Spectral Measurement using an Event-by-Event Energy Estimation Algorithm with the Milagro Detector

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Outline

- γ-ray detection methods overview.

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- Overview of the Milagro γ-ray observatory.

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- Eventy-by-Event Energy estimation and spectral determination with Milagro.
- Results for the Cosmic Ray Spectrum.

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- Results for the Cosmic Ray Spectrum.
- Results for the Crab Nebula.

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γ-ray Detection methods

Detector Type	Effective Area	Background Rejection	Resolution	Duty Cycle
ACT	Large	$\sim 95\%$	$\sim 0.15^\circ$	$\sim 5\%$
Satellite	Small	No Background	$\sim 0.3^\circ$	95%
Array	Moderate $\rightarrow$ Large	$\sim 95\%$	$\sim 0.4^\circ$	95%

Energy	Field of View	Examples
≥ 100 GeV	Small	HESS, HEGRA, CAT, Whipple
< 300 GeV	Large	COS-B, EGERET, GLAST
≥ 100 GeV	Full Overhead Sky	Milagro, Tibet

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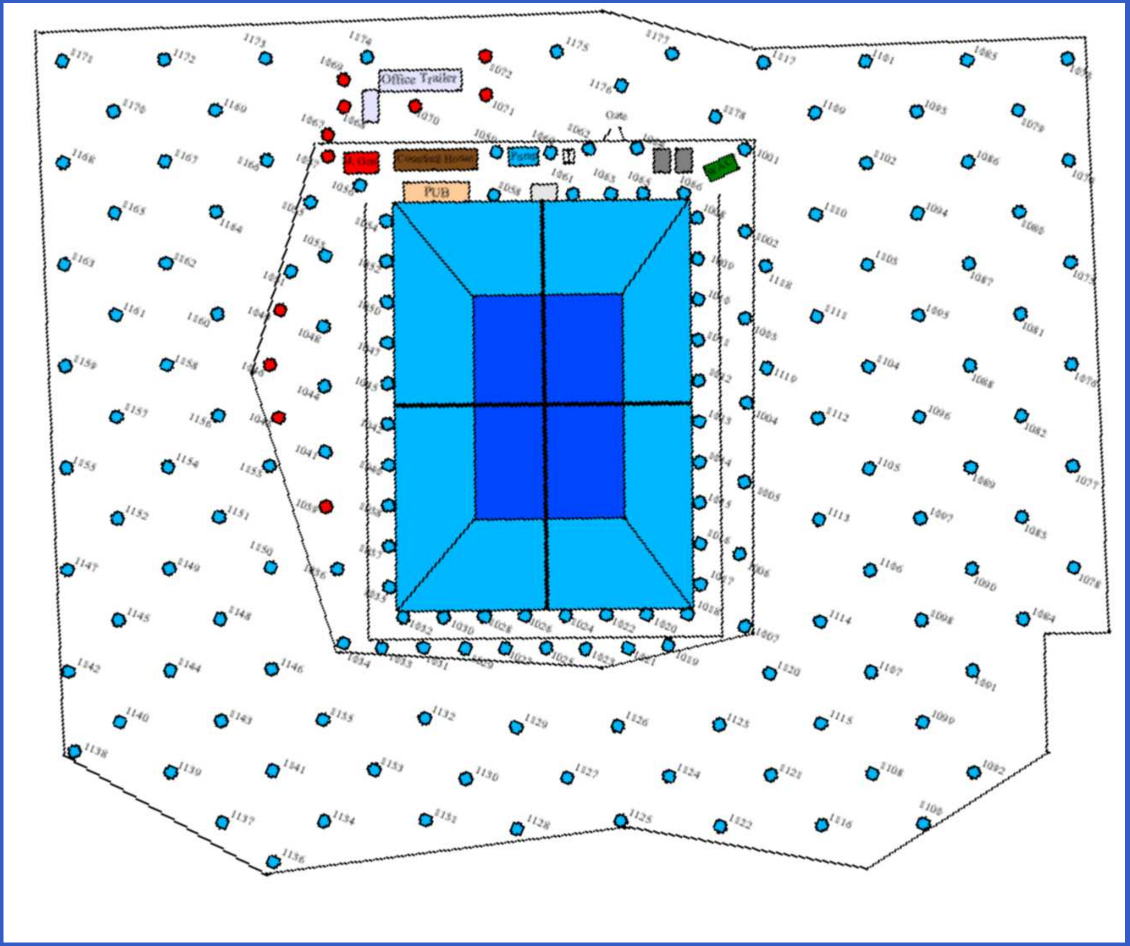
The Milagro γ-ray Observatory

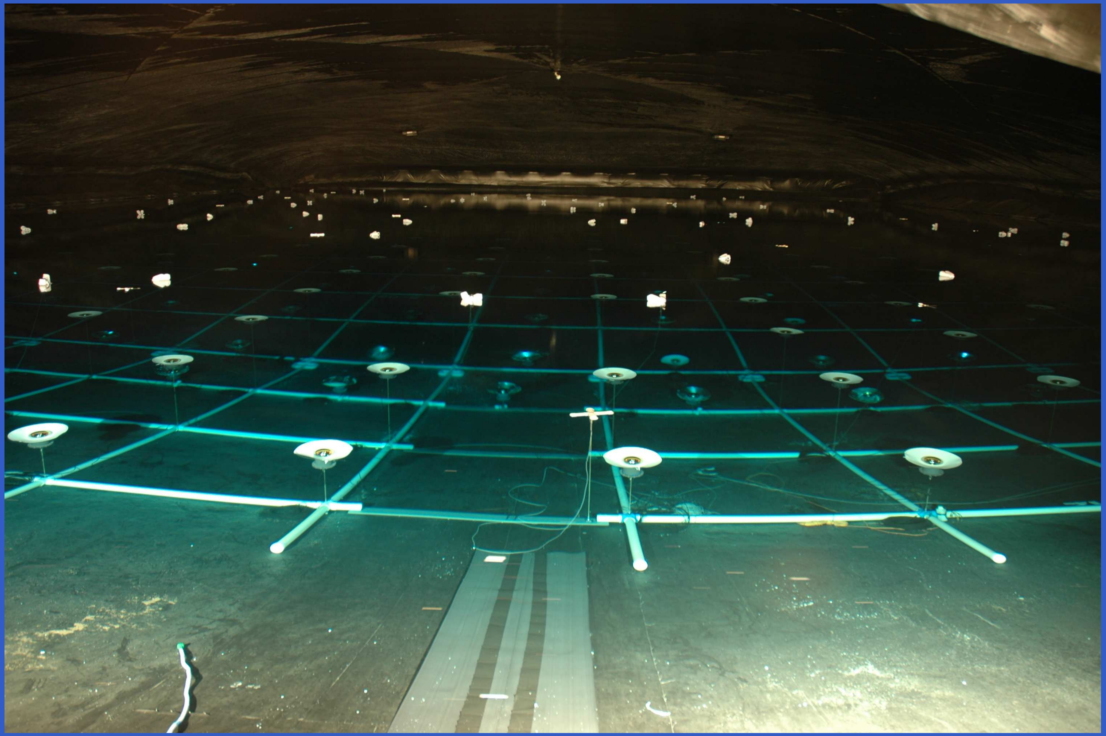
Detector Layout

- Located ~ 60 km
  NE of Los Alamos, NM
- 60 x 80 m Pond
- 200 m x 200 m
  "Outrigger" Array
- 2630 m Elevation

