Stereo imaging of the VHE γ-rays with HEGRA & H.E.S.S.

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- **New physics frontiers/Requirements to the instrument**
- **The advanced system of imaging Cherenkov telescopes**
- **Parameterization of air shower**
- **Further advancement in array performance**
- **H.E.S.S. sensitivity**

"On the way from HEGRA to H.E.S.S."

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New Physics Frontiers

"Study of Non-Thermal Phenomenon in the Universe"

Search and detailed study of the sites of particle acceleration up to TeV energies

Phenomena:

SNR: Origin of CRs

AGNs: Physics of the jets

IR absorption

Pulsars and Plerions

GRBs

...

Requirements to Experiment:

Lowering the energy threshold down to 100 GeV

High sensitivity to weak fluxes

Localization of emission with $< 1'$ accuracy

Search for the extended emission regions

Precise measurement of γ-ray energy spectra

Large dynamic energy range

Large event statistics at $< 1\ hr$ time scale

Detection of low energy events: < 100 GeV

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Hardware parameters of IACTs

	HEGRA	H.E.S.S.
• Reflector diameter	3 m	13 m
• Davies-Cotton design	Yes	Yes
• Focal length	5 m	15 m
• Number of channels	271	960
• Ang. pixel size, deg	0.25	0.15
• Field of view, deg	4.3	5.0
• PMTs	EMI	Photonis
• Signal sampling	120 MHz FADCs	1 GHz ARS
• Dynamic range	30	LG: 1-100 ph.e./HG: 16-1600 ph.e.
• Trigger	2NN/271	4/960(sect.)

H.E.S.S. will detect by factor of $\simeq 10$ more Č light from the same shower !

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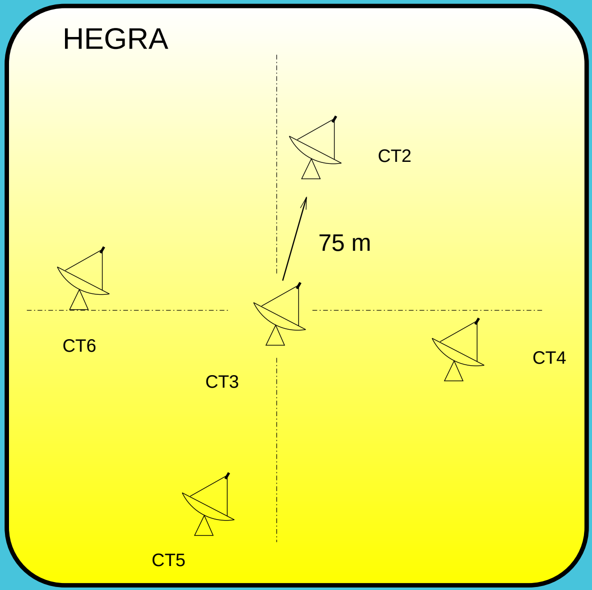
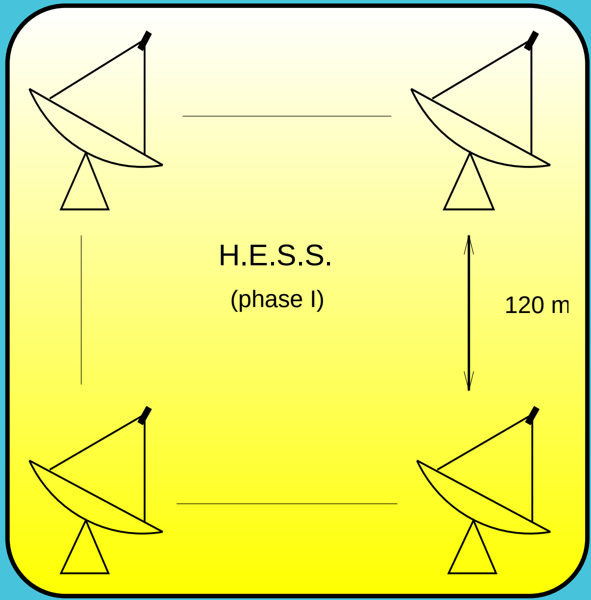
Layout of the telescopes

HEGRA:



H.E.S.S.:



MC & DATA optimization:

High quality stereoscopy needs larger separation: 100-140 m

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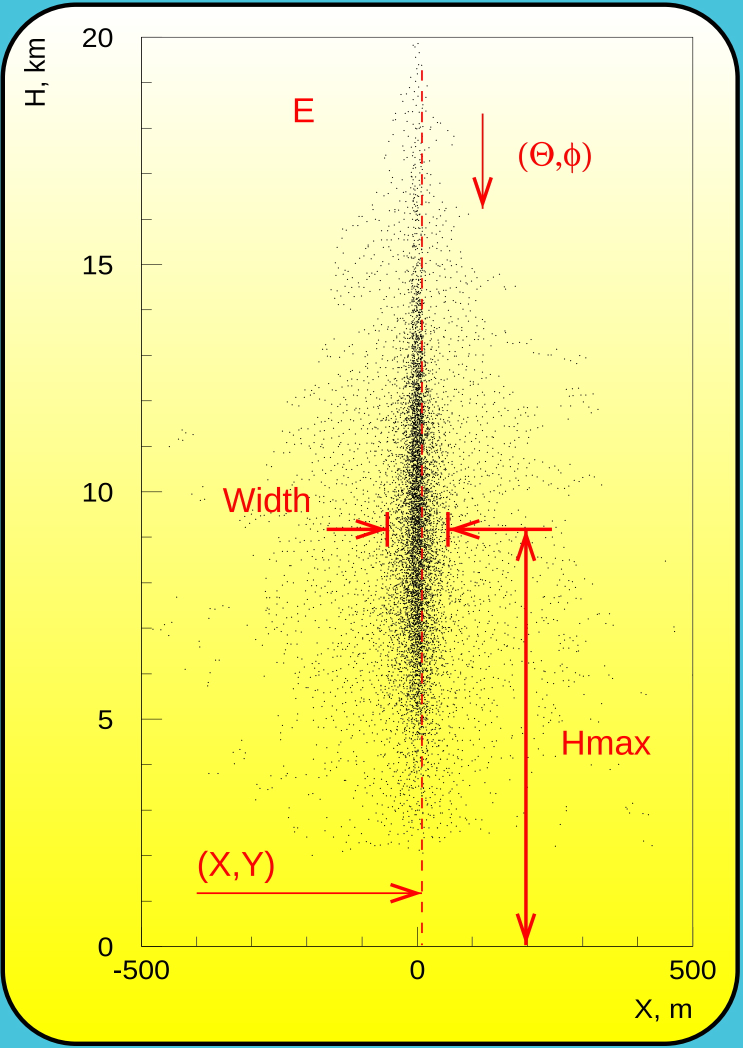
Imaging of γ-Ray Air Showers



