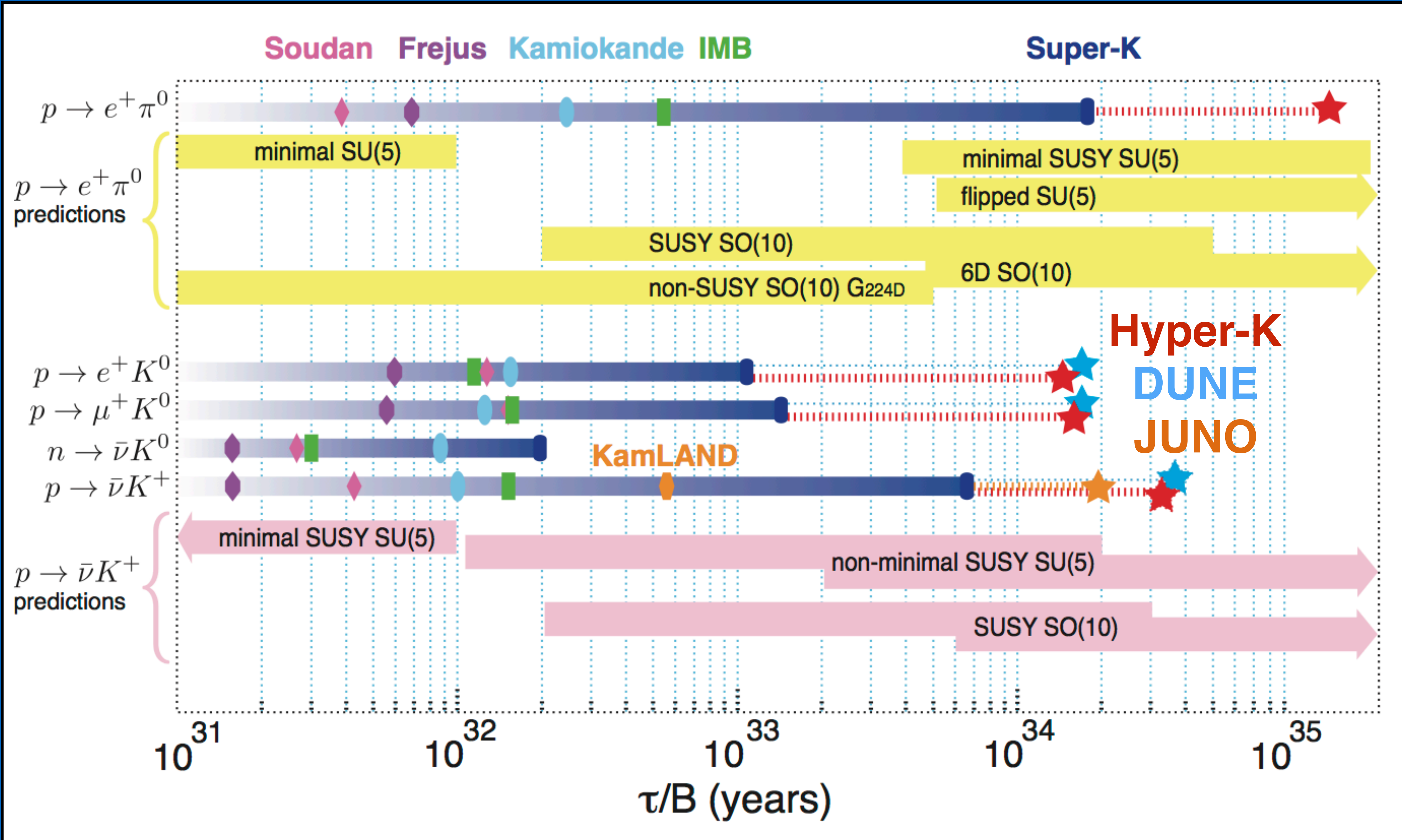
Thank You

1 Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
2 RCCN, ICRResearch, Univ. of Tokyo, Japan
3 University Autonoma Madrid, Spain
4 University of British Columbia, Canada
5 Boston University, USA
6 Brookhaven National Laboratory, USA
7 University of California, Irvine, USA
8 California State University, USA
9 Chonnam National University, Korea
10 Duke University, USA
11 Fukuoka Institute of Technology, Japan
12 Gifu University, Japan
13 GIST College, Korea
14 University of Hawaii, USA
15 KEK, Japan
16 Kobe University, Japan
17 Kyoto University, Japan
18 Miyagi University of Education, Japan
19 STE, Nagoya University, Japan
20 SUNY, Stony Brook, USA
21 Okayama University, Japan
22 Osaka University, Japan
23 University of Regina, Canada
24 Seoul National University, Korea
25 Shizuoka University of Welfare, Japan
26 Sungkyunkwan University, Korea
27 Tokai University, Japan
28 University of Tokyo, Japan
29 Kavli IPMU (WPI), University of Tokyo, Japan
30 Dep. of Phys., University of Toronto, Canada
31 TRIUMF, Canada
32 Tsinghua University, China
33 University of Washington, USA
34 National Centre For Nuclear Research, Poland

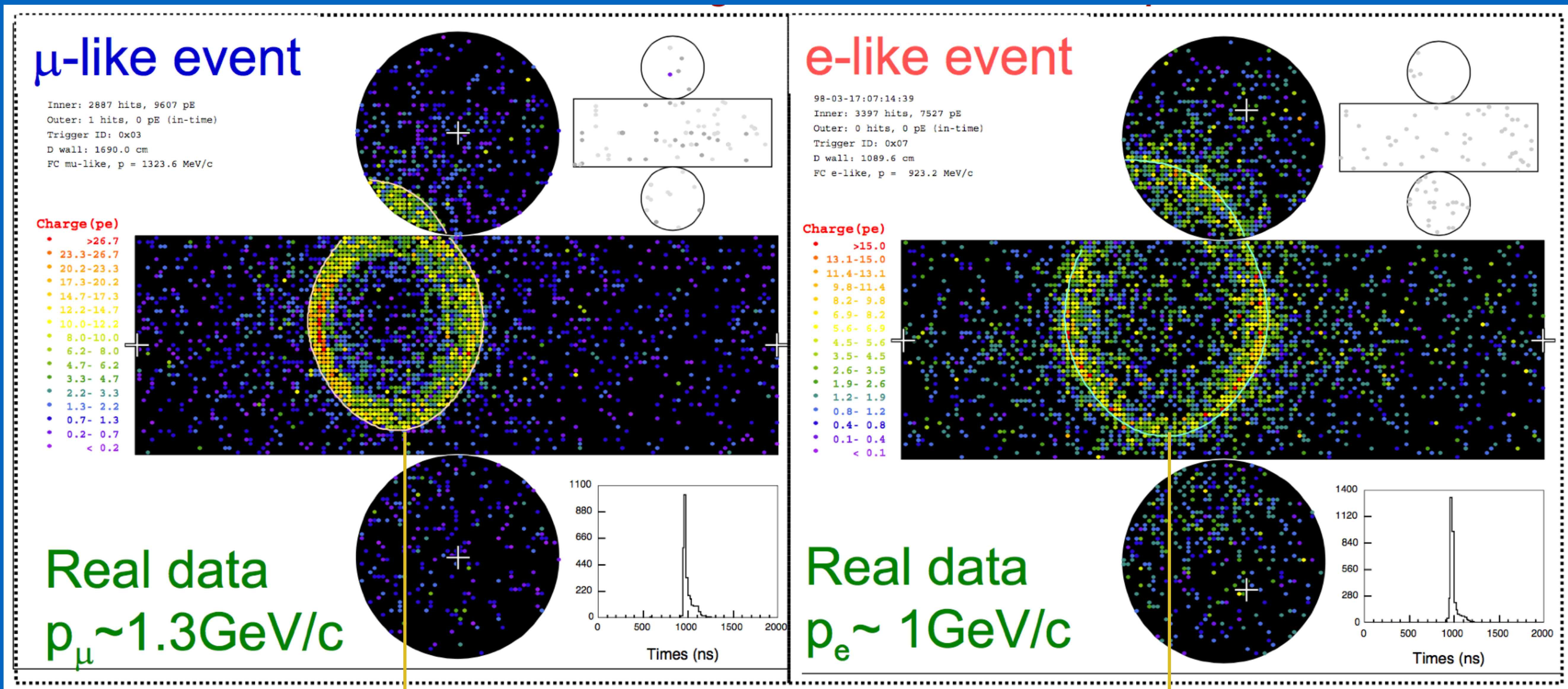
~120 collaborators
34 institutions
7 countries

