Experimental searches for neutron-antineutron oscillations in nuclei

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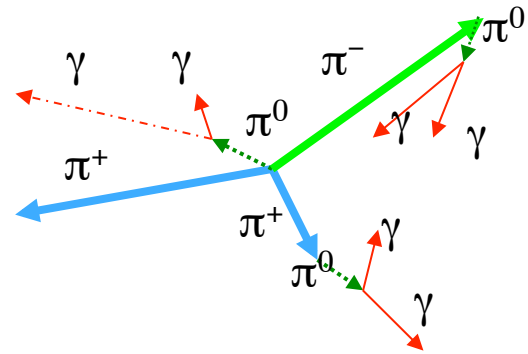
2012 Project X Physics Study

Motivation

- Analogous to well-observed $K^0 \longleftrightarrow K^0$-bar mixing
- Possible source of B-violation (BAU connection)
- Probes scales from multi-TeV to GUT
- Variety of interesting models make predictions
- Competitive with free neutron experiments

  after correction of nuclear potential suppression $\tau_{free} = \sqrt{\frac{T_{nuc}}{R}}$
- Long history of this search by proton decay expts.

Signature



- Created antineutron annihilates with nearby nucleon
- About 2x nucleon mass is released as pions
- Final states may be predicted from N-bar data
- Pion propagation in nucleus must be modeled

Summary of Results

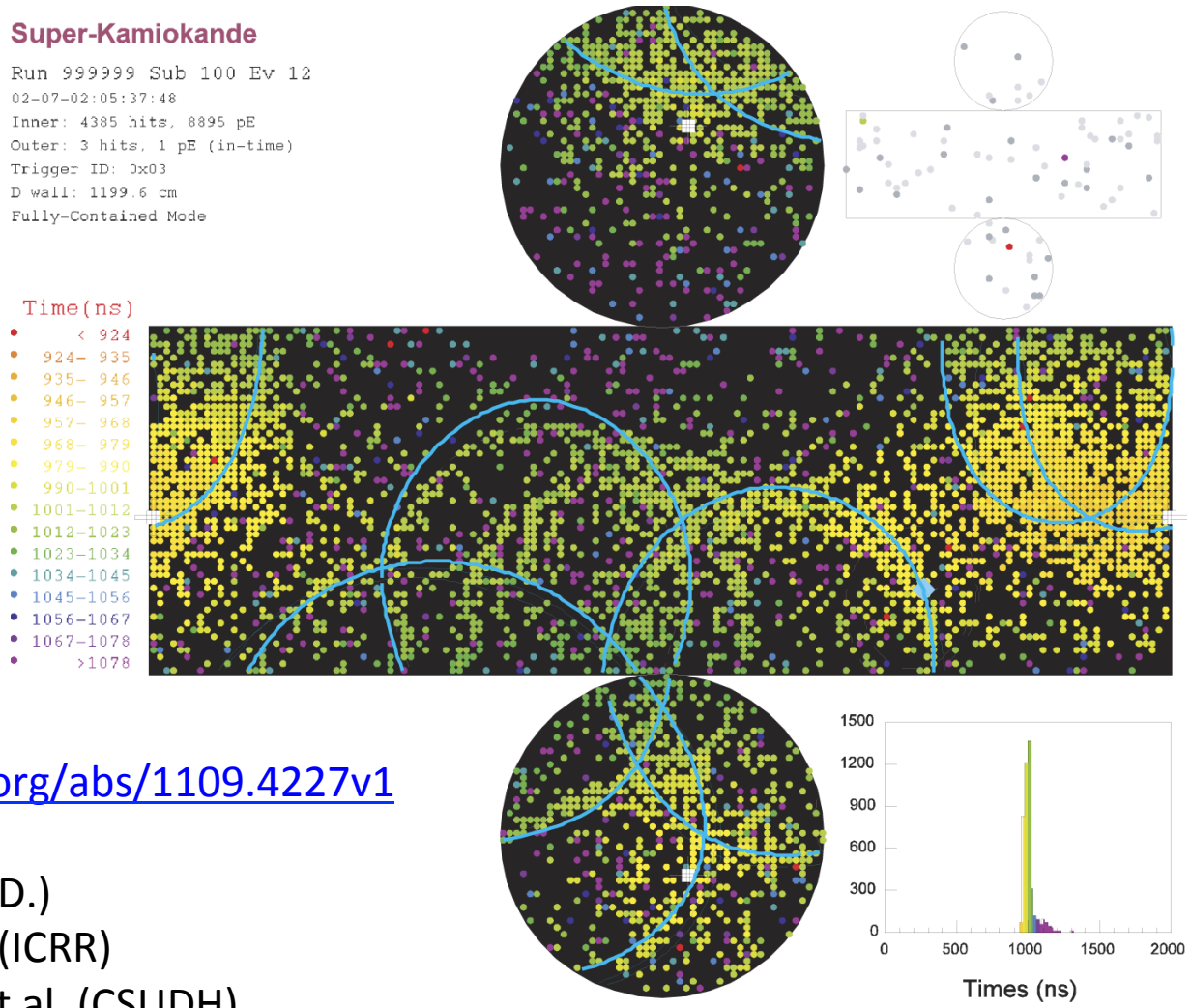
Cf. $\tau > 0.86 \times 10^8$ s [ILL/Grenoble]

