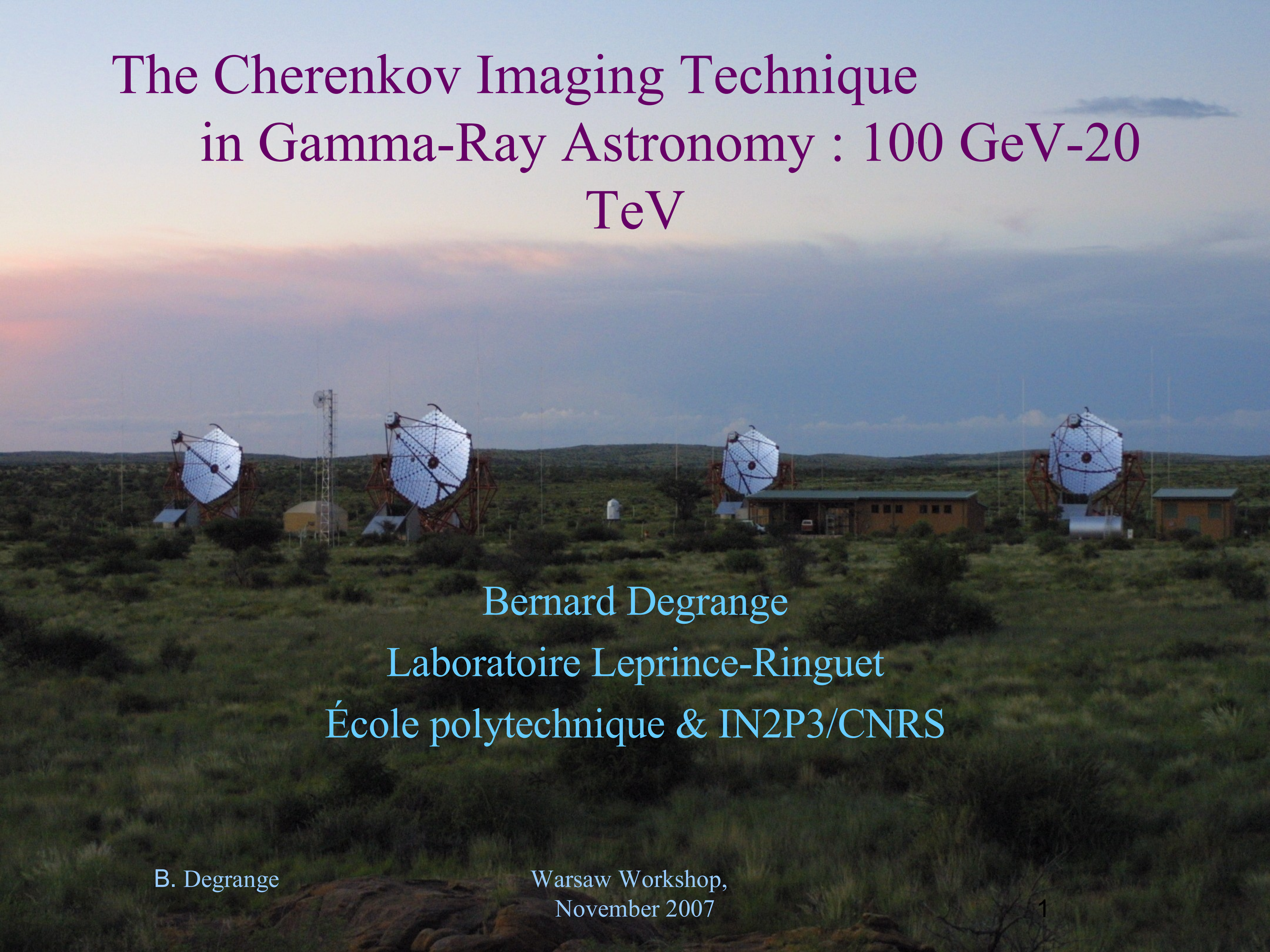
The Cherenkov Imaging Technique in Gamma-Ray Astronomy : 100 GeV-20 TeV



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Outline

- The experimental challenges of TeV astrophysics
- The basic principles of Cherenkov imaging
- Fighting against the night sky background
- Fighting against hadrons …
- … and taking advantage of muons
- Measuring the primary energy
- Conclusion : the main steps of the analysis

