PROTON DECAY SYSTEMATICS IN LONG BASE-LINE EXPERIMENTS

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MOTIVATIONS

- Proton decay into particles with momenta similar to those produced in few GeV neutrino interactions.
- Most protons in the experiment are inside nuclei.
- Atmospheric neutrinos are the main background for underground detectors (SK/HK/DUNE).

- Here are my personal opinions and not official statements from any of the future long base-line experiments (although I am members of those experiments)
- Many thanks for materials to Ed Kearns, Jen Raff and John Urheim

PROTON DECAY

- In the Standard Model Baryon Number is conserved → several reasons to belief that the SM is a “low energy” approximation of a larger symmetry group (Grand Unified Theories).

- One of the extension of the SM is to assume that SU(3)xSU2)xU(1) is a part of SU(5)

  ⇒ Single coupling constant

  ⇒ New gauge bosons (X, Y) with new interactions leading to proton decay

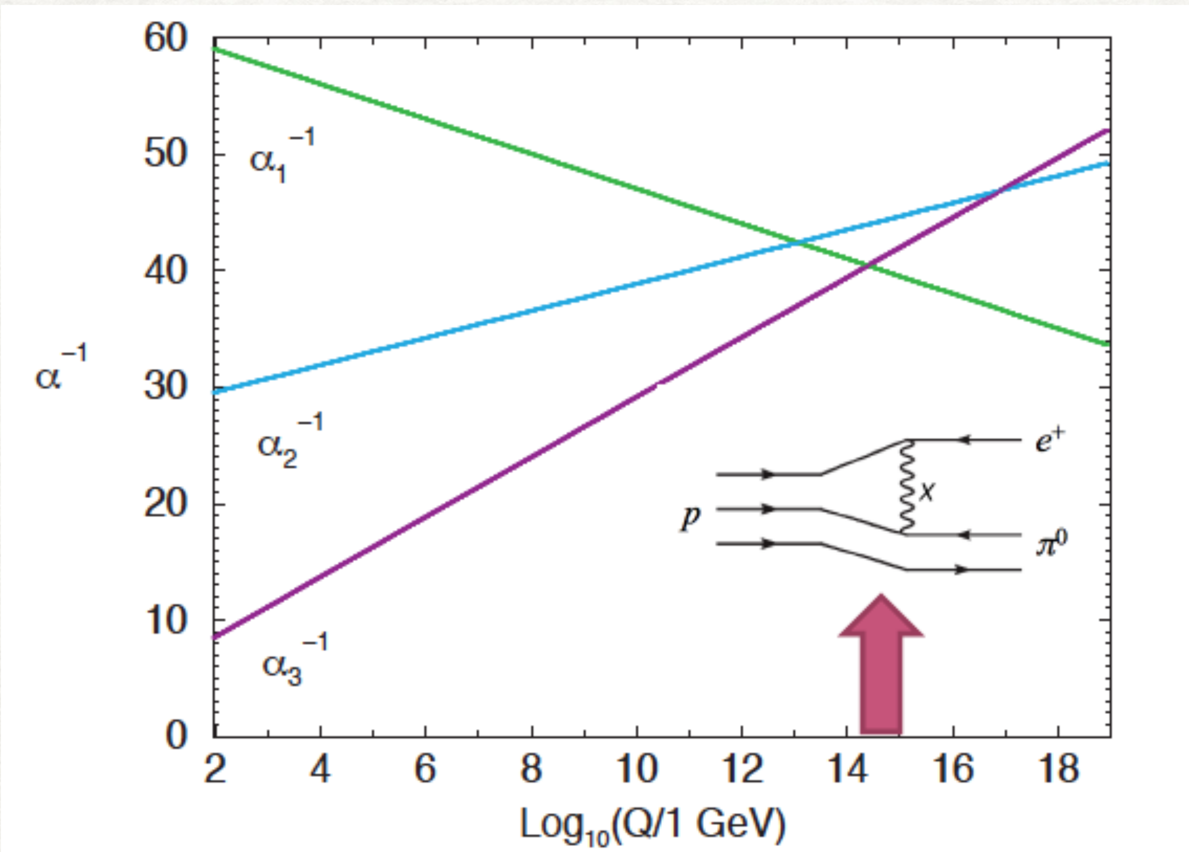
  ⇒ However SU(5) is not a good candidate as it also predicts massless neutrinos, magnetic monopoles and values of the weak mixing angle (but not consistent with experiments)

$$\overline{5} = \begin{pmatrix} \bar{d}_g \\ \bar{d}_r \\ \bar{d}_b \\ e^- \\ -\nu_e \end{pmatrix}_L$$

