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Test Beam Results for the CLAS Electromagnetic Calorimeter Prototypes at ITEP

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1 Introduction

JLab has developed a plan to increase the energy of the CEBAF accelerator to 12 GeV. Hall B is considering upgrades of the CLAS detector systems for operations at higher energies [1]. One of the proposals is to cover the inside of the torus coils with photon detectors. This Inner Electromagnetic Calorimeter (IECAL) has to operate in limited space (thickness $< 200\ mm$) and under stray magnetic fields up to 1 T. To study energy and spatial resolutions and to estimate cost, two promising options were chosen: SHASHLYK (tungsten/scintillator sandwich sampling calorimeter) and heavy $PbWO_4$ homogeneous (lead - tungstanate) crystals. As photodetectors insensitive to the magnetic field, Avalanche Photo Diodes (Hamamatsu and EG&G) were used.

An alternative way is to use PMT's located outside of the magnetic field, and to use transparent fibers with large attenuation length for the light transport.

At the beginning of this work, Russian Avalanche Photodiodes with a gain of $\sim$ 3000 and a 1 *mm* diameter sensitive window were tested. Nine APD's were optically connected with the wavelength shifting optical fibers of one SHASHLYK prototype tower and tested at the ITEP test beam. The noise level was very high. We didn't sense the beam, and didn't see any way to improve the APD quality in reasonable time, so this project was abandoned. In the future, Vacuum PhotoDiodes (VPD) will be tested.

2 Prototypes

1. For the SHASHLYK calorimeter prototype, tungsten plates and scintillator tiles from the HERA B inner ECAL [2] were used. The 25 channel prototype is made of a square cross section tower with side length of 112 *mm*. Active scintillator layers (thickness 2 *mm*) alternate with tungsten (thickness 2 *mm*) layers (Fig. 1,2 and photographs at http://www.jlab.org/$\sim$ pogorelk/). The tower is all being crossed by 225 wave shifting Bicron fibers with a length of 250 *mm* and a diameter of 1.2 *mm*. Nine wave shifting fibers were either connected to an APD, or each fiber was glued to a 3 m long transparent fiber to guide the light to a PMT. The total number of layers is 37 (21 radiation lengths).

2. For the $PbWO_4$ prototype, 25 crystals produced by the Bogorodisk plant in Russia with dimensions 22x22x160 *mm* (18 radiation lengths)

were used. An Al box was fabricated for tests (See Fig. 3–5, and photographs at http://www.jlab.org/∼ pogorelk/). Three cooling panels can be used to stabilize the temperature inside the box. Each crystal is wrapped with Al foil of thickness 0.1 *mm*. APD's (Hamamatsu or EG&G) were used as photodetectors.

3 Beam

For testing, a 0.75–4 GeV secondary electron beam produced by 8 GeV protons from an internal target of the ITEP synchrotron (Fig. 6) was used. For a 3 GeV secondary beam, the e/π ratio was 6%. Scintillator counters S1-S2-S3-S4 were used for the trigger, a Cherenkov counter was used for π^- rejection, a small 5x5 mm^2 S3 counter was installed very close (5 *cm*) to the calorimeter, the S4 counter behind the calorimeter improved the signal from Minimum Ionizing Particle (*mip*). All alignments were done with a laser.

4 Electronics

An APD converts visible light photons into an electrical charge. A photon is converted in an electron-hole pair, the electron is accelerated in the high electric field with multiplication, and then the "cloud" drifts into a region of intrinsic silicon and is finally collected. In these silicon sensors the conversion layer($\sim 2\mu m$ thick) is followed by a high electric field region (6 μm) where the photoelectrons are accelerated and multiplied with a gain of about 50-200. High stability in the applied voltage and low temperature dependence of the gain are required for stable operating conditions. The maximum size of suitable APD's available at present is about 5x5 mm^2. It is 5.6% of the surface of the crystal, so two APD's can be used per crystal to decrease the contribution of the photostatistics to the stochastic term. Two companies produce APD's which match well the $PbWO_4$ emission spectrum: Hamamatsu and EG&G. The main characteristics of both APD's are very close [3].

The signals from the APD went into a fast, low-noise Russian preamplifiers Garantiya. The preamplifier output was connected to the input of the main amplifier to fully utilize the dynamic range of the ADC. LeCroy CAMAC 2249A ADC modules were used in the readout setup. The charge integrating ADC's have 12 inputs with 10 bit range (0.25 pC per channel).

5 Monte-Carlo simulations

For the simulation, the 3 GeV π^- and e^- beam and 2 GeV proton beam with $\sigma_p/p = 2\%$, size 5x5 mm^2 were used.

Results of the GEANT simulations for a single $PbWO_4$ crystal with 2 inch photocathode PMT readout, surrounded by 25 mm thickness tungsten bricks for 3 GeV electrons and π^- are presented in Fig. 7 (a,c) for energy deposition and (b,d) for photostatistics. The GEANT simulations for 2 GeV protons are shown in Fig. 8 (a,b). A light yield of 100 photons per MeV was used for $PbWO_4$ crystals. Similar results for one APD (5x5 mm^2 window) are shown in Fig. 9 (a–d).

The SHASHLYK energy depositions for the central tower (20x20 mm^2) are shown in Fig. 8 (c,d) for 3 GeV pions and electrons.

The detailed light guide simulation for the SHASHLYK is not complete at the present time. The number of photoelectrons from one tower for 3 GeV electrons is of order of 100.

6 Data taking

During the period from January 2000 till July 2000, three 3–week runs for different calorimeters and photodetectors (see http://www.jlab.org/∼pogorelk/) were executed, and 220 data files were recorded. Beam conditions, backgrouns, scintillators tiles for SHASHLYK, PMT's, preamplifiers, pedestals, grounding conditions and so on were studied. Unfortunately, we had only one APD(Hamamatsu), 11 APD(EG&G), and had no PMT's with a diameter of less than 20 mm to study the 5x5 matrix of crystals. Therefore, single crystals and the central SHASHLYK tower were studied to select more promising photodetectors.

7 Test results

The main test results for the two prototypes with different photodetectors obtained with 3 GeV π^- and 2 GeV protons are shown in Table 1. Measured and the GEANT simulated energy resolutions for single tower readout for different prototypes and photodetectors are shown in Table 2.

7.1 $PbWO_4$

Figure 10 shows fitted ADC spectra for a single $PbWO_4$ crystal surrounded by 25 mm thickness tungsten bricks. Data were taken with a 3 GeV π^- beam. A Hamamatsu PMT with a 2" photocathode was used as a photodetector. The narrow signal from mip (π^-) and the signal from electrons provide the possibility to measure the energy resolution of a single $PbWO_4$ crystal. The energy deposition from mip based on the GEANT simulation is 192 MeV for 3 GeV π^-, and 170 MeV for 2 GeV protons. The energy resolution σ_E/E of the $PbWO_4$ crystal can be estimated from the fitted Gaussian width, and the mean of the mip and electron energy deposition. The test results are shown in Fig. 11(a,b). The same measurements were done with an APD(Hamamatsu). Test results are shown in Fig. 12. The energy resolution can be approximated by equation:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus b \oplus \frac{c}{E} \tag{1}$$

where E is the energy in GeV, $\frac{\sigma}{E}$ is the energy resolution, a is the stochastic term - mainly governed by photostatistics and sampling fluctuations, b is the constant term – mainly from shower containment limitations and calorimeter non-uniformities, c is the noise term. We have estimated the noise term c in the energy resolution from fits to the pedestal, mip and electron signals as 36 MeV. In practice, the observed energy equivalent noise of a sum of nine channels will be 3 times higher $\sim$ 100 MeV.

The test results for a single crystal with PMT, APD(Hamamatsu) and APD(EG&G) with a 2 GeV protons with mip counter $S4$ after additional alignments of the beam and APD's preamlifier improvements are presented in Fig. 11.

