COMPASS Calorimetry in view of future plans

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Abstract. The COMPASS experiment at the CERN SPS is dedicated to hadron physics with a broad research programme, including the study of the nucleon spin structure using muons as a probe and a variety of issues in meson spectroscopy using hadron beams. The two stage fixed target spectrometer with electromagnetic (em) and hadronic calorimetry in both stages provides photon detection in a wide angular range. As discussed in this paper, the COMPASS em calorimetry plays a crucial rôle for the Hadron programme started in 2008 as well as for the planned COMPASS future programme of measuring GPDs via exclusive DVCS photons. We present the photon detection coverage foreseen, and first, preliminary results characterising the present performances of both existing COMPASS electromagnetic calorimeters, based on test beam data taken at CERN T9 facility end of 2007.

1 Introduction & motivation

1.1 The COMPASS experiment

The COMPASS fixed target experiment [1] at CERN SPS is dedicated to the study of nucleon spin structure and hadron spectroscopy, addressing the question of how nucleons and hadrons in general are built up from quarks and gluons [2]. The COMPASS Collaboration has already collected data scattering polarised muon beam of $160\,\mathrm{GeV/c}$ on polarised deuteron (^{6}LiD) and proton (NH$_3$) targets during the years 2002-2004 and 2006-2007. The gluon contribution to the nucleon spin is one example of physics determined from these data. For the hadron programme, merely a pilot run was performed in 2004, focusing on measuring the Primakoff reaction on a Pb target. Also some diffractive pion data on that target had been taken and pion dissociation into $\pi^-\pi^-\pi^+$ have been analysed [3].

In 2008 we have started to take high statistics data for spectroscopy of the light hadron sector at high energy ($190\,\mathrm{GeV/c}$, π^- beam). Pion-proton reactions comprising both diffractive and centrally produced final states allow the search for J^{PC}-exotic mesons, glueballs and hybrids. A sketch of the COMPASS spectrometer as used in 2008 is shown in Fig.1, for details see [1]. Emphasised are the existing em-calorimeters ECAL1, ECAL2 as well as ECAL0, which is foreseen to detect DVCS photons under angles larger than 12 degree, cf. Sec. 1.2. In 2008, a $40\,\mathrm{cm}$ long liquid hydrogen target (LH2) is used. To ensure the exclusivity of the measurements, it is surrounded by a newly introduced Recoil Proton Detector (RPD) performing a time-of-flight measurement of recoiling particles like protons. It consists of two concentric barrels of scintillator counters, read-out at both sides. It provides particle-identification capability and measures the recoiling proton momentum at few percent accuracy.

1.2 Future plans

The COMPASS Collaboration has expressed the interest for pursuing an experiment dedicated to the measurement of Generalised Parton Distributions (GPDs) [4]. This novel formalism
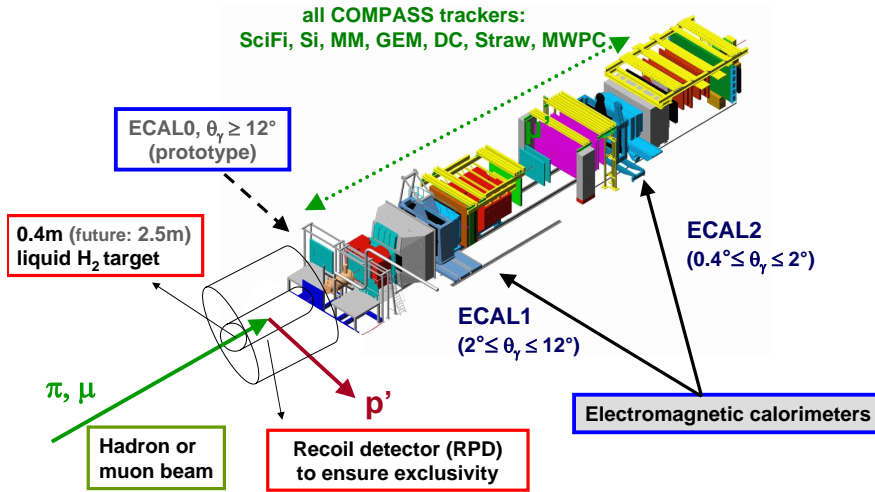
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Fig. 1. *Sketch of the COMPASS experimental setup as used in 2008 and beyond - not to scale.*

provides a three dimensional picture of partons inside the nucleon (longitudinal momentum fraction x and transverse impact parameter). In addition, the second moment of GPDs gives access to the total angular momentum carried by the partons inside the nucleon via the Ji sum rule [5], and hence they can provide new insights on the nucleon spin puzzle. The GPDs are accessible via hard exclusive reactions like Deep Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP), see Fig. 2. The plan is to measure them on (liquid) proton and deuterium targets.

