Prospects and Challenges for Proton Decay

Ed Kearns, Boston University

June 14, 2012

2012 Project X Physics Study

Project X

Intense Neutrino Beam

Large Detector

Proton Decay??

Scientific Impact of Proton Decay

- Tests a fundamental, but unexplained conservation law: baryon number.
- Grand Unified Theories make predictions: decay modes, lifetimes, branching ratios.
- Probes scales forever inaccessible to accelerators.
- New force carrying fields.
- Deep connections with other physics: cosmology, inflation, BAU, neutrino mass.
- Even if no signal is detected, limits constrain theoretical options.

Theoretical Outlook

- Numerous and various models exist.
- Lifetime predictions are not precise –
  typically uncertain by 2-3 orders of magnitude.
- There are two favored and benchmark decay modes:
  $e^+\pi^0$ (gauge mediated) and νK^+ (SUSY D=5)
  good for water good for Lar and Liq. Scint.
- There are other modes and processes:
  $\mu^+\pi^0$ (flipped), μ^+K^0 (SUSY), $\nu\pi^+$ and $\nu\pi^0$, etc.
  among a total of 27 two-body antilepton+meson
- There are also invisible modes, dinucleon decay,
  three-body B-L modes, B+L modes ...
- Some theories suppress or exclude nucleon decay.

Experimental Outlook

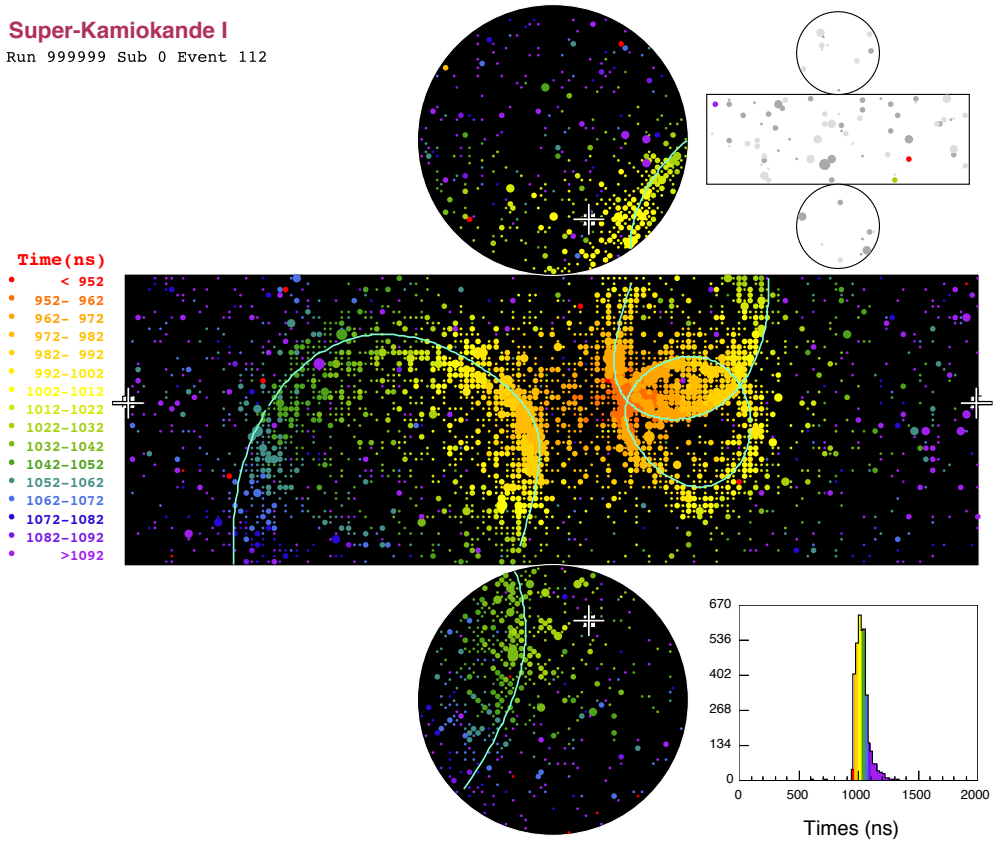
- Sensitivity is based on:

$$\frac{\tau}{B} = \frac{N_0 \ \Delta t \ \epsilon}{n_{obs} - n_{bg}}$$

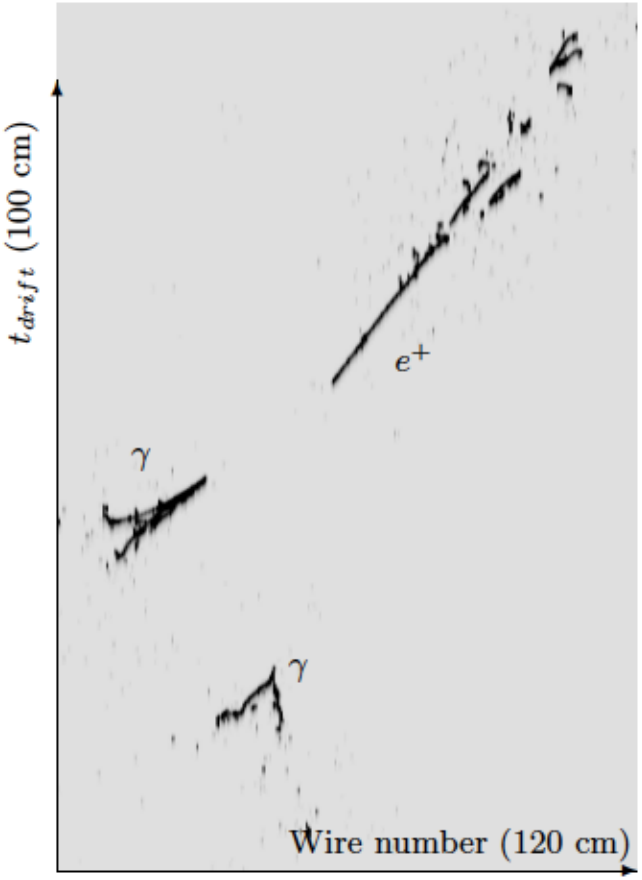
- Achieve: Large mass, highest efficiency, low background rate
- Water cherenkov best for $e^+\pi^0$
  LAr TPC / Liquid Scintillator best for $K^+\nu$
- What's on the table?

Hyper-Kamiokande	560 kton water cherenkov	99K PMTs (20% coverage)
LBNE	10/20/30 kton LAr TPC	surface/underground?
GLACIER/LBNO	20 kton LAr TPC	2-phase
LENA	51 kton liquid scintillator	30,000 PMTs

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



A. Bueno et al. hep-ph/0701101



Key points:

WC - efficiency and background estimates nearly identical for SK1 and SK2

LAr - similar efficiency & background as water, but low mass makes it uncompetitive

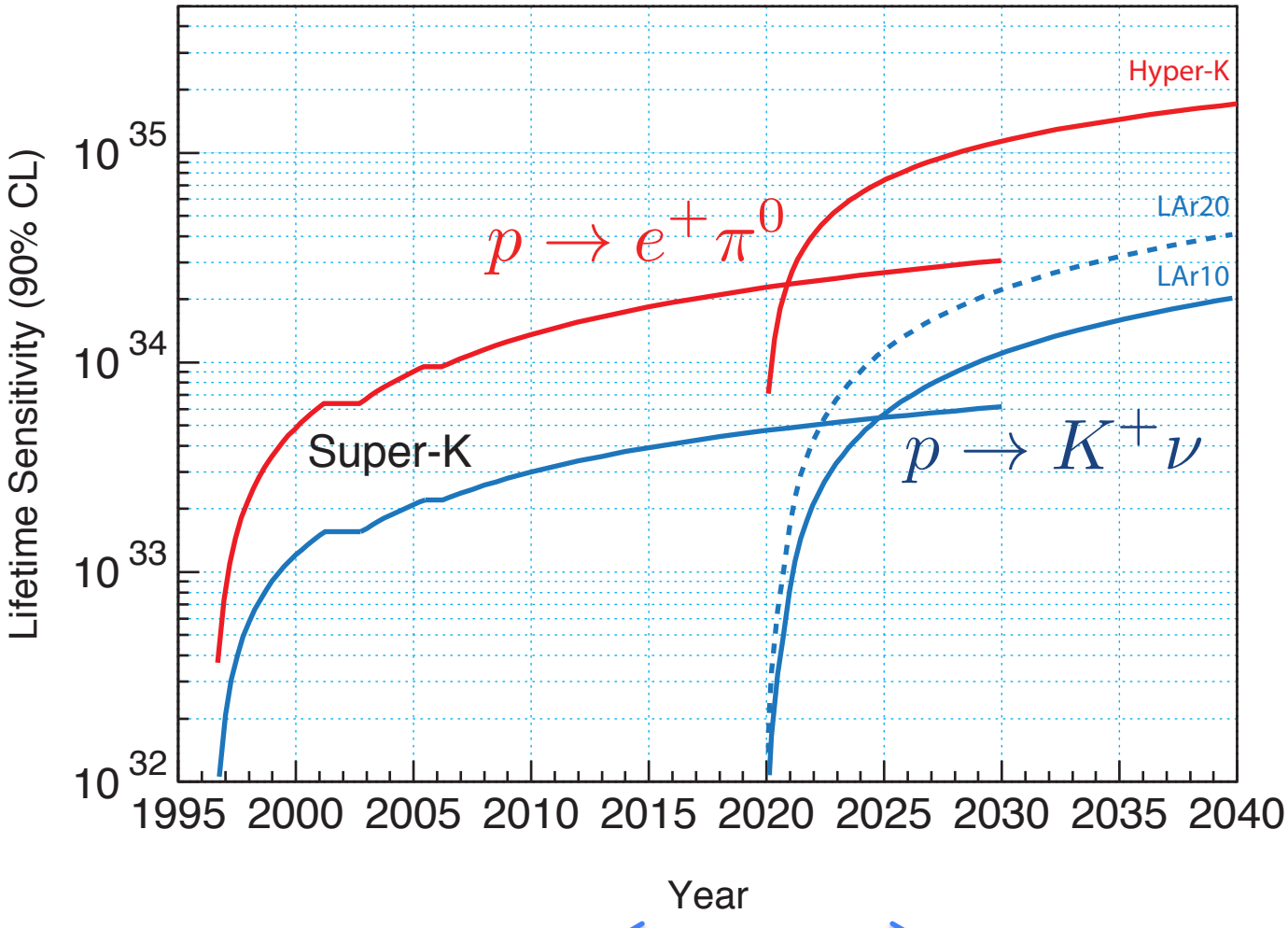
Background: events/100 kt•yr

	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow e^+\pi^0$	45%	0.2	45% ?	0.1
$p \rightarrow \nu K^+$	14%	0.6	97%	0.1
$p \rightarrow \mu^+K^0$	8%	0.8	47%	0.2
n-nbar	10%	21	?	?

