Understanding Very High Energy Cosmic Rays with VERITAS

Andriy Petrashyk
for the VERITAS collaboration

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

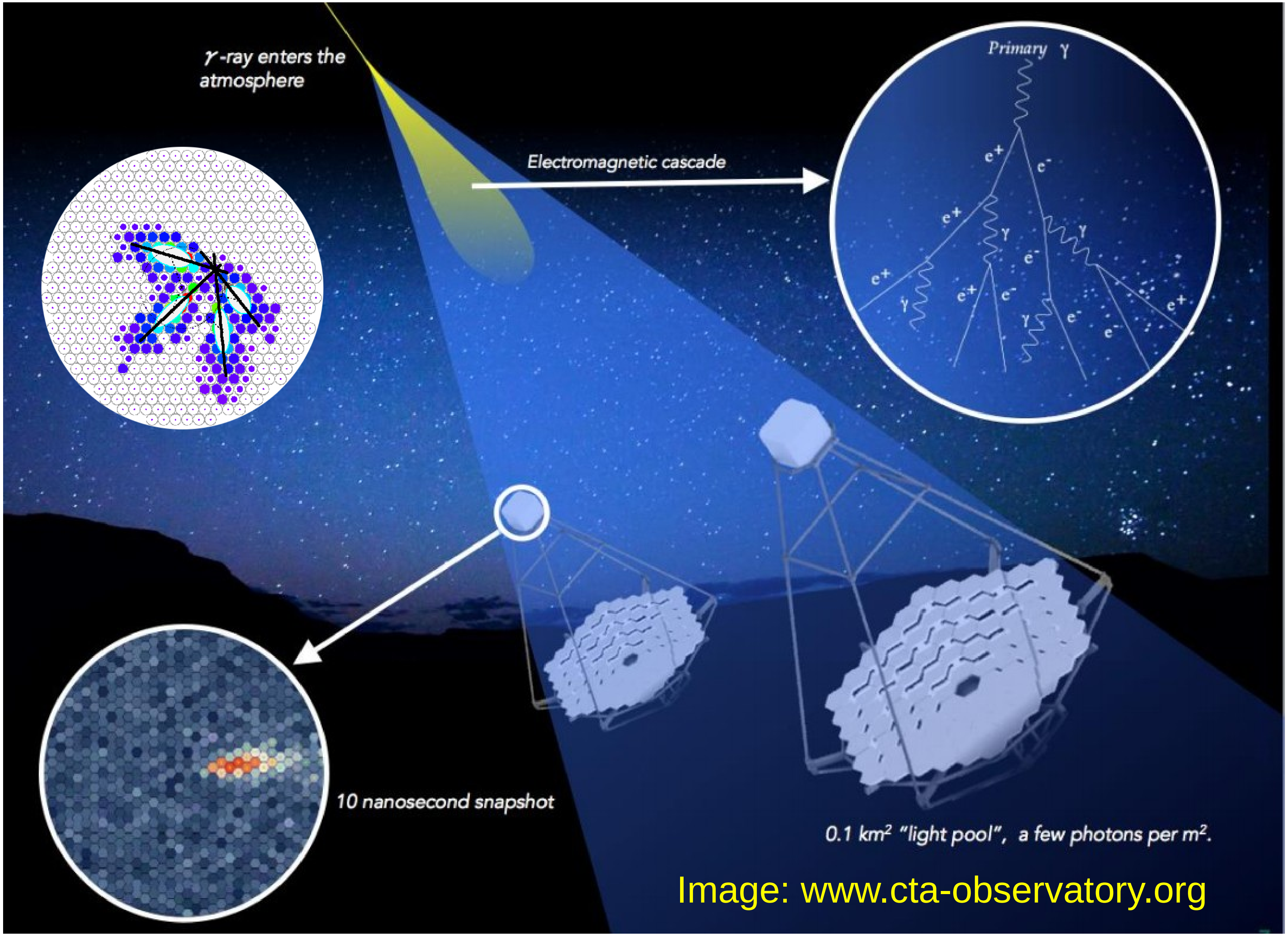
Outline

- Brief introduction to VERITAS and the Imaging Atmospheric Cherenkov Technique
- Cosmic ray electron spectrum
- Cosmic ray iron spectrum
- An update on the starburst galaxy M82

Introduction to VERITAS

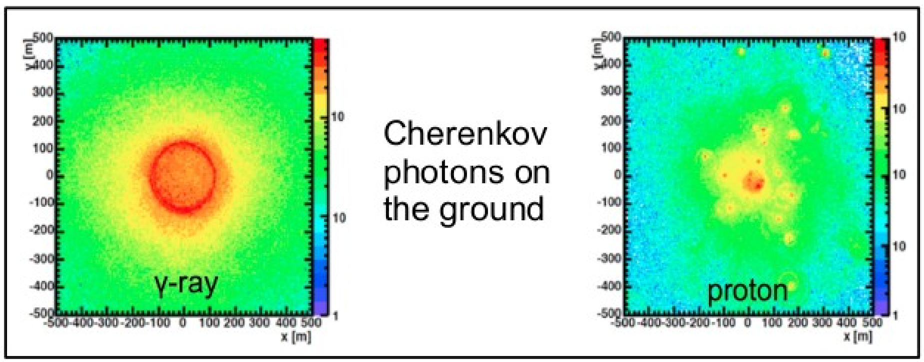
- Array of four 12m IACTs in Southern Arizona, USA
- Employs ~100 scientists
- Full operation started in Fall 2007
- Two major upgrades:
  - Relocation of T1 in Summer 2009
  - Camera upgrade in Summer 2012
- Energy range 85 GeV – 30 TeV for gamma rays
- Energy resolution 15-25%
- Angular resolution < 0.1° at 1TeV
- Pointing error < 50″