All 25 $PbWO_4$ crystals were tested with a 2 GeV proton beam. The ADC spectra were fitted to a Gaussian. The average mip signal, $\sigma(mip)$, $\sigma(mip)/mip$ and $\sigma(mip)/mip{*}\sqrt{0.170}$ are shown in Fig. 13. The distributions of mip , $\sigma(mip)$ and $\sigma(mip)/mip$ for 25 crystals are shown in Fig. 15. The last one characterizes the difference in energy resolution of 25 crystals as 12%.

7.2 SHASHLYK

Two types of photodetectors were used for the SHASHLYK option:

1. Nine wave shifting fibers transported the light to an APD.
2. Each wave shifting fiber was connected via a 3 m transparent fiber to a light guide and then to a PMT.

Fitted ADC spectra for the photodetectors PMT, APD(Hamamatsu) and APD (EG&G) are presented in Fig. 14.

8 Conclusions

1. SHASHLYK calorimeter can be used for the Inner Electromagnetic Calorimeter CLAS upgrade. APD's and transparent fibers with PMT's can be used as photodetectors. An energy resolution $\sigma_E/E = 10\%$ can be reached for 3 GeV electrons.
2. An energy resolution $\sigma_E/E = 5\%$ is obtained for 3 GeV electrons with a single $PbWO_4$ crystal and APD readout. This result is close to the GEANT simulation of 4.5%. The noise term c is 36 MeV.
3. Results presented in Fig.13 and 15 demonstrate the energy resolution of 25 Bogorodisk crystals. The difference in energy resolution is 12%.
4. The cost of $PbWO_4$ crystal is 3 times higher than for a SHASHLYK tower with the same dimensions (the cost of photodetector and electronics is not included).
5. The ITEP test beams can be used for CLAS ECAL upgrade studies.

We have only started the tests of the prototypes, and mostly used only one channel in a 5x5 matrix for the SHASHLYK and $PbWO_4$ prototypes. We are planning to use 25 Philips 1911 PMT's for the crystal calorimeter calibrations, and 50 APD (Hamamatsu) for full tests of $PbWO_4$ prototypes with the temperature stabilized at 16 C^0, and gain monitoring by 25 LED.

Table 1: Pedestals, MIP and Electron signals in ADC units

Run	Prototype	Photodetector	Beam		Pedestal	MIP	Electron
604	$PbWO_4$	PMT	$\pi^-, 3\ GeV$		18.4	81.8	795.5
				σ	0.6	5.4	34.1
619,622	$PbWO_4$	APD(H)			21.4	49.53	551.3
				σ	4.2	5.3	28.3
623			$\hat{C}$		21.4		555.7
				σ	4.2		26.7
655,646	$PbWO_4$	PMT	$p, 2\ GeV$		21.0	48.7	
				σ	1.0	3.0	
625,626	$PbWO_4$	APD(H)	$p, 2\ GeV$		19.9	47.2	
				σ	5.7	7.0	
627			$+mip$		19.9	60.1	
				σ	5.7	9.5	
628					19.9	52.7	
				σ	5.7	4.4	
629,630					20.5	45.42	
				σ	5.4	12.8	
631,632	$PbWO_4$	APD(EG)	$p, 2\ GeV$		18.8	237.7	
				σ	5.8	80.9	
633			$+mip$		18.8	229.6	
				σ	5.8	70.9	
607	Shashlyk	PMT-9	$\hat{C}$		32.3		909.0
				σ	2.0		91.6
608			$\pi^-, 3\ GeV$		32.3	98.7	912.9
				σ	2.0	16.3	81.8
612,614	Shashlyk	APD(H)	$\pi^-, 3\ GeV$		10.0		830.0
				σ	10.0		94.0
613			$\hat{C}$		10.0		850.9
				σ	10.0		102.0
616,617	Shashlyk	APD(EG)			277.3	333.1	944.2
				σ	19.2	27.1	78.1
618			$\hat{C}$				960.9
				σ			76.0

Table 2: Energy resolution for the different prototypes. Beam: $\pi^-, 3\ GeV$, (5.5% electrons). $\frac{\sigma}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus b \oplus \frac{c}{E}$

Prototype	Photodetector	σ/E	GEANT σ/E	Noise c
$PbWO_4$	PMT	4.40 ± 0.05 %	3.7 %	2 MeV
	APD(H)	5.0 ± 0.5 %	4.5 %	36 MeV
Shashlyk	PMT-9	9.3 ± 1.2 %	7.3 % (No	6 MeV
	APD(H)	12.1 ± 0.4 %	Photostatistics	30 MeV
	APD(EG)	11.1 ± 0.6 %	Included)	70 MeV

References

[1] Upgrading CLAS to higher energy. Draft 1- June-2000

[2] A. Zoccoli. The electromagnetic calorimeter of the HERA-B experiment. NIM in Physics Research A 446 (2000) p. 246-252

[3] E. Longo. Avalanche Photodiodes for the CMS Electromagnetic Calorimeter. CMS CR 1998/002

