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Calibration and Monitoring of the TESLA Tile Hadron Calorimeter

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1 Introduction

The TESLA linear collider facility produces $e^+ \, e^-$ interactions with collision energies of 500 to 800 GeV. The future High Energy Physics Research Program and the actually proposed TESLA particle detector for the measurement of particles and jets are described in detail in [1].

The HCAL, a hadronic sampling-sandwich calorimeter with scintillator tile readout is also described in [1, 2]. Technical details on the mechanical calorimeter stack design, construction and installation are given in [3], the optical and electronic readout (RO) chain envisaged is presented in [4]. A detailed research and development (R&D) program for the study and optimization of all calorimeter components and the simulation and reconstruction software is given in [5]

The reconstruction of all particles and jets of individual events is the base for identification of the physical origin of the interaction, of the new final states produced and their subsequent decay. A promising method for optimal reconstruction of angle and energy of jets is the so called 'Energy-flow method' [6] which uses

– the tracker information to reconstruct the tracks of charged particles with high precision,

– the electromagnetic calorimeter ECAL in front of the HCAL for the measurement of the photons and electrons produced,

– the HCAL to measure all of the hadronic showers produced inside the HCAL volume.

When all clusters produced by charged tracks as measured in the trackers are identified and correctly subtracted, the remaining clusters in the ECAL and HCAL can be applied to neutral particles. Photons are completely contained in the $24X_0$ depth of the ECAL, neutron and long living neutral kaon showers are detected with the combined ECAL-HCAL calorimeter with a depth of 5.4λ, $(0.9\lambda + 4.5\lambda)$. Such neutral cluster information will be added for event reconstruction to the charged track information.

2 Basic requirements for optimal energy resolution

To compete with the excellent momentum resolution of the trackers (for the charged tracks) both calorimeters

– have to be uniform in response for equal sized cells,

– have to be uniform across the cell area,

– a design with excellent stability in cell response has to be found,

– this stability has to be optimally surveyed and monitored, and

– precise and reliable calibration procedures have to be developed.

The number of calorimeter cells to be handled in the HCAL is large, 128 500 in the barrel, 73 500 in both end caps and 2000 in the pole tips of the endcap tail catchers, all together 204 000 channels. The calorimeter cells have a tower structure with 3 to 7 individual sandwiched tiles with scintillator tile thickness of 5.0 mm and tile sizes of approximately 5×5 to $25 \times 25 cm^2$ as described in detail in [4]. To have equal response of all tiles a careful design of the tile-WLS tile readout is needed. The variation in response and the homogeneity across the tile area should not reduce the energy resolution induced by the sampling and should be less then 2%.

3 Pre-calibration procedures

Before the final insertion of the tile plates into the HCAL sandwich structure all assembled tile plates have to be tested, tile by tile, and scanned with a collimated radioactive source along the tile-plate. All read out fibres (≤ 810) of a tile-plate coupled to the individual tiles have to be bundled together and illuminated via an appropriate light mixer, the photocathode of a 2-3" photo multiplier (PM) with high gain. During the scan a current amplifier records continuously the light response as function of the source coordinate. This method allows the combined measurement of the absolute response and the homogeneity of all tiles. Individual tiles with insufficient response or homogeneity have to be repaired. Finally, the extracted results will be stored in a 'tile pre-calibration data-base'. An appropriate software has to be developed for this test set-up.

When the stacks are assembled and the readout fibres ordered according to cells and equipped with the proper readout electronics, within a second pre-calibration step still without magnetic field all the individual cells can be calibrated with vertical cosmic muons with online subtraction of pedestals and noise and stored in a 'relative calibration data-base'.

4 The calibration procedure

To convert the electronic signal as recorded with an ADC or FADC into the real energy as deposed in the calorimeter cell, several calibration coefficients have to be determined for the individual calorimeter cells i. These coefficients, extracted from pre-calibration measurements and cosmic muon, test studies will be stored in data-bases and used for the reconstruction of the real physical energy deposed in each individual cell. Then the individual cells are added to the subclusters and later to the clusters. A possible calibration procedure can be described by the following:

$E_i = (NADC_i - ped_i) \times \epsilon_i \times K^{ampl} \times K^{particle} \times K^{mass}$

where:

E_i – cell energy in physical scale [GeV],

$NADC_i$ – ADC count of cell (integer),

ped_i – online pedestal count of cell (mean value of last n pedestal readings),

ϵ_i – equalizes the response of all cells in deposed visible muon energy, corrects for variations in light yield, attenuation, photo cathode efficiency, gain of the photodetectors and also compensates the ADC calibration differences,

$K^{sampl}/;[GeV/channel]$ – converts the corrected visible energy to real deposed energy (physical scale),

$K^{particle}$ – depends on the particle ID and corrects for the different e/π - response of a non-compensating calorimeter,

K^{mass} – global mass correction as taken, e.g. from di-jets like $q\bar{q}$ from Z^0 or $W^{\pm}$, corrects for fluctuations in cluster energy induced by the inhomogeneity of the magnetic field and also by other possible geometrical effects like the influence of gaps and dead zones.

