STAR TPC: Do Eight Bits Suffice?

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Introduction

The STAR TPC will use a 10-bit ADC because of the need for a large dynamic range (dE/dx information on protons with momenta from 200 MeV/c to minimum ionizing with reasonable precision).[1] However, the information content in the ADC's for even 200 MeV/c protons in a couple of centimeters of gas is rather low, certainly less than 10 bits worth. It should be harmless to bin the large ADC values more coursely, thereby reducing the amount of data to transmit and store. The computational and memory cost of such a mapping can be minimal, requiring only 1024 entries in a lookup table—such a possibility was, in fact, already mentioned in the STAR Conceptual Design Report (CDR).

The fractional width of dE/dx distributions varies slowly with dE/dx, suggesting the use of a logarithmic mapping onto fewer bits. Eight bits is an obvious choice to try, as it would eliminate the need for bit-level manipulation of compressed data. Figure 1 shows a possible scheme. The mapping is 1:1 for the first 96 channels, which includes the region where dE/dx distributions for different particle types will merge. An integer number of 10-bit codes map to each 8-bit code (making the slope of the curve in Fig.1a piece-wise linear). Several 8-bit codes (250–255) are left undefined, allowing their use for overflow, underflow, error conditions, flags, etc.

The STAR CDR envisions particle identification by dE/dx for:

- $-1 < \eta < 1$ or, equivalently, $40.4° < \theta_{\mathrm{polar}} < 139.6°$.
- Protons down to 200 MeV/c and up to 1000-1100 MeV/c momenta .
- Kaons up to 600-700 MeV/c momenta.

[1] STAR Conceptual Design Report, Sec. 4.C.2.o and 4D-1; the estimates in these two sections are not quite consistent.

The pixel geometry is (roughly):

- Inner TPC: 0.335 cm $\times$ 1.20 cm $\times$ 0.410 cm ($\Delta x \times \Delta y \times \Delta z$).
- Outer TPC: 0.670 cm $\times$ 2.00 cm $\times$ 0.410 cm.

However, the 180-ns amplifier shaping time smears the pixels in z, making the pulse height from particles at small polar angles larger than is would be for the path length through one pixel. The number of merged pixels will be roughly (180 ns)/(81 ns) $\sim$2.22, covering 2.22 $\times$ 0.410 cm = 0.91 cm in the drift direction. We can consider our pixels to have overlapping lengths of $\sim$0.91 cm along z.

Gas Ionization Simulation

Consider three cases:

1. A 200 MeV/c proton with $\theta = 54°$ in a 0.5 Tesla magnetic field has a radius of curvature of 107.7 cm and passes through both the inner and outer TPC volumes. Its maximum path length though a pixel is 2.30 cm along the diagonal: this should give close to the maximum pulse heights to be handled.

2. Pions and kaons traveling normal to the beam axis with momenta around 700 MeV/cm are near the limit of particle separation via dE/dx; path lengths will be around 2.1 cm in the pixels of the outer TPC volume.

3. Pions and kaons traveling normal to the beam axis with momenta around 1100 MeV/cm will give some of the smallest pulses likely to be used for particle ID; the dE/dx distributions are merged for these two, but are still somewhat distinct from the proton distribution. Path lengths will be close to 2.0 cm in the pixels of the outer TPC volume.

In all three cases, the simulation was simplified by approximating the data as 32 samples (representing 32, outer TPC pads) from the same distribution (i.e., neglecting data from adjacent pixels and the inner TPC volume, as well as electronic noise, etc.).

To verify that little information is lost in the 8-bit mapping and the eventual inverse mapping, Monte Carlo simulations of gas ionization statistics were done in P10 gas (Ar:CH_4, 90%/10%) at 1 Bar. The simple-minded ionization model used the Bethe-Bloch equation to find the average energy loss; an equation by Bethe which estimates the average number of primary delta rays as a function of the incident particle momentum; and sampling from a $[1-\beta^2(t/t_{max})]/t^2$ distribution, where t is the kinetic energy given to a knock-on electron. The number of primaries was normalized to that found from Sauli's tables[2] for a minimum-ionizing particle—28.1/cm.

