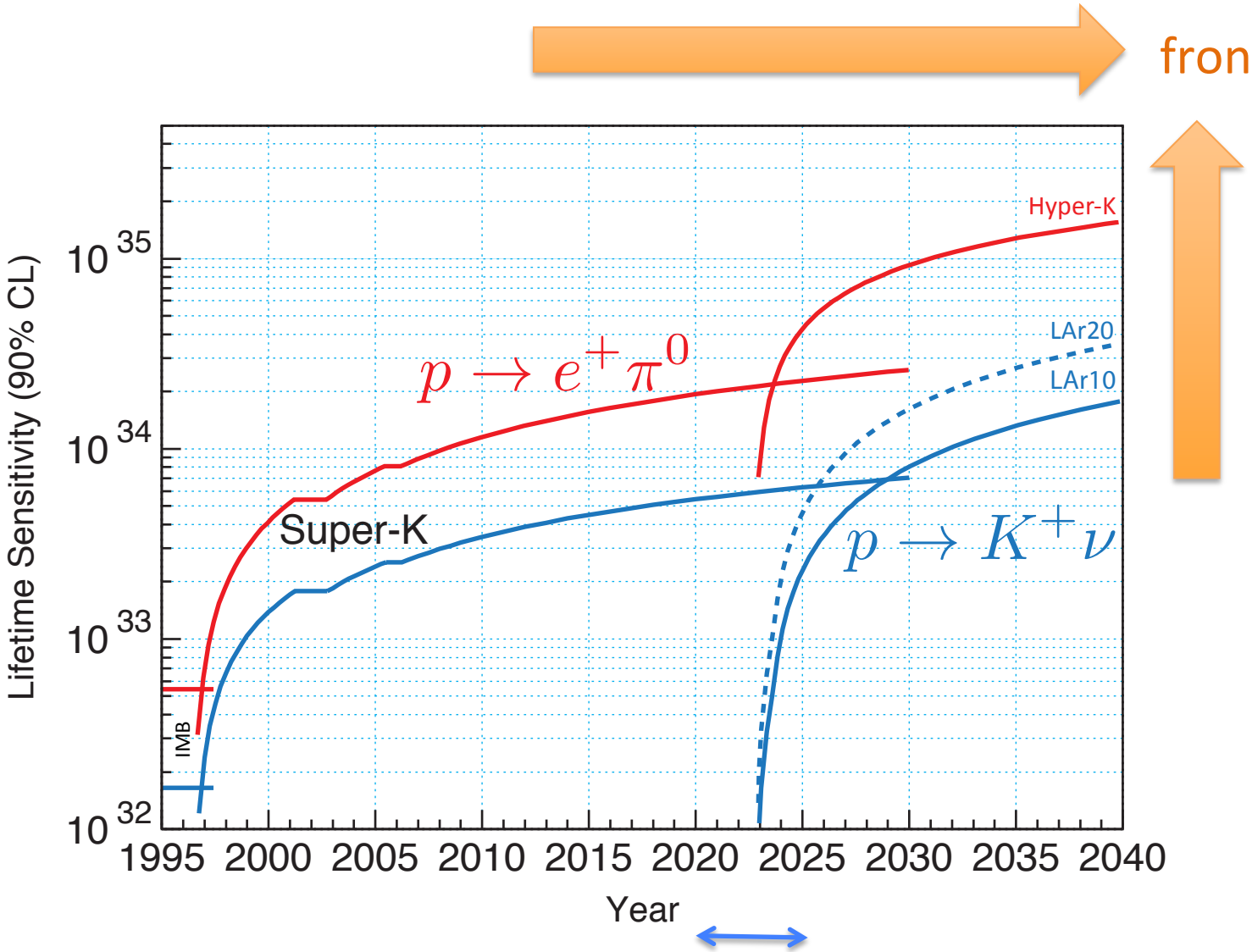
Experimental Frontiers in Nucleon Decay

Ed Kearns, Boston University

NNN 2012
Next Generation Nucleon Decay and Neutrino Detectors

October 4 - 6, 2012 Fermi National Accelerator Laboratory



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

Starting time? Guess 1 decade from now.
Adjust starting time as you wish.

What moves us towards the frontiers?

- Continue exposure
- Improve analysis
- Search in new channels

} Super-K

- Next generation experiments
  - Detector R&D
  - Experiment proposals

} NNN

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

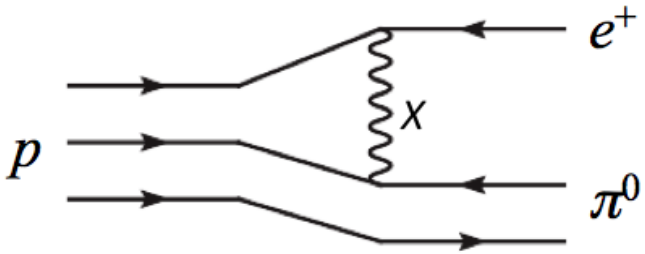
How to improve existing analyses

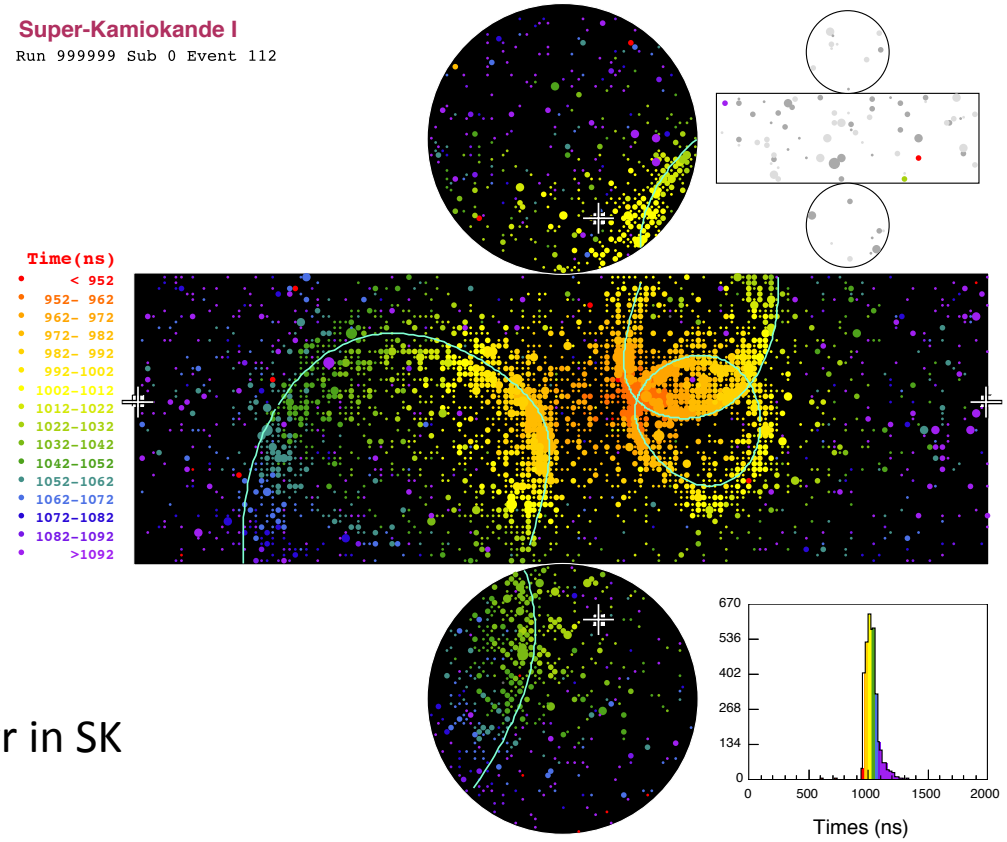
- Sensitivity is based on:

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

- Achieve: higher efficiency, lower background rate
- Also important: improve accuracy of model (signal and/or BG) (which may increase or reduce sensitivity)
- Also: reduce systematic uncertainty
- None of this is easy – gains will be small and hard fought
- Increased exposure – gains are now minimal

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



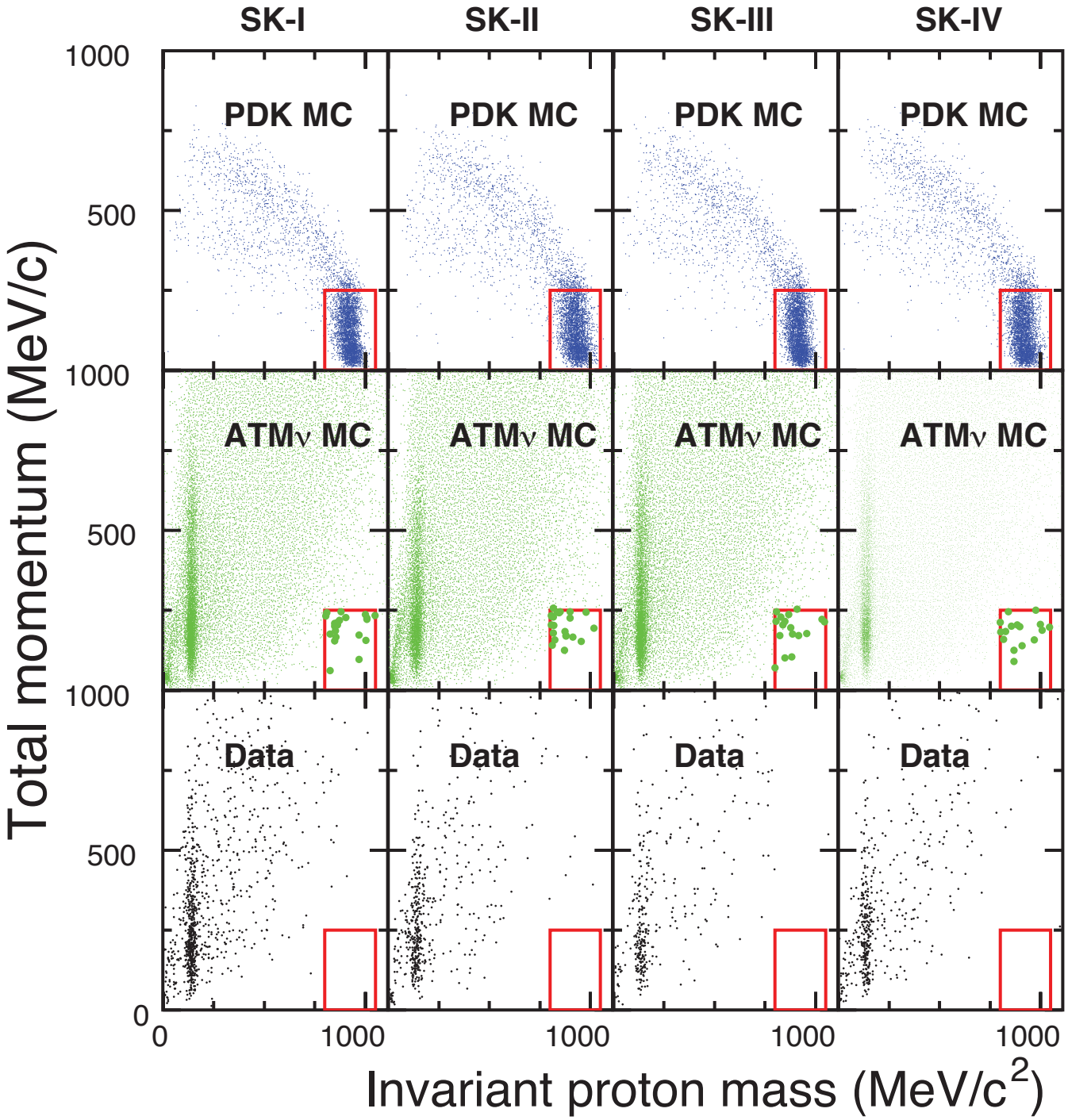


Simple signature: back-to-back reconstruction of EM showers.

