Optimizing the Physics Output of Milagro
Or
Tuning the Trigger for Low Energies
Or
Gamma-Hadron Separation in Hardware
Or
Why do We Have Patches Anyway?

Very Preliminary
Work-In-Progress

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Introduction, or Confessions

The eventual trigger condition for Milagro is yet-to-be-determined. We operated Milagrito with a multiplicity trigger picked only by the condition that we write approximately 1 tape of output per day of operation. While this is one way to select a trigger condition, it is not necessarily the best choice for the physics reach of Milagro. In this memo, I report on studies of alternative triggers for Milagro based on the multiplicity of hits in the patches in Milagro.

The PMTs in Milagro (and Milagrito) are grouped into 4x4 square "patches" in both the air-shower and hadron/muon layers. This grouping is not just because the front-end boards have 16 channels, but also because of the hope that the *pattern* of hits can be used to lower our threshold and/or avoid triggering on distant, low-energy cosmic-ray showers. Because the number of rows or columns in Milagro are not divisible by 4, some of our patches are not 4x4 groups, but lines, and some do not have 16 PMTs. For now, these differences are ignored. Herein the term "patch trigger" will be used to describe any trigger based on the multiplicity of hits in patches and/or the multiplicity of patches that are hit in a shower.

To determine an "optimal trigger," it is necessary to define optimal. So, let me state my motives right up front. In this study, I am trying to optimize the trigger for low-energy gamma-ray showers. My motivation is (perhaps obviously) driven by my desire to observe cosmological GRBs and distant AGNs (or any other source) whose spectrum is broken/softened due to absorption by IR/CMBR photons. In addition, I hope we may observe particles from CME/solar flares in reconstructed showers, and in this case, the sun may not accelerate particles to sufficiently high energies to be seen with a multiplicity trigger in Milagro. For several reasons, I consider events that land on the pond to be of higher value, so it would be nice to have a trigger that especially likes to keep these low-energy events with cores on Milagro, though this is not explicitly required.

Of course, one can simply turn the multiplicity of the trigger down to increase our effective area for low-energy showers. This comes at the expense of dramatically increased trigger rate. Obviously, though straightforward, this is not an “optimal” way to lower our threshold. It is also necessary to have a “benchmark” to compare with alternative triggers. In this study, my benchmark will be what most collaborators consider a fairly low-level, and therefore low-threshold, multiplicity trigger of 50 PMTs (from now on called PMT trigger) hit in the shower layer. So, when I choose proposed trigger criteria, I will compare my results against a 50 PMT trigger, and I will chose the trigger-level to (as best I can with the statistics at hand) match the rate of proton showers. A measure of optimal is also needed. Because of the aforementioned bias to lower our threshold, I will use the so-called quality factor, Q, defined as the number of gamma-ray showers divided by the square root of the number of proton showers for low-energy events (less than 750 GeV primary energy), as my metric. Since the number proton events is chosen to be nearly the same for the two triggers, the Q factor is approximately the efficiency for triggering on gamma-ray events

Background, or What Has Gone Before and What I Have Done

Soon after Milagrito was completed, Scott Hugenberger and I studied patch triggers (I believe Scott reported these results at a collaboration meeting.) using Monte Carlo events. We required that we not change the rate of cosmic-ray triggers above the 100 PMT trigger. When doing so, it was clear that the overall Q could not be significantly changed. Gus also performed similar studies for Milagrito, with similar results reported at a collaboration meeting. At the last collaboration meeting, Richard showed results in which he suggested we choose our multiplicity trigger level based on optimizing the expected signal from the Crab.

Here I use simulated samples of proton and gamma-ray events. So that we have some hits to reconstruct the shower directions (and to avoid single muon triggers), I require at least 10 PMT hits in the air-shower layer. There are 13,708 total gamma-ray events passing this cut that were thrown from 500 GeV to 15 TeV on a differential power law spectrum with index –2.0. 9,780 proton events are used to simulate the cosmic-ray background. The protons were also from 500 GeV to 15 TeV, but on a spectrum with index –2.7. Both of these samples were thrown over an energy-dependent area (higher energy events were thrown over a larger area), and were thrown to 60 degrees in zenith angle.

The number of PMT hits in each separate patch in Milagro is counted for each event. The 5 “hottest” patches (those with the most hits) are found separately for the air-shower and hadron/muon layer; these are ordered from hottest (called e.g. Npatas1, for number-in-1st-hottest-air-shower-patch) to least hot (Npatas5), and the results (e.g. number of hits in each of the hottest patches, energy, zenith angle, core position) recorded. I chose the 5 hottest completely arbitrarily, but you will see that this was sufficient.

Let me give a couple of example triggers here to help everyone in thinking about the results below. Suppose we wanted a trigger that required at least 5 hits in at least 3 air-shower layer patches. This would be the same as requiring that the 3rd “hottest” patch have at least 5 hits. Or perhaps we want a trigger requireiment that was no patches with more than 10 hits. This is the same as requiring the hottest patch have 10 or fewer hits. These kinds of triggers are fairly simple to implement in hardware using the patch-multiplicity outputs from the front-end boards and standard NIM discriminators and logic modules.

Intriguing Results, or What I Found

First I examined the response of the air-shower layer. Shown in the first pair of figures is the distribution of number of hits in the 3rd hottest air-shower layer patch (Npatas3) for gamma-ray and proton events from 500 GeV to 750 GeV primary energies that land on Milagro (defined as simulated core distance of less than 35 meters). There is not a very large difference between the gamma-ray and proton events in these figures, suggesting that such a trigger would not be particularly useful.

In fact, I find no significant difference in the pattern of hits in the air shower layer, as characterized by the number of hits in the hot patches, between gamma-ray and proton events, either on-pond or off-pond, at either low- or high-energies; I will not boar you with lots of plots showing this fact. This result is confirmed by our experience with Milagrito, in which we did not find a large difference between gamma-ray or proton events using patch-based triggers. It is also confirmed by the results of those who have studied the pattern of hits in the air-shower layer as a method of cosmic-ray background suppression. The differences found by these analyses are important, but do not result in a particularly large "Q" factor.

A very significant difference between low-energy gamma-ray and proton events is found in the number of hits in the hottest muon-layer patch (Npatmu1), shown in Figures 2. There you see that proton events tend to have at least one fairly hot patch, whereas the gamma-ray events do not. Said differently, the proton events tend to be "patchy" as seen in the muon/hadron layer, whereas the gamma-rays appear to be fairly smooth. Little difference is seen in the distributions for the 2nd (shown in Figures 3), etc., hottest patches. An Npatmu1 ≤ 6 trigger (called PATCH for brevity) gives about the same rate of proton events as the 50 PMT multiplicity trigger, so here I propose it as an alternative trigger and study the differences between the PMT and PATCH triggers. **This PATCH trigger has a Q-factor of 2 when compared with the number of low-energy on-pond events saved by the PMT trigger!** Said differently, it saves twice as many low-energy gamma-ray events as the PMT trigger.

Perhaps most striking is that, of the 4,556 gamma-ray events that satisfy the PMT trigger, only 88 satsify the PATCH trigger; the opposite is also true. Clearly these two types of triggers are complementary.

Shown in Figure 4 is the energy distribution that results from the PMT and PATCH triggers. You can see that, as chosen, the PATCH trigger selects lower-energy events when compared with the PMT trigger, but it also keeps high-energy events.

The distribution of number of hits in the air-shower layer for the PATCH and PMT triggers is shown in Figure 5. The PATCH trigger keeps events of relatively low numbers of hits in the air-shower layer. This results is fairly obvious, given that the two triggers pick different sets of events, and the PMT trigger is based on hits in the air-shower layer.

Given the PATCH trigger was optimized to select low-energy events, one can wonder about the high-energy events selected by the PATCH trigger that are not found by the PMT trigger. Shown in Figure 6 is the distribution of zenith angles for high-energy gamma-ray events (>5 TeV) for the PATCH and PMT triggers, and in Figure 7 the distribution of core distances. The PATCH trigger picks up events from relatively larger zenith angles than the PMT trigger, resulting in a larger aperture (aka solid angle, or sky view) for these events.

Supporting Results, or What Andy Found

One clear concern about the PATCH trigger is whether or not these events with fairly low numbers of air-shower hits can be reconstructed. Andy has provided a tentative answer based on Monte Carlo analysis that I reproduce in the following Table:

Range of air-shower PMT hits	Angular Resolution (degrees)
10 – 20	2.5
20 - 30	1.9
30 – 40	1.6
40 – 50	1.3
50 – 75	1.1
75 – 100	1.0
100 – 200	0.7
200 – 450	0.36

From this we see that the very small events that the PATCH trigger finds can be reconstructed relatively well, though obviously not as good as those with more hits in the shower layer.

