Proton decay search with LAr

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based primarily on the LAGUNA-LBNO and LBNE studies

First simulations

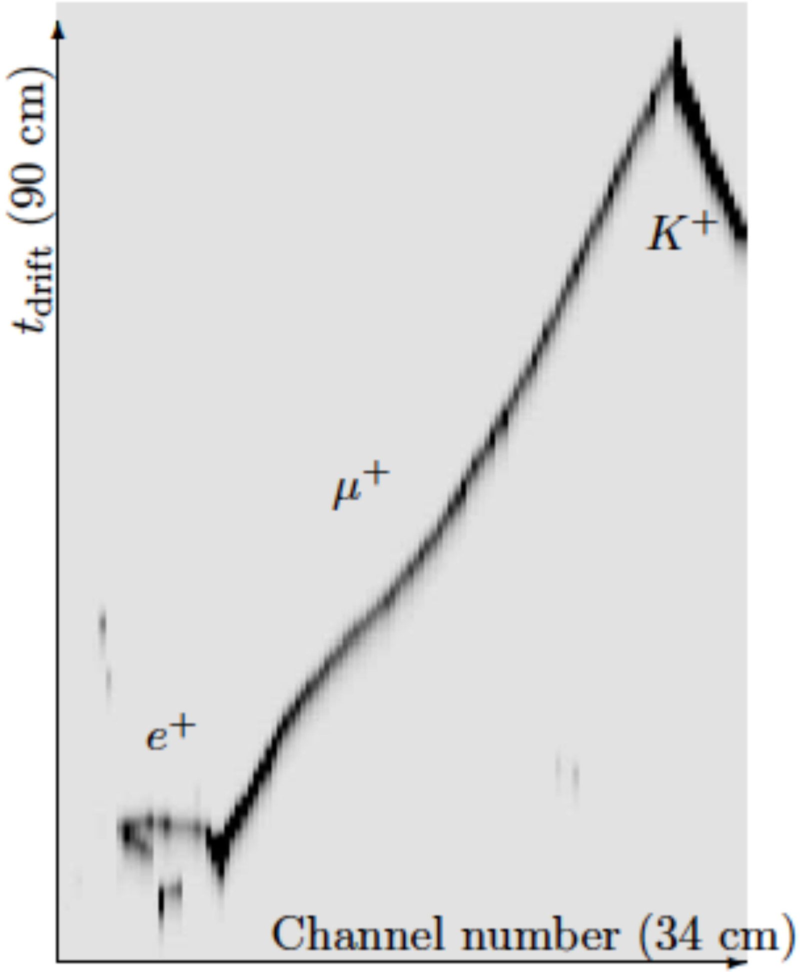
Model	Ref.	Modes	τ_N (years)
Minimal SU(5)	Georgi, Glashow [2]	$p \to e^+\pi^0$	$10^{30} - 10^{31}$
Minimal SUSY SU(5)	Dimopoulos, Georgi [11], Sakai [12] Lifetime Calculations: Hisano, Murayama, Yanagida [13]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{28} - 10^{34}$
SUGRA SU(5)	Nath, Arnowitt [14, 15]	$p \to \bar{\nu}K^+$	$10^{32} - 10^{34}$
SUSY SO(10) with anomalous flavor U(1)	Shafi, Tavartkiladze [16]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$ $p \to \mu^+K^0$	$10^{32} - 10^{35}$
SUSY SO(10) MSSM (std. $d=5$)	Lucas, Raby [17], Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$
		$n \to \bar{\nu}K^0$	$10^{32} - 10^{33}$
SUSY SO(10) ESSM (std. $d=5$)	Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$
SUSY SO(10)/$G(224)$ MSSM or ESSM (new $d=5$)	Babu, Pati, Wilczek [19–21], Pati [18]	$p \to \bar{\nu}K^+$	$\lesssim 2 \cdot 10^{34}$
		$p \to \mu^+K^0$	$B \sim (1-50)\%$
SUSY SU(5) or SO(10) MSSM ($d=6$)	Pati [18]	$p \to e^+\pi^0$	$\sim 10^{34.9\pm1}$
Flipped SU(5) in CMSSM	Ellis, Nanopoulos and Wlaker [22]	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{36}$
Split SU(5) SUSY	Arkani-Hamed, *et. al.* [23]	$p \to e^+\pi^0$	$10^{35} - 10^{37}$
Minimal non-SUSY SU(5)	Dorsner, Perez [24]	$p \to \nu + (K^+, \pi^+, \rho^+)$ $n \to \nu + (\pi^0, \rho^0, \eta^0, \omega^0, K^0)$	$10^{31} - 10^{38}$
SU(5) in 5 dimensions	Hebecker, March-Russell [25]	$p \to \mu^+K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$
SU(5) in 5 dimensions option II	Alciati *et. al.* [26]	$p \to \bar{\nu}K^+$	$10^{36} - 10^{39}$
GUT-like models from Type IIA string with D6-branes	Klebanov, Witten [27]	$p \to e^+\pi^0$	$\sim 10^{36}$

