STAR Note SN0306
Version 1.0
September 26, 1997

The Case For An EMC Preradiator

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1 Introduction and History

The original EMC design had two layers of depth segmentation: calorimeter energy deposited in the first 5 layers was read out independently of the energy in the last 15 layers. To get the total energy, these two energies were summed. The 5/15 separation was chosen so that real electrons would deposit roughly equal amounts of energy in the two sections. 10/10 splitting was also considered.

1.1 EMCal Review

In December, 1996, the EMC was reviewed by Tom Ludlam's committee. The committee felt that we should not give any further consideration to depth segmentation. There were a number of reasons given:

- The physics gained (vs. cost incurred) was not well motivated
- Calibrating such a split calorimeter could be extremely difficult.
- Reworking the optical connections to go from 20 fibers on a tube to 5 on one and 15 on another is a complicated and difficult process.

This note is an attempt to design a depth-segmented calorimeter in a way that addresses these issues: the physics gain in $e - h$ separation is discussed, the cost is reduced, and the calibration and construction are greatly simplified. My personal opinion is that they were completely correct about the calibration: calibrating such a split calorimeter would be a nightmare, especially since we don't have a muon detector at STAR.

1.2 STAR Note 77

STAR Note 77 [1] discussed the advantages and disadvantages of three types of direct photon identification: using a shower maximum detector (a la STAR), using a fine-segmented tower geometry (a la PHENIX), and using a preshower detector (see below). The conclusion of this note was that for direct photons in the spin program, if the choice were *only* a preshower detector or *only* a shower maximum detector, the SMD is better. However, it did not ask whether or not there is an advantage to having both detectors given that you already have a shower maximum detector.

1.3 A Preshower Detector

Preradiators/precoverters/preshower detectors have been used in many experiments. Typically, they are separate detectors mounted in front of the main calorimeter, and either are $1 - 2X_0$ in thickness, or are behind a similar amount of structural material (usually cryostats). They are often gas based, in an attempt to improve position resolution. In our case, we would instrument the first layer of the EMC in such a way that would permit it to be read out separately, providing the same information as a stand-alone preconverter. This would have the same position resolution as an EMC tower, 0.05 x 0.05 ($\eta - \phi$).

2 Physics Improvements

2.1 Direct Photons

Preradiators have been used in very many direct photon experiments. (I personally have used them in both Fermilab E-705 and CDF). The basic idea is this: scintillator (or gas) response to a photon is negligible compared to an electron, so the first layer of detectors only sees photons that have begun to shower. In a thin calorimeter, or the first think layer of a thick one, the probability of a π^0 showering is twice that of a single photon. By comparing the number of events with at least one shower with events that do not shower, one can get the γ/π^0 ratio. This is independent of other methods (such as the shower profile at the point of maximum development), so each measurement can serve to check the other.

The question of optimal depth id critical in the design of such a detector. Clearly, the thinner the material, the more separation between the average photon and the average π^0's. However, the thinner the material, the less likely you will have an interaction in either case. Put another way, if the detector is too thick, both single photons and π^0's will always interact, and there is no distinguishing power. On the other hand, if it's too thin, there is plenty of distinguishing power when there is an interaction, but you never get any interactions.

People have done long simulations with EGS, GEANT and their ilk, and the conclusion seems to be a sampling layer after $1X_0$ is optimal. There is a simple, physical argument that says that this is about the right place. Ideally, there should be approximately as many entries in the "interacted" and "did not interact" bins for direct photons. The depth where that occurs is given by:

$$d = \frac{9}{7} \ln 2 X_0 \ \approx 0.89 X_0$$

The STAR calorimeter is behind approximately $0.6X_0$ of material: (measured at $\eta = 0$) the calorimeter front plate, the CTB, etc., so instrumenting layer 1 separately is close to ideal for a preconverter. An alternative (not investigated in this note) is to instrument layers one and two as a preconverter.

