PROCEEDINGS OF SCIENCE

The muon measurements at Haverah Park and their connection to the muon puzzle

L. Cazon,[a] **H. P. Dembinski,**[b] **G. Parente,**[a] **F. Riehn**[a,*] **and A. A. Watson**[c]

[a] *Universidade de Santiago de Compostela, Instituto Galego de Física de Altas Enerxías (IGFAE), Rúa de Xoaquín Díaz de Rábago s/n, 15705 Santiago de Compostela, Spain*

[b] *Technische Universität Dortmund, Fakultät Physik, Otto-Hahn-Straße 4a, 44227 Dortmund, Germany*

[c] *University of Leeds, School of Physics and Astronomy, Woodhouse Ln, Leeds, UK*

E-mail: lorenzo.cazon@usc.es, hans.dembinski@tu-dortmund.de, gonzalo.parente@usc.es, friehn@lip.pt, a.a.watson@leeds.ac.uk

The number of muons is one of the key observables in the analysis of extensive air showers from ultra-high energy cosmic rays. Several experiments, which together cover a large range in primary energies, report the observation of an excess in the number of muons over the expectation from air shower simulations. In this work, we extend the catalogue of muon densities by the measurements that were carried out at the Haverah Park Array. We calculate the corresponding Haverah Park muon scale with respect to post-LHC hadronic interaction models, as defined by WHISP. We shift the original Haverah Park energy scale to the energy scale of the Pierre Auger Observatory by matching the spectra of the two experiments to one another. Comparing the measurements we find that the muon content measured at Haverah Park is not compatible with the one measured at the Pierre Auger Observatory. In particular Haverah Park measurements are close to the predictions from composition measurements and models.

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*Speaker

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1. Introduction

Recent measurements of the number of muons in extensive air showers by the Pierre Auger Observatory [1–3] have revealed that the high-energy interaction models tuned after LHC which are used in air shower simulations produce insufficient muons during the cascading process (the so-called muon puzzle). The Working group on Hadronic Interactions and Shower Physics (WHISP) [4, 5] has compiled data from many other active and non-active experiments, aiming to cross-check and comprehend the energy range where the muon discrepancy is present. A thorough review of the muon puzzle from the perspective of particle physics can be found in [6].

Here we extend the catalogue of muon densities by the measurements that were carried out at the Haverah Park Array.

2. The Haverah Park Array and the Central Muon Detector

The Haverah Park air-shower array, which covered 12 km^2, operated continuously from early 1967 to mid-1987. Four 34 m^2 water-Cherenkov detectors of 120 cm depth, on a 500 m star-shaped pattern, acted as a trigger for showers produced by primary cosmic rays of energy > 0.1 EeV. This central array was surrounded by six smaller sub-arrays at a mean distance of 2 km from the central station. Throughout the period of operation, a muon detector made up of four closely packed liquid scintillator units, totalling 10 m^2, was operated adjacent to the central water-Cherenkov detector. The muon detectors were shielded with lead and iron to give a muon threshold of 320 MeV. In an early phase, an array of muon flash tubes was deployed above the scintillators to verify the performance of the shielded detectors [7]. The separation between the centre of the 10 m^2 muon detector and the 34 m^2 water-Cherenkov detector was ≈ 3 m.

The muon data discussed in this paper are taken from a summary report [8].

