January 5-11 21st Rencontres du Vietnam

ICISE

2025 Theory meeting experiment

Cosmic-Ray Electron spectrum with IACTs

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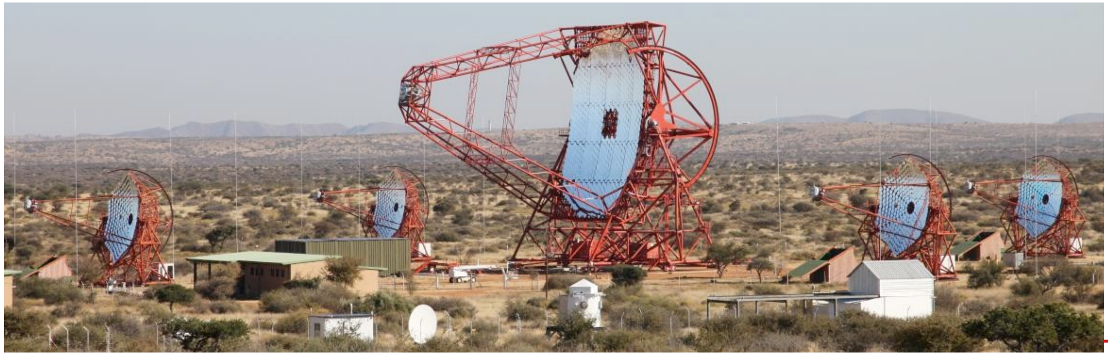
LLR Ecole Polytechnique



Created with DALL-E:
/imagine “High energy cosmic electrons reaching the Earth”

Why look at electrons?

- Electrons make a small fraction of CRs (< 1%)
- Important measurement for the community (acceleration, escape & propagation of CR's from leptonic sources)
- Electron suffer strong cooling (synchrotron & IC) and cannot travel far from sources ⇒ nearby sources
- Electrons cannot travel "incognito" (IC & synchrotron unavoidable) ⇒ can reveal sources
- Possible handle to dark matter (e^+ fraction)

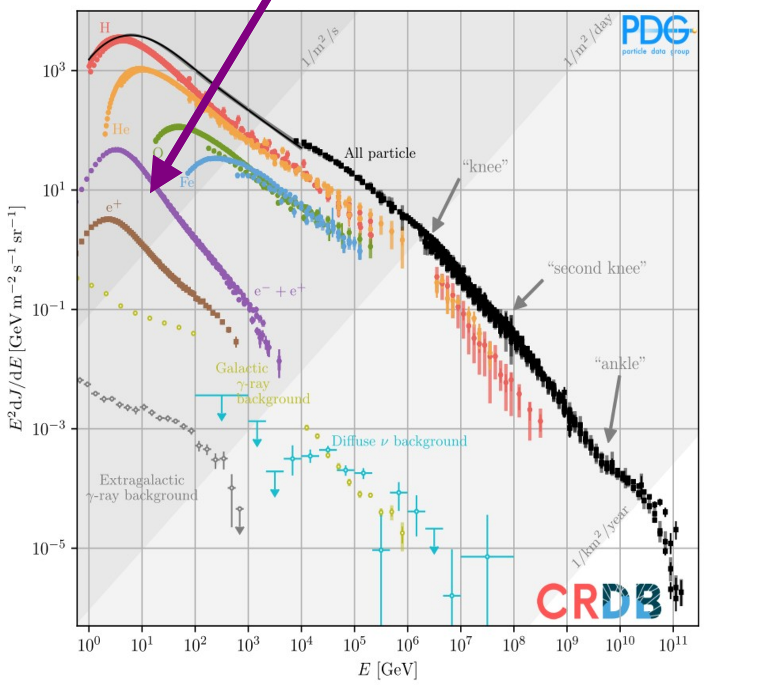
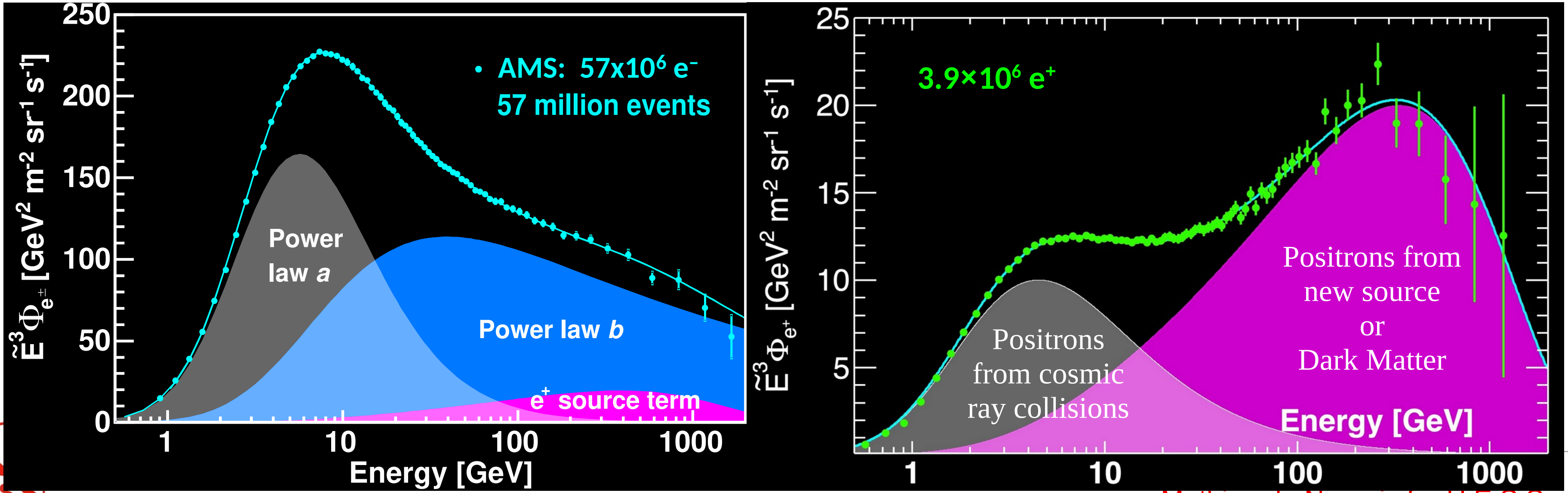


Figure 30.1: The spectrum of cosmic rays (CRs). Shown are measurements of the intensity of charged and neutral CRs, multiplied

S.Navas et al, PDG, 2024

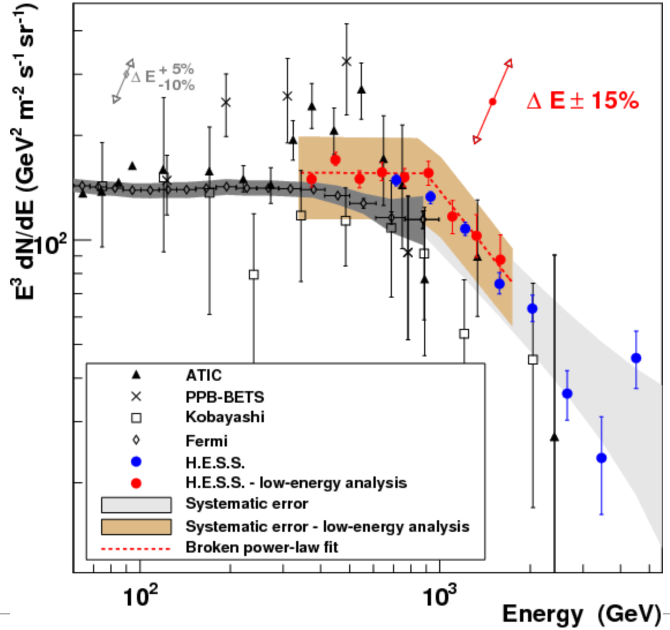
Electrons from space

- AMS data show complicated lepton spectra:
  - e^+ data consistent with secondaries + a high energy source term (cutoff @ 749 GeV)
  - e^- data consistent with 2 power law + source term similar to that of e^+
- Interpretation in terms of classical CR source (SNR, PWN, …) + a leptonic (e^+e^-) source (pulsars?) and/or Dark Matter



