Li-9 Summary - April 3, 2006

1. Normalization

The total muon flux at 450 MWE is 0.2/m^2/s from P&H. In the MC, events are generated over a logrithmically flat interval from 100 MeV-1 TeV (muon.ps). For the zenith angle, events are generated over cos_theta_z= (-1,-0.3) and then weighted. A key point in the weighting of a logrithmic histogram is getting the binning in the correct dimensions. In this case, the normalization is carried out between the upper and lower left histograms in muon.ps. The integral of the upper left histogram is 80/s (0.2 muons/m^2-s x 400 m^2=80/s) and the integral of the lower left is 1.682. Multipliying the lower by 47.56 gives the same integral as the upper (not they look different because the upper is counts/GeV-m^2-s, a more appropriate comparison is upper left with lower right).

Thus, all other weighted histograms should be multiplied by 47.56 to render them in counts/s in each bin.

2. Hagner cross section

As mentioned before the MC has been run in something approximating the Hagner geometry. 190 GeV muons are put in and Li-9 generated from neutrons according to the cross section:

sigma=0 T<50 MeV
=0.01 mb *(70 MeV - 50 MeV) 50 MeV < T < 70 MeV
= 0.2 mb 70 MeV < T

the cross section really has one parameter: the constant value above T=70 MeV. the idea is to count Li-9 production in the Hagner target cell and then normalize the cross section for T>70 MeV to reproduce the Hagner cross section of of sigma(mu+C-12 -> Li-9 + X)=2.12+/- 0.35 ub.
The results of 5 2 million muon event runs are:

	2Feb	26 aug	3 Feb	30 Jan	31 jan
Total Li-9	879	948	959	937	901
Li-9 in cell	17	18	10	3	11
Li-9 in z-slice	108	99	126	112	116

Total Li-9 = total number of Li-9 events
Li-9 in cell = number of Li-9 events in Hagner cell
Li-9 in z-slice = number of Li-9 in same z interval as cell.

The average number of Li-9 is 11.8 +/- 5.6 if you look at the table, first time i run this I got 18, the second time 3! so, I spent a week trying to figure out what was wrong...

Getting everything right is tricky: the number density of C-12 in the simulation is 4.7e22/cm^2 (C_9 H_10, rho=1 g/cm^2). In the Hagner setup, the number density is 3.7e22/cm^3 (from NS spreadsheet), so the number of Li-9 in the cell must be reduced by 3.7/4.7=0.79, N(Li-9)=9.3 +/ 4.4. then, sigma(mu+C-12->Li-9 + X)=9.3/(2e6 x 88 cm x 3.7e22 /cm^3)=1.4e-30 cm^2 = 1.4 +/- 0.7 ub.

Then, in order to get Hagner correct, I need to increase the constant part of the cross section by a factor of 2.12/1.4=1.5 to give 0.30 +/- 0.16 mb.

3. Expected rate a Braidwood

Next, run the cosmic muon simulation for Braidwood, weighting as outlined above. The unweighted and weighted distributions are shown in li9.ps. In addition to the normalization factor of 47, a factor of 0.85 has been applied to account for the different in the C-12 in the simulation (1 g/cm^3) and at Braidwood (0.85 g/cm^3, NS spreadshhet) and a factor of 1.5 for the Li-9 production cross section in the simulation (0.2 mb) and scaled from hanger in section 2 above (0.3 mb).

In li9.ps, the upper panel shows unweighted counts and lower is weight.

	Weighted	Unweighted
Li-9 total	32.78/day	129
Li-9 r<2.6m	18.04/day	61

In a previous message, I had given ~5/day for Li-9, r<2.6 m. the factor of three difference comes form removing a cut which did not propagate neutrons with energies above 1 GeV.

4. Rejection by energy in vessel

i have a crude method for computing total energy in the vessel. for each charged particle except electrons, I compute the pathlength in the vessel and then take an energy based on minimum ionizing dE/dx. For electrons and photons, I assume all of the energy is captured. evessel.ps shows the energy deposition in the vessel for all muon events and events in which Li-9 is produced inside the 2.6 m.

