

Latest Results from the Pierre Auger Cosmic Ray Observatory

Outline

- •Energy spectrum
- Composition
	- charged particles
	- neutrinos/photons
- **Anisotropy**

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Cosmic rays at highest energies

Goal:

Understand the mechanism that produces UHECR particles

- What and where are the sources?
- How do they work?

We need to measure:

- direction
- energy
- particle-type

To determine

- Spectral features
	- knee
	- (second knee ??)
	- ankle
- Chemical composition
- Anisotropy

Galactic cosmic rays

Extragalactic cosmic rays? A guess

Accelerators for 1020eV protons

Accelerators for 1020eV protons

Astrophysical candidates

$$
E_{\rm max} \propto Z \beta_s BL
$$

Z: charge of the CR ß: shock velocity B: magnetic field strength L: size of the accel. region

Particle horizon / Greisen-Zatsepin-Kuzmin effect

Planck spectrum
for T = 2.73 K

 \mathbf{u}

Pre Auger data

Inconsistent with GZK ?? Consistent with GZK ??

The Pierre Auger Collaboration

- ✦ Argentina
- ✦ Australia
- ✦ Brasil
- ✦ Bolivia*
- ✦ Czech Republic
- ✦ France
- ✦ Germany
- ✦ Italy
- ✦ Mexico
- ✦ Netherlands
- ✦ Poland
- ✦ Portugal
- ✦ Slovenia
- ✦ Spain
- ✦ United Kingdom
- ✦ USA
- ✦ Vietnam*

- 300 PhD scientists from ~70 Institutions and 17 countries
	- *Associate Countries

The Pierre Auger Observatory

- *Southern site: Hybrid detector* near Malargüe/Argentina
- June 13th 2008 : 1660 tanks deployed 1637 with water 1603 totally equipped
- All 4 fluorescence buildings complete each with 6 telescopes since February 2007

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Montag, 27. Juli 2009

The Southern Observatory

The Southern Observatory

A surface detector station

A surface detector station

A fluorescence telescope

A fluorescence telescope

The hybrid nature of Auger

The surface detector

The surface detector

The surface detector

- 1600 Water Cherenkov tanks $(1.2 \text{ m height}, 10 \text{ m}^2 \text{ area})$
- 12,000 ltrs of purified Water
- Three 9" PMTs
- 40 MHz FADCs
- solar powered
- GPS based timing
- micro-wave communication

The fluorescence detector

The fluorescence detector

The hybrid era

4-fold event

Energy spectrum

- Hybrid spectrum (FD & SD)
- Surface detector spectrum
- Auger spectrum (i.e. combined)
- (Horizontal EAS spectrum)

Hybrid spectrum

Geometrical reconstruction

Precise shower geometry from breaking degeneracy using SD timing

times, t_i , at angles χ_i , are key to finding R_p

$$
t_i = t_0 + \frac{R_p}{c} \cdot \tan\left(\frac{\chi_0 - \chi_i}{2}\right)
$$

Geometrical reconstruction

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$$

FD energy calibration

How to determine the hybrid spectrum

Aim: Flux measurement

$$
J(E) = \frac{d^4N}{dE \, dS \, d\Omega \, dt} \simeq \frac{1}{\Delta E} \frac{\Delta N(E)}{\mathcal{E}(E)}
$$

Event selection of high quality events:

- Geometrical reconstruction
	- \bullet Zenith $\leq 60^{\circ}$
	- Station within 1500m from shower axis
	- Energy dependent distance between core and FD site (Astropart. Phys. 27, 2007)
	- Energy dependent filed of view (Unger, ICRC Merida 2007)
- Profile reconstruction
	- Gaisser-Hillas fit with χ^2 /ndof <2.5
- \bullet X_{max} contained in the observed depth range
- Cherenkov light < 50%
- $σ(E) < 20%$
- Atmospheric conditions
	- Measurement of atmospheric parameters available
- Cloud coverage from Lidar measurements $< 25%$

Hybrid spectrum

core-telescope distance [km]

5 10 15 20 25 30

Fig. 2. Comparison between hybrid data and the Monte Carlo

simulations used for the determination of the hybrid exposure.

