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ABSTRACT

Radiative energy losses of 300 GeV muons in the prototype calorimeters (Liquid Argon, e.m., and Fe+Scintillator tiles, hadronic) of the ATLAS collaboration for LHC have been measured in a dedicated run. These results allow to check the existing theoretical predictions, which still have some uncertainties. The spectrum of released energy has been measured up to the end-point, and it is has been compared to detailed Monte Carlo calculations.

1 Introduction

From the point of view of the e.m. interactions, muons can be considered just as heavy electrons. Therefore they undergo all the same processes as electrons, including bremsstrahlung and pair production. Excellent reviews of muon e.m. interactions are given in refs. [3], [4], [8]. However, it must be pointed out that while the radiative processes by electrons and positrons are by now well understood and checked against the QED predictions, a few uncertainties still exist for muons. The main reasons stem both from theoretical aspects (as summarized later in this paper) and experimental problems: in fact one has to consider that these interactions must be studied with high energy muons, and a large statistics is needed. In the literature a few works can be found where high energy cosmic muon events have been analysed [1, 5], and, to our knowledge, only one [6] with a monochromatic 200 GeV beam. These analyses are appreciable, but suffer from lack of statistics in the crucial region of the radiated energy spectrum, and in the case of cosmic rays studies, also from the uncertainties on the knowledge of local energy spectrum. A more precise investigation of these phenomena, using data taken in well controlled conditions, is therefore necessary, not only because it is interesting in itself, but also because of some specific experimental needs. For instance, a precise knowledge of these phenomena will allow a more reliable calculation of the survival probabilities of multi-TeV muons for large depths of soil, rock or water, and this can be

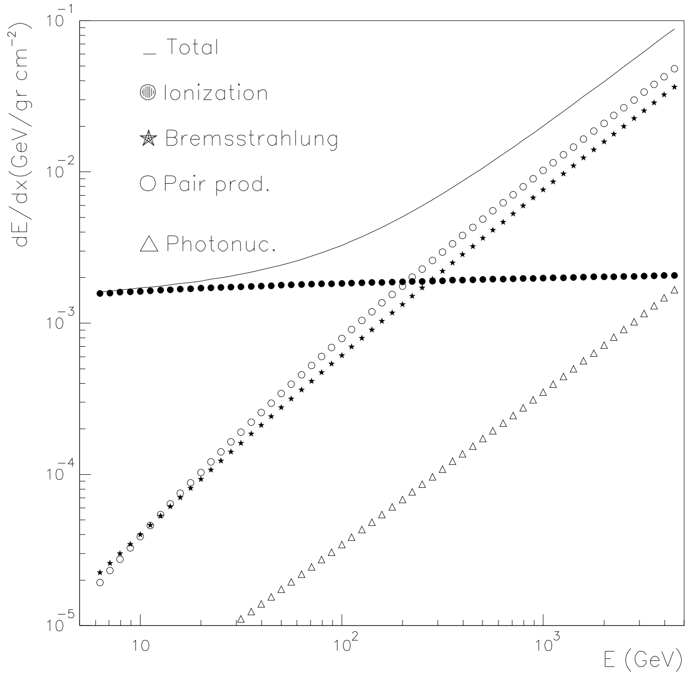

Figure 1: Total and partial energy losses for muons in lead as a function of muon energy

essential for some non-accelerator experiments [7]. Another important example is the analysis of the systematics in muon detection at the future hadron colliders.

2 Muon Interactions

Beyond atomic ionization (including δ-ray production) and excitation processes, the most important processes that muons undergo are: bremsstrahlung, e^+e^- pair production and photo-nuclear interactions . The relative importance of these processes depends both on the target material, and on muon energy. As shown in fig1 for Lead, radiative processes start to dominate the muon $\frac{dE}{dx}$ when the muon energy exceeds a few hundred GeV. Their contribution, however, is made up by relatively rare events with significant fractional energy losses (we define, as usual, the fractional energy loss as $v = \frac{\Delta E_\mu}{E_\mu}$), as shown in fig.2 for 300 GeV muons in Lead. Bremsstrahlung dominates the hardest part of the energy loss spectrum, while pair production the intermediate part.