Values of t were chosen with $t\epsilon(t_{\rm min}, t_{\rm max})$, where $t_{\rm max}$ is determined by kinematics and $t_{\rm min}$ was used as a normalization constant to give one ion pair per 26.2 eV of energy loss. This is necessary because the sampled distribution breaks down (diverges) for low-energy knock-on electrons. The resulting distribution is somewhat narrower than is shown in published data for Ar:CH_4, 93%/7%, although the published data appear to be broadened by noise, given that the number of ion pairs plotted at zero is not as small as one would expect.[3] Regardless, the current issue is only whether or not information is lost in mapping the TPC ADC's onto 8 bits; if the information content of a slightly too-narrow dE/dx distribution is not compromised, the real situation should be no worse.

Results

Figure 2 shows a possible mapping of the number of ionization electrons onto the 10-bit ADC scale (and also shows representative ionization distributions). The normalization (3.0 electrons per ADC count) was chosen so that the main body of the dE/dx distribution from a 200 MeV/c proton passing through 2.30 cm of gas is on scale. As expected, the pion, kaon and proton dE/dx distributions all have similar widths on this scale. The spikes on the distributions are caused by the discontinuities in the derivative of the mapping in Fig.1a; they disappear under the inverse mapping.

If we now use a 10–70% truncated mean as a dE/dx estimator (i.e., rejecting the smallest three and largest ten ADC's from our 32 samples), we get excellent particle separation at 200 MeV/c; see Fig.3. The means are almost unchanged if one maps onto 8 bits, then back to 10 bits. Figure 4 shows the net effect of the mapping in 2D.

At 700 MeV/c the pion and kaon peaks are beginning to overlap, although the protons are still cleanly separated, as shown in Fig.5. The path length is 2.10 cm. The mapping for most of the pion and kaon peaks is 1:1, so almost no information is lost for these distributions. The proton distribution shows a very slight broadening.

Figure 6 shows the proton dE/dx distribution beginning to overlap the kaon and pion distributions at 1100 MeV/c. The path length was 2.00 cm in each pixel. The mapping for almost all of the data samples included in the truncated mean was 1:1.

[2]F.Sauli, CERN 77-09 (1977).

[3]See W.W.M.Allison and J.H.Cobb, Ann. Rev. Nucl. Sci. 30, 253 (1980).

Conclusion

Mapping from a 10-bit ADC onto an 8-bit, non-linear scale for data transmission and storage does not cause significant bias or information loss for purposes of particle identification. Eight bits cover enough dynamic range to allow a finely grained mapping at the low end of the ADC range where dE/dx distributions for different particles merge, and a (relatively) course-grained mapping where the ADC distributions are wide (in an absolute sense) and well-separated. A re-inspection of Figs. 3, 5 and 6, in fact, convinces one that particle identification would not be too adversely affected if one were to map 7 bits, although one would be discarding *some* information.

The remaining question is whether or not using only 8 bits degrades the momentum resolution in the tracking. This could still occur because, even though the statistical width of the ionization distributions is large, the pulse height *division* between pads within a pad row is not determined by this width, and may, in principle, benefit from more precise representation. A similar argument applies to the detection of the edge of a cluster in time. However, since the 8-bit mapping discussed gives approximately equal fractional precision at all ADC values, one would not expect this to have much impact on the overall tracking; the fractional ADC precision is being set to that already used for minimum-ionizing particles.