Suppose we reject all events in which had an event with E_v>1 GeV in the past 1 sec. 1 s=5.6 halflives of Li-9, so 18 x (2^-5.6)=0.4 event/day remains. Above 1 GeV, there are 2511 events/day, so this would mean a deadtime fraction of 2511 x 1s/(24 x 3600)=0.03 or 3% deadtime. Note: the events shown in this plot are only events in which a neutron is produced somewhere in the event.

5. Comparison with KamLAND
This is even more confusing!
a) First estimate: average muon energy is 340 GeV for KamLAND and flux is 0.0221/cm^2-day (both form NS). For Braidwood at 450 MWE, I get 18 Li-9 events in the 62 ton inner 2.6 m inner volume. Then I scale by the volumes and total number of neutrons:

18/day x (340 GeV/78 GeV)^0.74 x (1/s) x (1/80) x (1000 ton/62 ton) =11/day

NS gets 3/day

b) MC
For simplicity, assume the muon flux at KamLAND depth is a delta function at 340 GeV with a flux of 0.0221 mu/cm^2-day (From NS), with the same angular distribution at at 450 MWE (NB: should not make any real difference, spherical geometry). the idea now is to carry out the calculation in exactly the same manner as above:

Make a histogram with an entry in the 354-331 GeV bin (bin 85) which is 0.0011 mu/m^2-s-GeV. Run 100,000 muon events in Pass1, weighting as usual. this gives a value of 0.0229 in bin 85, so the normalization is 3.92e6/day, i.e. I scale any other histogram by this factor and get counts/day.

In the second pass, I loop over the Pass 1 events which make at least one neutron in the event twenty times. The file li9_kl.ps shows the resulting radius distributions, properly scaled. for r<2.6 m, there is one event (!) with weight 0.43; this is the rate for 62 tons of Braidwood. For Kamland, this gives,

0.43/day x (3.74e22/4.01e22) x (1000 ton/62 ton)=6.2/day in Kamland. NS gets 3/day.

for one event, the Poisson statistics are 1 +1.7/-0.45, so the rate for KamLAND is 6.3 +10.4/-3.5/day.

8. Determination of IBD rate
NS points out that, rather than simply removing all Li-9 background and incurring some deadtime by cutting for ~1 s after a big (E_vessel>1 GeV) event, it would be better to fit the time distribution of IBD-like events and make use of the Li-9 lifetime in the fit.