1. The experimental challenges of TeV astrophysics

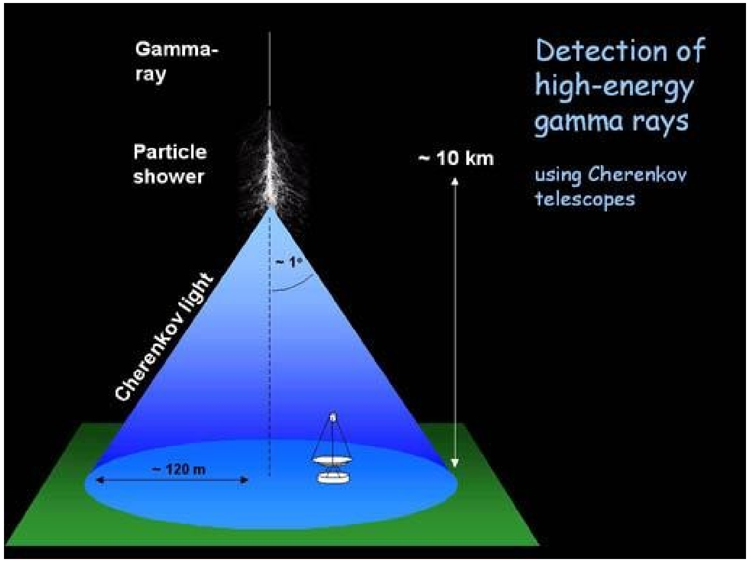
- Very low γ-ray fluxes in the TeV range:

  e.g. Crab nebula: flux($E > 1$ TeV) $= 2 \times 10^{-11}$ cm^{-2} s^{-1}

  Large effective detection areas (>30 000 m^{2}) needed

  → ground-based detectors

- Use the atmosphere as a huge calorimeter and detect γ-ray-induced atmospheric showers through Cherenkov light:



Light pool on the ground: 300 m diameter

Atmospheric_Cherenkov techniques involve some constraints …

- Only working by clear moonless nights
  → Duty cycle ≈ 10 % or less
- Detection area ≈ size of the Cherenkov light pool on the ground
  - Cherenkov angle ≈ 1° at ground level
  - Light pool diameter ≈ 300 m at 2000 m a.s.l.
- Very brief flash of Cherenkov light (a few nanoseconds) → need fast photodetectors
- Limited field of view (a few degrees) → *tracking instrument*

… but the most difficult challenge is the rejection of hadronic showers !

- Detecting cosmic-ray showers through the Cherenkov light they produce in the atmosphere is a rather old technique (Galbraith and Jelley 1953) …
- … but selecting gamma-ray-induced showers turned out to be a very hard task: *the needle in the haystack.*
- No confirmed results before 1989 → scepticism of the astrophysical community until recently.
- Still a few confirmed sources in 2002.

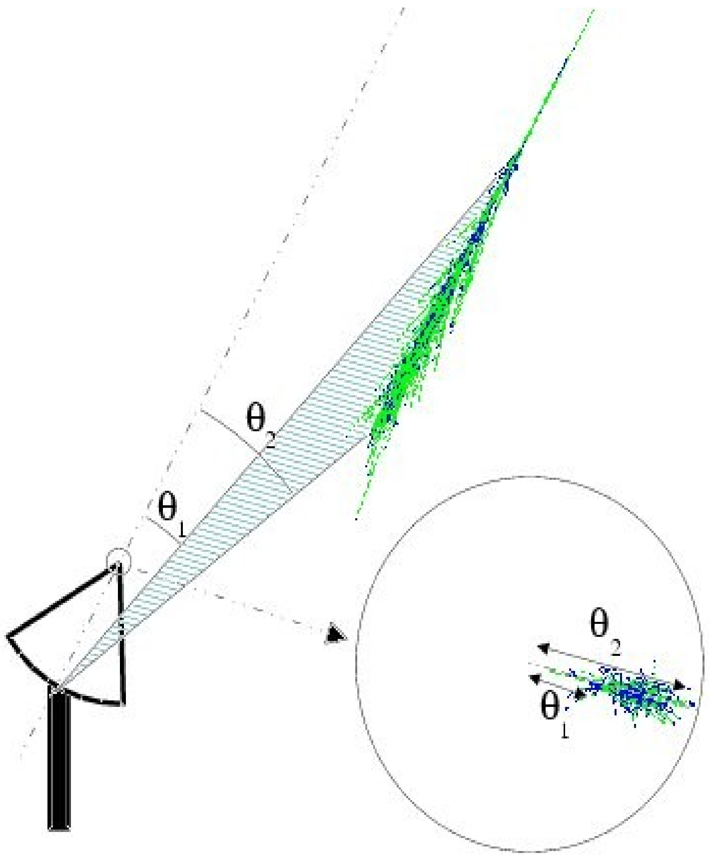
Some important steps in Cherenkov imaging

- 1985 Shower imaging, a method for discriminating gamma-rays from hadrons (A.M. Hillas)
- 1986 Whipple Observatory (Arizona), 75 m^2 reflector

  First imaging camera (37 pixels)
- 1989 Whipple Observatory: discovery of the Crab nebula TeV signal (T.C. Weekes et al.)
- 1995 HEGRA experiment (Canary Islands) : First stereoscopic system (5 tel. × 8.5 m^2)
- 1996 CAT (French Pyrenees): fast electronics + high-definition camera (600 pixels)→ 250 GeV threshold with one 18 m^2 telescope
- 2003 H.E.S.S. (Namibia) : (4 tel. × 108 m^2 × 960 pixels)
- 2004 MAGIC (Canary Islands) : (1 tel. × 234 m^2 × 577 pixels)
- 2009 H.E.S.S. II (Namibia) : addition of a very large telescope (1 tel. × 596 m^2 × 2048 pixels)

