New Gamma-Hadron Separation Technique and Variables in Milagro

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Abstract

In this memo I introduce new γ-h separation variables, with these new variables total Q-Factors greater than 2.5 are obtainable, and Q-Factors for on the pond events greater than 1.5 are also obtainable.

1 Obtaining the Variables

In My search for new variables I studied many different 2D distributions of the following parameters, nOut, nTop, nBot, nFit, nb2, mxPE, and cxPE, where:

nOut	:	number of outriggers hit.
nTop	:	number of PMTs hit in the top layer(air shower layer).
nBot	:	number of PMTs hit in the bottom layer(muon layer).
nFit	:	number of PMTs entered in the fit.
nb2	:	number of muon layer tubes with at least 2PEs.
mxPE	:	number of PEs in the muon layer tube with the highest number of PEs.
cxPE	:	number of PEs in the muon layer tube with the highest number of PEs where a region of 10m around the core is excluded from consideration.

The 2D distributions were generated for both gamma and proton MonteCarlo. In this MC sample a Crab-like spectrum for the energy was used, i.e. $E^{-2.49}$. Gamma MC events were thrown with energies in the range 100 GeV to 100 TeV while proton MC events had an energy range of 500 GeV to 100 TeV. I used Tony Shoup's all-layer fitting routines, in these routines all three layers are used for both the angular and core position fittings. The multiplicity trigger of 55 PMTs was used in this study. For all the distributions studied I used nFit $\geq$ 80. I also required gamma MC events to be reconstructed within 0.7^o of their true direction. I looked at these distributions and concentrated on the ones that showed the most differences between the gammas and the protons, I then looked at the Q-Factor and efficiency plots for these distributions. From these plots I decided on the cuts that I want to apply to optimize the Q-Factor.

2 Distributions

2.1 ((nOut*nFit*nTop)/cxPE) Vs. (nb2/cxPE)

Distributions of $\frac{(nOut*nFit*nTop)}{cxPE}$ Vs. $\frac{nb2}{cxPE}$ for gamma and proton MC are shown in figure 1. There are no restriction on the location of the fit core for these events, i.e. events may be on or off the pond. From the distributions we see that for protons the distribution is concentrated in the region $\frac{(nOut*nFit*nTop)}{cxPE} < 15000$ and $\frac{nb2}{cxPE} < 4$ while for gammas the distribution is concentrated in the region $\frac{(nOut*nFit*nTop)}{cxPE} < 40000$ and $\frac{nb2}{cxPE} < 6$.
Figure 2 shows a three dimensional plot of the Q-Factor for these distributions. Figure 3 shows the top view of the Q-Factor plot. Here we see a smooth constant peak for which the Q-Factor is ≥ 2.5, this region is bounded by $\frac{nOut*nFit*nTop}{cxPE} \geq 80*10^3$ and $3 < \frac{nb2}{cxPE} < 6$. [1]
For on the pond events we expect the Q-Factor distributions to peak at lower values than those for the total Q-Factor, this is seen in figure 4 which shows the Q-Factor for events on the pond. From the figure we see that the Q-Factor peaks around 1.4. We also notice that this peak occurs at a closer region to the origin than that for the total Q-Factor. This tells us that we will keep more gammas if we were to make a cut on this peak compared to the total Q-Factor cut. Figure 5 shows a top view of the Q-Factor distribution for on-pond events.

[1] By definition, the Quality Factor of a cut is equal to:
$Q^i = \frac{\epsilon^i_\gamma}{\sqrt{\epsilon^i_p}}$
were ϵ^i_γ and ϵ^i_p are the efficiencies of the ith cut for gamma and proton, respectively.

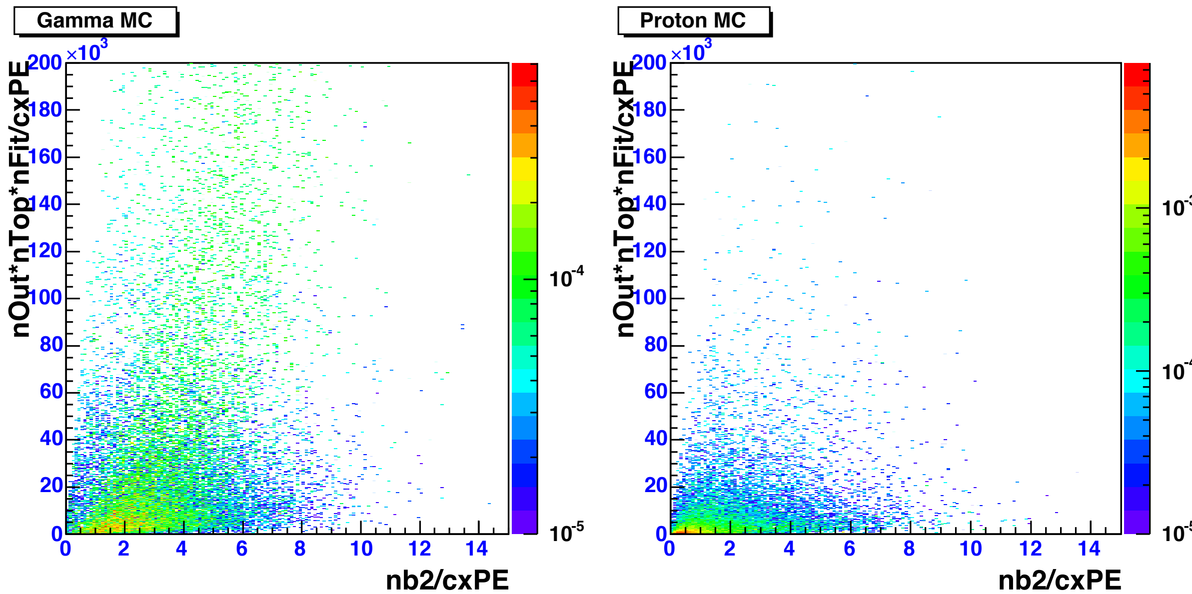

Figure 1: $\frac{nOut*nFit*nTop}{cxPE}$ vs $\frac{nb2}{cxPE}$ for Gamma and Proton MC, events may be on or off the pond.

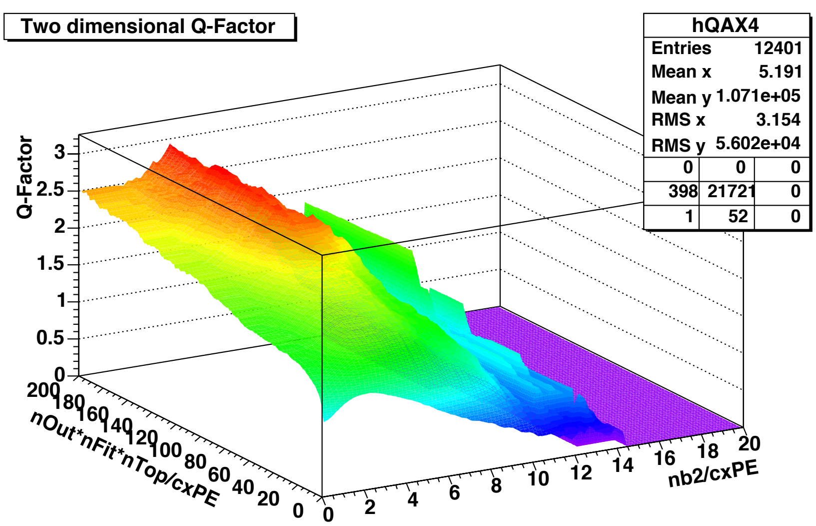

Figure 2: Two Dimensional Q-Factor distribution for the distributions in figure 1. Notice the smooth constant peak(red region) for which the Q-Factor is ≥ 2.5 .

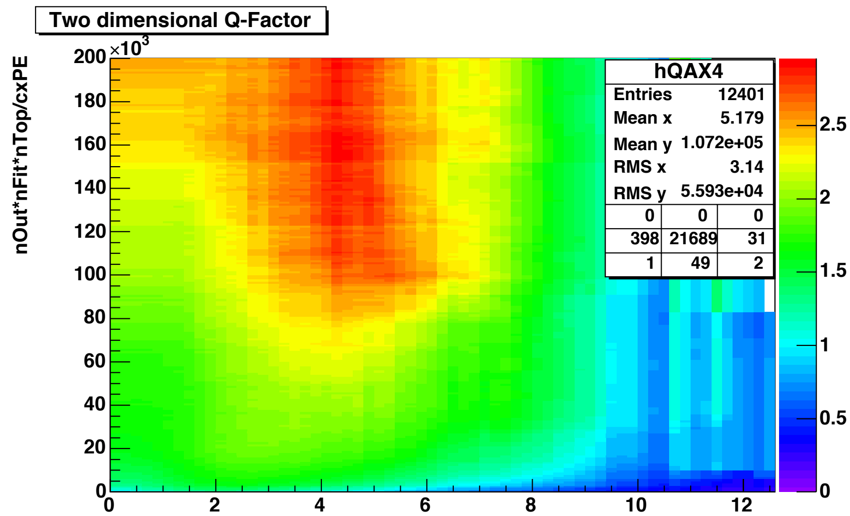

Figure 3: Top view of the Q-Factor distribution for the distributions in figure 1. The peak, red region, is bounded by $\frac{nOut*nFit*nTop}{cxPE} \geq 80 * 10^3$ and $3 < \frac{nb2}{cxPE} < 6$.