Very-High-Energy electrons (≥ 1 TeV) with IACTs

- Very low fluxes ⇒ challenging, but important measurement
- Despite large effective areas, IACTs are not made for measuring electron spectra (dominant hadronic background) ⇒ Difficult, non-standard analyses
- H.E.S.S. publications in 2008, 2009
- Preliminary H.E.S.S. High-Energy spectrum shown at ICRC 2017 + final analysis at ICRC 2023
- MAGIC spectrum shown at ICRC 2023
- Recent PRL publication with final spectrum Phys. Rev. Lett. 133, 221001, 2024



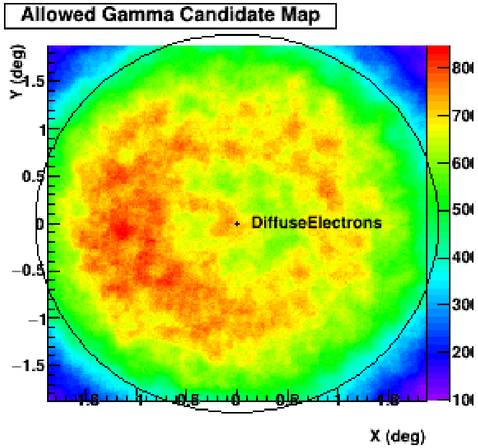
HESS 2009

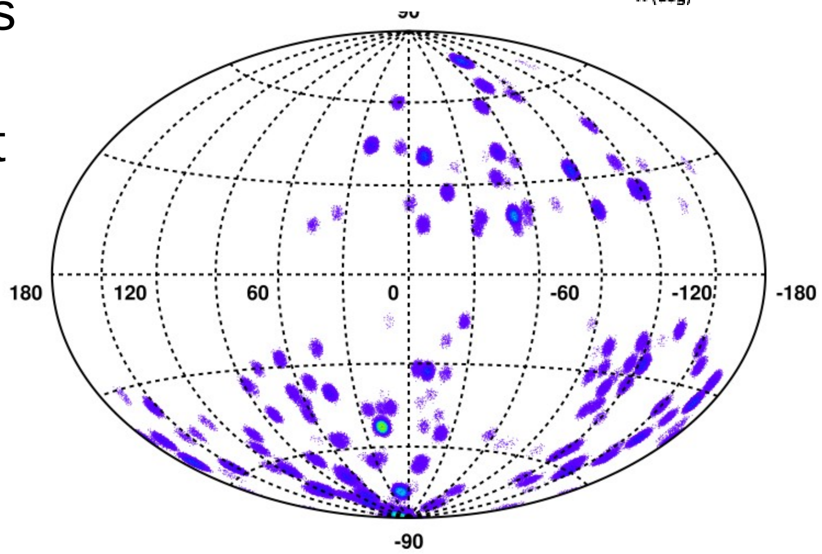
Challenges for IACTs

- Electron induced showers almost indistinguishable from gamma induced ones
- Hadronic background >> electron flux, cannot be subtracted like we do for γ-ray sources (diffuse emission)
  $\Rightarrow$ need to estimate remaining hadronic contamination (and possibly subtract)
- Very low fluxes at high energy
  $\Rightarrow$ need very large data sets
  $\Rightarrow$ need excellent Data/MC agreement to control the systematics

HESS 2023 – 2024 Analysis

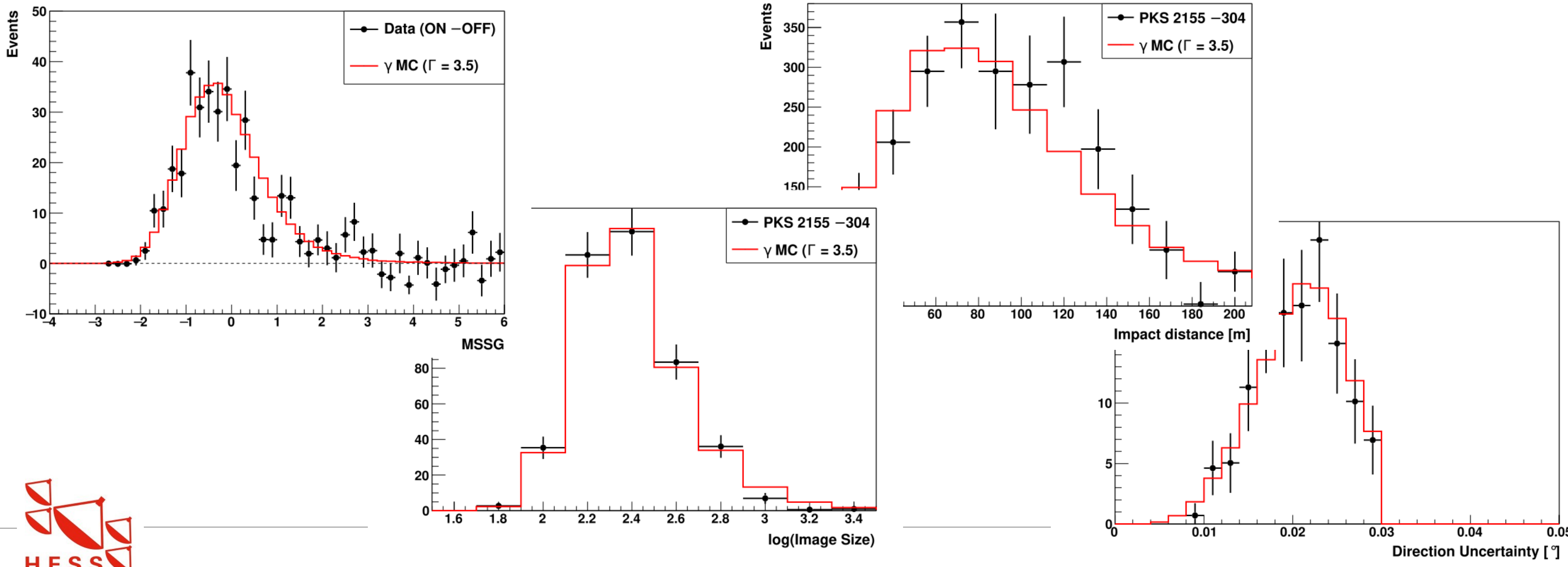
- 6830 HESS-I runs (> 3000 hr) excl. Gal. Plane (|l| > 15°)
- 2° circular region, excluding all known γ-ray sources
- Based on Model++ HESS-I (de Naurois et al. 2009) (log-likelihood fitting of shower images on pre-calculated templates)
- Additional cuts to enrich the sample in electrons
- RunWise (Holler et al, 2020) response function (one MC per run), ~perfect data-MC agreement
- Spectrum determination with forward folding (proper treatment of biases)
- Many systematics checks performed