ϵ_i is approximately one, due to the hardware physicists efforts to build a detector that is homogeneous in response. The K^{sampl} will be extracted from simulation and test beam studies. The $K^{particle}$ again is approximately one, depending on the particle momenta and corrects for the particle ID as found in a first fast step of reconstruction taking into account the different response of minimum ionizing particles, electromagnetic and hadronic showers.

Refined e/π weighting using detailed cluster pattern study from test beam data will be applied in a final reconstruction improvement step, when also global tail and crack leakage corrections are inserted and the global error estimate is extracted.

The correction for electromagnetic subcluster fractions is known as 'energy weighting' and applied e.g. in the shower energy reconstruction, in the H1 experiment at HERA/DESY. The method reduces the response of individual cells with large signals where intermediate produced π^0 showers are developed by a 'weighting factor' that compensates for the different response of electrons and hadrons. The weighting factors can be extracted from test data, where in detailed analysis the cell signal amplitudes are varied, according to fitted damping functions, in order to get the best possible energy resolution. The fitted damping parameters vary with the cell sizes and trajectory angles and will be made available in an additional database.

The K^{mass} describes a correction needed to compensate, e.g. for neutrino losses, systematic jet energy and angle reconstruction errors, and can be taken from simulation and test runs. Such a correction should move the mass of Z^0 and $W^{\pm}$ to the correct value.

In the following paragraphs some possible final calibration procedures are discussed:

5 Calibration with test beam

Some representative calorimeter modules - most probably one barrel and one endcap module only - have to be studied and calibrated in test beams with muons, pions, protons and electrons up to energies of 400 GeV. To keep such a calibration valid during transportation to other laboratories a stable and continuously running gain monitoring system, as described in chapter 9, has to be used.

For a realistic test beam calibration of the TESLA calorimeter a small size ECAL prototype has to be included in front with a depth of $24X_0$ or 0.9λ. This calorimeter has different response to electrons and hadrons, the corresponding calibration coefficients can be measured simultaneously within the same test runs.

The electromagnetic calibration of the HCAL has to be measured in various shower depths,

– with no ECAL in front,

– with electrons entering via the side walls or

– by small beam holes of different longitudinal depth for injection of the beam deep into the absorber stack structure, allowing the electrons (or hadrons) direct entry into the calorimeter volume region to be studied. The scintillator tiles concerned should not be perforated and can be used for track/beam tagging.

Different angles of particle incidence across the test module, e.g. 0^o to 60^o also have to be studied, by rotating the test module around the vertical axis.

6 Calibration with real events in the detector

Such calibration within the original magnetic field can be applied to all calorimeter modules in the real detector positions. Unfortunately they suffer, as discussed in the following, from low real event rates/cell and therefore need long calibration times.

I. Isolated charged tracks in real events

A direct method of HCAL calibration uses isolated charged hadronic tracks as being already measured in the tracker system. Such selected particles should not have any overlay with other clusters in the calorimeters within impact point distance >12 cm, by other words at such an input distance two hadronic showers can be separated in the reconstruction procedure. In addition energy faking overlay can be reduced by rejection of calorimeter clusters with asymmetric shape. Direct HCAL calibration is possible - if particles are used which do not interact inside the ECAL. In case where hadronic shower development is already observed in the ECAL the combined calorimeter system can be hadronicaly calibrated.

For 1000 events the rates of useful particles above 2 and 5 GeV momentum with a track separation of at least 12 cm at the ECAL front face are shown in Fig. 1a,b and Fig. 2a,b for $W^{\pm}$ and light quark pair production. The charged hadron rates are given, and polar angle bin of 2^o for 500 GeV collision energy, as a function of the production angle.

The area of a polar angle bin of $\Delta\theta = 2^o$ at 90^o is covered by ≈ 254 HCAL front cells with additional 8 more cell layers following in depth with increasing cell size. With the rates quoted in Fig. 1,2 the computed useful particle rates/month are quite low as shown in Table 1, but within a year probably sufficient amount of events can be collected for calibration. These low rates at 90^o are the worst case, towards smaller polar angles the single separated particle rate increases by factors 4 to 9.

II. Light quark + anti-quark final states

Narrow jets from light quark (u,d,s, and c) pair production can be used for calibration of the energy and angle measurements of jets. The useful energies extend up to a maximum beam energy of 250 GeV.

	Collision final states:		
Hadron energy:	WW	qq	sum
$> 2\ GeV$	170	114	284
$> 5\ GeV$	57	40	97

Table 1: Rates for in situ HCAL calibration, real events, shown are rates/month/HCAL cell of $5 \times 5 cm^2$ at polar surface angle 90^o and 500 GeV E_{cms}.