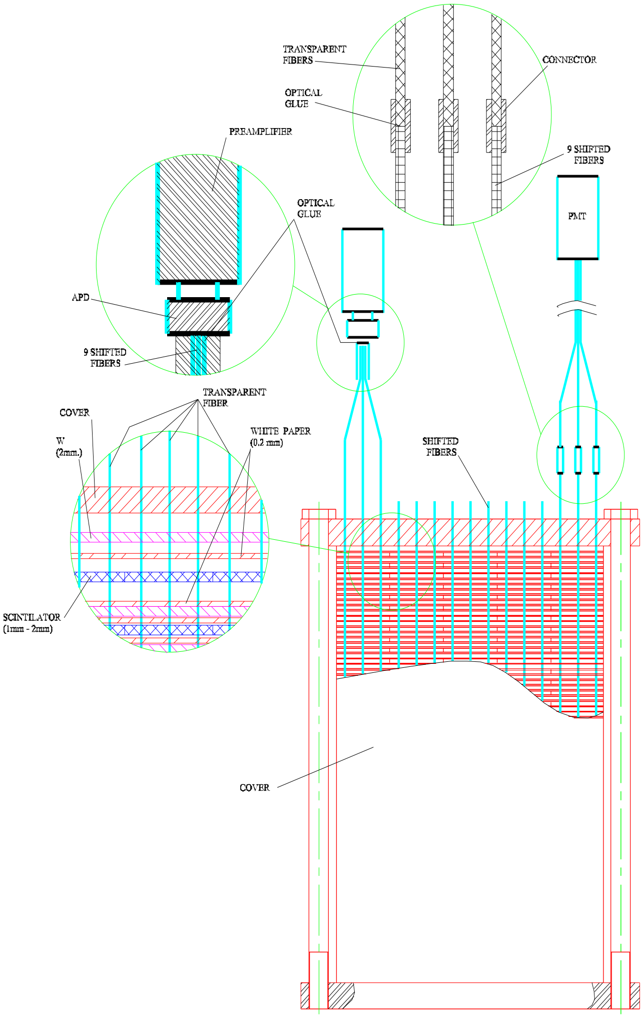


Figure 1: Shashlyk prototype drawing

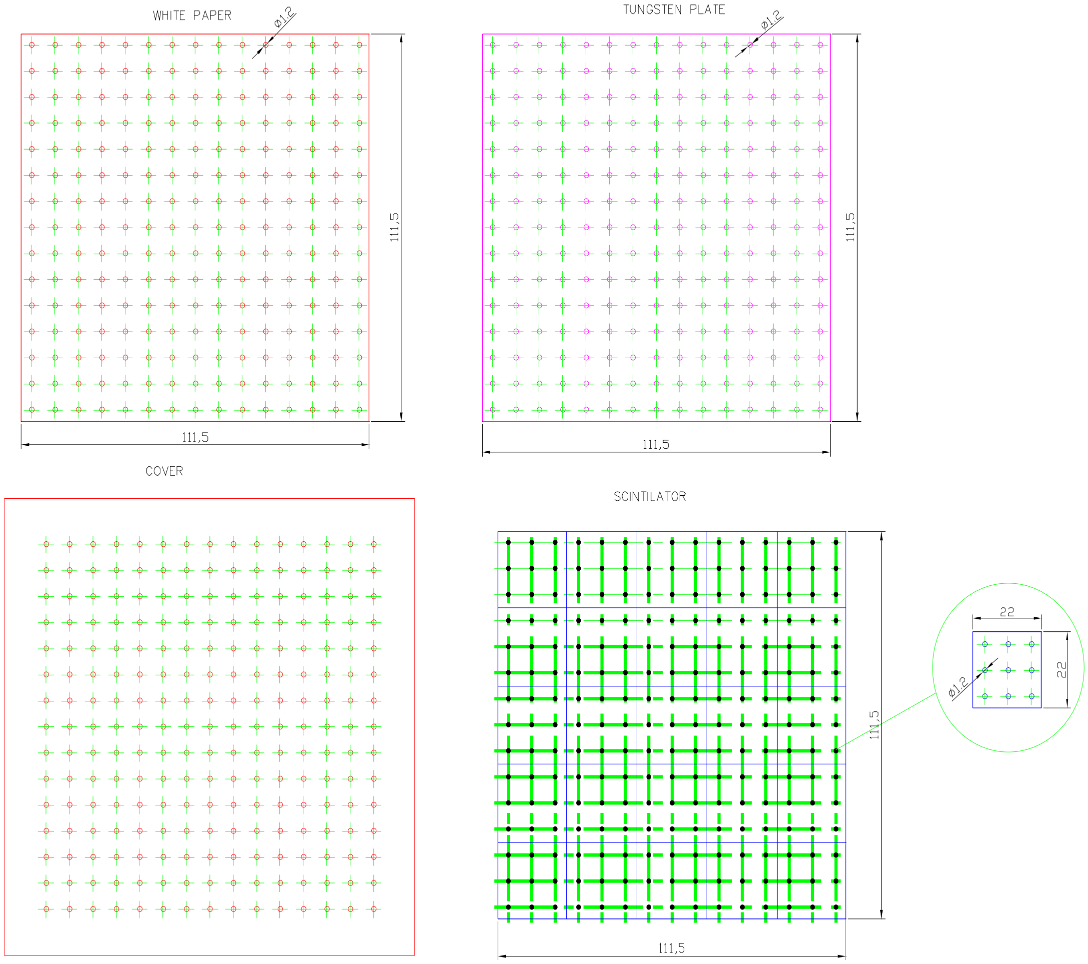


Figure 2: Shashlyk prototype drawing

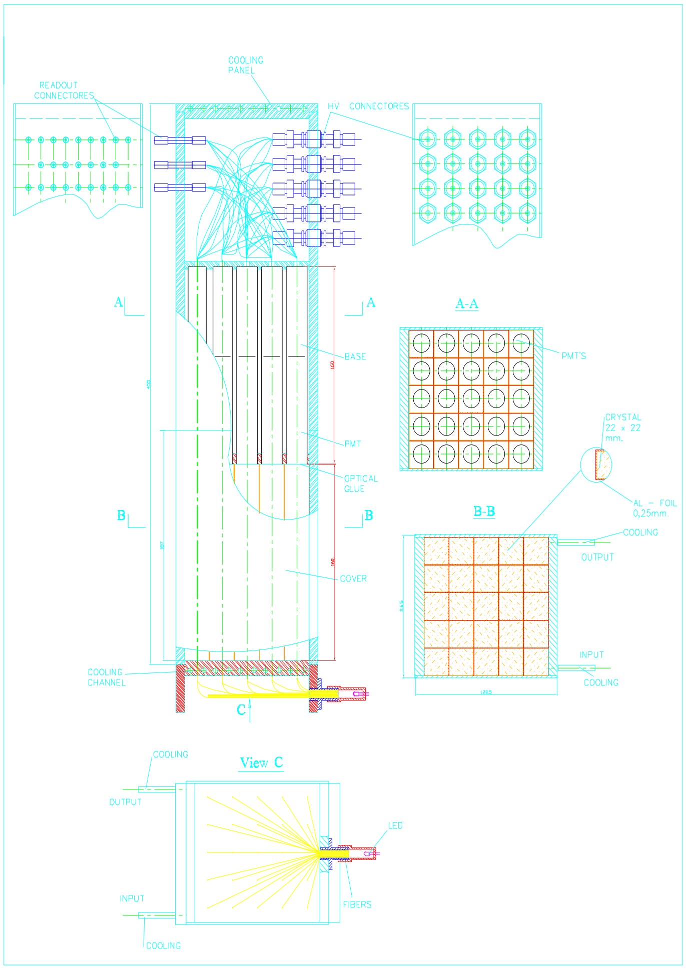


Figure 3: $PbWO_4$ prototype drawing

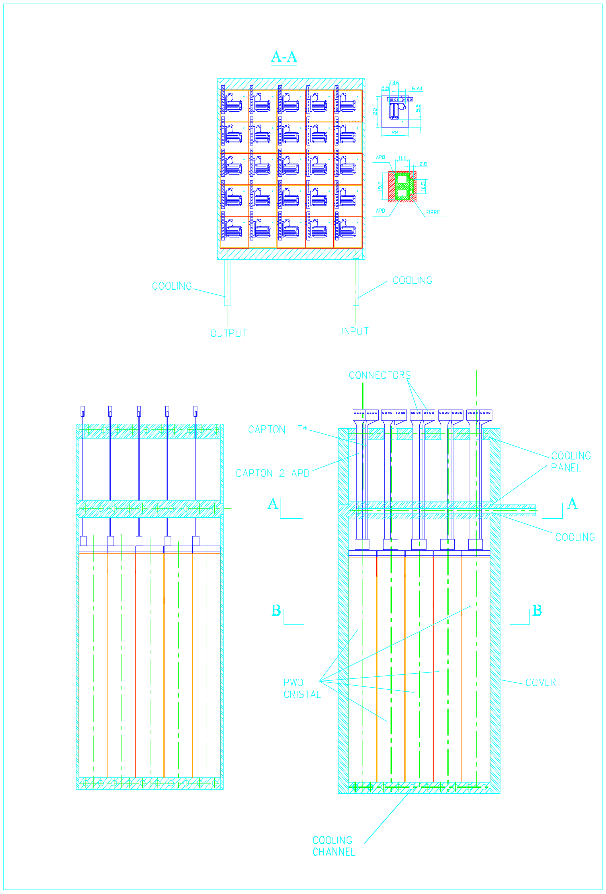