MC Validation

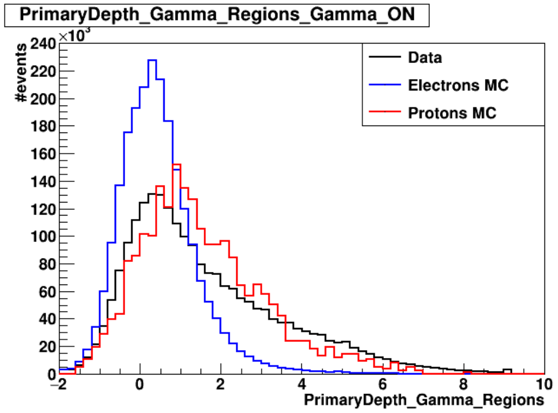
- Extensive checks on γ-ray source PKS 2155-304, in electron-like cuts, shows a perfect agreement ⇒ validation of RWS approach

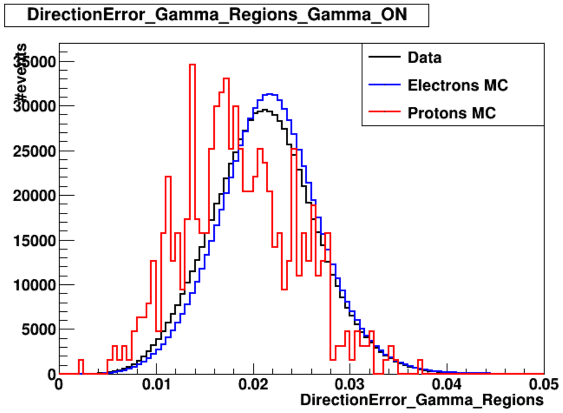


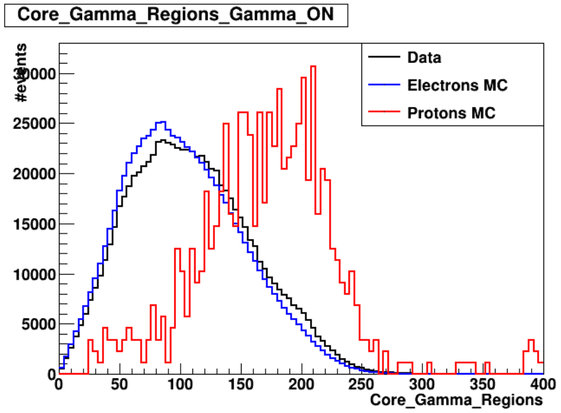
Selection Variables

- 4 Variables used to increase the electron fractions:
  - Primary Interaction Depth
  - Direction Uncertainty
  - Impact Distance
  - Telescope Multiplicity

Note: Proton MC not fully reliable!

