DIRECT CHERENKOV LIGHT FROM HEAVY NUCLEI IN COSMIC RAYS.

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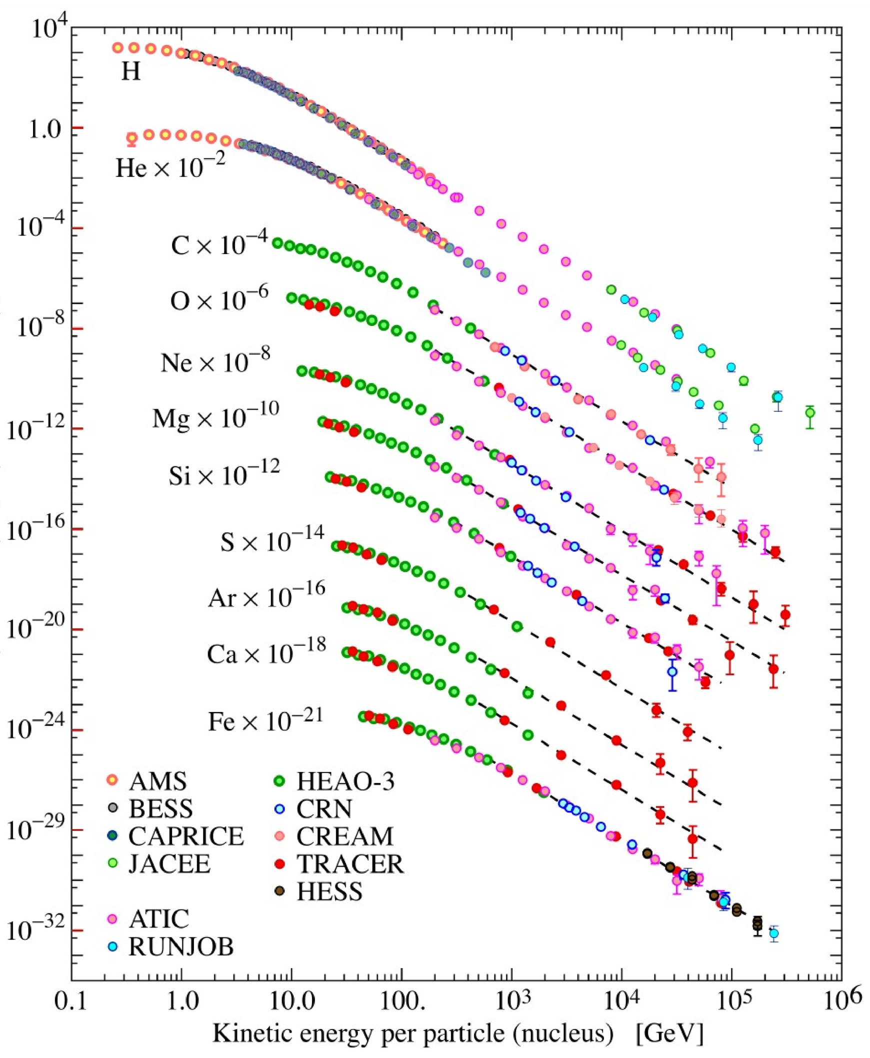
Introduction

> Existence of cosmic rays known for more than hundred years.
> Make-up: Protons and other fully ionized nuclei.
> Energy spectrum: Almost smooth power law.
> Origin and composition not fully understood.

Direct detection experiments
> Balloons/space borne detectors.
> Good at small Z.
> Detection area ~1 m²
> Best at MeV to TeV energies.
> See e.g. Ahn 2009.

Indirect detection - EAS arrays
> Detect remnants of air shower on ground
> Charge determination difficult
> Detection area ~10¹² m²
> Best at energies of 10¹³ eV and above.
> See e.g. Abbasi 2010, Cazon 2012.