Back-Up

Proton Decay Modes and Predictions



e-mu Separation

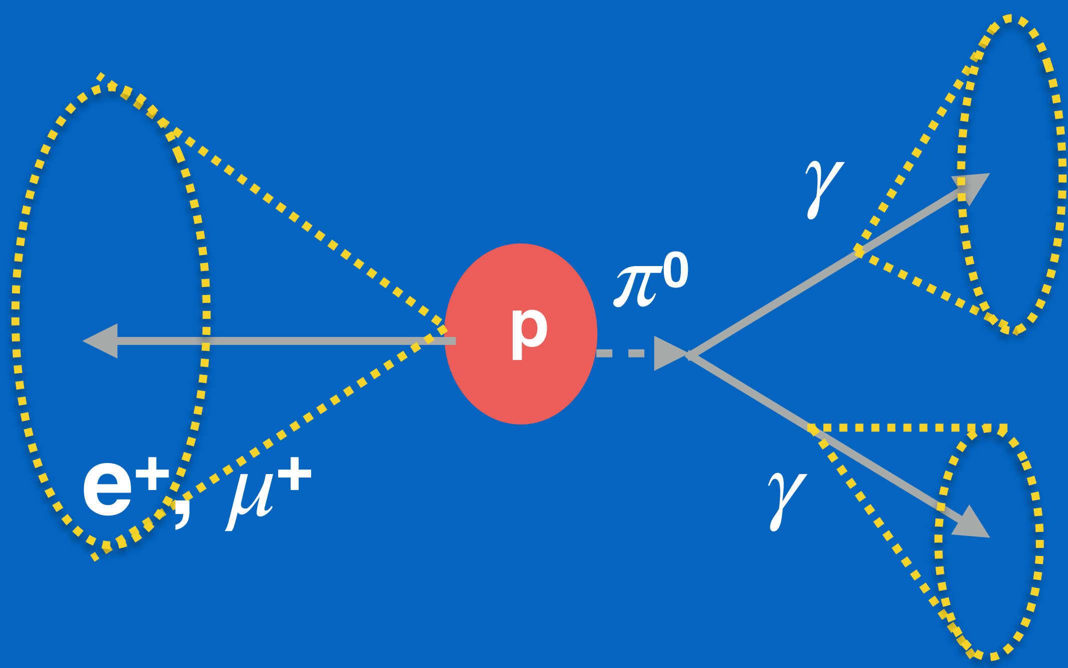


Sharp edge

Fuzzy edge

The modes: $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$

PRD 95, 12004 (2017)



Event Characteristics

- The l^+ and π^0 are back-to-back (459 MeV/c).
- $\pi^0 \to \gamma\gamma$: all final state particles are detectable.
- Able to reconstruct **proton mass** and **momentum**.
- Atmospheric neutrino interactions can mimic this type of signal.