Summary, or We've Got More Work

In closing, several remarks are in order. The first, and perhaps most important, is that we can chose to tune the trigger to our expectations and physics priorities because the multiplicity trigger condition that we operate Milagro with is fairly arbitrary. My view is that we should make such a choice and tune our trigger, or triggers, to maximize our physics output.

A trigger that targets fairly feeble low-energy showers may be very useful for studying GRBs, AGNs, and solar CMEs. At least for the case of GRBs, we will not be background limited, so excellent angular resolution is less important than for sources where we are background dominated. Another consideration to remember is that, for a given primary energy, the PATCH trigger "sees" events at larger zenith angles, thus opening up our effective aperture for burst-type sources. Our primary energy resolution near threshold is extremely poor because we are seeing only those events that have undergone an extreme fluctuation as the shower propagated through the atmosphere. Another point worthy of study is whether or not we can improve our energy resolution by having a trigger that sees much smaller gamma-ray showers. The complementary nature of the PMT and the PATCH trigger considered here suggests an eventual configuration in which we have an "or" of both triggers as our eventual operating configuration.

It is obvious that these preliminary results are based on the "wrong" Monte Carlo data set. The MC file I used started with events at 500 GeV, but I should study even lower-energy events. These results qualitatively confirm the previous studies of patch triggers by Scott and I, and Gus, that the air-shower layer is a poor discriminant between gamma-ray and proton showers; they also confirm the image-analysis/pattern recognition studies by Rich and others which have shown similar results. One may wonder about any effects caused by the differences in input spectral index between the gamma-ray and proton Monte Carlo samples. It is partly for this reason that I chose to compare events and choose the PATCH trigger over a very limited energy range of 500 – 750 GeV; differences in spectral index over a limited energy range like this should be minimized.

Another issue that needs to be addressed is the PATCH trigger being fired by single muons; this is true for the multiplicity trigger as well. This will be studied, but past experience leads me to believe it should not be too bad of a problem. In trigger studies that I did for a similar situation, single muons were easy to not trigger on, but multiple muon showers (w/out an electromagnetic component) are much more difficult to avoid; this remark is especially true for the PMT trigger. Remember the proposed PATCH trigger is one in which we ask for a relatively smooth distribution of hits in the bottom layer, the antitheses of what is expected for a muon. Soon I plan to gather a sample of muons for calibration by requiring at least one *hot* patch. The requirement of a modest (10) hits in the top layer was applied to the data to "veto" most single muons, and those at large zenith angles that would fulfill this criteria should also cause a lot of hits in the muon layer.

There is one last bias that I should state here. I think that triggers similar to that proposed herein would work better by looking at the "high-TOT" discriminator level and requiring few high-TOT hits in patches in the muon layer. However, I am worried about two problems with such an approach. First of all, we have not gain-matched our PMTs, so each patch/PMT has a different high-TOT threshold in terms of light-level hitting the PMT. Therefore, the effective trigger level may depend a lot on the patch/PMT; I think this should be less so for the low discriminator level. Secondly, the same effects make simulation of such a trigger difficult, if not impossible. Thus, we would have a hard time calculating our effective area, or flux and spectrum, for gamma-ray showers. Rather than worry about these problems, for now I avoid them by not considering a trigger based on high-threshold hits. Further work is merited here.

Let me finish here by asking for comments, questions, and help. It is clear that the above is very early work-in-progress, and may be buggy or have mistakes; it is offered here to motivate people to consider how we should trigger Milagro. I welcome input from everyone as we together should determine the optimum operating configuration for our experiment.

Figure Captions

Figures 1a & b. Showing the distribution, normalized to unit area, of the number of hits in the 3rd hottest air-shower layer patch. These figures are for gamma-ray (a) or proton (b) showers of primary energy between 500 and 750 GeV. Note there is little difference between them.

Figs. 2a & b. The distribution of Npatmu1, the number of hits in the hottest muon-layer patch, for on-pond low-energy gamma-ray (a) and proton (b) events. Note the gamma-ray showers are less "patchy." The gamma-ray events with large values also have fairly high (~50) numbers of hits in the air-shower layer.

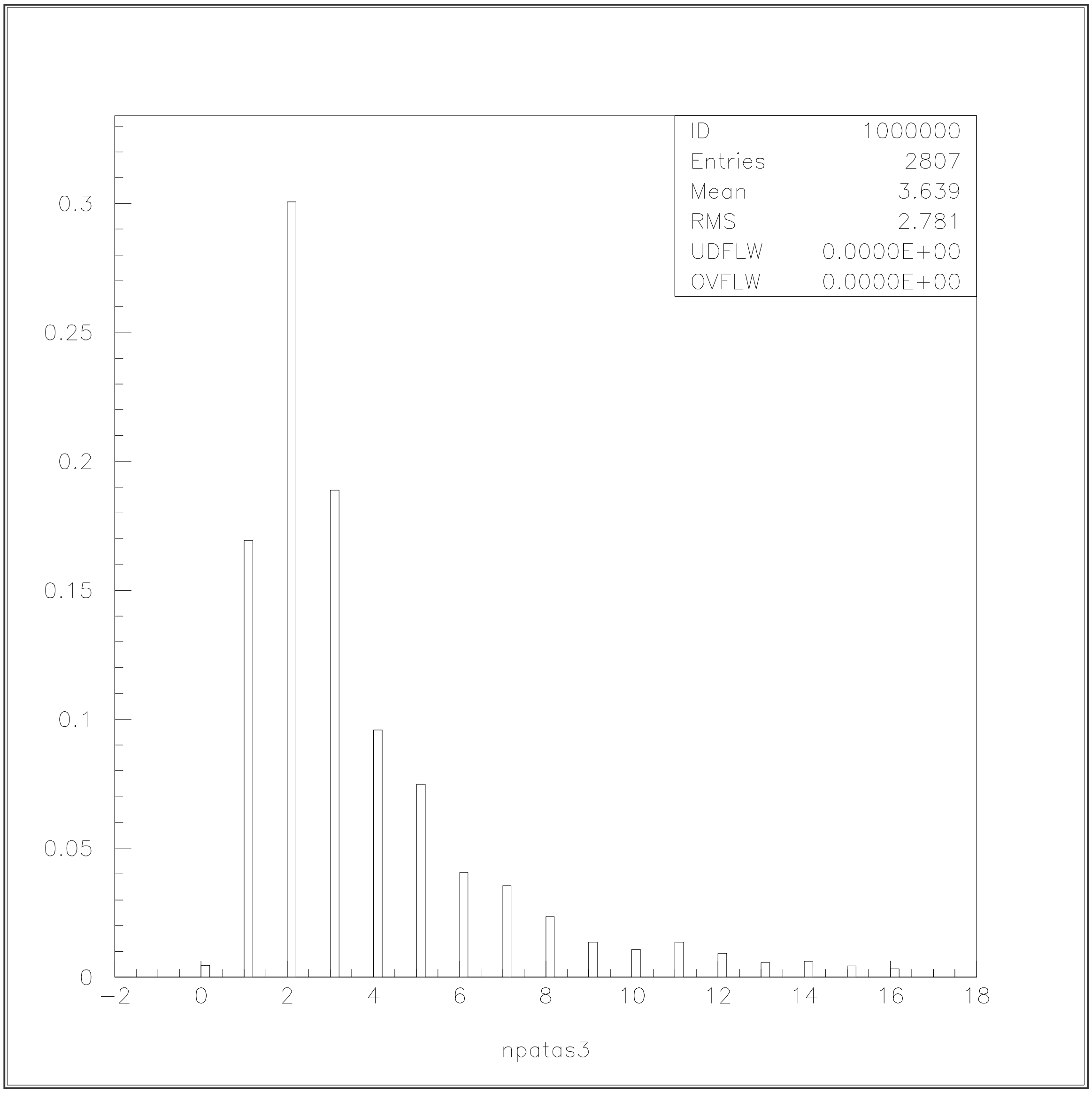
Figs. 3a & b. Same as Figs. 2 except for the 2nd hottest muon-layer patch. One may be able to take advantage of the slight differences between these distributions.