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

Low background ~0.2 events/100 ktyr in SK

Relatively insensitive to PMT density.



SK 1+2+3+4
$\tau/B > 1.3 \times 10^{34}$yr
PhysRevD.85.112001

Efficiency and Background

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 (ev/Mt y)	SK1	SK2	SK3	SK4
$e^+\pi^0$	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

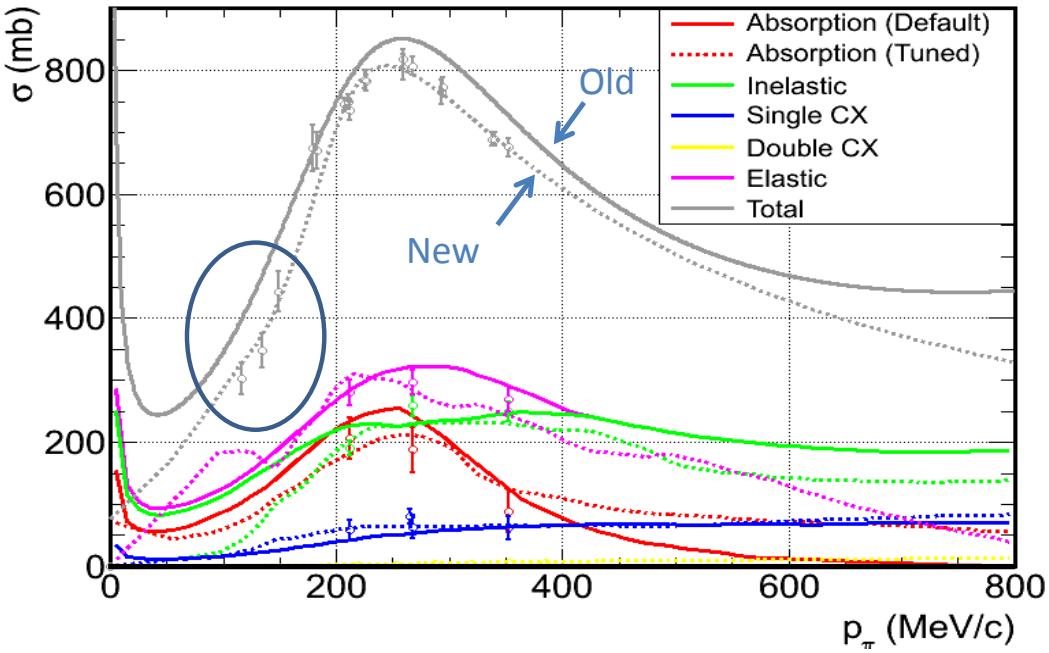
- Background rate checked using K2K near detector:

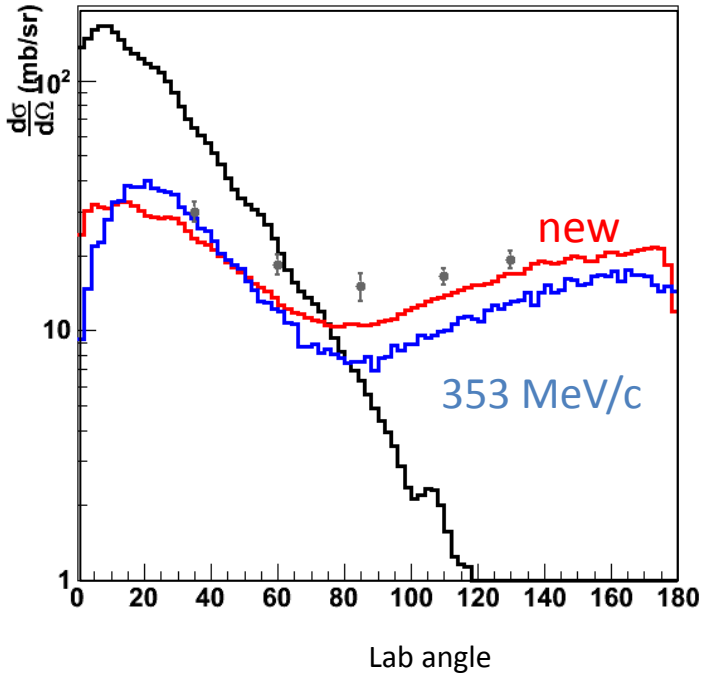
$$e^+\pi^0 \text{ BG} = 1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{sys.}) \text{ evts/Mt} \cdot \text{yr}$$

PHYSICAL REVIEW D 77, 032003 (2008)

Continual Improvements

E.g. Pion interaction Monte Carlo (NEUT) – intranuclear scattering





Also:

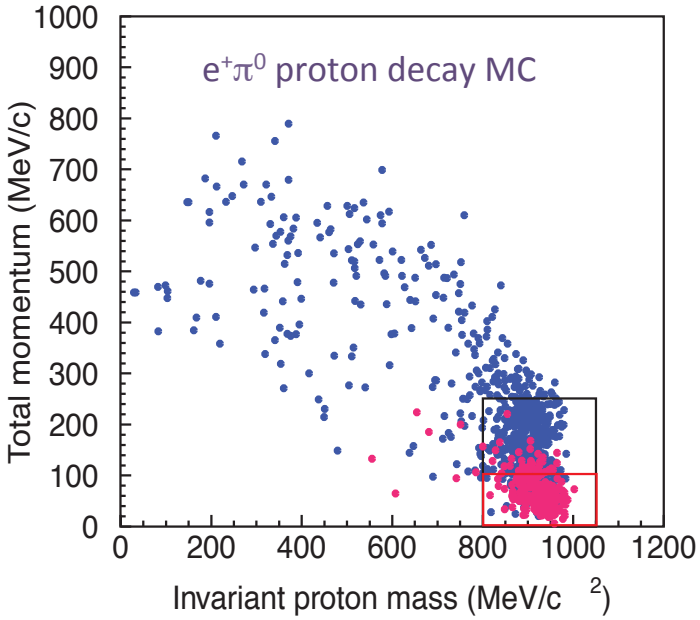
Detector simulation tuning

Improved reconstruction ("all new" is in the works)

Atmospheric neutrino flux, cross section

Background Reduction Strategies

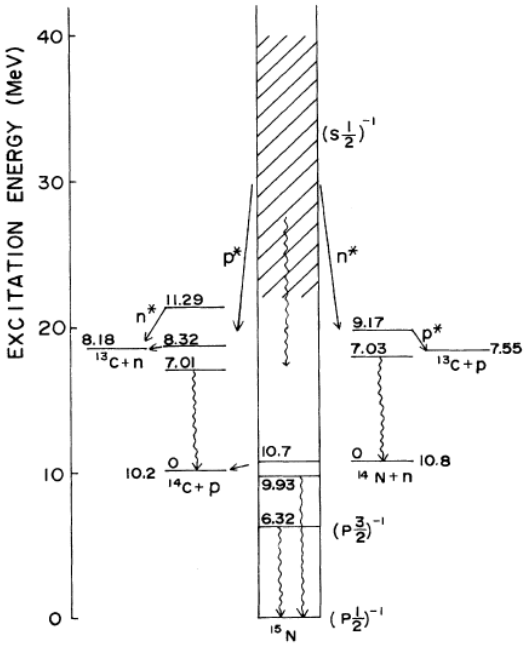
- Tight Cuts on Free Proton
  - efficiency ~ 17%
  - BG 0.015 evts/100 kton yr
  - change over around 10-20 Mton yr
- Gadolinium
  - high energy neutrino events are accompanied by n
  - assume proton decay is not accompanied by n
    - * surely not for free proton
    - * also not for γ-tag states
 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



Background events for $p \rightarrow e^+\pi^0$ (4.5Megaton years)

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

M. Shiozawa NNN09



Nuclear Physics of Proton Decay in ^{16}O

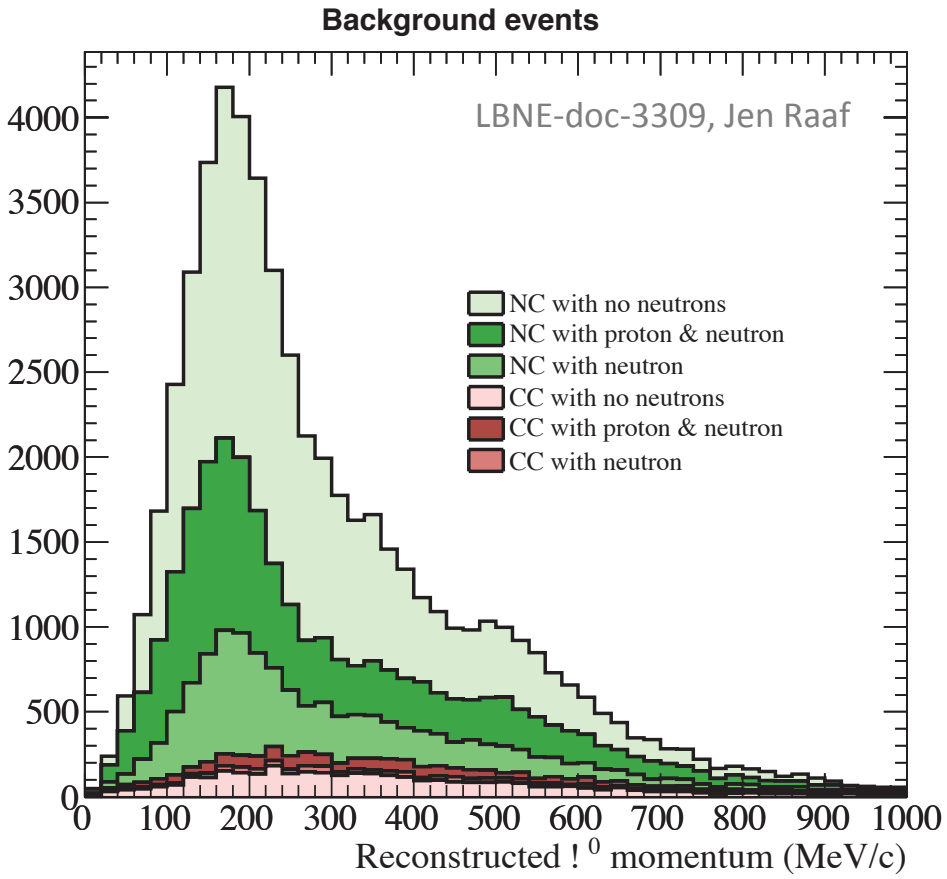
Spectroscopic factors measured in $^{16}O(e,ep)^{15}N$ experiment