No advantage for LAr over water for e^+pi^0: efficiency dominated by nuclear absorption of the pi^0 – for both.

I should update this table with numbers for LENA (sorry)

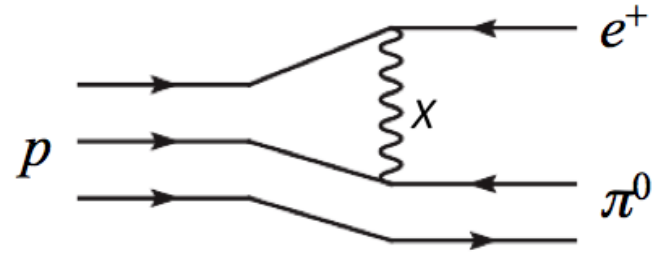
~ 0.5 Mt yr exposure
by Super-K before next
generation experiments

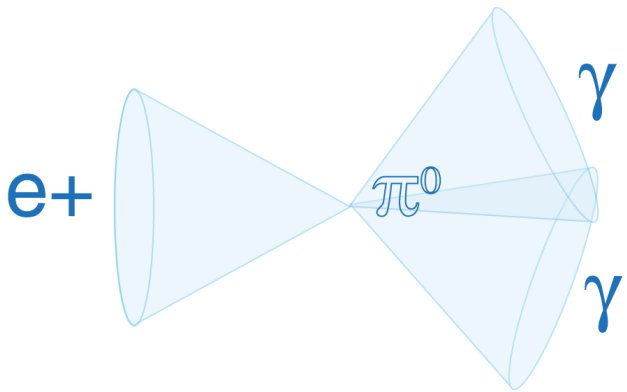


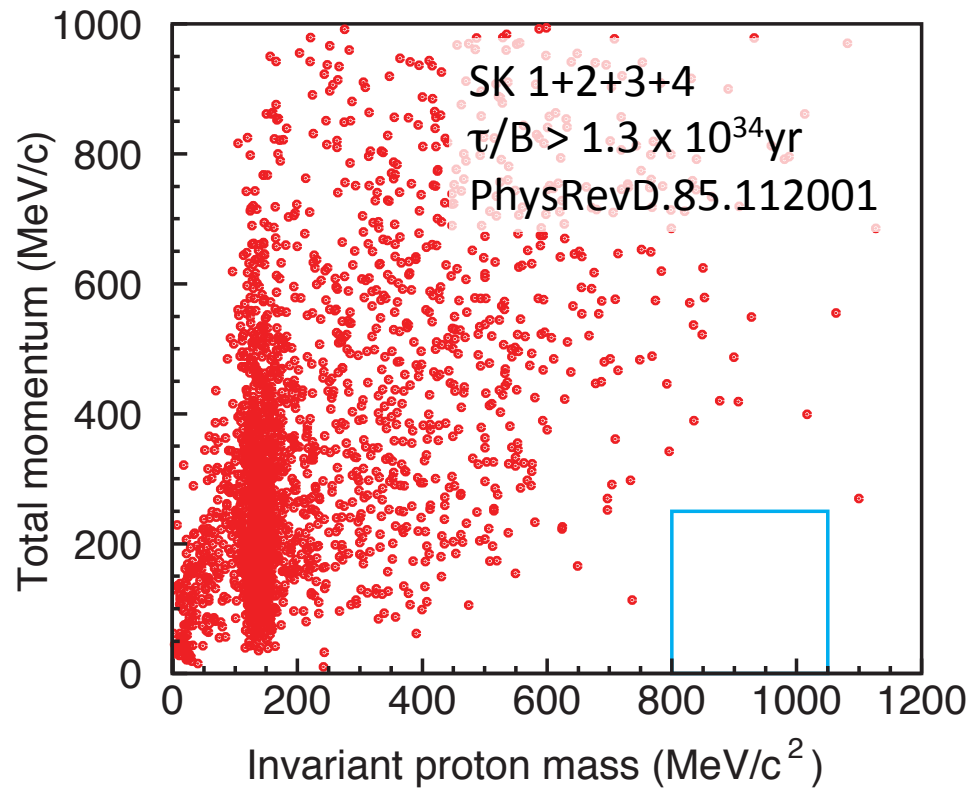
Asymptotic due to log-lin plot (not bkg limitation)

Adjust starting time as you see fit

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







Simple signature: back-to-back reconstruction of EM showers.

Efficiency ~45% dominated by nuclear absorption of π^0

Low background ~0.2 events/100 ktyr in SK

Relatively insensitive to PMT density.

Efficiency and Background for WC

EFFICIENCY	SK1	SK2	SK3	SK4
$e^+\pi^0$	44.6 ± 0.7 %	43.5 ± 0.7 %	45.2 ± 0.7 %	45.0 ± 0.7 %
$\mu^+\pi^0$	35.5 ± 0.7 %	34.7 ± 0.6 %	36.3 ± 0.7 %	43.9 ± 0.7 %

- Determined by Super-K proton decay Monte Carlo simulation
- Lower efficiency for $\mu^+\pi^0$ is due to required decay electron tag, but effect of better electronics in SK4 can be seen

BKG RATE	SK1	SK2	SK3	SK4
$e^+\pi^0$	(NEUT) 2.1 ± 0.5	2.2 ± 0.5	1.9 ± 0.5	1.6 ± 0.4
$\mu^+\pi^0$	2.6 ± 0.5	2.1 ± 0.4	2.6 ± 0.5	3.6 ± 0.5

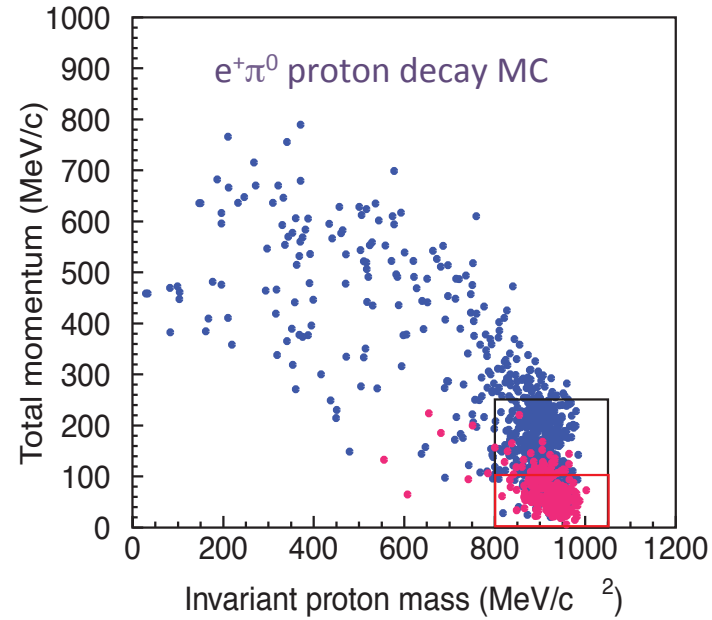
- Background rate checked using K2K near detector:

$$e^+\pi^0 \text{ BG} = 1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{sys.}) \text{ evts/Mt} \cdot \text{yr}$$

PHYSICAL REVIEW D 77, 032003 (2008)

