A combined fit of energy spectrum, shower depth distribution and arrival directions to constrain astrophysical models of UHECR sources

Teresa Bister\textsuperscript{a,}\textasteriskcentered on behalf of the Pierre Auger\textsuperscript{b} Collaboration

\textsuperscript{a}Physics Institute IIA, RWTH Aachen University, Otto-Blumenthal-Str., 52074 Aachen, Germany
\textsuperscript{b}Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

E-mail: spokespersons@auger.org

The combined fit of the measured energy spectrum and distribution of depths of shower maximum of ultra-high-energy cosmic rays is known to constrain the parameters of astrophysical scenarios with homogeneous source distributions. Further measurements show that the cosmic-ray arrival directions agree better with the directions and fluxes of catalogs of starburst galaxies and active galactic nuclei than with isotropy.

Here, we present a novel combination of both analyses. For that, a three-dimensional universe model containing a nearby source population and a homogeneous background source distribution is built, and its parameters are adapted using a combined fit of the energy spectrum, depth of shower maximum distribution and energy-dependent arrival directions. The model takes into account a symmetric magnetic field blurring, source evolution and interactions during propagation.

We use simulated data, which resemble measurements of the Pierre Auger Observatory, to evaluate the method’s sensitivity. With this, we are able to verify that the source parameters as well as the fraction of events from the nearby source population and the size of the magnetic field blurring are determined correctly, and that the data is described by the fitted model including the catalog sources with their respective fluxes and three-dimensional positions. We demonstrate that by combining all three measurements we reach the sensitivity necessary to discriminate between the catalogs of starburst galaxies and active galactic nuclei.
1. Introduction

At the Pierre Auger Observatory, cosmic rays (CRs) with energies up to $O(100)\text{ EeV}$ can be detected and their properties can be measured, including energy, depth of the shower maximum $X_{\text{max}}$ and arrival direction. The cosmic ray energy can be determined with the 1660 surface detector (SD) stations, which are distributed over an area of 3000 km$^2$ and which detect extensive air showers produced by the primary CR during interactions with the atmosphere. For some events, $X_{\text{max}}$ can be measured with the fluorescence detector (FD) on dark, cloudless nights. The charge of the primary particle cannot be measured directly, but $X_{\text{max}}$ is related to it. Both measurements have been combined in [1] to fit a model containing a homogeneous distribution of sources to the data, and to gain knowledge about parameters of the sources of ultra-high-energy CRs. The identification of sources that are powerful enough to accelerate CRs to the highest energies is one of the prime goals of the Pierre Auger Observatory. Here, we demonstrate that by also using the arrival directions as a third observable in the fit, we can additionally model the energy-dependent contribution of a catalog of specific foreground sources.

These foreground sources are based on the findings in [2, 3], where the Pierre Auger Collaboration demonstrated that the measured arrival directions (ADs) agree better with catalogs of starburst galaxies (SBGs) or gamma-ray emitting active galactic nuclei (AGNs) than with isotropy. Currently, the correlation is detected at the $4.0\sigma$ and $3.1\sigma$ confidence levels [4], respectively, but differentiation between the two source classes remains challenging as the strongest sources of both catalogs are located at very similar directions. That analysis uses only the arrival directions $\vec{v}_i$ to calculate the likelihood $\mathcal{L}_{\text{AD-only}}$, which compares the directions with a model containing a sum of an isotropic component $B$, which follows the observatory exposure, and an anisotropic component $S$, which consists of Fisher distributions centered on each source, multiplied with a flux weight and accounting for the attenuation and the observatory exposure [2]:

$$\log \mathcal{L}_{\text{AD-only}}(f, \delta) = \sum_i \log \left( f \cdot S_\delta(\vec{v}_i) + (1 - f)B(\vec{v}_i) \right) = \sum_i \log(\text{pdf}_{\text{AD-only}}(\vec{v}_i))$$