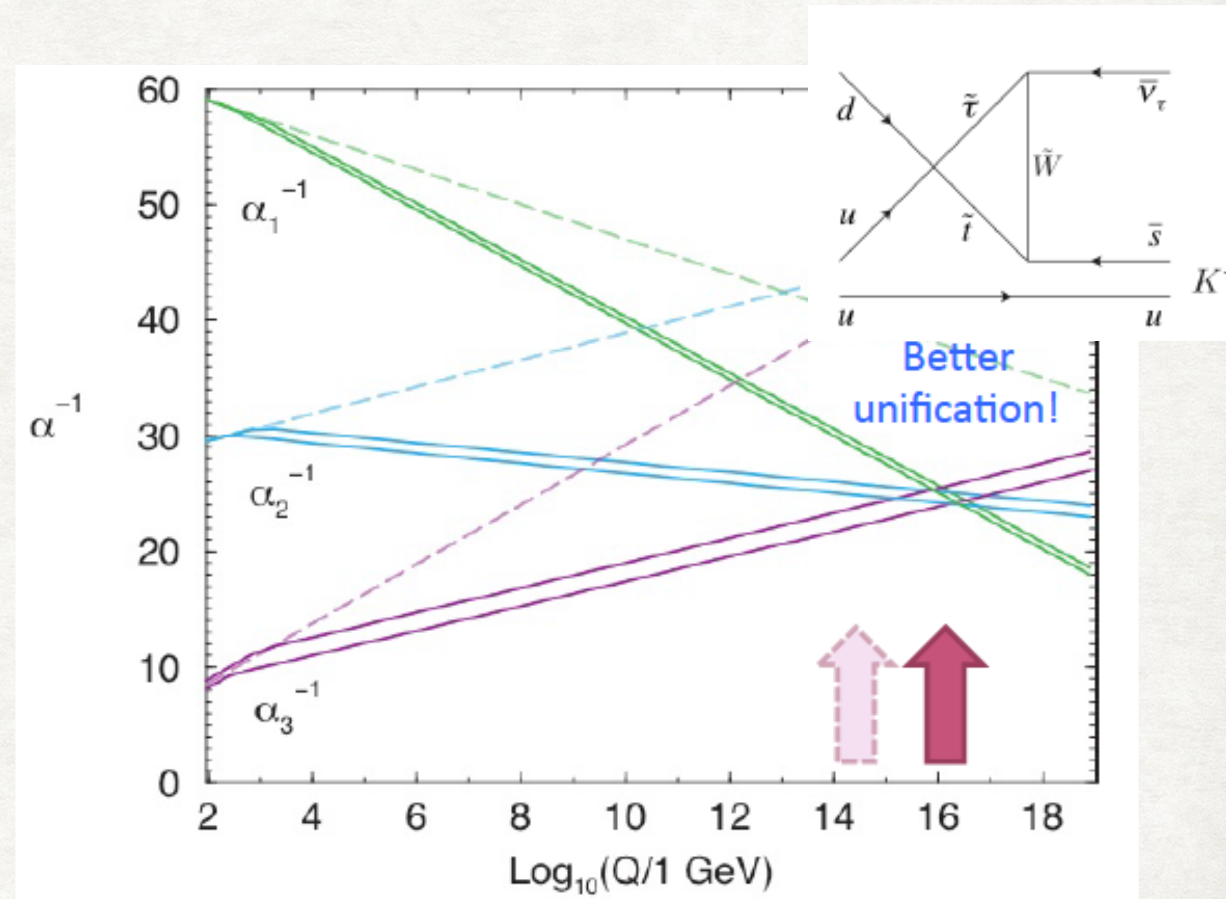
COUPLINGS UNIFICATION

$$\tau \approx \frac{M_X^4}{\alpha^2 M_p^5}$$

SU(5) Model



SUSY Models



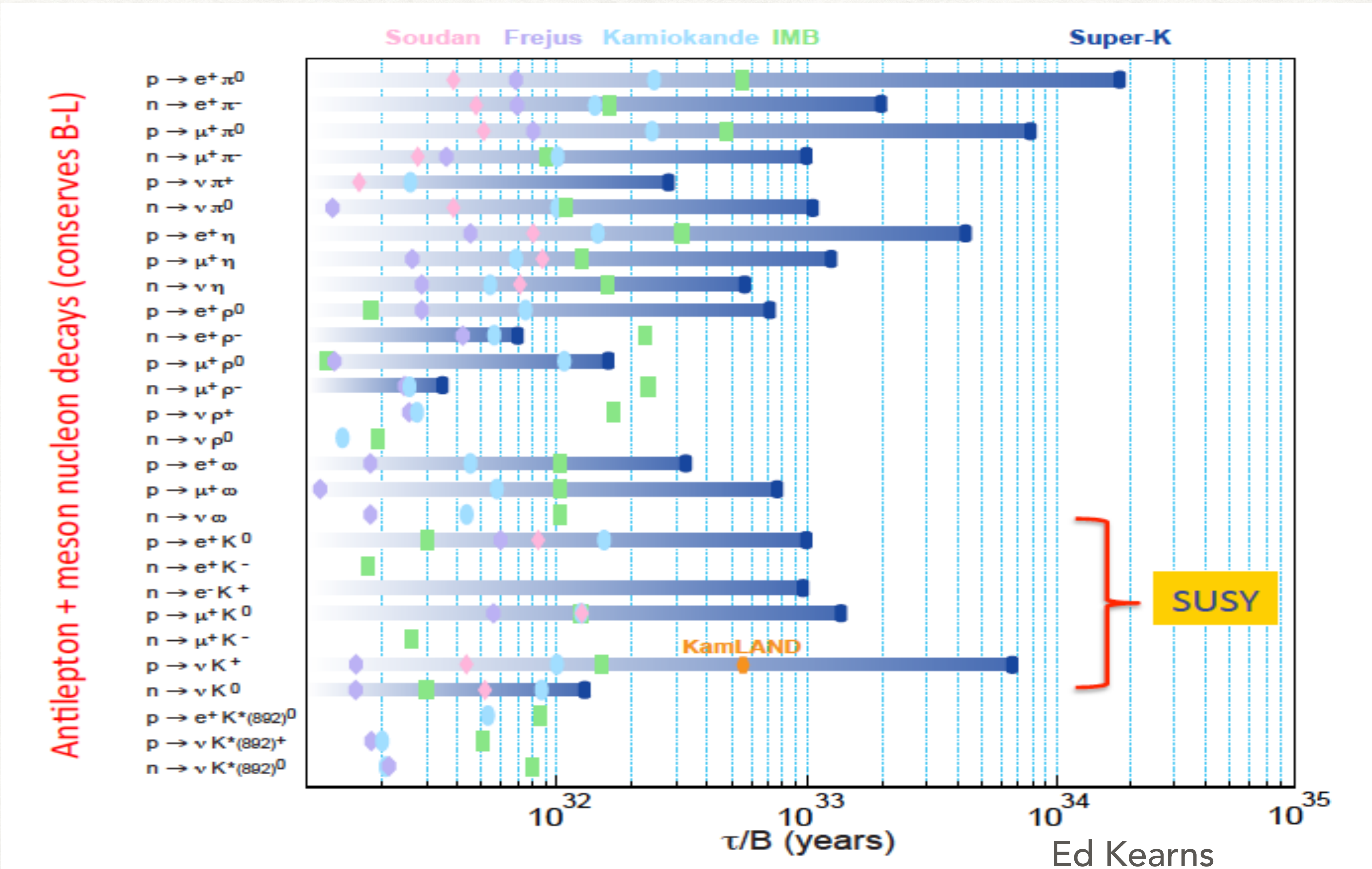
$$\tau(e^+\pi^0) = 4.5\times 10^{29\pm 1.7}\ years\ \text{(predicted)}$$

$$\tau(e^+\pi^0) > 5.5\times 10^{32}\ years\ \text{(IMB/1990)}$$

$$\tau(e^+\pi^0) \approx 10^{35-38}\ \text{years}$$

$$\tau(\nu K^+) \approx 10^{29-35}\ \text{years}$$

NUCLEON DECAY LIMITS



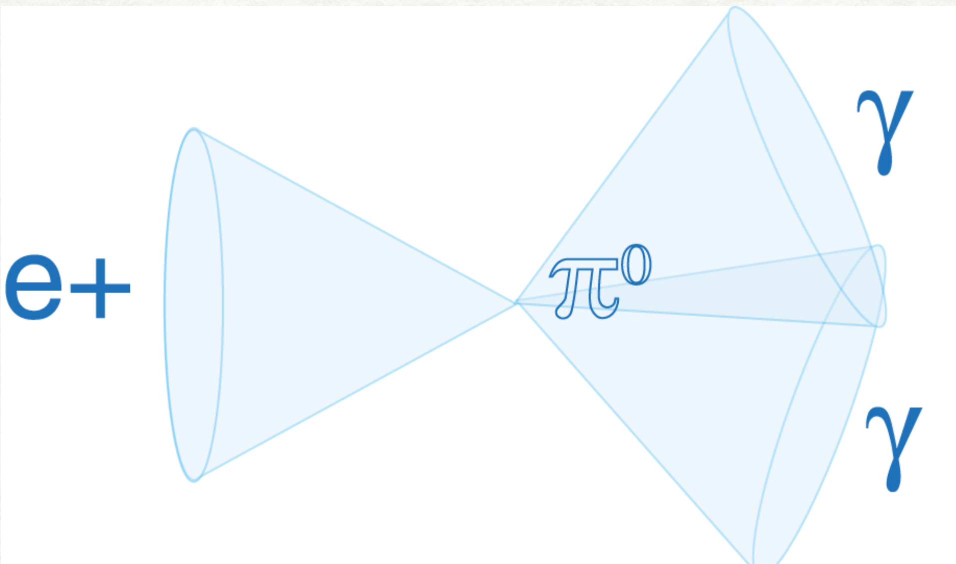
PROTON DECAY CHANNELS

- There are about 100 excusive nucleon day modes
  - B-L conserving, B+L conserving, 3-body final state, neutron-antineutrino oscillation ($\Delta B=2$)
  - Beyond Standard Models predictions for proton decay channels can differ by a few orders of magnitude -> good way to test the models.
  - Some channels may not be allowed in given group of theories
- Two benchmark modes

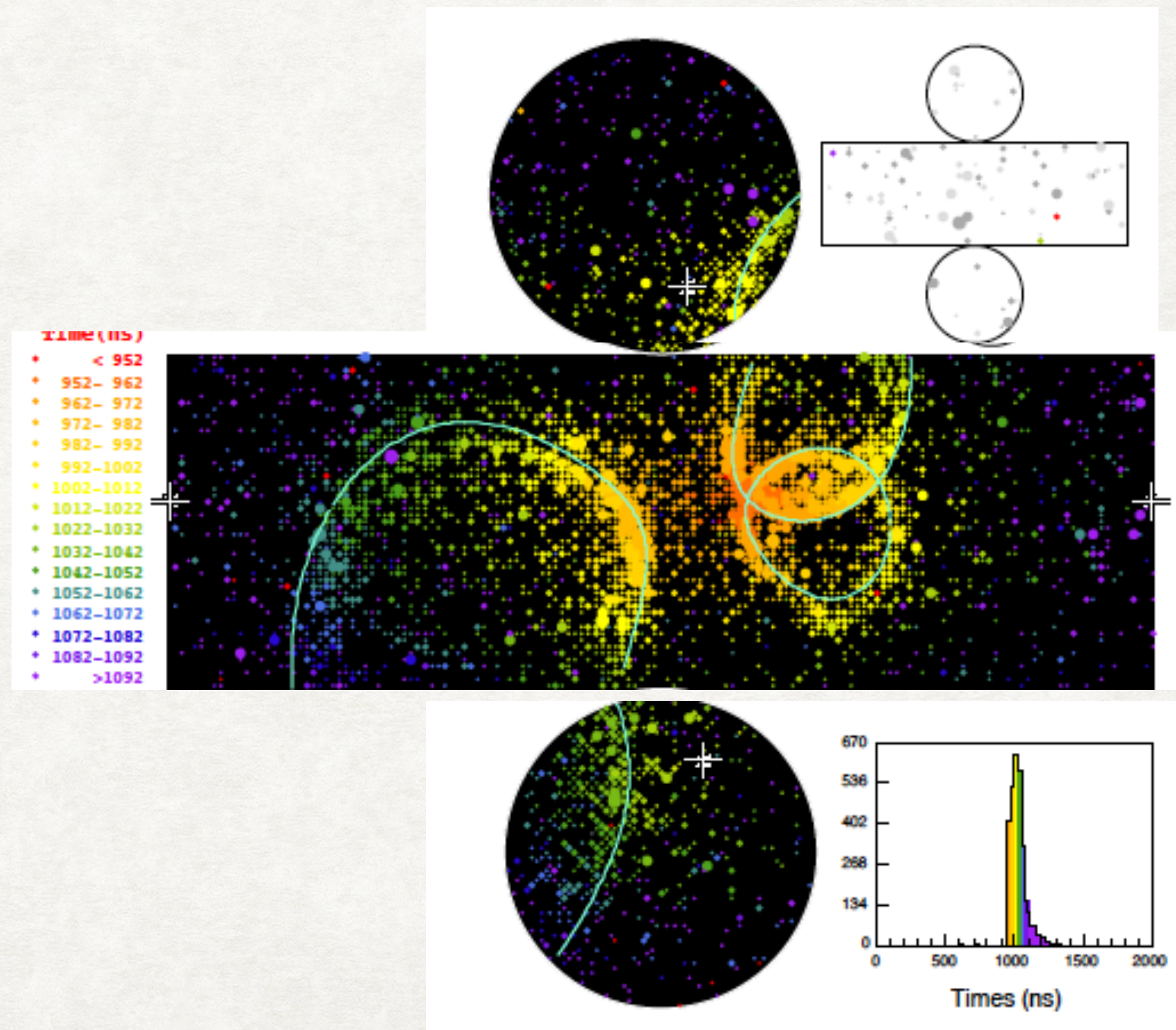
$e^+\pi^0$ Gauge mediated $\bar{\nu}K^+$ SUSY models

SUPER-KAMIOKANDE

- If there is a limit for the given proton decay channel it belongs to S-K, but the most important is p-> $e^+\pi^0$