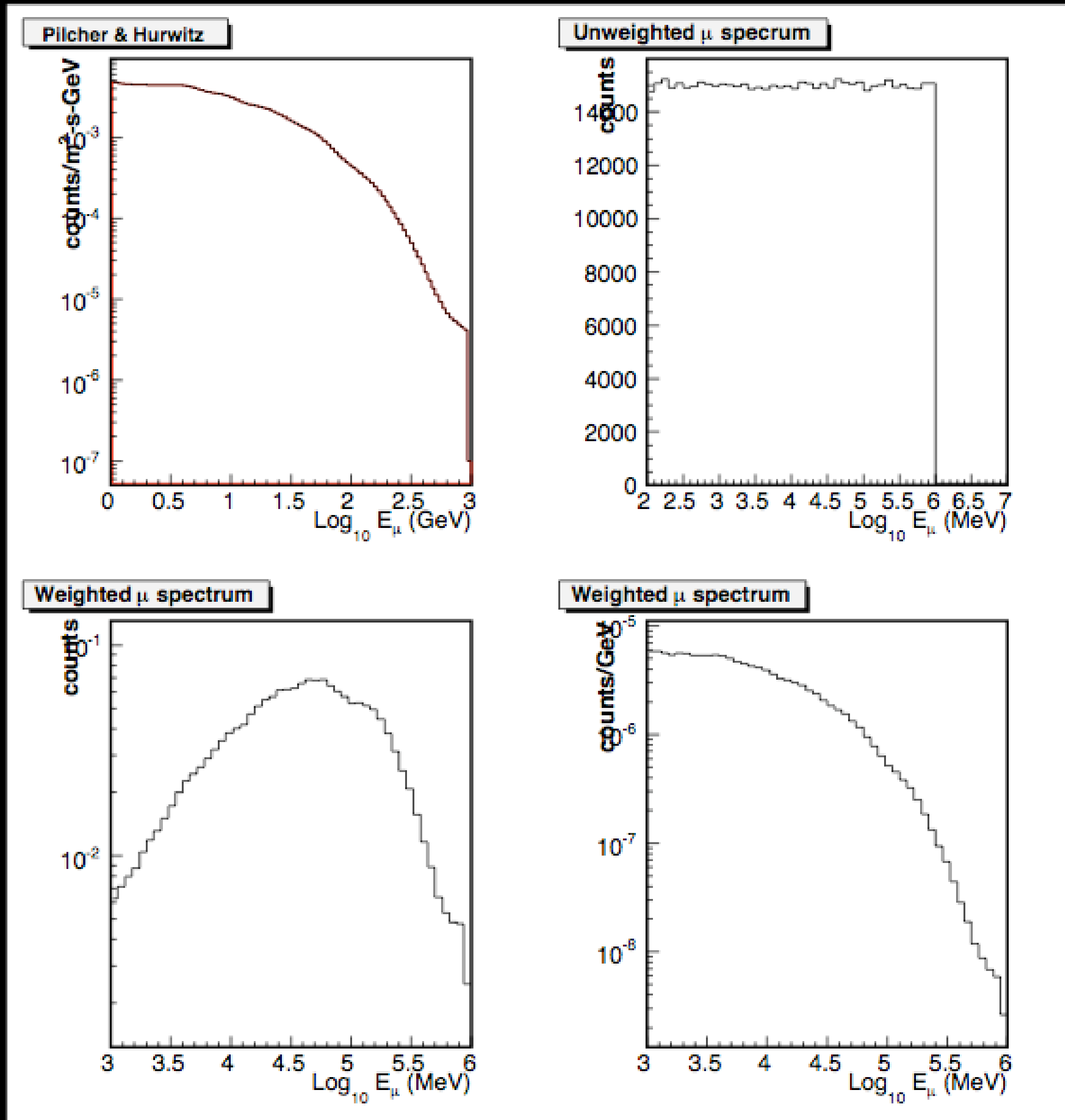
Big events occur on average of once every 33 s (see above), so their rate is 0.03/s. After running for three years, we will have a total of 122,990 neutrino events in the far detector. If we want the time distribution of how long before a neutrino event a big event occurred, this is given by N_far*lambda_Big*exp(-lambda_Big*t). Over the same time, the calculation above predicts 19,867 Li-9 decays preceeded by big events with a time distribution N_Li9*lambda_Li9*exp(-lambda_Li9*t).

Generating the histograms and fitting for four parameters (lambda_Big, lambda_Li9, N_nu, N_li9) gives:

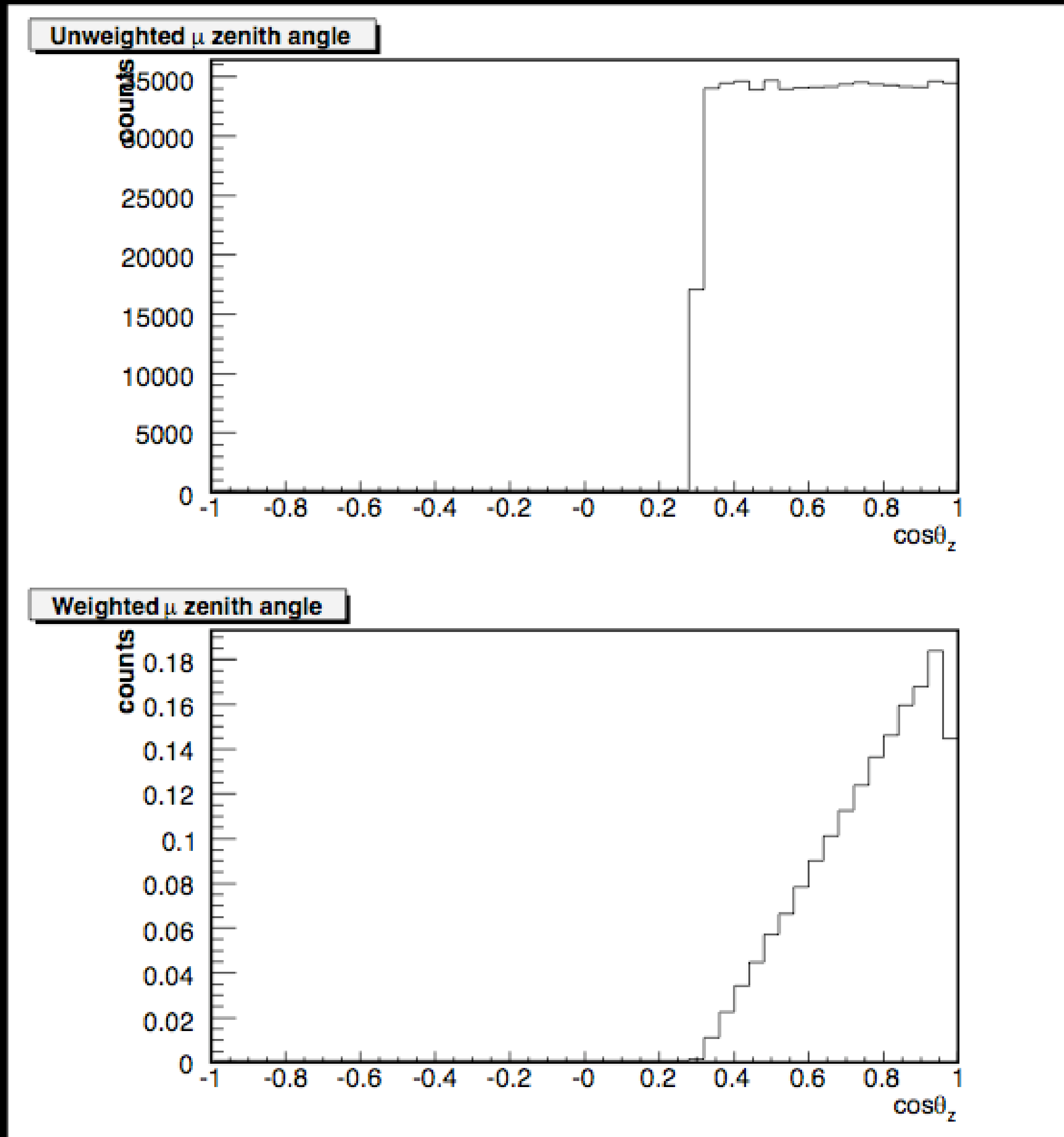
```
 FCN=714.299 FROM MINOS     STATUS=SUCCESSFUL    308 CALLS         394 TOTAL
                     EDM=1.19162    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                  PARABOLIC         MINOS ERRORS
  NO.   NAME      VALUE            ERROR      NEGATIVE      POSITIVE
   1  Li9 Halflife     1.78569e-01   1.97673e-03  -2.29559e-03   2.68730e-03
   2  Total Li-9       1.97639e+04   1.58311e+02  -8.92451e+01   3.11012e+02
   3  Total nu-e-bar   1.22211e+05   3.58551e+02
   4  BigRate          3.02362e-02   1.00121e-04  -1.00351e-04   1.53125e-04
```

