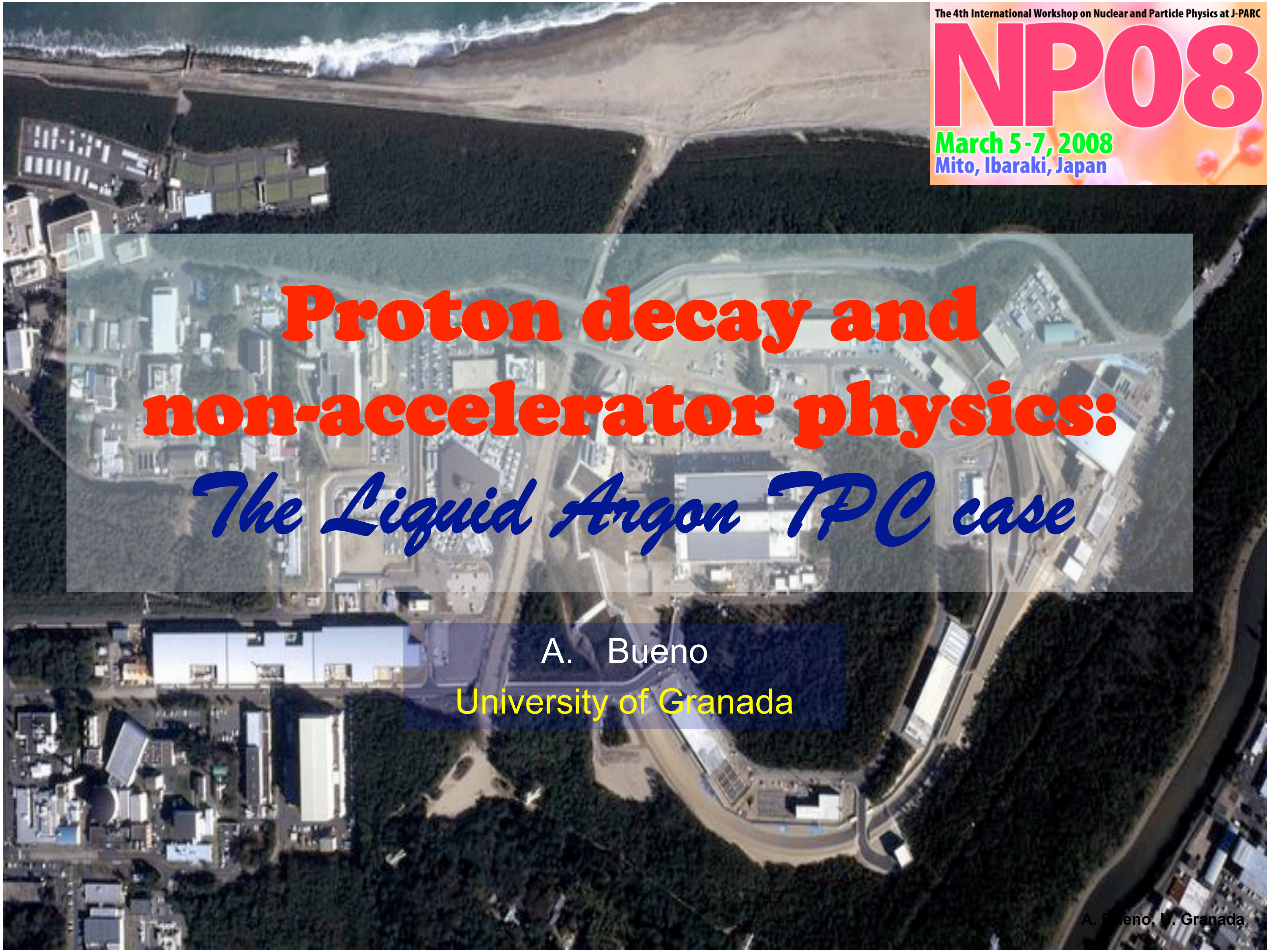


The 4th International Workshop on Nuclear and Particle Physics at J-PARC
NP08
March 5-7, 2008
Mito, Ibaraki, Japan

Proton decay and non-accelerator physics:

The Liquid Argon TPC case

A. Bueno
University of Granada

Motivations for next-generation large underground observatories

- Discover proton decay or reach sensitivities in the range of 10^{34}-10^{35} years for the proton lifetime.
- Study with higher statistics neutrinos from supernovae explosions
  - Better understanding of the evolution mechanism that leads to the collapse of a star
  - Observation of extragalactic supernovae
  - Identification of the diffuse supernovae neutrino background
- Resolve subdominant oscillation phenomena with more statistics from atmospheric neutrinos
- Better understanding of the Solar interior
- Study Earth´s interior with geo-neutrinos
- The unexpected?

See JCAP11(2007)011

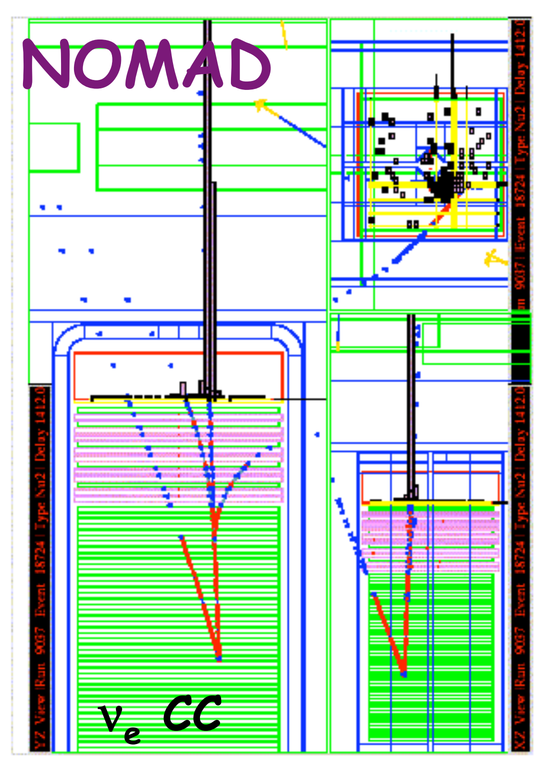
A new generation of bubble chambers

Gargamelle Bubble Chamber

3 ton sensitive mass

Heavy Freon

Bubble ∅ (mm)	3
Density (g/cm^3)	1.5
X_0 (cm)	11.0
λ_T (cm)	49.5
dE/dx (MeV/cm)	2.3



NOMAD

2.7 tons drift chambers target

Density (g/cm^3) 0.1

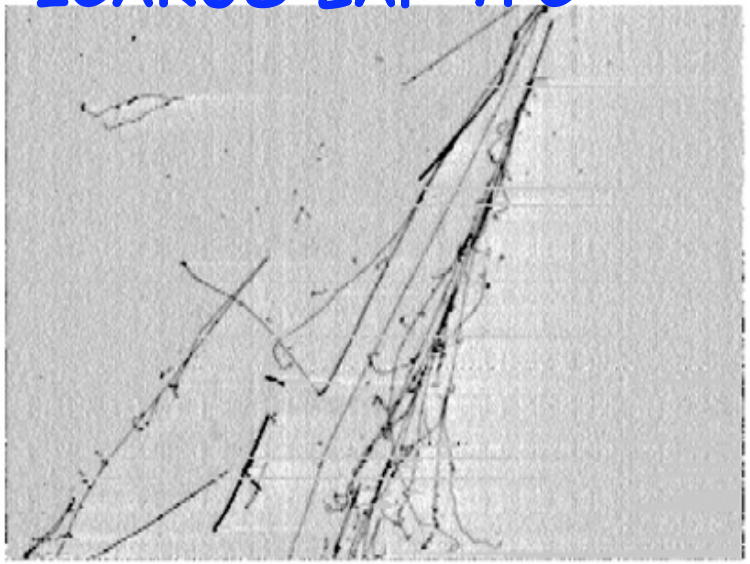
2% X_0/chamber

0.4 T magnetic field

TRD detector

Lead glass calorimeter

ICARUS LAr TPC



Resolution (mm^3)	2×2×0.2
Density (g/cm^3)	1.4
X_0 (cm)	14.0
λ_T (cm)	54.8
dE/dx (MeV/cm)	2.1

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LAr TPC: A tracking calorimeter

Fully homogenous, full sampling calorimeter

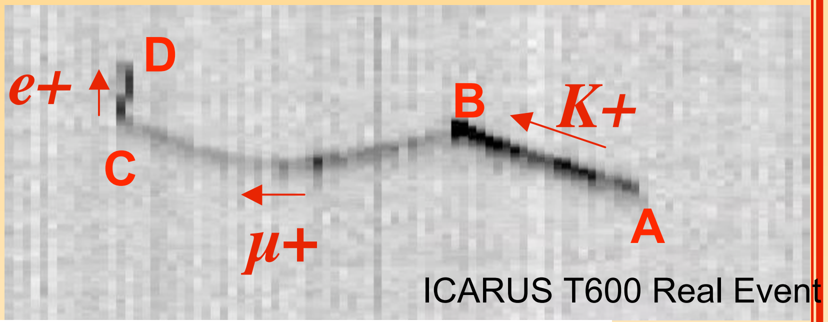
RESOLUTIONS FOR OUR SIMULATION FRAMEWORK

Electromagn. showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)} \oplus 1.5\%$ → From MC

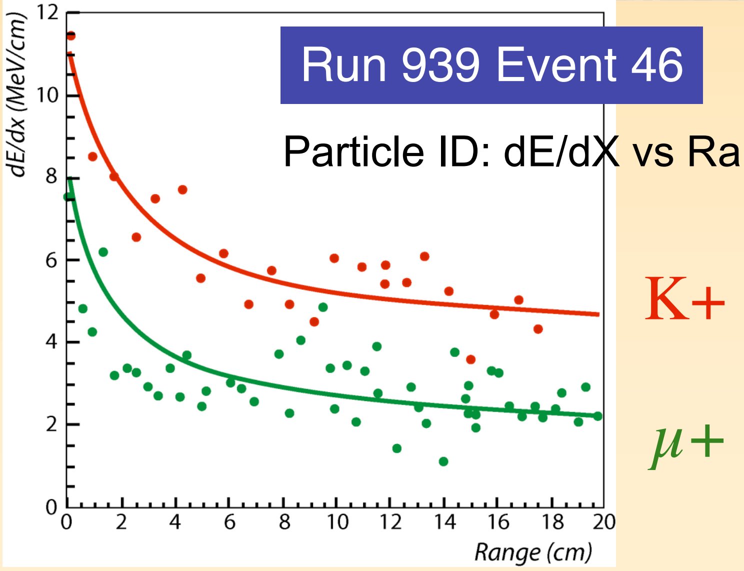
Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)} \oplus 10\%$ → From MC

Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} \oplus 2\%$

$$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$$

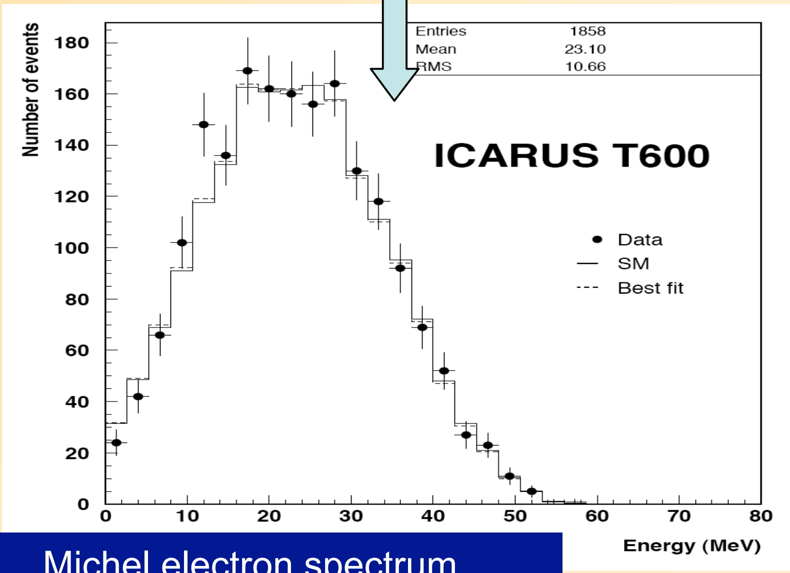


ICARUS T600 Real Event



Run 939 Event 46

Particle ID: dE/dX vs Range



Michel electron spectrum

(Eur. Phys. J. C33 (2004) 233)

High granularity: readout pitch ≈3 mm, local energy deposition measurement, particle type identification

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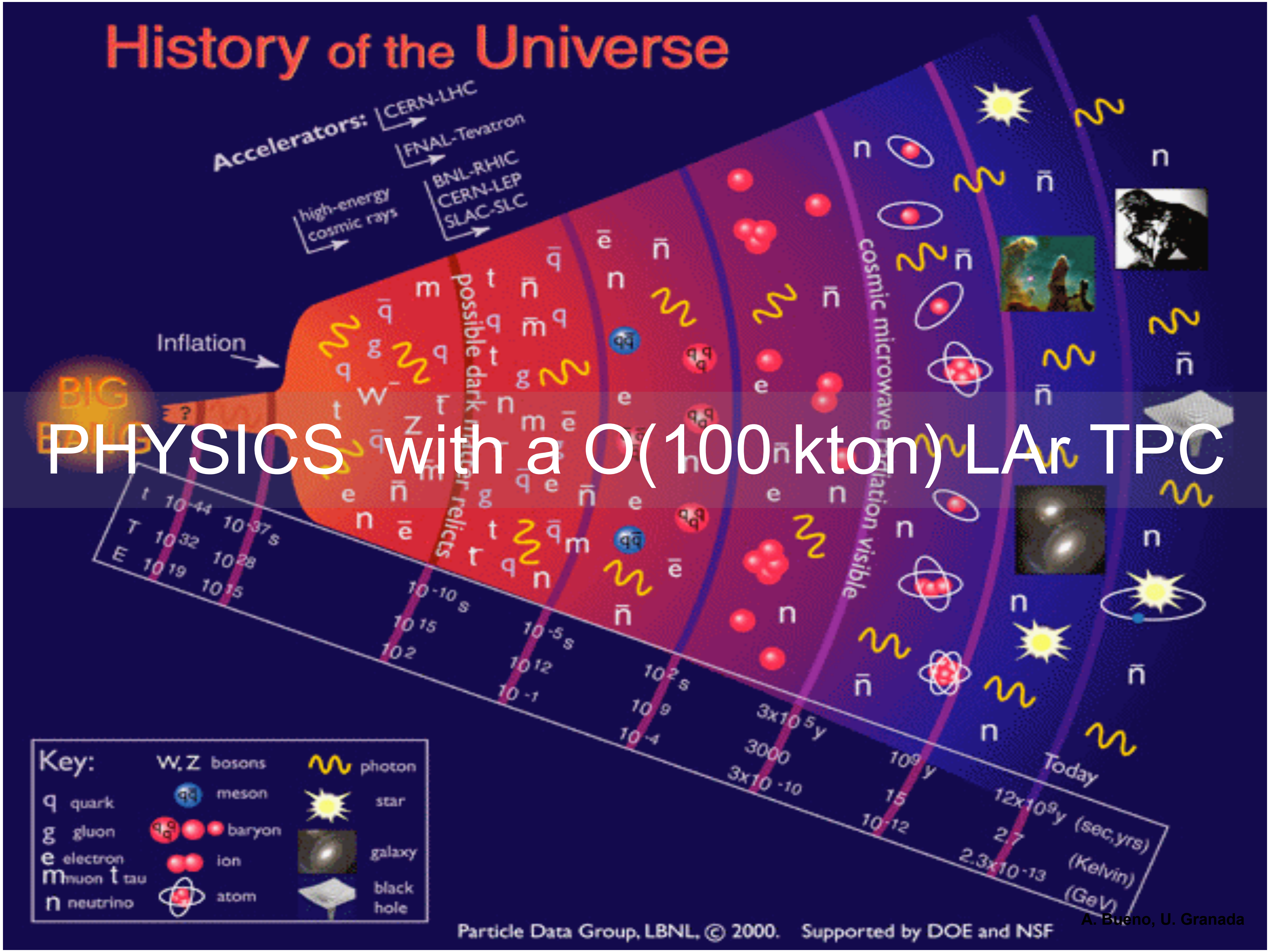
PHYSICS with a O(100 kton) LAr TPC