Figs. 4a & b. The primary energy of all simulated gamma-ray events that fulfill the PATCH (a) and PMT (b) trigger requirements. The spike just below 1 TeV in the PMT trigger is due to the method the showers were thrown. Note this spike is apparently reduced in height, due to the events in the 1-2 TeV region being recovered more efficiently.

Figs. 5a & b. The number of air-shower hits for the gamma-ray events fulfilling the PATCH and PMT triggers. Note the presence of the 10 (and 50) PMT requirements on the PATCH and PMT triggers.

Figs. 6a & b. Same as Figs. 4 except that the zenith angle of the event is shown. The PATCH trigger tends to see more events at larger zenith angles than the PMT trigger.

Figs. 7a & b. Same as Figs. 4 except the simulated core distance from the center of Milagro is plotted. The double-bump structure in the PATCH triggered events is due to the method that the events were thrown (larger energy events were artificially thrown over a larger area).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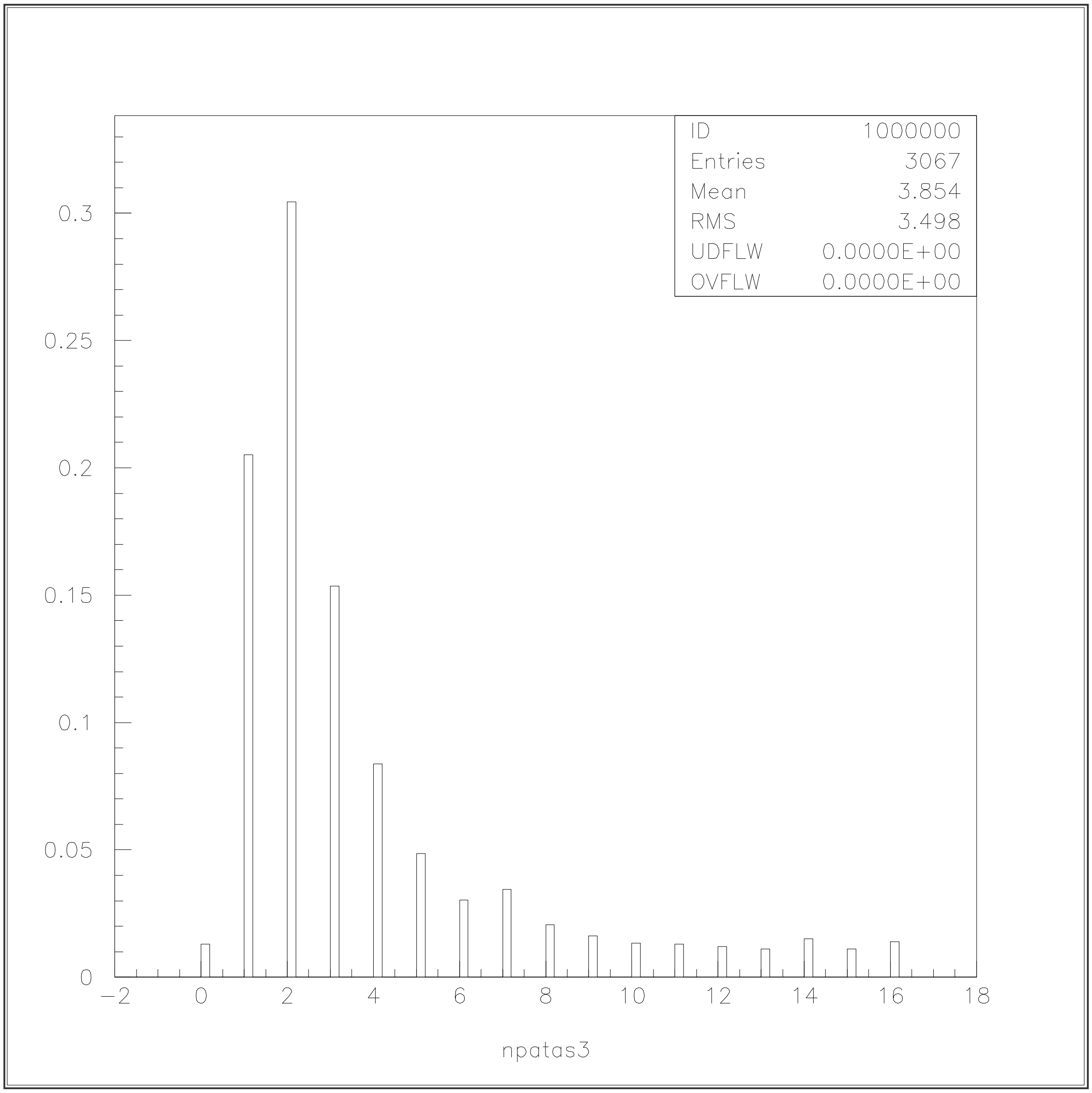
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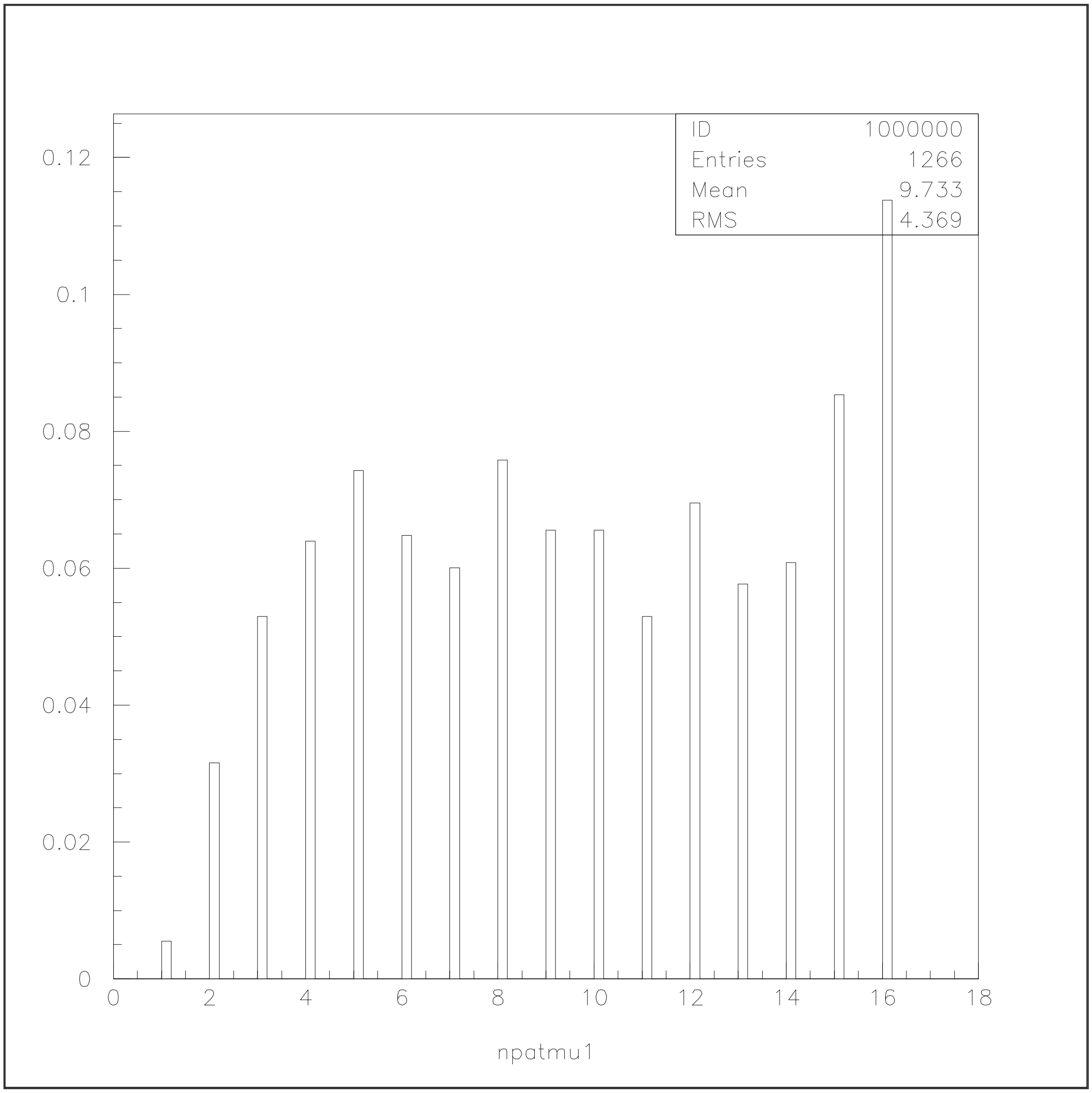
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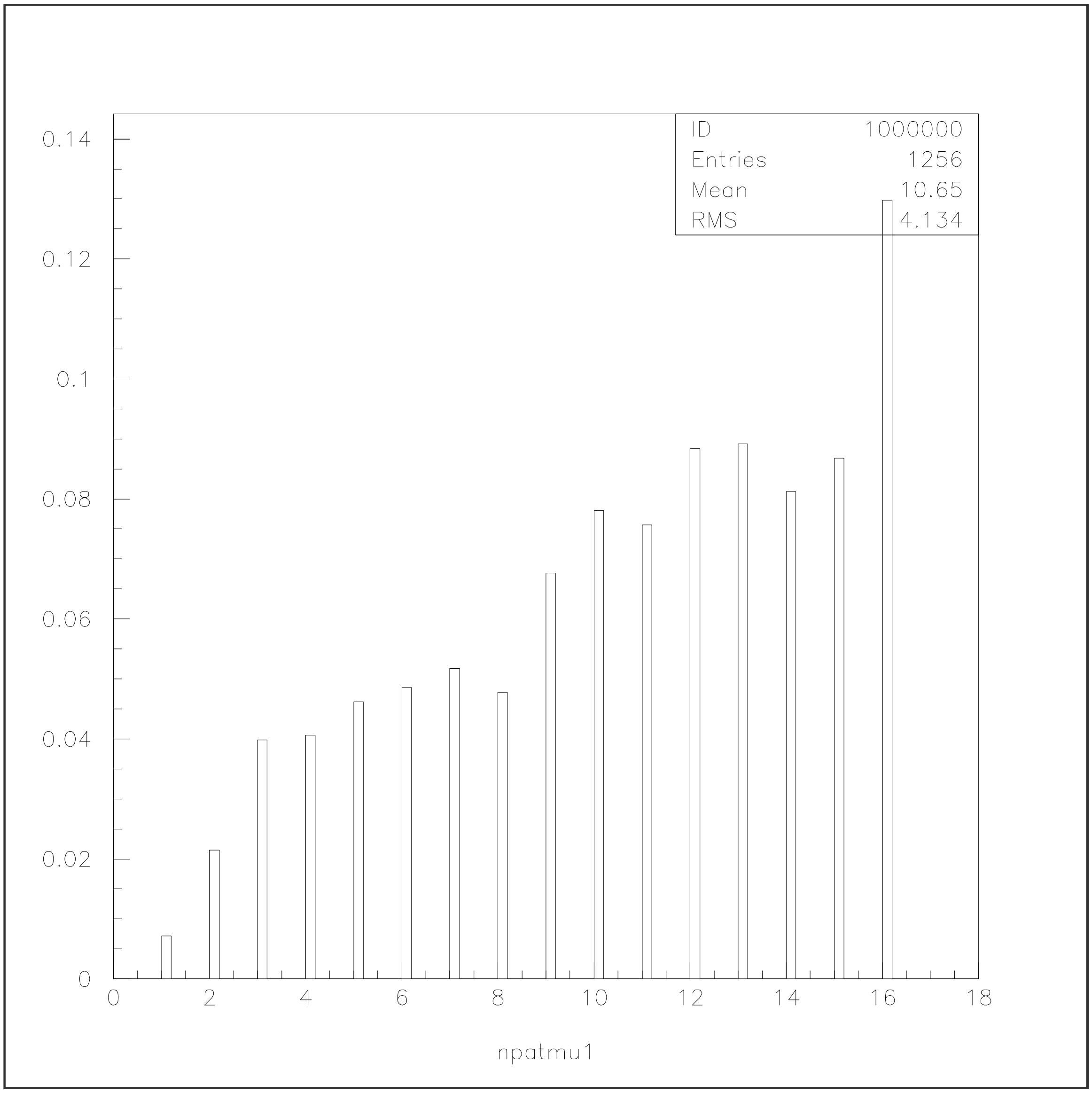
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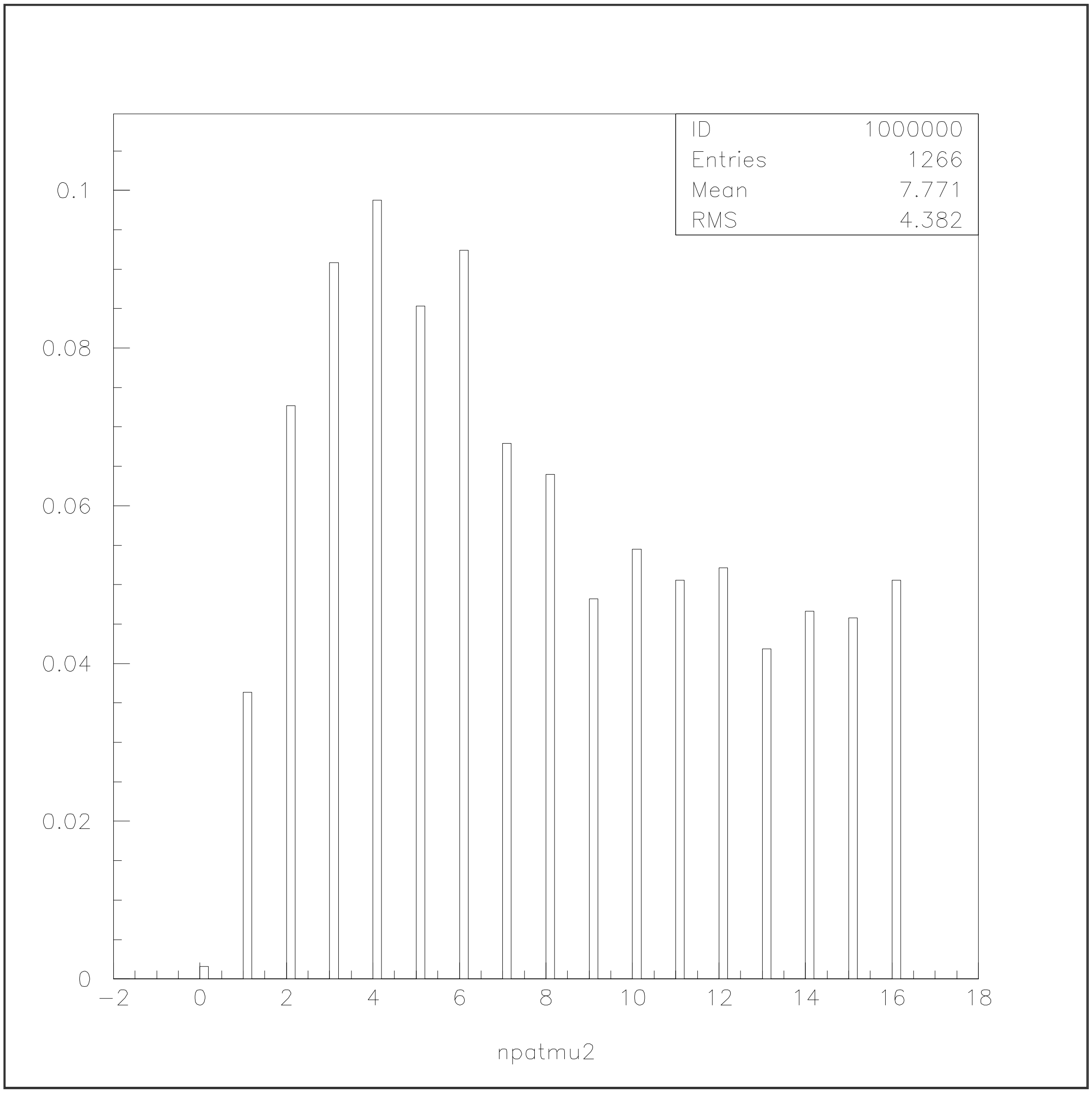
