THE COSMIC-RAY ELECTRON SPECTRUM MEASURED WITH H.E.S.S.

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Outline

- Cosmic-Ray Electrons at Very High Energies
- The H.E.S.S. Experiment
- The H.E.S.S. Electron Measurement
  - Gamma-Ray Background
  - Hadronic Background
  - Spectrum Determination
  - CR Electron Spectrum
- Systematics + Interpretation
- Conclusion + Outlook
Cosmic-Ray Electrons

- "Electrons" = e^+ + e^-
- Cosmic-ray nuclei spectrum covers range of >11 decades in energy
- TeV electron flux ≈0.1% of hadron flux
- Electrons have a steeper spectrum
- Up to 2008: No electron measurement beyond 2 TeV
Cosmic-Ray Electrons

Electron spectrum (2008)

Flux (m$^2$·s$^{-1}$·sr$^{-1}$·GeV$^{-1}$)

Energy (GeV)

Energy (eV)

AMS  M. Aguilar et al. 2002
HEAT  S.W. Barick et al. 1998
HEAT 94-95 DuVernois et al. 2001
BETS  S.Torii et al. 2001
Kobayashi  Kobayashi et al. 2004
ATIC  J.Chang et al. 2006
Cosmic-Ray Electrons

- Sources of TeV electrons must be young and nearby
  - Energy losses of TeV electrons by inverse Compton and synchrotron radiation
    \[ \frac{dE}{dt} = -k E^2 \]
    \[ \Rightarrow E_{\text{max}} = \frac{1}{kt} \iff T_{\text{life}} = \frac{1}{kE} \]
    \[ \lambda \approx 2 \sqrt{D T_{\text{life}}} \]
    - Distance: \( \lambda \approx 2 \sqrt{D T_{\text{life}}} \)
      - \( D \): diffusion coefficient

- Signatures of dark matter annihilation might be visible in the electron spectrum
  - \( W^-, Z, q, e^\pm \ldots \rightarrow e^\pm, p \ldots \)
  - \( W^+, Z, q, e^\pm \ldots \rightarrow e^\pm, p \ldots \)


Measurement of Cosmic-Ray Electrons

So far: With balloon and satellite experiments
Difficult because of low electron fluxes and limited detector area/observation time

Why measure CR electrons ground-based?

Compared to direct measurements:
- High statistics (collection areas $\approx 10^5$ m$^2$)
- Energy resolution improving with energy
- High background level
- Large systematics

Imaging Atmospheric Cherenkov Technique
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Imaging Atmospheric Cherenkov Technique
The High Energy Stereoscopic System (H.E.S.S.)

- Four imaging atmospheric Cherenkov telescopes in Namibia
- Energy threshold > 100 GeV (depending on event selection cuts and data set)
- Sensitivity (5σ):
  - 5% of Crab in 1 h
  - 1% of Crab in 25 h
  - HEGRA: 5% of Crab in 100 h
- Angular resolution ~0.1°
  - Pointing accuracy < 20"
- 1000 h of observations / year during moonless nights
The Mirrors

- 13 m diameter
- 382 mirror facets with 60 cm diameter
- Total mirror area of 107 m²
The H.E.S.S. Cameras

- 960 PMTs with 0.16° aperture each
- 5° diameter field of view
- total weight of ~800 kg
The H.E.S.S. Electron Measurement

- Electron and gamma-ray air showers are very similar
- Electrons isotropic: any (gamma-ray free) data can be used for the analysis
- 2 analyses optimized for high energies and low energies
- Data sets:
  - Central 3° of field of view, gamma-ray sources within 0.4° excluded
  - Livetime: 239 h (high-energy analysis) / 77 h (low-energy analysis)
  - Effective area: $5 \times 10^4 \text{ m}^2$ at 1 TeV / $4 \times 10^4 \text{ m}^2$ at 340 GeV
  - Effective exposure: $8.5 \times 10^7 \text{ m}^2 \text{ sr s}$ at 1 TeV / $2.2 \times 10^7 \text{ m}^2 \text{ sr s}$ at 340 GeV
  - Different fields in the sky are covered