WC Background Rate Discussion

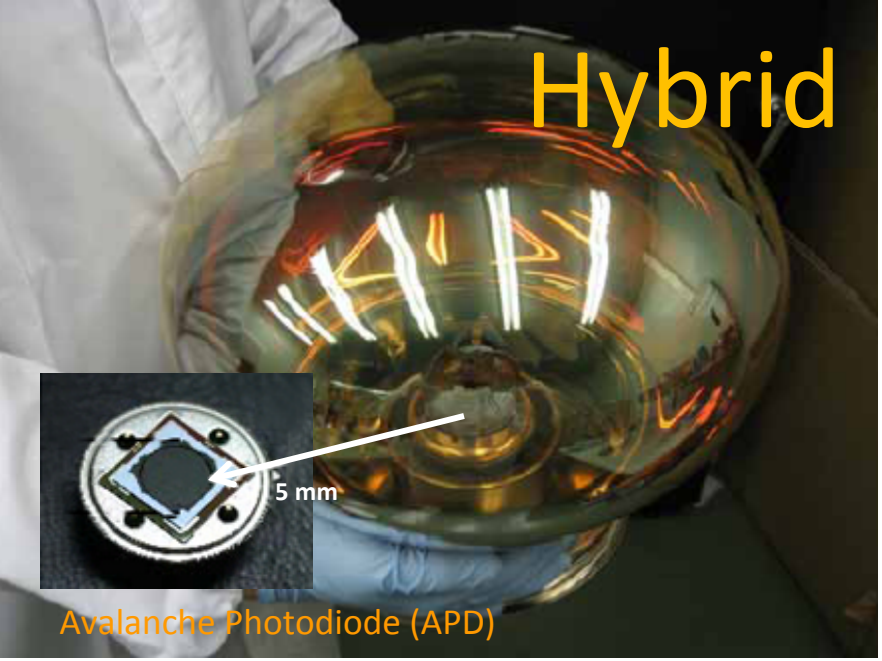
- Tight Cuts on Free Proton
  - efficiency ~ 17%
  - BG 0.015 evts/100 kton yr
  - change over ~10-20 Mton yr
- Gadolinium
  - high energy neutrino events are accompanied by n
  - assume proton decay is not accompanied by n
    - * surely not for free proton
    - * also not for γ-tag states
  - consider Gd addition to WC to increase n-capture tag efficiency
  - Gadolinium R&D underway at SK

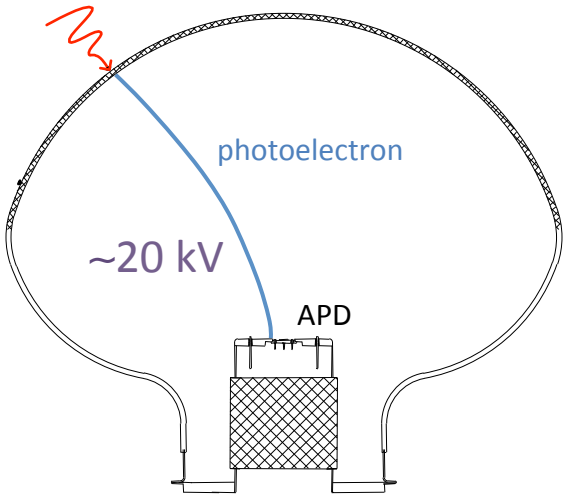


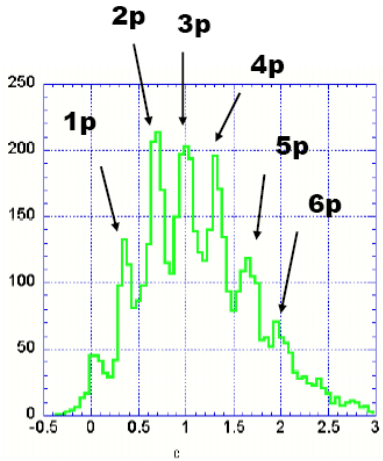
Background events for $p \to e^+\pi^0$ (4.5Megaton years)		
	ν interactions	secondary interactions in water
1	$\nu n \to e^- p \pi^0$	Neutron production by the proton
2	$\nu p \to e^- p \pi^+$	Neutron by π^+
3	$\nu p \to e^- p(\pi^+)\pi^0$	
4	$\nu n \to \nu p \pi^- \pi^0$	
5	$\nu n \to e^- p$	Neutron by the proton
6	$\nu n \to e^- n \pi^+ \pi^-$	
7	$\nu p \to e^- p(\pi^+)\pi^0$	
8	$\nu p \to \nu p \rho$	
9	$\nu O \to e^- O \pi^+$	Neutron by π^+
10	$\nu n \to n \rho$	neutron and π^- by the neutron