Most of present calculations concerning muon transport are based on the cross sections reviewed in ref. [8]; there, the formulation of A.A.Petrukhin and V.V.Shestakov [2] for muon bremsstrahlung is considered. However, as already pointed out in [9, 10], a few uncertainties still exist, concerning mainly the treatment of nuclear screening, Coulomb and radiative corrections in the cross section [9, 10, 3, 4, 11, 2, 1]. The difference in the total differential cross section

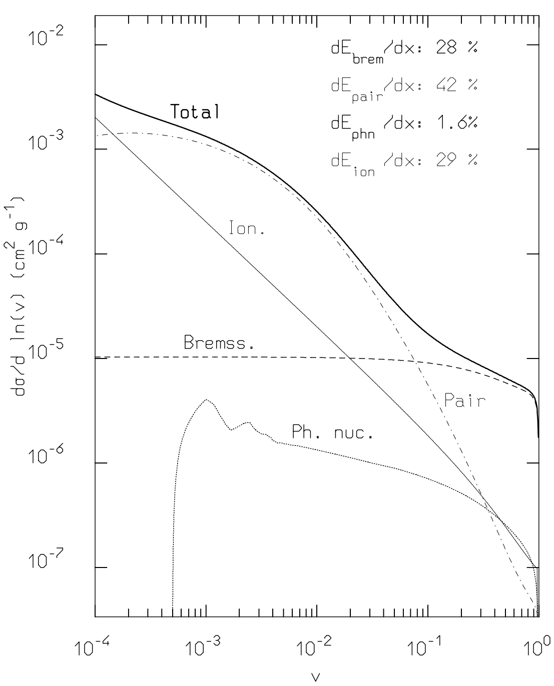

Figure 2: Differential cross sections as a function of v for the radiative processes of 300 GeV muons in lead.

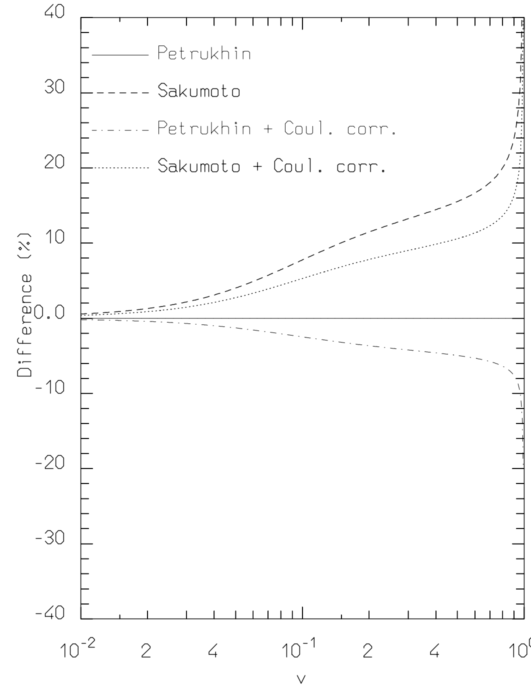

Figure 3: Energy loss difference for 300 GeV muons in lead using refs. 1) and 2) for bremsstrahlung.

$\frac{d\sigma}{dv}$ as a function of v, for 300 GeV muons in lead is presented in fig. 3, assuming two different formulations for muon bremsstrahlung: the one of Petrukhin et al. [2] and the one of Sakumoto et al. [1].