Experiment	nucleus	N(10^{32}) [n years]	Effic.	Bkgd.	Cand.	R (10^{23}) [s^{-1}]	$T_{nucl.}$(10^{32}) [yr]
IMB	^{16}O	3.2	50%	-	3	1.0	0.24 $\tau > 0.9 \times 10^8$ s
Kamiokande	^{16}O	3.0	33%	0.9	0	1.0	0.43 $\tau > 1.2 \times 10^8$ s
Frejus	^{56}Fe	5.0	30%	2.5	0	1.4	0.65 $\tau > 1.2 \times 10^8$ s
Soudan 2	^{56}Fe	21.9	18%	4.5	5	1.4	0.72 $\tau > 1.3 \times 10^8$ s
Super-K	^{16}O	245.5	12%	24.1	24	1.0	1.89 $\tau > 2.4 \times 10^8$ s
SNO	$^{2}H/^{16}O$	2.7	52%	9.7	4	0.85	1.52 $\tau > 2.4 \times 10^8$ s

Notes: just reusing published adopted values
Most (all?) limits based on volume, not peripheral, suppression

Super-Kamiokande Result

The Search for $n - \bar{n}$ Oscillation in Super-Kamiokande I



http://arxiv.org/abs/1109.4227v1

J.S. Jang (Ph.D.)
Jun Kameda (ICRR)
K. Ganezer et al. (CSUDH)

Super-Kamiokande Result

$\bar{n}$+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%

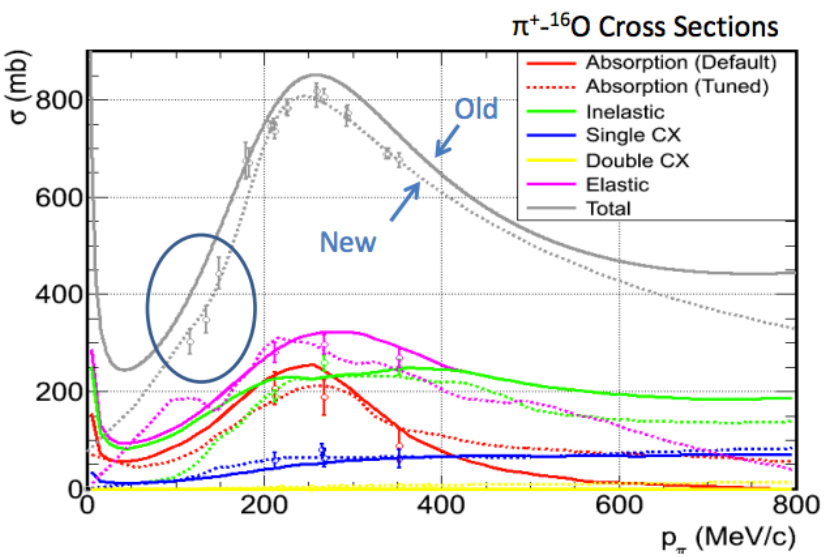
TABLE I: The branching ratios for the $\bar{n}$+nucleon annihilations in our simulations. These factors were derived from $\bar{p}p$ and $\bar{p}d$ bubble chamber data[12][13][14].

Signal Monte Carlo

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	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].

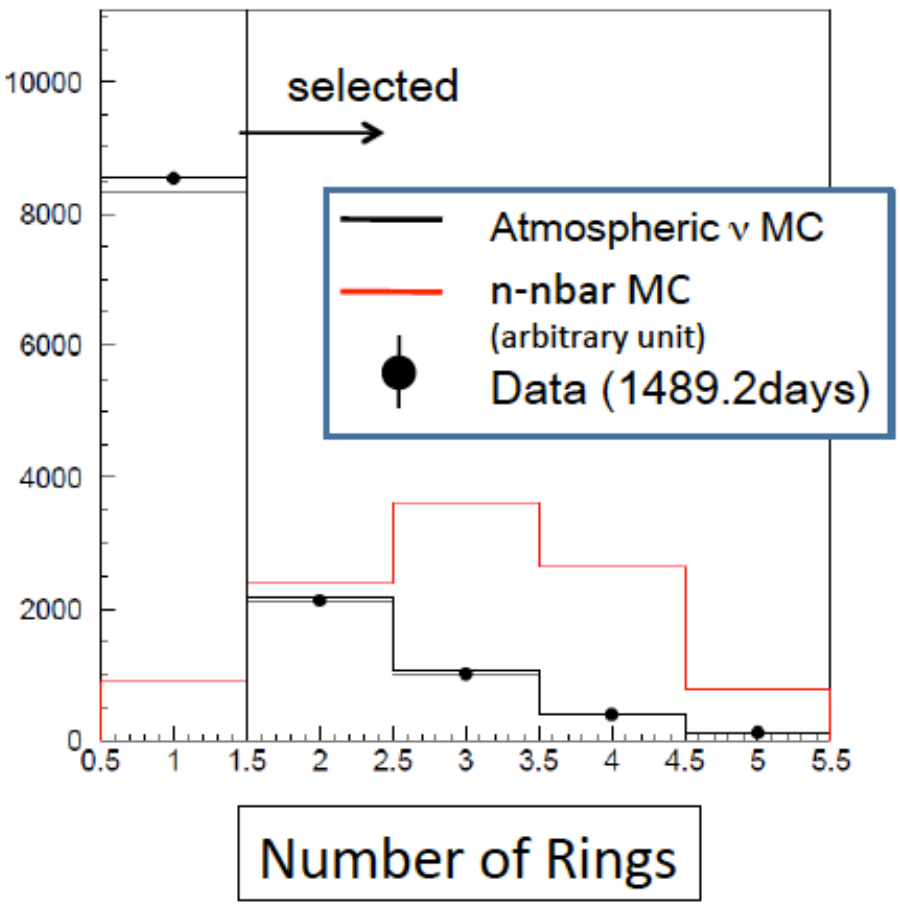
Final states taken from nuclear annihilation data



