Applying Extensive Air Shower Universality to Ground Detector Data

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Outline

- EAS universality at large core distances
- Ground signal parametrization based on universality
- Determining number of muons and model-independent energy scale
- Conclusion
Energy calibration of ground arrays

Standard procedure so far:

- determine $S(r_{\text{opt}})$ from detector signals
  - $r_{\text{opt}}$ depends on experiment (detector spacing)
- calibrate $S(r_{\text{opt}})$ – E relation with simulations
- large systematic uncertainties in E calibration
  - due to unknown hadronic interaction physics

Can we circumvent these unknowns?
Idea of EAS Universality

- UHECR air shower: $\sim 10^{10}$ particles
- Details of hadronic interactions quickly washed out for EM particles ($e^+/e^-/\gamma$)
- Particle flux at ground only function of:
  - energy $E$
  - zenith angle $\theta$
  - distance to ground $DG$ of shower maximum
Universality of EM component

- Evolution of signals from EM particles in water Cherenkov tank – proton / iron at $10^{19}$ eV

- At 1000m from shower core
- ```Flat tank''` approximation
  -> no $\theta$-dependence
- Not including muon decay products
- CORSIKA simulations with QGSJetII / Fluka
Universality of EM component

- ~12% difference b/w p/Fe - universality violation
- independent of shower evolution

Signals for different primaries/models relative to proton-QGSJetII
Universality of $\mu$ component?

- Again water Cherenkov signals at 1000m
- Strong primary/model dependence

![Graph showing $s_{\mu}$ vs. DG with different markers for proton and iron from QGSJetII and Sibyll models.](image)
Universality of $\mu$ component

- Primary/model dependence in signal normalization, *not* evolution!

$\mu$ signals relative to proton QGSJetII
Signal parametrization

- Based on universality:
  - $S_{EM}$ known (*given DG*)
  - $S_{\mu}$ evolution known
  - $\mu$ signal normalization $N_{\mu}$ unknown
    - $\rightarrow$ to be determined from data
  - $DG$ given by mean depth of showers $<X_{\text{max}}>$

\[
S(E, \theta, DG) = S_{EM}(E, \theta, DG) + N_{\mu} \cdot S_{\mu,\text{ref}}(\theta, DG)
\]

Reference: proton-QGSJetII at $10^{19}$ eV
Determining $N_\mu$ from data

- Use isotropy of cosmic ray flux

**constant intensity method:**

$N_{\text{events}} (>E)$ is equal in equal exposure bins in $\theta$

- Showers at different zenith angles probe different DG -> discern $S_{\text{EM}}$ from $S_\mu$
Constant intensity method

- $N_\mu = 0.5$: too small ...

Energy fixed at $10^{19}$ eV

Signal at 1000m vs sec $\theta$

$N_{\text{events}} (> S)$ in equal exposure bins $(\sin^2 \theta)$
Constant intensity method

- $N_\mu = 2.0$: too large ...

Energy fixed at $10^{19} \text{ eV}$

Signal at 1000m vs sec $\theta$

$N_{\text{events}} (> S)$ in equal exposure bins (sin$^2 \theta$)
Constant intensity method

- \( N_{\mu} = 1.0: \) right ...

Energy fixed at \( 10^{19} \text{ eV} \)

![Graph](image)

- Signal at 1000m vs sec \( \theta \)
- \( N_{\text{events}} (> S) \) in equal exposure bins (\( \sin^2 \theta \))
$N_\mu$ and the ground detector energy scale

- $N_\mu$ determined from data yields

  model- and primary-independent ground detector energy scale:

  \[
  \text{Ground signal } (E, \theta) = S_{EM}(E, \theta) + N_{\mu,\text{exp}}(E) \cdot S_{\mu,\text{ref}}(\theta)
  \]

- based on universality
  - systematic error in $N_\mu$ around 0.1 due to universality violation and uncertainty on $<X_{\text{max}}>$
  - statistical error for Auger-like data set $\sim 0.1$
Validation with hybrid events

- Combination of **fluorescence tel.** and **ground array**: independent event-by-event energy and \( X_{\text{max}} \)
- Directly measure \( S_{\mu} \) (relying on known \( S_{\text{EM}} \)):
  \[
  S_{\mu,i} = S_i - S_{\text{EM}}(E_i, \theta_i, X_{\text{max},i})
  \]
- probe muon signal evolution \( S_{\mu} \) (DG)
- measure \( N_{\mu} \) at different \( \theta \):
  - consistency check of universality
- **Caveat**: have to rely on fluorescence energy scale
Conclusions

- EM signal and muon signal evolution universal
- Muon normalization can be inferred from data
- Method yields model- and primary-independent energy scale for ground detectors
- Measured $N_\mu$ places constraints on hadronic interaction models
- New model EPOS under investigation
- Application to Auger data presented by R. Engel, #605