Search for Neutron Antineutron Oscillations at Super Kamiokande I

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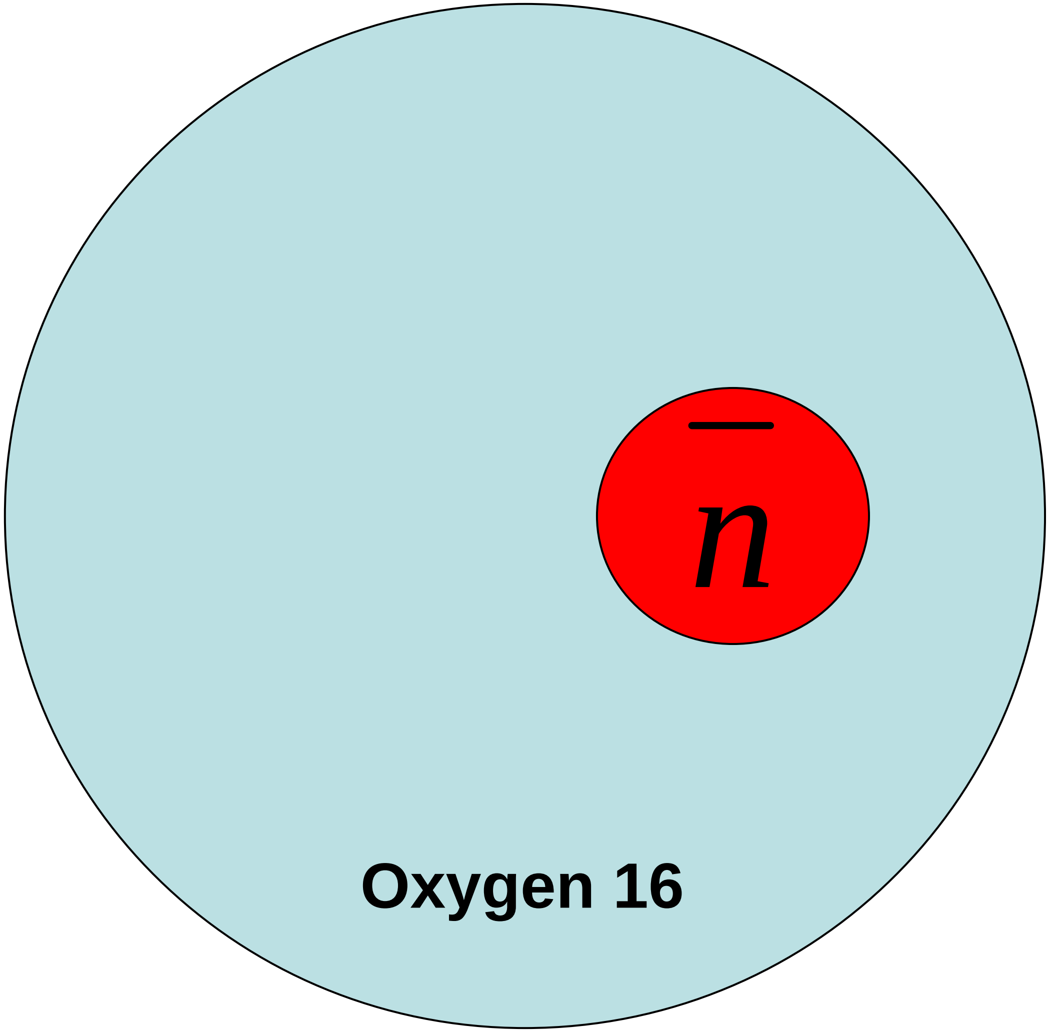
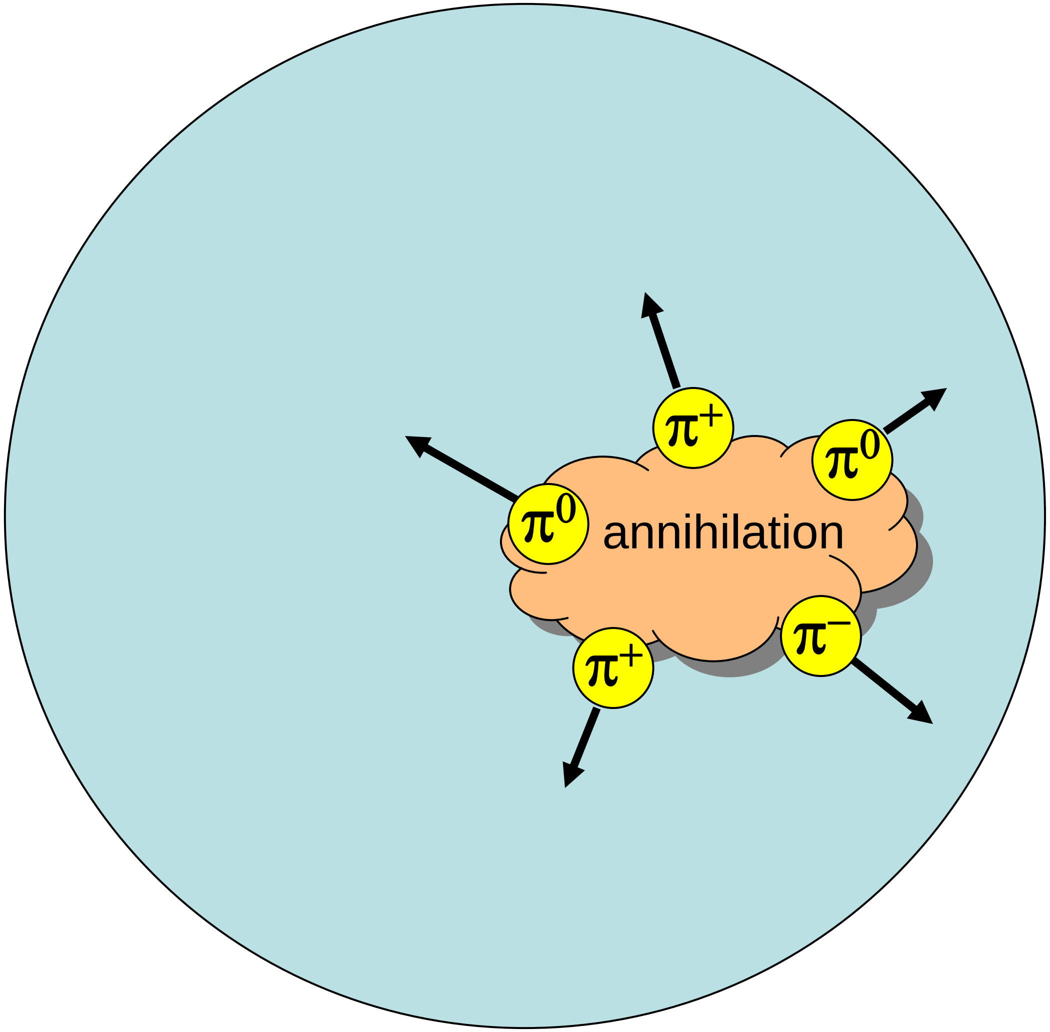
May 1 2007