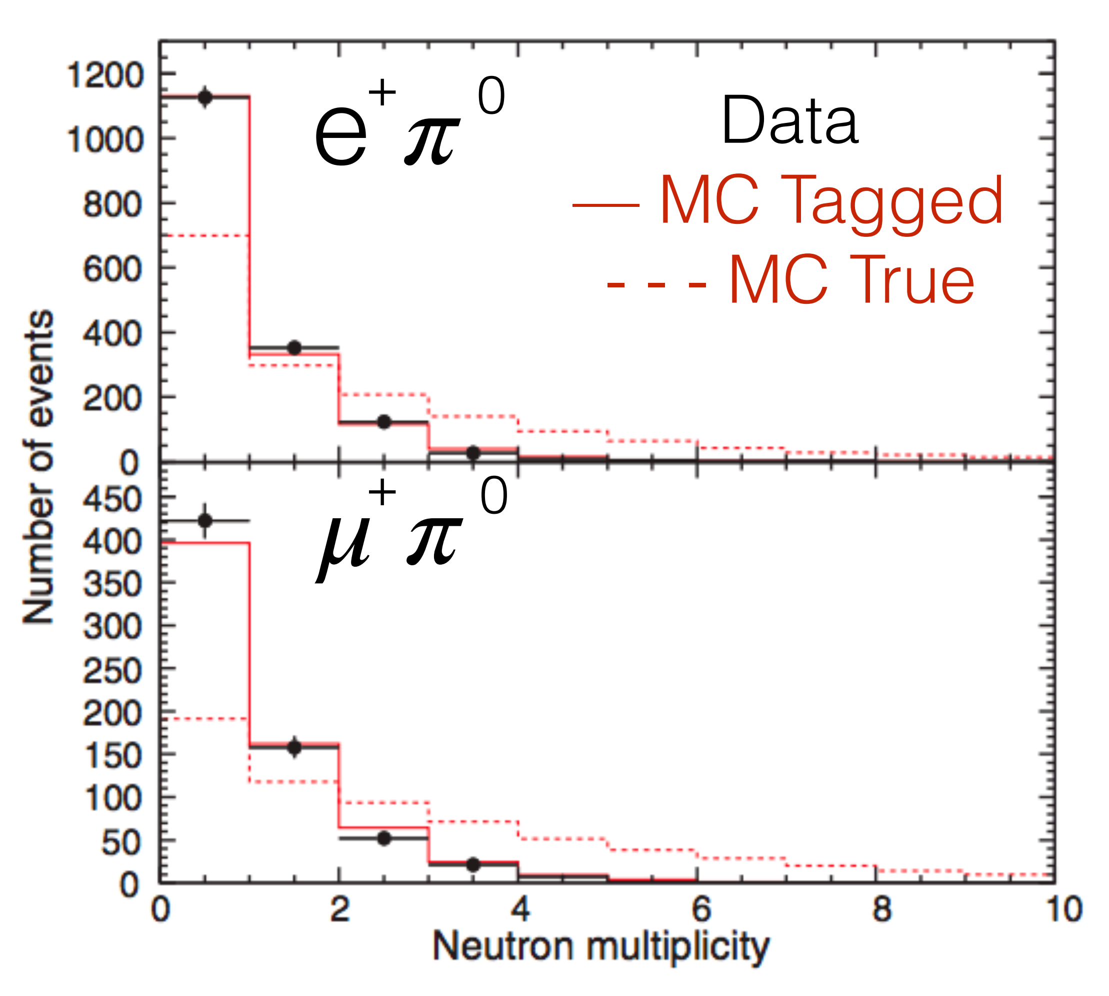
Event Selection

- All rings are fully contained inside the tank and inside the fiducial volume (2 m away from inner wall) - FCFV.
- 2 or 3-ring event.
- $e^+\pi^0$: all rings are e-like and without a decay-e.
- $\mu^+\pi^0$: 1 μ-like ring + 1 or 2 e-like rings with 1 decay-e.
- $85 < M_{\pi^0} < 185$ MeV/c^2 (only for 3-ring case).
- $800 < M_{Tot} < 1050$ MeV/c^2 and $P_{Tot} < 250$ MeV/c.

Neutron Capture

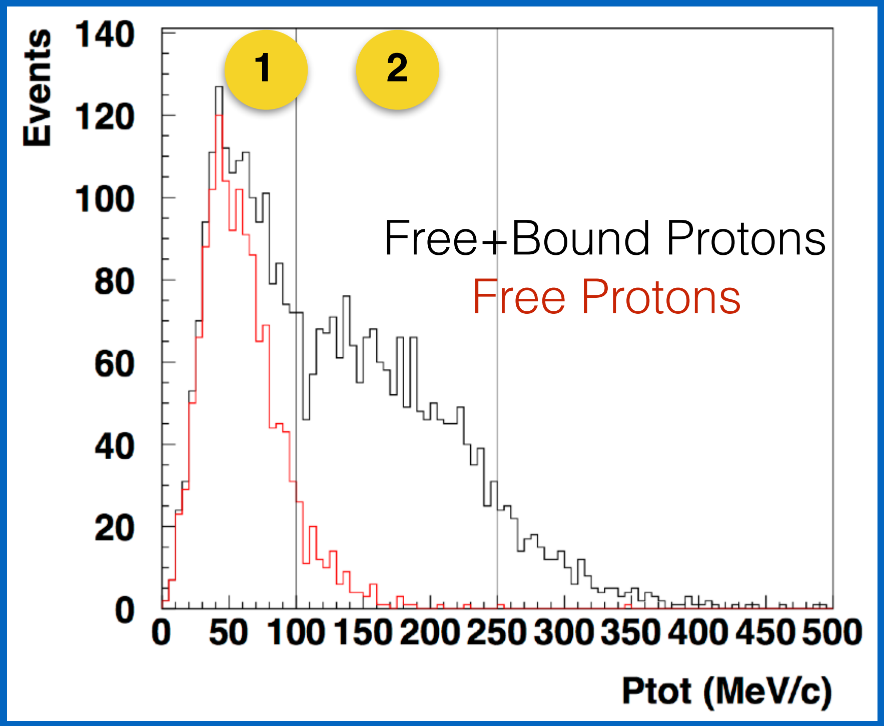
- **Most of the atm-ν interactions produce neutrons in the final state.**
- **A neutron can be capture by a Hydrogen atom (~200 μs) and emit a 2.2 MeV photon: n + p → d + γ.**
- **SK-IV new electronics allow to search for hits coming from this photon using a neural network.**
- **Half of the remaining background can be removed using neutron tagging.**

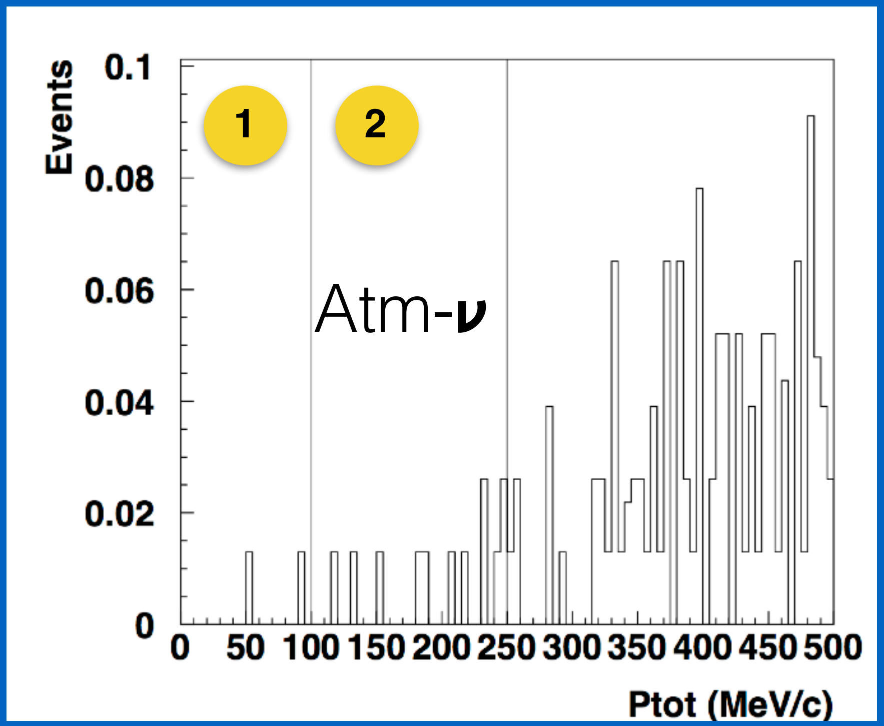
Efficiency	**20.5%**
MisTag Rate	**1.8%**



Two Box Analysis

- Signal Box defined by $800 < M_{Tot} < 1050$ MeV/c and $P_{Tot} < 250$ MeV/c is divided into 2 regions to improve sensitivity:
  1. Lower box: $P_{Tot} < 100$ MeV/c
     - The region is dominated by free proton (H) decays and almost background free.
     - Less systematics due to no nuclear effects.
  2. Higher box: $100 < P_{Tot} < 250$ MeV/c
     - Dominated by bound protons (0) and background events are more likely.
     - Systematic uncertainty is higher due to nuclear effects.





N → l^+ + meson

Number of Rings

- lepton*: 1 e-like ring with no decay-e for l = e and 1 μ-like ring with 1 decay-e for l=μ.
- η → $\gamma\gamma$: 2 e-like rings.
- η → $3\pi^0$: 3 or 4 e-like rings.
- ρ → $\pi^+\pi^-$: 2 μ-like rings.
- ω → $\pi^0\gamma$: 2 or 3 e-like rings.
- ω → $\pi^+\pi^-\pi^0$: 1 μ-like rings and 2 e-like ring.
- π^-: 1 μ-like ring.
- ρ^-→ $\pi^-\pi^0$ 1 μ-like rings and 2 e-like ring.

