Investigation of Hadronic Interactions at Ultra-High Energies with the Pierre Auger Observatory

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Moriond QCD - 03/2009
Cosmic Ray Energy Scale

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5} J(E)$ (m$^2$ sec$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

Energy (eV/particle)

- ATIC
- PROTON
- RUNJOB
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- KASCADE-Grande (prel.)
- Tibet ASg (SIBYLL 2.1)
- HiRes-MIA
- HiRes I
- HiRes II
- Auger SD 2008

Auger

LHC

HERA ($\gamma$-p)
RHIC (p-p)
Tevatron (p-p)

Investigation of Hadronic Interactions at Ultra-High Energies with the Pierre Auger Observatory
The Observatory
Data and Observables at the Pierre Auger Observatory

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Data and Observables at the Pierre Auger Observatory

\[ \text{Los Leones} \]

\[ \text{Los Morados} \]

\[ \text{Cohueco} \]

\[ \text{Loma Amarilla} \]

\[ \frac{dE}{dX} \text{ [PeV/(gcm}^{-2}\text{)]} \]

\[ \text{Atmospheric depth [gcm}^{-2}\text{]} \]

\[ \begin{array}{ccccccc}
\text{Height [km]} & \text{10} & \text{12} & \text{14} & \text{16} & \text{18} & \text{20} \\
\text{Atmospheric depth [gcm}^{-2}\text{]} & \text{500} & \text{1000} & \text{1500} & \text{2000} & \text{2500} & \text{3000} \\
\end{array} \]

\[ \sigma_{X_{\text{max}}} < 20 \text{ g/cm}^2 \]

\[ \Delta_{\text{sys}} \approx 15 \text{ g/cm}^2 \]

\[ E_{\text{cal}} = \int dX \frac{dE}{dX} \]

\[ \sigma_{E/E} \sim 8\% \]

\[ \Delta_{\text{sys}} \approx 22\% \]
Data and Observables at the Pierre Auger Observatory

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\[ \chi_{\text{max}} \]

\[ \sigma_E/E \sim 8\% \]

\[ \Delta_{\text{sys}} \approx 22\% \]

\[ S_{1000} \]

\[ E_{\text{surface}} = f(S_{1000}, \theta) \]
Some Physics Results and Analyses
Flux - Compatible with Proton Cosmic Ray Composition

(Auger spectrum: ICRC, arXiv:0707.2638 [astro-ph] and PRL (2008) 101:061101, arXiv:0806.4302 [astro-ph])
Flux - Compatible with Proton Cosmic Ray Composition

Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]

Scaled flux $E^{2.7} J(E)$ [km$^{-2}$·yr$^{-1}$·sr$^{-1}$·eV$^{-1}$]

Energy [eV/particle]

(Tevatron (p--p) LHC (p--p)

(Auger spectrum: ICRC, arXiv:0707.2638 [astro-ph] and PRL (2008) 101:061101, arXiv:0806.4302 [astro-ph])

(Proton model by Berezinski et al.)

Pair production ?!

Photo-pion production ?!

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Cosmic ray events above 56 EeV correlate within 3.1° with a selection of astrophysical objects within a sphere of 75 Mpc

Given a galactic magnetic field of $\sim \mu$G only protons are able to explain this
Cosmic ray events above 56 EeV correlate within $3.1^\circ$ with a selection of astrophysical objects within a sphere of 75 Mpc.

Given a galactic magnetic field of $\sim \mu$G only protons are able to explain this.
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\[ E \sim 10^{19} \text{ eV} \]
Longitudinal Profile

Energy deposit \([\text{PeV/g/cm}^2]\) vs. Depth \([\text{g/cm}^2]\) vs. Height a.s.l. (m)

\[E \sim 10^{19} \text{ eV}\]
Longitudinal Profile

Energy deposit $[\text{PeV/g/cm}^2]$  

Height a.s.l. (m)  

Auger event  

Nitrogen  

Depth $[\text{g/cm}^2]$  

$E \sim 10^{19} \text{ eV}$
$E \sim 10^{19} \text{ eV}$
Mean $X_{\text{max}}$, Elongation Rate - Mixed Primary Composition

⇒ mixed composition: $\langle A \rangle \sim 7$

(Auger $X_{\text{max}}$: ICRC 2007, arXiv:0706.1495 [astro-ph])
Auger cannot directly measure muons

→ Several indirect methods are developed

E.g.: muons from hybrid events:

Muon signal at 1000 m

Energy scale: +26 %

$S_\mu$ [VEM]

$D_X = X_{\text{obs}} - X_{\text{max}}$

Data $< 60$ deg

Data $> 60$ deg

Iron

Proton
Muons at $10^{19}$ eV - Overview

Very Heavy Composition already at $10^{19}$ eV?

\[ N_\mu = \frac{S_{\mu}^{\text{data}}(1000 \text{ m})}{S_{\mu}^{\text{QGSJetII}(1000 \text{ m})}} \]