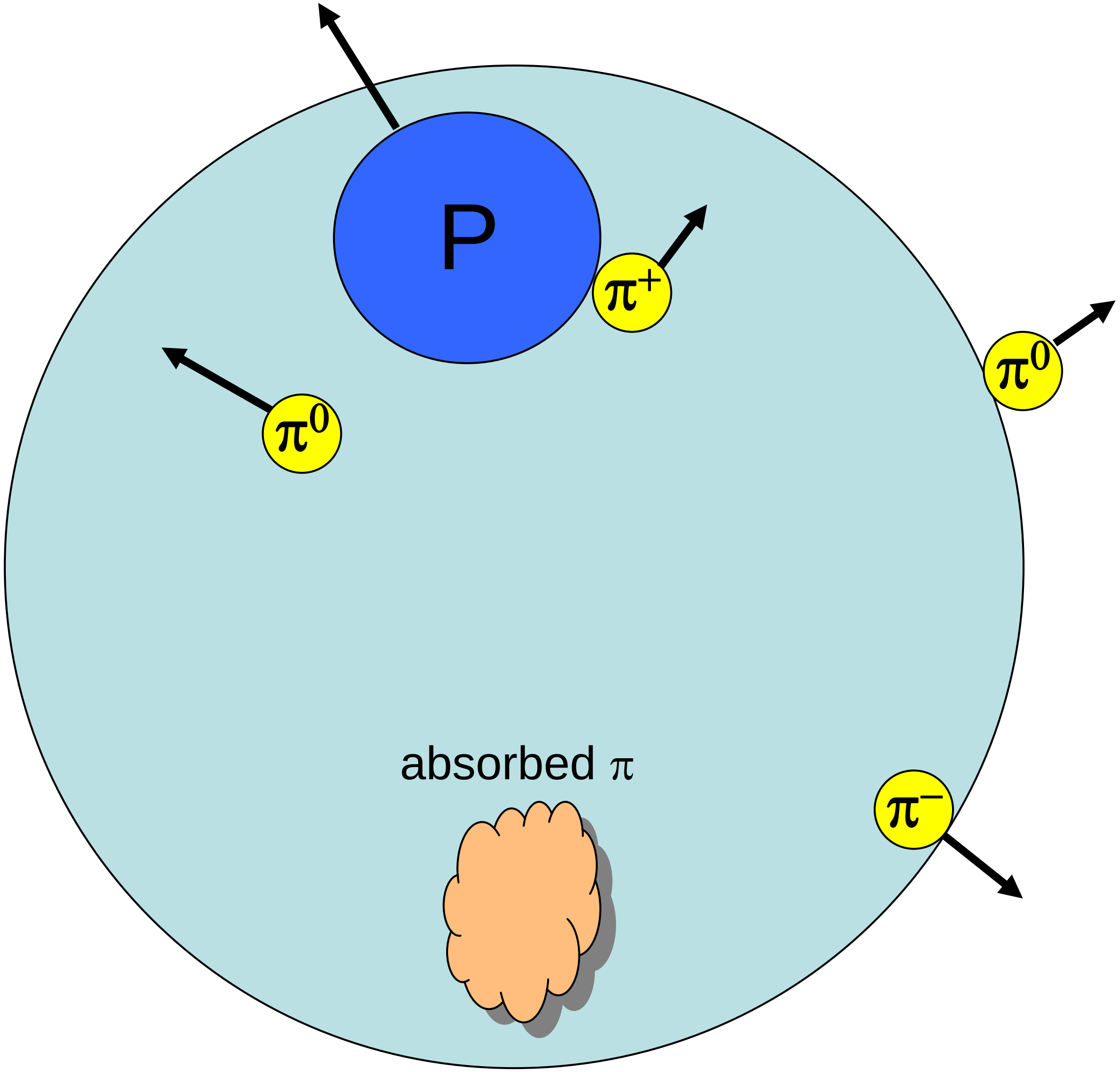
time 10^{33} years

- a neutron oscillates into an antineutron



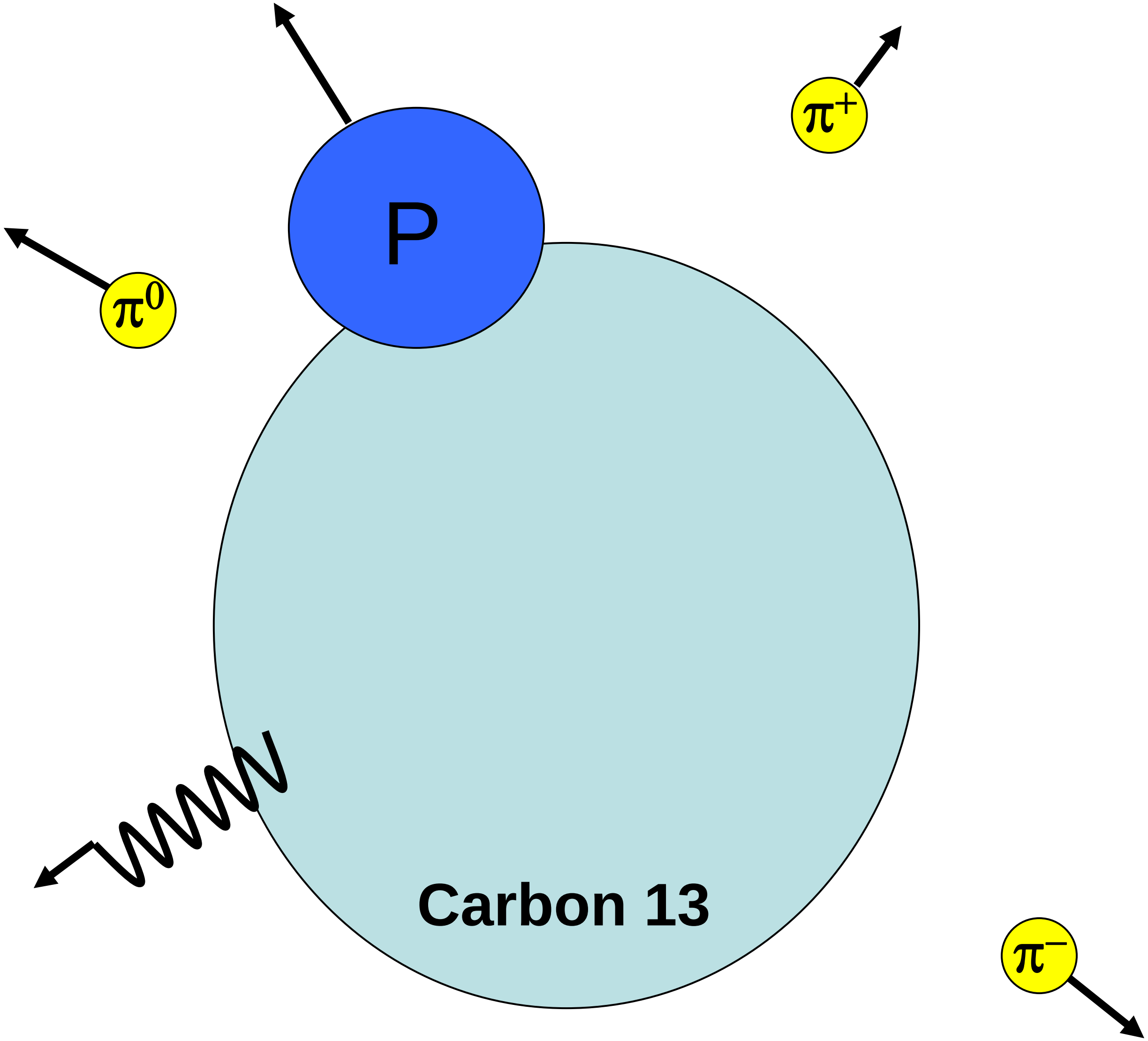
time ~5 x10^{-24} seconds

- the antineutron annihilates with another nucleon → pions



time ~2 x10^{-23} seconds

- the pions traverse and interact with the residual nucleus



- the residual nucleus de-excites and/or breaks up.

time <<1 x10^{-8} seconds

Outline

- R - Nuclear Suppression Factor
- Signal MC
- Detector
- Background – Atmospheric Neutrinos
- Analysis
- Future

Oscillation Suppression in Nuclei

Neutron Antineutron Oscillations

Two State non relativistic Schrodingers Equation

$$\begin{pmatrix} \frac{p^2}{2m} + \Delta E & \varepsilon \\ \varepsilon & \frac{p^2}{2m} - \Delta E \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \end{pmatrix} = E \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

where ΔE represents differing responses of n and nbar to the environment: Earth's magnetic field, Surrounding nuclear medium etc

if $\Delta E \ll \varepsilon$

Free oscillation probability = $\varepsilon^2 t^2$

wavefunction curvature

Oscillations in Nuclei

$(p^2/2m + U_n - E)\ n = -\varepsilon\ \text{nbar} \sim 0$

1) Adjust E to make n square normalizable.

$(p^2/2m + U_{nbar} + i\ W_{nbar} - E)\ \text{nbar} = -\varepsilon\ n$

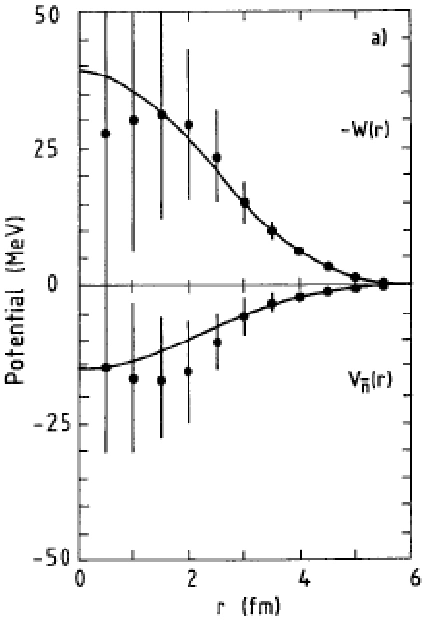
2) Adjust nbar/n

scattering

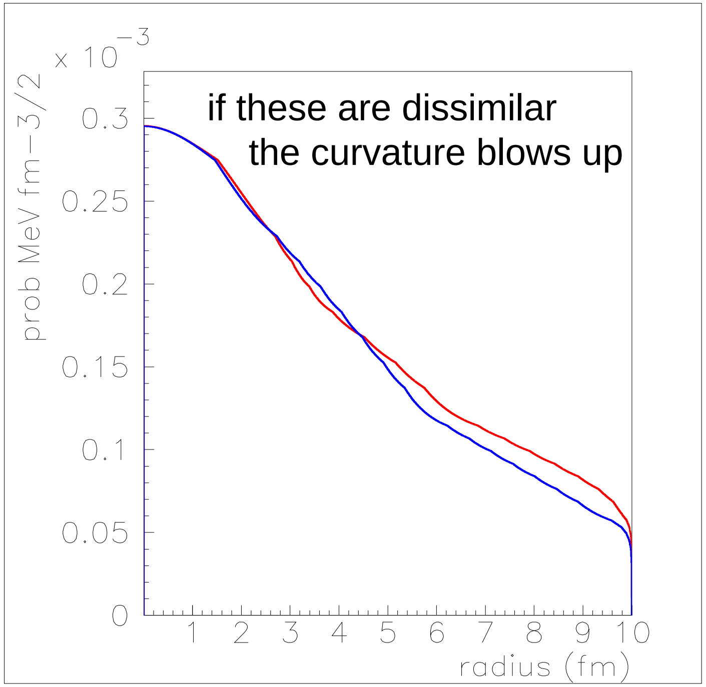
absorption

Taken from antiproton-nucleus scattering experiments.

Batty Nuc Phys A 466(1987)



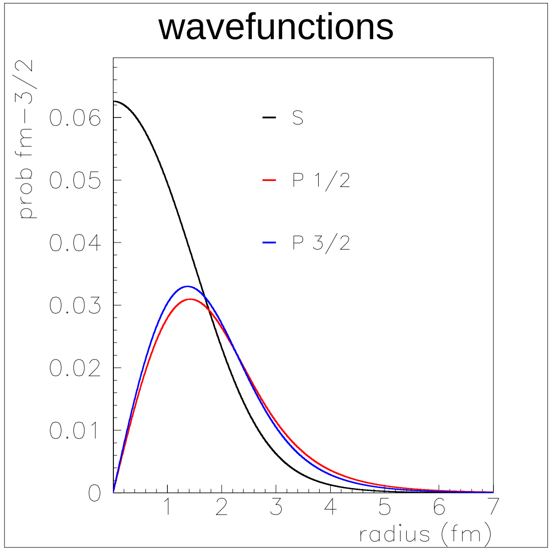
The problem is we only have data near the nuclear surface

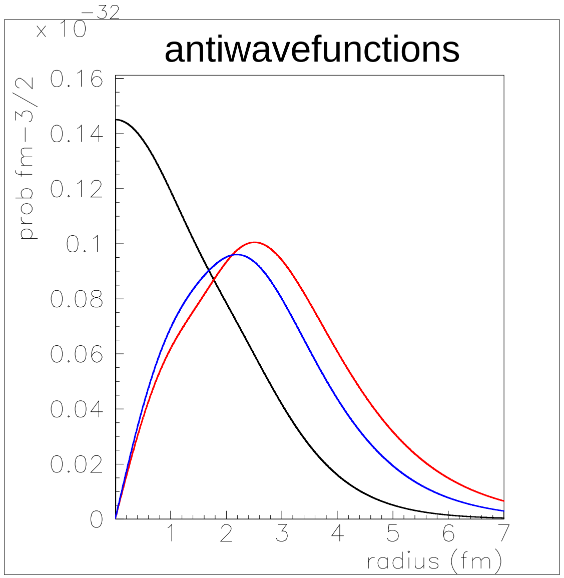


if these are dissimilar the curvature blows up

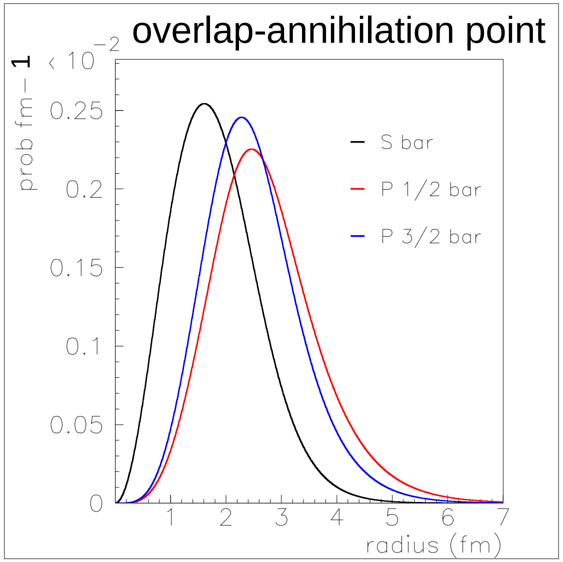
n and nbar wavefunctions

(based roughly on Dover. For qualitative illustration only)





roughly follows shape of $|n|^2$



$$\frac{1}{\tau} = \Gamma = -2\int d^3x \left|\bar{n}(x)\right|^2 W(x)$$

from previous page $\bar{n} \propto \varepsilon \propto \frac{1}{\tau_{free}}$

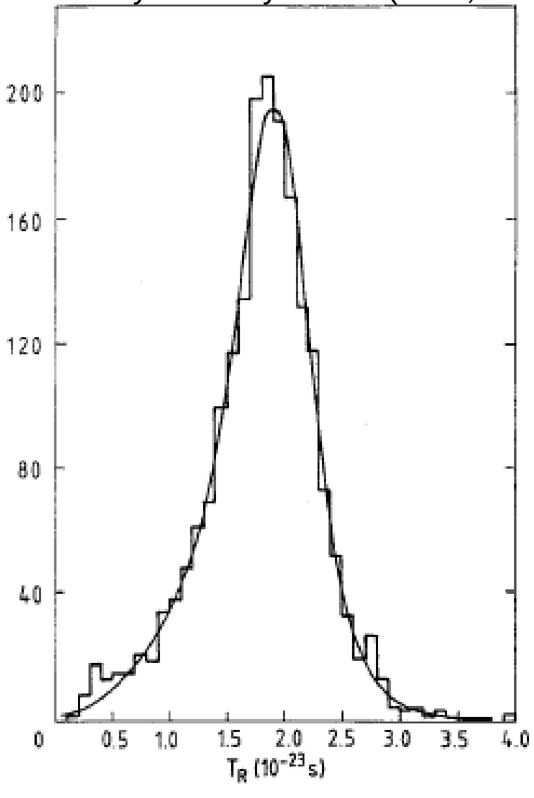
so we can define $R = \frac{\tau}{\tau_{free}^2}$

* in our current analysis the annihilation location is based on $|n|^2$

Some calculations of R

Author	Year	Potential	R (10^{23}sec $^{-1}$)	R_O/R_{Fe}
Dover	1983	249+i107	1.2	.71
Dover	1983	107+i222	.8	.71
Alberico	1991	Various	1.7-2.6	?
Hufner	1998	40+i40	.69	1.11
Hufner	1998	200+i40	3.6	.92

From previously shown potential uncertainty



Batty Nuc Phys A 466(1987)

We use the most conservative values 3.6×10^{23} sec^{-1} for comparing with τ_{free} and .71 when comparing with τ_{free}

Signal MC

Fermi Momentum / Quasi-Invariant Mass

- annihilating antineutron and nucleon are in energy eigenstates.