Pion interactions modeled intranuclear propagation

("Old" was used– we are Improving our pion model)

Super-Kamiokande Data



Selection Criteria:

Fully Contained – Fiducial Volume

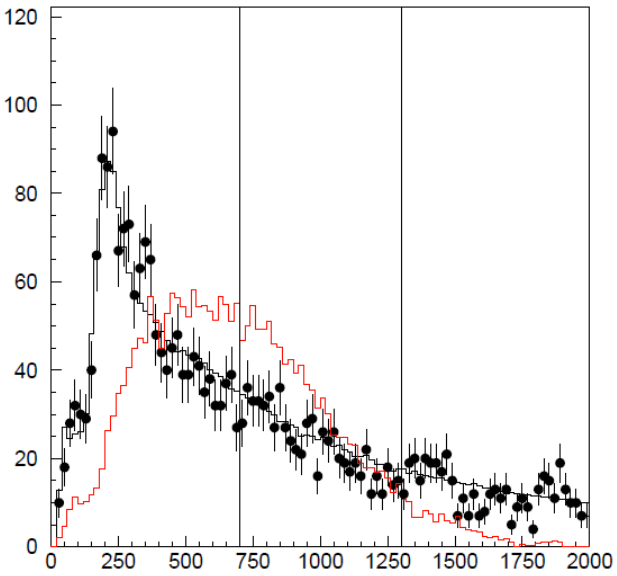
$N_{ring} > 1$

E_{vis} between 700-1300 MeV

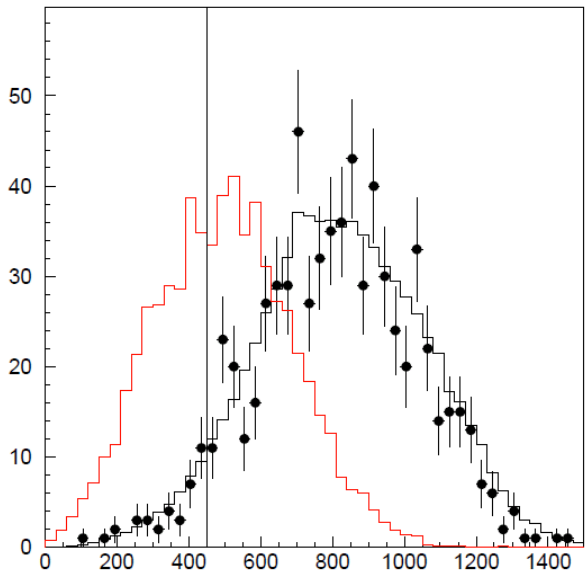
$|p_{net}| < 450$ MeV/c

Invariant mass between 750 – 1800 MeV/c^2

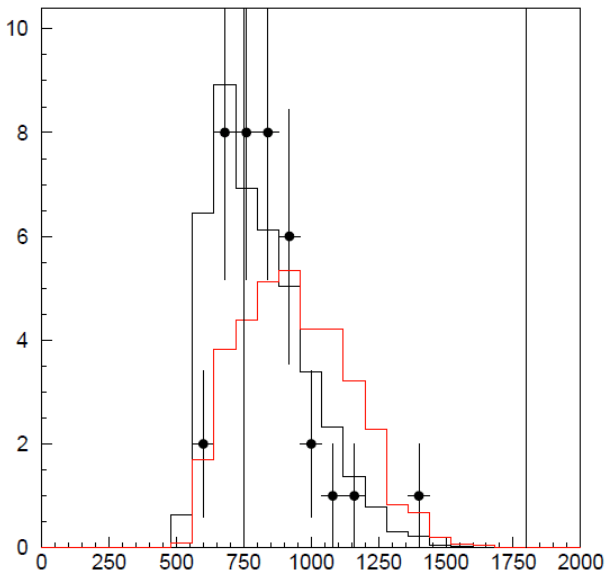
Super-Kamiokande Result



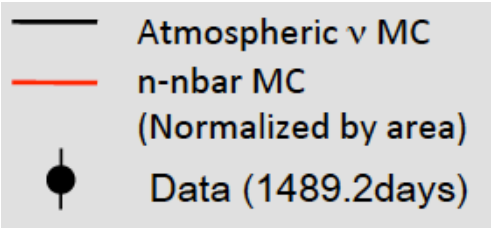
Visible Energy (MeV)



