The cosmic-ray electron spectrum measured up to $\sim$ 20 TeV with H.E.S.S.

Daniel Kerszberg

Seminar at the Laboratoire Leprince-Ringuet

École polytechnique IN2P3/CNRS

Cosmic ray diffuse emissions

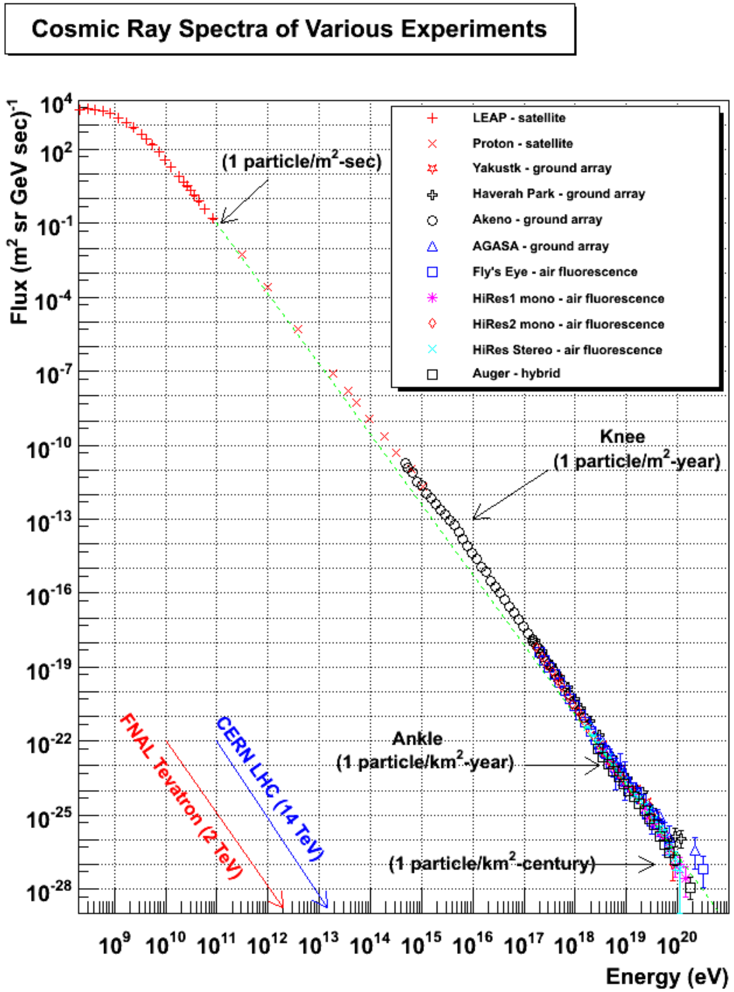
Concerns particles elelectrically charged and neutral.

The 3 components of the diffuse emission are:

- hadrons
- leptons
- photons

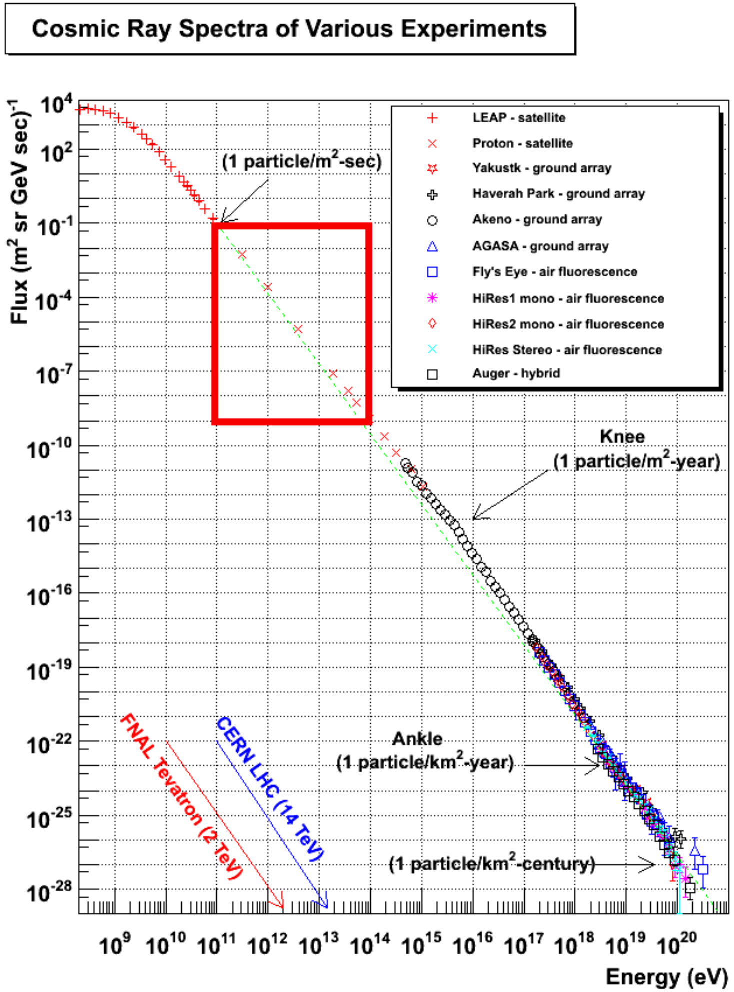
The knowledge of their structure tells us about the mechanisms of production and propagation of these particles.

Cosmic rays



Cosmic Ray Spectra of Various Experiments
Flux (m² sr GeV sec)⁻¹
Energy (eV)
(1 particle/m²-sec)
Knee
(1 particle/m²-year)
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid

Cosmic rays



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Flux (m² sr GeV sec)⁻¹
10⁴
10²
10⁻¹
10⁻⁴
10⁻⁷
10⁻¹⁰
10⁻¹³
10⁻¹⁶
10⁻¹⁹
10⁻²²
10⁻²⁵
10⁻²⁸
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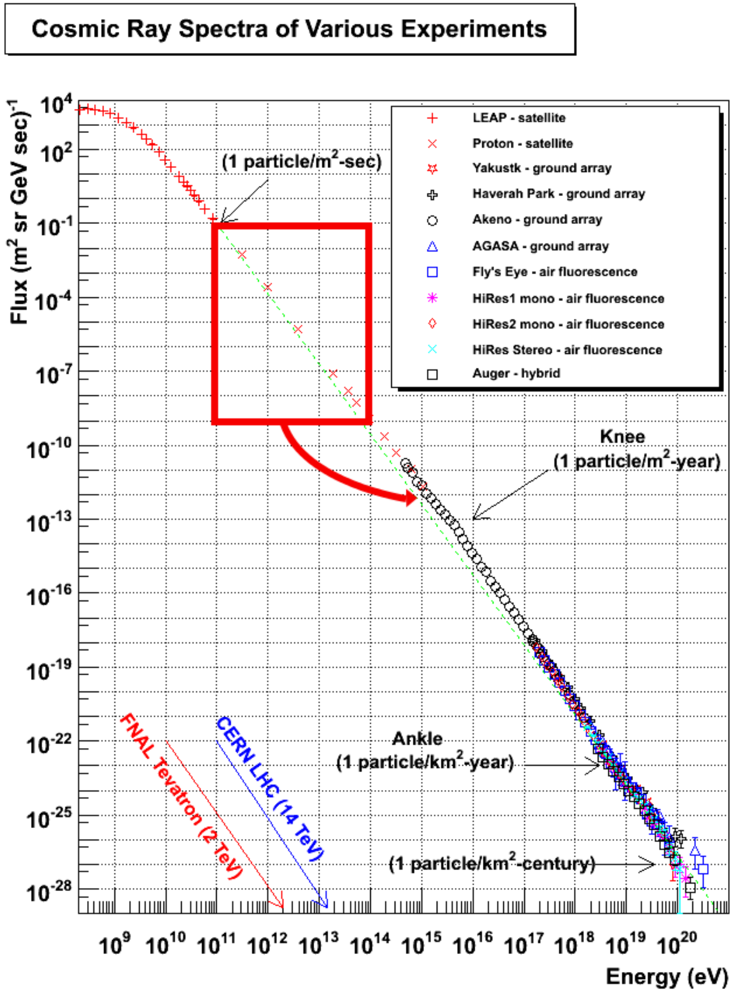
Energy (eV)

Cosmic rays



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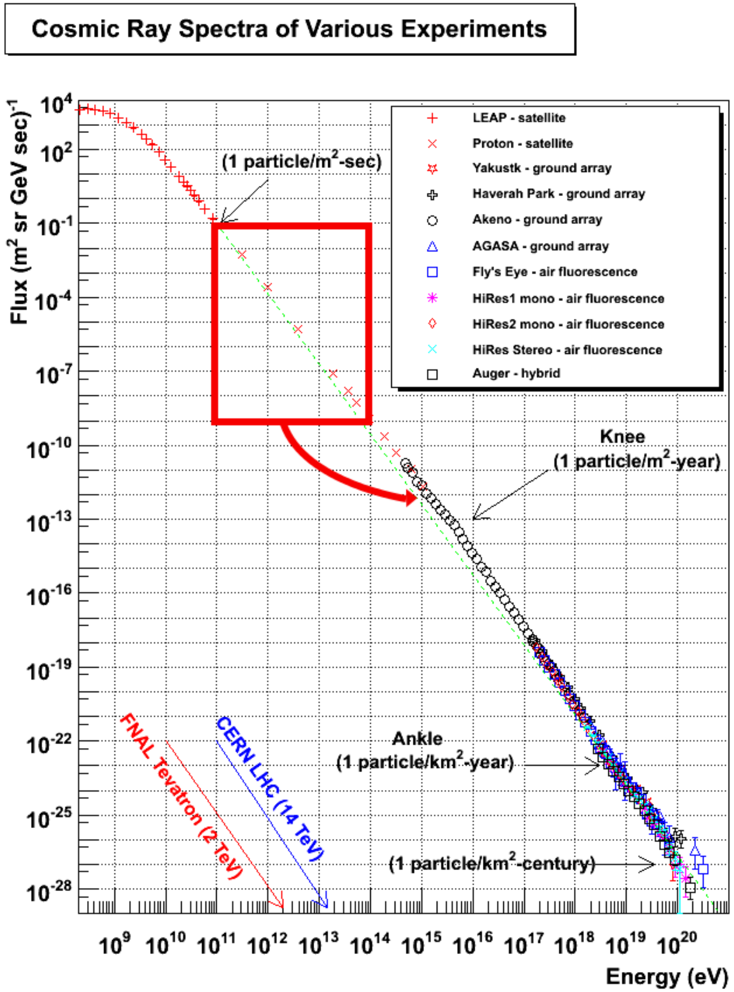

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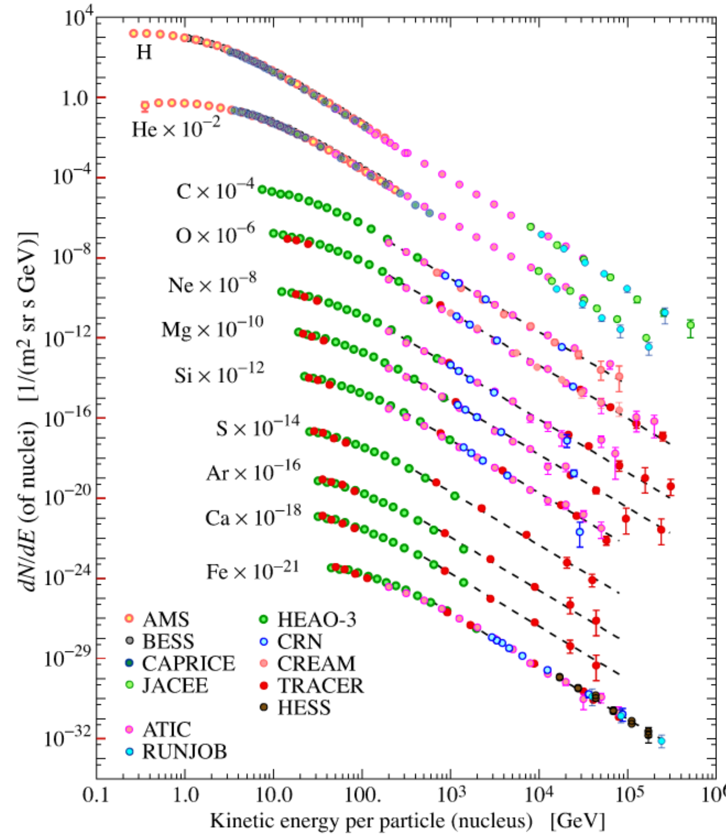
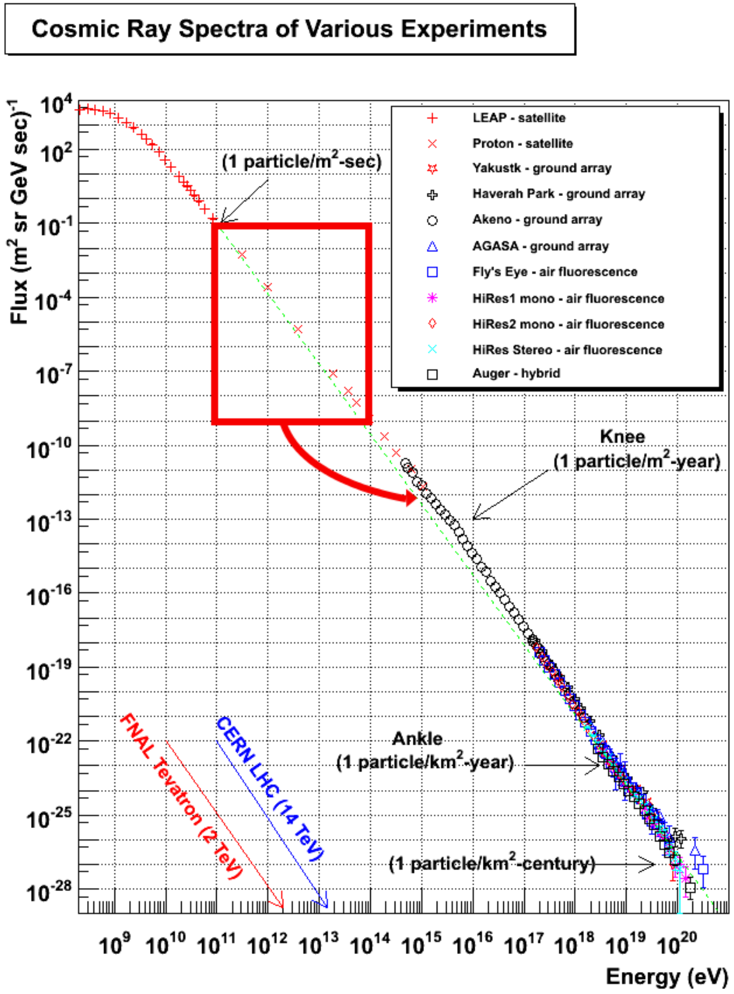


dN/dE (of nuclei) [1/(m² sr s GeV)]
Kinetic energy per particle (nucleus) [GeV]
H
He × 10⁻²
C × 10⁻⁴
O × 10⁻⁶
Ne × 10⁻⁸
Mg × 10⁻¹⁰
Si × 10⁻¹²
S × 10⁻¹⁴
Ar × 10⁻¹⁶
Ca × 10⁻¹⁸
Fe × 10⁻²¹
AMS
BESS
CAPRICE
JACEE
ATIC
RUNJOB
HEAO-3
CRN
CREAM
TRACER
HESS

Cosmic rays



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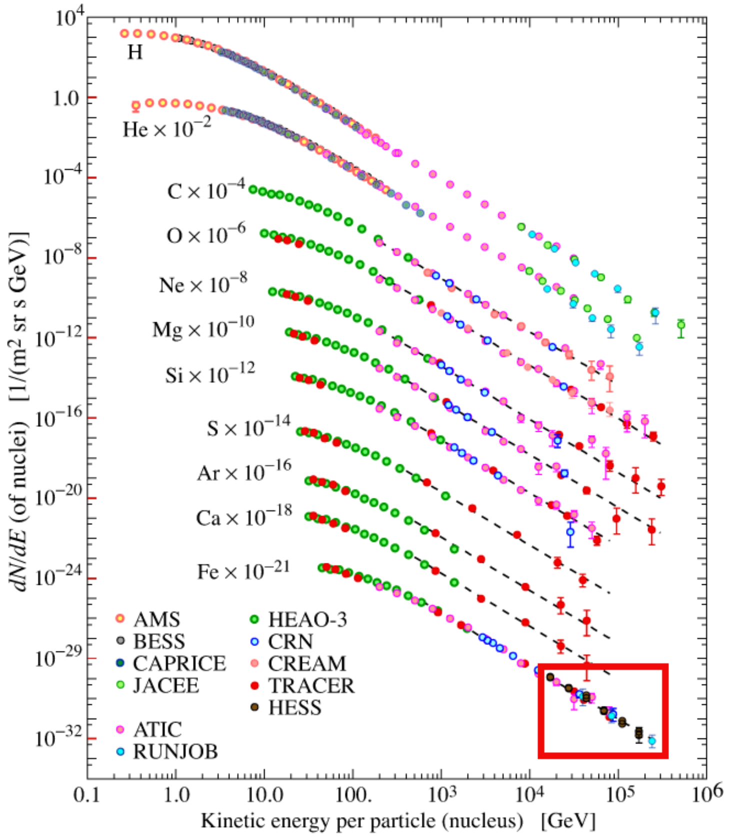