As an aside, one can also count photons by this method. Counting photons by counting the number of towers with no energy deposition has already been discussed in other venues. Having two complementary measurements will improve the systematic uncertainties on the measurement.

2.2 $e - h$ Separation

Additionally, a preconverter provides additional electron-hadron separation. A typical electron has dE/dx almost twice that of a pion even if it doesn't shower, and almost two-thirds of the electrons begin to shower before Layer 1. The preconverter energy distribution (c.f. Fig 1) is therefore quite different between electrons and pions. Even if a pion interacts, and the hadronic shower looks sufficiently electromagnetic to "fake" an electron, it is unlikely to do so within the first radiation length.

For heavy ion physics, this is probably the most attractive feature of this design. It improves the hadron rejection by typically a factor of 3 at a loss of typically 10% of the signal. For $J/\psi \to e^+e^-$ or $c \to se^+\nu$ events, this improvement results in a substantial reduction of the background.

Results of some GEANT studies (the bulk of this note) are described below:

Momentum (GeV)	Number of generated e^+	Number of generated π^+
1	2000	76000
1.5	2000	20000
2	2000	62000
5	2000	30000

Cut	1 GeV	1.5 GeV	2 GeV	5 GeV
E/p	±30%	±24%	±21%	±14%
E(SMD) (mips)	0.6	2.3	3.75	16.4
$\Delta(x)$ (strips)	2.15	1.85	1.6	1.5
$\Delta(z)$ (strips)	2.7	2.4	2.1	1.8
$\sigma(x)$ (strips)	6.6	6.9	5.8	6.7
$\sigma(z)$ (strips)	10.4	10.2	9.0	10.5

3 GEANT Studies

We studied the effect of a preradiator on $e-h$ separation using GSTAR. The geometry and program parameters were the default, and jobs were run on both the RHIC Pentium Pro computers and on an ANL Silicon Graphics Indy-R5000. Single positrons or π^+ mesons were directed into the center of a single EMCal tower (at $\eta = 0.35$) in the STAR detector, and this process was repeated for thousands of events. (The number of events is listed in the following table) The magnetic field was off in these runs, so that particles of varying energy would all end up in the same spot. This removed the uncertainties associated with particle position, and made the analysis program simpler.

A set of cuts is then set up to identify electrons. Each cut was selected to be roughly 95% efficient for electrons in isolation. Measuring the SMD in "mips" here is only approximate. The cuts are shown below.

We can then measure the cumulative probability of an electron or a pion passing a given set of cuts. We also adopt a "standard" set of cuts, which is:

- E/p as in the preceeding table.
- E(SMD) > 3.75 mips
- $\Delta(x) < 1.6$ strips
- $\Delta(z) < 2.0$ strips
- $\sigma(x) < 6$ strips

Efficiency	1 GeV	1.5 GeV	2 GeV	5 GeV
Electrons	81%	82%	81%	81%
Electrons (std cuts)	50%	72%	81%	85%
Pions	1.0%	0.26%	0.18%	0.08%
Pions (std cuts)	0.25%	0.21%	0.18%	0.10%

	1 GeV	1.5 GeV	2 GeV	5 GeV
Electron Efficiency	84%	88%	90%	95%
Pion Rejection	3.2 ± 0.4	3.5 ± 1.0	3.0 ± 0.5	1.7 ± 0.5

Table 1: $e - h$ results for a 2 mip preconverter cut

- $\sigma(z) < 10$ strips

We can then calculate combined efficiencies, as shown below:

We then ask the question of what a preradiator would buy us. We consider three possible cuts: requiring pre-radiator energy in excess of 2, 3 and 4 mips. The following tables show the electron efficiency (this is the additional electron efficiency; it must be multiplied by the number in the previous table to get the total efficiency) and the hadron rejection factor (e.g. a hadron rejection factor of 3 means that only 1/3 of the hadrons survive this cut) for hadrons that *otherwise would have been misidentified as electrons*. We use the "standard cuts" here.