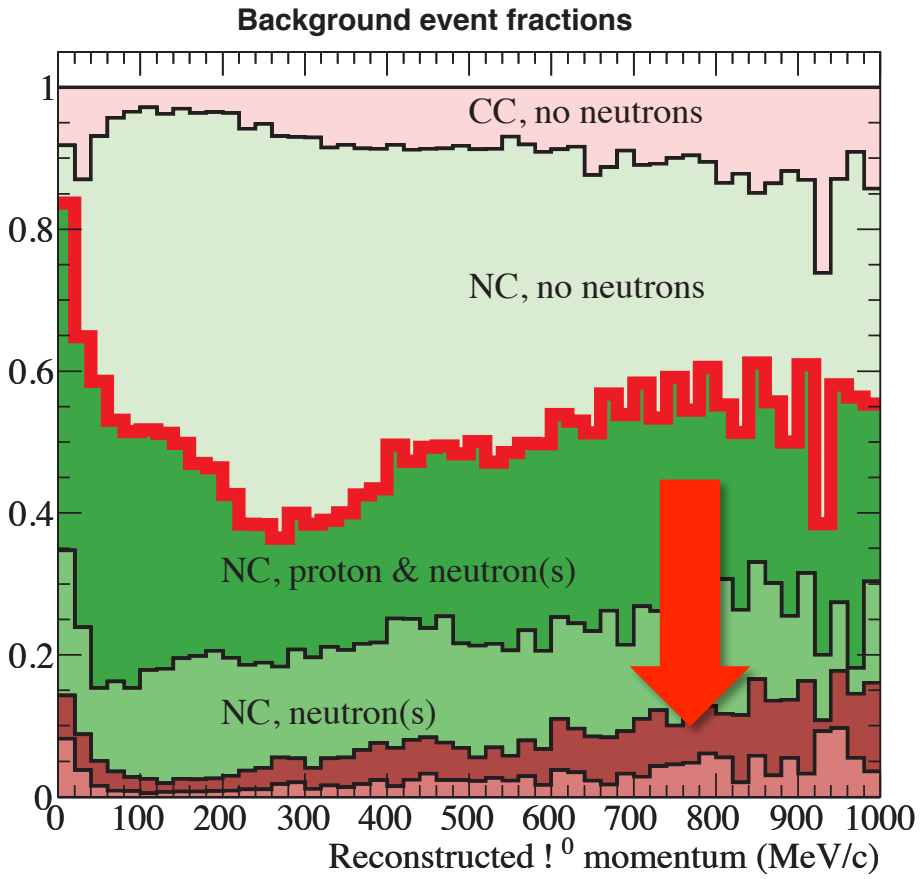
Gamma-ray emission measured in $^{16}O(p,2p)^{15}N$ experiment

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)

Neutron Production Study





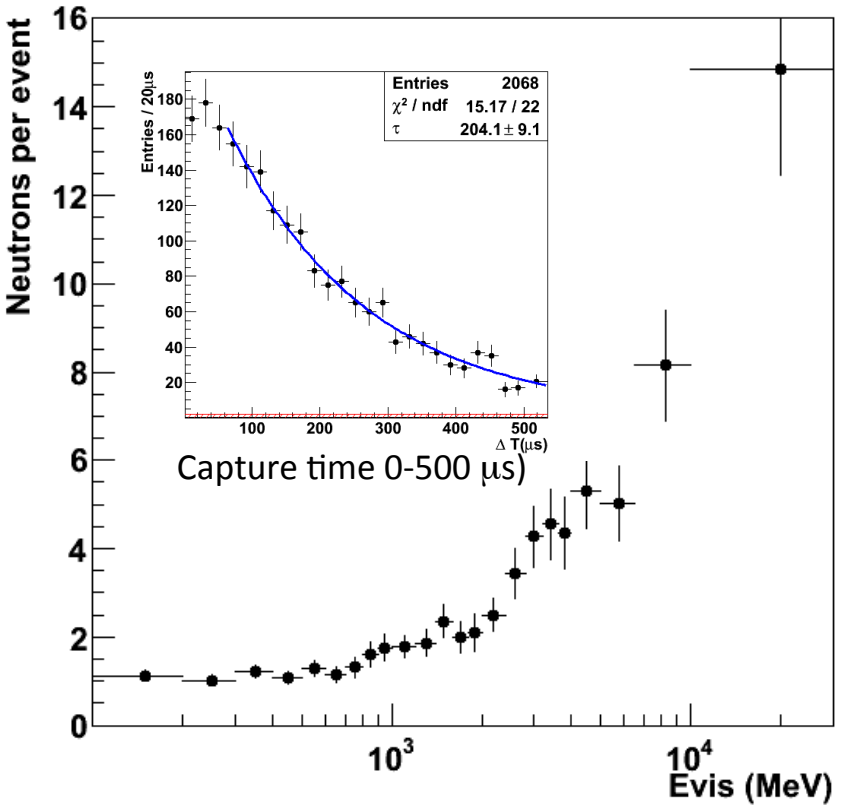
SK Atmospheric neutrino single π^0 events
Direct background to $n \rightarrow \pi^0 \nu$
Related process to backgrounds for $p \rightarrow e^+ \pi^0$

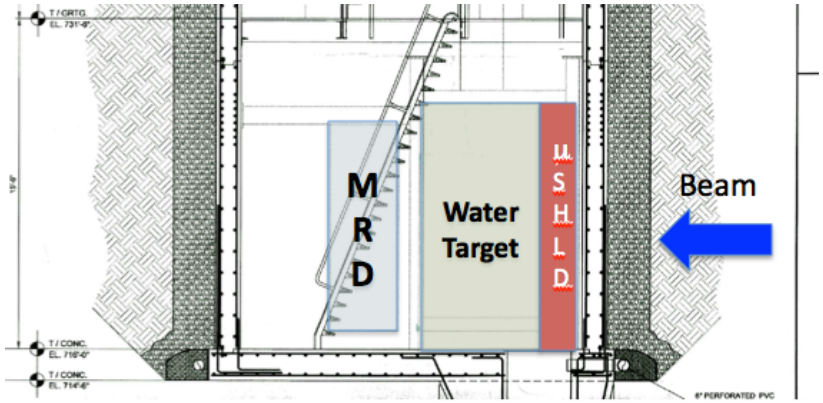
46% of background events with neutrons

Neutron Production with ν: Experiments

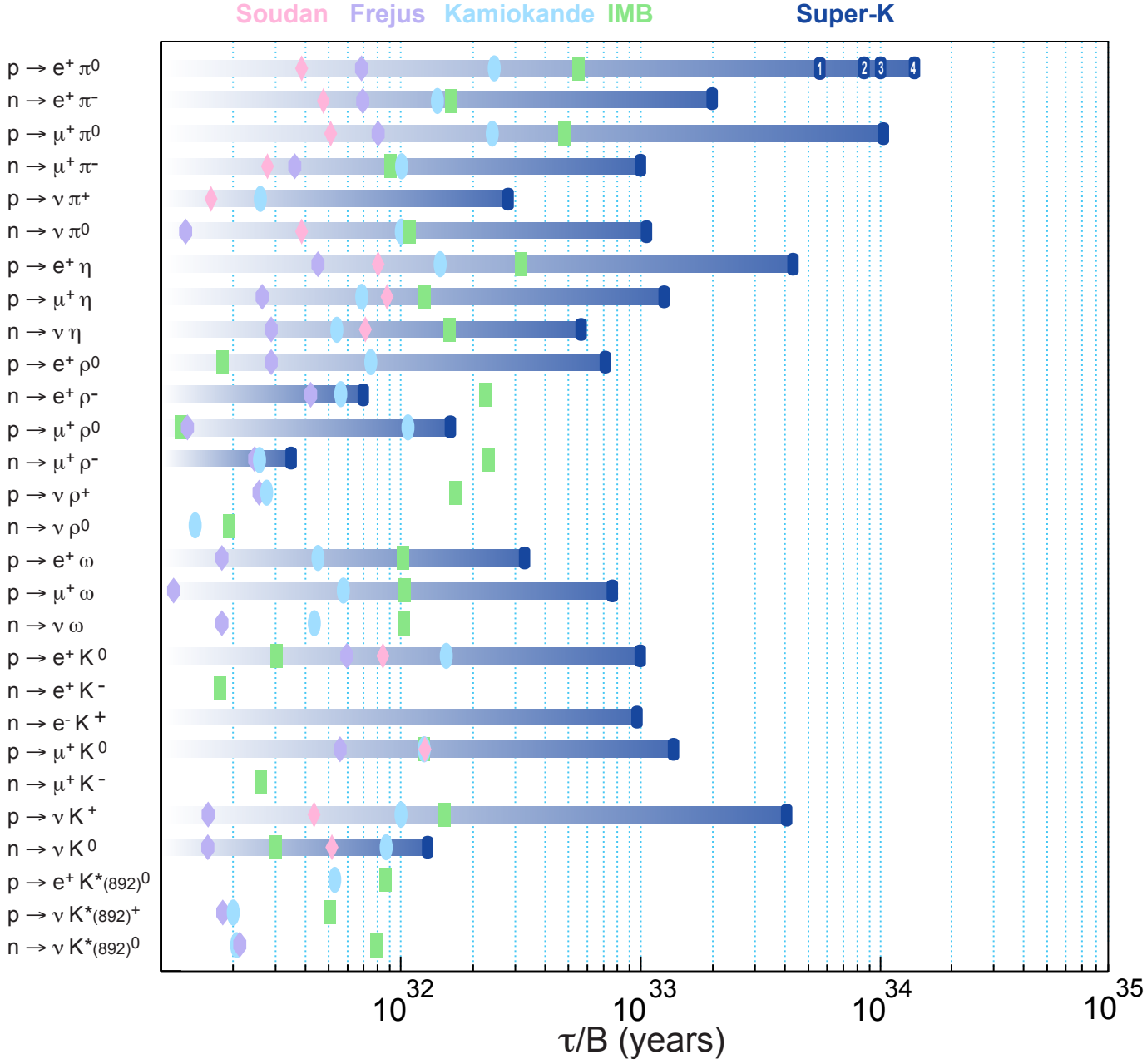
- New SK electronics (SK4 only) allows search for neutron associated with atmospheric neutrinos (capture on free proton, 2.2 MeV γ).
- Other current, near future, and recent past experiments can also search. T2K, SciBooNE e.g.
- Dedicated new experiment (ANNIE) under discussion.