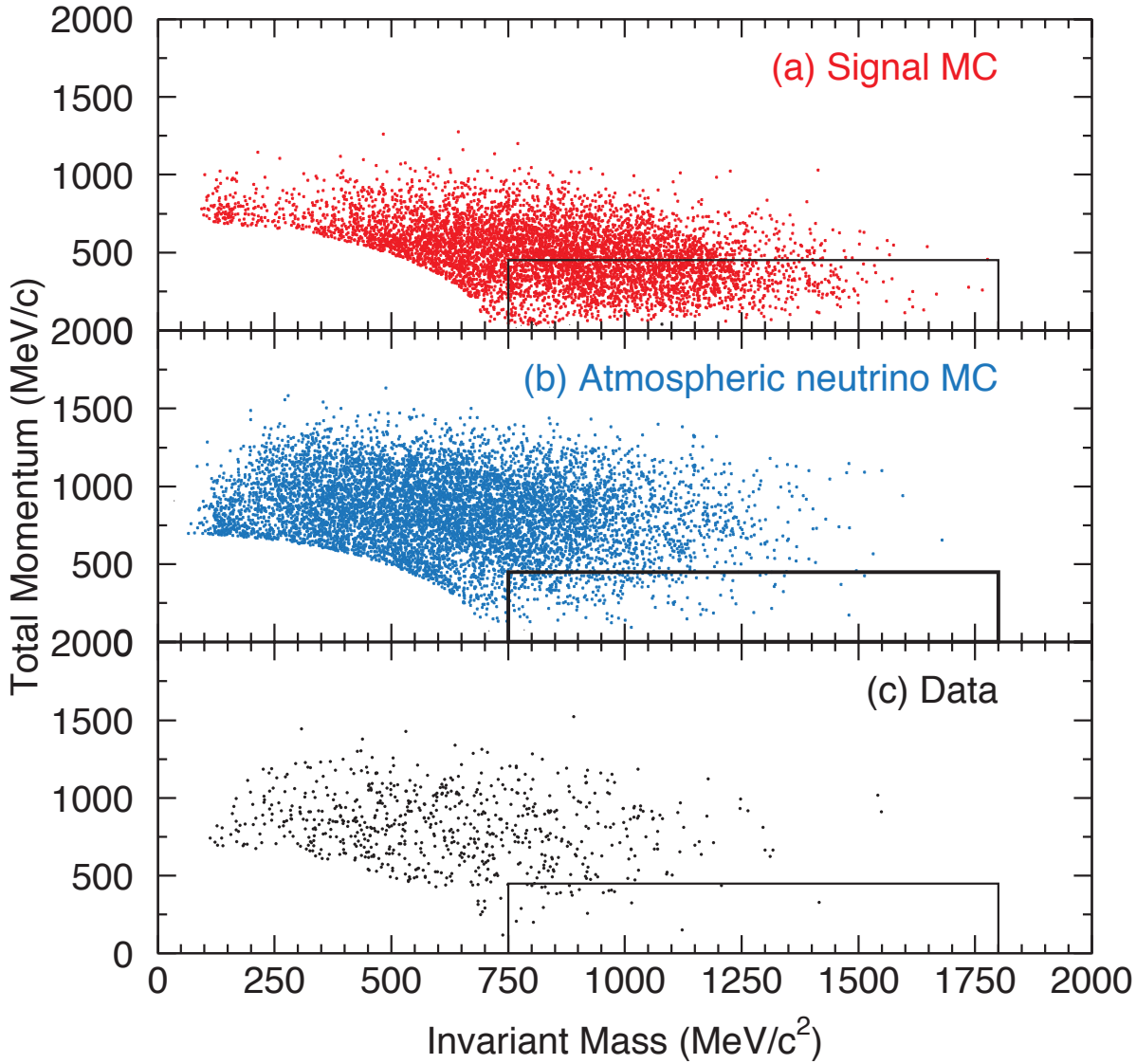
Net Momentum (MeV/c)



Invariant Mass (MeV/c2)



Super-Kamiokande Result



12 % detection efficiency
sys. uncertainty 23%
(mostly intranuclear scattering)

24.1 background events
ν osc. effects are included
sys. uncertainty 24%
(mostly flux, cross sections)

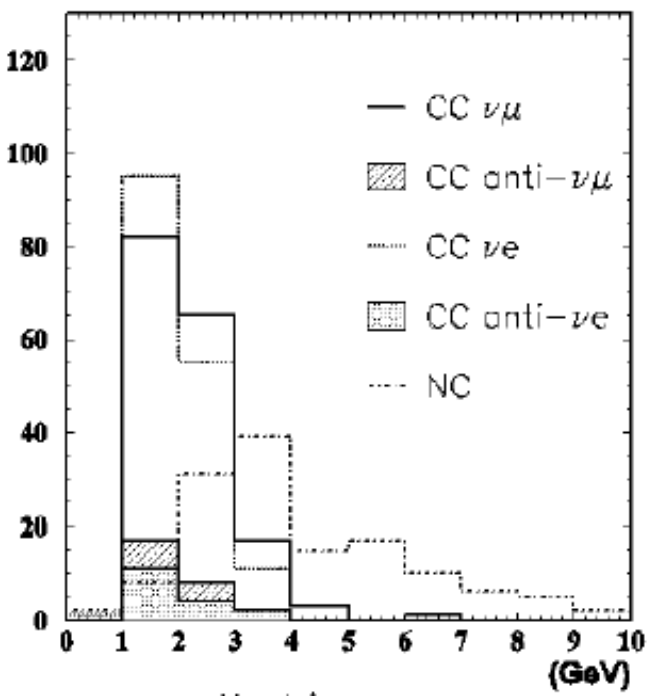
24 candidates

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

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

$$= 2.4 \times 10^{8} \text{ s}$$

Atmospheric Neutrino Background



Neutrino Energy

DIS :	58%
1-meson resonance :	37%
CC/NC ES :	5%

Interaction Type:

CC 1π : 27.2% (6.5 evt)

NC 1π : 4.1% (1.0 evt)