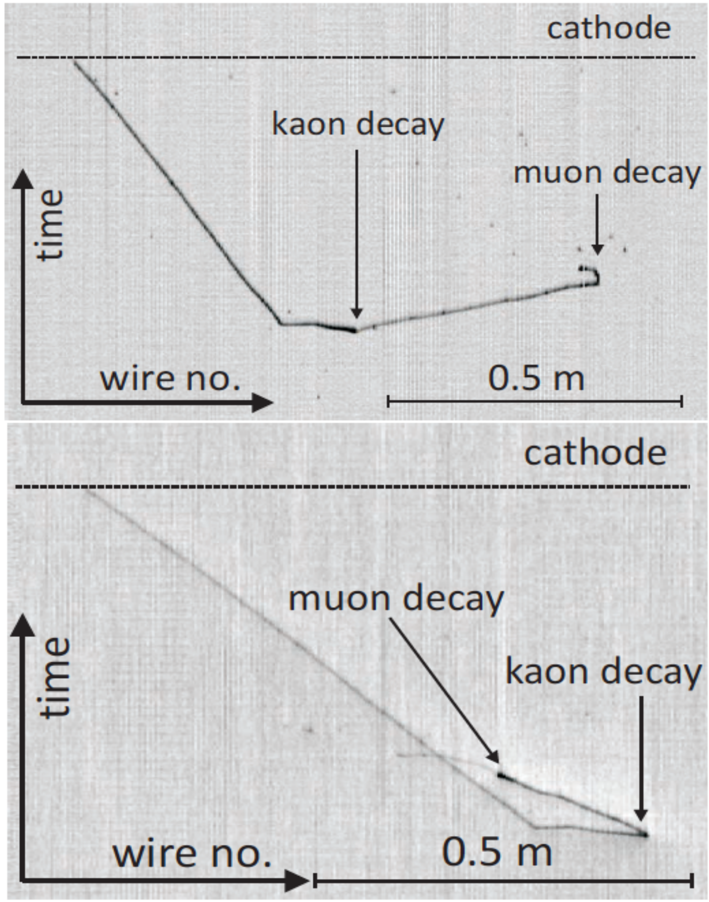
- **First simulations for LAr Bueno et al. JHEP04 (2007) 041. Also in Autiero et al. JCAP11 (2007) 011.**
- **The most promising mode**

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

- **Advantage over water Cherenkov – high efficiency.**
- **In general, better event reconstruction and PID in LAr.**

Events with kaons





- Event simulation from Bueno et al. JHEP04 (2007) 041.
- ICARUS T600 event from Antonello et al. Adv. High Energy Phys. (2013) 260820.