- Fermi momentum can be taken from scattering data (should match the Fourier Transform of the wavefunctions)

- quasi-invariant mass $m^2 = E^2 - p_F^2$

- During roughly 10% of the events, the matter nucleon will be interacting with another nucleon
  during the annihilation – giving a smaller invariant mass –
  Yamazaki Phys Lett B 453 (not implemented yet)
  However, we aren't very sensitive to these effects,
  setting the Fermi momentum to zero only changes
  our efficiency by ~10%

Leads to <4.2% uncertainty in final efficiency

Branching Fractions

n pbar annihilations (from pbar deuterium data)

Channel	Tegid's Memo	Our Analysis	Bettini (1967)
$\pi^+ \pi^0$	0%	1%(±1.0)	≤ 0.7%
$\pi^+ \pi^0 \pi^0$	9%	8%(±1.2)	*
$\pi^+ \pi^0 \pi^0 \pi^0$	10%	10%(±1.2)	16.4 ± 0.5%
$\pi^+ \pi^+ \pi^- \pi^0$	22%	22%(±1.8)	21.8 ± 2.2%*
$\pi^+ \pi^+ \pi^- \pi^0 \pi^0$	36%	36%(±1.8)	59.7 ± 1.2%
$2\pi^+ \pi^- \omega$	*	16%(±4)	12.0 ± 3.0%*
$3\pi^+ 2\pi^- \pi^0$	23%	7%(±4)	23.4 ± 0.7%
$4\pi^+ 3\pi^- m\pi^0$	0%	0%	0.39 ± 0.07%
$\pi^+ \pi^+ \pi^-$	0%	0%	1.57 ± 0.21%

p pbar annihilations (use isospin invariance)

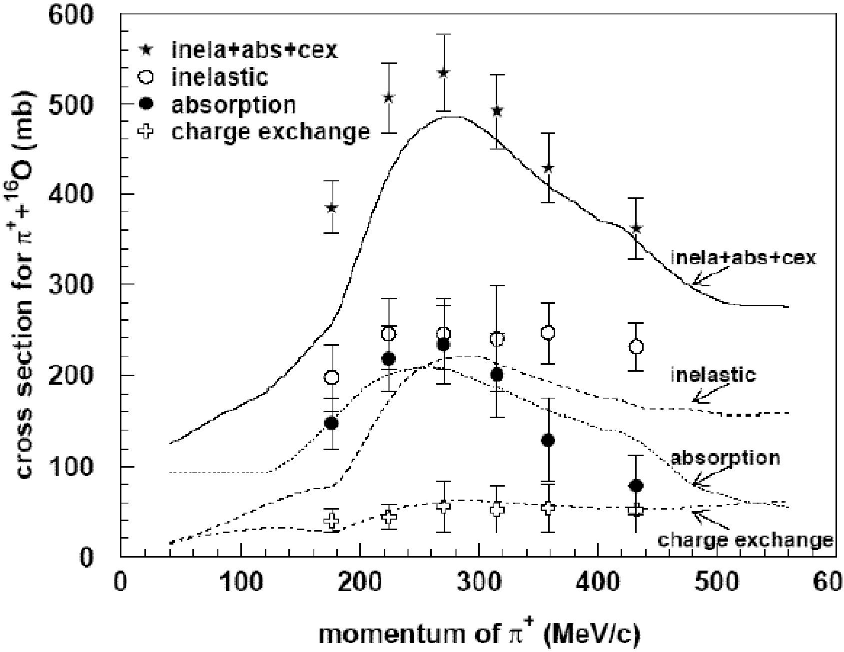
Channel	Tegid's Memo	Our Analysis	Cresti Paper (1963)	Baltay (1966)
$\pi^+ \pi^-$	0%	2%(±.4)	0.33 ± 0.48%	0.32 ± 0.03%
$\pi^0 \pi^0$	0%	1.52%(±.4)		3.20 ± 0.50%
$\pi^+ \pi^- \pi^0$	10%	6.48%(±.7)	5.4 ± 0.7%	7.8 ± 0.9%
$\pi^+ \pi^- \pi^0 \pi^0$	11%	11%(±1.3)		*
$\pi^+ \pi^- \pi^0 \pi^0 \pi^0$	26%	28%(±1.3)		34.5 ± 1.2%
$2\pi^+ 2\pi^-$	7%	7%(±1.4)	5.4 ± 0.3%	5.8 ± 0.3%
$2\pi^+ 2\pi^- \pi^0$	22%	24%(±3.4)	22.6 ± 0.7%	18.7 ± 0.9%
$\pi^+ \pi^- \pi^0 \omega$	*	10%(±0.9)		*
$2\pi^+ 2\pi^- \pi^0 \pi^0$	20%	10%(±0.9)		21.3 ± 1.1%
$3\pi^+ 3\pi^-$	0%	0%	1.7 ± 0.2%	1.9 ± 0.2%
$3\pi^+ 3\pi^- \pi^0$	0%	0%	1.7 ± 0.2%	1.6 ± 0.3%

Decays are according to phase space (Genbod)

Leads to 5.2% uncertainty in final efficiency

more recent ppbar BF's
astro-ph/0005419
kaons 7%
eta 3%
won't change our results

Pion (and Omega) Propagation

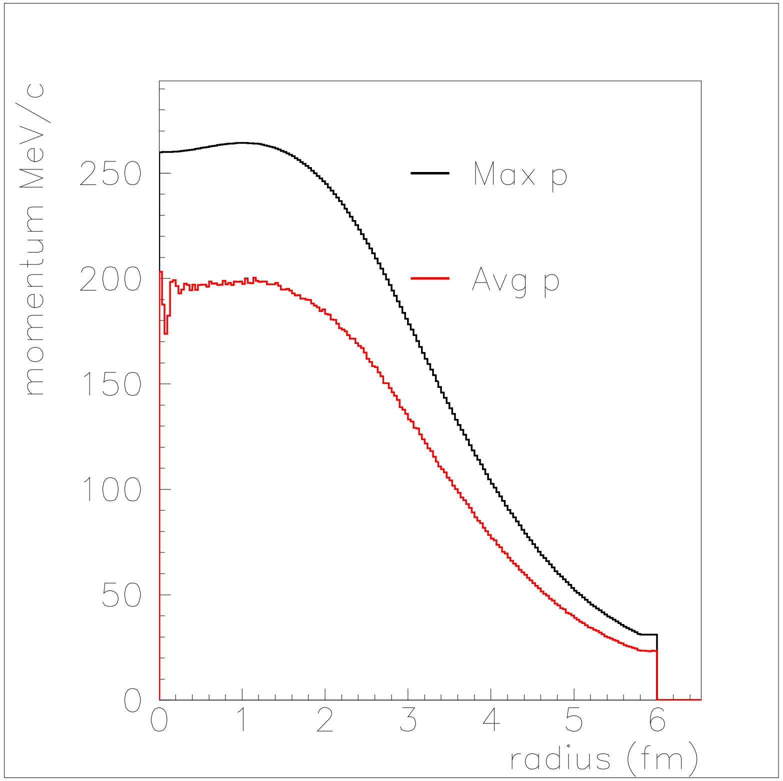


25% of pions absorbed 25%scattered
2.2 charged 1.3 neutral pions escape

- Pions propagate through the residual nucleus in .2 fm steps.
- Total pion-nucleus cross section is taken from scattering experiments and distributed throughout the residual nucleus according to the nuclear density
- Cross section peak due to $\Delta(1232)$

Leads to 12.5% uncertainty in final efficiency

Fermi Momentum / Pauli Blocking



- Nucleons of the residual nucleus are assigned a fermi momentum.
- For a fermi gas of local density ρ

$$p_{\max} \propto \rho^{1/3}$$

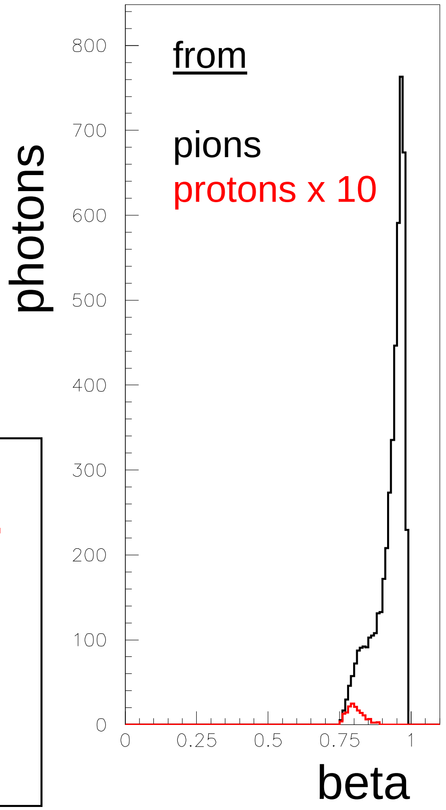
- Reactions that would result in a final state momentum > $p_{\max}$ are not allowed – Pauli Blocking

Nuclear De-excitation / Break-up

Gamma rays- P 3/2 holes will decay with the emission of a 6 MeV gamma – but this overlaps the rest of our signal.

In events with a pion interaction we currently create nuclear fragments (p n d He etc.) that statistically match inclusive multiplicities from antiproton-nucleus data.

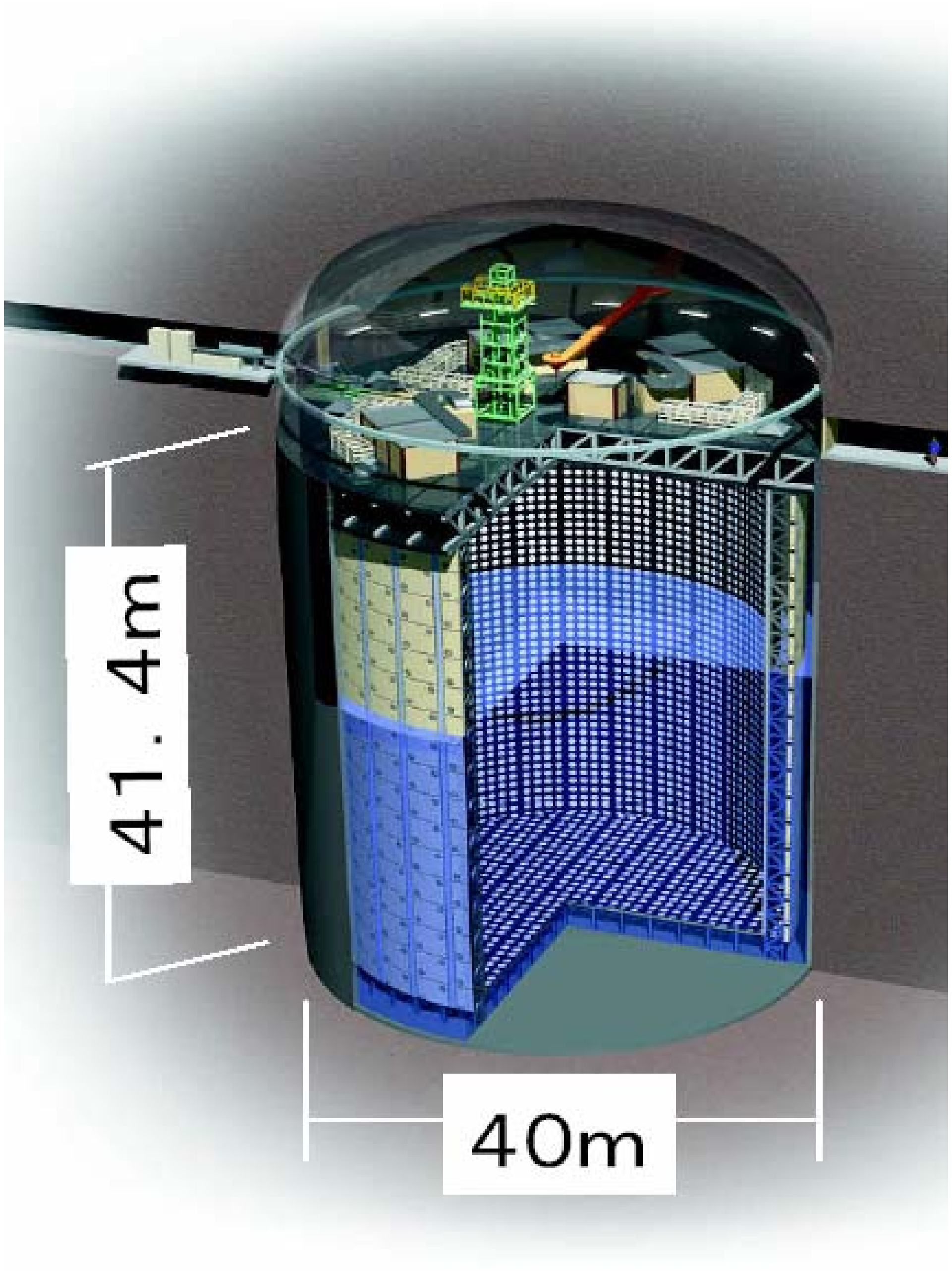
Cherenkov Light - some proton fragments will be above threshold, but the amount of light is insignificant compared to the pion contribution.