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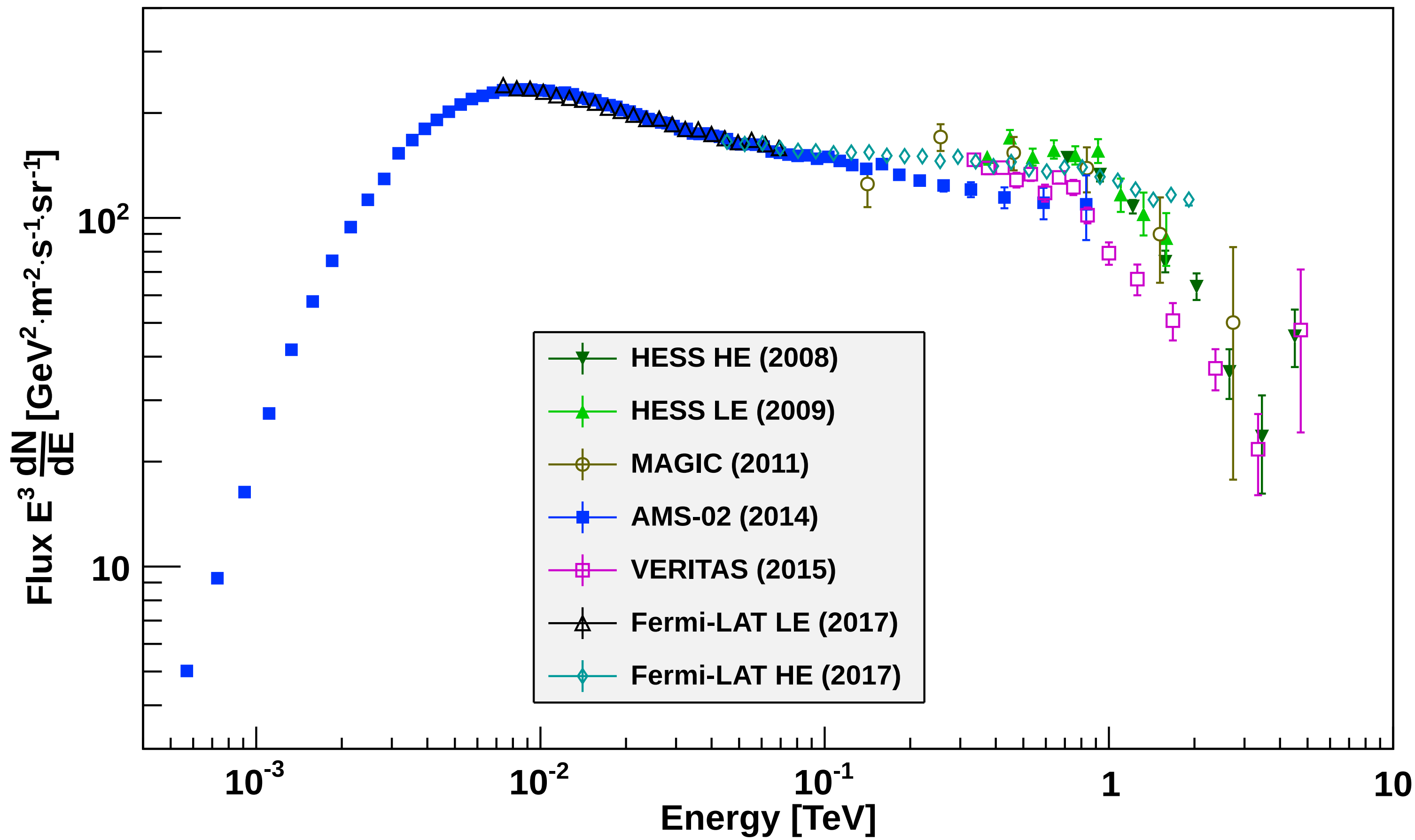
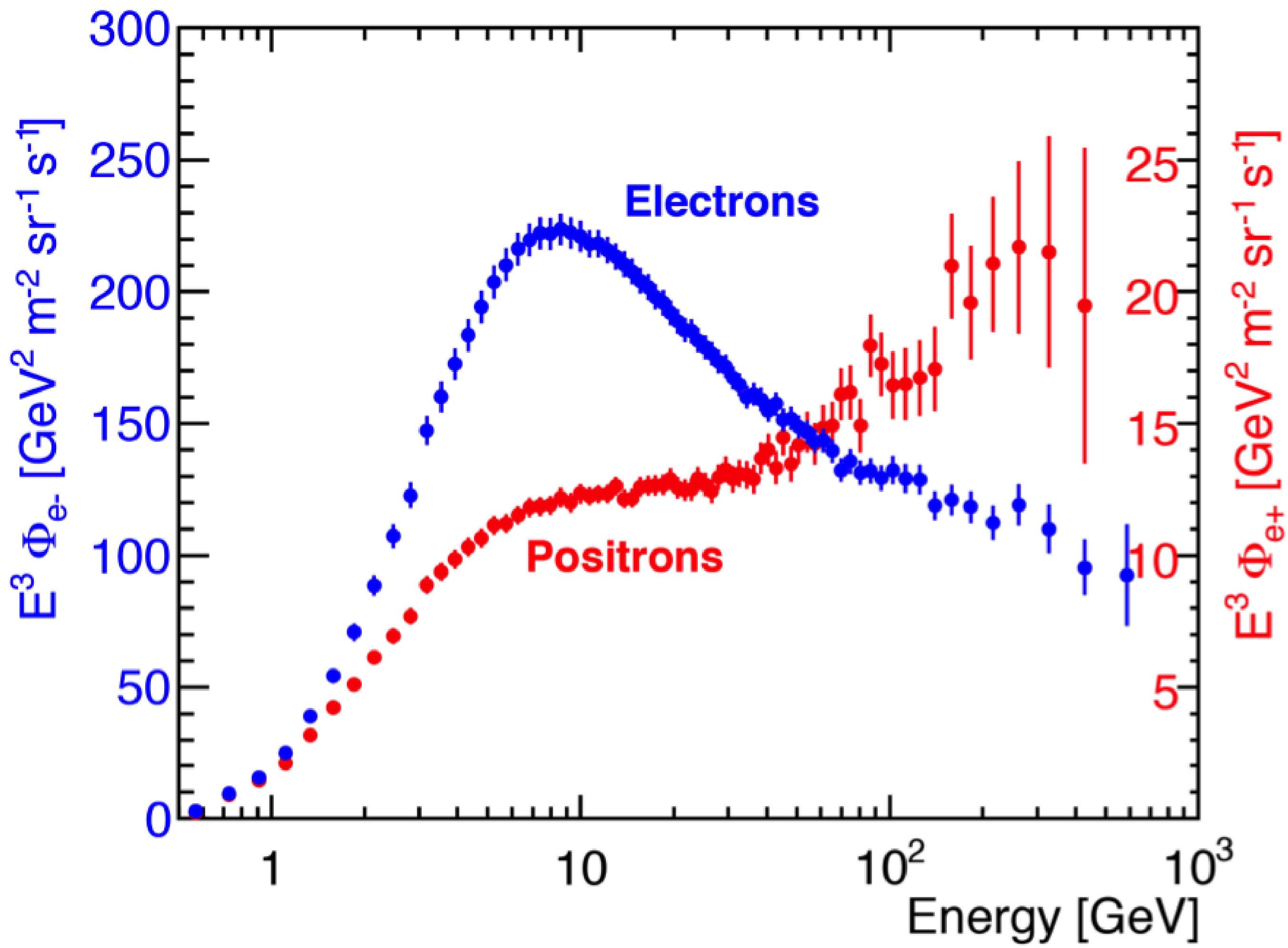
Measurements of the electron+positron spectrum: status

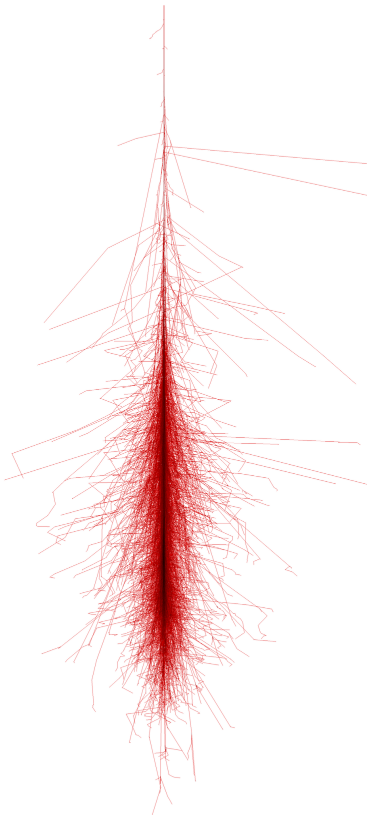


Electrons and positrons with AMS-02



Credit : AMS Collaboration

Atmospheric showers



Photon/electron of 100 GeV

Credit : CORSIKA website

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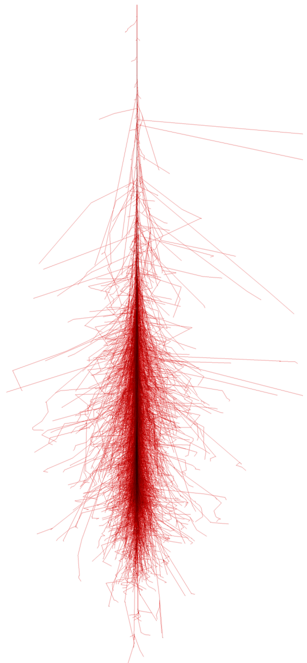

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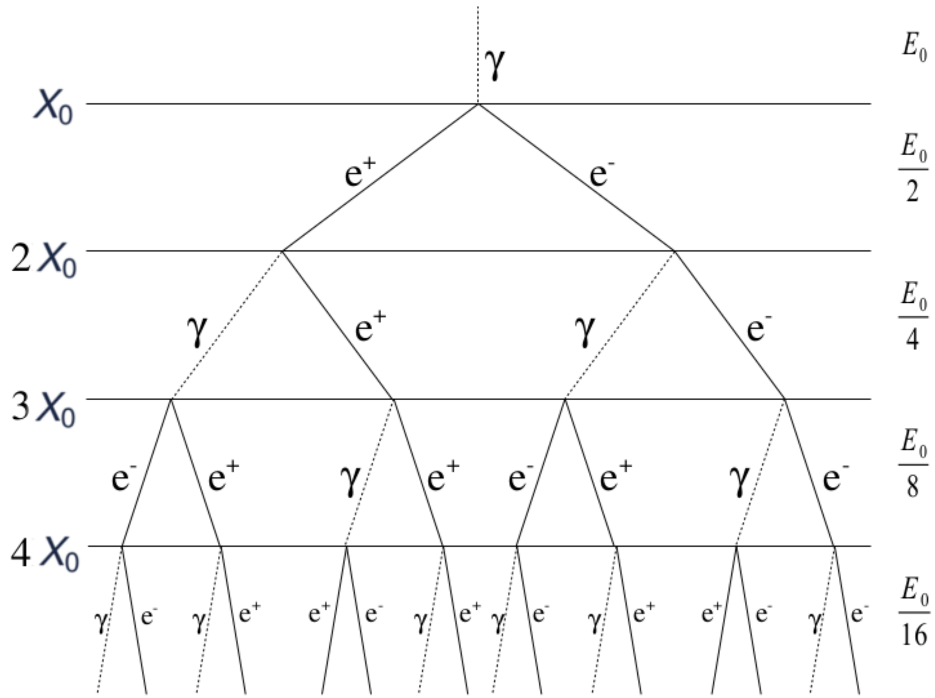
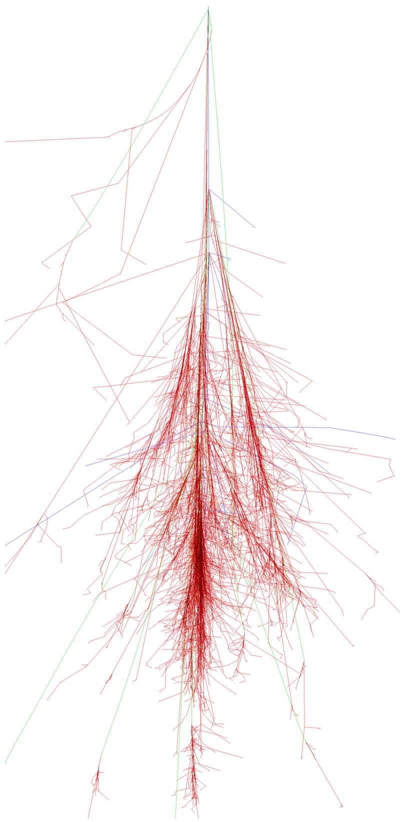


Heitler model

Atmospheric showers



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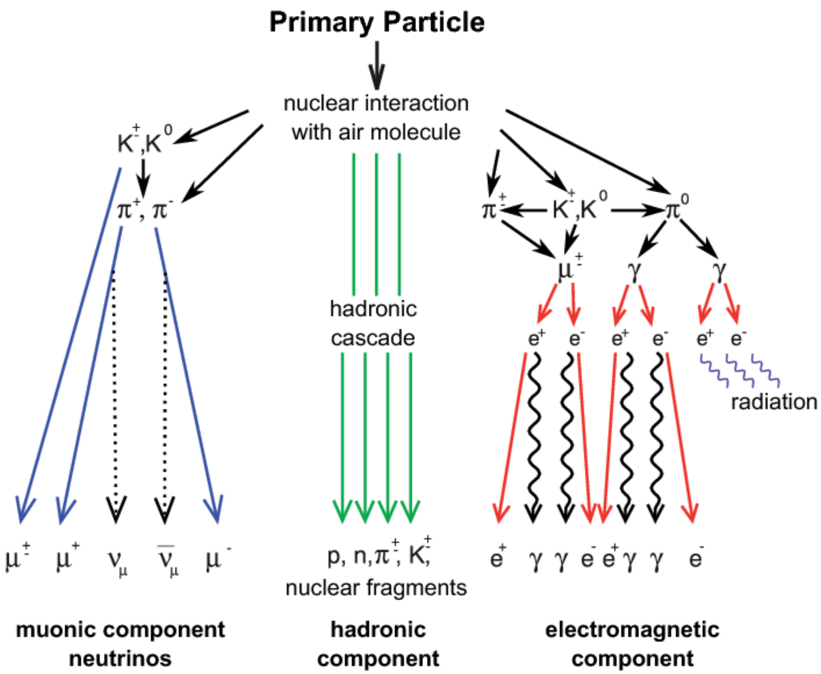

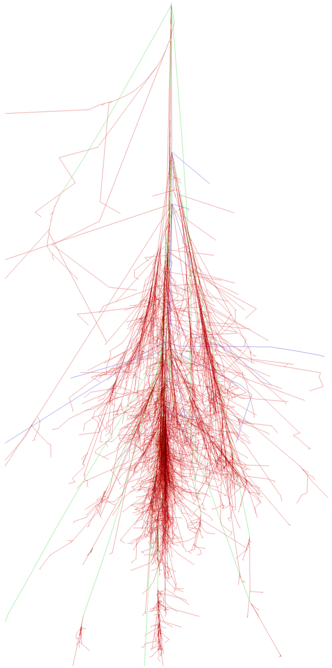

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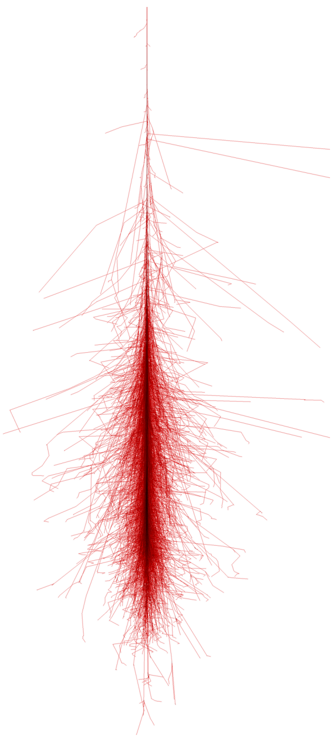