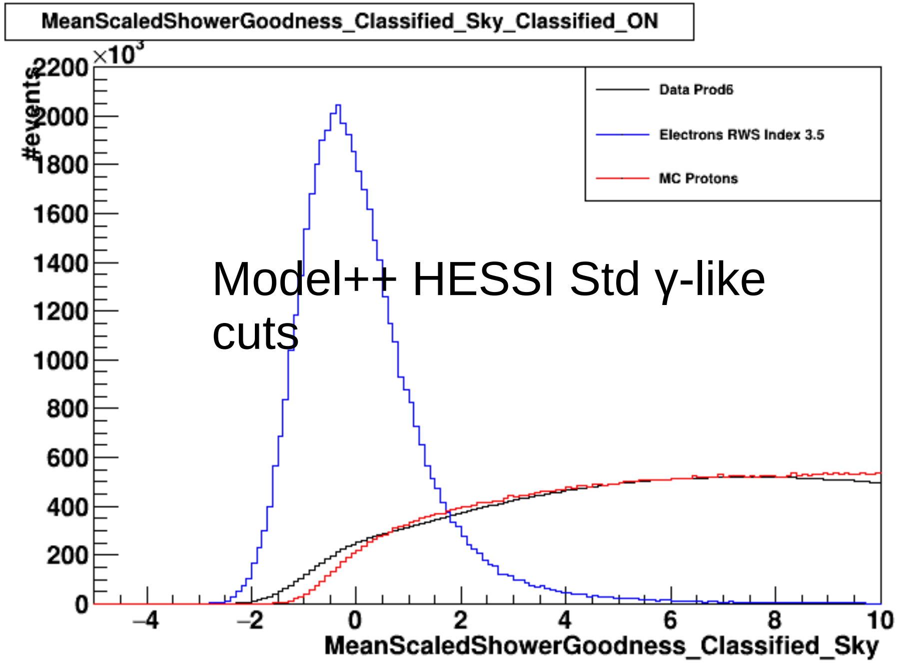


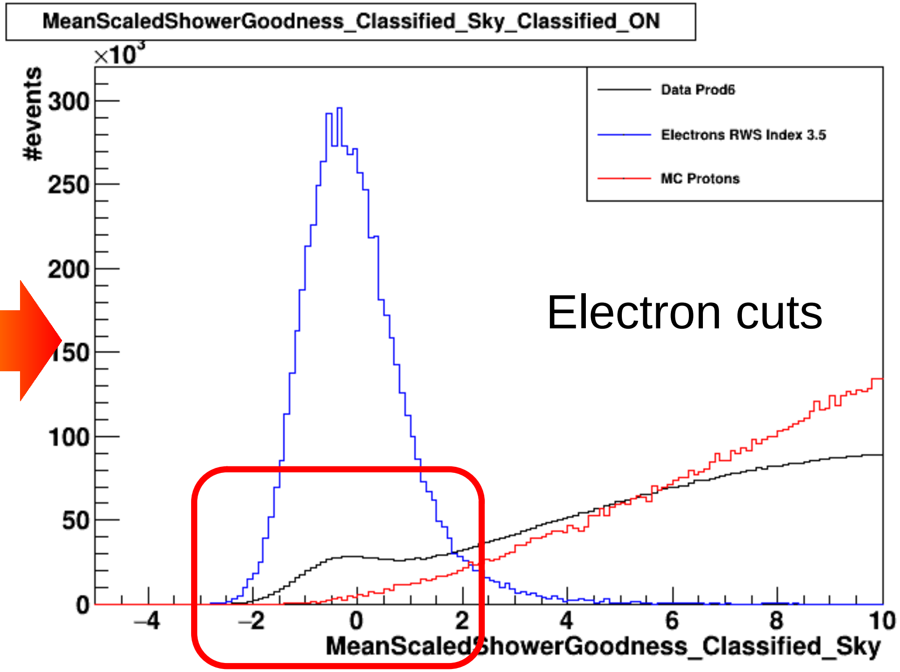




Electrons in the data sample

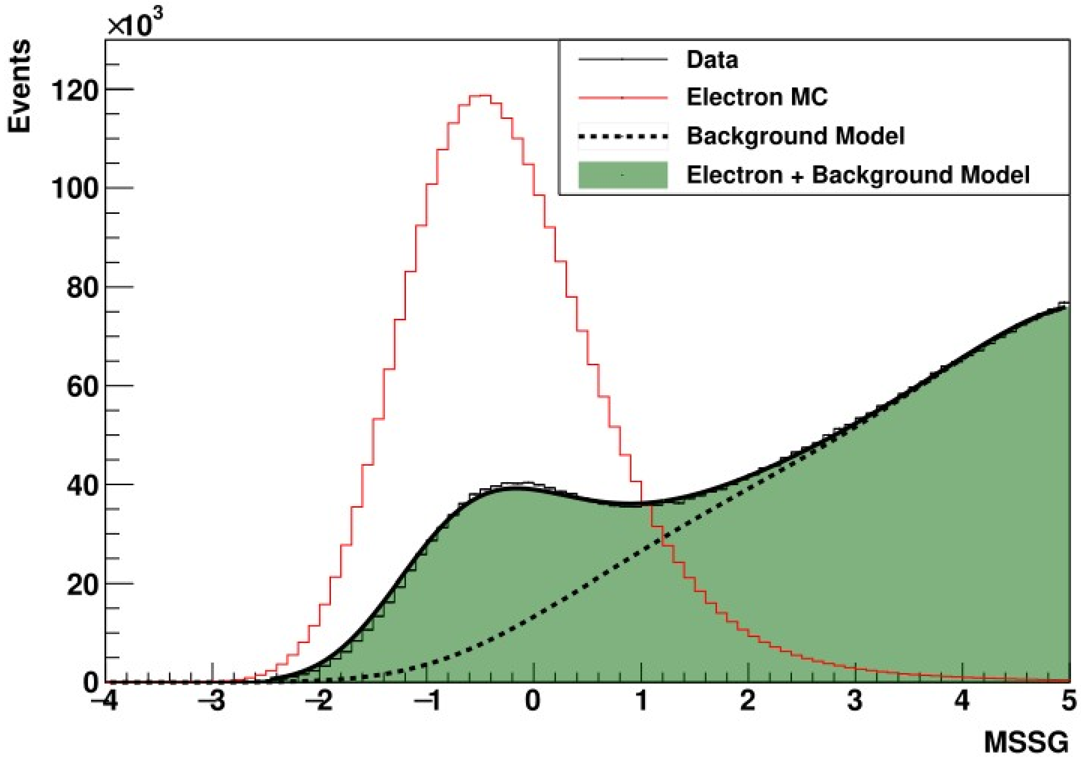
- Mean Scale Shower Goodness (MSSG) is the main Model++ discrimination variable.
- Electron cuts make electron population **appear clearly** in MSSG





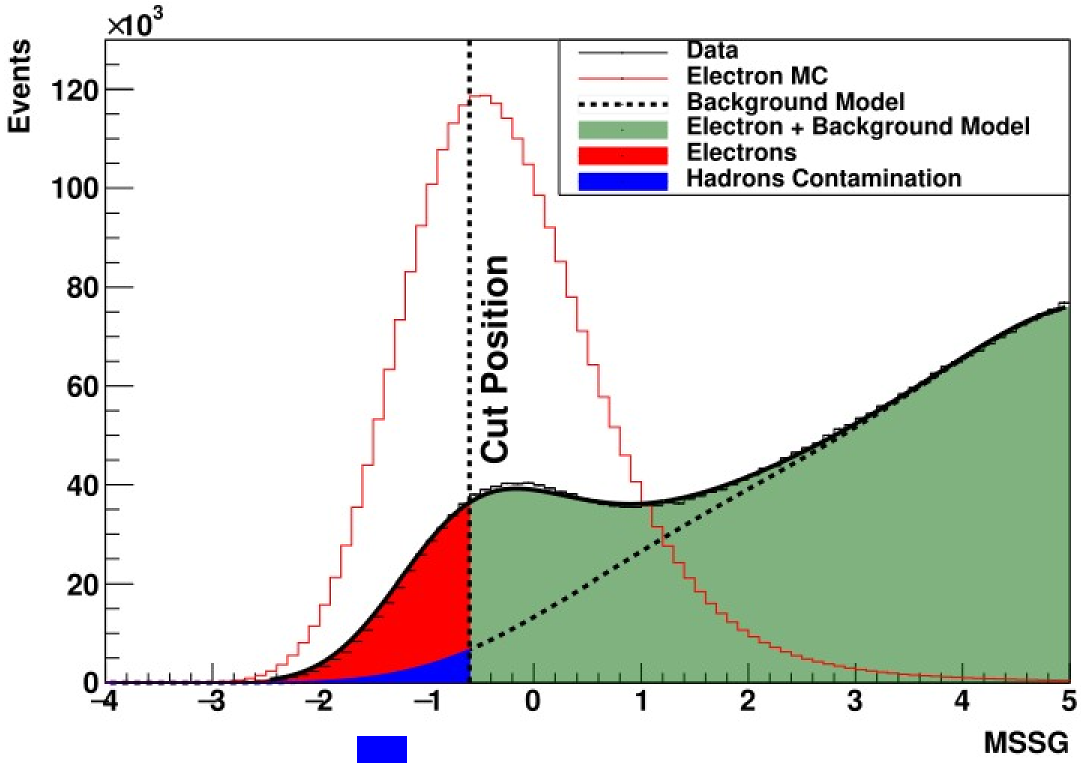
Hadronic Contamination

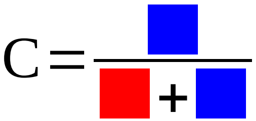
- Model the electron peak with an analytical shape
- Assume a “regular” shape for the hadronic background
- Fit the data with superposition of
  - Electron contribution (fixed shape, free normalisation)
  - Background distribution



Hadronic Contamination

- Model the electron peak with an analytical shape
- Assume a “regular” shape for the hadronic background
- Fit the data with superposition of
  - Electron contribution (fixed shape, free normalisation)
  - Background distribution
- For a given cut position
  - Contamination obtained by ratio of areas under curves
  - Average value ~ 20%
  - Depends on assumption for background



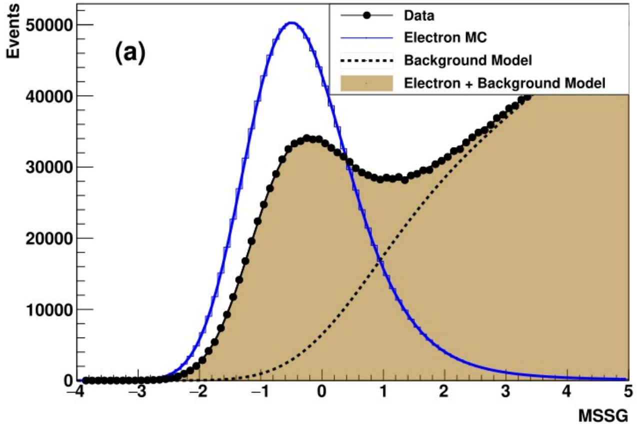


Up to which energy?

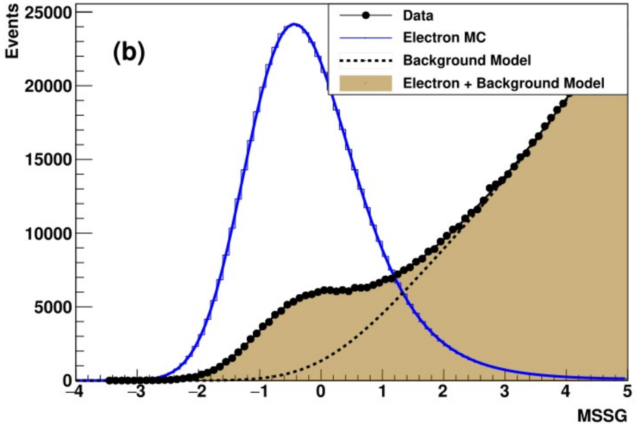
- Electrons clearly visible up to ~ 3 TeV at least
- Faint electron peak above 3 TeV

  ⇒ not possible to firmly state max. energy of electrons
- Contamination expected to rise with energy (harder proton spectrum)