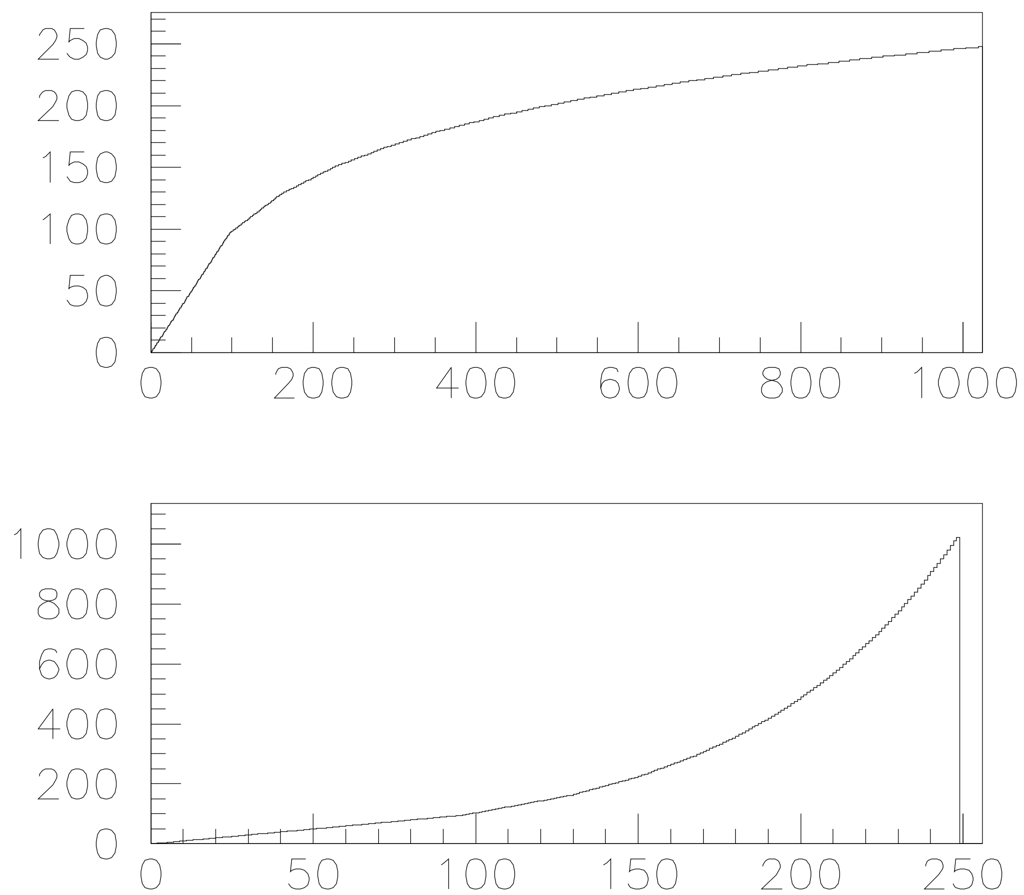

Figure 1: (a) Roughly logarithmic mapping from 10-bit ADC onto 8 bits. (b) Inverse mapping re-linearizing 8-bit data.