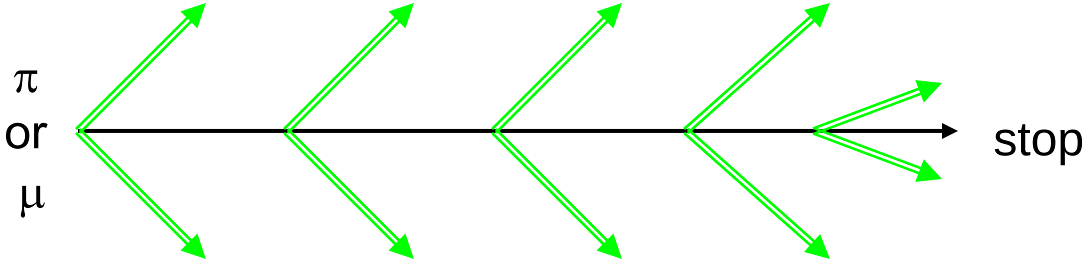
Neutron decay – another analysis group is working on a special trigger for neutron decay. However it is not clear that a background DIS atmospheric neutrino event would break up differently than a signal nucleus, so a more sophisticated break-up model is probably not worth the effort for this analysis.

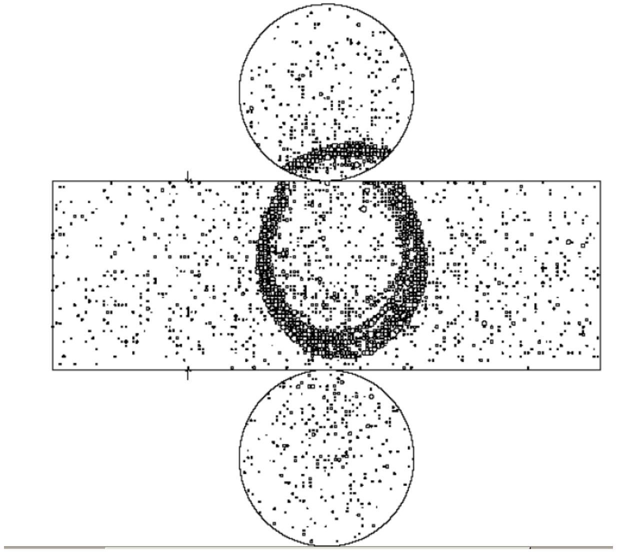
Detector

- 22.5 Kton Fiducial
- 2,700 m water equivalent overburden
- 11,146 inner PMTs
- 1,885 outer PMTs
- SK1 4.1 yr (this analysis)
- SK2 ~ 2 yr (1/2 PMTs)
- SK3 ~ 1 yr
- 2.2 nsec timing
- Can see 4.5 MeV neutrinos

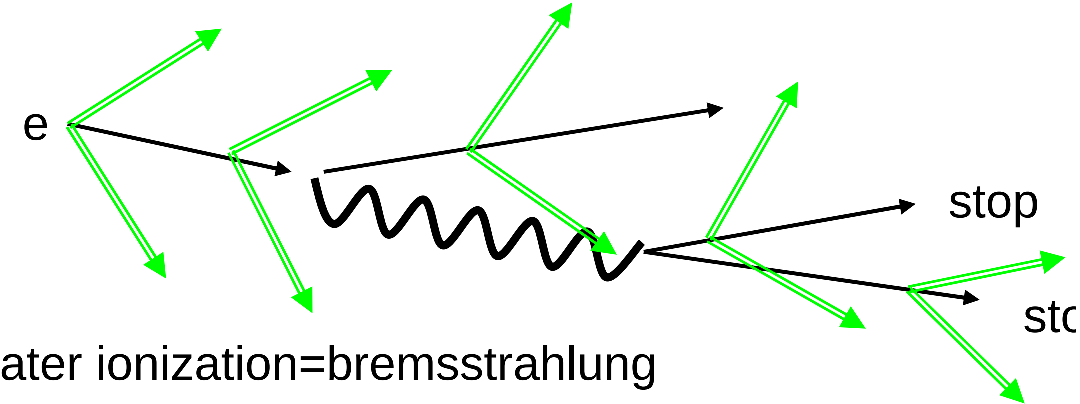


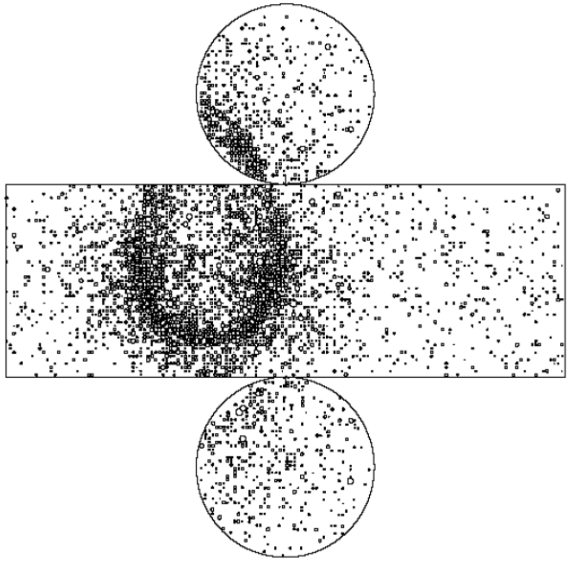
Cherenkov Rings





losing 2 MeV/cm to ionization





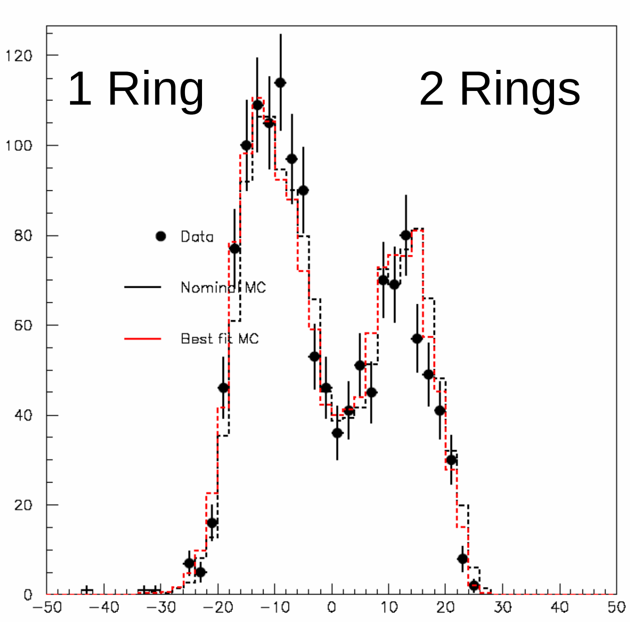
in water ionization=bremsstrahlung
at ~93 MeV

Ring Reconstruction

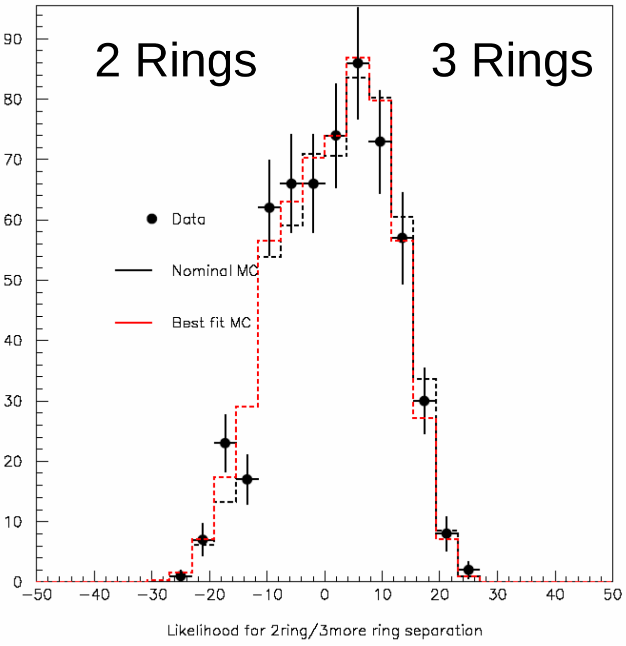
1) Place vertex at point which time of flight is equal to all hit PMTs. Resolution ~30 cm

2) For each PMT plot all possible track directions which could have resulted in a 42 degree Cherenkov angle photon hitting the tube. Look for overlaps.

3) Reconstruct entire length of track (~1 meter for our events.)



Log (likelihood) difference



Track Momentum/Event Energy

- The track mometum is determined from the total number of photo-electrons seen near the ring (70 degree ½ angle for single ring events)
- In single ring events the momentum resolution is (2.5/sqrt(GeV) + .5)% for electrons.

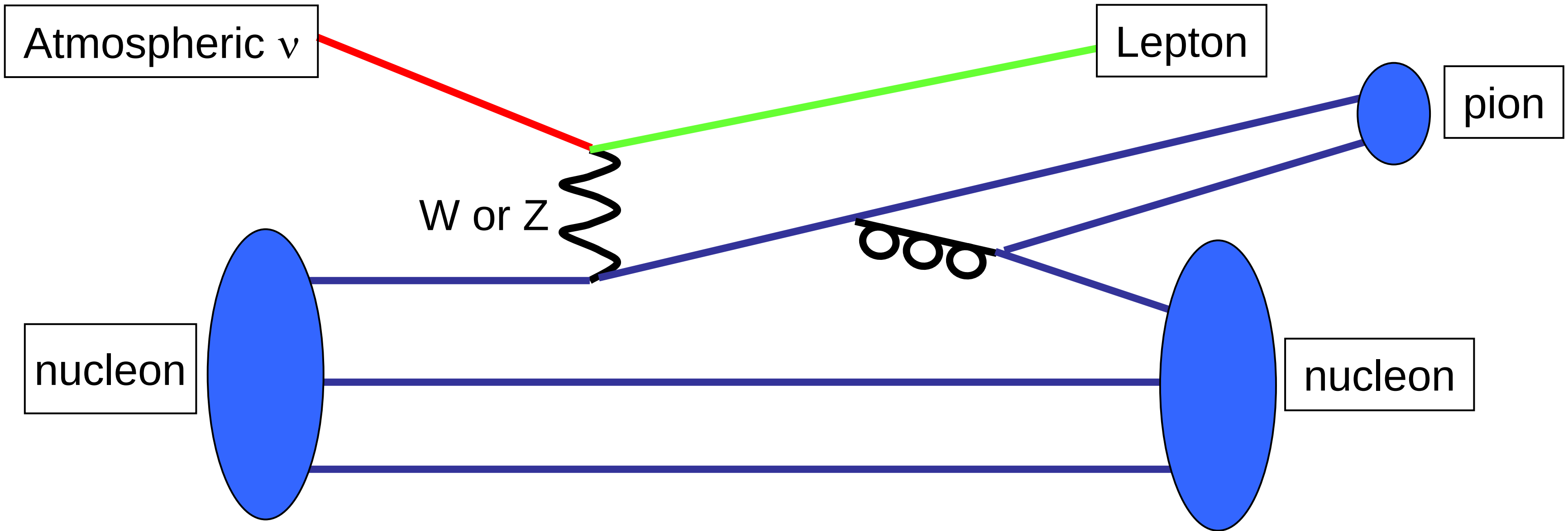
  and 3% for muons
- “Visible Enegry” for an event is defined as the energy of an electromagnetic shower giving the number of photo-electrons we see.