As for the Hadron programme, the RPD detector is crucial to ensure exclusivity for measurements of DVCS and HEMP, for the former the calorimetry plays a mandatory rôle in addition. Even though the future GPD measurements are planned on a longer LH2 target, namely the order of a few meters, and ECAL0 is not yet designed, the ideal synergy and complementarity of both programmes is obvious. Since no big change over of the spectrometer is needed, both hadron and muon beams are available at CERN/SPS and easily switchable, we will go for a GPD pilot run during the 2009 Hadron run to study and optimise the feasibility for GPD via DVCS measurements.
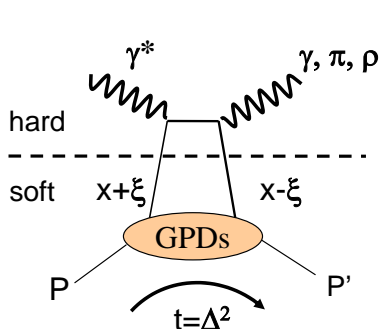

Fig. 2. *Handbag diagram for DVCS and HEMP reactions: longitudinal quark momentum fraction x, longitudinal momentum transfer $\xi = x_{\rm Bj}/(2 - x_{\rm Bj})$ to the nucleon, and the momentum transfer squared t to the target nucleon.*
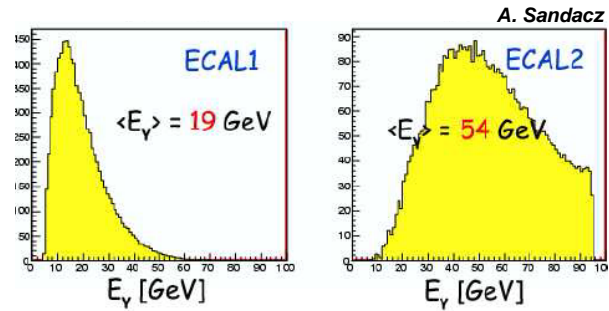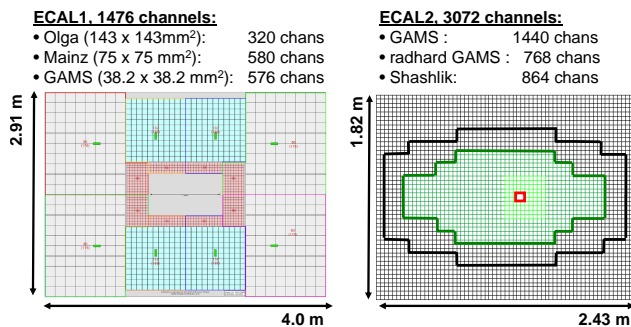

Fig. 3. *Simulated energy distribution of DVCS photons to be detected in ECAL1 and ECAL2. The minimum energies of DVCS photons to be detected in ECAL1 and ECAL2 are $5\,GeV$ and $10\,GeV$ respectively.*

Fig. 4. *Scheme of existing em-calorimeters - (left) ECAL1: Homogene lead glass Cherenkov counters of different cross sections - (right) ECAL2: New Shashlik sampling modules in central region, radiation hard lead glass (between green and black border), and GAMS lead glass blocks (outer region same as in ECAL1).*
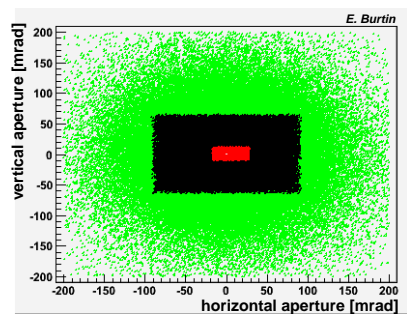
Fig. 5. *Calorimeter coverage foreseen: Simulated DVCS γ impact point at location of ECAL0. (ECAL0-green at 2.5 m downstream of the target, to be built; ECAL1-black at 11.1 m and ECAL2-red at 33.25 m, both existing)*

