High purity 100 GeV electron identification with synchrotron radiation

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ABSTRACT

In high energy experiments such as active beam dump searches for rare decays and missing energy events, the beam purity is a crucial parameter. In this paper we present a technique to reject heavy charged particle contamination in the 100 GeV electron beam of the H4 beam line at CERN SPS. The method is based on the detection with BGO scintillators of the synchrotron radiation emitted by the electrons passing through a bending dipole magnet. A 100 GeV π^- beam is used to test the method in the NA64 experiment resulting in a suppression factor of 10^{-5} while the efficiency for electron detection is ∼95%. The spectra and the rejection factors are in very good agreement with the Monte Carlo simulation. The reported suppression factors are significantly better than previously achieved.

1. Introduction

Many high energy experiments require pure electron beams. Despite the steady improvement, the available energy of pure primary beams from electron machines is limited. Furthermore, the specific time structure made of very short pulse trains is not suitable for counting experiments. Secondary electron beams can provide higher beam energies with a uniform time structure. However, in secondary beams a contamination of particles other than electrons below a level of few % is basically unavoidable. An example is the NA64 experiment at CERN in which it is mandatory to suppress hadron and muon contamination in the electron beam since such particles can generate irreducible background processes mimicking the experimental signature of a dark photon [1,2]. NA64 uses 100 GeV electrons from the H4 SPS beam line at CERN which is one of the best existing beam lines at this energy in terms of beam purity [3].
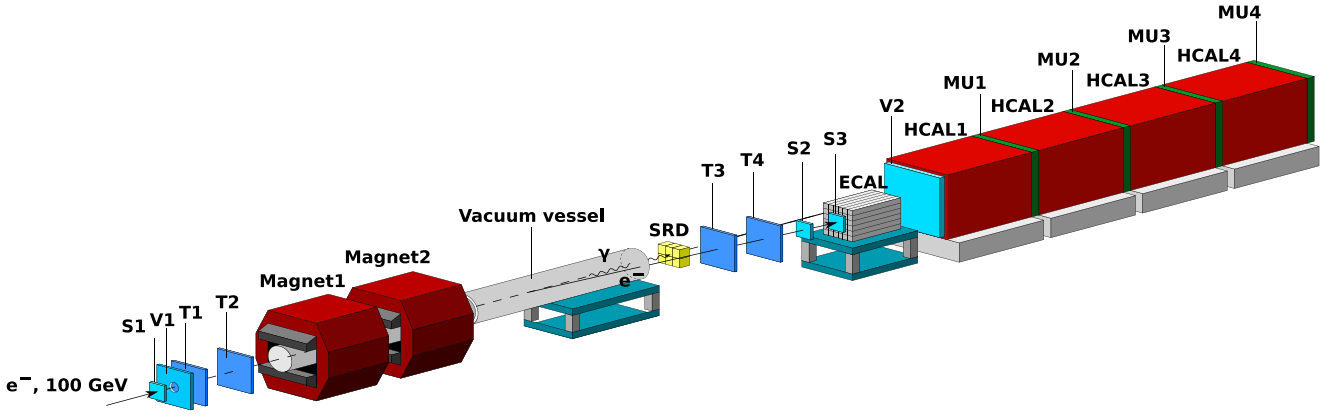
Fig. 1. Drawing of the NA64 experimental setup used for these measurements (from [2]).

The standard technique of detecting Cherenkov radiation to distinguish between electrons and heavy charged particles is very inefficient at energies of 100 GeV [4]. Instead in NA64 we detect the synchrotron radiation, produced by the electrons passing through a dipole bending magnet, using BGO crystals located downstream of the magnet. NA64 is a fixed-target experiment at the CERN SPS [2] combining the active beam dump and missing energy techniques to search for rare events predicted in Dark Sector models [5]. The electron beam is dumped in an active target, an electromagnetic calorimeter (ECAL) made of lead and scintillators in a sandwich geometry of shashlik type (corresponding to about 40 radiation lengths) [2]. If Dark Sectors exist, bremsstrahlung photons generated in the target could produce dark photons (A') via kinetic mixing [6–8]. The dark photons could then decay to a pair of particles in the Dark Sector (χ) which will escape the setup undetected.

