High-energy interactions at the Pierre Auger Observatory

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for the Pierre Auger Collaboration
Ultra High Energy Cosmic Rays

*Cosmic ray energy spectrum*

![Graph of Cosmic Ray Energy Spectrum](image)
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum

$F \left( m^2 \text{sr s GeV}^{-1} \right)$

$1 \text{ m}^2 \text{ s}^{-1}$

$1 \text{ km}^{-2} \text{ yr}^{-1}$

$E \ (\text{eV})$

$10^9$ $10^{11}$ $10^{13}$ $10^{15}$ $10^{17}$ $10^{19}$ $10^{21}$
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum

Tevatron (p-p)  LHC (p-p) 13 TeV

R. Conceição
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum

- UHECRs
  - Opportunity to understand high-energy Universe
    - Production (sources; acceleration mechanisms...)
    - Propagation (Magnetic fields...)
  - Opportunity to investigate particle physics at energies above the LHC
    - High-energy interactions
      - $E = 10^{19} \text{ eV} \Rightarrow \sqrt{s} \sim 130 \text{ TeV}$
    - Different kinematic regimes
      - $E_{\text{beam}}$ up to $10^8 \text{ TeV}$
Pierre Auger Observatory

UHECR flux:
\(~ 1 \text{ km}^{-2}\text{ century}^{-1}\)

Located in the Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

\(~ 60 \text{ km} ~\)
Pierre Auger Observatory

Data taking since 2004
Installation completed in 2008

• ~ 1600 Surface Detector (SD) Stations
• 1.5 km spacing
• 3000 km²

Low energy extension
• Aim to $E \approx 10^{17}$ eV
• AMIGA
  – Denser array plus muon detectors
• HEAT
  – 3 additional FD telescopes with a high elevation FoV

~ 60 km
• 4 Fluorescence Detectors (FD)
• 6 x 4 Fluorescence Telescopes
What is measured?

- FD: Collects the fluorescence light produced by the e.m. shower component in moonless night
  - Energy from integral
    - Quasi-calorimetric measurement
  - Depth of shower maximum ($X_{\text{max}}$)
    - Composition sensitive
What is measured?

- SD: Sample the charged secondary particles that arrive at ground
  - 100% duty cycle
  - Shower direction: from arrival time
  - Energy estimator: signal at 1000 m from the core
• Muon Production Depth (MPD)
  – Use arrival time at ground plus shower geometry to reconstruct MPD
**UHECRs Energy Spectrum**

- **Energy Spectrum**: Combined energy spectrum of UHECRs.
  - Combined fit of energy calibrations and smearing corrections.
  - Including statistical and systematic uncertainties from energy calibrations and folding methods.

- **Flux Systematic Uncertainties**:
  - SD vertical: \(-6\%\)
  - Hybrid: \(10\% (6\%)\), \(1 \text{ EeV} (10 \text{ EeV})\)

- **Normalizations**:
  - Hybrid: 0.94, 750 m array: 1.02, Inclined: 1.05

- **Fluorescence Yield**: \(-4\%\)

- **Shower Reconstruction**: \(6\%\)

- **Atmospheric Conditions**: \(3\%\)

(talk by V. Verzi, paper 0928)
Combined energy spectrum of UHECRs

Including statistical and systematic uncertainties from energy calibrations and folding methods.

Ankle

GZK effect

Normalizations: 
- Hybrid: 0.94
- 750 m array: 1.02
- Inclined: 1.05

Energy systematic uncertainties:
- FD energy scale: 14%
- Absolute calibration: 9%
- Fluorescence yield: \(< 4\%
- Shower reconstruction: 6%
- Atmospheric conditions: 3%

Flux systematic uncertainties:
- SD vertical: \(< 6\%
- Hybrid: 10\% (6\%), 1 EeV (10 EeV)

Auger 2013 preliminary
UHECRs Energy Spectrum

Pure proton or Fe nuclei at source
Cutoff caused by GZK or photo-disintegration

Mixed composition at source
Cutoff caused by source energy exhaustion

The UHECR composition is the key to understand
the spectrum features cause
Average $X_{\text{max}}$, and its RMS consistent with a lighter/heavier composition at lower/higher energies

- Change on elongation rate around $\log(E/\text{eV}) = 18.2$
• Interpretation of the $X_{\text{max}}$ distribution in terms of mass composition
  – Depends on the performance of hadronic interaction models
Mass composition interpretation

Phys.Rev. D90 (2014) 12, 122006

Figure 2.9: Estimate of the composition of ultra-high energy cosmic rays at the top of the atmosphere. The $X_{\text{max}}$ distributions measured with the Auger Observatory have been fitted by a superposition of four mass groups accounting for detector resolution and acceptance effects. The error bars show the combined statistical and systematic uncertainties of the mass estimates, except those related to the choice of the hadronic interaction models.