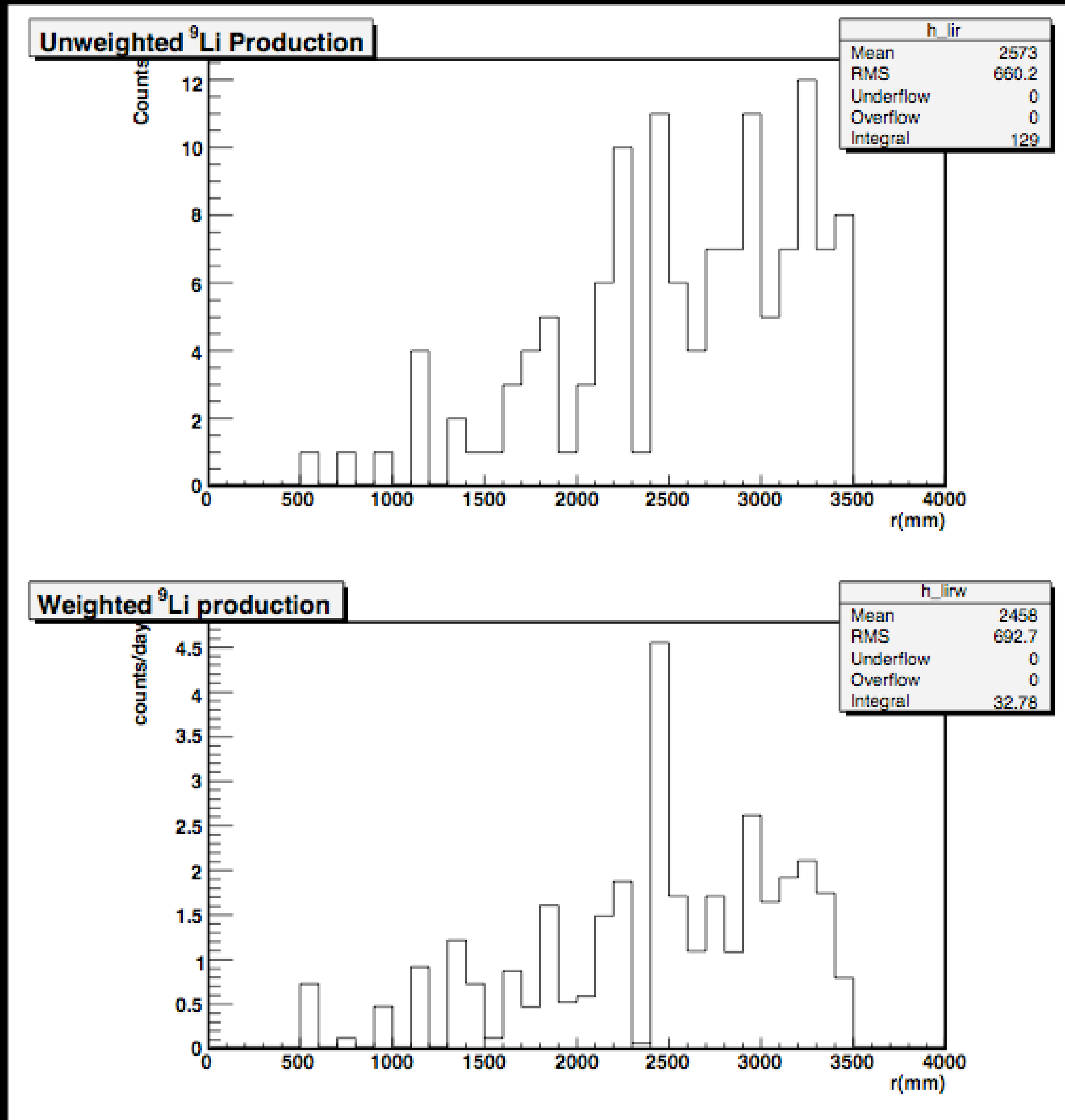
The measurement of the number of neutrino events is 12,2210 +/- 358, to be compared with the uncertainty in the absence of any background, which is 12,2210 +/- 349. Systematics need to be included. It is interesting to note the same method could be used for neutrons and, for both Li-9 and neutrons, energy information could be added. Generated and fit spectra are shown in lifit1.ps and lifit2.ps.