*except for p→μ^+ω and n→$\mu^+\rho^-$.

Reconstructed Meson Mass

- η: (480, 620) MeV/c^2.
- ρ: (600, 900) MeV/c^2.
- ω: (650, 900) MeV/c^2.

Reconstructed Nucleon Mass

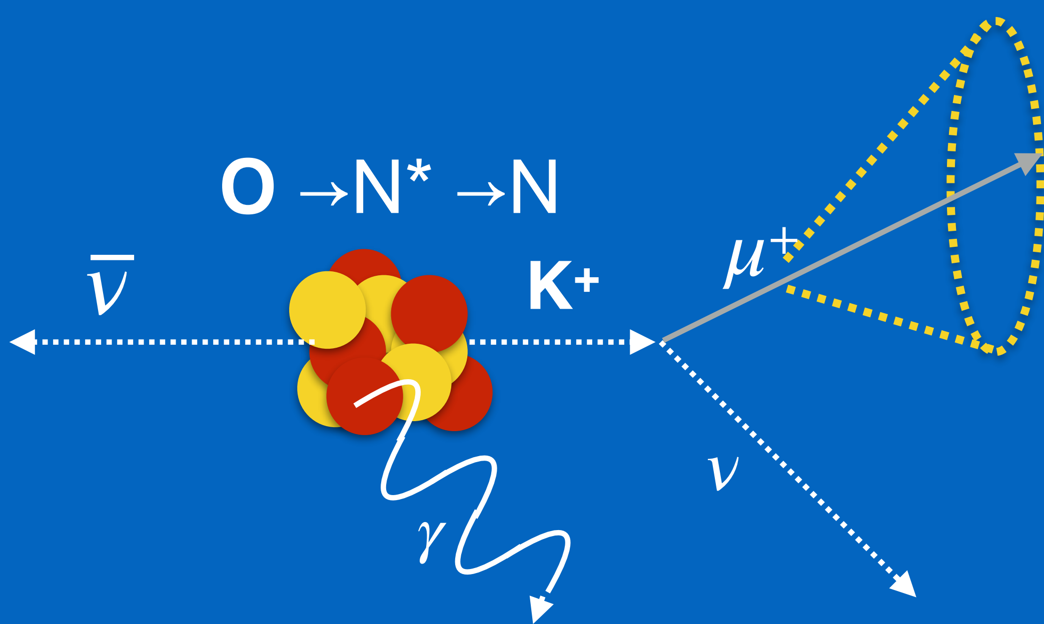
- Total Mass: (800, 1050) MeV/c^2.
- (600,800) MeV/c^2 for e^+ω.
- (450,700) MeV/c^2 for μ^+ω.

Reconstructed Nucleon Momentum

- Total momentum < 250 MeV/c.
- < 150 for η → $3\pi^0$.
- < 200 for ω → $\pi^+\pi^-\pi^0$.

p → $\bar{\nu}$ K$^+$: Prompt-γ Search

PRD 90, 072005 (2014)

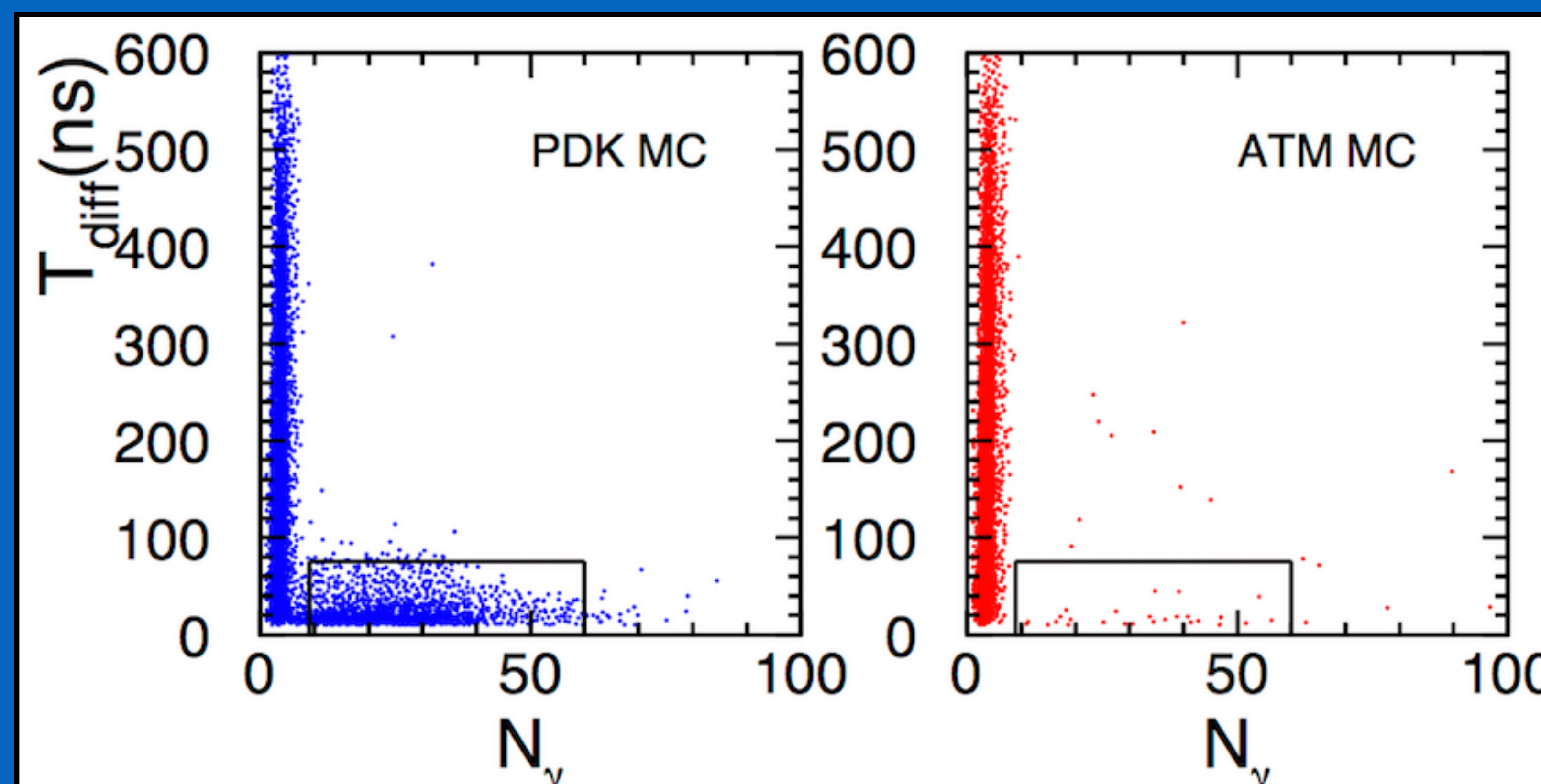


Event Characteristics

- Neutrino and Kaon are invisible.
- Dominant Kaon decay mode: μ is mono-chromatic ~236 MeV/c.
- Nuclear De-excitation: ~6 MeV gamma.
- Coincidence measurement of low-E γ and a mono-energetic μ.

