CR Primary Mass Identification with Lateral Muon Profile of EAS

Moon Moon Devi\textsuperscript{1,2}, Ran Budnik\textsuperscript{1}

\textsuperscript{1}Department of Particle Physics and Astrophysics
Weizmann Institute of Science, Rehovot, Israel
\textsuperscript{2}Presently at: Department of Physics
Tezpur University, Assam, India.

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Goal

- Identifying primary particle shower–by–shower using muons
- The information on the muons in a simulated EAS, combined with $X_{max}$ and energy of the primary $E_p$, are used for a log likelihood analysis to distinguish primaries
- Future prospect for detectors: Low-cost Large Area Detector Arrays can be employed to detect muon tracks
- We perform an operational research on feasibility of such detectors
Current limitations

- **EM component:**
  - Gives $E_p, X_{max}$, direction, timing
  - However washes out the hadronic history
  - No way to resolve the stochastic $1^{st}$ interaction jitter

- **Muon measurements: current limits**
  - Measurements on only muon component: done for numbers and spectrum
  - Limited to a single position, making results meaningful only when integrated over many events (except IceCube+IceTop)
Simulation details

EAS:
- CORSIKA v7.4002
- Primaries: Proton, Iron
- Energy: $10^{16}$ eV - $10^{19}$ eV
- Zenith Angle: 0°
- Hadron Model: QGSJET-II
- 110m above sea level

Detector:
- 2m X 2m stations
- Stations apart by: 0m, 20m, 50m, 200m
  (Collection: 100%, 1%, 0.16%, 0.01%)
- $E_\mu = 0.5 - 50$ GeV
- $E_\mu$ resolution: 0, 50%
The number of muons and $X_{\text{max}}$

- $E_p = 10^{16}\text{eV}$

![Graphs showing the relationship between $X_{\text{max}}$ and $N^\mu$ for different energy ranges.]

- $0.44\text{ GeV} < E_\mu < 0.65\text{ GeV}, 100\text{ m} < R < 144\text{ m}$

- $1.41\text{ GeV} < E_\mu < 2.08\text{ GeV}, 100\text{ m} < R < 144\text{ m}$

- $4.52\text{ GeV} < E_\mu < 6.66\text{ GeV}, 100\text{ m} < R < 144\text{ m}$

- $14.45\text{ GeV} < E_\mu < 21.29\text{ GeV}, 100\text{ m} < R < 144\text{ m}$
We try to map the possibilities of using the spectral + radial shape of the muon component.

We build a ‘map’ in \((E_\mu, R)\) for each primary and use \(X_{max}\) from an external measurement to account for its specific value.

We use a likelihood test for differentiating between hypotheses, taking into account each individually measured muon.
The Lateral Spread

\[ \rho (\text{GeV}^{-1} \text{ m}^{-2}) \text{ for P shower, } X_{\text{max}} = 621 \text{ g cm}^{-2} \]

\[ \rho (\text{GeV}^{-1} \text{ m}^{-2}) \text{ for Fe shower, } X_{\text{max}} = 620 \text{ g cm}^{-2} \]
\[ \rho_{E R^2} = \frac{dN_\mu}{dE_\mu dR^2} [X_{max}, E_\mu, R] = Ce^{-\frac{R}{R_0} + (R_1 R^{-D} + K) X_{max}} \]

- The formulation gives stable fit results (should be redone for changing E, primary, models, angle...)
- Makes calculations efficient compared to e.g. binned data
Construction of a likelihood function:
\[ \ln L = \ln L_{\text{shape}} + \ln L_n \]

\[ L_{\text{shape}} = \prod_{i=1}^{N_{\mu}^{\text{obs}}} \rho_{i,ER}^2(E_{\mu}^i, R^i) \]
Takes into account the normalized expected shape of the muonic shower in \((E_\mu, R)\) plane

\[ L_{\text{number}} = \text{Poisson}(N_{\mu}^{\text{obs}} | N_{\mu}^{\text{exp}}) \]
Takes into account the total number of muons

\[ \Lambda = \ln L(\text{data}) - \ln L(\text{model}) = \Lambda_{\text{shape}} + \Lambda_n \]
Results: At Different Collection Efficiencies

- $E_p = 10^{16}$ eV, ideal muon detectors
Results: At Different $E_p$

- Ideal muon detectors, 0.16% Collection

![Graphs showing data for different $E_p$ values](image-url)
Results: With Detector Resolution

- $\sigma_1$: 50%
- $\sigma_2$: 20% ($E_\mu \leq 10 \text{ GeV}$) & 50% (rest)
- $\sigma_3$: 20% ($10 \text{ GeV} \leq E_\mu \leq 20 \text{ GeV}$) & 50% (rest)
- $\sigma_4$: 20% ($E_\mu \geq 20 \text{ GeV}$) & 50% (rest)
Results: With Hadron Models

\[ E_p = 10^{16} \text{ eV}, \, 0.16\% \text{ collection, } \sigma_2 \]
Results: for more primaries

- 0.16% Collection
- Group I ($A \leq 4$), Group II ($4 < A \leq 25$), Group III ($25 < A \leq 56$)
Prospects of upgrading existing surface arrays

- Introduction of muon tracker arrays would provide us the necessary information on muons
- 2m X 2m detectors 50 m apart provides significant identification between P and Fe primaries
- Arrays of large area low cost detectors are suitable for the primary identification
- Reasonable options: Gaseous large area detectors with suitable pickup strip pixels, e.g, THGEM, RPWELL
Concluding Remarks

- The shape of the muon shower component in an EAS has been parametrized.
- Information on the shape and flux are used to identify primaries.
- Identification of primaries with muons collected is possible with a realistic surface array.
- Separation of primaries improves with increase in primary energy. At higher energies the flux is much lower, but more precise information on the primaries are obtainable.
- Muon spectrometry has the potential to become a reasonable option for ground arrays.

Thank you!