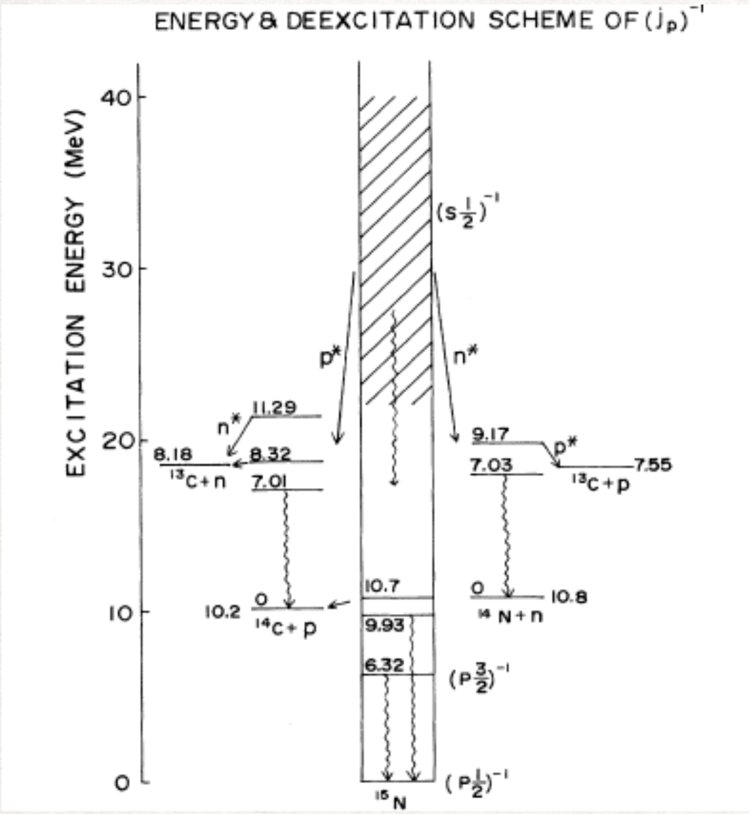


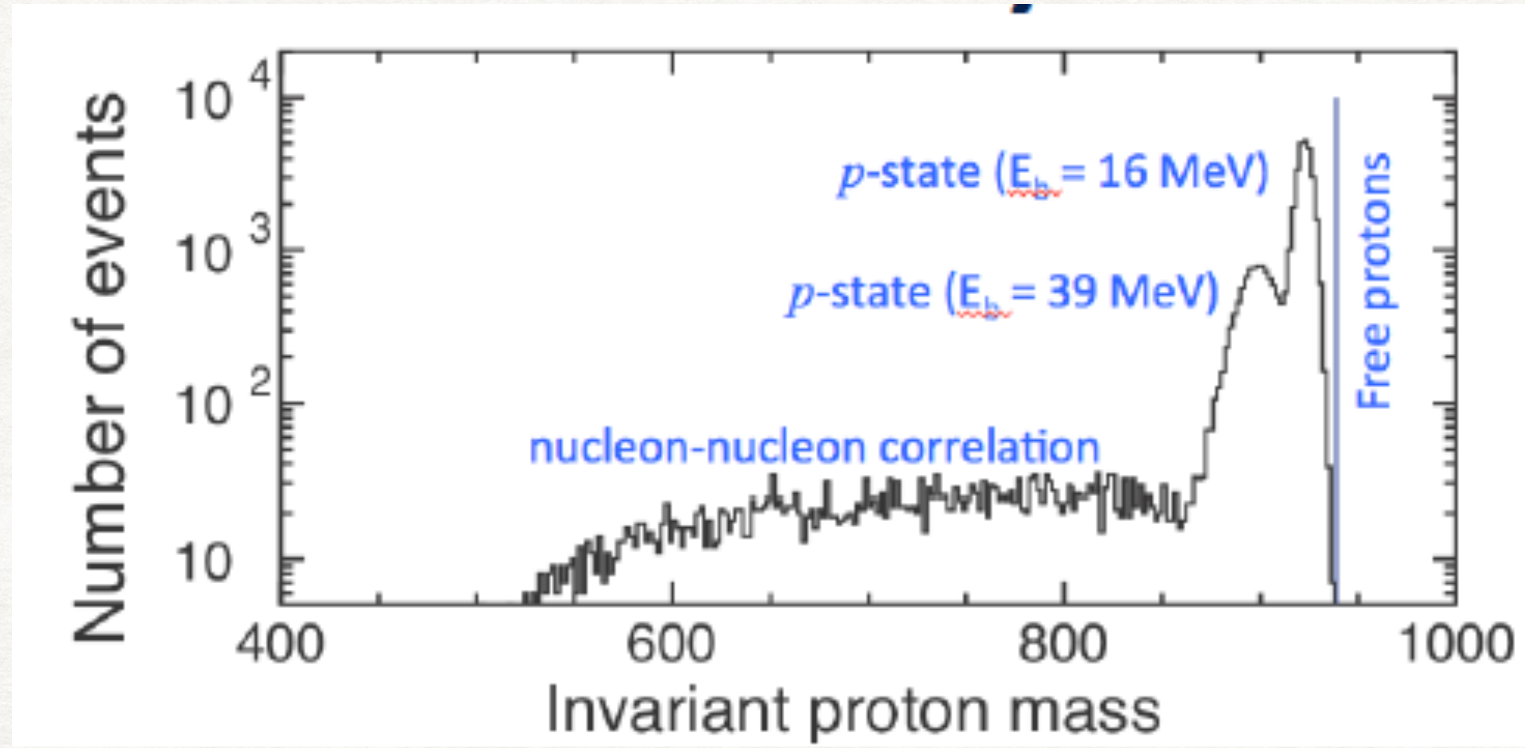
Good event criteria:
- Fully contained
- Fiducial volume
- 2 or 3 rings
- All rings are EM showers
- π^0 mass 85-185 MeV/c2
- No μ-decay electrons
- Mass range 800-1050 MeV/c2
- p_{net}< 250 MeV/c
- tight cut: p_{net}< 100 MeV/c



Ed Kearns

NUCLEAR PHYSICS





Hole	Residual	States	(k)	E_γ	E_p	E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5	0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0	~ 20	0.02
	7.03	2^+	^{14}N	7.03	0	~ 13	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	1.6	~ 11	0.01
	g.s.	0^+	^{14}C	0	~ 21	0	0.02
	7.01	2^+	^{14}C	7.01	~ 14	0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~ 11	~ 2	0.03
$(j)_p^{-1}$	others		many states	≤ 3–4			0.16

gammas

H. Ejiri Phys. Rev. C48 (1993)

MAIN (EFFICIENCY) UNCERTAINTIES

- Nuclear effects – meson (π, **η**, **ω**) nuclear effects affect the detection efficiency. The biggest error source

- π nuclear effect – the systematics obtained from comparison between two models (as there is no suitable data). Detection efficiency depends on the probability for the π to escape with out any scattering.

- Fraction of NN-corelated decays -10% of the decays are assumed to come from nucleon correlated to another nucleon (3 body decay). That leads to lower detection efficiency.

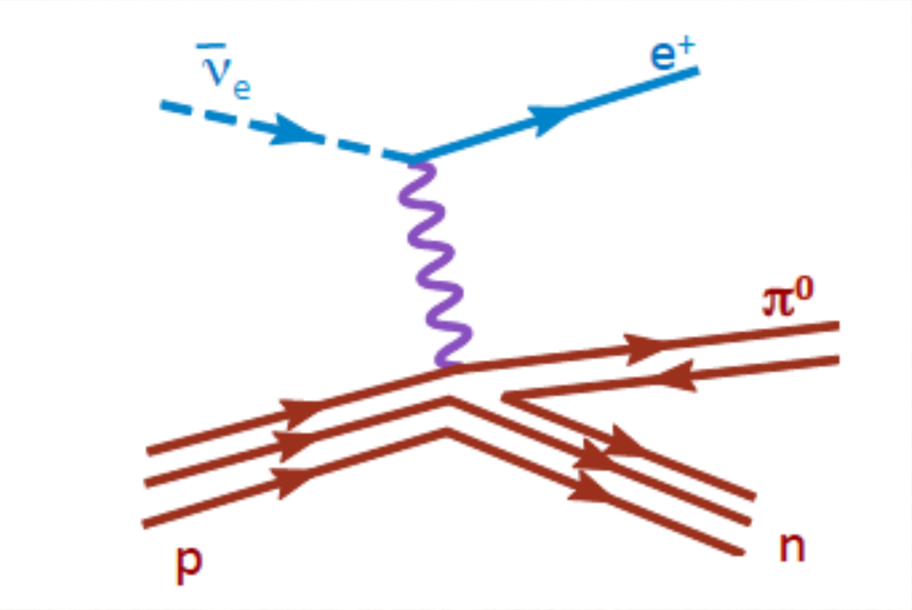
- Fermi motion – modeling of the nucleon momenta

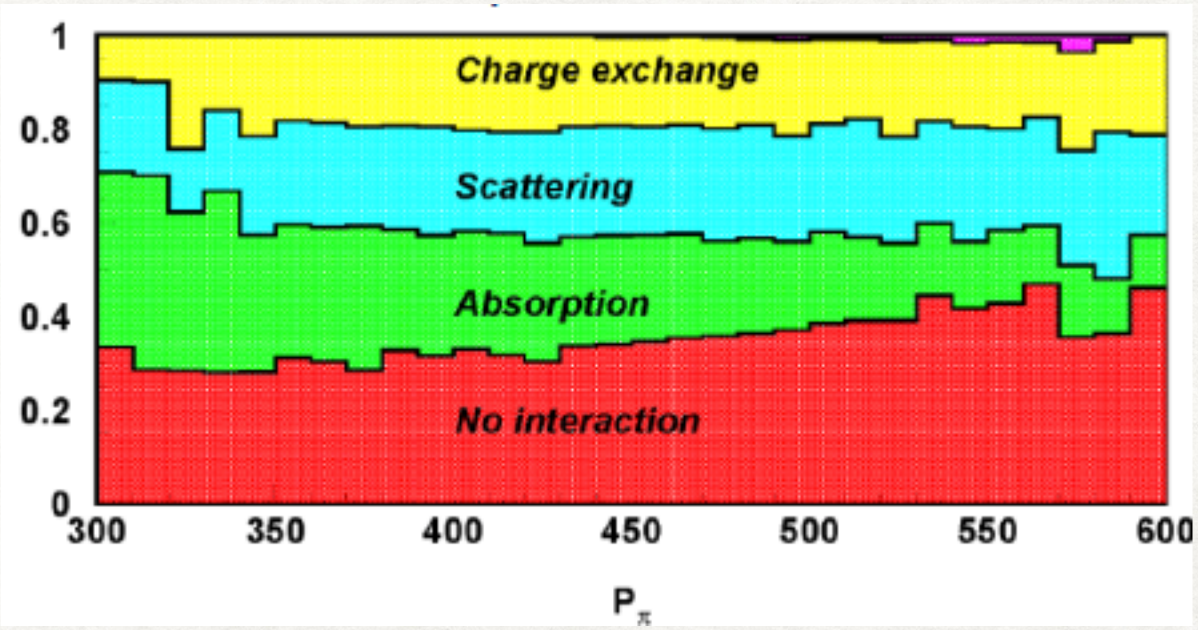
Uncertainties for detection efficiency Phys.RevD85,112001

Mode	Meson nuclear effect	Hadron propagation in water	*N*-*N* correlated decay	Fermi momentum	Detector performances	Total
$p \to e^+ \pi^0$	15%	⋯	7%	8%	4%	19%
$p \to \mu^+ \pi^0$	15%	⋯	7%	8%	4%	19%

BACKGROUND: ATMOSPHERIC NEUTRINOS

- Modelling of the neutrino interactions and intranuclear pion scattering are crucial for background estimation.
- The background rate uncertainty typically 40%-60%, dominated by the hadronic interaction uncertainty.