Observables:

E – primary energy;

(Θ, ϕ) – orientation of shower axis;

(X, Y) – impact distance;

Width – width of the shower;

H_{max} – height of shower maximum;

Stereo imaging:

Reconstruction of shower in 3D space

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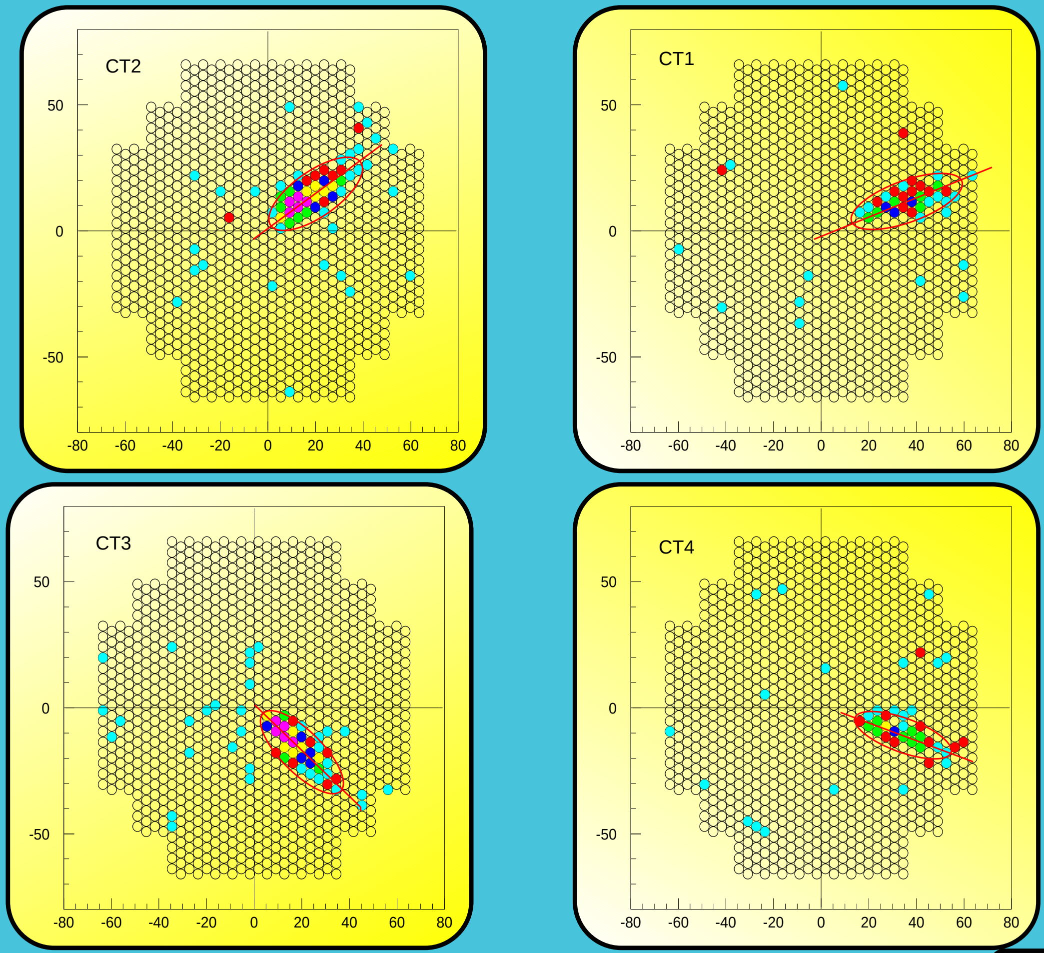
Stereo image of γ-ray air shower with H.E.S.S.

E = 150 GeV, Shower Axis: (-133.6 m; 0.6 m)