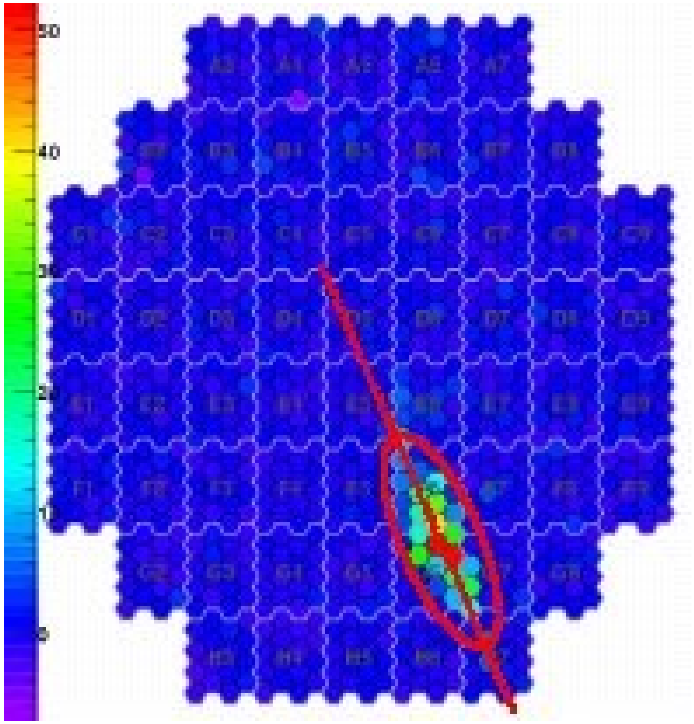
2. Basic principles of Cherenkov imaging

- Build up shower image in the focal plane
- Gamma vs. Hadron discrimination based on
  - Image shape
  - Image direction (for point-like sources)
- Cherenkov light profile → impact distance and primary energy



The asset of imaging telescopes: High hadronic rejection factor (10^2 to 10^4)

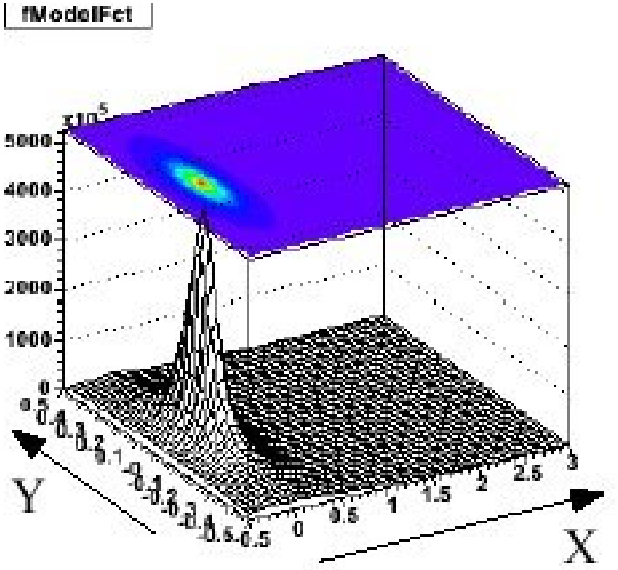
→ High flux sensitivity



- **Image shape:**
  - Electromagnetic showers: elongated, quasi-elliptic shape
  - Hadronic showers: more irregular or patchy
- **Image direction:** should point to the source
- **Image light profiles** (longitudinal and transverse)

help find the source position along the major axis even with a single telescope.