- Background contributions:
  - Gamma rays
  - Hadrons
Gamma-Ray Background

- Hard to distinguish from electrons
- Avoided by choice of data set: Galactic plane and potential gamma-ray sources are excluded
- Remaining background: diffuse extragalactic gammas
  - Very low fluxes are expected due to pair creation on radiation fields
  - Experimental discrimination: $X_{\text{max}}$
    - Occurs $\frac{1}{2}$ radiation length higher for electrons
    - Cannot exclude maximum of 50% gamma contamination
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⇒ Have to rely on theoretical predictions for extragalactic gamma-ray background
Hadronic Background

- Broader and less regular than electromagnetic showers
- Electron-hadron separation with the machine-learning algorithm **Random Forest** (RF)
- RF converts image parameters into output parameter $\zeta \in [0,1]$:  
  - $\zeta=1$: electron-like  
  - $\zeta=0$: background
- $\zeta$ describes *electron-likeness* of an event
- Cut $\zeta > 0.6$ is applied for a 98-99.5% background suppression
Hadronic Background

- Remaining background level determined by a fit in $\zeta$ with electron and proton simulations
- The hadronic background can be modelled with protons only because heavier nuclei are sufficiently suppressed by $\zeta$ cut

Dependence on hadronic model!
Spectrum Determination

- Fit in $\zeta$ in independent energy bands
  \[ \Rightarrow \text{determine number of electrons } N_e \text{ in each band} \]

\[ \Rightarrow dN/dE = N_e / (A_{\text{eff}} \times T_{\text{live}} \times \Omega \times \Delta E) \]
The H.E.S.S. Electron Spectrum

High energies (blue)

- Cuts:
  - impact distance < 200 m
  - image size in each camera > 200 photo electrons

- Spectral index:
  \[3.9 \pm 0.1_{\text{stat.}} \pm 0.3_{\text{syst}}\]

- Syst. uncertainty: atmospheric variations + model dependence of proton simulations (SIBYLL vs. QGSJET-II)

- H.E.S.S. energy scale uncertainty of 15%

The H.E.S.S. Electron Spectrum

Low energies (red)

- **Cuts:**
  - impact distance < 100 m
  - image size in each camera > 80 photo electrons
  - Data set of 2004/2005

- **Spectral index:**
  \[ \Gamma_1 = 3.0 \pm 0.1_{\text{stat.}} \pm 0.3_{\text{syst.}} \]
  \[ \Gamma_2 = 4.1 \pm 0.3_{\text{stat.}} \pm 0.3_{\text{syst.}} \]

- **Syst. uncertainty:** atmospheric variations + model dependence of proton simulations (SIBYLL vs. QGSJET-II)

- **H.E.S.S.S. energy scale uncertainty of 15%**

Systematics

- Systematic studies:
  - Data - investigation of dependence on: sky field, zenith angle, event selection cuts, distance from Galactic plane
  - Analysis – comparison of different fitting parameters (instead of $\zeta$), different hadronic models
- Normalisation varies → band of systematic uncertainty
- Spectral shape is very stable ($\Delta \Gamma \leq 0.3$)
Interpretation

High-energy spectrum:

- Existence of a local accelerator within $\approx 1$ kpc
- Some scenarios of close sources can be excluded

Low-energy spectrum:

- Very good agreement with Fermi data within systematic errors in the region of overlap
- No indication of a bump in the spectrum as observed by ATIC (potential dark matter signal)
Conclusion

- H.E.S.S. measured cosmic-ray electrons between 340 GeV and 5 TeV
- This is the first ground-based measurement of cosmic-ray electrons and serves as proof of principle
- Ground-based measurements are an attractive alternative to direct measurements especially at high energies
- Systematic uncertainties include atmospheric variations, uncertainties in hadronic interaction models and H.E.S.S. energy scale uncertainty
Outlook:
Future ground-based measurements?

- H.E.S.S. Phase II
  - 600 m² mirror area
  - 20 GeV energy threshold
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Low energies: difficult
+ already covered by Fermi

High energies: maybe...
Outlook: Future ground-based measurements?

- H.E.S.S. Phase II
- Cherenkov Telescope Array (CTA)
  - Telescope array observatory
  - 5-10 x sensitivity of H.E.S.S.
  - Energy range: a few tens of GeV up to 100 TeV and higher
  - In the phase of design study
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High energies: potential to see signatures of local sources in the electron spectrum

Thank you!