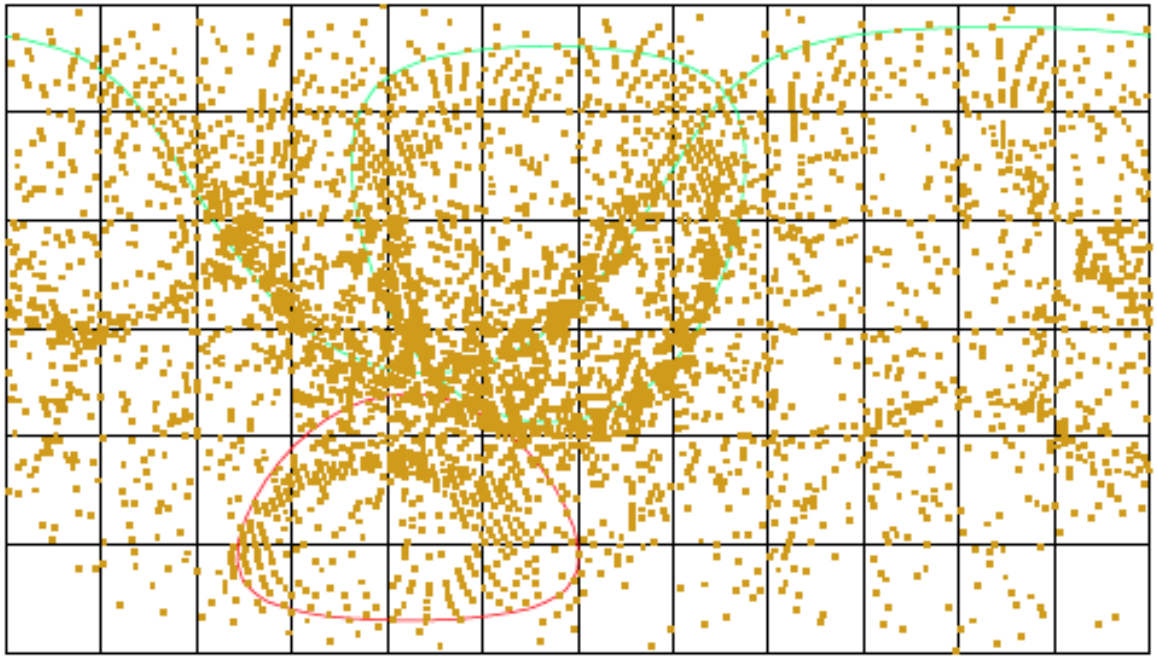
CC mπ : 32.5% (7.8 evt)

NC mπ : 25.4% (6.1 evt)

Most CC atm. nu BG comes from
nu (not nubar) due to higher momentum transfer

SNO Result

M. Bergevin (Ph.D. thesis, Guelph)

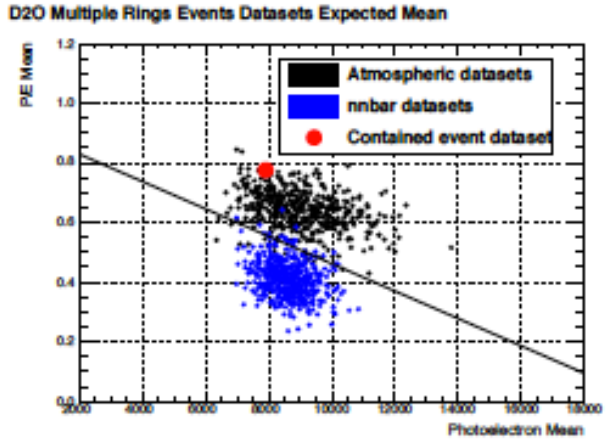


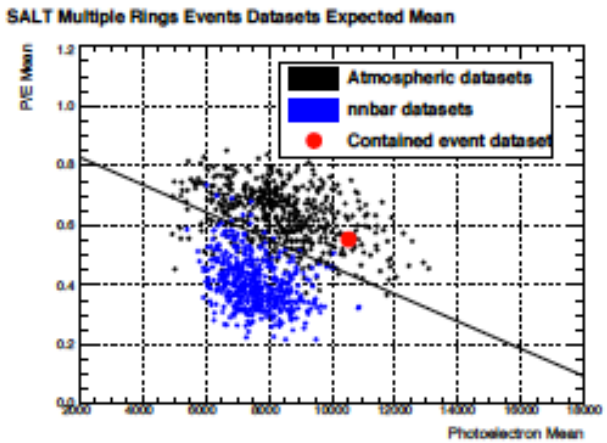
Less nuclear suppression expected for deuterium:

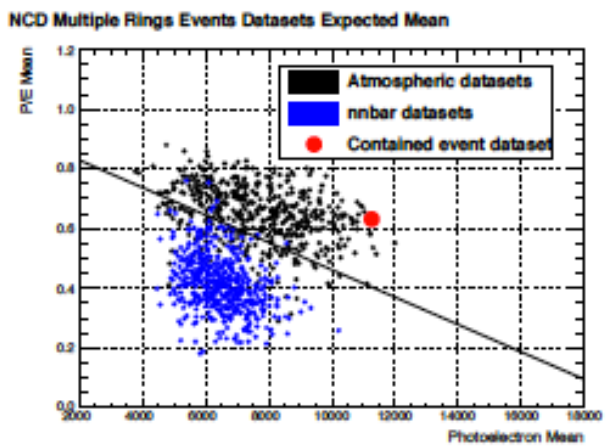
$R(D_2O) = 0.25 \times 10^{23}\ s^{-1}$

$R(D_2O+^{16}O) = 0.85 \times 10^{23}\ s^{-1}$

SNO Result







Exp.	Neutron source	Exposure 10^{32} n-yr	ϵ (%)	Cand.	BG
Super-K I	^{16}O	245.4	10.4	20	21.3
SNO ($\zeta_{tresh} = 15$)	D	0.54	40.7	2	4.75
SNO ($\zeta_{tresh} = 13$)	D	0.54	51.8	4	9.73
SNO($\zeta_{tresh} = 15$)	D_2O	2.68	$40.7^{\dagger}$	2	4.75
SNO($\zeta_{tresh} = 13$)	D_2O	2.68	$51.8^{\dagger}$	4	9.73