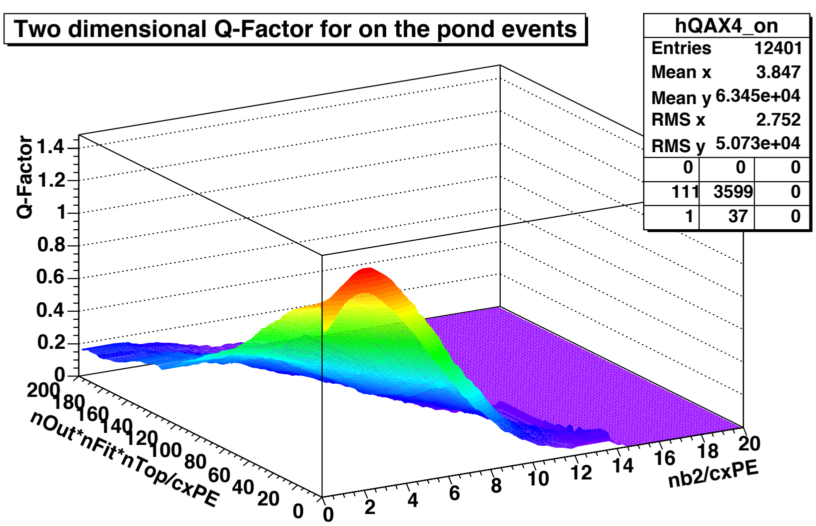

Figure 4: Two dimensional Q-Factor distribution for on the pond events for the distributions in figure 1. The peak, red region, is close to the origin which means we will keep more gammas if we were to make a cut around that region.

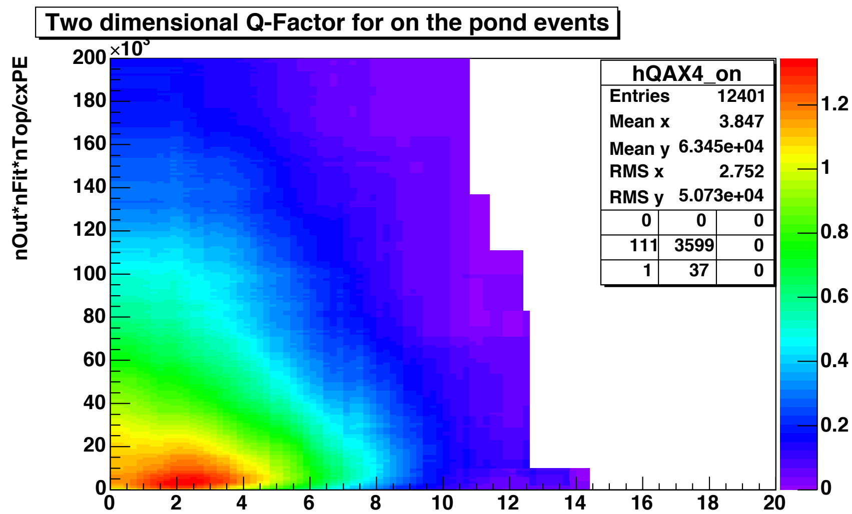

Figure 5: Top view of the Q-Factor distribution shown in figure 4.

2.2 ((nOut + nTop)*nFit/cxPE) Vs. (nb2/cxPE).

Here I examine different distributions of the same parameters, nOut, nTop, nFit, nb2, and cxPE. Figure 6 shows the distribution of $\frac{(nOut+nTop)*nFit}{cxPE}$ Vs. $\frac{nb2}{cxPE}$ for gamma and proton. Again we see the offset of the peaks for gamma and proton distributions, the peak for gammas occurs around the region $\frac{(nOut+nTop)*nFit}{cxPE} \sim 1000$ and $\frac{nb2}{cxPE} \sim 2$ while for protons the peak occurs around the region $\frac{(nOut+nTop)*nFit}{cxPE} \sim 200$ and $\frac{nb2}{cxPE} \sim 0.5$. The Q-Factor distribution for these distributions is shown in figure 7, the distribution peaks at around 2.8. Figure 8 shows the top view of the Q-Factor distribution. We see that the peak, red region, is bounded by $3500 < \frac{(nOut+nTop)*nFit}{cxPE} < 5500$ and $\frac{nb2}{cxPE} < 6$. Figure 9 shows the Q-Factor distribution for events on the pond. A top view of the Q-Factor distribution is shown in figure 10, the Q-Factor peaks at around 1.5, the hot region is bounded by $\frac{(nOut+nTop)*nFit}{cxPE} < 2000$ and $\frac{nb2}{cxPE} < 4$.

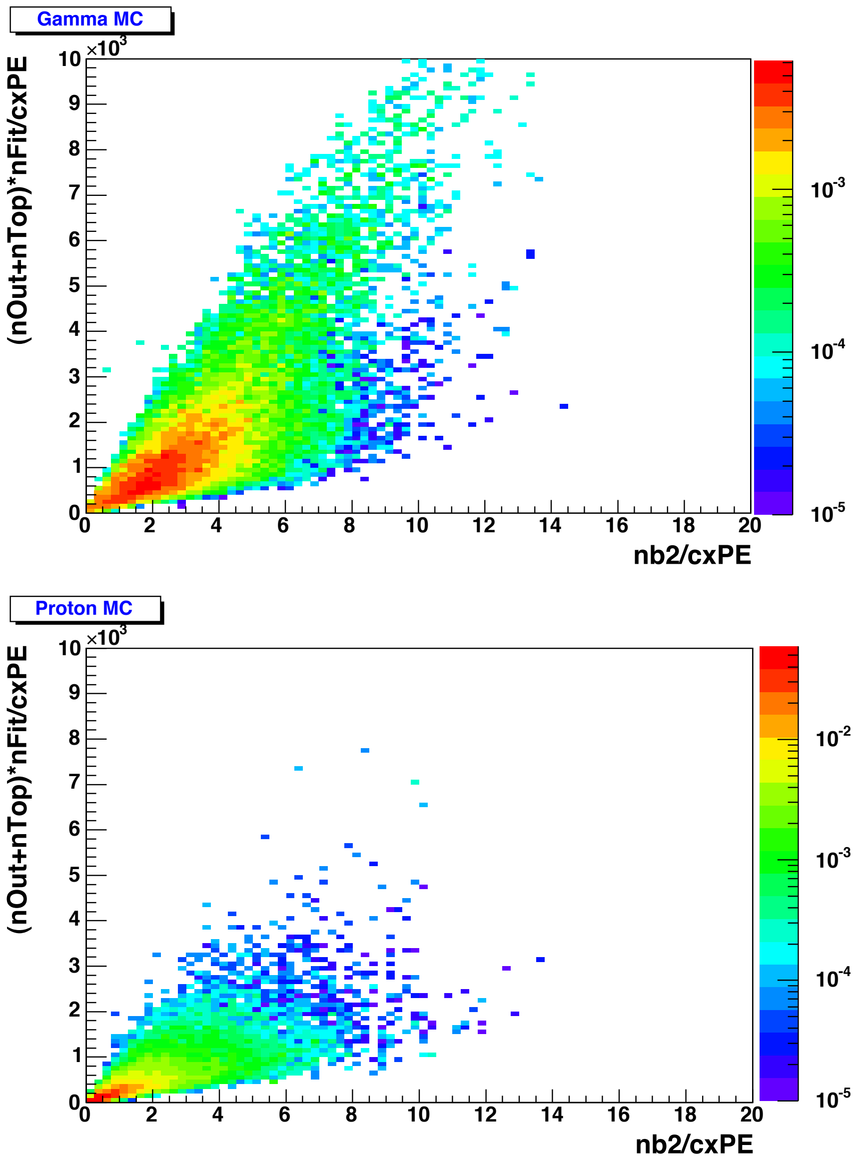

Figure 6: $\frac{(nOut+nTop)*nFit}{cxPE}$ vs $\frac{nb2}{cxPE}$ for Gamma and Proton MC, events may be on or off the pond.

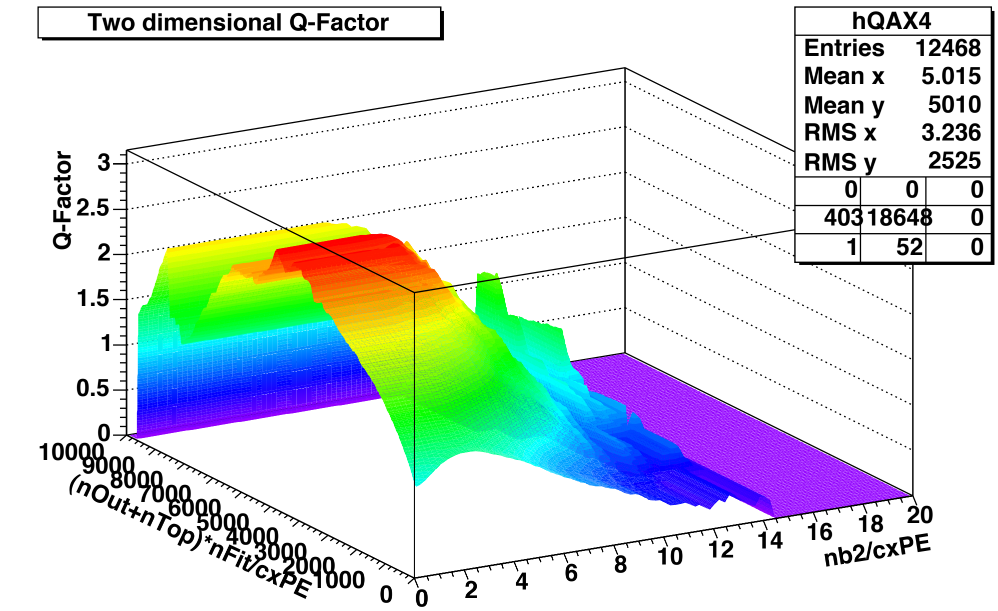

Figure 7: Two Dimensional Q-Factor for the distributions in figure 6.