First simulations

Channel	Cut efficiency (%)	Total background per year in fiducial volume	τ/B limit (years) 1 year exposure	τ/B limit (years) 10 years exposure
(p1) $p \to e^+ \pi^0$	45.3	0.1	0.5 $\times 10^{34}$	0.4 $\times 10^{35}$
(p2) $p \to \pi^+ \bar{\nu}$	41.9	82 (3 km w.e.)	0.7 $\times 10^{33}$	0.3 $\times 10^{34}$
		151 (1 km w.e.)	0.5 $\times 10^{33}$	0.2 $\times 10^{34}$
		148 (0.5 km w.e.)	0.5 $\times 10^{33}$	0.2 $\times 10^{34}$
		143 (Under the hill)	0.4 $\times 10^{33}$	0.2 $\times 10^{34}$
		149 (Under the hill+2 veto planes)	0.5 $\times 10^{33}$	0.2 $\times 10^{34}$
		152 (Under the hill+3 veto planes)	0.5 $\times 10^{33}$	0.2 $\times 10^{34}$
(p3) $p \to K^+ \bar{\nu}$	96.8	0.2 (3 km w.e.)	1.0 $\times 10^{34}$	0.6 $\times 10^{35}$
		0.2 (1 km w.e.)	0.8 $\times 10^{34}$	0.6 $\times 10^{35}$
		0.2 (0.5 km w.e.)	0.8 $\times 10^{34}$	0.4 $\times 10^{35}$
		0.2 (Under the hill)	(0.8–0.7) $\times 10^{34}$	(0.5–0.4) $\times 10^{35}$
		0.2 (Under the hill+ 2 veto planes)	(0.9–0.8) $\times 10^{34}$	(0.5–0.5) $\times 10^{35}$
		0.2 (Under the hill+ 3 veto planes)	(1.0–0.8) $\times 10^{34}$	(0.6–0.5) $\times 10^{35}$
(p4) $p \to \mu^+ \pi^0$	44.8	0.8	0.4 $\times 10^{34}$	0.2 $\times 10^{35}$
(p5) $p \to \mu^+ K^0$	46.7	< 0.2	0.5 $\times 10^{34}$	0.5 $\times 10^{35}$
(p6) $p \to e^+ K^0$	47.0	< 0.2	0.5 $\times 10^{34}$	0.5 $\times 10^{35}$
(p7) $p \to e^+ \gamma$	98.0	< 0.2	1.1 $\times 10^{34}$	1.1 $\times 10^{35}$
(p8) $p \to \mu^+ \gamma$	98.0	< 0.2	1.1 $\times 10^{34}$	1.1 $\times 10^{35}$
(p9) $p \to \mu^- \pi^+ K^+$	97.6	0.1	1.1 $\times 10^{34}$	0.8 $\times 10^{35}$
(p10) $p \to e^+ \pi^+ \pi^-$	18.6	2.5	0.1 $\times 10^{34}$	0.5 $\times 10^{34}$
(n1) $n \to \pi^0 \bar{\nu}$	45.1	50 (3 km w.e.)	0.1 $\times 10^{34}$	0.5 $\times 10^{34}$
		92 (1 km w.e.)	0.1 $\times 10^{34}$	0.4 $\times 10^{34}$
		89 (0.5 km w.e.)	0.1 $\times 10^{34}$	0.4 $\times 10^{34}$
		86 (Under the hill)	0.1 $\times 10^{34}$	0.3 $\times 10^{34}$
		90 (Under the hill+ 2 veto planes)	0.1 $\times 10^{34}$	0.4 $\times 10^{34}$
		91 (Under the hill+ 3 veto planes)	0.1 $\times 10^{34}$	0.4 $\times 10^{34}$
(n2) $n \to e^- K^+$	96.0	< 0.2	1.4 $\times 10^{34}$	1.4 $\times 10^{35}$
(n3) $n \to e^+ \pi^-$	44.4	0.8	0.4 $\times 10^{34}$	0.2 $\times 10^{35}$
(n4) $n \to \mu^- \pi^+$	44.8	2.6	0.4 $\times 10^{34}$	0.2 $\times 10^{35}$

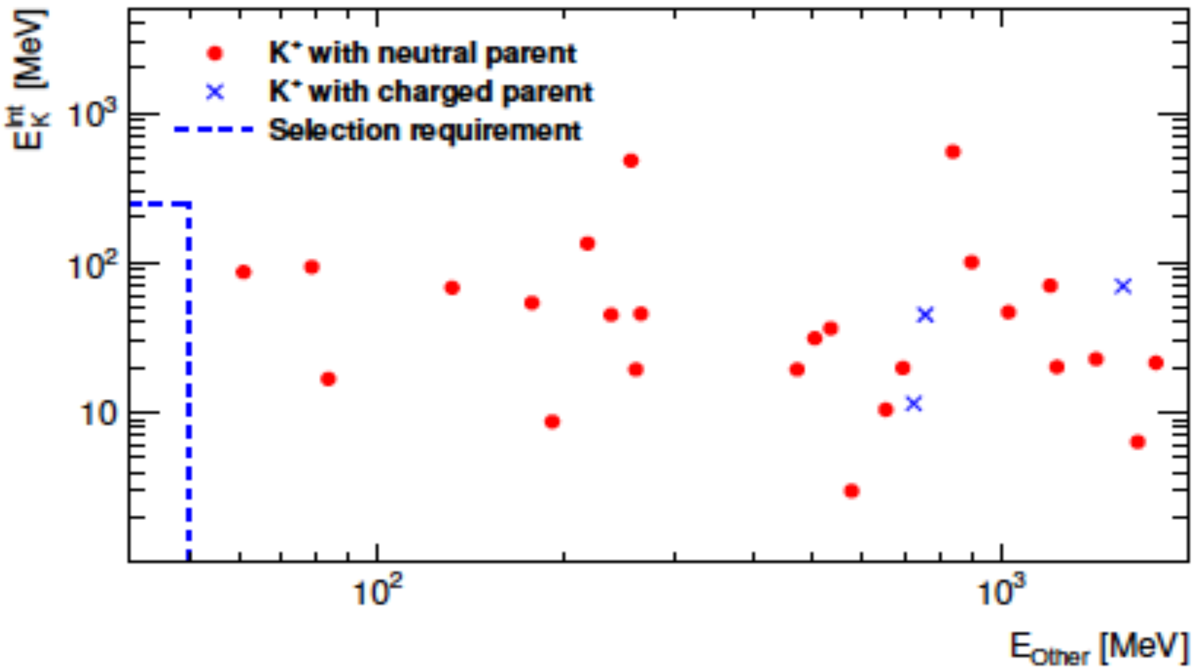
- **Sensitivities for 100 kT active mass LAr detector.**
- **Cylindrical (two-phase), 100 kt.**
- **From Bueno et al. JHEP04 (2007) 041.**
- **Muon background reduced by fiducialisation and small dead time.**
- **Total background is dominated by atmospheric neutrinos.**