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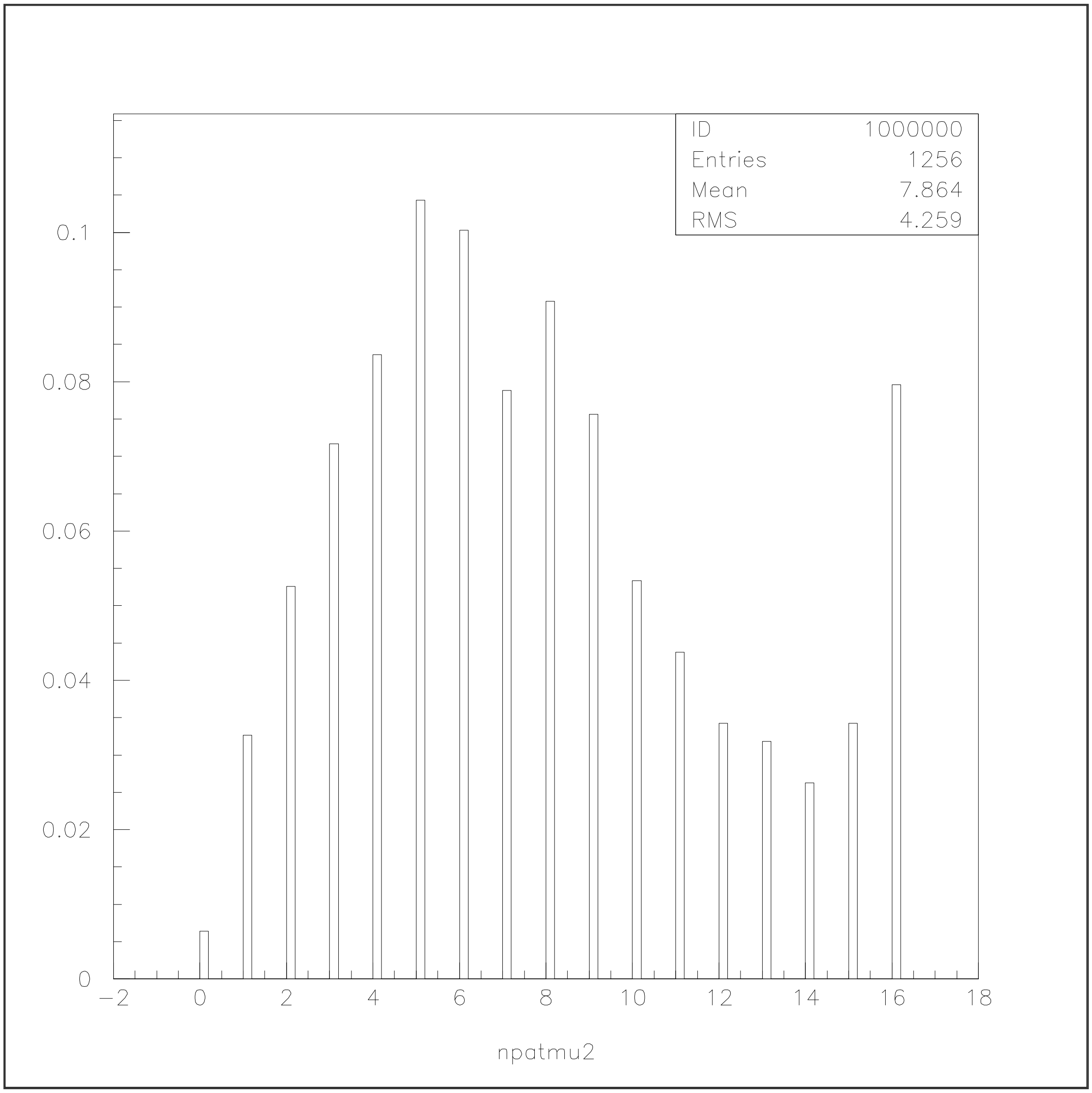
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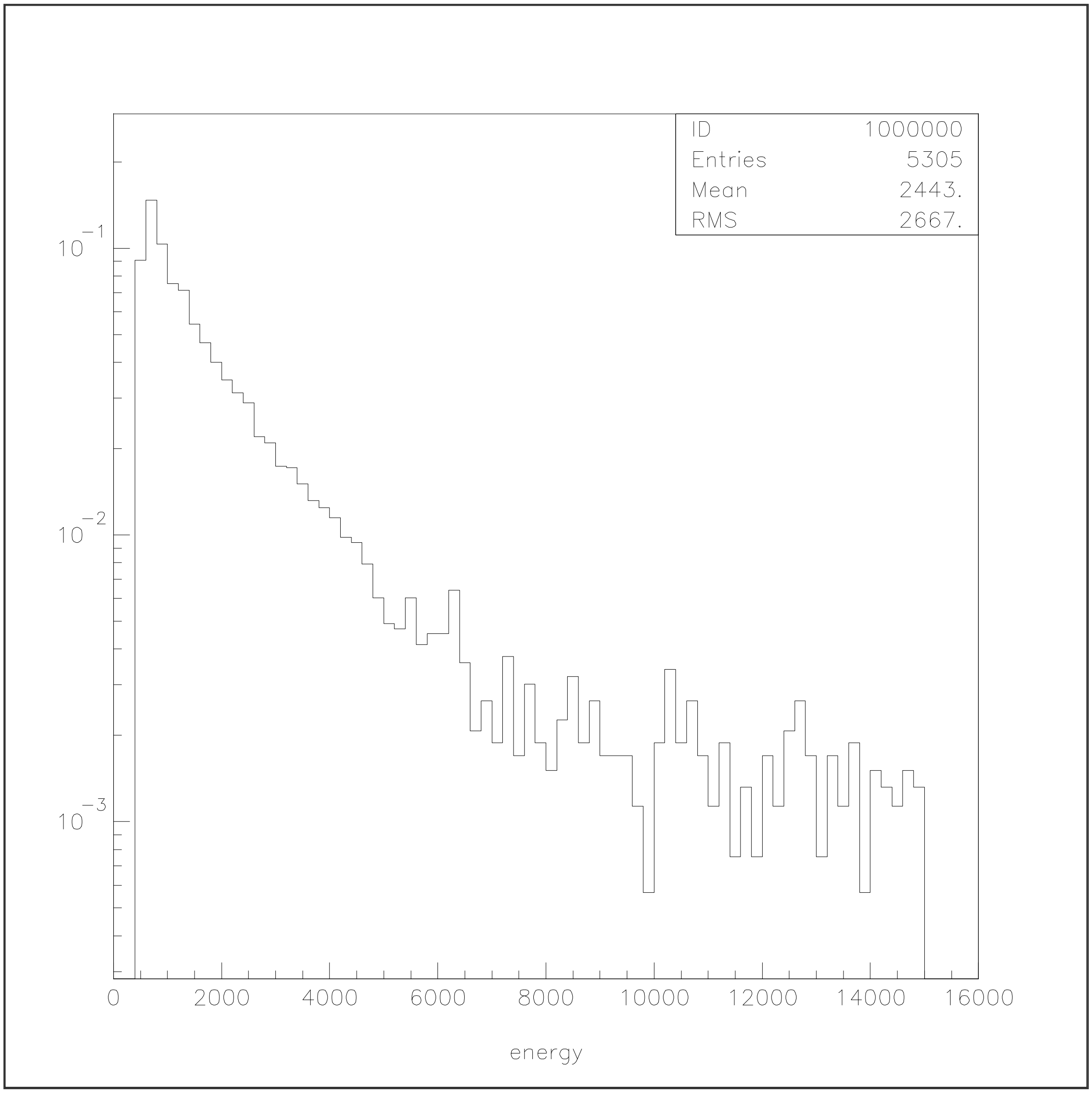
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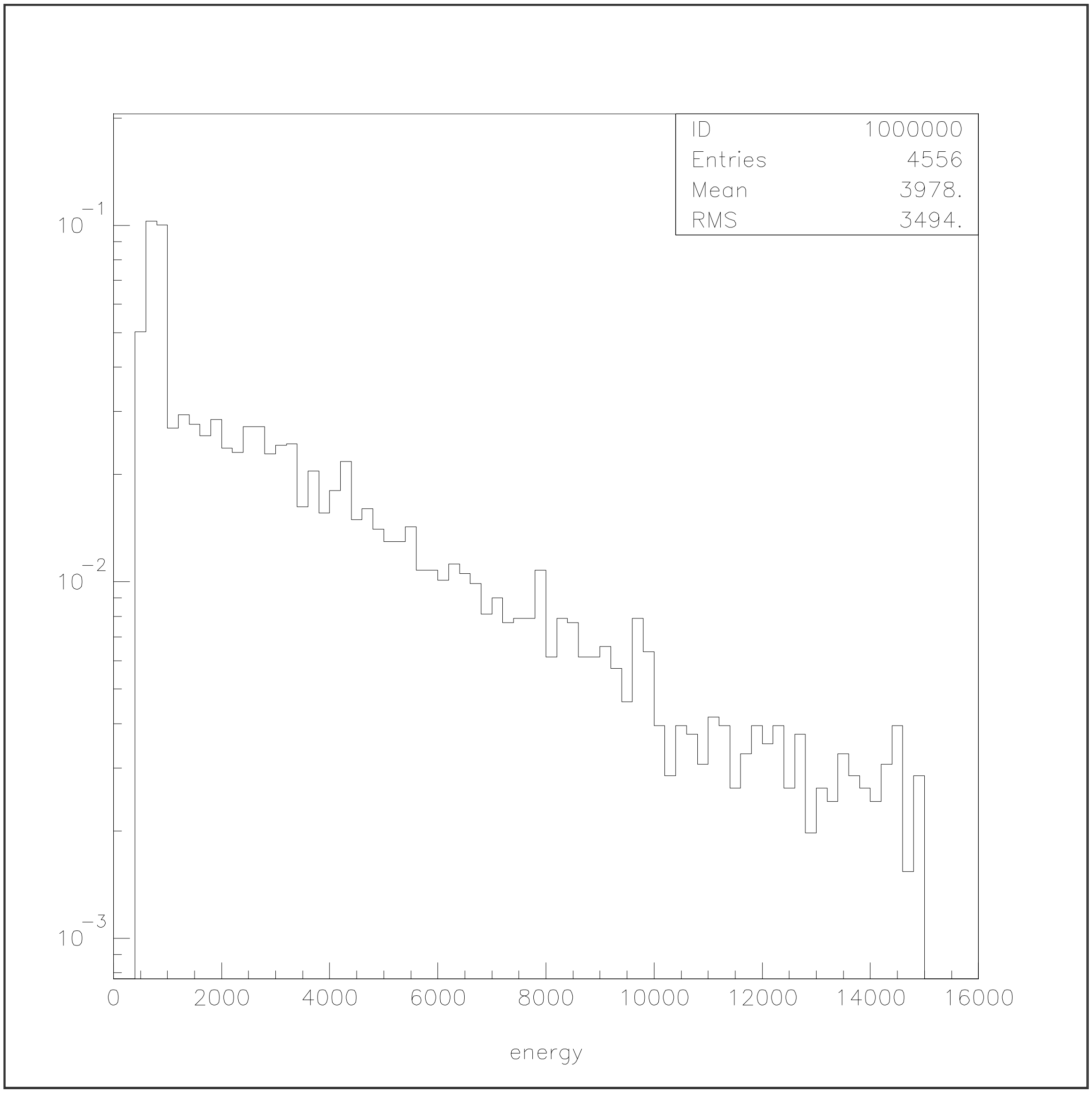
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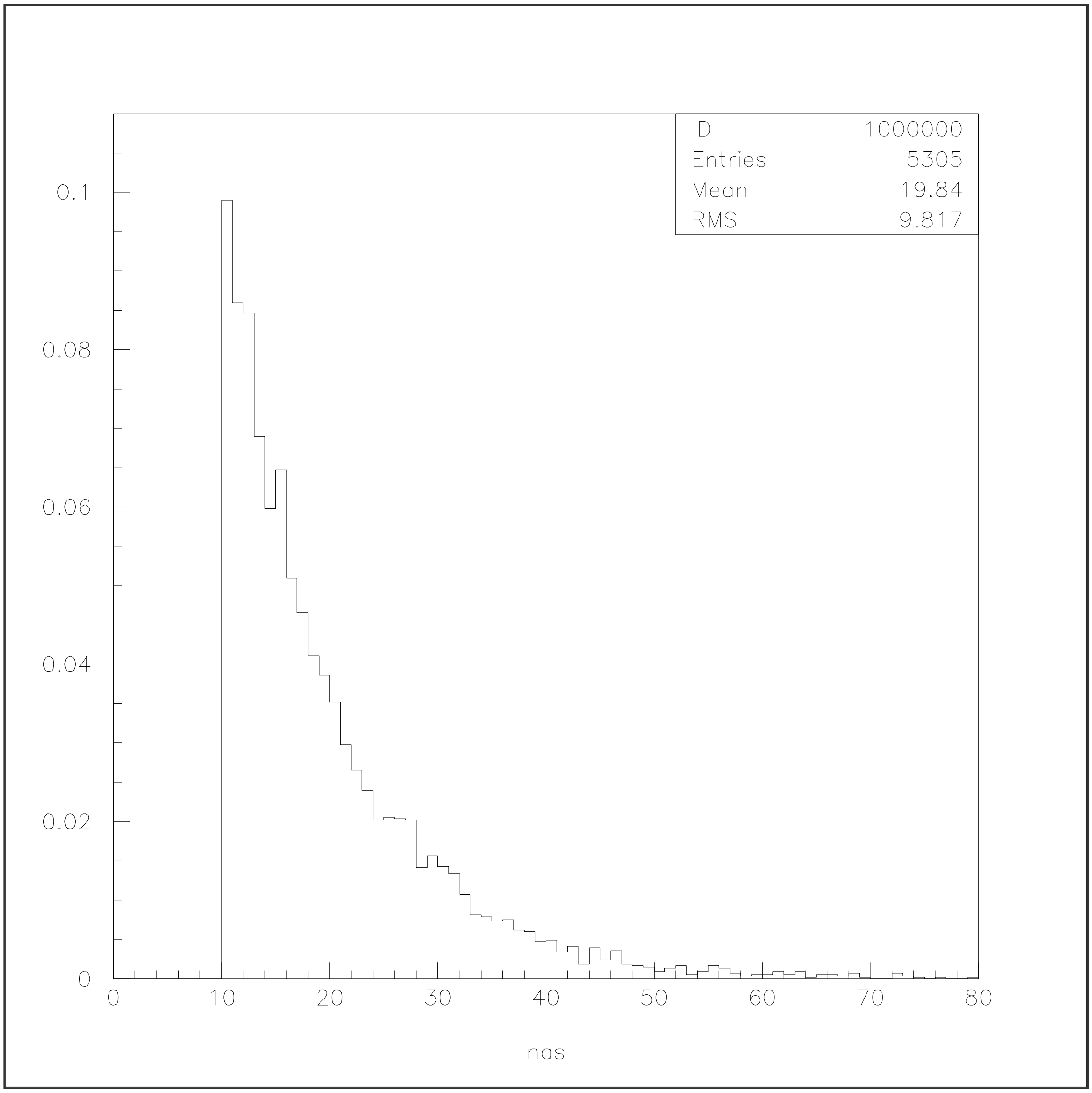
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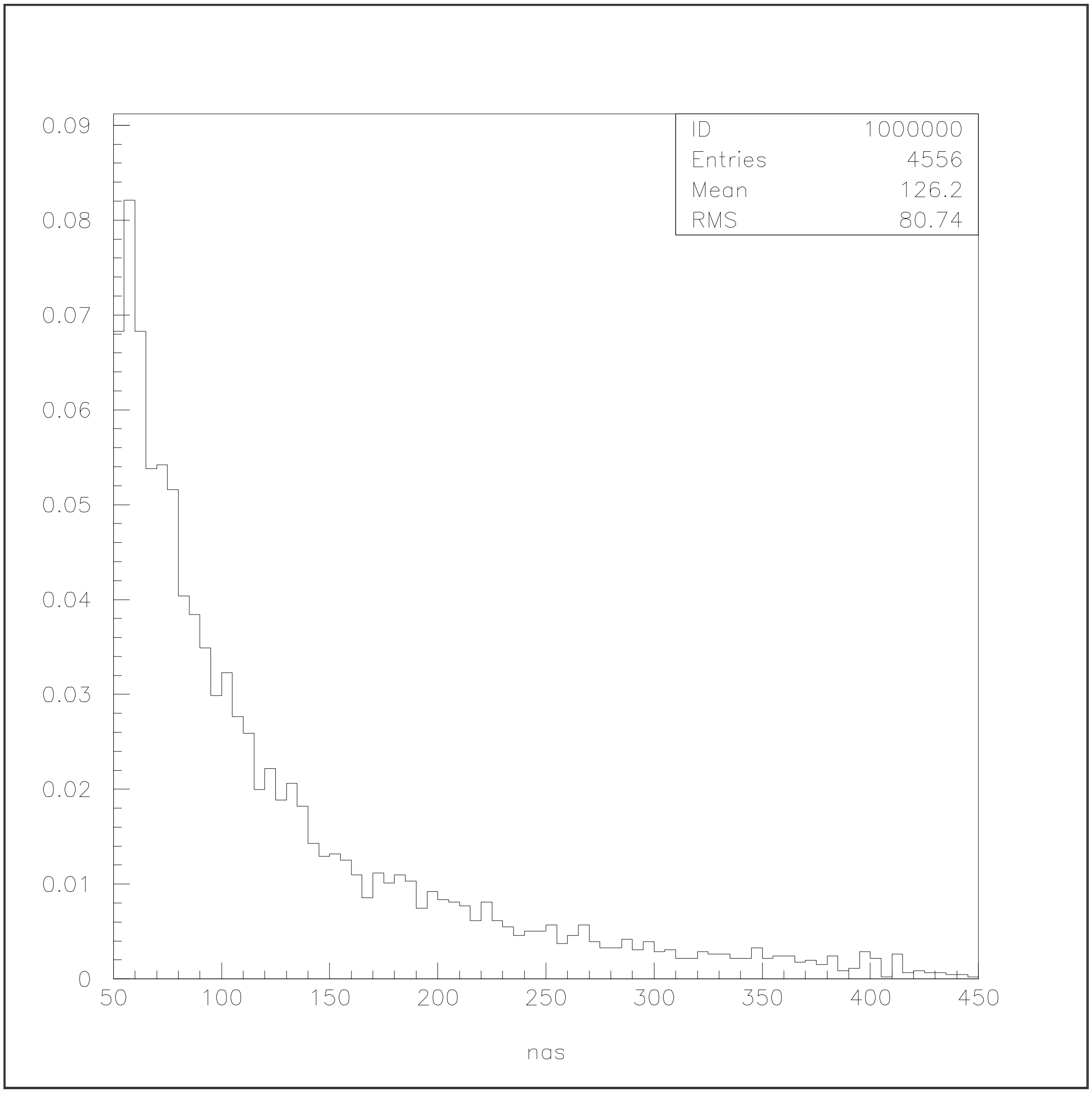