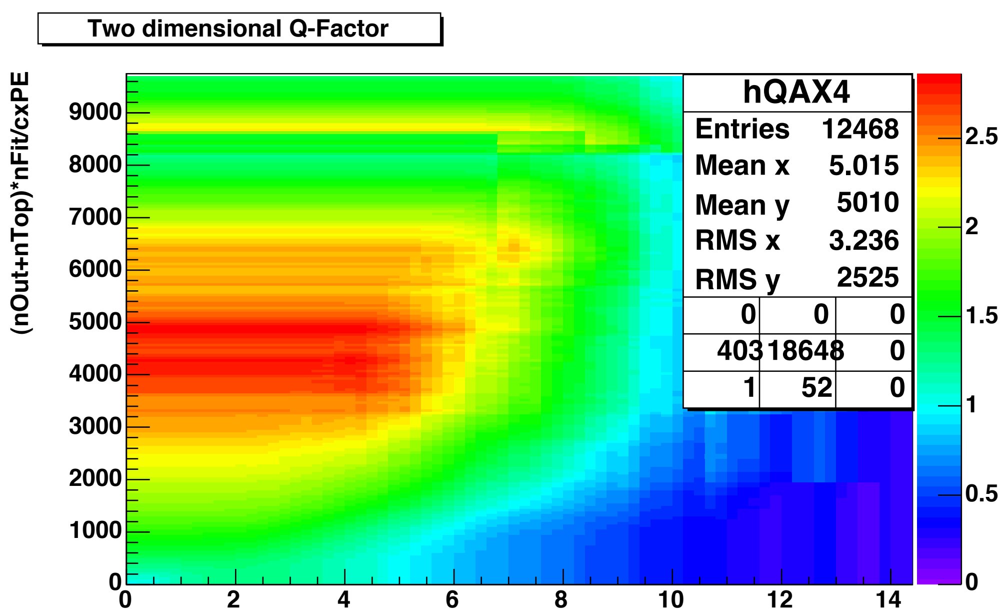

Figure 8: Top view of the Q-Factor distribution shown in figure 7. The peak, red region, is bounded by $3500 < \frac{(nOut+nTop)*nFit}{cxPE} < 5500$ and $\frac{nb2}{cxPE} < 6$.

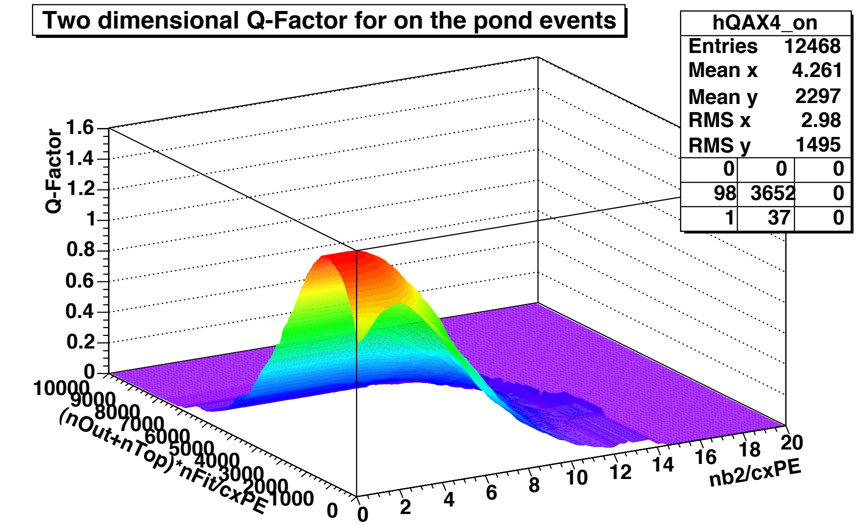

Figure 9: Two dimensional Q-Factor for on the pond events for the distributions shown in figure 6. Again we see that the peak, red region, is close to the origin which means we will keep more gammas if we were to make a cut around that region.

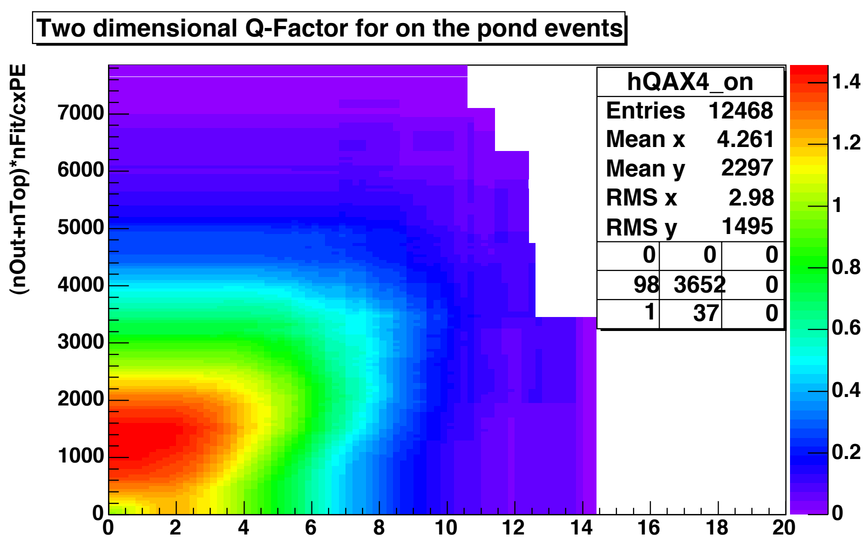

Figure 10: Top view of the Q-Factor distribution shown in figure 9. The Q-Factor peaks at around 1.5, the hot region is bounded by $\frac{(nOut+nTop)*nFit}{cxPE} <$ 2000 and $\frac{nb2}{cxPE} < 4$.

2.3 (nFit*nTop/cxPE) Vs. nb2

Distributions of $\frac{(nFit*nTop)}{cxPE}$ Vs. $(nb2)$ are shown in figure 11. The offset of the gamma and proton peaks is very clear here. The peak for gamma MC is bounded by the region $\frac{(nFit*nTop)}{cxPE} < 2000$ and $(nb2) < 50$, while the peak for proton MC is bounded by the region $\frac{(nFit*nTop)}{cxPE} < 800$ and $20 < (nb2) < 90$. A Q-Factor plot is shown in figure 12. A top view of the Q-factor distribution is shown in figure 13. The peak, in red, for which the Q-Factor is ~ 5, is not a wide peak as we would like it to be, i.e. it is not wide and smooth enough to be trusted and could just be due to fluctuations in the MonteCarlo that may not appear with a different set of the MonteCarlo. Figure 14 shows the Q-factor distribution with this peak excluded, we can still see a smooth peak for which the Q-Factor is ~ 3.

The Q-Factor for on the pond events is shown in figure 15. We see a smooth peak for which the Q-Factor is ~ 2, figure 16 shows the top view of this Q-Factor distribution, here we notice that the peak is wider and higher than the two previous peaks for on the pond events for the first two distributions.