Ed Kearns

MAIN (BACKGROUND) UNCERTAINTIES

- The background comes from atmospheric neutrinos interactions.

Uncertainties for neutrino interaction background

Mode	Neutrino flux	Neutrino cross section	Pion nuclear effect	Hadron propagation in water	Detector performances	Total
$p \to e^+ \pi^0$	8%	8%	8%	36%	22%	44%
$p \to \mu^+ \pi^0$	8%	8%			43%	58%

Background events

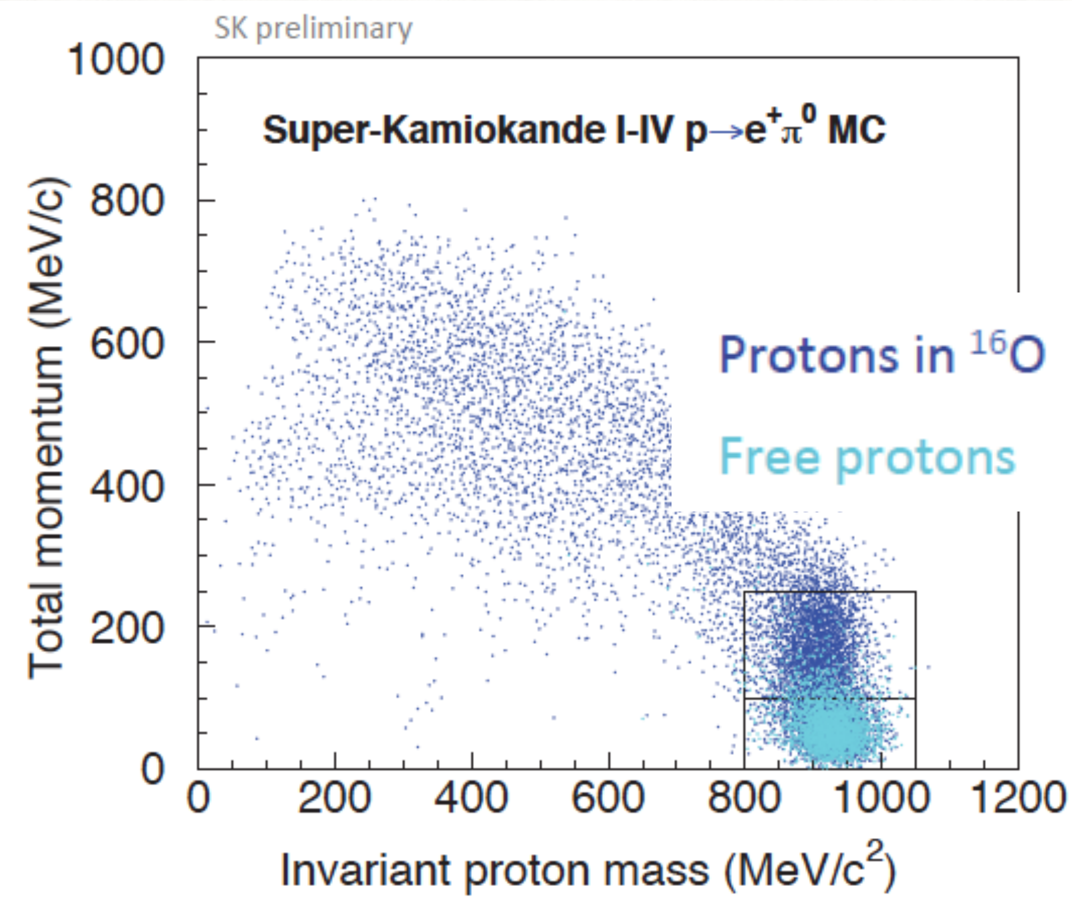
Mode	$p \to e^+ \pi^0$	$N \to l^+ \pi$	$p \to l^+ \eta$	$p \to l^+ \omega$	$N \to l^+ \rho$
CCQE	28%	21%	5%	4%	9%
CC 1-π	32%	51%	20%	25%	45%
CC multi-π	19%	14%	24%	29%	14%
CC others	2%	6%	13%	7%	4%
NC	19%	9%	37%	35%	28%

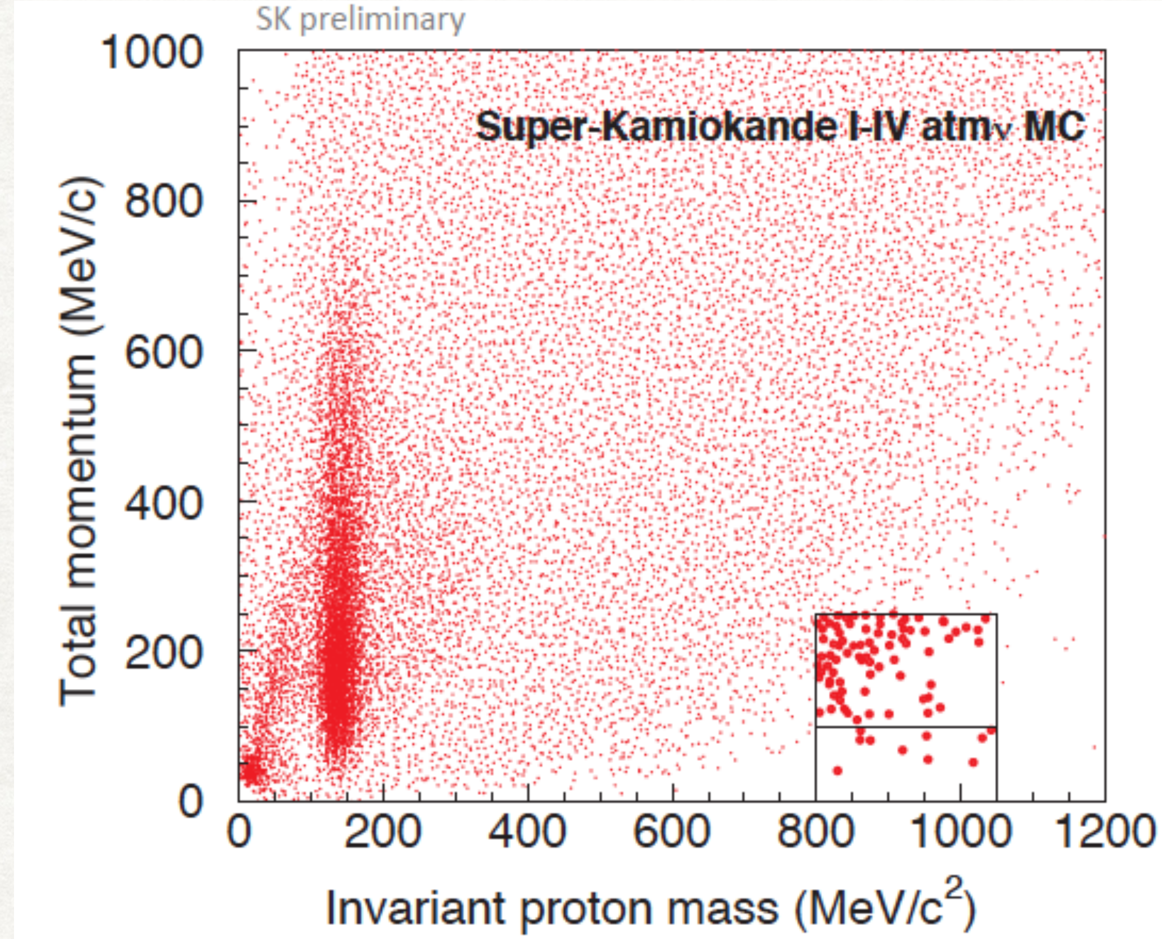
Phys.RevD85,112001

SIGNAL MC

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

ATMOSPHERIC BACKGROUND MC





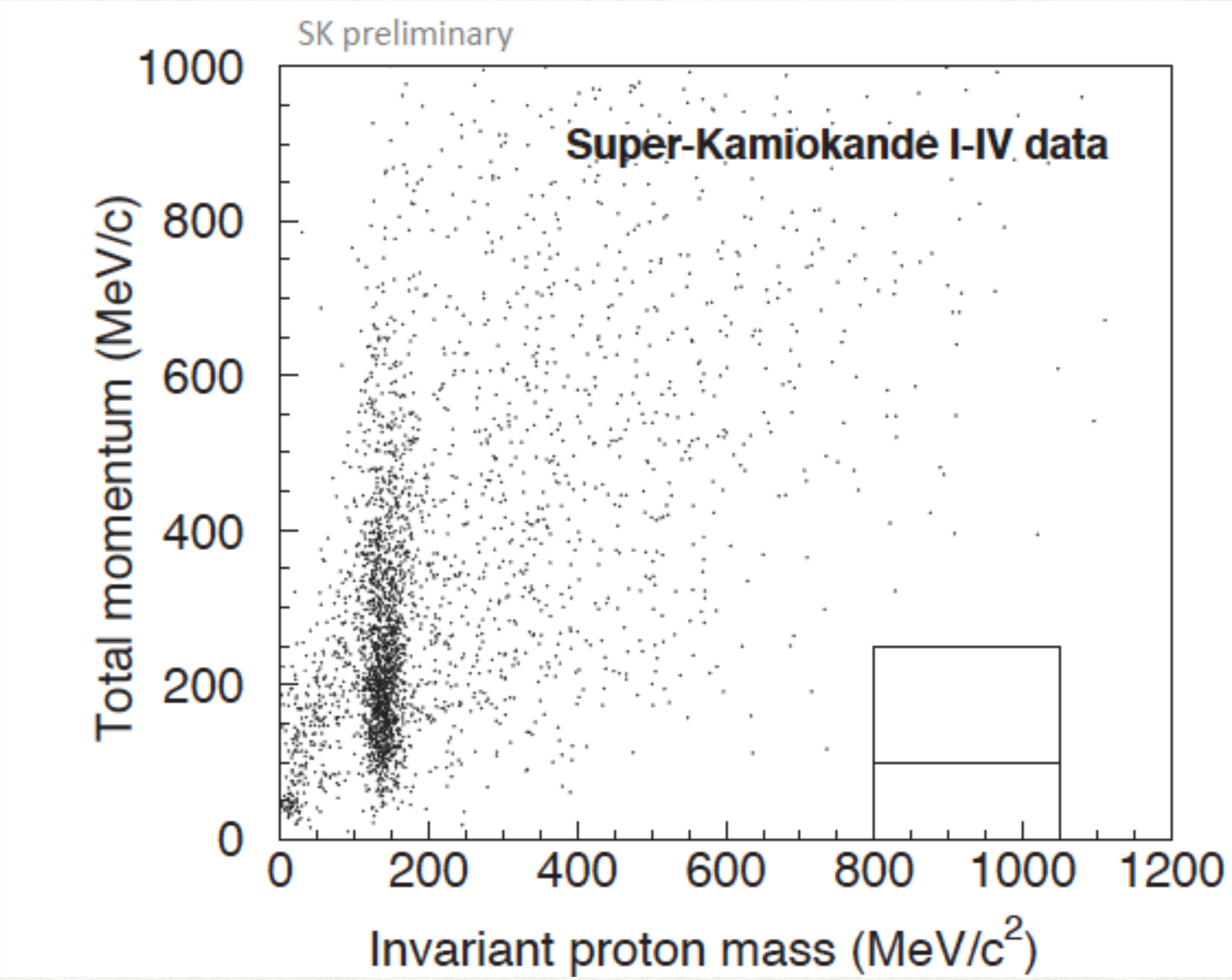
Signal Efficiency (%)	SK-I	SK-II	SK-III	SK-IV w. n cap.
$100 < p_{net} < 200$ MeV/c	20.4 ± 3.1	20.2 ± 3.1	20.5 ± 3.2	19.4 ± 1.2
$p_{net} < 100$ MeV/c	18.8 ± 0.9	18.3 ± 1.0	19.6 ± 1.3	18.7 ± 1.2