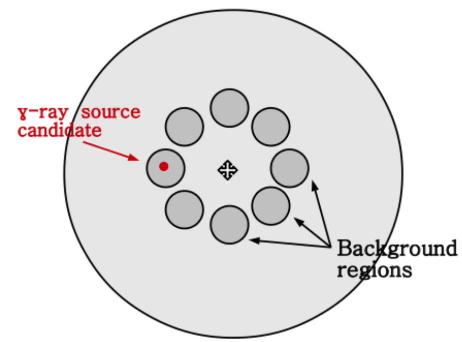
Atmospheric Cherenkov Technique

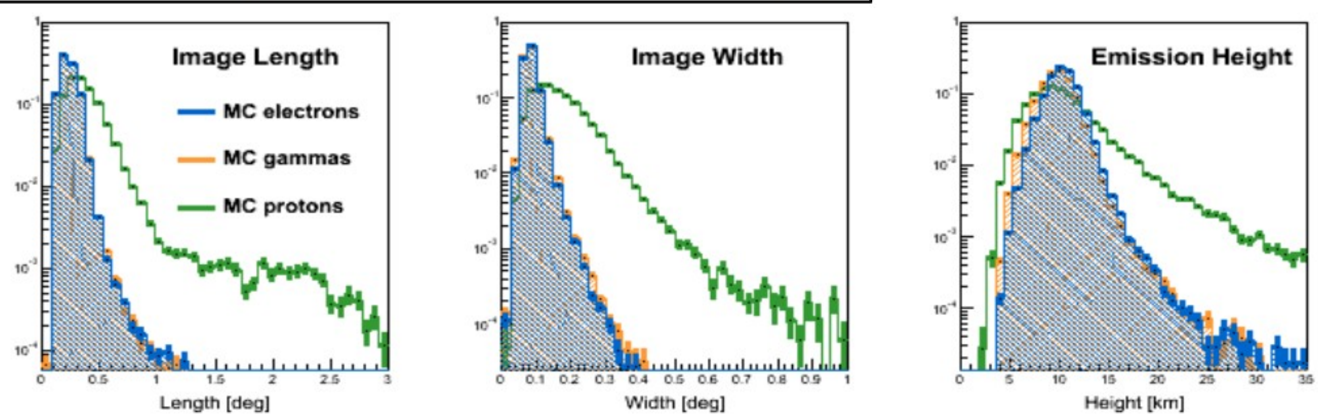


Atmospheric Cherenkov Technique

- Hadronic showers are much less uniform than EM showers → traditionally, use Hillas parameters to discriminate between them
- Direction cut is one of the most powerful ways to get rid of background as the majority of VERITAS sources are point-like



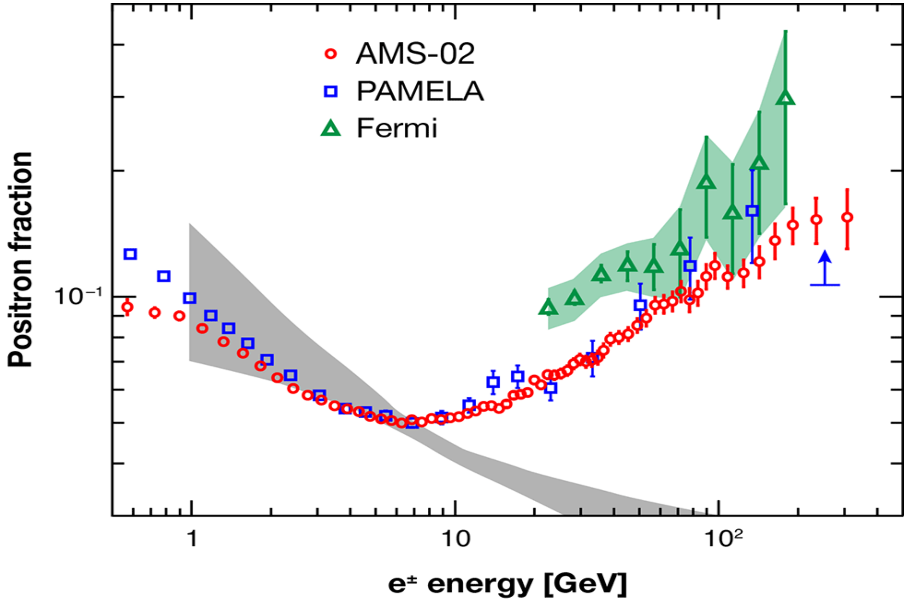




- γ-rays become background when looking for electrons
- No way to define background regions when detecting cosmic rays

VERITAS CR Electron Spectrum

- TeV electrons lose energy very quickly while propagating in the Galaxy via synchrotron radiation and inverse-Compton scattering → propagation distance ~1 kpc → important probe of the local accelerating and diffusive processes



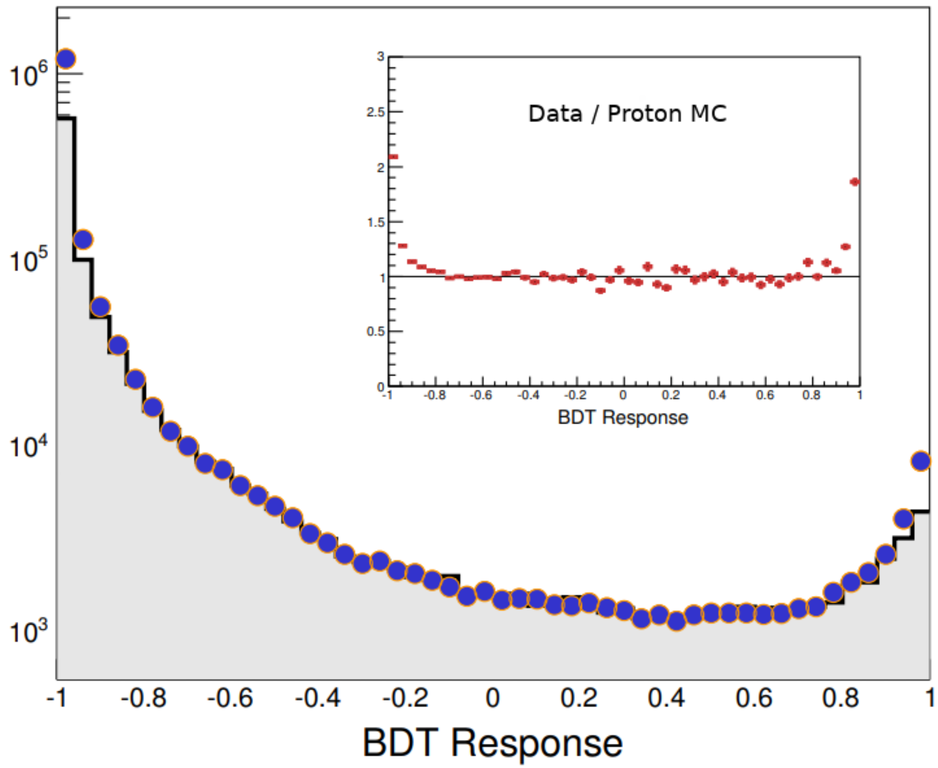
AMS Collaboration 2011

- Existence of a positron-rich excess with several possible explanations
  - Cosmic ray diffusion/interaction models are wrong
  - Local source of positrons, like a nearby pulsar or SNR
  - More exotic causes, like dark matter