M. Shiozawa NNN09

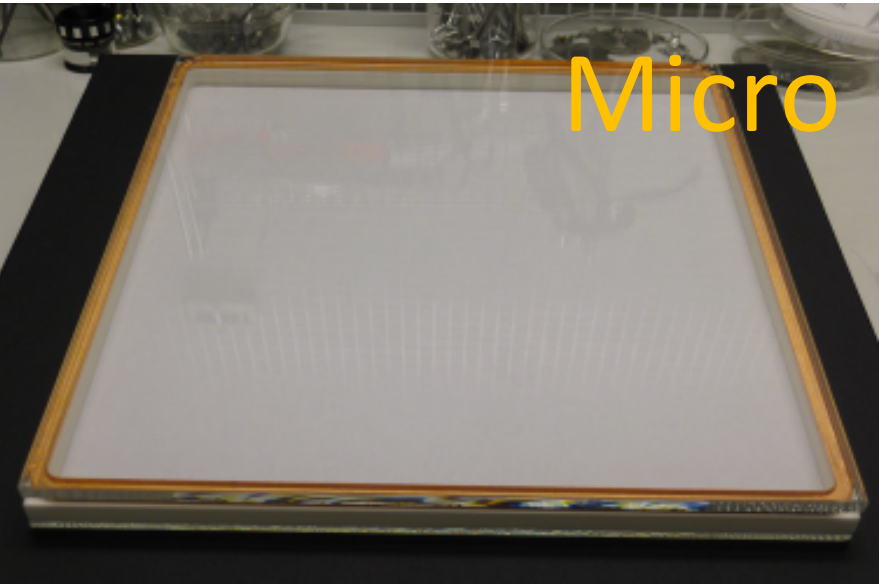
Hybrid Photo-Detector

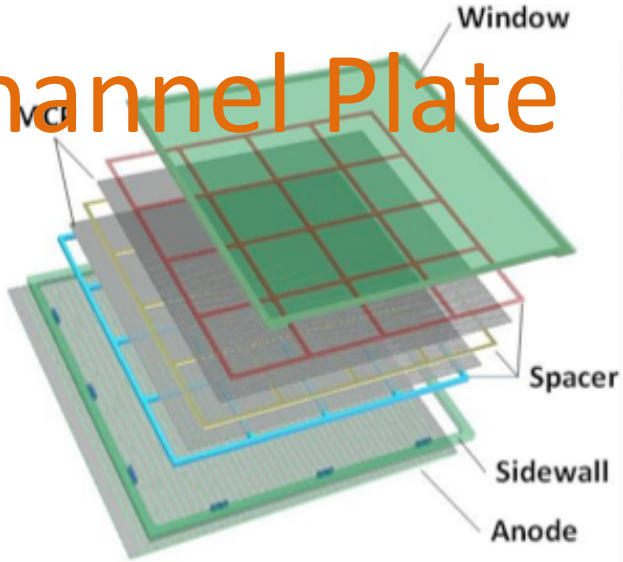






Micro Channel Plate



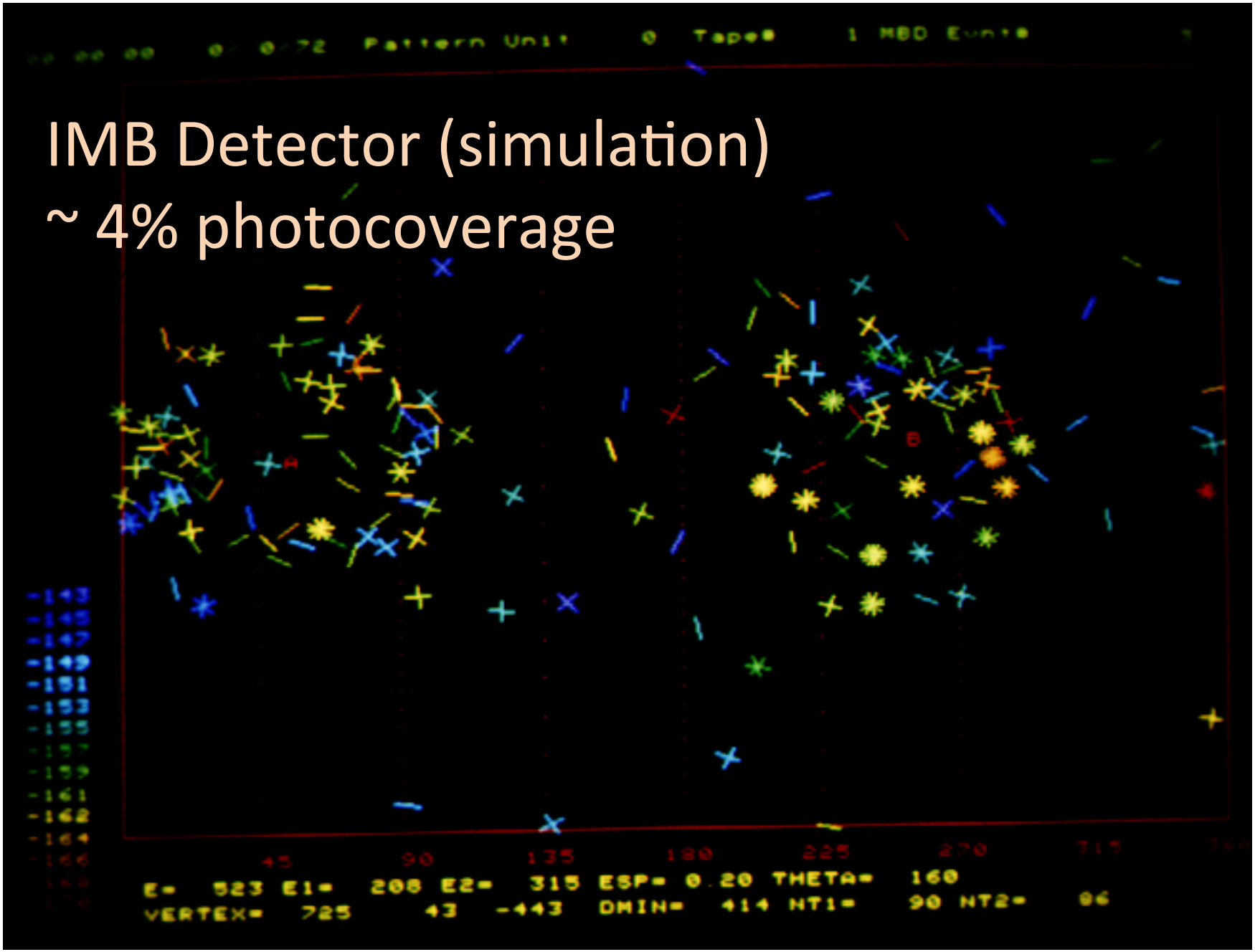


<100 ps timing

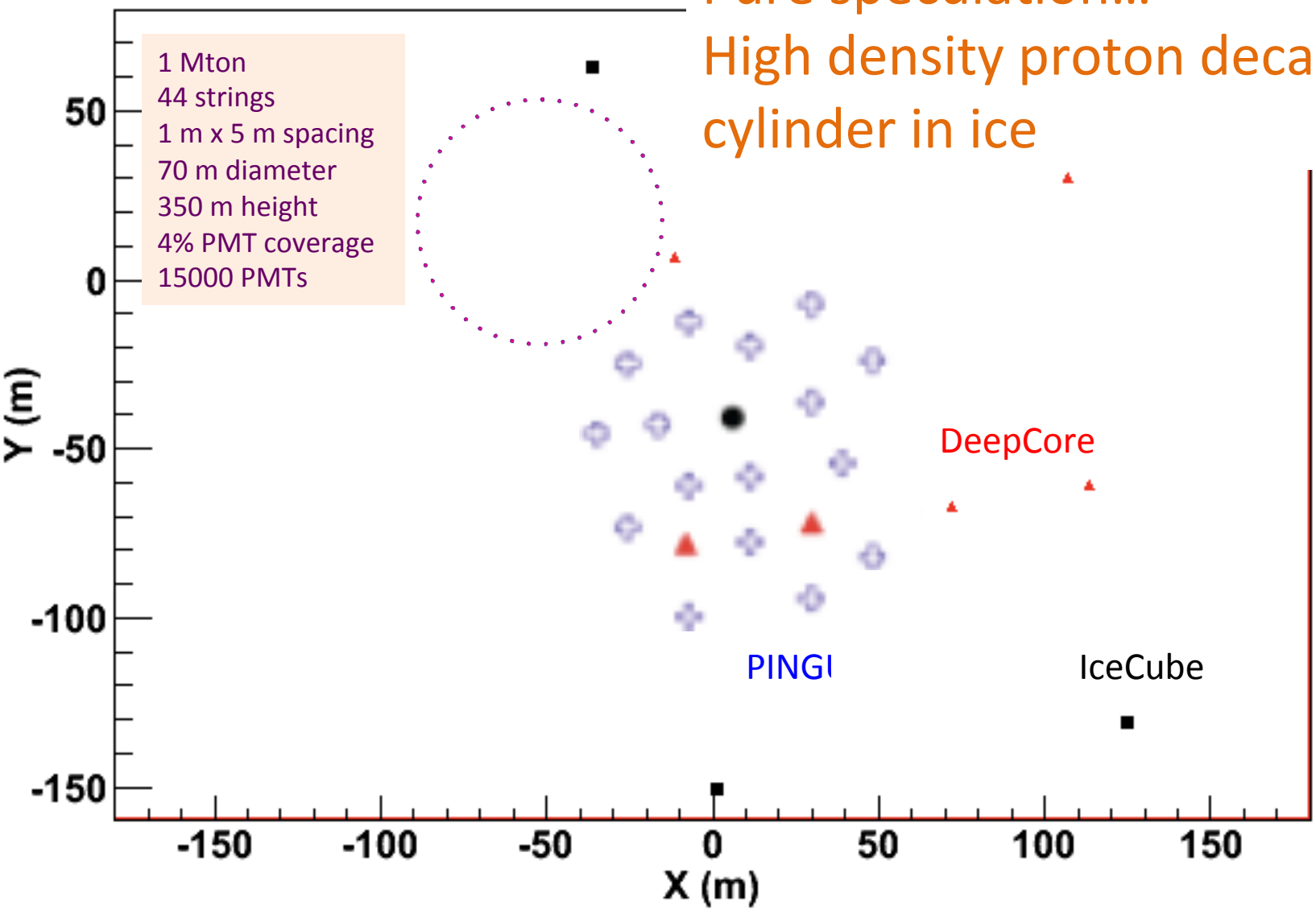
BUT…

Most important for Large Area Cost Effective Proton Decay Detectors: **COST** (and light collection)

IMB Detector (simulation)
~ 4% photocoverage

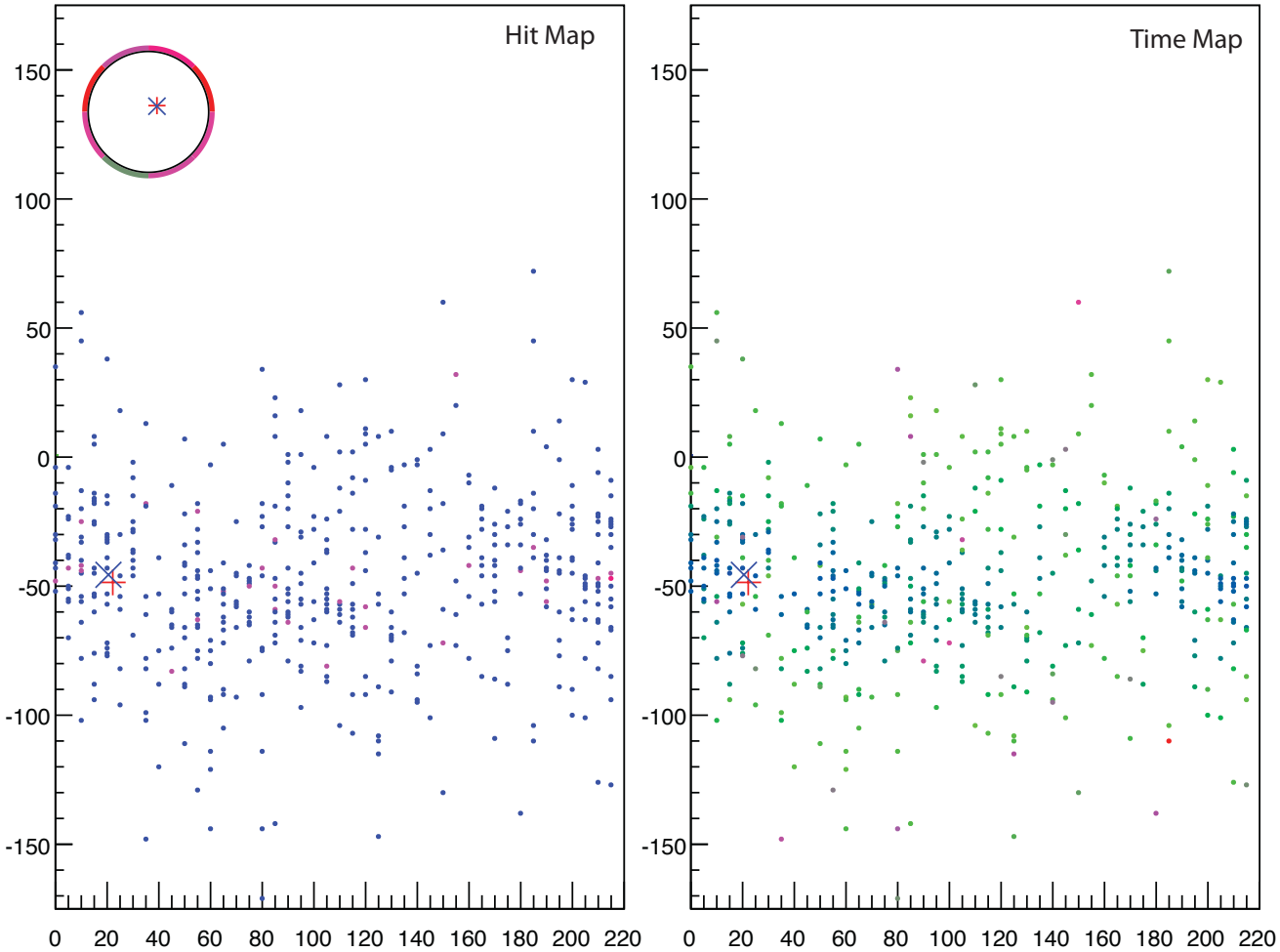


Pure speculation…
High density proton decay cylinder in ice



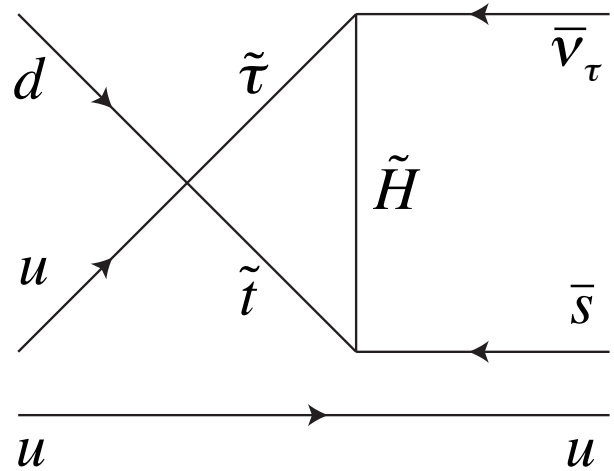
Example event

~ 1 pe/MeV
IceCube published scattering parameters



Chris Kachulis/B.U.