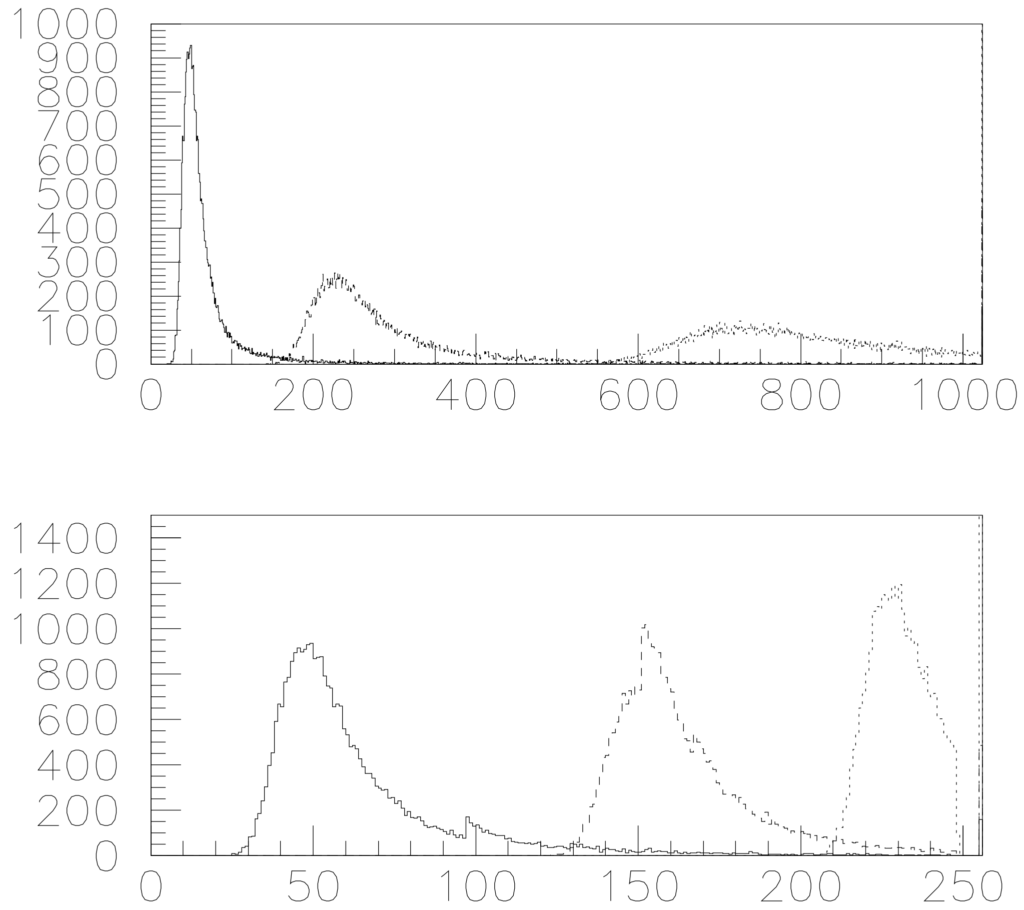

Figure 2: (a) 10-bit electron number distributions for 200 MeV/c $\pi^{\pm}$'s, $K^{\pm}$'s and p's (left to right) in 2.30 cm of P10 gas at 1 Bar. One ADC count represents 3.0 electrons. (b) Same distributions mapped onto 8 bits.

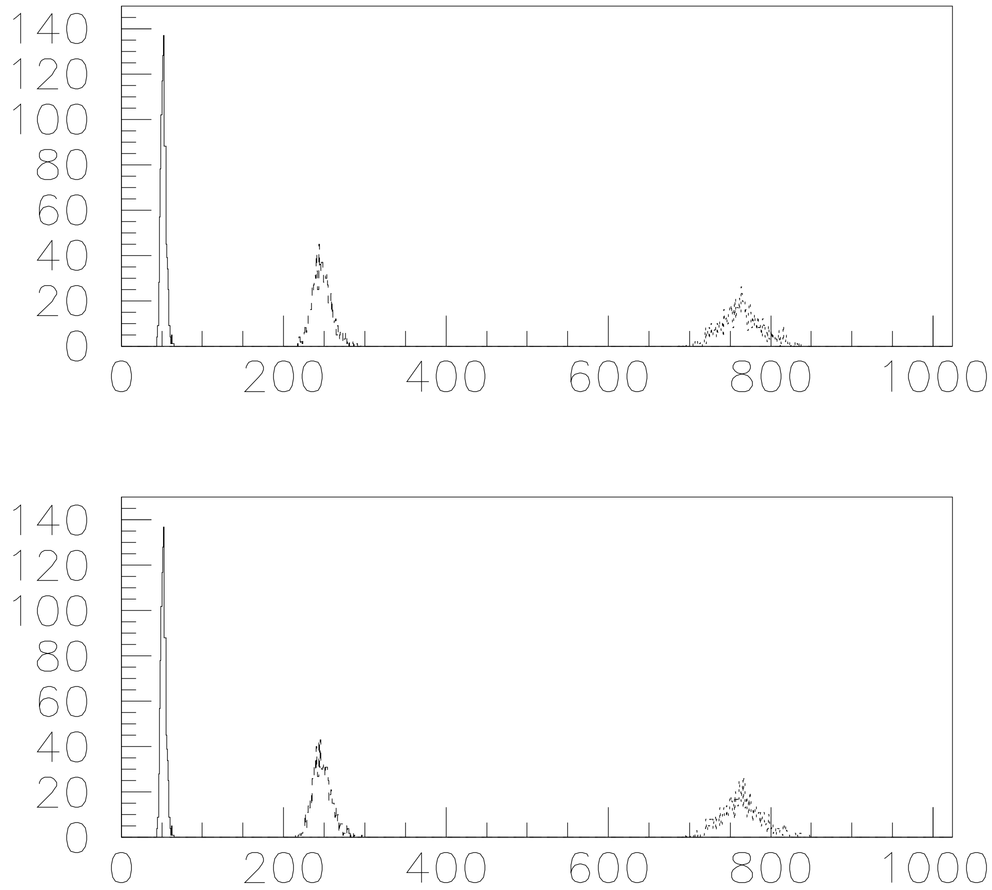

Figure 3: (a) Truncated means for 10-bit ADC's for the 200 MeV/c $\pi^{\pm}$, $K^{\pm}$ and p distributions in Fig. 1. The three smallest and ten largest ADC's were rejected from the average. (b) Distributions obtained when the ADC's are mapped onto 8 bits, then remapped to 10 bits.