Background
Atmospheric Neutrinos

Selected background events

	νμ	Anti-νμ	νe	Anti-νe
Q.E.	11 (2.0%)	0 (0%)	7 (1.3%)	0 (0%)
CC 1pi	50 (9.6%)	10 (1.9%)	47 (9.0%)	7 (1.3%)
CC Mpi	101 (19.4%)	10 (1.9%)	103 (19.8%)	9 (1.7%)
CC K,eta	6 (1.2%)	6 (1.1%)	8 (1.5%)	1 (.2%)

NC 1pi	17 (3.3%)
NC mpi	125(24.0%)
NC K,eta	2(0.4%)
NC elastic	1(0.2%)



Atmospheric ν

Lepton

pion

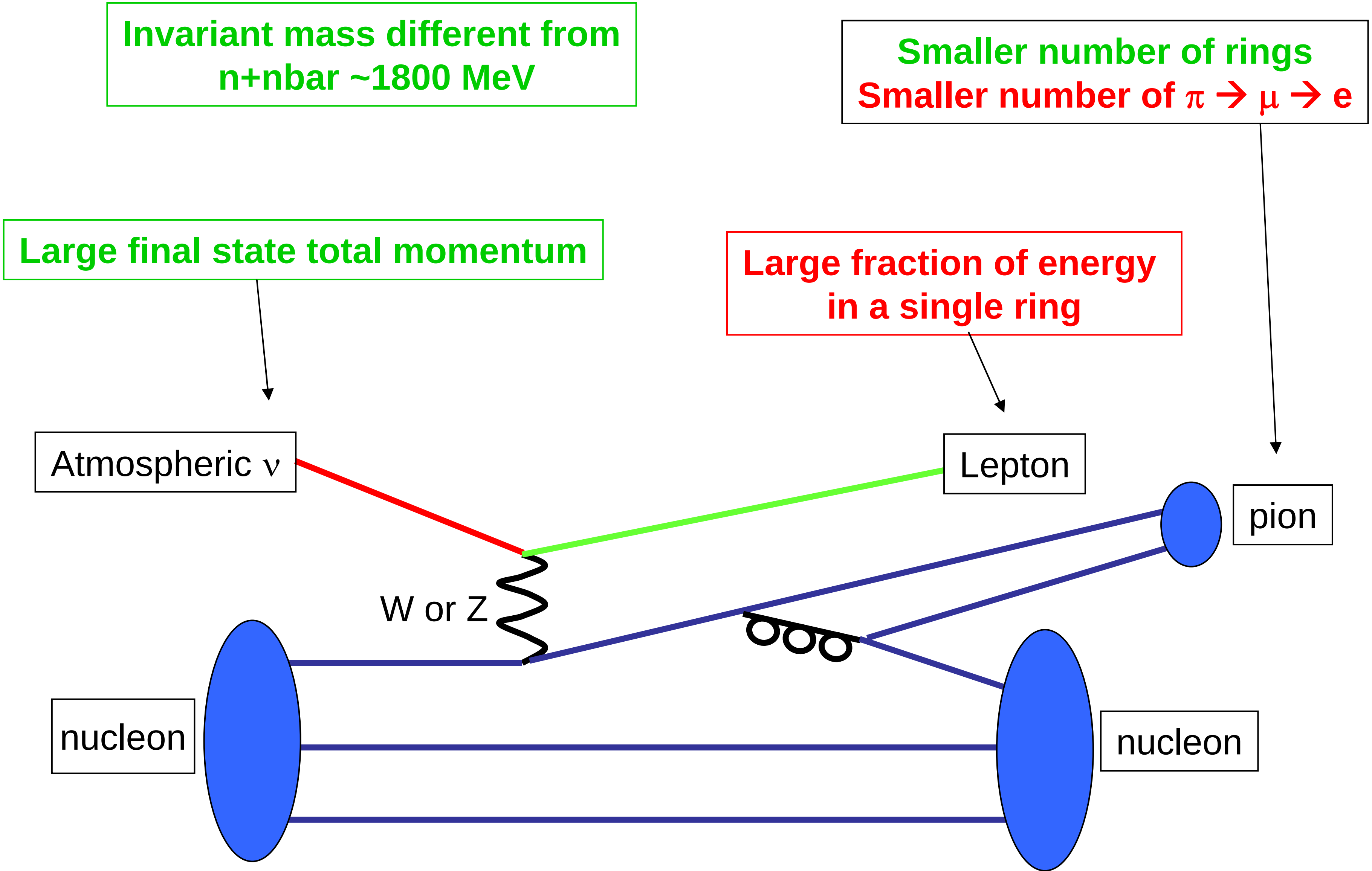
W or Z

nucleon

nucleon

Background Signatures

* red criteria not currently used



Invariant mass different from n+nbar ~1800 MeV

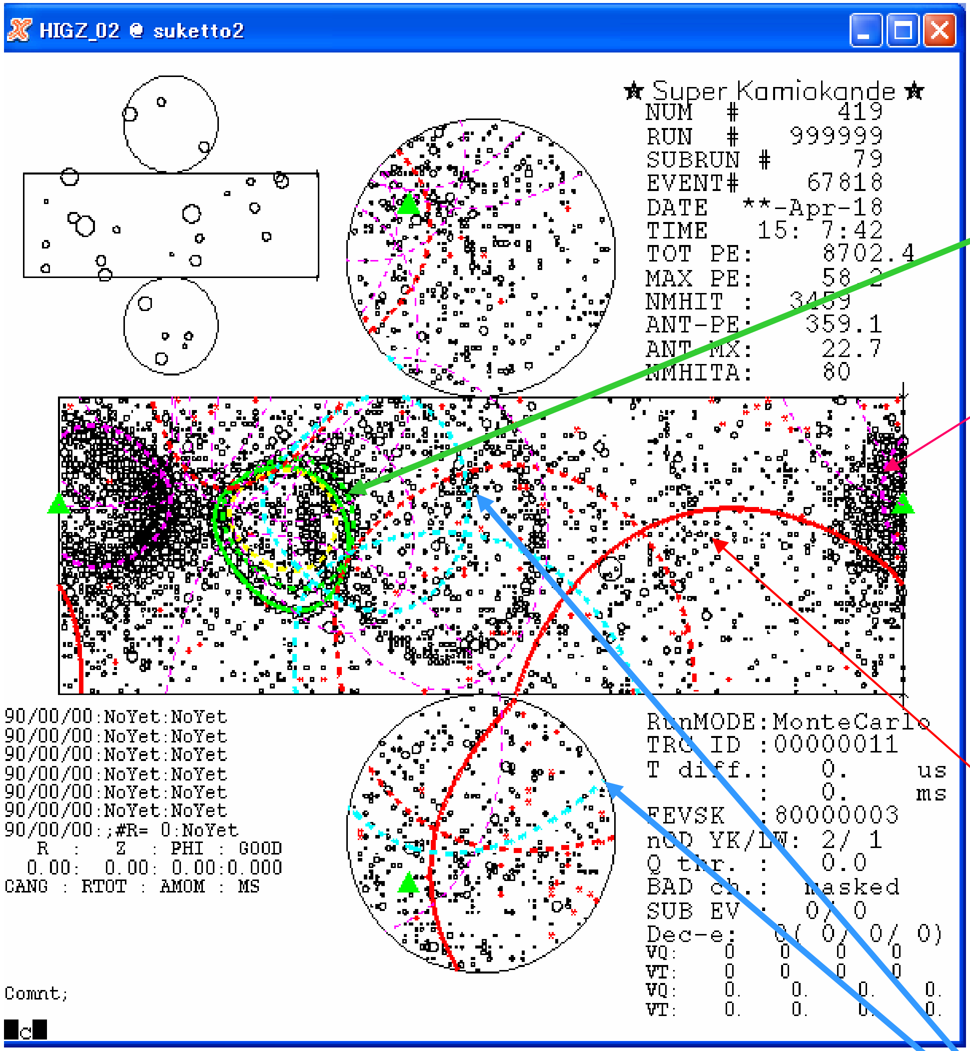
Smaller number of rings

Smaller number of $\pi \rightarrow \mu \rightarrow e$

Large final state total momentum

Large fraction of energy in a single ring

Charged Current Background



```
★ Super Kamiokande ★
NUM   #       419
RUN   #    999999
SUBRUN #       79
EVENT#      67818
DATE   **-Apr-18
TIME    15: 7:42
TOT PE:     8702.4
MAX PE:       58.2
NMHIT :    3459
ANT-PE:     359.1
ANT MX:      22.7
NMHITA:      80
```

```
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:;#R= 0:NoYet
   R  :    Z   : PHI  : GOOD
  0.00:   0.00:  0.00:0.000
CANG  : RTOT  : AMOM  : MS

Comnt;
```

```
RunMODE:MonteCarlo
TRG ID :00000011
T diff.:    0.      us
       :    0.      ms
FEVSK  :80000003
nOD YK/LW:  2/ 1
Q thr. :    0.0
BAD ch.:   masked
SUB EV :   0/ 0
Dec-e:    0( 0/  0/  0)
VQ:     0     0     0     0
VT:     0     0     0     0
VQ:     0.     0.     0.     0.
VT:     0.     0.     0.     0.
```

proton

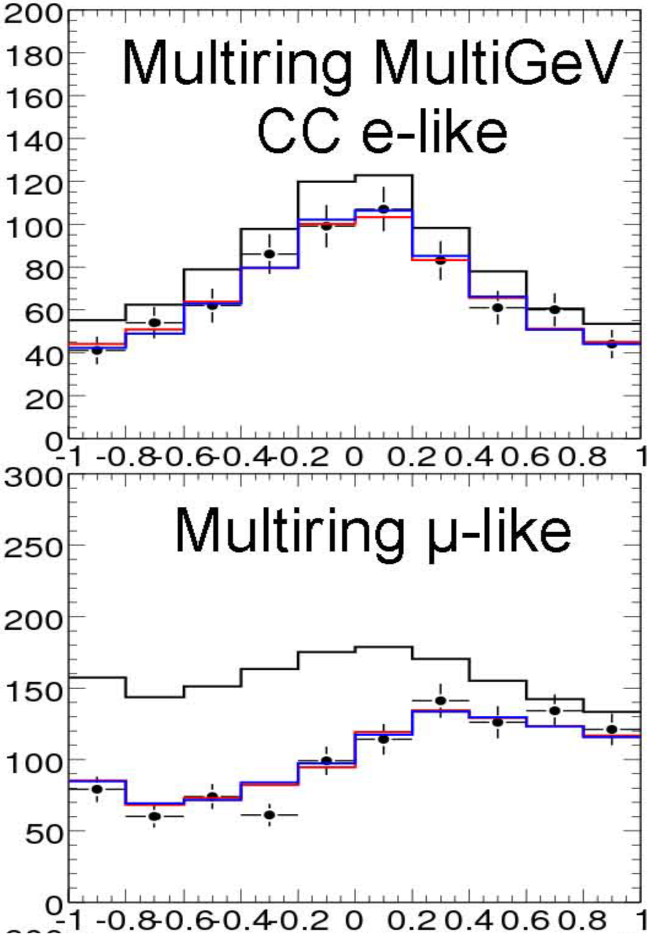
γ from π0

electron (45MeV)