$p \rightarrow K^+ \nu$

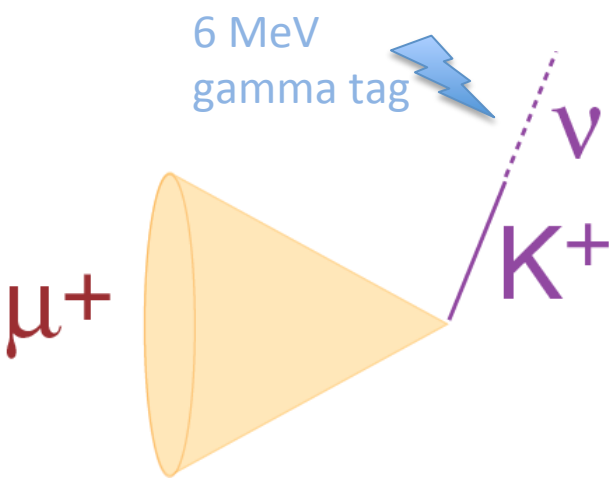


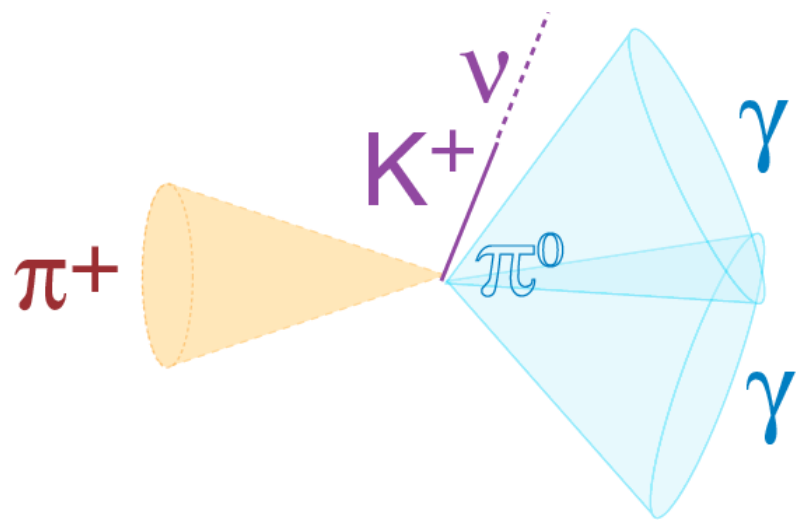
SUSY, better gauge unification
D=5 operator

Water: charged kaon below ch-threshold
but ^{16}O gamma can be used to tag in WC

Kaon decay energy and time well measured in LS

Charged kaon leaves distinctive track in LAr

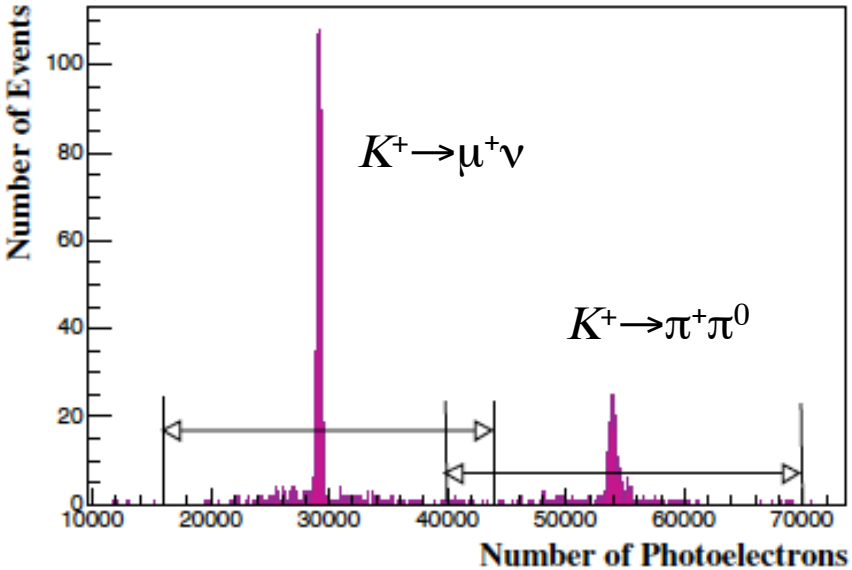




LENA

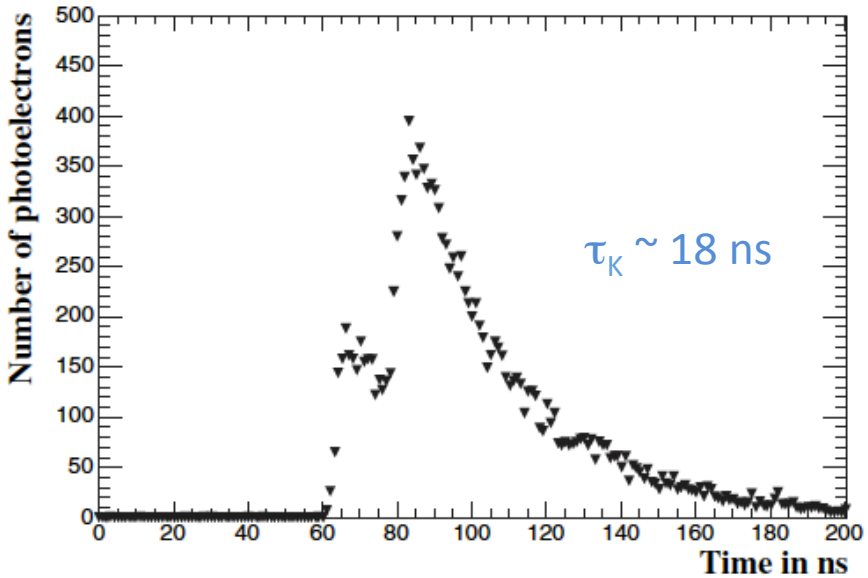
Low Energy Neutrino Astronomy

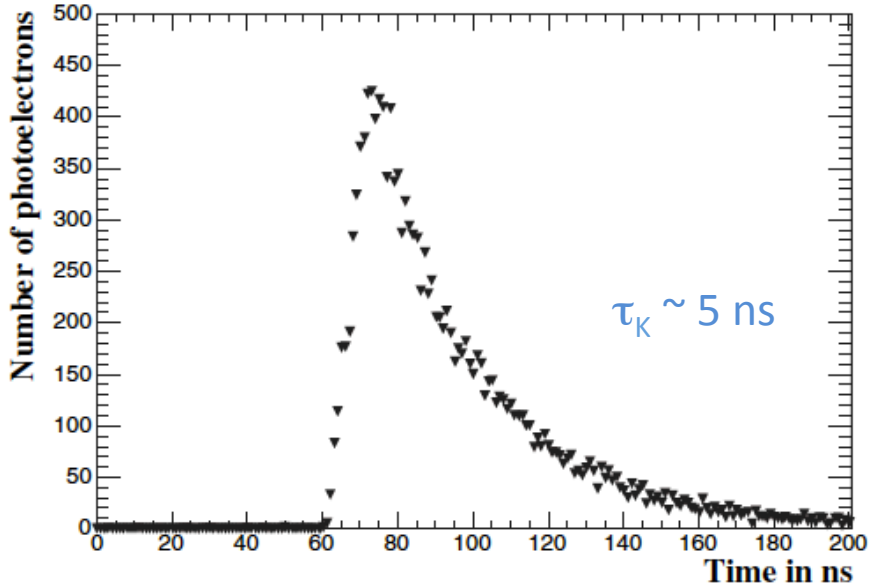
- 51 kt liquid scintilator (FV)
- 32m x 100m
- 30000 PMTs (30% with Winston cones)
- Water Cherenkov veto
- **200 photoelectrons/MeV (40x Super-K)**



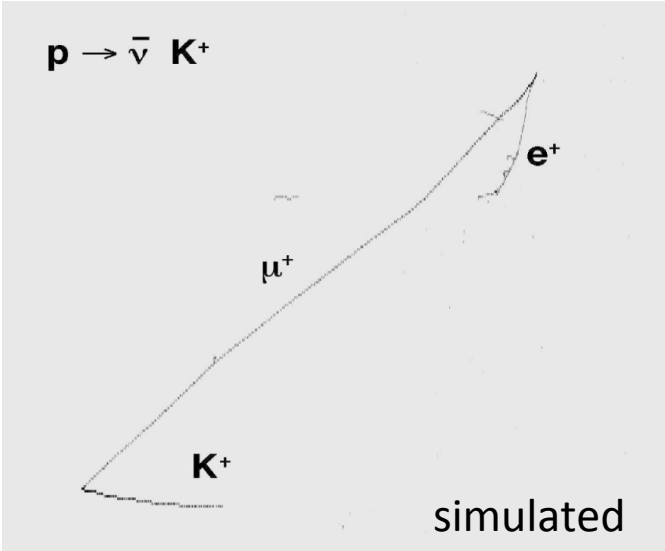
Astroparticle Physics 35 (2012) 685–732

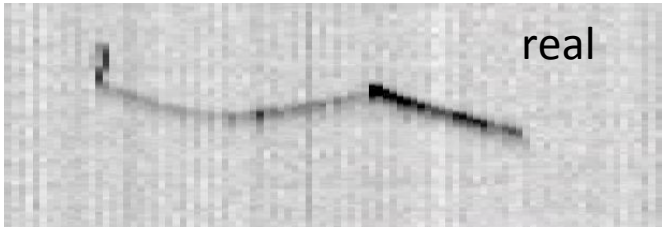
Residual Timing Distributions (single events)