Particle Data Group, LBNL, © 2000.   Supported by DOE and NSF

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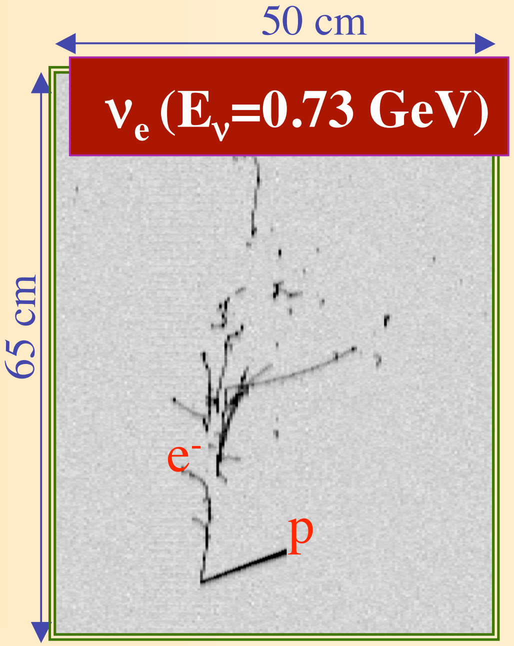
O(100 Kton) LAr TPC as ν a detector

- ICARUS Coll., "The ICARUS Experiment: a second-generation Proton decay experiment and Neutrino Observatory at Gran Sasso Observatory - Initial Physics Program", LNGS-P28/2001, March, 2001
- F. Sergiampietri, "On the possibility to extrapolate liquid argon technology to a super massive detector for a future neutrino factory", NUFACT01, Tsukuba, 2001
- A. Rubbia, "Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment?", hep-ph/0402110, Workshop on Neutrinos in Venice, 2003
- L. Bartoszek et al.,"FLARE, Fermilab liquid argon experiments: Letter of intent", hep-ex/0408121, Aug. 2004
- A. Meregaglia and A. Rubbia, "Contribution of a liquid argon TPC to T2K neutrino experiment", Acta Phys. Polon. B37 (2006) 2387, 20th Max Born Symposium, Wroclaw, Poland, Dec 2005
- D. Finley et al."A large liquid argon time projection chamber for long baseline, off-axis neutrino oscillation physics with the NuMI beam", FERMILAB-FN-0776-E, Sept. 2005
- A.Meregaglia, A. Rubbia, "Neutrino oscillation physics at an upgraded CNGS with large next generation liquid argon TPC detectors", JHEP 0611:032, 2006
- B. Baibussinov et al., "A new, very massive modular Liquid Argon Imaging Chamber to detect low energy off-axis neutrinos from the CNGS beam. (Project MODULAr)", arXiv:0704.1422 [hep-ph]
- V. Barger et al., "Report of the US long baseline neutrino experiment study", arXiv:0705.4396, May 2007
- A. Meregaglia, A. Rubbia, "Neutrino Oscillations With A Next Generation LAr TPC Detector in Kamioka or Korea Along The J-PARC Neutrino Beam ", arXiv:0801.4035

Neutrino detection capabilities

- Provides high efficiency for ν_e charged current interaction identification
- **Adequate rejection against ν_μ NC and CC backgrounds**
  - e/π^0 separation
    - ✓ Fine longitudinal segmentation (few % X0)
    - ✓ Fine transverse segmentation, finer than the typical spatial separation of the 2 photons from π^0 decay
  - e/μ,h separation
- Embedded in a magnetic field provides the possibility to measure both wrong sign muons and wrong sign electrons samples in a neutrino factory beam



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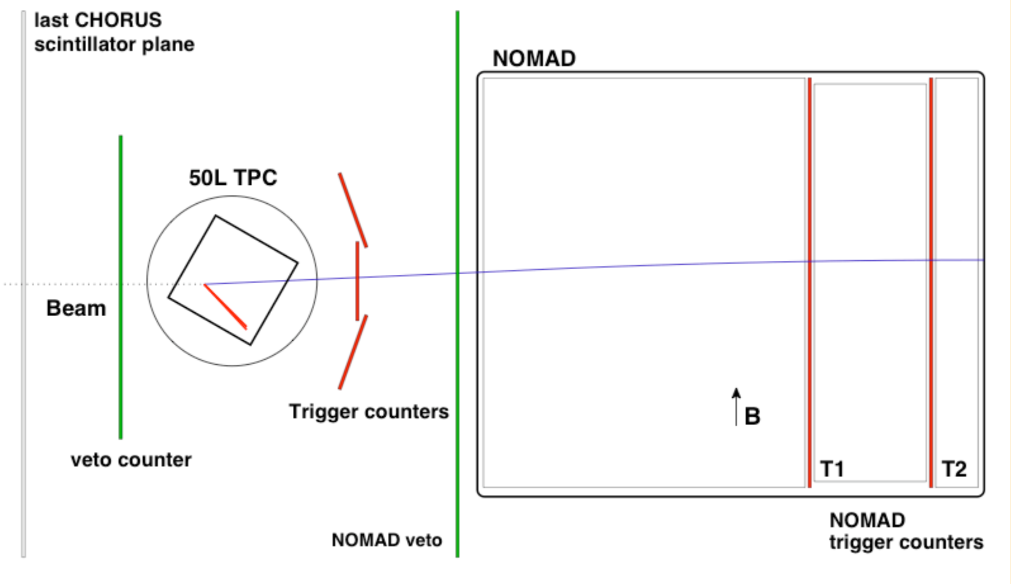
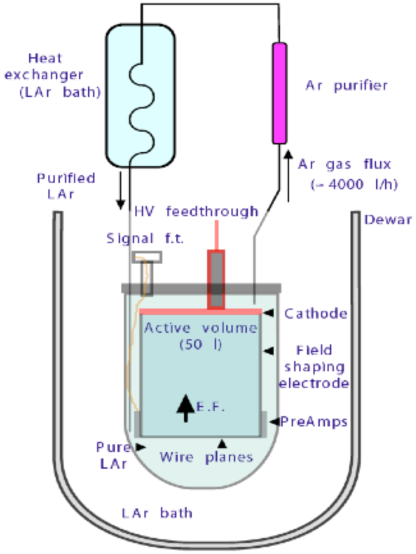
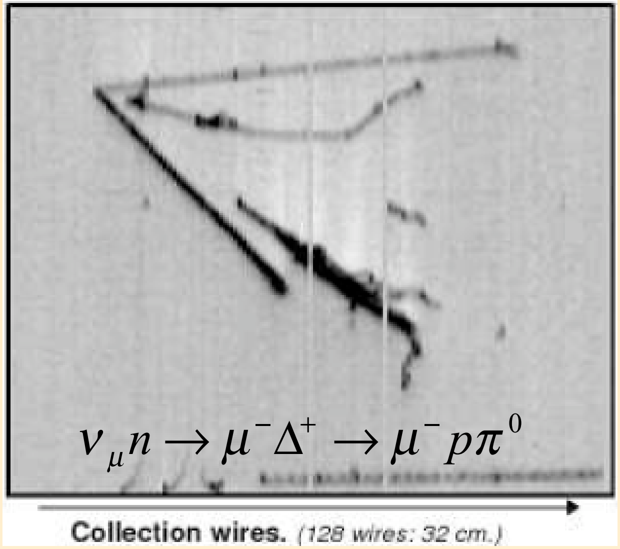
LAr TPC performance for QE events




50 liter chamber

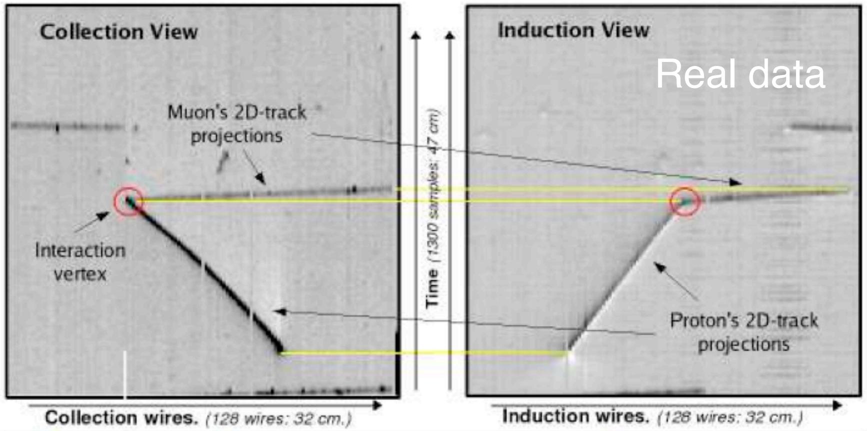


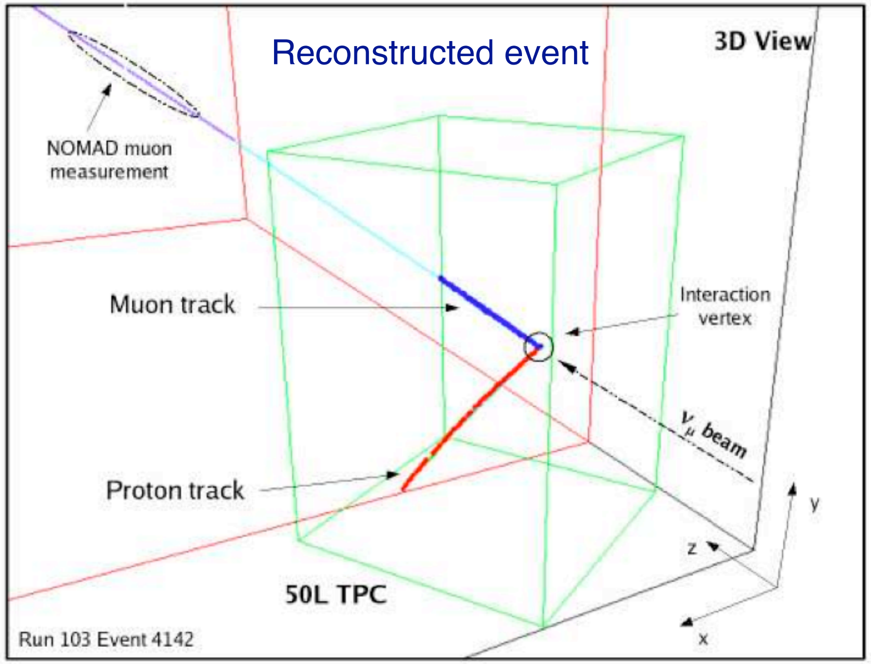

$$\nu_\mu n \rightarrow \mu^- \Delta^+ \rightarrow \mu^- p \pi^0$$

(Phys. Rev. D 74 (2006) 112001)

Data collected in 1997 at CERN WANF neutrino beam line

Search for QE events with 50 liter chamber

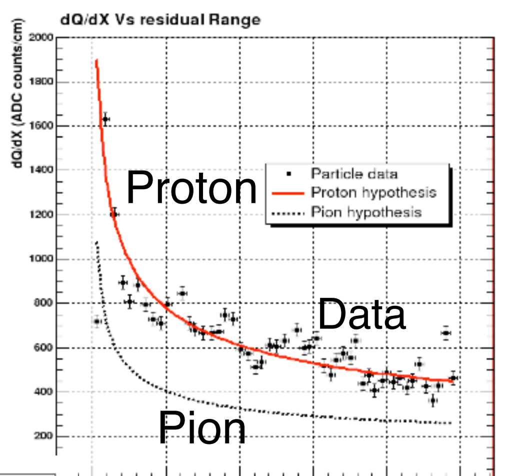


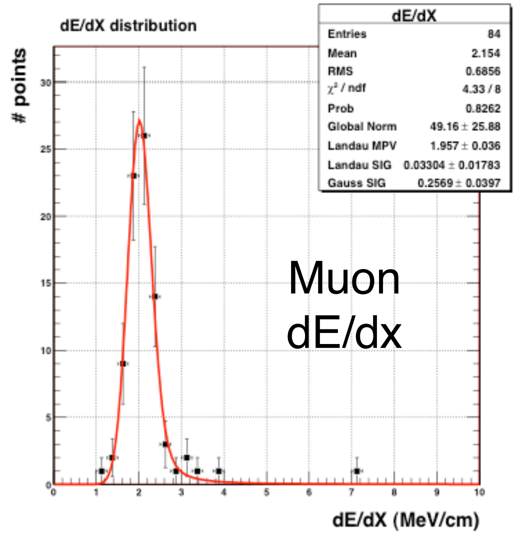


(Phys. Rev. D 74 (2006) 112001)

86 "golden" events

- one muon matching NOMAD reconstruction
- one fully contained proton with kinetic energy ≥ 40 MeV





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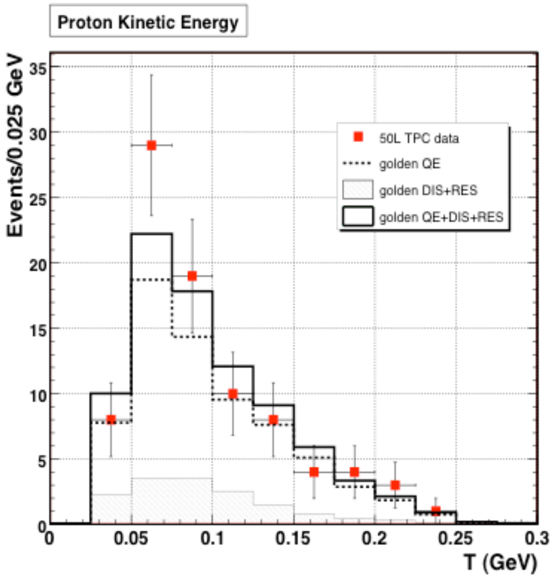
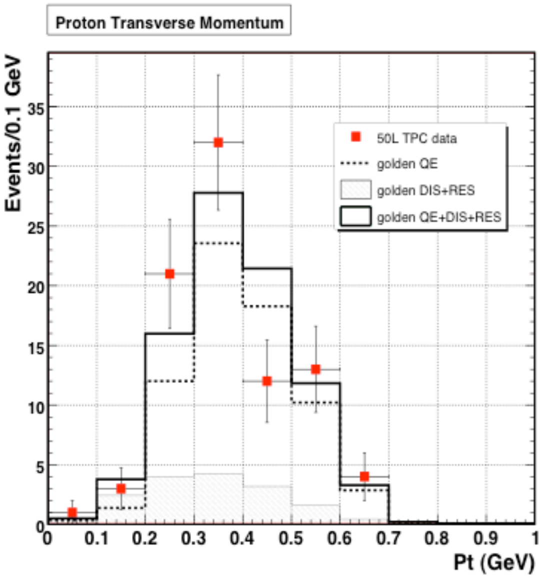
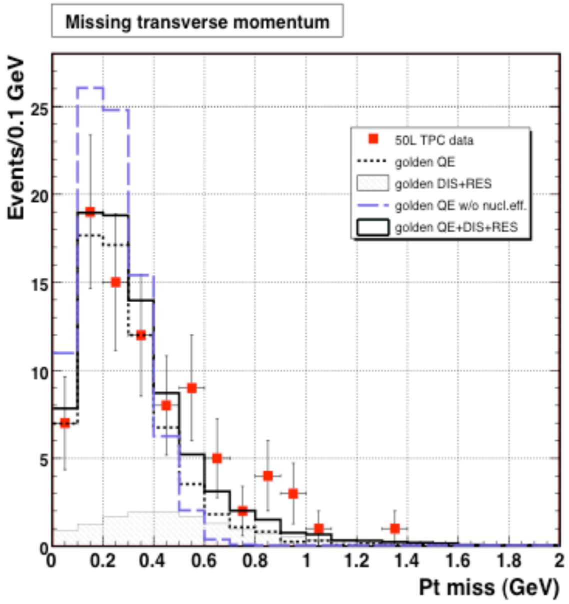
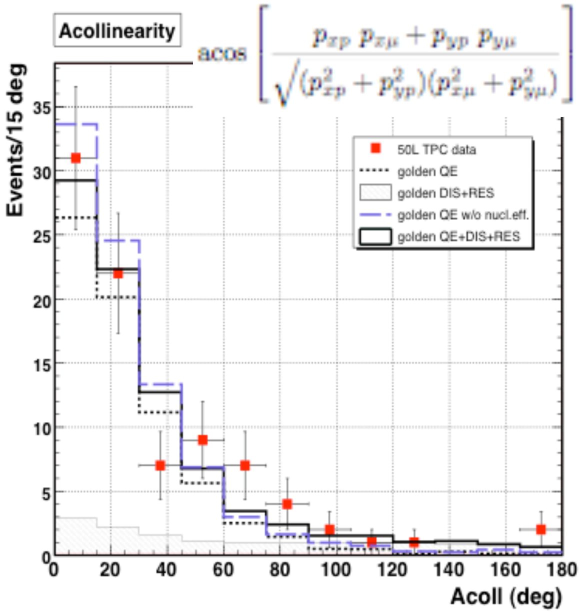
Kinematics reconstruction for golden QE



