The Use of WLS Fibers in a Hadronic Calorimeter for the FNAL E871 Experiment

Casey Durandet
(For the E871 Fermilab Experiment)

<u>Abstract:</u> We present preliminary results of E871 from the recent Fermilab Fixed Target run on the operational aspects of the iron-scintillator sampling hadronic calorimeter which used wavelength-shifter fibers for light collection from scintillator sheets. Details of how the 2 m$\times$2 mm Bicron BCF-92 fibers were polished, sputtered, and used for the readout will be discussed. The average reflectivity of fibers with sputtered ends was 87%, and an attenuation length of 3 meters was measured. The calorimeter energy resolution of $\sigma/E = 117\%/\sqrt{E}$ was obtained.

The Fermilab E871 Hadronic Calorimeter

Casey Durandet
(For the E871 Fermilab Experiment)

Abstract: **We present preliminary results from the recent Fermilab Fixed Target run on the operational aspects of the E871 iron-scintillator hadronic calorimeter which used wavelength-shifter fibers for light collection from scintillating sheets. The main purpose of the calorimeter was to serve as a muon-blind component to a particle-multiplicity trigger, thus reducing the trigger rate due to background muons. The fibers had end-sputtered surfaces with average reflectivity of 87% and attenuation lengths of 3 meters. An energy resolution of** $\sigma/E = 117\%/\sqrt{E}$ **was obtained.**

E871 Experimental Goals

After 30 years of experimental effort, the origin of CP violation remains unknown. In particular, despite an impressive amount of experimental effort:

1. **No experiment has seen CP violation outside of the K_L system.**
2. **There is no compelling evidence for direct CP violation.**

Primary goal of HyperCP is to look for direct CP violation in non-leptonic decays of the Ξ and Λ hyperons,

$$\Xi^- \rightarrow \Lambda^\circ \pi^-, \; \Lambda^\circ \rightarrow p \pi^-$$

$$\overline{\Xi}^+ \rightarrow \overline{\Lambda}^\circ \pi^+, \; \overline{\Lambda}^\circ \rightarrow \overline{p} \pi^+$$

This will allow us to probe CP violation two orders of magnitude beyond the current limit, to about 2 $\times$ 10^{-4}.

The measurement is performed by studying the difference in the angular distributions between the hyperon and the anti-hyperon decays. Any difference between these distributions along the helicity axis is evidence of CP violation.

What Do We Really Measure?

If CP is good, the $cos(\theta)$ slopes of the p and $\overline{p}$ are identical:

$$\alpha_{\Xi}\alpha_{\Lambda} = \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}$$

If CP is violated in Ξ decays, then we do not produce Λ's and $\overline{\Lambda}$'s with identical polarization:

$$|\vec{P}_{\Lambda}| = \alpha_{\Xi} \neq \alpha_{\overline{\Xi}} = |\vec{P}_{\overline{\Lambda}}|$$

That is, we are sensitive to CP violation in both Ξ and Λ decays:

$$A_{\Xi\Lambda} = \frac{\alpha_{\Xi}\alpha_{\Lambda} - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}}{\alpha_{\Xi}\alpha_{\Lambda} + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}},$$

where

$$A_{\Xi} = \frac{\alpha_{\Xi} + \alpha_{\overline{\Xi}}}{\alpha_{\Xi} - \alpha_{\overline{\Xi}}},$$

$$A_{\Lambda} = \frac{\alpha_{\Lambda} + \alpha_{\overline{\Lambda}}}{\alpha_{\Lambda} - \alpha_{\overline{\Lambda}}}$$

Hadronic Calorimeter

1. **Designed to provide a muon-blind component to the proton and anti-proton trigger.**

2. **Reduces trigger rate due to interactions in spectrometer material, due to background muons.**

3. **Requirements:**

   (a) **Must be fast: expect $>$ 100 kHz hadronic flux.**

   (b) **Hadronic energy resolution:** $\sigma/E = 117\%/\sqrt{E}$.

   (c) **Position resolution: not necessary.**

   (d) **Calibration: must be maintained in real time.**

   (e) **Must be able to see muons.**

Calorimeter Properties

1. **64-layered sampling device, each layer consisting of:**
   (a) **2.4 cm Fe.**
   (b) **0.5 cm PS scintillator.**
   (c) **0.90 cm air, Tyvek (Q173D), Tedlar, and Al.**
2. **Device enclosed in a light tight box.**

Table 1: HyperCP hadronic calorimeter specifications.