The model has two fit parameters, the size of the symmetric magnetic field smearing $\delta = \delta_{\text{AD-only}}$ and the signal fraction $f = f_{\text{AD-only}}$ which weights the isotropic and anisotropic contributions. Both parameters are determined by maximizing a likelihood ratio, the test statistic $\text{TS}_{\text{AD}}$:

$$\text{TS}_{\text{AD-only}} = 2 \log \left( \mathcal{L}(f_{\text{AD-only}}, \delta_{\text{AD-only}}) / \mathcal{L}(f_{\text{AD-only}} = 0) \right)$$

The ratio is calculated for several energy thresholds and the best-fit values for $f$ and $\delta$ are determined independently for each threshold. Currently, the highest $\text{TS} = 24.8$ is reached for $f_{\text{AD-only}} \approx 9\%$ and $\delta_{\text{AD-only}} \approx 15^\circ$ for an energy threshold of 38 EeV [4] for the SBG catalog.

2. Universe model

In the following, we will present a combined fit which includes not only the energies and depths of shower maximum of the CRs, but also the energy-dependent arrival directions. For that, we will first introduce the universe model that can be fit to the data.
We model the nearby universe as a sum of two parts, the foreground sources which are given by a catalog of either 44 starburst galaxies or 23 active galactic nuclei as in [4], and a background accounting for further unknown sources of the same type. All sources accelerate CRs to a maximum rigidity $R_{\text{cut}}$, so that the injected flux $J_{\text{inj}}$ follows a power-law with a broken exponential cutoff:

$$J_{\text{inj}}(E_{\text{inj}}, A_{\text{inj}}) = J_0 \cdot a_i(A_{\text{inj}}) \left( \frac{E_{\text{inj}}}{10^{18} \text{ eV}} \right)^{-\gamma} \begin{cases} 1 & Z_{\text{inj}}R_{\text{cut}} < E_{\text{inj}} \\ \exp \left( 1 - \frac{E_{\text{inj}}}{Z_{\text{inj}}R_{\text{cut}}} \right) & Z_{\text{inj}}R_{\text{cut}} \geq E_{\text{inj}} \end{cases} \tag{3}$$

Here, $a_i(A_{\text{inj}})$ is the fraction of the element with mass number $A$ defined below the cutoff, $E_{\text{inj}}$ is the energy and $J_0$ is a normalization.

Since the goal of this method is a quickly adaptable model, we use 1-dimensional CRPropa3 simulations to account for the propagation between each source and Earth [5]. We produce a simulation database, consisting of $10^6$ CRs for each energy bin ($10^{18.00}$ eV, $10^{18.02}$ eV... $10^{21.00}$ eV) for each representative element (H, He, N, Si, Fe) and each distance, binned logarithmically between 1 Mpc and 5700 Mpc (redshift $z \approx 2$) in 118 bins. We use the Gilmore model [6] for the extragalactic background light and the TALYS model [7] for the photodisintegration, which corresponds to the CTGE setup used in [1, 8]. The catalog sources are placed at their respective distances and their total flux is weighted according to the flux weight, both from [4]. The background sources are placed continuously following a source evolution $\propto (1 + z)^m$, with either $m = 0$, $m = 5.0$ as expected for AGNs, or the star formation rate as given in [9] for SGBs ($m = 3.4$ for $z < 0.97$). For this first test of the method no cosmological expansion of the universe is considered.