LAGUNA-LBNO

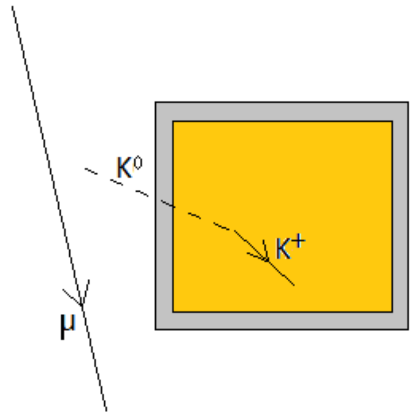
Channel	Cut efficiency (%)	Total background in fiducial volume	τ/B limit (years) 10 years exposure
(p1) $p \to e^+ \pi^0$	45.3	0.2	1×10^{34}
(p2) $p \to \pi^+ \bar{\nu}$	41.9	164	0.1×10^{34}
(p3) $p \to K^+ \bar{\nu}$	96.8	0.4	2×10^{34}
(p4) $p \to \mu^+ \pi^0$	44.8	1.6	0.8×10^{34}
(p5) $p \to \mu^+ K^0$	46.7	< 0.4	1×10^{34}
(p6) $p \to e^+ K^0$	47.0	< 0.4	1×10^{34}
(p7) $p \to e^+ \gamma$	98.0	< 0.4	2×10^{34}
(p8) $p \to \mu^+ \gamma$	98.0	< 0.4	2×10^{34}
(p9) $p \to \mu^- \pi^+ K^+$	97.6	0.2	2×10^{34}
(p10) $p \to e^+ \pi^+ \pi^-$	18.6	5	0.2×10^{34}
(n1) $n \to \pi^0 \bar{\nu}$	45.1	100	0.2×10^{34}
(n2) $n \to e^- K^+$	96.0	< 0.4	2×10^{34}
(n3) $n \to e^+ \pi^-$	44.4	1.6	0.8×10^{34}
(n4) $n \to \mu^- \pi^+$	44.8	5.2	0.5×10^{34}

- **From EoI from LBNO to CERN: LBNO Collaboration: CERN-SPSC-2012-021, SPSC-EOI-007.**
- **Events in 20 kT (two-phase, spherical), 10 years running.**
- **Background is from atmospheric neutrinos.**