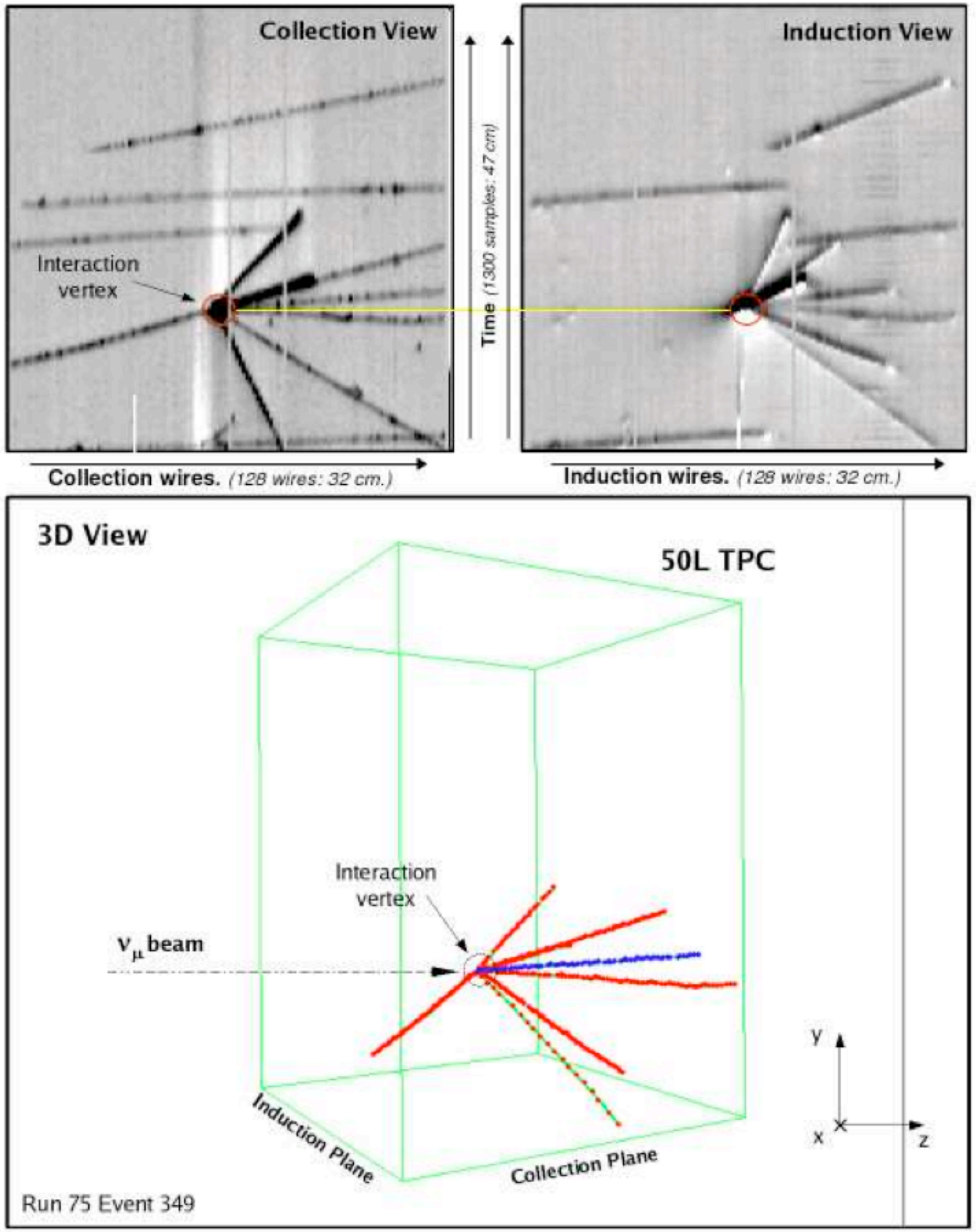


Precise reconstruction of event kinematics





3D reconstruction of multi-prong ν_μ CC



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Expected event rates

Physics Topic	**100 Kton LAr detector**
Proton decay **(# of protons)**	2.7×10^{34}
SuperNova ν **(at 10 kpc)**	5.6×10^{4} (includes CC, NC and ES events)
Solar ν **(E>5 MeV)**	4.5×10^{4}/year
Atmospheric ν	1.1×10^{4}/year (100 ν_τ CC/year from oscillations)

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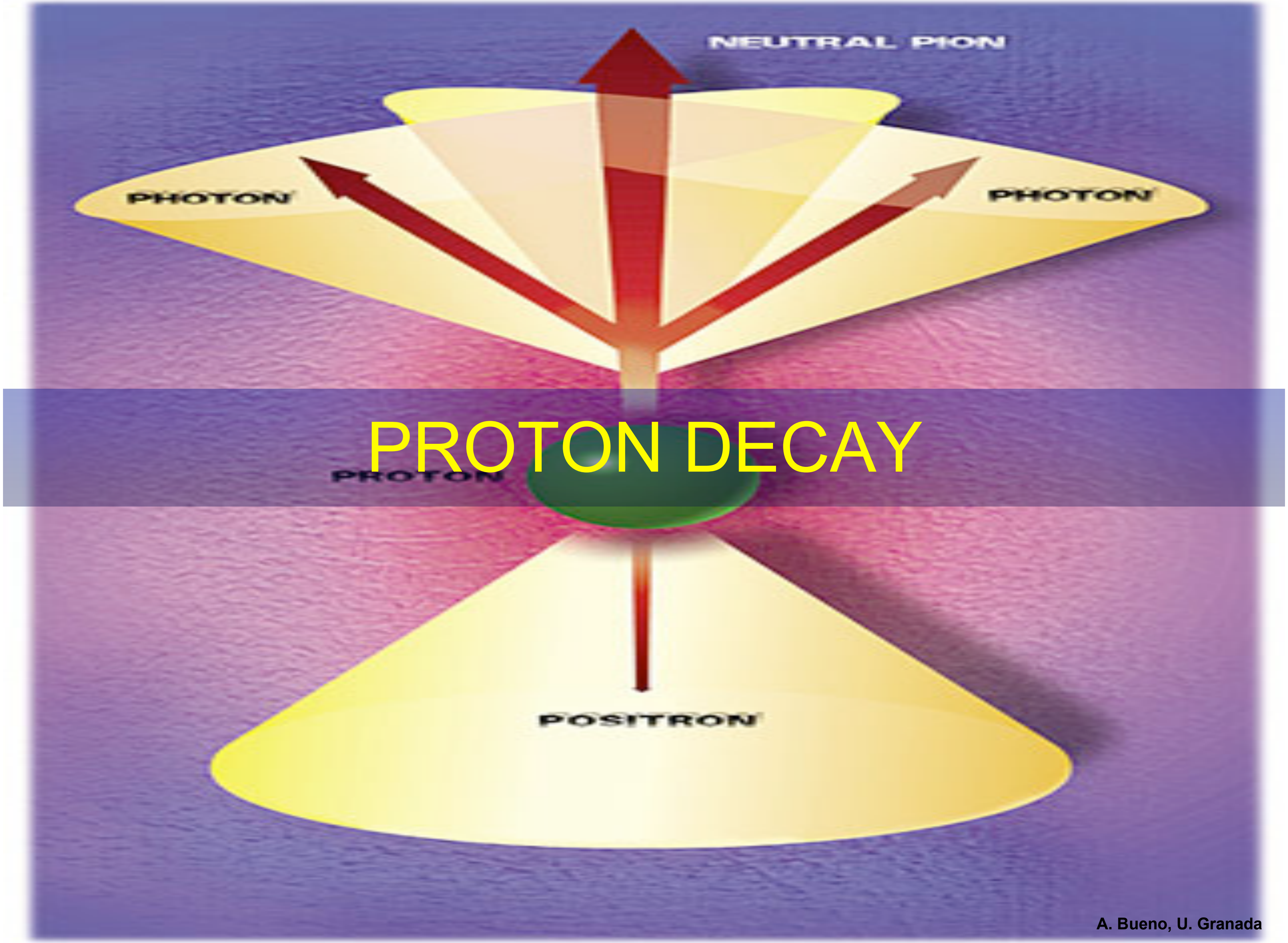

PROTON DECAY

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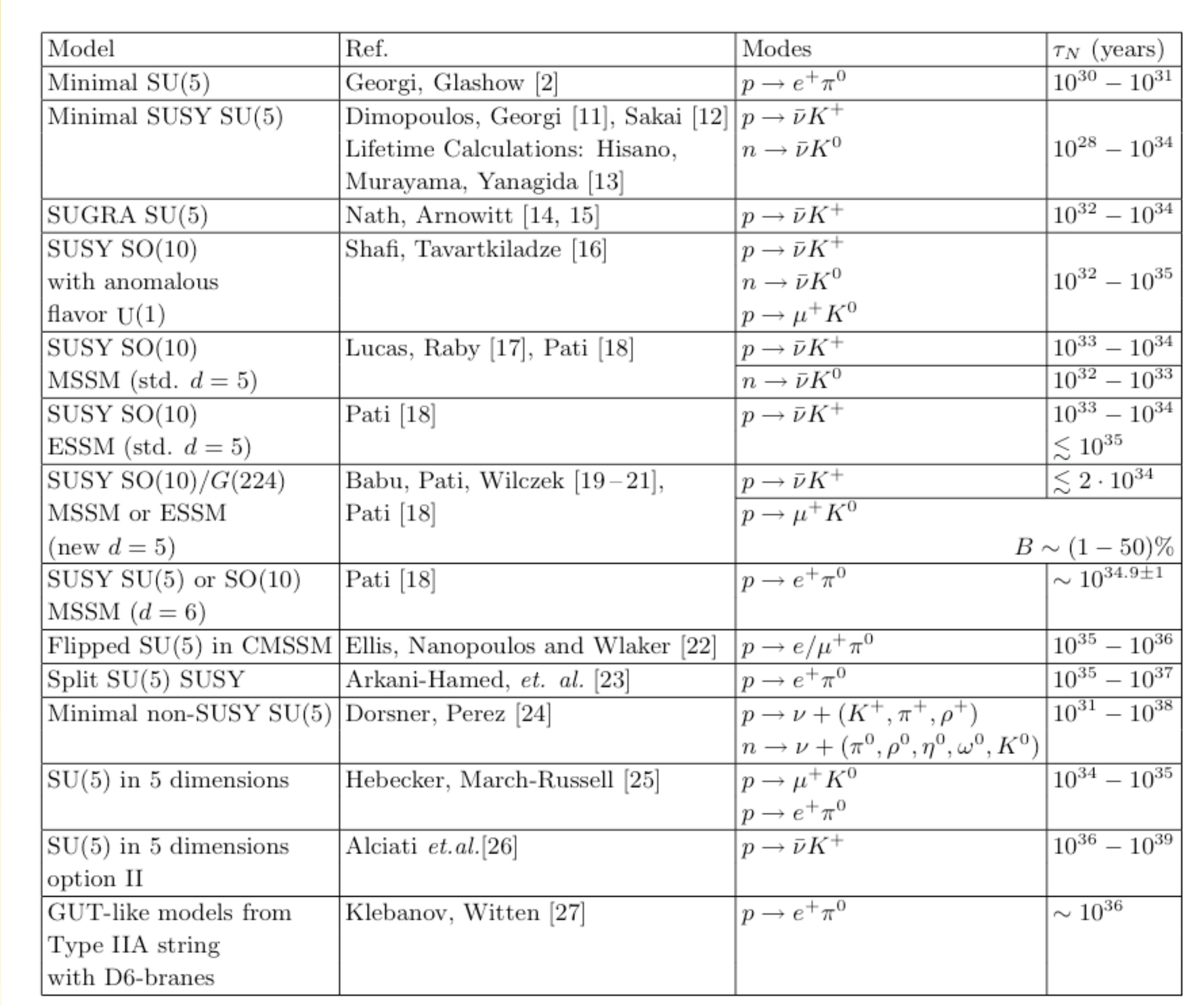
Theory tells us…



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]	$p \to e^+\pi^0$	$\sim 10^{36}$

taken from JHEP04(2007)041

…lifetimes could be between 10^{33}-10^{37}

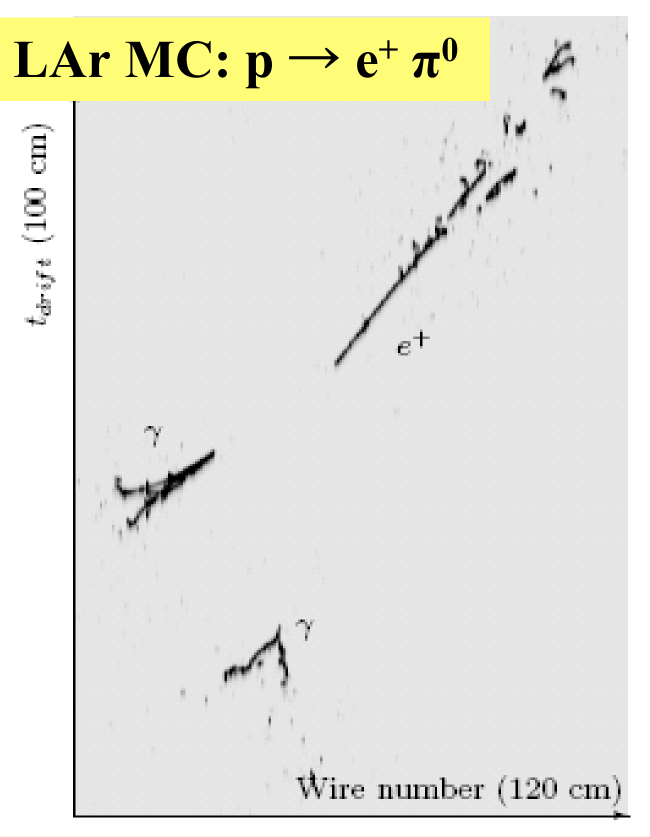
LAr TPC as a proton decay detector

K.L. Giboni "A two kiloton liquid Argon detector for solar neutrinos and proton decay", NIM 225 (1984) 579