SK4 Preliminary
Efficiency corrected n yield





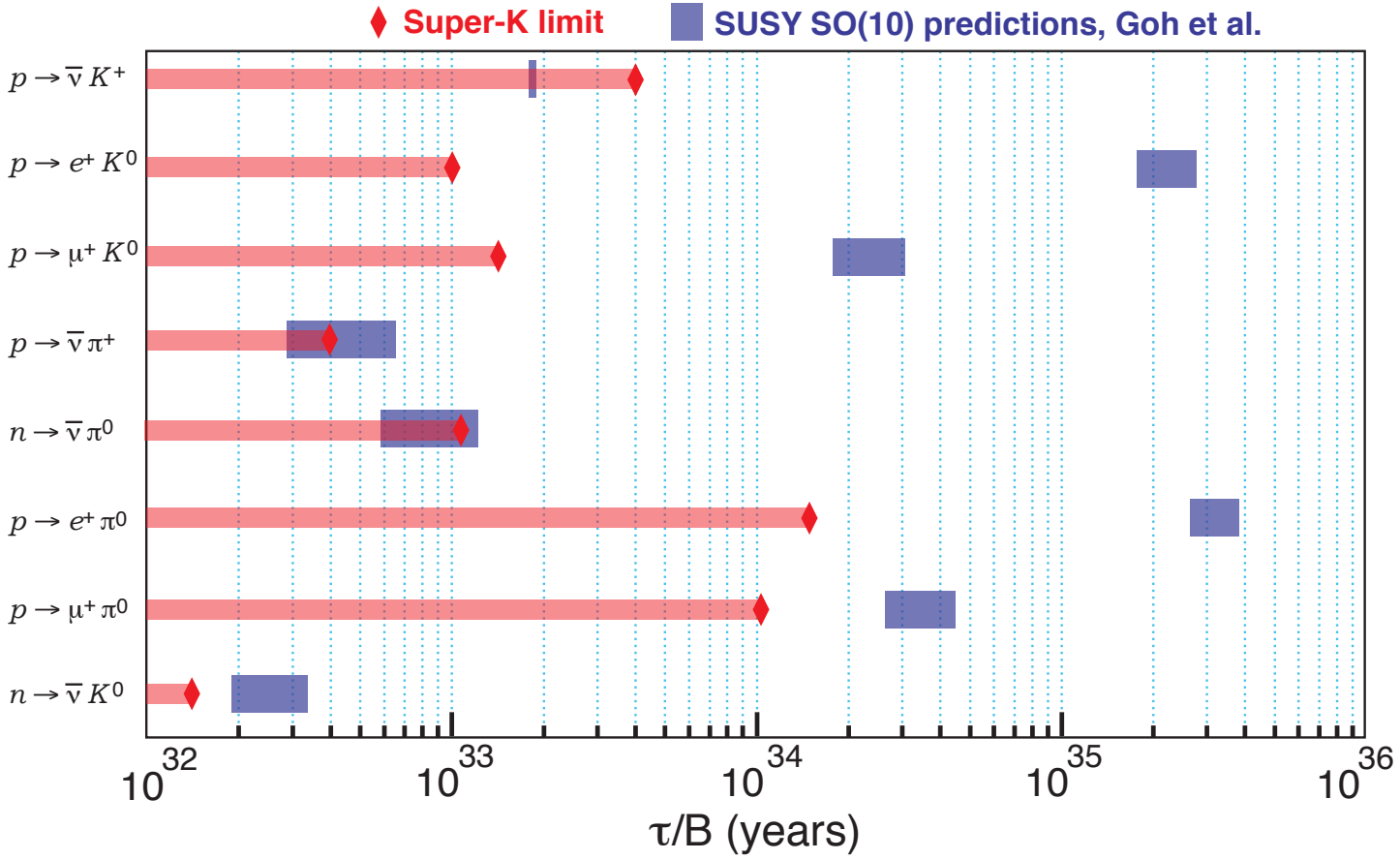
Antilepton + Meson Two-Body Modes



CASE STUDY:
Using inclusive searches to constrain a particular model

SUSY SO(10), B-L broken by 126-Higgs† H.S.Goh, R.N.Mohapatra, S.Nasri, S-P. Ng, Phys Lett B587:105-116 (2004)

- predicts neutrino mixing well
- scan over parameter space – find unconstrained branching fraction
  - maximize n → ν π^0
  - N.B.: old ν K^+ limit used as fixed constraint



		× 10^{30} years	
τ_1	$N \to e^+ \pi$	13000 SK1+2+3+4*	
	...	> 158 (n), > 8200 (p)	90%
τ_{16}	$N \to \mu^+ K$	1600 SK1+2+3**	
	...	> 26 (n), > 120 (p)	90%
τ_{19}	$N \to \nu K$	4000 SK1+2+3+4 preliminary	
	...	> 86 (n), > 670 (p)	90%

22 antilepton + meson modes (B-L)*
7 antilepton + mesons (3-body) modes
12 lepton + meson modes (B+L)***
16 more exclusive modes
5 inclusive modes
13 dinucleon decay modes

* H. Nishino *et al.* Phys.Rev.D.85.112001 (12 modes)
** C. Regis *et al.* Phys.Rev.D.86.012006 (K_S + K_L)

*** Super-K preliminary
$n \longrightarrow e^- K^+$ $\tau/B > 9.9 \times 10^{32}$ yr (90% CL)

Q: What other modes are interesting?

CASE STUDY:
Dinucleon Decay $pp \longrightarrow K^+K^+$

Allow R-parity violation to reduce fine-tuning†

† L. Carpenter, D.E., Kaplan S.Nasri, E. Rhee, hep-ph/0607204v3

- allows one to sneak in a light Higgs
- avoid fast proton decay by allowing B-violation only and not also L

$$W \supset \mu_i L_i \bar{H} + \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k \quad \Leftarrow \text{violates Lepton number}$$

$$+ \lambda''_{ijk} U^c_i D^c_j D^c_k, \quad \Leftarrow \text{violates Baryon number}$$

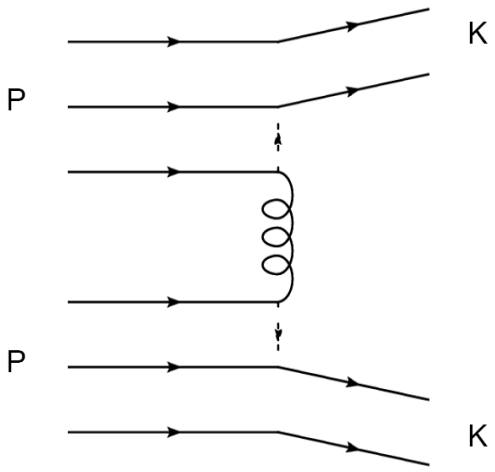
- existing constraints on coupling λ'' taken from dinucleon decay (!)

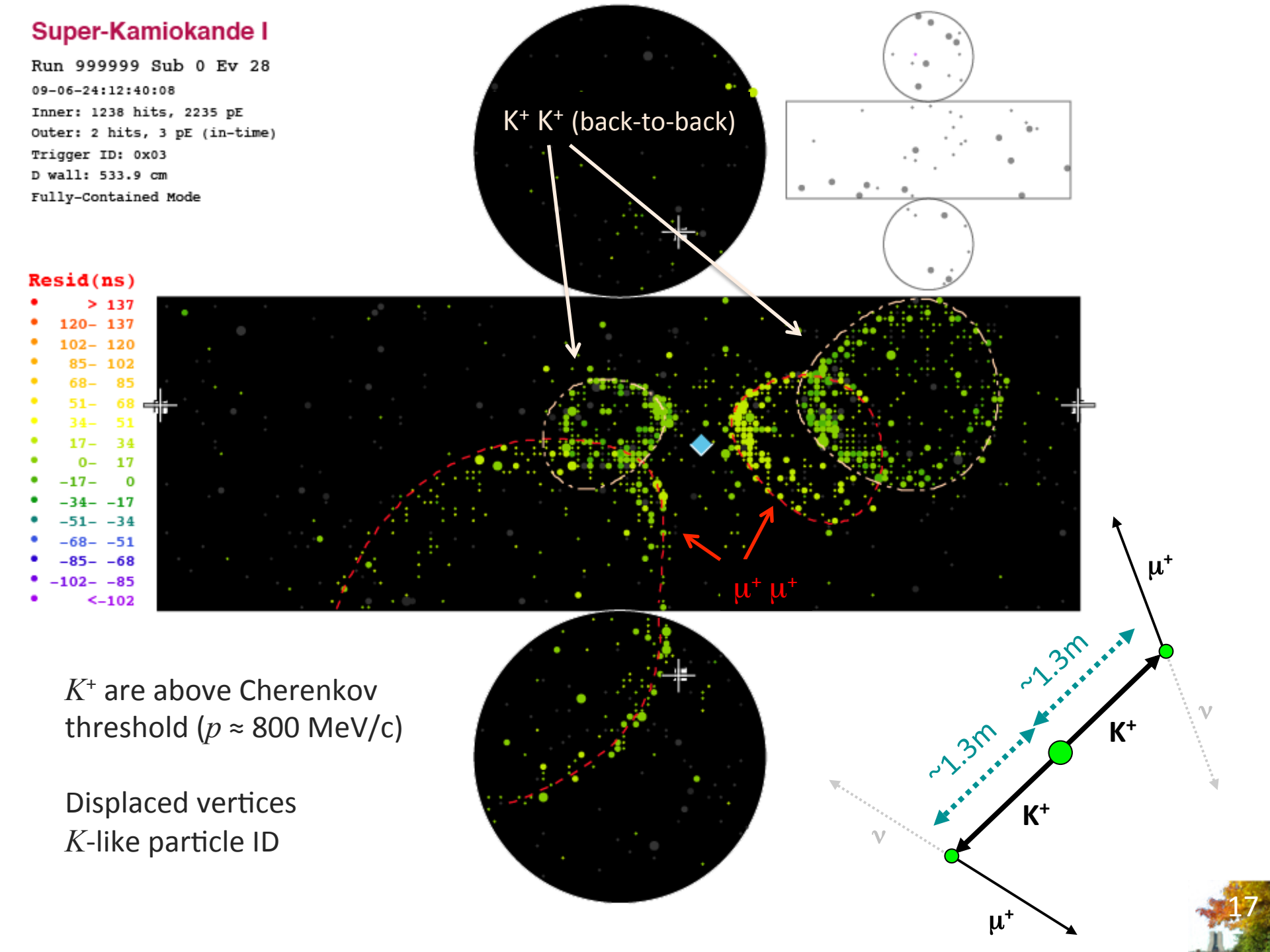
$\Delta B = 2$ dinucleon modes

The following are lifetime limits per iron nucleus.

τ_{64}	$pp \to$	$\pi^+\pi^+$	> 0.7
τ_{65}	$pn \to$	$\pi^+\pi^0$	> 2
τ_{66}	$nn \to$	$\pi^+\pi^-$	> 0.7
τ_{67}	$nn \to$	$\pi^0\pi^0$	> 3.4
τ_{68}	$pp \to$	e^+e^+	> 5.8
τ_{69}	$pp \to$	$e^+\mu^+$	> 3.6
τ_{70}	$pp \to$	$\mu^+\mu^+$	> 1.7
τ_{71}	$pn \to$	$e^+\overline{\nu}$	> 2.8
τ_{72}	$pn \to$	$\mu^+\overline{\nu}$	> 1.6
τ_{73}	$nn \to$	$\nu_e\overline{\nu}_e$	> 0.000049
τ_{74}	$nn \to$	$\nu_\mu\overline{\nu}_\mu$	
τ_{75}	$pn \to$	invisible	$>2.1 \times 10^{-5}$
τ_{76}	$pp \to$	invisible	> 0.00005

- These limits are per Fe nucleus, from Frejus experiment, circa 1991
- No searches for $NN \to KK$



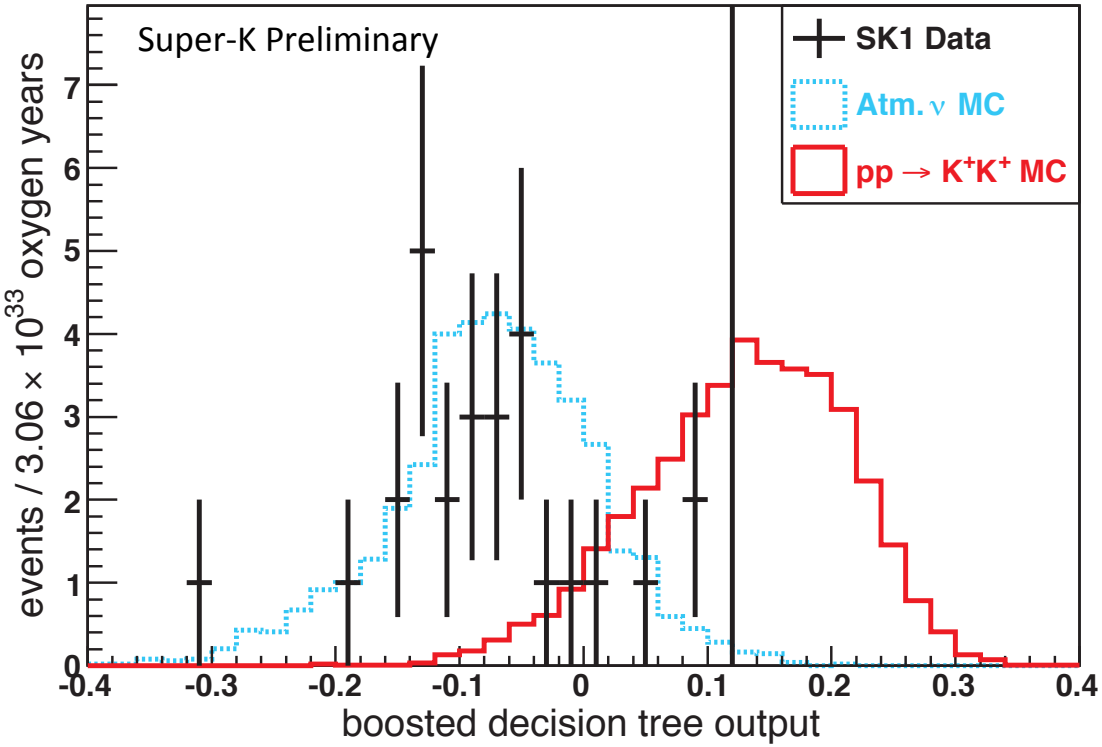


K^+ are above Cherenkov threshold ($p \approx 800$ MeV/c)