Type:	Sampling (Fe:Scintillator, 5:1)
Composition:	2.41 cm Fe, 0.50 cm PS
Layer length:	3.693 cm (1.454 in)
	2.41 cm Fe, 0.50 cm PS, 0.78 cm air
	0.950 in Fe, 0.197 in PS, 0.307 in air
Number of layers:	64
Transverse size:	99.0×98.0 cm^2 (38.98×38.58) in^2
Longitudinal size:	238.92 cm (94.0625 in)
Mass per layer:	189.95 kg Fe, 5.006 kg PS
	418.8 lb Fe, 11.0 lb PS
Total mass:	12,667 kg (27,926 lb)
Cell size:	49.5 cm $\times$ 98 cm $\times$ 16 layers
Total cells:	8 (2x $\times$ 1y $\times$ 4z)
Fiber diameter:	0.20 cm
Fibers per cell:	$16 \times 16 = 256$
Total fibers:	$8 \times 256 = 2{,}018$
Interaction length:	$\lambda_I = 24.6$ cm (9.7 in)
	0.150 λ_I per layer
	2.40 λ_I per cell
	9.62 λ_I total
Radiation length:	$X_0 = 2.67$ cm (1.05 in)
	1.38 X_0 per layer
	22.1 X_0 per cell
	88.5 X_0 total
Sampling fraction:	3.54%
MIP per cell:	16×0.50 cm $\times$ 2.019 MeV = 16.15 MeV

Scintillators

1. $0.5 \times 99 \times 98$ cm^3 Kuraray SCSN-38 scintillators.

2. Has a polystyrene base, butyl-PBD first fluor, PBD second fluor.

3. Has an emission frequency centered at 428 nm.

Fibers

1. Why Fibers?
   (a) Allowed for a more hermetic calorimeter.
   (b) Minimized the needed photocathode area.
   (c) Greatly simplified the mechanical design.

2. 2,048 waveshifting 2 mm$\times$2 m Bicron BCF-92 fibers.

3. Special G2 waveshift: bright and fast, τ=2.7 ns.

4. Absorbs light at 405 ns, and emits at 492 nm.

5. Combination of scintillator and waveshifter allows 90% of signal to be integrated in 25 ns.

6. Fibers read out at one end. Other end polished and sputtered with an aluminum reflective coating evaporated onto it.

7. UV-curing epoxy put on sputtered end for protection.

Fiber Polishing

1. **Fibers installed in a 6 ft. 3/4" PVC tube that could hold 75 fibers.**

2. **Ends to be polished installed in a mold to provide rigidity, with kapton tape sealing the bottom.**

3. **Water added to the mold and mold immersed in liquid nitrogen for 15 minutes to ensure individual fibers were frozen as a complete unit for polishing.**

4. **Mold inserted into diamond-cutting machine clamp.**

5. **Polishing done using a 2-cutting head machine.**
   (a) **1^{st} head - roughing cut - 4 carbon steel blades, series of 3 passes, each passing cutting $\sim$1/16".**
   (b) **2^{nd} head - fine cut - 2 diamond blades, 2 passes, one taking 1 mil step, other taking 1/2 mil step.**

6. **Individual polished fiber ends inspected individually for defects. Rejects, accounting for 2%, were polished again.**

Fiber Sputtering

(Sputtering performed at FNAL Lab 7 by Eileen Hahn.)

1. Fibers were aluminized in a 10 foot tube vessel system utilizing a 3 inch Mighty Mak sputtering magnetron gun driven by a DC power supply at 300 W.
2. Average sputtering time was 20 minutes.
3. For good reflectivity, 99.999% pure aluminum targets were used at a distance of 6 inches from the substrate.
4. Sputtering process started after achieving a low 10^{-6} Torr vacuum, then backfilling with "sputtering grade" Argon gas to 2 mTorr pressure.
5. Coating was approximately 2500 Å thick.
6. Groups of 500 fibers were coated at a time.
7. Failure rate of sputtered fibers was less than 1%.

UV Fiber Test

1. Sputtered fiber tested by exciting it with a UV lamp and measuring its response using a photodiode, picoampmeter, PC set-up.
2. Lamp moved in increments along fiber length and response of the diode was recorded.
3. Sputtered end was cut at a 45° angle, ~5 mm from end, and painted black. Light yield was measured again.
4. Ratio of two light yields was used to determine the reflectivity, averaging 87%.
5. Attenuation length (long component) of 3 m was measured.

Calorimeter Readout

1. 8 cells each of $16 \times 16 = 256$ fibers potted in an opaque epoxy fixture (to get rid of cladding light), fixture attached to an acrylic light guide which mixed light before reaching PMT's.

2. PMTs:
   (a) R329 Hamamatsu green extended.
   (b) Very stable with small rate dependence.
   (c) High-rate base home-designed and used to provide good gain stability with rate.
   (d) Summed output of all PMTs was discriminated to provide an energy cut.
   (e) Cell-to-cell gains were adjusted using muons which produced $\sim$1.5 photoelectrons per plane of scintillator.
   (f) Light pulser system using a Nitrogen laser and PIN diodes was also used to monitor the time dependence of the calibration.

3. 14 bit, 3 MHz ADC specifically designed for this use.