Some additionally produced neutrinos decrease slightly the measured mean jet energy and produce small low energy tails, requiring a detailed MC simulation for optimal calibration. Such events can also be used to study the p_t balance and calibrate the p_t measurement.

III. Single Z-Boson production

At a collision energy of 500 GeV no direct single s-channel Z production is possible. The observed single Z's are produced together with a high energy photon emitted in beam direction. The decay of such boosted Z's emits jets in the forward hemispheres. Such 2 jet events can be used with or without detection of the high energy photon for:

– energy calibration studies,
– p_t balance studies,
– the study of the Z-mass resolution and,
– the mass calibration at the Z-scale with the combined tracker-calorimeter system.

The result of Z mass reconstruction from simulated 2 quark jet events is shown in Fig. 3. Calorimeter cells with less than 60 MeV energy deposit are not included. Such a cut is far above the expected noise level. The Z-mass shown is calculated from hadronic jets with the 'Energy flow' method. With $\approx 100\ Z^0$ particles measured, at an overall precision of the E-flow method can be controlled at the level of 0.5 GeV.

IV. Pair production of heavy particles

In a similar but more complicated way W^+W^-, Z^0Z^0 and Z^0H^0 (if H^0 exists) production can be used for mass calibration, with now 4-6 jets in the final state. Reconstruction of the total energy and the di-jet masses have to be studied.

7 Calibration with cosmic muons after final installation

Penetrating cosmic ray muons offer an easy way for calibration of calorimeters with large number of calorimeter cells. Such muons are rather common, but such MIP's unfortunately have low signals compared to the energy deposed in standard showers of several steps of ten GeV's. This is one of the reasons why a high gain and low noise detector system is required.

Muons are identified as MIP tracks through at the whole detector volume. A trigger is not available, therefore software tools are needed to identify the track of hits and to measure the effective track length. About 200 muons per cell are sufficient for calibration within a 2% precision level.

Cosmic muons have a strongly decreasing momentum spectrum, but fortunately vertical incident muons dominates. Most of them can be used, if penetrating enough to reach the underground detector, for the cell calibration.

To penetrate the complete concrete shielding roof, the return flux iron yoke, the coil with cryostat and a complete HCAL/ECAL barrel cylinder shell, the energy should exceed 4.5 GeV. When such muons have momenta above 5.5 GeV, both shells of the upper and the lower barrel calorimeter modules will be crossed. The barrel calorimeter side modules (between 2 and 5 o'clock and opposite) can also be calibrated with muons of 1-3 GeV final energy after penetration of the upper barrel modules which are strongly bent inside the detector volume.

Nearly all muons within an angular cone of 35^o to the vertical, cross the barrel calorimeter top and bottom modules. The expected rate at Hamburg is $86 \times 10^6 (54 \times 10^6)$ muons/day, above momenta of 4.5 (5.5) GeV [7]. These cosmic muons deliver the possibility of a permanent online calibration with a constant rate of $\geq$6900 (4300) muons/calorimeter cell/day yielding a calibration precision of 0.3% (0.38%). The rates for such cosmic muons above various momentum cuts are plotted in Fig. 4.

Such a calibration does not need any information from the tracker, the muon tracks and the momenta will be measured precisely enough by HCAL and ECAL - with the $1cm^2$ cell size - allowing to calculate

– the real track path and length in the cells and

– the rough muon energy for actual dE/dx correction.

Fig. 5 shows the cell amplitude distribution for 20 GeV muons with an incidence angle of 90^o. Three equidistant peaks corresponding roughly to 23, 46 and 69 MeV physical energy deposit are produced by such muons that do not cross the sandwich structure of the cells completely. 1, 2 or 3 cell-layers hits are often observed (Fig. 5,b). Fig. 5,a shows how, due to the Landau tail and some hadronic interactions the energy deposit in individual cells extends up to several GeV.

8 The calibration with beam halo muons

The angular region of the endcaps suffers from the low rate of approximately horizontal incident cosmic muons. Only the beam halo muons can be used here. They have momenta in the range of the beam energy and penetrate both endcaps, the trajectories are measured by the tracker system. The rate depends on the final realization of the beam line, beam delivery system and shielding, but at least several muons per second are expected. With a rate of 1 Hz only 9 muon tracks/day will be collected in the smallest cells ($5 \times 5cm^2$). Within a month the achievable calibration precision is only 6.1%.

With dedicated endcap calibration runs with defocused e-beams and 10 000 Hz halo muons, a calibration precision of 1 % in a day (5.2 % in an hour) can be reached.