3 Experimental set-up

In september 1994 the first combined test of the ATLAS hadronic and electromagnetic prototype calorimeters has been performed. The electromagnetic (e.m.) calorimeter was the Lead-Liquid Argon "2 metres" prototype built by the RD3 collaboration [12]. It has an accordion geometry, with a $\Delta\phi \approx 0.02$, $\Delta\eta \approx 0.018$ granularity, and it is fully pointing. The total thickness is $25X_0$ at $\eta = 0$, subdivided into three longitudinal samplings. The resolution measured with electron beams is $\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.5\%$ plus a noise term. In this test beam it was preceeded by a separate preshower detector, also using LAr as active material [12].The need for a good coupling with the hadronic calorimeter compelled to shift the e.m. one toward the back of its cryostat, in a position that spoiled its pointing properties. Behind the e.m. calorimeter the prototype of the Tile [13] hadronic (HAD) calorimeter was placed. This is a Iron-scintillator calorimeter, with an Fe:Sci ratio around five in volume. Its total thickness is 180 cm (about 9 λ_i) and it is read-out in 4 longitudinal sections. The Tile calorimeter was followed by a "muon wall", consisting of an array of scintillator detectors. A special beam setup was prepared to obtain a 300 GeV muon beam with almost no pion contamination and a calculated momentum spread smaller than 1% [14]. The beam was impinging on the e.m. calorimeter at about $11°$, and the beam spot was confined in a 3×3 cm square by a couple of scintillation detectors acting as a trigger. A total of about 700000 events have been recorded.

4 Simulations

The simulations have been performed with the standalone FLUKA code [15]. This choice has been validated by extensive comparisons with other codes about high energy muon propagation [16], and by the good agreement between simulations and test beam results on electron and pions. It is possible to choose the prescription for the effect of the nuclear form factor in muon bremsstrahlung among those of ref. [4, 1, 2], and the Coulomb correction can be optionally considered, as suggested by Tsai [3]. The treatment of photo-nuclear interactions basically follows ref. [17], with the cross section integrated down to the lowest possible q^2 values, including the existing resonances in the γN cross section. Pair-production is sampled according to the double differential cross section of ref. [18]. In the bremsstrahlung treatment, the screening factor of [2] without Coulomb correction has been chosen, since it is the most widely used formulation.

The setup and detector geometries have been modelled in great detail. The MonteCarlo calibration factors for the two detectors have been determined simulating the response to monoenergetic electrons. No other normalization factor has been applied to the simulated data. About $7 \cdot 10^5$ 300 GeV muons have been simulated. The effects of random noise and photostatistics [19] have been convoluted with MC data, while charge collection in the accordion and quenching in the scintillator have been implemented directly in the simulations.

5 Data analysis and comparison with simulations

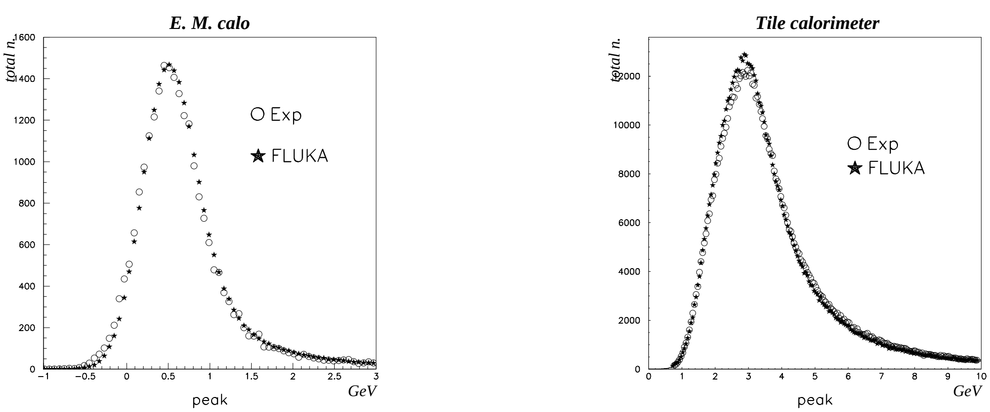

Figure 4: Absolute comparison between calculated and experimental ionization peaks in the electromagnetic(left) and hadronic (right) prototypes

Experimental and MonteCarlo data have been analysed following the same algorithms and applying the same cuts. Up to now, the two calorimeters have been considered separately, mainly because of some uncertainty in the amount of dead material in between the two and of the still existing difficulties in the electromagnetic data reduction.