- Ground-based electron measurements can extend spectra out to higher energies thanks to much higher effective areas

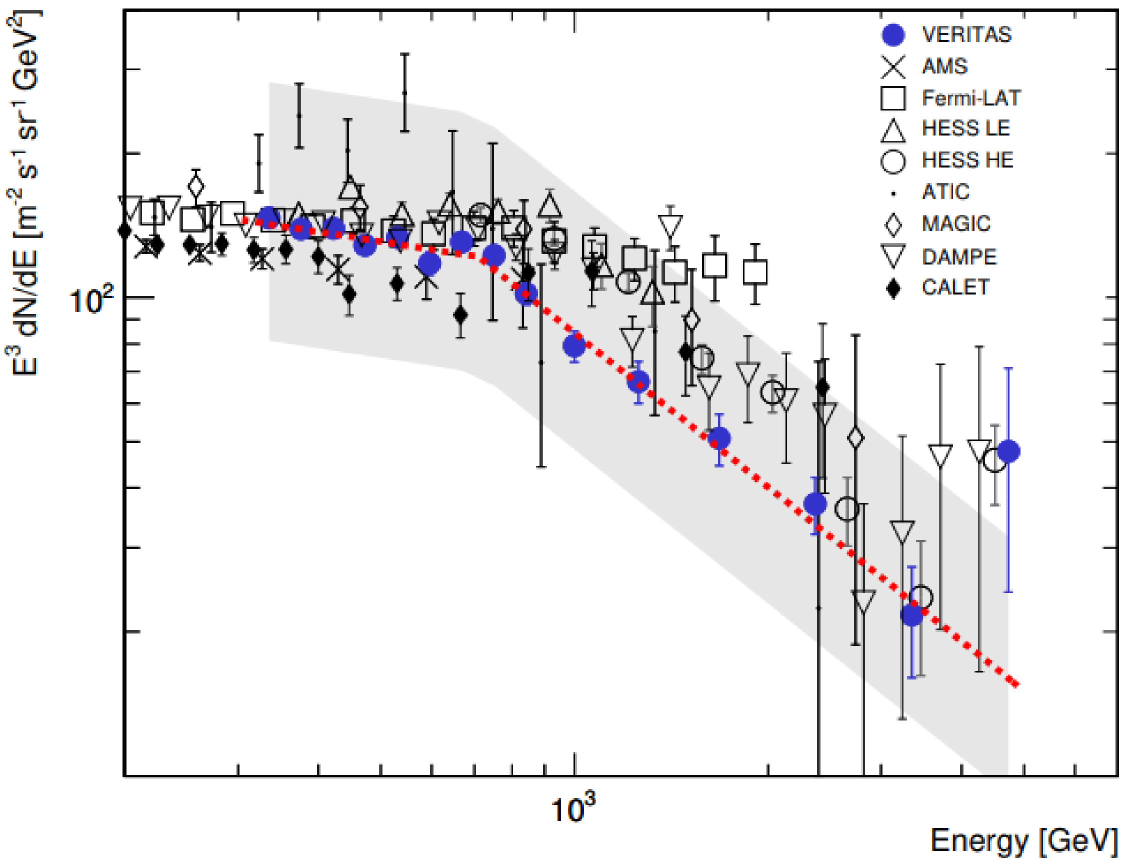
VERITAS CR Electron Spectrum

- Use Boosted Decision Trees, a machine learning technique, to discriminate between electrons and protons: maps a large parameter space into a single score (signal-like vs background-like)
  - Signal training done on electron simulations
  - Background training done on real data, masking out the galactic plane and known sources of gammas



- Low BDT score excess due to Helium and higher-Z elements
- High BDT score excess due to electrons
- The two populations are not completely separated – use binned extended likelihood fit on electron and proton simulations for BDT > 0.7 to find the fraction of electrons

VERITAS CR Electron Spectrum



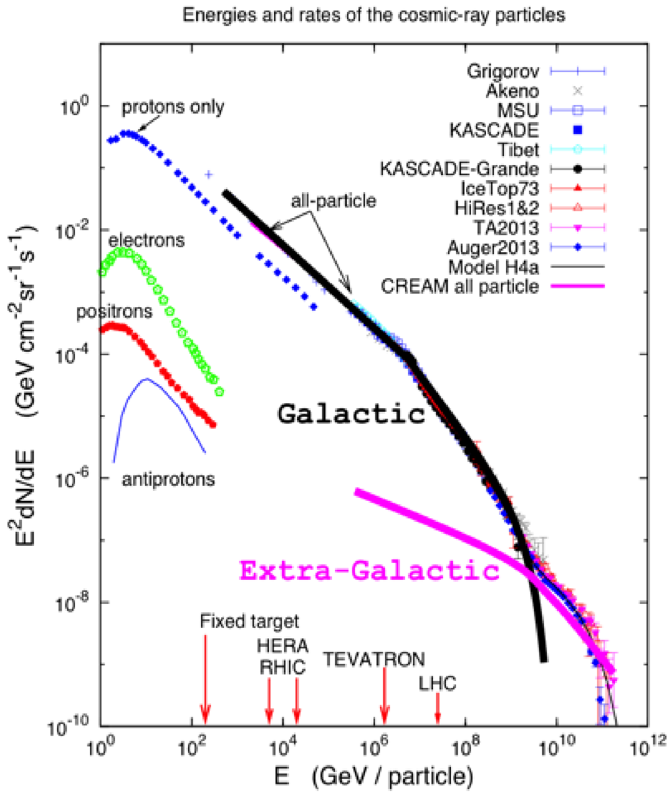
- 296 hours of post-T1 move, pre-camera upgrade data
- Covers 300 GeV to 5 TeV
- Broken power law with a break at 710 ± 40_{stat} GeV
- Index transitions from $3.2 \pm 0.1_{stat}$ below to $4.1 \pm 0.1_{stat}$ above the break

- Consistent with previous measurements
- Second ground-based high-statistics measurement of a break at ~1TeV