Muon-induced background

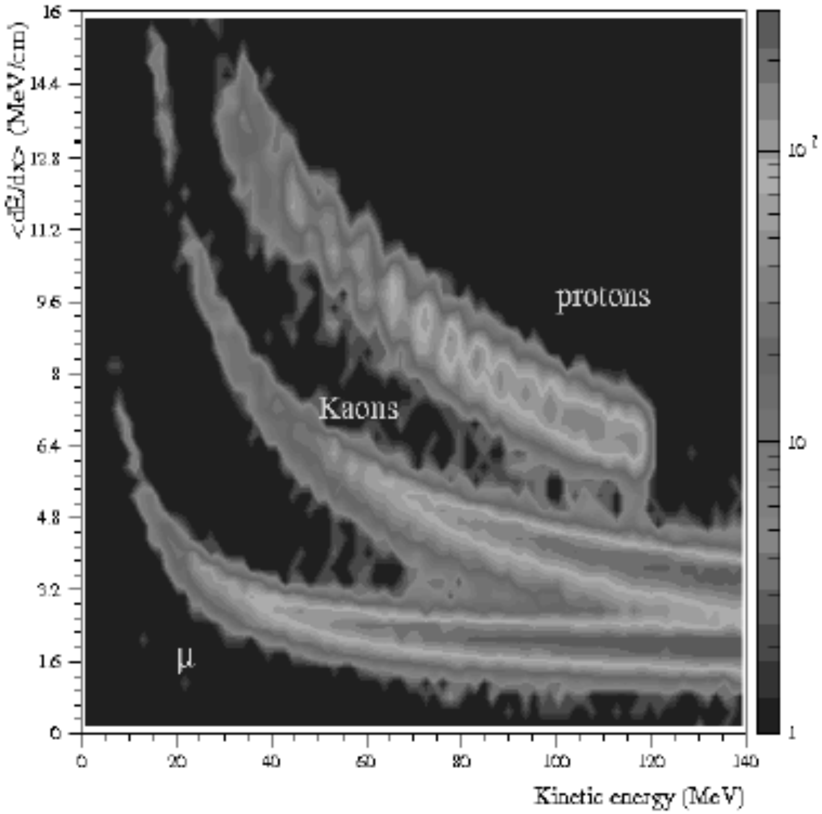


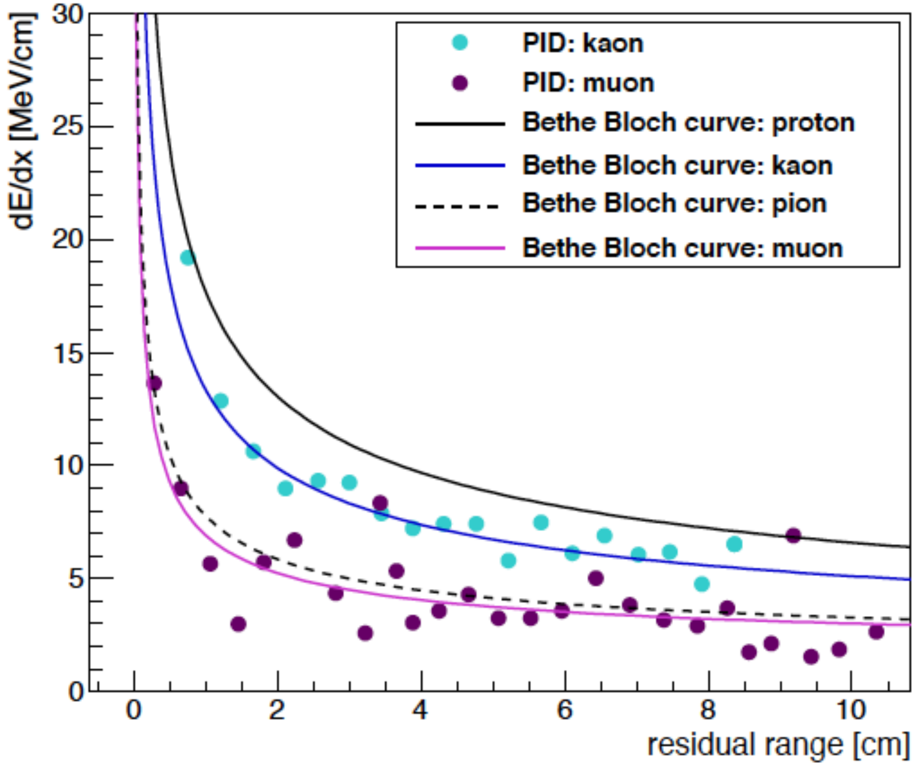
- No muon in the detector (track length < 20 cm). Loss of efficiency < 0.1%.
- Unambiguous identification of a charged kaon.
- No activity near the wall (<10 cm).



- From Klinger and Kudryavtsev. LAGUNA-LBNO talk.
- Kaon energy deposition < 250 MeV. Includes Fermi motion, nuclear cascade and smearing.
- Total energy deposition < 1 GeV.
- Energy deposition from non-kaons < 50 MeV.