9 The monitoring of the stability

The low online single hadron and jet rates are not sufficient for a permanent survey of the stability of the complete readout chain. A method that is currently used in all modern high energy detectors relies on the injection of pulsed LED or laser light into the optical readout path [9]. The light injection at the level of the photo cathode of the photodetectors in the HCAL is proposed. The monitoring light can be distributed from only a few light sources, stabilized in temperature and voltage supply. Thin optical fibres guide the light to all the individual cell photodetectors. Some of the fibres will be guided to additional stable silicon photodiodes housed in a cooled box, that controls the light output of the original light monitoring sources. The stability of such photodiodes can be kept well below a fraction of 1%. An appropriate monitoring system has to be developed. The actual state of the art is described in [8].

Calibration with radioactive sources could be useful to survey long term stability on single tile level but is applicable only for relatively few cells. Low intensity (few hundred Bequerel) alpha sources could be directly put on the tile surface. If ^{241}Am is used with 5.4 MeV alphas the monitor signal is of the order of MIP signals of most of the cells.

The calibration (monitoring) with LED or Laser signals - fed to the light mixer - controls the stability of all individual electronic channels and can be applied continuously in the time gap between bunch crossings.

Since this method does not survey the scintillator-WLS-ROF path, the injection of UV-light in the tiles is desirable. The UV-light could be fed and injected, into the tiles via very thin and flexible quartz fibres.

10 Software requirements

Many large databases for the calibration corrections will be needed, offering all constants measured, as described in the previous chapters.

Also the muon tracks have to be reconstructed from the 9 HCAL cells hit by a module crossing muon and track length corrections have to be applied.

The use of single separated tracks from hadrons and jets for cell calibration needs a comparison with a simulation studies for crack and leakage corrections.

Due to the limited statistics of test beam data the energy weighting method for correction of the different e/π response has to be studied with simulated events deposed in the real detector structure for various beam particles, energies and angles.

11 Conclusions

The full calibration of a large hadronic calorimeter like the HCAL with more than 200 000 calorimeter cells can not be done with test beam studies alone. The online measurement of cosmic muons and beam halo muons is absolutely necessary to measure the actual relative calibration coefficients with a precision of order of 1%. For the endcaps, dedicated short calibration runs with strongly increased halo rates are needed about once a week.

The low real event rates and the small number of tracks separated from jets with measured momentum, hinder a fast calibration with high energy hadrons. Thus test beam measurements for all relevant energies and particle types have to be made and the calibration level has to be saved by the use of a stable, transportable monitoring system.

The stability of the monitoring system has to be better than 1%, and is of the order of around a tenth of a percent, experimental methods to achieve this are known. A reliable solution for large scale has to be established.

12 Acknowledgments

Thanks to P. Steffen (DESY) for discussions on the range of linearity required to have a reliable extension from MIPs to high energy shower energy deposit of up to 70 GeV in individual cells and the possible coverage of this energy range of about 3000 with appropriate nonlinear FADC's.