ICARUS Coll. "ICARUS II. A second generation proton decay experiment and neutrino observatory at the Gran Sasso Laboratory", Sept. 1993

A. Bueno, M. Campanelli, A. Ferrari, A. Rubbia "Nucleon decay studies in a large liquid Argon detector", AIP Conf. proc. 533 (2000) 12

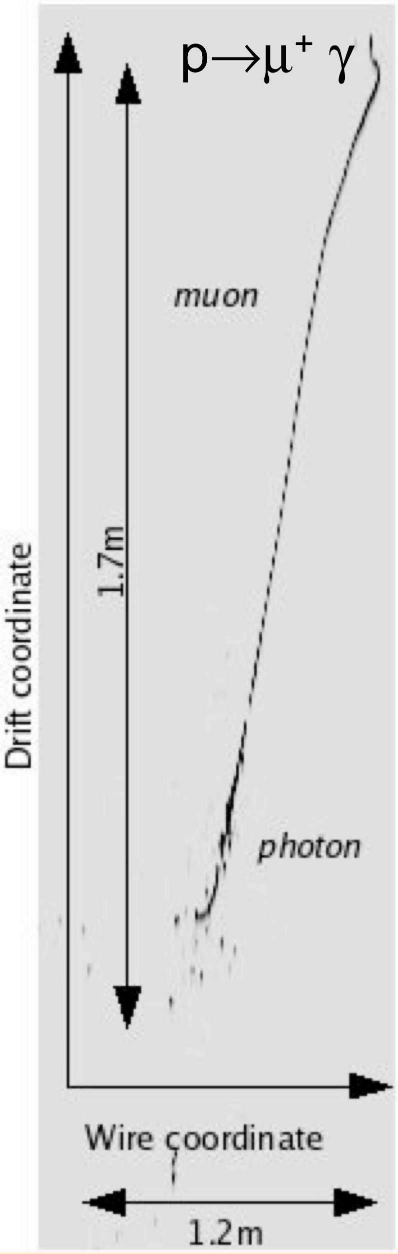
A. Bueno et al. "Nucleon decay searches with large liquid Argon TPC detectors at shallow depths: atmospheric neutrinos and cosmogenic background", JHEP04 (2007) 041

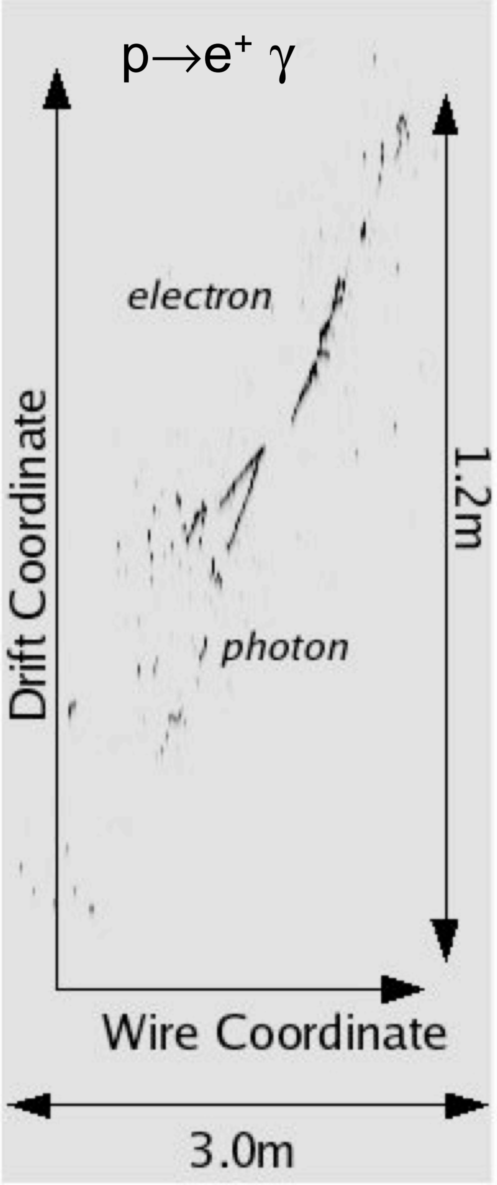


LAr MC: $p \rightarrow e^+ \pi^0$

What LAr can offer in nucleon decay searches

- Excellent tracking and calorimetric reconstruction
  - Good constrain of final state kinematics
  - Efficient suppression of atmospheric neutrino background
- Superb particle identification capabilities
  - Versatile detector
  - Allows to study a wealthy variety of decay modes to constrain the ultimate nature of the disintegration mechanism
- Scalable technology to reach large masses (O[100 ktons])
- Discovery potential at one event level





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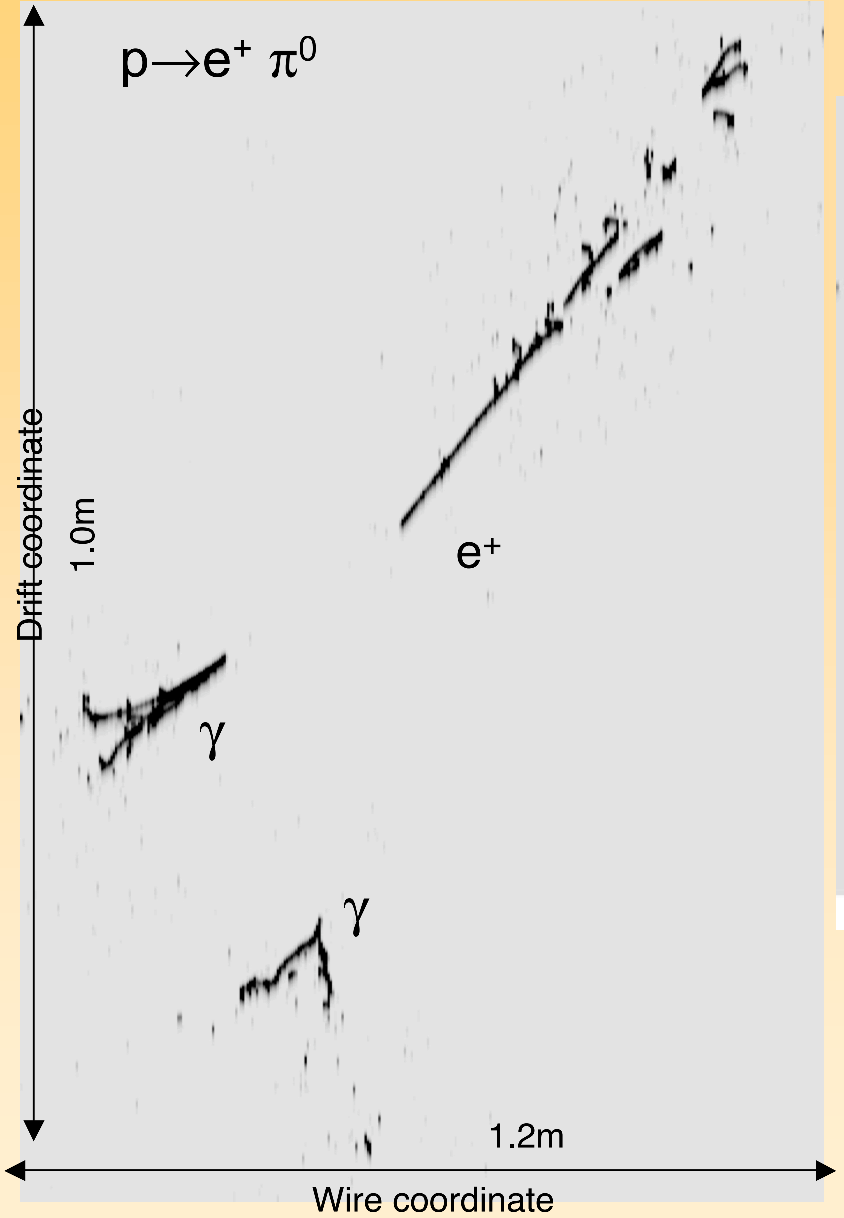
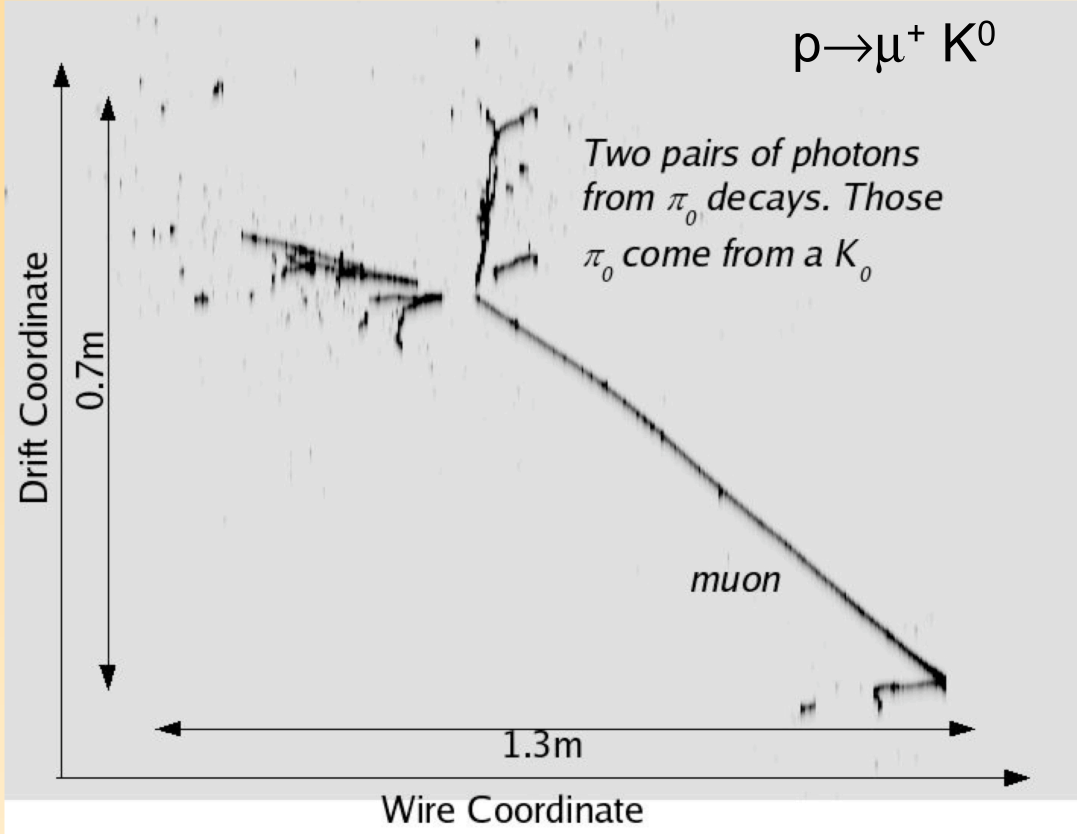
Simulated events





Two pairs of photons from π_0 decays. Those π_0 come from a K_0

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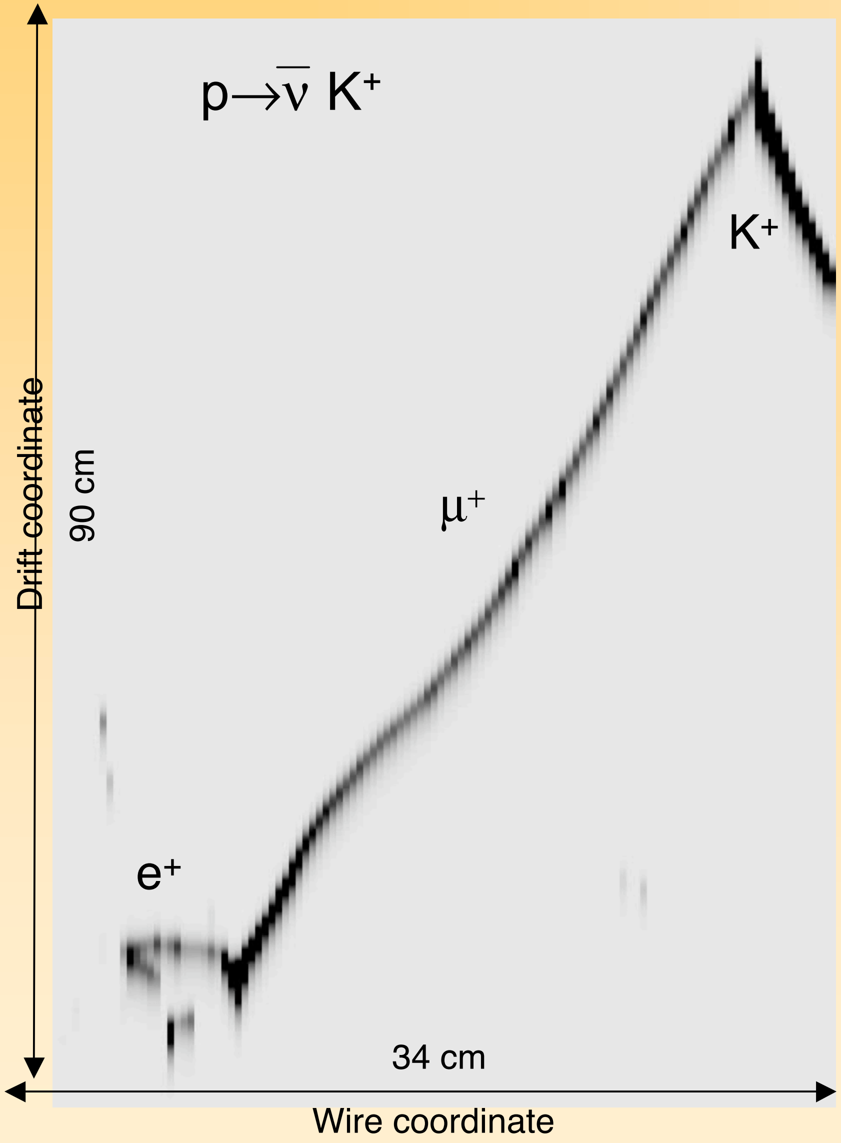
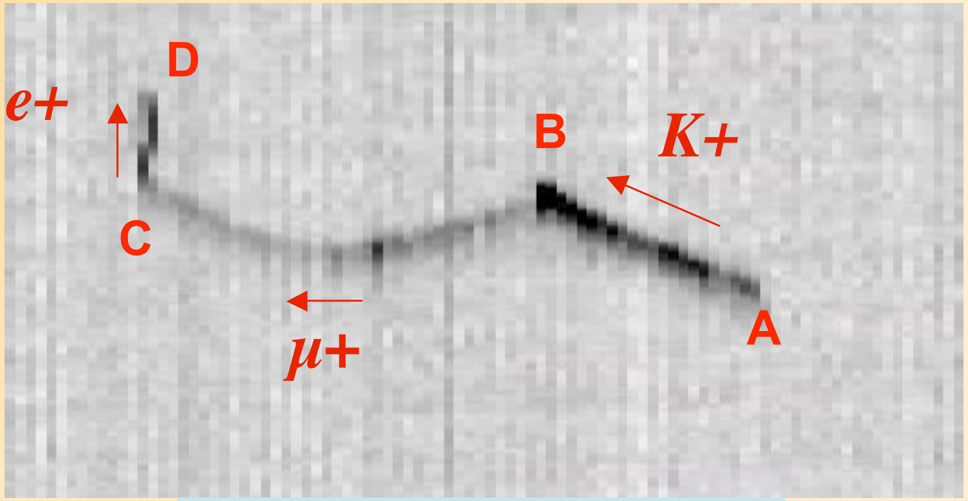
Super-symmetric decay mode



$$K^+[AB] \to \mu^+[BC] \to e^+[CD]$$



Real event recorded by ICARUS T600 detector while surface tests were carried out in 2001