The calibration issue is perhaps the most critical one in these comparisons. Any normalization factor based on the average muon energy loss or on the v spectral shape would be equivalent to assuming a perfect theoretical description of the radiative processes, that is exactly what we are investigating. The endpoint is not sharp enough, due to the scarcity of events, to provide a calibration. A calibration of both data and MonteCarlo on the ionization peak position would be possible, but this would prevent any verification of the correctness of the simulations, or at least of their capability to reproduce the experimental $\frac{e}{\mu}$ ratio. Moreover, the sampling fraction for muon energy losses decreases with v, since at large v most of the energy is deposited through electromagnetic cascades indistinguishable from electron-initiated ones, while at low v's ionization energy losses are more effectively sampled, resulting in a $\frac{\mu}{e}$ ratio larger than one. This is properly taken into account in the MonteCarlo simulation, while it is neglected in analytical calculations such as those performed in [20]. The approach followed in this work is the only self consistent one, that is an independent calibration with electrons, both of experimental and calculated data. The e.m. calibration is well known from many beam tests [12], and for the Tile calorimeter we used the electron calibration factor quoted in [19] : 5.59 pC/GeV.

As a validation of the simulations the computed and measured ionization peaks, for which no theoretical uncertainties should exist, are compared in fig. 4 (see later for details). It is worthwhile to stress that the electromagnetic energy scale has been used both for MonteCarlo and data, with no mutual normalization. The perfect agreement on the position and shape of the peak proves that the $\frac{e}{\mu}$ ratio is correctly reproduced by the simulations.

5.1 LAr calorimeter

Due to the non optimal combined test geometry, the accordion calorimeter was hit by the beam at a non-pointing angle, i.e. 11 degree on a cell where the pointing angle is around 24 degrees. Therefore the standard clustering algorithms for electrons and muons cannot be used. An event-dependent clustering algorithm is under development: the goal is to keep the noise level as low as possible by using the minimal number of cells. The muon track position is reconstructed a priori using the beam chamber informations. The major problem we are currently facing is the presence of coherent noise, whose level and rms are not stable with time, that is hardly reproducible in the simulations. This work is still in progress, nevertheless we show in fig. 4 a comparison between the MonteCarlo and experimental ionization peak in a 3×3 cluster. Only a selected (from the noise point of view) set of data files has been used. As already said, the comparison is absolute, without any scale normalization, and shows that the MonteCarlo reproduction of the calorimeter structure and response is very good.

The presented radiative energy loss analysis is still a preliminary one (see also [21]), performed keeping a large, fixed window (almost 11×11 cells , bringing in a noise of 1.4 GeV rms). An upper limit to the energy detected in the hadronic calorimeter was set to discriminate

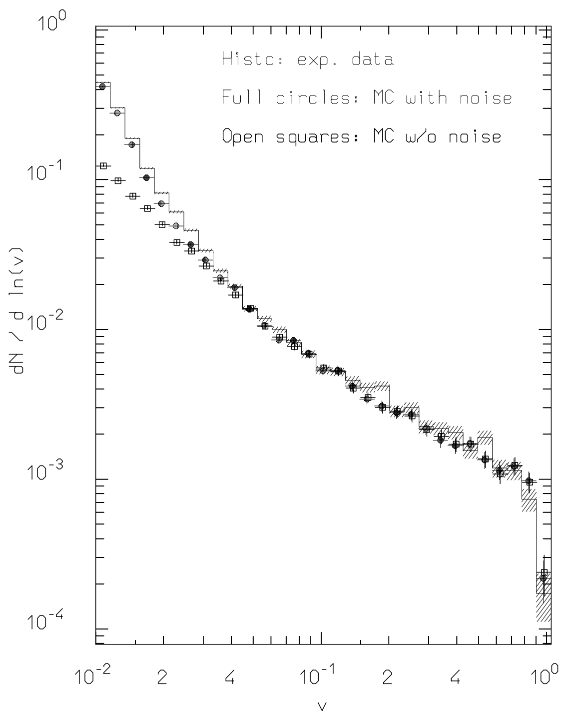

Figure 5: *300 GeV muon energy loss spectrum per incident muon in the ATLAS e.m. calorimeter prototype*