The basic concept of using the synchrotron radiation emitted from high-energy electrons to reject heavy charged particles is to exploit the high suppression of the radiated power emitted by particles heavier than electrons passing through a magnetic field in order to discriminate them. The use of this technique is not new. Detection of electrons or positrons in electron beams with momenta ranging from 30 to 50 GeV has been reported earlier by [9–11] and the achieved suppression factor was around 1%. However, here we present the results obtained with this method using the BGO detector employed in NA64. As will be shown, our results have a very good overall efficiency 95% and 3 orders of magnitude better rejection factor than previously reported using a similar scheme [10].

A charged particle in a magnetic field moves in a circular motion, emitting photons along its trajectory due to the basic principles of electrodynamics. Both quantum and classical theory of synchrotron radiation (SR) are well understood [4]. In the range of interest for our experiment both treatments are equivalent and we can therefore use the classical approximation for our calculations. The total power S emitted per unit length by a relativistic charged particle of energy E with mass M and with bending radius R in a magnetic field B perpendicular to its velocity is given by:

$$S = \frac{q^2 c}{6\pi} \frac{1}{(Mc^2)^4} \frac{E^4}{R^2} \tag{1}$$

where q is the charge of the particle and c the speed of light. Since the emission angle of the synchrotron photons is proportional to the inverse of the Lorentz factor γ, the photons are emitted tangentially to the particle trajectory.

The total emitted power has an inverse scaling to the fourth power of the charged particle mass. Therefore, heavy charged particles emit orders of magnitude less synchrotron radiation than light ones. For $\mu^{+/-}$ and $\pi^{+/-}$ with about 200 e^- mass, one can estimate that they radiate $\sim 10^{-9}$ times less than an electron. This would be the case if the particles propagate in an ideal vacuum. However, in a real experimental setup,

vacuum windows, residual gas, beam counters such as scintillators and trackers result in interactions of the incoming particles with material. Therefore, the suppression factor when crossing materials is limited by the emission of secondary electrons with enough kinetic energy (several MeV) to leave a synchrotron-like signal in the detector. Although most of the ionization loss of heavy charged particles is only a few keV, rare high energy transfer to the secondary electrons is possible. The distribution of such secondary electrons with kinetic energy $T \gg I$, where I is the mean excitation energy of the atom/molecule, for a particle with velocity $\beta = v/c$ and charge z passing through a material with atomic number Z, mass number A and thickness dx is described by [12]:

$$\frac{d^2 N}{dT\,dx} = \frac{1}{2} K z^2 \frac{Z}{A} \frac{1}{\beta^2} \frac{F(T)}{T^2}. \tag{2}$$

The constant K is defined as $K = 4\pi N_A r_e^2 m_e c^2$ where N_A is Avogadro's number, r_e is the classical electron radius and m_e the electron mass. $F(T)$ is a spin-dependent factor, which in our case for $T \ll W_{max}$ is very close to unity. W_{max} is the maximal energy transfer in a single collision to the electron:

$$W_{max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}. \tag{3}$$

For a π^- at 100 GeV, W_{max} is roughly 1 GeV which covers completely the energy range where synchrotron radiation is emitted. Eq. (2) is valid in the range $I \ll T \leq W_{max}$.

The total emitted power scales with the energy of the charged particle to the fourth power. In principle, this scaling would make it possible to correlate the total energy emitted via synchrotron radiation with the momentum of the particle. However, the broad total energy distribution of the synchrotron radiation would result in a very low efficiency for rejecting 50 GeV electrons in a 100 GeV beam. Furthermore, experimental issues limit this approach. In fact, electrons interacting with the material or the residual gas can generate Bremsstrahlung photons that overlap with the synchrotron radiation spectrum and spoil the energy reconstruction capability. For this reason, in NA64 such an approach alone is not enough to achieve the sensitivity required by the experiment and therefore a tracking system is mandatory to reject low energy electrons [13].