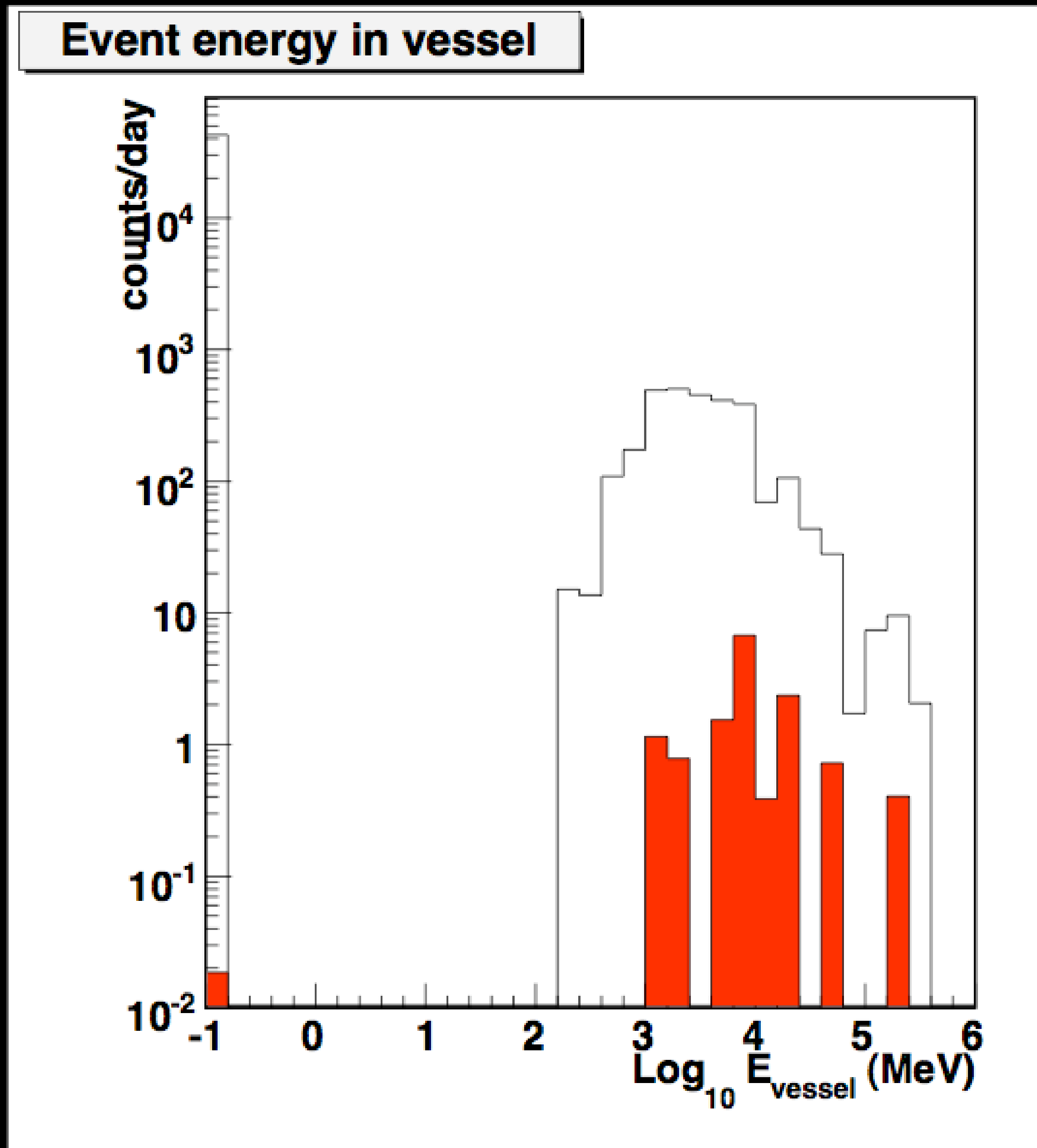
For comparison, if we just cut all IBD-like events for 1 s after a big event, we would lose 3% or 3666 of the IBD events while keeping 71 Li-9 events.