The distribution of light in the image

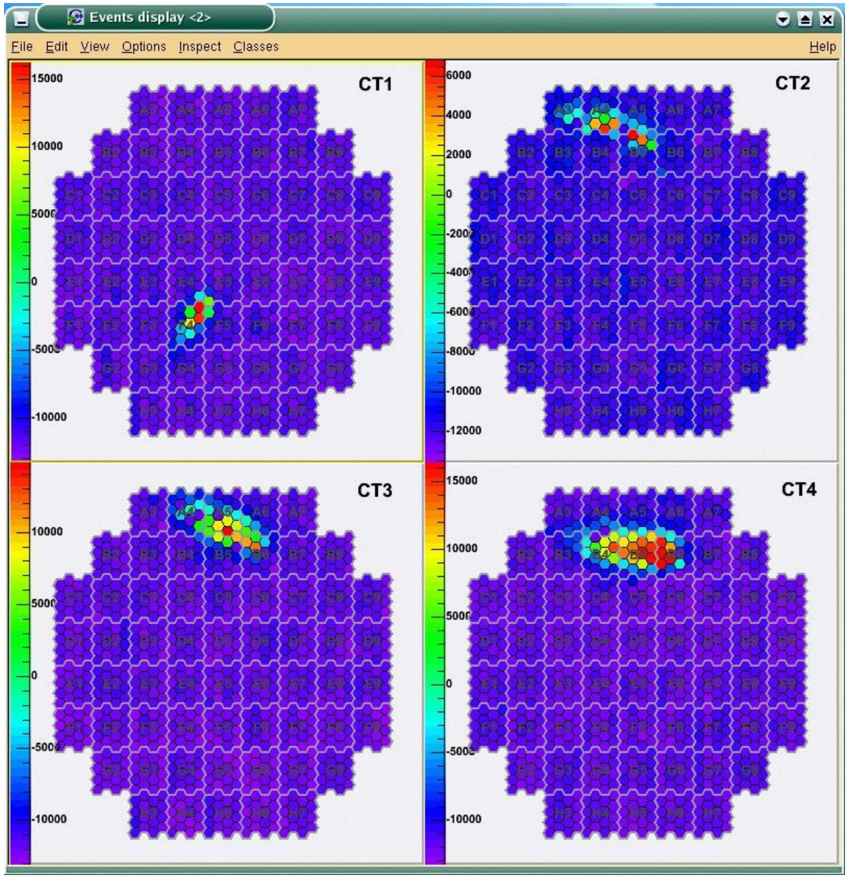


- A shower, as seen in Cherenkov is not a usual luminous object.
- The emission is strongly anisotropic.
  - Quite different from fluorescence light emitted by ultra-high-energy showers !
- Photon yields at different altitudes are sampled differently from different observation positions.
- The position of the source along the image axis can be deduced from the longitudinal light profile (see figure):
  - useful with one single telescope (CAT, MAGIC, HESS II)
  - but this requires a high-definition image …
  - and stereoscopy provides a better angular resolution and, over all, a much better rejection of the hadronic background.

Stereoscopic analysis (e.g. HEGRA, H.E.S.S.)

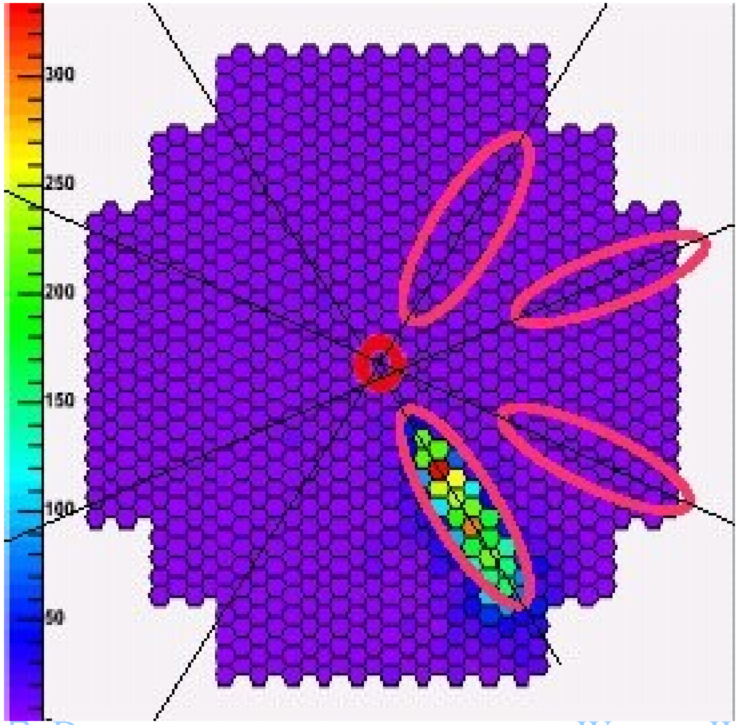
- Showers viewed by several telescopes
- Considerable hadronic rejection (> 1000)

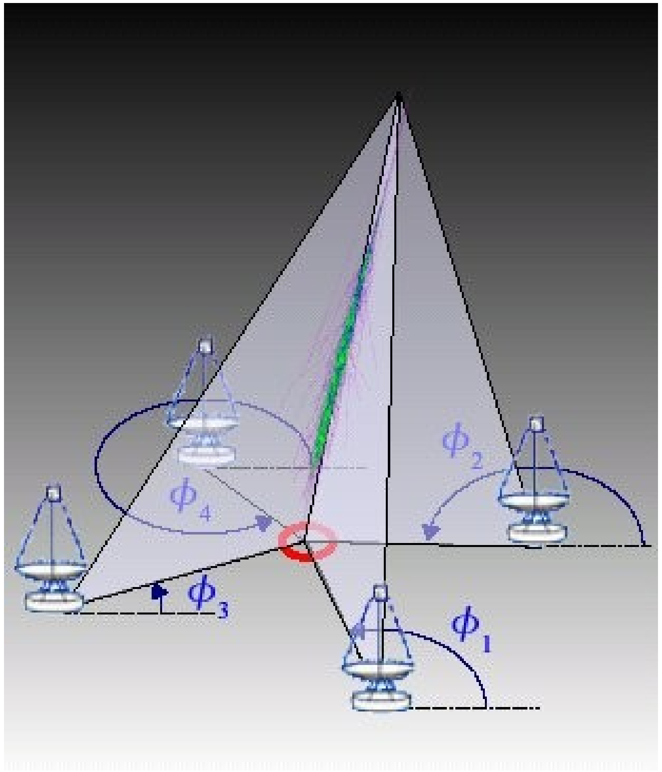
  Use the constraint of rotational symmetry
- Much better angular resolution (4 to 6 arc min.)
- Better energy resolution (15%)



Stereoscopic analysis (e.g. HEGRA, H.E.S.S.)