2. Experimental setup

The NA64 experimental setup [2] used for this measurement is shown in Fig. 1. As shown in Fig. 1, a set of veto counters (denoted as V2 in the drawing) and 4 hadronic-calorimeter (HCAL) modules placed directly after the ECAL ensures the Hermiticity required to search for the missing momentum with the aimed sensitivity. The experimental signature is thus an energy deposition below a given threshold (around 50 GeV in NA64) in the ECAL, no activity in V2 and no energy deposition in the HCAL. In Fig. 2 the energy deposition in the ECAL for a 100 GeV
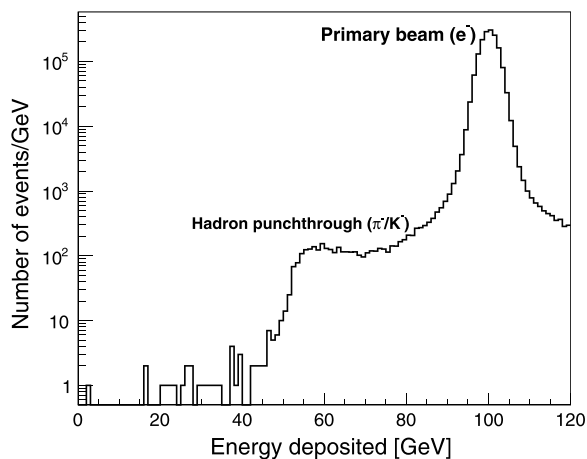
Fig. 2. Measured spectra of the energy deposited in the ECAL for the 100 GeV electrons delivered by the H4 beam line.

Fig. 3. Result of the Geant 4 simulation for the energy detected by the SR detector for 50/100 GeV e⁻ (black dashed/solid line) and 50/100 GeV π^- (red dashed/solid line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

electron beam is shown. In addition to the expected peak at 100 GeV from electrons, one can see the presence of hadrons punching through the ECAL and the peak close to zero from minimum ionizing particles (MIP). Since hadrons and muons are a source of background for the experiment [1], their contamination in the beam has to be suppressed at a level of 10^{-5}. The synchrotron radiation detector (SRD) described in this paper was designed to serve this purpose.

To reject low-energy electrons and heavier charged particles, a synchrotron radiation detector (SRD) is required to have a good energy resolution (see Eq. (1)). Moreover, in order to work efficiently at high rates of 1×10^5 particles/s good timing properties are necessary.

We chose $Bi_4Ge_3O_{12}$ (BGO) crystals the properties of which are a good compromise in terms of energy and time resolution. The detector consists of 8 hexagonal crystals with an external diameter of 55 mm and a length of 200 mm. The crystals are grouped into two modules. Each crystal is wrapped in Teflon tape for efficient light collection and one of the base of the hexagon is glued to a 2 inch ETL 9954 photomultipliers (PMT). The gain of the PMTs was set using a 100 GeV π^- beam impinging directly on the SRD. The pions crossing the BGO have a mean energy deposition of about 60 MeV, as expected for a MIP particle, which is in the range of the SR radiation.

The BGO has a density of 7.13 g/cm³ and a light yield of about 8500 photons/MeV, this coupled to the transportation losses and quantum efficiency of the PMT gives an energy resolution of about 17% (FWHM) at 1.27 MeV (measured with a²²Na radioactive source). All the crystals were tested using cosmic muons and their decay time was measured to be about 300 ns in good agreement with the value quoted in literature [14]. The BGO's signals are digitized by the MSADC system [15] which is connected to the DAQ of the experiment. The DAQ is stripped-down version of the COMPASS iFDAQ system [16].