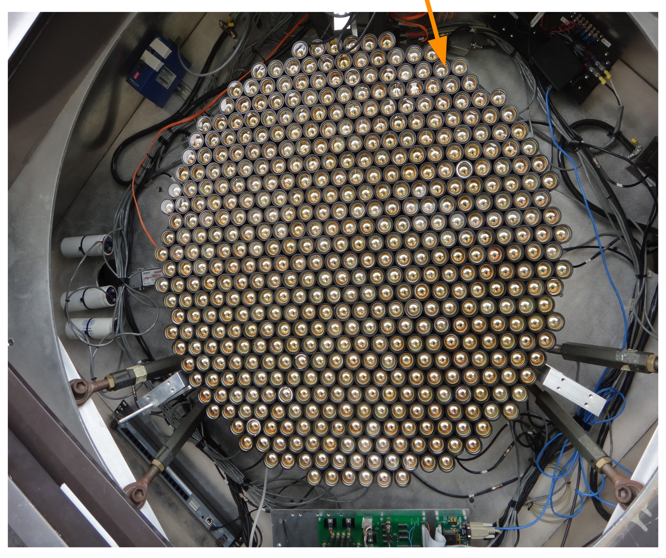
Indirect detection - IACTs
> Detect Cherenkov light from air showers
> Charge/energy reconstruction challenging, but possible
> Detection area ~10⁴ m²
> Cover intermediate energies (TeV range).
> See Aharonian 2007.



Cosmic ray flux for different elements. Plot from the 2013 Review of Particle Physics, J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

The VERITAS Array

> Very Energetic Radiation Imaging Telescope Array System.
> Array of four IACTs, located in southern Arizona, USA.
> Started operations in 2007.
> Mirror diameter 12 m.
> FOV 3.5 degrees, about 500 pixels per camera.
> Sensitive to gamma-ray induced showers from 80 GeV to tens of TeV.
> Several upgrades: one telescope moved in 2009, cameras upgraded in 2012.
> Science topics include gamma ray astronomy, dark matter searches, astroparticle physics.
> See Holder 2008.