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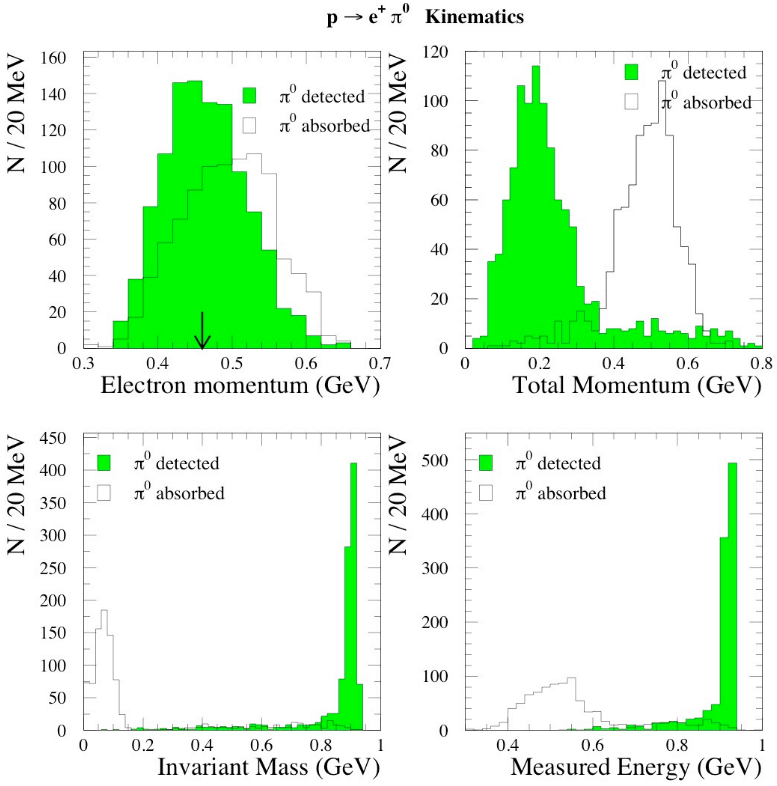
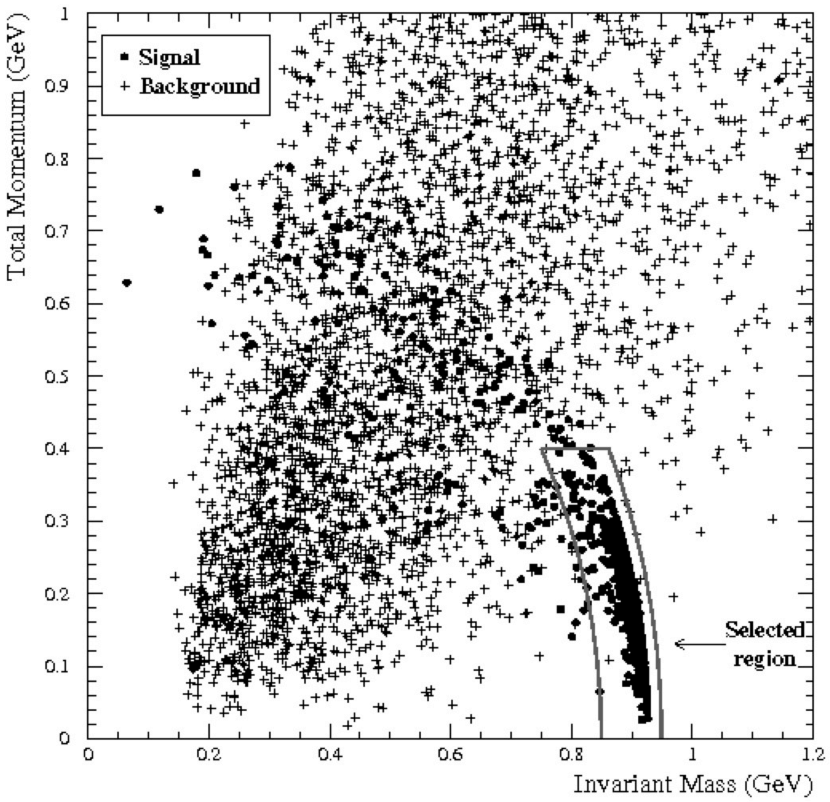
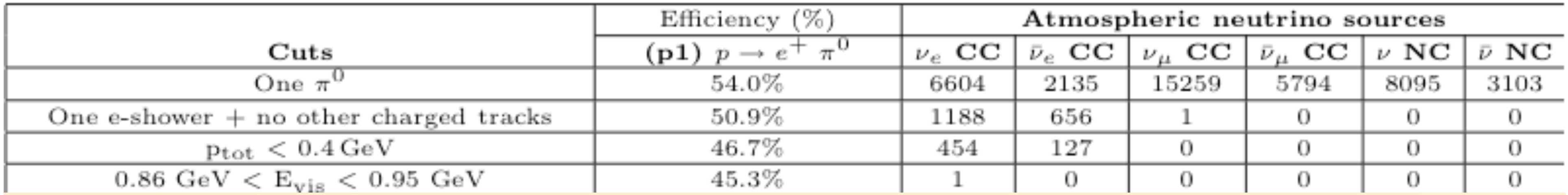
Event kinematics: $p \rightarrow e^+ \pi^0$







Cuts	Efficiency (%)	Atmospheric neutrino sources					
	(p1) $p \rightarrow e^+ \pi^0$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One π^0	54.0%	6604	2135	15259	5794	8095	3103
One e-shower + no other charged tracks	50.9%	1188	656	1	0	0	0
$P_{tot} < 0.4$ GeV	46.7%	454	127	0	0	0	0
0.86 GeV $< E_{vis} < 0.95$ GeV	45.3%	1	0	0	0	0	0

- About 50% of the π^0 are absorbed
- Overall selection efficiency amounts to 45%
- One ν_e CC atm background expected (normalized to 1 Mton × year)

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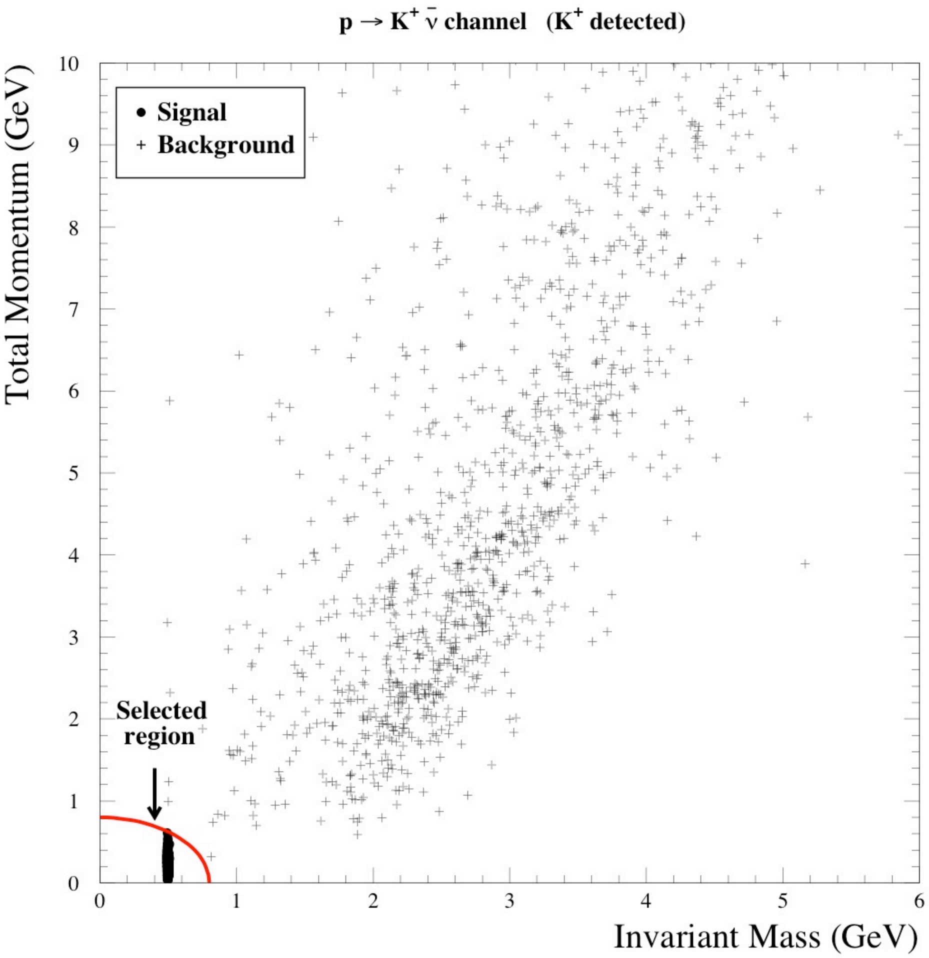
Event kinematics: $p\rightarrow K^+$ anti-ν

- Cuts:
    - One identified kaon
    - No additional charged tracks or π^0
    - $E_{visible} < 0.8$ GeV
- Overall selection efficiency amounts to 97%
- One ν NC atmospheric background expected (normalized to 1 Mton × year)



Cuts	(p3) $p \rightarrow K^+ \bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no π^0	96.8%	0	0	0	0	57	9
$E_{vis} < 0.8$ GeV	96.8%	0	0	0	0	1	0

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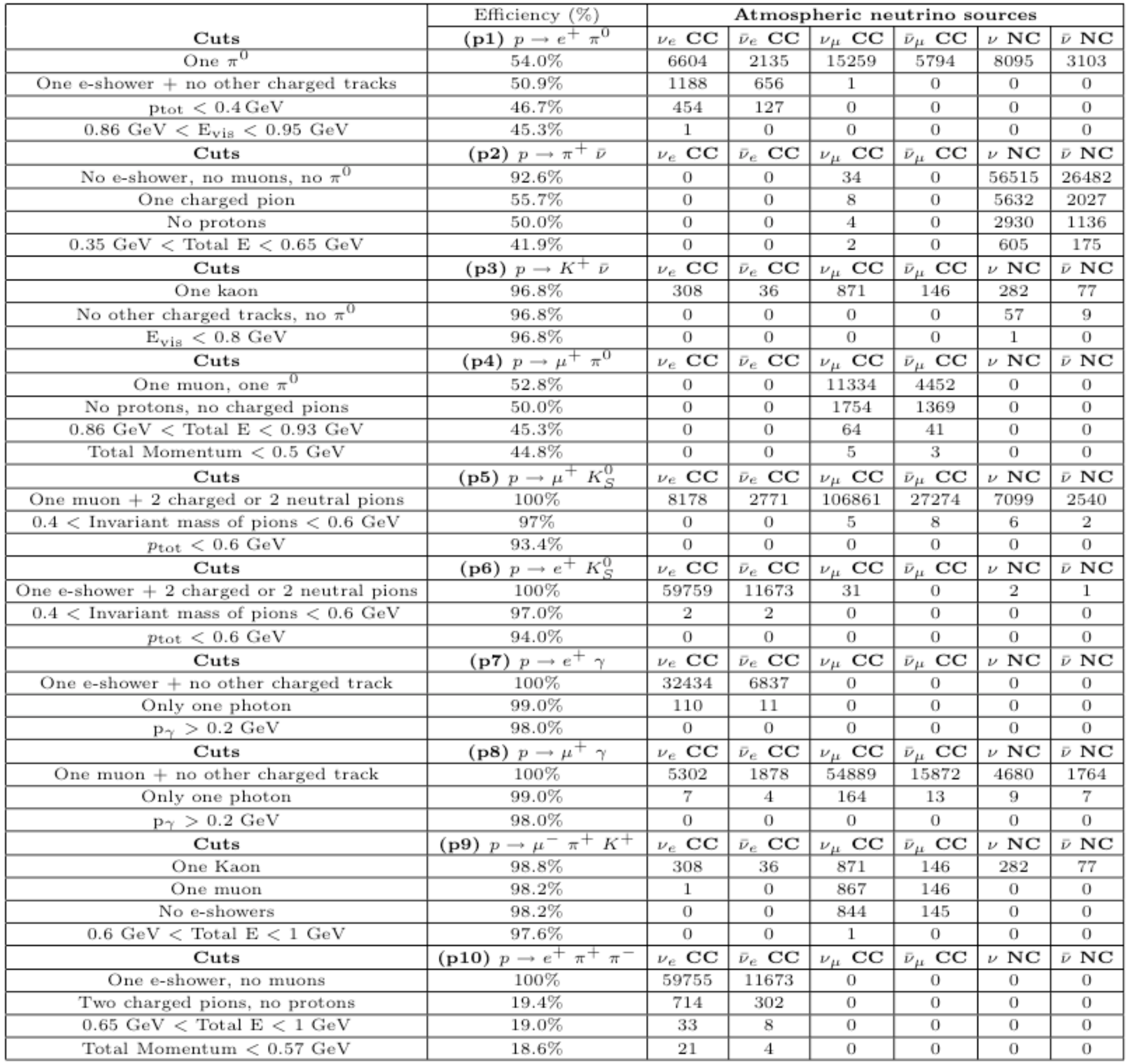
Summary of proton decay analysis



	Efficiency (%)	Atmospheric neutrino sources					
Cuts	**(p1)** $p \rightarrow e^+ \pi^0$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One π^0	54.0%	6604	2135	15259	5794	8095	3103
One e-shower + no other charged tracks	50.9%	1188	656	1	0	0	0
$\mathrm{p_{tot}} < 0.4\,\mathrm{GeV}$	46.7%	454	127	0	0	0	0
$0.86\ \mathrm{GeV} < \mathrm{E_{vis}} < 0.95\ \mathrm{GeV}$	45.3%	1	0	0	0	0	0
Cuts	**(p2)** $p \rightarrow \pi^+ \bar{\nu}$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
No e-shower, no muons, no π^0	92.6%	0	0	34	0	56515	26482
One charged pion	55.7%	0	0	8	0	5632	2027
No protons	50.0%	0	0	4	0	2930	1136
$0.35\ \mathrm{GeV} < \mathrm{Total\ E} < 0.65\ \mathrm{GeV}$	41.9%	0	0	2	0	605	175
Cuts	**(p3)** $p \rightarrow K^+ \bar{\nu}$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no π^0	96.8%	0	0	0	0	57	9
$\mathrm{E_{vis}} < 0.8\ \mathrm{GeV}$	96.8%	0	0	0	0	1	0
Cuts	**(p4)** $p \rightarrow \mu^+ \pi^0$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One muon, one π^0	52.8%	0	0	11334	4452	0	0
No protons, no charged pions	50.0%	0	0	1754	1369	0	0
$0.86\ \mathrm{GeV} < \mathrm{Total\ E} < 0.93\ \mathrm{GeV}$	45.3%	0	0	64	41	0	0
Total Momentum < 0.5 GeV	44.8%	0	0	5	3	0	0
Cuts	**(p5)** $p \rightarrow \mu^+ K^0_S$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One muon + 2 charged or 2 neutral pions	100%	8178	2771	106861	27274	7099	2540
0.4 < Invariant mass of pions < 0.6 GeV	97%	0	0	5	8	6	2
$p_{\mathrm{tot}} < 0.6\ \mathrm{GeV}$	93.4%	0	0	0	0	0	0
Cuts	**(p6)** $p \rightarrow e^+ K^0_S$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One e-shower + 2 charged or 2 neutral pions	100%	59759	11673	31	0	2	1
0.4 < Invariant mass of pions < 0.6 GeV	97.0%	2	2	0	0	0	0
$p_{\mathrm{tot}} < 0.6\ \mathrm{GeV}$	94.0%	0	0	0	0	0	0
Cuts	**(p7)** $p \rightarrow e^+ \gamma$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One e-shower + no other charged track	100%	32434	6837	0	0	0	0
Only one photon	99.0%	110	11	0	0	0	0
$\mathrm{p}_\gamma > 0.2\ \mathrm{GeV}$	98.0%	0	0	0	0	0	0
Cuts	**(p8)** $p \rightarrow \mu^+ \gamma$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One muon + no other charged track	100%	5302	1878	54889	15872	4680	1764
Only one photon	99.0%	7	4	164	13	9	7
$\mathrm{p}_\gamma > 0.2\ \mathrm{GeV}$	98.0%	0	0	0	0	0	0
Cuts	**(p9)** $p \rightarrow \mu^- \pi^+ K^+$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One Kaon	98.8%	308	36	871	146	282	77
One muon	98.2%	1	0	867	146	0	0
No e-showers	98.2%	0	0	844	145	0	0
0.6 GeV < Total E < 1 GeV	97.6%	0	0	1	0	0	0
Cuts	**(p10)** $p \rightarrow e^+ \pi^+ \pi^-$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One e-shower, no muons	100%	59755	11673	0	0	0	0
Two charged pions, no protons	19.4%	714	302	0	0	0	0
0.65 GeV < Total E < 1 GeV	19.0%	33	8	0	0	0	0
Total Momentum < 0.57 GeV	18.6%	21	4	0	0	0	0

Table 7: Detailed list of cuts for the considered proton decay channels. Survival fraction of signal (first column) and background events through event selections applied in succession. Backgrounds are normalized to an exposure of 1 Mton×year.