To compare this with the 5/15 model of depth segmentation, we make cuts on $E_{\mathrm{front}}/(E_{\mathrm{front}} + E_{\mathrm{back}})$ such that the electron efficiency is identical to that of the corresponding preradiator cut. (We cut symmetrically around the peak in this variable). Additionally, we compare with simply cutting tighter on the energy deposited in the Shower Maximum Detector, again holding the electron efficiency constant.

At these momenta, particularly the lowest ones (where we need the best $e - h$ separation, both the 5/15 depth segmentation and the preconverter are better than simply cutting harder on shower maximum energy. The 5/15 design and the preconverter design are comparable, with perhaps a slight (10-20%) edge going to the preconverter.

	1 GeV	1.5 GeV	2 GeV	5 GeV
Electron Efficiency	72%	79%	83%	92%
Pion Rejection	4.3 ± 0.6	7.0 ± 2.9	3.8 ± 0.7	1.9 ± 0.5

Table 2: $e - h$ results for a 3 mip preconverter cut

	1 GeV	1.5 GeV	2 GeV	5 GeV
Electron Efficiency	59%	70%	75%	87%
Pion Rejection	5.9 ± 1.0	7.0 ± 2.9	5.0 ± 1.1	1.9 ± 0.5

Table 3: $e - h$ results for a 4 mip preconverter cut

	1 GeV	1.5 GeV	2 GeV	5 GeV
Preradiator Energy	59	12	37	20
5/15 depth Segmentation	69	11	39	20
SMD Energy	163	35	87	23

Table 4: Number of pions passing all electron cuts for a 2 mip preconverter cut or equivalent

	1 GeV	1.5 GeV	2 GeV	5 GeV
Preradiator Energy	44	6	29	17
5/15 depth Segmentation	54	9	34	19
SMD Energy	147	27	79	22

Table 5: Number of pions passing all electron cuts for a 3 mip preconverter cut or equivalent

	1 GeV	1.5 GeV	2 GeV	5 GeV
Preradiator Energy	32	6	22	17
5/15 depth Segmentation	41	9	29	15
SMD Energy	126	22	65	19

Table 6: Number of pions passing all electron cuts for a 4 mip preconverter cut or equivalent

4 Conceptual Design

The design that I forsee adopting has two fibers coming out of the first layer tiles, and one fiber coming out of the others. Whether this is accomplished with an α-groove or a double σ-grove is a decision that can be based on other factors: light yield, construction ease, cost, etc. One of the fibers is bundled with the remaining fibers and connected to a photomultiplier tube, and the other fiber is routed separately to a second tube.

One difficulty with this scheme is that a two-fiber readout does not produce twice the light of a one-fiber readout. The energy in the first layer is therefore underestimated. Typically, only a few percent of the shower's energy is deposited in the first layer, and typically two-fiber readouts are up to 70% as efficient in light collection as one-fiber readouts, so the net effect is a loss of about 1% of the shower's energy. This worsens the resolution, but also introduces a small non-linearity. This can be easily rectified, however. If the light loss in this readout scheme is 30%, using scintillator that is 30% brighter exactly compensates. (It also improves the photostatistics on the preradiator energy) Using Bicron scintillator on just the first calorimeter layer increases the cost by approximately $60,000.

Because fibers from all of the tiles go to a single phototube, that phototube measures the total energy of the shower. The other phototube, the one for the preconverter, does not have as stringent operational requirements as the energy measuring phototube. The light yield is low, so the tube needs to have good quantum efficiency, but it does not need to be as linear, nor as stable as the energy measuring tube. Because only one fiber goes to this tube, the active area does not need to be any larger than a single fiber. Multichannel photomultipliers, such as the Hamamatsu R5900 may be a simple and cost-effective solution.

Each module has 40 towers, and four modules are mounted on a single backleg. Ten R5900's can service an entire backleg, and there are 30 backlegs: we need 300 of these tubes. Today, these cost $800 each (quantity 1) including the base, for a total tube cost of $240,000. The total cost of this solution is therefore $300,000. To take into account things like cables, power supplies, and incidentals, I somewhat arbitrarily double this, to $600,000. This needs to be compared to the cost for the traditional depth segmentation. There have been several estimates for this, but typically they are around $1.5M, plus or minus about $500,000.