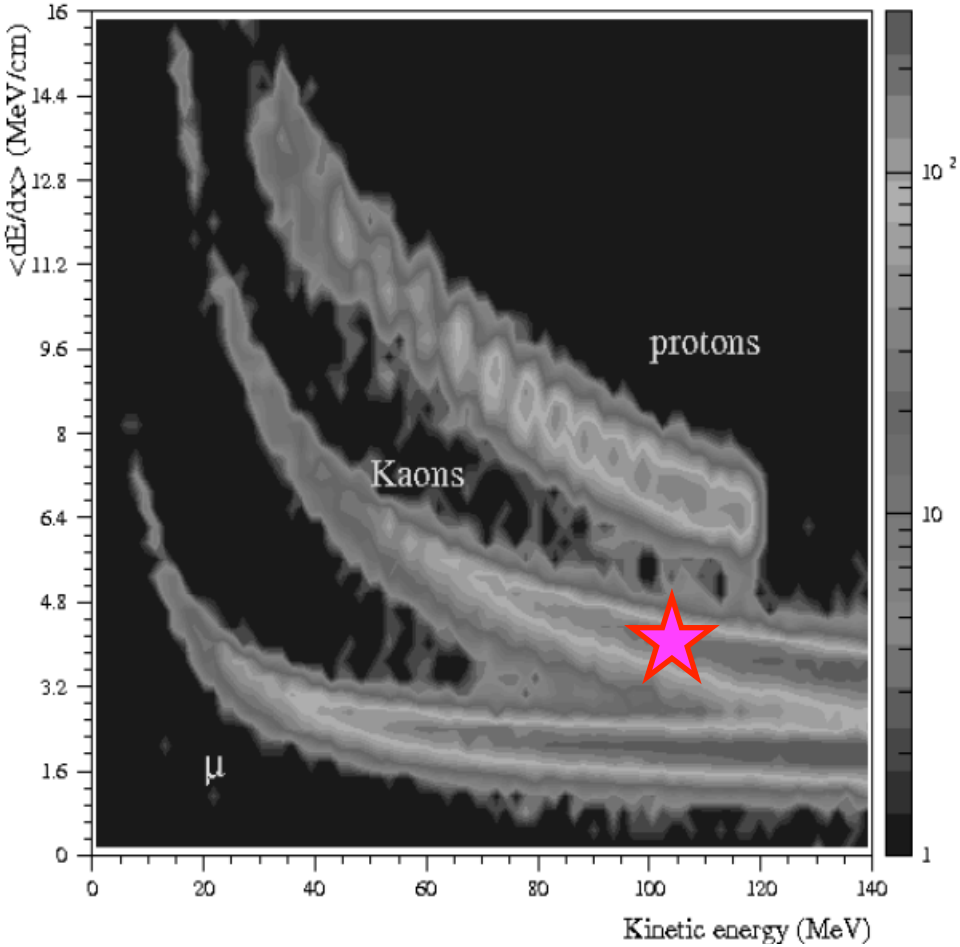




νK^+ in LAr





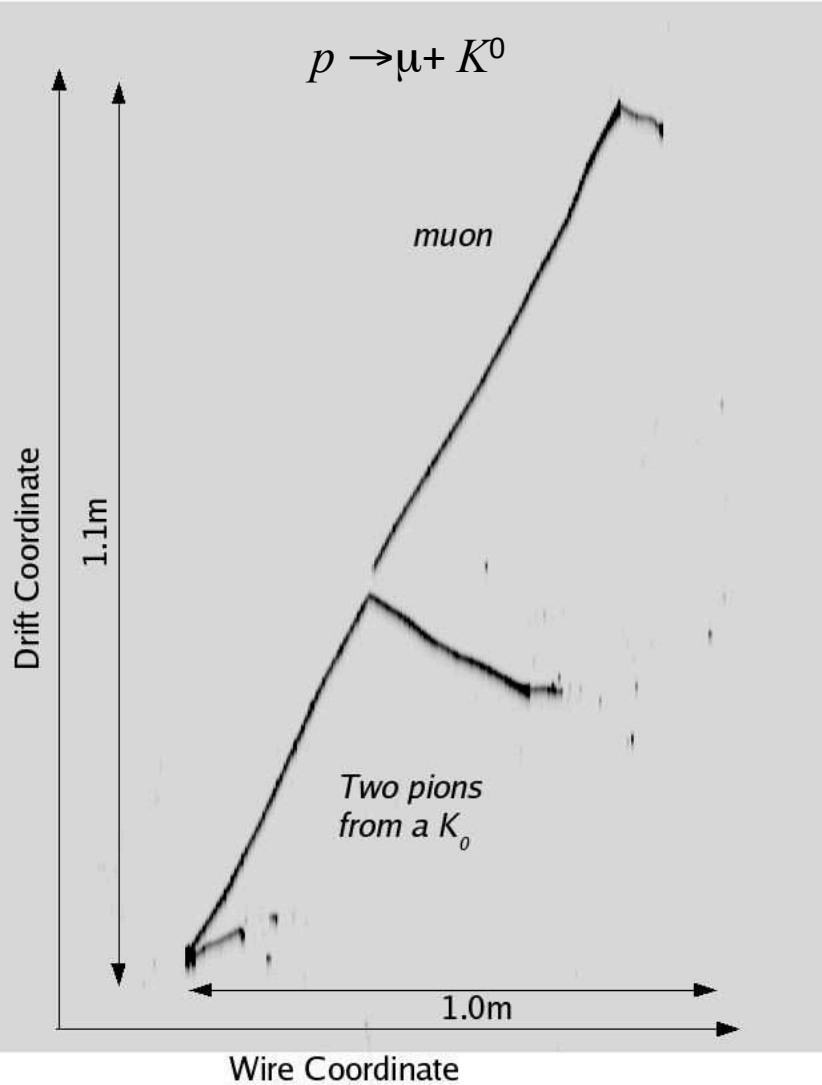


Cuts	(p3) $p \to K^+ \bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no π^0	96.8%	0	0	0	0	57	9
$E_{vis} < 0.8$ GeV	96.8%	0	0	0	0	1	0

Bueno et al.

What Other Modes are Good for LAr?

- Modes with charged kaon in final state
- Modes with displaced vertices ⇒
- Multiprong modes with no neutrino
- Lepton + light meson are no better than water due to nuclear absorption of the light meson.



What Other Modes are Good for LAr? (2)

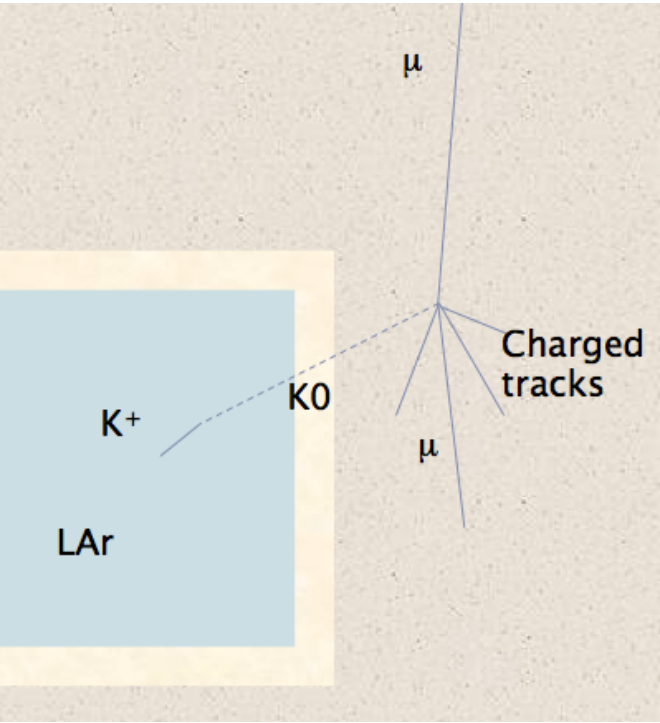
	Mode	Super-K Water Ch.		LAr (generic)	
		Efficiency	BG Rate (/Mt y)	Efficiency	BG Rate (/Mt y)
B-L	$e^+\pi^0$	45%	2	45%	1
B-L	νK^+	16%	7	**97%**	**1**
B-L	$\mu + K^0$	10%	5-10	**47%**	**<2**
B+L	$\mu^- \pi^+ K^+$	?	?	**97%**	**1**
B+L	$e^- K^+$	10%	3	**96%**	**<2**
$\Delta B=2$	n nbar	12%	260	**?**	**?**