Displaced vertices

K-like particle ID

Dinucleon Decay $pp \longrightarrow K^+K^+$ Results

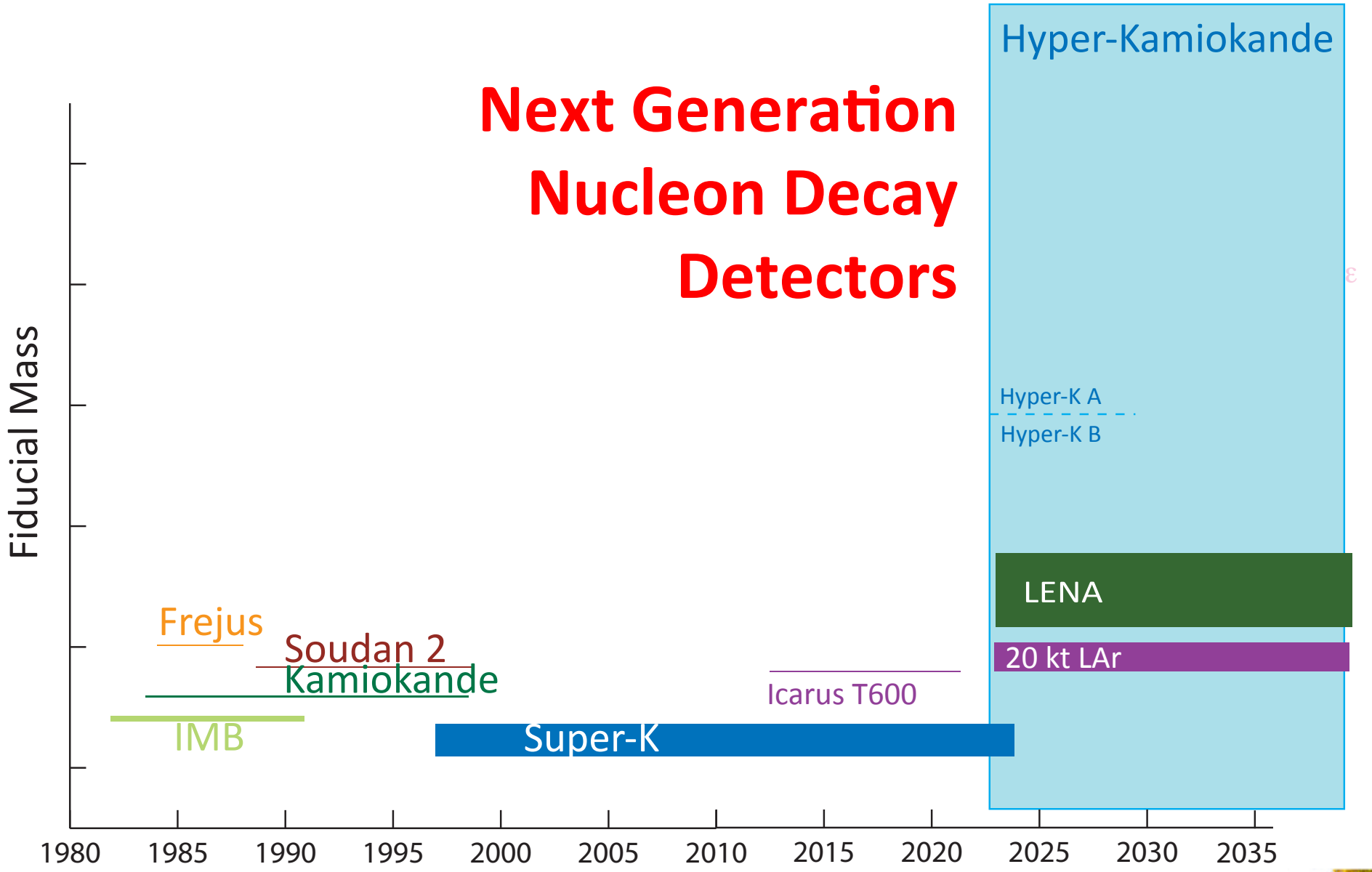


M. Litos, Ph.D. thesis

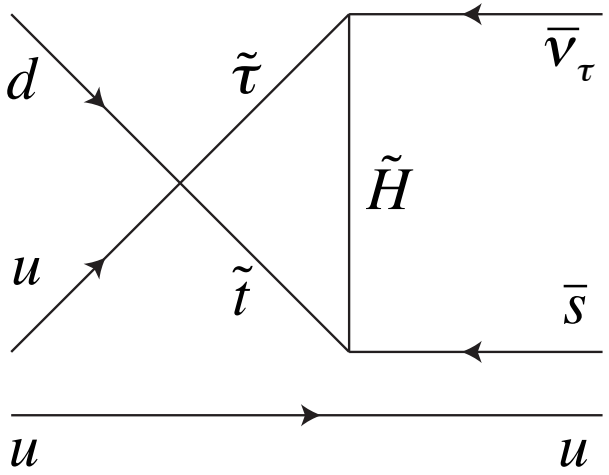
$\tau/B > 1.7 \times 10^{32}$ years
(90% CL, SK1)
$\lambda''_{112} < 8 \times 10^{-9}$

Two orders of magnitude smaller than limit inferred from Frejus results (non KK): Goity & Sher, PLB346 (1995)

Next Generation Nucleon Decay Detectors



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



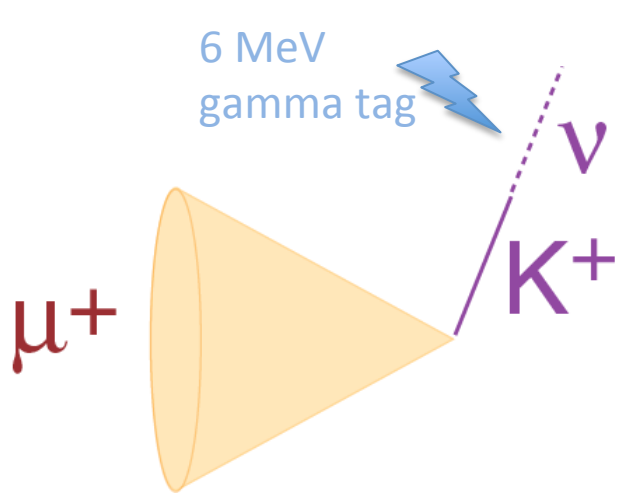
SUSY, better gauge unification
D=5 operator

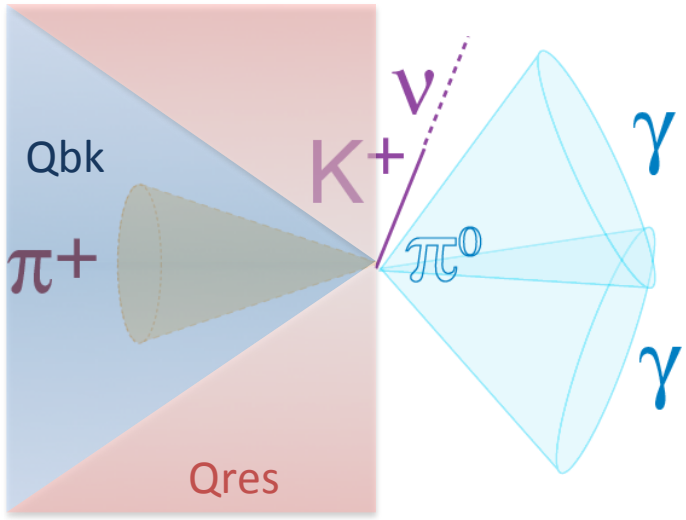
Water: charged kaon below Cherenkov threshold but ^{16}O gamma can be used to tag in WC (ε ~ 16% for 2 low BG kaon modes)

Liquid Scintillator: Kaon decay energy and time well measured in LS (ε ~ 65%)

LAr TPC: Charged kaon leaves track with correct dE/dx (ε ~ 97%)

νK^+ in Water Cherenkov





γ-tag and $\pi^+\pi^0$	SK1	SK2	SK3	SK4
Efficiency	13.7 %	11.1 %	13.9 %	16.1 %
Background rate (/Mt y)	6.7 ± 0.7	8.3 ± 0.8	5.7 ± 0.8	8.0 ± 0.8

No candidates, 220 kton yr (SK 1+2+3+4):

$$p \to \nu K^+ \tau / B > 4.0 \times 10^{33} \text{ years}, 90\%\text{CL}$$

LENA

Low Energy Neutrino Astronomy

- 51 kt liquid scintillator (FV)
- 32m x 100m
- 30000 PMTs (30% with Winston cones)
- Water Cherenkov veto