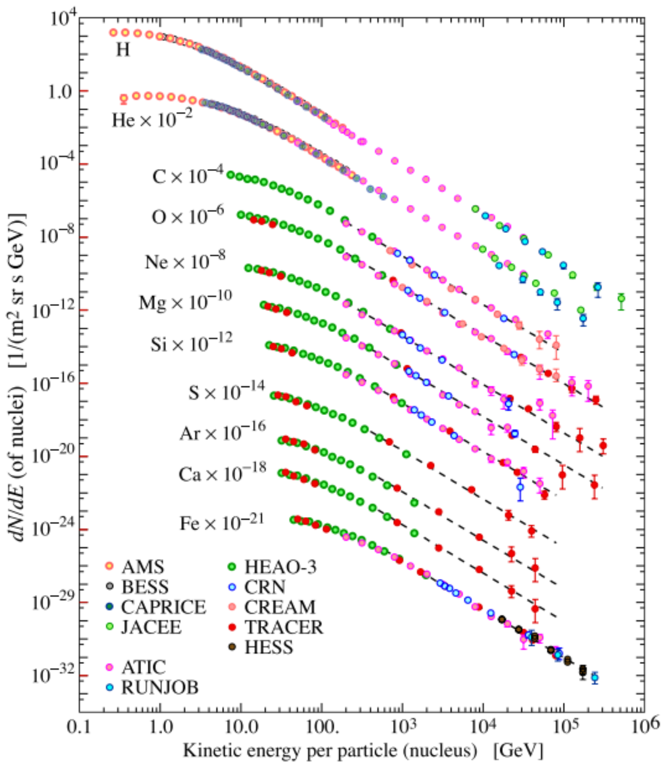
- Paper submitted to *Phys. Rev. D*

VERITAS CR Iron Spectrum

- Measuring the cosmic ray elemental composition to energies as high as the 'knee' can provide clues to cosmic ray origins and acceleration mechanisms
- Composition of cosmic rays as a function of energy can teach us about their sources



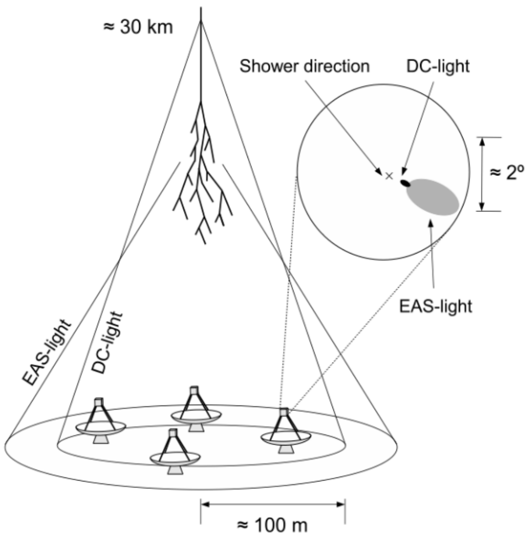
IceCube Collaboration

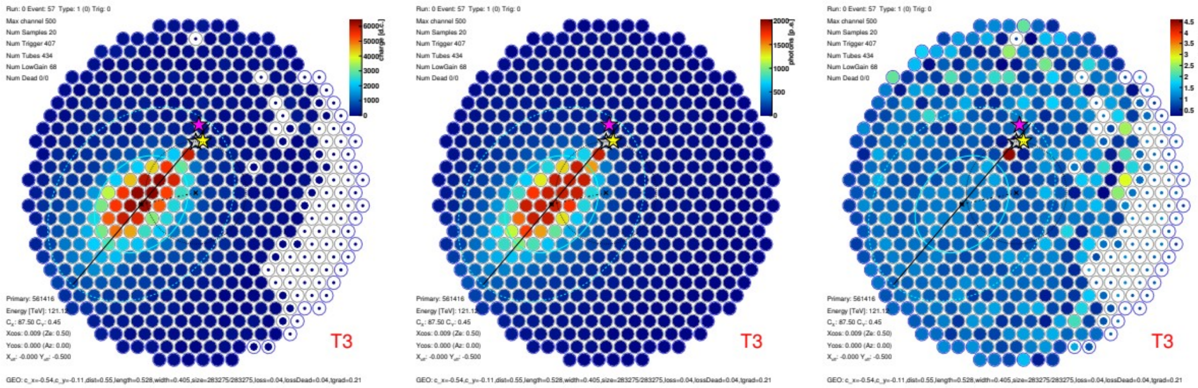


Particle Data Group

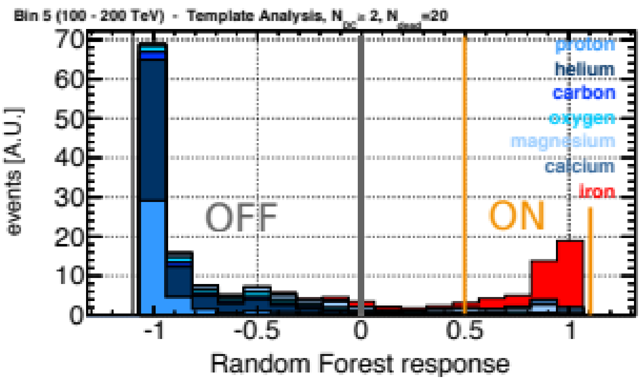
VERITAS CR Iron Spectrum

- Use Direct Cherenkov (DC) light emitted by cosmic ray primaries in the atmosphere before the first interaction
  - Intensity proportional to Z^2 → can be used to identify a heavy primary particle