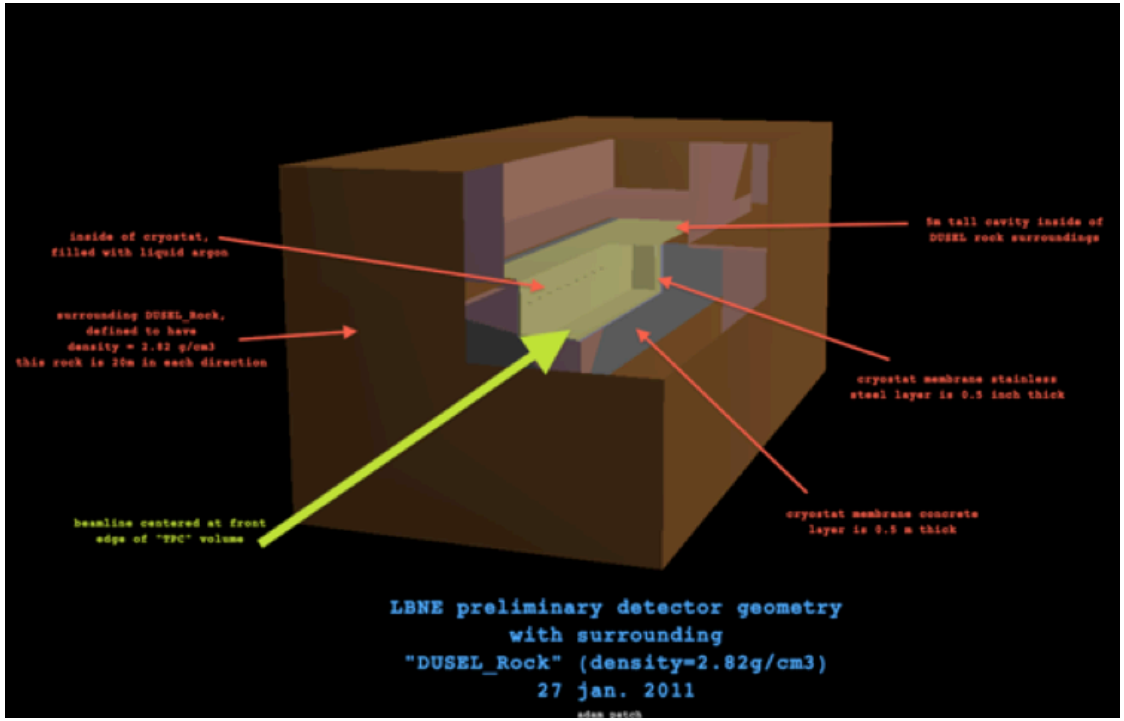
Rough and unofficial
SK efficiency & BG - ETK

A. Bueno et al.
hep-ph/0701101

LAr Veto

- Background is entering K^0 with charge exchange from nearby cosmic ray interactions
- Assume that an active veto can be constructed to achieve a background rate reduction comparable to simply going to great depth
- Still require 1.8 m fiducial boundary for self-shielding
  - 20 kton detector with 17 kton FV will have 14 kton FV for νK^+ proton decay



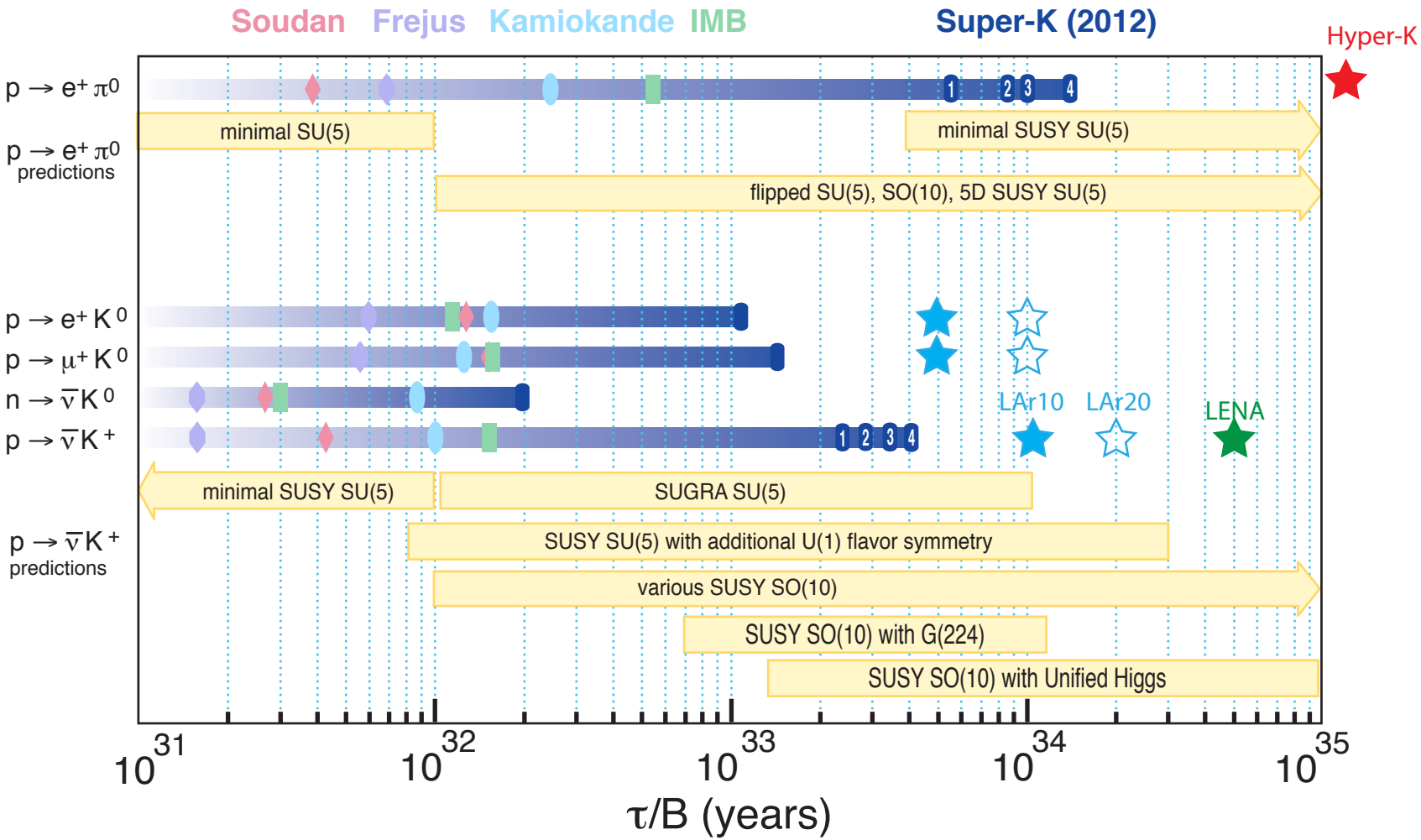


Summary for Project X Workshop

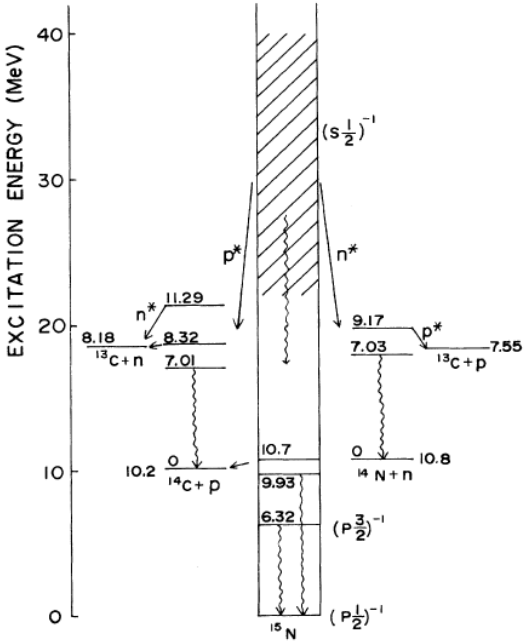
- See full talks on LBNE, Hyper-K, LENA
- LBNE is evaluating reconfiguration options
  - going underground, to achieve good shielding, enables a rich program including proton decay and nnbar
- Next generation proton decay projects are gaining steam in Europe and Japan (NEXT SLIDE)
- R&D needed to make these experiments economical

  See talks on photodetector R&D, water based LS, Light collection, reconstruction, modeling…

10 year exposures



BACKUP & EXTRA



Nuclear Physics of Proton Decay in ^{16}O

Spectroscopic factors measured in ^{16}O(e,ep)^{15}N experiment

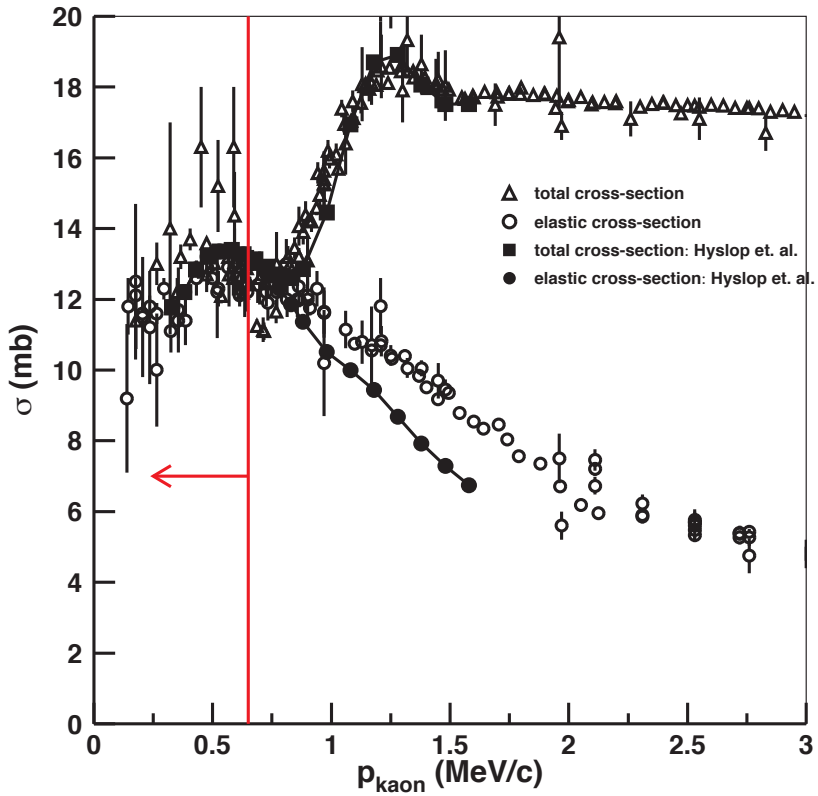
Gamma-ray emission measured in ^{16}O(p,2p)^{15}N experiment

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

H. Ejiri Phys. Rev. C48 (1993)

Are Nuclear Effects Important for K?