$p \longrightarrow \nu K+$

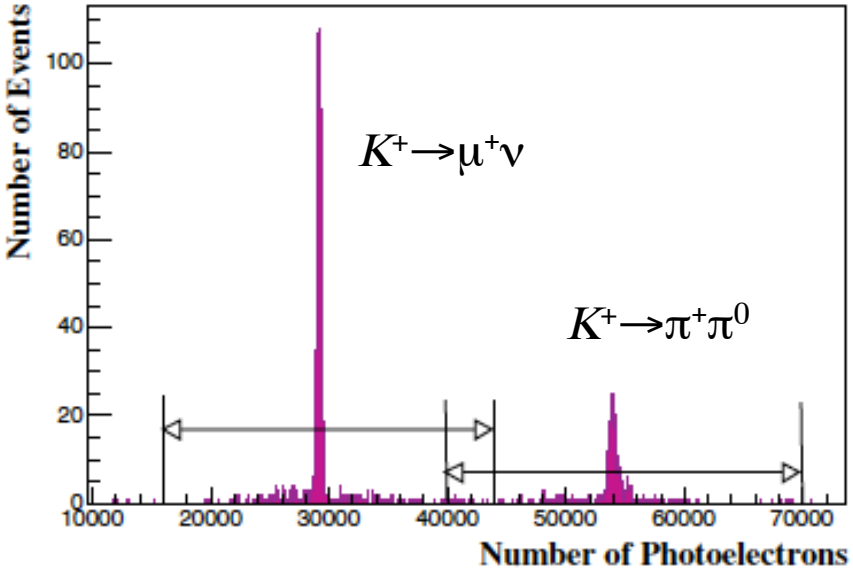
Efficiency estimate ~ 65%

Background rate ~ 1/yr/50 kton

Astroparticle Physics 35 (2012) 685–732

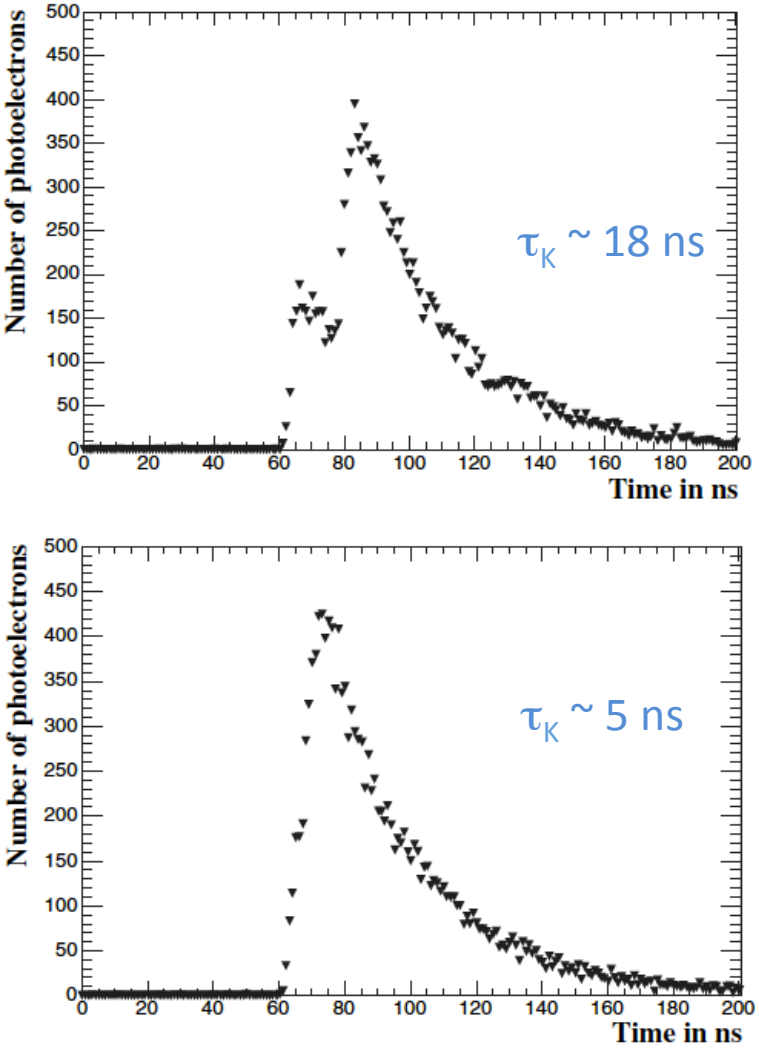
LENA

Energy Response

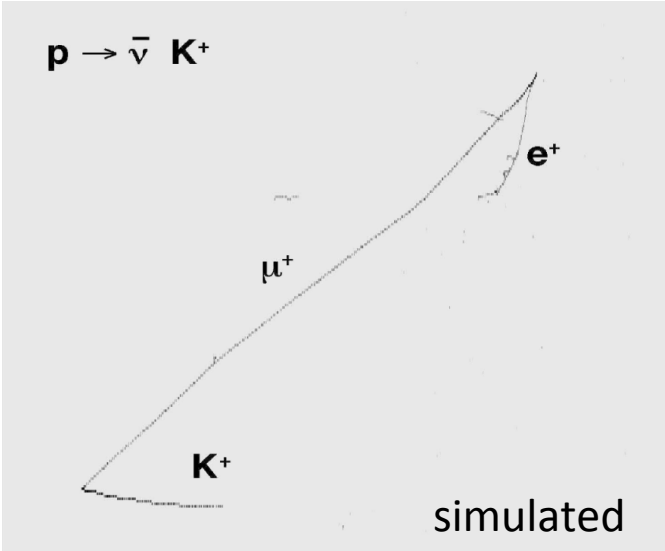


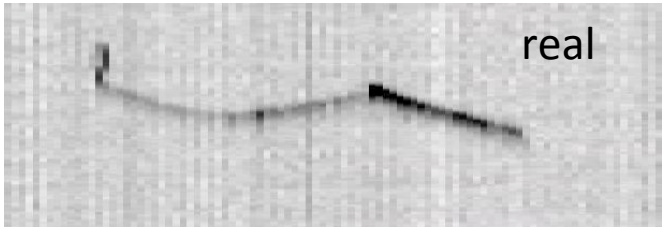
- 200 photoelectrons/MeV (40x Super-K)

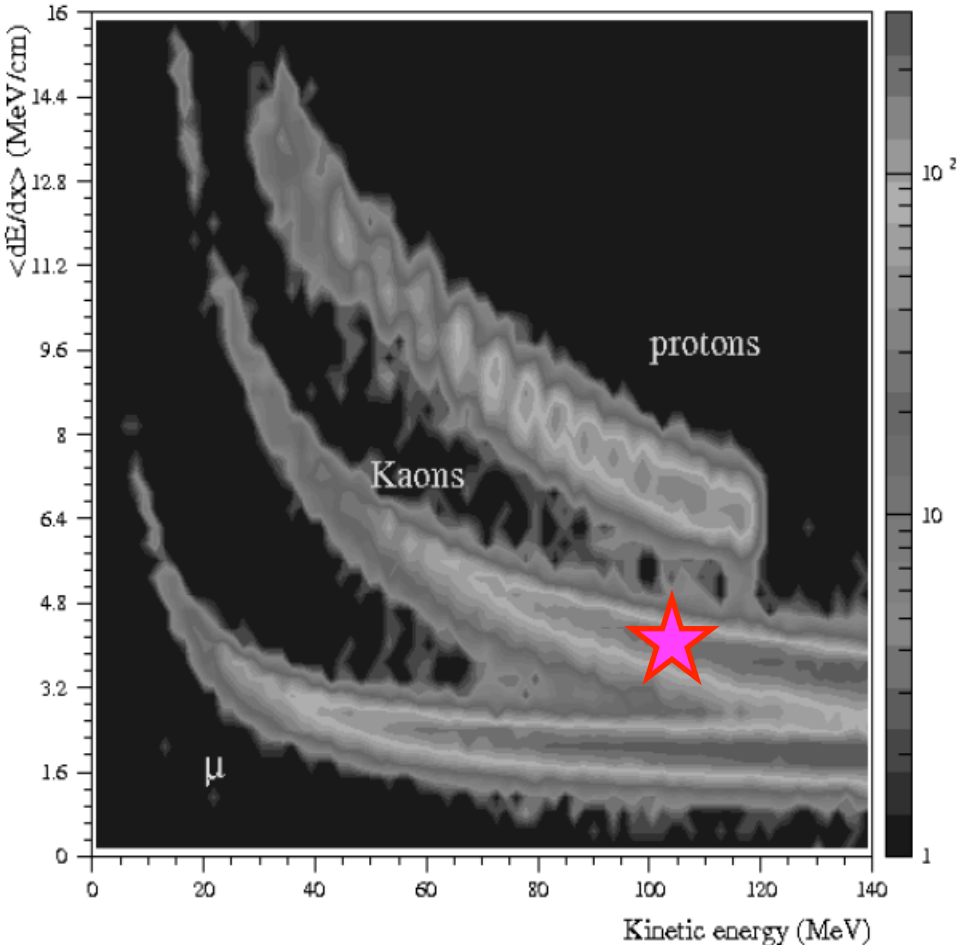
Residual Timing Distributions (single events)



νK⁺ in LAr



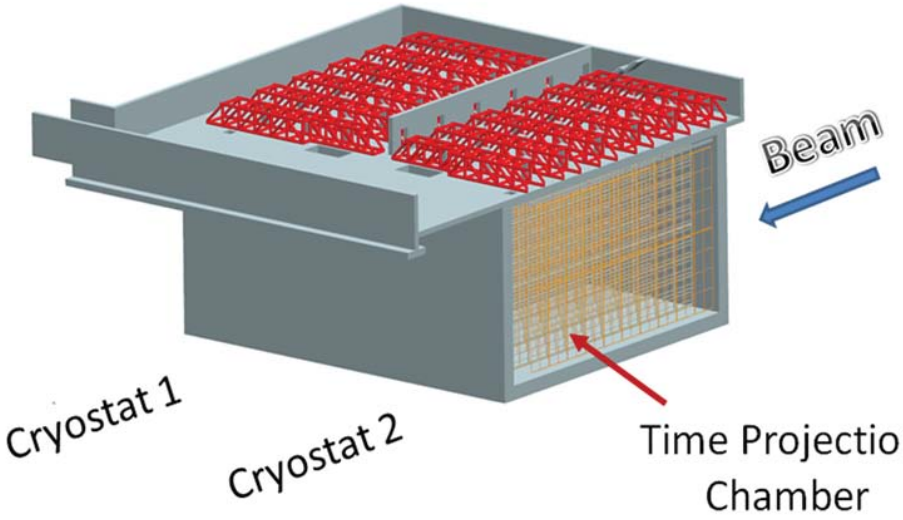


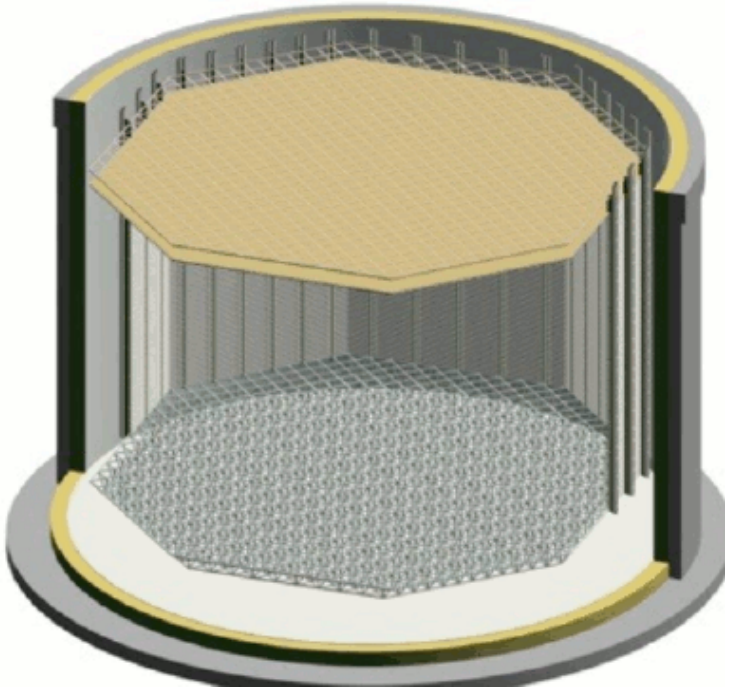


Cuts	(p3) $p \to K^+ \bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no π^0	96.8%	0	0	0	0	57	9
$E_{vis} < 0.8$ GeV	96.8%	0	0	0	0	1	0

Bueno et al.