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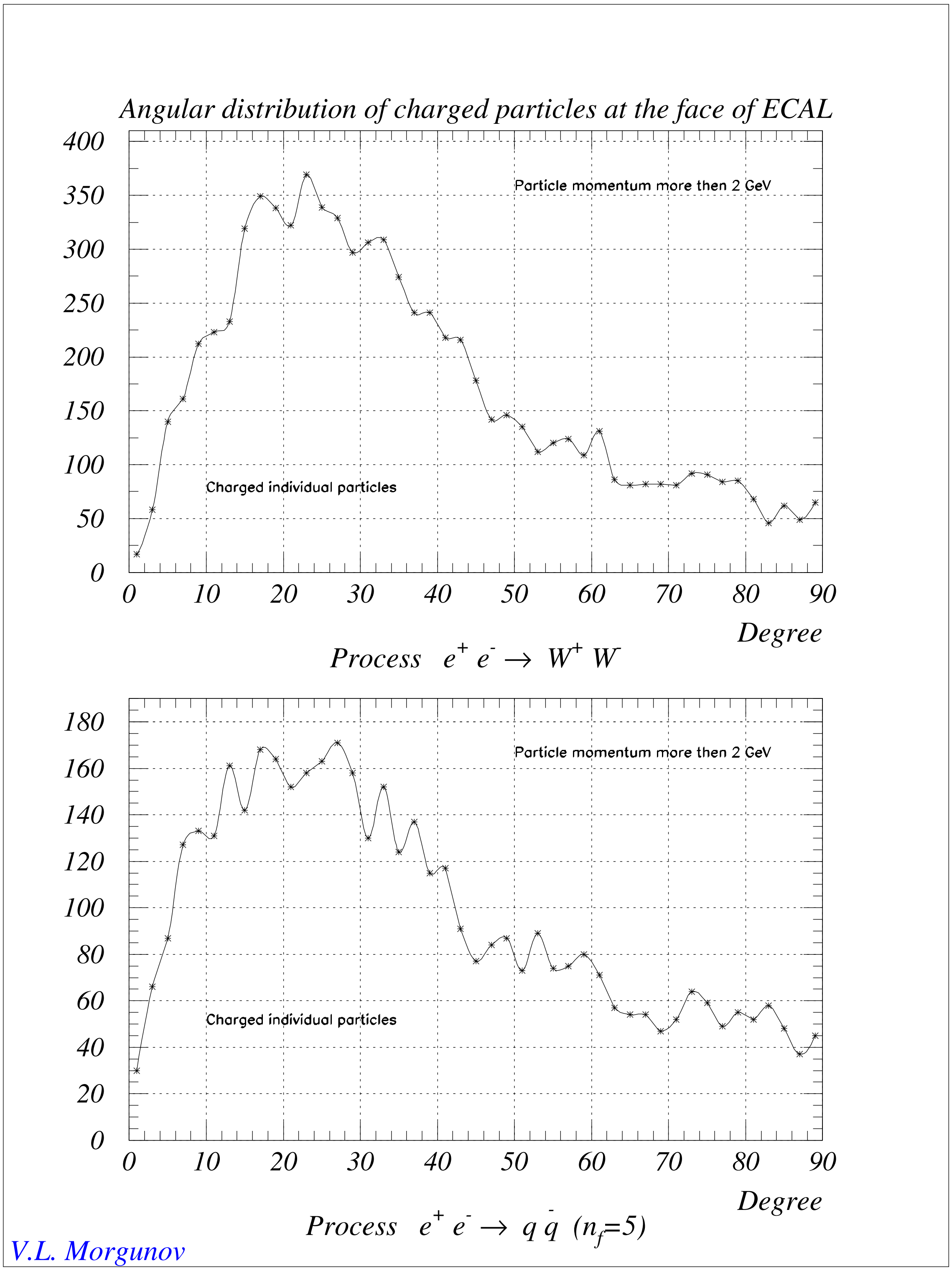