1.3 The rôle of COMPASS calorimetry

The em-calorimeters play a crucial rôle for both the hadron programme as well as the GPD measurements via DVCS, since neutral particle detection over a wide angular range are mandatory. On the one hand $\pi^0\pi^0$, $\eta\eta$ etc. final states are to be measured in order to search for exotics, hybrids and glueballs. On the other hand the goal is to detect DVCS photons at largest statistics, wherefore also the two photons from π^0's decaying need to be detected at high efficiency in order to ensure excellent background suppression. ECAL1 is $3.97 \times 2.86\,\mathrm{m}^2$ large, consists of lead glass blocks of three different sizes and has 1492 channels, whereas ECAL2 measures $2.44 \times 1.83\,\mathrm{m}^2$, applies three different type of modules (all of same size) and comprises 3072 channels in total, see also [1]. ECAL1 is in operation since 2006, and ECAL2 has partly been upgraded for the 2008 running: For the central part the lead glass GAMS blocks have been replaced by so-called Shashlik sampling modules newly developed at IHEP Protvino to cope with the higher irradiation dose and to improve the energy resolution for the small angle regime at high energies. In addition, most part of ECAL2 read-electronics have been upgraded (from 10 to 12 bit SADCs). ECAL1 provides a larger angular acceptance and detects on average photons of lower energy as compared to ECAL2, see Figs. 3 and 4.

The minimum DVCS photon energy to be detected in ECAL1 and ECAL2 is 5 GeV and 10 GeV respectively. Consequently, also π^0 of same energies have to be detected for background suppression. Since the π^0 decays into two photons, the lower energy threshold needed for efficient background suppression is determined by the lower energetic photon from the decay. A kinematics calculation deliver a lower energy threshold of less than 1.25 GeV (0.73 GeV) and 2.5 GeV (1.5 GeV) for ECAL1 and ECAL2 respectively in order to achieve a detection probability of better than 50 % (70 %). In Fig. 5 the calorimeter coverage of DVCS photon detection in terms of aperture (as foreseen for the future) is shown. In such a scenario[1] we were able to detect ∼ 90 % of the total number of DVCS photons produced. Nearly half of these photons, namely 43 %, would have to be detected by ECAL1, and about a quarter by ECAL2 (23 %) and ECAL0 (22 %) respectively.

In conclusion, for DVCS photon detection and good γ/π^0 separation, we need lower energy thresholds of ∼ 1 GeV and ∼ 2 GeV in ECAL1 and ECAL2 respectively; since the hardware thresholds are in the order of 150 MeV, there is, a priori, no limitation for lower energy thresholds below 1 GeV.

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[1] ECAL0 assumed to be $2 \times 2\,\mathrm{m}^2$ large, having a central hole of $1.2 \times 1.0\,\mathrm{m}^2$ and being located at about 2.5 m downstream of the target.
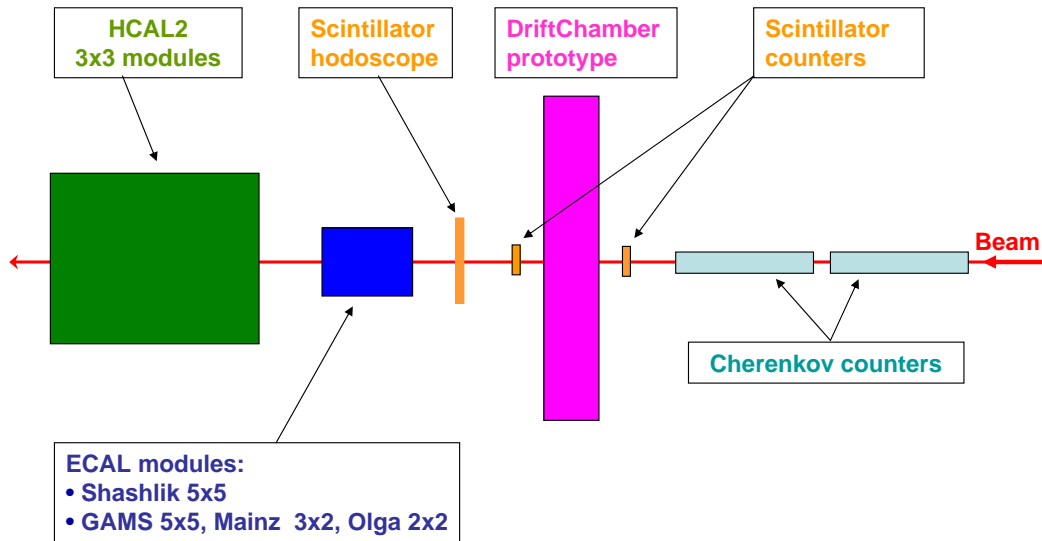
Fig. 6. *Experimental setup at CERN T9 test beam facility.*