- Direct measurement of the **γ-ray origin** in the field of view (important for extended sources)
- Direct measurement of the **impact on the ground** (important for energy measurement)





3. Fighting against the night sky background

- Night sky background light : on average
  $\sim 10^{12}$ photons m^{-2} sr^{-1} s^{-1}
- Sets a lower limit on the energy threshold of the telescope : the trigger condition must considerably reduce the rate of random coincidences.
- Induces some pollution in shower images.
- Modifies the “pedestals” of phototubes (i.e. the average ADC output for a null signal).
- Particularly important effects in a pixel coinciding with the image of a star; *(in case of a bright star, the HV is switched off in the pixel).*

The energy threshold

Night sky background light ~ 10^{12} photons m^{-2} sr^{-1} s^{-1}

$$\frac{Signal}{\sqrt{Night\ \ sky\ \ backgnd.}} \propto \frac{A_{col}\ \tau\ \Omega_s\ \varepsilon}{\sqrt{A_{col}\ \Delta t\ \ \Delta\Omega\ \ \varepsilon}} \propto \sqrt{\frac{A_{col}\ \ \varepsilon}{\Delta t\ \ \Delta\Omega}}$$

- Increase photon collection area ≈ reflector area A_{col}

- Increase photon detection efficiency ε (reflectivity, light collectors, phototube quantum efficiency)

- Coincidence time Δt should not be much greater than the time spread τ of Cherenkov photons → isochronous mirror, fast trigger

- Solid angle on which photons are summed up ΔΩ should not be much greater than the angular size of the shower Ω_s

  → small pixels, trigger based on sectors of the field of view

Hence, the concept of a high-definition camera

- 960 phototubes …
- … equipped with light collectors (Winston cones).
- Trigger electronics within the camera (overlapping sectors typical shower size; majority logic).
- Readout from analogue memories (1 GHz sampling) within the camera.
- Analogue signal integrated over 12 ns → ADC

Correcting the pollution of shower images : Two different methods

- Cleaning procedure (simple but irreversible):
  - simple criteria based on the charge content of a pixel and those of its neighbours (« tail cuts »).
  - Reset the pixel content to zero if criterium is not satisfied (e.g. isolated hits).
  - Further analysis is restricted to « significant pixels ».
- Maximum likelihood method combined with shower analysis (« model analysis », *see Mathieu's talk*). All pixels are included in the analysis → can afford a rather high night-sky background, at the expense of a longer computing time.

Night-sky background vs. PMT calibration

- Capacitive coupling between the PMT and the electronics (cf. RC circuit) → fast (few ns) positive pulse followed by a long negative tail (overshoot) lasting during a few µs.
- During the integration window, the probability to collect one or more photo-electrons is quite low, but the overshoots from previous photons from the night-sky background add up and shift the baseline to negative values with respect to that obtained in a completely dark environment.
- « Sky pedestals » are thus different from « dark pedestals »; they depend on the night-sky background and must be continuously monitored.
- The effect is more important in regions rich in stars (Galactic Centre, globular clusters etc.)

4. Fighting against the hadronic background

- Electromagnetic showers :
  - Essentially electrons, positrons and secondary gamma-rays emitted at small angles with respect to the shower axis (very small transverse momenta in Coulomb interactions) → narrow images
  - Except at energies of a few 10 GeV, large number of particles at shower maximum
  - Hence → quasi-rotational symmetry of the light distribution.
- Hadronic showers :
  - Various hadronic processes in competition → large fluctuations.
  - Larger transverse momenta in nuclear interactions.→ broader images
  - Lack of rotational symmetry → different aspects from different points of view (stereoscopy).
  - Muons (from $\pi^{\pm}$ and $K^{\pm}$ decays) reaching the ground → arc-like images