Figure 4: $PbWO_4$ prototype drawing

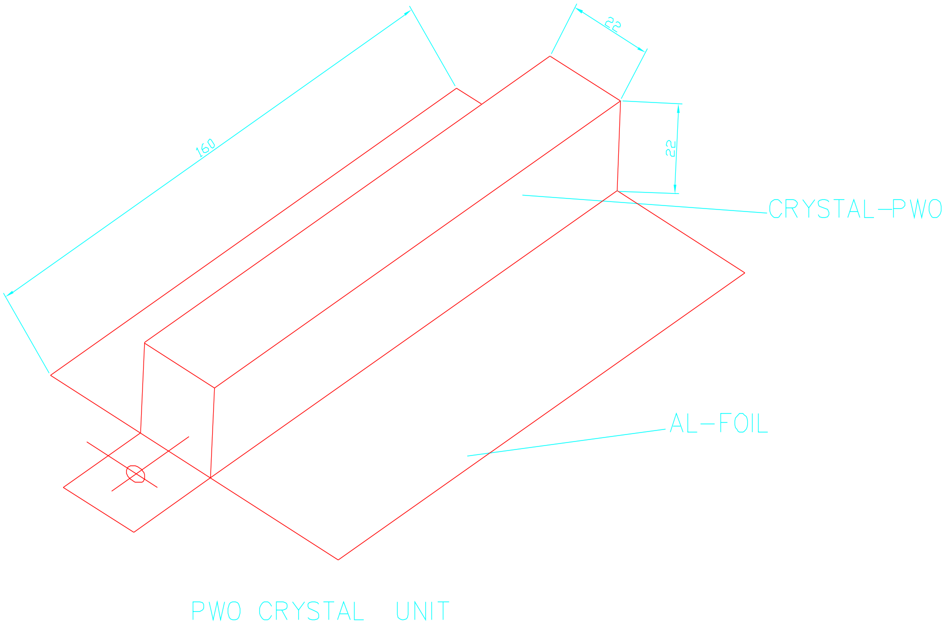


Figure 5: $PbWO_4$ prototype drawing

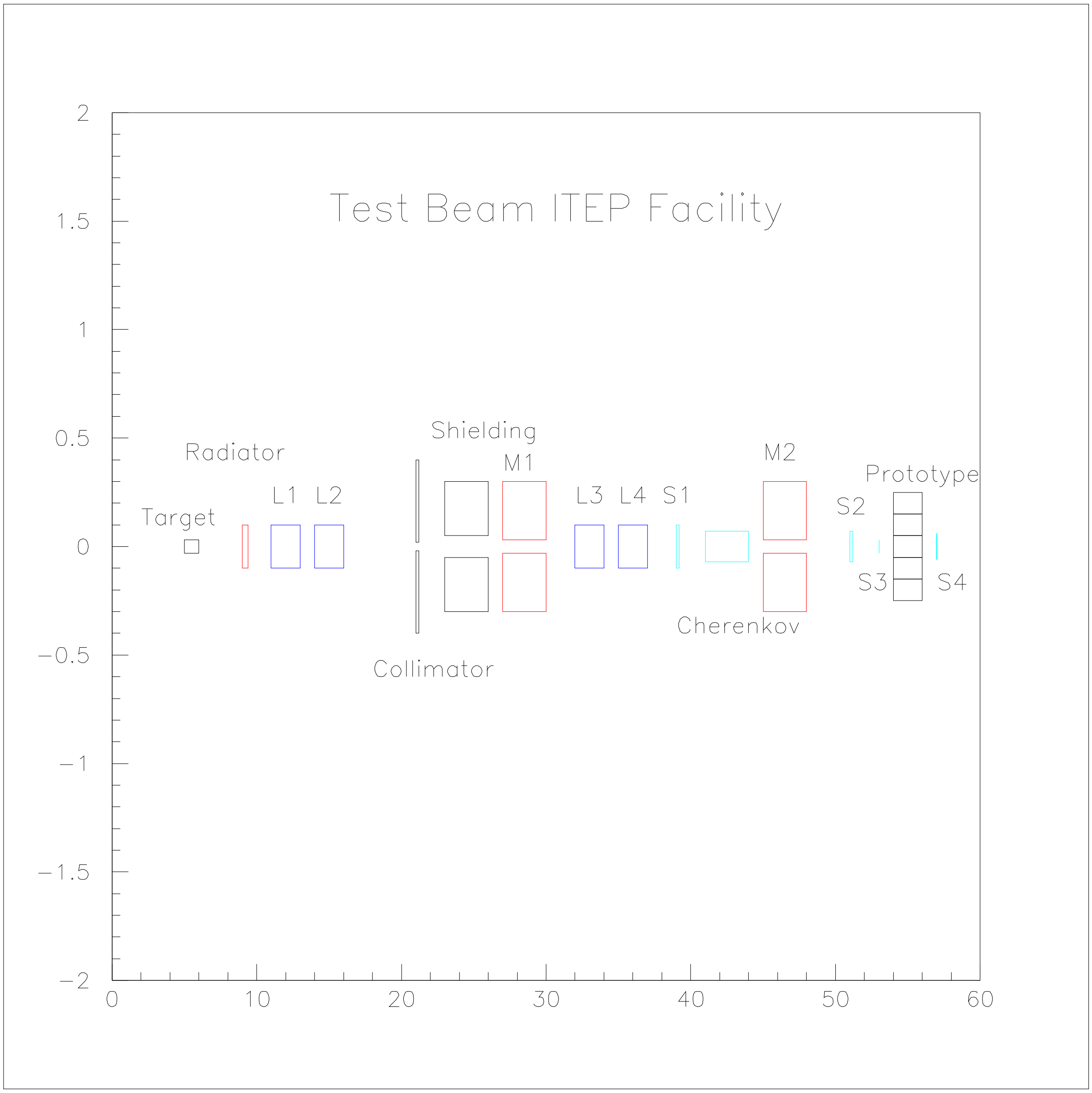


Figure 6: Test beam ITEP facility. L1-L2, L3-L4 lenses, M1-M2 magnets, S1-S4 scintillator counters.