3. Geant 4 simulation of SR spectra

Simulation of the expected SR signal was performed with the Geant 4 package [17]. The geometry of the NA64 experiment was coded in Geant 4, including the 200 μm mylar vacuum windows, the detailed composition of the trackers, scintillators and the residual gas was set at a level of 10^{-3} mBar as in the measurements. Saturation of BGO was taken into account using Birks' law with the constants taken from [18].

The expected SR spectra for pions and electrons with energies of 50 GeV and 100 GeV are shown in Fig. 3. The plot shows the expected dependence on the incoming electron energy in the emission spectra for the realistic experimental conditions. Moreover, the comparison between the SR spectra of pions and electrons illustrates clearly the principle of this technique that allows to discriminate between them
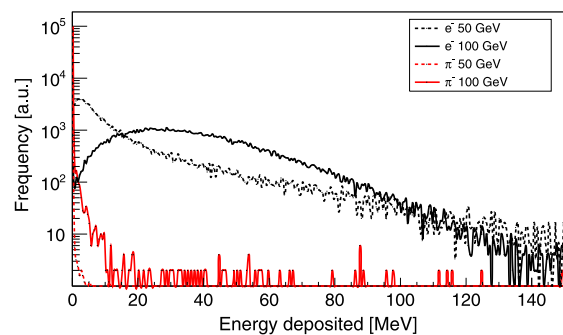
by requiring an energy threshold in the synchrotron detector. For pions, one can see that the probability of detecting an event with energy above 1 MeV (the threshold in our detector) is about $\sim 10^{-3} - 10^{-4}$. These SR-like signals originate from the interactions of the incoming pions with material which they ionize as predicted by Eq. (2).

Furthermore, Geant 4 reproduces the critical energy E_c which divides the spectrum into two parts of equal power is:

$$E_c = \frac{3\hbar c \gamma^3}{2R} \tag{4}$$

with the reduced Planck constant $\hbar$ and the bending radius R. For 100 GeV electrons in the $B = 1.7$ T bending field this corresponds to $E_c \sim 11.35$ MeV. The expected mean energy of a synchrotron photon $E_m = E_c/\pi \simeq 3.6$ MeV is in very good agreement with simulation. The number of photons emitted per revolution in this energy range in the field of 7 T m is defined as:

$$N_\gamma = \frac{5\pi\alpha}{\sqrt{3}}\gamma \tag{5}$$

where α is the fine structure constant. By scaling this equation for the fraction of the circle where the particles are inside the magnetic field, one obtains a mean number of emitted photon of about 24. The SRD geometrical acceptance is about one third, thus one can estimate that the sum of deposited energy is approximately 29.35 MeV in good agreement with the results of the simulation as shown in Fig. 3.

4. Experimental results

The SRD detector was tested during the NA64 test beam run in July 2016. The two BGO rows are parallel to the primary beam direction as shown in Fig. 4. The dipole magnets installed in series (see Fig. 1) produce a total integrated magnetic field of 7 T·m [2] resulting in a nominal displacement for the incoming electrons at the SRD/ECAL positions of 31/34 cm from the undeflected beam axis. The SRD was placed between the undeflected and the deflected beam axis at a distance of approximately 9 cm from both (Fig. 4). This separation minimizes the possibility for Bremsstrahlung photons and neutral particles produced by interactions of the beam particle with materials upstream (vacuum windows, collimators, trackers...) and for particles in the beam halo (the FWHM of the beam is approximately 1.5 cm) to hit the SRD. In fact, such interactions result in the saturation of the SRD with a significant loss of efficiency due to the long decay time of the BGOs.