Background (evts)	SK-I	SK-II	SK-III	SK-IV w. n cap.
$100 < p_{net} < 200$ MeV/c	0.22 ± 0.06	0.12 ± 0.04	0.06 ± 0.02	0.15 ± 0.05
$p_{net} < 100$ MeV/c	0.03 ± 0.01	0.01 ± 0.003	0.003 ± 0.001	0.02 ± 0.01

Monte Carlo estimates. Background rate also measured using K2K 1KT near detector.

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

SUPER-K Data 306 kt y



Zero candidate events

$$\frac{\tau}{B} > 1.67 \times 10^{34}\ \mathrm{y}$$

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

$$\frac{\tau}{B} > 6.61 \times 10^{33}\ \mathrm{y}$$

- Kaon is below Cherenkov threshold. Search for Kaon decay at rest.

γ-tag plus $\pi^{+}\pi^{0}$	SK1	(20% coverage) SK2	SK3	(new electronics) SK4 → w. n-cap
Efficiency	15.7 %	13.0 %	15.6 %	~~18.9 %~~ → 17.5 %
Background rate (ev/100 kty)	0.28	0.63	0.38	~~0.4~~ → 0.19 %

No candidates, 306 kton yr (SK 1+2+3+4 w. n-cap):

SK preliminary

$p \longrightarrow \bar{\nu} K^+$ A GOLDEN CHANNEL FOR LAr DETECTORS

- Two-body decay: for free protons, K^+ momentum 340 MeV
- Below inelastic collision threshold → no absorption of K^+ within Argon nucleus → K^+ emerges intact in ~97% of p → $K^+\nu$ decays.
- However, all decays are inside the nucleus. No free protons as in the case od SK.

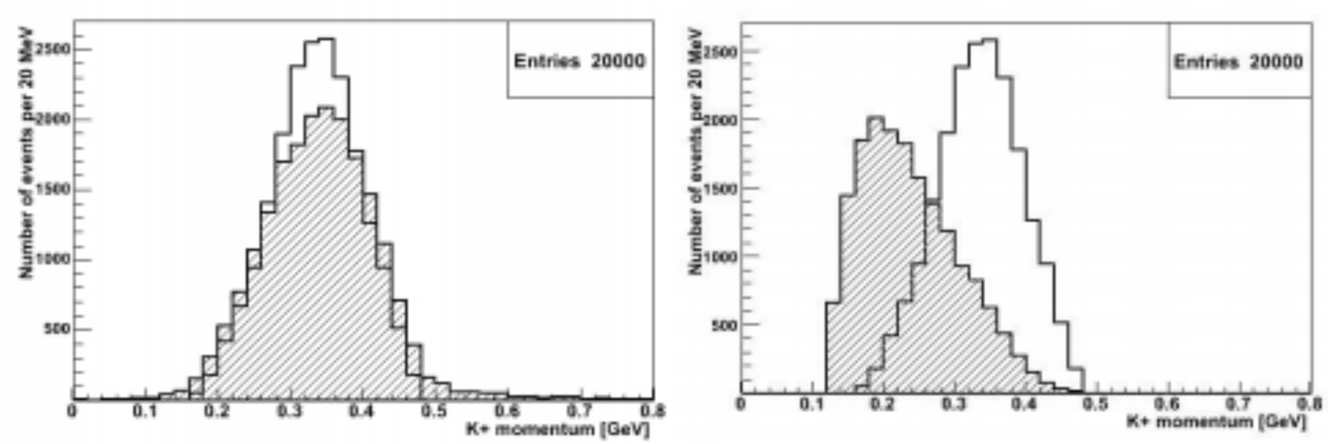
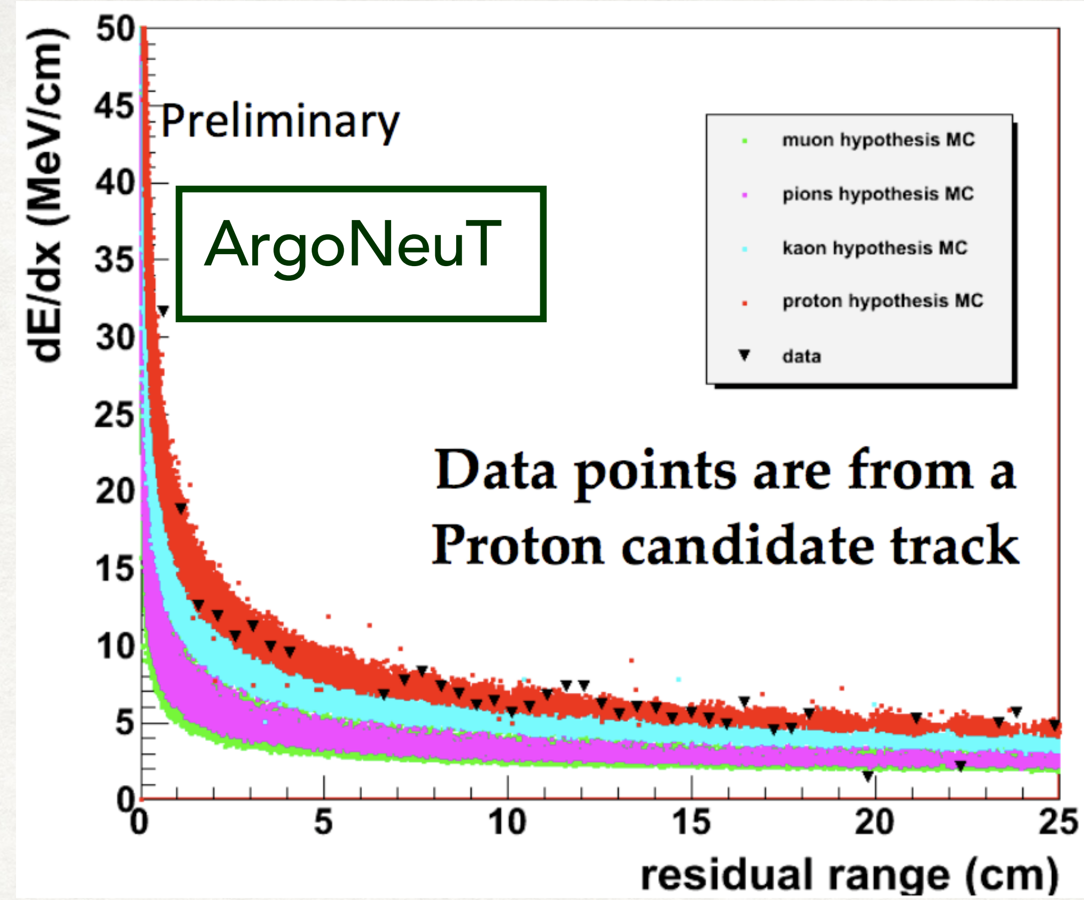


Fig. 1. Momentum distribution of kaons produced in the $p \rightarrow \bar{\nu}K^+$ decay inside the argon nucleus predicted by different approaches. Left: Calculations for the spectral function of argon (hatched) compared to the local Fermi gas model from GEANT4 without the intranuclear cascade (plain histogram). Right: GEANT4 with (hatched) and without (plain histogram) the cascade.