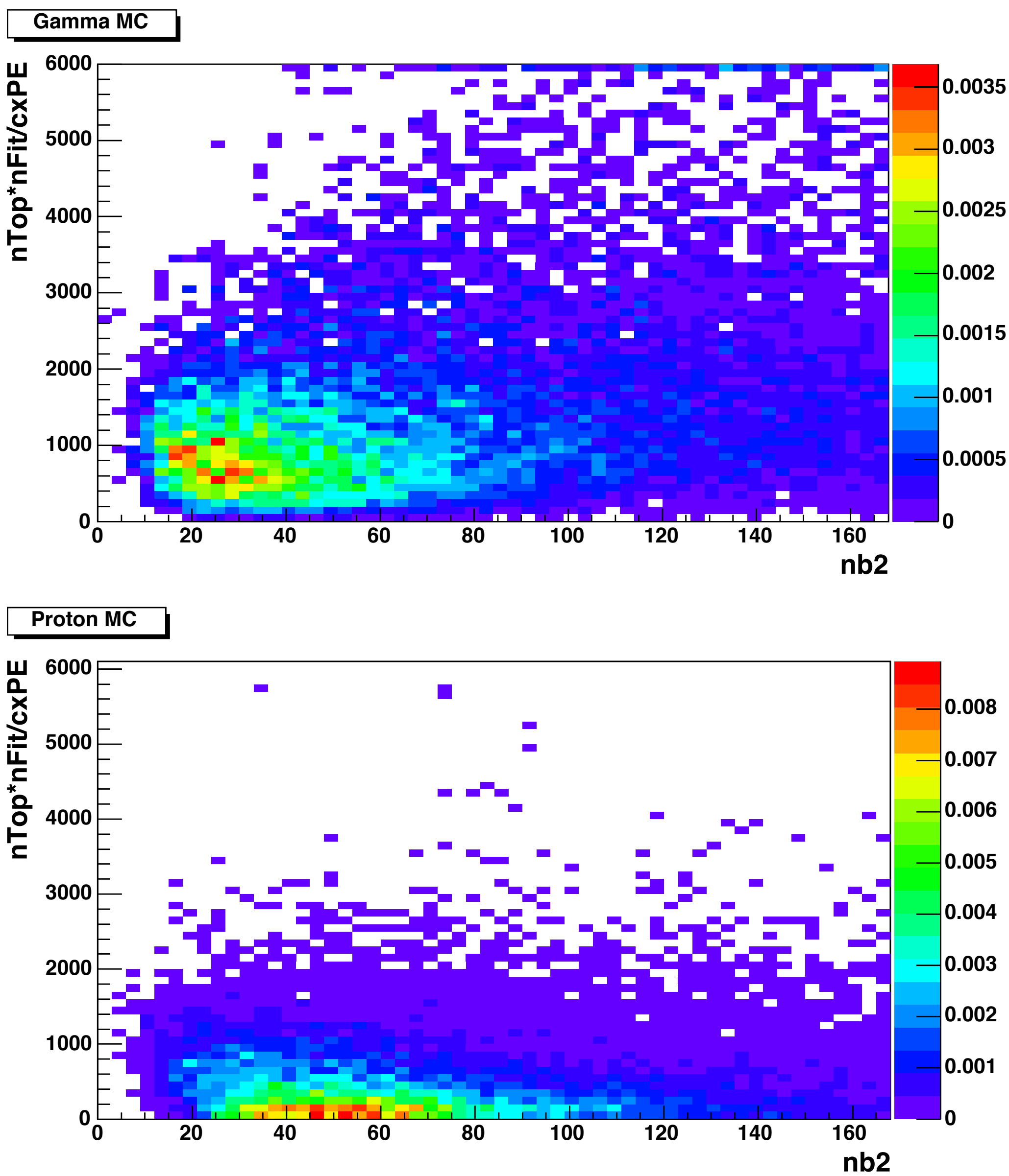

Figure 11: $\frac{(nTop*nFit)}{cxPE}$ vs $nb2$ for Gamma and Proton MC, events may be on or off the pond.

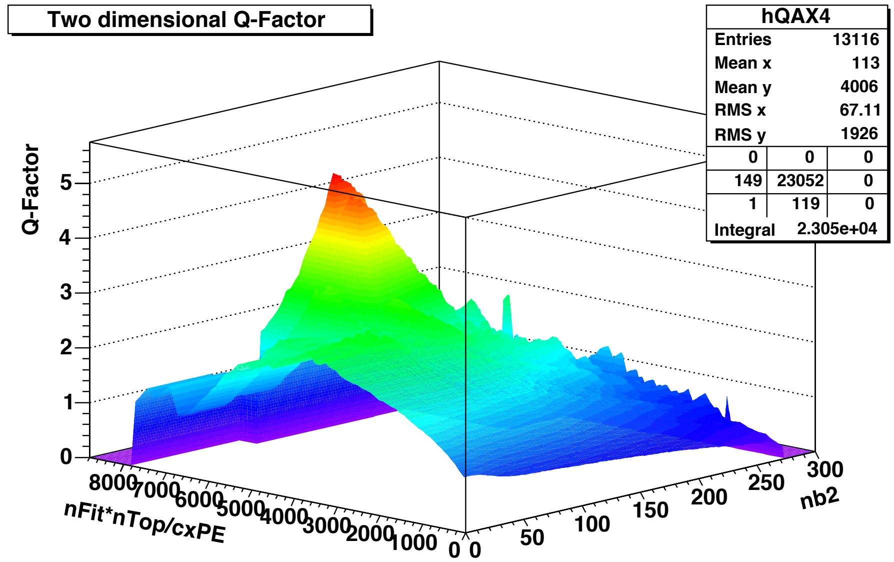

Figure 12: Two dimensional Q-Factor distribution for the distributions in figure 11.

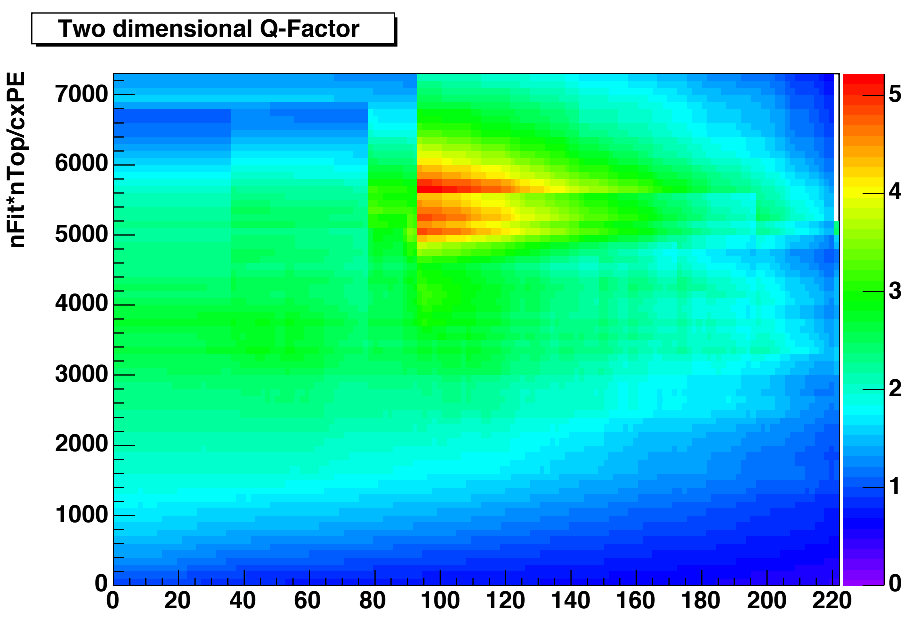

Figure 13: Top view of the Q-Factor distribution shown in figure 12.

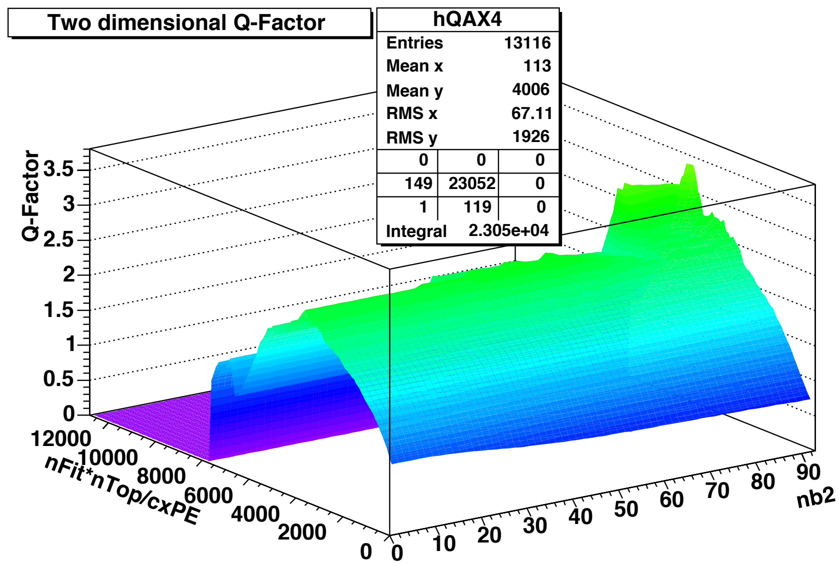

Figure 14: Two dimensional Q-Factor distribution for the distribution in figure 11 with the peak in red excluded, we can get a Q-factor of up to ~ 3.

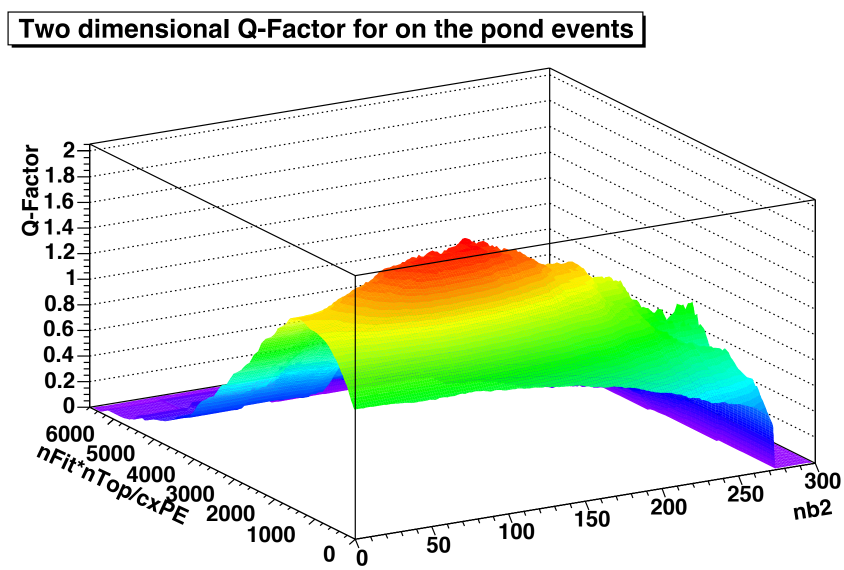

Figure 15: Two dimensional Q-Factor distribution for on the pond events for the distributions shown in figure 11.