The two crystals facing the beam (labeled 3 and 7 in Fig. 4) detect most of the energy emitted by synchrotron radiation. We will refer to those as SRD BGOs from now on. The remaining six crystals are used to detect events with high energy deposition in the SRD. In particular the last two crystals of each row (labeled 0 and 4 in Fig. 4) detect some energy only in the case of very energetic Bremsstrahlung events and thus can be used as a veto (see Fig. 4). The six crystals after the SRD
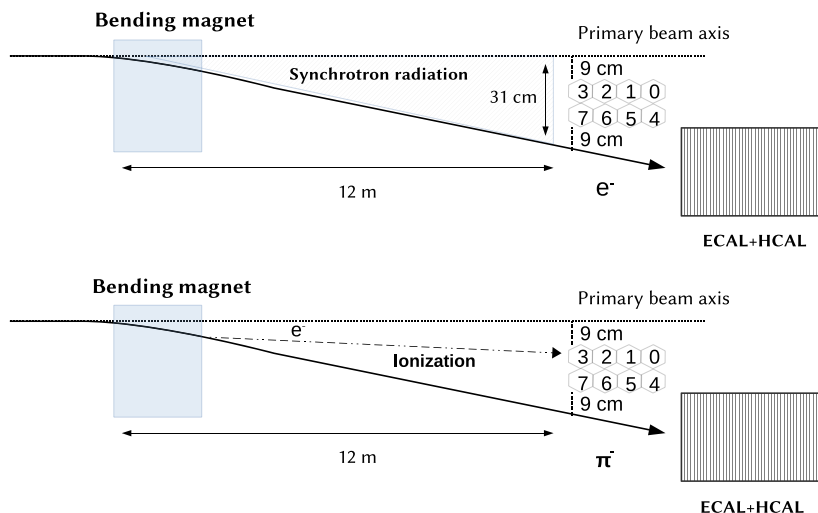
Fig. 4. Geometry of the BGO crystals. Crystals 7, 3 (SRD BGO) collect most of the synchrotron radiation spectrum. Crystals 4, 0 (VETO BGO) on the other hand are effected only in case of a high energy event and are thus used as a veto. The remaining crystals serve as a shield for the SRD from backscattering particles coming from the ECAL. Top: illustration of event leaving a SR signal in the SRD. Bottom: illustration of a SR-like signal in the SRD for a knock-on electron produced by pions.

BGOs act also as a shield from backscattering particles coming from the ECAL suppressing pions by an additional order of magnitude. Finally in this geometry it is possible to use the coincidence of the two SRD BGO crystals to improve the tagging of synchrotron photons by rejecting knock-on electrons produced by incoming pions. In fact synchrotron radiation has a homogeneous spectrum in the whole arc described by the primary and deflected beam and thus a signal is detected in both SRD BGOs. On the contrary, electrons generated by a π^- undergoing ionization will mostly leave energy only in a single crystal as illustrated in Fig. 4. With the requirement of detecting in both SRD BGOs an energy deposition above a 1 MeV the suppression factor is improved up to a level of 10^{-5}.

Data with a 100 GeV π^- beam were taken to have a direct measurement of the suppression factor achievable through synchrotron radiation measurements. The beam intensity was 5.3×10^4 particles per spill. The trigger was given by the coincidence of the three plastic scintillator counters (S1, S2 and S3 shown in Fig. 1). The additional requirement of an energy deposition below 60 GeV in the ECAL was applied in order to select an almost pure π^- sample of $\sim 10^5$ collected events. The probability for electrons to punch through the 40 radiation lengths of the ECAL was estimated to be at a level of 10^{-12} [2].

For the 100 GeV electron beam run, a total of 220 spills were recorded with an intensity of 3.4×10^5/spill. The same trigger used in the pion run was used for the electron data. In this case though, in order to reduce the pion contamination which is at a level of few % and obtain a pure sample of electrons-only events with a total energy deposition in ECAL + HCAL above 90 GeV but with less than 20 GeV energy in the HCAL were used.

The energy spectra recorded by the SRD BGO with electrons and pions are shown in Fig. 5. The SR spectra obtained with the electron beam are used to perform the BGO calibration by comparison with the simulation. With this method a very good agreement of data and MC is achieved (see plot on the left of Fig. 5). As a cross check, using the obtained calibration constants, the data from the pion beam impinging directly on the SRD are fitted with a Landau distribution. The obtained peak position of 60 MeV is in good agreement with the prediction of the MC.