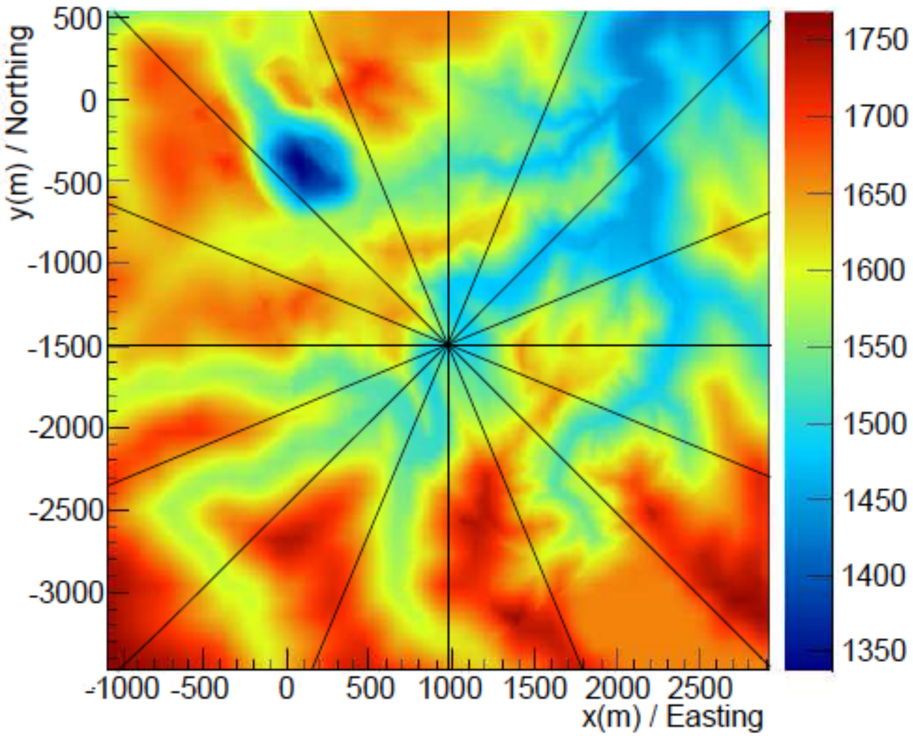
Particle ID

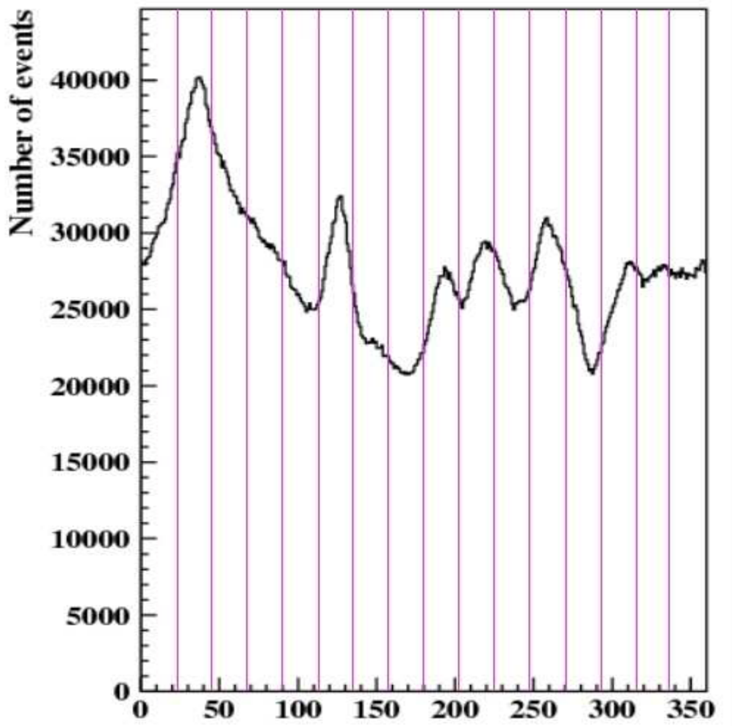




- **Simulated and measured d*E*/d*x* for different particles.**
- **Left: simulations from Bueno et al. JHEP04 (2007) 041.**
- **Right: measurements and simulations from Antonello et al. Adv. High Energy Phys. (2013) 260820.**