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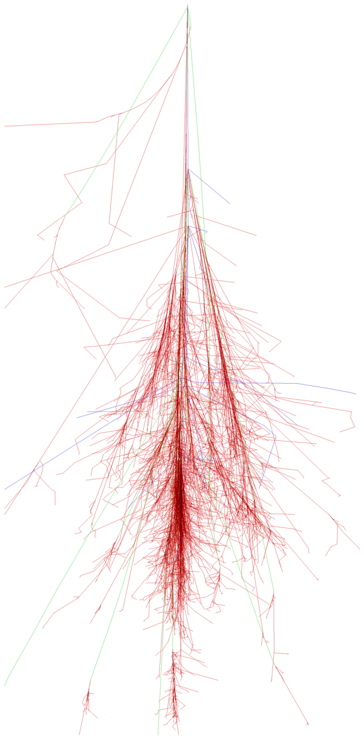
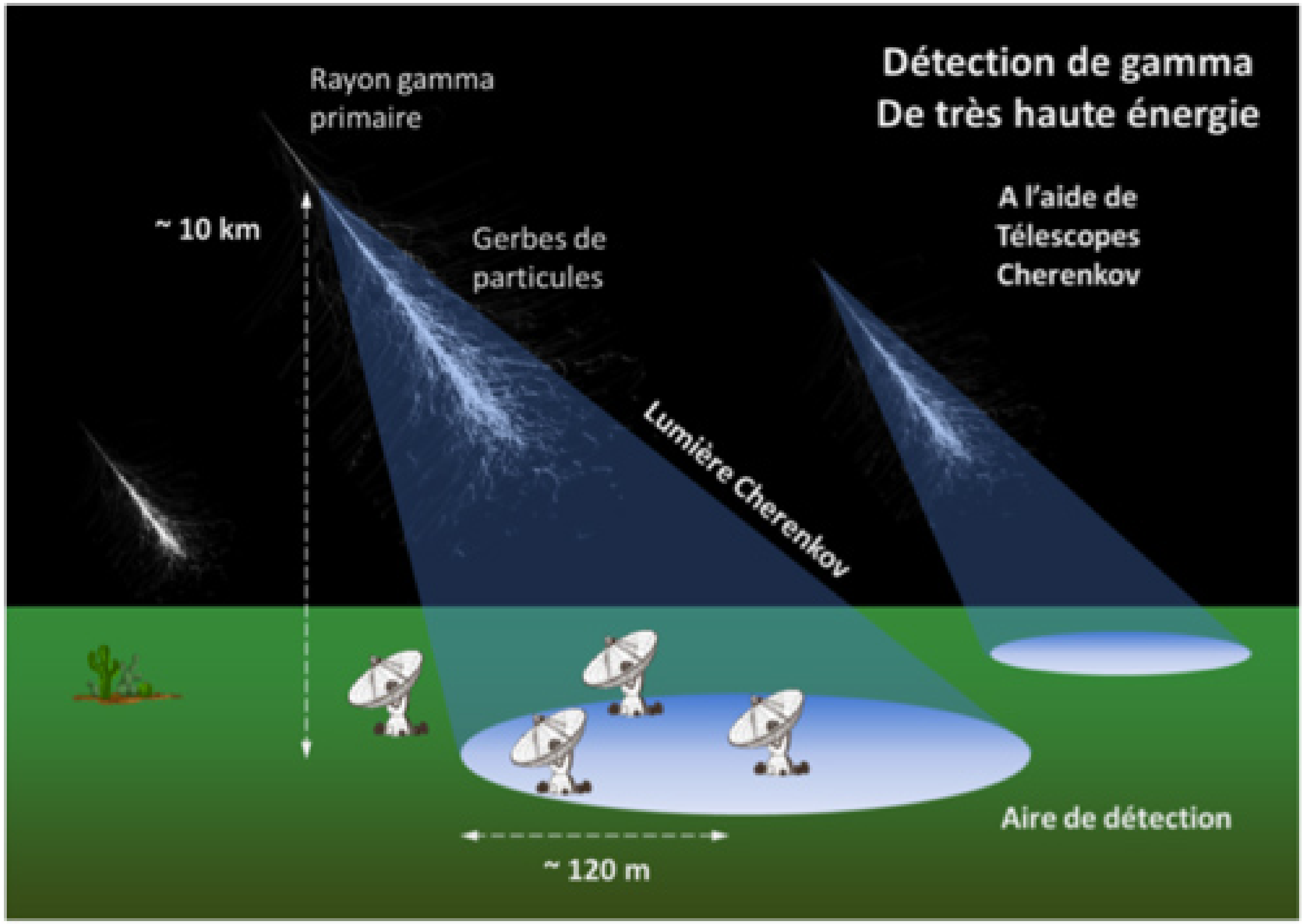


Proton of 100 GeV

—> We detect the Cherenkov light emitted by charged particles

Atmospheric Cherenkov light



The H.E.S.S. experiment

Phase I:

- 4 telescopes since 2003
- 960 PMT/camera
- Fiel of view 5°
- Stereoscopic reconstruction

Phase II:

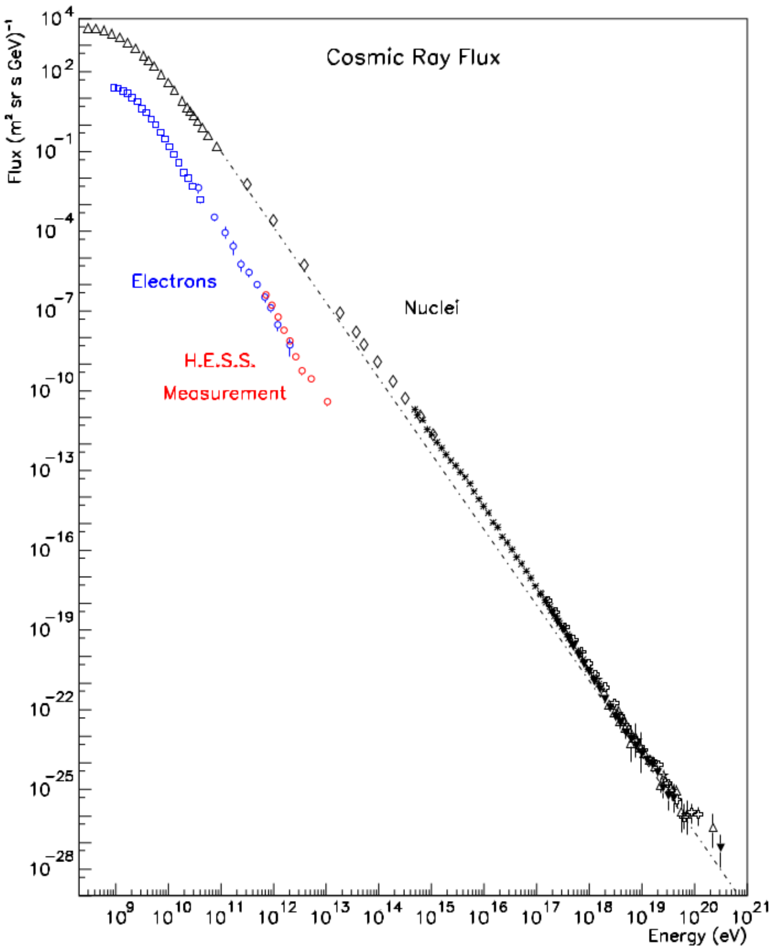
- 5th telescope in 2012
- 2048 PMT
- Field of view of 3,5°
- Monoscopic and stereoscopic reconstruction

Designed for γ-ray detection.

Flux difference between species

We are looking for the contributions of:

- hadrons
- electrons/positrons
- γ



Crédit : K. Egberts

Flux difference between species

We are looking for the contributions of:

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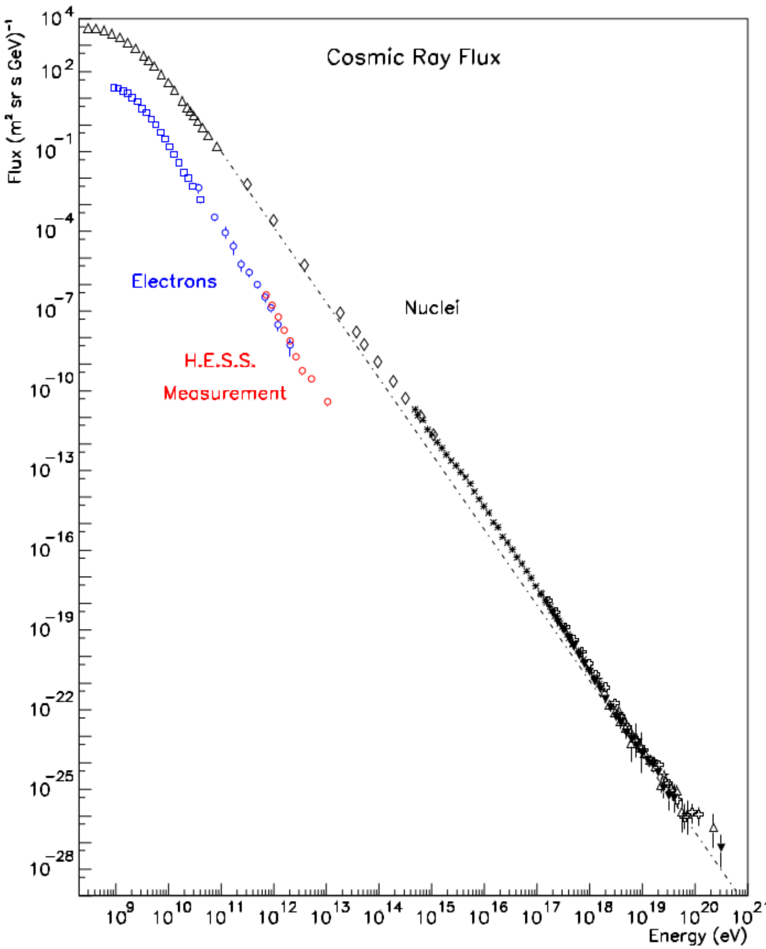
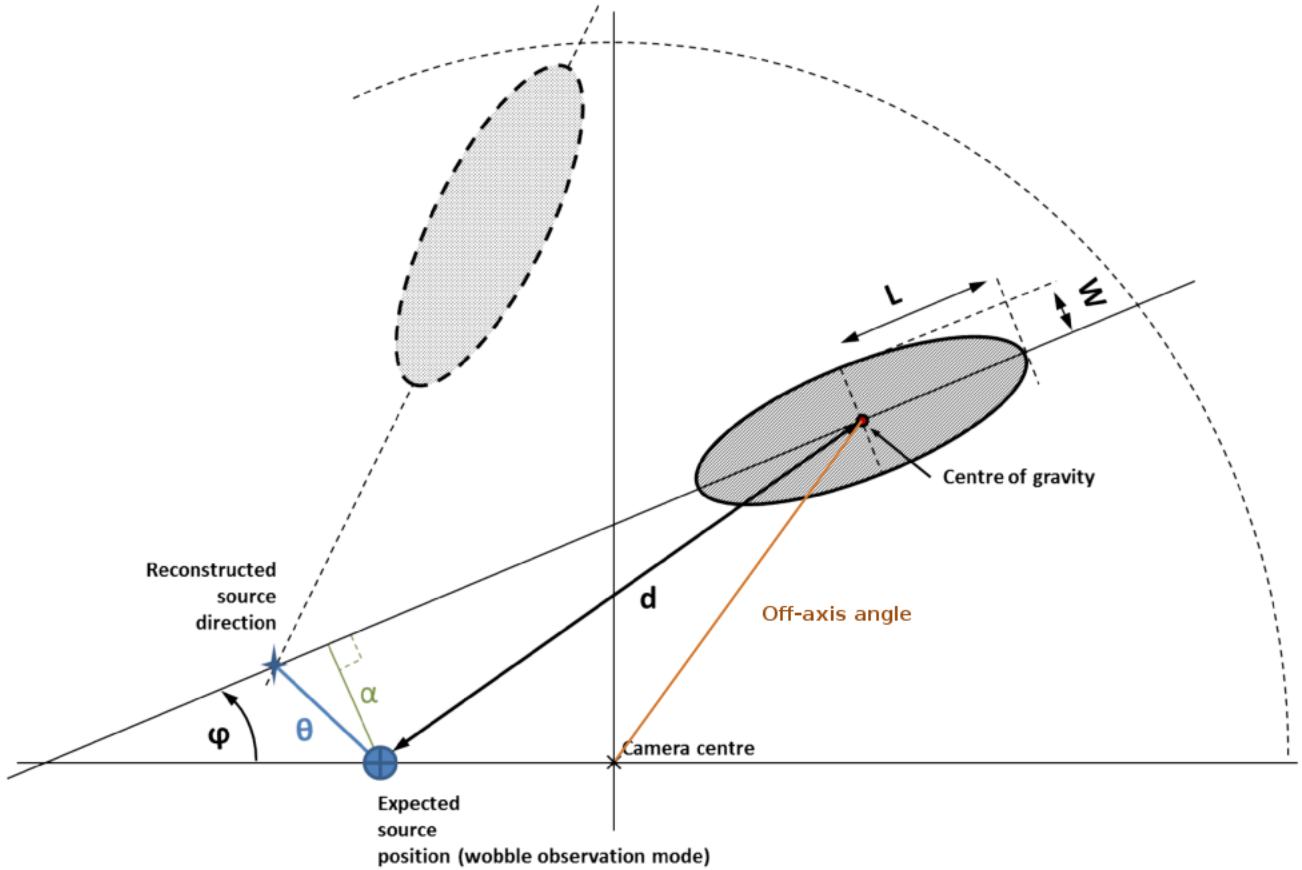
—> The event reconstruction techniques provide discriminating variables :

- the Hillas method
- the semi-analytic method or Model

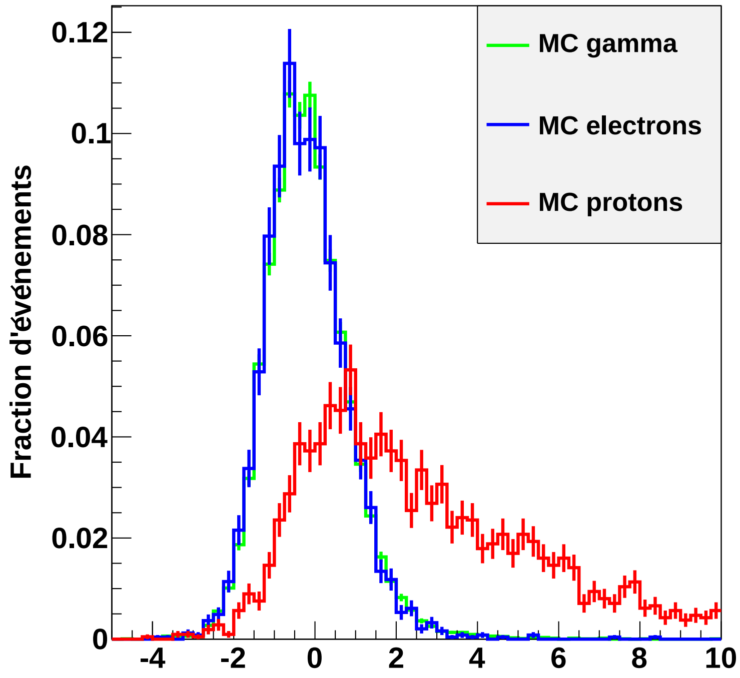


Crédit : K. Egberts

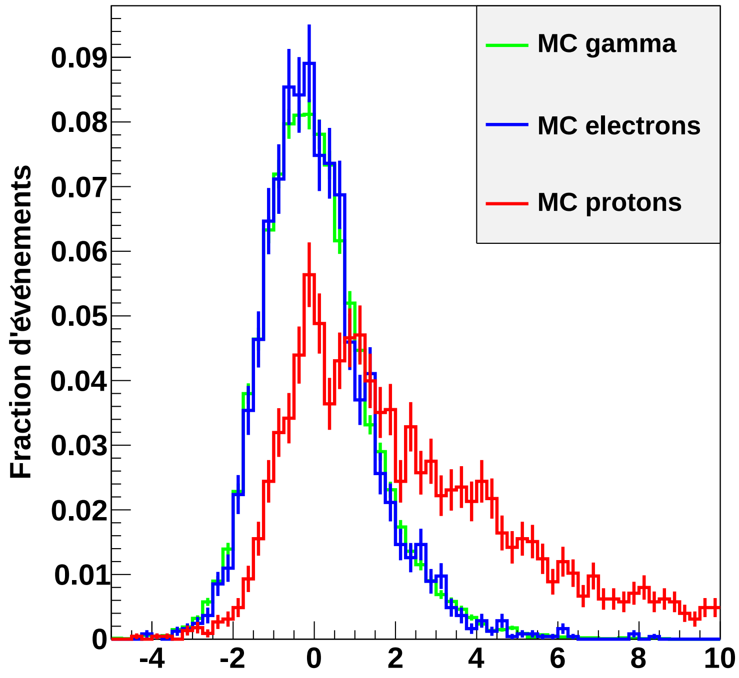
Event reconstruction: Hillas



Event reconstruction: Hillas



Mean Scaled Width (MSW)