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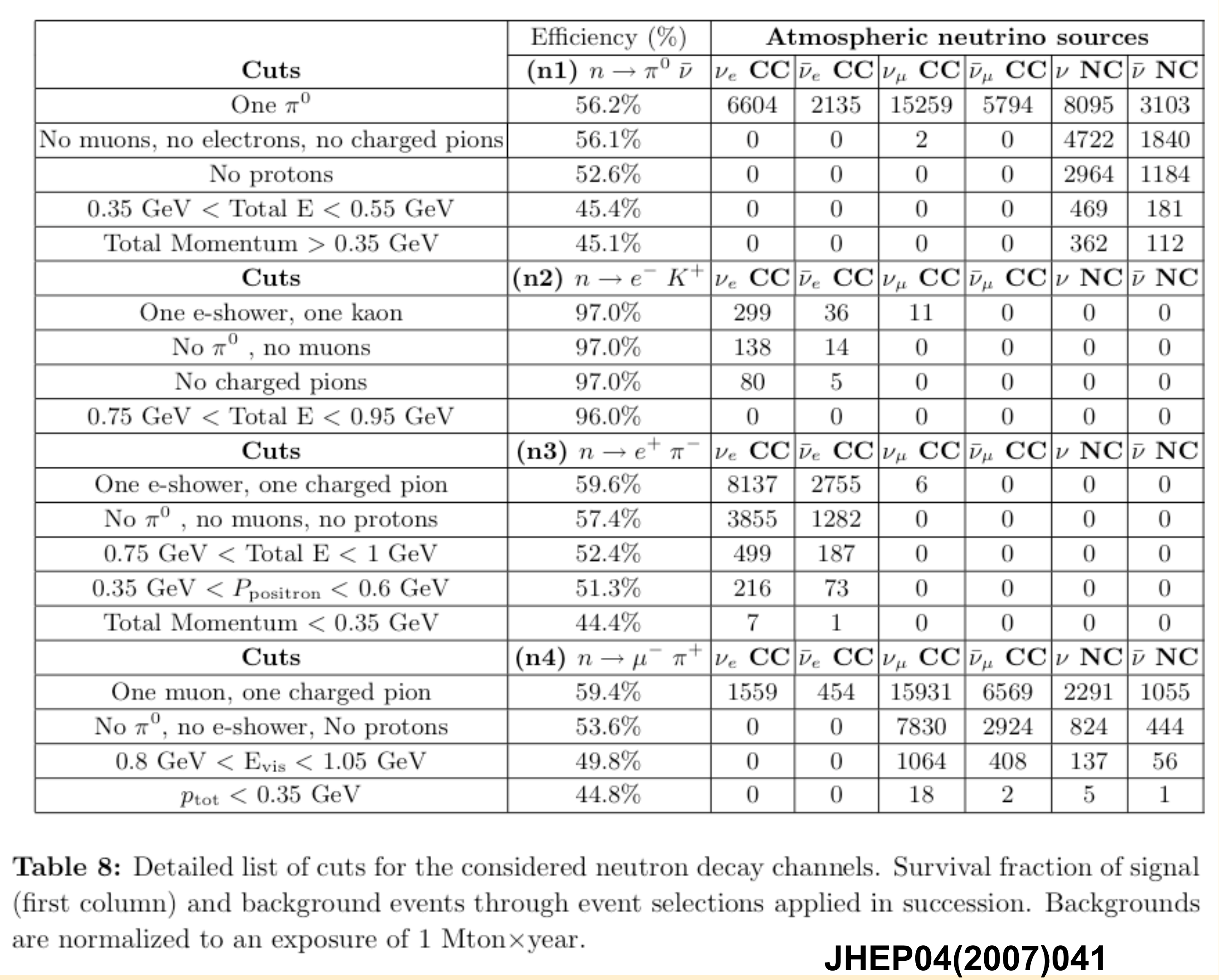
Summary of neutron decay analysis



Cuts	Efficiency (%)	**Atmospheric neutrino sources**					
Cuts	**(n1)** $n \to \pi^0 \, \bar{\nu}$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One π^0	56.2%	6604	2135	15259	5794	8095	3103
No muons, no electrons, no charged pions	56.1%	0	0	2	0	4722	1840
No protons	52.6%	0	0	0	0	2964	1184
0.35 GeV $<$ Total E $<$ 0.55 GeV	45.4%	0	0	0	0	469	181
Total Momentum $>$ 0.35 GeV	45.1%	0	0	0	0	362	112
Cuts	**(n2)** $n \to e^- \, K^+$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One e-shower, one kaon	97.0%	299	36	11	0	0	0
No π^0 , no muons	97.0%	138	14	0	0	0	0
No charged pions	97.0%	80	5	0	0	0	0
0.75 GeV $<$ Total E $<$ 0.95 GeV	96.0%	0	0	0	0	0	0
Cuts	**(n3)** $n \to e^+ \, \pi^-$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One e-shower, one charged pion	59.6%	8137	2755	6	0	0	0
No π^0 , no muons, no protons	57.4%	3855	1282	0	0	0	0
0.75 GeV $<$ Total E $<$ 1 GeV	52.4%	499	187	0	0	0	0
0.35 GeV $< P_{\text{positron}} <$ 0.6 GeV	51.3%	216	73	0	0	0	0
Total Momentum $<$ 0.35 GeV	44.4%	7	1	0	0	0	0
Cuts	**(n4)** $n \to \mu^- \, \pi^+$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One muon, one charged pion	59.4%	1559	454	15931	6569	2291	1055
No π^0, no e-shower, No protons	53.6%	0	0	7830	2924	824	444
0.8 GeV $<$ E_{vis} $<$ 1.05 GeV	49.8%	0	0	1064	408	137	56
$p_{\text{tot}} <$ 0.35 GeV	44.8%	0	0	18	2	5	1

Table 8: Detailed list of cuts for the considered neutron decay channels. Survival fraction of signal (first column) and background events through event selections applied in succession. Backgrounds are normalized to an exposure of 1 Mton×year.

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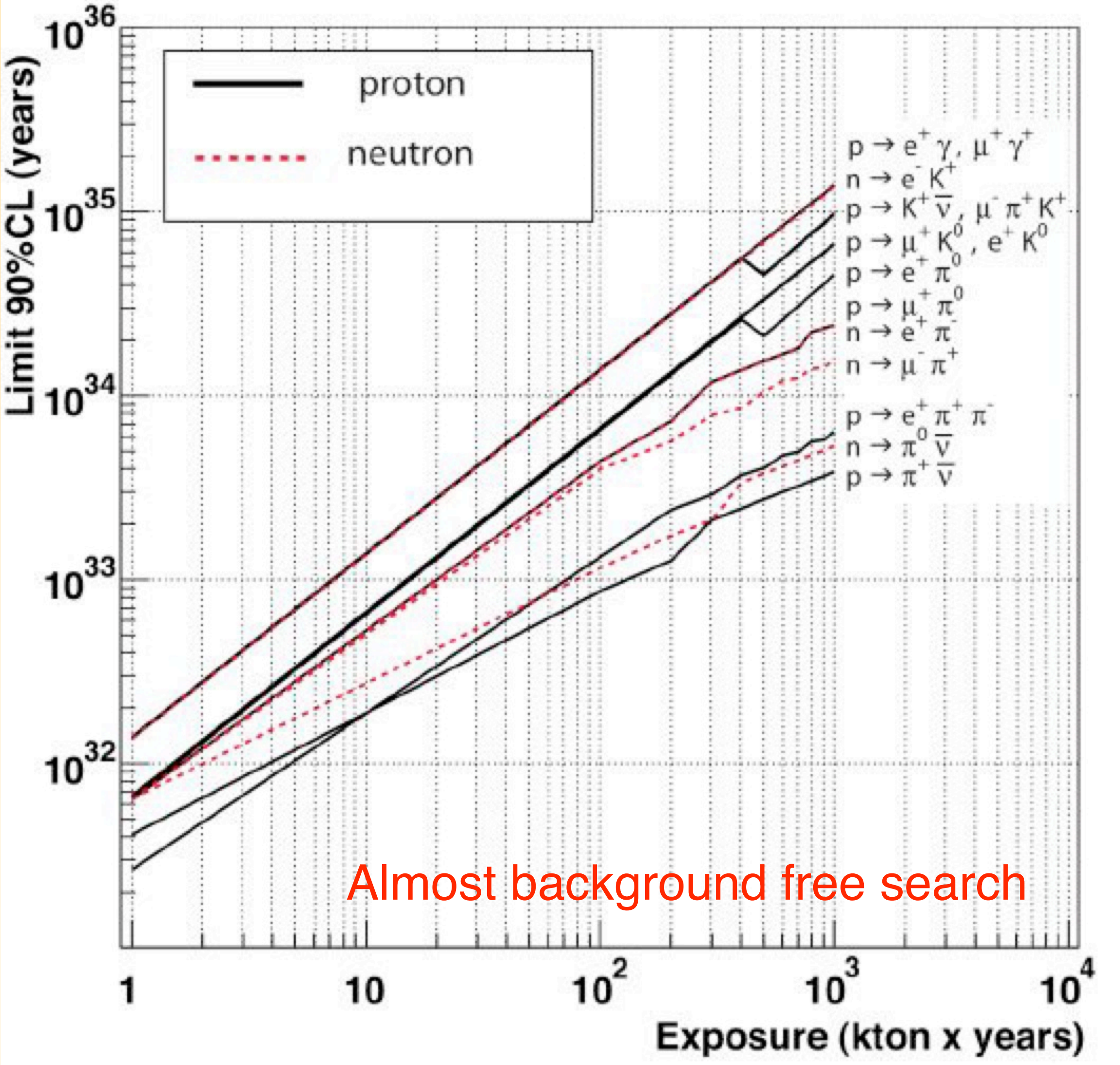
Sensitivity to nucleon partial lifetime

Only atmospheric neutrino background is included



Almost background free search

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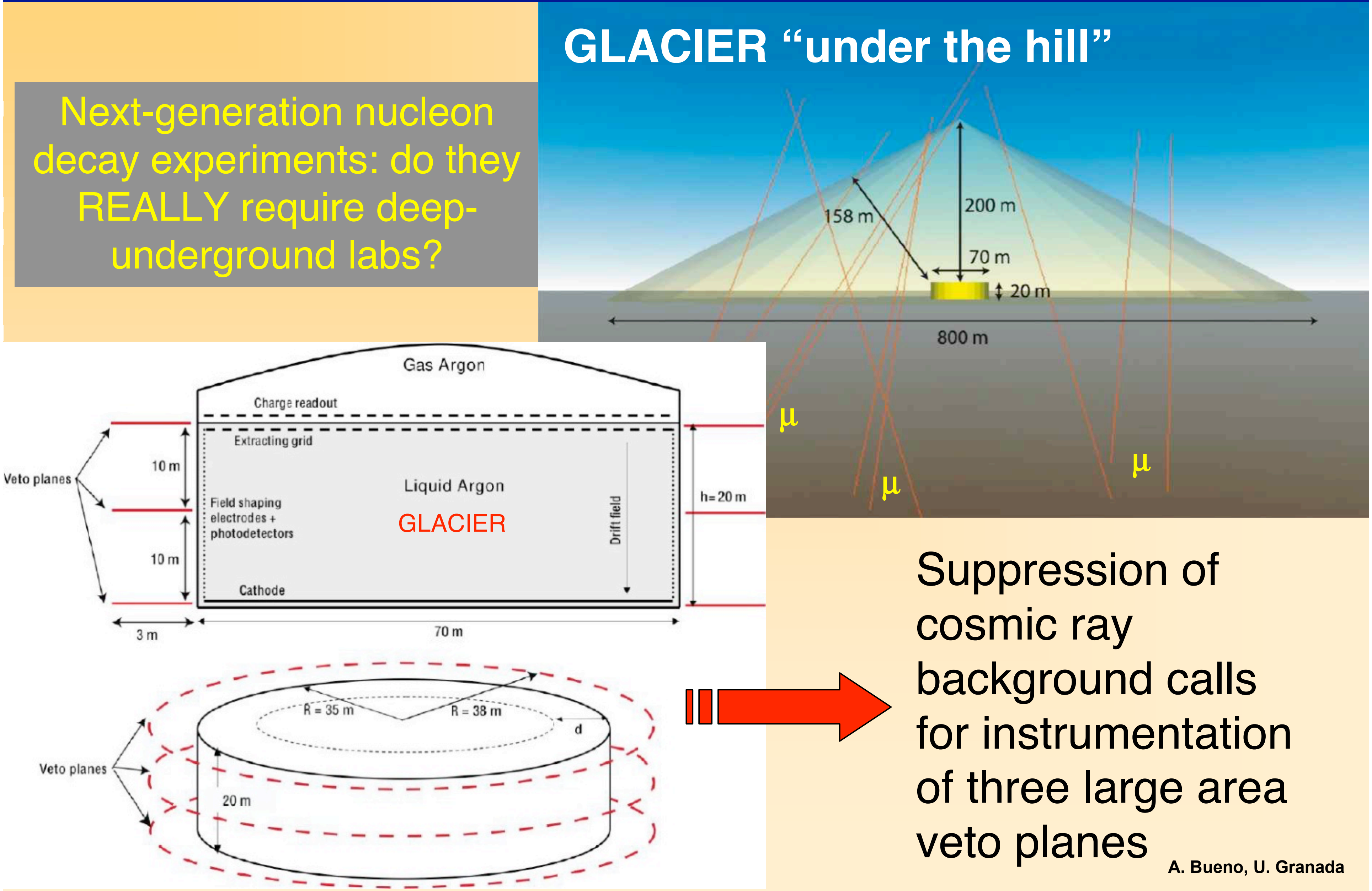
Proton decay searches at “shallow depth”?

Next-generation nucleon decay experiments: do they REALLY require deep-underground labs?