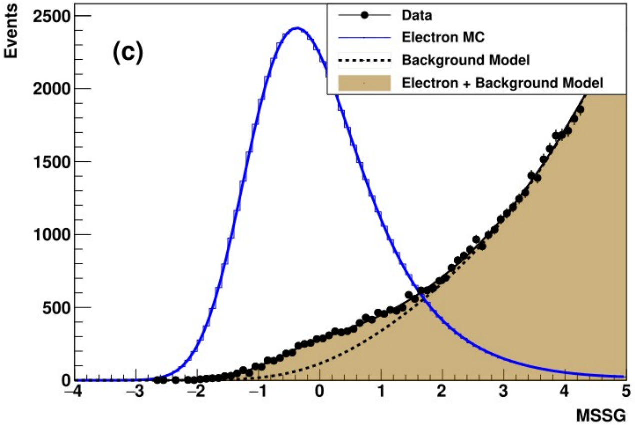
250 GeV – 1 TeV



1 TeV – 3 TeV



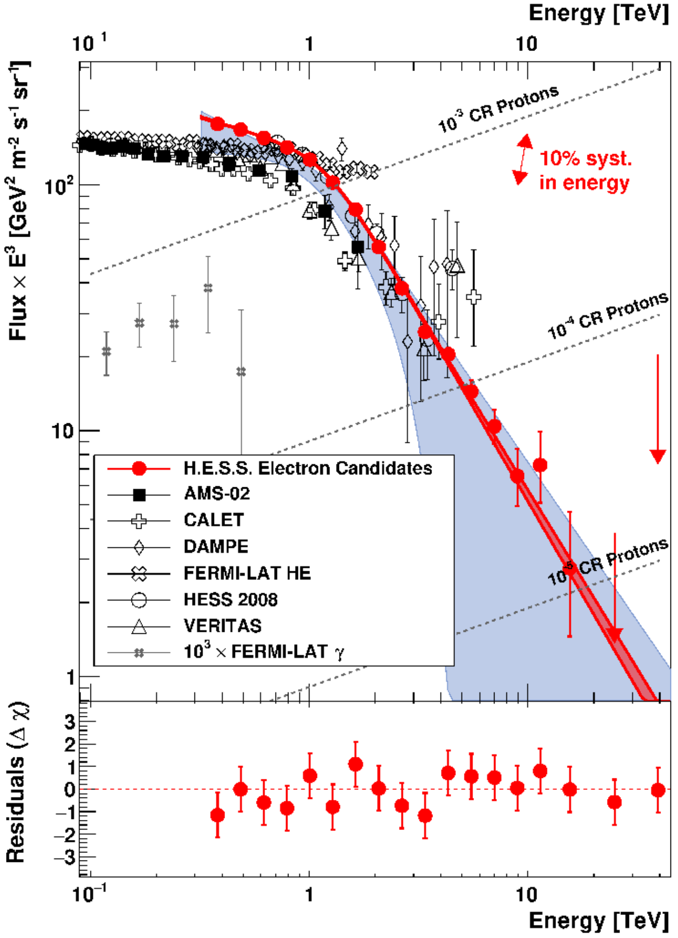
≥ 3 TeV



Final Spectrum

- Highly significant (> 100 σ) spectral break
- Best fit parameters:
  - $\Gamma_1 = 3.25 \pm 0.02_{stat} \pm 0.2_{syst}$
  - $\Gamma_2 = 4.49 \pm 0.04_{stat} \pm 0.2_{syst}$
  - $E_{break} = (1.17 \pm 0.04_{stat} \pm 0.1_{syst})$ TeV
  - Sharpness $s = 0.21 \pm 0.02_{stat}$
  - @ 1 TeV:
    $E^3 \times \Phi(E) = (126.1 \pm 0.5_{stat})$ GeV^2 m^{-2} s^{-1} sr^{-1}
    (not corrected for contamination)

$$\frac{dN}{dE} = \Phi_0 \times \left(\frac{E}{E_0}\right)^{-\Gamma_1} \times \left(1 + \left(\frac{E}{E_{cut}}\right)^{1/s}\right)^{s \times (\Gamma_1 - \Gamma_2)}$$



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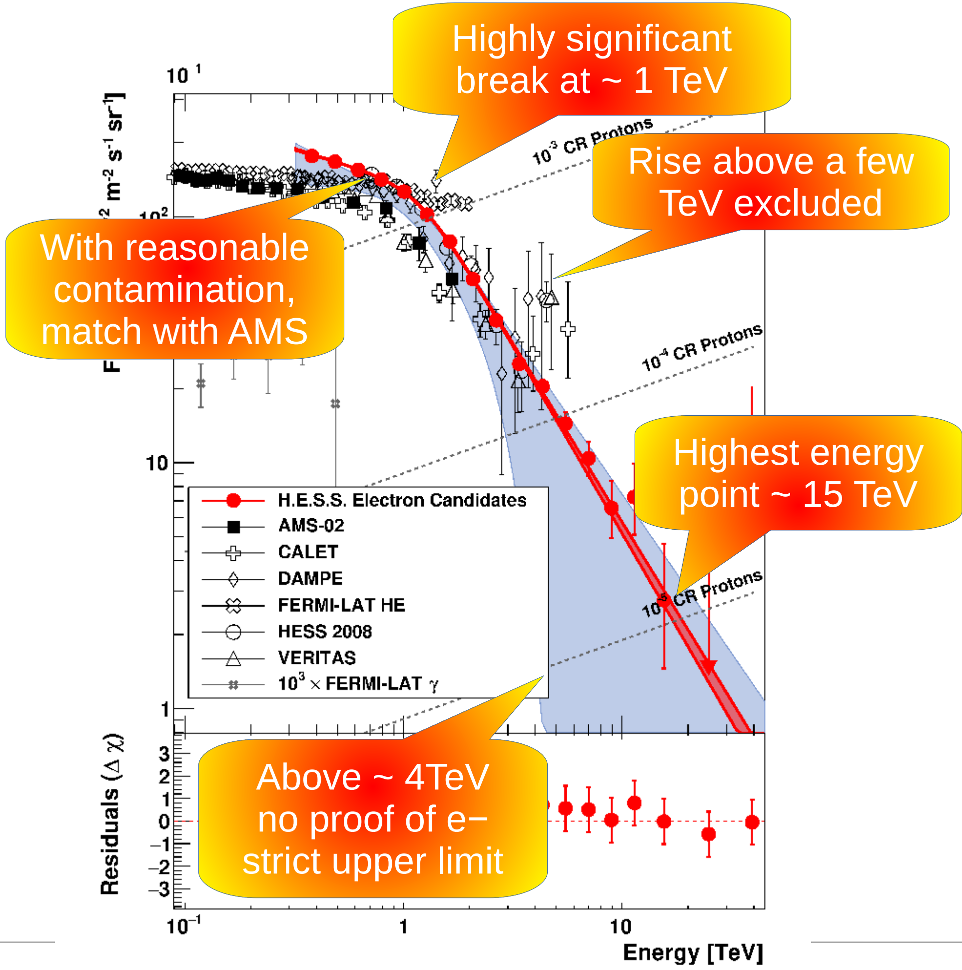


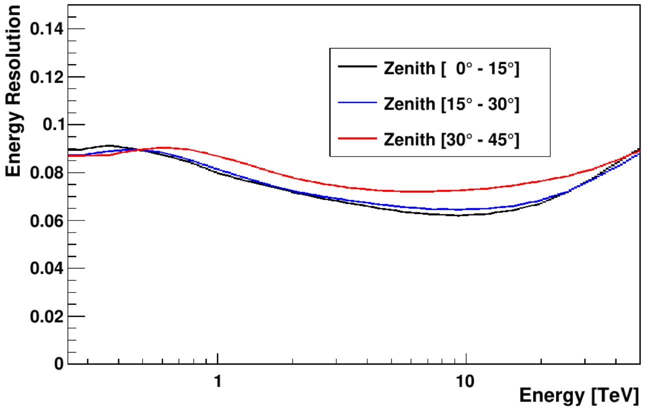
H.E.S.S.