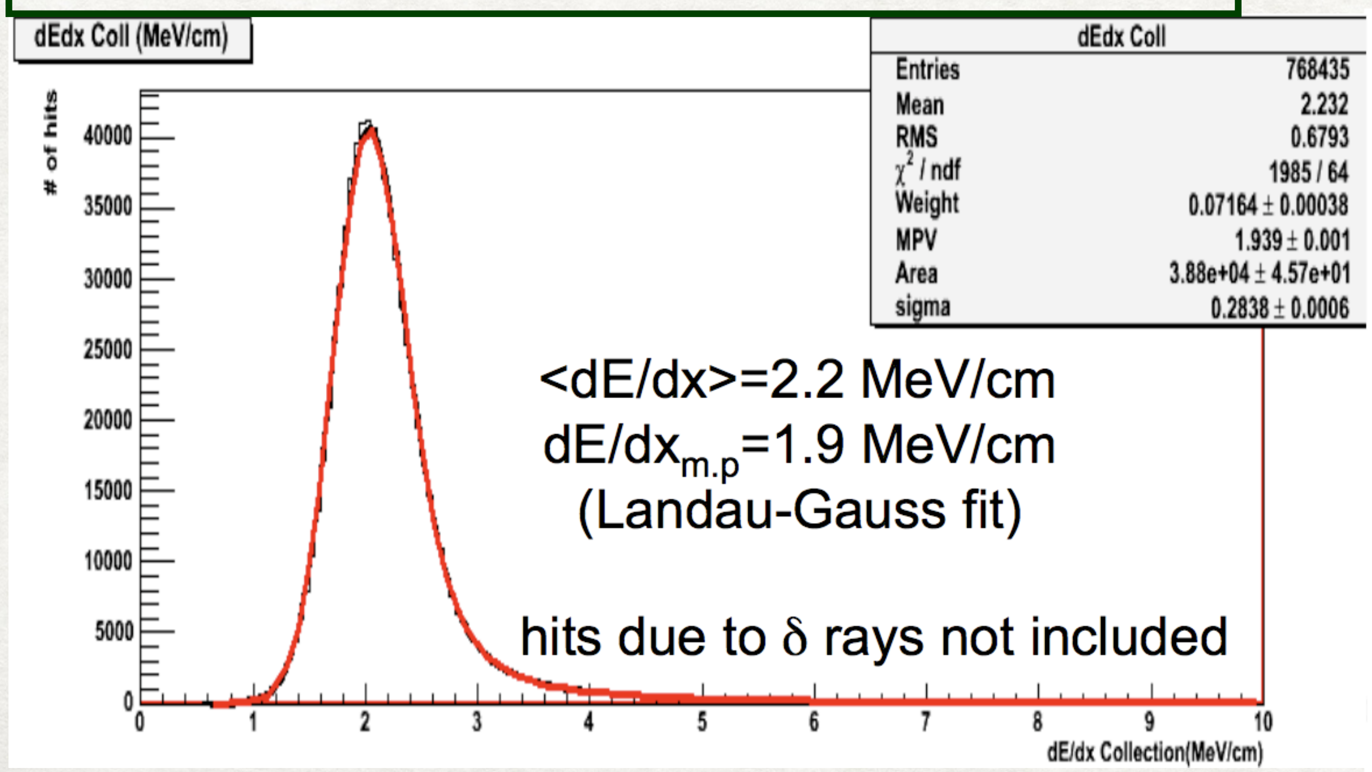
from Stefan & Ankowski, ArXiv:0811.1892 [nucl-th], 2009

K$^+$ momentum 340 MeV → range ~14cm

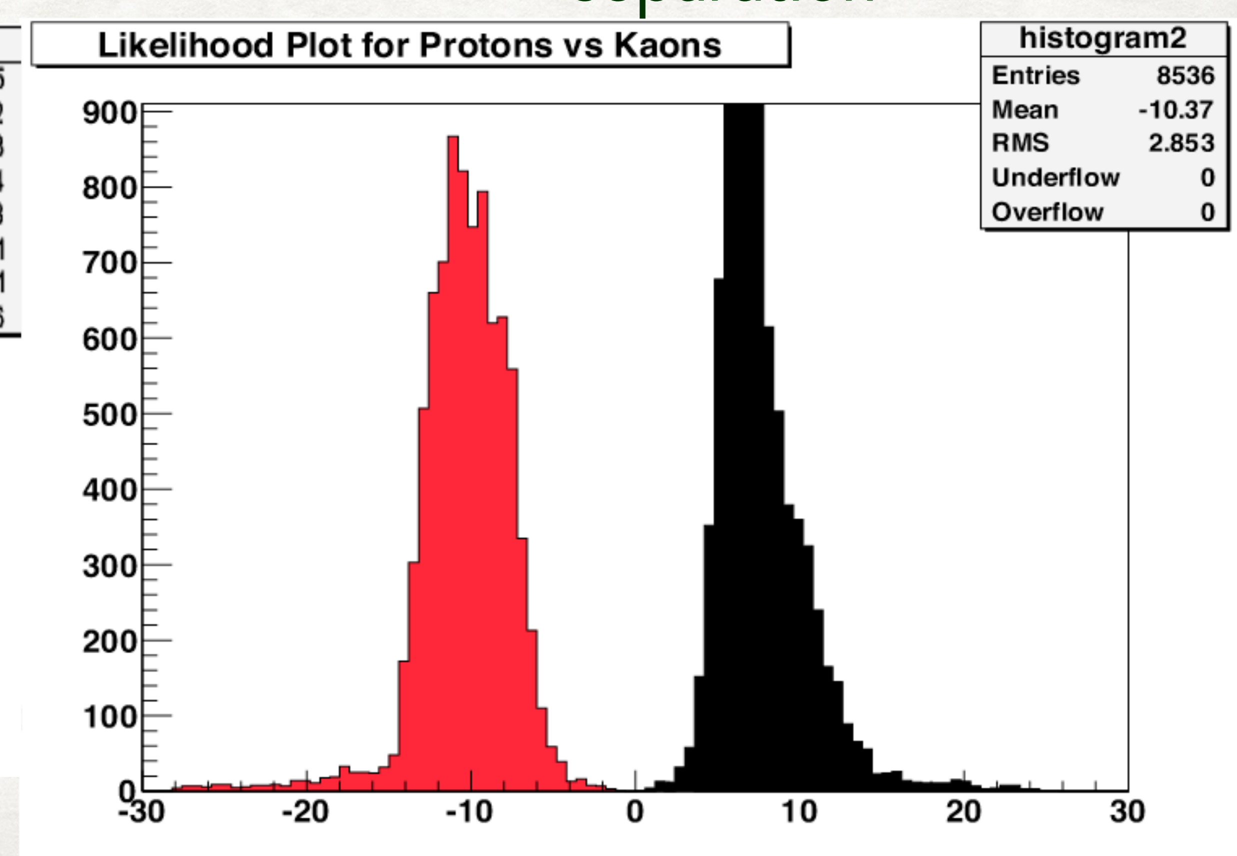
- distinctive dE/dx signatures already seen in ICARUS and ArgoNeuT
- Will also be studied in detail with planned LArTPC R&D efforts (protoDUNE, WA105)



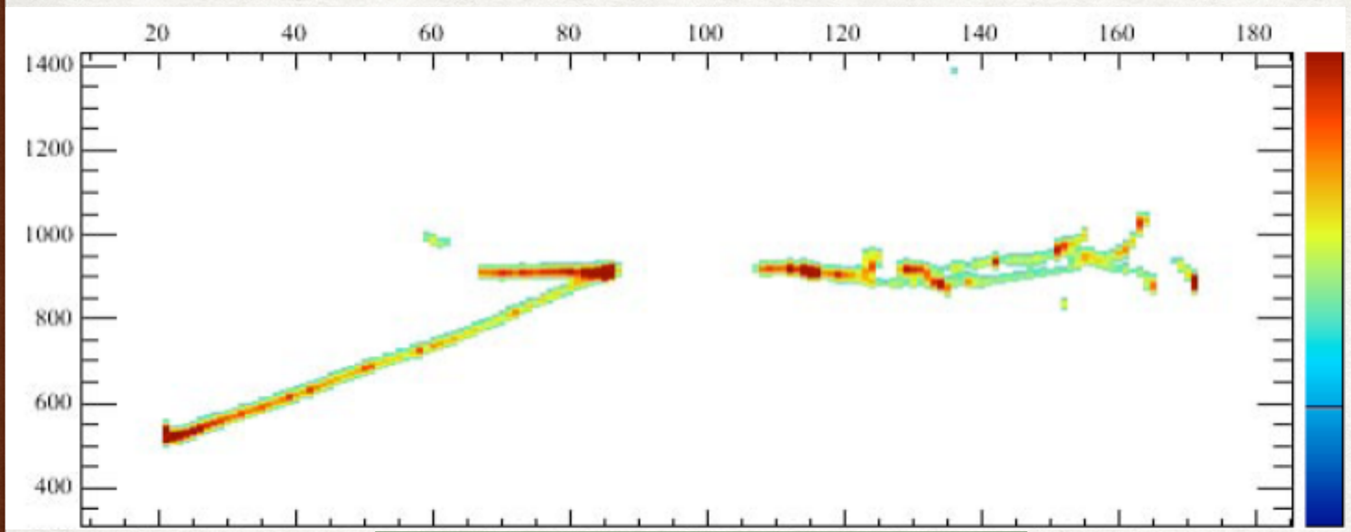
dE/dx for muons in ArgoNeuT Data



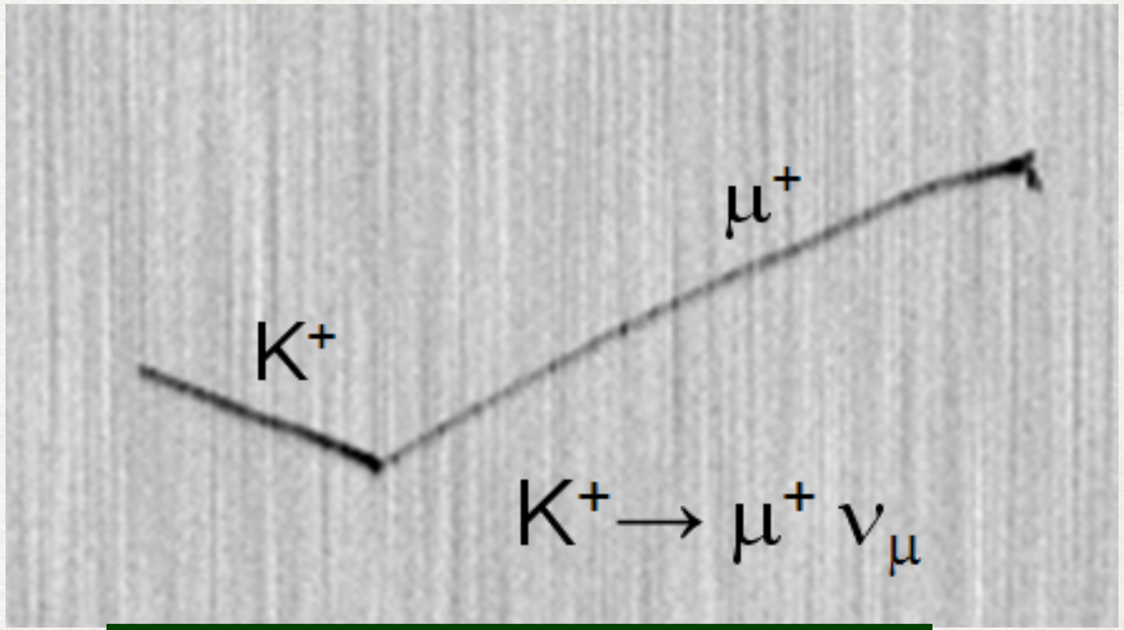
From LArSoft Simulation: K/p separation



- K^+ decay at rest: Simple topologies !
  - $\mu + \nu$ (63.6% BR): monochromatic μ: p_μ = 236 MeV
    - Minimum-ionizing track, momentum by range/multiple scattering/energy deposition
      - Note: muon from π+ decay-at-rest has p_μ = 30 MeV
    - Followed by decay electron.
  - $\pi + \pi^0$ (20.7% BR): fully reconstructable final state
  - 3π (7.4% BR): fully reconstructable final states
  - $\pi^0 l^+ \nu$ (8.3% BR): kinematically constrained final states