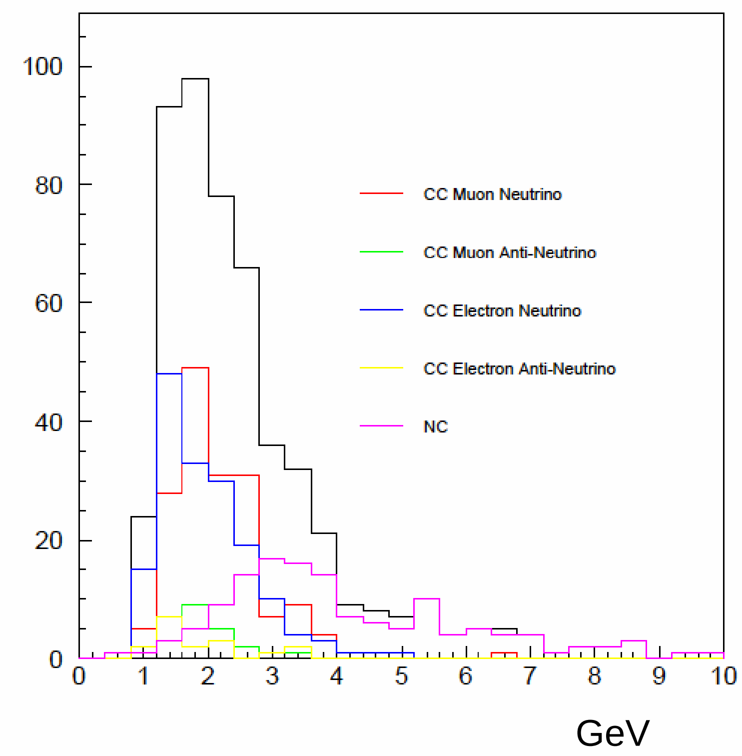
pions

$\nu_e + n \rightarrow e^- + p + \pi^+ + \pi^- + \pi^0$

Background Direction and Energy



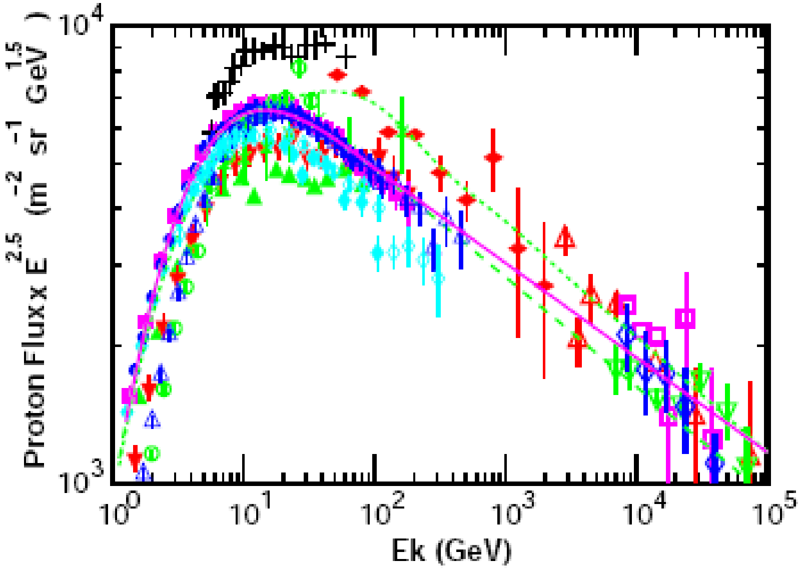
from oscillation analysis



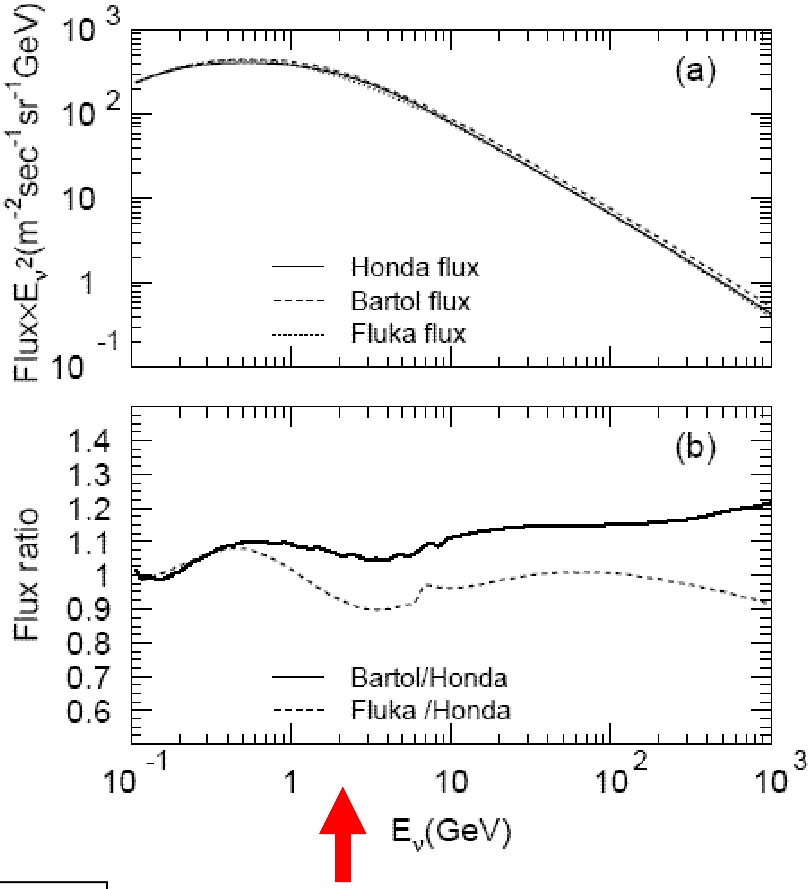
background more likely to come from above
(we are currently not using this)

Cosmic Ray and Neutrino Flux

Primary Proton Flux



Model Dependence of Resulting Neutrino Flux



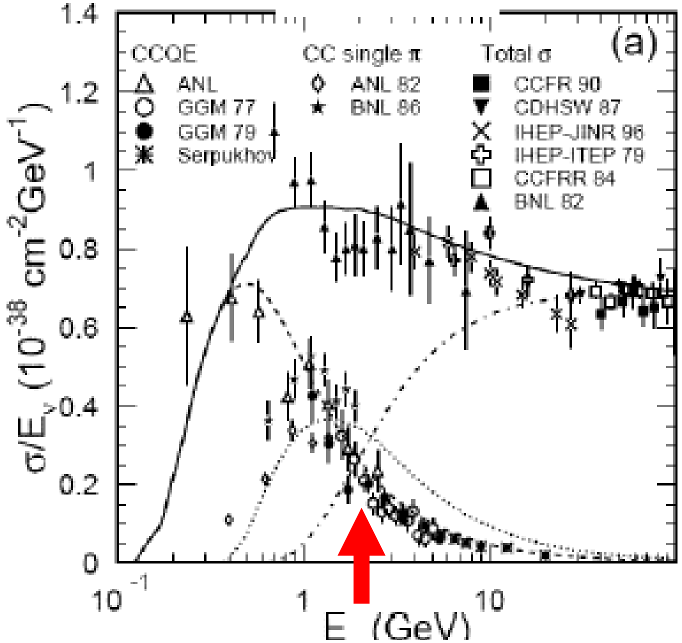
Neutrino flux is our largest systematic. It leads to 20% uncertainty in final background rate

Neutrino cross sections

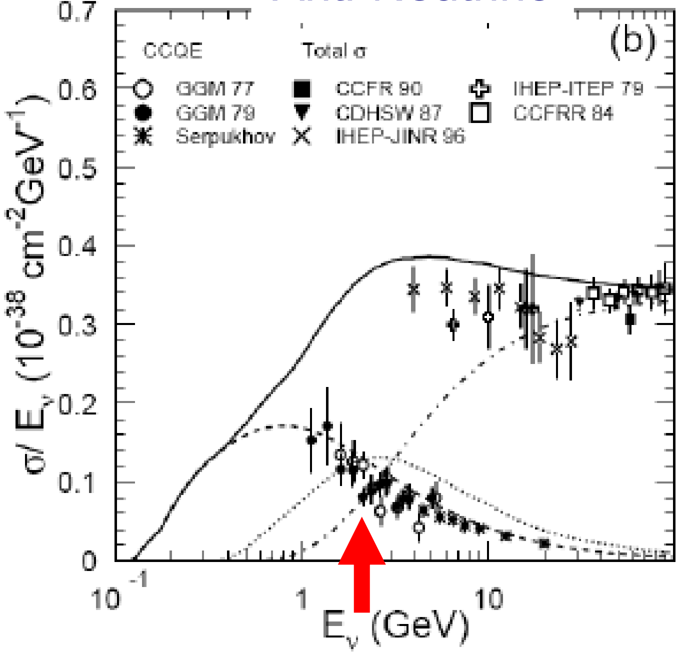
Solid – Total
Dash – Quasi-elastic
Dot – single pion
Dash-Dot – multi-pion

Cross section in multi-pion events leads to 3.4% uncertainty in final background rate

Neutrino



Anti-Neutrino



Multiple pions production models

- For hadronic mass 1.4<W<2.0 GeV, we fit Koba, Nielsen, Olesen (KNO) scaling to experimental pion multiplicities and forward/backward asymmetries from BECB and Gargamelle
- For W>2.0 we use Jetset.

Model dependence leads to 15.5% uncertainty in final background rate

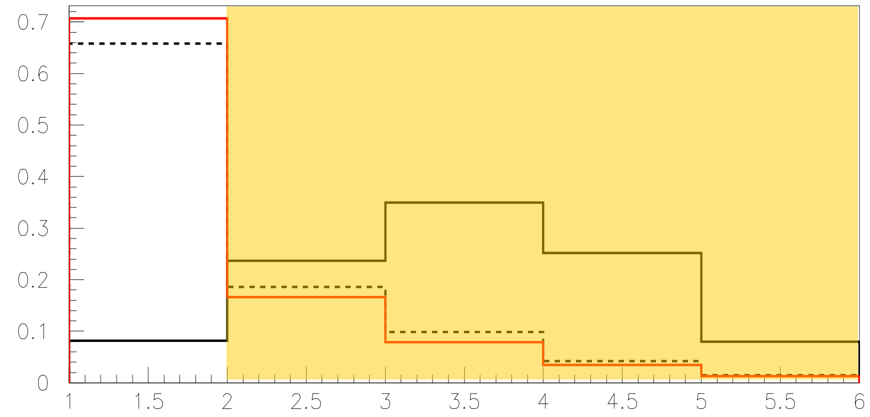
Analysis

Reduction to “Fully Contained” Data Sample

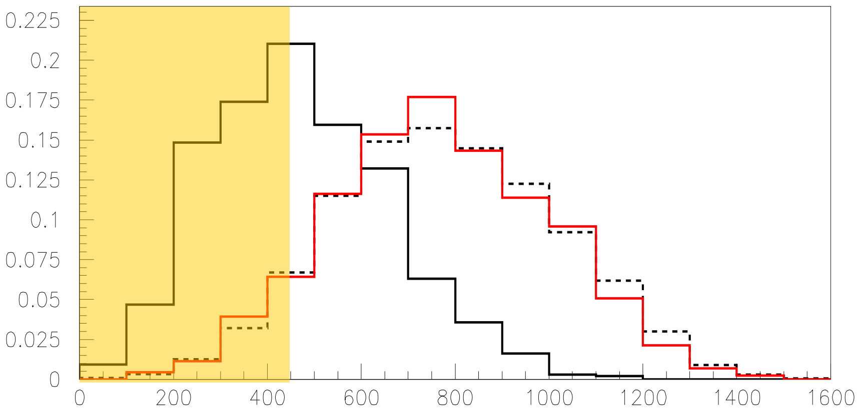
Step	Data	FC MC
Trigger	1.9G	100%
200 PE within 300 nsec, <1/2 of PE in one PMT,<25 Outer Detector (OD) hits,>.1 msec since last event.	302K	99.94
<10 OD hits aligned with an inner muon track. >50 PMT hits within 50 nsec after TOF (eliminates low energy events)	67K	99.83
Elimination of Flashing PMTs -Broad timing distributions eliminated. Hit patterns similar to earlier events removed.	27K	99.17
<10 OD hits in any 200 nsec window in the last 9 μs. (removes muons which drop below Cherenkov threshold inside the detector then decay.	24K	97.59
Within fiducial volume (2m from wall). Visible Energy >30 MeV	12K	97.59

Cuts

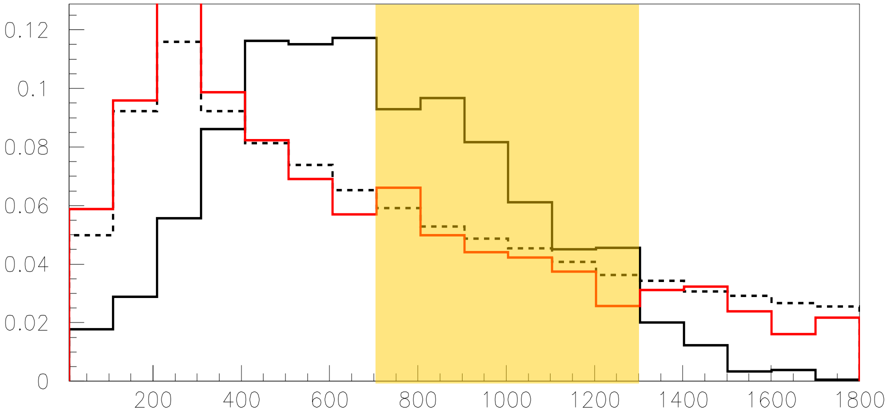
Red – atmospheric ν MC
Black – signal MC
Dotted - data