2.1 Energy measurement

The primary energy of the showers in Haverah Park is determined from the signals in the water-Cherenkov detectors. The precise composition of this signal in terms of muons, electrons and photons varies with the distance from the shower axis. A measurement campaign using scintillators co-located with the water-Cherenkov detectors it was found that even up to distances of 1 km the contribution from electrons and photons to the signal does not diminish [9]. The calibration is done with model E of A. M. Hillas [10] according to which the primary energy of a shower, E_p, is related to the signal in a water-Cherenkov detector located 600 m from the impact point of the shower on the ground by

$$E_\mathrm{p} \;=\; 7.04 \times 10^{17}\,\mathrm{eV} \left(\frac{\rho_\mathrm{c}(600\mathrm{m})}{1\,\mathrm{VEM/m^2}}\right)^{1.018} . \tag{1}$$

Note that we are using here the same calibration that was used by Lawrence, Reid and Watson [11] for the determination of the Haverah Park spectrum. In their original publication on muons measured at Haverah Park [8], Blake and Nash use a different calibration, based on a different model by Hillas. Since we want to cross-calibrate the Haverah Park measurements with the Auger measurements by matching the spectra we need to use the same calibration that was used for the

Haverah Park spectrum. Luckily Blake and Nash also included tables of the energy estimator ρ_c in their publication.

2.2 Systematic uncertainty

There is no explicit discussion of any systematic uncertainty in the measurements of the muon detectors by Blake and Nash. However the measurement of the muon lateral distribution (LDF) at Haverah Park agrees well with the measurement of the muon LDF by Dixon et al. [12–14]. The latter group studied muons with momentum above 1 GeV/c using a magnetic spectrograph. In addition the Haverah Park scintillators were validated with flash tubes [7]. There is some ambiguity concerning the exact value of the energy threshold of the muon detectors that are reported, with values that vary by 4%. Staying conservative we assign the systematic uncertainty in ρ_μ to be better than 5%.

Similar arguments hold for the systematic uncertainty in the energy estimator ρ_c which, with some exceptions, we also assign to be below 5%. The first restriction concerns the measurements at low energies (below 0.3 EeV). Here a different set of detectors (50 m and 150 m from the muon detectors) was used to trigger the readout. As the exact relation with the remaining data is not known we exclude these data for the time being. Similarly we exclude data above 1 EeV. While the measurement of ρ_c can still be considered reliable here, the statistical uncertainty in the spectrum becomes sizeable. In addition the spectrum measured by the Pierre Auger Observatory shows that the spectral index starts to change around 1 EeV. Since we are aiming to calibrate the Haverah Park energies by matching the spectrum to the Auger spectrum we limit ourselves to the region between 0.3 EeV and 1 EeV where the statistical precision of the Haverah Park spectrum is $< 8\%$, and the spectral index does not change.

$\rho_\mu(600\,\mathrm{m})$ (m^{-2})	$\rho_c(600\,\mathrm{m})$ (m^{-2})	$\sim E_p$ (eV)
0.125 ± 0.04	0.199	1.38×10^{17}
0.184 ± 0.02	0.285	1.96×10^{17}
0.302 ± 0.016	0.449	3.11×10^{17}
0.449 ± 0.017	0.706	4.91×10^{17}
0.662 ± 0.017	1.128	7.86×10^{17}
0.95 ± 0.055	1.67	1.18×10^{18}
1.55 ± 0.05	2.78	1.93×10^{18}
2.25 ± 0.1	4.21	3.05×10^{18}
3.72 ± 0.2	7.16	5.24×10^{18}
4.58 ± 0.3	8.97	6.55×10^{18}

Table 1: Mean muon densities from Haverah Park at 600 m from the shower axis. ρ_c is the mean water Cherenkov response also measured 600 m from the shower axis and E_p is the primary energy calculated using model E due to A. M. Hillas [10].

2.3 Simulations

We compare the muon measurements at Haverah Park with predictions from air shower simulations using current interaction models EPOS-LHC [15], QGSJetII-04 [16] and Sibyll 2.3d [17]. To