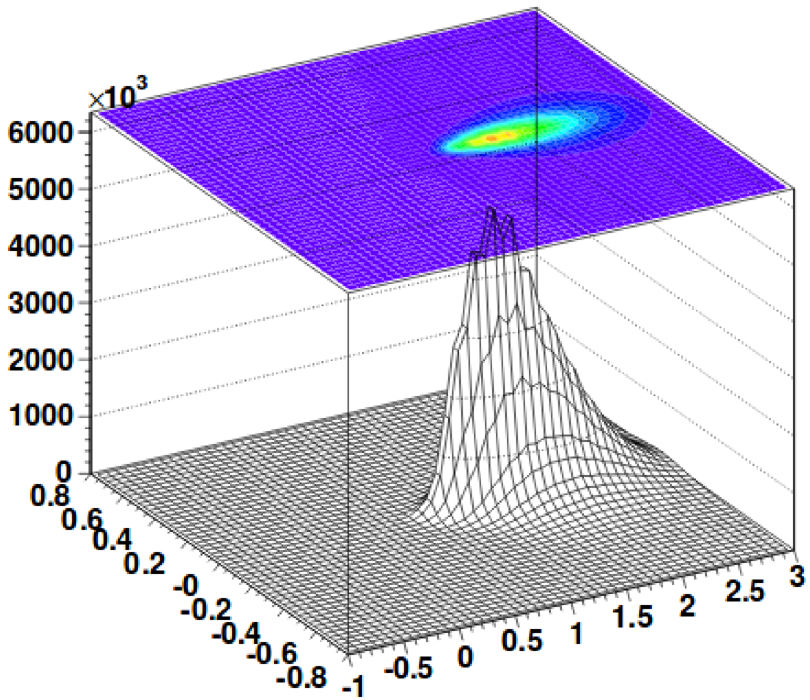


Mean Scaled Length (MSL)

Event reconstruction: Model

The **Model** analysis:

Log-likelihood comparison between recorded images and pre-calculated templates including Night Sky Background



M. de Naurois & L. Rolland, Astropart. Phys., 32 (2009), 231-252

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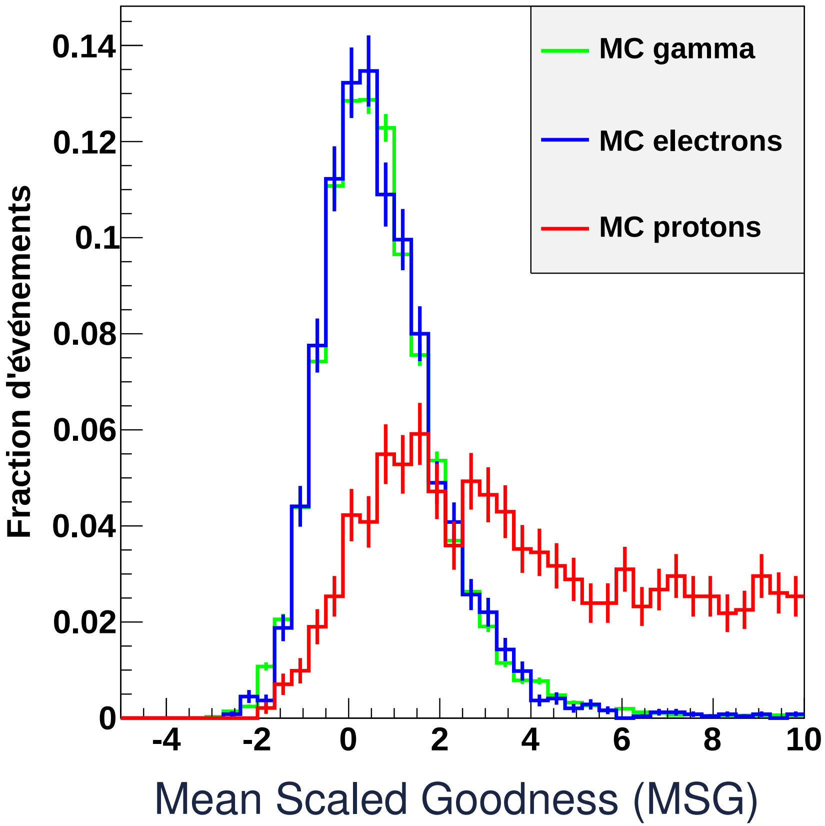

Discrimination strategies

Diffuse signal —> need to remove the γ component!

2 possibilities:

- Using discriminating variables from the event reconstruction method
- Using a suitable observation strategy

Differences between γ-ray and electrons induced showers

- X_0 : radiation length of the electrons
- λ_π : conversion length of the γ-rays

$$X_0 = \frac{7}{9}\lambda_\pi$$

$$X_0 \text{ et } \lambda_\pi \ll \lambda_I$$

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- $X_{\max}$: maximum depth of the shower

$$X_{\max} = \mathrm{A} \ln \frac{E_0}{E_{\mathrm{C}}} + \mathrm{B}$$

with:

- A = 1,0 $\quad$ B_γ = -0,5 $\quad$ B_{electron} = -1,0 (B. Rossi, High Energy Particles, 1952)
- A = 1,0 $\quad$ B_γ = -0,3 $\quad$ B_{electron} = -1,1 (U. Amaldi, Phys. Scripta 23, 409, 1981)

$$\Delta B \in [0,5\ ;\ 0,8] \times X_0$$

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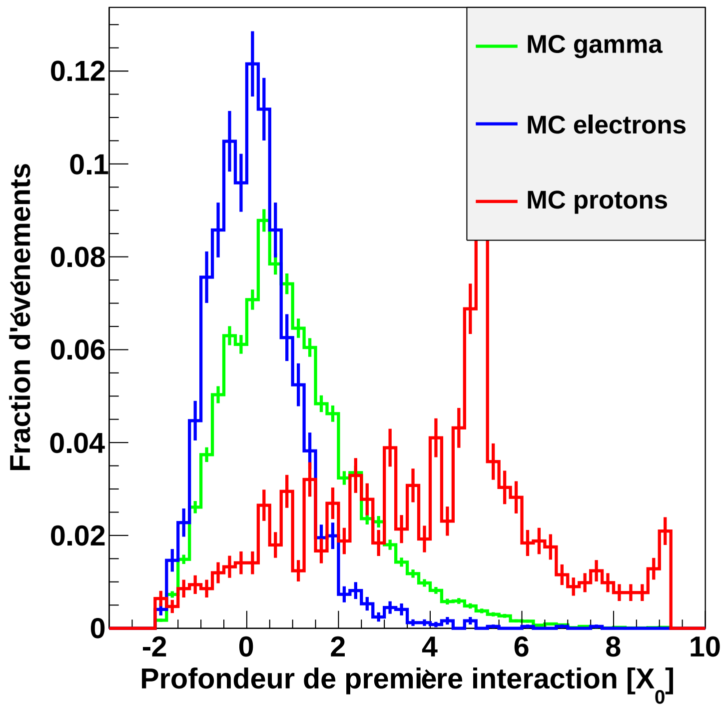
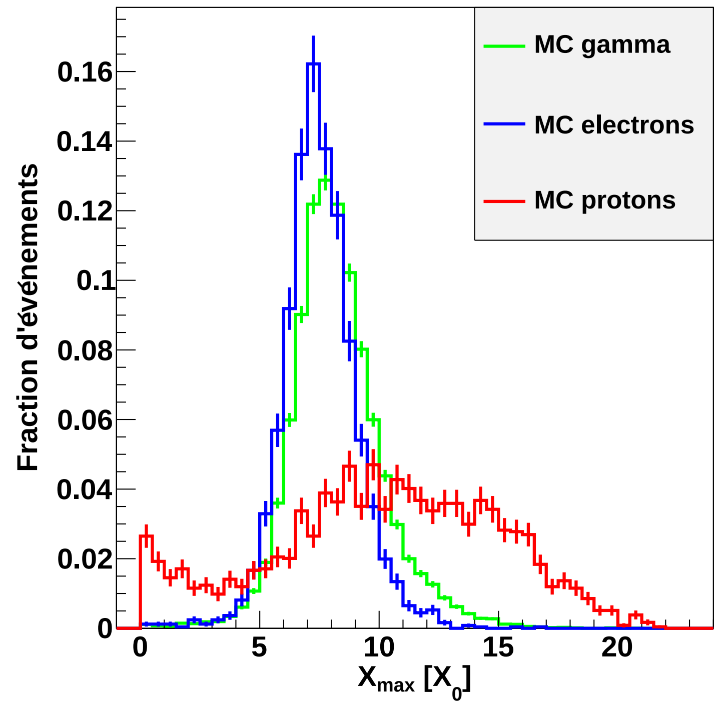
- Direct Cherenkov light

Discriminating variables: Primary depth and Maximum depth



Primary depth (PDH)



Maximum depth (MDH)

Discriminating between particles: summary

- Excellent γ/hadrons discrimination with 2 methodes (Hillas and Model)
- Better discrimination with Model
- 2 variables (PDH and MDH) exhibit a small discriminating power between γ and electrons
- Direct Cherenkov light from electrons not detected to date with H.E.S.S.

—> γ/electron separation from a suitable observation strategy

Standard H.E.S.S. observations

Limited fiel of view of 5° with H.E.S.S.

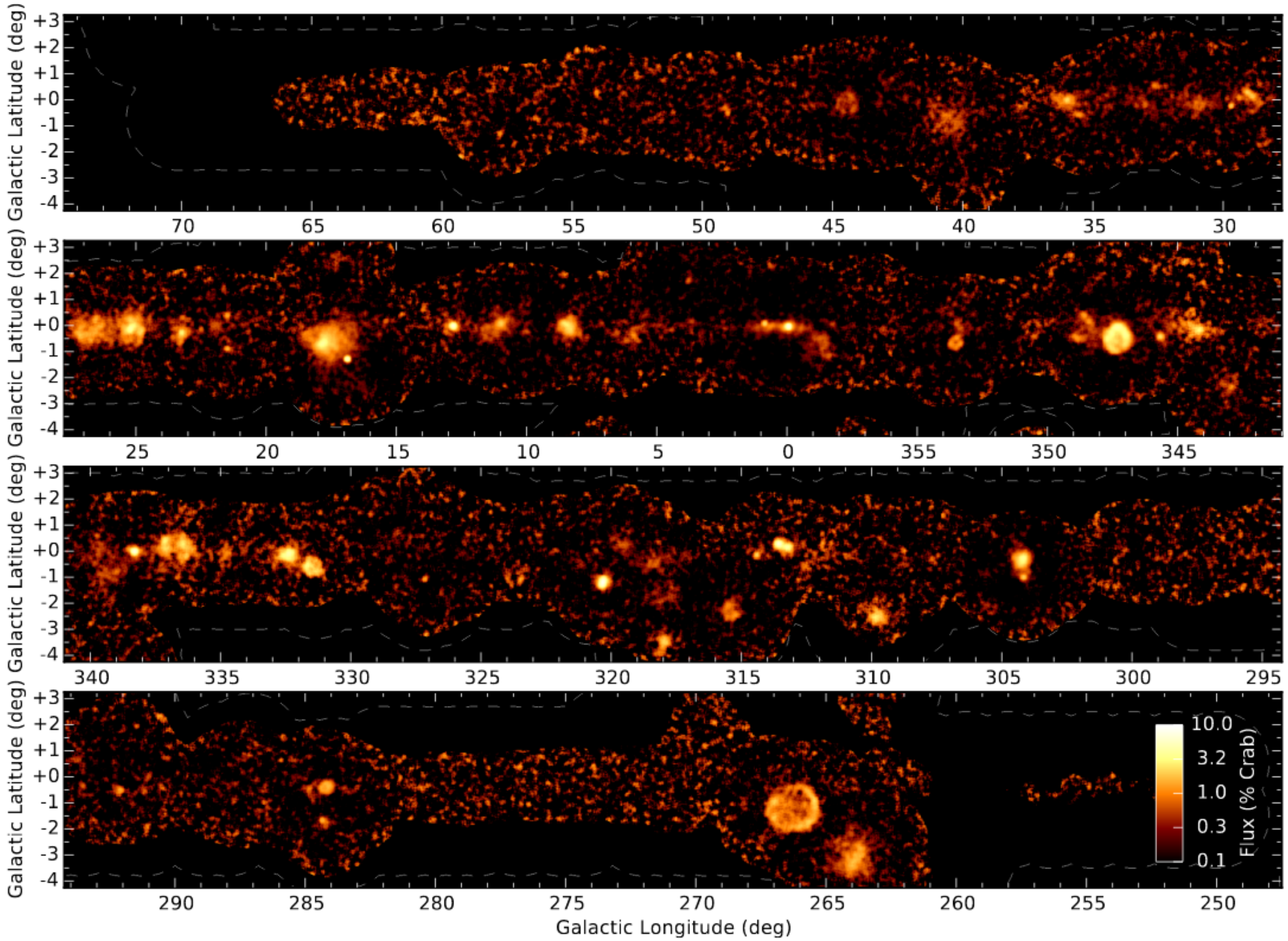
Two major center of interest of H.E.S.S.:

- galactic sources

  —> mostly in the Galactic plane

- extragalactic sources

The Galactic plane with H.E.S.S.



R. D. Parsons et al. (ICRC 2017)

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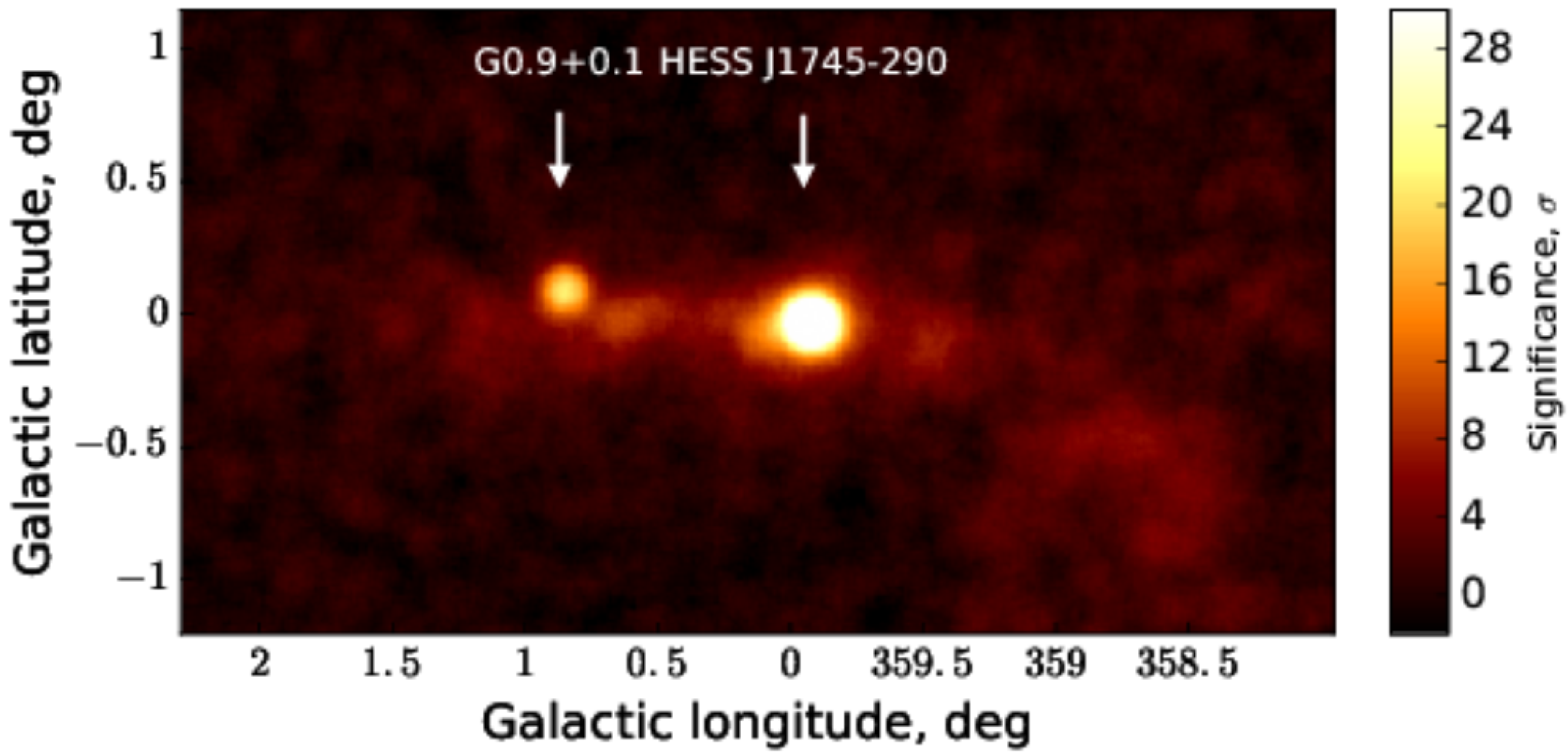