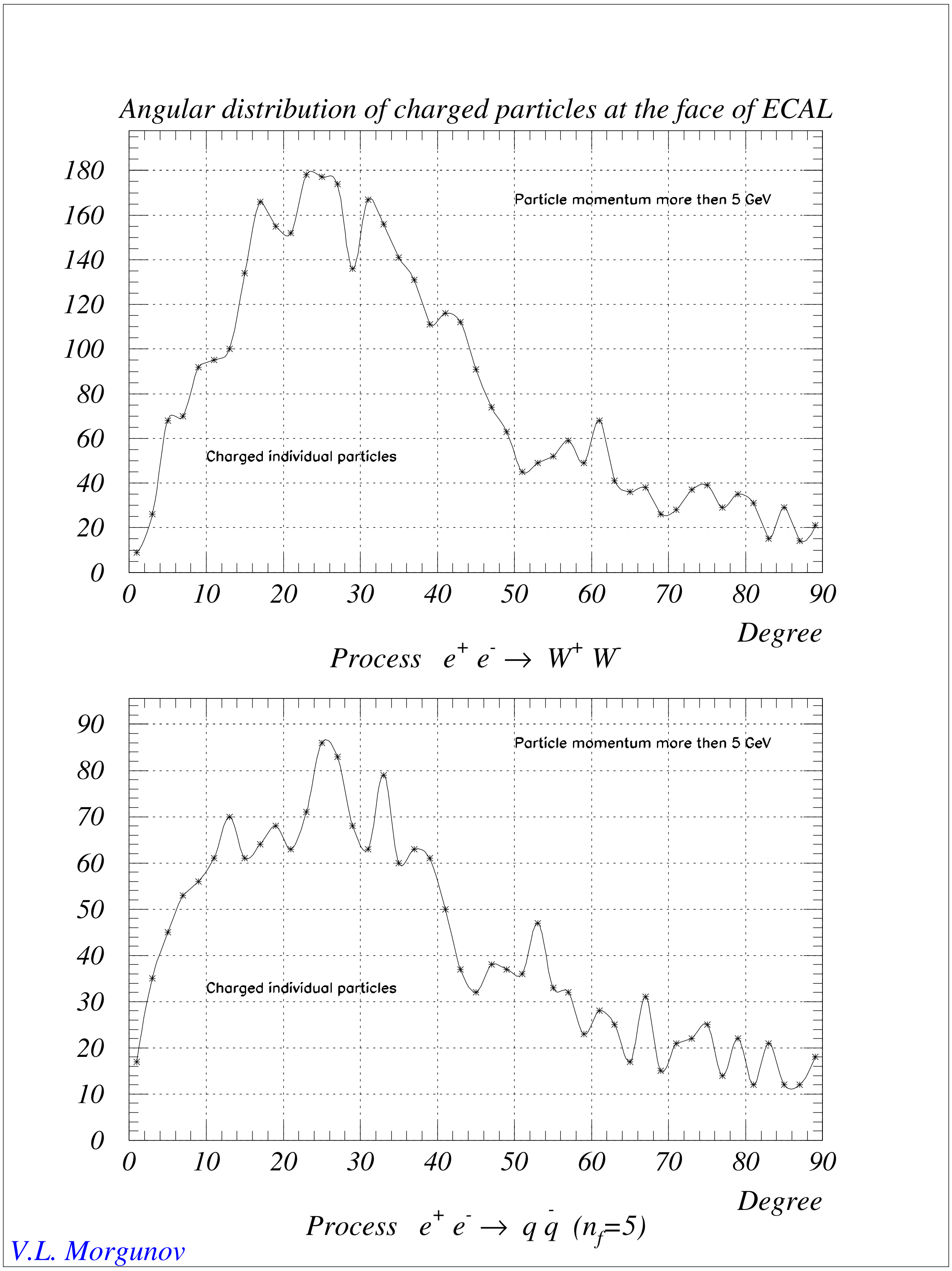
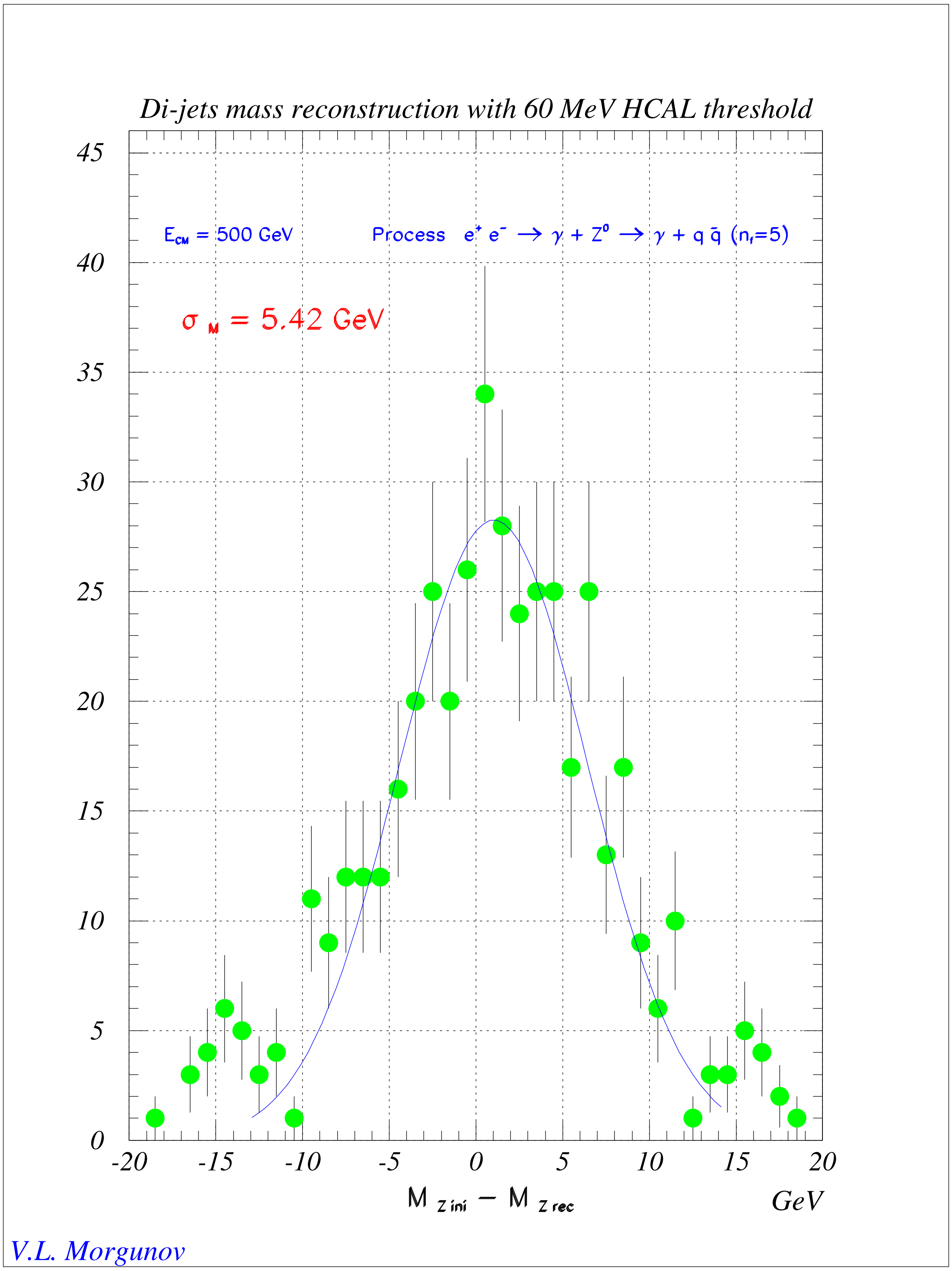