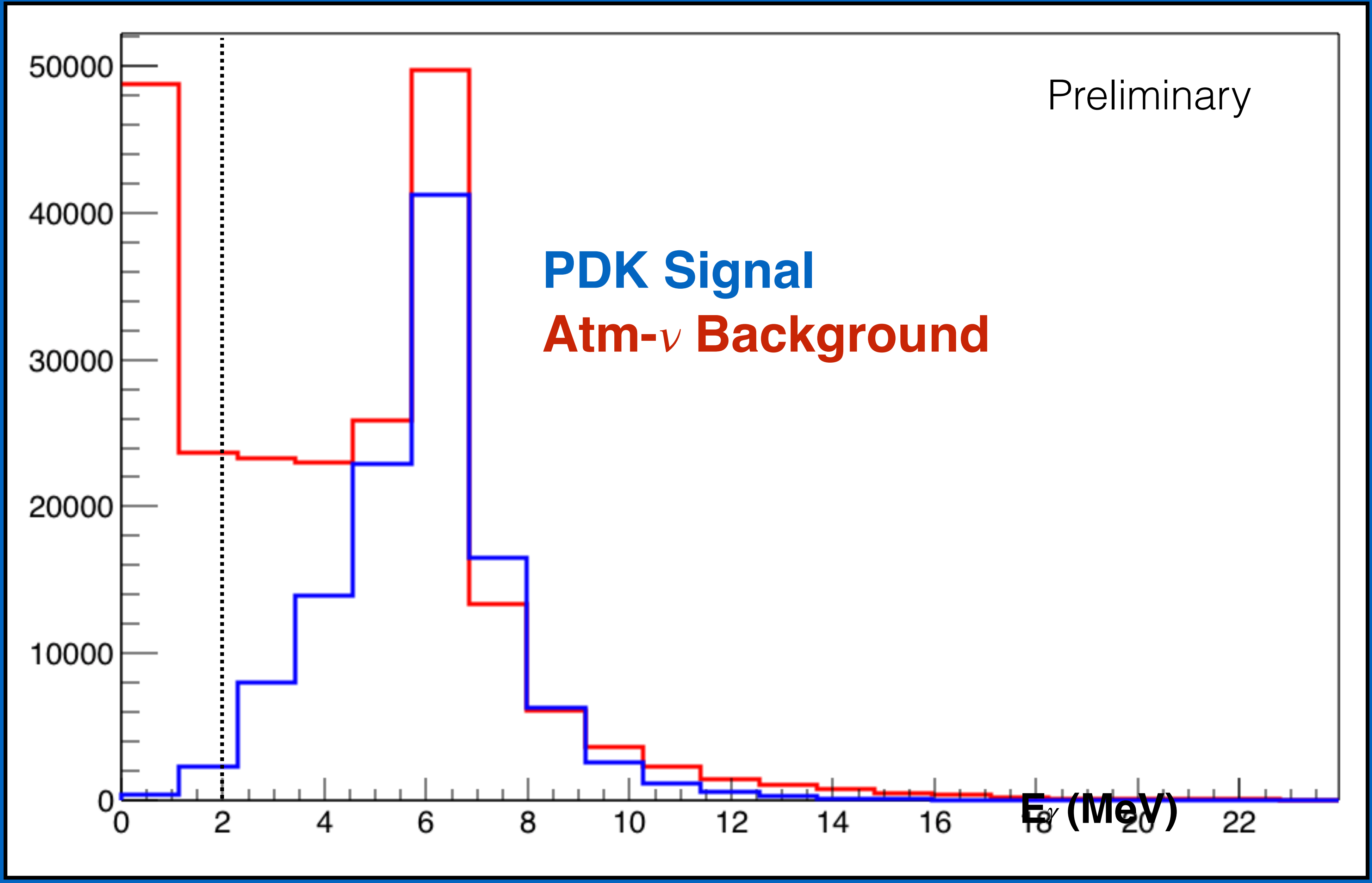
Event Selection

- 1-ring μ-like with a decay-e.
- 215 < P_μ < 260 MeV/c.
- Search for hit cluster with a sliding window of 12 ns:
  - ⋆ 8 < N_γ < 60 hits (SK-I, III, IV)
  - ⋆ 4 < N_γ < 30 hits (SK-II)
- Time Difference < 75 ns.
- No neutrons in SK-IV.