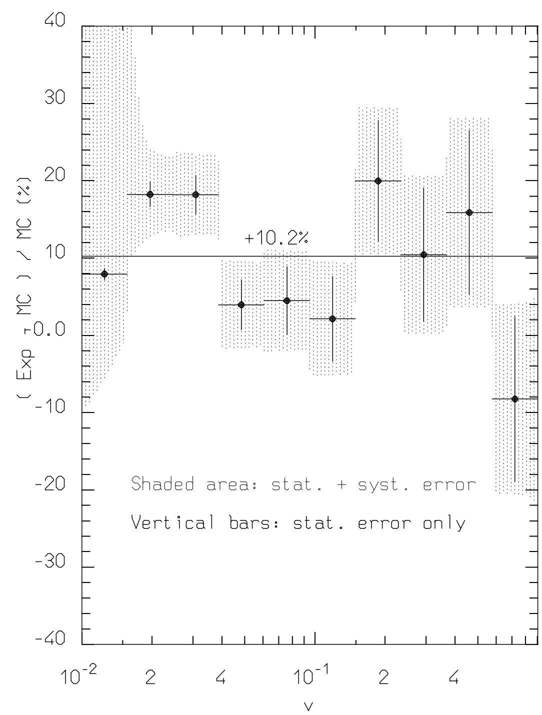

Figure 6: *Percentage difference between exp. and simulated spectra, including systematic errors.*

events with showers not fully contained in the e.m. calorimeter. The comparison between exp. and simulated energy loss spectra is shown in fig. 5 for $v > 0.01$, before and after the convolution with noise in the simulated results. All spectra are normalized to one incident muon. The strong influence of the noise on the soft part of the spectrum and the overall agreement of MonteCarlo with data are evident. The agreement is not complete, however. In fig. 6 the percentage difference between the two spectra is shown as a function of v. The average difference is around 10.2%, with more energetic events in the experimental data. The main error sources are the systematic ones, which were tentatively estimated in a conservative way with a toy model. The shaded systematic plus statistic errors area in fig. 6 is obtained by allowing a ±1% error on energy scale, a ±50 MeV error on pedestal subtraction, and ±50 MeV on the noise rms.

5.2 Tile Calorimeter

Two cuts have been used to select clean primary muons: a first one on the energy deposited in the e.m. calorimeter, to discard muons that have already undergone hard energy losses, a second on the energy deposited in the muon wall, to discriminate against pions. The pion contamination of the beam as resulting from the muon wall cut was very small: around 0.01%. After these cuts 743729 muon events have been analysed. Pedestal subtraction has been performed for each run using the random trigger events.

An off-line correction has been applied to take into account the position-dependence of the tile light yield. The correction has been derived from the experimental profile, and applied only in the fourth longitudinal sampling, where tiles are larger. No effect was visible in the other samplings. The value of noise has been extracted from the random trigger distribution, and convoluted with the MonteCarlo results. Care has been taken in reproducing correctly both the rms (0.56 GeV) and the shape of the noise, that was strongly non-gaussian due to the presence of a sizeable coherent noise.

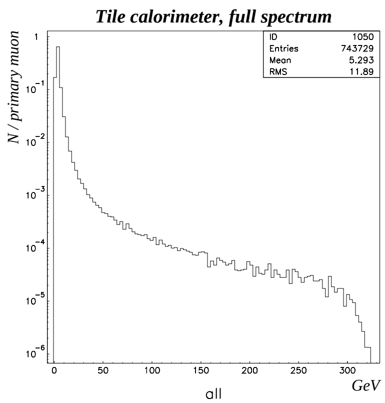

Figure 7: Total experimental spectrum in the Tile calorimeter.