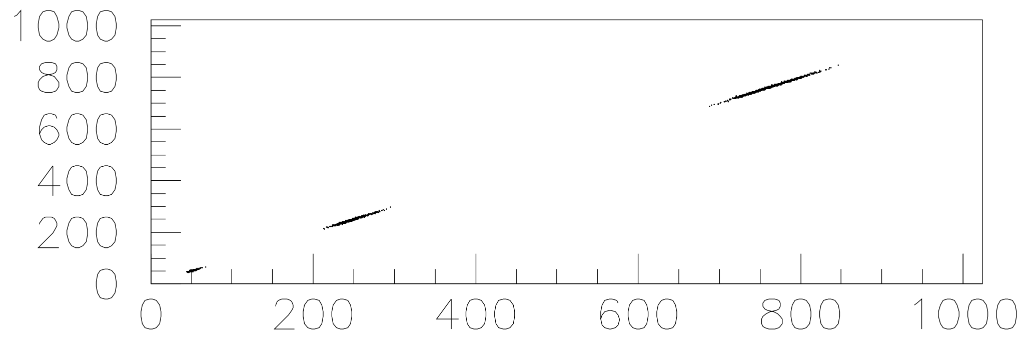

Figure 4: Truncated means calculated from 8-bit non-linear ADC's vs. those from the full, 10-bit ADC's for $\pi^{\pm}$'s, $K^{\pm}$'s and p's at 200 MeV/c in 2.30 cm of P10 gas.

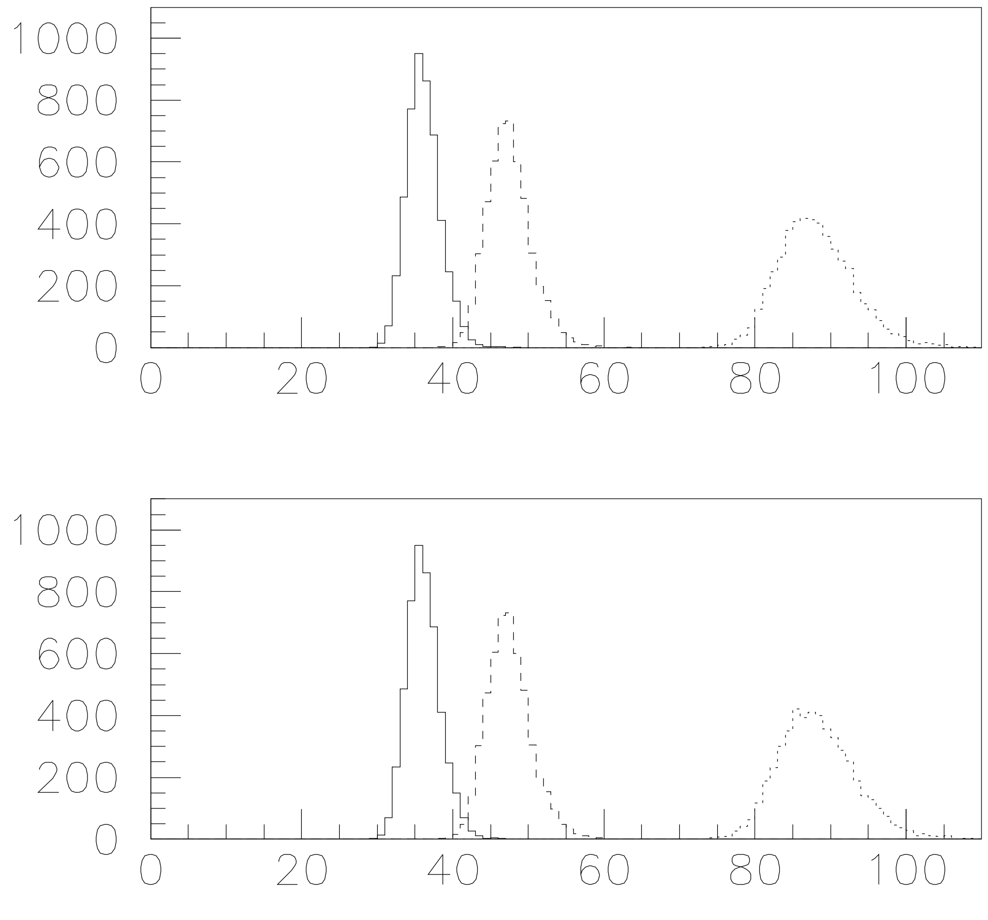

Figure 5: (a) Truncated means of 10-bit ADC's for 700 MeV/c $\pi^{\pm}$'s, $K^{\pm}$'s and p's. (b) Distributions obtained when the ADC's are mapped onto 8 bits, then back to 10 bits.