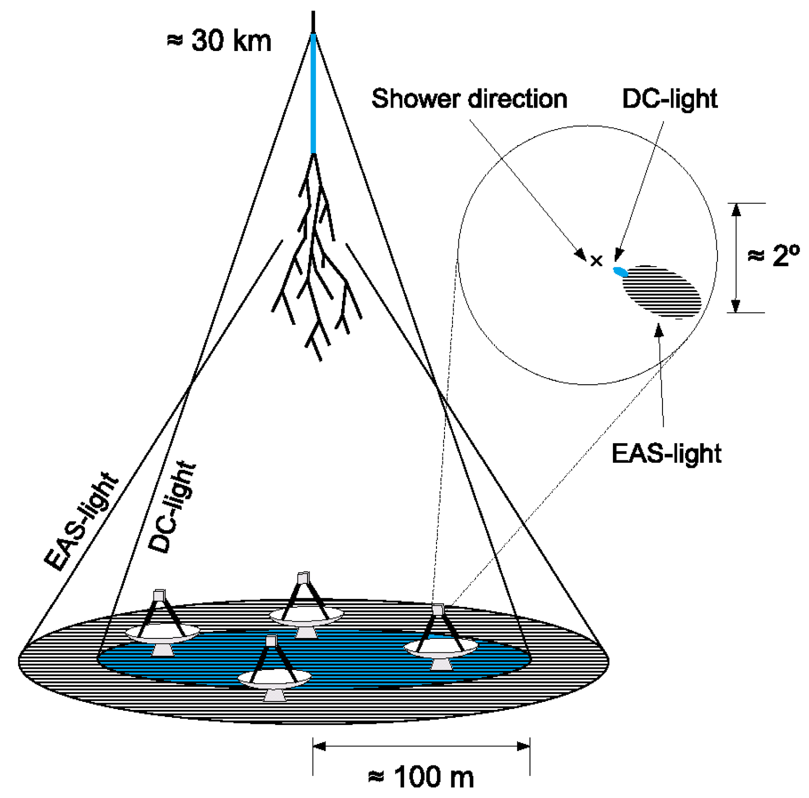


One of the VERITAS cameras

Imaging Air Showers & Direct Cherenkov Technique

Imaging of Air Showers
> **I**maging **A**ir **C**herenkov **T**elescopes (IACTs)
> Charged components of air showers radiate Cherenkov light.
> Light pool on ground: few hundred m radius.
> Air shower imaged by IACT camera, typical extentsion 1°.
> Size, shape, orientation of image used to reconstruct energy, direction, species of primary.
> Improvements by telescope arrays due to stereoscopic reconstruction.
> Main goal is γ-ray astronomy, large background of charged cosmic rays.

Direct Cherenov Technique
> Charged primary particles radiate direct Cherenkov (DC) light even before starting a shower.
> DC light very concentrated in camera (~1 pixel), at the front of the shower image.
> DC Intensity **~Z²** -> separation of heavy and light nuclei.
> Separation best at large Z.
> Use shower image to reconstruct energy.
> See Kieda 2001, Aharonian 2007

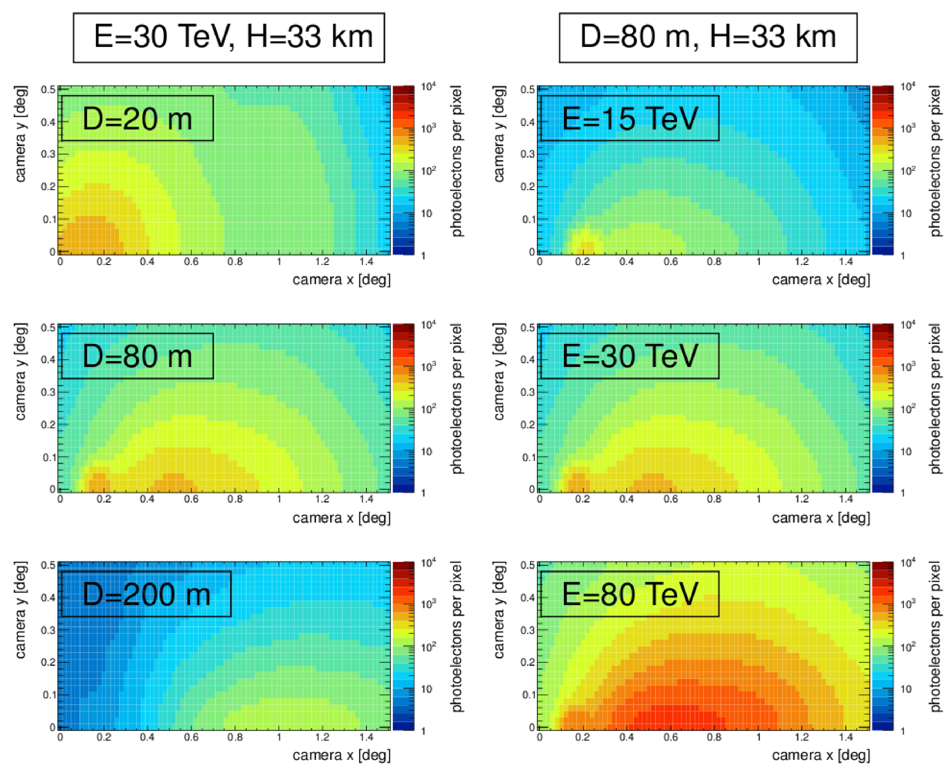


Hadronic air shower, from Aharonian 2007

Advantages:
> Can combine data taken on all targets (up to 1000 h/year).
> Most detected showers induced by cosmic rays.
> Systematic uncertainty complementary to other cosmic ray experiments (atmosphere largest source of systematic uncertainty).