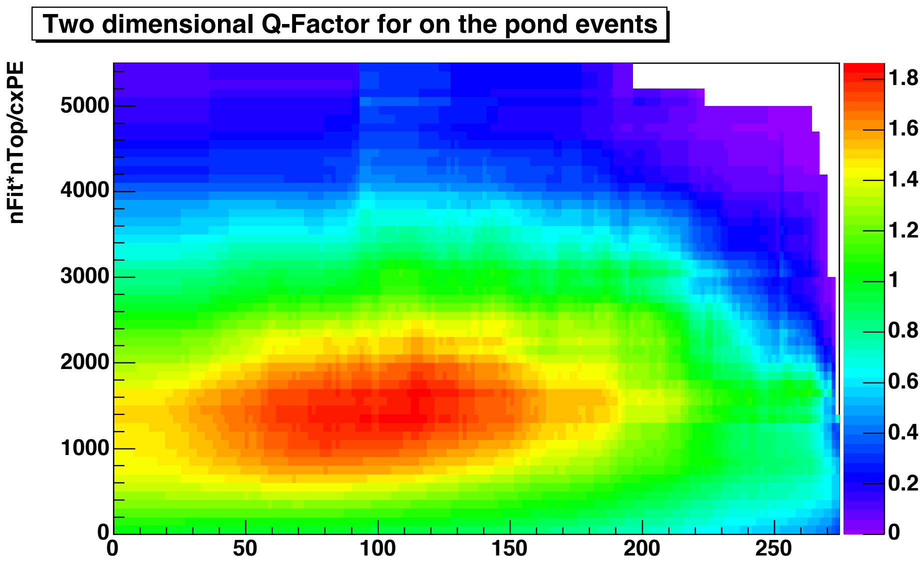

Figure 16: Top view of the Q-Factor distribution shown in figure 15.

3 Cuts

For each of the distributions shown in the previous sections, I studied the Q-Factor distributions and looked for the best cuts that will optimize the Q-Factor , I then tested these cuts on the Monte Carlo and the Crab data (416 days of data). For each of these cuts I calculate the Q-Factor, the efficiency of the cut for gamma and proton Monte Carlo, and the energy dependence on these cuts. I also looked at the Crab for each cut and compared it to what the Crab looks like with the standard cut, i.e. nFit $\geq$ 20 and $X_2 \geq 2.5$. Figure 17 shows the Crab with the standard cut. On the same graph I show:

Crab significance	:	the significance of the Crab for the cut.
Crab On	:	the number of events from the Crab.
Crab Off	:	the number of background events from the Crab region.
Crab Excess	:	signal from the Crab = Crab On - Crab Off

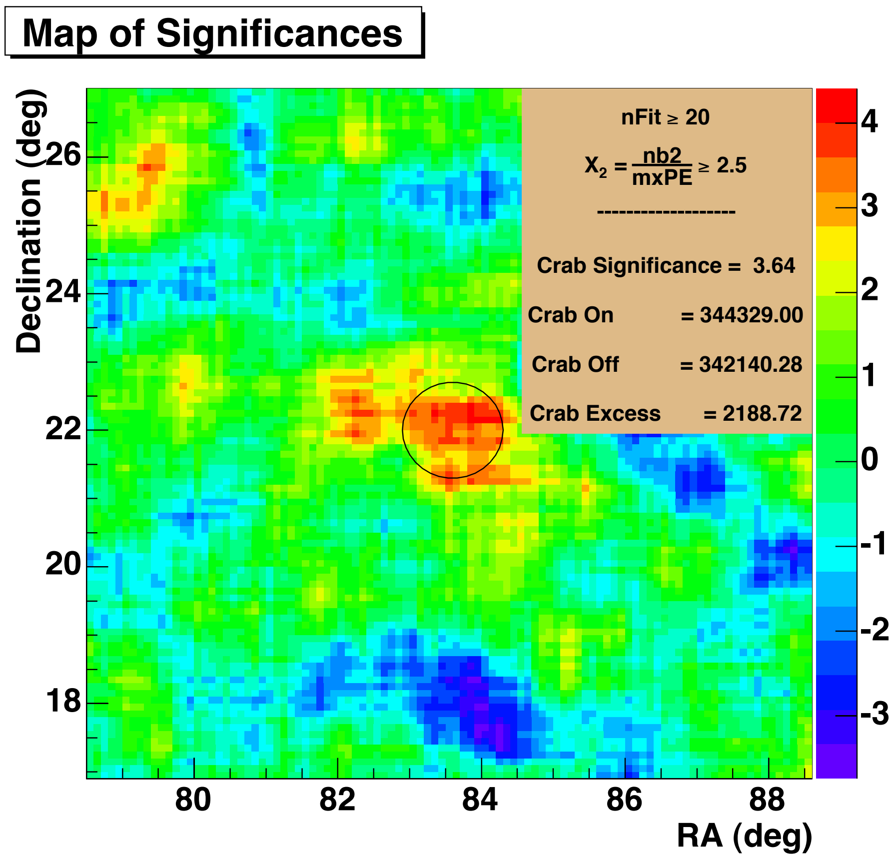

Figure 17: The Crab region with the Standard cuts (nFit $\geq$ 20 and $X_2 \geq 2.5$) applied.

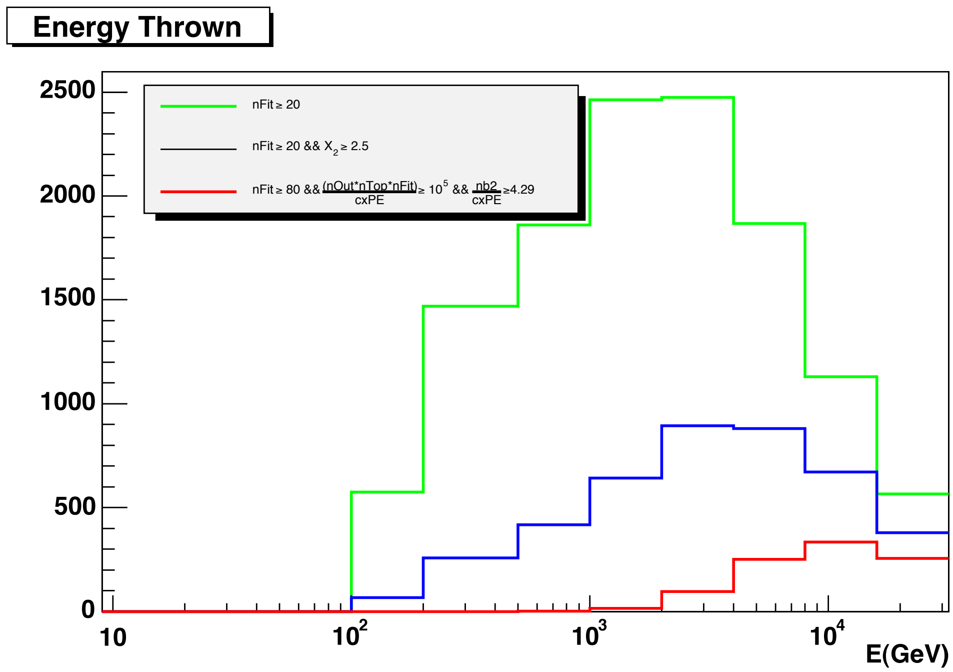

Figure 18: Energy distribution for three classes of events, events that passed the nFit $\geq$ 20 Cut (in green), events that passed the standard cut (nFit $\geq$ 20 and $X_2 \geq 2.5$) (in blue), and events that passed the new cut $nFit \geq 80$ and $\frac{(nOut*nFit*nTop)}{cxPE} \geq 10^5$ and $\frac{nb2}{cxPE} \geq 4.28$ (in red).

3.1 ((nOut*nFit*nTop)/cxPE) Vs. (nb2/cxPE) cuts

For this distribution, if we apply the following cuts:

$$nFit \geq 80 \text{ and } \frac{(nOut*nFit*nTop)}{cxPE} \geq 10^5 \text{ and } \frac{nb2}{cxPE} \geq 4.28$$

we get a Q-Factor of **2.7** and keep **15**% of the gamma and **0.3**% of the protons. Figure 18 shows the energy distribution for three classes of events, events that passed the nFit $\geq$ 20 Cut, events that passed the standard cut (nFit $\geq$ 20 and $X_2 \geq 2.5$), and events that passed the new cut ($nFit \geq 80$ and $\frac{(nOut*nFit*nTop)}{cxPE} \geq 10^5$ and $\frac{nb2}{cxPE} \geq 4.28$). As expected, the new cut is biased towards high energy events[2] .

In figure 19 I show the Crab region with these cuts applied. We notice an increase of the significance of the Crab region form **3.64** for the standard cut to **5.05** for the new cut, this value is close to what we expect when we compare the new cut to the standard cut, namely **6.14**. [3] We also notice the decrease of the number of events from the Crab from **2078**, for the standard cut, to **403** for the new cut.