LBNE GLACIER/LBNO

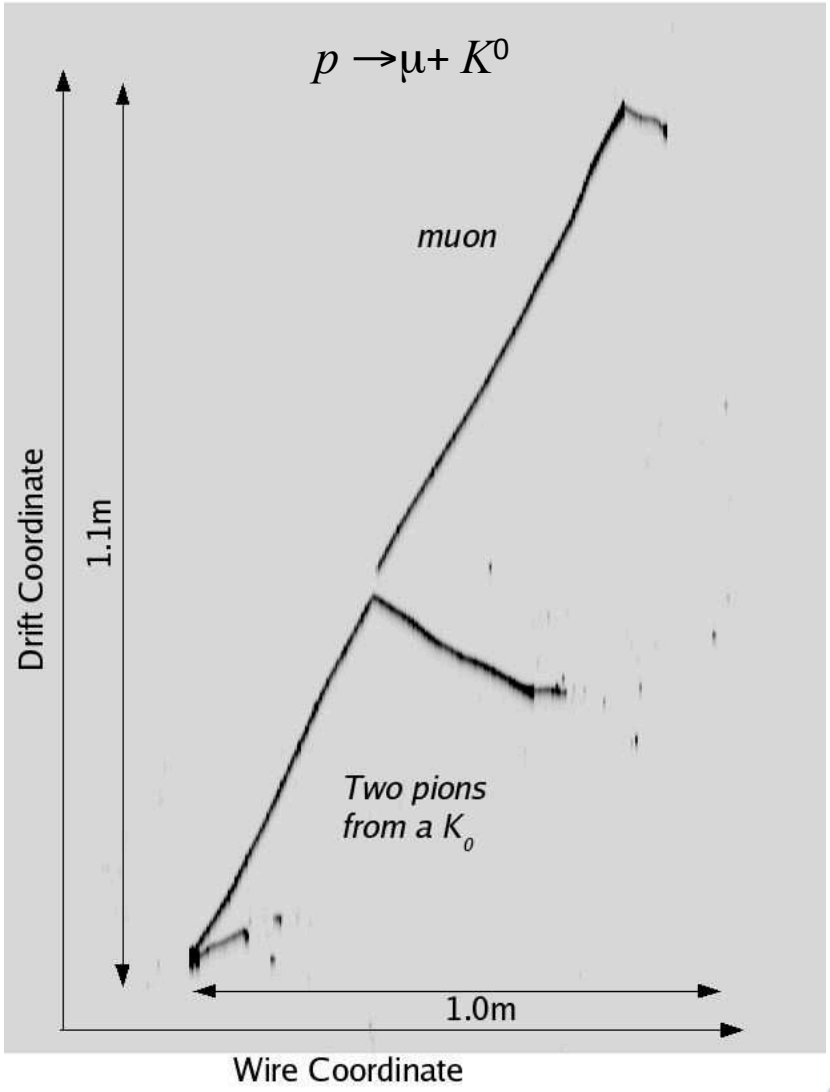




- Two very different technical designs – which is best?
- Validate the 97% efficiency assumption, as well as low BG
- Essential to get LBNE underground, and with no beam trigger
- At least 20 kton is preferred – proton decay needs MASS.

What Other Modes are Good for LAr?

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

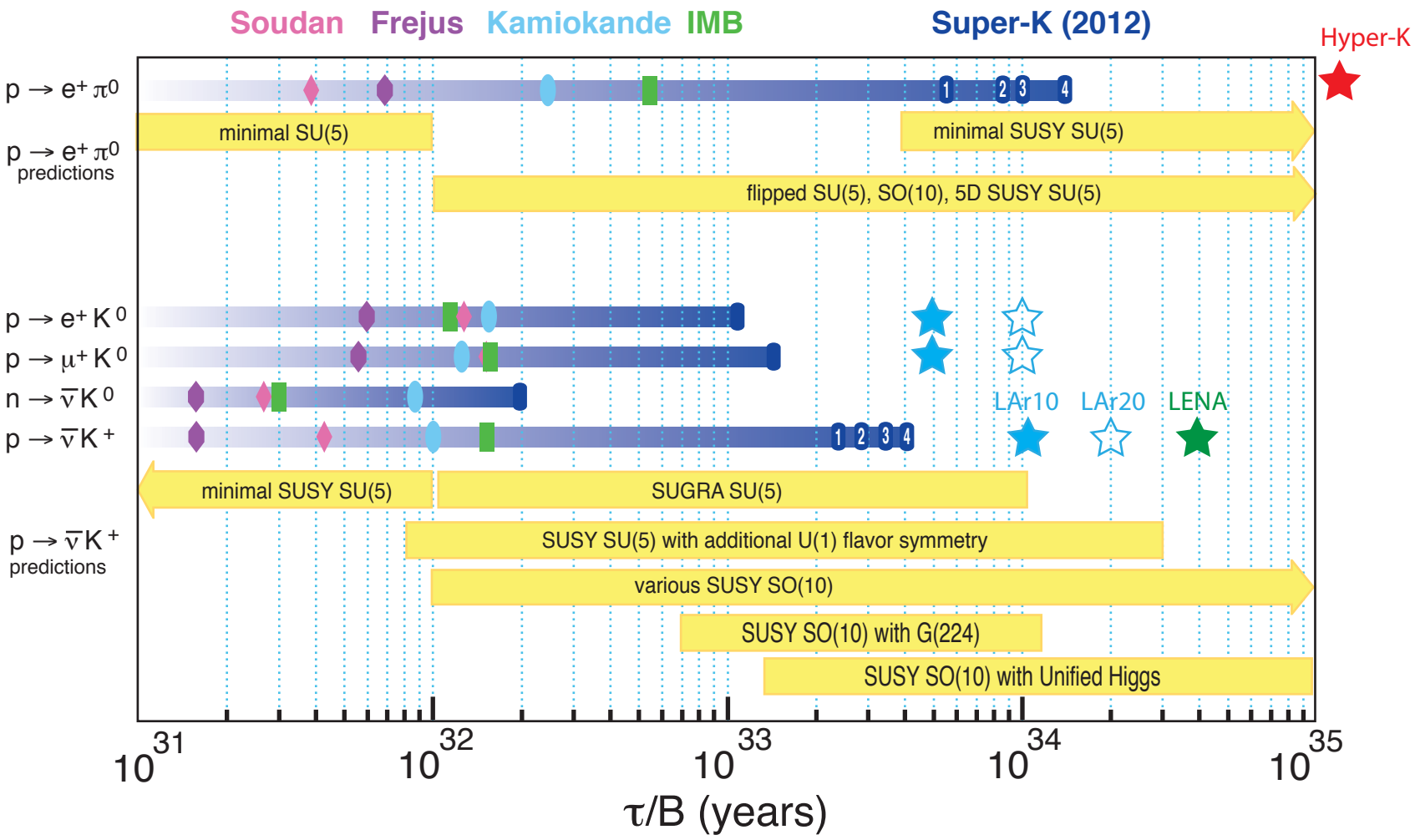


What Other Modes are Good for LAr? (2)

	Mode	Super-K Water Ch. 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



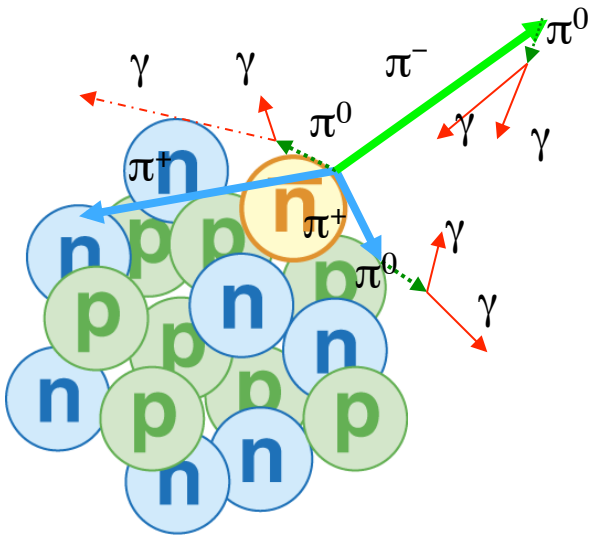
10 year exposures

Conclusion

- The frontier is, for now, defined by further SK running, improvements, and new analyses
- The next generation experiment is needed to gain an order of magnitude in nucleon decay sensitivity
- The motivating factors are as strong as ever
- The motivation could become stronger with
  - Clear signs of SUSY at the LHC
  - Candidate events at SK
  - Serious reduction in cost to do the experiment

EXTRA

Neutron Antineutron Oscillation

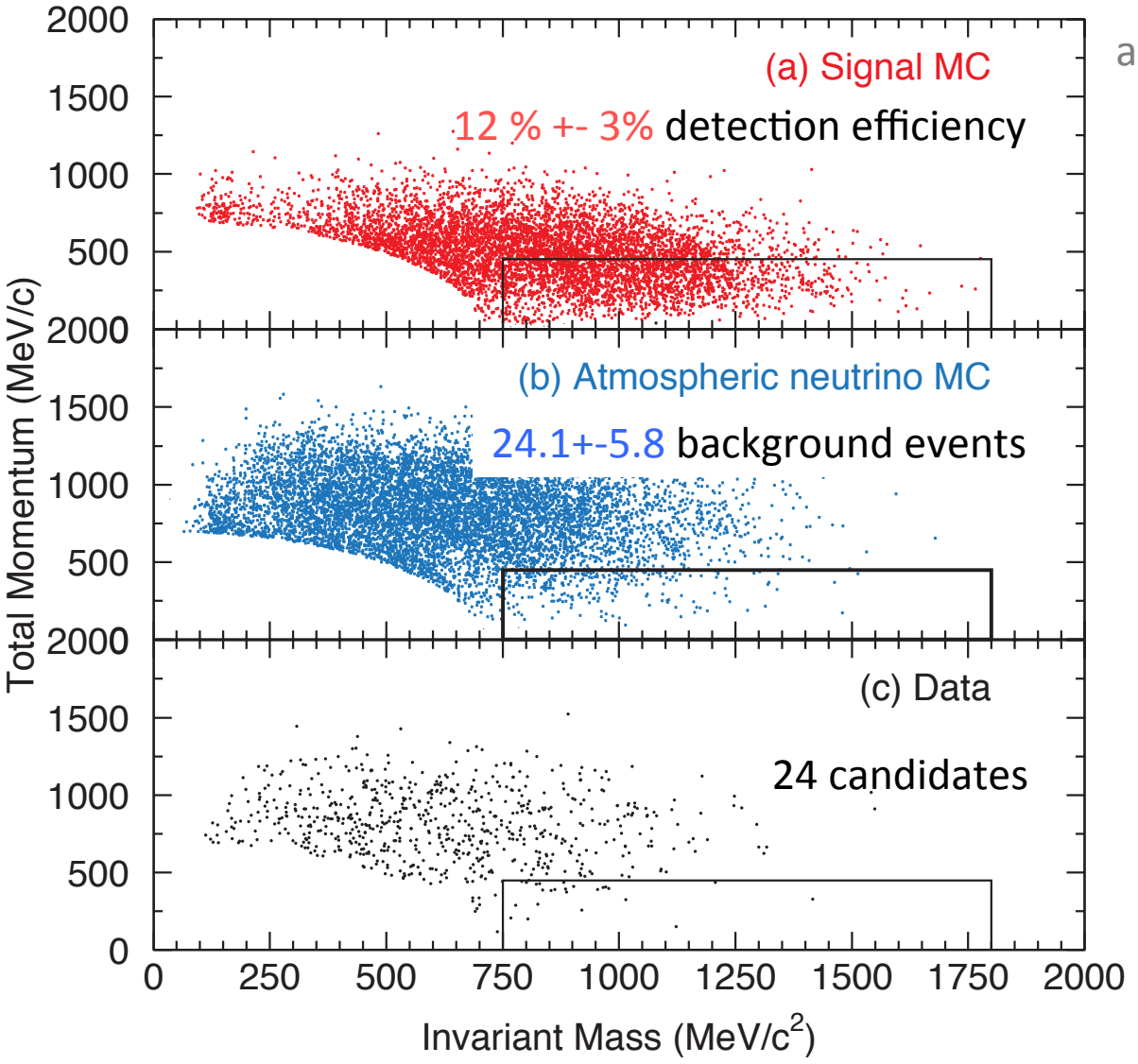


$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

TABLE I: The branching ratios for the $\bar{n}$+nucleon annihilations in our simulations. These factors were derived from $\bar{p}p$ and $\bar{p}d$ bubble chamber data[12][13][14].