A gamma-ray induced electromagnetic shower

On average

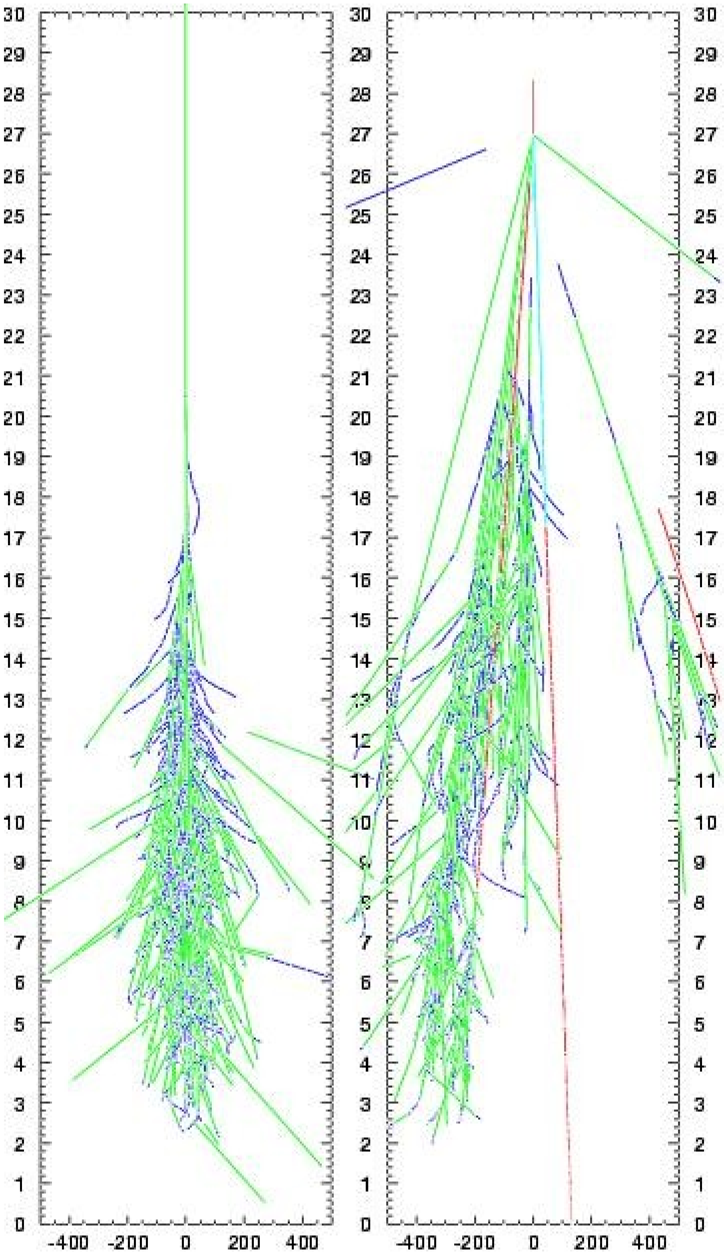
rotational symmetry

Small transverse momenta

(Almost) no muons

Essentially

e+ e- and secondary γ-rays



A proton-induced hadronic shower

Larger tranverse momenta

Presence of muons from meson decays

(in red on the figure)

Figures from Mathieu de Naurois

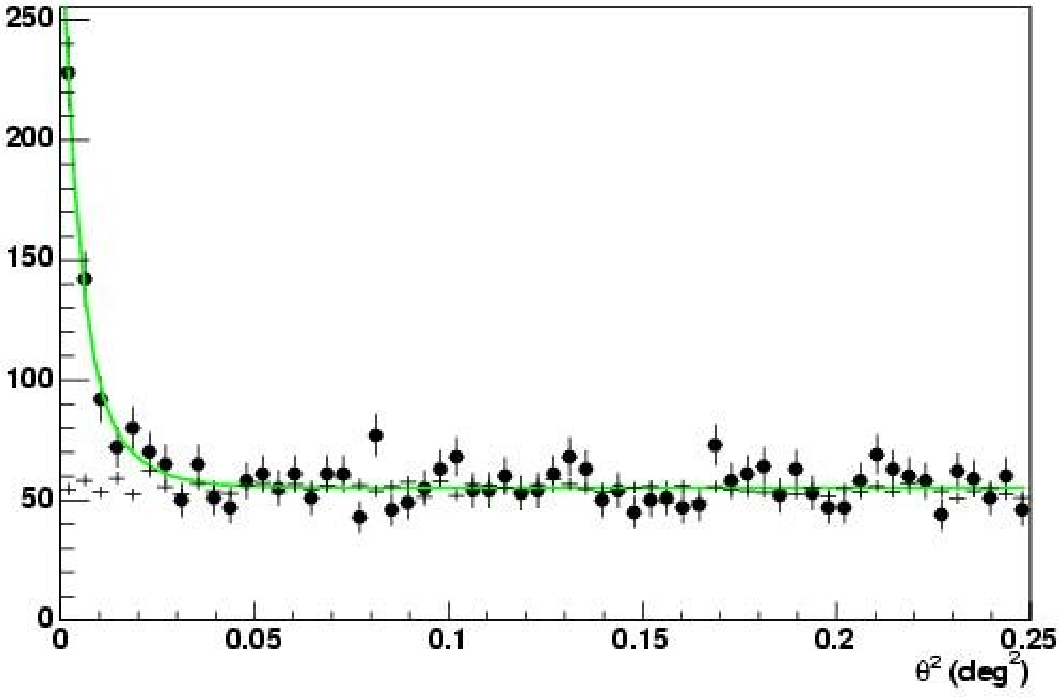
Reduction of the hadronic background (Image shape)

- A fraction of hadronic showers is rejected at the trigger level (sector size matches typical e.-m. shower image size):
  - e.g. patchy images
  - single muons (due to low-energy proton or nucleus-induced showers) only affect one telescope → rejected by central (multi-telescope) trigger in a stereoscopic system
- Most of hadronic events are eliminated at the analysis stage, mostly by requiring consistency with an electromagnetic shower (« goodness » of fit in « Model », rotational symmetry in « 3D-model ») and narrow images (mean-scale width, 3D-width); *(see Mathieu's talk)*
- The contribution of the remaining background events must be further estimated and subtracted *(see Arache's talk).*

Reduction of the hadronic background (Shower direction)

In case of a point-like source, the angular resolution provides an additional rejection factor and the θ^2 distribution (θ = angular deviation from source position) yields the respective contributions of the signal and of the remaining background.