Since these tubes are quite compact, the space needed for them in the phototube box is relatively small, so the phototube box needs to be only about half the size as in the present design. This will make installation and systems integration substantially easier.

Finally, since the dominant cost is in photomultipliers, this can be staged as an upgrade. This may be a sensible option, since RHIC will not provide enough luminosity for J/ψ physics at STAR in the early part of the running. We don't need this e/h separation early on, and we don't have to pay for it until just before we need it. The EMC Review Committee was opposed to staging, but this opposition was based on the additional labor in reconfiguring the calorimeter from a non-depth segmented one to a depth segmented one: particular the labor in detaching and reattaching bundles of fibers to and from phototubes. In this design, all that needs to be done is a single attachment.

5 Future Studies

There are a number of studies that should be done. One is to repeat everything done here using FLUKA, the other GEANT hadronic shower package. (GHEISHA is the default) GEANT is basically a compilation of the world's understanding of particle interactions with material, and the details of pion response in the 1-2 GeV region are not perfectly understood. The difference between the two models can serve as an estimate of the uncertainty.

Another is to determine whether the EMCal front plate design is optimal. The present design assumes a 2 cm aluminum front plate. Replacing this with a 1 cm stainless steel front plate keeps the number of interaction lengths roughly constant (around 0.16 λ_A) but increases the number of radiation lengths to approximately $1X_0$. This is equivalent to adding an additional 2mm of lead in front of scintillator layer 1.

An alternative to this would be to instrument Layer 1 and Layer 2 as preconverters. This produces substantially more light (a factor of approximately 4) and also places the preconverter at (on average) approximately $1X_0$. The additional light may be important - this study does not yet include photostatistics. A follow-up study is planned for that.

Finally, we need to tune or scale GEANT to match our test beam results. This is an important job that needs to be done, but is not within the scope of this note.

6 Conclusion

This design has several advantages over the 5/15 depth segmentation, listed below.

- Hadron rejection is improved by a factor of 3, which is also what 5/15 depth segmentation provides.

• Unlike 5/15 depth segmentation, which can be used only for electron-pion separation, a preconverter can also be used to improve the direct photon signal. This may be crucial in going down to lower E_T, improving our low x measurements of gluon shadowing, spin structure functions, and possibly photon-jet balancing in AuAu collisions.

• Mechanically, the design is simpler.

• Calibrating the calorimeter is no more difficult than a single depth calorimeter.

• There exists a sensible staging option.

• The design allows us to relax our design specifications, allowing us to use 4100 fewer phototubes, saving hundreds of thousands of dollars.

An additional factor of 3 in hadron rejection gives us almost an order of magnitude improvement in signal to background for the J/ψ. Whereas the single depth calorimeter would have allowed some J/ψ physics, the order of magnitude improvement opens up new opportunities: lower p_T J/ψ's, binning of the J/ψ yield in bins of some other variable (multiplicity, strangeness, etc.)