LBNE – muon model





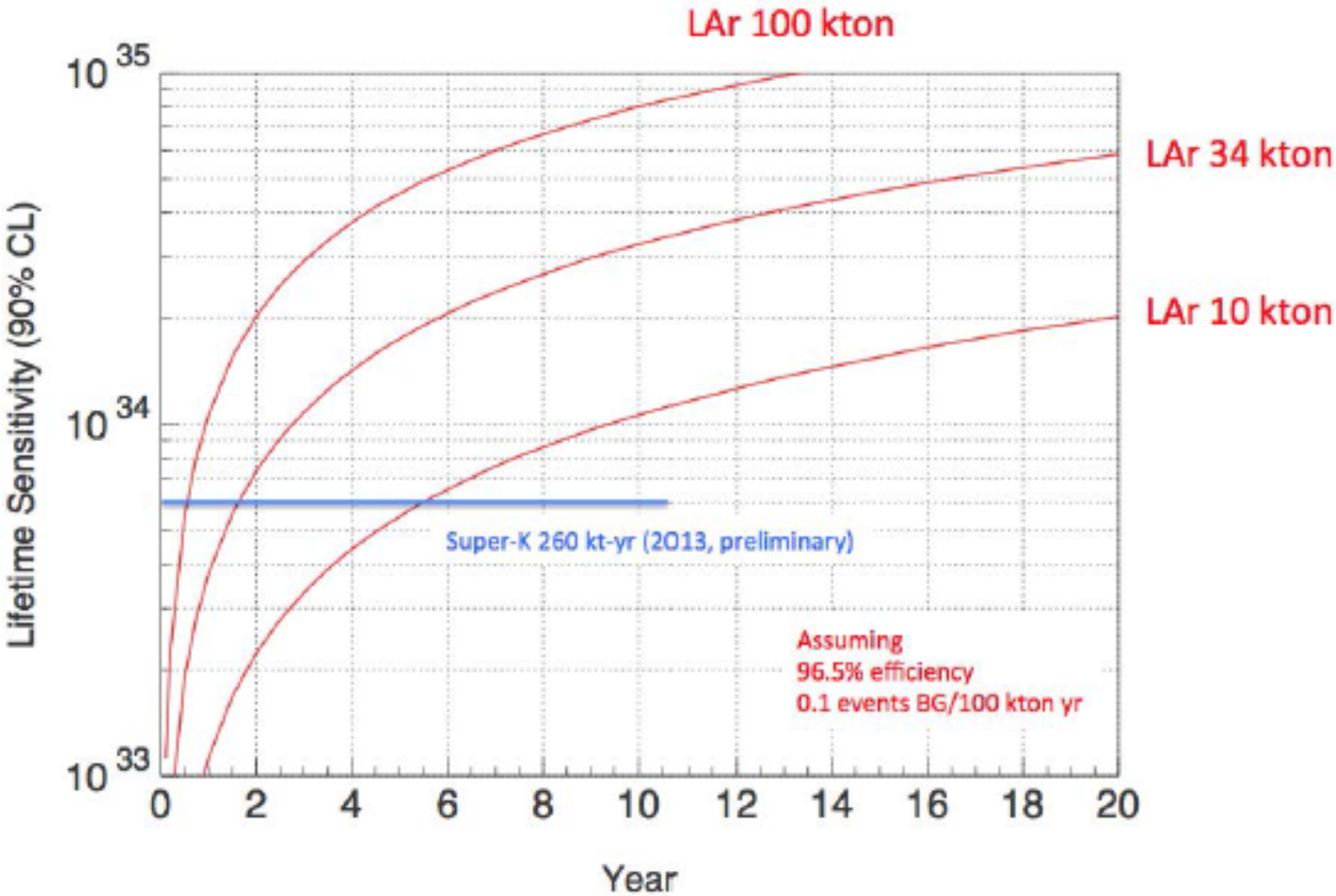
- **Using currently expected location of a cavern for 10 kt, surface profile and rock composition.**
- **Muons transported and then sampled underground.**
- **Kudryavtsev et al. LBNE-doc-9673.**

LBNE – atmospheric neutrinos

- **The main background may come from NC interactions resulting in a K^+ and no other charged particles, such as:** $\nu p \rightarrow \nu K^+ \Lambda^0 (\Sigma^0)$
- **There are also processes with a K^0 production followed by the charge exchange reaction and a K^+ as a result.**
- **Table taken from A. Blake. LBNE-doc-8836. 34.8 Mt×years.**