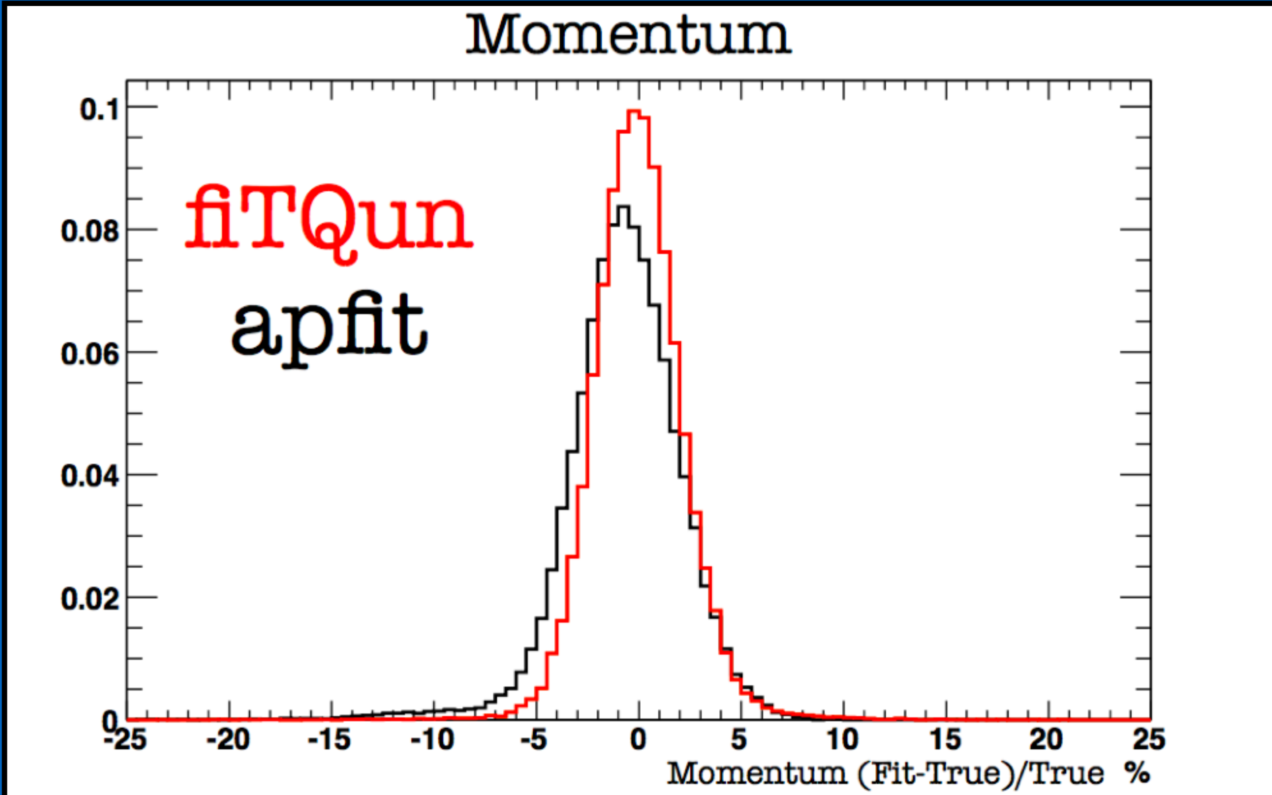


p → $\bar{\nu}$ K$^+$: Prompt-γ Search with fiTQun

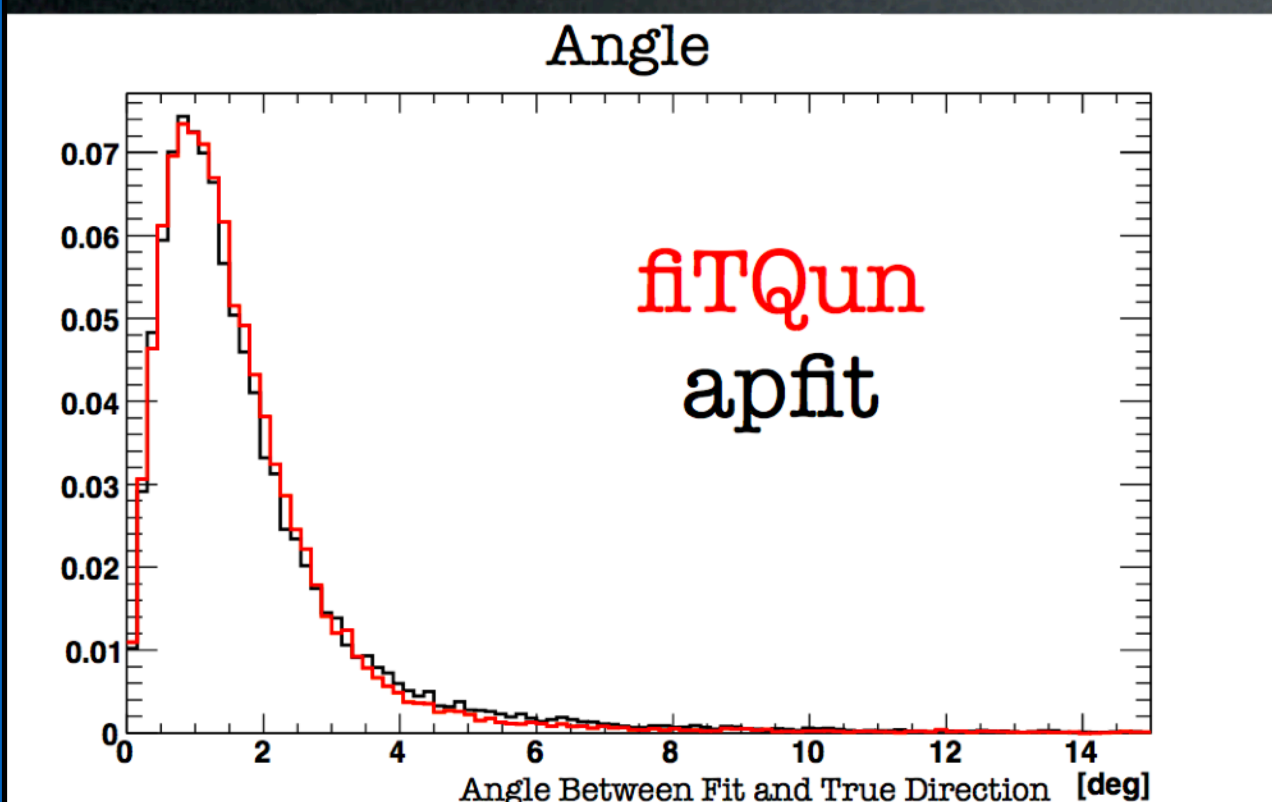
Reconstructed γ Energy

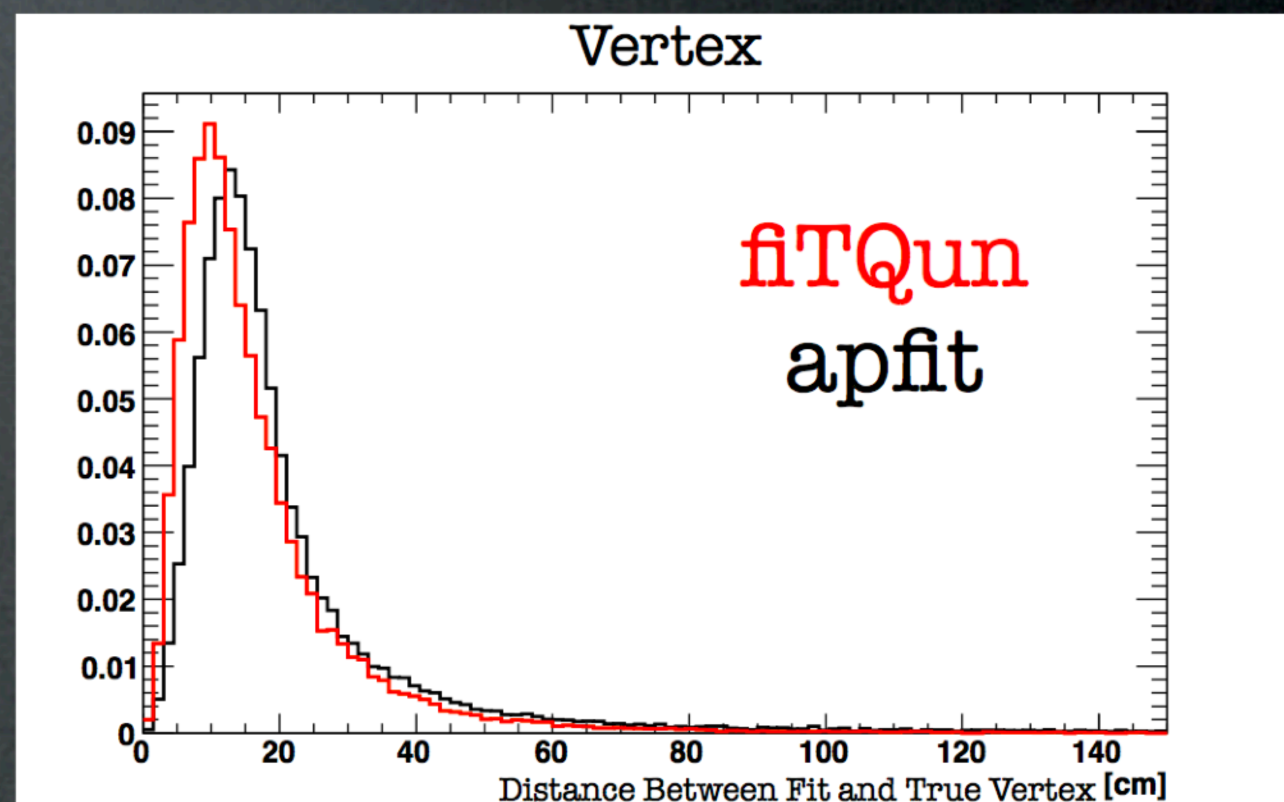


Muons with fiTQun