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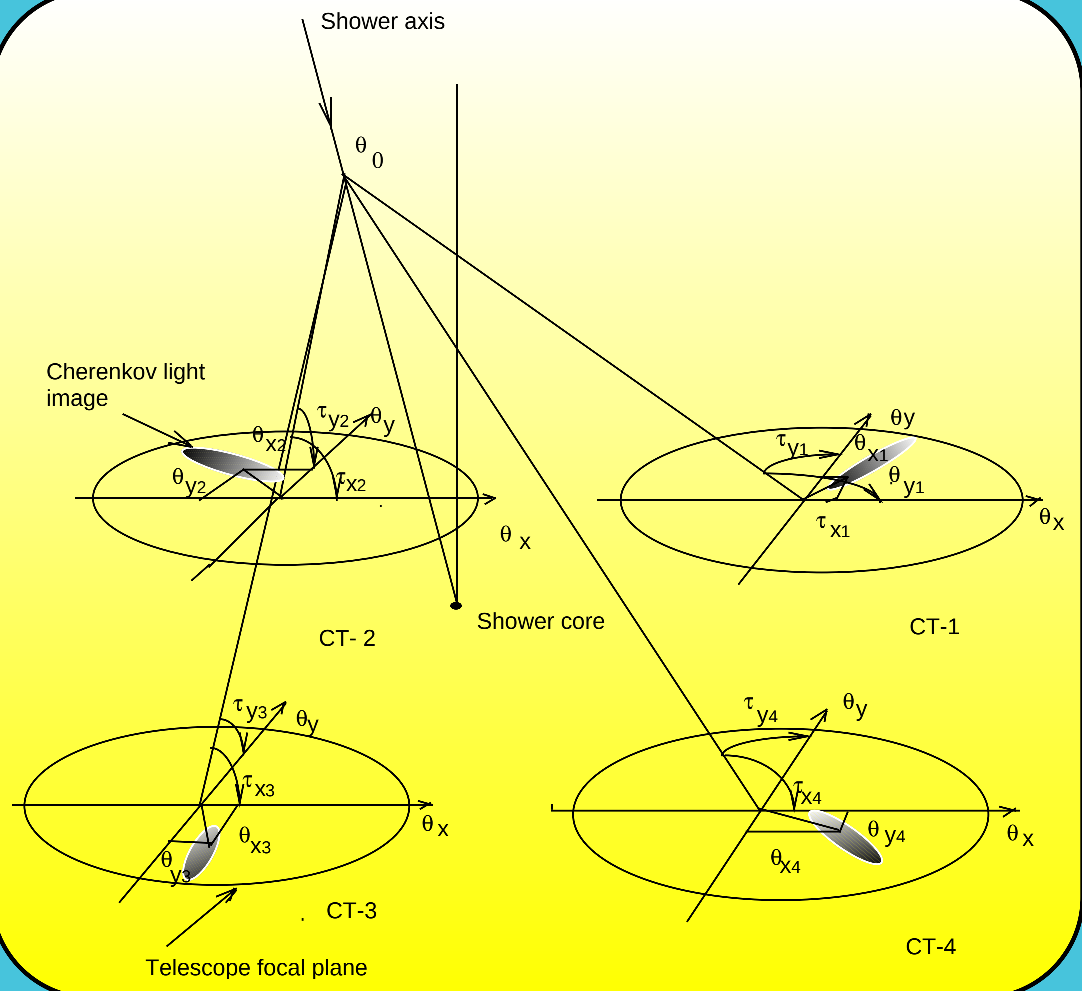
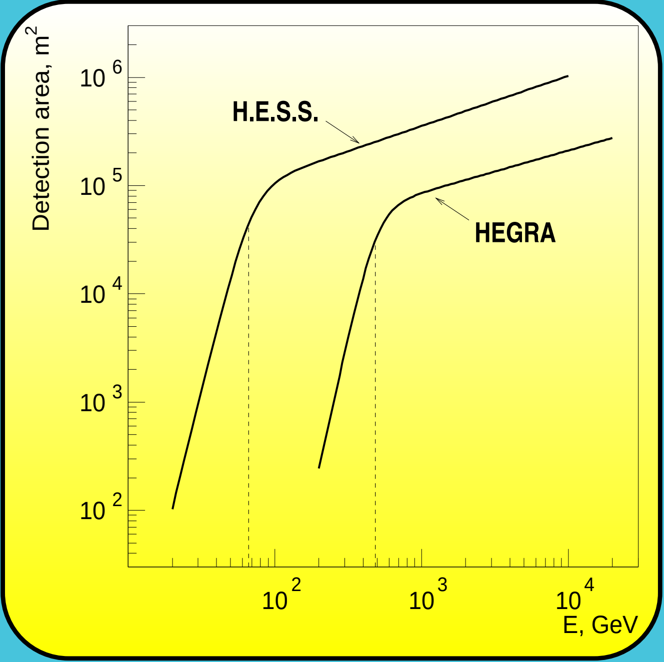
Geometrical Reconstruction of γ-Ray Air Shower



Gamma Ray Detection Areas & Rates



Useful fit:

$S(E) = a_0 E^{a_1} / (1 + (E/a_2)^{a_3})$

a_2 **is about the energy threshold**

HEGRA E_{th} **≃500 GeV**

H.E.S.S. E_{th} **≃80 GeV**

Gamma Ray rate from Crab Nebula

(no cuts)

$J_\gamma(E) = 2.8 \cdot 10^{-11} E^{-2.7}$,

$[photons\, m^{-2}\, s^{-1}\, TeV^{-1}]$

HEGRA (measured): $R_\gamma \simeq$ **120** $\gamma' s$**/hr**

H.E.S.S. (MC): $R_\gamma \simeq$ **150** $\gamma' s$**/min**

HEGRA:

5 CTs; Trigger: 2/5, 2NN/271>8 ph.e.

H.E.S.S.:

4 CTs; Trigger: 2/4, 4/960(sect.)>4 ph.e.

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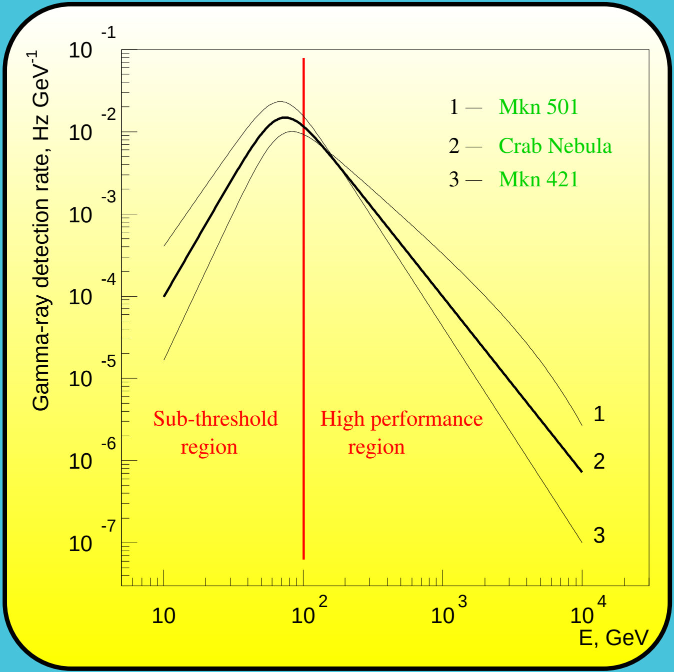
Energy Threshold of H.E.S.S.