Time coincidence of signals above the energy threshold of 1 MeV from both SRD counters is required and high energy Bremsstrahlung events are removed using the veto BGO. The suppression of synchrotron radiation emission detected for pions compared to electrons is clearly visible by comparing the two plots. For the electron spectrum, a 1% pileup beam events have been added to the simulation as predicted for

Table 1
Fraction of pion and electron events for different hit multiplicity in the SRD from the data.

Events hit multiplicity (%)	0 BGO	1 BGO	2 BGOs
Pions	98.77	1.21	1.4×10^{-3}
Electrons	2.4×10^{-1}	2.60	97.37

the given spill intensity and with the known decay time of BGOs. Both spectra are in very good agreement with the simulation.

The efficiency for the electrons and the suppression factor for the pions are plotted in Fig. 6 as a function of the threshold on the energy deposited in the SRD. We distinguish between two cases:

1. The threshold is set on the total energy deposited in the SRD.
2. Both SRD signals have to be in-time and above the threshold of 1 MeV (multiplicity requirement).

One can see that applying the criterion (2) the efficiency only decreases slightly compared to (1), while the suppression factor for pions is dramatically increased (by two orders of magnitude) with the requirement of having the two BGOs in coincidence. This can be understood because the SR-like signal generated from secondary electron will leave a signal only in one of the two BGOs while the SR from electrons is spread out uniformly as explained above. This is also nicely evidenced by Table 1 where the fraction of events with different hit multiplicity in the SRD BGO for both pion and electron runs are reported.