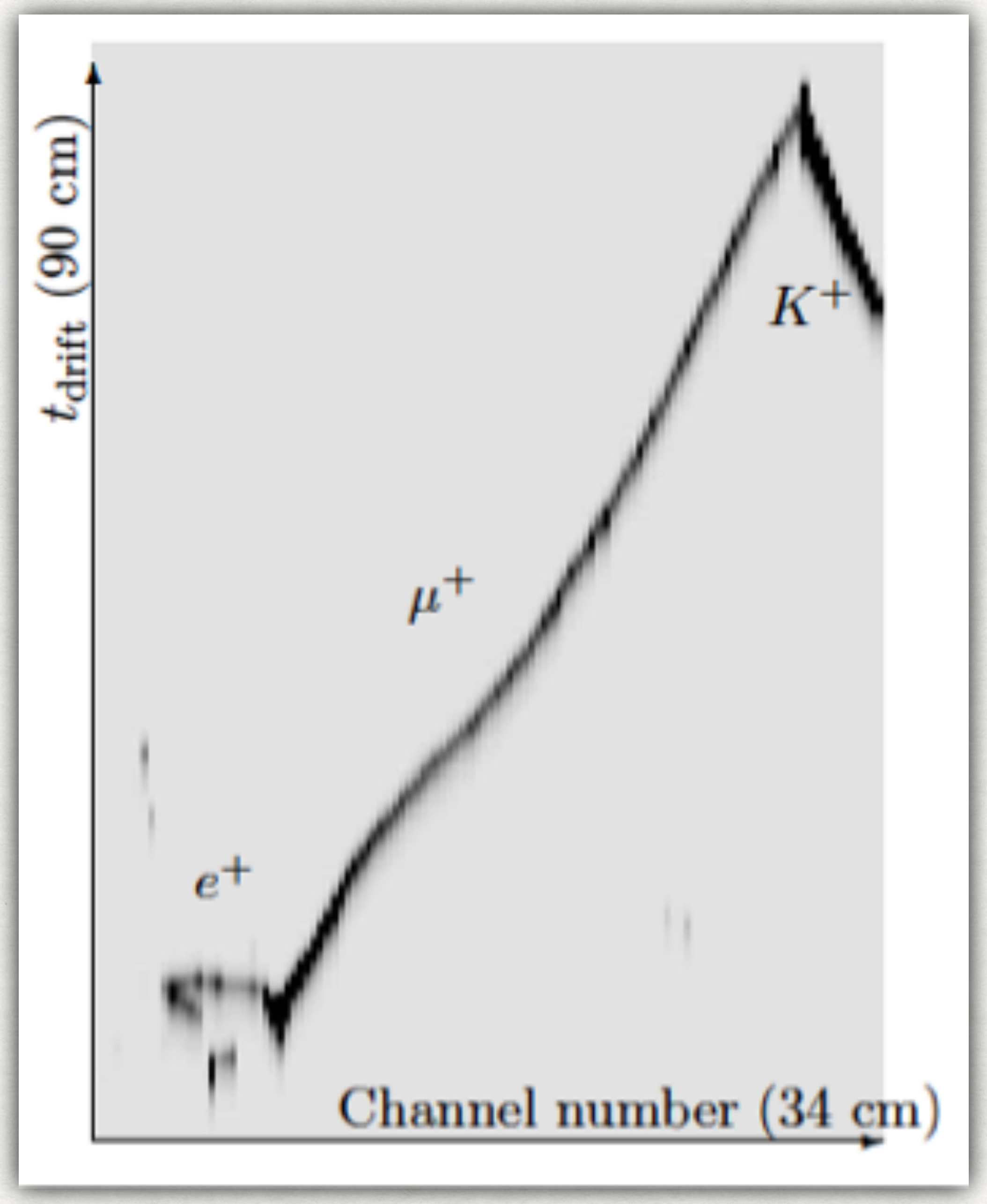


LArSoft $K^+ \rightarrow \pi^+ \pi^0$

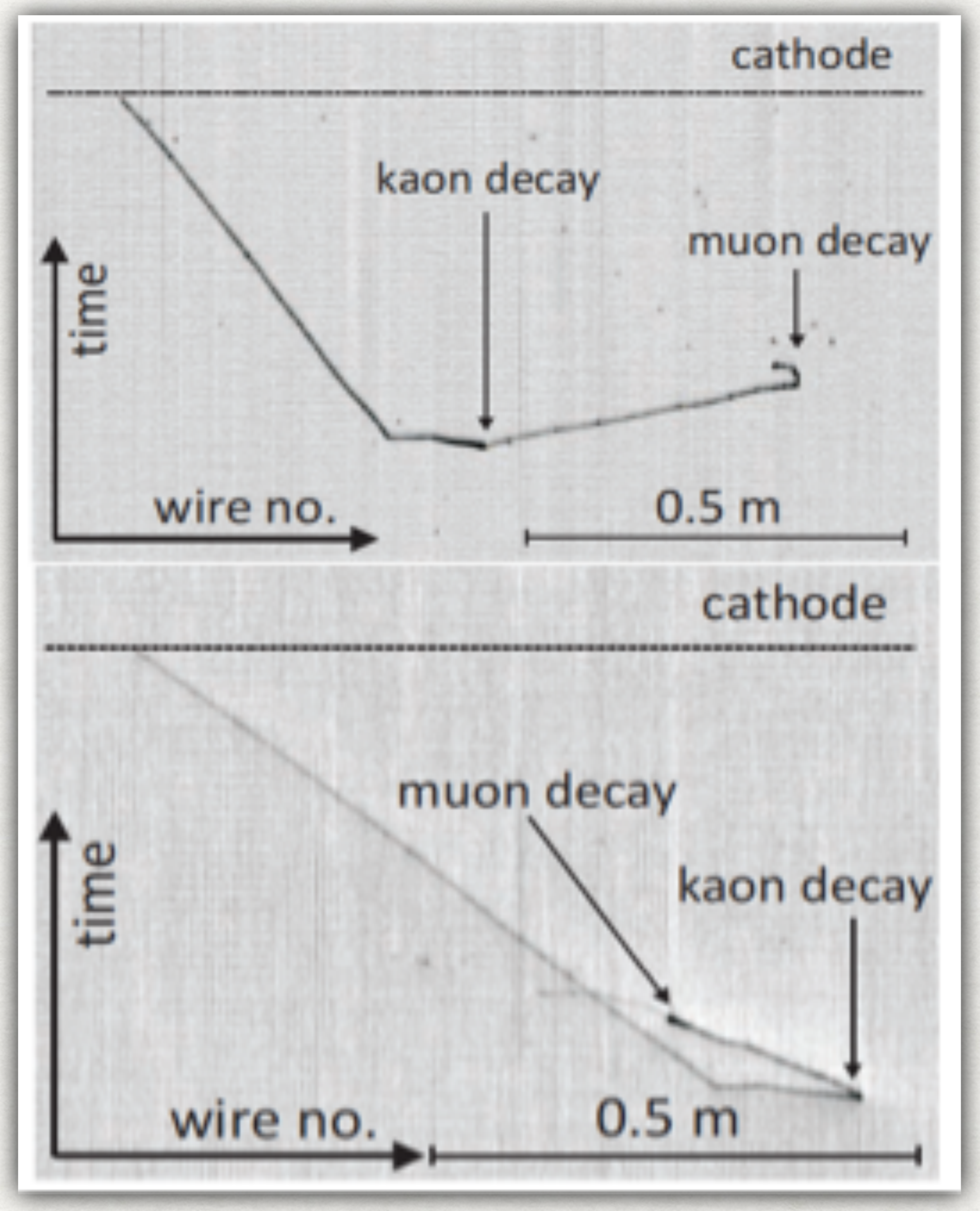


ICARUS T300 data from 2001 surface run @ Pavia

PROTON DECAY CHANNELS WITH KAONS



Event simulation from
Bueno et al. JHEP04 (2007) 041.