HEGRA: 500 GeV

H.E.S.S.: 40 - 70 GeV

High performance region:

High quality stereoscopic observations with ability of high precision spectroscopy

Sub-threshold region:

γ-ray detection

Search for the periodic signals at low energies

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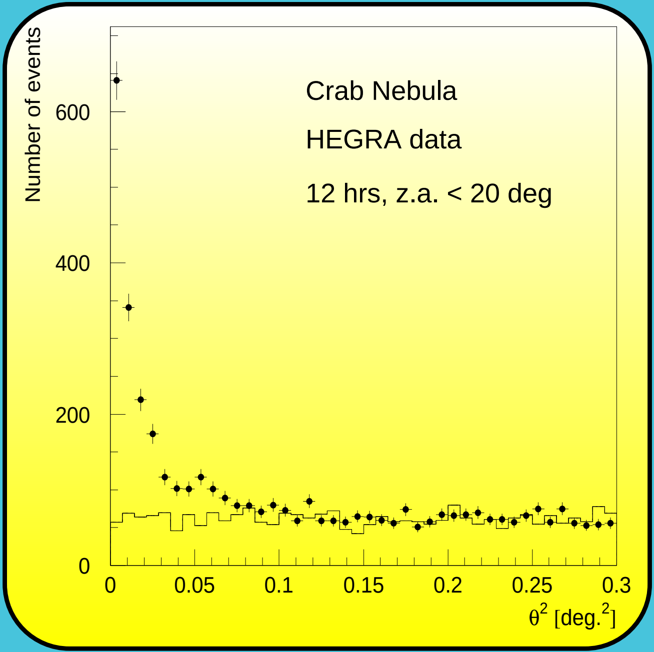
Angular Resolution: Point Gamma Ray Source

HEGRA data: **Crab Nebula, Mkn 501**

Conventional analysis:

2 images - $\Delta\theta \simeq 0.14^\circ$

4 images - $\Delta\theta \simeq 0.07^\circ$

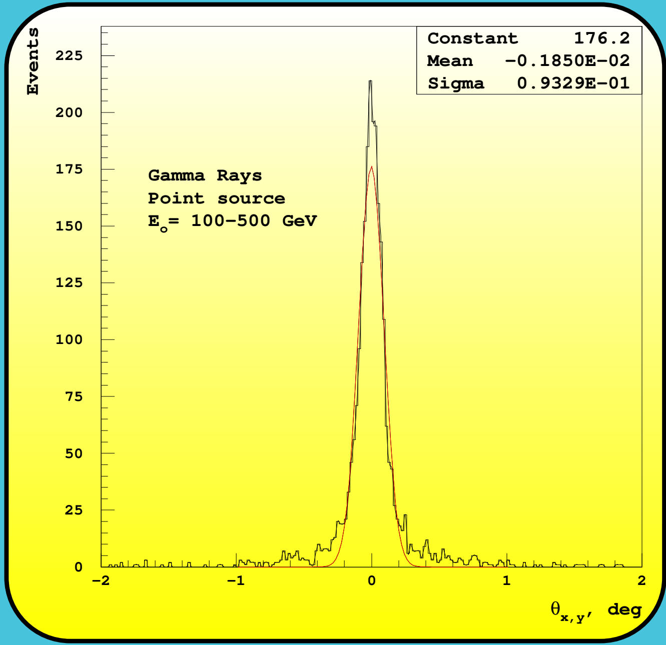


H.E.S.S. simulations:

Conventional analysis:

4 images - $\Delta\theta \simeq 0.1^\circ$

Localization: $<$ **1 arcmin**

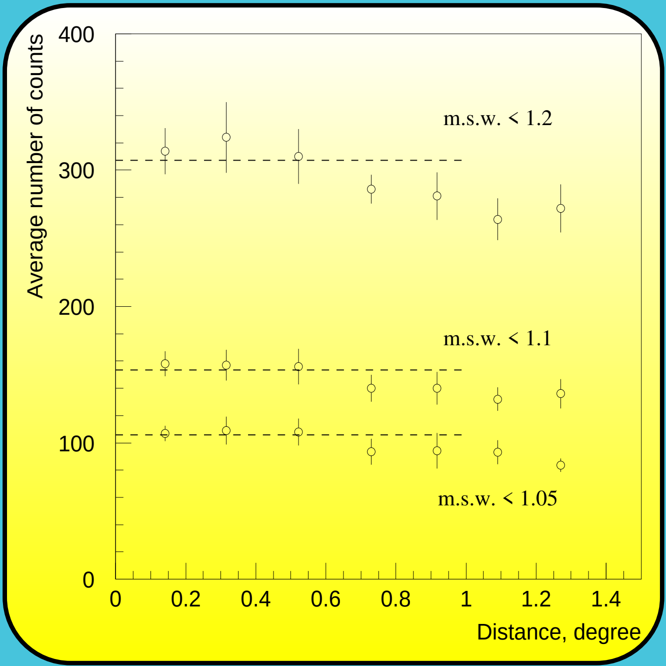


Sensitive area over field of view

HEGRA data:

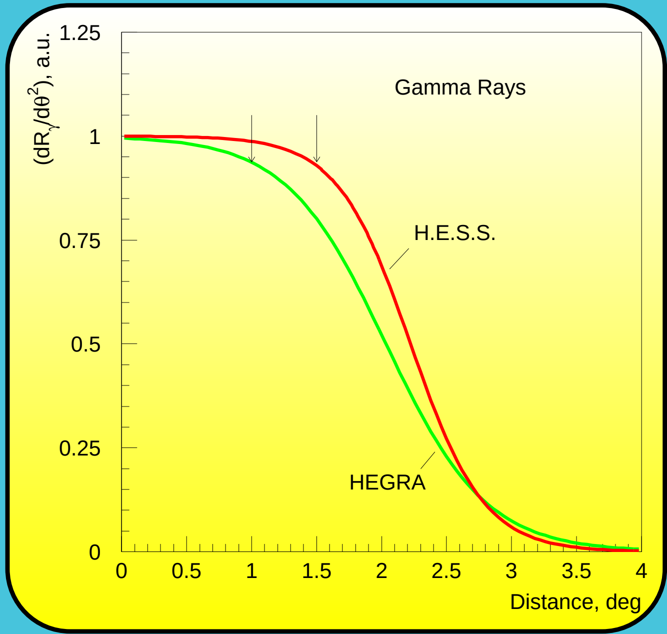
Trigger: 2/4, 2nn/271>8 ph.e.

Cosmic Rays (Monoceros SNR region)



HEGRA & H.E.S.S simulations:

All triggered events



H.E.S.S.: CR & γ-Ray rate is constant within $1.5°$ radius

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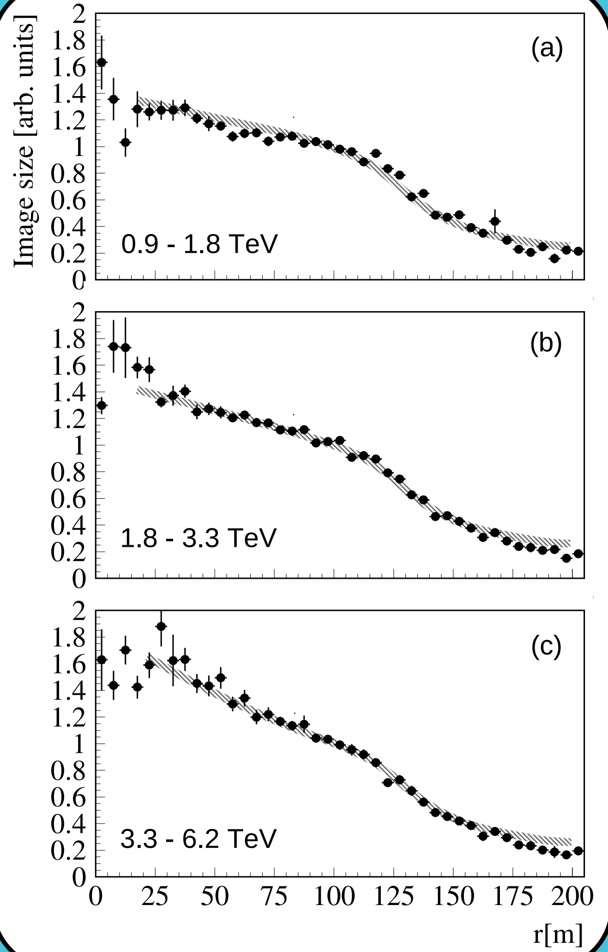
Measurement of impact parameter

HEGRA data (Mkn 501):



HEGRA:

($R \leq 100$ **m**) $\Delta R \leq 6$ m

($100\,\mathrm{m} \geq R \leq 150\,\mathrm{m}$) $\Delta R \leq 10$ m

H.E.S.S.:

Similar to HEGRA

HEGRA & H.E.S.S. can measure

(i) the position of shower core

for each event !

(ii) the radial size of γ-ray pool –

collection area !

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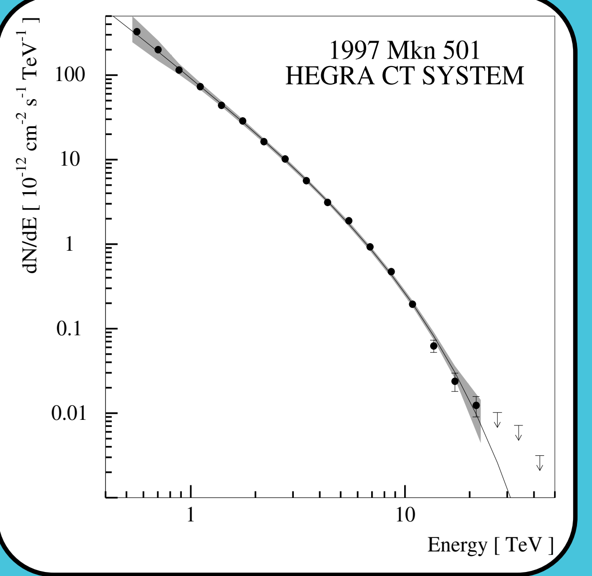
Energy resolution

HEGRA:



Energy range: 500 GeV - 20 TeV

Resolution: standard approach - $\simeq 20\%$;

advanced analysis - $\simeq 10\%$

Data: Crab Nebula, Mkn 501, Mkn 421

Error of spectrum slope:

systematic - ~ 0.05; **statistic -** $\lesssim 0.05$

H.E.S.S.:

Energy range: 40 GeV - 20 TeV

Resolution: standard approach -$\simeq 17\%$;

advanced analysis - $\lesssim 10\%$

Error of spectrum slope: systematic - ~ 0.01; **statistic -** ~ 0.01 !