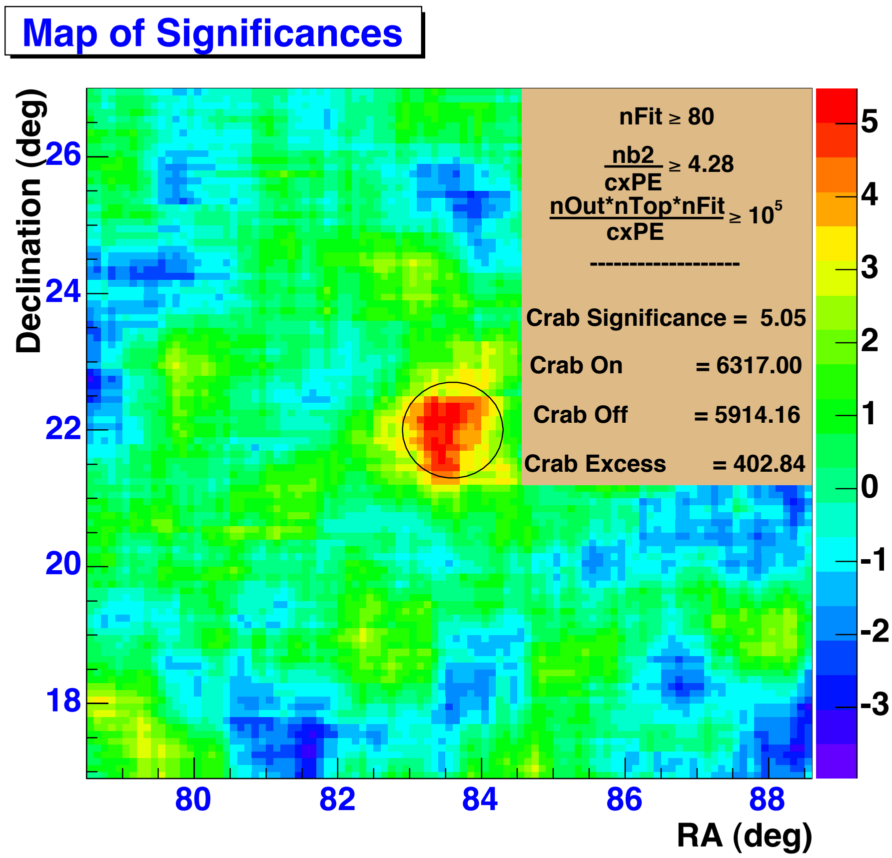

Figure 19: The Crab region with the $nFit \geq 80$ and $\frac{(nOut*nFit*nTop)}{cxPE} \geq 10^5$ and $\frac{nb2}{cxPE} \geq 4.28$ cuts applied.

[2]This is due to the fact that I require a high number of nFit.

[3]This is true since the ratio of two Q-factors is equal to the ratio of the corresponding significances, i.e. $\frac{Q_1}{Q_2} = \frac{Signif_1}{Signif_2}$

For on the pond events, if we apply the following cuts:

$$nFit \geq 80 \text{ and } \frac{(nOut*nFit*nTop)}{cxPE} \geq 3200 \text{ and } \frac{nb2}{cxPE} \geq 2.1$$

we get a Q-Factor of **1.4** and keep **60**% of the gamma and **18**% of the protons. Figure 20 shows the Crab region with these cuts applied, As expected, we see a decrease of the significance of the Crab to **2.55**, this is in very good agreement with what we expect by comparing this cut to the previous cut, namely **2.6**, we also notice the decrease of the number of events to **1118**.

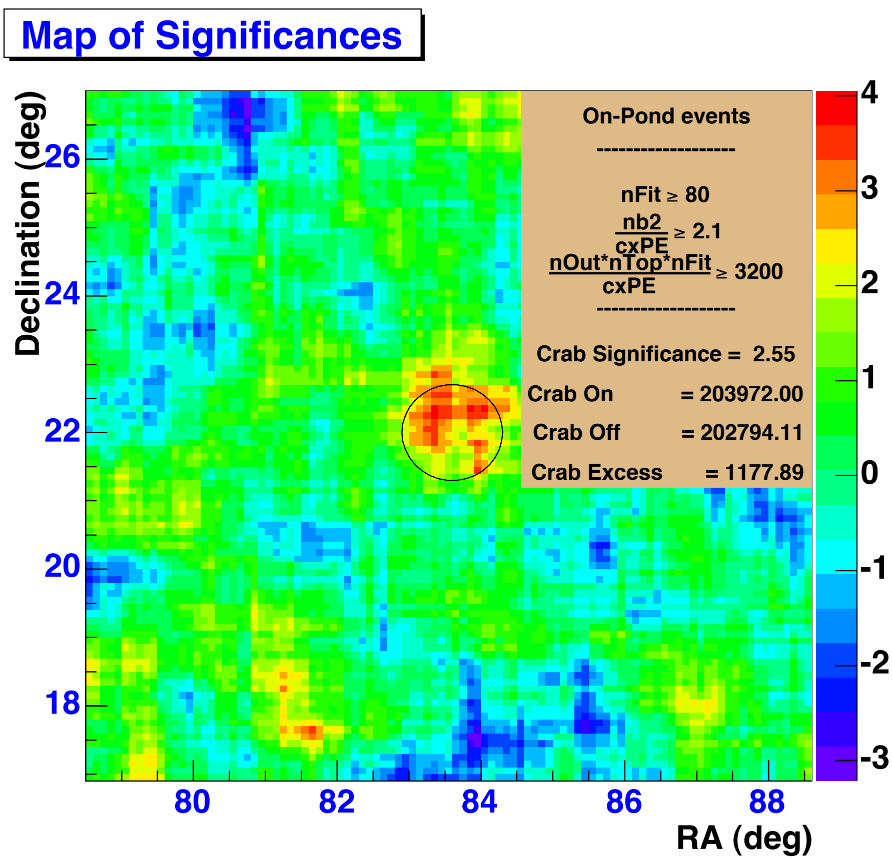

Figure 20: The Crab region with the $nFit \geq 80$ and $\frac{(nOut*nFit*nTop)}{cxPE} \geq 3200$ and $\frac{nb2}{cxPE} \geq 2.1$ cuts applied for on-pond events.

3.2 ((nOut+nTop)*nFit/cxPE) Vs. (nb2/cxPE) cuts

For this distribution, if we apply the following cuts:

$$nFit \geq 80 \text{ and } \frac{(nOut+nTop)*nFit}{cxPE} \geq 3800 \text{ and } \frac{nb2}{cxPE} \geq 4.00$$

we get a Q-Factor of **2.7** and keep **15**% of the gamma and **0.3**% of the protons. Figure 21 shows the energy distribution for three classes of events, events that passed the nFit $\geq$ 20 cut, events that passed the standard (nFit $\geq$ 20 and $X_2 \geq 2.5$) cut, and events that passed the new cut ($nFit \geq$ 80 and $\frac{(nOut+nTop)*nFit}{cxPE} \geq 3800$ and $\frac{nb2}{cxPE} \geq 4.00$). As expected, the new cut is biased towards high energy events. Figure 22 shows the Crab region with these cuts applied, again we notice the increase of the significance of the Crab region to **3.94** , this is close to what we expect by comparing this cut to the first cut, namely **5.05**, we also notice the decrease of the number of events to **240**.

For on the pond events, if we apply the following cuts:

$$nFit \geq 80 \text{ and } \frac{(nOut+nTop)*nFit}{cxPE} \geq 800$$

we get a Q-Factor of **1.4** and keep **72**% of the gamma and **26**% of the protons. Figure 23 shows the Crab region with these cuts applied, As expected, we see a decrease of the significance of the Crab to **2.00**, this is in good agreement with what we expect by comparing this cut to the first cut, namely **2.6**, we also notice the decrease of the number of events to **835**.

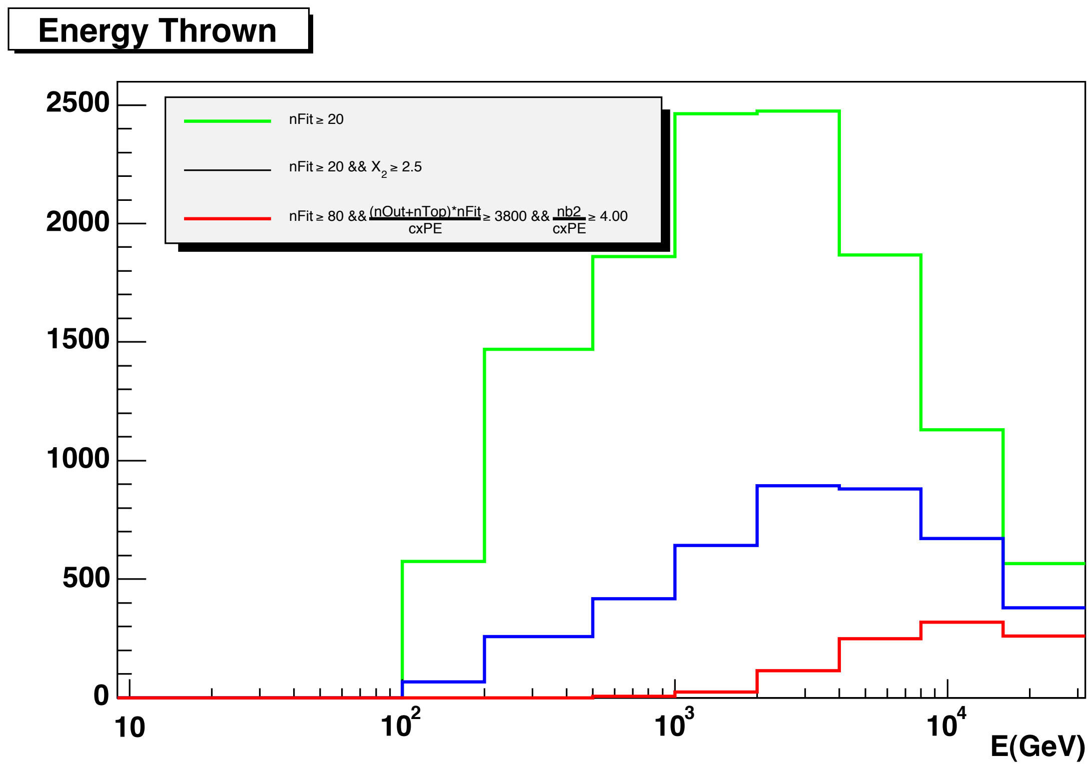

Figure 21: Energy distribution for three classes of events, events that passed the nFit $\geq$ 20 Cut (in green), events that passed the standard cut (nFit $\geq$ 20 and $X_2 \geq 2.5$) (in blue), and events that passed the new cut $nFit \geq 80$ and $\frac{(nOut+nTop)*nFit}{cxPE} \geq 3800$ and $\frac{nb2}{cxPE} \geq 4.00$ (in red).