5. Conclusions

In this paper we demonstrated that detection of synchrotron radiation using BGO crystals is a very powerful method to tag 100 GeV electrons bending in a 7 T m magnetic field. Discriminating on the total energy deposited in the SRD by setting a threshold of 10 MeV, the contamination of pions in the beam can be suppressed down to a level of 10^{-3} (see Fig. 6). Moreover, we have shown that exploiting the granularity of the detector one can suppress the signal from secondary electrons generated via hadron ionization resulting in a suppression of hadron contamination down to a level 10^{-5} maintaining an electron identification efficiency of $\sim 95\%$. According to the Geant 4 simulation validated with our measurements a further improvement by an additional order of magnitude is expected by increasing the detector granularity. In order not to degrade the efficiency due to pileup effects
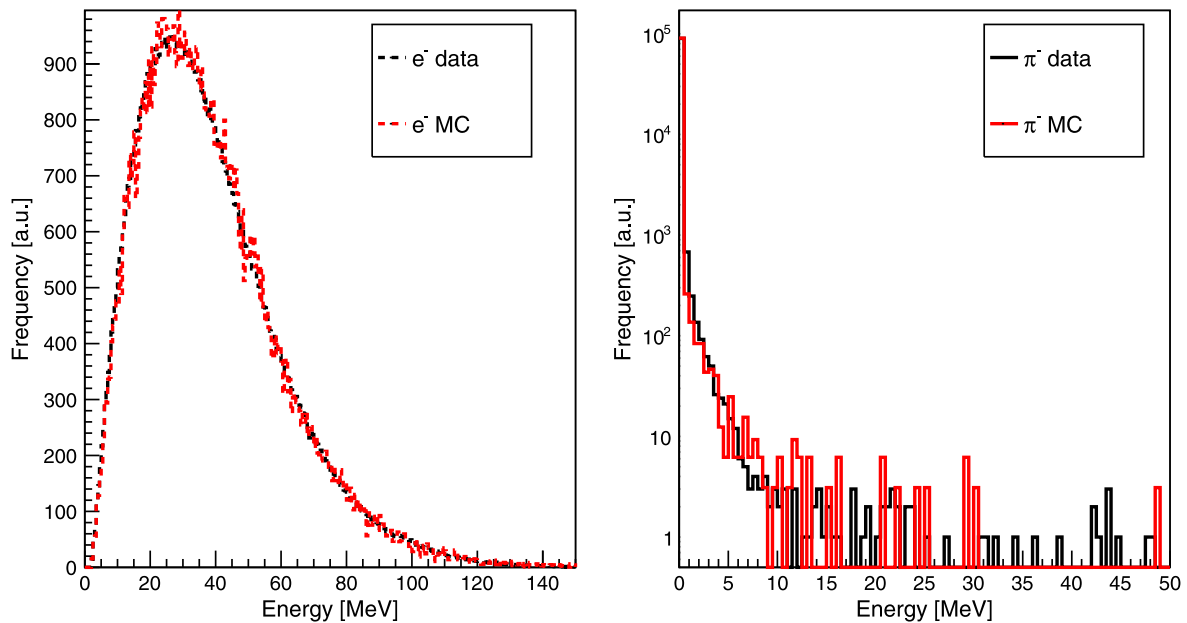
Fig. 5. Comparison between data and simulation (MC) of the synchrotron radiation spectrum detected for 100 GeV electrons (left) and pions (right).
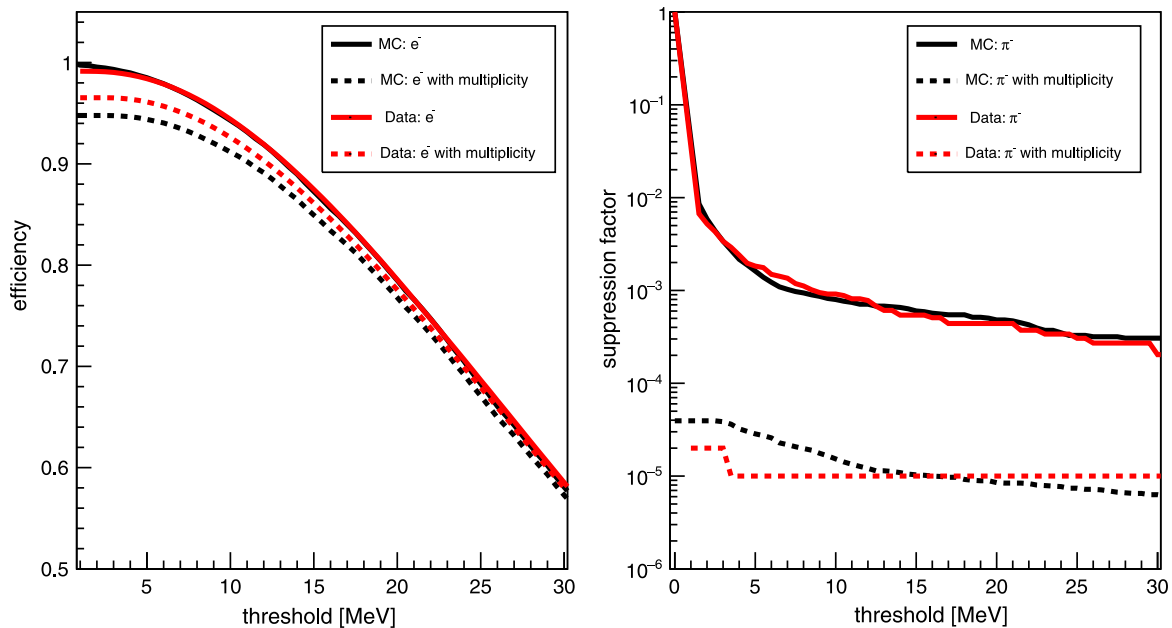

Fig. 6. Left: Comparison between data and simulation (MC) for electrons of the efficiency as a function of threshold set on the total energy deposited in the SRD BGO and for the requirement that this is deposited in each single crystal (multiplicity). Right: Comparison between data and simulation for pions and electrons of the suppression factor as a function of the threshold set on the total energy deposited in the SRD BGO and for the multiplicity requirement.

at higher beam intensity of 1×10^6 electrons/s as achievable in the H4 beam line at the CERN SPS, one should use faster detectors such as a PbSc sampling calorimeter or LYSO crystals. These options will be tested by the NA64 collaboration in the near future.

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