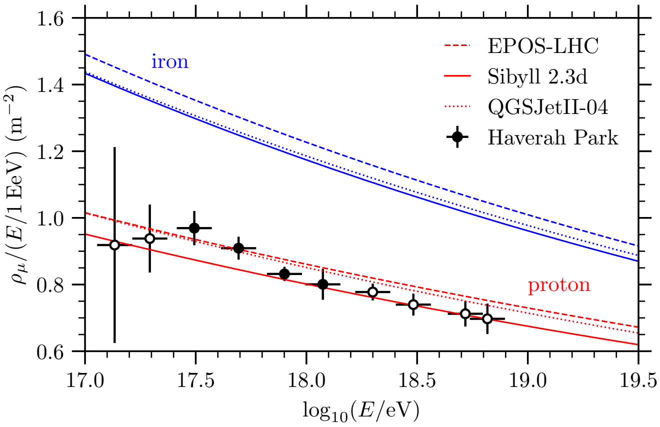

Figure 1: Muon density at 600 m measured by Haverah Park. Filled symbols are the data where the systematic uncertainty is better than 5%. Predictions by interaction models are shown for proton- (red) and iron-induced (blue) showers.

match the experimental conditions as closely as possible, we track particles down to the threshold of the muon detectors of 320 MeV and an altitude of 220 m above sea-level (mean atmospheric depth of 1018 g/cm^2). The magnetic field strength in the horizontal (vertical) direction is set to 17.8 nT (45.2 nT), which are the values of Earth's magnetic field for the location of Haverah Park (53° 58′ N, 1° 38′ W) according to the IGRF2020 model [18] averaged over the period of measurement. The dip angle is 68°. For the air shower simulations we use CORSIKA 7.7402 [19] with FLUKA as low energy hadronic interaction model [20]. We simulate primaries in the energy range from 0.1 EeV to 100 EeV and with zenith angles $\sec\theta < 1.1$ ($\theta < 24.5°$).

In Fig. 1 the measurement of Haverah Park using the energy scale in Eq. (1) is compared with the model predictions. The data mostly follow the proton prediction.

3. Comparison with the Pierre Auger Observatory

3.1 Energy scale

The muon density at Haverah Park is measured rather directly and reliably using shielded scintillators. However the absolute energy scale of the water-Cherenkov detectors is derived from a theoretical model and thus, at the very least, depends on the assumption of the primary composition, not to mention the undertainties inherent in any theoretical model. The energy scale of the Pierre Auger Observatory in contrast is derived from data and thus we consider it superior. We therefore re-calibrate the Haverah Park measurements by aligning the spectrum [11] to the Auger spectrum [21, 22]. We do this in the range between 0.3 and 1 EeV where the slope of the spectrum does not change. We find that the spectra match (within the sizeable statistical uncertainty) if the Haverah Park energies are scaled down by a factor of 1.22. The two spectra as well as the rescaled Haverah Park spectrum are shown in Fig. 2.

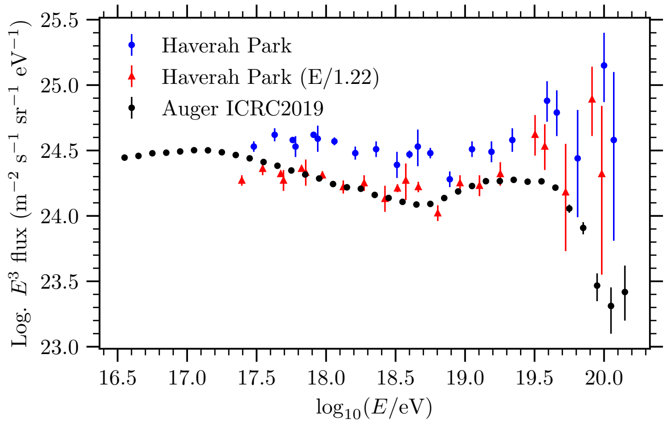

Figure 2: Cosmic ray flux measured at Haverah Park and the Pierre Auger Observatory. These two fluxes can be brought into agreement within the statistical uncertainty by rescaling the energies by 1.22.