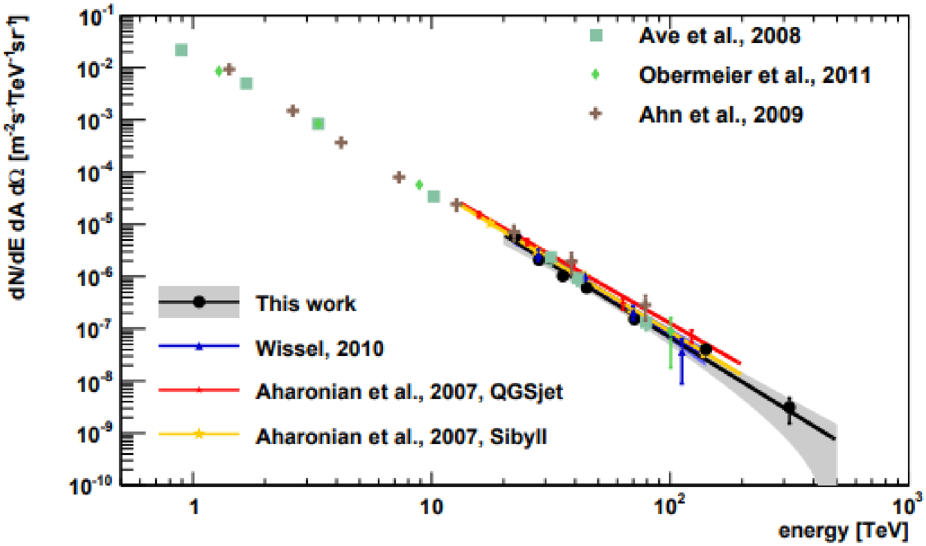


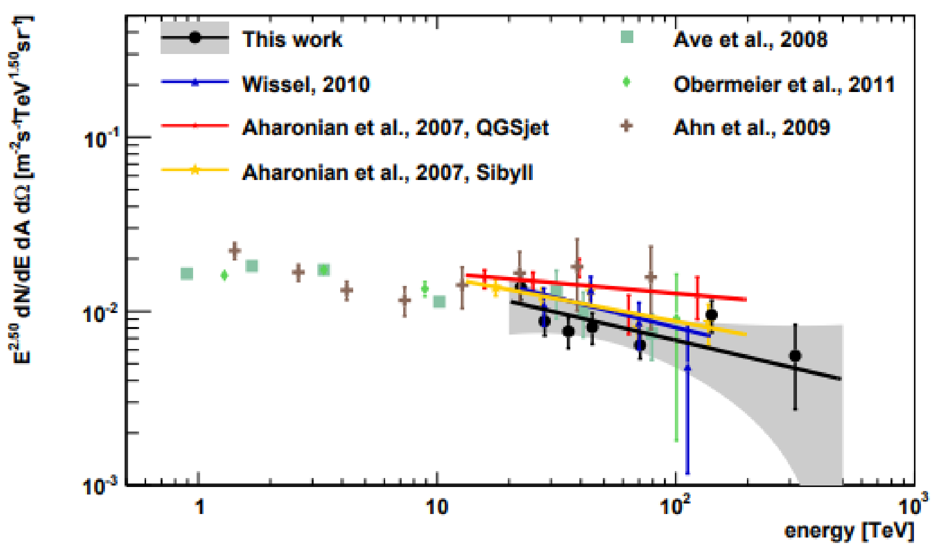
- Use Image Template fitting to select DC-only images
- Use Random Forests to estimate background



VERITAS CR Iron Spectrum

- 71 hours of post-T1 move, pre-camera upgrade high-quality data
- Covers 20 TeV – 500 TeV



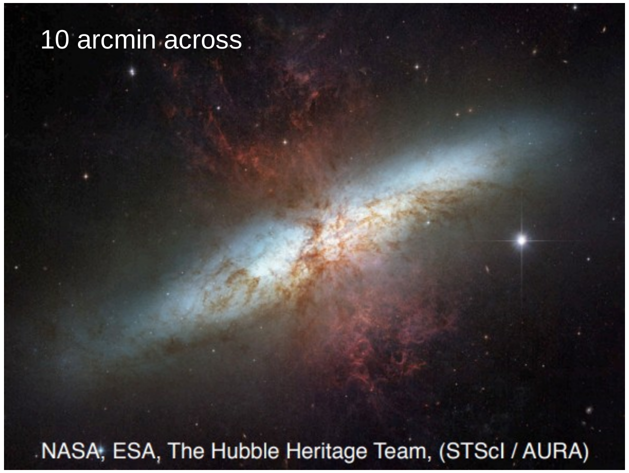


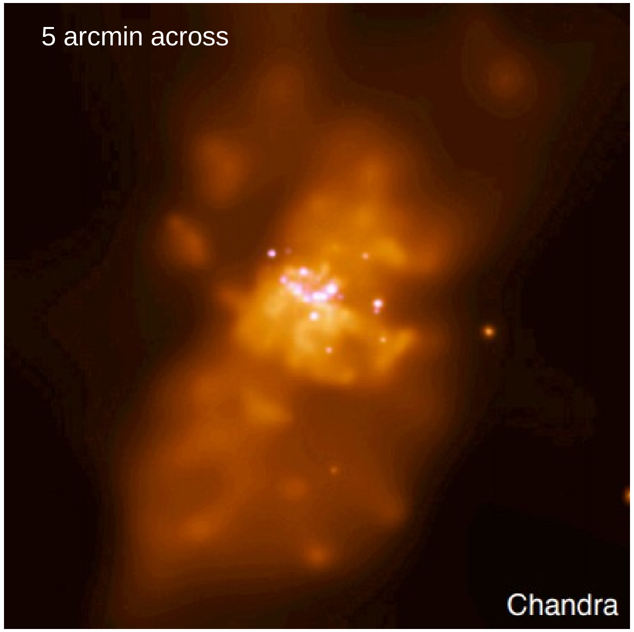
- Power law with index $2.82 \pm 0.3_{stat}$
- Agrees well with previous measurements
- Extends the spectrum to higher energies

- Paper accepted by *Phys. Rev. D*

An update on M82

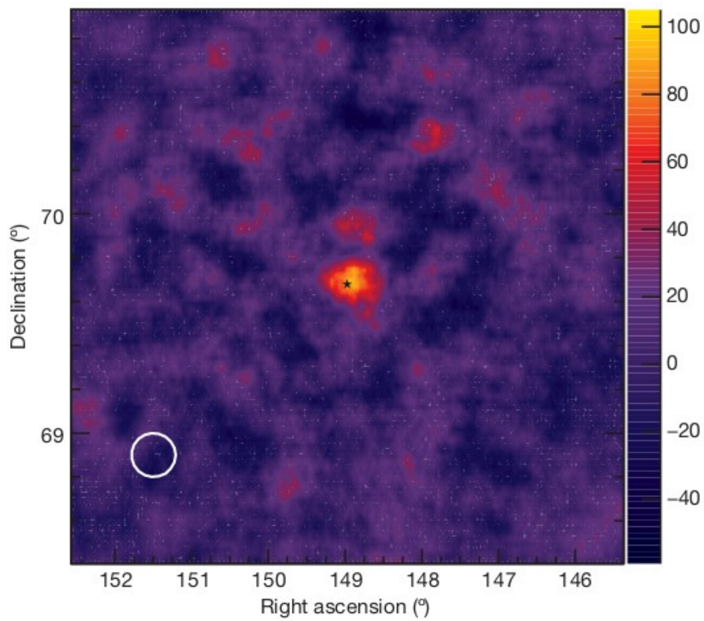
- M82 is the prototypical starburst galaxy
- Interacting with a group of galaxies
  - At least one major interaction with the larger spiral M81
  - Tidal forces → active starburst region
- High star formation rate: ~10x Milky Way
  - High supernova rate: ~0.1-0.3/year
- CR origin? SNR + wind-zones of massive stars
  - High CR density: ~100x Milky Way
  - High gas density: ~150 particles/cm^3
  - CR hadrons + gas → pions → γ
  - CR electrons + ambient photons → γ