From all arriving CRs we calculate probability distributions for each of the three observables, that we can compare with the data to find the best fit parameters, in a very similar way to [1]. For the energy, we bin the arriving CRs into 24 bins ($10^{18.0}$ eV, $10^{18.1}$ eV... $10^{20.4}$ eV). For $X_{\text{max}}$, we calculate the expected probability distribution from the Gumbel distributions [10] as in [1] with the EPOS-LHC hadronic interaction model, using $X_{\text{max}}$ bins of width 20 g cm$^{-2}$ and the same energy bins as for the spectrum up to $10^{19.6}$ eV plus one combined energy bin above. For the arrival directions, we produce probability maps that would be expected for CRs deflected by local turbulent magnetic fields, where the deflection angle scales in proportion to the inverse of the rigidity. This is done by introducing Fisher distributions around each catalog source with a width $\delta_S = \delta_0 Z_{\text{det}} \frac{10^{10}}{E_{\text{det}}}$, using the representative elemental charges $Z_{\text{det}} = 1, 2, 7, 14$ and 26 for $A_{\text{det}} \in \{1\}, \{2, 3, 4\}, \{5, ..., 22\}, \{23, ..., 38\}$ and $\{39, ..., 56\}$ respectively. Each Fisher distribution is weighted by the observatory exposure in the arrival direction as well as the number of arriving events with the respective charge $Z_{\text{det}}$ in the energy bin $E_{\text{det}}$, which depends on the source weight and distance. Hence, the size of the Fisher distributions decreases as the rigidity increases with energy, and the widths and depths of the distributions contain information about the injected particles at the sources as well as the propagation distance and the size of the turbulent smearing. The background probability map follows the observatory exposure, as expected for an isotropic distribution of farther away background sources.

The background and catalog contributions are then combined into the total model of the measured observables, after weighting them with a signal fraction $f_0$. This signal fraction is defined for all events above $\log_{10}(E_{\text{det}}/\text{eV}) = 18.7$ as this is the energy threshold that we will later use for
the fit. For the probability maps, this leads to a combined pdf in each energy bin \( e \), defined as:

\[
\text{pdf}_e = f_S(f_0, E_{\text{det}}^e) \cdot S(E_{\text{det}}^e, \delta S(E_{\text{det}}^e)) + (1 - f_S(f_0, E_{\text{det}}^e)) \cdot B
\]  

(4)

Here, the function \( f_S(f_0, E_{\text{det}}^e) \) describes the dependence of the catalog contribution on the energy. For close sources like the SBGs the catalog contribution increases with energy, as far away background sources do not contribute at the highest energies. We have now built a model of observed energies, energy-dependent depths of shower maximum as well as energy-dependent arrival direction probabilities which can be compared with the data to determine the model parameters.

3. Fit method

In total, the model has nine fit parameters: the spectral index \( \gamma \), the maximum rigidity \( R_{\text{cut}} \), four out of the five element fractions \( a_i \),\(^1\) the flux normalization \( J_0 \), the magnetic field blurring angle \( \delta_0 \) and the total signal fraction \( f_0 \). Additionally, it is possible to include systematic shifts of the energy and \( X_{\text{max}} \) scales as nuisance parameters \( v \). The systematic uncertainty on the FD energy scale is 14\% [12] and that for \( X_{\text{max}} \) is energy dependent, between 6 g cm\(^{-2} \) and 8 g cm\(^{-2} \) [11]. It was shown in [1, 8] that the hadronic interaction model can have a major impact on the fit results, and this can in part be parameterized by the shift of the \( X_{\text{max}} \) scale. We determine all fit parameters simultaneously via a Bayesian method using a Markov Chain Monte Carlo (MCMC) sampler, which samples the posterior distribution and hence enables us to determine the fit parameters as well as their uncertainties. The prior distributions are the same as in [1].\(^2\) Also, the likelihood function for the measured energy spectrum is modeled as a Poissonian and the \( X_{\text{max}} \) likelihood as a multinomial as in [1]. For the arrival directions, we use a similar likelihood function to eq. 1, only that we bin the events into the detected energy bins \( j \) and use the modeled energy-dependent probability maps pdf\(_j\) instead of pdf\(_{AP}\). As the three observables are independent measurements, the total likelihood function is given as a multiplication of the single likelihood functions.

We choose to only include \( E_{\text{det}} \) bins above \( \log_{10}(E_{\text{det}}/eV) = 19.0 \) in the energy and the \( X_{\text{max}} \) likelihoods, as we expect contributions apart from our catalog sources below this energy, e.g. from Galactic or other lower-energy extragalactic source classes, which is supported by the findings of [8]. But, since we do not want our model to produce more low-energy particles below this threshold than are measured by Auger, we include the three energy bins with \( \log_{10}(E_{\text{det}}/eV) \) between 18.7 and 19.0 in the energy likelihood only if the model flux becomes higher than the measured one. For the arrival directions, we set an energy threshold at \( \log_{10}(E_{\text{det}}/eV) = 19.3 \), as we do not intend to model the measured large-scale dipole [13] in the arrival probability maps.

4. Benchmark simulations

We demonstrate the method’s sensitivity using simulations, which resemble the measured data in all three observables. For that, we apply the fit to the data of the Pierre Auger Observatory, using only the homogeneous background model \( (f_0 = 0) \), which corresponds to the setup in [1] without

\(^1\)The condition \( \sum a_i = 1 \) is already incorporated.

\(^2\)Gaussian priors for systematic uncertainties, uninformed prior for \( J_0 \), uniform bounded priors for other parameters.
any contribution of the arrival directions observable. We use the $X_{\text{max}}$ distributions from [11] and the SD energy spectrum from [12], including a forward folding method and detector effects on $X_{\text{max}}$ as in [1]. The source evolution parameter is $m = 3.4$. The best-fit parameters can be seen in table 1. We find that a negative spectral index $\gamma$ describes the data best for this evolution, similar to what was also found in [1]. As one can see, the best-fit energy scale shift is 0, as is also found in [8], and for speed reasons we will refrain from including it as a nuisance parameter in all following fits.

\[ \log_{10}(R_{\text{cut}}/V) \quad a_{\text{He}} \quad a_{\text{N}} \quad a_{\text{Si}} \quad a_{\text{Fe}} \quad v_{\text{max}}/\sigma \quad v_{\text{Fe}}/\sigma \]

<table>
<thead>
<tr>
<th>$\gamma$</th>
<th>$\log_{10}(R_{\text{cut}}/V)$</th>
<th>$a_{\text{He}}$</th>
<th>$a_{\text{N}}$</th>
<th>$a_{\text{Si}}$</th>
<th>$a_{\text{Fe}}$</th>
<th>$v_{\text{max}}/\sigma$</th>
<th>$v_{\text{Fe}}/\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.65</td>
<td>18.29</td>
<td>23%</td>
<td>2%</td>
<td>70%</td>
<td>4.0%</td>
<td>0.15%</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

**Table 1**: Best-fit parameters used for benchmark simulation

To this simulation, we add a contribution from the SBG catalog with a signal fraction of only $f_0 = 1.2\%$ above $10^{18.7}$ eV and a smearing of $\delta_0 = 14.3^\circ$, which means a CR with rigidity 10 EV is smeared by a Fisher distribution with this width. These parameters were chosen so that $T_{\text{AD}}^{\text{SBG}}$ approximately matches between the simulation and the measured data, as can be seen in fig. 1 (left). Even though the simulation parameters were not chosen to also get an agreement between $T_{\text{AD}}^{\text{AGN}}$ on the benchmark simulation and the data, they are still of the same order of magnitude. The arrival directions of all events with $E_{\text{det}} \geq 38$ EeV are visualized in fig. 1 (right), along with the locations of the strongest sources. As one can see in fig. 2, the energy spectrum and $X_{\text{max}}$ distributions of the simulation still match the measured ones because of the small signal fraction. The dashed line shows the contribution of the catalog sources and it is visible that even though $f_0$ is so small, the contribution becomes significant ($f_S(f_0 = 1.2\%, E_{\text{det}} \geq 10^{20}$ eV) $\approx 40\%$) at the highest energies because the SBGs are close and their relative flux increases compared to the further away background sources. The number of events ejected at the source is adjusted, so that the flux on Earth matches the measured one from [12], as visible in fig. 2. Additionally, we adapt the number of events with $X_{\text{max}}$ values in each energy bin to match data from [11], it is only a fraction of all events due to the limited FD duty cycle. We now have a simulation which resembles the measured data in all three observables and we can hence determine the expected sensitivity of the fit in a realistic scenario.

5. Results and Discussion

We apply different models to the benchmark simulation to determine if the fit is able to differentiate between the true\(^3\) (SBGs) and false (AGNs) source classes and between the true source evolution (SFR evolution, $m \approx 3.4$) and the false ones ($m = 0.0, m = 5.0$). A visual representation of the best-fit results for the different models is shown in fig. 3. We give the confidence regions using the MCMC sampler for posterior sampling as well as the maximum a posteriori (MAP). The spectral parameters can be reconstructed well even with the reference models not including a catalog, although they get shifted for the different source evolutions. The clear correlation between $\gamma$ and $R_{\text{cut}}$ is visible, as also observed in [1]. Additionally, the signal fraction and the smearing are highly correlated, as also observed in [2]. The fit also determines a non-zero signal fraction for the AGN models, but the uncertainties are much larger. From the confidence regions, it becomes

\(^3\)Here, true and false only refer to the simulated truth and do not have any connection to the real universe.
Combined fit of energy spectrum, shower depth distribution and arrival directions

Teresa Bister

Figure 1: Test statistic of the arrival directions analysis (left) for the benchmark simulation as well as the data from [4]. A good agreement between both is visible for the AGN and SBG models. Arrival directions (right) for $E_{\text{det}} \geq 38$ EeV for detected CRs of the benchmark simulation with charges $Z_{\text{det}}$ as a colorbar.

Figure 2: Energy spectrum (left) and mean (upper right), standard deviation (lower right) of the $X_{\text{max}}$ distributions of the benchmark simulation, marked with round markers. The model, reweighted using the benchmark parameters, is shown as lines. The contribution by the SBG catalog is shown as dashed lines in the energy spectrum. For comparison, the data measured by the Pierre Auger Observatory [11, 12] is shown as cross markers, with $X_{\text{max}}$ shifted by $-2\sigma_{\text{sys}}$. The gray shaded area below $\log_{10}(E_{\text{det}}) = 19.0$ is not part of the fit in the following, apart from the bins between $\log_{10}(E_{\text{det}}) = [18.7-19.0]$ for the spectrum, see text.

apparent that the primary Helium and Hydrogen fractions are basically unknown, which makes sense as the cutoff energies of these light particles turn out to be below the energy threshold. The heavier fractions are better constrained. From the best-fit parameters at the MAP we can calculate the log-likelihood $\log L$ ratio, multiplied with a factor 2 in analogy to eq. 2 [2], and the deviance for each model and thereby determine which model best describes the benchmark simulation. The results are given in table 2. One can see that the spectrum deviance $D_E$ is very small, especially for the true source evolution of $m = 3.4$. A good description of the data with a small $D$ is possible also for $m = 0$, even though the spectrum parameters are not close to the truth, as shown in fig. 3. The log-likelihood values demonstrate that the true model can be clearly identified to fit best. The AGN model cannot describe the energy-dependent arrival directions of the benchmark simulation.

---

Note: The text includes references to figures and equations not shown here. For a full understanding, please refer to the original document or the cited sources.
as well as the SBG model, even when using the true source evolution \( m = 3.4 \), which shows that using these as an additional observable is a powerful tool to distinguish different source catalogs. The expected sensitivity of the method and hence the conversion of the log-likelihood ratios to a \( p \)-value, calculated from isotropic simulations, is discussed in the following.

<table>
<thead>
<tr>
<th></th>
<th>( D_E )</th>
<th>( D_{X_{\text{max}}} )</th>
<th>( D_{\text{total}} )</th>
<th>( 2 \log \frac{\mathcal{L}<em>{\text{AD}}}{\mathcal{L}</em>{\text{ref}, m=3.4}} )</th>
<th>( 2 \log \frac{\mathcal{L}<em>{\text{tot}}}{\mathcal{L}</em>{\text{ref}, m=3.4}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref. model ((f_0 = 0, m = 0))</td>
<td>6.0</td>
<td>82.1</td>
<td>88.1</td>
<td>0</td>
<td>-0.8</td>
</tr>
<tr>
<td>ref. model ((f_0 = 0, m = 3.4))</td>
<td>5.8</td>
<td>81.5</td>
<td>87.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ref. model ((f_0 = 0, m = 5.0))</td>
<td>12.9</td>
<td>84.0</td>
<td>96.9</td>
<td>0</td>
<td>-9.6</td>
</tr>
<tr>
<td>SBG model ((m = 3.4) \rightarrow \text{sim. truth})</td>
<td>5.5</td>
<td>80.2</td>
<td>85.7</td>
<td>30.6</td>
<td>32.4</td>
</tr>
<tr>
<td>AGN model ((m = 3.4))</td>
<td>6.0</td>
<td>81.8</td>
<td>87.8</td>
<td>11.2</td>
<td>10.8</td>
</tr>
<tr>
<td>AGN model ((m = 5.0))</td>
<td>5.6</td>
<td>84.1</td>
<td>89.9</td>
<td>1.4</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