SD-array spectrum (<60°)

4-fold event (SD part)

Detector signal at 1000 m from shower core

- S(1000)
- determined for each surface detector event

$S(1000) \sim E$
Energy calibration with the fluorescence detector

 $\frac{1}{2}$

 $\text{calibration curve:} \qquad \qquad \alpha^{\text{max}}$ calibration curve.

- 7% at 10 EeV
- 15% at 100 EeV $\ddot{\theta}$ and $\ddot{\theta}$ are described by a power-law function, $\ddot{\theta}$

Improves with increased hybrid statistics and results of a fit to the shown in figure 6. The results of a fit to the data areas of a fi

 $a = (1.51 \pm 0.06(stat) \pm 0.12(syst)) \times 10^{17} eV,$ $b = 1.07 \pm 0.01(stat) \pm 0.04(syst),$

Note: $\frac{1}{2}$

0

Both S_{38°} and E_{SD} are determined experimentally. We do not rely on shower recorded showers: the most energy energy showers: the most energy energy selected events of the most energy selected $t_{\rm{back}}$ \sim $t_{\rm{max}}$ \sim $t_{\rm{max}}$ $\frac{1}{2}$ good agreement with the statistical sum of the stat $\sum_{i=1}^{n}$

Fig. 6. Correlation between lg S38 and lg EFD for the 795 hybrid

the measured VAOD profile, σatm. The total relative

Energy calibration with the fluorescence detector

Energy uncertainty from calibration curve:

- 7% at 10 EeV
- 15% at 100 EeV

Improves with increased hybrid statistics

Note:

Both S_{38°} and E_{SD} are determined experimentally. We do not rely on shower simulation.

18.5 19 19.5

Fig. 6. Correlation between lg S38 and lg EFD for the 795 hybrid

Energy determination with FD

FD energy: statistical uncertainty <6% determined with

- detector simulation
- validated by stereo events

FD energy: systematic uncertainty ~22%

Montag, 27. Juli 2009. The array configuration are monitored through the array configuration are monotoned through the array configuration are monotoned through the array configuration are monotoned through the array confi

Above 135,250 SD events with E > 3 · 10¹⁸ eV

ergies being explored using a novel technique that

exploits the hybrid strengths of the instrument.

The systematic uncertainties, and in particular the

influence of the energy resolution on the spectral

shape, are addressed. The spectrum can be described

by a broken power-law of index 3.3 **below the**

ankle which is measured at lg(Eankle/eV) = 18.6**.**

I. INTRODUCTION

Auger Observatory to study extensive air showers cre-

ated by ultra-high energy cosmic rays in the atmosphere,

a ground array of more than 1600 water-Cherenkov

detectors and a set of 24 fluorescence telescopes. Con-

struction of the baseline design was completed in June

2008. With stable data taking starting in January 2004,

the world's largest dataset of cosmic ray observations

*Keywords***: Auger Energy Spectrum** Corrected for energy resolution by a forward folding procedure

- energy dependent
- T_{eff} and temperatures are used at the Pierre •less than 20% over the full range

explanations of the shape of the energy spectrum and the

World FRL 101, 061101 (2008)

Syst. uncertainty on flux <4%

40

The Auger spectrum 4×4 F. Schussler (Pierre August Collaboration) august ~ 2 F. Schussler (Pierre August Collaboration) and \overline{a} and a more gradual suppression of the flux su **1 Ine Auger spect** The August spectrum covering the full range of the full rang The Auger spectrum the two measurements discussed above. The combinaappears more sharp in our data.