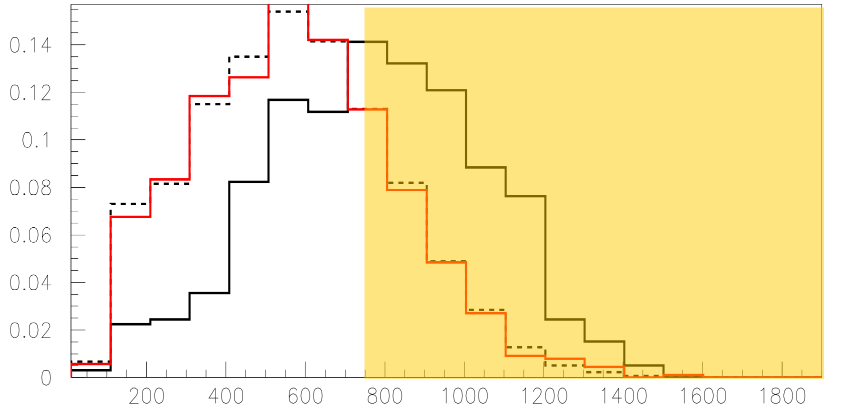
Number of Rings



Total momentum(MeV/c) after Ring,Evis cut

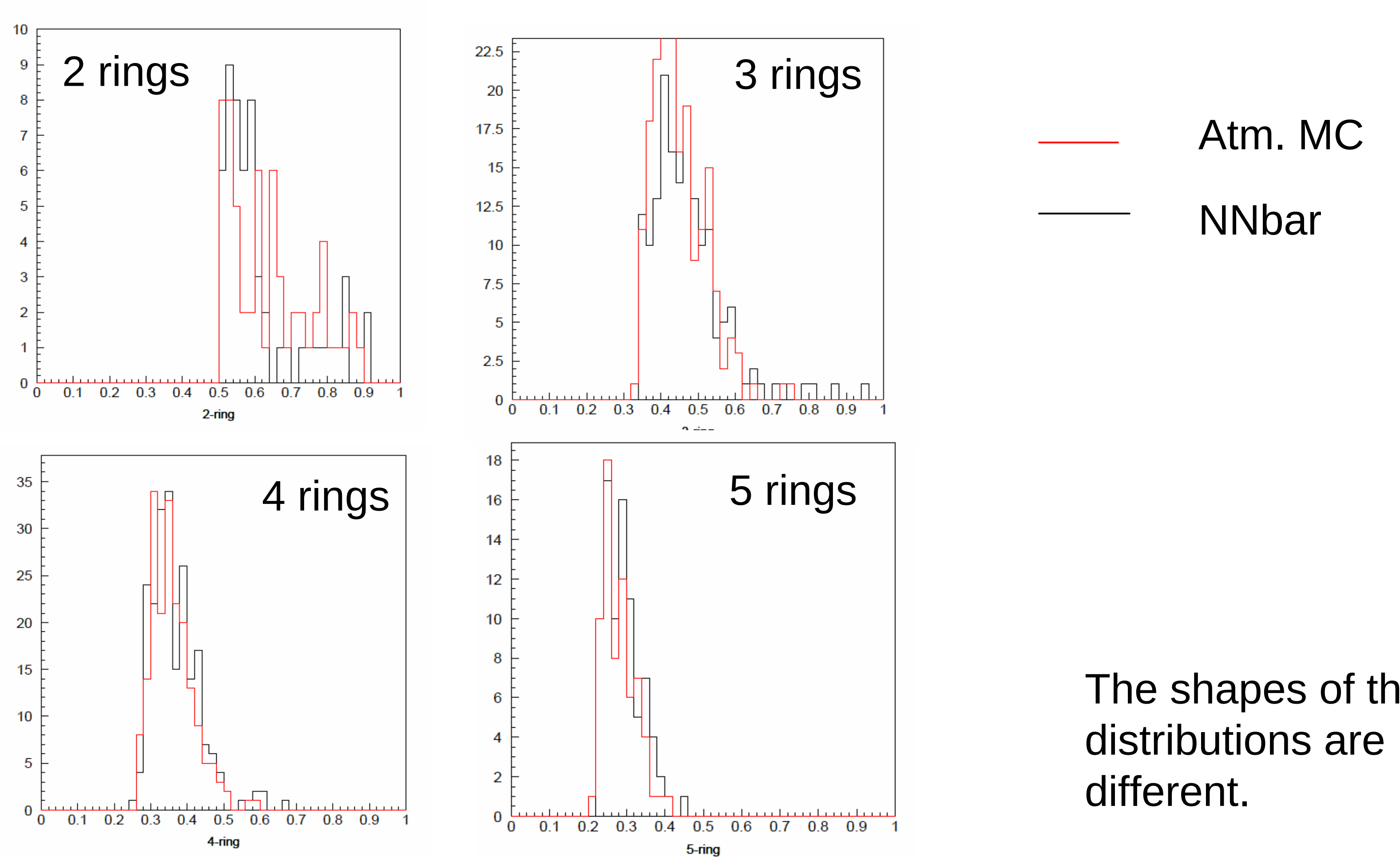


Visible energy(MeV/c) after Ring cut



Invariant mass(MeV/C^2) after Ring,Evis cut

High energy leptons from charged current events



plotting highest ring momentum / total energy

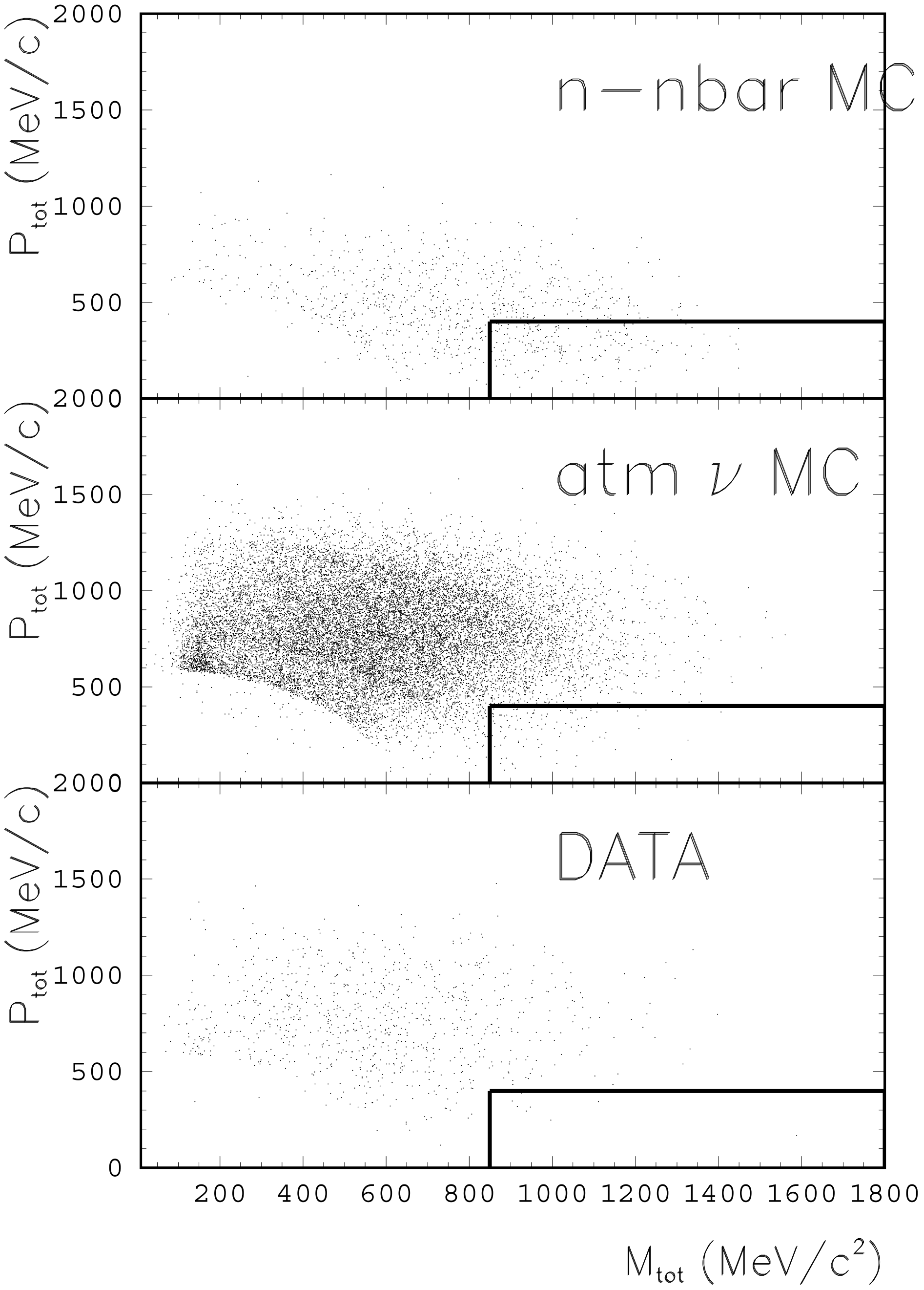
The shapes of the distributions are not very different.

→ cannot use for reduction.

Systematic uncertainties in the efficiency

	error	Uncertainty
Detection efficiency		**14.9 %**
Fermi momentum	20% of P_f	<4.2%
Annihilation branching ratio (model dependence)	Baltay('66), Bettini('67)	5.2%
Non-uniformity of detector gain	+/-1.2% of Ptot	4.0%
Energy scale	+/-2.5% of evis	1.7%
Ring counting		0.6%
Nuclear propagation (model dependence)	NEUT	1.7%
Nuclear propagation (cross section)	Elastic 20%, Charge ex 30%, Abs 25%, Pi prod 30%	12.5%
Exposure		**< 3.2%**
Detector livetime		< 0.1%
Fiducial volume		3.2%
TOTAL		**< 15.2%**

	error	Uncertainty
Un-uniformity of detector gain	+/-1.2% of Ptot	**9.0%**
Energy scale	+/-2.5% of evis	**12.0%**
Ring counting		**4.3%**
Neutrino flux	**21.5%**	
flux absolute normalization	20%	20%
flavor ratios (En<5GeV,>5GeV)	3%, 3-10%	-, 0.1%
ν*bar*/ν ratio for νe (Eν<10GeV, >10GeV)	5%, 5-10%	0.9, -%
ν*bar*/ν ratio for νμ (Eν<10GeV, >10GeV)	5%, 5-10%	0.8, -%
Up/down ratio	0.4-2.1%	- %
Hor./vertical ratio	0.3-2.8% (3D calc.)	- %
K/π ratio	20.0%	5.2%
Energy spectrum	0.05 for Ep>100GeV	5.8%
Neutrino cross section	**18%**	
M_A in quasi-elastic and single-pi	10% in M_A	4.4%
Quasi elastic scattering (model dependence)	1σ = Fermi-gas vs. Oset	- %
Quasi elastic scattering (cross section)	10%	0.4%
single-pion production (cross section)	10%	2.8%
multi-pion production (model dependence)	1σ = w/, vs. w/o Bodek	15.5%
multi-pion production (cross section)	5%	3.4%
coherent pion production (cross section)	30%	0.1%
NC/(CC) ratio	20%	6.2%
Nuclear effect in 16O (mean free path)	30%	2.7%
TOTAL	**32.1%**	



Result

efficiency = 10.4% ± 1.6%
number of neutrons = 6.02 x 10^{33}
SK-I livetime = 4.077 years
observed candidates = 20
expected background = 21.31 ± 6.84
Bayesian statistics

Official Result 90% CL
1.77 x 10^{32} years

with R=3.6 x 10^{23} this corresponds to τ_{free} = 1.25 x 10^8 seconds compared to .87 x 10^8 at Grenoble

Frequentist result = 2.45 x 10^{32} years

Frequentist result
without systematics= 4.45 10^{32} years
(as in previous experiments)

Bayes vs Frequentist

with no systematic errors we have …

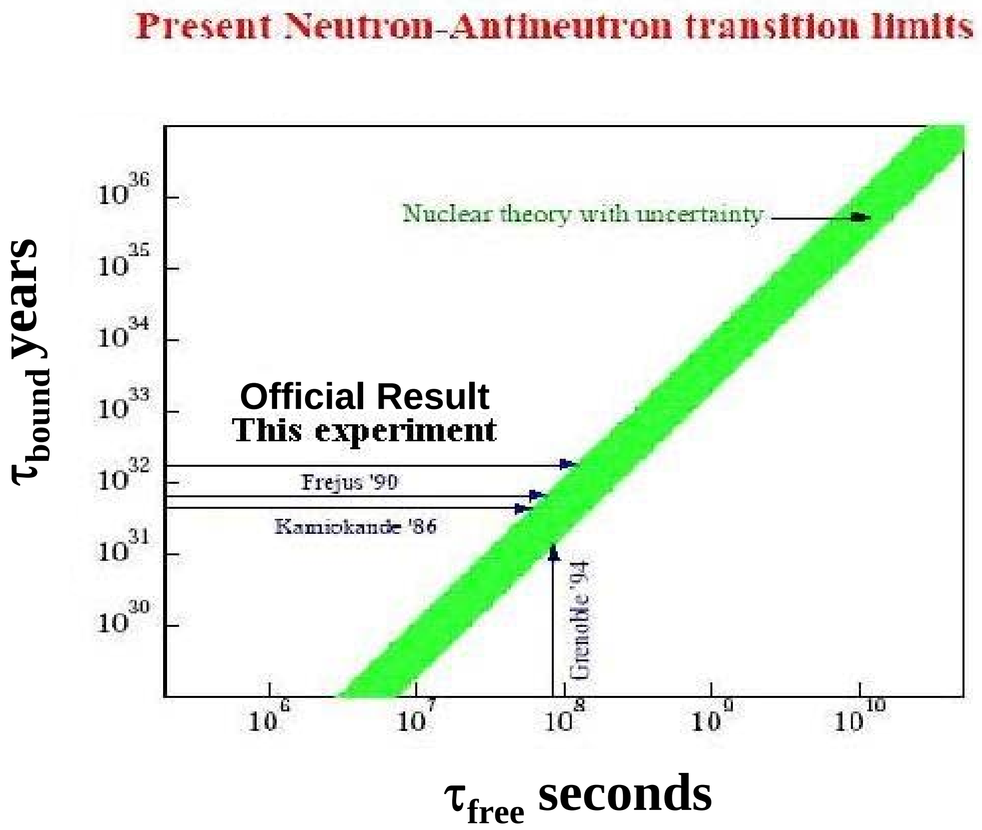
$$\text{Frequentist}\; CL = 1 - e^{-(b+s)} \sum_{n=0}^{n_0} \frac{(b+s)^n}{n!}$$

s= signal limit
b=expected background
n=selected data events

$$\text{Bayes}\; CL = 1 - \frac{e^{-(b+s)} \sum_{n=0}^{n_0} \frac{(b+s)^n}{n!}}{e^{-b} \sum_{n=0}^{n_0} \frac{(b)^n}{n!}}$$