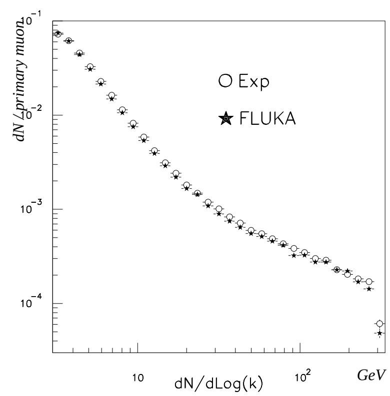

Figure 8: Comparison between calculated and experimental spectra in the tile calorimeter for $v > 0.01$

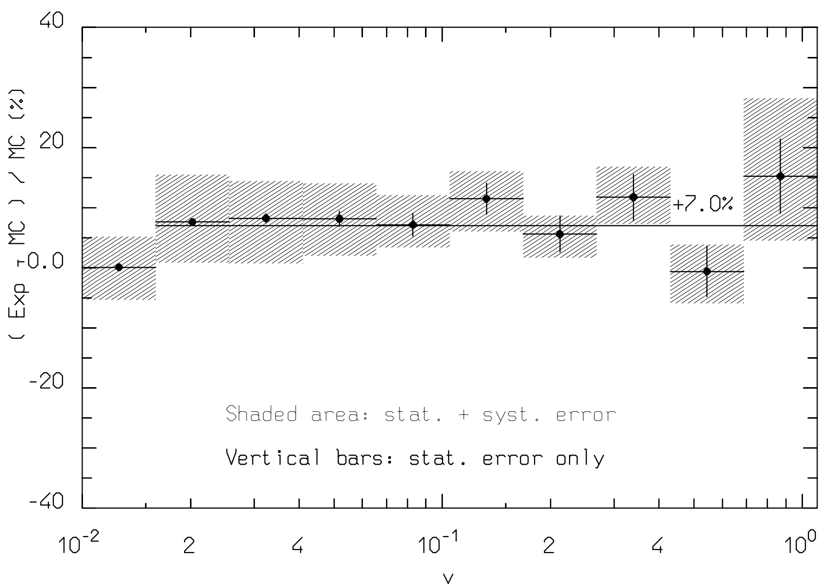

Figure 9: Percentage difference between experimental and MonteCarlo events as a function of v in the Tile calorimeter. Statistical only and statistical + systematic errors are shown.

The total deposited energy spectrum in the hadronic calorimeter is shown in fig. 7. The spectra of computed and measured energy losses ($v > 0.01$) are compared in fig. 8, normalized to one primary muon. The overall shape of the spectrum and the position of the endpoint are well reproduced by FLUKA, while a small difference shows up for events above the ionization peak.

Since statistical errors are already small, an effort has been made to investigate possible sources of systematic errors. These include errors on pedestal subtraction, noise evaluation, calibration constants, and on the relative effectiveness of the cut on the e.m. calorimeter. Systematic effects have been estimated by varying the aforementioned quantities in the reconstruction of the MonteCarlo data. Reasonable limits of variation have been chosen:

- An offset of ± 50 MeV on the pedestal values. Since pedestals are actually evaluated from out-of-burst events, this variation could be overestimated.
- A variation of ±5% in the noise rms. The same considerations of the previous point apply here.
- A variation of $= +4, -1$ GeV around the adopted 6 GeV cut on the e.m. energy, used to remove muons showering in the accordion This accounts for possible mismatches in the exp. and MC e.m. calibrations and noise convolution. The effect is negligible.
- A ±3% variation on the energy scale, as quoted in the Tile calibration [22]. This gives the largest effect, but it should be stressed that a 3% variation on the energy scale would spoil the nice agreement on the ionization peak.

The percentage difference between experimental and MonteCarlo events as a function of v is shown in fig. 9 on a condensed binning. It is consistent with a $7.0 \pm 0.4(stat) \pm 1.62(syst)$ constant difference for $v > 0.015$, that is just beyond the ionization peak.

6 Conclusions

The experimental results show an excess of about 7–10% when compared with standard theoretical assumptions for radiative energy losses, already for $v > 0.015$. In this range both pair production and bremsstrahlung are important. These results must be taken with care since systematic effects could be comparable to the observed discrepancy; work is in progress to further reduce such effects with a more refined data analysis.

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