Energy [eV]

Fitter and State State State

Fig. 5. The compared energy spectrum computer with several assuming a pure computer \mathbf{r} $\mathbf v$ irira cosmological evolution of Emax $\mathbf v$ The source luminosity of $(z + 1)^m$ flux values can be found at $\frac{22}{22}$. With a cosmological evolution of *Cosmic Ray Conf. (Lodz, Poland)*, 2009. the source luminosity of $(z + 1)^m$ *Cosmic Ray Conf. (Lodz, Poland)*, 2009. source flux following ∝ E[−]2.⁶ one obtains a spectrum

Some earlier measurements from the HiRes experi-

[1] J. Abraham et al. (Pierre Auger Collaboration). *Physical Review*

Letters, 101:061101, 2008.

 $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$

been estimated [11].

We presented two independent measurements of the two independent measurements of the two independent measurements of

 $\mathcal{T}_{\mathcal{A}}$ the fractional difference of the combined energy $\mathcal{T}_{\mathcal{A}}$

systematic uncertainty of the energy scale of 22% has

spectrum with respect to an assumed flux ∝ E−2.6 is an assumed flux ∝ E−2.6 is an assumed flux ∞ E−2.6 is a E−2

shown in Fig. 4. Two spectral features are evident: an

Fig. 4. The fractional difference between the combined energy spectrum of the Pierre Auger Observatory and a spectrum with an index of

is shown in Fig. 3. The shown in Fig. 3. \sim

 2.6 Data from the Hires instrument \sim

Elemental composition - Charged particles

FD: Longitudinal Shower Profiles

Average shower maximum X_{max} Average Shower Maximum, !*X*max"

Primary protons:

primary protons:

 $\langle X_{\text{max}} \rangle = D_{10} \lg(E) + \text{const}$

superposition model: Superposition model:

elongation rate theorem:

 $\langle X_{\text{max}}\rangle$ = D₁₀ lg(E/A) + const

!*X*max" = *D*¹⁰ lg(*E*/*A*)+const

Shower to shower fluctuations Shower-to-Shower Fluctuations, RMS(*X*max)

Primary protons:

primary protons

 $RMS(X_{max})^2 = \lambda_0 + V(\text{shower})$ $RMS(X_{max})^{2} = \lambda_{p} + V(\text{shower})$

Superposition model ...

 $RMS(A) = RMS(n)/\sqrt{A}$ $RMS(A) = RMS(p)/\sqrt{A}$

> A does not work here *A* (fragmentation), but qualitatively

> > $RMS(A_1) < RMS(A_2)$

 Λ not work here (frage-fra $\frac{1}{\sqrt{2}}$ for $A_1 > A_2$

FD results

 $\langle X_{\text{max}} \rangle$ and RMS vs E

FD Results

! !*X*max" and RMS vs *E* **Explore correction Broken line fit:** $\frac{1}{2}$ broken $\frac{1}{2}$ Slopes D [g/cm²/decade]

! comparison to air shower

! published HiRes data

Elemental composition - Neutrinos

Detection

A vertical shower

 $\overline{\mathsf{I}}$

A vertical shower

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«Young» vs «old» showers

Neutrinos vs hadronic showers

Only a neutrino can induce a young horizontal shower

Neutrino signatures

2 D. GORA ´ *et al.* NEUTRINO SIGNATURES IN THE AUGER OBSERVATORY

Neutrino flux limits

Photon flux limit

 $T_{\rm eff}$ site of the Observatory will be

other opportunity related to the UHE photon search.

Thanks to the difference between the local geomag-

netic fields at the two sites a possible detection of

 $U_{\rm eff}$ at $V_{\rm eff}$ at $V_{\rm eff}$

an unambiguous way at Auger North by observing the

well predictable change in the signal from geomagnetic

oration also address fundamental physics questions. The

 G

a few Mpc by pair production $\mathcal{P}_\mathcal{P}$

if Lorentz symmetry holds. On the other hand, violation

of Lorentz invariance could lead to the observation of

an increased photon flux. The new constraints placed on

the violation of Lorentz invariance based on our photon

 $T_{\rm eff}$ photon upper limits placed by the Auger Collaboration μ

cascading of UHE photon showers [11].