θ^2 distribution PKS2155-304 (3D-model), events viewed by 3 or 4 telescopes



5. Taking advantage of muons

- Muons are a plague for single telescope experiments: if they fall within ≈50 m from the telescope, they produce little arc-like images which may fake low-energy e.-m. showers :
  - A part of them can be removed using the Length/Size (i.e. image length over photo-electron content of the image) distribution (strongly peaked for muon arcs).
  - All of them are removed in a stereoscopic system, but …
- Muons falling onto the reflector are very useful allies
  - they produce ring-like images …
  - which allow an accurate calibration of the acquisition chain (low-altitude atmosphere; optical chain; electronic chain).

The geometry of muon-induced images

G. Vacanti et al., Astropart. Phys.2 (1994) 1

- Muon track emits light on a cone
  - → ring-like image if impact lies within the mirror (right-handed figure)
  - → arc-like image otherwise (left-handed figure)
- Azimuthal distribution of light proportional to D(Φ)

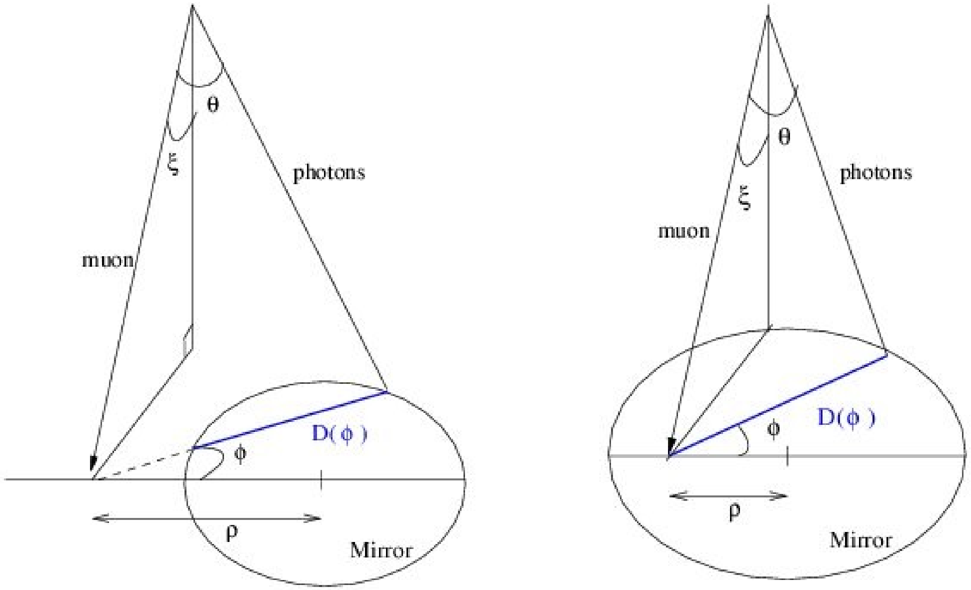
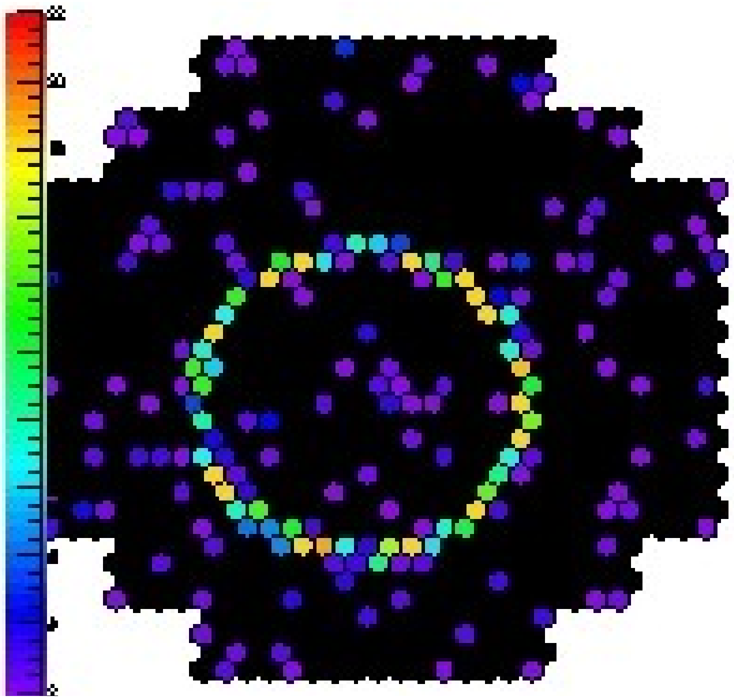
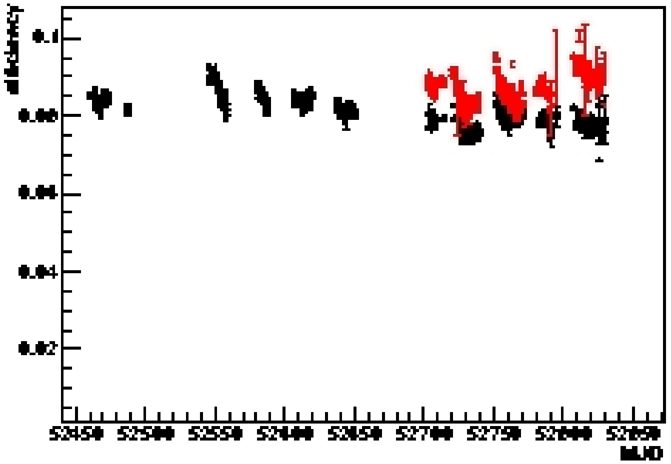