2 Measurements at CERN T9 test beam facility

A test beam campaign has been performed at the T9 PS beam line in October 2007. The project was organised by the Protvino IHEP Group, first of all to characterise the new COMPASS radiation hard Shashlik modules developed at IHEP, and also to study the present performance of the COMPASS Calorimetry for better understanding and improving the capability for excellent calorimetry as needed for the COMPASS Hadron and DVCS future programmes.

At the CERN PS T9, a beam containing electrons, muons, pions and protons is available[2] in the energy range of 1-15 GeV. Two Cherenkov threshold counters belong to the infra-structure and allow for triggering on the different particles in the beam. Fig. 6 shows the experimental setup. Different types of COMPASS ECAL modules as well as 3x3 HCAL modules (and a drift chamber in front, as in the spectrometer) had been installed.

Different measurements were performed. Main goals of the measurements were the determination of energy resolution and uniformity of the different ECAL modules (5x5 matrix of GAMS modules, 3x2 matrix for Mainz and 2x2 for Olga were used), especially the performance comparison between the GAMS to the newly developed Shashlik modules, which replace the GAMS modules in the central part of ECAL2 for the 2008 run, cf. Fig. 4. For these studies, electrons were selected in the beam momentum range of 1-5 GeV, also data with muons and electrons of known energy, in the trigger were taken, cf. Sec. 2.2. Moreover, data were taken with pions in the beam momentum range of 1-10 GeV in order to study the combined response of electromagnetic and hadronic calorimeters.

Not all studies are yet enclosed. First results needed for the 2008 run preparation and as input for the DVCS physics proposal currently under work are discussed. Preliminary results of performance studies of the existing GAMS lead glass modules are exemplary shown in Sec. 2.1, and investigations on how to use muon signals for calibration and monitoring issues are discussed in Sec. 2.2.

2.1 ECAL performances based on T9 test beam data

For the GAMS blocks, a 5×5 matrix was installed and calibrated using the T9 electron beam of known energy, namely 4 and 5 GeV respectively. Calibration involves two main steps:

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[2] The beam charge is revertable at T9; due to the higher flux we used positive particles (electrons and muons for the studies presented).
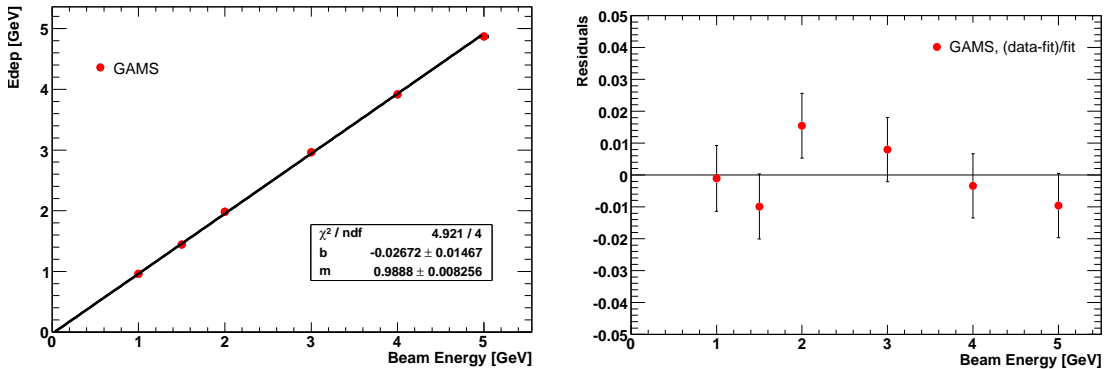
Fig. 7. *Linearity of COMPASS ECAL GAMS modules as measured at T9:* (left) *Measured energy deposit vs. beam energy;* (right) *Residuals of fit to the data points as shown left. (Preliminary)*