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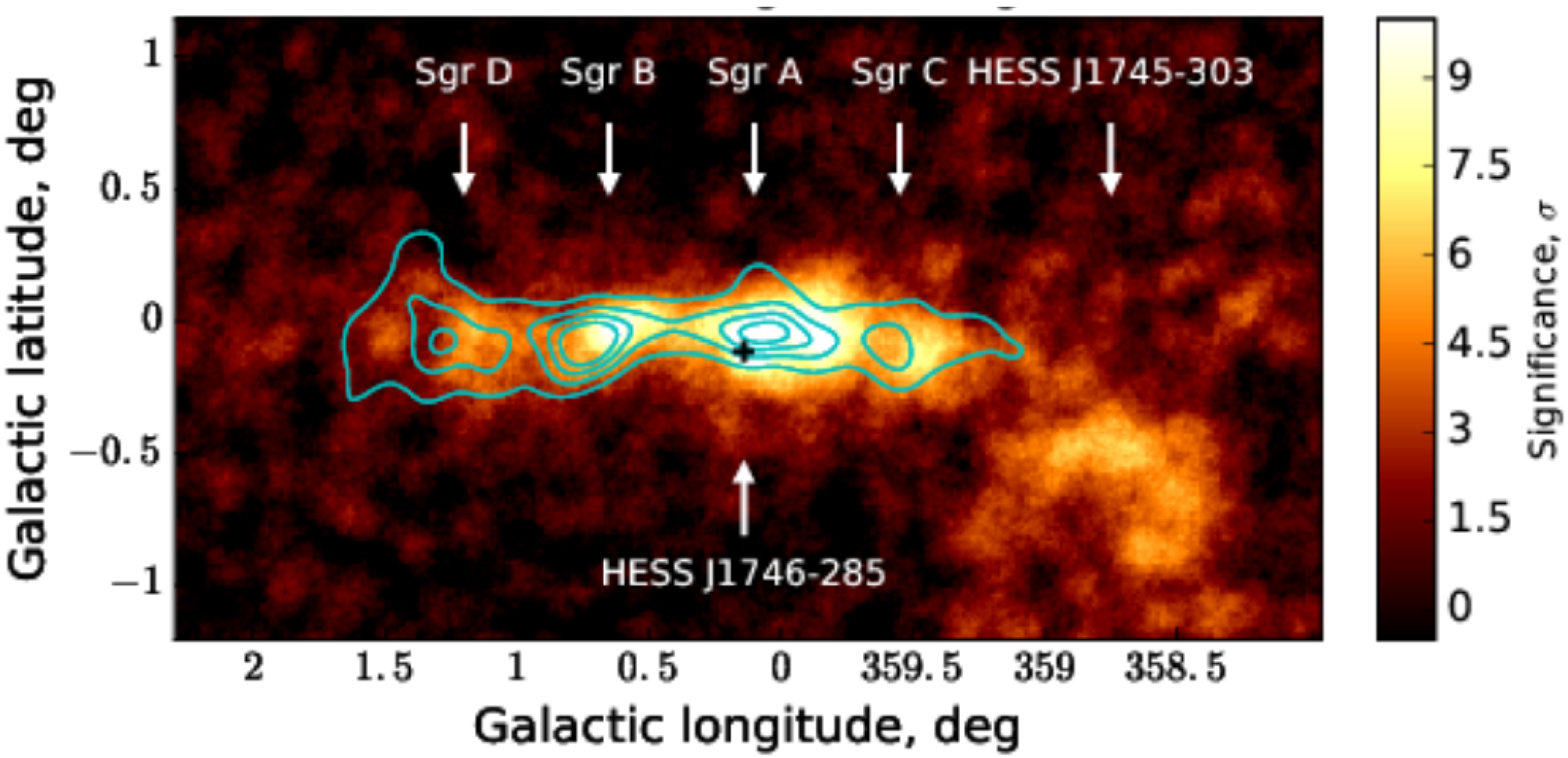

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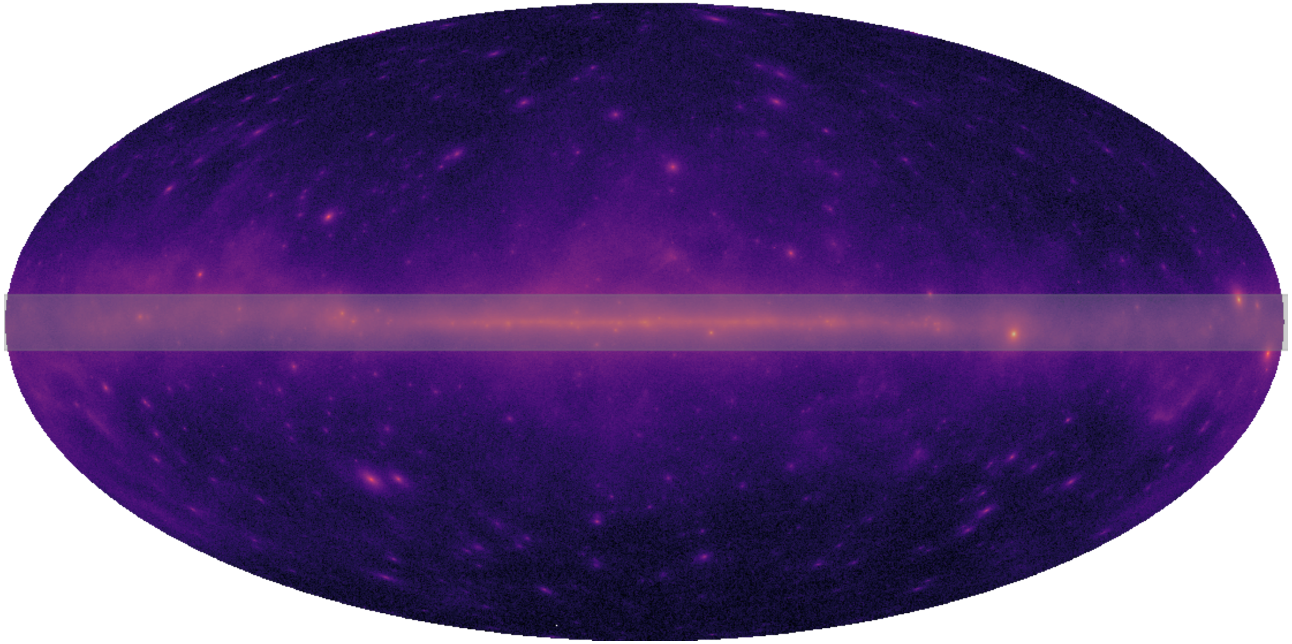
Data selection: exclusion of the Galactic plane

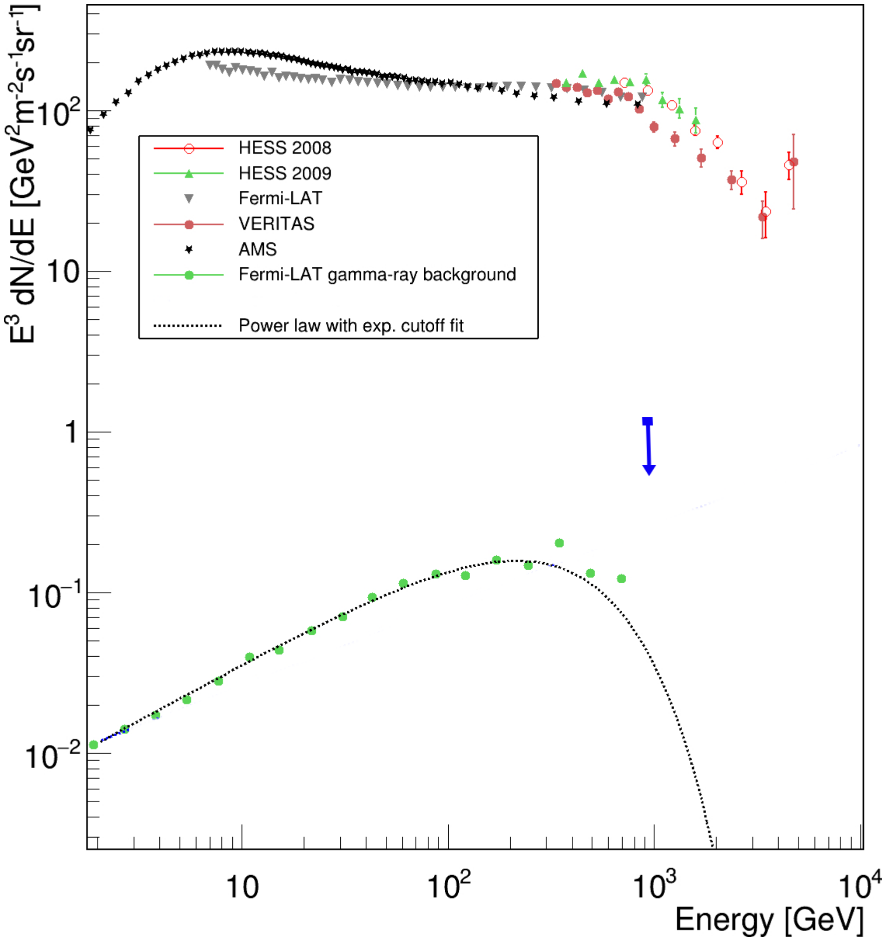


Extragalactic diffuse emission of γ-ray

Upper limit at 1 TeV in blue on the figure:

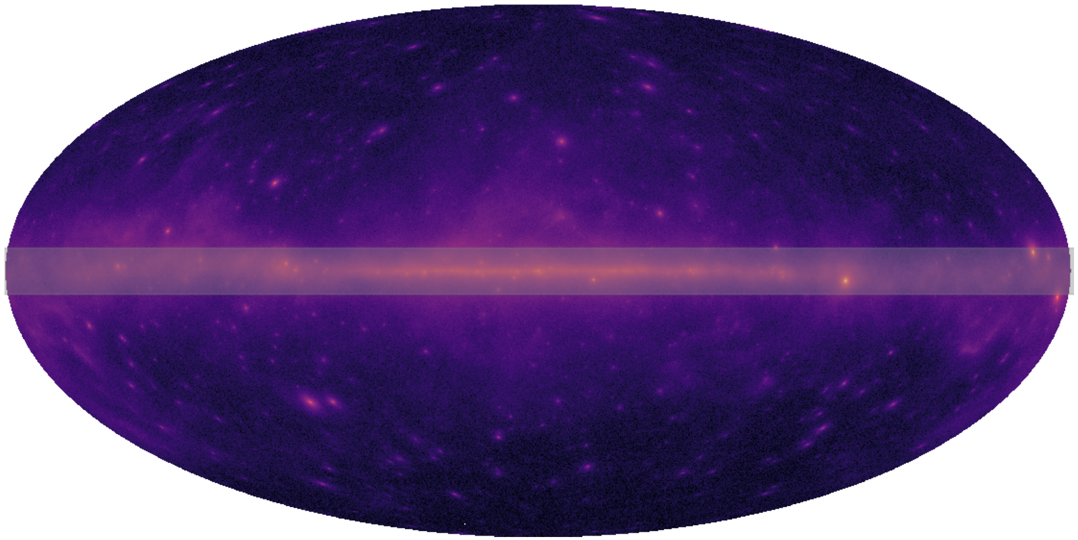
$1,09 \pm 0,05\ \mathrm{GeV}^2 \cdot \mathrm{m}^{-2} \cdot \mathrm{sr}^{-1} \cdot \mathrm{s}^{-1}$

(value from T. Garrigoux PhD thesis)



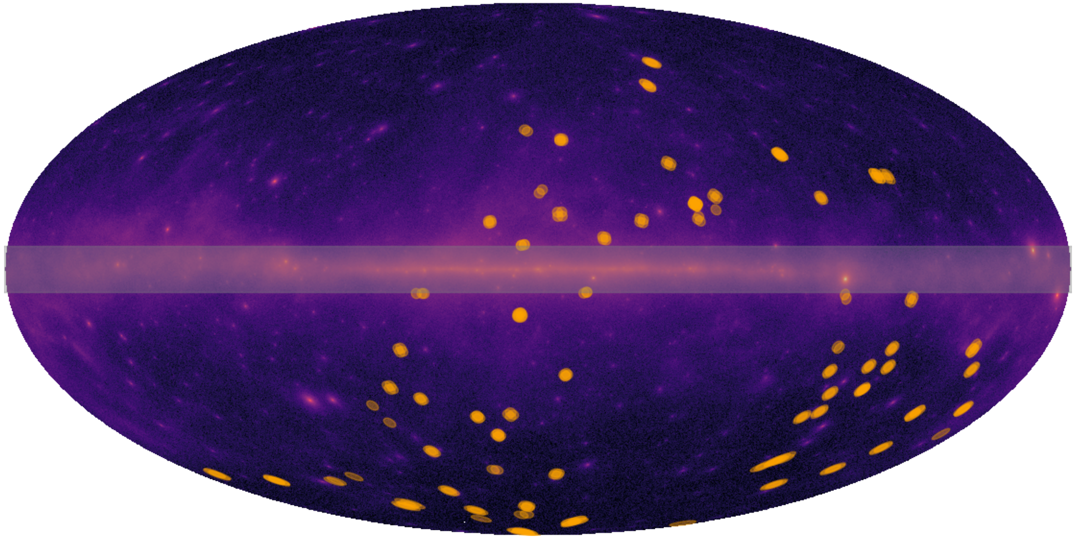
Crédit : D. Kolitzus

Data selection



- Pointing position is **more than 7 degrees** away from the Galactic plane
- H.E.S.S. I runs with **4 telescopes** operational
- Mean zenithal angle < **28°**

Data selection



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—> Final dataset consists in 2742 runs for a total livetime of $\sim$ **1186 hours**.

—> Total number of events: 460 346 321.