GLACIER “under the hill”



Suppression of cosmic ray background calls for instrumentation of three large area veto planes

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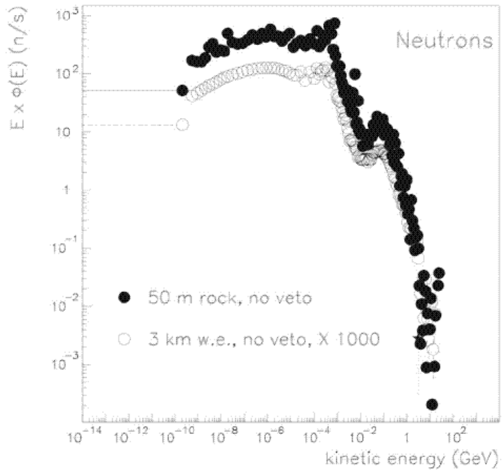
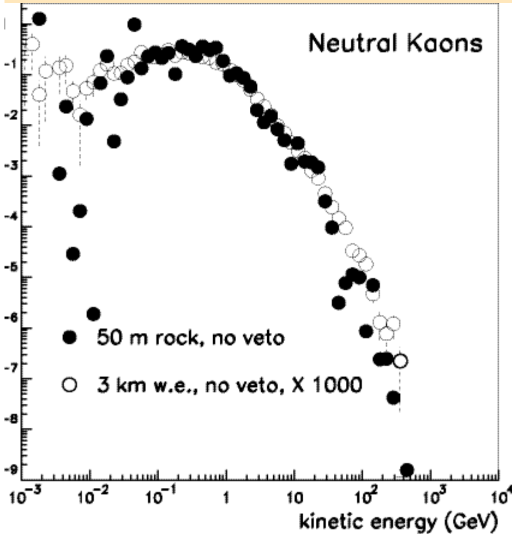
Muon-induced hadrons as a function of depth

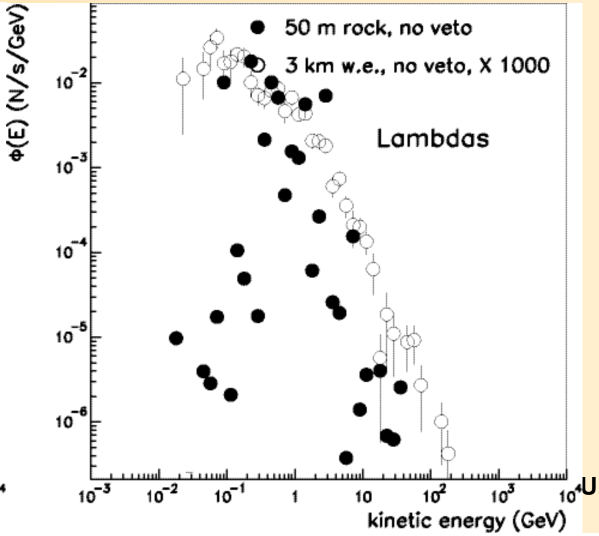
Full simulation

Configuration/ Depth	Simulation	Average number μ's entering LAr per 10 ms	Neutrons per year	Neutrons per μ in LAr per 10 ms	Neutral kaons per year	Neutral kaons per μ in LAr per 10 ms	Lambdas
$\simeq$ 0.5 km w.e. (188 m rock)	FLUKA	3.3	$1.9{\times}10^6$	$1.8{\times}10^{-4}$	4500	$4.3{\times}10^{-7}$	$\approx 0.04 \times N_{K^0}$
$\simeq$ 1 km w.e. (377 m rock)	FLUKA	0.66	$5.5{\times}10^5$	$2.6{\times}10^{-4}$	1300	$6.2{\times}10^{-7}$	$\approx 0.05 \times N_{K^0}$
$\simeq$ 3 km w.e. (1.13 km rock)	FLUKA	0.01	$1.1{\times}10^4$	$3.6{\times}10^{-4}$	25	$8.2{\times}10^{-7}$	$\approx 0.06 \times N_{K^0}$
Under the hill (see figure 4)	GEANT4 FLUKA rescaled	9.6	$9.7{\times}10^6$	3.2×10^{-4}	$1.2{\times}10^3$ $\approx 1.2{\times}10^4$	$4.0{\times}10^{-8}$ $\approx 4.0{\times}10^{-7}$	– $\approx 0.05 \times N_{K^0}$

Table 4: Cosmogenic background as a function of assumed depth: estimated number of neutrons (with kinetic energy above 20 MeV), neutral kaons and lambda's entering the detector per year, and normalised on the average number of muons entering the active volume per 10 ms, produced in cosmic muon interactions (hadrons accompanied by a detected muon inside LAr imaging have been vetoed).

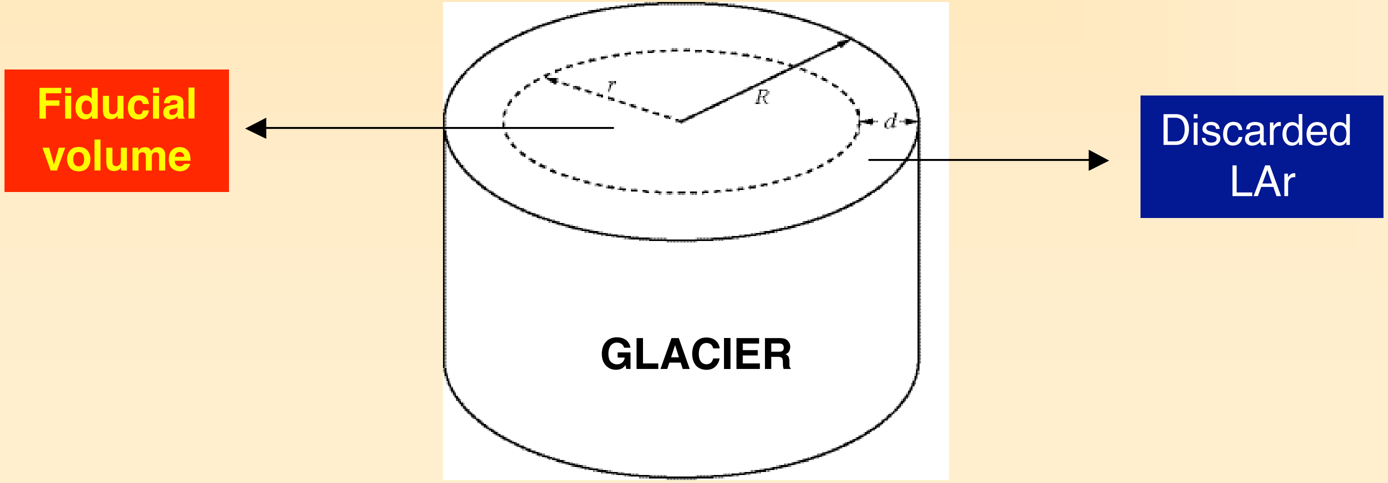






Reduction of muon-induced background

- Neutral particles (n, K^0, Λ) propagated inside LAr until they interact or decay
  - Their products constitute potential backgrounds
- Apply kinematical cuts (similar to those applied to reduce atmospheric backgrounds)
- Exclude events produced at a distance *d* or smaller from the detector walls
  - Reduction of fiducial volume
  - *d* chosen such that muon-induced background is equal to contamination produced by atmospheric events



Fiducial volume

Discarded LAr

GLACIER

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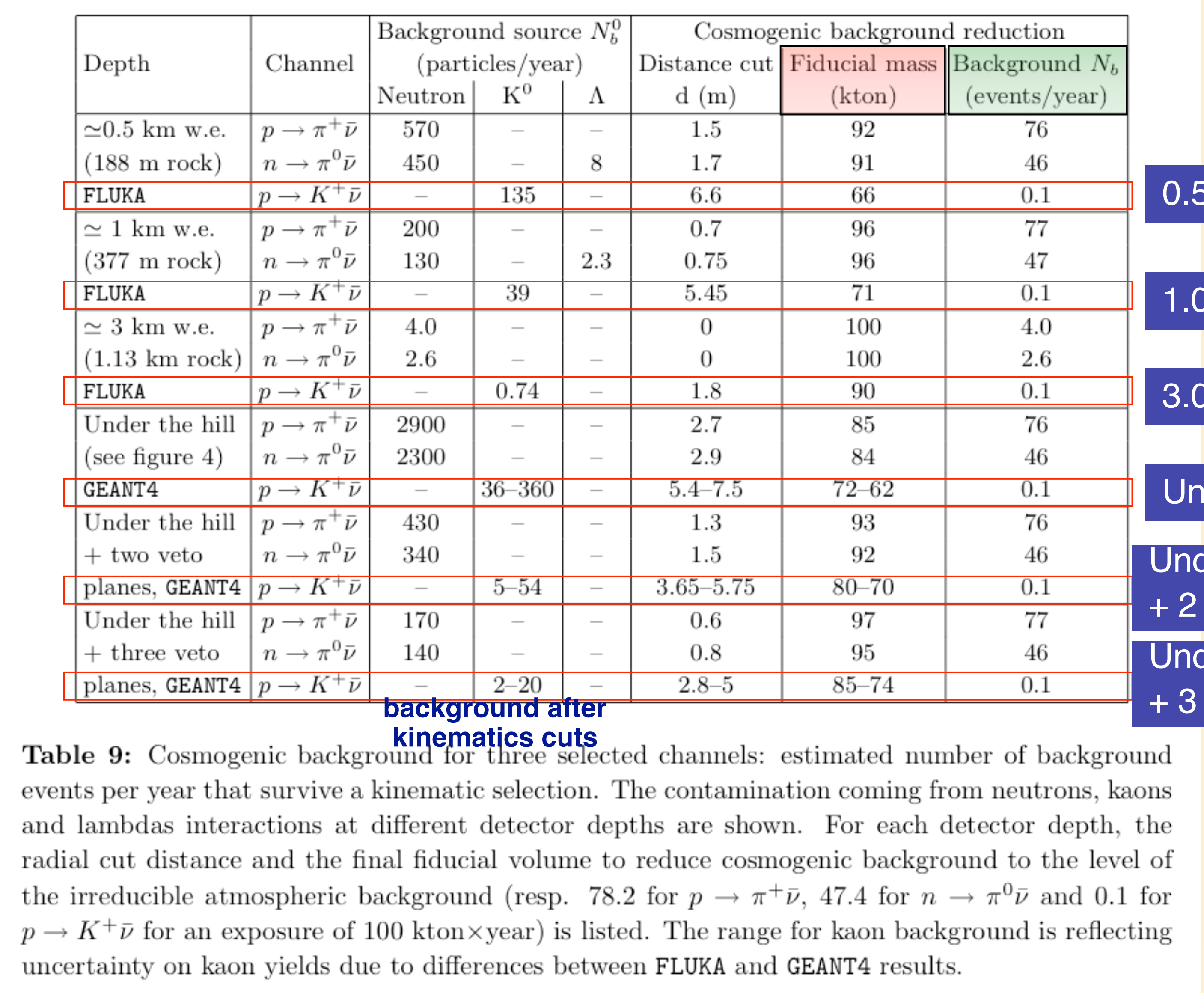
Expected cosmogenic background



		Background source N_b^0 (particles/year)			Cosmogenic background reduction		
Depth	Channel	Neutron	K^0	Λ	Distance cut d (m)	Fiducial mass (kton)	Background N_b (events/year)
≃0.5 km w.e.	$p \to \pi^+ \bar{\nu}$	570	–	–	1.5	92	76
(188 m rock)	$n \to \pi^0 \bar{\nu}$	450	–	8	1.7	91	46
`FLUKA`	$p \to K^+ \bar{\nu}$	–	135	–	6.6	66	0.1
≃ 1 km w.e.	$p \to \pi^+ \bar{\nu}$	200	–	–	0.7	96	77
(377 m rock)	$n \to \pi^0 \bar{\nu}$	130	–	2.3	0.75	96	47
`FLUKA`	$p \to K^+ \bar{\nu}$	–	39	–	5.45	71	0.1
≃ 3 km w.e.	$p \to \pi^+ \bar{\nu}$	4.0	–	–	0	100	4.0
(1.13 km rock)	$n \to \pi^0 \bar{\nu}$	2.6	–	–	0	100	2.6
`FLUKA`	$p \to K^+ \bar{\nu}$	–	0.74	–	1.8	90	0.1
Under the hill	$p \to \pi^+ \bar{\nu}$	2900	–	–	2.7	85	76
(see figure 4)	$n \to \pi^0 \bar{\nu}$	2300	–	–	2.9	84	46
`GEANT4`	$p \to K^+ \bar{\nu}$	–	36–360	–	5.4–7.5	72–62	0.1
Under the hill	$p \to \pi^+ \bar{\nu}$	430	–	–	1.3	93	76
+ two veto	$n \to \pi^0 \bar{\nu}$	340	–	–	1.5	92	46
planes, `GEANT4`	$p \to K^+ \bar{\nu}$	–	5–54	–	3.65–5.75	80–70	0.1
Under the hill	$p \to \pi^+ \bar{\nu}$	170	–	–	0.6	97	77
+ three veto	$n \to \pi^0 \bar{\nu}$	140	–	–	0.8	95	46
planes, `GEANT4`	$p \to K^+ \bar{\nu}$	–	2–20	–	2.8–5	85–74	0.1

background after kinematics cuts

Table 9: Cosmogenic background for three selected channels: estimated number of background events per year that survive a kinematic selection. The contamination coming from neutrons, kaons and lambdas interactions at different detector depths are shown. For each detector depth, the radial cut distance and the final fiducial volume to reduce cosmogenic background to the level of the irreducible atmospheric background (resp. 78.2 for $p \to \pi^+ \bar{\nu}$, 47.4 for $n \to \pi^0 \bar{\nu}$ and 0.1 for $p \to K^+ \bar{\nu}$ for an exposure of 100 kton×year) is listed. The range for kaon background is reflecting uncertainty on kaon yields due to differences between `FLUKA` and `GEANT4` results.

0.5 km w.e.

1.0 km w.e.

3.0 km w.e.

Under the hill

Under the hill
+ 2 veto planes

Under the hill
+ 3 veto planes

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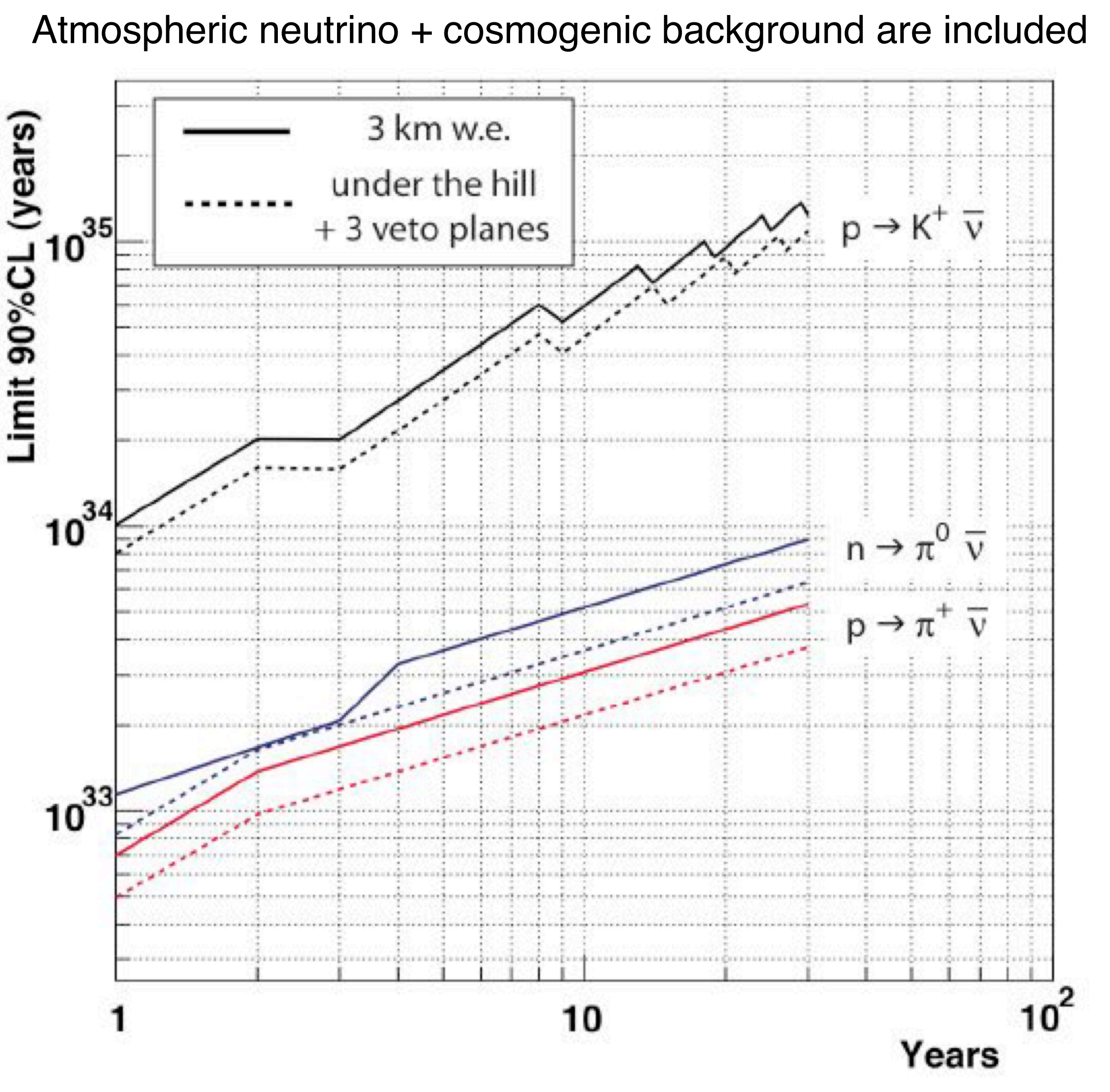
Sensitivity to nucleon partial lifetime at shallow depth