References

[1] M. Beddo *et al.* STAR Note 77

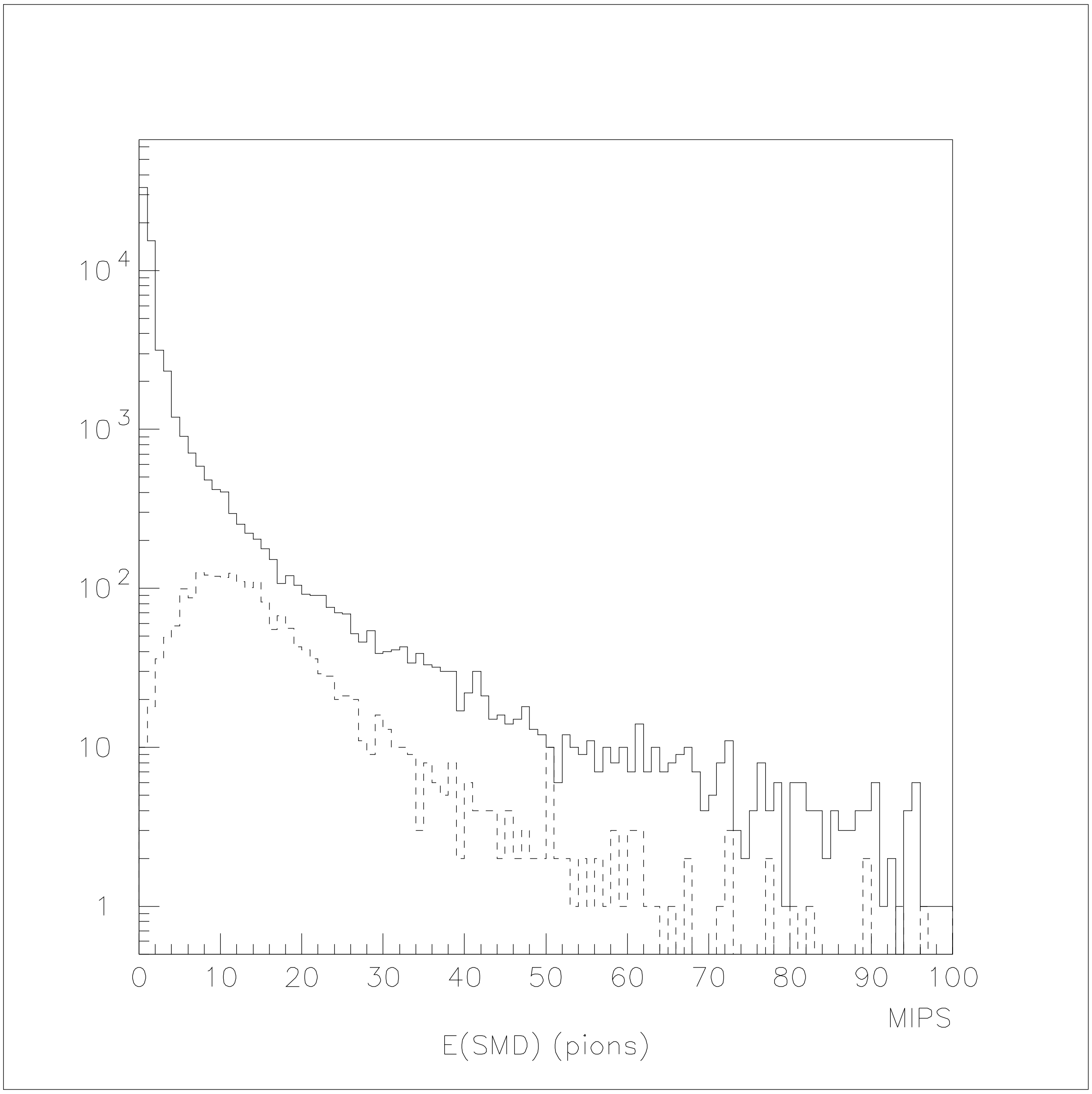

Figure 1: Energy deposited in the shower maximum detector for GEANT 2 GeV π^+'s (solid) and e^+'s (dashed). No other cuts have been applied. The high energy tail in the pions are believed to be from highly ionizing nuclear fragments.