Analysis cuts

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- **Standard** cut from the Model analysis:
  - -1 < Primary depth < 4

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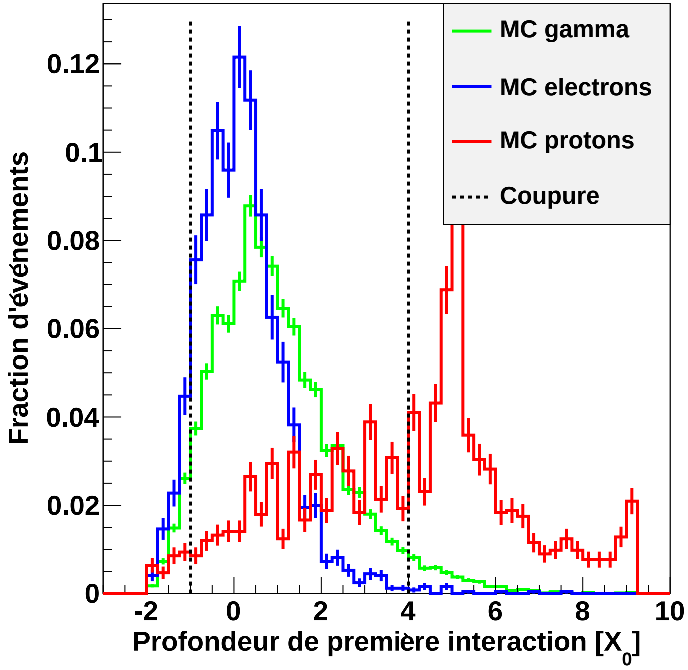

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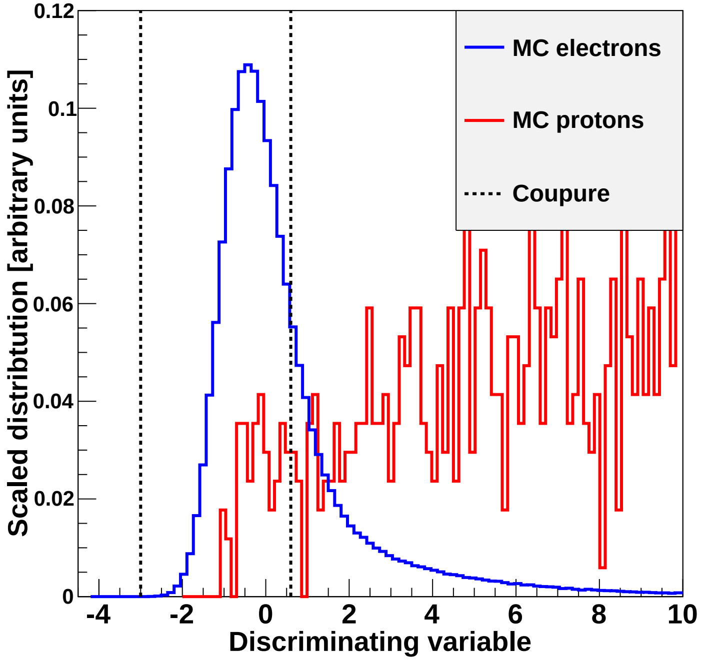

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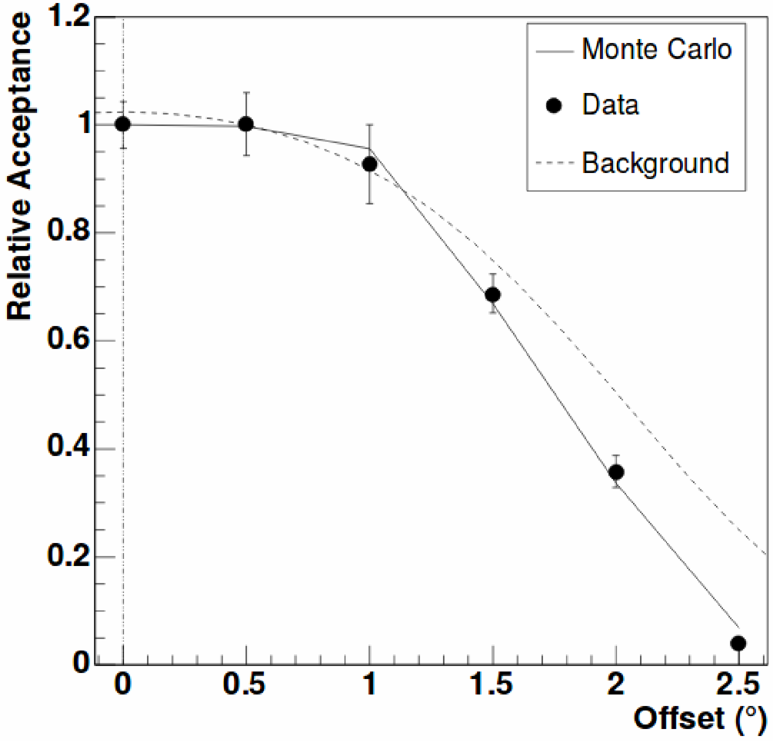

F. Aharonian et al., A& A 457 (2006) 899–915

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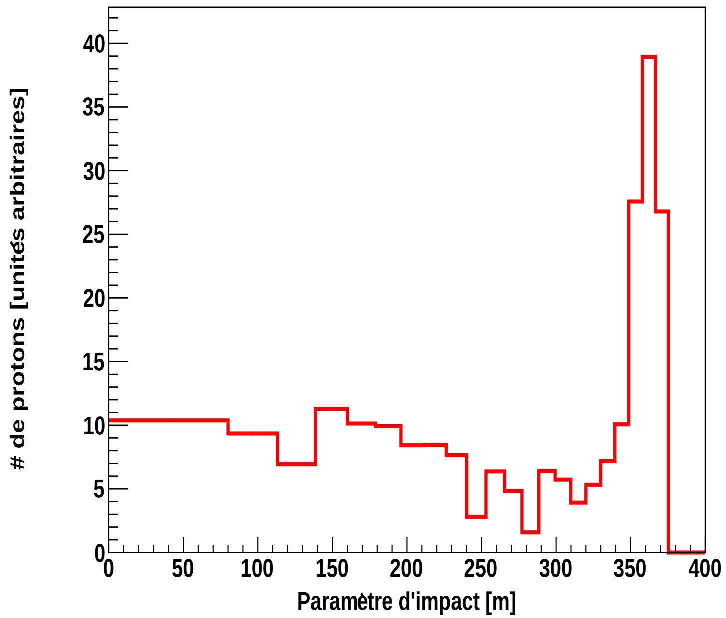
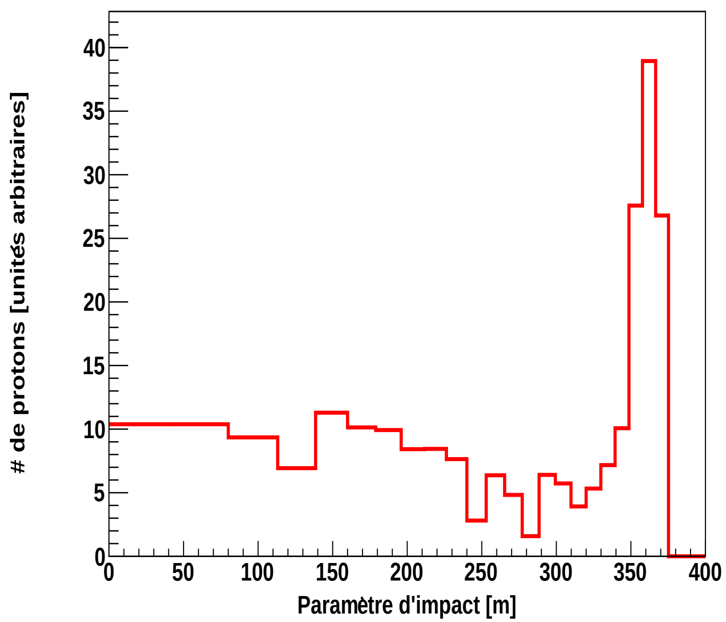
  - Impact parameter < 150 m

Impact parameter cut



Energy < 4 TeV

Impact parameter cut



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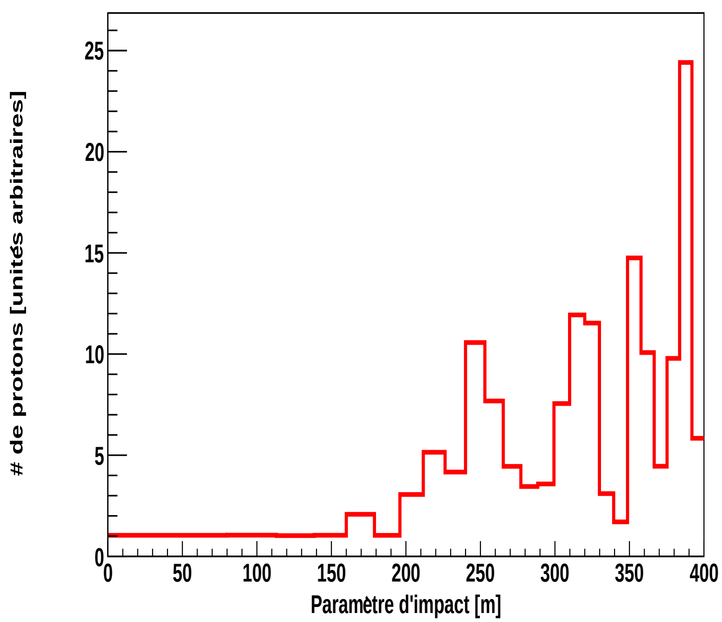
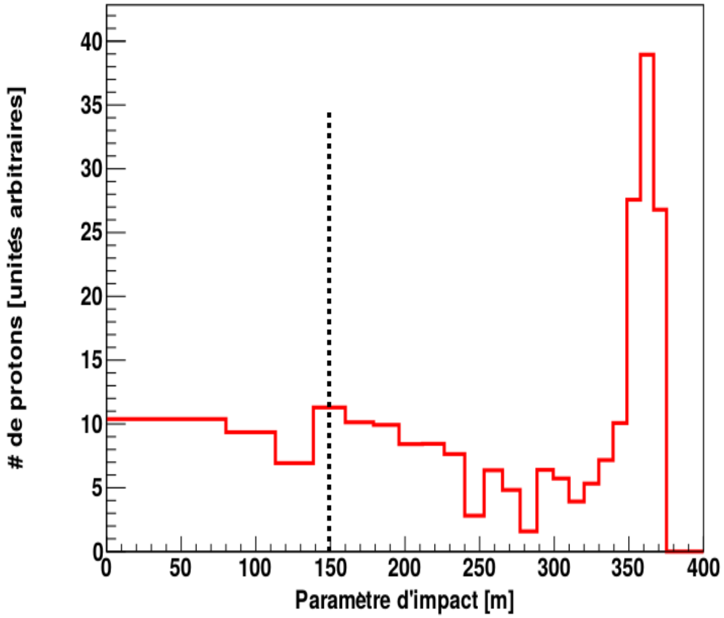
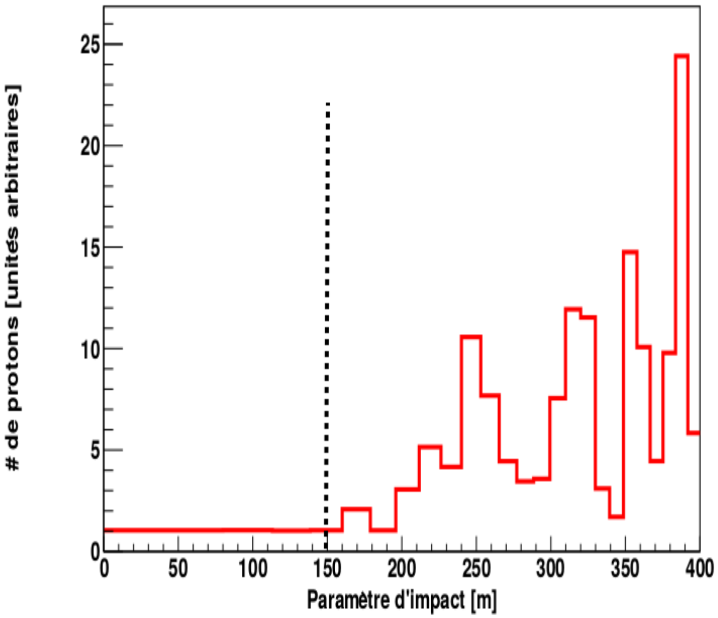


Energy > 4 TeV

Impact parameter cut





Energy < 4 TeV

Energy > 4 TeV

Cut: impact parameter < 150 m

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  - -1 < Primary depth < 4
  - -3 < Mean Scaled Shower Goodness < 0.6
- Additional cuts :
  - 0° < Off-axis angle < 1,5°
  - Impact parameter < 150 m
  - Number of triggering telescopes = 4

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  - $\theta^2 > 0,16$ deg^2

Number of events after all cuts : 480 739

Flux calculation

Flux in a bin $[E_{\mathrm{min}}\ ;\ E_{\mathrm{max}}]$ in energy :

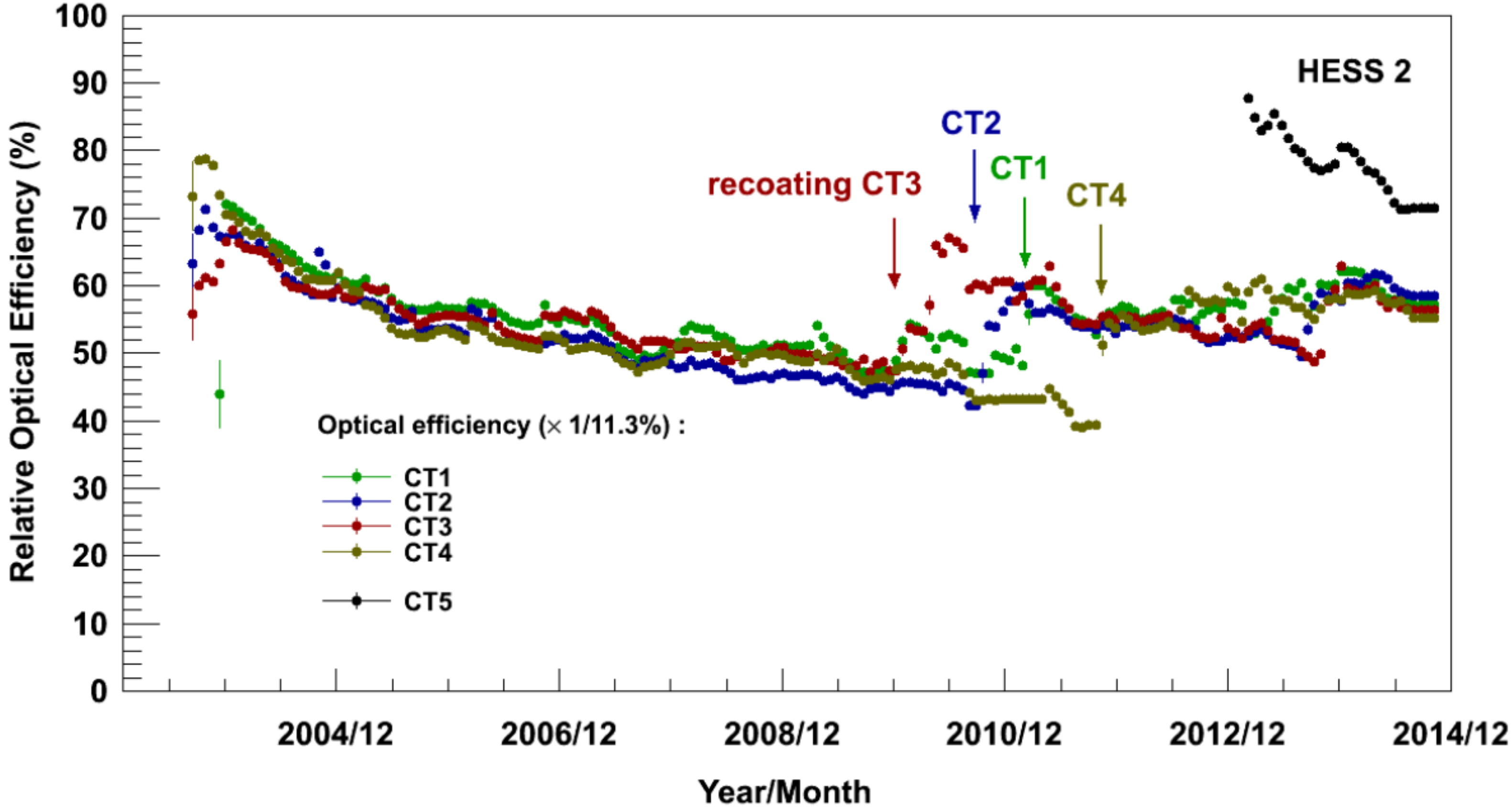
$$[\Phi] = \mathrm{Energy}^{-1} \cdot \mathrm{Time}^{-1} \cdot \mathrm{Distance}^{-2} \cdot \mathrm{Solid\ angle}^{-1}$$

$$\Phi(E_{\mathrm{min}}, E_{\mathrm{max}}) = \frac{N(E_{\mathrm{min}}, E_{\mathrm{max}})}{(E_{\mathrm{max}} - E_{\mathrm{min}}) \times T_{\mathrm{obs}} \times \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} A(E, \delta; \theta, \varepsilon) \times \mathrm{P}(E, \tilde{E}; \varepsilon)\, \mathrm{d}E}$$