- Interpretaion of the $X_{\text{max}}$ distribution in terms of mass composition
  - Depends on the performance of hadronic interaction models
    - Mostly proton at low energies
    - Intermediate mass states at the highest available energies
    - Nearly no iron

Energy flux suppression region

- Ankle

E [eV]
Proton-air Cross-section ($\sqrt{s}=57$ TeV)

- $X_{\text{max}}$ distribution tail is sensitive to the primary cross-section
- If there is enough proton it is possible to measure the p-air cross-section at very high energies

![Proton-air Cross-section graph]

$\langle E \rangle = 10^{18.24}$ eV

Measurement performed at:
- $E = 10^{18.25}$ eV
- $\sqrt{s} = 57$ TeV

Using Glauber theory is possible to translate this result into p-p cross-section
Proton-air Cross-section

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*Phys. Rev. Lett. 109, 062002 (2012)*
Muon content in air showers

- Muon EAS content is directly related with the hadronic shower component
- Through inclined showers is possible to measure directly the muon content ($R_\mu$) in the SD
  - Electromagnetic shower component gets attenuated
Muons in Air Showers at the Pierre Auger

- Muon EAS content is directly related with the hadronic shower component
- Through inclined showers is possible to measure directly the muon content ($R_{\mu}$) in the SD
  - Electromagnetic shower component gets attenuated
- Mean muon number compatible with iron showers within systematic uncertainties
- Combination of the $R_{\mu}$ with $X_{\text{max}}$ shows tension between data and all hadronic interaction models

\[ \mu_X \text{max} \]

\[ \text{Auger measurements at} \]

\[ \text{predicted logarithmic muon content of} \]

\[ \text{can be done in Eq.} \]

\[ \text{accurate. Based on the small deviations, we estimate} \]

\[ \text{The three values would be identical if the Heitler model was} \]

\[ \text{are computed with the Heitler model described in the text.} \]

\[ \text{obtain equal numbers of events per bin.} \]

\[ \text{uncertainty of the fitted line. Shown for comparison are theo-} \]

\[ \text{shifts in the energy scale. The grey band indicates the statistical} \]

\[ \text{et al.} \]

\[ \text{where} \]

\[ \text{as obtained from the fit. The deviation of} \]

\[ \text{is only 2% so that the conversion does not lead to a} \]

\[ \text{A. AAB} \]

\[ \text{We estimate the systematic uncertainty of the approxi-} \]

\[ \text{LHC is shown in Fig.} \]

\[ \text{h} \]

\[ \text{h} \]

\[ \text{N} \]

\[ \text{μ} \]

\[ \text{μ} \]

\[ \text{X} \]

\[ \text{X} \]

\[ \text{X} \]

\[ \text{X} \]

R. Conceiçao
Shower consistency

- Muon Production Depth
  - Sensitive to composition
- Mean $X_{\text{max}}$ and $X^{\mu}_{\text{max}}$ should give the same average mass composition
  - EPOS-LHC fails to provide a consistent solution

**Graphs**

- QGSJetII-04
  - $X_{\text{max}}$ and $X^{\mu}_{\text{max}}$

- Epos-LHC
  - $X_{\text{max}}$ and $X^{\mu}_{\text{max}}$

- Proton

- Iron

- EPOS-LHC

- QGSJetII-04

- Total 17
- Seasonal effect 12
- Atmospheric measurements 122
- Iron 92
- Proton 42
- Random 27
- Production depth 42
- Bias in our data.

- Atmospheric profile.
- Selection efficiency.
- Shower consistency.

- Phys. Rev. D90 (2014) 1, 012012
Auger upgrade

Fraction of Cherenkov tanks in operation

- **Auger PRIME** – “Primary cosmic Ray Identification through Muons and Electrons”
  - Scintillator on top of the tank to measure directly e.m. shower component
  - WCD measures e.m. + muons
  - Upgrade to:
    - Enhance primary identification
    - Improve shower description
    - Reduce systematic uncertainties
• UHECRs measured at Pierre Auger Observatory
  • Opportunity to study the high-energy Universe and Particle Physics at the highest energies

• Pierre Auger Observatory has delivered many important results
  • GZK-like suppression established
  • Unexpected primary mass composition scenarios
  • Current hadronic interaction models not able to describe consistently the air shower observables

• Upgrade: Auger PRIME
  • Measure independently the e.m. and muonic component at ground
Acknowledgments
BACKUP SLIDES
A binned maximum-likelihood method is used to find the best-fitting combination of the various species. For a given energy bin, the likelihood value obtained when considering, we remove the factorials by dividing the predicted templates with size equal to the real data set. The fit quality is measured by the $p$-value, which is defined as the probability of obtaining a worse fit (larger negative log-likelihood) than the data, assuming that the data, with the $p$-value was calculated as the fraction of mock data sets that best fit the data are found by minimizing the negative log-likelihood expression. As this value is a constant factor, the maximization is not affected by this $p$-value. The species fractions are the corresponding MC prediction. As a practical interpretation, we remove the factorials by dividing the likelihood ratio can also be used as an estimator for the $p$-value.

<table>
<thead>
<tr>
<th>E [eV]</th>
<th>p fraction</th>
<th>He fraction</th>
<th>N fraction</th>
<th>Fe fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{18}$</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
</tr>
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<td>$10^{19}$</td>
<td>0.2</td>
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The upper panels show the species fractions and the lower panel shows the DEPTH OF MAXIMUM OF AIR-SHOWER PROFILES AT...