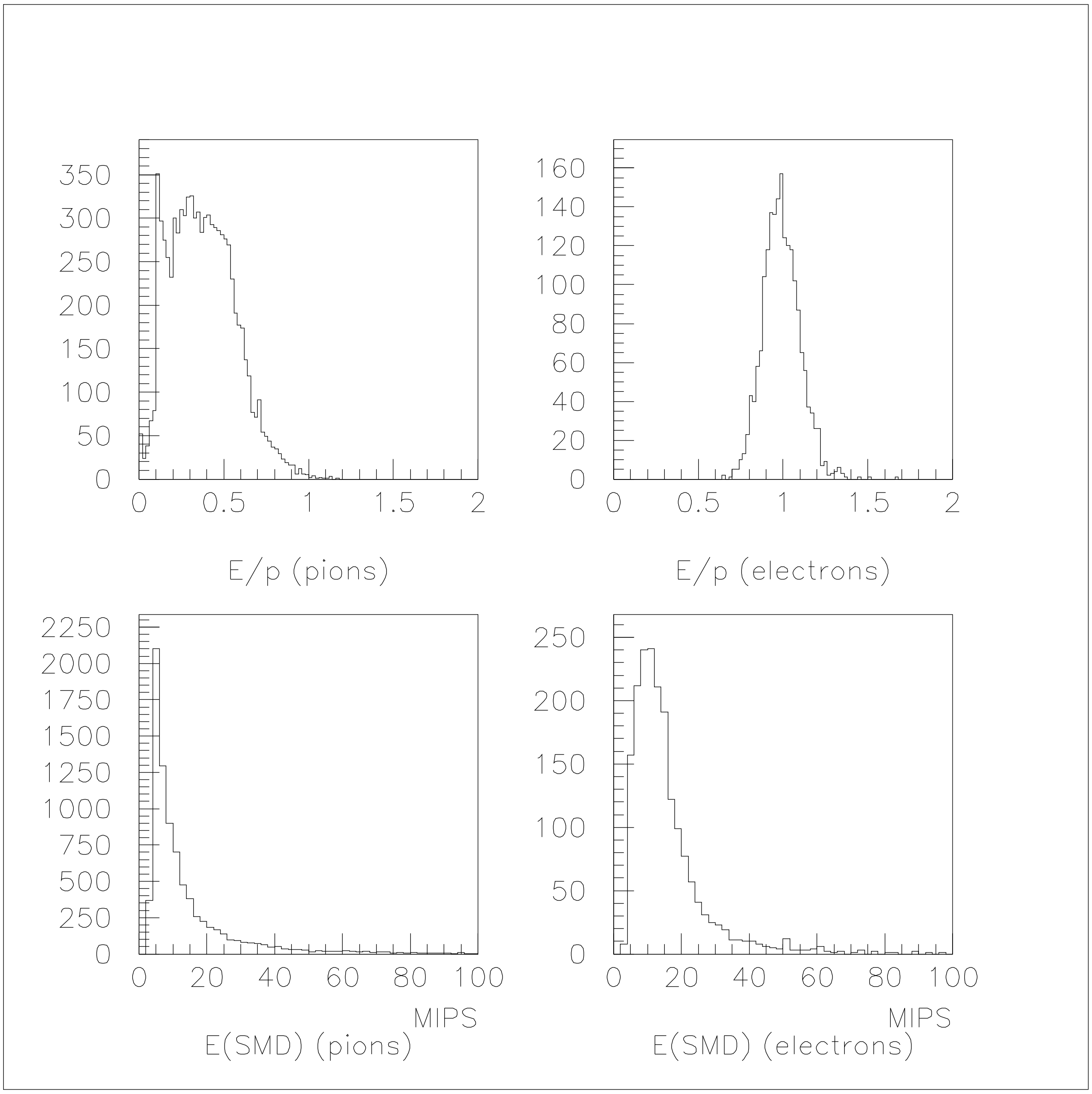

Figure 2: Various electron identification quantities for GEANT 2 GeV π^+'s (left) and e^+'s (right). Events were selected that had at least 4 MIP-equivalents of energy deposited in the shower maximum detector.