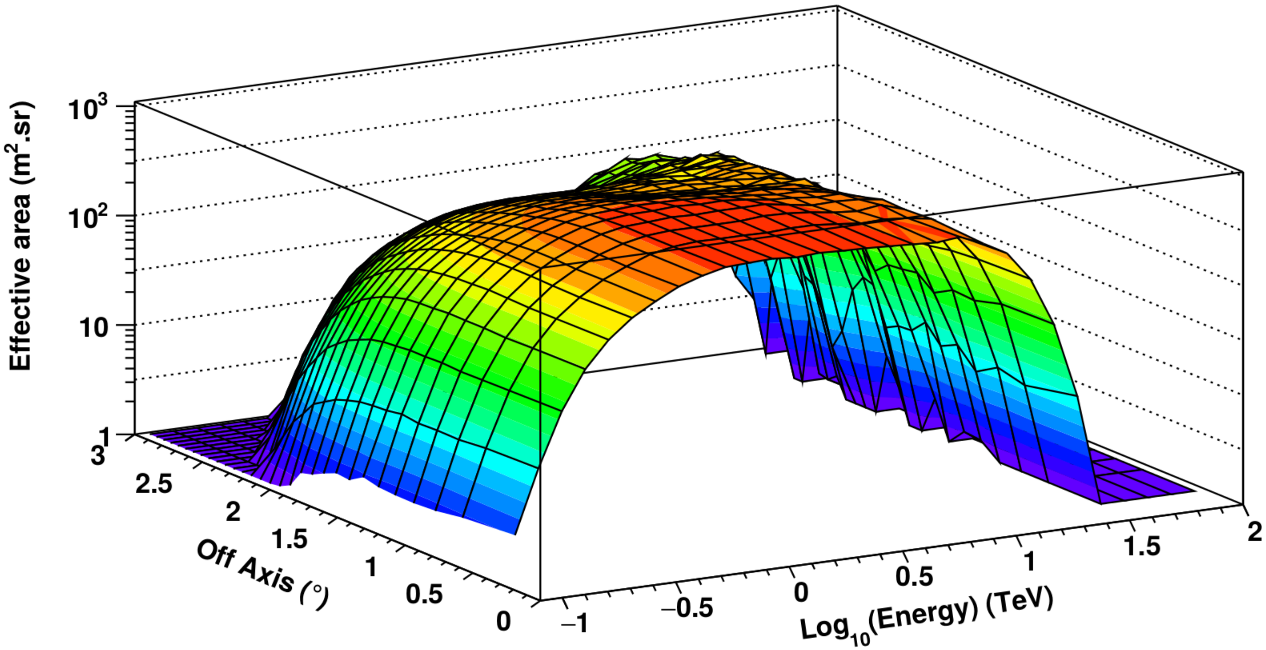
where:

- $N(E_{\mathrm{min}}, E_{\mathrm{max}})$ is the number of events in the bin $[E_{\mathrm{min}}\ ;\ E_{\mathrm{max}}]$
- T_{obs} is the observation time (corrected from the deadtime)
- $A(E, \delta; \theta, \varepsilon)$ is the effective area (in m^2 .sr)
- $P(E, \tilde{E}; \varepsilon)$ is a probability to determine E (true E) from $\tilde{E}$ (reconstruct E)

Evolution of the H.E.S.S. optical efficiency



Effective areas



The effective areas are computed for given configuration :

- zenithal angle θ = 0°, 18°, 26°, 32° et 46°
- relative optical efficiency ε = 40%, 50%, 60%, 70%, 80%, 90%, 100%

Tests of the analysis chain

First, tests de la chaîne d'analyse:

- on Monte-Carlo simulations
- on the data of a known source, here PKS2155-304

Once the tests are valid:

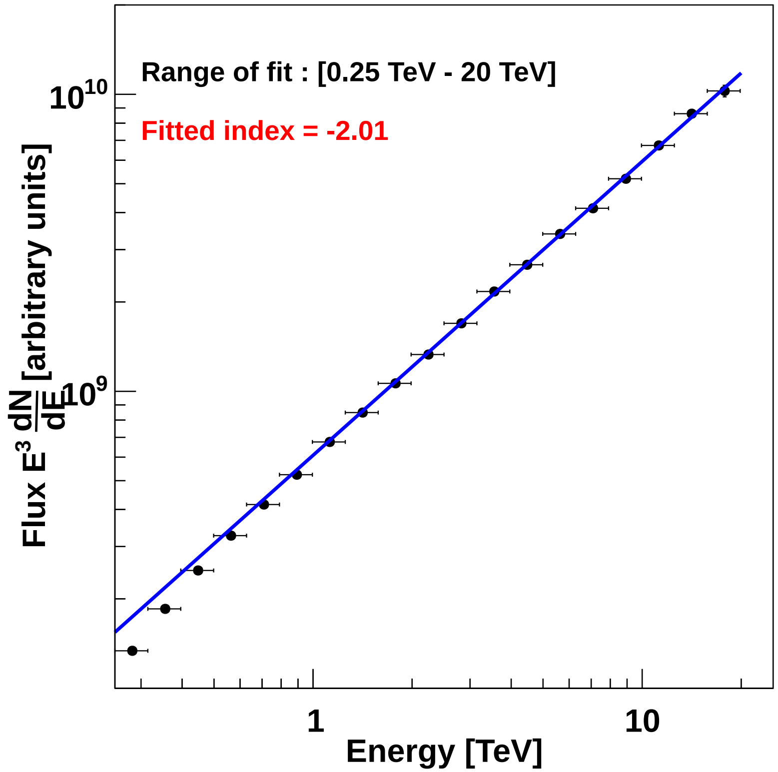
—> Application to the data

Validation of the analysis chain on simulations

With MC simulations of diffuse electrons.

Injected spectral index = -2.

Standard analysis cuts.



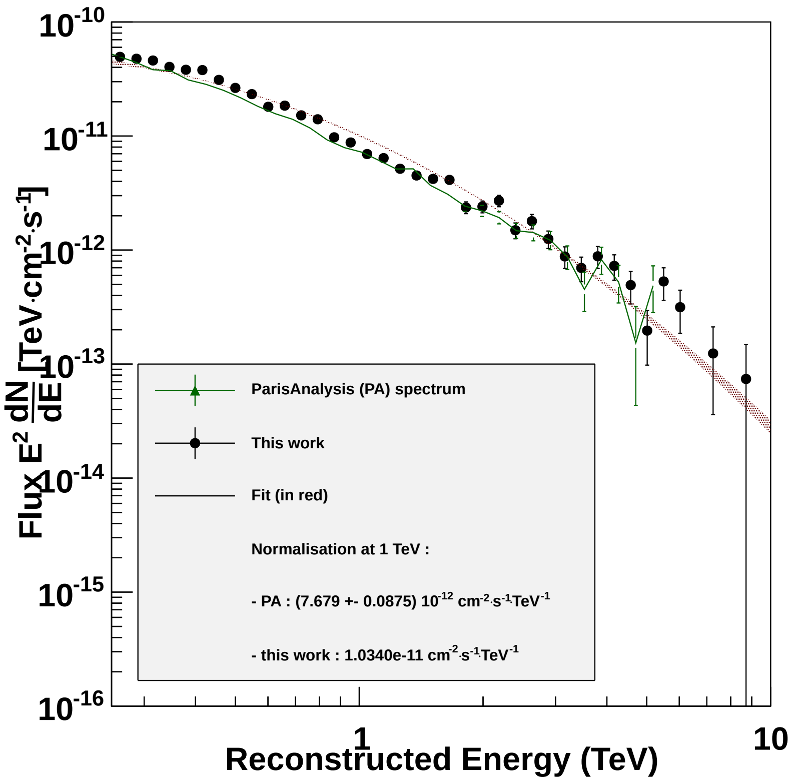
Simulations

Validation of the analysis chain on data

Test on a known source: PKS2155-304.

Change for effective areas computed for point-like γ.

Comparison with the result of the "regular" analysis chain.



Real data

Estimated background contamination

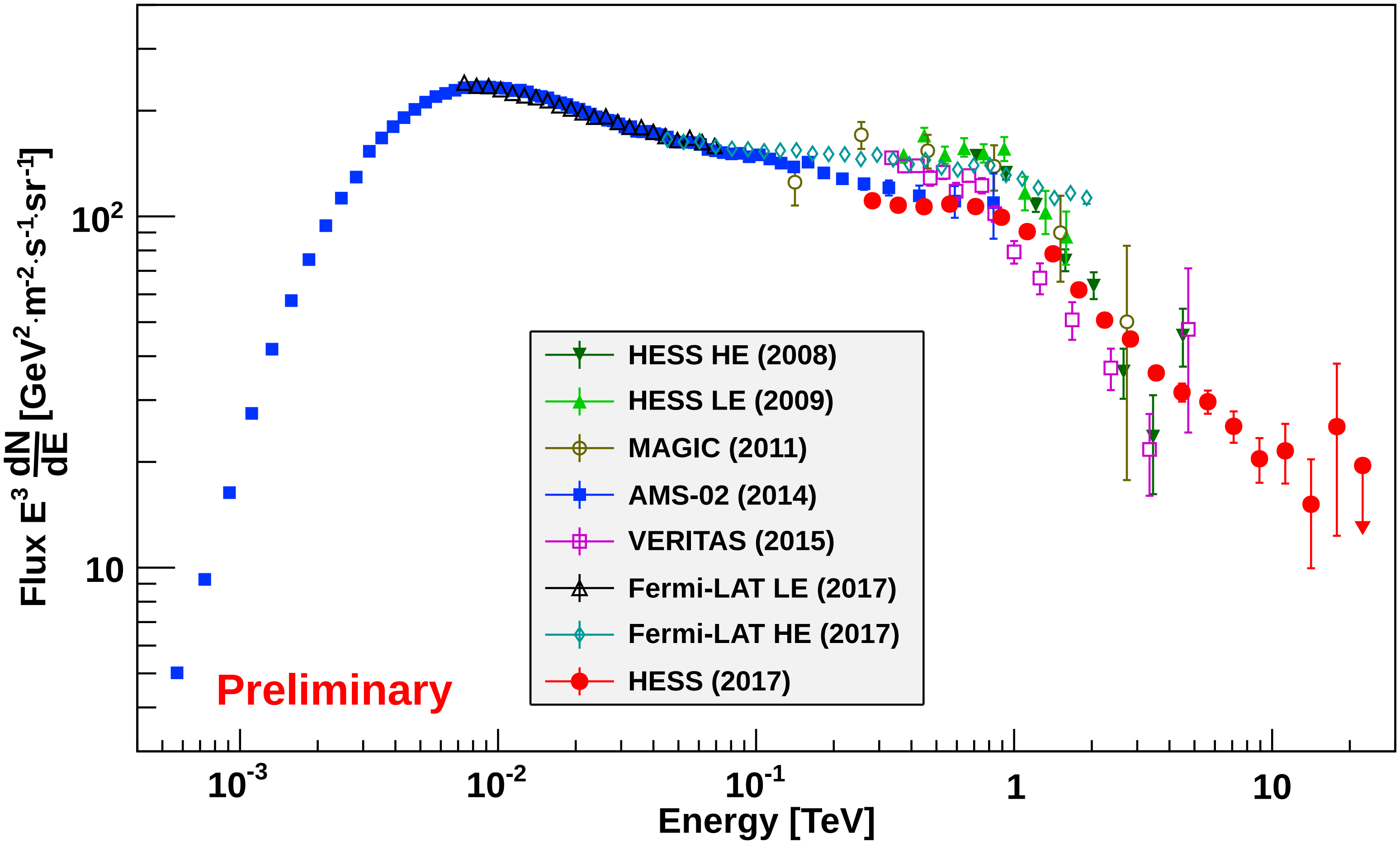
Preliminary estimation of proton contamination with MC simulations (knowing the actual measured fluxes of electrons and protons):

Energy	Expected contamination from protons
1 TeV	$\sim 15\%$
2 TeV	$\sim 7\%$
$>$ 5 TeV	$< 10\%$

Energy range of the analysis : **[0.25 TeV; 25 TeV]**

Total number of electron-like detected events : **480 739**

New H.E.S.S. cosmic ray electron+positron spectrum



Fitting of the spectrum

Fit function is a smooth broken power law:

$$E^3\ \frac{\mathrm{d}N}{\mathrm{d}E} = N_0\left(\frac{E}{(1\ \mathrm{TeV})}\right)^{3-\Gamma_1}\left(1+\left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right)^{-(\Gamma_2-\Gamma_1)\alpha}$$

Result of the fit :

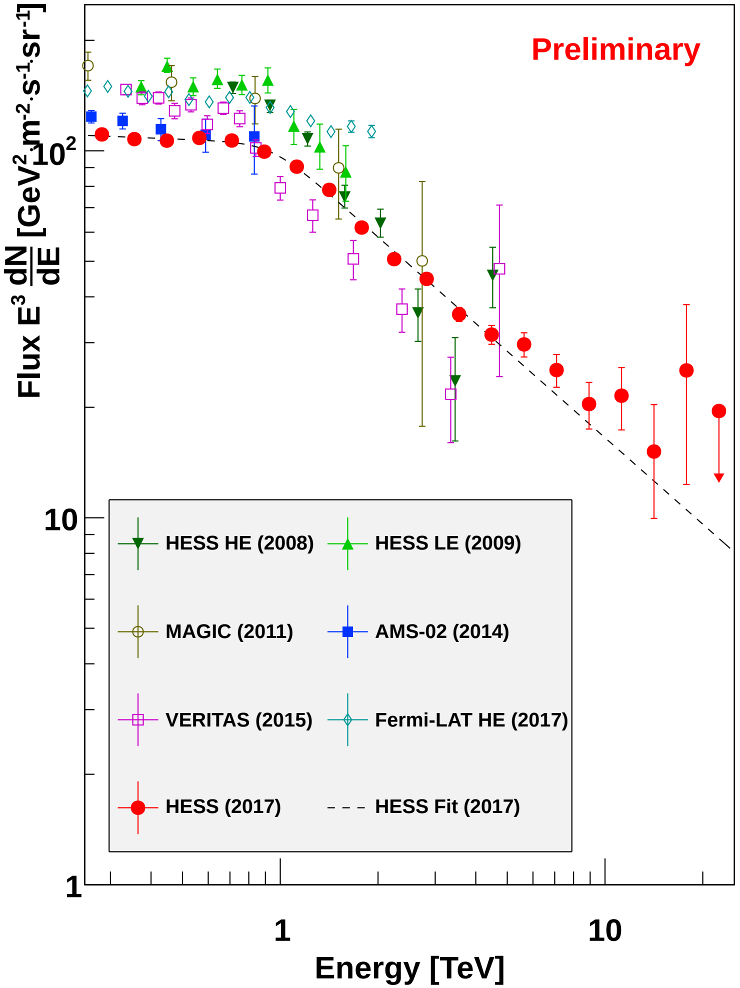
$\Gamma_1 = 3.04 \pm 0.01$ (stat)

$\Gamma_2 = 3.78 \pm 0.02$ (stat)

$E_b = 0.94 \pm 0.02$ (stat) TeV

$N_0 = 104.9 \pm 0.6$ (stat) $\mathrm{GeV}^2 \cdot \mathrm{m}^{-2} \cdot \mathrm{sr}^{-1} \cdot \mathrm{s}^{-1}$

$\alpha = 0.12 \pm 0.01$ (stat)



Systematic errors

The study of systematic errors included:

- Tests on all the analysis cuts:
  - *Mean Scaled Shower Goodness*
  - impact parameter
  - primary depth
  - off-axis angle
- Dependency on the zenithal angle
- Dependency over the years
- Dependancy on the atmospheric conditions

Systematic errors: preliminary results

	$\Gamma_1 = 3,04$	$\Gamma_2 = 3,78$	$E_b = 0,94$ [TeV]	$N_0 = 104,9$ [$GeV^2.m^{-2}.sr^{-1}.s^{-1}$]
MSSG	$^{+0,01}_{-0,01}$	$^{+0,06}_{-0,04}$	$^{+0,02}_{-0,01}$	$^{+12,0}_{-7,1}$
Impact parameter	$^{+0,04}_{-0,07}$	$^{+0,03}_{-0,01}$	$^{+0,19}_{-0,24}$	$^{+18,5}_{-4,1}$
Primary depth	$^{+0,04}_{-0,11}$	$^{+0,03}_{-0,01}$	$^{+0,03}_{-0,04}$	$^{+1,1}_{-3,5}$
Off-axis angle	$^{+0,05}_{-0,01}$	$^{+0,08}_{-0,02}$	$^{+0,11}_{-0,01}$	$^{+14,5}_{-4,4}$
Zenithal angle	$^{+0,06}_{-0,00}$	$^{+0,05}_{-0,00}$	$^{+0,10}_{-0,00}$	$^{+0.0}_{-11,8}$
Annual effect	$^{+0,04}_{-0,13}$	$^{+0,12}_{-0,03}$	$^{+0,16}_{-0,07}$	$^{+5,5}_{-3,6}$
Seasonal effect	$^{+0,00}_{-0,01}$	$^{+0,02}_{-0,02}$	$^{+0,02}_{-0,04}$	$^{+1,3}_{-0,3}$

Systematic errors: preliminary results

	$\Gamma_1 = 3,04$	$\Gamma_2 = 3,78$	$E_b = 0,94$ [TeV]	$N_0 = 104,9$ [$GeV^2.m^{-2}.sr^{-1}.s^{-1}$]
MSSG	$+0{,}01$ $-0{,}01$	$+0{,}06$ $-0{,}04$	$+0{,}02$ $-0{,}01$	$+12{,}0$ $-7{,}1$
Impact parameter	$+0{,}04$ $-0{,}07$	$+0{,}03$ $-0{,}01$	$+0{,}19$ $-0{,}24$	$+18{,}5$ $-4{,}1$
Primary depth	$+0{,}04$ $-0{,}11$	$+0{,}03$ $-0{,}01$	$+0{,}03$ $-0{,}04$	$+1{,}1$ $-3{,}5$
Off-axis angle	$+0{,}05$ $-0{,}01$	$+0{,}08$ $-0{,}02$	$+0{,}11$ $-0{,}01$	$+14{,}5$ $-4{,}4$
Zenithal angle	$+0{,}06$ $-0{,}00$	$+0{,}05$ $-0{,}00$	$+0{,}10$ $-0{,}00$	$+0.0$ $-11{,}8$
Annual effect	$+0{,}04$ $-0{,}13$	$+0{,}12$ $-0{,}03$	$+0{,}16$ $-0{,}07$	$+5{,}5$ $-3{,}6$
Seasonal effect	$+0{,}00$ $-0{,}01$	$+0{,}02$ $-0{,}02$	$+0{,}02$ $-0{,}04$	$+1{,}3$ $-0{,}3$
Total	$+0{,}10$ $-0{,}18$	$+0{,}17$ $-0{,}06$	$+0{,}29$ $-0{,}26$	$+27{,}0$ $-15{,}8$

Conservative approach: the total systematic error is the quadratic sum of the errors for each "effect".