Energy Resolution from (σ/E) vs. E

ADC Rate Dependence and Linear Performance

Calorimeter Performance - Conclusions

1. **Calorimeter trigger proved to be a vital component of the main triggers given the large rate of interactions of the channeled beam with material in the spectrometer.**

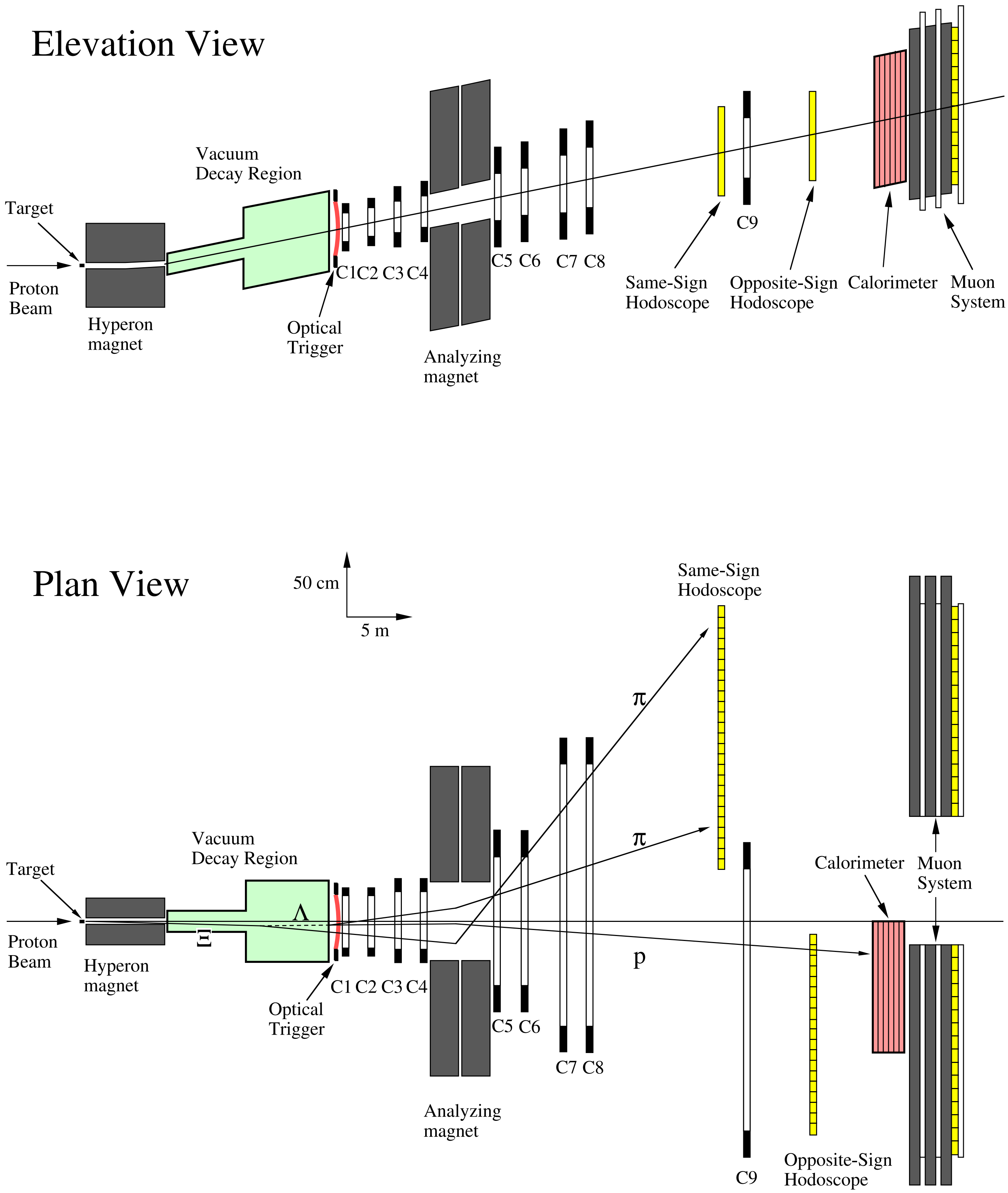
2. **Calorimeter reduced the Ξ and K trigger rates by about a factor of six, with a very conservative minimum energy threshold.**

3. **Energy resolution of $\sigma/\mathrm{E} = 117\%/\sqrt{E}{+}2.5\%$ was measured.**

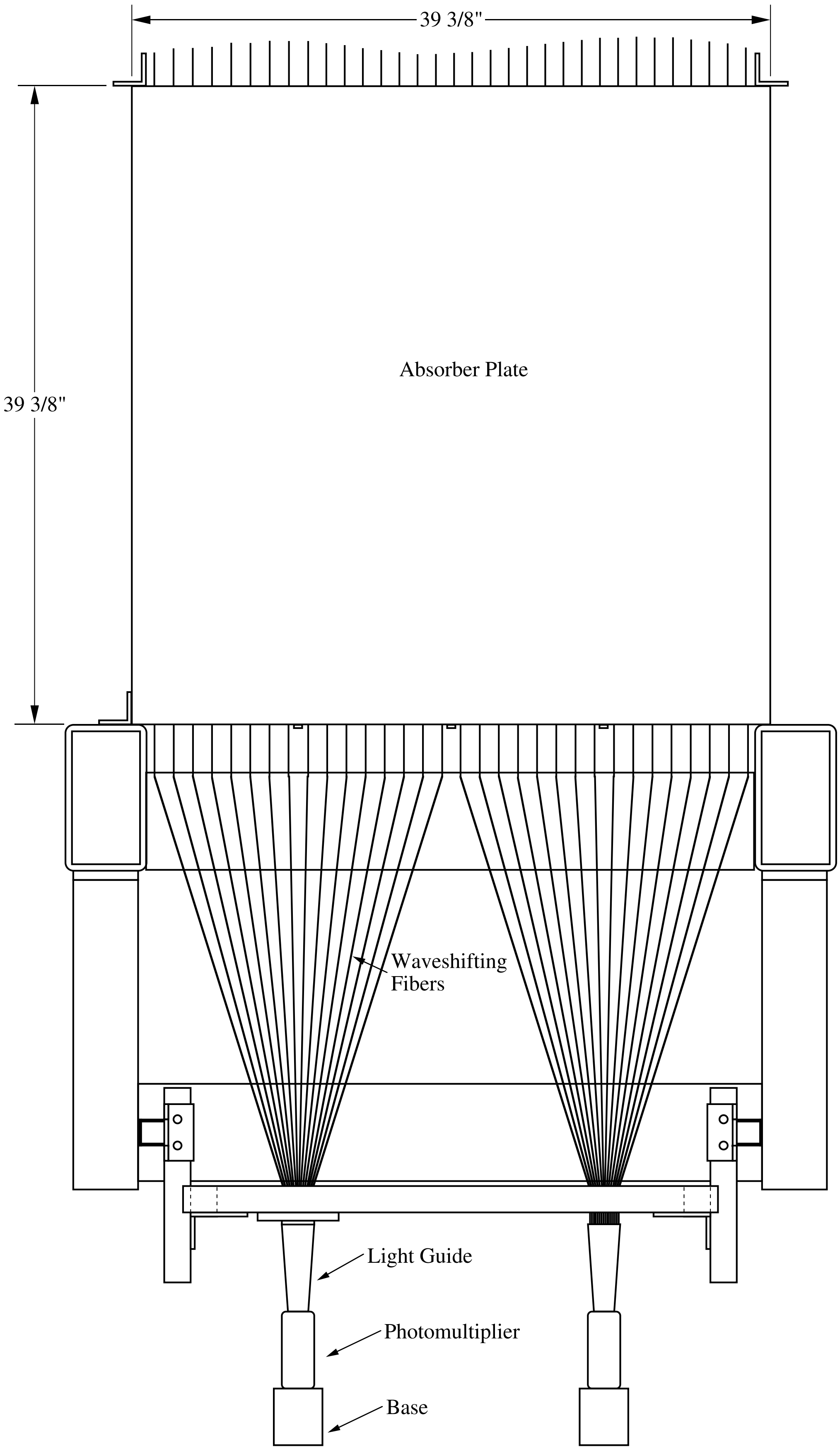
Calorimeter Trigger Acceptance

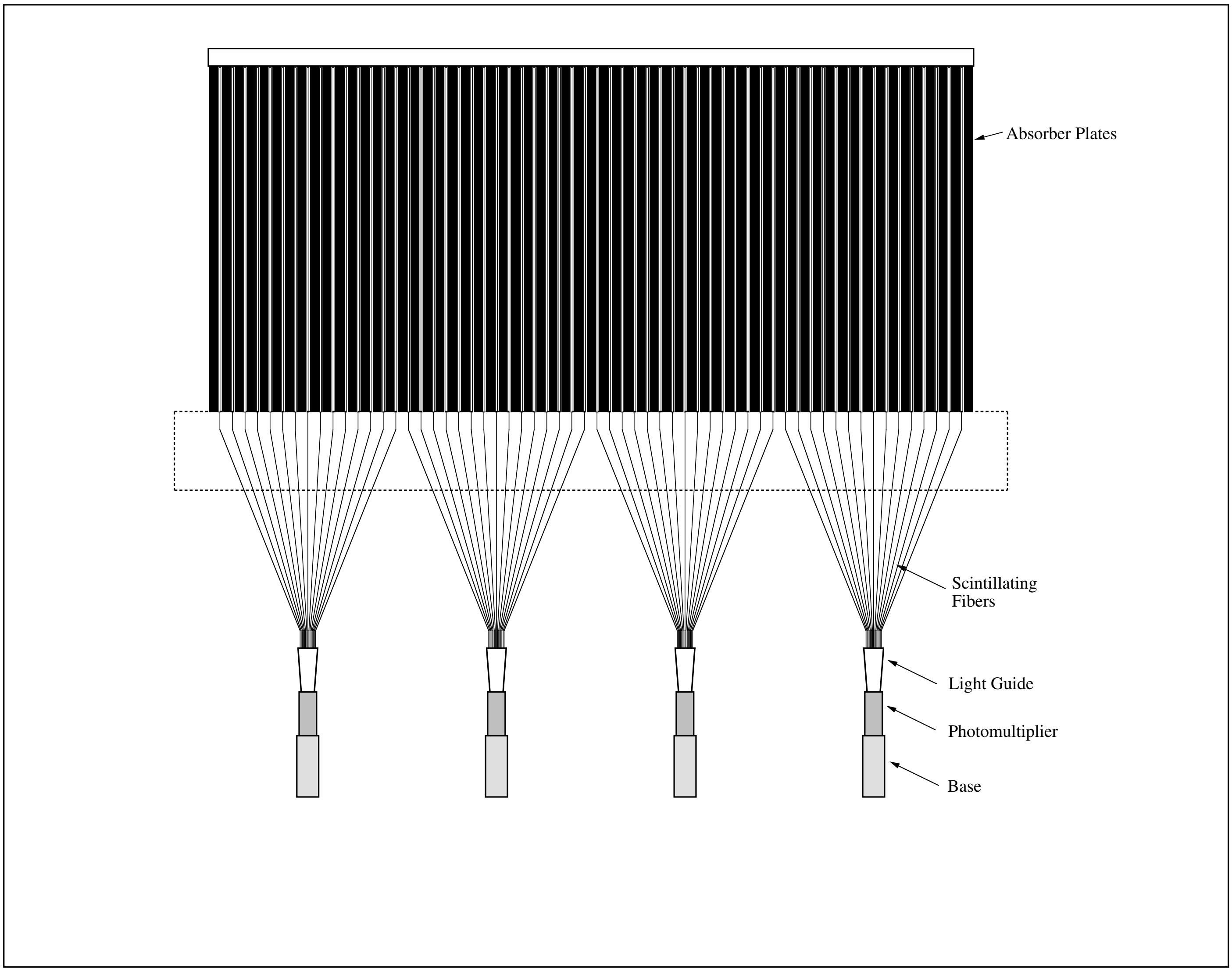
In order to reject μ's, cut on energy threshold (Min. E