- Created antineutron annihilates with nearby nucleon
- About 2x nucleon mass is released as pions
- Final states may be predicted from annihilation data

Super-Kamiokande nnbar Result



arXiv:1109.4227

BG Interactions:

CC 1π : 27.2% (6.5 evt)

NC 1π : 4.1% (1.0 evt)

CC mπ : 32.5% (7.8 evt)

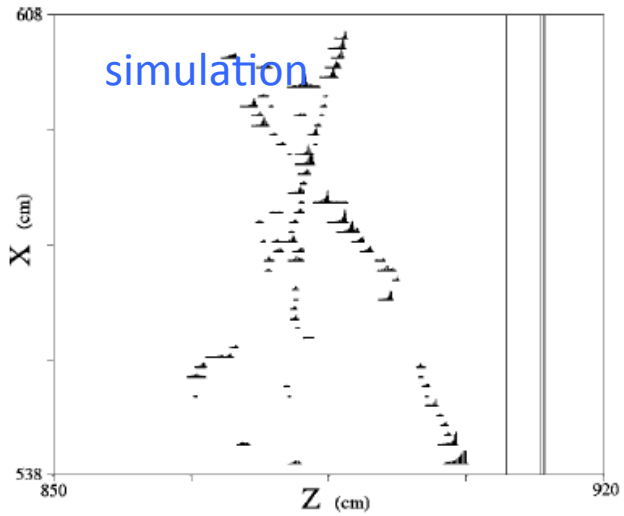
NC mπ : 25.4% (6.1 evt)

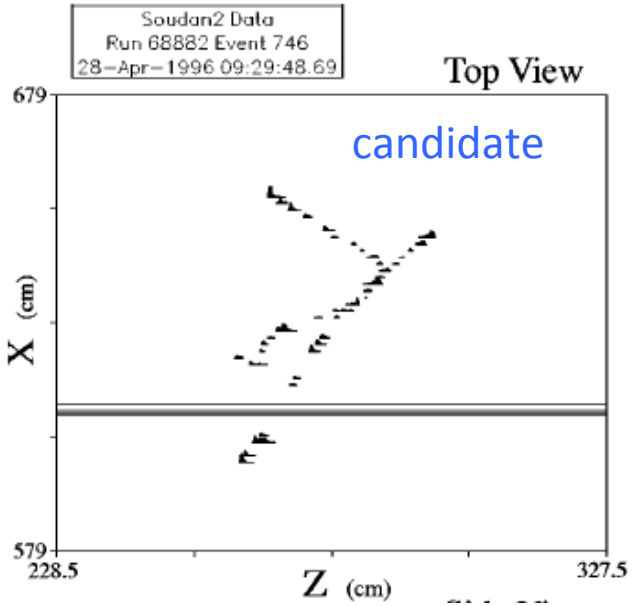
$$T_{bound} > 1.89 \times 10^{32} \text{ years}$$

$$\tau_{free} = \sqrt{\frac{T_{bound}}{1 \times 10^{23} \text{ s}^{-1}}} = 2.4 \times 10^{8} \text{ s}$$

Iron Calorimeters

(Get a feel for how a Lar TPC analysis might proceed)





Soudan 2:

- hand scan
- require n-charged ≥ 4
- eliminate protons, muons
- kinematic cuts

LAr compared to Iron Calorimeters:

- can do better than requiring n_{ch} >= 4

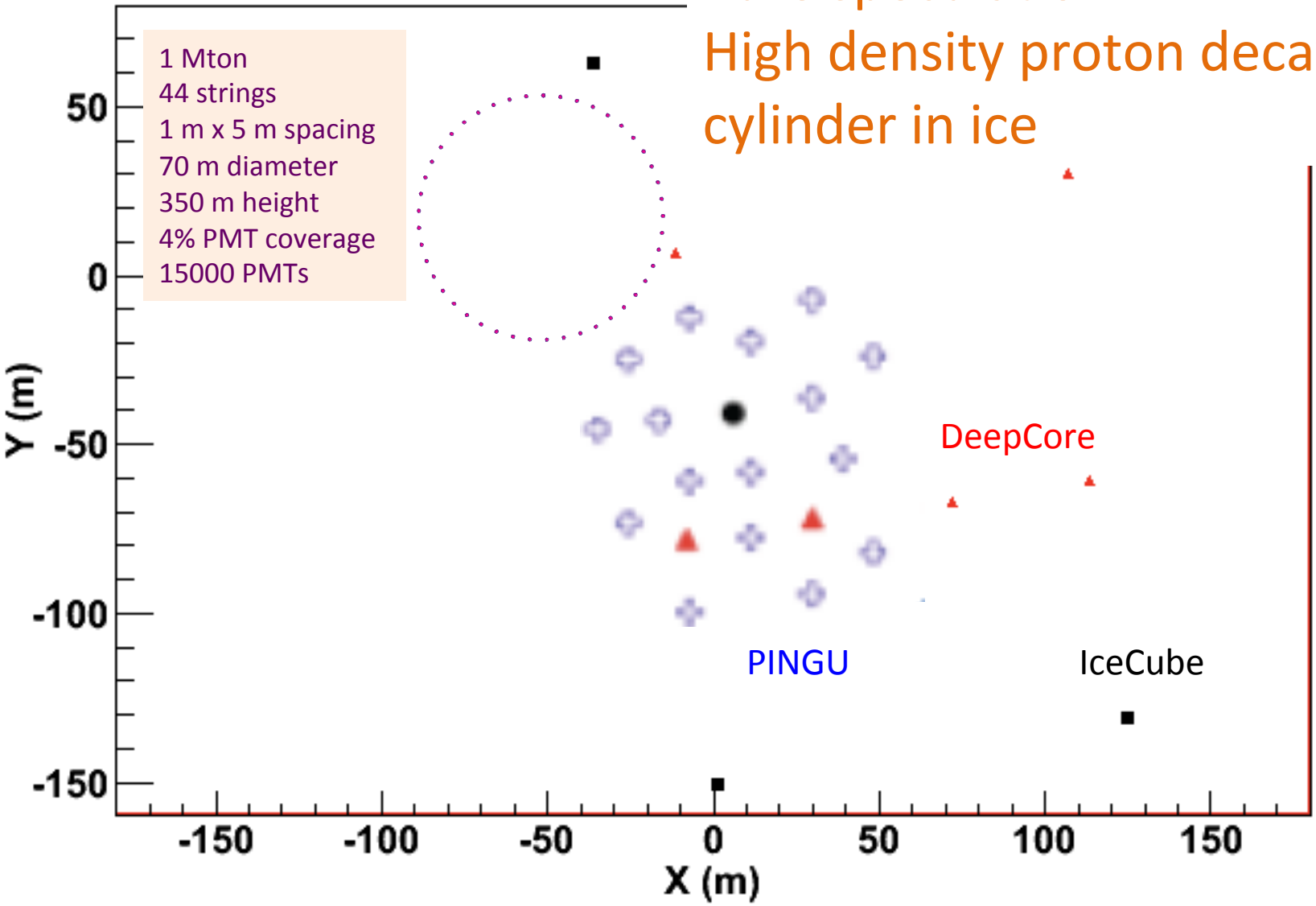
LAr compared to WC

- can resolve recoil proton, charged current lepton

Back of the envelope estimate suggests even 10 kton LAr can do x10 better than SK

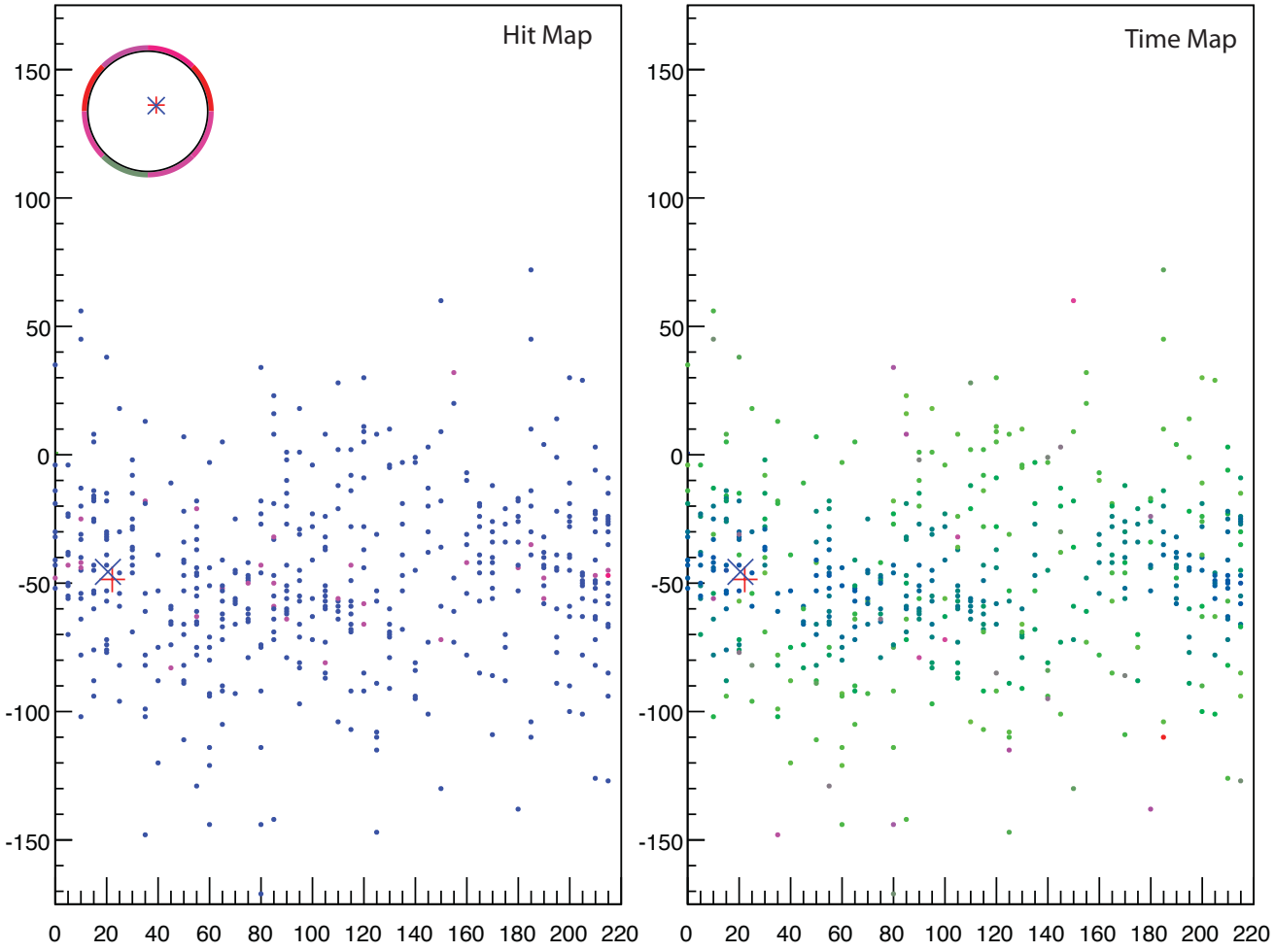
EXTRA
EXTRA

Pure speculation…
High density proton decay cylinder in ice



Example event

~ 1 pe/MeV
IceCube published scattering parameters



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