Angular distribution of charged particles at the face of ECAL
Particle momentum more then 2 GeV
Charged individual particles
Degree
Process $e^+ e^- \to W^+ W^-$
Particle momentum more then 2 GeV
Charged individual particles
Degree
Process $e^+ e^- \to q \bar{q}$ $(n_f=5)$
V.L. Morgunov

Figure 1:



Angular distribution of charged particles at the face of ECAL
Particle momentum more then 5 GeV
Charged individual particles
Degree
Process $e^+ e^- \to W^+ W^-$
Particle momentum more then 5 GeV
Charged individual particles
Degree
Process $e^+ e^- \to q \bar{q}$ (n_f=5)
V.L. Morgunov

Figure 2:



Di-jets mass reconstruction with 60 MeV HCAL threshold
E_CM = 500 GeV
Process e+ e- → γ + Z0 → γ + q q̄ (n_f=5)
σ_M = 5.42 GeV
M_Z ini − M_Z rec
GeV
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Figure 3:

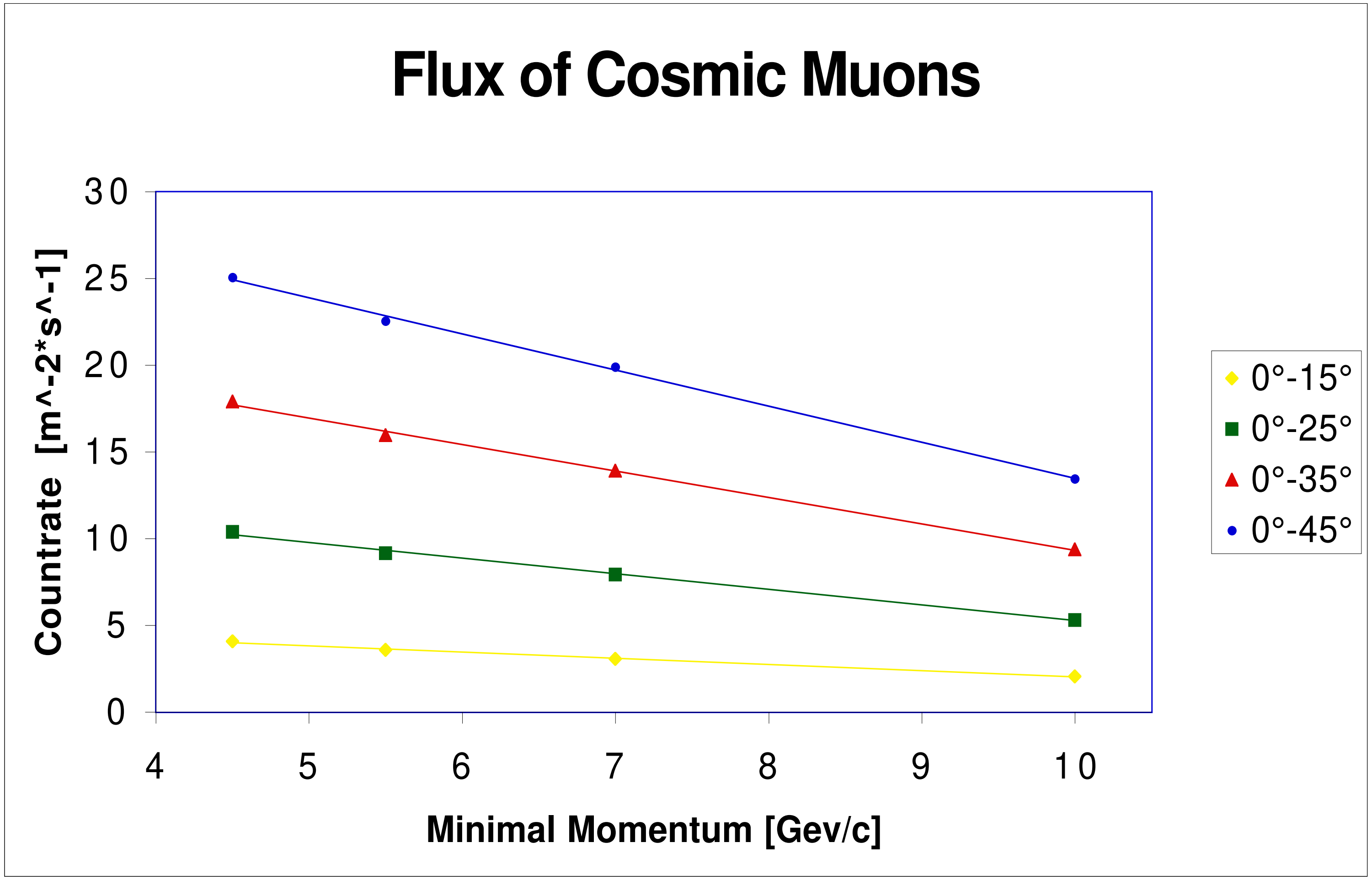
Flux of Cosmic Muons
Countrate [m^-2*s^-1]
30
25
20
15
10
5
0
4
5
6
7
8
9
10
Minimal Momentum [Gev/c]
0°-15°
0°-25°
0°-35°
0°-45°