Exp.	T_{nucl} 10^{31} yr	T_R 10^{23} s^{-1}	τ_{nnbar} 10^8 s (B/UB)
Super-K I	(18.8/19.0)	1.0	(2.44/2.45)*
SNO ($\zeta_{tresh} = 15$)	(0.96/2.45)	0.248	(1.11/1.77)*
SNO ($\zeta_{tresh} = 13$)	(1.09/3.01)	0.248	(1.18/1.96)*
SNO($\zeta_{tresh} = 15$)	(4.90/12.3)	0.85	$(1.35/2.14)^{\dagger}$*
SNO($\zeta_{tresh} = 13$)	(5.42/15.1)	0.85	$(1.42/2.37)^{\dagger}$*

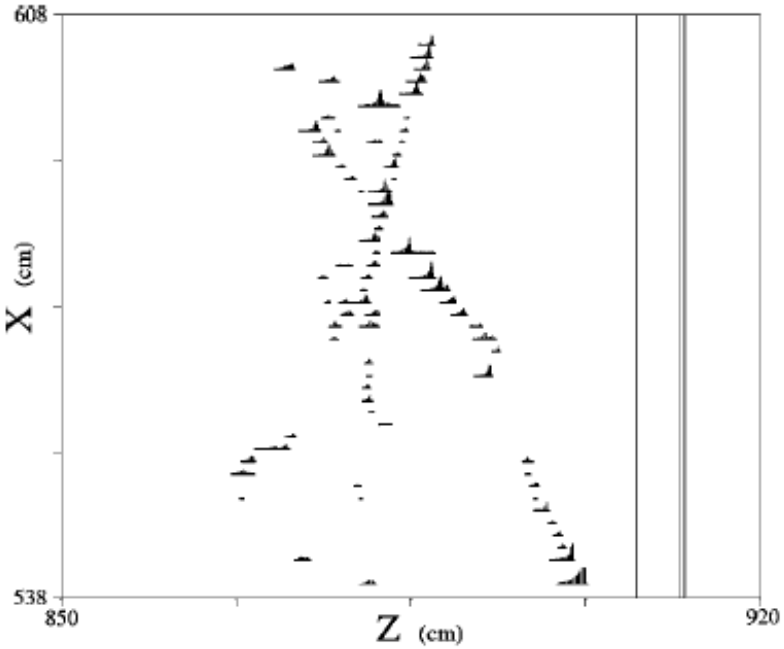
Future analysis should update from 326 days to 1242 days.

Iron Calorimeters

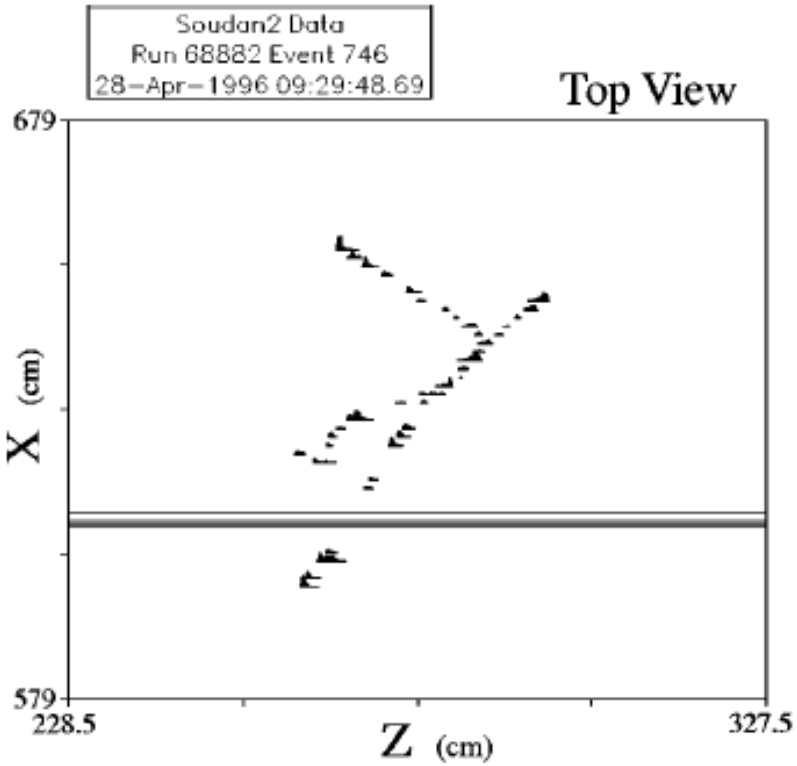
Review to get a feel for how a LAr TPC analysis might proceed

Soudan 2:

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

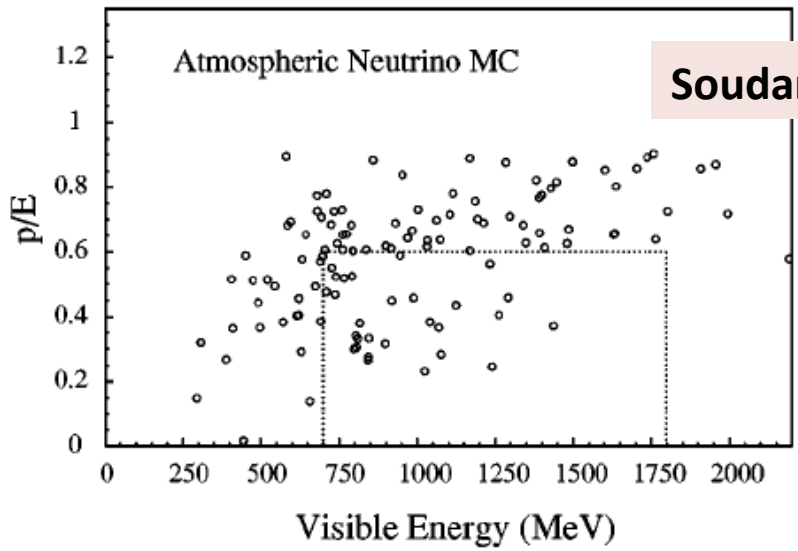


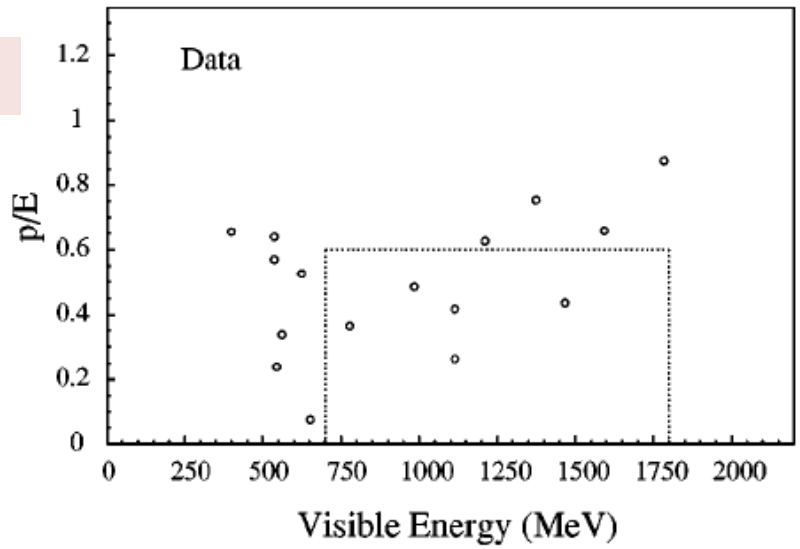
simulation

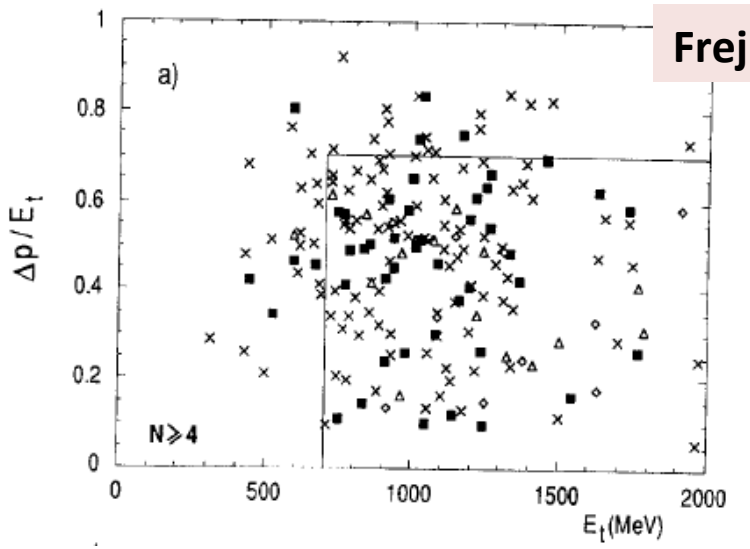


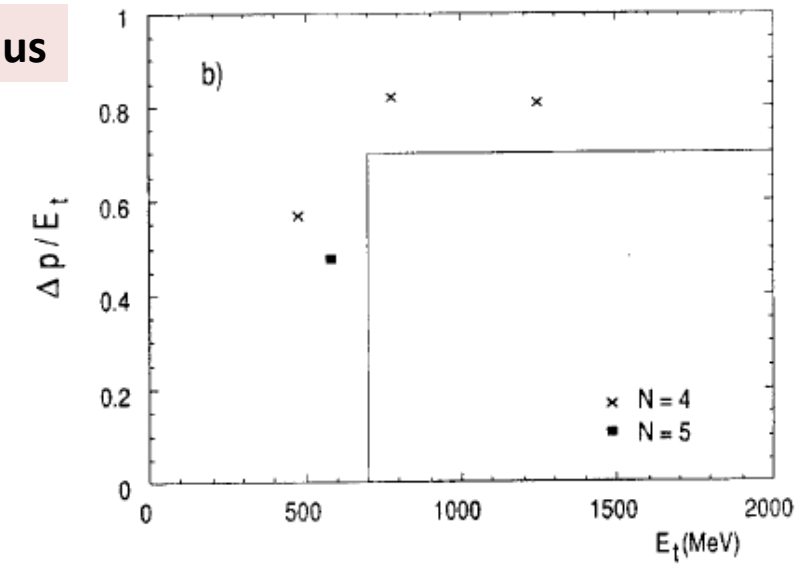
candidate

Iron Calorimeters









Liquid Argon TPC

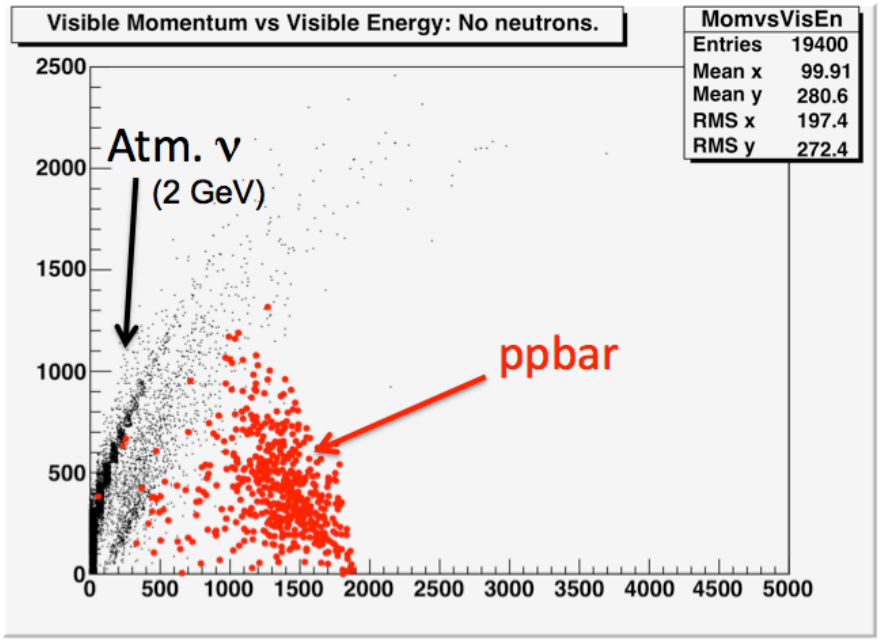
Compared to Iron Calorimeters:

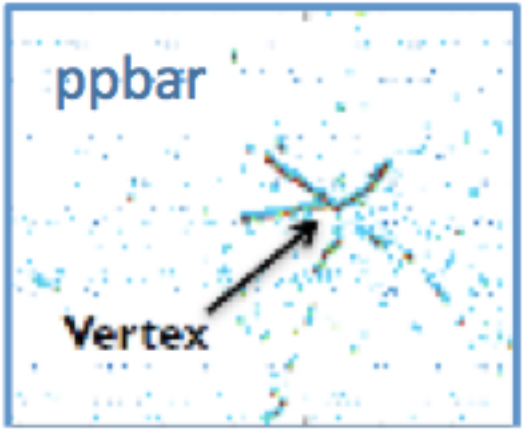
- can do better than requiring n_{ch} >= 4

Compared to WC

- can resolve recoil proton, charged current lepton

Potentially big gains in efficiency and BG rejection!





Good discrimination at least at truth level.

G. Karagiorgi, LBNE-docdb-5645

Cf. $\tau > 0.86 \times 10^8$ s [ILL/Grenoble]

Experiment	nucleus	N(10^{32}) [n years]	Effic.	Bkgd.	Cand.	R (10^{23}) [s^{-1}]	$T_{nucl.}$(10^{32}) [yr]
Super-K	^{16}O	245.5	12%	24.1	24	1.0	1.89 $\tau > 2.4 \times 10^8$ s
LBNE (10 kt x 5 yr)	*^{40}Ar*	*165.5*	*30%*	*5*	*5*	*1.0*	*10* *$\tau > 6 \times 10^8$ s*
LBNE (10 kt x 5 yr)	*^{40}Ar*	*165.5*	*20%*	*1*	*1*	*1.0*	*10* *$\tau > 6 \times 10^8$ s*
LBNE (10 kt x 5 yr)	*^{40}Ar*	*165.5*	*50%*	*0.5*	*0.5*	*1.0*	*30* *$\tau > 10^9$ s*

Pure speculation…. Hopefully conservative

Observations