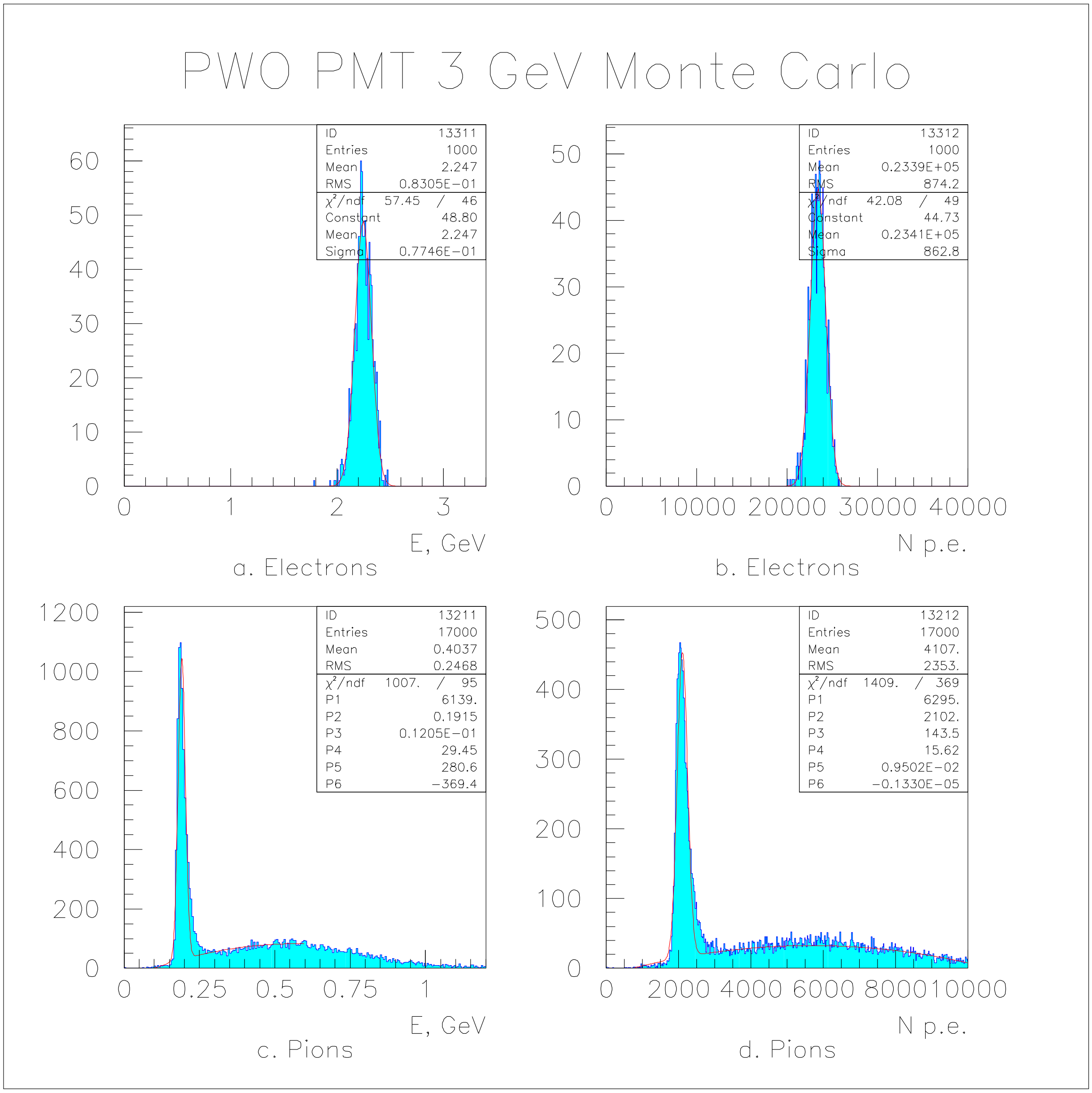
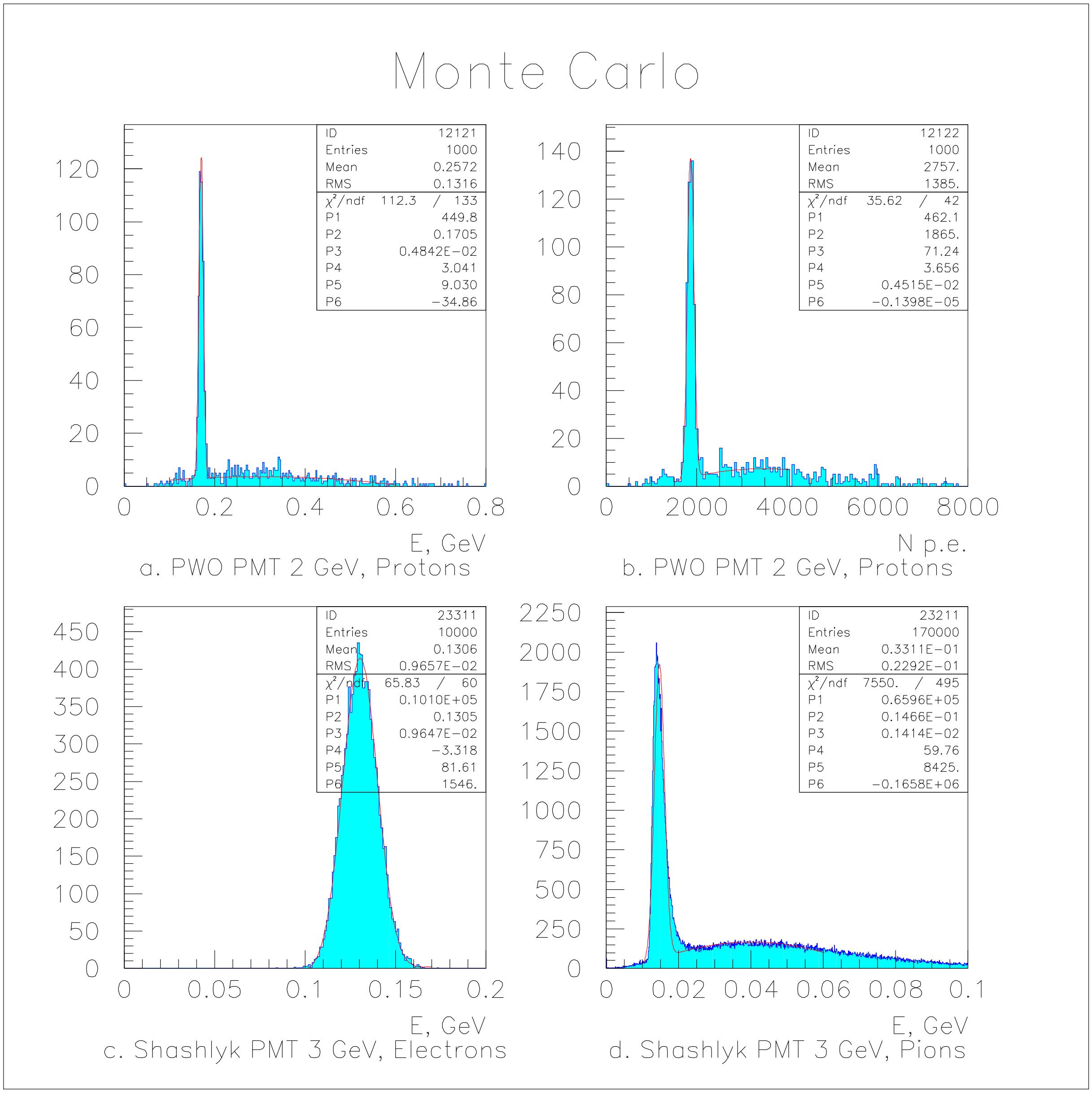


Figure 7: $PbWO_4$, PMT, 3 GeV Electrons(a. and b.) and Pions(c. and d.)



a. PWO PMT 2 GeV, Protons

b. PWO PMT 2 GeV, Protons

c. Shashlyk PMT 3 GeV, Electrons