Figure 4:

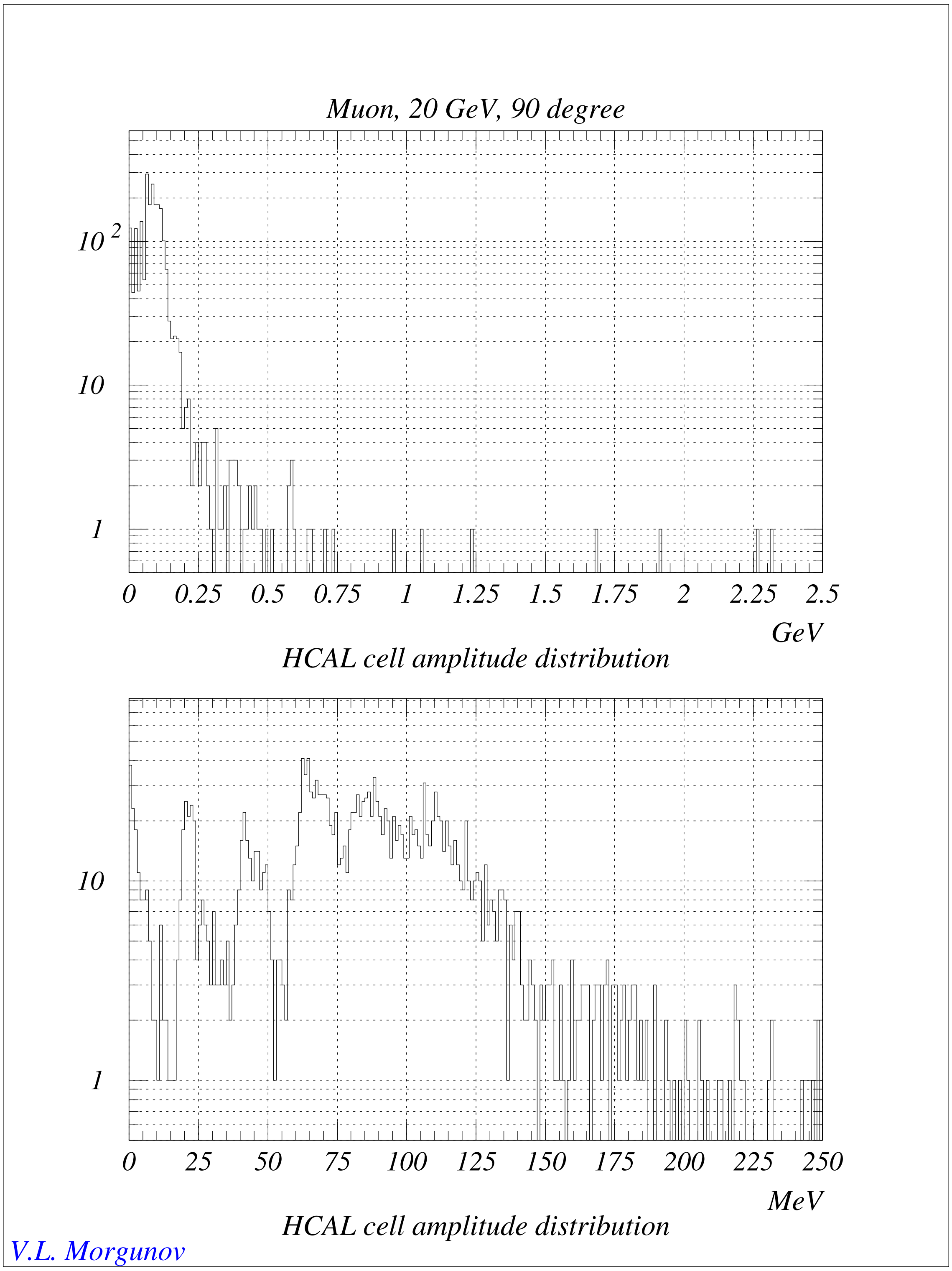
Muon, 20 GeV, 90 degree
10 2
10
1
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
GeV
HCAL cell amplitude distribution
10
1
0
25
50
75
100
125
150
175
200
225
250
MeV
HCAL cell amplitude distribution
V.L. Morgunov

Figure 5: