A flux of neutrons from an astrophysical source in the Galaxy can be detected in the Pierre Auger Observatory as an excess of cosmic-ray air showers arriving from the direction of the source. To avoid the statistical penalty for making many trials, classes of objects are tested in combinations as nine “target sets,” in addition to the search for an excess of cosmic-ray air showers arriving from that direction within the angular resolution of the Observatory. The mean decay path length for a neutron of energy $E$ (measured in EeV) is $9.2E^{2}$ kpc. Above 1 EeV, the Galactic center is within the mean decay length, and above 2 EeV most of the Galactic disk is within range for neutron astronomy.

In a previous paper (Abreu et al. 2012a), the Pierre Auger Collaboration published a blind search for a neutron flux from any point of the sky with declination less than $+15^\circ$, and celestial maps of flux upper limits were presented. No point stood out as statistically significant among the large number of trial source locations. In this paper, the search is limited to a small number of trials, each being a kind of “stacked analysis” for a set of candidate sources from an astrophysical catalog. The hypothesis is that many (or all) of the candidate sources of a given class are indeed emitting neutrons, so the combined signal should be

1. INTRODUCTION

The Pierre Auger Observatory measures cosmic-ray air showers near 1 EeV and higher energies (1 EeV $= 10^{18}$ eV). An air shower produced by a neutron is indistinguishable from an air shower produced by a proton. Unlike protons and other nuclei, neutrons are not deflected by magnetic fields in the Galaxy, so their arrival directions point back to their sources. A flux of neutrons from a single direction can be detected as an excess of air showers arriving from that direction within the angular resolution of the Observatory. The mean decay path length for a neutron of energy $E$ (measured in EeV) is $9.2E^{2}$ kpc. Above 1 EeV, the Galactic center is within the mean decay length, and above 2 EeV most of the Galactic disk is within range for neutron astronomy.

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Key words: cosmic rays – Galaxy: disk – methods: data analysis
more significant than that of a single target by itself. Performing the analysis on only a small number of target sets avoids a large statistical penalty.

The “ankle” of the energy spectrum (at about 5 EeV; Abraham et al. 2010a; Schulz et al. 2013) may represent a transition from Galactic to extragalactic sources of cosmic rays (Linsley 1963; Hillas 1984), although an alternative scenario holds that the “dip” of the ankle is formed by $e^\pm$ pair production in a spectrum of extragalactic protons (Berezinsky et al. 2006). At energies in the range 1–5 EeV, Auger, HiRes, and Telescope Array have all found their data to be consistent with a significant component of protons among the cosmic rays (Abreu et al. 2012b; Abraham et al. 2010c; Abbasi et al. 2010; Jui et al. 2012). It is of particular interest to determine whether or not EeV protons are being produced at discrete sources in the Galaxy. A sensitive search for large scale anisotropy (Abreu et al. 2013) has found that the dipole anisotropy near 1 EeV is lower than what would be expected for protons emitted from the disk of the Galaxy. However, those expectations necessarily rely on general properties of the magnetic field in the Galaxy and its halo that have some uncertainties. The search for sources of EeV protons in the Galaxy is still highly motivated.

Any proton source is expected to produce some neutrons due to pion photo-production and nuclear interactions of the protons near the source. The detection of hadronic production of TeV gamma rays in some Galactic sources (Ackermann et al. 2013) provides direct evidence that the conditions for neutron production are favorable at least in those sources. TeV gamma-ray sources in the Galaxy are among the candidate sources targeted in this study. A $1/E^2$ differential energy spectrum of protons from TeV to EeV in some of the H.E.S.S. sources$^{102}$ would produce a neutron flux that is readily detectable by Auger. The Galactic center is a special candidate source that is well exposed to the Auger Observatory. The results here also update an earlier search for neutral particles from the Galactic center (Abraham et al. 2007).

The production of neutrons with the hadronic production of $\pi^\pm$ mesons is necessarily accompanied by photons from decay of similarly produced neutral pions. The Auger Observatory can search for the existence of EeV photon fluxes using the hybrid data set that includes air fluorescence measurements. The search for point sources of photons near 1 EeV will be reported separately.

2. THE DATA SET

The Pierre Auger Observatory (Abraham et al. 2004) is centered at latitude 35°33 S, longitude 69°3 W, near Malargüe, Argentina, with mean altitude 1400 m above sea level (870 g cm$^{-2}$ atmospheric depth). The completed surface detector array consists of 1660 water-Cherenkov stations covering an area of about 3000 km$^2$ on a triangular grid with 1.5 km spacing, allowing secondary muons, electrons, and photons to be sampled at ground level with a duty cycle of nearly 100%.

The data set analyzed here consists of events recorded by the surface detector (SD) from 2004 January 1 to 2013 October 31. Events used in this analysis have zenith angles less than 60°. Moreover, an event is accepted only if all six nearest neighbors of the station with the highest signal were operational at the time of the event. This is the standard geometrical aperture cut that ensures good event reconstruction (Abraham et al. 2010b). Periods of array instability have been omitted from the data set.

The total exposure of the array with these cuts is 35,967 km$^2$ sr yr for the period of time analyzed here, yielding 854,270 events with $E \geq 1$ EeV.

3. TARGET SETS AND WEIGHTED TARGET SETS

The search is performed on nine target sets of astrophysically interesting directions. These classes of candidate sources are the millisecond pulsars (Manchester et al. 2005), $\gamma$-ray pulsars (Abdo et al. 2013), low-mass X-ray binaries (LMXBs; Liu et al. 2007b), high-mass X-ray binaries (HMXBs; Liu et al. 2007b), H.E.S.S. Pulsar Wind Nebulae, the other H.E.S.S. identified sources, the H.E.S.S. unidentified sources, microquasars,$^{103}$ and magnetars.$^{104}$ In addition to these target sets, the Galactic plane and the Galactic center are considered as 2 additional single-element sets for a total of 11 target sets. In order to have independent target sets, a source that appears in two or more sets is retained only in the most exclusive set (smallest set) while removed from the others. (The large Galactic plane target is allowed to contain targets from other sets.) Target sets are tested with and without statistical weights. A weight is assigned to each candidate source in proportion to its electromagnetic flux (recorded in the catalog), in proportion to its exposure to the Auger Observatory, and in proportion to the expected flux attenuation factor due to neutron decay. The flux attenuation factor is the fraction of emitted neutrons expected to survive decay from the distance of the candidate source assuming a $1/E^2$ energy spectrum for emitted neutrons.$^{105}$ The target weights are normalized so that their sum is 1 in each target set.

The results without the weights are also reported since they are independent of the assumption that neutron emissions are proportional to the low-energy photon emissions and independent of the choice to make the weights proportional to each of the three factors.

4. METHOD

Four energy ranges are used: 1 EeV $\leq E < 2$ EeV (621,375 events), 2 EeV $\leq E < 3$ EeV (135,444 events), $E \geq 3$ EeV (97,451 events), as well as $E \geq 1$ EeV. The first three are independent data sets, while the final cumulative data set should give maximum sensitivity to a flux that extends over the entire energy range. The Auger energy scale has a systematic uncertainty of 14% (Verzi et al. 2013).

The solid angle size for each target is optimized based on the average angular resolution for its declination and the energy range as explained in (Abreu et al. 2012a). The solid angle is a target circle of radius 1.05 times the angle within which 68% of neutron arrival directions from the candidate source should be included after the event reconstruction. For the special case of the Galactic plane, the signal-to-noise ratio is optimized by a strip centered on Galactic latitude $b = 0°$ with half thickness $|b| < 0.93 \psi$, where $\psi$ is the mean angular resolution along the Galactic plane (and within the exposure of the Observatory) for a given energy range. For the four energy ranges above, the half thicknesses are, respectively, 1:28, 1:02, 0:72, and 1:17.

To recognize the existence of an excess of events in any target circle and any of the energy ranges, it is necessary to know the number that is expected in that circle without the neutron flux.

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102 http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources
103 http://www.aim.univ-paris7.fr/CHATY
105 Since the H.E.S.S. unidentified sources do not have a precise distance measurement, the flux attenuation factor is not considered for this target set.
The expected number of events in a given target circle is taken to be the average number found in 10,000 simulated data sets, each having the same number of events as in the actual data set. As in Abreu et al. (2012a), the arrival directions in a simulation event set are produced by sampling independently from the measured distributions for zenith angle, azimuth angle, and sidereal time. The average of many simulated data sets has no structure on small angular scales, providing a robust measure of the expected cosmic-ray background in each target.

The result for any target \( i \) is summarized by a \( p \)-value \( p_i \). This \( p \)-value is here defined by \( p_i \equiv 1/2[\text{Poisson}(n, b) + \text{Poisson}(n + 1, b)] \), where Poisson\((n, b)\) is the probability of getting \( n \) or more arrival directions in the target when the observed value is \( n \), and the expected number from the background is \( b \), as determined using simulated data sets. Averaging the values for \( n \) and \( n + 1 \) avoids the bias toward high \( p \)-values that occurs with Poisson\((n, b)\) and the bias toward low \( p \)-values that occurs with Poisson\((n + 1, b)\) for pure background fluctuations. When combining probabilities from a large target set with the Fisher formula (Fisher 1925), it is important that the individual \( p \)-values \( p_i \) have uniform expected distributions in the absence of any signal. Then for \( N \) targets with probabilities \( p_i, i = 1, 2, \ldots, N \), the chance probability for their product \( \Pi \) not to be greater than their actual product \( \Pi_0 \) is:

\[
P(\Pi \leq \Pi_0) = \prod_{i=0}^{N-1} \left( 1 - \text{Poisson}(N, -\log \Pi_0) \right)
\]

For a weighted set of \( N \) targets with weights \( w_i \), the combined \( p \)-value \( w \) is given by Good’s formula (Good 1955). It is the chance probability for the weighted product of \( p \)-values (but sampled from uniform distributions) not to be greater than the actual weighted product \( \Pi_0 \). The weighted product is the product of factors \( p_i^{w_i} \). Each \( p \)-value \( p_i \) is raised to the power \( w_i \) in the product of \( p \)-values, so the weight \( w_i \) can be regarded as the “number of times” the result for target \( i \) is counted relative to other targets of the set. In practice, the Good combined \( P_0 \) is evaluated numerically using an ensemble of sets \( p_i (i = 1, 2, \ldots, N) \) with every \( p_i \) sampled randomly between 0 and 1.

## 5. RESULTS FOR THE TARGET SETS

Results are shown in Tables 1 and 2. The first table gives the unweighted combined \( p \)-value \( P \) for each of the 11 target sets and for each of the four energy ranges. The weighted combined \( p \)-value \( w \) is also given for each of the nine target sets that have multiple targets.

The second table presents specific information for each target set about the candidate source that had the smallest individual \( p \)-value \( p_i \) for the full energy range \( E \geq 1 \text{ EeV} \). The direction of the source is given together with the observed number of events in the target, the expected number, the neutron flux upper limit, energy flux upper limit (assuming a 1/\( E^2 \) spectrum), and the \( p \)-value. The final column gives the penalized \( p \)-value \( P^* \equiv 1 - (1 - p)^N \). This is the chance probability that one or more of the \( N \) candidate sources in the target set would have a

### Table 1

Results of the Combined Analysis for each Target Set and Each Energy Range

<table>
<thead>
<tr>
<th>Class</th>
<th>No.</th>
<th>( \geq 1 \text{ EeV} )</th>
<th>( 1–2 \text{ EeV} )</th>
<th>( 2–3 \text{ EeV} )</th>
<th>( \geq 3 \text{ EeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>msec PSRs</td>
<td>68</td>
<td>0.48</td>
<td>0.40</td>
<td>0.22</td>
<td>0.61</td>
</tr>
<tr>
<td>( \gamma )-ray PSRs</td>
<td>77</td>
<td>0.23</td>
<td>0.13</td>
<td>0.71</td>
<td>0.24</td>
</tr>
<tr>
<td>LMXB</td>
<td>87</td>
<td>0.37</td>
<td>0.43</td>
<td>0.81</td>
<td>0.40</td>
</tr>
<tr>
<td>HMXB</td>
<td>48</td>
<td>0.014</td>
<td>0.011</td>
<td>0.061</td>
<td>0.27</td>
</tr>
<tr>
<td>H.E.S.S. PWN</td>
<td>17</td>
<td>0.083</td>
<td>0.021</td>
<td>0.98</td>
<td>0.21</td>
</tr>
<tr>
<td>H.E.S.S. other</td>
<td>16</td>
<td>0.91</td>
<td>0.93</td>
<td>0.94</td>
<td>0.35</td>
</tr>
<tr>
<td>H.E.S.S. UNID</td>
<td>15</td>
<td>0.82</td>
<td>0.78</td>
<td>0.98</td>
<td>0.94</td>
</tr>
<tr>
<td>Microquasars</td>
<td>13</td>
<td>0.28</td>
<td>0.16</td>
<td>0.85</td>
<td>0.96</td>
</tr>
<tr>
<td>Magnetars</td>
<td>16</td>
<td>0.69</td>
<td>0.52</td>
<td>0.60</td>
<td>0.46</td>
</tr>
<tr>
<td>Gal. center</td>
<td>1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Gal. plane</td>
<td>1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

### Table 2

Results for the Most Significant Target from Each Target Set

<table>
<thead>
<tr>
<th>Class</th>
<th>R.A. [°]</th>
<th>Decl. [°]</th>
<th>Obs</th>
<th>Exp</th>
<th>Flux U.L. (km(^{-2}) yr(^{-1}))</th>
<th>E-Flux U.L. (eV cm(^{-2}) s(^{-1}))</th>
<th>( p )-value</th>
<th>( p )-value (penalized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>msec PSRs</td>
<td>260.27</td>
<td>−24.95</td>
<td>237</td>
<td>214</td>
<td>0.019</td>
<td>0.14</td>
<td>0.058</td>
<td>0.98</td>
</tr>
<tr>
<td>( \gamma )-ray PSRs</td>
<td>8.59</td>
<td>−5.58</td>
<td>176</td>
<td>149</td>
<td>0.024</td>
<td>0.18</td>
<td>0.016</td>
<td>0.70</td>
</tr>
<tr>
<td>LMXB</td>
<td>264.57</td>
<td>−26.99</td>
<td>265</td>
<td>219</td>
<td>0.028</td>
<td>0.20</td>
<td>0.0012</td>
<td>0.10</td>
</tr>
<tr>
<td>HMXB</td>
<td>152.45</td>
<td>−58.29</td>
<td>283</td>
<td>248</td>
<td>0.019</td>
<td>0.14</td>
<td>0.014</td>
<td>0.49</td>
</tr>
<tr>
<td>H.E.S.S. PWN</td>
<td>128.75</td>
<td>−45.60</td>
<td>275</td>
<td>248</td>
<td>0.018</td>
<td>0.13</td>
<td>0.043</td>
<td>0.53</td>
</tr>
<tr>
<td>H.E.S.S. other</td>
<td>269.72</td>
<td>−24.05</td>
<td>235</td>
<td>211</td>
<td>0.019</td>
<td>0.14</td>
<td>0.054</td>
<td>0.59</td>
</tr>
<tr>
<td>H.E.S.S. UNID</td>
<td>266.26</td>
<td>−30.37</td>
<td>251</td>
<td>227</td>
<td>0.018</td>
<td>0.13</td>
<td>0.055</td>
<td>0.57</td>
</tr>
<tr>
<td>Microquasars</td>
<td>262.75</td>
<td>−26.00</td>
<td>247</td>
<td>216</td>
<td>0.022</td>
<td>0.16</td>
<td>0.020</td>
<td>0.23</td>
</tr>
<tr>
<td>Magnetars</td>
<td>81.50</td>
<td>−66.08</td>
<td>268</td>
<td>241</td>
<td>0.016</td>
<td>0.11</td>
<td>0.040</td>
<td>0.48</td>
</tr>
<tr>
<td>Gal. center</td>
<td>266.42</td>
<td>−29.01</td>
<td>234</td>
<td>223</td>
<td>0.014</td>
<td>0.10</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>Gal. plane</td>
<td>16965</td>
<td>17197</td>
<td>0.077</td>
<td>0.56</td>
<td>0.96</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Note. The upper limits are computed at 95% confidence level.


\[ F_{\text{GP}} = \eta 4\pi f_p \frac{H}{ct} \int_{R_{\text{min}}}^{R_{\text{max}}} \exp\left(-\frac{r}{D}\right) \frac{2\pi r}{4\pi r^2} \, dr \]

Integrating over an annulus of the Galactic plane centered on Earth gives an expected flux of neutrons:

Here \( R_{\text{min}} \) is the distance at which most of the source disk fits within the angle (based on the angular resolution) used in collecting the signal from the Galactic plane, and \( R_{\text{max}} \) is the distance to the edge of the Galaxy. Roughly, \( R_{\text{min}} \approx 1 \text{kpc} \) and \( R_{\text{max}} \approx 20 \text{kpc} \). Using \( D = 9.2 \text{E kpc} \) (with \( E \) measured in EeV units), the final integral on the right has the following values: 1.97, 2.32, 2.53, and 2.27 respectively for the four energy ranges 1–2, 2–3, 3–4, and \( \geq 4 \text{EeV} \). Each is somewhat less than \( \ln(20/1) = 2.996 \), which would be obtained in the limit \( D \gg 20 \text{kpc} \), and it should be noted that the expected flux has only an (approximately) logarithmic dependence on \( R_{\text{max}}/R_{\text{min}} \), so the flux estimates are not terribly sensitive to the particular values adopted here. The proton fraction \( f_p \) just below the ankle of the cosmic-ray energy spectrum is believed to be at least 30\% (Abreu et al. 2012b; Abraham et al. 2010c). A rough estimate for \( H/ct \) is 0.1, based on proton escape times and density scale heights using model magnetic fields in the Galaxy. Using these estimates, together with \( I \approx 29 \text{ km}^2 \text{ sr} \text{ yr}^{-1} \) for \( E \geq 1 \text{EeV} \), the upper limit \( F_{\text{UL}} \) on a neutron flux from the Galactic plane yields a qualified upper limit on \( \eta \) given by \( \eta_{\text{UL}} = 0.08 F_{\text{UL}} \).

The upper limit \( F_{\text{UL}} \) is 0.077 (km$^2$ sr yr)$^{-1}$ in Table 2 then implies \( \eta_{\text{UL}} \approx 0.006 \), which is a significant constraint on models for continuous production of EeV protons in the Galaxy.

While the scope of this paper is a search for Galactic point sources, it should be noted that a flux of neutrons may be produced diffusely at a small level by interactions of EeV cosmic-ray protons in the Galactic disk. Our bound on \( \eta \) might therefore be slightly conservative.

A positive detection of neutron sources would have identified sources of EeV protons in the Galaxy. The null results here leave open the question of whether the observed EeV protons are produced in the Galaxy or whether they fill the space also between galaxies. They might be produced in transient events within the Galaxy, like supernova explosions or rare gamma ray bursts. The Auger Observatory could detect a strong flow of neutrons only at times of the bursts. The non-detection of any neutron flux averaged over the Auger exposure time does not constrain models for infrequent transient sources of EeV protons in the Galaxy. Also, protons emitted in jets would produce neutron jets with possibly none of them pointing toward Earth. Models with transient sources or such jet sources are better constrained by the absence of any strong anisotropy of the protons themselves (Abreu et al. 2011, 2012c).

The successful installation, commissioning, and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe.

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