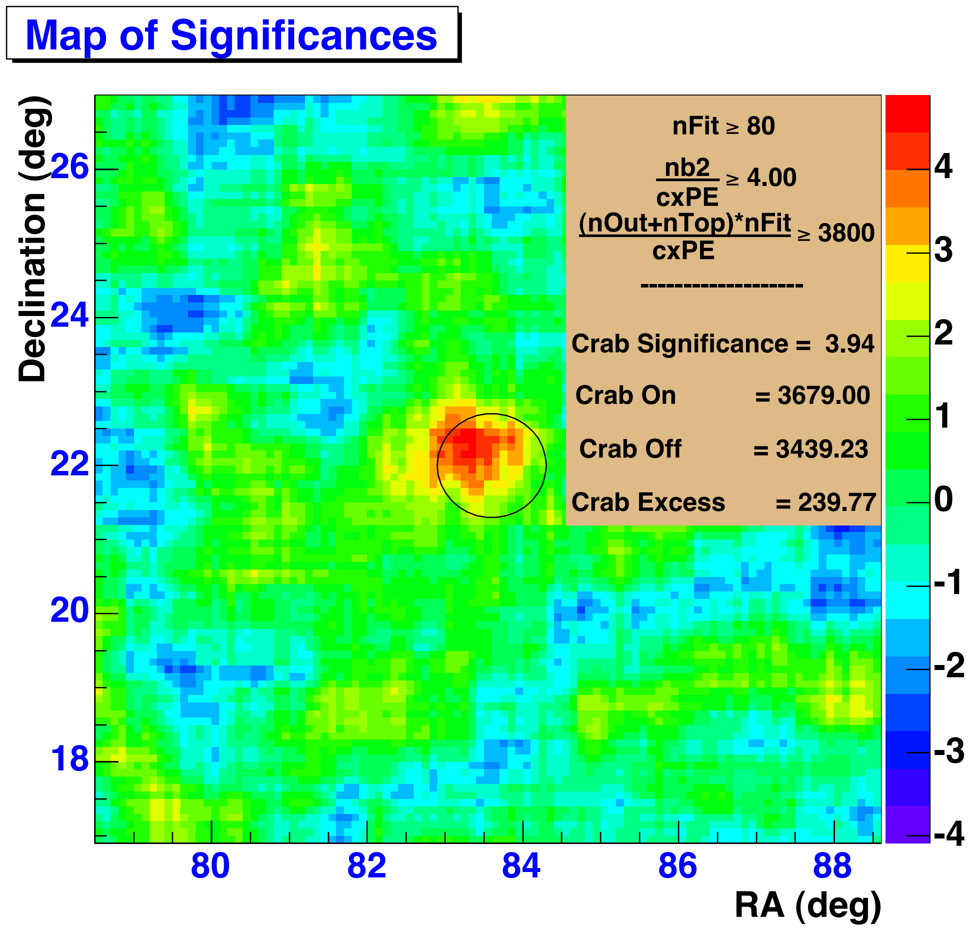

Figure 22: The Crab region with the $nFit \geq 80$ and $\frac{(nOut+nTop)*nFit}{cxPE} \geq 3800$ and $\frac{nb2}{cxPE} \geq 4.00$ cuts applied.

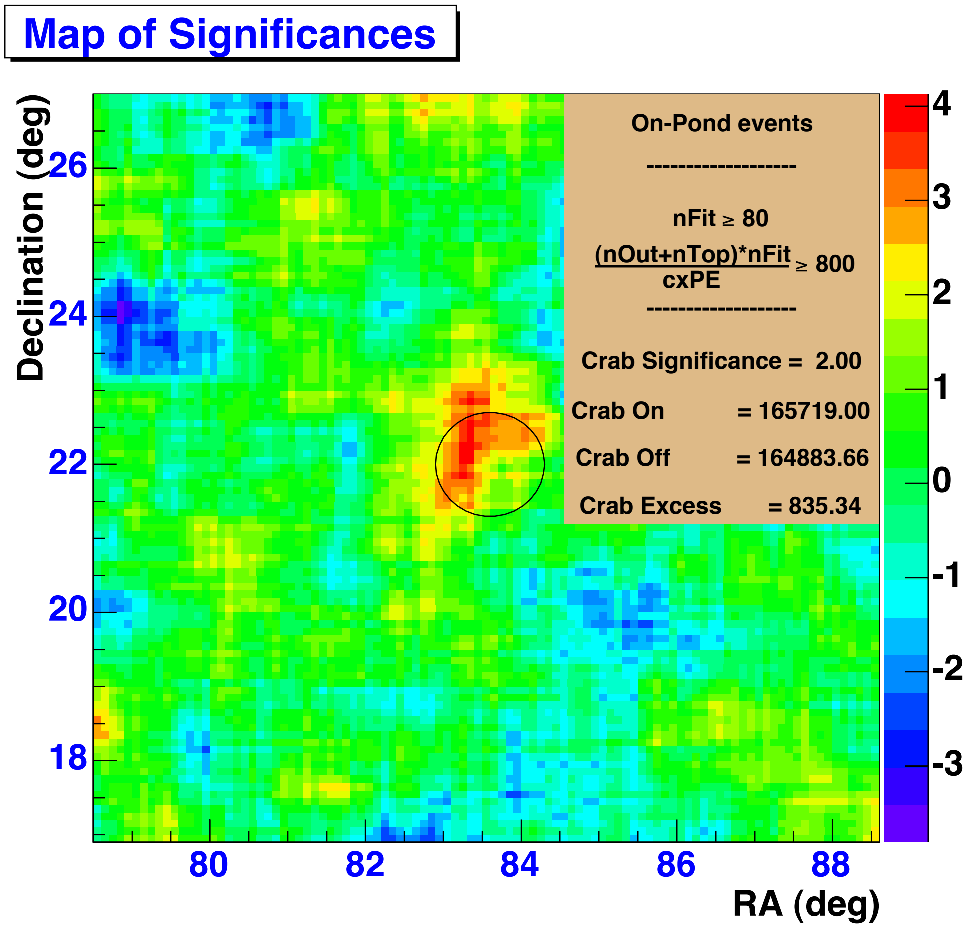

Figure 23: The Crab region with the $nFit \geq 80$ and $\frac{(nOut+nTop)*nFit}{cxPE} \geq 800$ cuts applied for on-pond events.

3.3 nTop*nFit/cxPE Vs. nb2 cuts

For this distribution, if we apply the following cuts:

$$nFit \geq 80 \text{ and } \frac{nTop*nFit}{cxPE} \geq 4000$$

we get a Q-Factor of **2.66** and keep **10**% of the gamma and **0.14**% of the protons. Figure 24 shows the energy distribution for three classes of events, events that passed the nFit $\geq$ 20 Cut, events that passed the standard cut (nFit $\geq$ 20 and $X_2 \geq 2.5$), and events that passed the new cut ($nFit \geq 80$ and $\frac{(nFit*nTop)}{cxPE} \geq 4000$). As expected, the new cut is biased towards high energy event.

In figure 25 I show the Crab region with these cuts applied, again we notice the increase of the significance of the Crab region to **4.89** which is in exact agreement with the value we obtain by comparing this cut to the first cut , we also notice the decrease of the number of events from the Crab to **166** for this cut.

For on-pond events I applied the following cuts:

$$nFit \geq 80 \text{ and } nb2 \geq 60 \text{ and } \frac{nTop*nFit}{cxPE} \geq 1000$$

we get a Q-Factor of **1.57** and keep **47**% of the gamma and **8.9**% of the protons. Figure 26 shows the Crab region with these cuts applied, As expected, we see a decrease of the significance of the Crab to **2.34**, this is close to what we expect by comparing this cut to the first cut, namely **2.9**, we also notice the decrease of the number of events to **553**.