1.) Inter-calibration between different cells with the beam centered in each cell.
2.) Global calibration by summing up the energy deposit using the surrounding cells - summation $1 + 8 = 9$ is done (the central one and the 8 neighbours of the one the beam is centered on.) - and the summed energy is then scaled to the reference, namely the beam energy.

The final calibration using this approach reads as $E_{\mathrm{dep}} = 1/C \cdot \sum c_\mathrm{i} \cdot A_{\mathrm{el}}^\mathrm{i}$, where A_{el}^i are the measured electron amplitudes in individual cells, c_i the corresponding calibration coefficients obtained by the 1st step, the inter-calibration, and C the global calibration coefficient from the 2nd step. The measured energy deposit E_{dep} summing up i=9 modules for incident electron energies ranging from 1-5 GeV of the GAMS modules is exemplary shown in Fig. 7 - left. The deviations from the linear fit: $(\mathrm{data} - \mathrm{fit})/\mathrm{fit}$, is given by Fig. 7 - right. The error bars along the ordinate take into account only the statistical error, whereas for the abscissa, an uncertainty of beam particle momenta of 1.0 % has been estimated. The relative differences from the linearity of up to 2 % in the energy range studied are mainly within the uncertainty of the initial beam energy. The beam energy error has been incorporated into the statistical error on the ordinate. These differences could hint at a small but systematic effect, non-linearity of 1 to 2 % have also been observed for lead glass calorimeters by other experiments at few GeV energies [6].
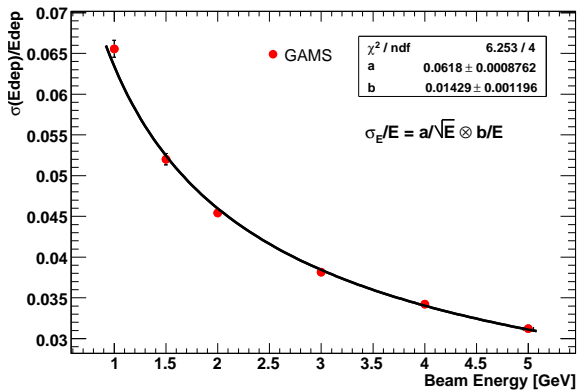

Fig. 8. *Energy resolution of GAMS lead glass modules as measured at T9 test beam facility. (Preliminary)*

Fig. 8 shows the relative width of the energy deposit $\sigma(E_{\mathrm{dep}})/E_{\mathrm{dep}}$ (energy resolution) distribution as a function of the incident beam energy and the corresponding fit using two parameters.

In conclusion, the present resolution of the GAMS modules is determined to be $\sigma_\mathrm{E}/E = 6.2\,\%/\sqrt{E}$ and a constant term of 1.4 %. Corresponding studies for Mainz and Olga modules[3] (not explicitly shown here) deliver $7.0\,\%/\sqrt{E} \oplus 1.8\,\%$ and $4.3\,\%/\sqrt{E} \oplus 3.2\,\%$ respectively, where $\oplus$ denotes the quadratic sum $a \oplus b = \sqrt{a^2 + b^2}$. All these values have to be taken as preliminary, since analysis of T9 test beam data is not yet enclosed.