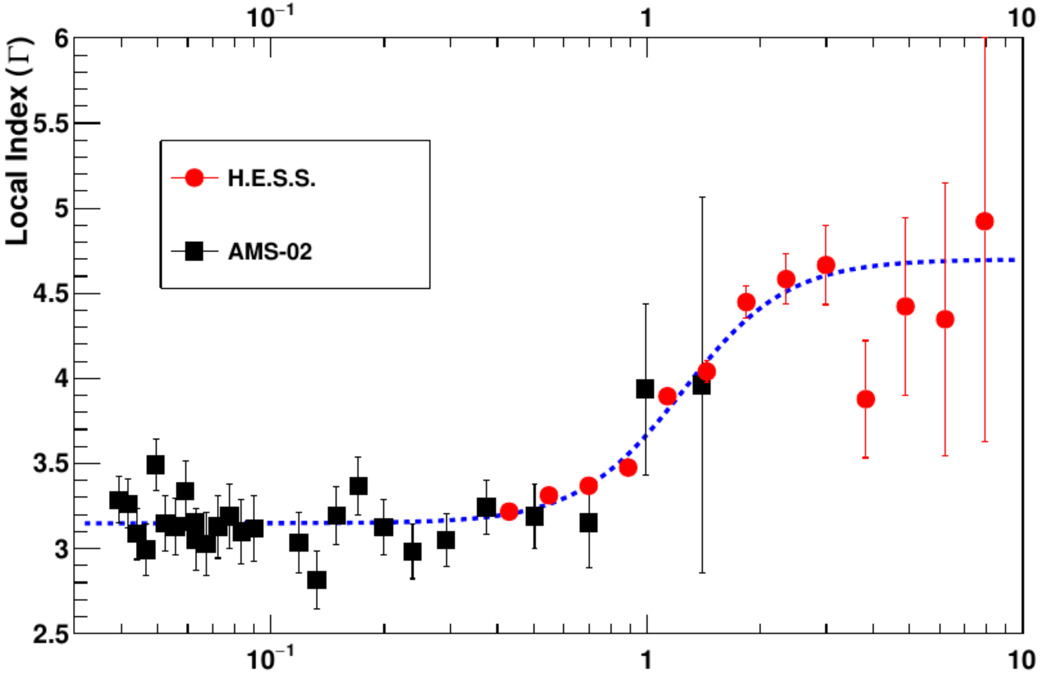
Spectral Shape – Smooth Transition

- Smoothness parameter s:

$$\frac{dN}{dE} = \Phi_0 \times \left(\frac{E}{E_0}\right)^{-\Gamma_1} \times \left(1 + \left(\frac{E}{E_{cut}}\right)^{1/s}\right)^{s\times(\Gamma_1-\Gamma_2)}$$

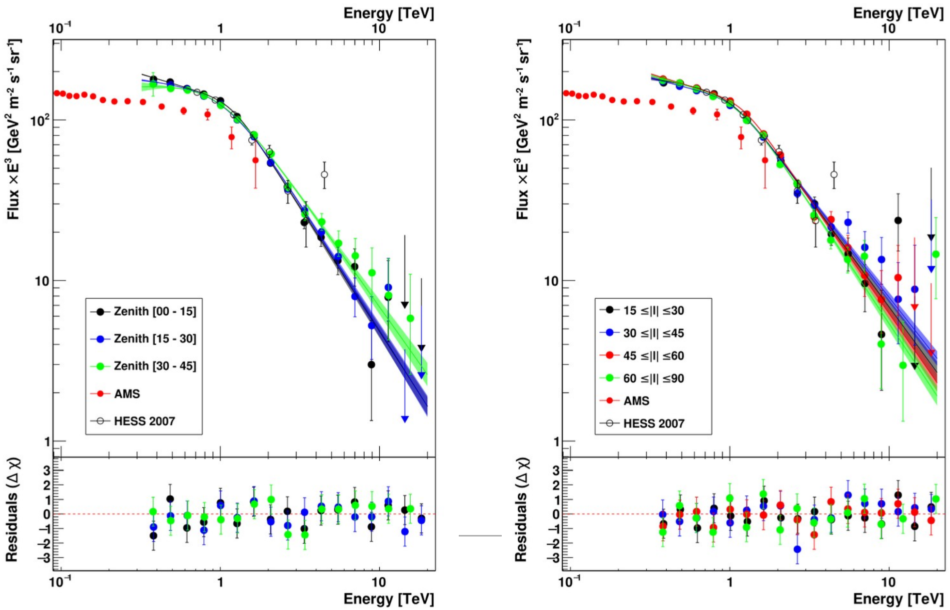
- Results:
  - $\Delta\chi^2 = 55.08 \Rightarrow$ **7.4 σ**)
  - $s = 0.21 \pm 0.02_{stat} + 0.10_{sys} - 0.06_{sys}$
- Energy resolution ~ 9%





Systematic Checks

- Electron flux stable (within systematics) with:
  - Zenith Angle (0 to 45°)
  - Galactic Latitude ⇒ same feature throughout the Milky Way, no Gal. Plan contamination
  - Variation of cut values (impact, ...) ⇒ stability of analysis
  - ...



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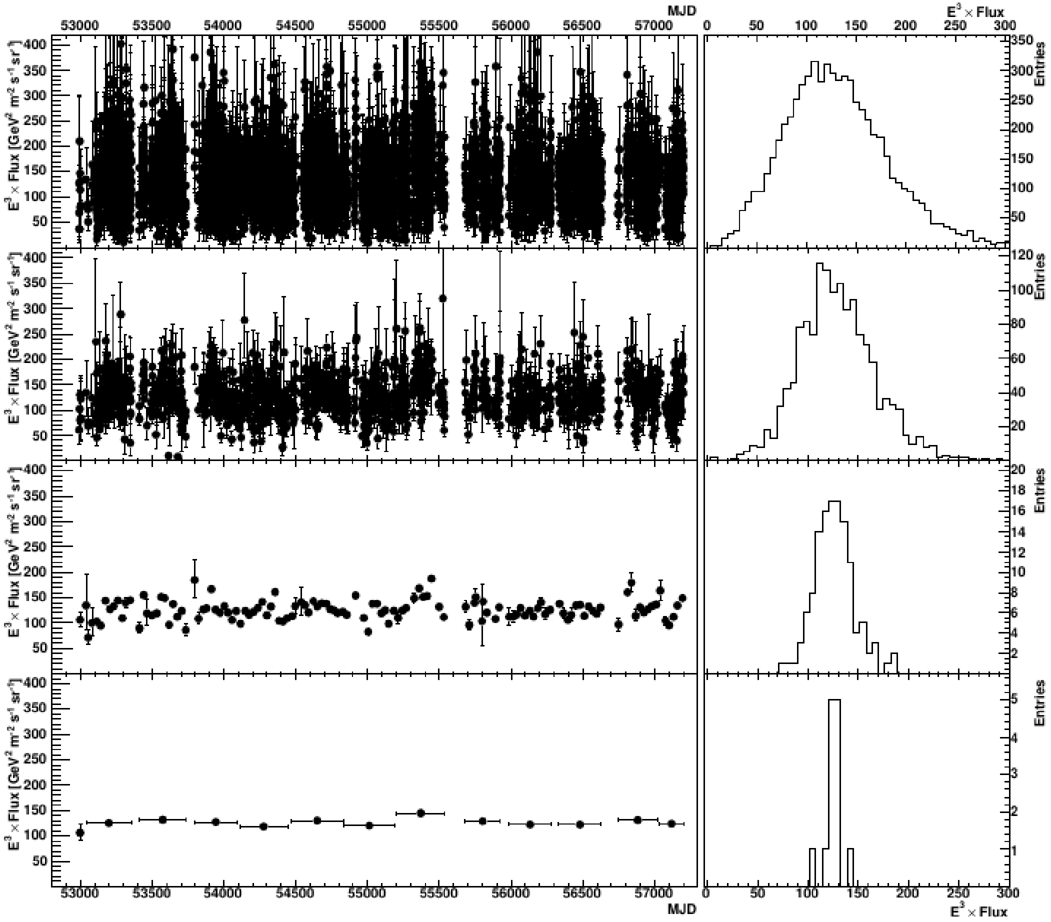
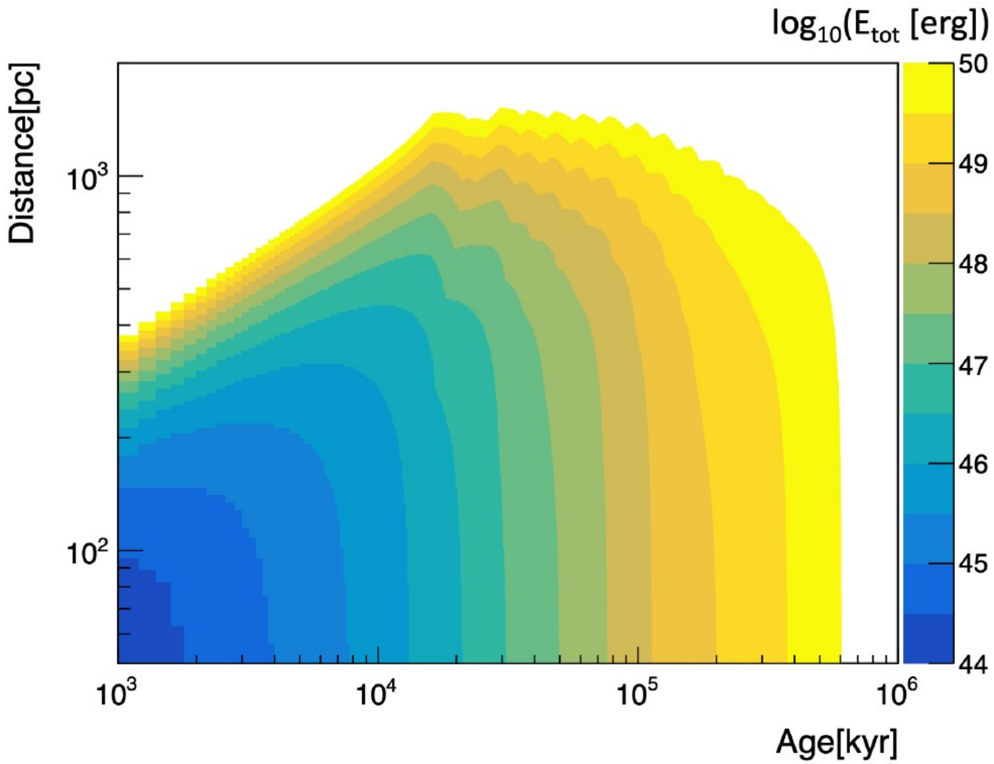
Lightcurves