- Proton decay detectors have a long history of studying nnbar. Usual qualities apply:
  large mass, high efficiency, low background

- Analyses have been fairly crude so far.
  No modern MVA techniques. High background rate in water cherenkov is daunting.

- LAr TPC, even one as small as LBNE/10 kton should do very well. Let's study!

BACKUP & EXTRA

Detection Efficiency

Sources	Uncertainty (%)
Fermi momentum of nucleons	6.2
Annihilation branching ratio of $\bar{n}$+nucleons	4.6
π propagation modeling	6.1
π-nucleon cross section in the nucleus	20.0
Energy scale	1.7
Asymmetry of detector gain	0.4
Cherenkov ring finding	2.2
Total	22.9

Background Rate

Sources	Uncertainty(%)
$(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu), \nu/\bar{\nu}$ ratio	0.1, 1.0
Up/down, horizontal/vertical flux ratios	$\ll$1
K/π ratio	3.1
Neutrino energy spectrum (<1GeV, >1GeV)	6.1,3.6
Neutrino cross sections	
QE	5.8
1-π production	2.4
DIS	14.1
coherent π productions	$\ll$1
CC/NC cross section ratio	5.0
Axial vector mass in QE and 1π production	0.6
Fermi momentum for QE	$\ll$1
π propagation in ^{16}O	4.1
Energy scale	4.8
Asymmetry of detector gain	0.5
Cherenkov ring finding	14.1
Total	23.7