from Λ° decay p is ~70 GeV).

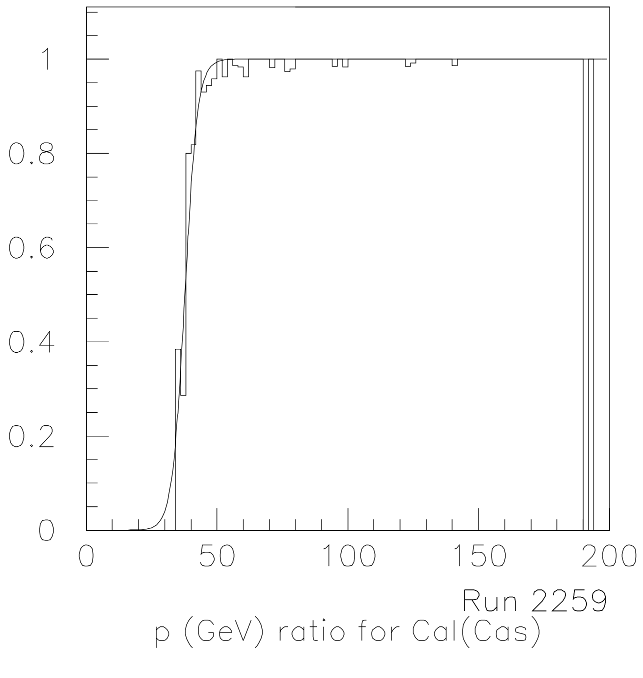
Trigger acceptance as a function of E for charged particles entering the calorimeter ~99.2%.