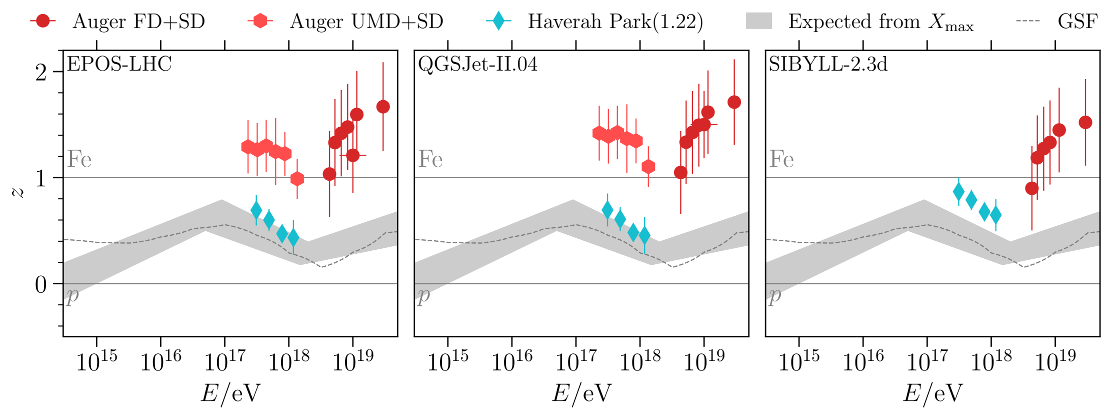

Figure 3: Measured muon content in Haverah Park and Auger. The Haverah Park data are shifted to the Auger energy scale (relative scaling 1.22). The grey band shows the region that is predicted by the models when using the composition obtained from measurements of the shower maximum [23, 24]. The dashed curve (GSF) is the prediction from the models using the composition derived from the global spectrum fit [25].

3.2 Muon scale

At Haverah Park the muon density was measured at 600 m. Using the underground muon detectors at the Pierre Auger Observatory the density was measured at 450 m [3], while in the analysis using inclined showers the integrated number of muons was measured [1, 2]. To compare such different measurements the z-parameter was introduced [26]. It is defined relative to the prediction of a specific interaction model using as scale the difference between proton and iron primaries for that model, thus

$$z = \frac{\ln \langle N_\mu \rangle - \ln \langle N_{\mu,\mathrm{p}} \rangle}{\ln \langle N_{\mu,\mathrm{Fe}} \rangle - \ln \langle N_{\mu,\mathrm{p}} \rangle} \,. \tag{2}$$

In Fig. 3 comparisons of the Haverah Park and Auger measurements on the z-scale are shown for three current interaction models. The prediction from the models based on the composition derived from measurements of the shower maximum is shown by the grey band. Note that in the case QGSJetII-04 this comparison has to be taken with caution as that model does not yield a satisfying description of the Auger $X_{\rm max}$ data at high energies [24, 27]. In addition the prediction using the composition extracted from a global fit to CR data (GSF) is shown by the dashed line [25].

4. Discussion

The comparison of measurements in Fig. 3 reveals a large discrepancy between the measurements done at the Pierre Auger Observatory and those at Haverah Park. At this point it is not at all clear where the origin of this discrepancy lies. Note that in the common energy range (roughly $10^{17.3}$ eV to 10^{18} eV) the measurements are even based on the same technique and observables, i.e. the density of muons at a fixed distance measured with shielded/buried scintillators! In both cases the energy measurement is provided by the water-Cherenkov detectors. The difference is only that the water-Cherenkov detector of the Pierre Auger Observatory is calibrated more directly using hybrid observations of showers with fluorescence detectors whereas in the case of Haverah Park the calibration is done through the spectrum. Whether this difference in the calibration is a relevant factor in the discrepancy should be investigated in the future.

The differences in basic observation parameters (e.g. elevation, zenith angle, muon energy threshold etc.) were already investigated in the context of WHISP in the past [28]. However then the focus lay mostly on the muon measurement itself but not on the energy estimator.

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