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NON-ACCELERATOR NEUTRINOS

Low energy neutrino interactions in LAr

✓ Elastic scattering on electrons (**ES**)

$$\overset{(-)}{\nu} + e^- \rightarrow \overset{(-)}{\nu} + e^-$$

✓ Charged-current (**CC**) interactions on Argon

$Q\nu_e$CC = 1.5 MeV
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

$Q\bar{\nu}_e$CC= 7.48 MeV
$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

✓ Neutral current (**NC**) interactions on Argon

Q_{NC} = 1.46 MeV
$$\overset{(-)}{\nu} + {}^{40}Ar \rightarrow \overset{(-)}{\nu} + {}^{40}Ar^*$$

Channel separation through:

- classification of **photons from the K, Cl or Ar deexcitation** (specific spectral lines for **CC** and **NC**)
- **absence of photons (ES)**

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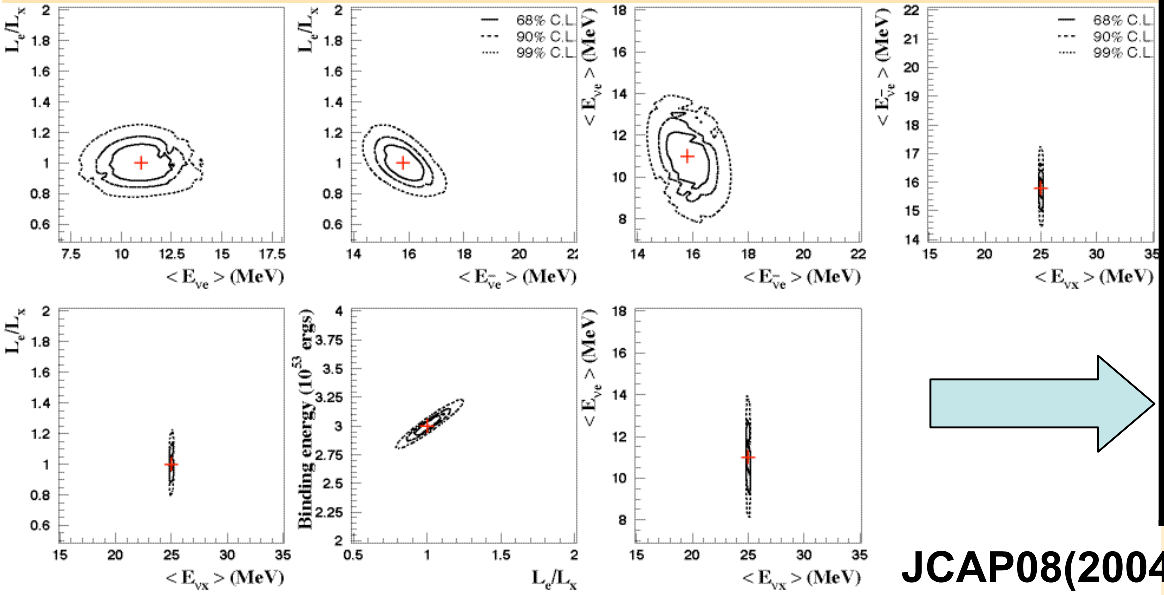
Supernova at 10 kpc

Interaction	Rates (×10^4)
ν_e CC (^{40}Ar, ^{40}K*)	2.5
ν_x NC (^{40}Ar*)	3.0
ν_x ES	0.1
anti–ν_e CC (^{40}Ar, ^{40}Cl*)	0.054

380 events from neutronization burst

Large statistics allow <u>decoupled studies</u> to:

- Probe explosion mechanism
- Measure intrinsic neutrino properties



Supernova property	Error (%)
Binding Energy	2-4
Average energy of electron neutrinos at the core	5-14
Average energy of electron anti-neutrinos at the core	3-9
Average energy of other (anti)neutrinos at the core	<1
Relative luminosity of electron to non-electron flavours	10-40

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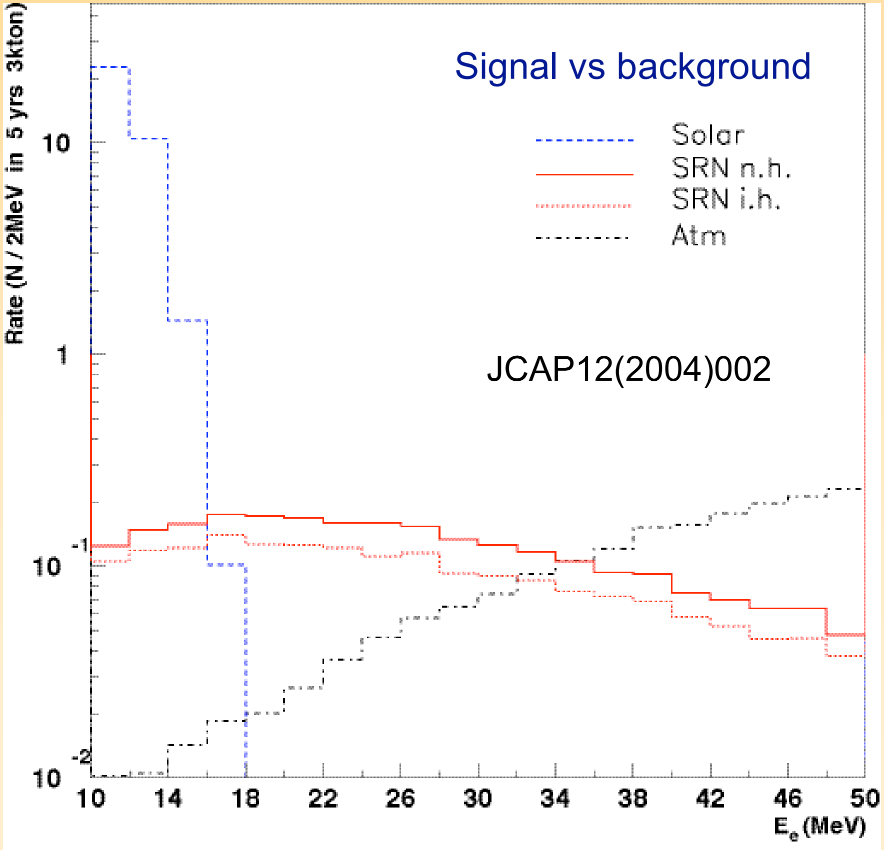
Supernova relic neutrinos

Assumed Supernova rate

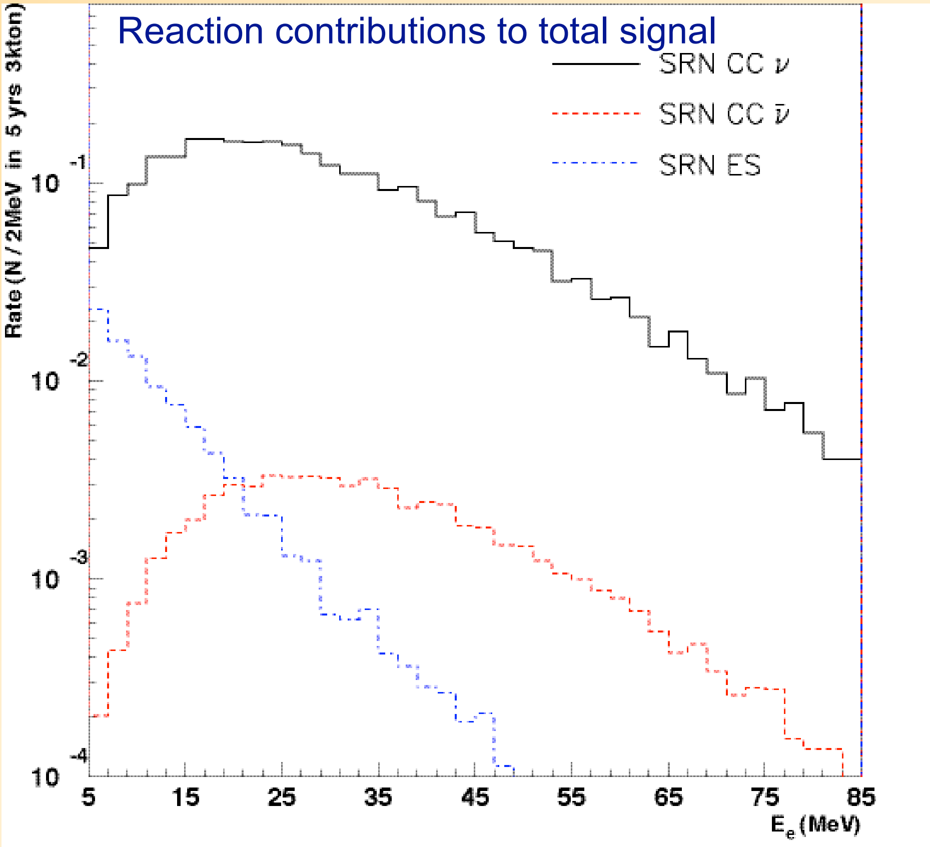
$$R_{SN}(z) = \begin{cases} R_0(1+z)^{\beta}, & z \le 1 \\ R_0 2^{\beta-\alpha}(1+z)^{\alpha}, & z > 1, \end{cases}$$

$R_0 = 2\times10^{-4}$ yr^{-1} Mpc^{-3}, $\beta=2.5$, $\alpha=1$

- Five years exposure will allow GLACIER to detect an effect at 4σ level
  - Expected number of signal events 57±12 in the energy window $16 \le E_e \le 40$ MeV; $N_{bckgnd} = 30$ events


Signal vs background

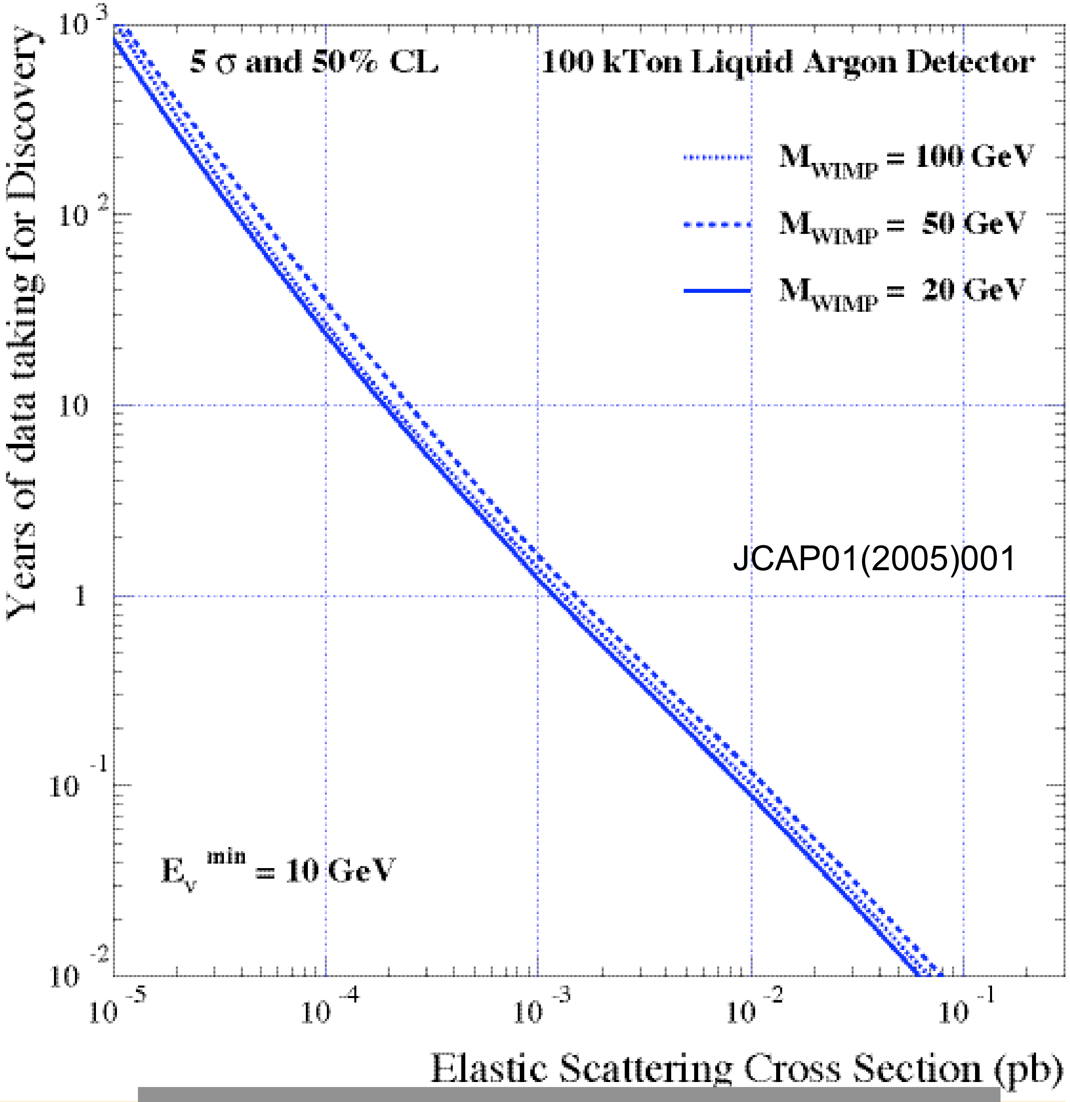
JCAP12(2004)002


Reaction contributions to total signal

a

Indirect Dark Matter detection

- WIMPS can be gravitationally trapped in the centre of celestial massive bodies (e.g. the Sun)
- They can annihilate and produce standard particles (among others high energy neutrinos)
- Look for high energy (anti-) ν_e pointing to the Sun
  - Take advantage of superb angular resolution and electron ID capabilities of LAr TPCs
- Clear WIMP signal expected if elastic cross section above 10^{-4} pb



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$$\sigma_{elastic} = \sigma_{H,SD} + \sigma_{H,SI} + \sigma_{He,SI}$$

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Conclusions

- A 100 Kton LAr TPC is a suitable detector for next generation proton decay searches.
  - Complementary to searches done with water Cerenkov detectors.
  - Largest sensitivity for super-symmetric channels (i.e., events with Kaons in the final state).
  - Allows to study a wealthy variety of decay modes to constrain the ultimate nature of the disintegration mechanism.
  - Proton decay searches at "shallow" depth are possible.
- Promising technology to study further neutrinos from Supernovae, the Sun, the atmosphere, accelerators and reactors.