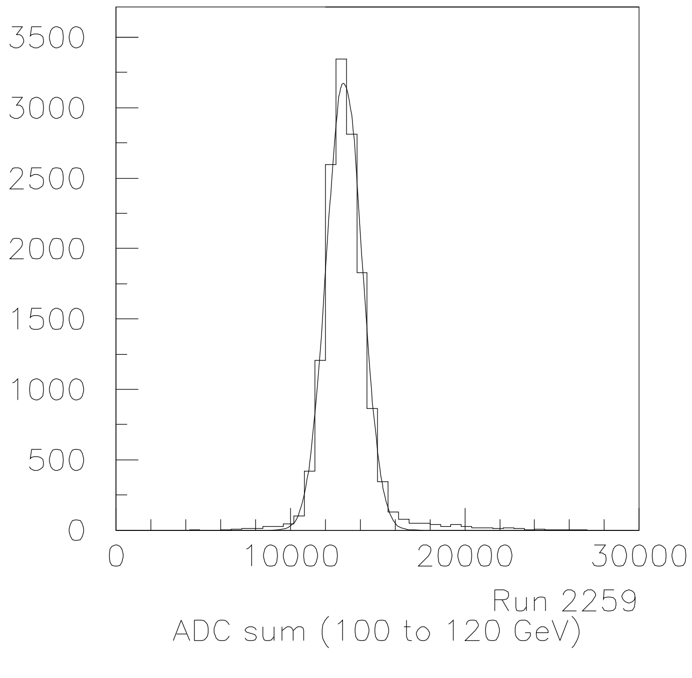
Elevation View
Vacuum
Decay Region
Target
Proton
Beam
Hyperon
magnet
Optical
Trigger
C1C2 C3 C4
Analyzing
magnet
C5 C6
C7 C8
C9
Same-Sign
Hodoscope
Opposite-Sign
Hodoscope
Calorimeter
Muon
System
Plan View
50 cm
5 m
Same-Sign
Hodoscope
π
π
Vacuum
Decay Region
Target
Λ
Ξ
Proton
Beam
Hyperon
magnet
Optical
Trigger
C1 C2 C3 C4
C5 C6
C7 C8
Analyzing
magnet
p
Calorimeter
Muon
System
C9
Opposite-Sign
Hodoscope


39 3/8"
39 3/8"
Absorber Plate
Waveshifting
Fibers
Light Guide
Photomultiplier
Base