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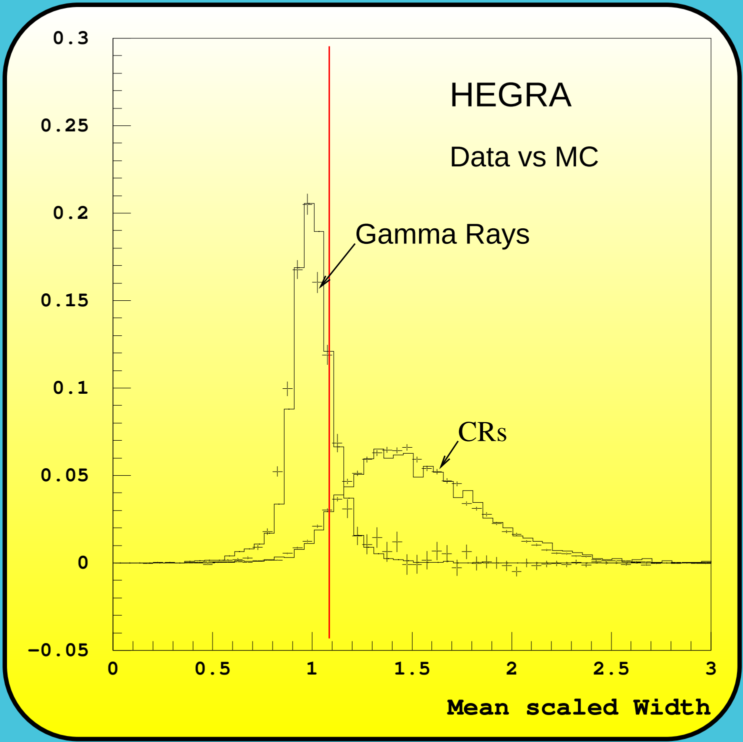
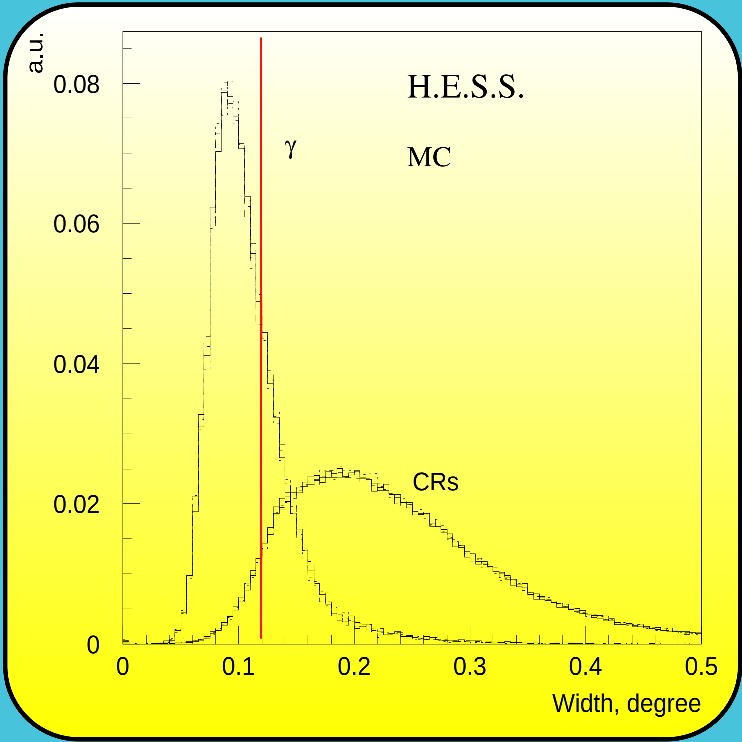
Selection of γ-Rays Using Image Shape Cut

4 IACTs: κ_γ **= 0.85;** κ_{CR} **=0.03; S/N = 4.9**σ





Mean scaled Width:

$$< \tilde{w} >= 1/N \sum_{k=1}^{N} w^k / < w >_{ij}^k$$

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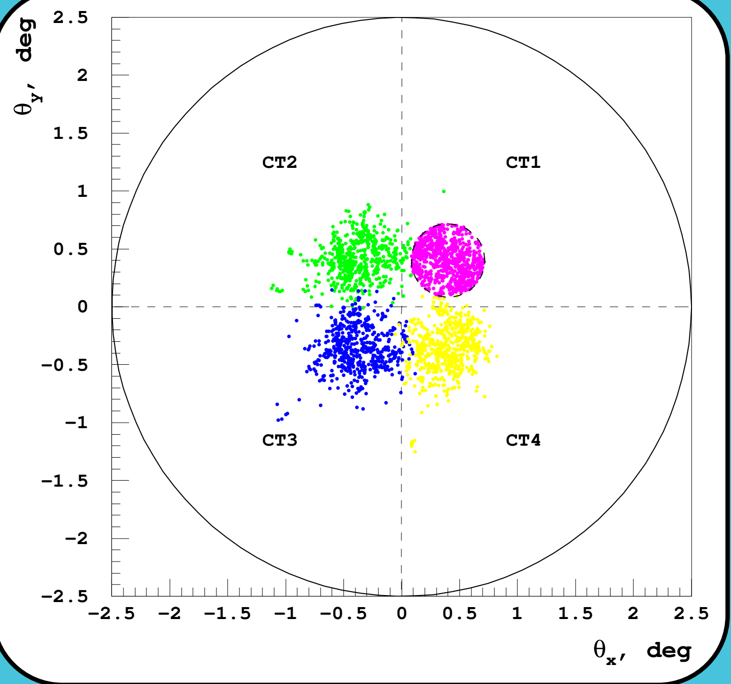
Extraction of Low Energy Gamma Rays

H.E.S.S camera field of view:

Image centroid position in CT(i) & CT1



Fitting procedure:

$x_c - x_d = a_1 + a_2\theta_x + a_3\theta_x^2 + a_4 S + a_5 S^2$

$y_c - y_d = a_6 + a_7\theta_y + a_8\theta_y^2 + a_9 S + a_{10} S^2$

(θ_x, θ_y) - centroid position, S - image size;