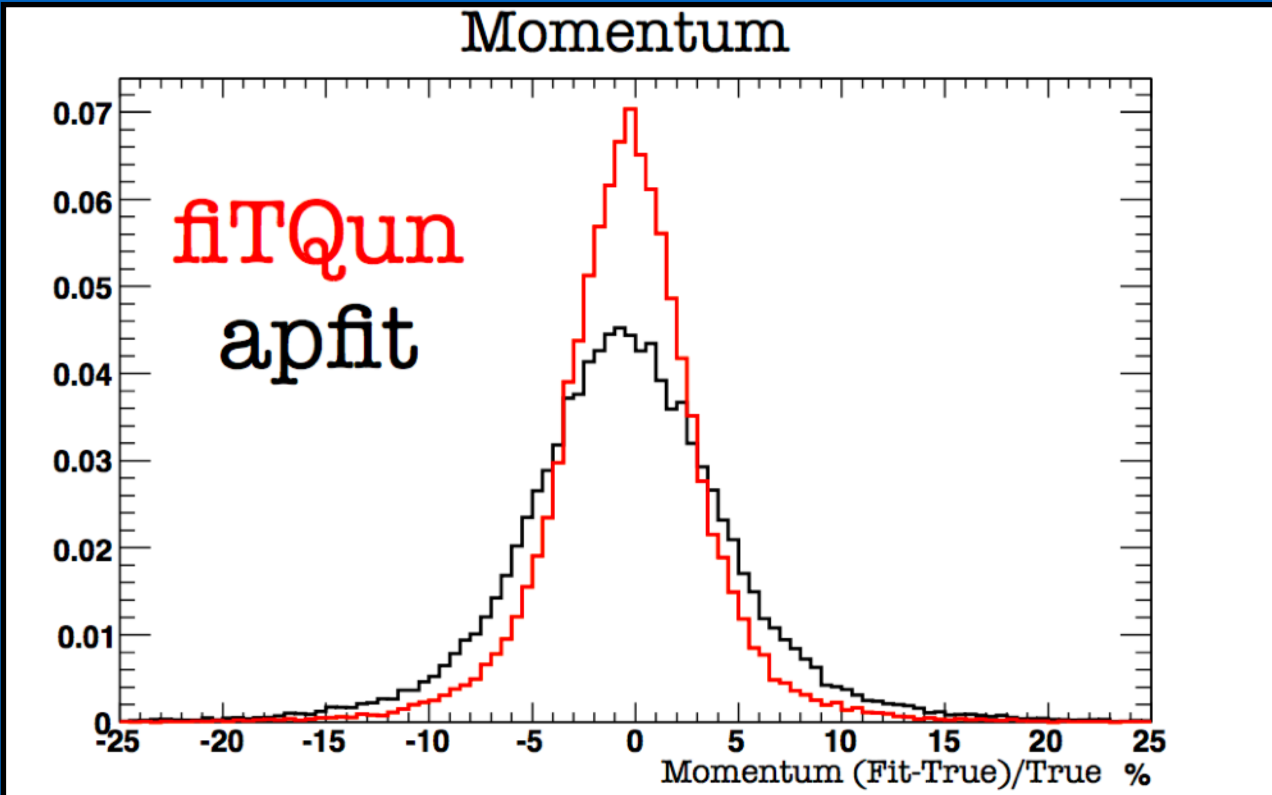


- Tested on a uniform distribution of muons between 0 and 1 GeV/c
  - Isotropic & random position (inside FV & charge>200pe)
- Significant improvements in the vertex and momentum resolution