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[3] Mainz and Olga modules are larger than GAMS by a factor of 3.85 and 14 respectively in cross-section so that summing up 3×3 modules is not needed to minimise transversal leakage; sum over 4 modules is however needed since the beam position was close to the centre of 4 modules.
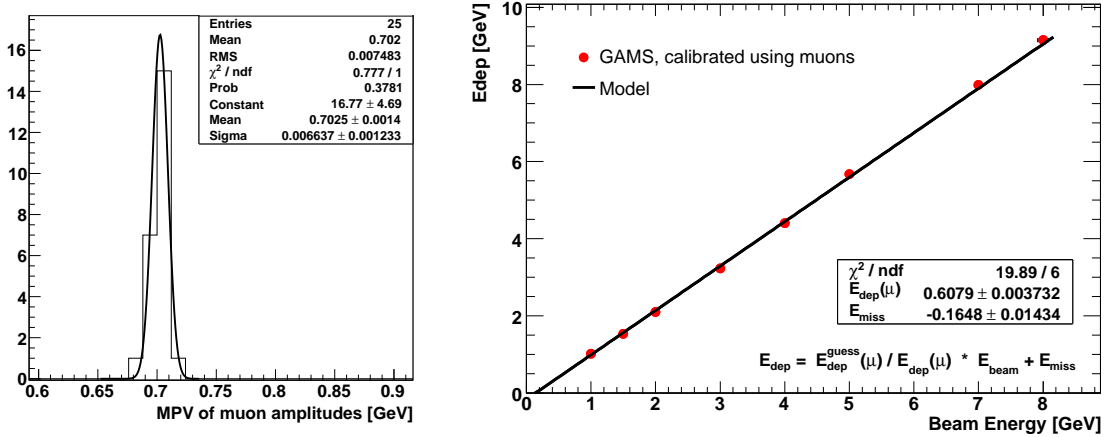
Fig. 9. (left) *Distribution of fitted muon amplitudes after inter-calibration using muon signals, mean value $A_\mu = 0.703$ ($\sigma = 0.007$) GeV. (right) A linear fit to E_{dep} values obtained for GAMS for T9 electron beam energies ranging from 1 to 8 GeV. Fitted parameters are $E_{\mathrm{dep}}(\mu) = 0.608 \pm 0.004\, GeV$ and $E_{\mathrm{miss}} = -0.165 \pm 0.014\, GeV$.*
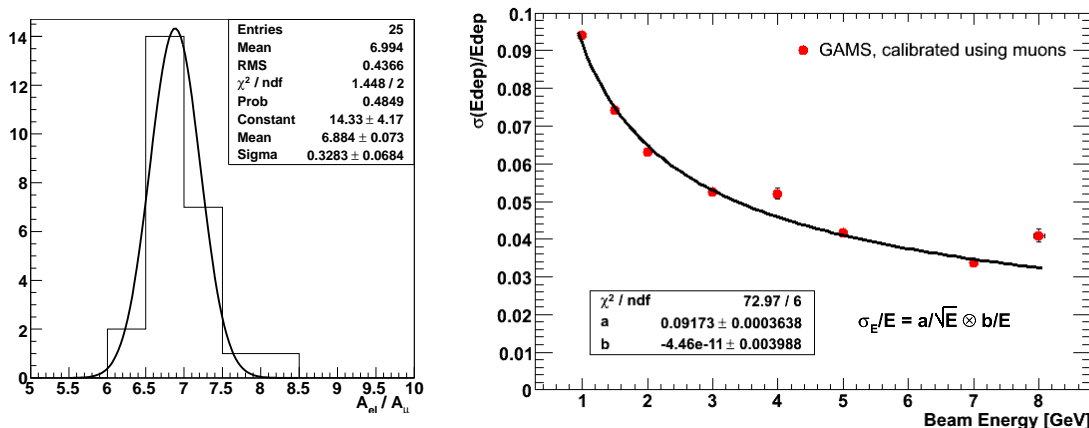
2.2 Calibration using muons

To calibrate the ECALs at place inside the spectrometer with electrons necessitates a special tuning of our beam line and also to move the ECAL structure across the beam line. Certain limitations are inherent to this method and alternative options, which allow to inter-calibrate the ECAL cells and also to monitor the gain stability, are exploited. Hadrons and muons, which deposit a non negligible amount of energy in the ECALs, can be used to complement calibration, as done in other experiments [7].