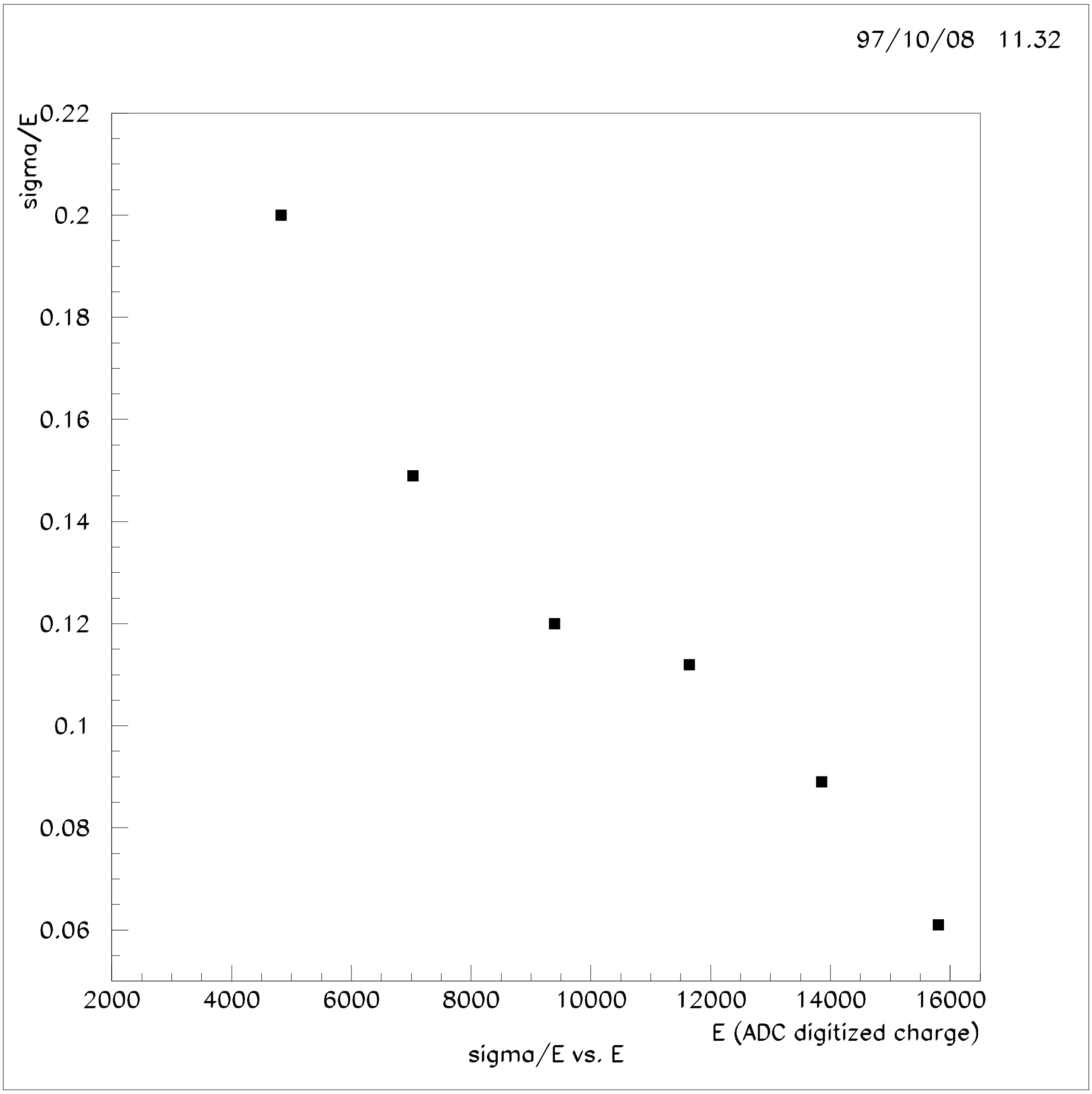

Absorber Plates
Scintillating
Fibers
Light Guide
Photomultiplier
Base

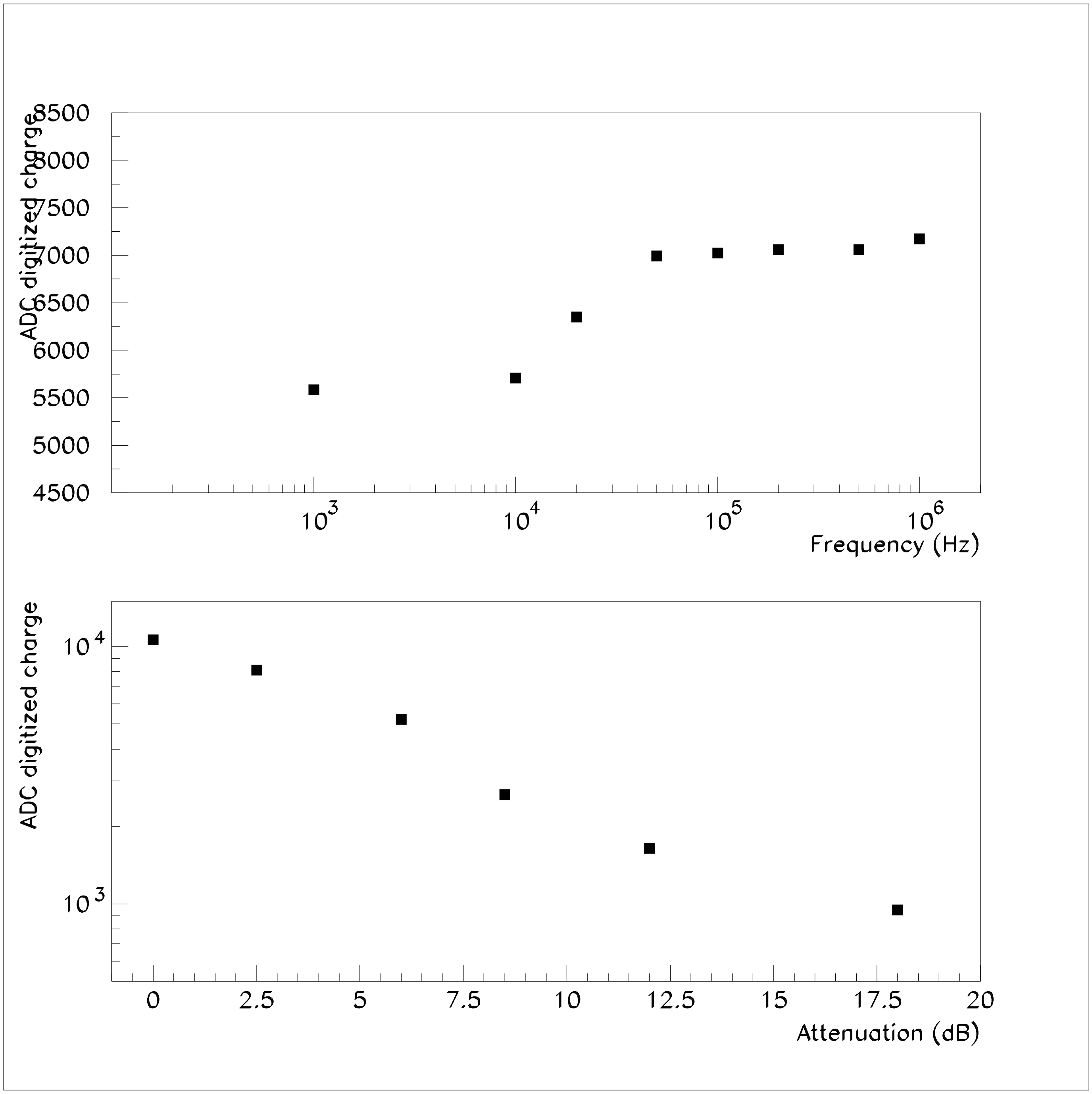


1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
Run 2259
p (GeV) ratio for Cal(Cas)

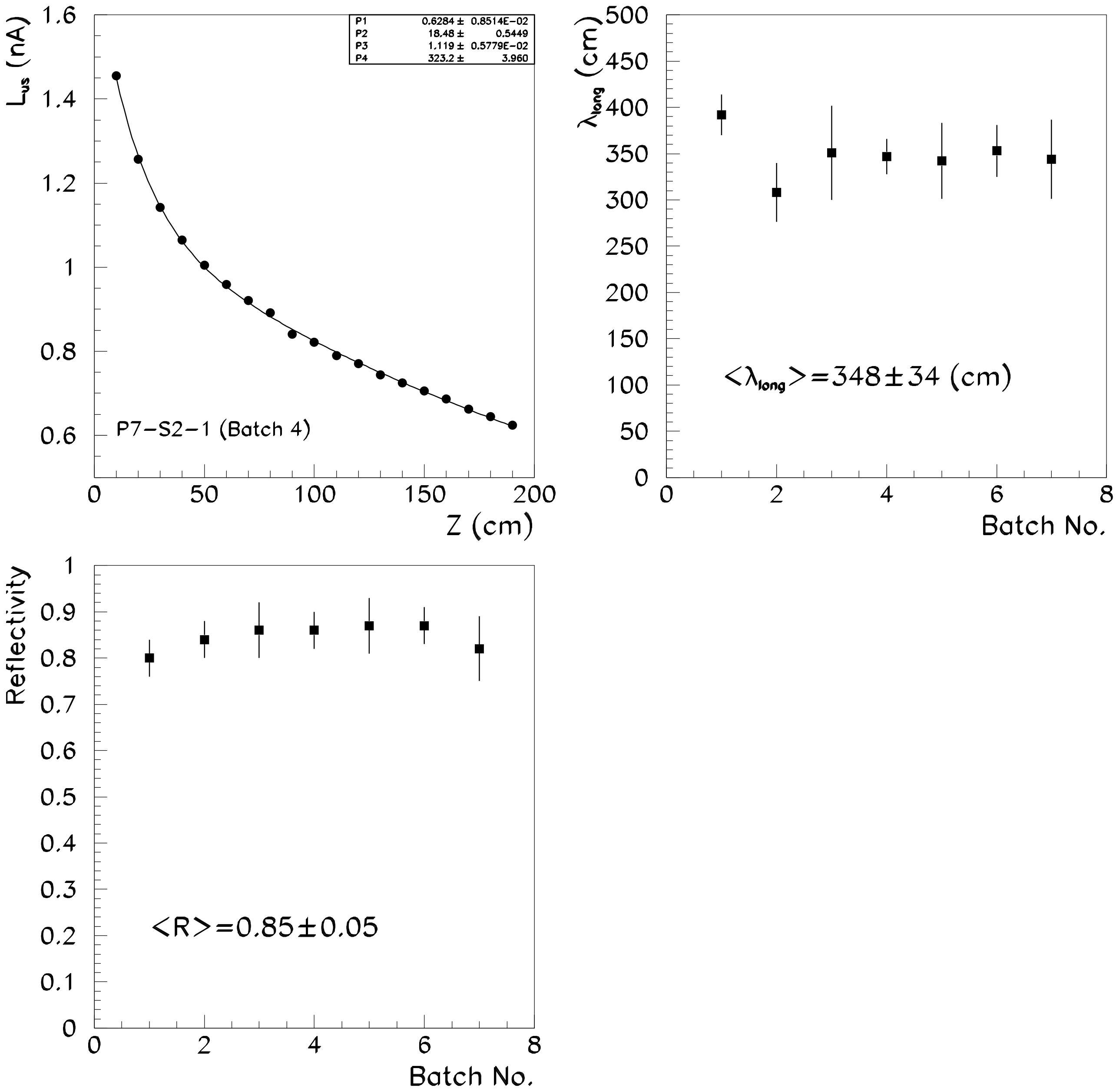


3500
3000
2500
2000
1500
1000
500
0
0
10000
20000
30000
Run 2259
ADC sum (100 to 120 GeV)


97/10/08 11.32
sigma/E
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
2000
4000
6000
8000
10000
12000
14000
16000
E (ADC digitized charge)
sigma/E vs. E



ADC digitized charge
8500
8000
7500
7000
6500
6000
5500
5000
4500
10^3
10^4
10^5
10^6
Frequency (Hz)
ADC digitized charge
10^4
10^3
0
2.5
5
7.5
10
12.5
15
17.5
20
Attenuation (dB)



P1 0.6284 ± 0.8514E-02
P2 18.48 ± 0.5449
P3 1.119 ± 0.5779E-02
P4 323.2 ± 3.960
L_vs (nA)
P7-S2-1 (Batch 4)
Z (cm)
λ_long (cm)
<λ_long>=348±34 (cm)
Batch No.
Reflectivity
<R>=0.85±0.05
Batch No.