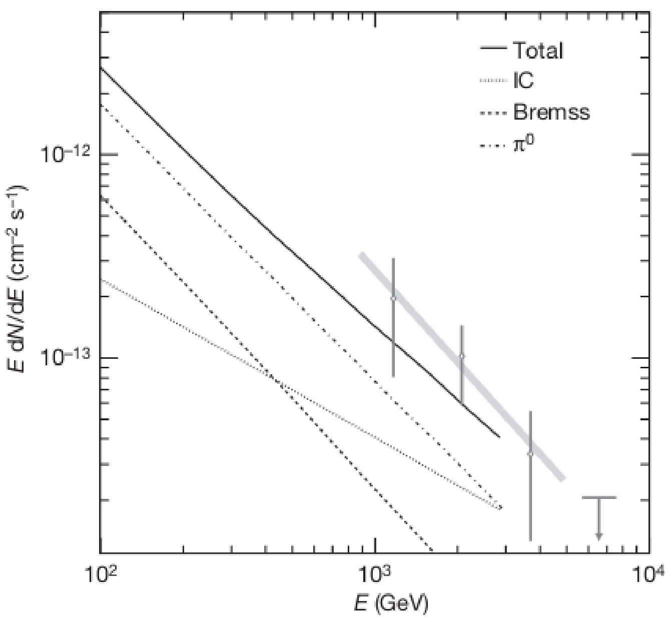




An update on M82

- VERITAS detected M82 in 2009
- Among weakest-ever VHE sources, 0.9% Crab
- No clear determination of the origin of the VHE emission

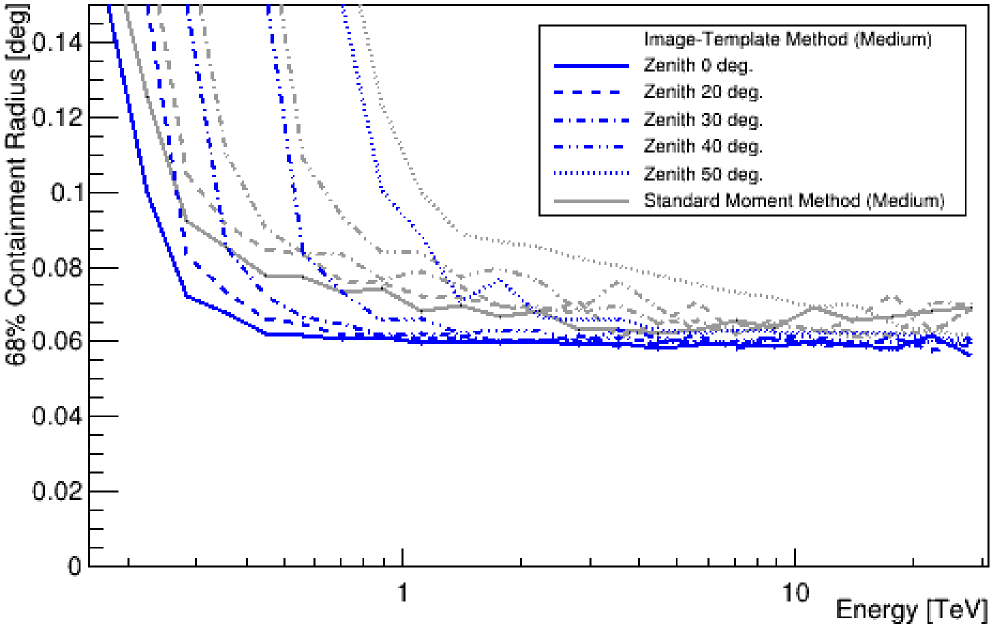


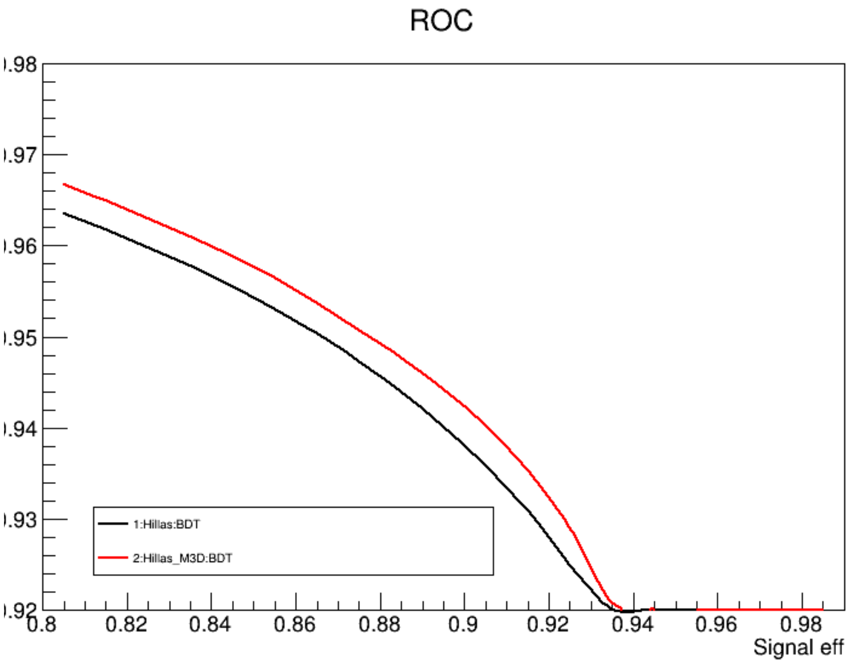


- VERITAS has since undergone two upgrades
- The exposure on M82 has increased: ~137 hours → ~240 hours
- We have deployed new analysis methods