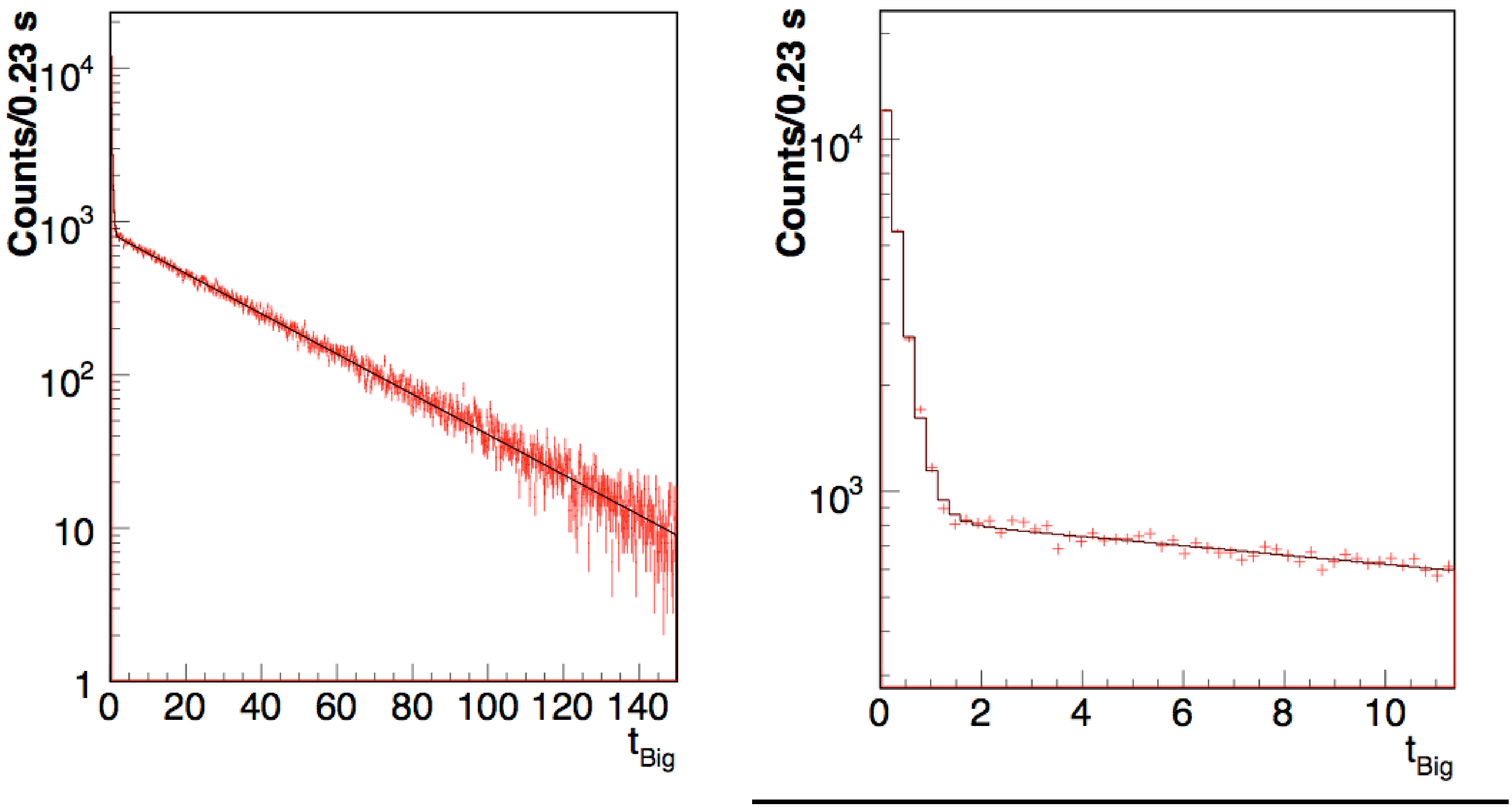
Pilcher & Hurwitz
counts/m^2-s-GeV
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0 0.5 1 1.5 2 2.5 3
Log_{10} E_{μ} (GeV)
Unweighted μ specrum
counts
14000
12000
10000
8000
6000
4000
2000
0
2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7
Log_{10} E_{μ} (MeV)
Weighted μ spectrum
counts
10^{-1}
10^{-2}
3 3.5 4 4.5 5 5.5 6
Log_{10} E_{μ} (MeV)
Weighted μ spectrum
counts/GeV
10^{-5}
10^{-6}
10^{-7}
10^{-8}
3 3.5 4 4.5 5 5.5 6
Log_{10} E_{μ} (MeV)


Unweighted μ zenith angle
counts
5000
10000
15000
20000
25000
0
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
cosθz
Weighted μ zenith angle
counts
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
cosθz


Unweighted 9Li Production
h_lir
Mean 2573
RMS 660.2
Underflow 0
Overflow 0
Integral 129
Counts
0
2
4
6
8
10
12
0
500
1000
1500
2000
2500
3000
3500
4000
r(mm)
Weighted 9Li production
h_lirw
Mean 2458
RMS 692.7
Underflow 0
Overflow 0
Integral 32.78
counts/day
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
500
1000
1500
2000
2500
3000
3500
4000
r(mm)



Event energy in vessel
counts/day
10^4
10^3
10^2
10
1
10^-1
10^-2
-1
0
1
2
3
4
5
6
Log10 Evessel (MeV)



Counts/0.23 s
10^4
10^3
10^2
10
1
0
20
40
60
80
100
120
140
t_{Big}
Counts/0.23 s
10^4
10^3
0
2
4
6
8
10
t_{Big}