Image can be fitted with a few parameters : Cherenkov angle, muon direction, impact parameter, ring thickness **and light-to-signal conversion factor**

Calibration by muon rings

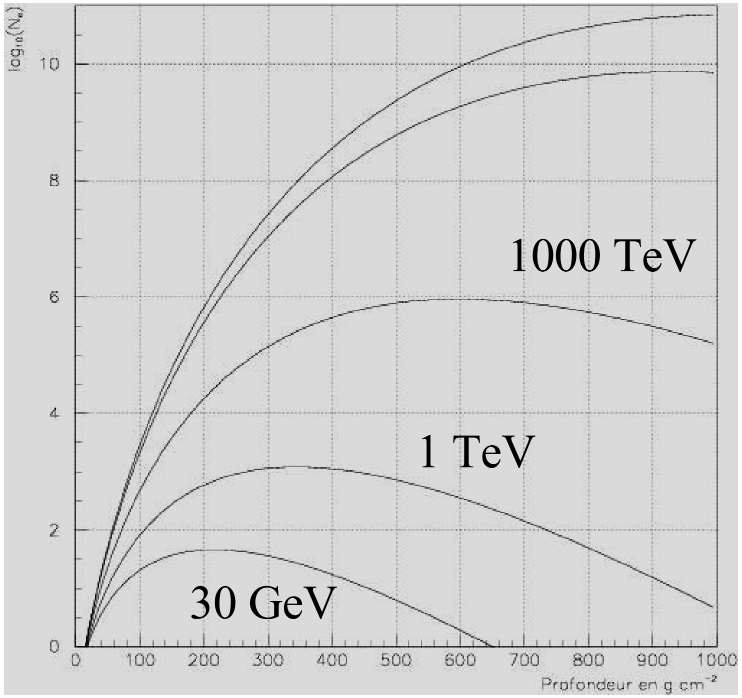
- Special data taking dedicated to muon rings→ conversion factors of all pixels.
- Include all effects (except that of higher atmosphere) : lower atmosphere, reflectivity of mirrors, of light cones, phototube efficiency, electronics etc.
- Allows to monitor the evolution with time of the average conversion factor for each telescope (lower figure)





6. Measuring the primary energy

- The atmosphere is an inhomogeneous calorimeter : the Cherenkov threshold depends on the altitude.
    - 189 MeV at h=30 km (10 g cm^{-2})
    - 35 MeV at h=10 km (350 g cm^{-2})
    - 21 MeV on the ground
- … but shower maximum generally lies between 200 and 600 g cm^{-2} for showers with energies in the 50 GeV to 100 TeV region.
- Few electron tracks at very high altitude + slow variation of the Cherenkov threshold at shower maximum → Primary energy almost proportional to total Cherenkov photon yield.
- But sampling depends on the relative position of the shower impact on the ground with respect to the telescope. The energy resolution depends on the number of telescopes viewing the shower (15% in the best case).
- Simulations allow to relate the primary energy to :
    - Detected photon yields
    - Shower impact position



Average development of an electromagnetic shower :
Average e$^{\pm}$ yield vs grammage

7. Conclusion : the main steps of the analysis

- Experiments using Cherenkov telescopes have been able to overcome the huge hadronic background at the expense of a strong instrumental effort: stereoscopy, high-definition camera, fast trigger and readout electronics.
- The data analysis requires a careful calibration procedure and a continuous monitoring of the detector characteristics → still difficult to provide public data.
- Nevertheless, the performance of such detectors is now higher than that of γ-ray space telescopes in angular resolution (4 to 6 arc min.) and in sensitivity (about 1% of the intensity of the Crab nebula for point-like sources).
- Forthcoming progresses : lower-energy threshold with HESS II and factor 10 in sensitivity in the TeV range with large arrays (Cherenkov Telescope Array).