Estimation of the invisible energy with the data collected by the Pierre Auger Observatory

Analisa Mariazzi
for the Pierre Auger Observatory

IFLP-CONICET, La Plata - Argentina

UHECR 2016
October 11-14, Kyoto-Japan
Outline

Physics of the invisible energy

Measurement of the invisible energy with the Surface Detector (SD) of the Pierre Auger Observatory:

• Near vertical events data sample ( \( \theta < 60^\circ \) )
• Inclined events data sample ( \( \theta > 60^\circ \) ) New result!

Parametrization of the average invisible energy as a function of the calorimetric energy
Auger hybrid detector

**Fluorescence detector FD**
Measures longitudinal development of the e.m component of EAS: $E_{\text{Cal}}$ and $X_{\text{max}}$

**Invisible energy ($E_{\text{inv}}$):** fraction of the primary energy carried away by neutrinos and high energy muons is a priori unknown ($\sim 15\%$ at 0.1 EeV decreasing with $E_0$).

**Calorimetric energy ($E_{\text{Cal}}$):** integral of the energy deposit profile

$$E_{\text{Cal}} = \int \frac{dE}{dX} \, dX$$

**Total energy ($E_0$):**

$$E_0 = E_{\text{Cal}} + E_{\text{Inv}}$$
Auger hybrid detector

**Surface detector SD**
Water Cherenkov detectors have enhanced sensitivity to muons.

Surface detector **inclined events**
Muon content can be measured directly as the electromagnetic component dies out.

S1000 $\sim E_0$
Invisible energy in MC simulations

Average invisible energy as a function of $E_{\text{cal}}$ depends on the assumed primary mass composition and the high energy hadronic interaction model used in the simulations.

$E_{\text{inv}}$ calculation done as in H. Barbosa et al., Astropart. Phys., 2004, 22:159
Measurement of $E_{\text{Inv}}$ at Auger

Muon EAS content is directly correlated with the invisible energy (confirmed using simulations by M. Nyclicek et al., Proc. 31st ICRC, Łódź, Poland, 2009)

$$E_{\text{Inv}} = \xi_c \pi N_{\mu}$$

$$E_0 = E_{\text{Cal}} + E_{\text{Inv}}$$

$$E_0 = \xi_c e N_e + \xi_c \pi N_{\mu}$$

$$N_{\mu} = \beta_0 \left( \frac{E_0}{\xi_c \pi} \right)^\beta$$

$$E_0 = \gamma_0 S(1000) \gamma$$

Near vertical showers

$E_0$ from $S(1000)$ + $\beta_0$ correction from $N_{19}$

Independent data sample - different SD reconstruction

$N_{\mu} \sim N_{19}$

Inclined showers

$N_{19}$: direct measurement of muons at ground as showers are dominated by muons

More straightforward
We used QGSJet-II mixed composition sample to estimate $A(\Delta X)$ and $B$

Fit in each bin of $\Delta X = X - X_{\text{max}}$

$$\log_{10} E_{\text{Inv}} = A(\Delta X) + B \log_{10} S_{1000}$$

$B = \gamma \beta \approx 0.98 \pm 0.04$

Assuming no variation of mass composition with energy

Invisible energy deviation from true value when reconstructed using $A(DX)$ and $B$ obtained from a QGSJet-II mixed composition simulated sample (left), corrected for attenuation and muon content (right).
$E_{Inv} (S1000)$

$$A^{MC}(DX) = A^{QII}(DX) + \log_{10} \left( \frac{\gamma_0^{MC}(DX)}{\gamma_0^{QII}(DX)} \right)^\beta \frac{\beta_0^{MC}}{\beta_0^{QII}}$$

$N_\mu = \left( \frac{\beta_0}{\xi_c \pi} \right)^\beta$  

**correction to $A(DX)$**  
**for attenuation and muon content**

$E_0 = \gamma_0 (S1000)$

**application to the data: correction to $A$ for attenuation (hybrid events) and muon content at a fixed mixed mass and $E_0=10^{19}$ eV ($N_{19}$ inclined showers)**
\[ E_{\text{Inv}}(S1000) \text{ parametrization with } E_{\text{Cal}} \]

\[ E_{\text{Inv}} = a_0 \ (E_{\text{Cal}})^{a_1} \]

**High quality selection of hybrid events**

\[ \theta < 60^\circ, \quad E_{\text{threshold}} = 3.1 \times 10^{18} \text{ eV} \]

**\( E_{\text{inv}}(E_{\text{Cal}}) \) systematic uncertainty:** propagated systematic uncertainty associated with the measurement of S1000 and Dx + systematic uncertainty of the method (propagating the uncertainties associated with the parameters of A(Dx) and B used to determine \( E_{\text{inv}} \) ).
Inclined showers (62°<θ<80°)

Muon dominated signals → size at ground from muon density maps

The shape of the maps is energy, mass & model independent

Reconstruction based on muon distribution maps at ground for $10^{19}$ eV protons QJSJetII03. Muon maps are fitted to observations to obtain the muon content from the normalization $\rightarrow N_{19}$ (muon scale reference value)

$$n_{\mu} = N_{19}(E_0, A) \ n_{\mu}(x, y, \theta, \phi)$$
The correlation is very good!

We will use from now on $E_{\text{Inv}} [\text{eV}] = p_0 (N_{19})^{p_1}$ with $p_0$ and $p_1$ obtained for QGSJetII04 mixed p-Fe composition sample.
Deviation reconstructed invisible energy from inclined showers for simulated data samples with different mass and high energy hadronic interaction models.

\[
E_{\text{Inv}} = p_0 \ (N_{19})^{p_1}
\]

reconstructed using \( p_0 \) and \( p_1 \) obtained for QGSJetII04 mixed P-Fe composition sample.
**$E_{\text{Inv}}(N_{19})$ parametrization with $E_{\text{Cal}}$**

$$E_{\text{Inv}} = a_0 \ (E_{\text{Cal}})^{a_1}$$

**High quality selection of hybrid events**

$$62^\circ < \theta < 80^\circ, \ E_{\text{threshold}} = 4.10^{18} \text{ eV}$$

**$E_{\text{inv}}(E_{\text{Cal}})$ systematic uncertainty:** propagated systematic uncertainty associated with the measurement of $N_{19}$ + systematic uncertainty of the method (due variation of mass composition and high energy hadronic interaction models).
$E_{\text{Inv}}$ parametrization with $E_{\text{Cal}}$

Average $E_{\text{Inv}}$ parametrization for two independent data samples

**Preliminary**

Inclined showers ($62^\circ < \theta < 80^\circ$)

Near vertical showers ($\theta < 60^\circ$)
$E_{\text{Inv}}$ parametrization with $E_{\text{Cal}}$

Average $E_{\text{Inv}}$ parameterizations used in Auger and TA

Auger $E_{\text{Inv}}$ is larger than $E_{\text{inv}}$ from Telescope Array [*]

Conclusions

- The invisible energy was obtained for two independent data samples of vertical and inclined hybrid events of the Pierre Auger Observatory.

- These novel estimations of $E_{\text{Inv}}$ from data are basically independent of the high energy hadronic interaction model used in Monte Carlo simulations.

- A parametrization of the average invisible energy as a function of the calorimetric energy was given. This parametrization could also be used by other FD experiments taking into account the relative difference in the energy scale.

- Analysis of the systematic uncertainties on the invisible energy shows a correlated uncertainty in the total energy which decreases with energy from 3% to 1.5% [#].