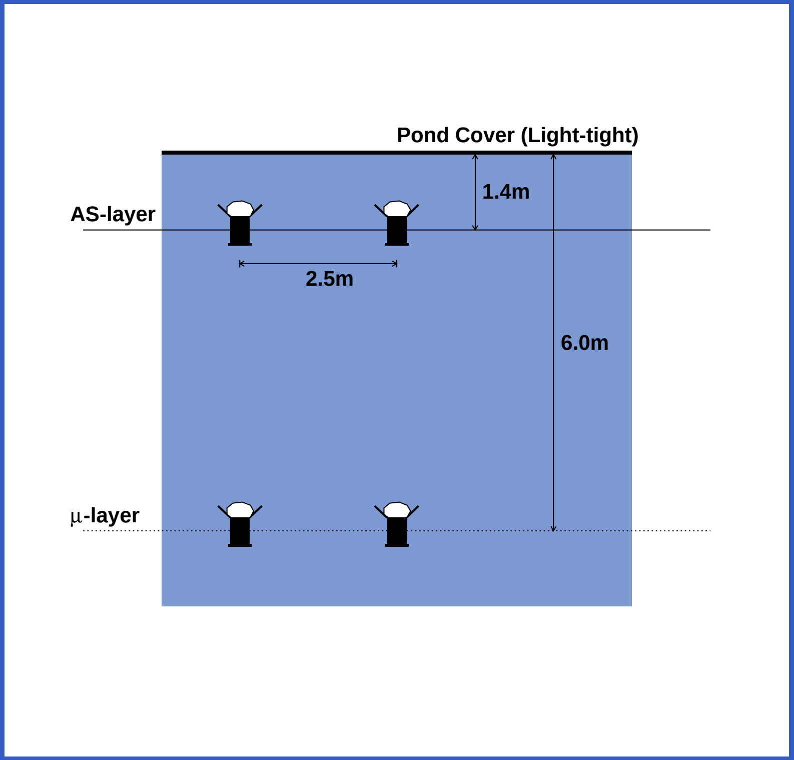


Detector Layout

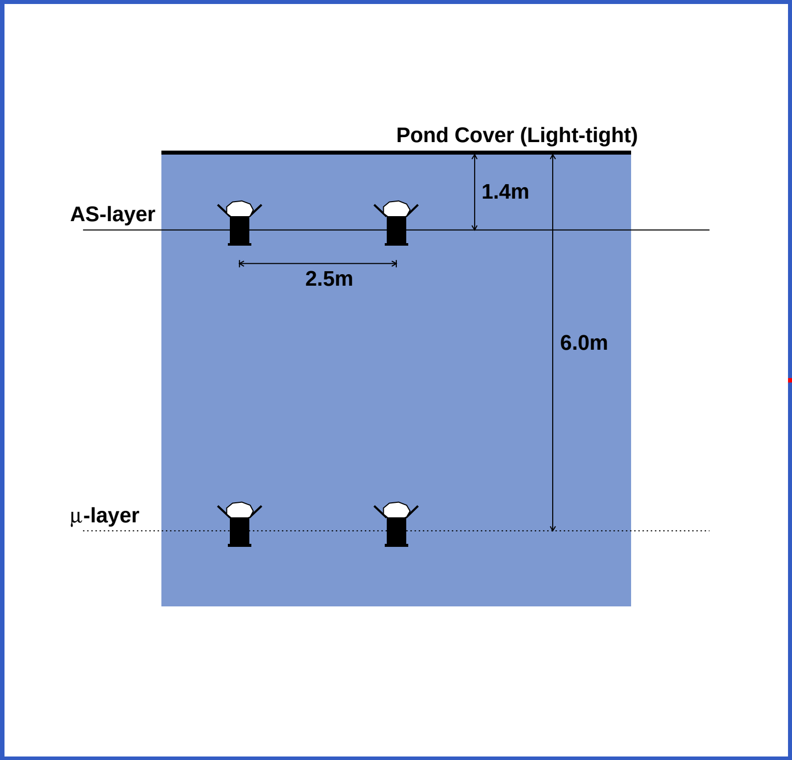
The Milagro pond



Detector Layout

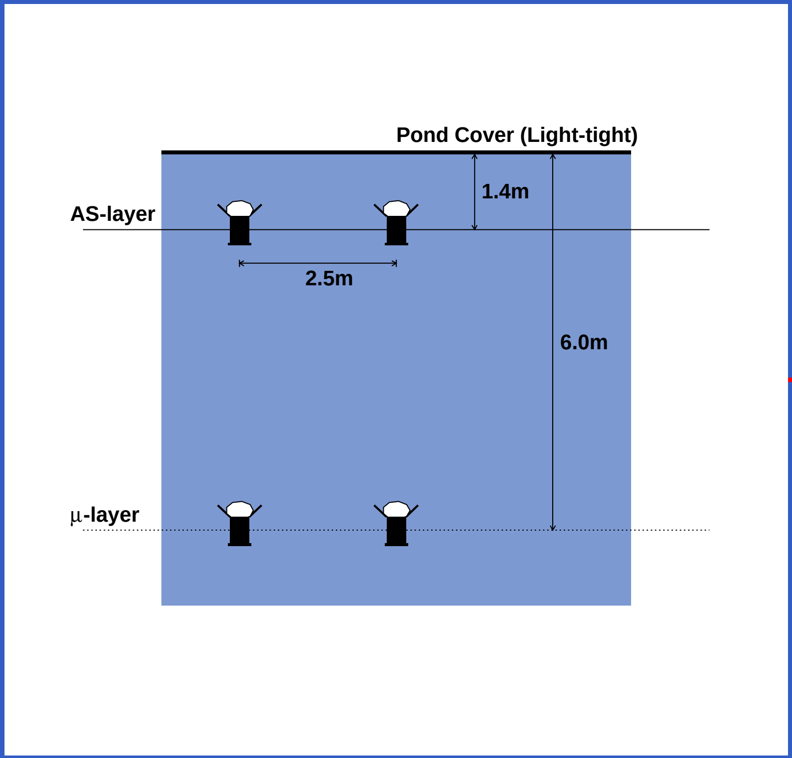


Detector Layout



723 Pond Photomultipliers

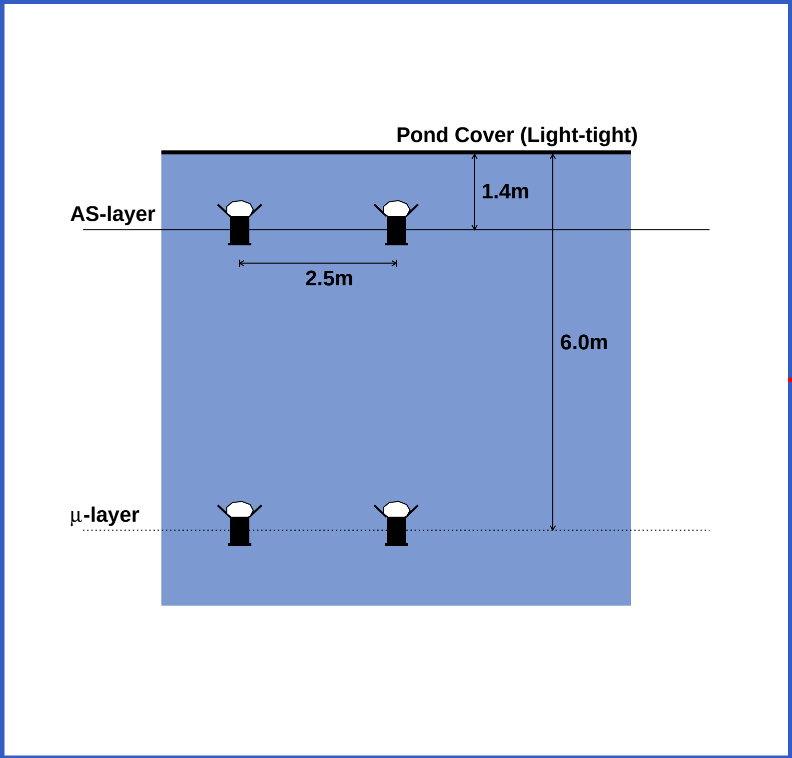
Detector Layout



723 Pond Photomultipliers

450 Air Shower

Detector Layout



723 Pond Photomultipliers

450 Air Shower

273 μ-Layer

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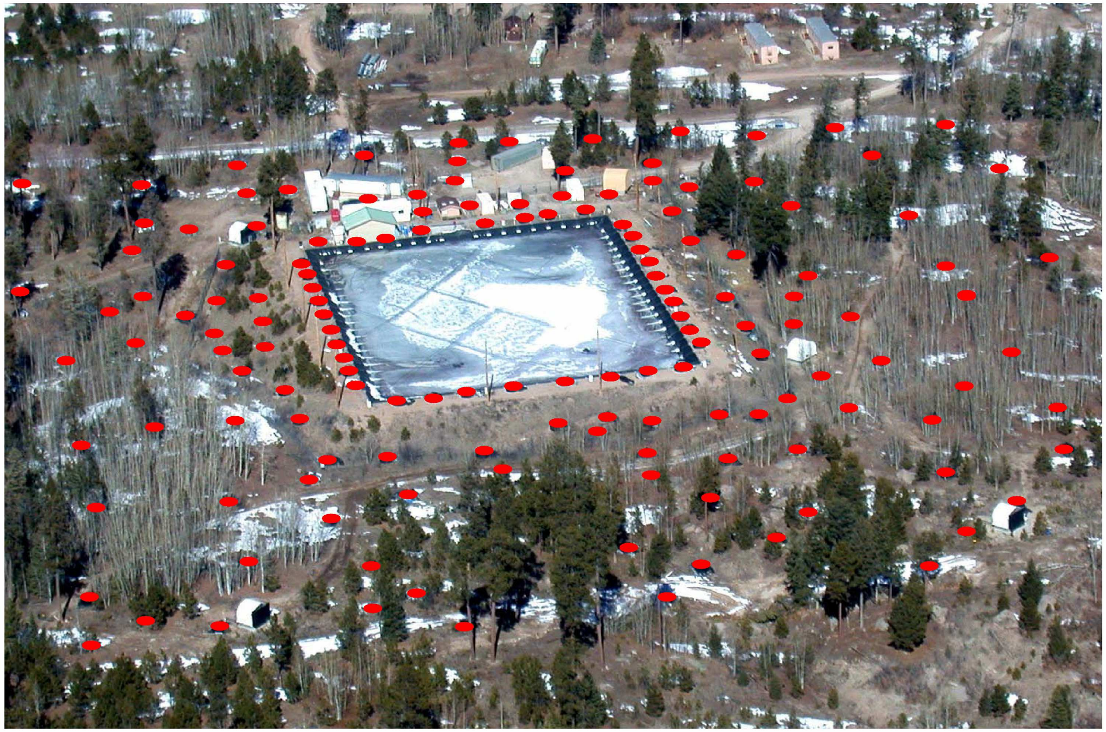
Detector Layout

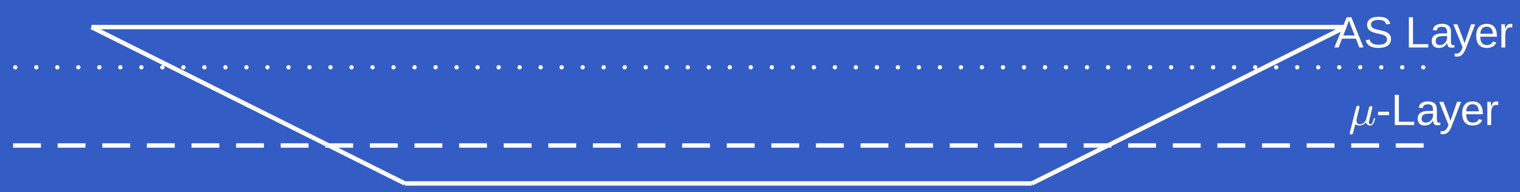
175 Outrigger Tanks

Detector Layout

175 Outrigger Tanks



Air Shower Detection With Milagro



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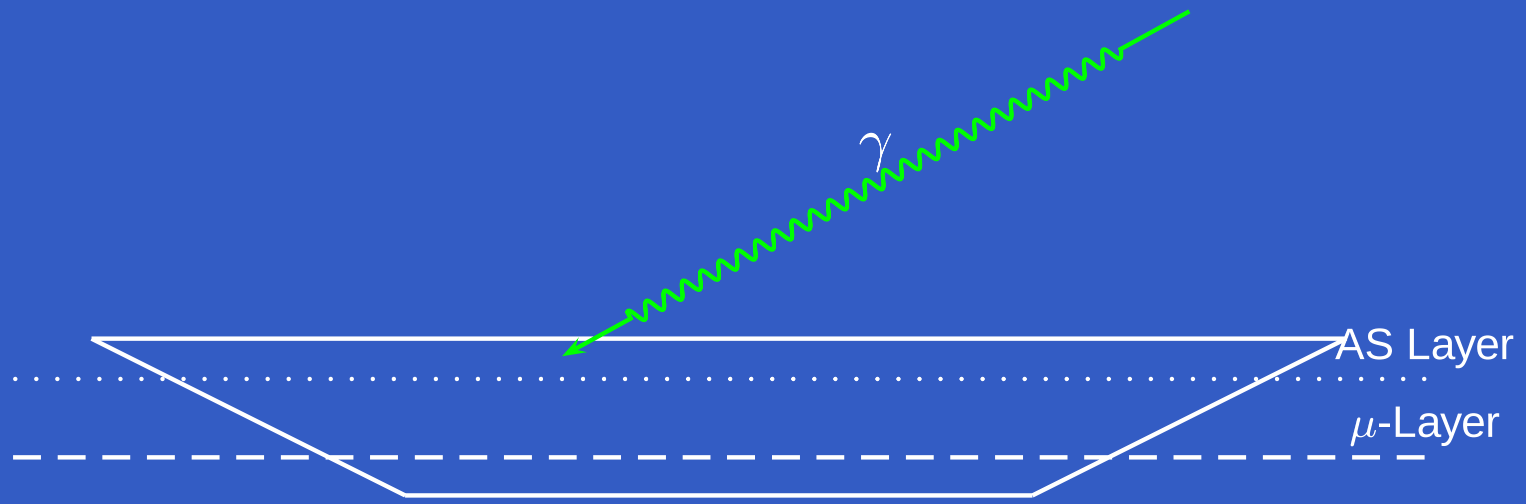

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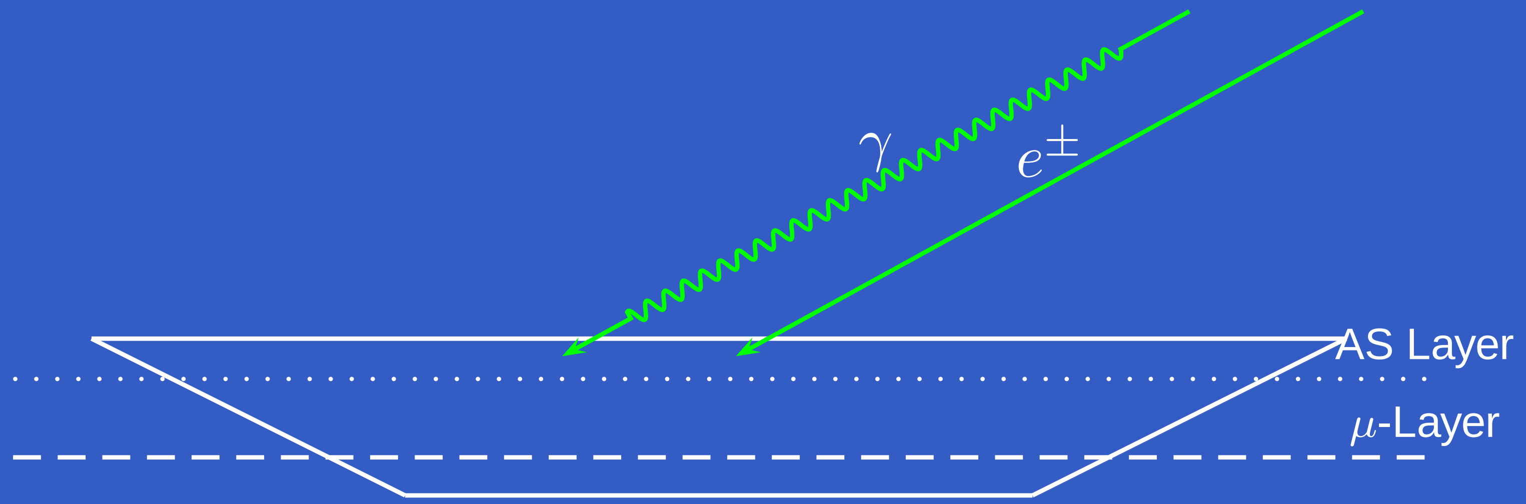

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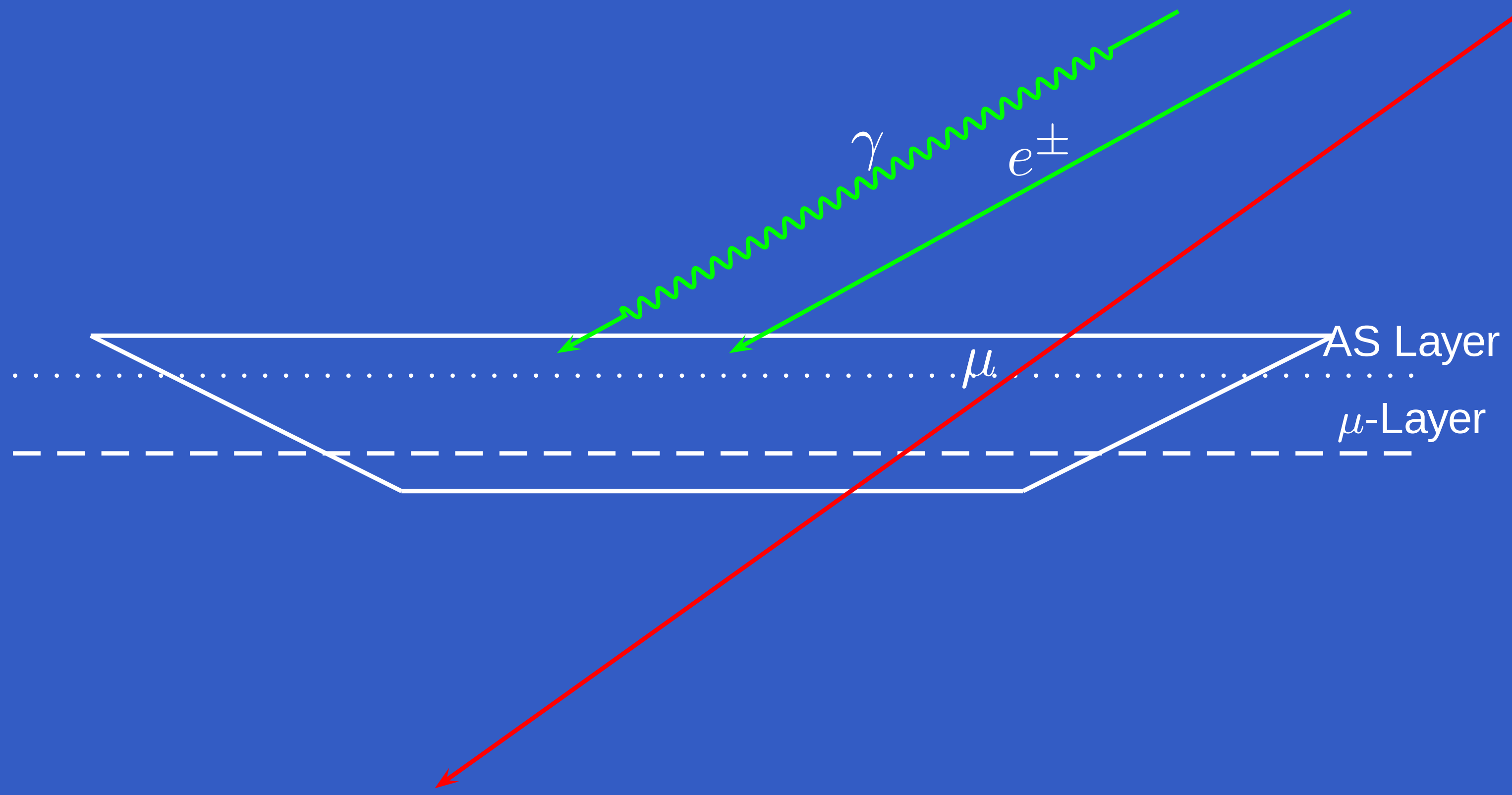

Air Shower Detection With Milagro

2TeVGamma

2TeVProton

2 TeV γ-ray primary

2 TeV proton primary

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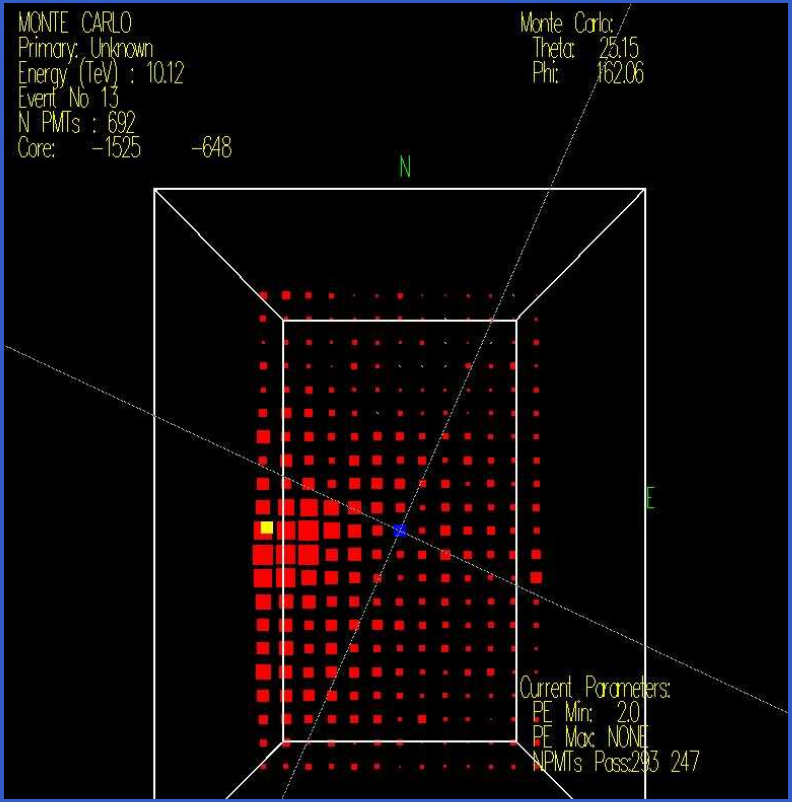
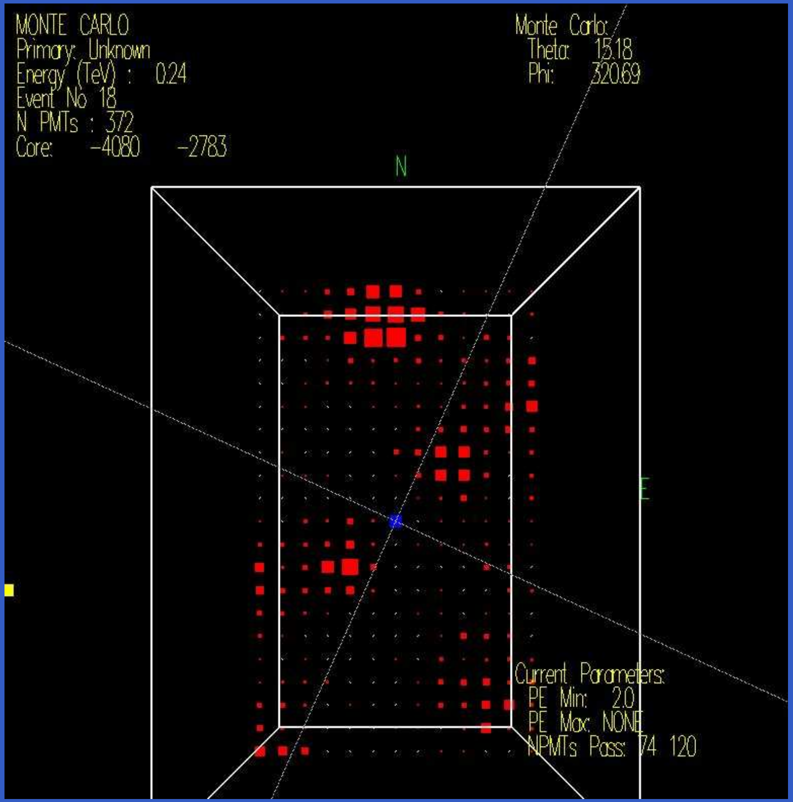
Air Shower Detection With Milagro



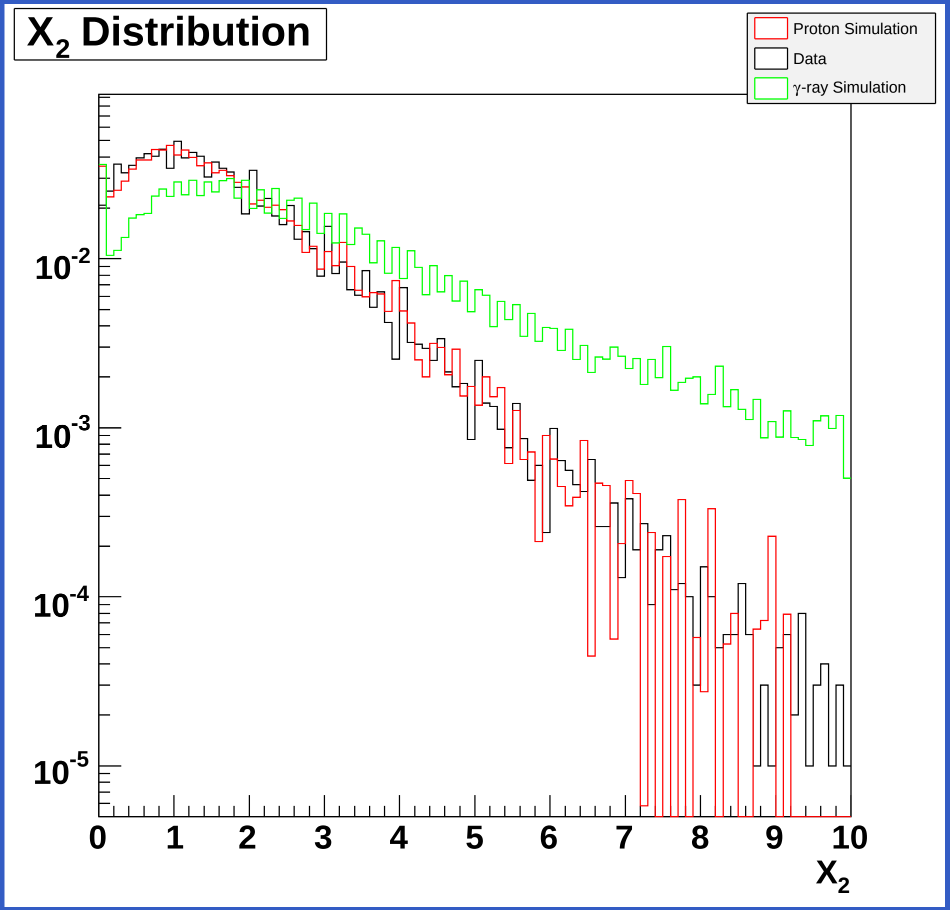
γ-ray primary



Proton primary

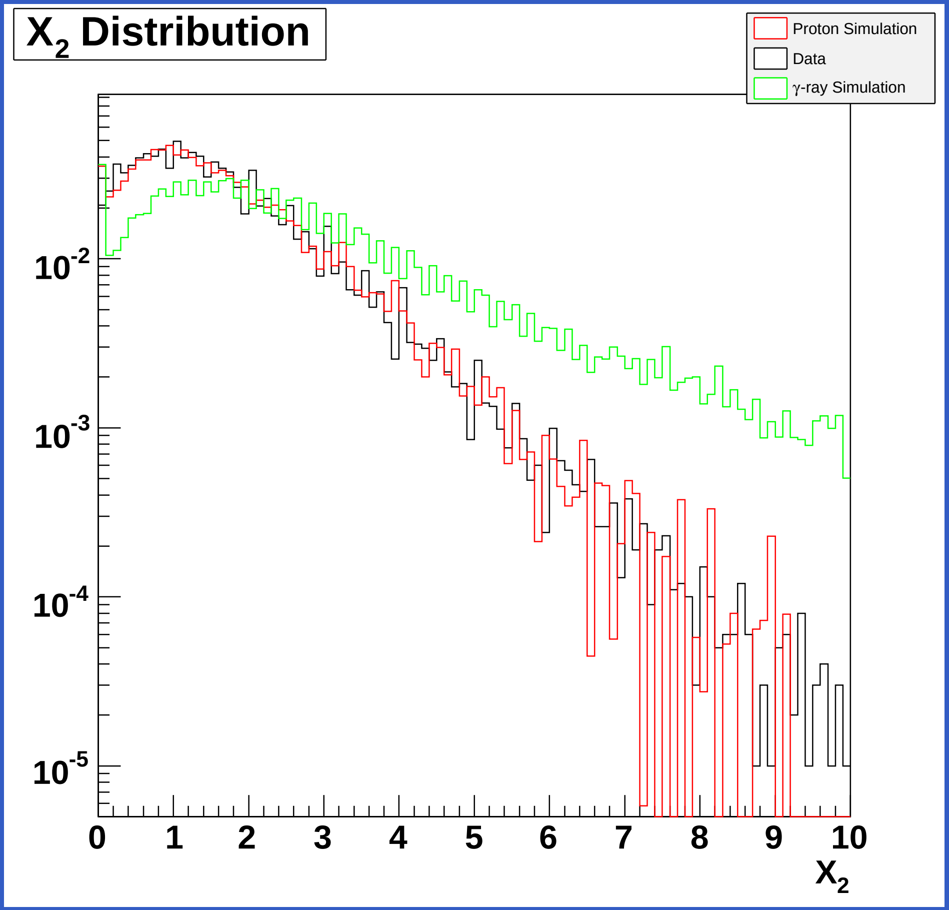
Air Shower Detection With Milagro

X_2 Parameter



Air Shower Detection With Milagro

$$X_2 = \frac{PE_{max,Bottom}}{N_{Bottom}}$$



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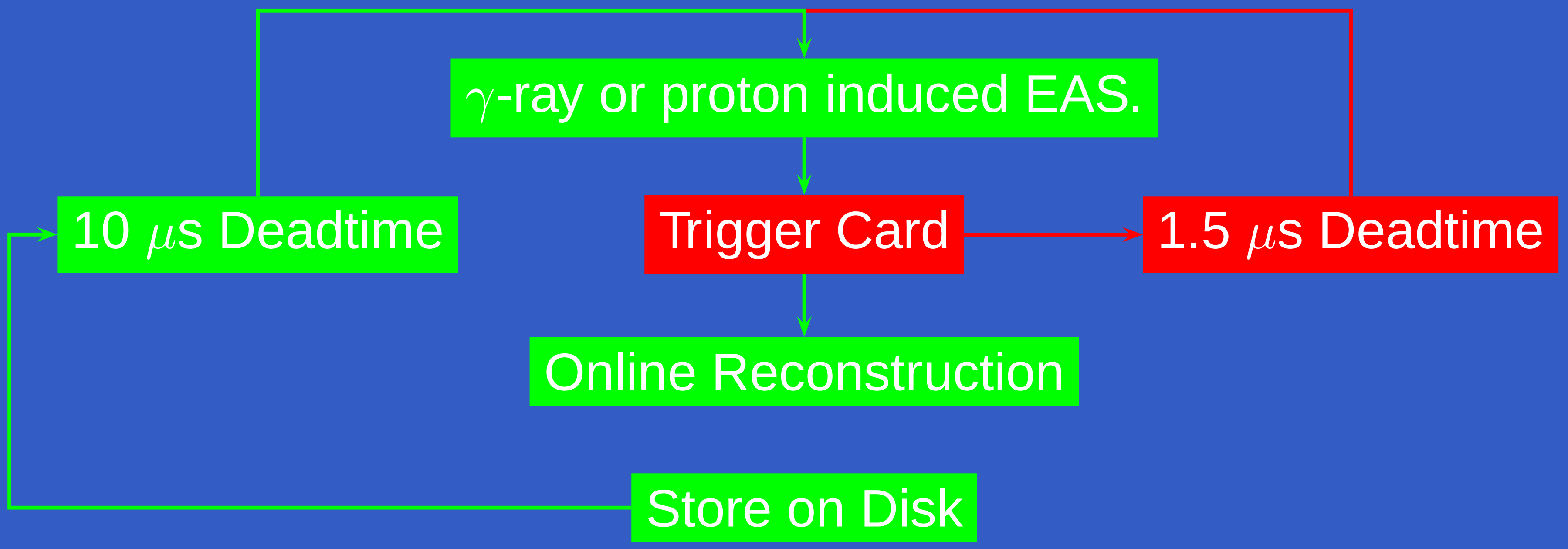

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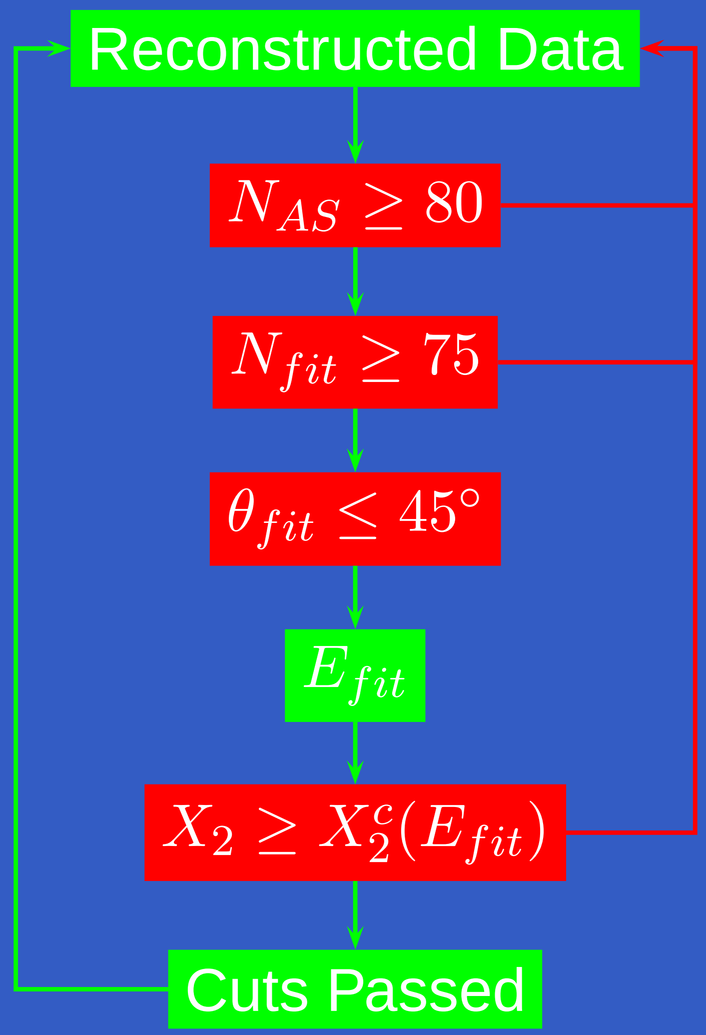

The Milagro Event-by-Event Energy Estimator

Energy estimation in Milagro is dependent upon:

- Number of AS PMT's triggered for a single event (N_{AS}).
- Number of outriggers triggered for a single event (N_{OR}).
- Reconstructed zenith angle (θ).
- Reconstructed distance of the core from the center of the pond (r_{core}).
- Outriggers necessary for accurate core reconstruction, and energy reconstruction. (2003 $\rightarrow$ 2006)

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The Milagro Event-by-Event Energy Estimator

Events are separated into 3 10° bins and 1 15° zenith angle bin. For each zenith angle bin each event is further separated into 6 r_{core} bins.

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The relationship for energy with the parameter p defined though

$$p = \frac{N_{AS}}{\cos(\theta)} + \bar{\omega} N_{OR}$$

is determined for each independent θ and r_{core} bin.

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$$p = \frac{N_{AS}}{\cos(\theta)} + \bar{\omega} N_{OR}$$

is determined for each independent θ and r_{core} bin.

$\bar{\omega}$ is the average weight applied to each outrigger tank to account for the relative difference in spacing between the OR tanks and the AS PMT's as well as the difference in triggering efficiency.

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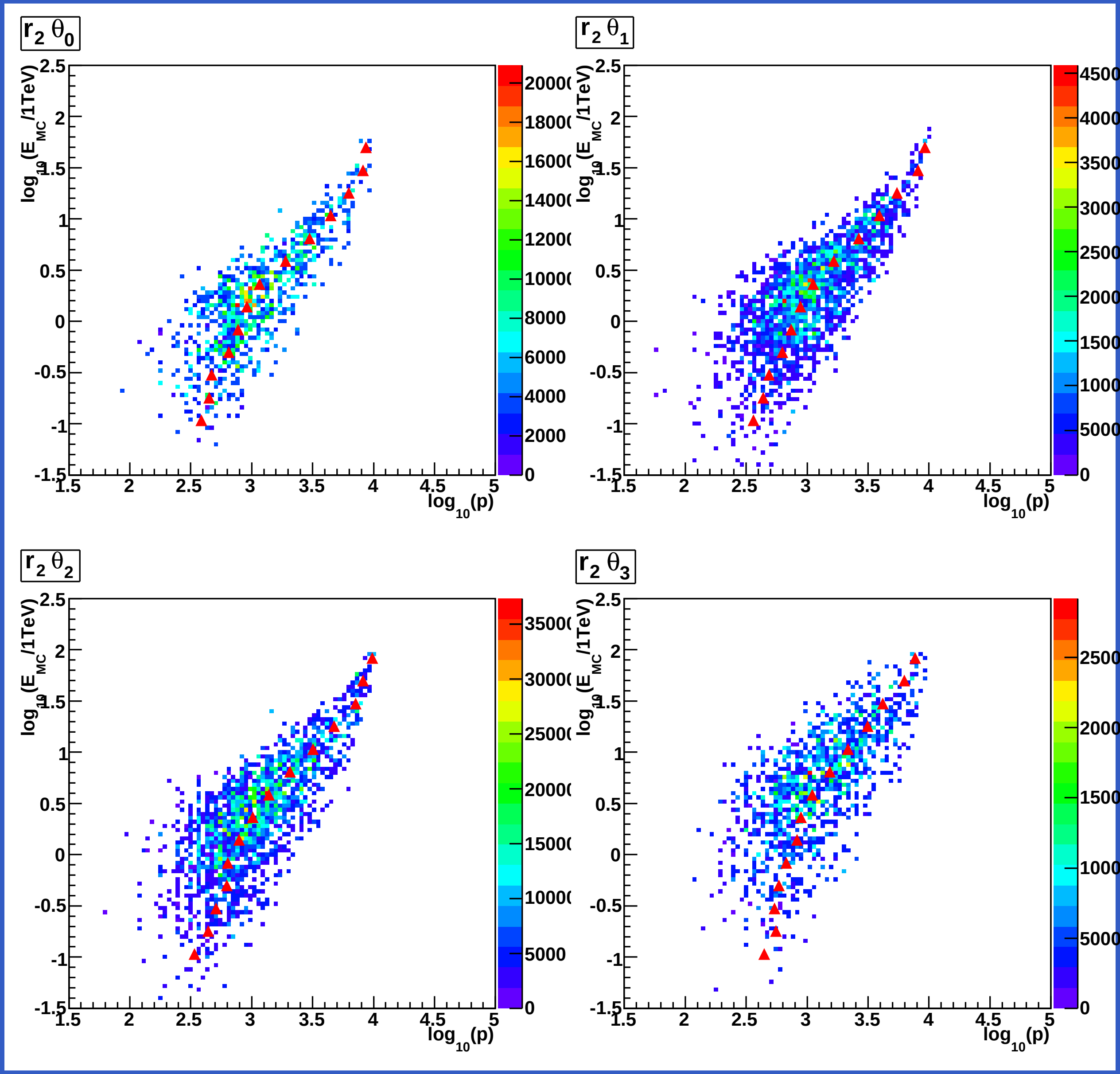
The Milagro Event-by-Event Energy Estimator



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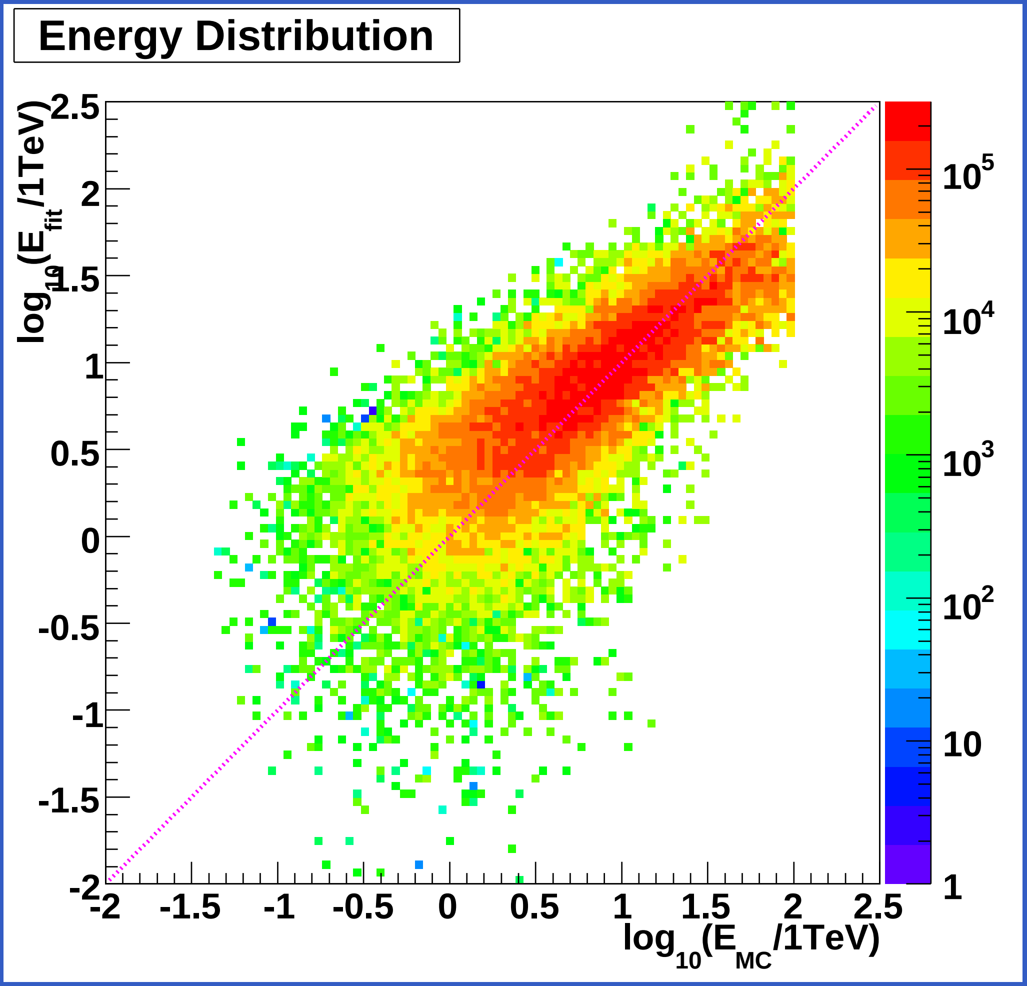
The Milagro Event-by-Event Energy Estimator

- E_{fit} vs. E_{mc}
- Energy resolutions of $\simeq$ 37% at high energies.



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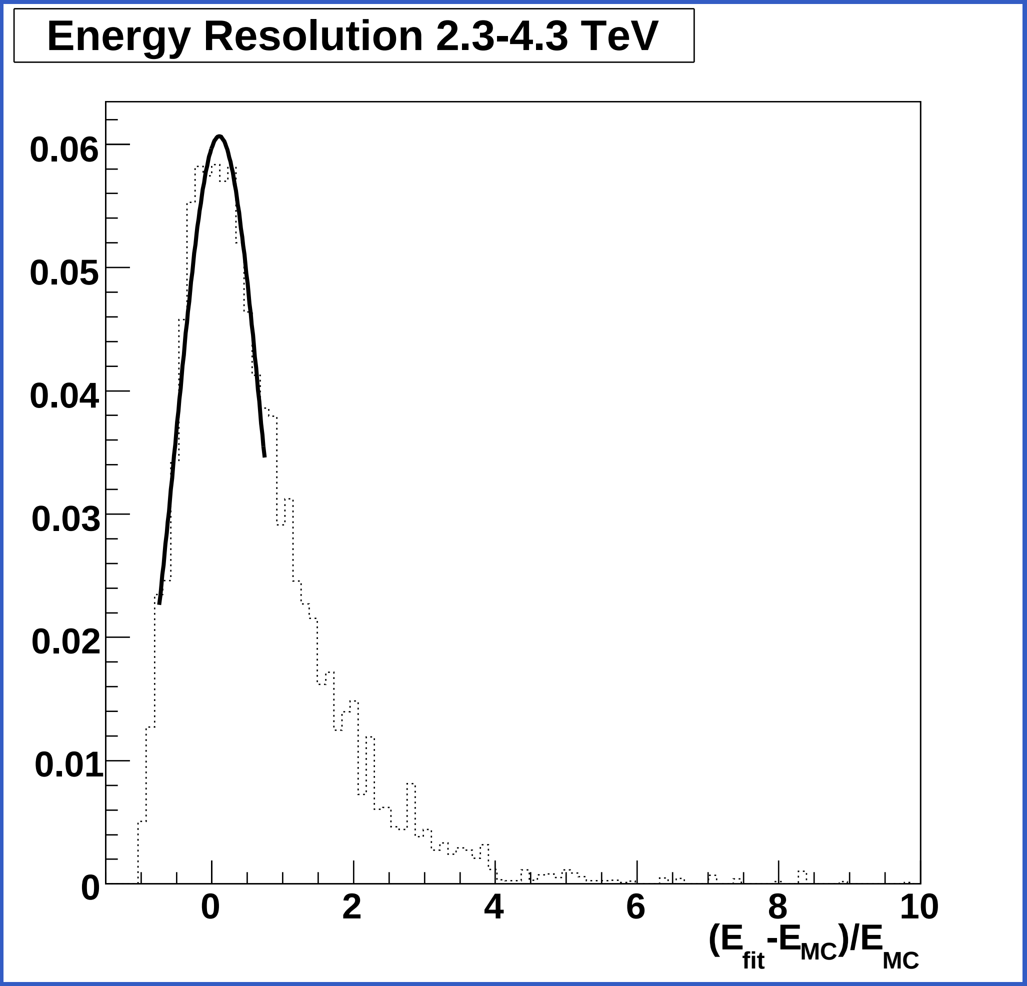

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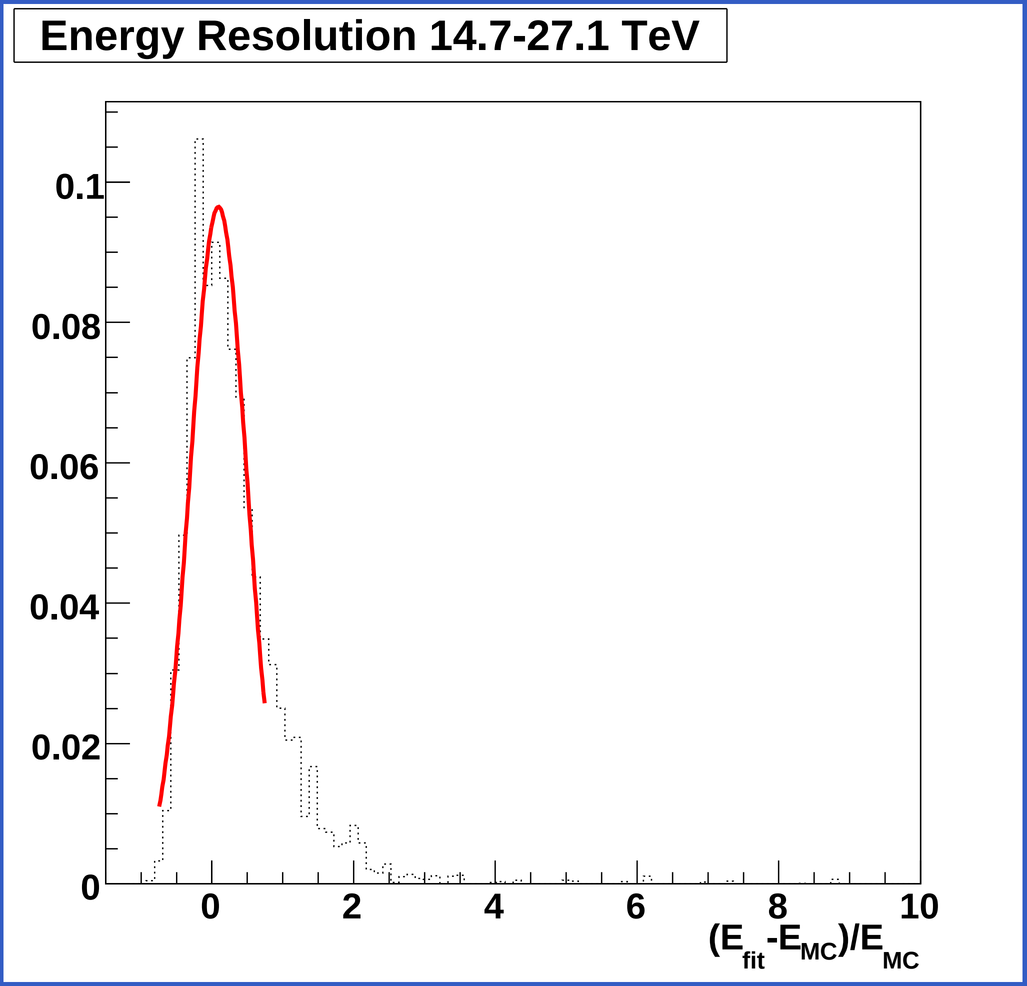

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Spectral Determination with Milagro

The number of expected events in the k-th bin may be computed through

$$N_k^{(e)} = \int_{0^\circ}^{45^\circ} d\theta \int_{0.1TeV}^{100TeV} dE \epsilon(\theta) j(E, \vec{\gamma}) f_k(E) A(E, \theta) w(E, \theta)$$

A χ^2 function is defined for an assumed spectrum $j(\vec{\gamma})$ given by

$$\sum_{i=0}^{N_{bins}} \left\{ \frac{N_k - N_k^{(e)}}{\sigma_k} \right\}^2$$

Spectral Determination with Milagro

The number of expected events in the k-th bin may be computed through

$$N_k^{(e)} = \sum_{i=1}^{45} \delta\theta_i \sum_{j=1}^{70} \delta E_j \epsilon(\theta_i) j(E_j, \vec{\gamma}) f_k(E_j) A(E_j, \theta_i) w(E_j, \theta_i)$$

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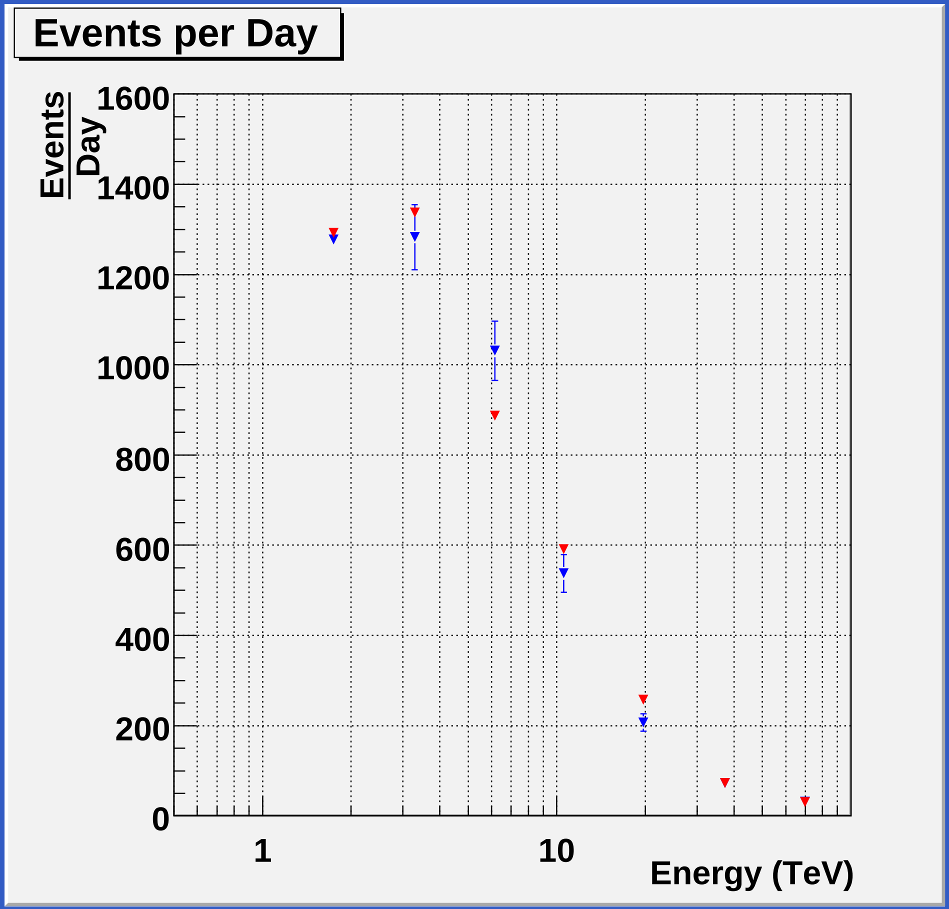
Milagro Measurement of the Cosmic Ray Spectrum

Number of Expected vs. Measured Events
for the optimum Cosmic Ray Spectrum.



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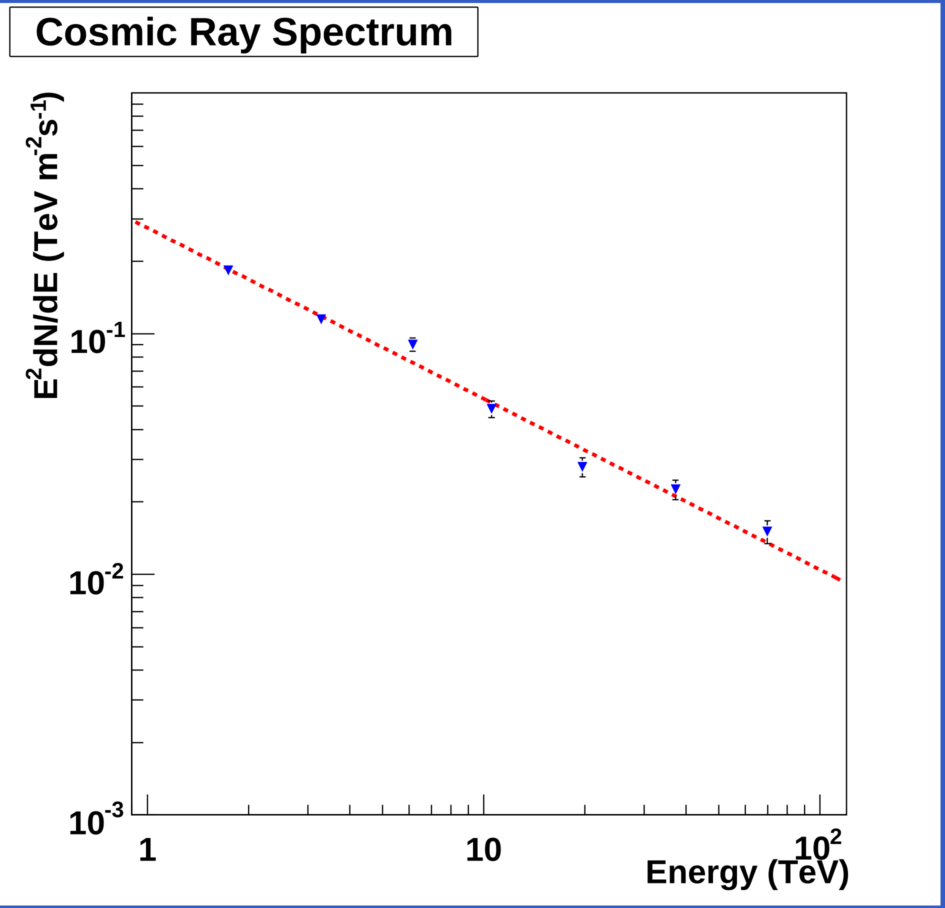
Milagro Measurement of the Cosmic Ray Spectrum

Milagro Cosmic Ray Spectrum



Milagro Measurement of the Cosmic Ray Spectrum

Milagro Cosmic Ray Spectrum

$$
\begin{aligned}
j(E) &= I_0 \left\{ \frac{E}{10TeV} \right\}^{\gamma} \\
I_0 &= (5.56 \pm 0.13) \times 10^{-4} TeV^{-1} s^{-1} m^{-2} sr^{-1} \\
\gamma &= -2.69 \pm 0.08 \\
\tilde{\chi}^2 &= 2.13
\end{aligned}
$$

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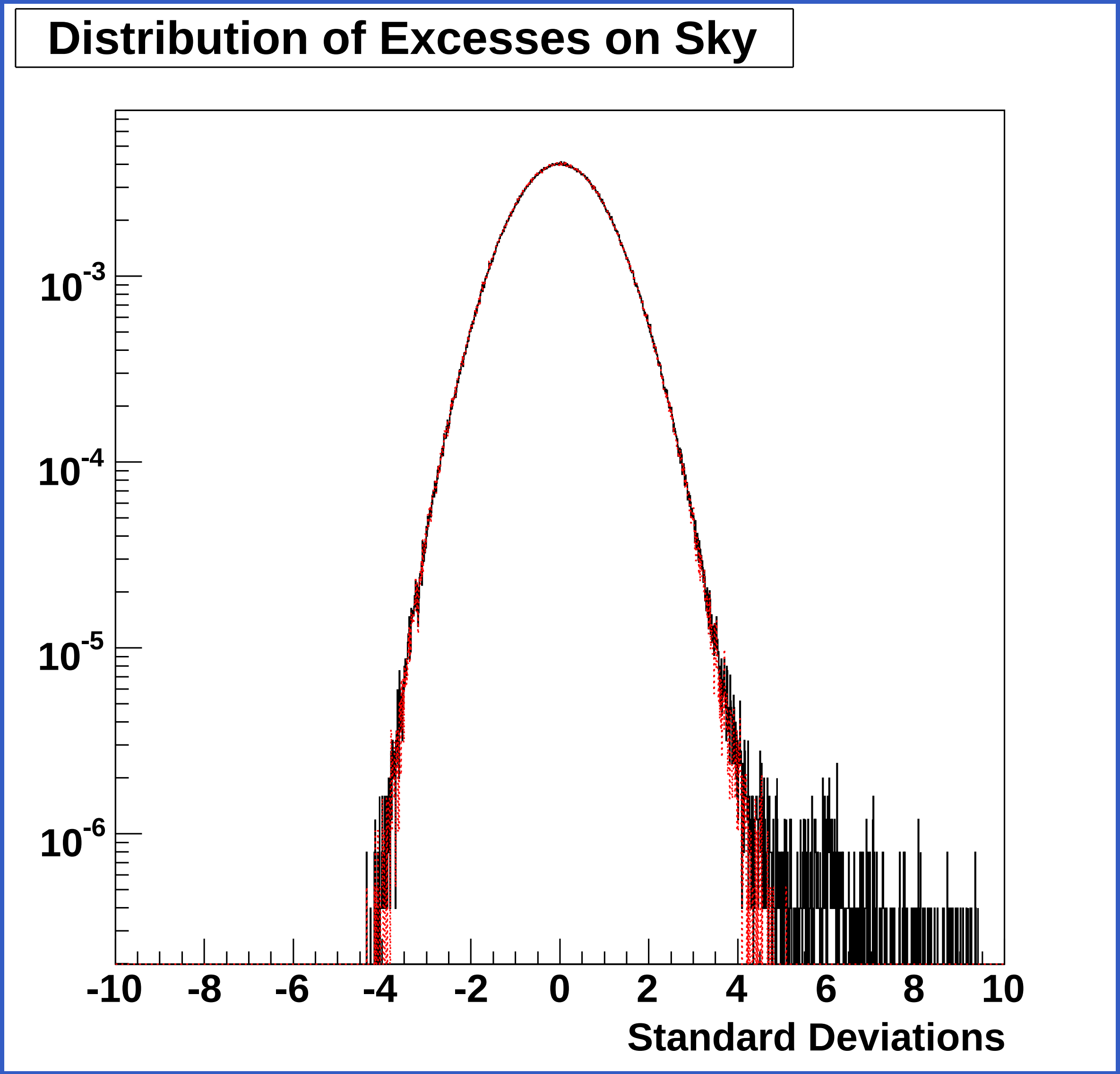
Sources Observed With Milagro

- Approximately 1000 days of data from March 2003 $\longrightarrow$ March 2006 available for spectral Analysis in Milagro.
- For this data set three sources

Sources Observed With Milagro



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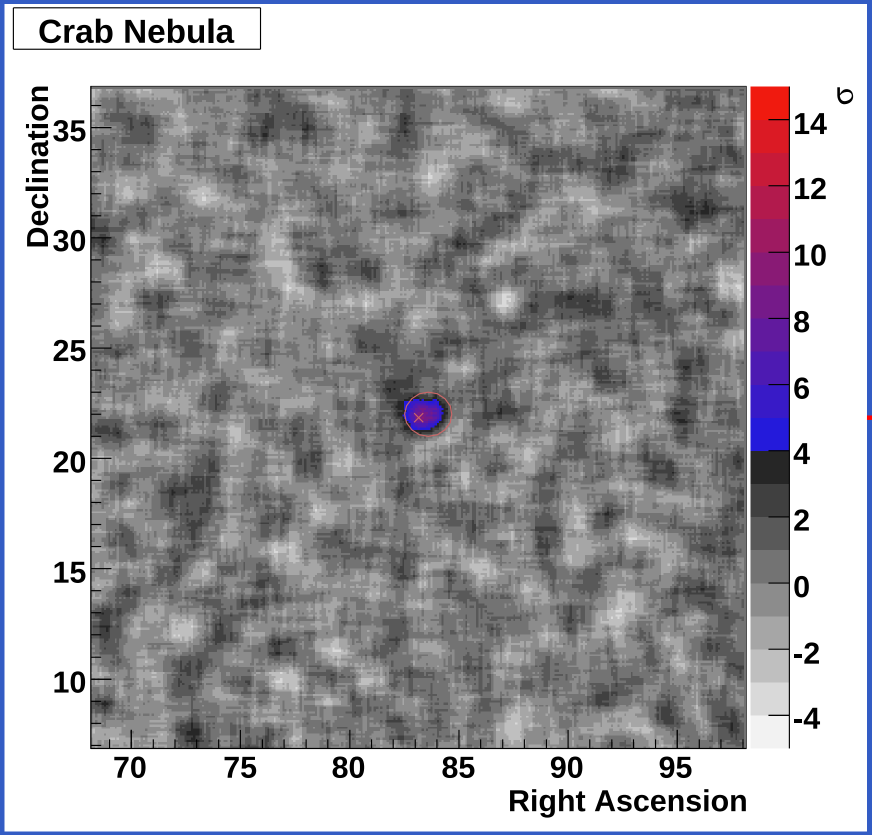

Source	Significance
Crab Nebula	9.24σ
Mrk 421	4.5σ
Cygnus Region	6.30σ

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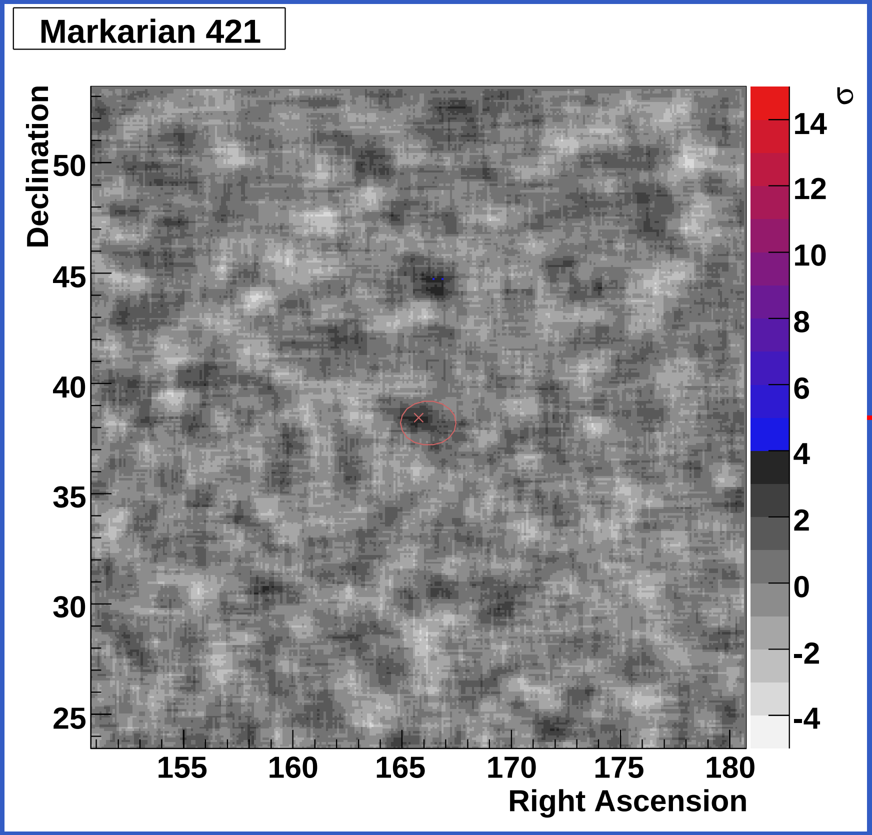

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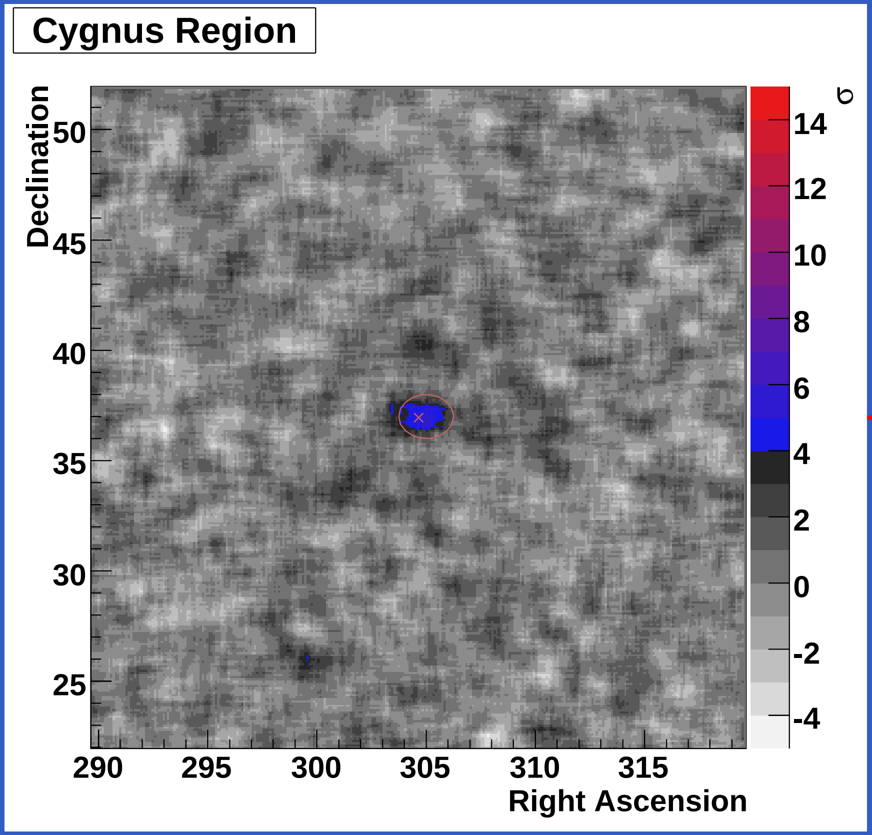

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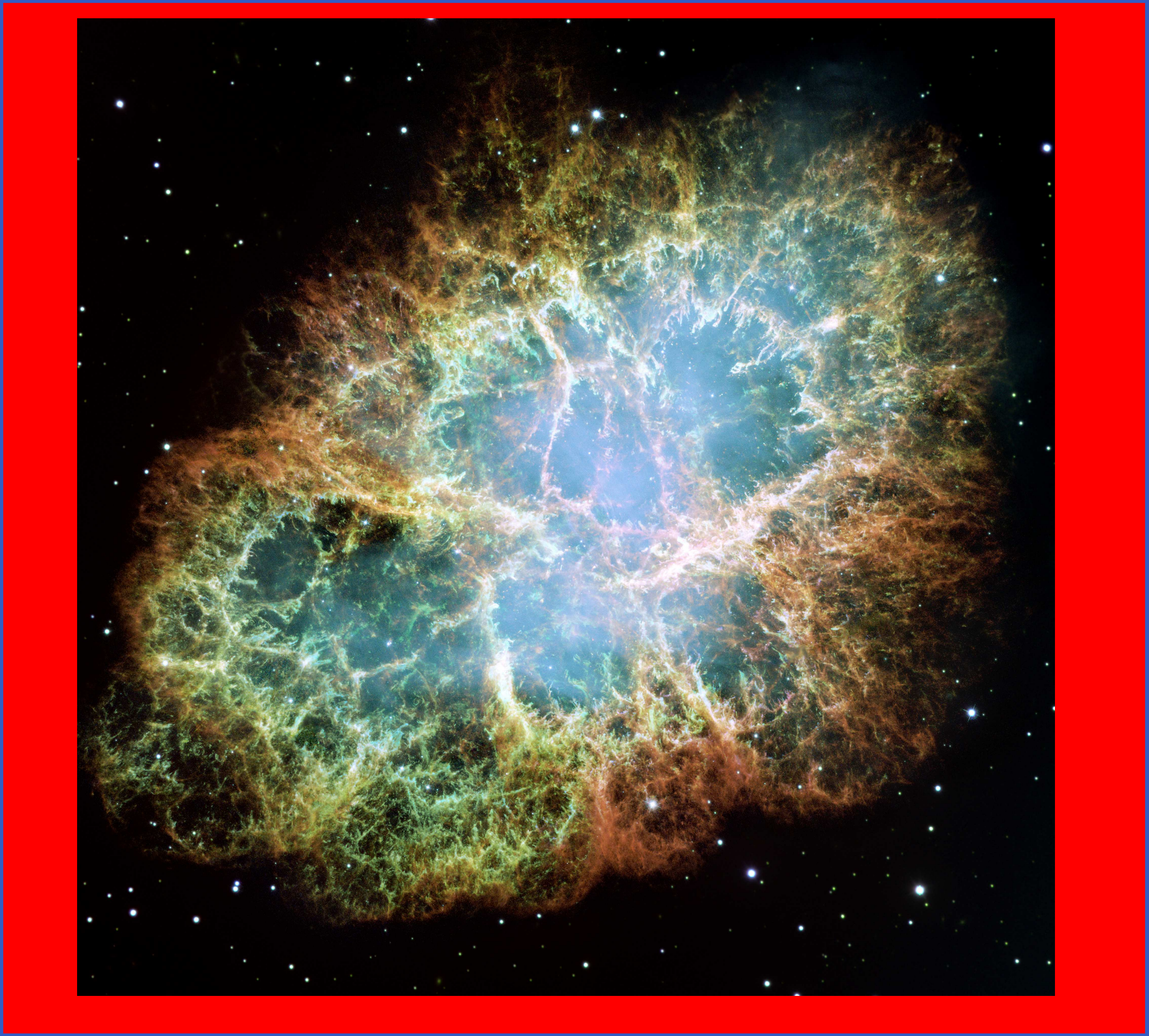
The Crab Nebula



The Crab Nebula

krebs

Hester, J. et. al. (NASA/AXA/ASU)

The Crab Nebula

- Since the first VHE detection by Whipple in 1989 (*Weeks et al 1989*) other ACT's have found the spectrum of the Crab Nebula to obey a power law

$$j(E) = I_0 E^{\gamma}$$

or a power law with an exponential cutoff

$$j_c(E) = I_0 E^{\gamma} e^{-\frac{E}{E_c}}$$

above 0.1 TeV. In good agreement with the SSC model.

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  above 0.1 TeV. In good agreement with the SSC model.
- Recent measurements from Cangaroo, HESS, and HEGRA give different cutoff values (E_c).

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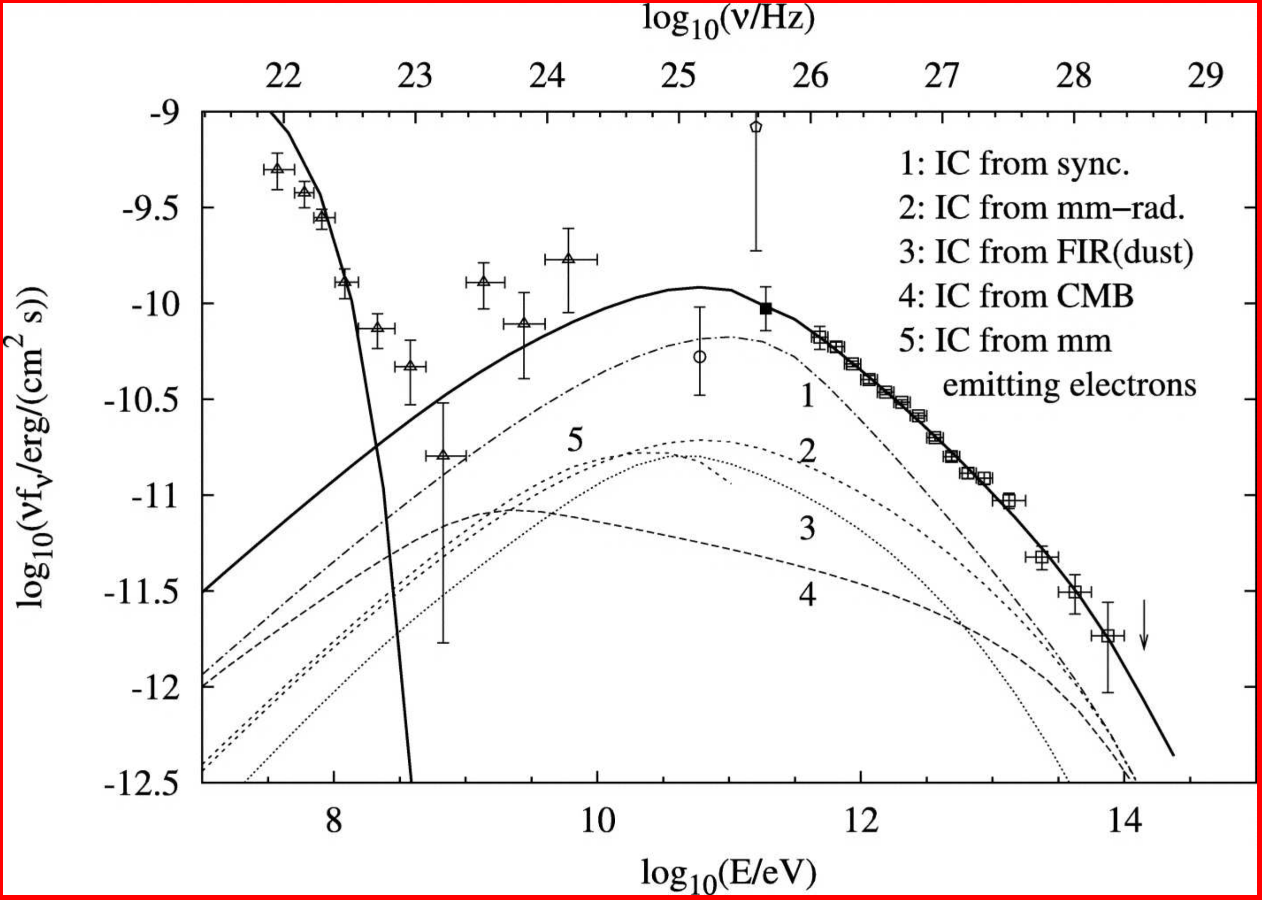
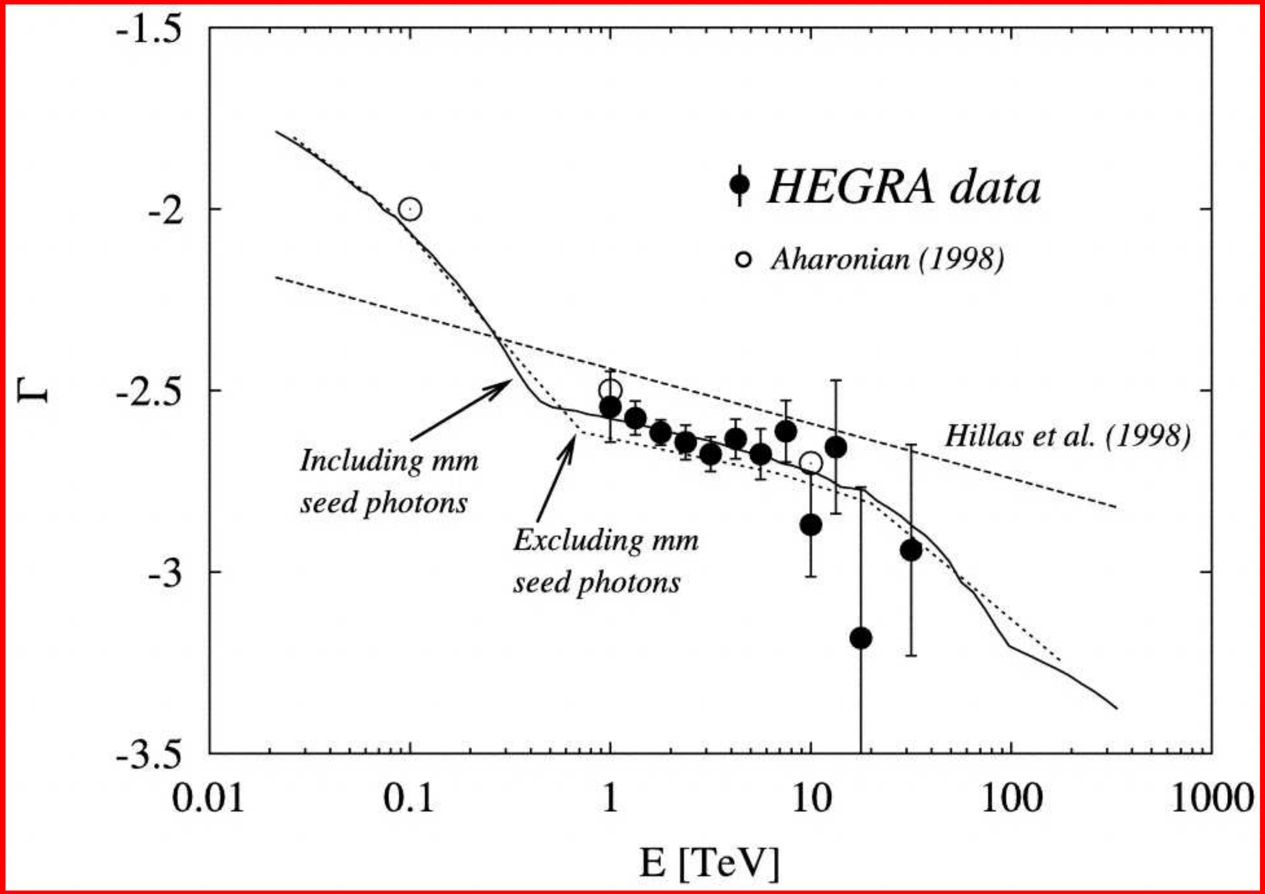
The Crab Nebula



(Aharononain, et. al. 2004) astro-ph/0407118

The Crab Nebula



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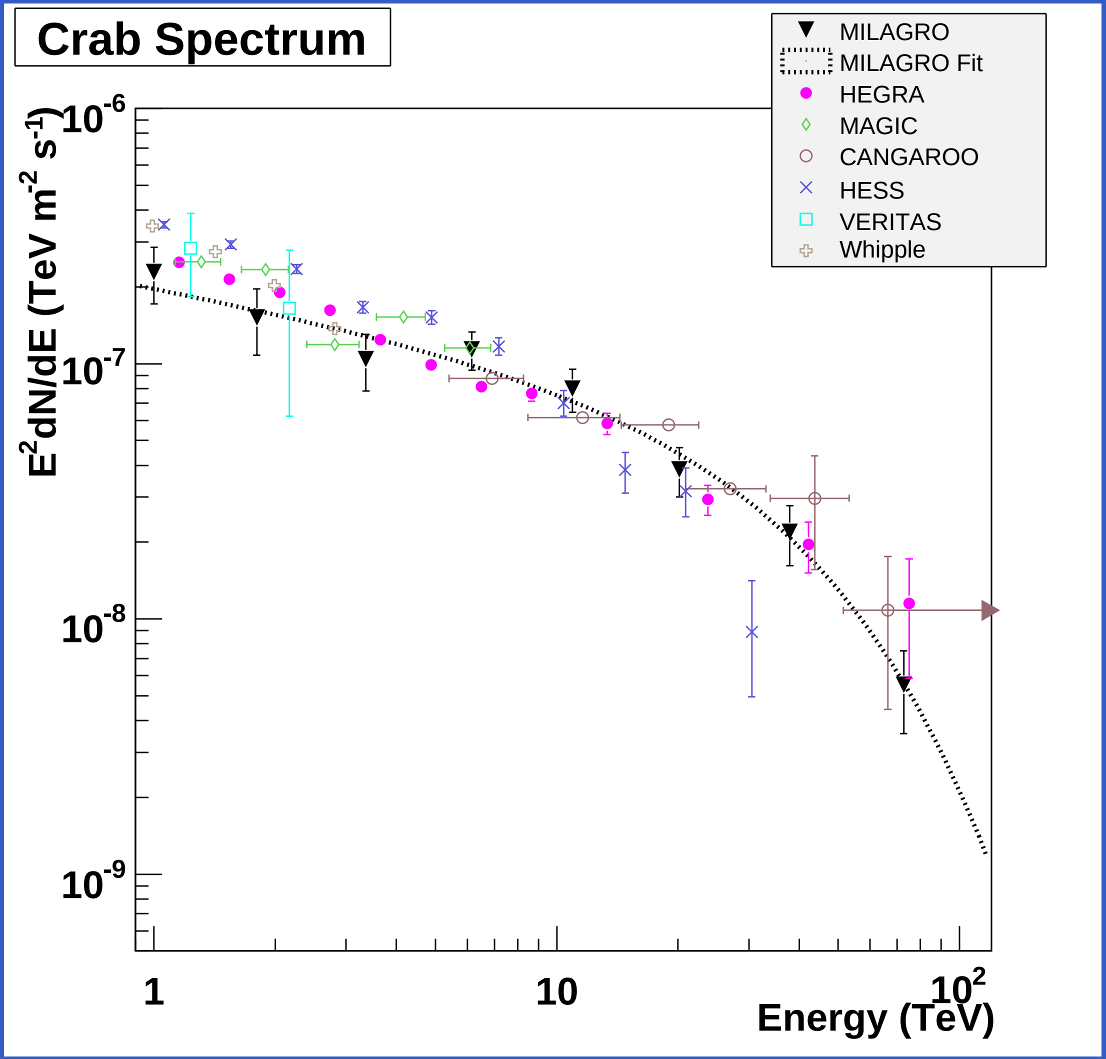
The Crab Nebula

Milagro Measurement of the Crab Spectrum



F. Aharonian, et. al. (2006)

F. Aharonian, et. al. (2004)

T. Tanimori, et. al. (1998)

A.M. Hillas, et. al. (1998)

J. Holder, et. al. (2006)

R.M. Wagner, et. al. (2005)

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The Crab Nebula

Measurements of E_c

Detector	E_c (TeV)
HEGRA	None
HESS	14.3 ± 1 TeV
Milagro	32 ± 20 TeV

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The Crab Nebula

Measurements of E_c

Detector	E_c (TeV)
HEGRA	None
HESS	14.3 ± 1 TeV
Milagro	32 ± 20 TeV
Milagro+HEGRA (*Preliminary*)	23 ± 3 TeV

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Summary

- Demonstration that energy spectra can be accurately reconstructed using the water cherenkov method.
- Provides a unique measurement of spectra averaged over years instead of days.
- Further motivation for the next generation water cherenkov telescopes, which may provide year round observation of spectral variability.

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