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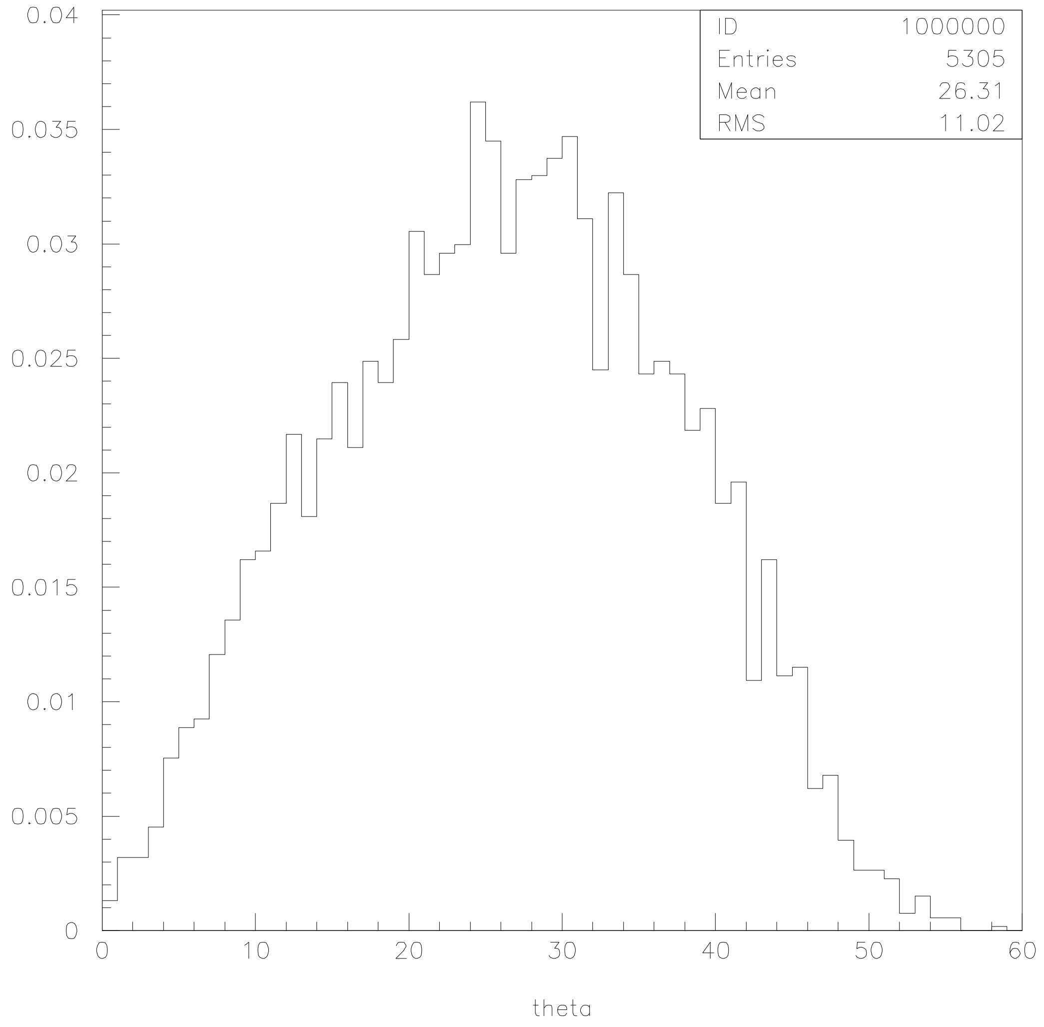
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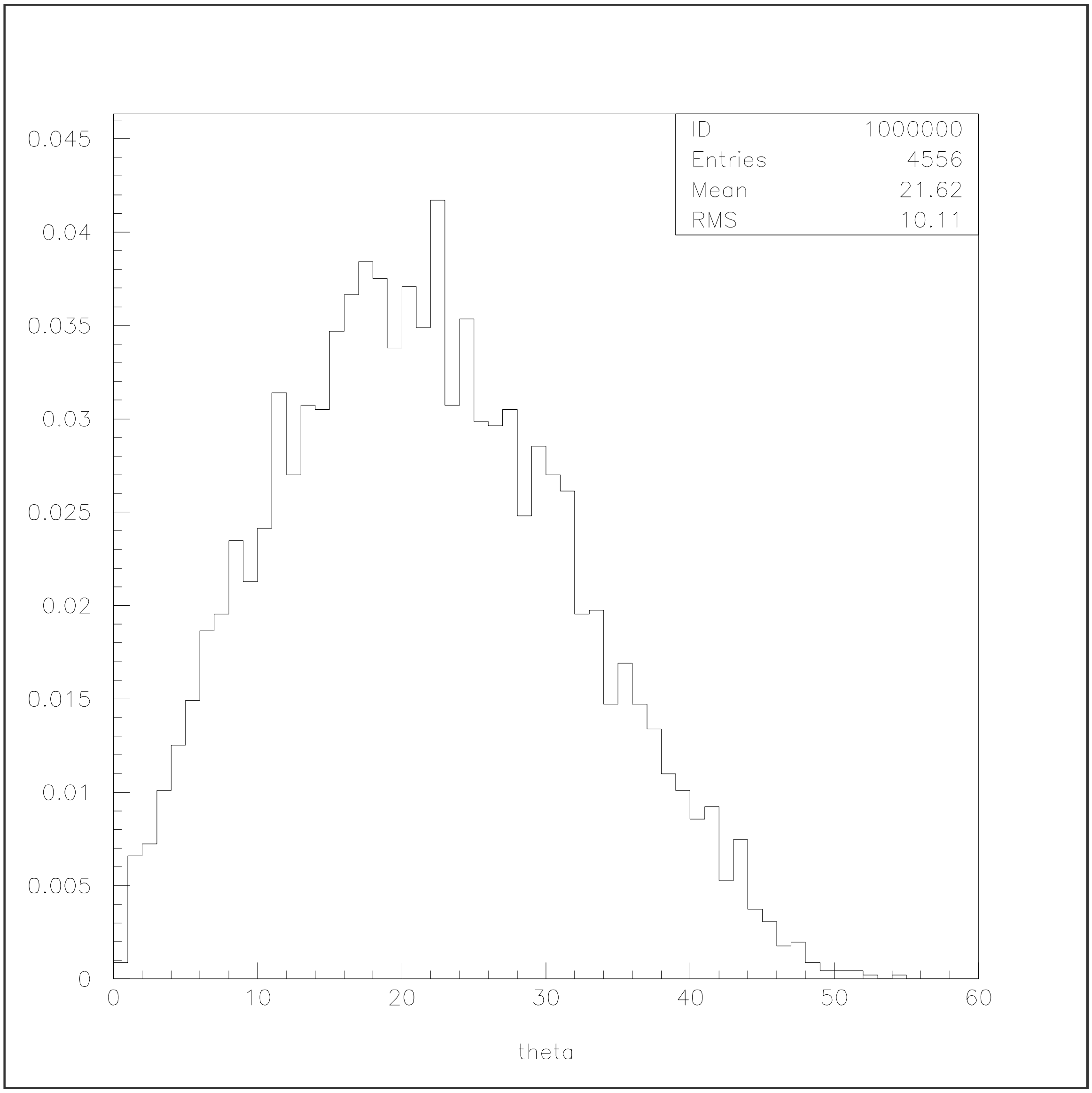