Template Analysis

Idea:
> Model probability distribution of collected charge per pixel given energy E, direction of primary particle (Xs, Ys), height of first interaction h and position of shower core (Xp, Yp).
> Also need uncertainty of detector response σ_{pe} and pedestal variance σ_{ped}
> Use maximum likelihood method to estimate parameters for a given shower by fitting camera images to model predictions.
> Use goodness of fit for background separation.
> Up to now only used for γ-ray astronomy, eg. Le Bohec 1998.
> For iron analysis: Extend template method to take shower-to-shower fluctuation into account.



Mean and spread of number of photo electrons in pixel (from simulations):

$$s = s(E, h, X_P, Y_P, X_S, Y_S), \quad \sigma_s = \sigma_s(E, h, X_P, Y_P, X_S, Y_S)$$

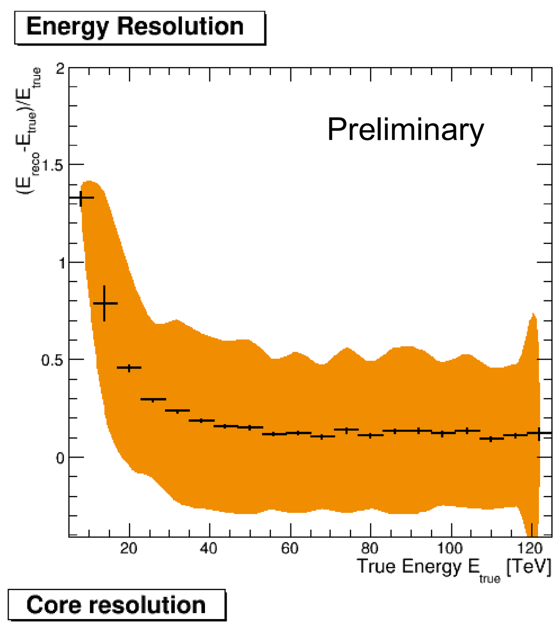
Likelihood per pixel:

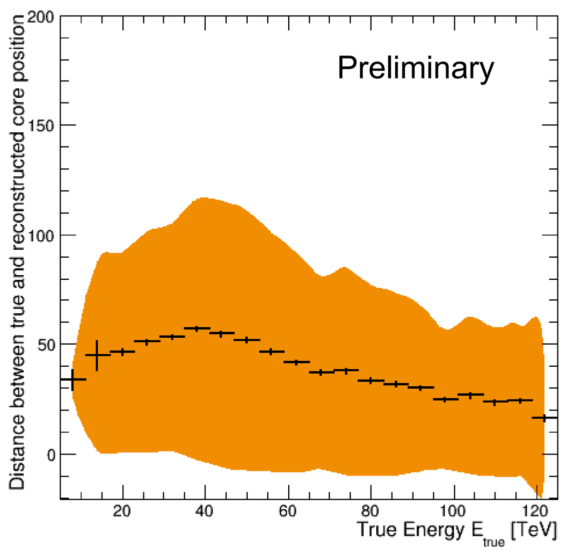
$$P(q|s, \sigma_p, \sigma_e, \sigma_s) = \int \mathrm{d}\mu\, Gaus(\mu|s, \sigma_s) \cdot \sum_n Pois(n|\mu) \cdot Gaus\left(q|n, \sqrt{\sigma_{ped}^2 + n\sigma_{pe}^2}\right)$$

Goodness-of-fit:

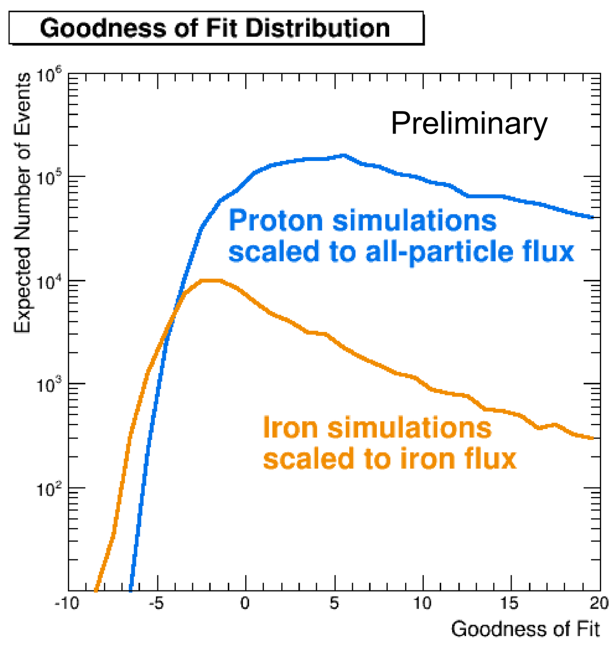
$$Goodness = \frac{\sum_{pix\ i} \left(\ln\ P(q_i|s_i, \sigma_s^i.\sigma_{ped}^i, \sigma_{pe}) - \langle \ln\ P(q|s_i, \sigma_s^i.\sigma_{ped}^i, \sigma_{pe}) \rangle\right)}{\sqrt{2 \cdot NDF}}$$

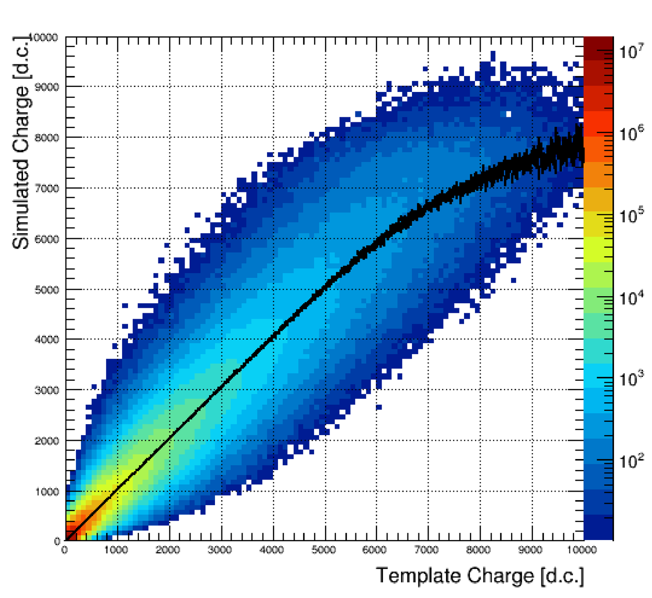
Template Method Validation





> Templates generated from simulated iron showers (Corsika 6.99, grisudet for ray tracing).
> Energy range 10 to 100 TeV.
> Tested template analysis on simulated iron showers after full detector simulation.
> Confirmed that template prediction, knowing true energy/ core position, reproduces mean collected charge per pixel.
> Checked energy resolution/bias and core position resolution when starting the fit at the true values. No bias in energy reconstruction for E>40 TeV.
> Tested reconstruction of core position and energy, using geometrical stereo-reconstruction as starting point.
> Geometrical reconstruction often gives a bad core position, leading to bad fit.
> Energy bias due to cut on image size, but improvement in core position.
> Working on improving starting poins for the likelihood fit.
> Goodness of fit distribution is shown for simulated iron showers (orange) and proton showers (blue; main background), scaled to expected number of events.
> In 3000 hours: expect about 78000 iron showers, 270000 showers from protons and other light elements (after pre-cuts).





Conclusions

> Template-based analysis can be used to extract energy of primary particles from iron-induced showers
> Goodness-of-fit can be used for background separation.

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VERITAS is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland (SFI 10/RFP/AST2748) and by STFC in the U.K. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.

Alliance for Astroparticle Physics