Anisotropy

Angular resolution

Angular accuracy depends on station multiplicity

9 stations ~10¹⁹ eV

Search for large scale anisotropy at EeV energies \textsf{E} energies and \textsf{E}

Are EeV CRs of galactic or extra-galactic origin?

2 possible scenarios

- Transition occuring at the ankle: amplitude of dipol pattern steadily increasing with energy up to the ankle (very model-dependent)
- $F_{\rm F}$ spectrum compared with several astrophysical models assuming a pure composition of protons (red lines) or protons (red l large scale distribution of CRs \parallel Measuring the large scale anisotropy vs \parallel Measuring the large scale anisotropy vs \parallel • Transition at lower energy: relative motion of the observer wrt the frame of the sources influences the

iron (blue line), a power-law injection spectrum following E−^β and a maximum energy of Emax = 1020.⁵ eV. The cosmological evolution flux values can be found at [22]. energy is one of the main tools for discriminating between the 2 scenarios

REFERENCES

[1] J. Abraham et al. (Pierre Auger Collaboration). *Physical Review*

Letters, 101:061101, 2008.

 $+$ smooth functions $+$

 $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$

Upper limit **SPPCI** IIIIIIII

all energies 0.48 0.27 \pm 0.48 \pm 0.48 \pm 0.48 \pm 0.5 \pm

\cdots of $\ddot{\hspace{1ex}}$ \cdots \cdots y at highest er Anisotropy at highest energies **#** 29:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/6 0.10 27:55 1/

way reduces the sensitivity of observations. Moreover, cosmic rays that arrive close to the galactic plane are likely to have been deflected by the magnetic field in the disk more $\tau_{\rm eff}$ than those with higher galactic latitudes. $T_{\rm eff}$ effects could have some impact upon the estimate some impact upon the estimate of the strength and of the parameters that characterises is considered by the characteri

#2:4\$ < d < 24:8\$ 1/6 0.23 107 Take CR source candidates from some catalog, Γ sponding fraction of the whole sky is also indicated. The last declination of the last declination of the last band represents the part of the sky outside the field of view of Auger for e.g. VCV (Veron-Cetty and Veron)

Fig. 2

Define probability to find a single event of AGN between 50 and 100 Mpc and for angular separations an isotropic distr. within a certain opening angle from a source: $p = p(\psi, n_{sources}) = p(\psi, z_{max})$ Exploratory scan < 26 May 2006: Angular Scan

Scan
$$
P = \sum_{j=k}^{N} {N \choose j} p^j (1-p)^{N-j}
$$

Energy Scan 0.0 0.01 a a 0.001 0.001 **Probability** 0.0001 0.0001 0.000 $1e-05$ 1e-05 $1e-05$ $1e-06$ $1e-06$ $1e-06$ $1e-07$ $1e-07$ $1e-07$ $1e-08$ $1e-08$ $1e-08$ $1e-09$ $1e.09$ 1e-09 2 3 4 5 6 7 8 $0 - 0.005 0.01 0.015 0.02$ 40 50 60 70 80 90 100 п. Maximum angulai distance (deg) Maximum AGN redshift Energy threshold (EeV).