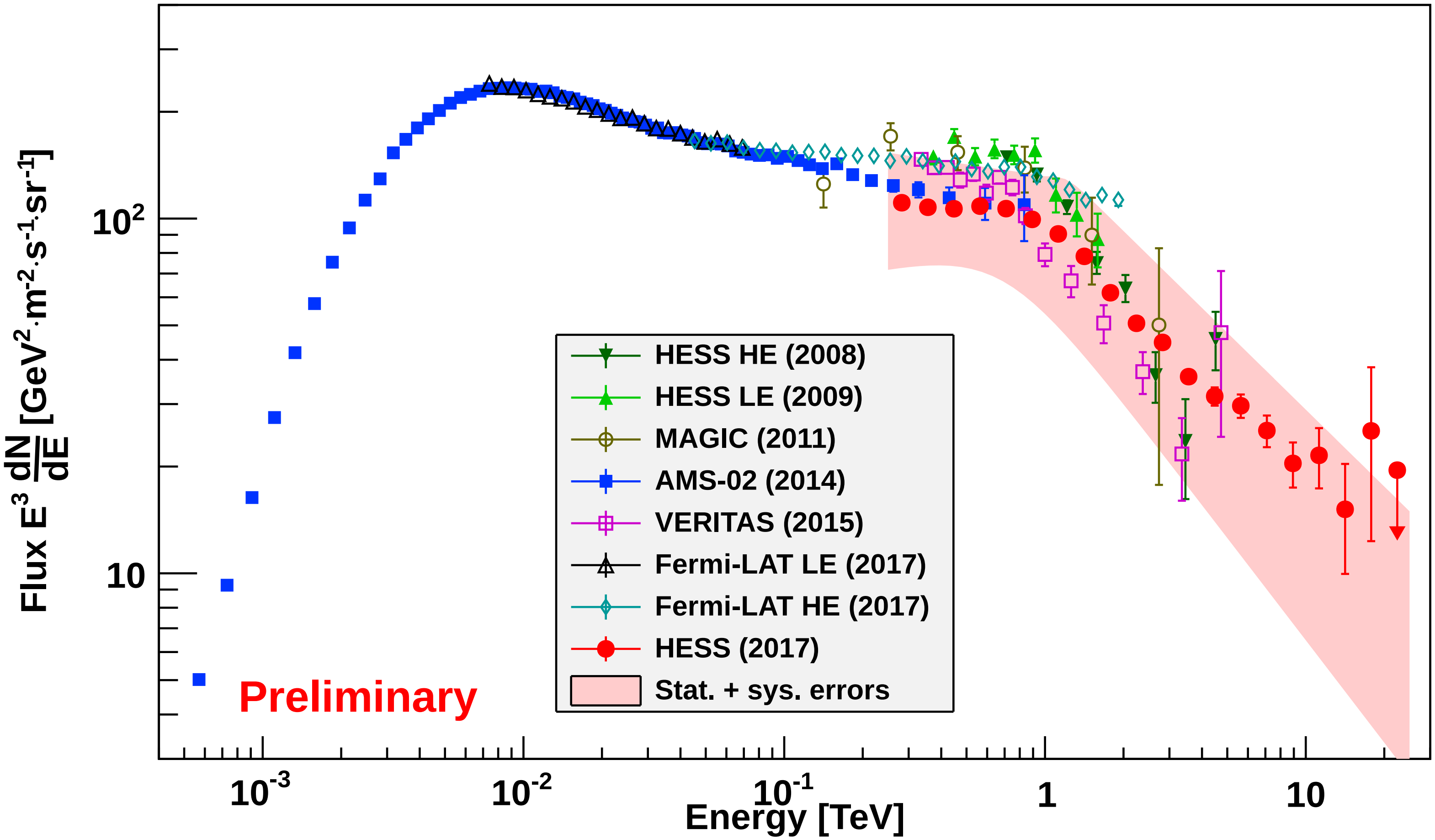
Systematic errors: results

$$\begin{aligned}
\Gamma_1 &= 3,04 \pm 0,01 \text{ (stat) } {}^{+0,10}_{-0,18} \text{ (sys)} \\
\Gamma_2 &= 3,78 \pm 0,02 \text{ (stat) } {}^{+0,17}_{-0,06} \text{ (sys)} \\
E_b &= 0,94 \pm 0,02 \text{ (stat) } {}^{+0,29}_{-0,26} \text{ (sys) TeV} \\
N_0 &= 104,9 \pm 0,6 \text{ (stat) } {}^{+27,0}_{-15,8} \text{ (sys) } \mathrm{GeV^2 \cdot m^{-2} \cdot sr^{-1} \cdot s^{-1}} \\
\alpha &= 0,12 \pm 0,01 \text{ (stat) } {}^{+0,19}_{-0,05} \text{ (sys)}
\end{aligned}$$

And the flux at 1 TeV:

$$\Phi(1\ \mathrm{TeV}) = 96,2 \pm 0,5 \text{ (stat) } {}^{+17,2}_{-16,8} \text{ (sys) } \mathrm{GeV^2.m^{-2}.sr^{-1}.s^{-1}}$$

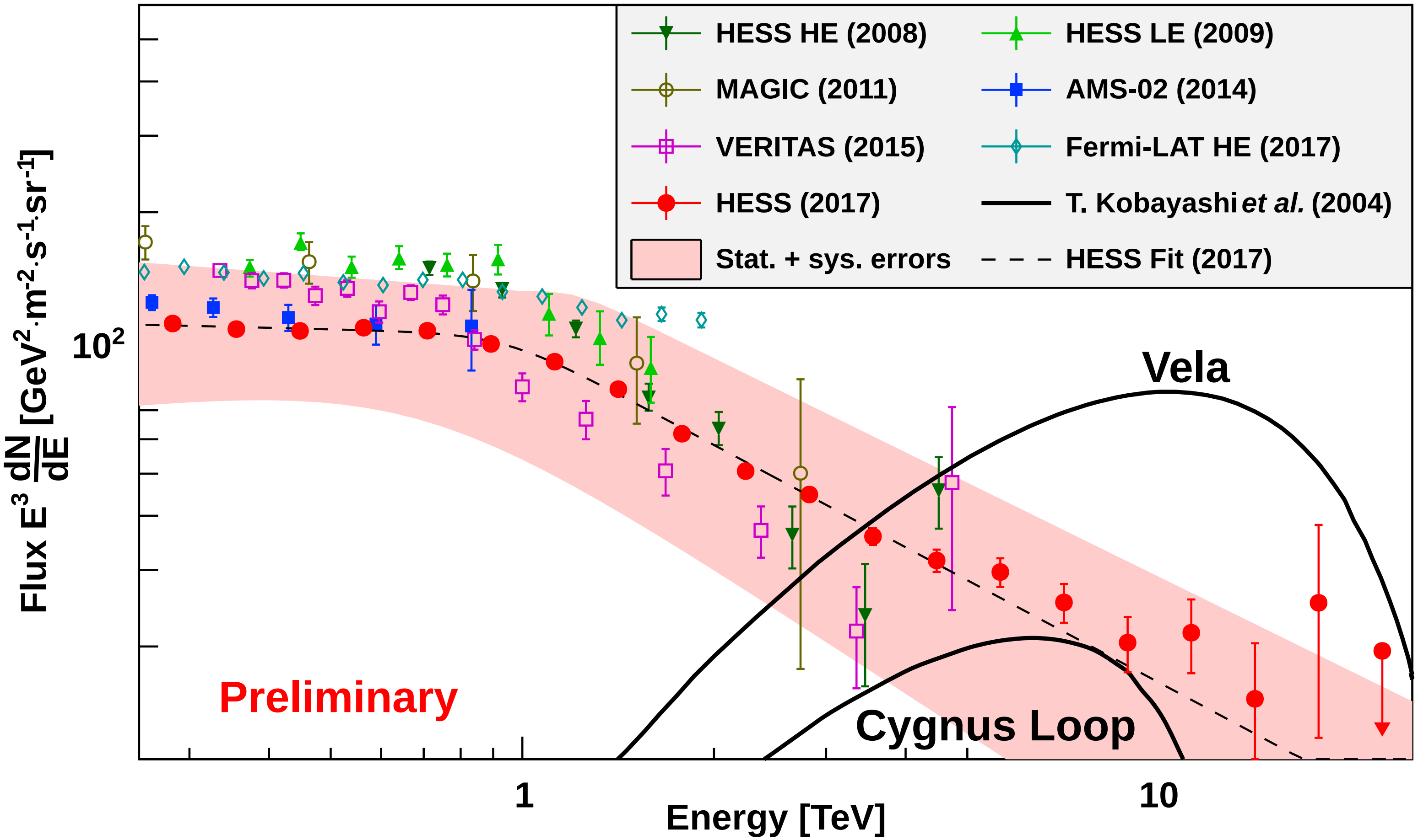
Electron spectrum with systematic uncertanties



Conclusions

- Determination of the electron+positron spectrum with a standard analysis method
- Chosen strategy of data selection exhibits a good stability for the spectral reconstruction
- Detection of 480 739 electron-like events
- Spectrum is in axcellent agreement with the AMS-02 one
- Extension of the measurement up to $\sim$ 20 TeV
- Allow to constrain models of leptons propagation and the origin of their emission

Example : modelisation of a pulsar

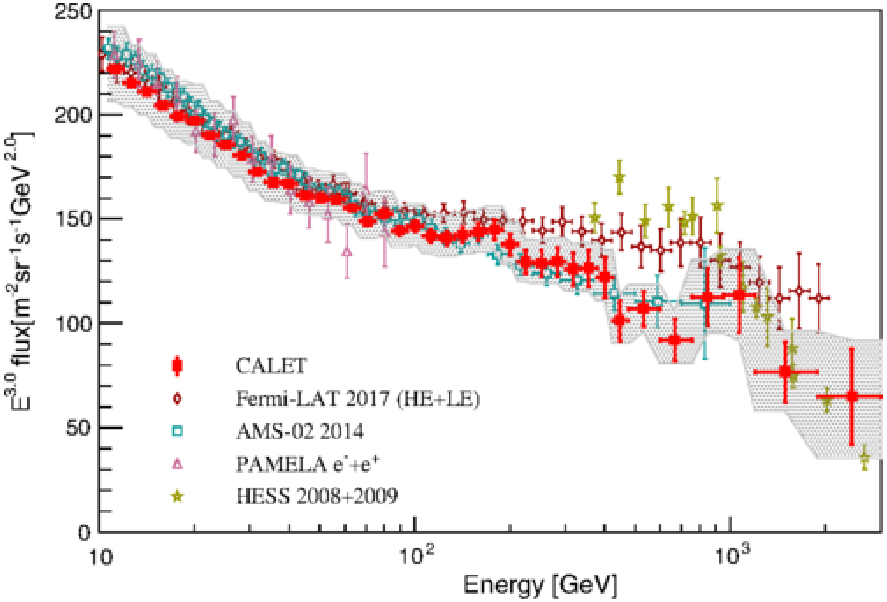


Perspectives

- With H.E.S.S.:
  - Improve hadron rejection
  - Take into account the hadronic component in the fit and subtract it
  - Go to lower energies with CT5

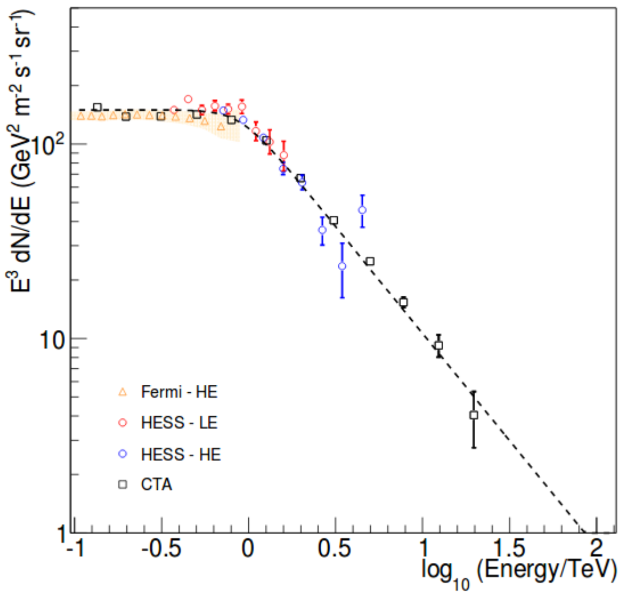
Perspectives

- With H.E.S.S.
- With the new generation of space-based instruments:
  - CALET
  - DAMPE



CALET Collaboration, Phys. Rev. Lett., 119.18, 181101 (2017)

Perspectives



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- With the new generation of space-based instruments:
  - CALET
  - DAMPE
- With the new generation of ground-based instruments:
  - CTA

Perspectives

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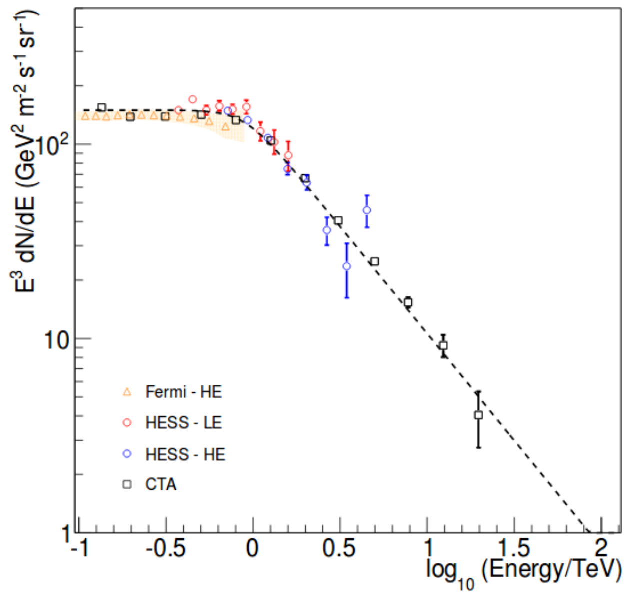

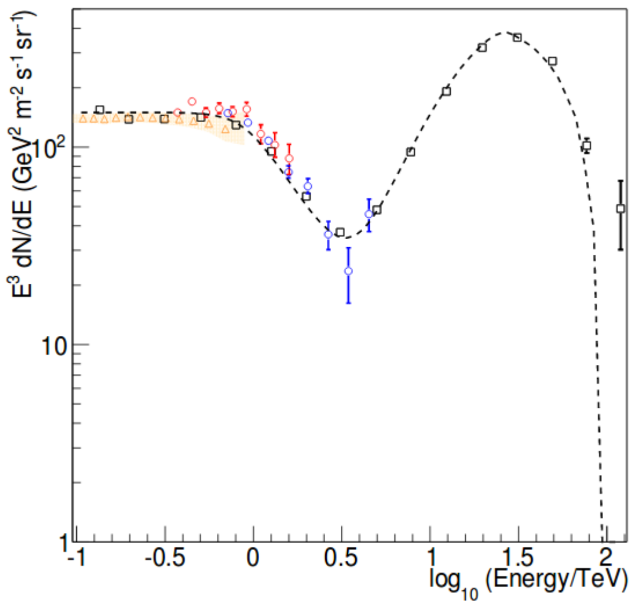

Science with the CTA (arXiv:1709.07997)

Merci pour votre attention !