- Diffusive propagation
  → no changes over ~ decades
- Flux is stable on various time-scales (day, month, year) over > 10 years



Implications

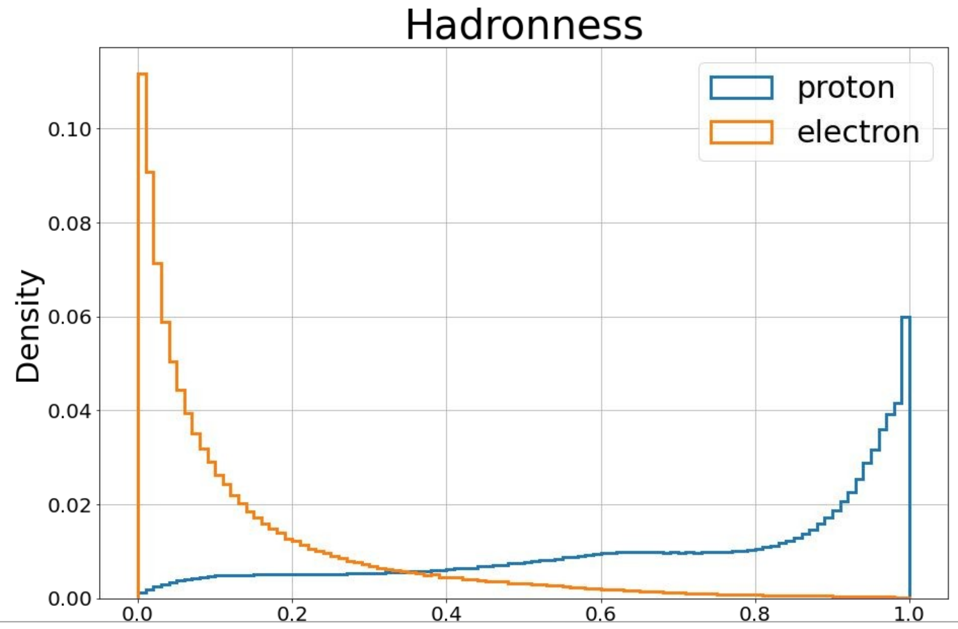
- >10 TeV electrons and break impose limitations on cooling time (~ 100 kyr) and propagation (~ few 100 pc).
- Rather strong constrain on energetics: e.g. burst of Vela-type (300 pc, 11 kyr, ~7×10^{36} erg/s) is limited to $E < 2 \times 10^{46}$ erg
- Fairly sharp break points towards handful (or single) nearby source(s) e.g. Mauro+14, Recchia+19, Drury 11



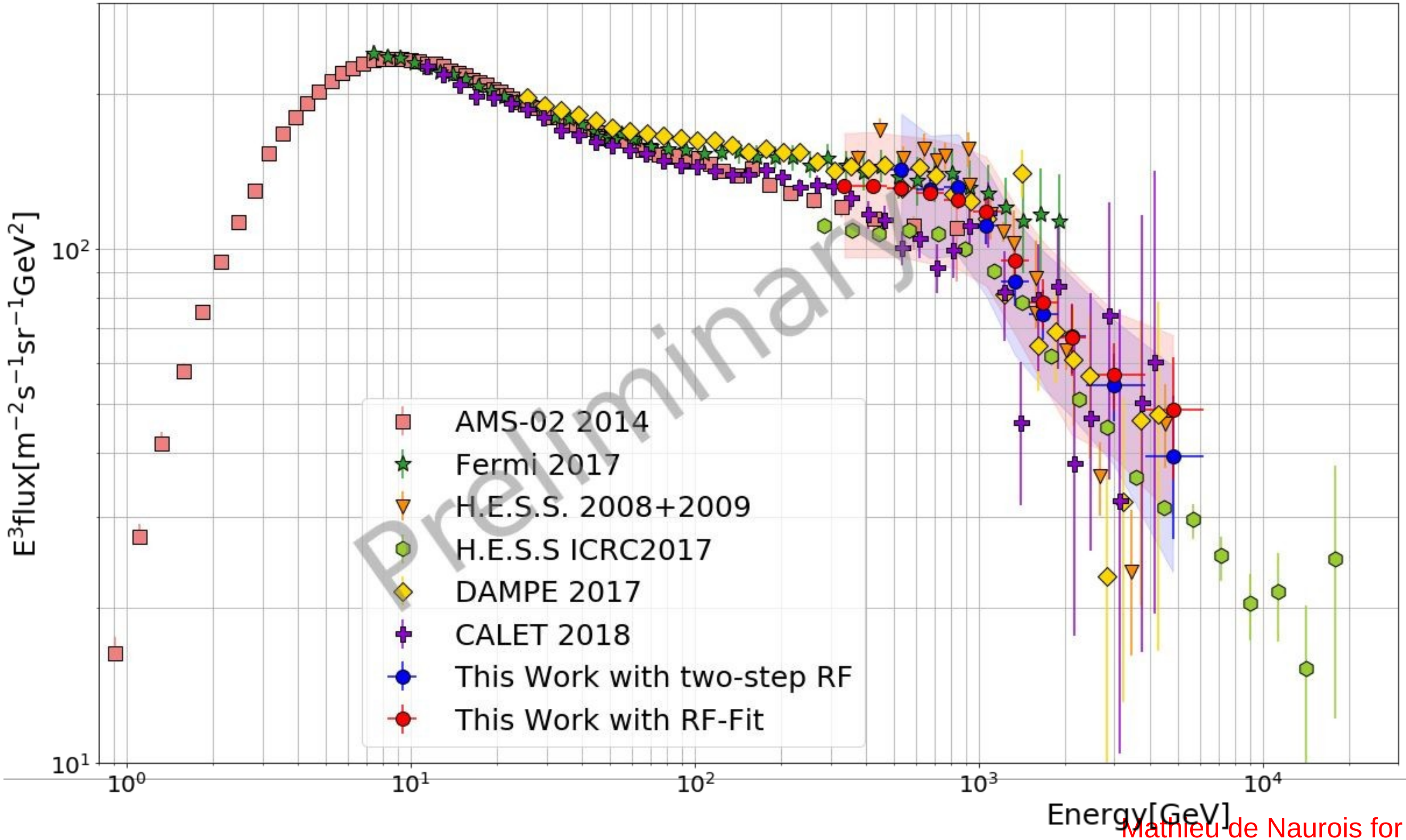
Max released energy as function of source age and distance