ICARUS T600 event from
Antonello et al. Adv. High Energy Phys. (2013) 260820

BACKGROUND AND EFFICIENCIES

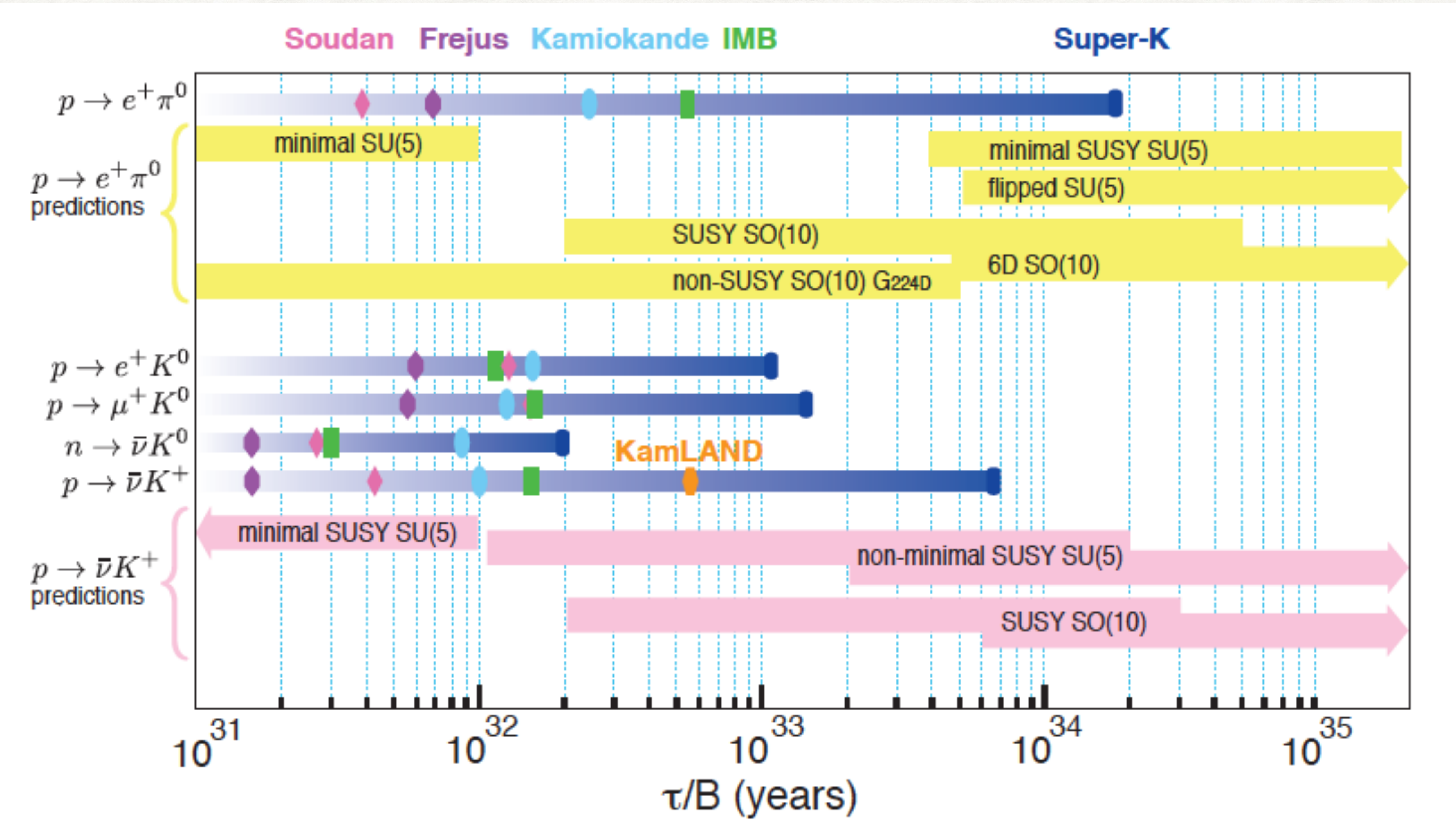
	Mode	Super-K Water Ch. Efficiency	Super-K Water Ch. BG Rate (/Mt y)	LAr (generic) Efficiency	LAr (generic) BG Rate (/Mt y)
B-L	$e^+\pi^0$	45%	2	45%	1
B-L	νK^+	16%	7	97%	1
B-L	$\mu^+ K^0$	10%	5-10	47%	<2
B+L	$\mu^- \pi^+ K^+$	?	?	97%	1
B+L	$e^- K^+$	10%	3	96%	<2
$\Delta B=2$	n nbar	12%	260	?	?

Rough and unofficial
SK efficiency & BG - ETK

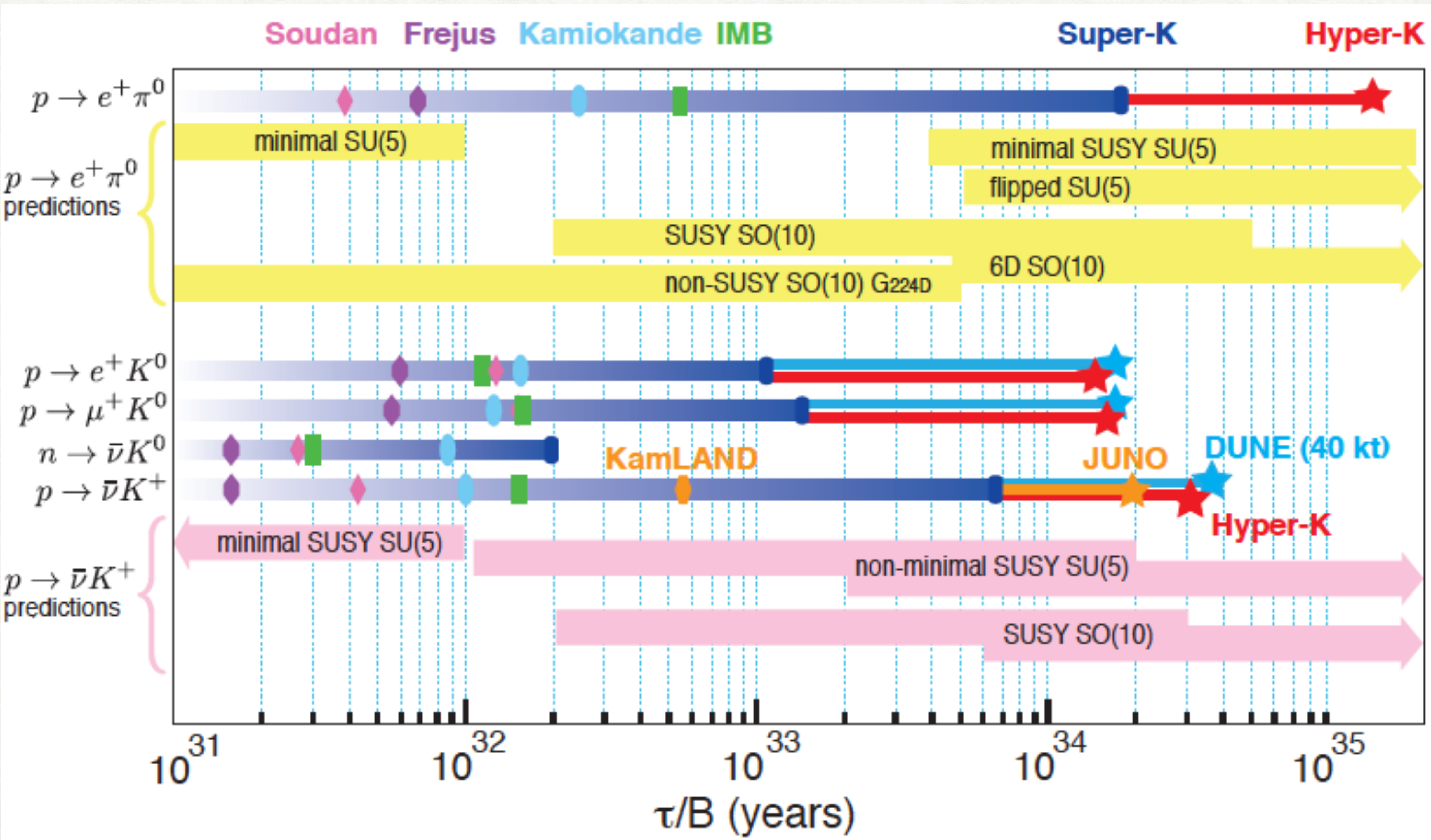
A. Bueno et al.
hep-ph/0701101

Estimate for water Cherenkov: Kearns (Snowmass, 2013).
For LAr: LBNE Collaboration, arXiv:1307.7335v3 based on Bueno et al. JHEP04 (2007) 041.
Several decay modes with high efficiency and low background in LAr.

CURRENT RESULTS



FUTURE EXPERIMENT SENSITIVITIES



CONCLUSIONS

- So far zero proton decay events!
- Better understanding of nuclear effect is necessary.
- Nucleon decay program of the future large underground detectors will make use of the developments in the nuclear effects presented and NuInt workshops.

BACKGROUND TO $p \rightarrow K^{+} \nu$ IN LAr:

"Nucleon decay searches with large liquid Argon TPC detectors at shallow depths: atmospheric neutrinos and cosmogenic backgrounds"

Comprehensive study based on well tested event generators & parametrized detector response

Projected DUNE capabilities currently based on these results

Decay mode	This paper (LAr TPC) Efficiency (%)	Atmospheric ν background 100 kton×year	Super-Kamiokande results [5, 10] Efficiency (%)	Atmospheric ν background 92 kton×year	Published limit 90% C.L.
(p1) $p \to e^{+}\,\pi^{0}$	45.3	0.1	40	0.2	1.6×10^{33}
(p2) $p \to \pi^{+}\,\bar{\nu}$	41.9	78.2			
(p3) $p \to K^{+}\,\bar{\nu}$	96.8	0.1	8.6 (prompt-γ)	0.7	2.3×10^{33}
			6.0 ($K^{+} \to \pi^{+}\pi^{0}$)	0.6	
(p4) $p \to \mu^{+}\,\pi^{0}$	44.8	0.8	32	0.2	
(p5) $p \to \mu^{+}\,K^{0}$	46.7	< 0.2	5.4 ($K^0_S \to \pi^{0}\pi^{0}$)	0.4	
			7.0 ($K^0_S \to \pi^{+}\pi^{-}$ method 1)	3.2	1.3×10^{33}
			2.8 ($K^0_S \to \pi^{+}\pi^{-}$ method 2)	0.3	
(p6) $p \to e^{+}\,K^{0}$	47.0	< 0.2	9.2 ($K^0_S \to \pi^{0}\pi^{0}$)	1.1	1.0×10^{33}
			7.9 ($K^0_S \to \pi^{+}\pi^{-}$ method 1)	3.6	
			1.3 ($K^0_S \to \pi^{+}\pi^{-}$ method 2)	0.04	
(p7) $p \to e^{+}\,\gamma$	98.0	< 0.2	73	0.1	
(p8) $p \to \mu^{+}\,\gamma$	98.0	< 0.2	51	0.2	
(p9) $p \to \mu^{-}\,\pi^{+}\,K^{+}$	97.6	0.1			
(p10) $p \to e^{+}\,\pi^{+}\,\pi^{-}$	18.6	2.5			
(n1) $n \to \pi^{0}\,\bar{\nu}$	45.1	47.4			
(n2) $n \to e^{-}\,K^{+}$	96.0	< 0.2			
(n3) $n \to e^{+}\,\pi^{-}$	44.4	0.8			
(n4) $n \to \mu^{-}\,\pi^{+}$	44.8	2.6			

Bueno et al., JHEP 04 (2007), 041

TABLE VI. Fraction of the final states of π^0 from the proton decay of $p \rightarrow e^+\pi^0$ in ^{16}O compared with the simulation used in the IMB experiment.

Nuclear effect	Our MC	IMB
No interaction	44%	54%
Absorption	22%	22%
Charge exchange	15%	10%
Scattered	19%	14%