**Table 2:** Deviance \( D \) and log-likelihood ratio (normalized to reference model with \( m = 3.4 \)) at maximum a posterior (MAP) for different models on the benchmark simulation.

For estimating the sensitivity of the method, we compare the observed log-likelihood ratio
\( 2 \log (\mathcal{L}_{\text{SBG}} / \mathcal{L}_{\text{ref}, m=3.4}) = 32.4 \) from the benchmark simulation to the expectation from isotropic simulations. These simulations contain the same source parameters as given in table 1, and only a homogeneous source distribution. In fig. 4, the log-likelihood ratios are displayed. One can see that the likelihood ratio observed on the benchmark simulation is exceptionally large compared to those from the isotropic simulations. The ratio can also be viewed separately for the three observables, even though only the total likelihood has been maximized. It is evident that the arrival directions are
Combined fit of energy spectrum, shower depth distribution and arrival directions

Teresa Bister

Figure 4: Log-likelihood ratio between SBG and reference model (compare table 2) on isotropic simulations (histogram) and on the benchmark simulation (red solid line). For comparison, the AGN ratio is also displayed (orange dashed line). The $\chi^2$ distribution with $n_{df} = 2$ is shown on the left for the total ratio (gray line).

most important for the determination of the correct source catalog. Fig. 4 (left) also shows that at least the tail of the isotropic histogram is well described by a $\chi^2$ distribution with two degrees of freedom, as is expected because the catalog model has two more fit parameters ($f_0, \delta_0$) than the reference model. From this, we can calculate $p$-values $p_{SBG} \approx 9 \cdot 10^{-8}$ and $p_{AGN} \approx 5 \cdot 10^{-3}$. These can be compared to the values for the arrival-directions only analysis [2] on the benchmark simulation (cf. fig. 1) which can also be calculated using the same $\chi^2$ distribution: $p_{SBG}^{AD-only, pre-trial} \approx 6.1 \cdot 10^{-6}$, $p_{AGN}^{AD-only, pre-trial} \approx 1.7 \cdot 10^{-3}$. The $p$-value for the false AGN model is approximately the same, while the energy-dependent fit including all observables noticeably increases the sensitivity for identifying the true SBG model on the benchmark simulation. Additionally, unlike [2] we do not need any scan of the energy threshold and hence no further penalization.

In summary, we have shown that the arrival direction observable can be included in the combined fit of energies and depth of shower maximum distributions, and that this enables us to determine the energy-dependent contribution of a source catalog to the flux of ultra-high-energy CRs at Earth. The fit including all three observables has a much better sensitivity to distinguish between the source catalogs of AGNs and SBGs.

References

The Pierre Auger Collaboration

Combined fit of energy spectrum, shower depth distribution and arrival directions