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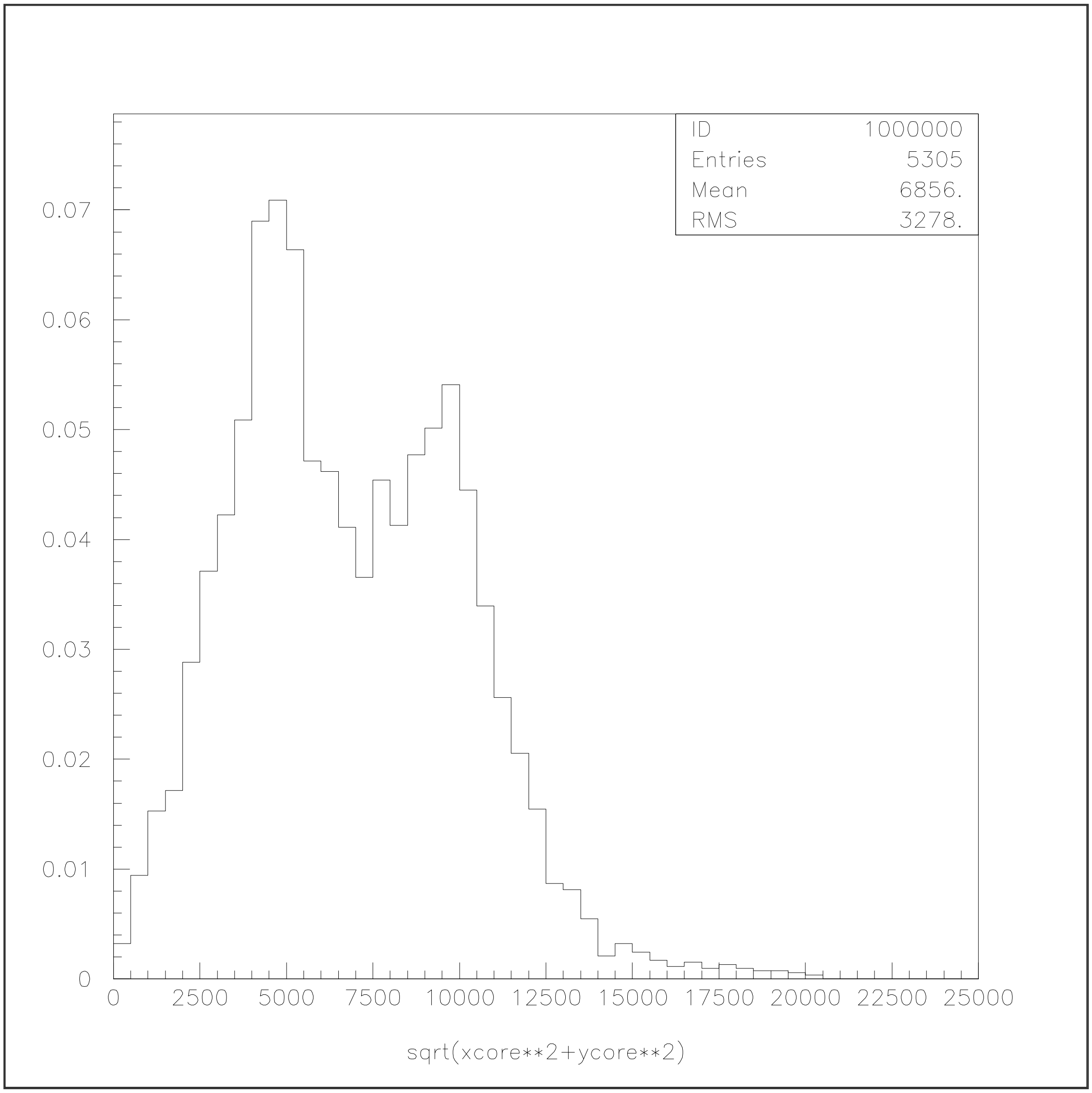
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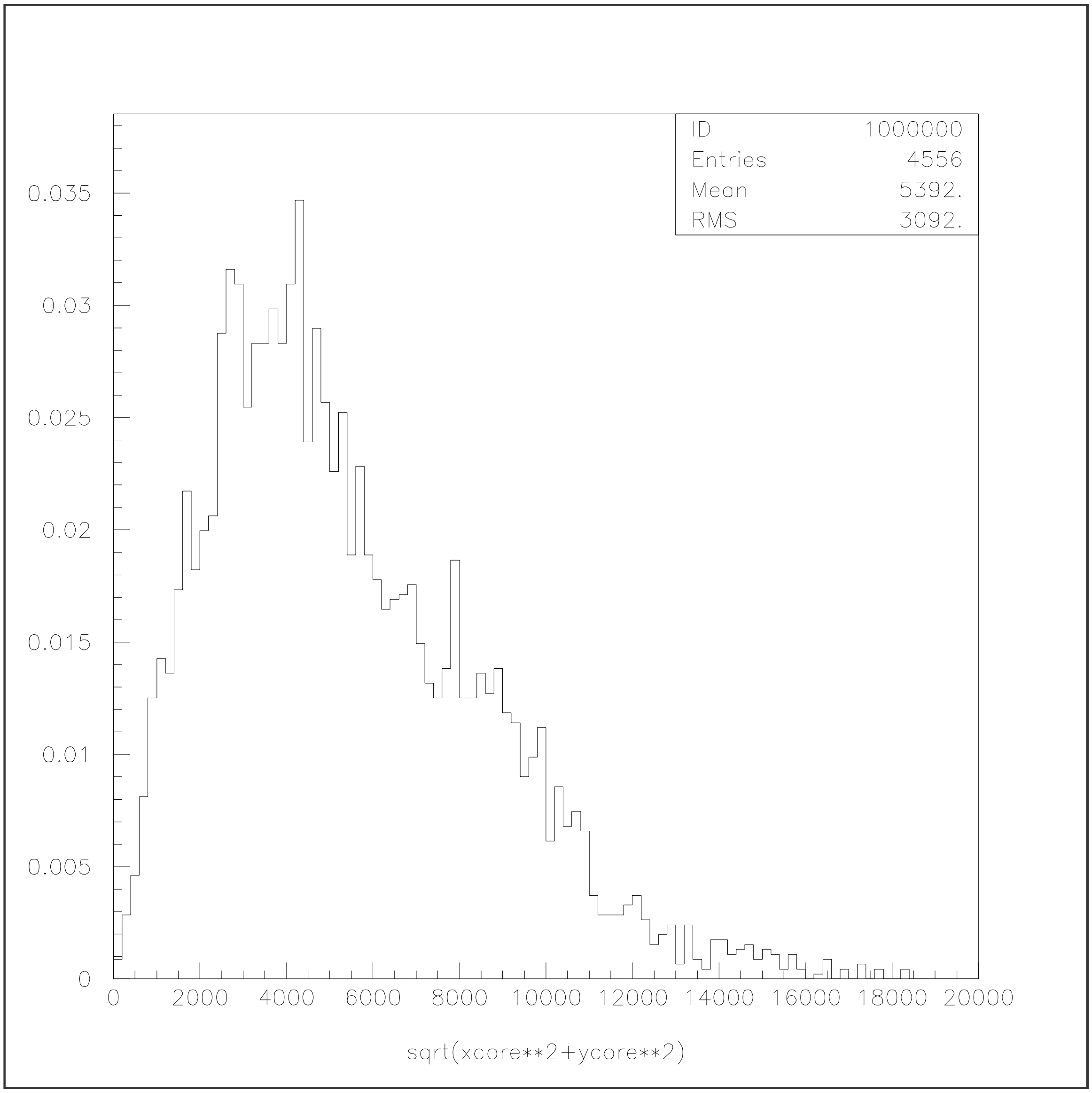
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