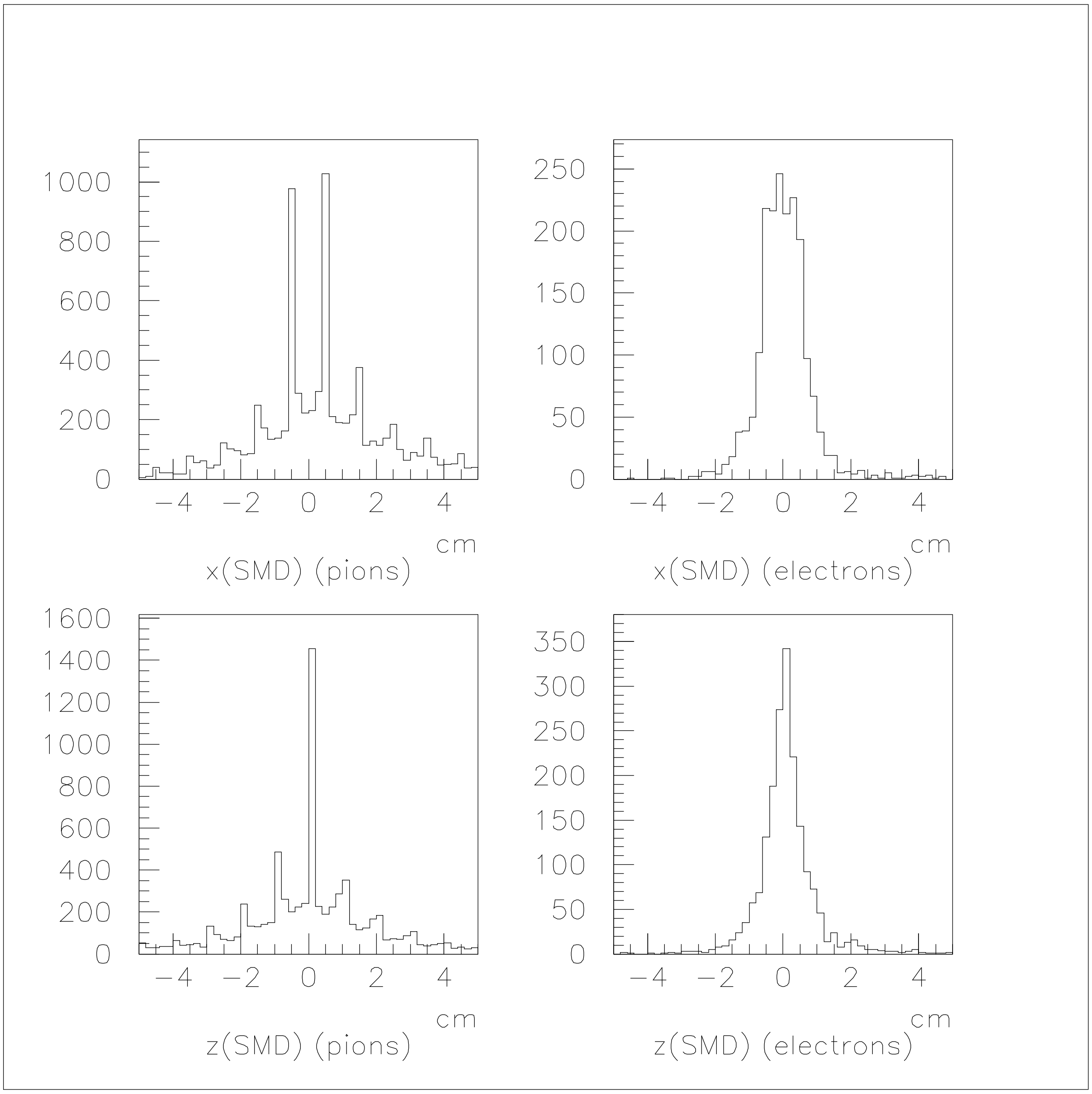

Figure 3: Various electron identification quantities for GEANT 2 GeV π^+'s (left) and e^+'s (right). Events were selected that had at least 4 MIP-equivalents of energy deposited in the shower maximum detector.