(x_c, y_c) - shower core; (x_d, y_d) - telescope position;

$a_i,\ i = 1, 10$ were derived for Gamma Rays

$\chi^2 = \sum_j^n (< \theta_{x,y} > - (\theta_{x,y})_j)^2/(n-1)$

Selection criterion: $lg(\chi^2) < 2.4$ at least 2 CTs

γ-rays - 0.87; CRs - 0.24; S/N = 1.8

Rejection of the n.s.b.l. triggers

Random distribution of the image centr.s

At least two telescopes in trigger

$\tilde{R}_{bg}/R_{bg} \simeq 10^{-2}$

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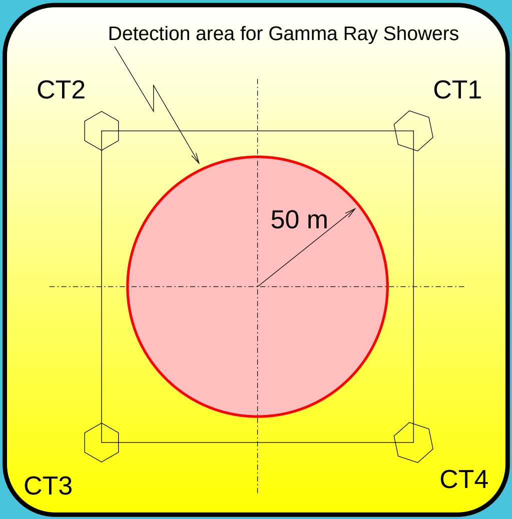
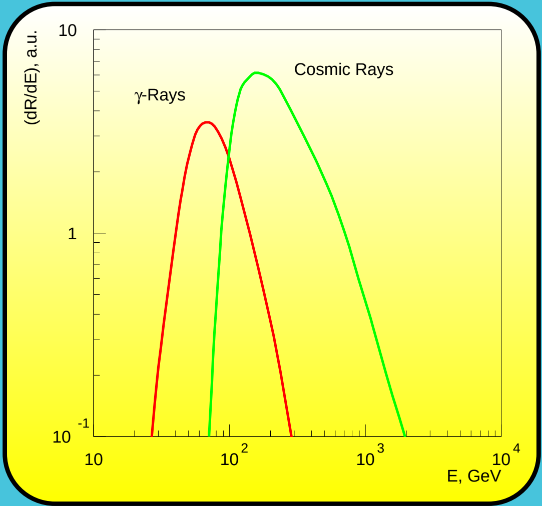
Low Energy Gamma Rays: Search for Pulsars





Specific selection of events:

4 telescopes are in trigger;

$$\left[\sum_{a=x,y}((\theta_a^*)_{CTi} - \theta_a)^2\right]^{1/2} \leq 0.4$$

$\theta^*_{x,y}$ is a center of circle limiting centr. pos.

$\theta_{x,y}$ is a centr. pos. of individual image

4-fold coincidences

Assumptions:

Crab Nebula spectrum

γ-ray flux at 0.1 Crab level

Pulsed emission has a phase peak of 0.1

No shape cuts

Results:

Sharp decrease in K_γ with energy

γ-ray rate: $3 \cdot 10^{-2}$ Hz; CR rate: 2.43 Hz

Time: 20 hrs; Signal-to-Noise Ratio: 5.2σ

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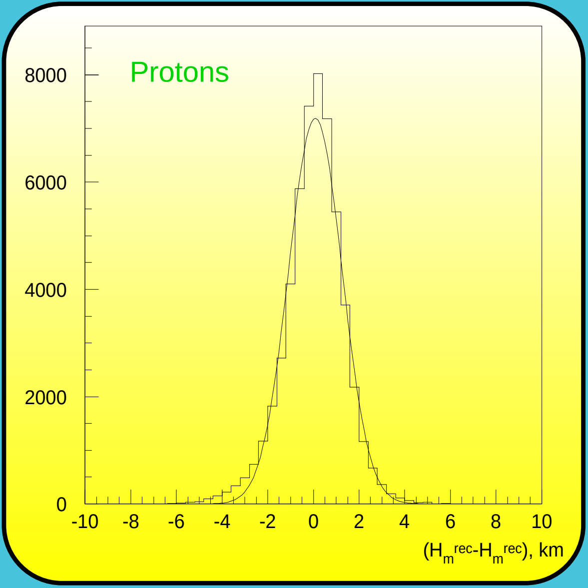
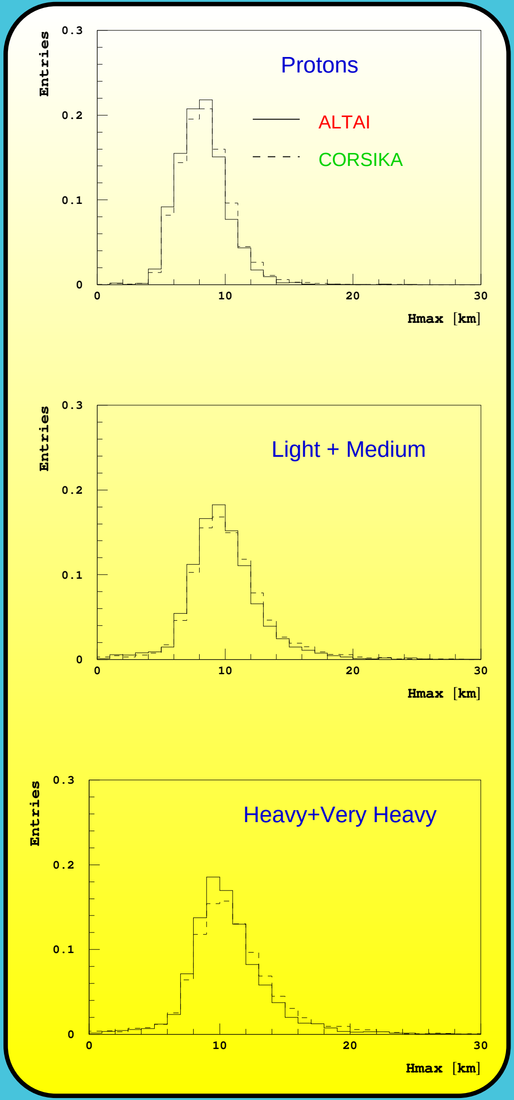
Measurements of Hmax (MC)