An update on M82

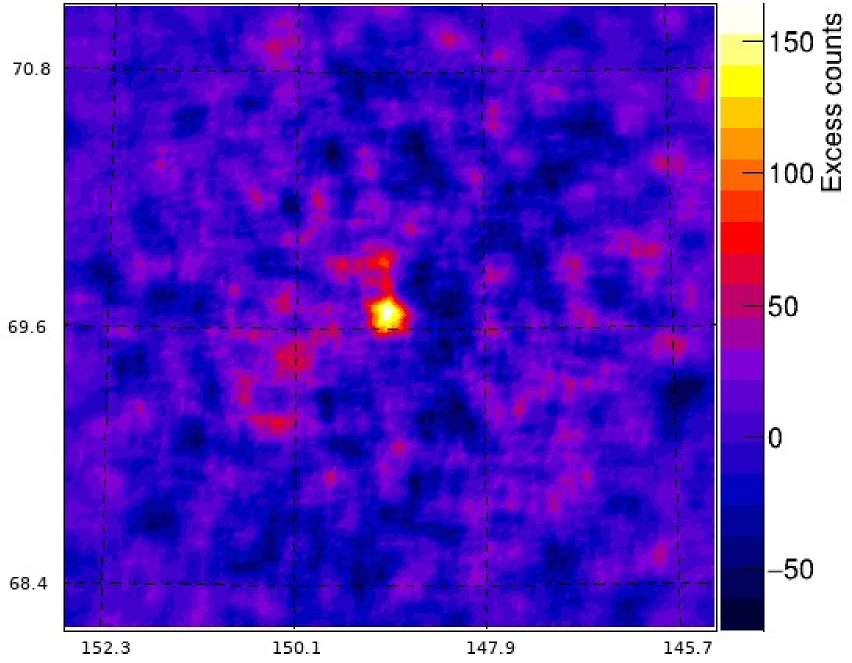
- Image template fitting offers superior reconstruction
- Multivariate analysis methods, specifically BDTs, give a better separating efficiency
- Both methods can be used in conjunction to significantly reduce background and increase γ sensitivity





An update on M82

- Post-camera upgrade data allow lowering the energy threshold
- Image template method and boosted decision trees offer a remarkable improvement over standard analysis
- Much tighter θ^2 cut of 0.006 deg² vs 0.01 for standard analysis

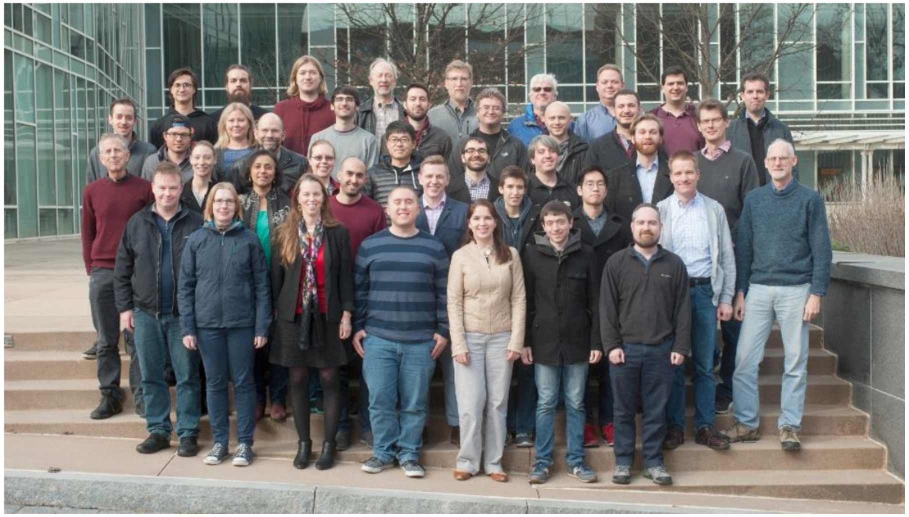


- New results consistent with the published ones within errors
- Total flux at the lower end of the published value – even weaker than initially estimated
- Analysis ongoing