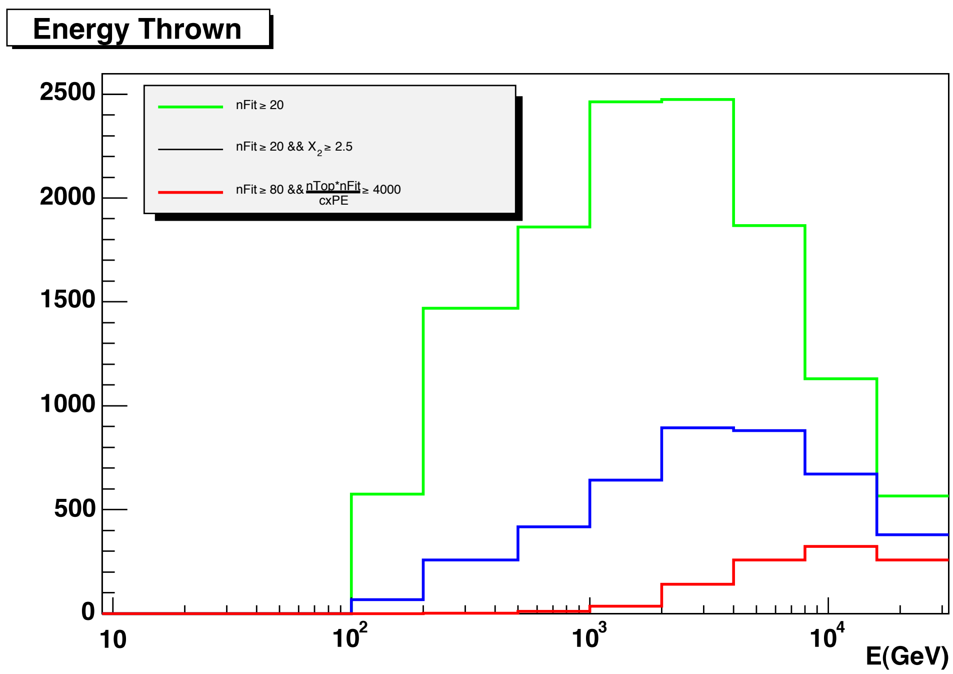

Figure 24: Energy distribution for three classes of events, events that passed the nFit $\geq$ 20 Cut (in green), events that passed the standard cut (nFit $\geq$ 20 and $X_2 \geq 2.5$) (in blue), and events that passed the new cut $nFit \geq 80$ and $\frac{nTop*nFit}{cxPE} \geq 4000$ (in red).

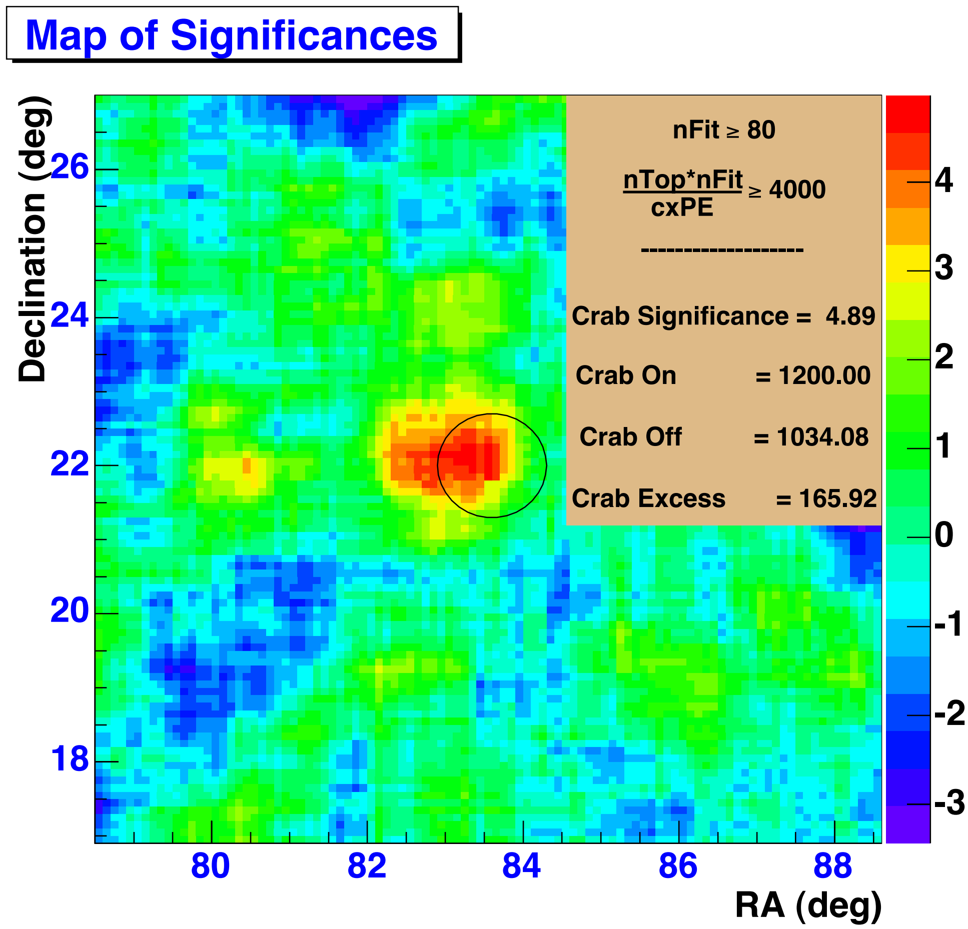

Figure 25: The Crab region with the $nFit \geq 80$ and $\frac{nTop*nFit}{cxPE} \geq 4000$ cut applied.

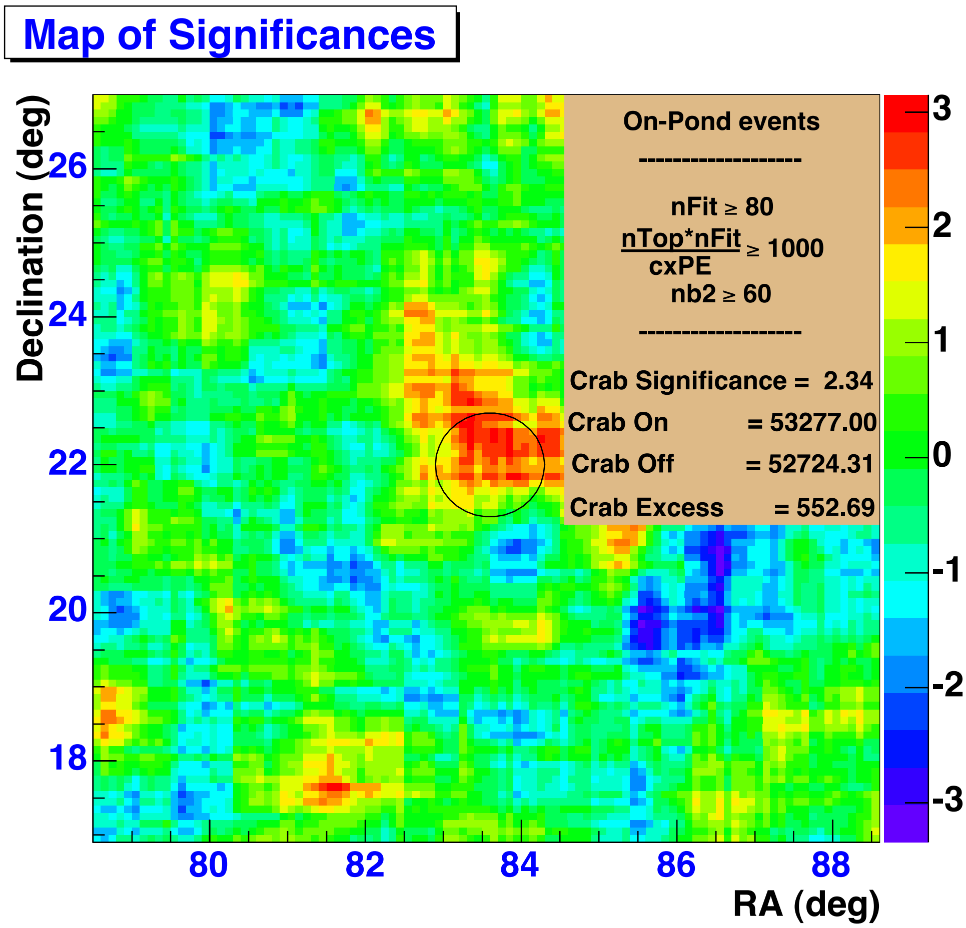

Figure 26: The Crab region with the $nFit \geq 80$ and $\frac{nTop*nFit}{cxPE} \geq 1000$ cuts applied for on-pond events.

Table 1 summarizes the cuts applied and what Q-factor expected from each cut, it also lists gamma and proton efficiencies for each set of cuts, along side with the Crab significance, Crab On, and Crab Excess values for that set of cuts. A more detalied study of these variables will be coming out in a separate memo shortly.

Cuts applied	**Q-Fact.**	**%γ Pass**	**% P Pass**	**Crab Sign.**	**Crab On**	**Crab Excs.**
$nFit \geq 20$ & $\frac{nb2}{mxPE} \geq 2.5$	1.60	51	10	3.64	344329	2188
$nFit \geq 80$ & $\frac{nb2}{cxPE} \geq 4.28$ & $\frac{(nOut*nFit*nTop)}{cxPE} \geq 10^5$	**2.71**	15	0.3	**5.05**	6317	403
$nFit \geq 80$ & $\frac{nb2}{cxPE} \geq 4.0$ & $\frac{(nOut+nTop)*nFit}{cxPE} \geq 3800$	**2.70**	15	0.3	**3.94**	3679	240
$nFit \geq 80$ & $\frac{(nFit*nTop)}{cxPE} \geq 4000$	**2.66**	10	0.14	**4.89**	1200	166
On pond events						
$nFit \geq 80$ & $\frac{nb2}{cxPE} \geq 2.1$ & $\frac{(nOut*nFit*nTop)}{cxPE} \geq 3200$	1.4	60	18	2.55	203972	1178
$nFit \geq 80$ & $\frac{(nOut+nTop)*nFit}{cxPE} \geq 800$	1.4	72	26	2.00	165719	835
$nFit \geq 80$ & $nb2 \geq 60$ & $\frac{(nFit*nTop)}{cxPE} \geq 1000$	1.57	47	8.9	2.34	53277	553

Table 1: Summary table