γ**-Rays: Hmax-resolution:** $\simeq$**500 m**



Protons: Hmax-resolution: $\lesssim 1$ km

$$H_{max} = a_1 + a_2 \cdot R^{a3} + a_4 \cdot \theta^{a5} \cdot R^{a6}$$



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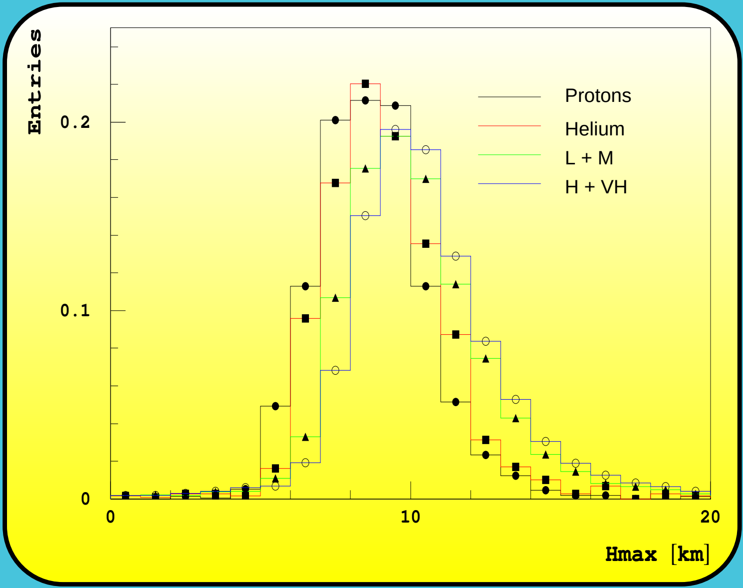
Study of the CR Chemical Composition



Approach:

Fitting the data – Hmax distribution – by mixing the MC data

Guess: Energy spectra & Composition

"Forward folding technique"

Advantages:

Based on image orientation & centroid

No need in use of image shape

H.E.S.S. is a powerful tool for study cosmic rays (e,p,nuclei) !

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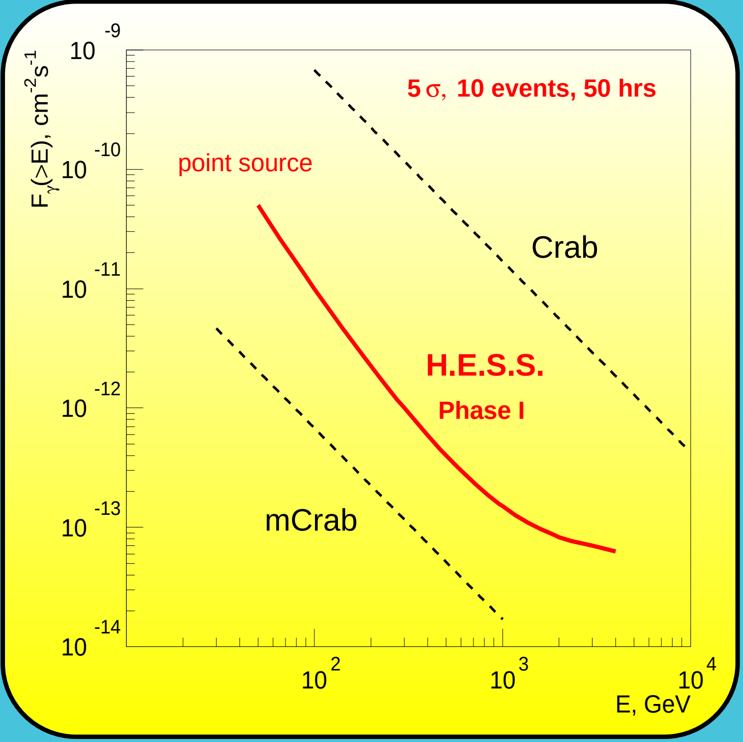
H.E.S.S. sensitivity



Point γ-ray source:

$$F_\gamma(>100\ \mathrm{GeV}) \simeq 10^{-11}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Extended source:

$$F_\gamma^{ext} \simeq (\Theta_0/0.1\mathrm{deg}) \cdot F_\gamma^{p.s.}$$

H.E.S.S. will see Crab in 5 min

t=1 hr	Flux:	ON	OFF	ON-OFF	S/N, σ
Whipple'95	1 Crab	323	271	106	4.6
HEGRA'98	1 Crab	87	25	62	5.9
H.E.S.S.'02	0.05 Crab	801	576	225	6.0

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Conclusions:

- Collection area: $\simeq 3 \cdot 10^5 \mathrm{m}^2$;
- γ-ray detection rate: 100 events/min;
- Energy threshold: $<$ 100 GeV;
- Angular resolution: better than 0.1 deg;
- Sensitive angular area: $\pi(1.5^\circ)^2$;
- Resolution in impact distance: $<$10 m;
- Energy resolution: $< 10\%$;
- High sensitivity to point like and extended γ-ray emission ...

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"Everything should be as simple as it is, but not simpler" Albert Einstein

Presented data & results belong to the HEGRA

(High Energy Gamma Ray Astronomy)

&

H.E.S.S.

(High Energy Stereoscopic System)

collaborations

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