A universal description of temporal and spacial distributions of ground particles in extensive air showers

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Reconstruction of surface detector data at e.g. Auger

- **Particle density**: 1D lateral distribution → shower size, core position
- **Arrival times**: Spherical shower front → shower axis
- **Fit parameters** are connected only indirectly to mass and properties of UHE interactions, e.g. Rise-time, curvature, LDF slope

Rich timing information (40 MHz sampling) is not used in standard reconstruction
Universal longitudinal profiles of the electromagnetic component of hadron induced showers

Simulated energy deposit along shower axis

Large fluctuations in shower development apparent

Longitudinal profiles depend on
  • Energy $E$
  • Distance to $X_{\text{max}}$: $\Delta X$
  but not on mass
Extension to Lateral distributions of four signal components

- Pure electromagnetic
- Muons
- Electromagnetic from muon decay
- Electromagnetic jets from hadrons

\[ S_{\text{tot}} = S_{\text{em}}(DX, E) + N_{\mu}^{\text{rel}} S_{\mu}^{\text{QGS}}(DX, E) + N_{\mu}^{\text{rel}} S_{\mu}^{\text{em}}(DX, E) + (N_{\mu}^{\text{rel}})^{\alpha} S_{\text{jet}}^{\text{em}}(DX, E) \]

\[ N_{\mu}^{\text{rel}} = \frac{S_{\mu}(DX, r, E)}{S_{\mu}^{\text{QGS}}(DX, r, E)} \]

determined by lateral distribution and thus correlated to \( S_{1000} \)

\[ \theta = 36^\circ \]
Signal contribution at 1000m

Top of the atmosphere

\[ \Delta X = \rho d \]

\[ \Delta X_2 \]

\[ X_{\text{max}} \]

\[ n \]

\[ s_0 \]

\[ 10^{19} \text{ eV} \]

M. Ave, J. Gonzalez, D. Maurel, M. Roth ICRC 2011 Beijing, 1025
Relative signal contribution of individual components

$S_{\text{e/\gamma}}/S$

$S_{\mu}/S$

$S_{\text{hadron jet}}/S$

$S_{\mu \text{ decay products}}/S$
Bulk of em. particles from high-energy $\pi^0$ decay (produced in high energy interactions) diffuses in the well-known standard electromagnetic cascade.

em. particles from low-energy $\pi^0$ produced in low-energy interactions at high $p_T$, muons and em. particles are directly correlated.

Four-component universality model

Courtesy J. Gonzalez

\[ \mu \]

\[ e/\gamma \]

\[ e/\gamma \text{ from } \mu \text{ decay} \]

\[ e/\gamma \text{ from late hadrons} \]
Parameterization of the time dependence

- Time-dependent detector response modeled by log-normal distribution (for each signal component)
- Start time $t_0$ given by first interaction $X_0$ (spherical front)
- Time shape (mean/spread) depends on $\Delta X$ and position in shower plane: $S(t) = f(t, t_0, DX, r, \psi)$
- Time structure is universal (no dependence on $N_\mu$)
Parameter dependencies

Parameters \( m \) and \( s \) depend on

- Energy \( E \)
- Distance to \( X_{\text{max}} \): \( \Delta X \)
- Core distance \( r \)
- Shower geometry \( \theta, \phi \)

No energy, \( \Delta X \) nor core distance dependent bias apparent
Validation of the time model
Time quantiles for muons

No bias for different $\Delta X$ nor signal size
Validation of the time model
Time quantiles for muons

No bias for different primaries nor interaction models used
Parameterizations used in a likelihood procedure

- Signal size \( S \)
- Start time \( t_0 \)
- Shape \( m, s \)

as a function of

- Energy \( E \)
- Relative muon number \( N_{\mu}^{\text{ref}} \)
- Distance to \( X_{\text{max}} \): \( \Delta X \)
- Shower geometry \( \theta, \phi \)
Fitting of a single event

Colored bands indicate corrections for up- and downstream asymmetry, e.g. different $\Delta X$, ground screening, detector response.

\[ E_{\gamma}/eV = 19.5 \]
\[ N_{\mu} = 1.25 \]
\[ \theta = 36^\circ \]
Reconstruction performance

Events reconstructed with
- Universality fit
- Standard LDF

$\theta = 38^\circ$
$\lg(E/eV) = 19.5$
**X_{\text{max}}** bias and resolution

**Largest systematic uncertainty:** Energy scale

+10% shift in energy $\rightarrow \Delta X_{\text{max}} = -10 \text{ g/cm}^2$
$N_\mu$ bias and resolution

**Largest systematic uncertainty:** Energy scale

$+10\%$ shift in energy $\rightarrow \Delta N_\mu = -0.15$
• Signals and time structure well described by shower universality
• Few parameters: \(N_\mu, E, X_{\text{max}}, X_0\) (+geometry)
• Reconstruction using only the time-dependent signal of ground based detectors

Outlook
• Composition sensitive parameters at 100% duty cycle
• Mass composition at the highest energies
• Mass-dependent search for correlations to astrophysical sources
• Applicable to other surface detector arrays
• Additional muon measurements will reduce \((N_\mu, E)\) correlation

See R. Engel on the Auger upgrade PoS686 and M. Josebachuili on AMIGA POS409
Muonic component in air showers

- Energy Deposit \([\text{GeV cm}^{-2}/\text{g}]\)
  - Depth \([\text{g/cm}^2]\)
  - Proton, \(10^{19}\text{eV}\)
  - 100 Highest Energy Interactions
  - Individual Sub-Showers

- Muons
  - Number of generations \(\sim 6\) at \(10^{19}\text{eV}\)
  - Amplified sensitivity to hadronic interactions

**R. Ulrich APS 2010**

- \(X_{\text{max}}\) is dominated by first interaction
- Muons are produced late in the shower cascade
- May allow to disentangle particle physics and composition using hybrid events (coincident measurement of SD and FD)