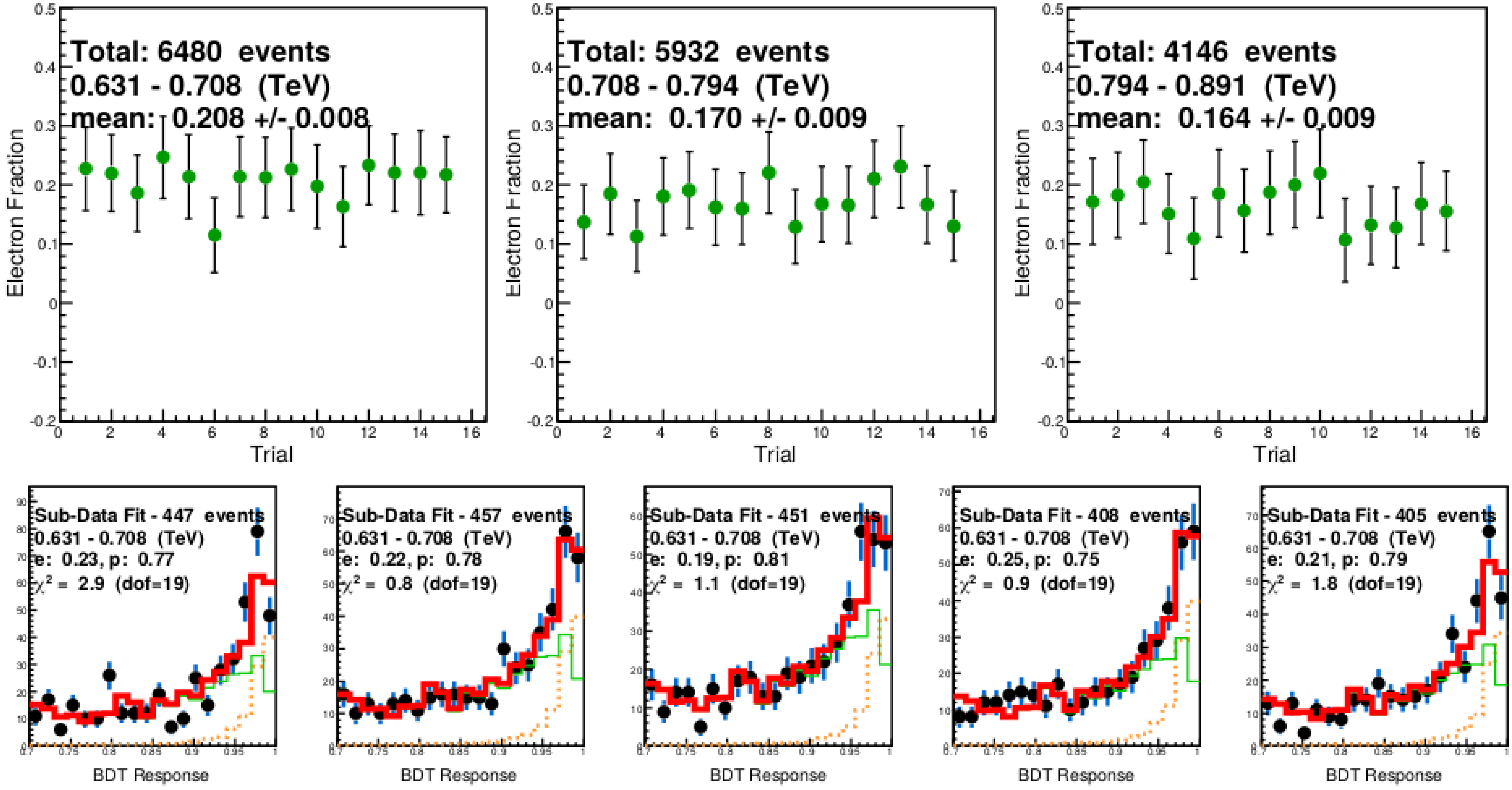
Conclusion

- VERITAS is a robust instrument for study of cosmic rays
- The measured cosmic ray electron spectrum is consistent with other instruments, supporting a spectral break at ~1TeV
- The cosmic ray iron spectrum has been extended to 500 TeV, and is consistent with previous measurements in the overlapping energy range
- The spectrum of M82 to be updated soon
- We welcome proposals from external collaborators for observing time, due ~early September for next season; contact Science Working Group Coordinators to get involved

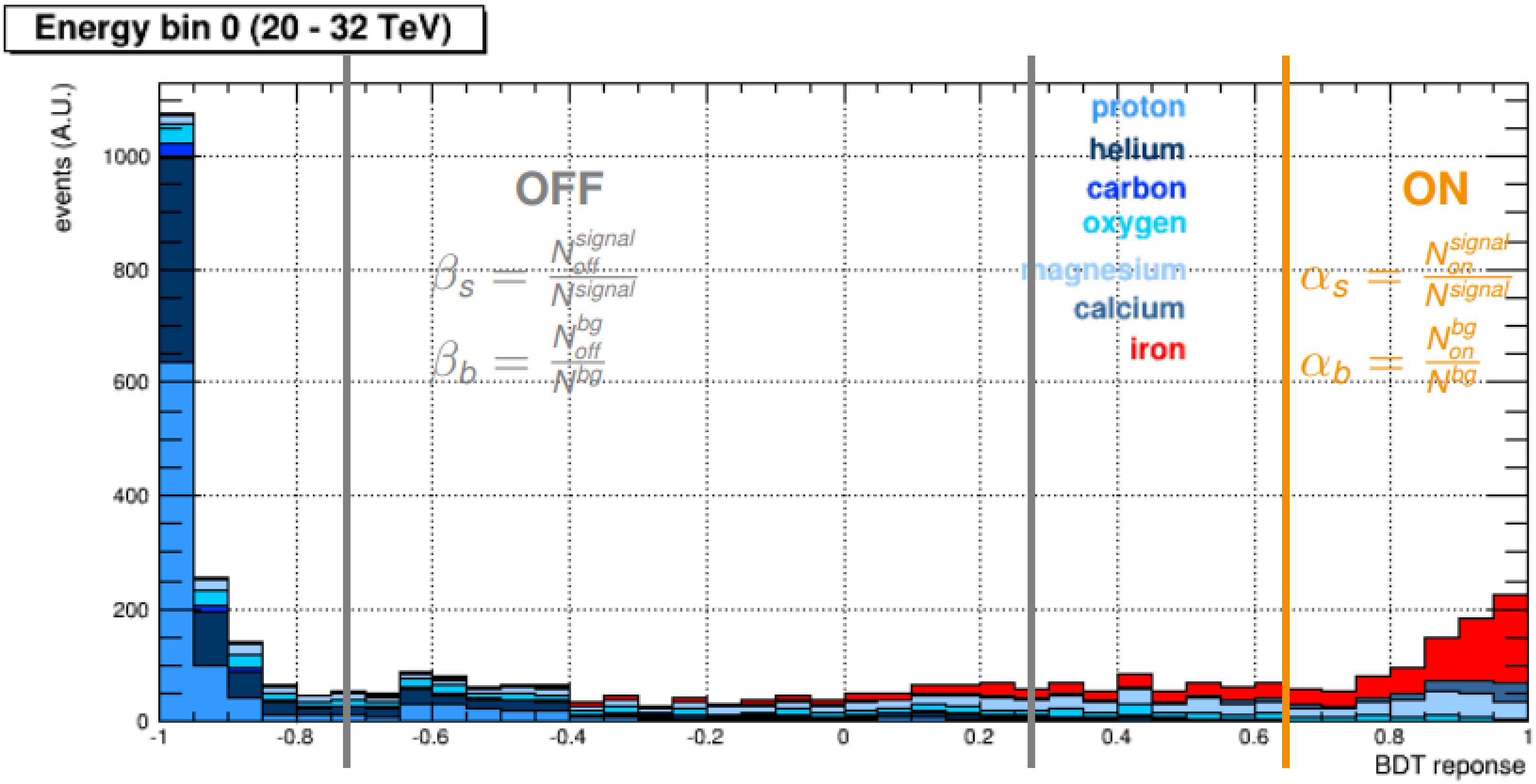
https://veritas.sao.arizona.edu



BACKUP: electron fraction fit



BACKUP: iron fraction estimate



$$N_{on}^{data} = \alpha_s \cdot N_s + \alpha_b \cdot N_b$$
$$N_{off}^{data} = \beta_s \cdot N_s + \beta_b \cdot N_b$$

$$\Longrightarrow N_s = \frac{N_{on}^{data} - \frac{\alpha_b}{\beta_b} \cdot N_{off}^{data}}{\alpha_s - \frac{\beta_s \cdot \alpha_b}{\beta_b}}$$