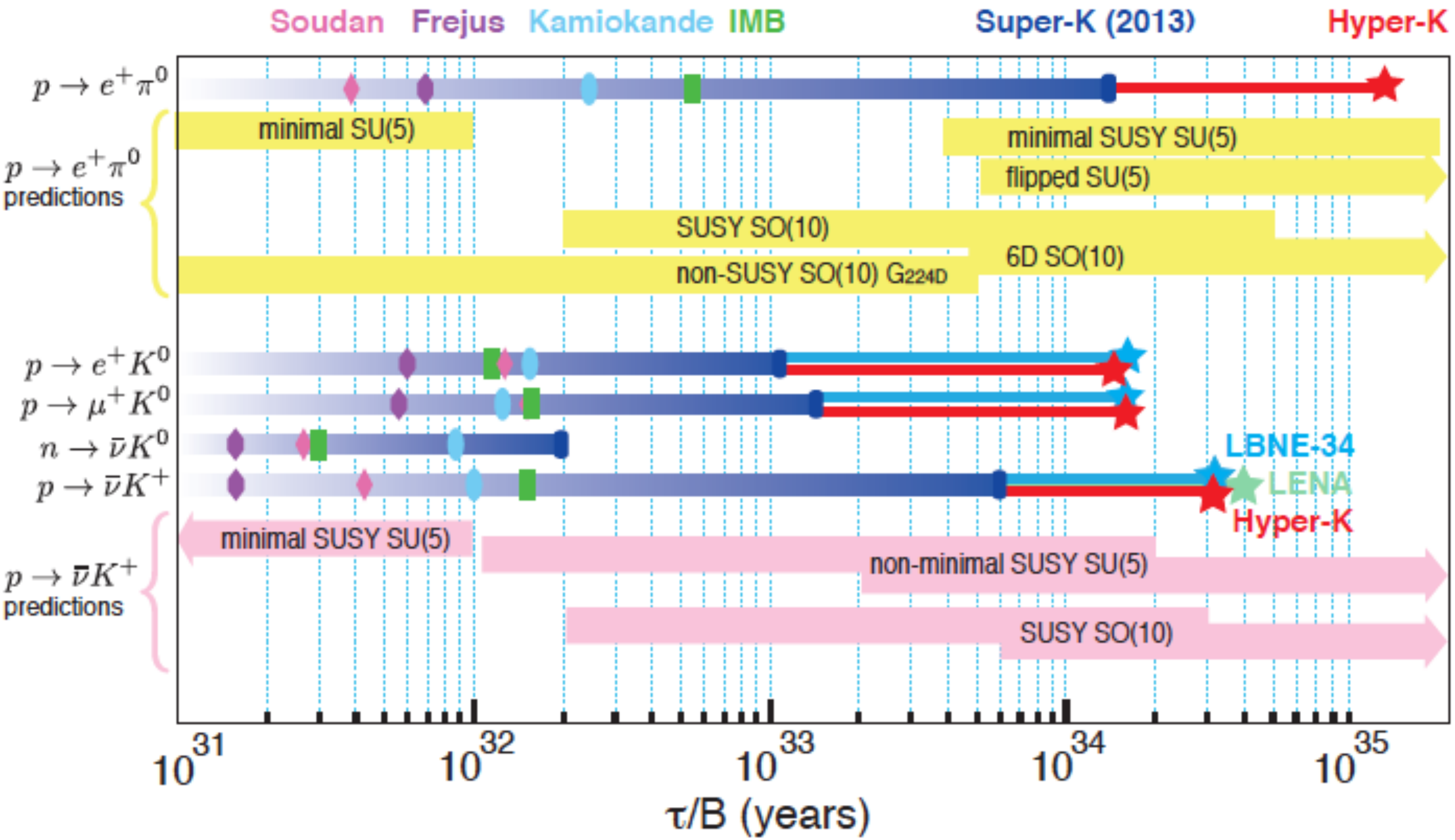
Selection	Events	Events/Mt-yr
All interactions	10,000,000	287,944
K^+ emitted by interaction	73,799	2,125
K^+ in final state ('kIsStableFinalState')	64,560	1,859
One K^+ in final state	63,576	1,831
No other charged particles	1,865	54
No photons or neutral pions	1,205	35
$p_K < 800$ MeV [see next slide]	701	20
Reject neutral hyperons (Λ^0, Σ^0)	1	<1
Reject neutral kaons (K^0)	0	0

LBNE - sensitivities



- **Sensitivity of about a few $\times 10^{34}$ years are within reach for this specific channel.**
- **From LBNE Collaboration. arXiv: 1307.7335 [hep-ex]**

LBNE - sensitivities



Outstanding questions

- Good start in the two collaborations showing the potential of LAr and complementarity (for some decay channels, superiority) to water Cherenkov detectors.
- However, most work is still preliminary.
- All simulations and simulated data analysis are done for ‘truth’ with parameterised detector response, no specific detector simulations, signal processing, reconstruction.
- So far within simplified detector geometry (only a fraction of neutrino events have been passed through LArSoft, E. Church, LBNE-doc-8729).
- Parameterised energy, position and angular resolutions.
- No TPC, no charge collection.
- No light collection to determine initial time.
- Full particle ID.
- Simplified nuclear effects.
- Most simulations for one specific decay mode.

Goals, priorities, issues

- **Not in any specific order.**
- **Experiment:**
  - **Define conceptual detector design, at least key features.**
  - **Define detector location and orientation (muon model).**
  - **Define software framework (art, LArSoft).**
  - **Improve event processing and reconstruction.**
  - **Check particle ID and misidentification.**
  - **Estimate efficiency / signal loss.**
- **Physics models:**
  - **Neutrino interactions and proton decay (GENIE).**
  - **Include nuclear effects.**
  - **…**

Possible first steps

- **Form a working group/subgroup. Identify people who will work.**
- **Complete atmospheric neutrino simulation/analysis for a mode with K^+.**
- **Complete muon event analysis for a single phase detector.**
- **Extend simulations to other decay modes (signal and background).**
- **Produce a complete picture of background based on truth and parameterised detector response.**
- **Add existing specific detector features (simulation within a specific software, such as LArSoft): cells/TPC, dead argon, details of environment.**
- **Use full event processing, reconstruction.**
- **…**

Help from R&D

- 35t prototype, LAr1-ND, LAriat, CERN neutrino platform…
- Particle identification, misidentification.
- Energy, spatial, angular resolution.
- Cross-sections of neutrino interactions with a production of kaons.
- Charge-exchange processes.
- Design optimisation.
- …