d. Shashlyk PMT 3 GeV, Pions

Figure 8: $PbWO_4$, PMT, 2 GeV Protons(a. and b.) Shashlyk, PMT, 3 GeV Electrons(c.) and Pions(d.)

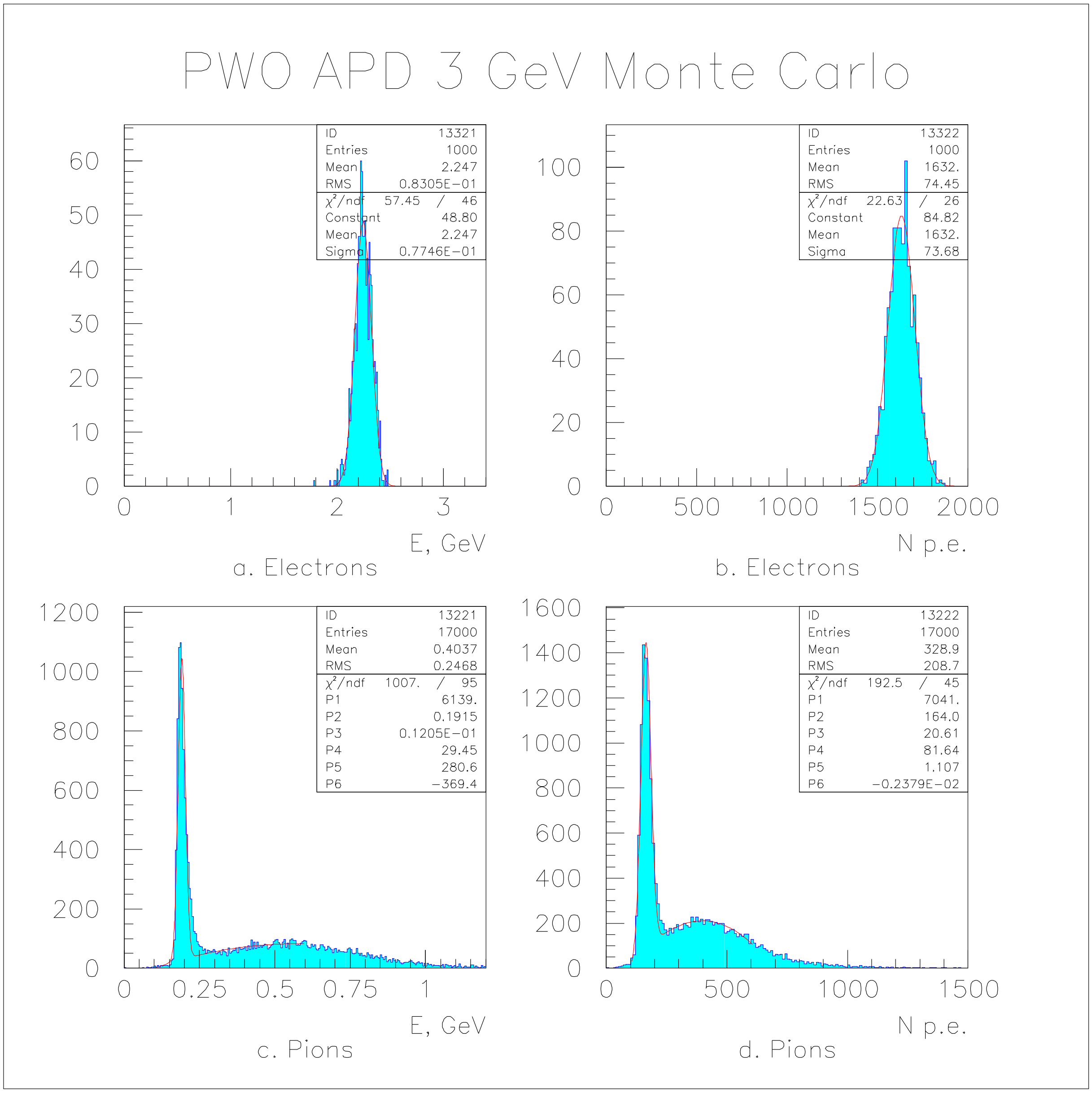


Figure 9: $PbWO_4$, APD, 3 GeV Electrons(a. and b.) and Pions(c. and d.)