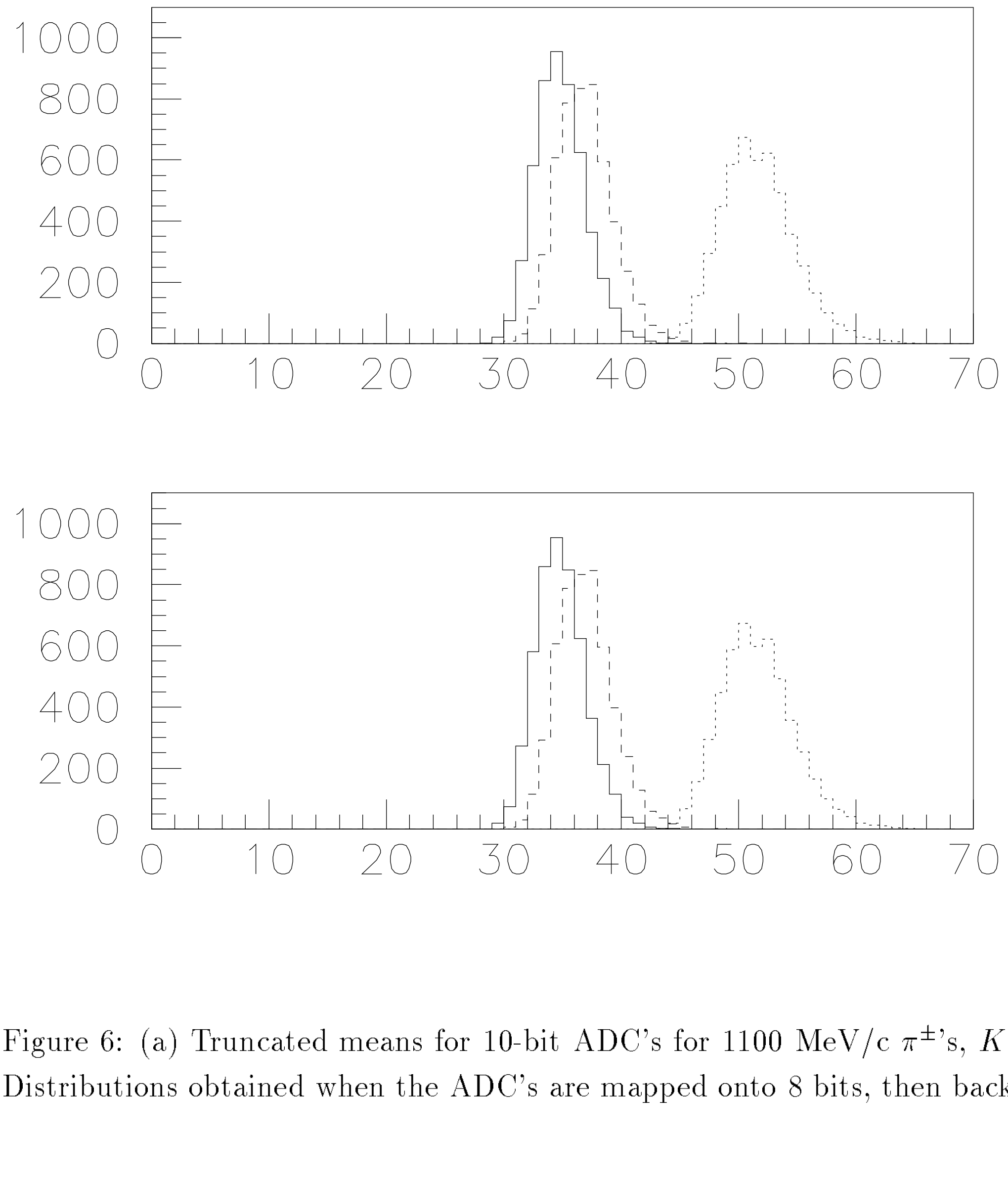

Figure 6: (a) Truncated means for 10-bit ADC's for 1100 MeV/c $\pi^{\pm}$'s, $K^{\pm}$'s and p's. (b) Distributions obtained when the ADC's are mapped onto 8 bits, then back to 10 bits.