ISVHECRI 2008, arXiv:0902.4613 [astro-ph]
APP (2008) 29:355, arXiv:0712.3750 [astro-ph]

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Muons at $10^{19}$ eV - Overview

Very Heavy Composition already at $10^{19}$ eV ?

\[ N_\mu = \frac{S^\text{data}}{S^\text{QGSJetII}(1000\, \text{m})} \]

\[ N_\mu^{\text{data}} = 1.5 \pm 0.1 \pm 0.1 \]

\[ N_\mu^{\text{iron}\,(\text{QGSJetII})} = 1.39 \]

\[ N_\mu^{\text{iron}\,(\text{SIBYLL})} = 1.27 \]

Energy scale factor

ISVHECRI 2008, arXiv:0902.4613 [astro-ph]
APP (2008) 29:355, arXiv:0712.3750 [astro-ph]
Dependence of $\langle X_{\text{max}} \rangle$ on Hadronic Interactions

![Graph showing the dependence of $\langle X_{\text{max}} \rangle$ on energy for different projectiles (protons and iron) measured by different experiments (Auger, Fly’s Eye, HiRes, MIA). The graph plots $\langle X_{\text{max}} \rangle$ in units of $[\text{g/cm}^2]$ against energy in [eV]. The data points are differentiated by symbols representing each experiment.]
Dependence of $\langle X_{\text{max}} \rangle$ on Hadronic Interactions

$\langle X_{\text{max}} \rangle$ vs. Energy [eV]

- EPOS (dev)
- Proton
- Iron

Data points from:
- Auger
- Fly's Eye
- HiRes
- MIA

See next talk by T. Pierog

Investigation of Hadronic Interactions at Ultra-High Energies with the Pierre Auger Observatory
Dependence of $\langle X_{\text{max}} \rangle$ on Hadronic Interactions

c.f.
R. Ulrich et al. ISVHECRI 2008
R. Ulrich et al. Blois2007 Forward physics and QCD 372 arXiv:0709.1392 [astro-ph]
Summary

High quality observations by the Pierre Auger Observatory

- Energy spectrum (ankle/cutoff)
- Anisotropies
- Shower profiles and $X_{\text{max}}$
- Muons

$\Rightarrow$ Discrepancy in the description of muon number and longitudinal shower development

$\Rightarrow$ Ambiguity between primary mass composition and hadronic interaction physics (and energy scale)

Outlook

Breaking the ambiguity:
Information about hadronic interactions at $\sqrt{s} \sim 100 - 500 \text{ TeV}$
Additional Slides
Air Shower Fluctuations

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\[ S_{\text{param}}(E, \theta, X_{\text{max}}, N_\mu) = S_{\text{em}}(E, \theta, DX(X_{\text{max}})) + N_\mu S_{\mu}^{QGSII,p}(10 \text{ EeV}, \theta, DX(X_{\text{max}})) \]

\[
\frac{dN_{\text{ev}}}{d \sin^2 \theta} \bigg|_{S(1000)>S_{\text{param}}(E=10 \text{ EeV}, \theta, \langle X_{\text{max}} \rangle, N_\mu)} = \text{const}
\]
Air Shower Development

**Primary particle**

- $X_1$
- $X_{\text{max}}$
- Slant depth
- Shower size

**Shower cascade**

**Shower startup**

**Cross section (proton-air) [mb]**

- $200$
- $300$
- $400$
- $500$
- $600$
- $700$
- $800$

**Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]**

- $10^3$
- $10^4$
- $10^5$

**Energy [eV]**

- $10^{13}$
- $10^{14}$
- $10^{15}$
- $10^{16}$
- $10^{17}$
- $10^{18}$
- $10^{19}$
- $10^{20}$

**[GeV]**

**[pp]**

**[mb]**

- **Tevatron**
- **LHC**

**Cross section (proton-air)**

**SIBYLL 2.1**

**accelerator data (p-p) + Glauber**

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Air Shower Development

Primary particle

Shower startup

Shower cascade

Slant depth

Shower size

X_1

X_{max}

Equivalent c.m. energy \sqrt{s_{pp}} [GeV]

Cross section (proton-air) [mb]

Energy [eV]

10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}

10^3 10^4 10^5

accelerator data (p–p) + Glauber

SIBYLL 2.1

SIBYLL 2.1, \sigma_{p\text{-air}} \times 1.2

SIBYLL 2.1, \sigma_{p\text{-air}} \times 0.8

Tevatron

LHC

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Investigation of Hadronic Interactions at Ultra-High Energies with the Pierre Auger Observatory
Results are independent of hadronic interaction models

**Anisotropies**
Light composition at \( E > 57 \text{ EeV} \)

**Total Flux**
Compatible with light composition:
Cutoff → GZK, Ankle → \( e^\pm \)-dip

\( X_{\text{max}} \)
Mixed composition, heavier at high energies

**Muons**
Very heavy composition (\( > \text{Iron} \)) already at 10EeV

Results are depending on hadronic interaction models