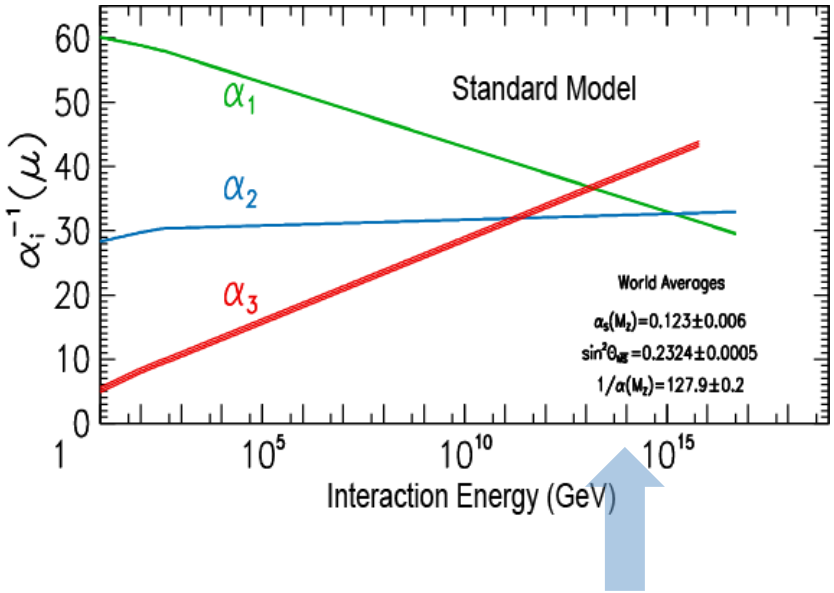
Kaon escapes the nucleus

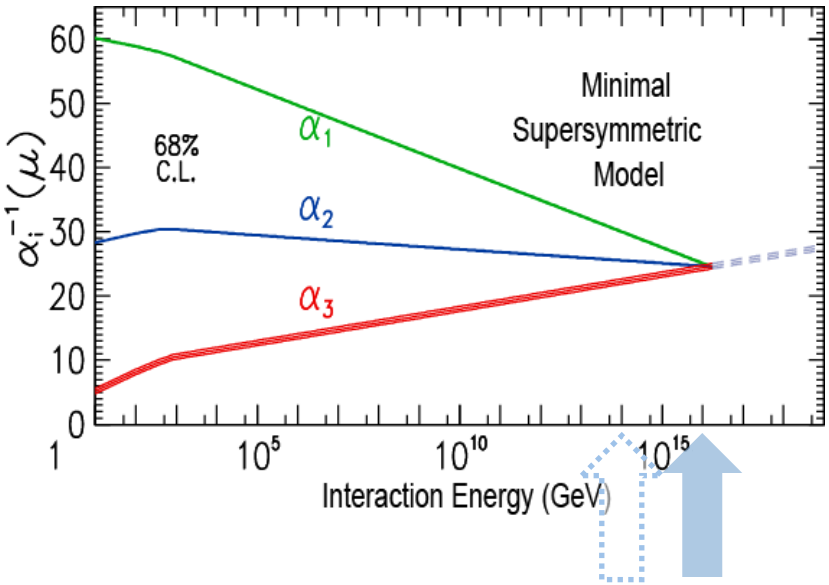


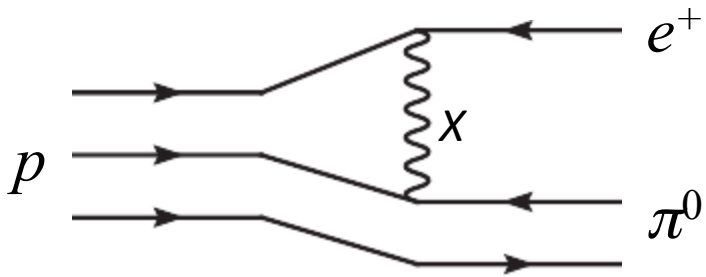
Full modeling involves:

- Woods-Saxon nuclear density distribution
- Fermi motion
- Effective mass distribution
- Intranuclear scattering

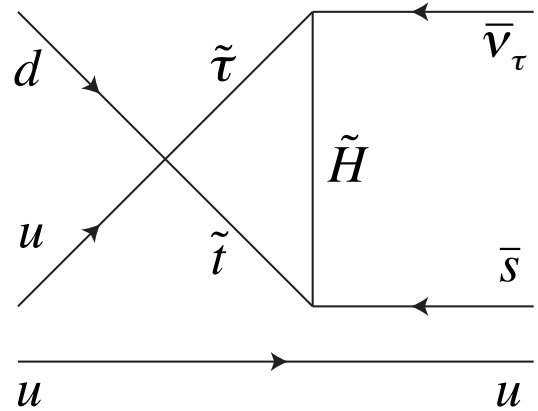
Unification of Running Coupling Constants

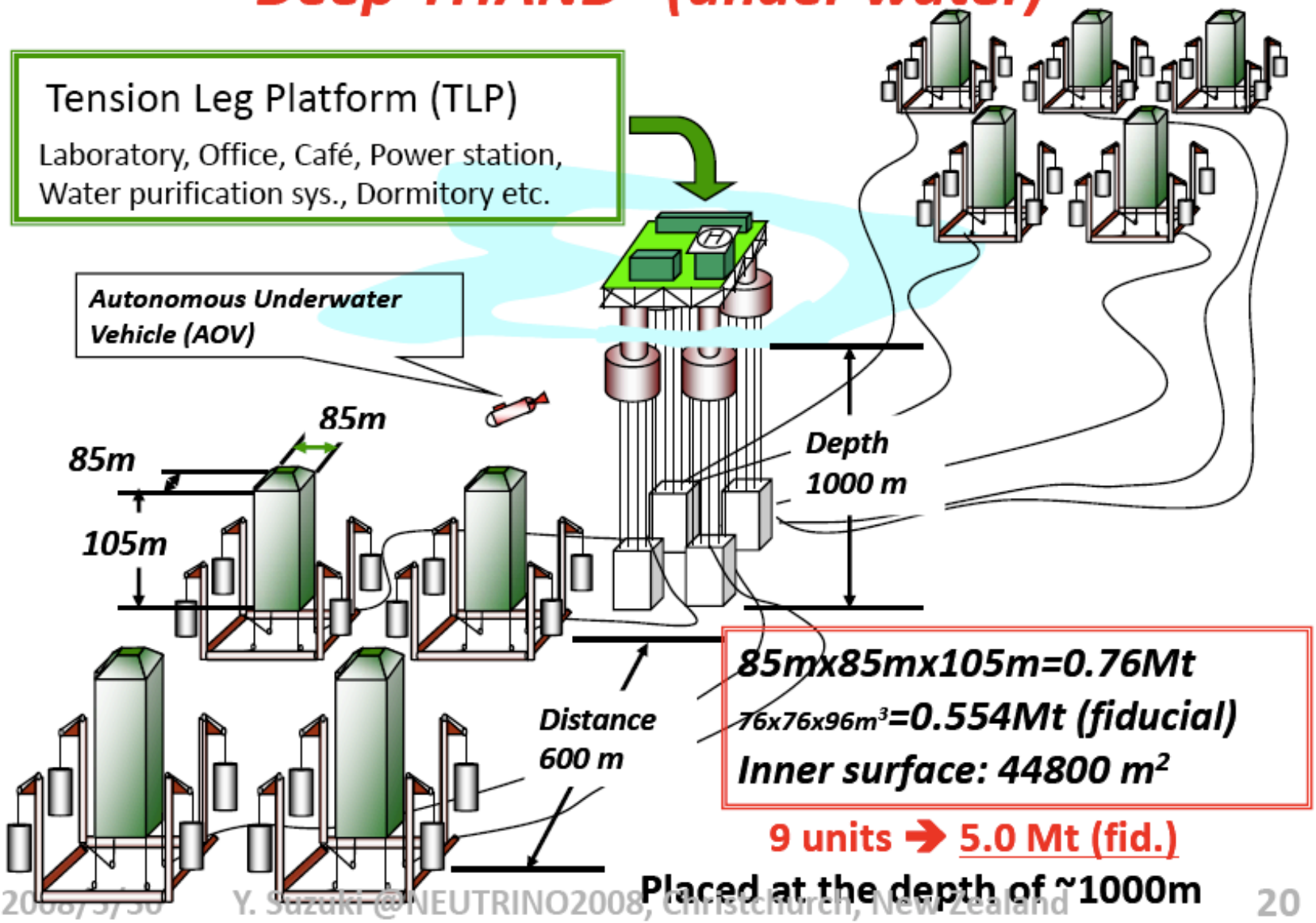






$\tau/B = 4.5 \times 10^{29\pm1.7}$years SU(5)



$\tau/B = 10^{29-35}$years SUSY

Deep-TITAND (under water)