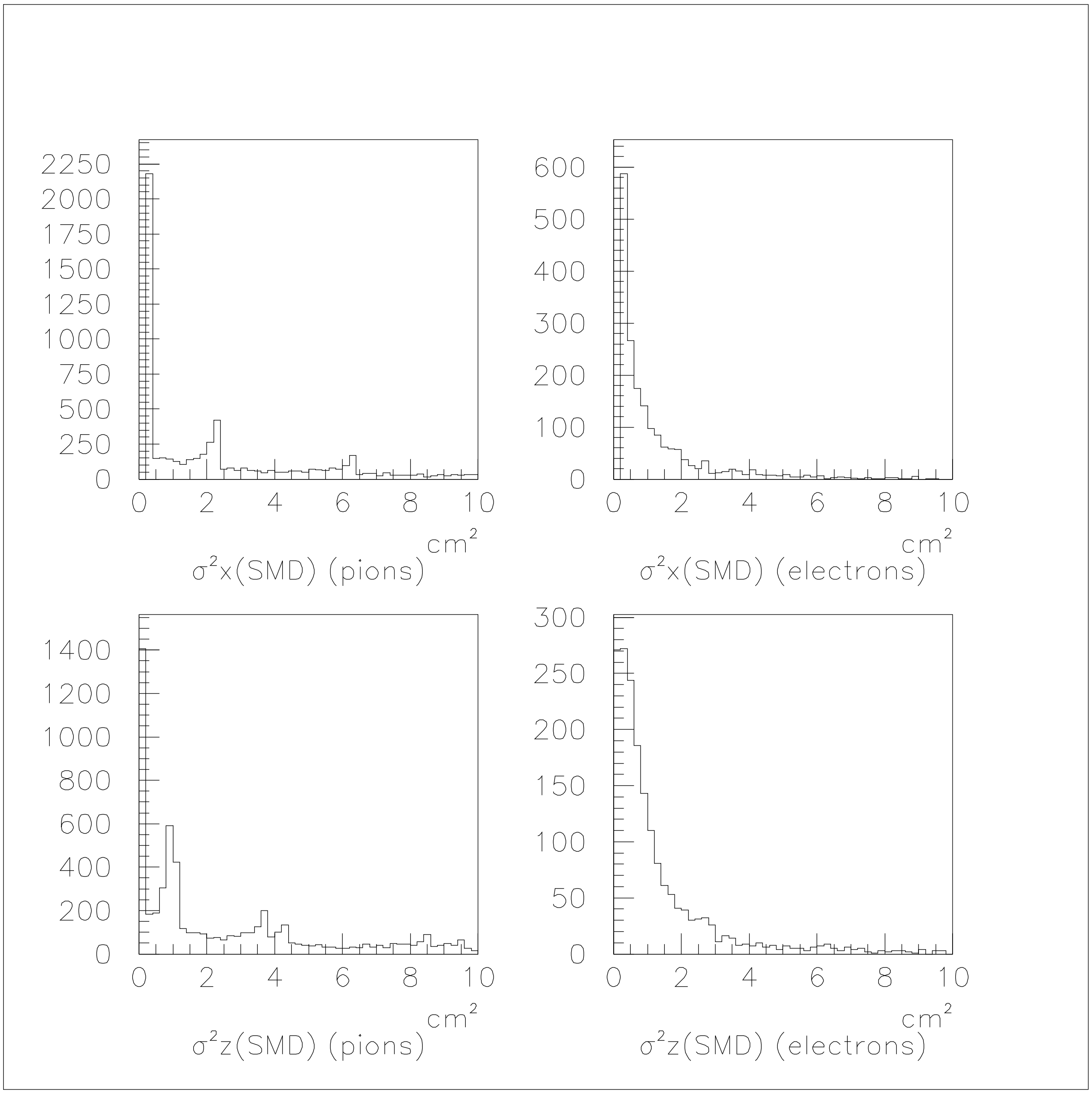

Figure 4: Various electron identification quantities for GEANT 2 GeV π^+'s (left) and e^+'s (right). Events were selected that had at least 4 MIP-equivalents of energy deposited in the shower maximum detector.