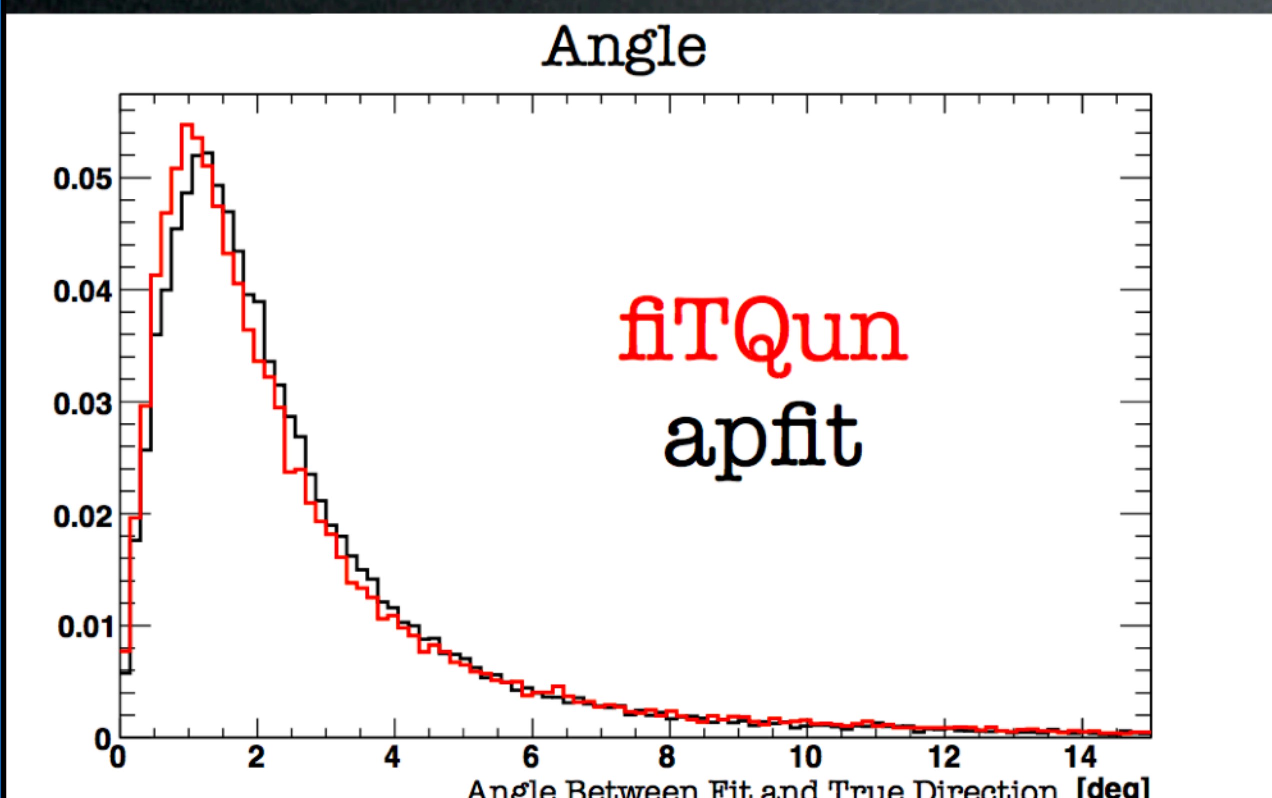


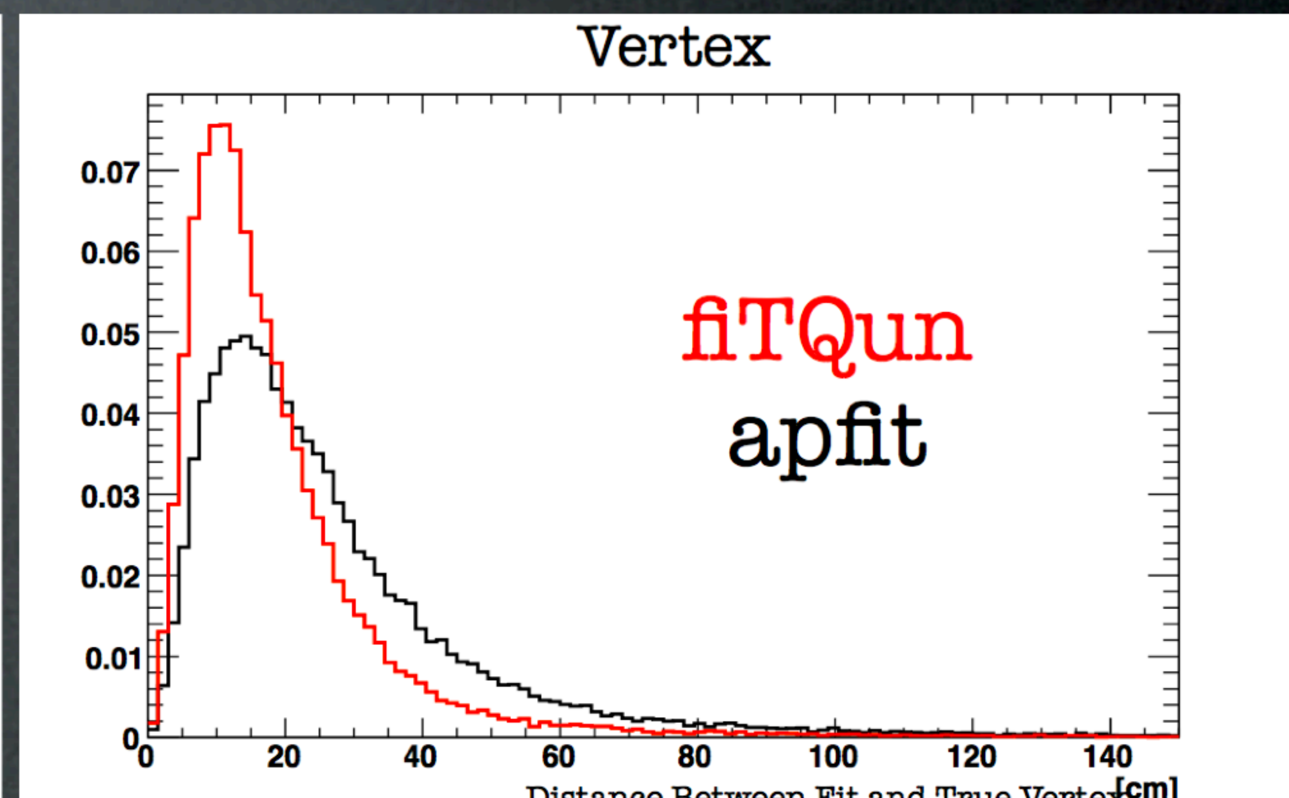


Electrons with fiTQun

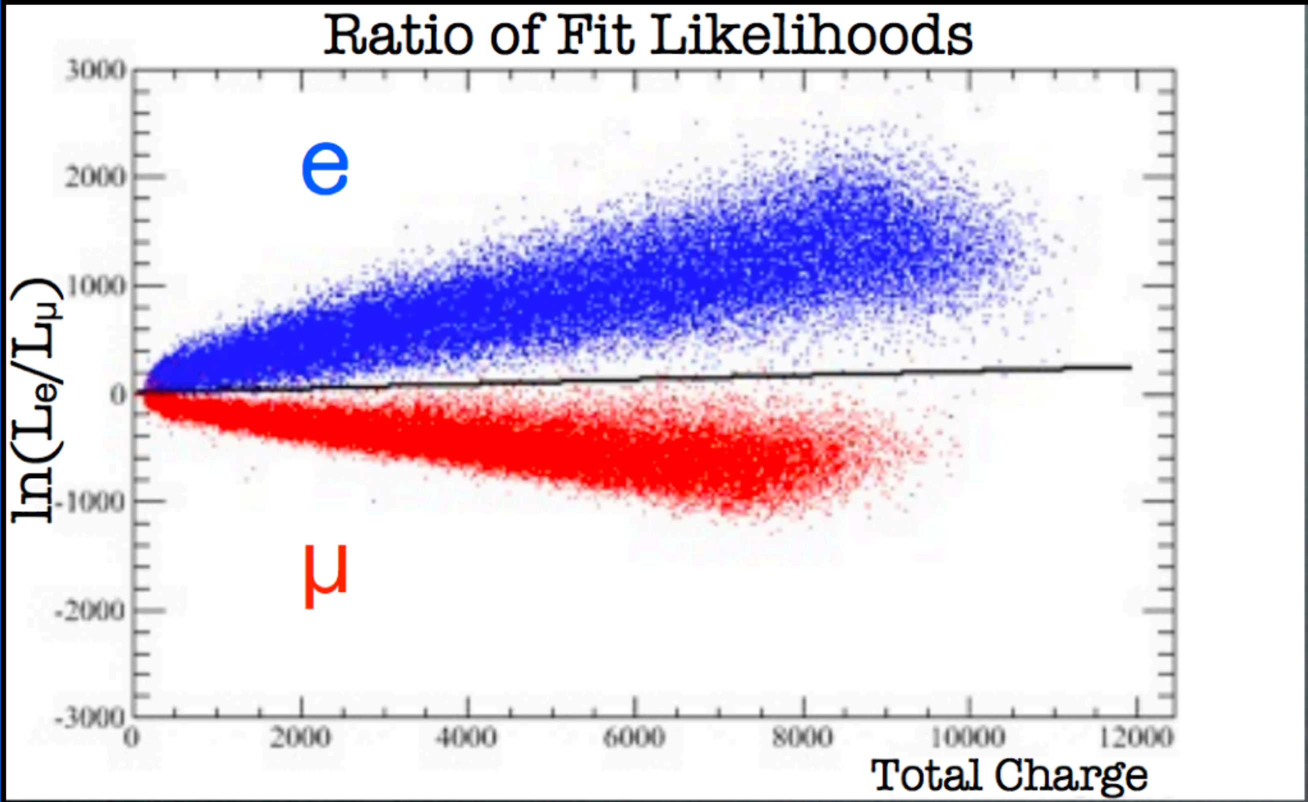


- Tested on a uniform distribution of e⁻ between 0 and 1 GeV/c
  - Isotropic & random position (inside FV & charge>200pe)
- Significant improvements in the vertex and momentum resolution





Single Track PID with fiTQun



- Simple line cut can be used to separate muons and electrons
- Significantly improved particle ID