Teresa Bister


1 Centro Atómico Bariloche and Instituto Balseiro (CNEA-UNCuyo-CONICET), San Carlos de Bariloche, Argentina
2 Centro de Investigaciones en Láseres y Aplicaciones, CITEDEF and CONICET, Villa Martelli, Argentina
3 Departamento de Física and Departamento de Ciencias de la atmósfera y los océanos, FCEyN, Universidad de Buenos Aires and CONICET, Buenos Aires, Argentina
4 IFLP, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
5 Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Buenos Aires, Argentina
6 Instituto de Física de Rosario (IFIR) – CONICET/U.N.R. and Facultad de Ciencias Bioquímicas y Farmacéuticas U.N.R., Rosario, Argentina
7 Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), and Universidad Tecnológica Nacional – Facultad Regional Mendoza (CONICET/CNEA), Mendoza, Argentina
8 Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), Buenos Aires, Argentina
9 International Center of Advanced Studies and Instituto de Ciencias Físicas, ECyT-UNSAM and CONICET, Campus Miguelete – San Martín, Buenos Aires, Argentina
10 Observatorio Pierre Auger, Malargüe, Argentina
11 Observatorio Pierre Auger and Comisión Nacional de Energía Atómica, Malargüe, Argentina
12 Universidad Tecnológica Nacional – Facultad Regional Buenos Aires, Buenos Aires, Argentina
13 University of Adelaide, Adelaide, S.A., Australia
14 Université Libre de Bruxelles (ULB), Brussels, Belgium
15 Vrije Universiteit Brussel, Brussels, Belgium
16 Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ, Brazil
17 Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Nova Friburgo, Brazil
18 Instituto Federal de Educação, Ciência e Tecnologia do Rio de Janeiro (IFRJ), Brazil
19 Universidade de São Paulo, Escola de Engenharia de Lorena, Lorena, SP, Brazil
20 Universidade de São Paulo, Instituto de Física, São Carlos, SP, Brazil
21 Universidade de São Paulo, Instituto de Física, São Paulo, SP, Brazil
22 Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil
23 Universidade Estadual de Feira de Santana, Feira de Santana, Brazil
24 Universidade Federal do ABC, Santo André, SP, Brazil
25 Universidade Federal do Paraná, Setor Palotina, Palotina, Brazil
26 Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil
27 Universidade Federal do Rio de Janeiro (UFRJ), Observatório do Valongo, Rio de Janeiro, RJ, Brazil
28 Universidade Federal Fluminense, EEMVR, Volta Redonda, RJ, Brazil
29 Universidad de Medellín, Medellín, Colombia
30 Universidad Industrial de Santander, Bucaramanga, Colombia
31 Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
32 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
Combined fit of energy spectrum, shower depth distribution and arrival directions

Teresa Bister
Combined fit of energy spectrum, shower depth distribution and arrival directions

Teresa Bister

80 IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands
81 Nationaal Instituut voor Kernfysische en Hoge Energie Fysica (NIKHEF), Science Park, Amsterdam, The Netherlands
82 Stichting Astronomisch Onderzoek in Nederland (ASTRON), Dwingeloo, The Netherlands
83 Universiteit van Amsterdam, Faculty of Science, Amsterdam, The Netherlands
84 University of Groningen, Kapteyn Astronomical Institute, Groningen, The Netherlands
85 Case Western Reserve University, Cleveland, OH, USA
86 Colorado School of Mines, Golden, CO, USA
87 Department of Physics and Astronomy, Lehman College, City University of New York, Bronx, NY, USA
88 Louisiana State University, Baton Rouge, LA, USA
89 Michigan Technological University, Houghton, MI, USA
90 New York University, New York, NY, USA
91 Pennsylvania State University, University Park, PA, USA
92 University of Chicago, Enrico Fermi Institute, Chicago, IL, USA
93 University of Delaware, Department of Physics and Astronomy, Bartol Research Institute, Newark, DE, USA
94 University of Wisconsin-Madison, Department of Physics and WIPAC, Madison, WI, USA

\( ^a \) Fermi National Accelerator Laboratory, Fermilab, Batavia, IL, USA
\( ^b \) Max-Planck-Institut für Radioastronomie, Bonn, Germany
\( ^c \) School of Physics and Astronomy, University of Leeds, Leeds, United Kingdom
\( ^d \) Colorado State University, Fort Collins, CO, USA
\( ^e \) now at Hakubi Center for Advanced Research and Graduate School of Science, Kyoto University, Kyoto, Japan
\( ^f \) also at University of Bucharest, Physics Department, Bucharest, Romania