Redshift Scan

for 3 free parameters

- $z_{max}:$ Number of sources
- Ψ: Allowed angular separation • z_{max} : Number of sources
• Ψ : Allowed angular separation
• E_{Thr} : Energy threshold
-

 \mathbf{F} is (isotropic distribution) variation (isotropic distribution) variation \mathbf{F} Minimum of P, i.e. largest deviation from **Minimum of P**, i.e. largest deviation from isotropy found for $z_{max} = 0.018$ (d_{max} = 75 Mpc) $= 3.1^\circ$

$$
E_{\text{Thr}} = 56 \text{ EeV}
$$

Result: 12 among 15 measured events correlate with at least one source 3.2 expected if flux was isotropic (p=0.21) and exposure was accounted for

Running prescription (27.5.06- ...) RESEARCH ARTICLES

Verify a posteriori result by applying these correlation parameters to new data instead of using penalty factors to account for $#$ of searches

Goal: confirm results from exploratory scan by new data set Cosmic Rays with Nearby (a priory search)

verse. One possible lo-

events (crosses) correlate with the distribution of local matter as $r_{\rm c}$

by tuning severalfactors: a cutoff for the max-

The correlation plot

Current status

17/44 events in correlation ($P=0.006$)

contradict the earlier result. The departure from isotropy

remains at the 1% level as measured by the 1% level as measured by the cumulative product of the cumulative pr
The cumulative product of the cumulative product of the cumulative product of the cumulative product of the cu

of correlation as a function of the total number of the total

time-ordered events observed since 27 May, 2006, i.e.

excluding the data used in the data used in the exploratory scan that leads the exploratory scan that leads th
In the exploratory scan that leads the exploratory scan that leads the exploratory scan that leads the explora

17/44 events in correlation (P=0.006) $p=17/44=0.38$ more than 2 s.d. from isotropy from 27 May, 2006 through 31 August, 2007 and period

III includes data collected after the collected after \mathcal{I}_1 , from 1 September, \mathcal{I}_2

a function of time-ordered events of time-ordered events α function of time-ordered events α

observed since 27 May, 2006. For each new event the

best estimate of *p*data is *k/N*. The 1σ and 2σ uncer-

to arise from an isotropic distribution (*p*iso = 0*.*21). *Right:* The most likely value of the binomial parameter *p*data = *k/N* is plotted with black The degree of correlation has decreased, but still provides \blacksquare Posidence for anisotropy of UHFCRs $>$ 55 FeV at $>$ 99% C.I. \blacksquare collective to that those to the right, collective \blacksquare to arise from an isotropic distribution (*p*iso = 0*.*21). *Right:* The most likely value of the binomial parameter *p*data = *k/N* is plotted with black \blacksquare Portugal is 0.000 \blacksquare and plots to the current estimate of the HFCRs > 55 \texttt{FeV} at $> 99\%$ C I evidence for anisotropy of UHECRs >55 EeV at > 99% C.L.

2006. The likelihood ratio log¹⁰ *R* (see Eqn (2)) for the data is plotted in black circles. Events that arrive within ψmax = 3*.*1◦ of an AGN with maximum redshift *z*max = 0*.*018 result in an up-tick of this line. Values above the area shaded in blue have less than 1% chance probability

2006. The likelihood ratio log¹⁰ *R* (see Eqn (2)) for the data is plotted in black circles. Events that arrive within ψmax = 3*.*1◦ of an AGN with maximum redshift *z*max = 0*.*018 result in an up-tick of this line. Values above the area shaded in blue have less than 1% chance probability

Table of Results with full data set

Anisotropy searches

Summary and outlook

- Spectrum measurement is fundamental to solve the UHECR puzzle, but in addition
- Deducing the mass is crucial incl. photons and neutrinos
	- p/Fe at highest energy? Neutrinos and photons?
	- Composition around 10^{18} eV will sheet light on the origin too: Extensions of the southern site;
		- HEAT (3 FD telescopes; elevation of 30-60°)
		- AMIGA; Muon counting,
- Anisotropy may ultimately pin point the sources We need more statistics

Northern Observatory in Colorado/USA

- 20,000 square kilometer
- ~40 FD telescopes
- > 4000 SD stations
- SD energy threshold of > 10^{19} eV

70

END

Hillas model Bereszinsky model

Uncertainty of S(1000)

Precision of S(1000) improves as energy increases

Figure 6.9: Most intensive transitions in the nitrogen spectrum emerge from three elec-