~1/2

Previous Results

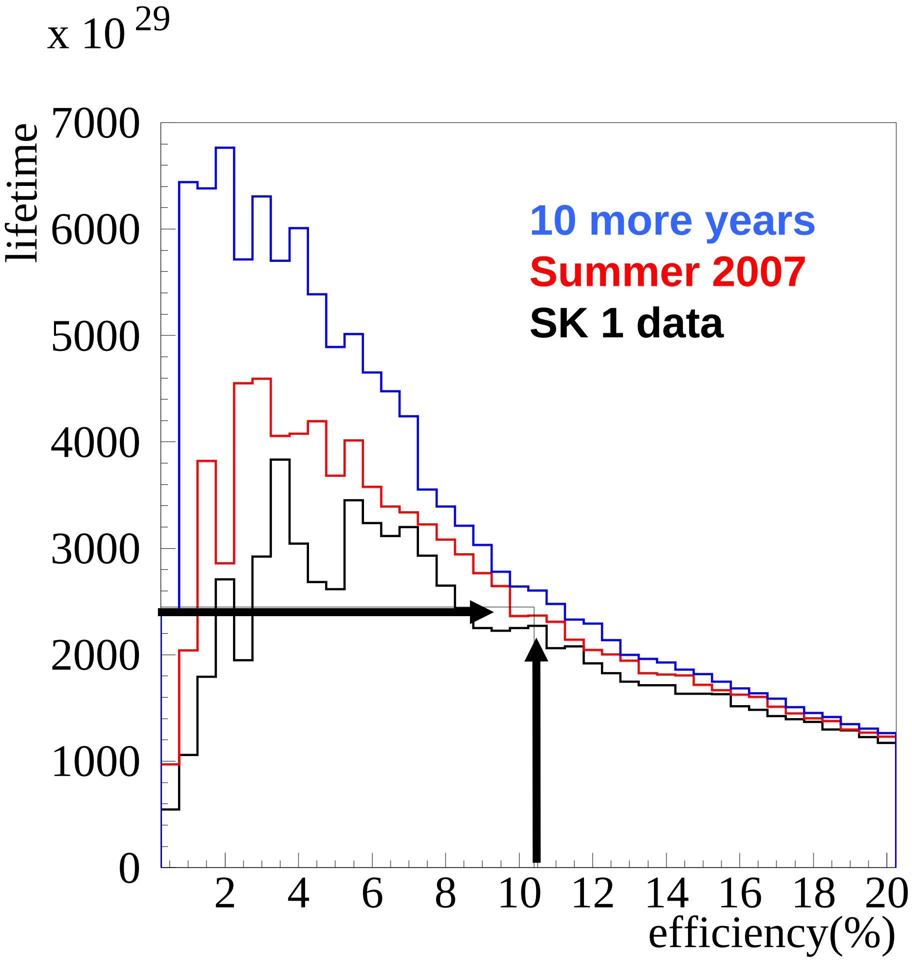


Experiment	Year	Exposure (10^{32} neutron-yr)	Efficiency	Data	BG	Signal Limit	Frequentist Limit no systematics (10^{32}yr)	Start point	Absorption cross section
SuperK I	2006	245	.104	20	21.3	5.7	4.45	Volume	Linear
Sudan II *	2002	2.15	.18	5	2.5	5.5	.72 (.84)*	Vol. (Dov.)	Linear
Frejus *	1990	5	.30	0	2.1	2.3	.65*	Volume	Linear
Kamiokande	1986	3	.33	0	1.2	2.3	.43	Dover	Linear
IMB	1983	3.2	.14	0	0	2.3	.17	Dover	Density^2

*Iron experiments have an additional suppression of ~1/.71 not included here (see slides 11 and 43)

Future

Future Results



- Predicted MC results for cuts resulting in different efficiencies.

- Frequentist result with systematic errors

- Upward fluctuations correspond to seeing one less event in the data.

- Future SK limit ~ 6x10^{32} years

Efficiency Correlations with "R"

$$\tau^2_{free} = \frac{\text{Exposure}}{\text{Signal limit}} \frac{E_s + 3E_p}{R_s + 3R_p}$$

experimentalists average

theorists average

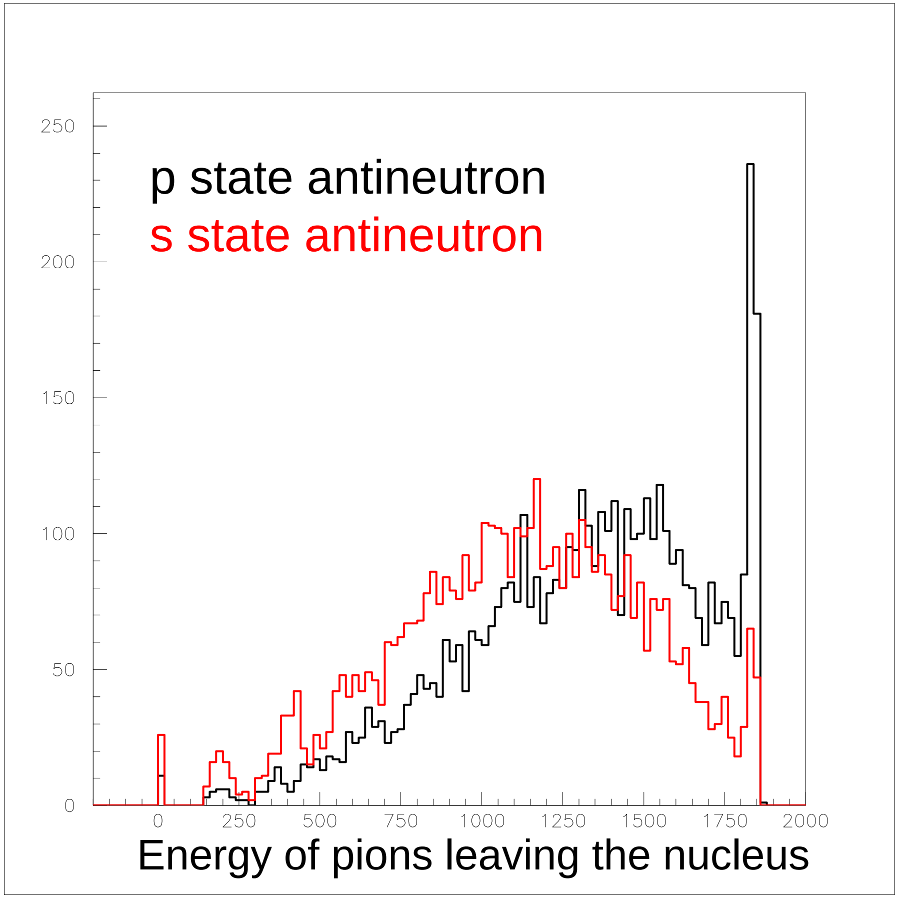
if we consider correlations
we have …

$$\tau^2_{free} = \frac{\text{Exposure}}{\text{Signal limit}} \left[\frac{E_s}{4R_s} + \frac{3E_p}{4R_p} \right]$$

<u>plugging in Dover</u>
R_s=1.21 R_p=.82 x 10^{23}

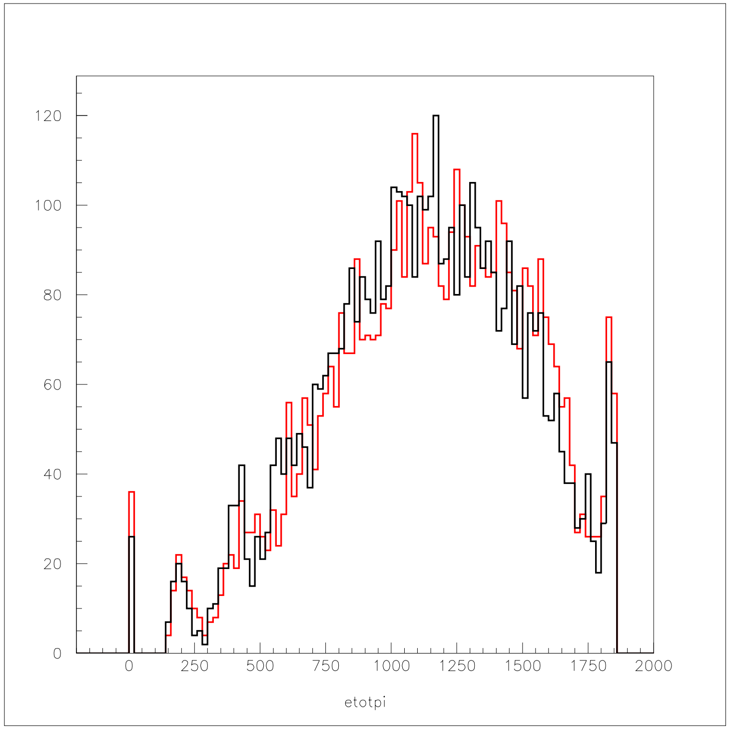
<u>and a guess from this plot</u> →
E_s=.06 E_p=.12

gives us 7% higher τ^2_{free}

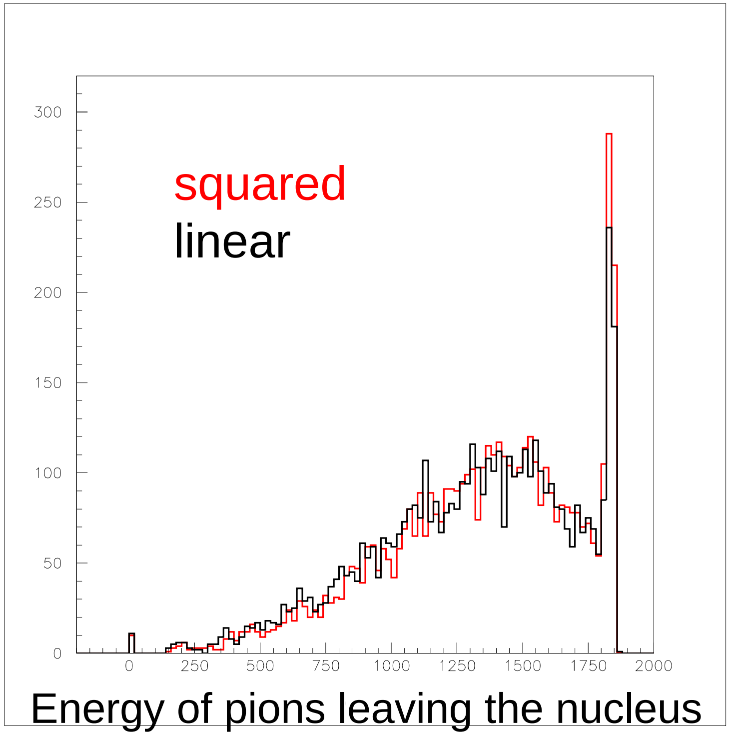


Should absorption cross section scale like the nuclear density squared?

S state antineutrons



P state antineutrons



Energy of pions leaving the nucleus

Absorption is a three body reaction, so IMB (1983) distributed the Oxygen-pion absorption cross section according to the nuclear density squared. No one has done this since then. Looks like it will result in a 5-10% improvement.

Conclusions

- Official Result $\tau = 1.77 \times 10^{32}$ years (Bayes, including systematic errors)
- Improvement of 4.4 times over previous measurement of τ_{nuclei} (When duplicating their procedure of using frequentist statistics without any systematic errors and $R_O/R_{Fe}=.71$)
- 44% better than Grenoble τ_{free} (Bayes, $R=3.6 \times 10^{23}$)