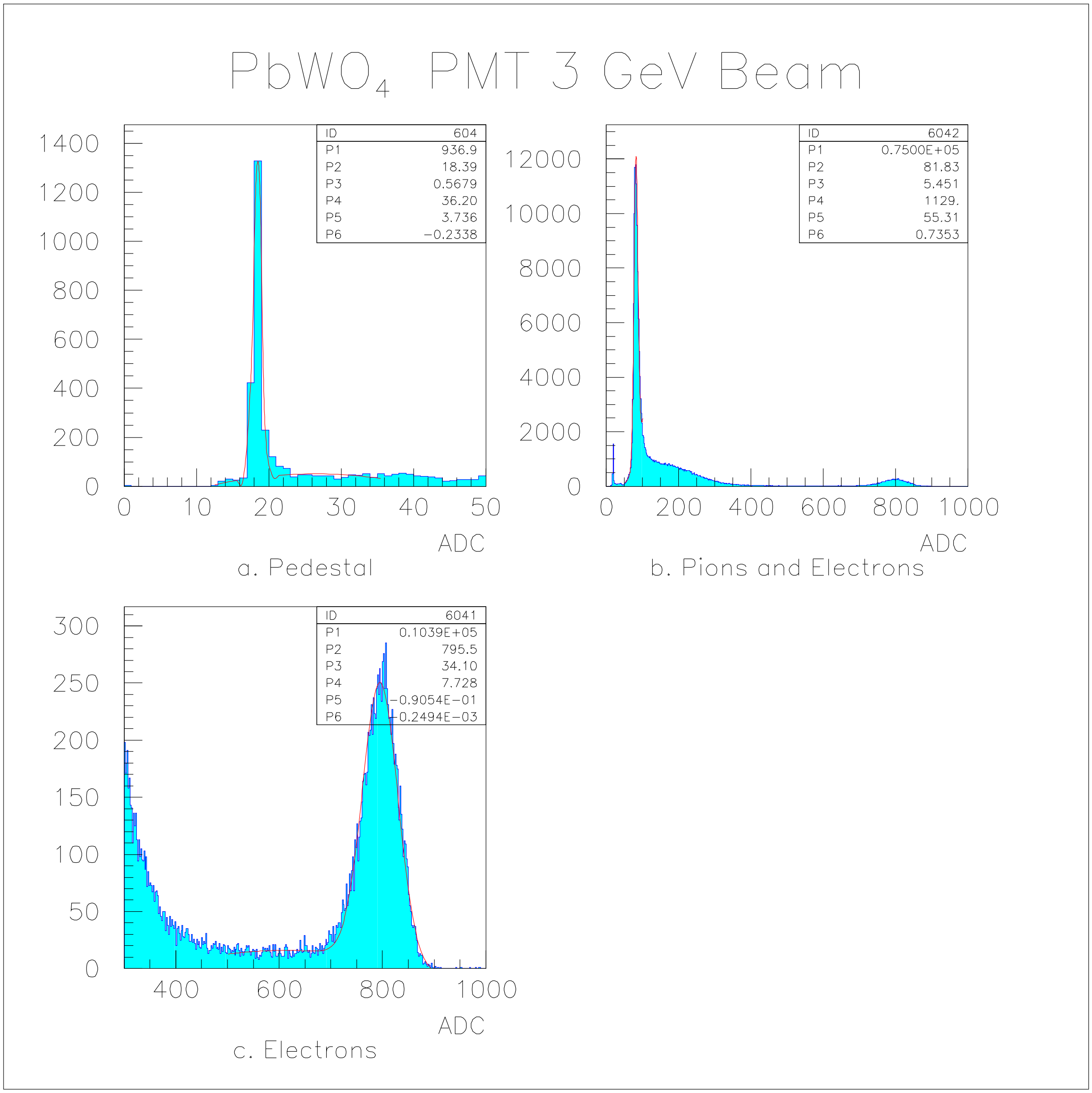


Figure 10: $PbWO_4$, PMT, 3 GeV Beam

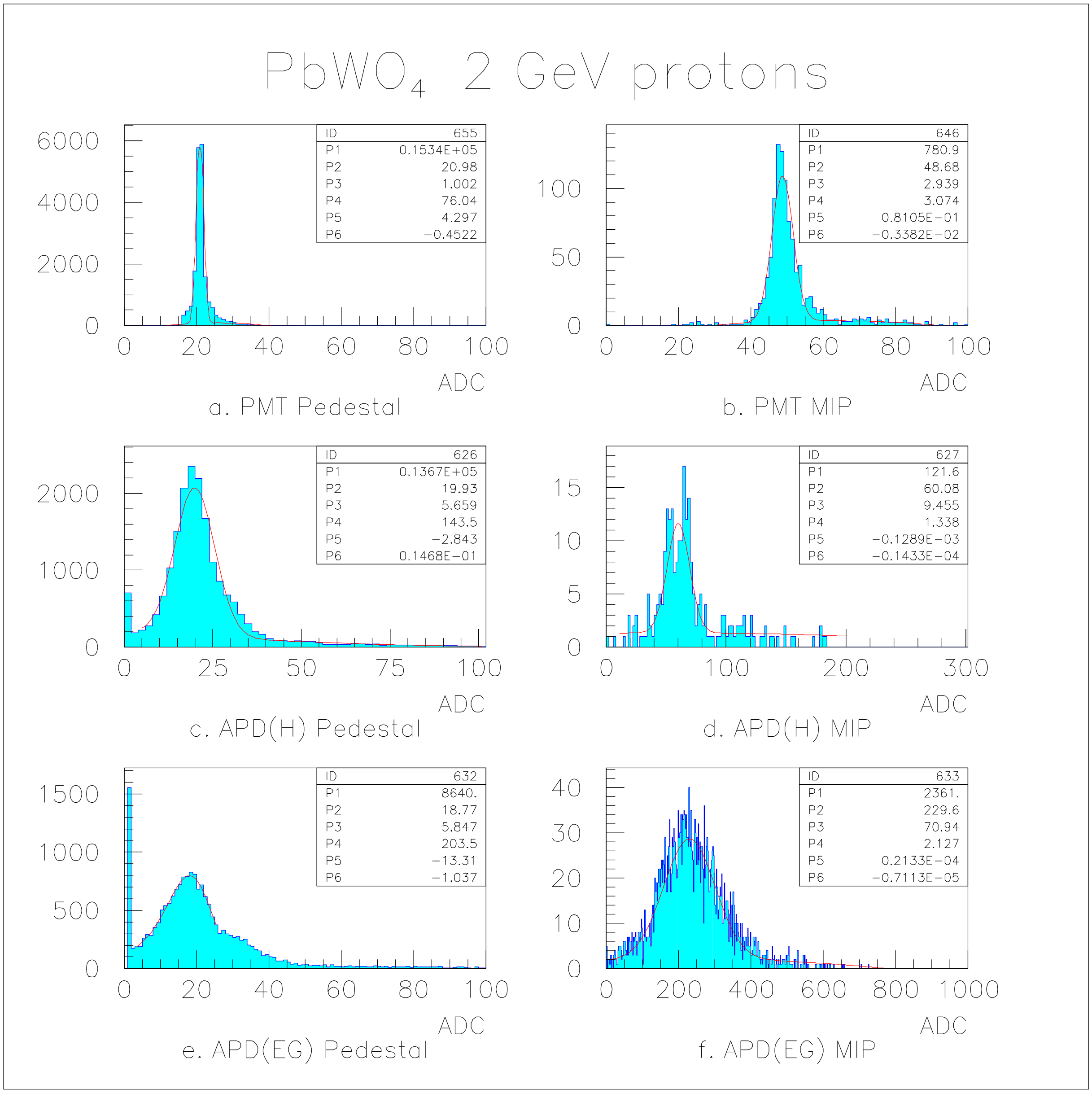
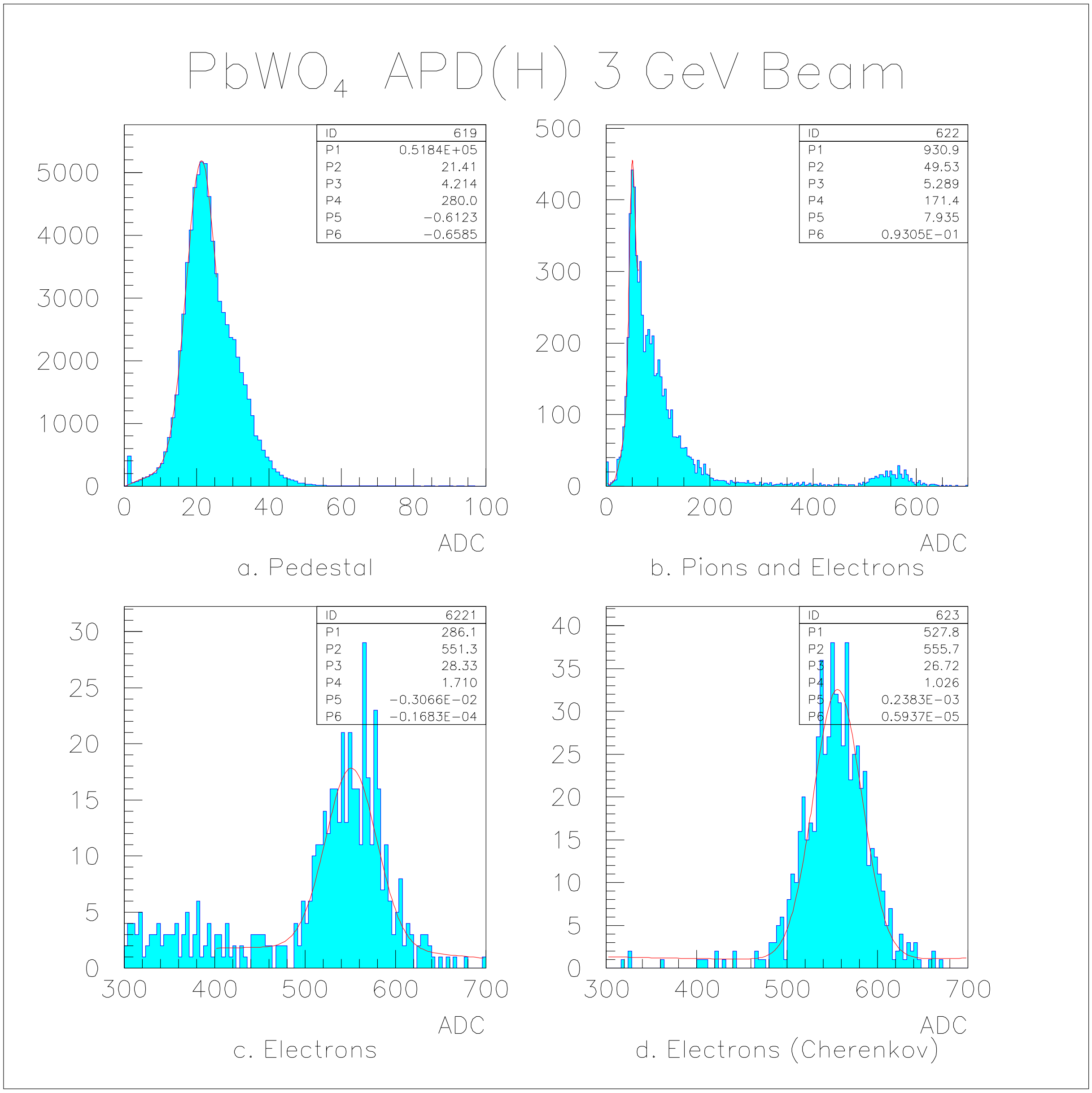


Figure 11: $PbWO_4$, 2 GeV protons



a. Pedestal

b. Pions and Electrons

c. Electrons

d. Electrons (Cherenkov)