MAGIC Spectrum

- Dataset of ~ 220 hours, Galactic latitude |b|>20°
- No known gamma-ray source in FoV
- Analysis based on an “hadroness” classifier (Random Forest method) in two steps, tight cuts approach
- Energy resolution ~ 15%



MAGIC spectrum @ ICRC 2023



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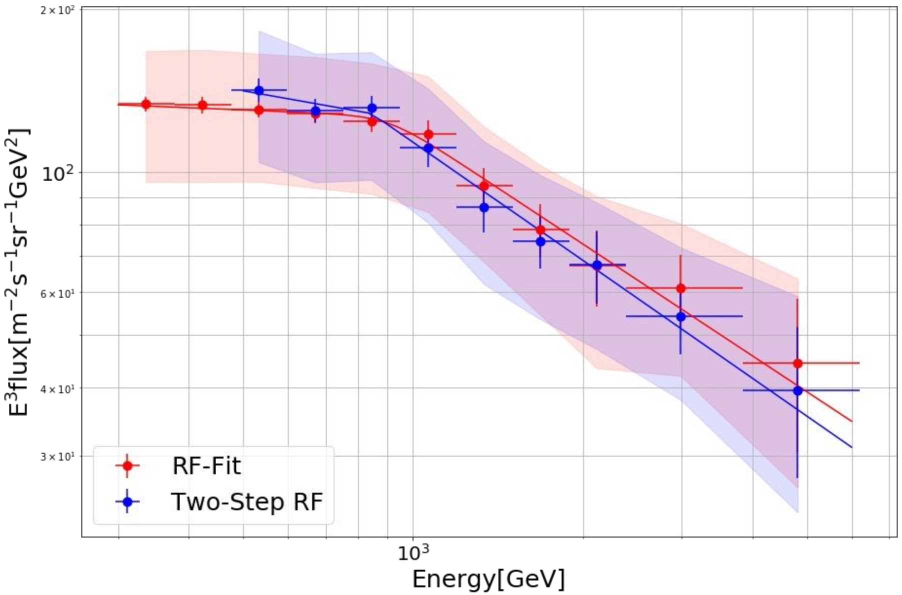
MAGIC spectrum @ ICRC 2023

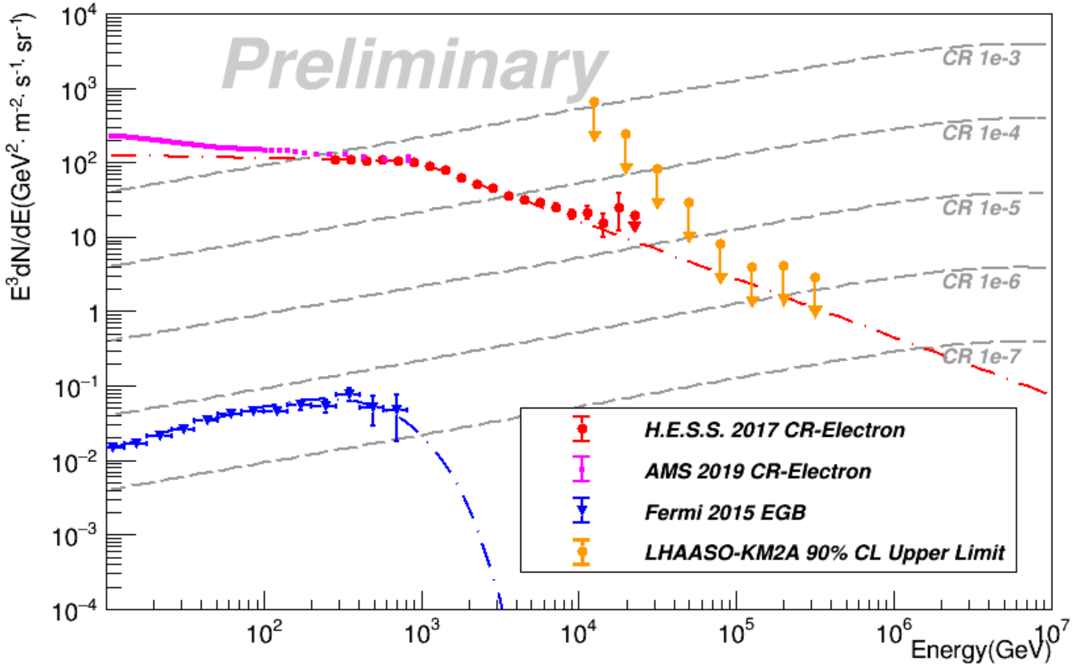
- Spectrum compatible with broken power-law
  - E_{break} ~ 0.9 TeV
  - High energy spectrum harder than that of HESS
    Remaining contamination?



RF-Fit	Two-Step RF
$\Gamma_1 = 3.04 \pm 0.08$	$\Gamma_1 = 3.18 \pm 0.15$
$\Gamma_2 = 3.69 \pm 0.13$	$\Gamma_2 = 3.72 \pm 0.09$
$E_{break} = 905.31 \pm 142.6$	$E_{break} = 845.25 \pm 37.62$
$N_0 = (1.71 \pm 0.90) \times 10^{-7}$	$N_0 = (2.12 \pm 0.34) \times 10^{-7}$
α=0.005	α=0.002
χ^2_R =2.44/6	χ^2_R =1.56/4

LHAASO – KM2A measurement

- Very large effective area, wide field of view
- Higher energy domain, complementary with IACTs
- ICRC 2023 results : upper limits only, no conflict with IACTs



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Conclusions

- Unprecedented dataset of ≥ 3000 hours of HESS-I data used in electron analysis
- High precision analysis with RunWise© simulations (every run simulated individually)
- Highly significant (and relatively sharp break) in electron spectrum at ~ 1 TeV
- Presence of electrons in data set demonstrated up to 3 TeV at least, spectrum extending to ~ 20 TeV
- Interpretation of break
  - Accumulation of sources of different ages and distances (natural would result in a smoother transition)
  - Contribution of a few, nearby sources more likely ⇒ possible anisotropies
  - (very) low fluxes ⇒ Challenging for space instruments!
  - Phys. Rev. Lett. 133, 221001, 2024