A cross-calibration using electrons and muons has been performed on the T9 test beam data reported here. The muon signal results from all the photons detected, which have two main sources: Cherenkov light produced directly by the muon (well above threshold) and Cherenkov light produced indirectly by the ionization losses processes (e.g. δ-electrons). Precise prediction of the muon signal amplitude in equivalent electromagnetic energy requires a full simulation (under way). For the cross-calibration technique, however, such complex task is, a priori, not essential since this method involves measuring the ratio A_{el}/A_μ between the muon and electron signal amplitudes.

The 5 GeV muon signal in the GAMS cells was assumed, as a first guess to correspond to $E_{\mathrm{dep}}(\mu) = 0.7\,\mathrm{GeV}$ providing the 1st calibration (better than 1 %), see Fig 9 - left, which can in principle be done with any value, cf. Sec. 2.1. The T9 electron beam energy was varied from 1-8 GeV and the corresponding energy deposit E_{dep} was measured, summing up 9 modules and using this 1st calibration. It was previously established, see Fig. 7, that the GAMS cells have excellent linear response to electrons in this energy range. A linear fit to the full set of E_{dep} measured after this inter-calibration was performed with two parameters: $E_{\mathrm{dep}}(\mu)$ corresponding to the true effective muon energy deposit and E_{miss} representing the minimum measurable E_{dep} (lower energy threshold). Result from the fit is shown in Fig. 9 - right. One sees that the first guess of $E_{\mathrm{dep}}(\mu) = 0.7$ GeV leads to an overestimate of electron energy by $\sim 15\%$ at e.g. 5 GeV. As a cross-check, the different cells were inter-calibrated using the value of $E_{\mathrm{dep}}(\mu)$ from this fit and the same quality in describing the data is achieved when just fitting the one parameter E_{miss}, i.e. the overestimation of electron energies is corrected when inter-calibrating the individual cells directly to $E_{\mathrm{dep}}(\mu) = 0.608\,\mathrm{GeV}$, namely the correct value as indirectly measured or obtained in Fig. 9 - right.

The resulting energy resolution $\sigma(E_{\mathrm{dep}})/(E_{\mathrm{dep}})$ as a function of electron beam energy is given in Fig. 10 - right. These results based on the inter-calibration of GAMS cells using muon signal and a cross-calibration to electron signals of known energy should be compared to the similar results shown in Figs. 7 and 8 obtained doing the full procedure using electrons only. The resolution obtained with this method is worse by merely ~ 2-3 %, which is consistent with

Fig. 10. (left) *Distribution of A_{el} to A_{mu} ratio of GAMS cells, mean value $A_{el}/A_\mu = 0.688$ ($\sigma = 0.328$). (right) Energy resolution of GAMS lead glass modules obtained using muon signals. The ECAL GAMS modules have been inter-calibrated with muon signals and cross-calibrated to electron signals of known energies as measured at T9 test beam facility, see also Fig. 9. (Preliminary)*

the spread observed in the distribution of A_{el}/A_μ ratios of individual cells, given in Fig. 10 - left. Indeed the spread for all 25 GAMS cells is about 5 %, however, the central GAMS cell contains about 85 % of total electron beam energy deposit (in the given range of few GeV), and the central one was checked to deviate by ~ 2.5 % from the mean value of all 25 A_{el}/A_μ ratios. The further 8 cells involved in the E_{dep} measurement show a spread of ~ 5 %. Weighting these inaccuracies correspondingly leads to a decrease in resolution by 2-3 %.

3 Conclusions

Excellent COMPASS calorimetry is mandatory for both, the present 2008/09 COMPASS Hadron running as well as the GPD measurements via DVCS as foreseen at COMPASS for the future. The present performances of existing ECAL lead glass blocks (GAMS, Mainz and Olga) have been quantified, and the derived numbers serve as realistic input for ongoing Monte Carlo Simulations. It should be noted that a simplified method for calibration was applied here as compared to the more sophisticated procedure within the official COMPASS reconstruction (of much larger number of ECAL channels) comprising multiple iterations. It has been shown that for calibration and monitoring issues, the signals from muons can be used for inter-calibration. Together with a cross-calibration to electron signals of known energy, this calibration procedure turns out to be merely worse by 2-3 % as compared to the full calibration using electrons. A proof of principle has been provided for the GAMS cells.

4 Acknowledgements

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