Figure 12: $PbWO_4$, APD(H), 3 GeV Beam

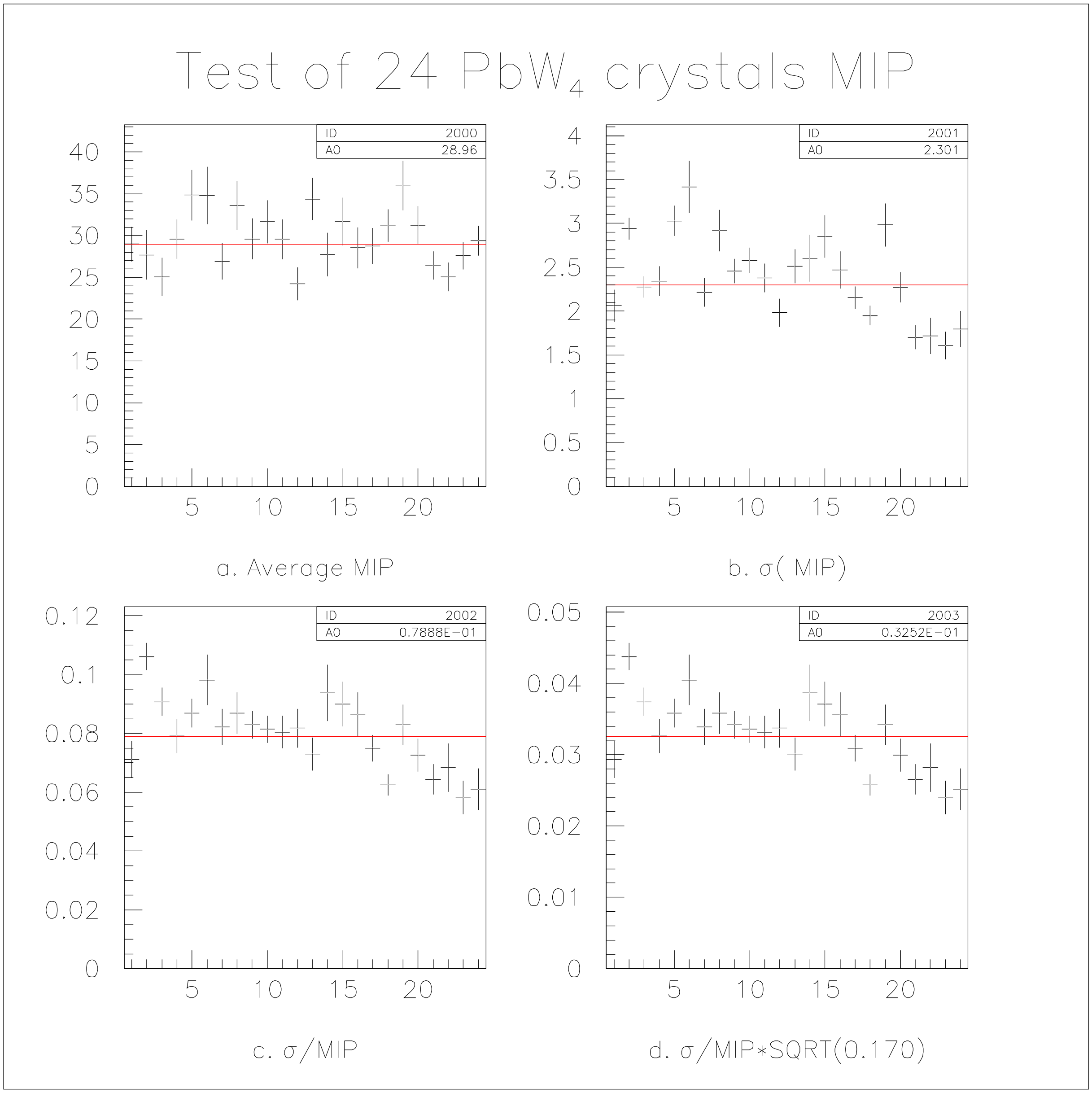


Figure 13: Test of 24 $PbWO_4$ crystals MIP

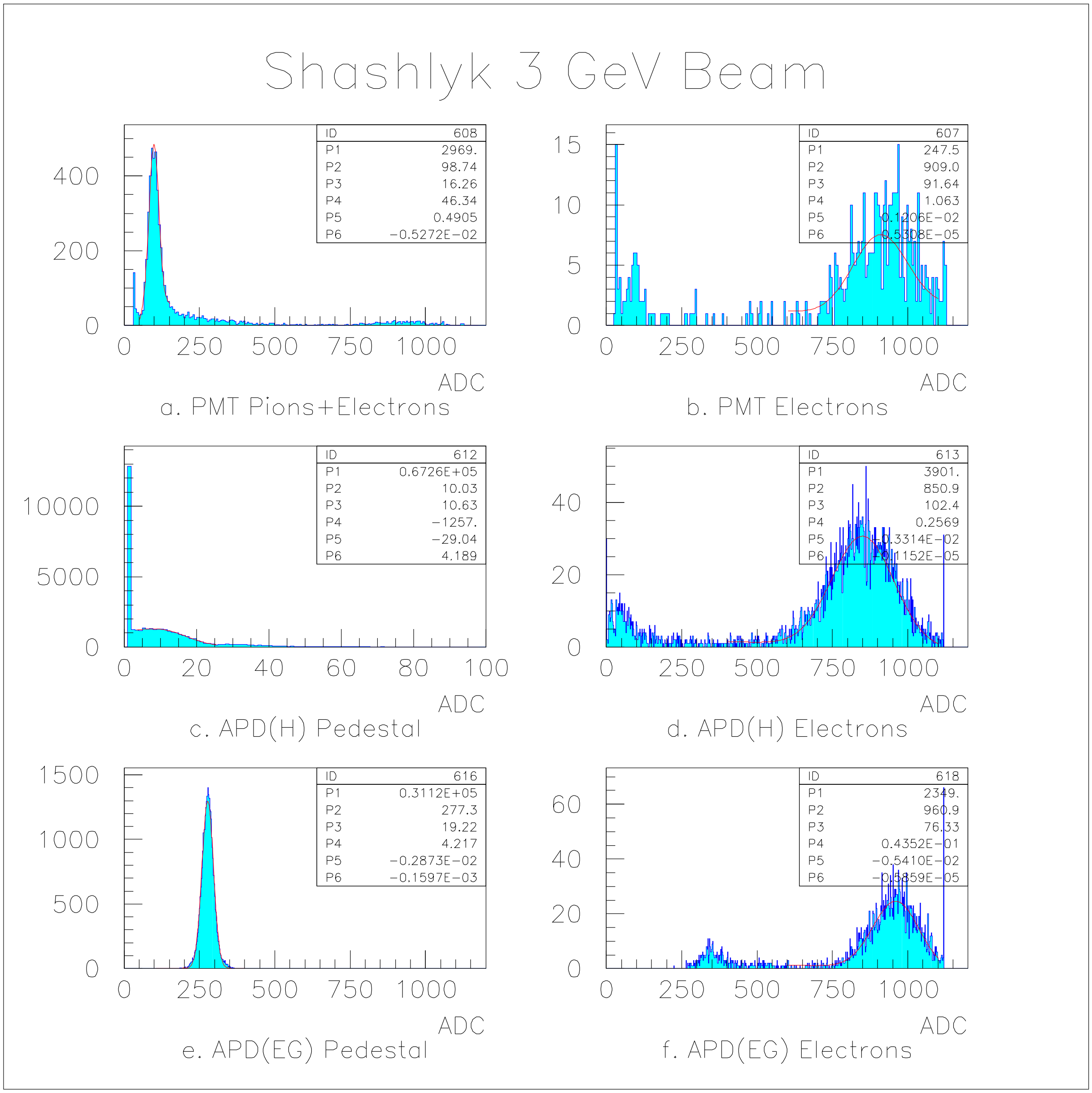


Figure 14: Shashlyk, 3 GeV Beam

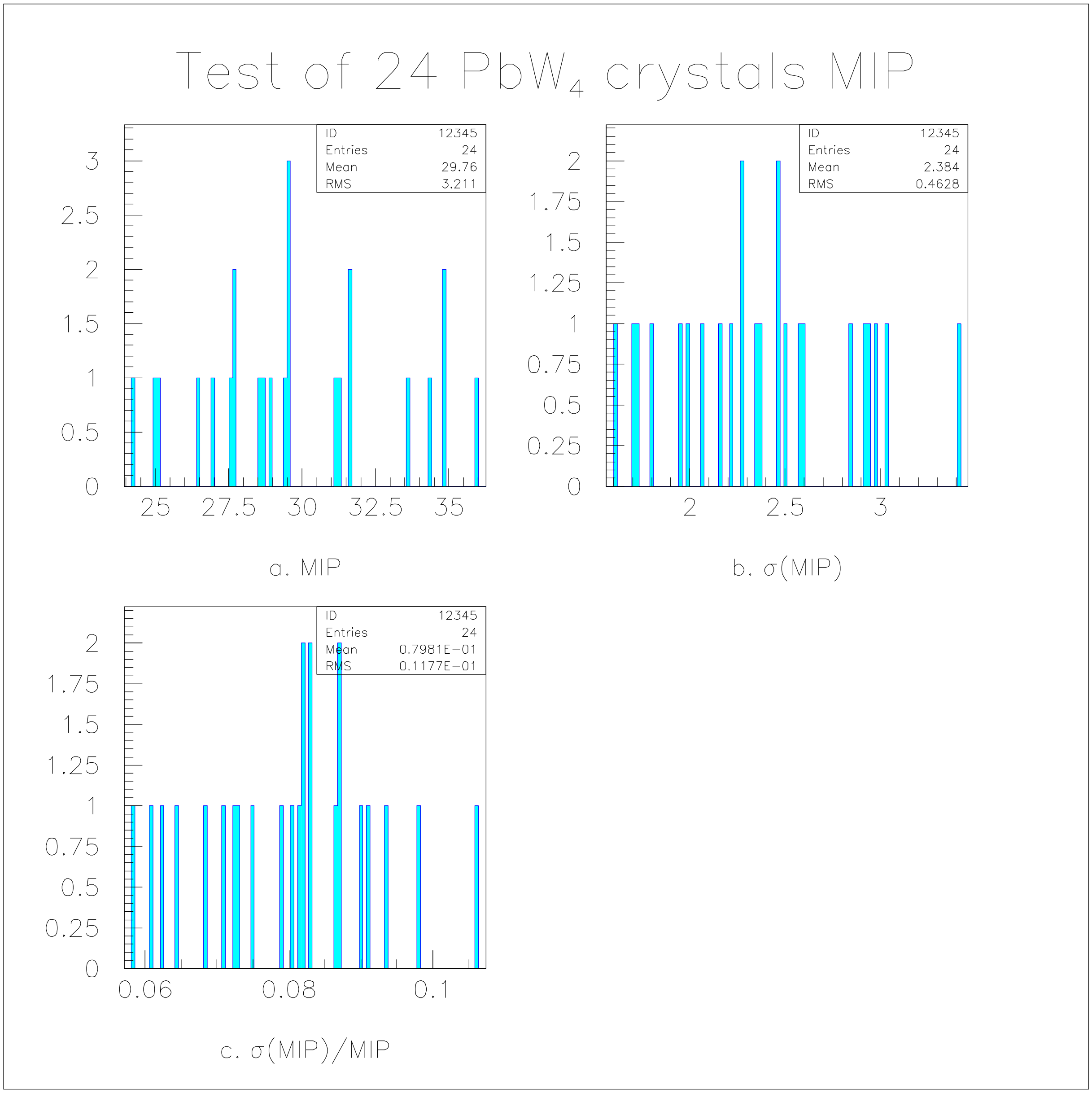


Figure 15: Test of 24 $PbWO_4$ crystals MIP