# Milagro, A Water Cherenkov Calorimeter for TeV Gamma Ray Astrophysics.

**Aous Abdo**

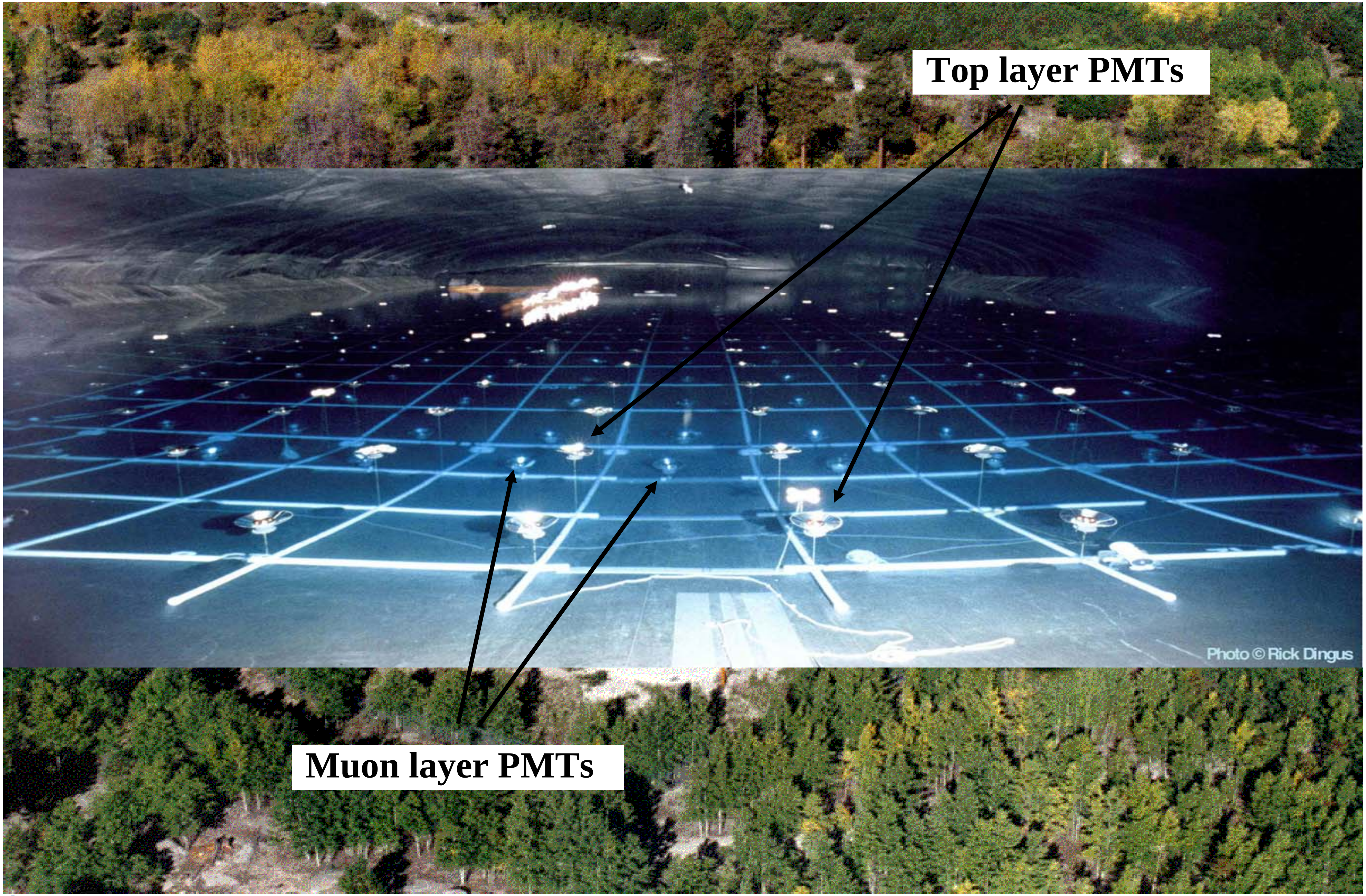
**For the Milagro Collaboration**

**June 6, 2006, Chicago, USA**

# The Milagro TeV γ-ray Detector:

- Water Cherenkov detector Located in Jemez Mountains near Los Alamos NM
- Elevation: 2630 m
- Central pond: 80m X 60m X 8m (depth) (5000 $m^2$)
  - Top layer: 450 PMTs under 1.4 m
  - Muon layer: 273 PMTs under 6 m
- Outrigger array: 175 4000 L water tanks ~ 40,000 $m^2$
- 2 Steradians field of view
- 1700 Hz trigger rate
- > 90 % duty cycle
- 0.6 – 0.3 degree PSF
- 0.1 – 100 TeV energy range

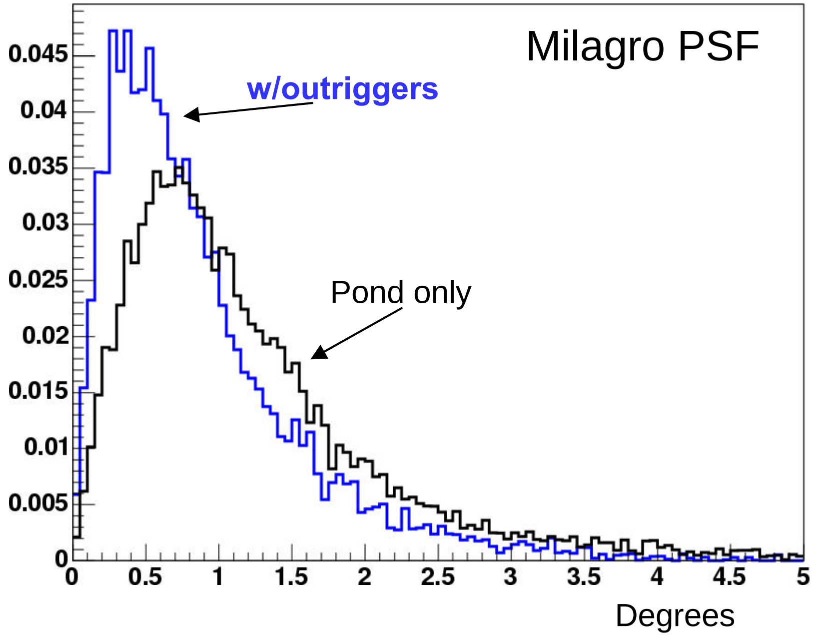
# The Central Pond

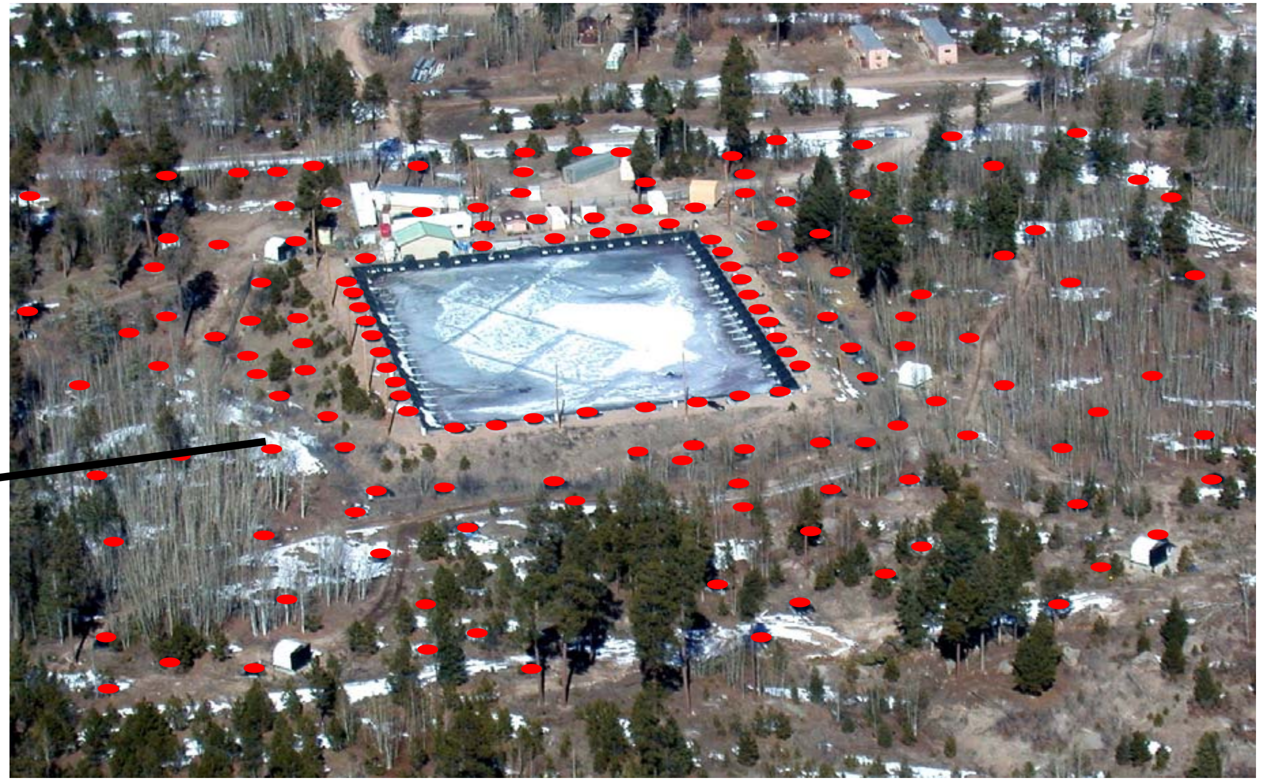


# The Outrigger Array

## Improved:

- Angular Resolution by a factor of 1.4
- Background Rejection
- Energy Resolution

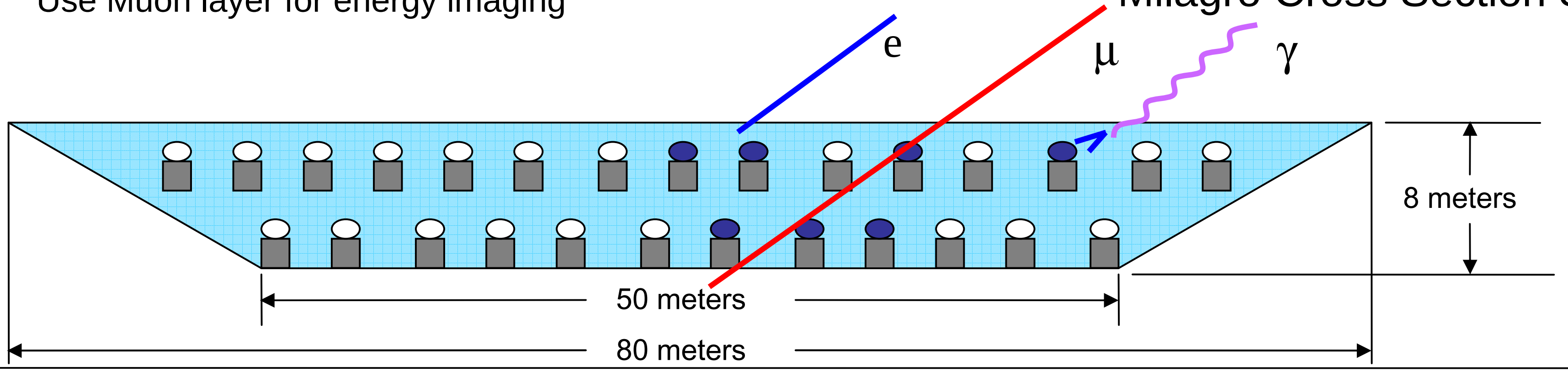


# Milagro: A TeV γ-ray Calorimeter

- Atmosphere acts as an absorber:
  - 750 g/cm$^2$ overburden (73% of Atmosphere)
  - 20.5 $X_o$ for gamma-ray showers and 8.3 $\lambda_I$ for hadronic showers
- Milagro is thus a " Tail catcher Calorimeter"
  - Water as detection medium
  - Detect Cherenkov light form secondary charged particles in the shower
- Top layer: 4 $X_o$ and 1.7 $\lambda_I$
  - $\gamma \rightarrow e^- + e^+ \rightarrow$ Cherenkov radiate
- Muon layer:17 $X_o$ and 7.2 $\lambda_I$
  - Most EM charged particles get absorbed
  - Muons with energy as low as 1.2 GeV penetrate and shower near the Muon layer
  - Use Muon layer for energy imaging

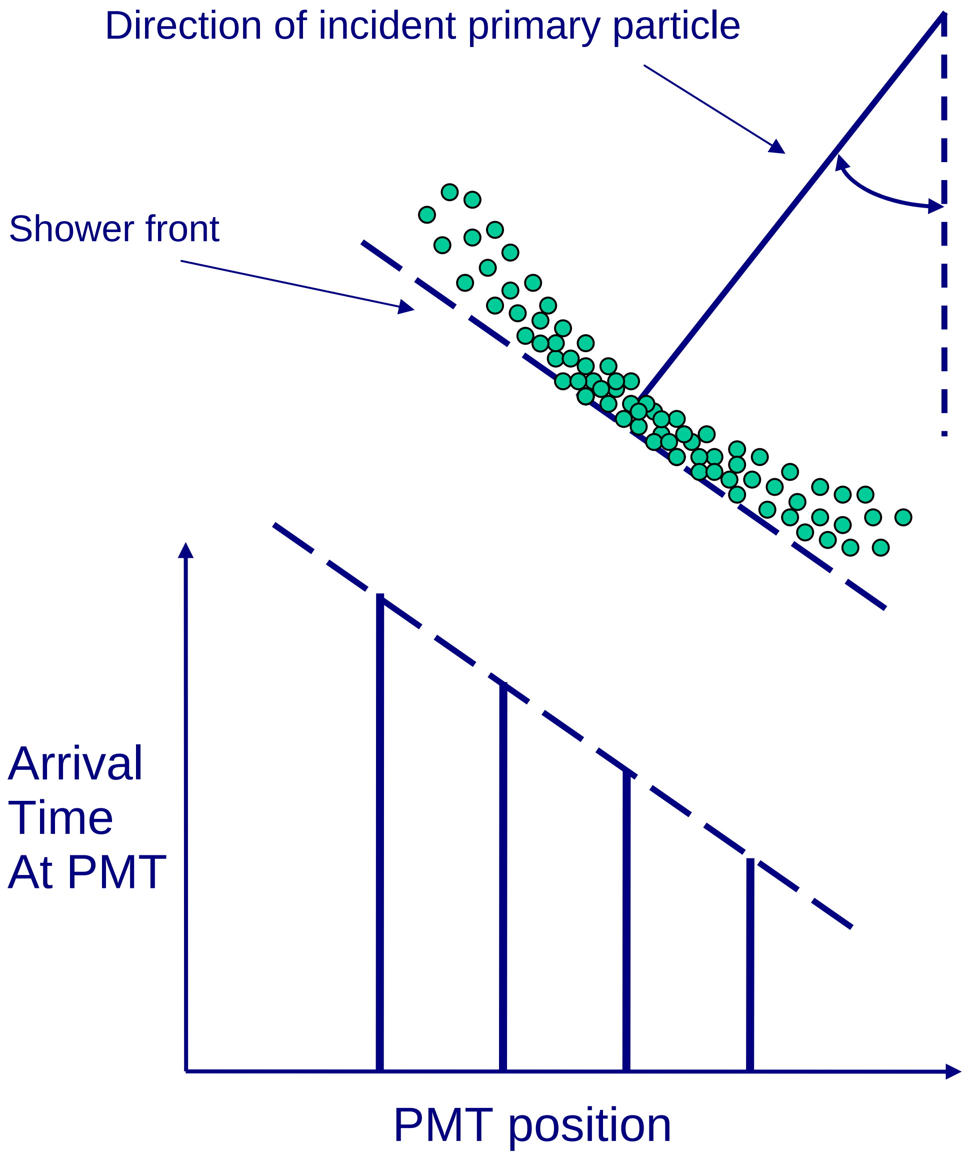
Milagro Cross Section Schematic

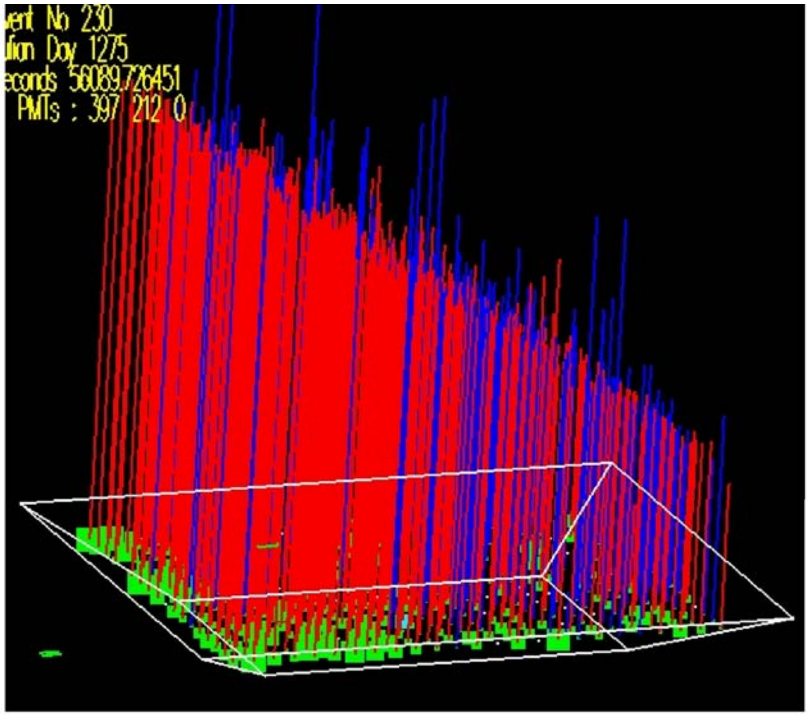


# Event Reconstruction

**Use nsec timing from each PMT hit to determine:**

- Core Location
- Direction of Primary Particle



# Background Rejection in Milagro

Hadronic EAS out number Gamma Ray EAS by 10,000:1

Differences between Hadron- and Gamma-ray- initiated EAS

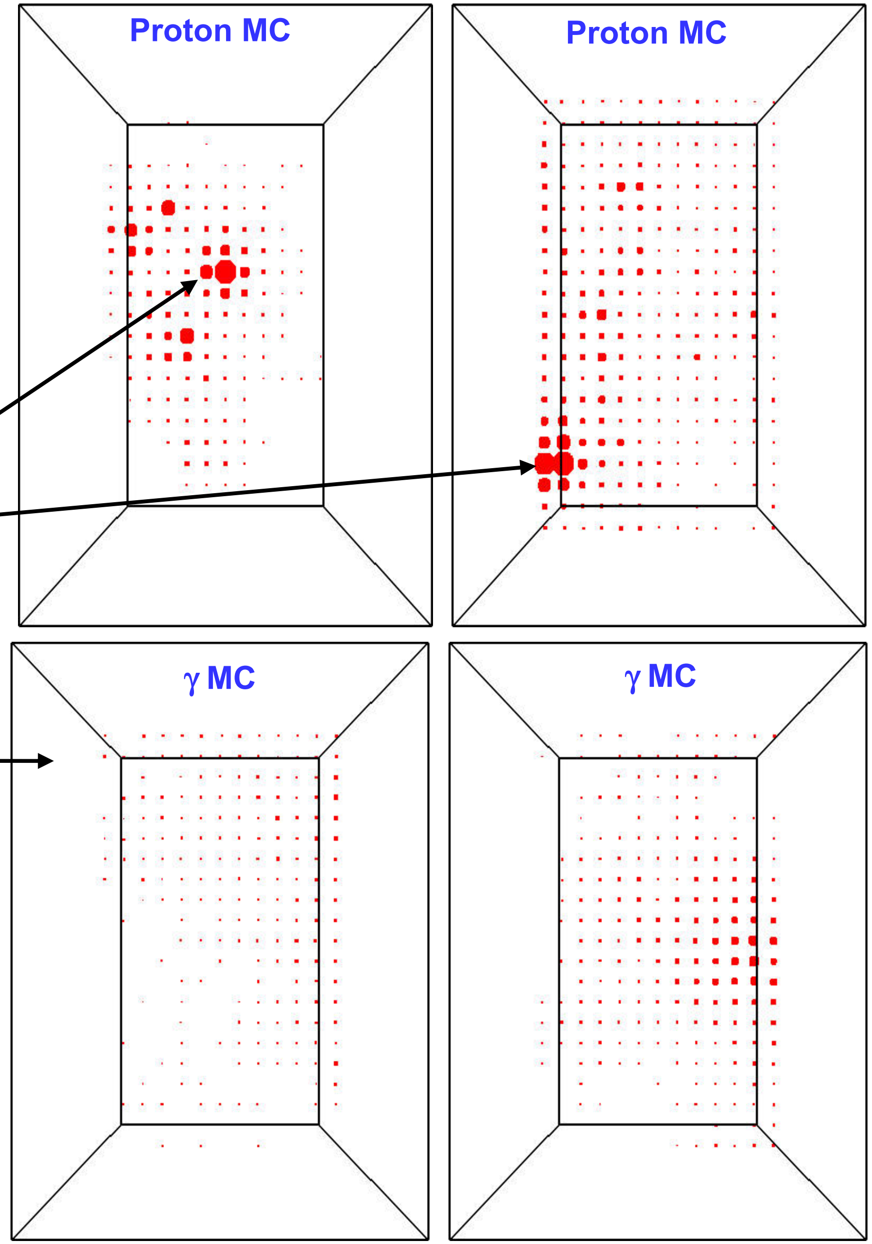
## Hadronic Showers

- Contain many more muons than those for gamma ray EAS
- ➔ Result in a bright, compact clusters of light in the Muon layer

## Gamma Ray Showers

- Gamma EAS illuminate the Muon layer uniformly, with small hits

Muon Layer Images



# Background Rejection (Cont'd)

- Parameterize "clumpiness" of the Muon layer hits with the $A_4$ Variable

$$A_4 = \frac{(fTop + fOut) * nFit}{mxPE}$$

Shower size

Clumpiness

How well the shower was fit

Apply a cut on $A_4$ to reject hadrons

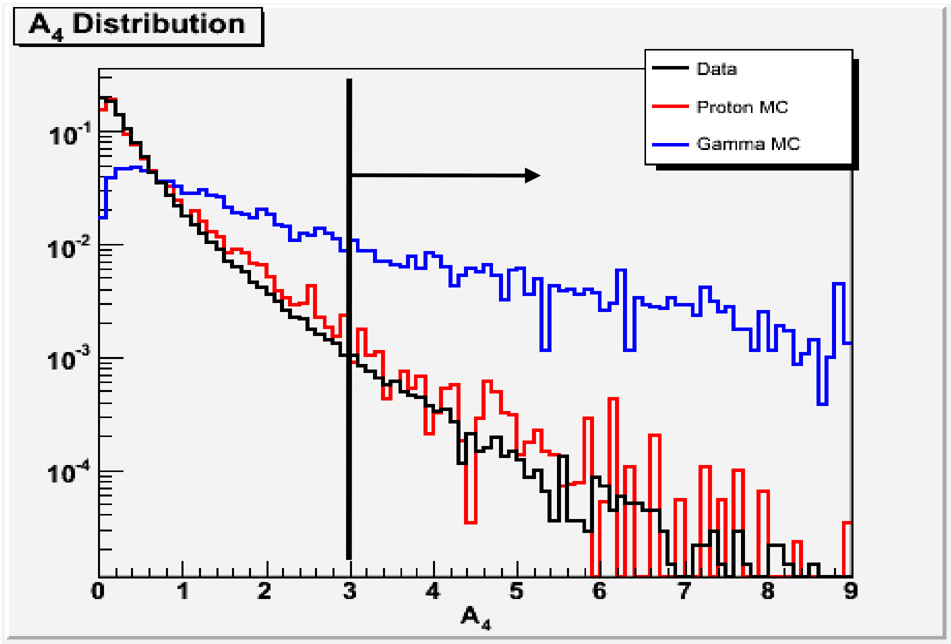
$A_4$ > 3 rejects 99% of Hadrons and keeps 20% of Gammas

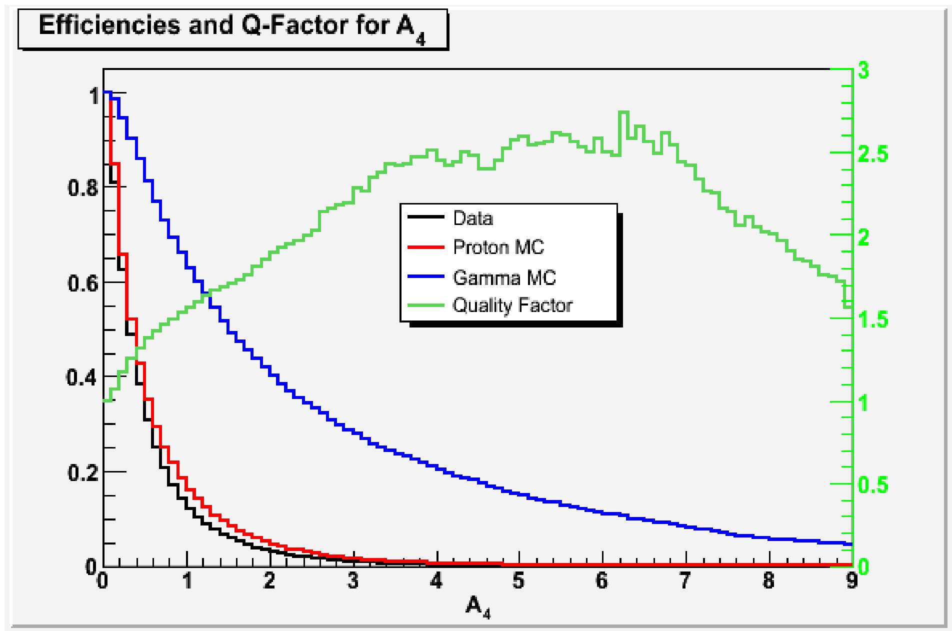
Result:

Increase in statistical significance over all triggered events by a factor of 2.

$$Q = \frac{\varepsilon_{gamma}}{\sqrt{\varepsilon_{proton}}} = \frac{0.2}{\sqrt{0.01}} = 2.0$$

| | |
|---|---|
| mxPE: | maximum # PEs in bottom layer PMT |
| fTop: | # fraction of hit PMTs in Top layer |
| fOut: | # fraction of hit PMTs in Outriggers |
| nFit: | # PMTs used in the angle reconstruction |



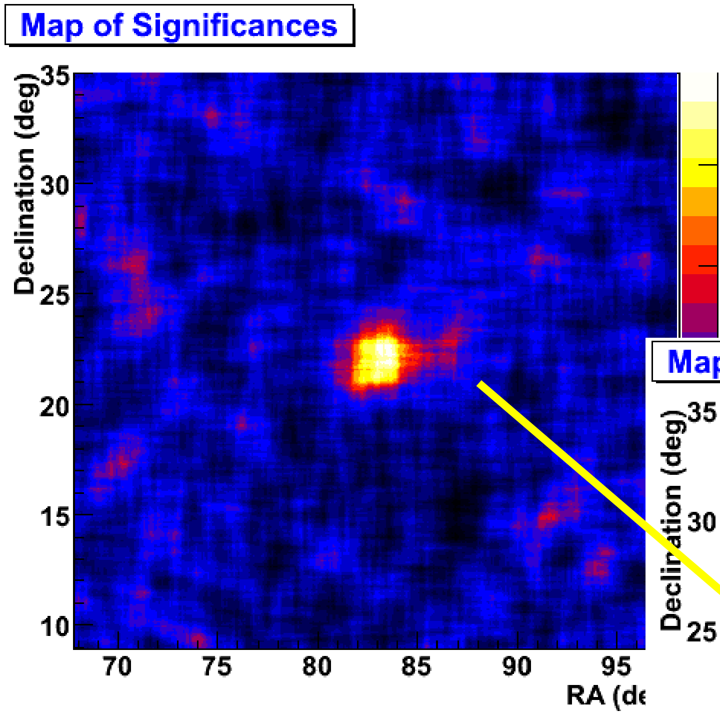
# Tests Of $A_4$ On The Crab Nebula

**Crab Nebula in Optical Wave length band**

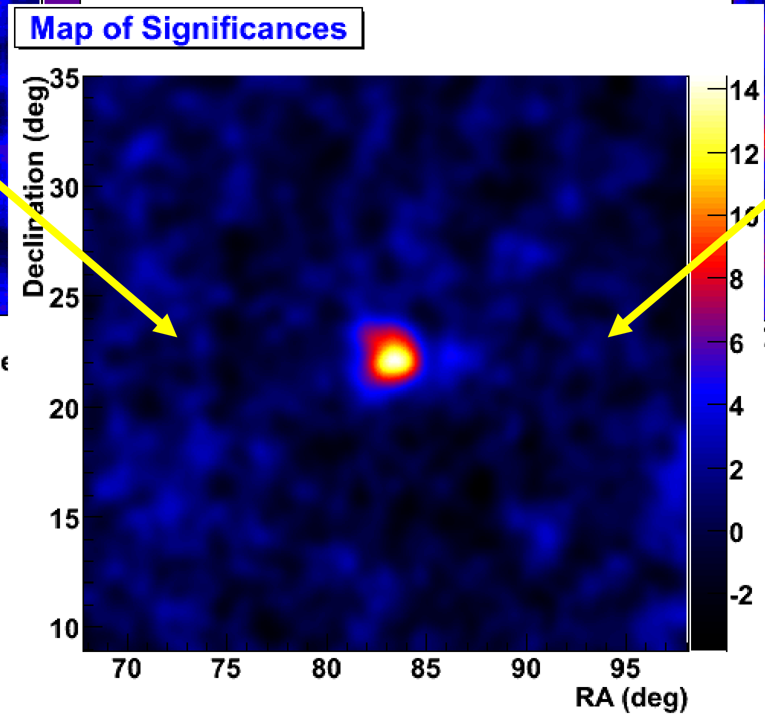
# $A_4$ Weighting Analysis on the Crab Nebula

## Combine $A_4$ with the weighting Analysis on 5 Years of Data

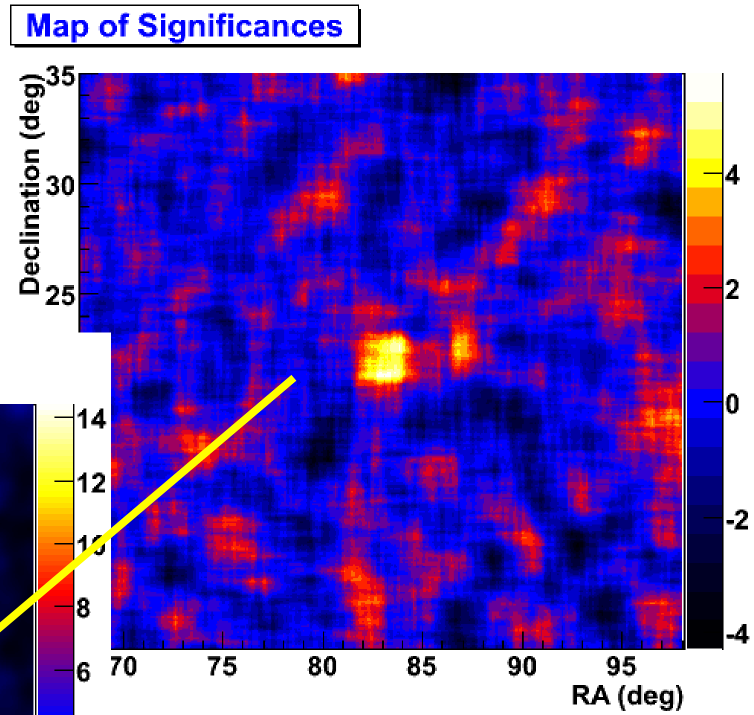
**$A_4 > 3.0$**




Weight each event by Expected S/B



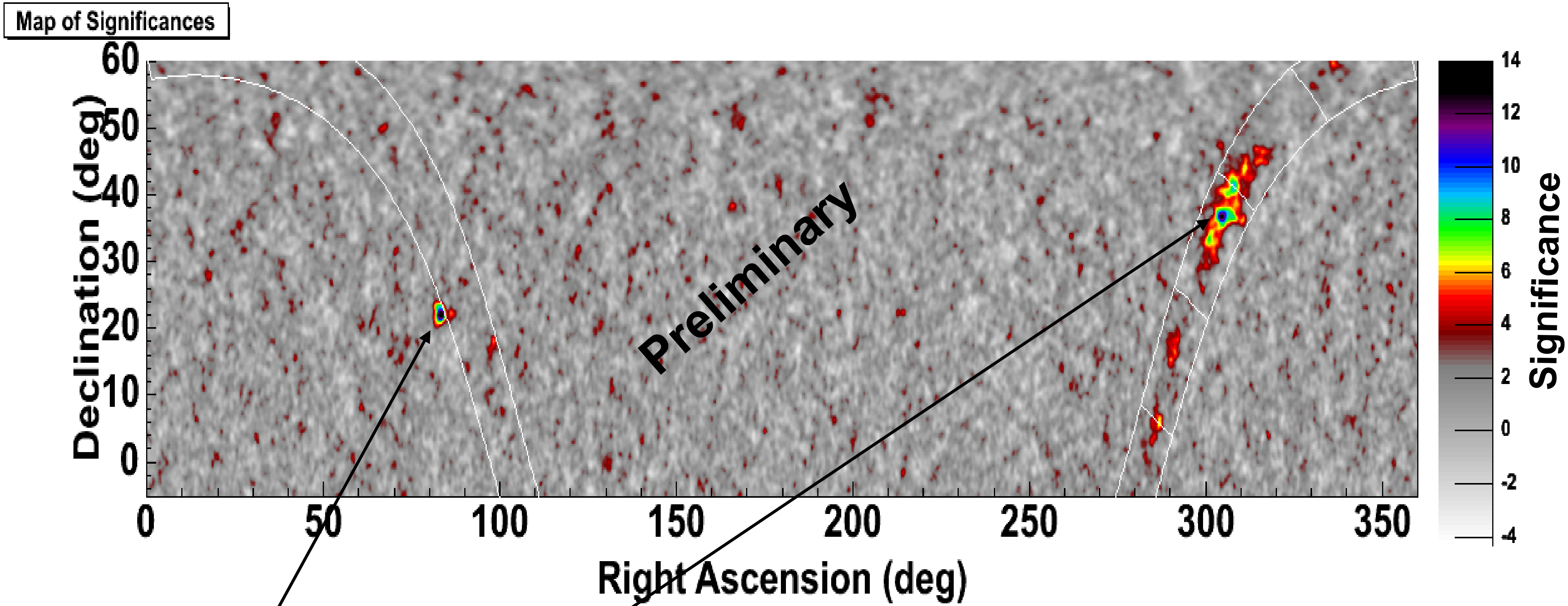

**$A_4 > 7.0$**




Excess Signal = 3397
Background = 221,263
S/B = 1.5 * $10^{-2}$

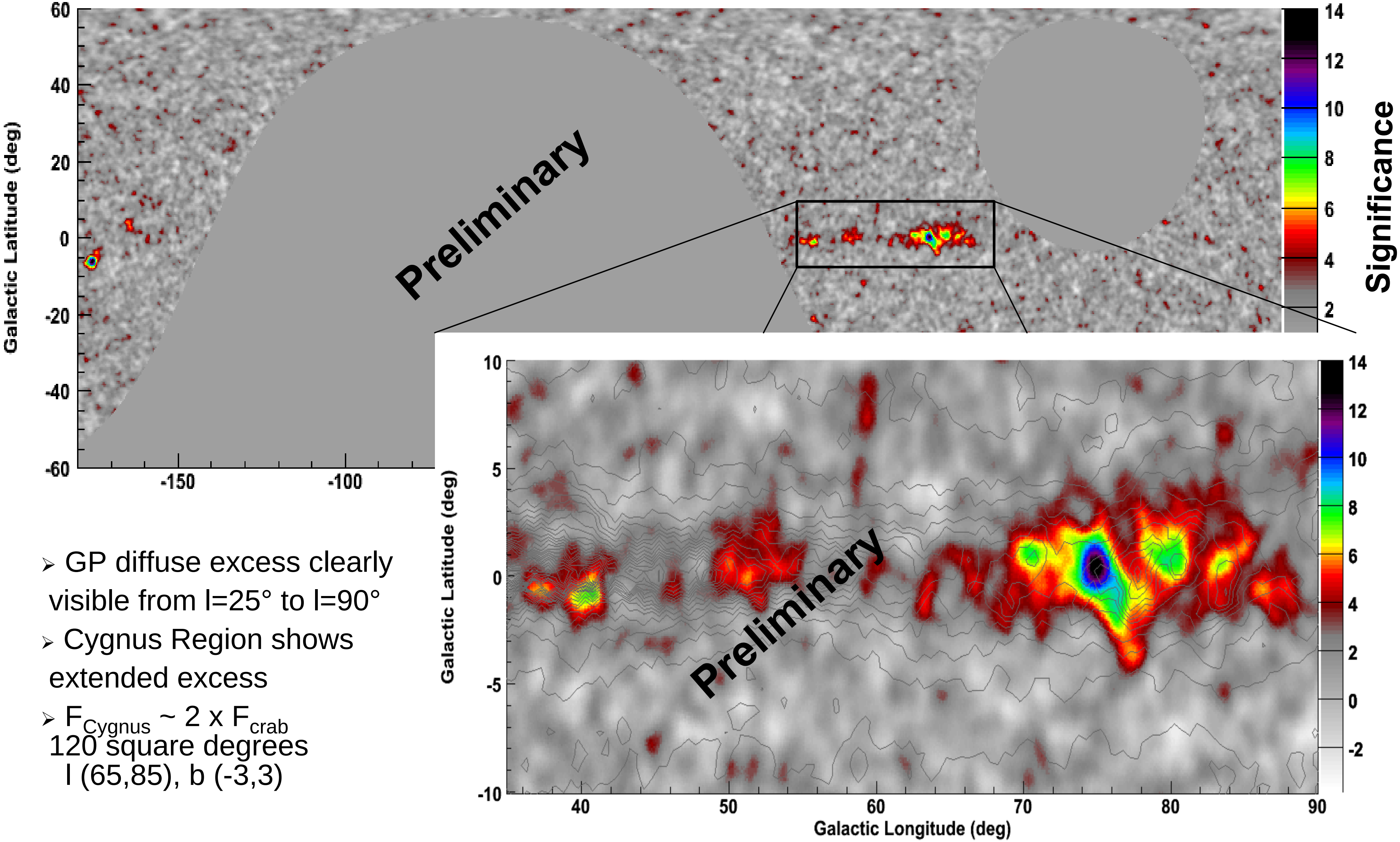
Excess Signal = 519
Background = 11726
S/B = 5.0 * $10^{-2}$

# TeV Sky Map Survey 2006




- Crab Nebula: 14 $\sigma$
- Cygnus Region : 12 $\sigma$
- Galactic Ridge clearly visible

# A Closer Look at the Galactic Plane

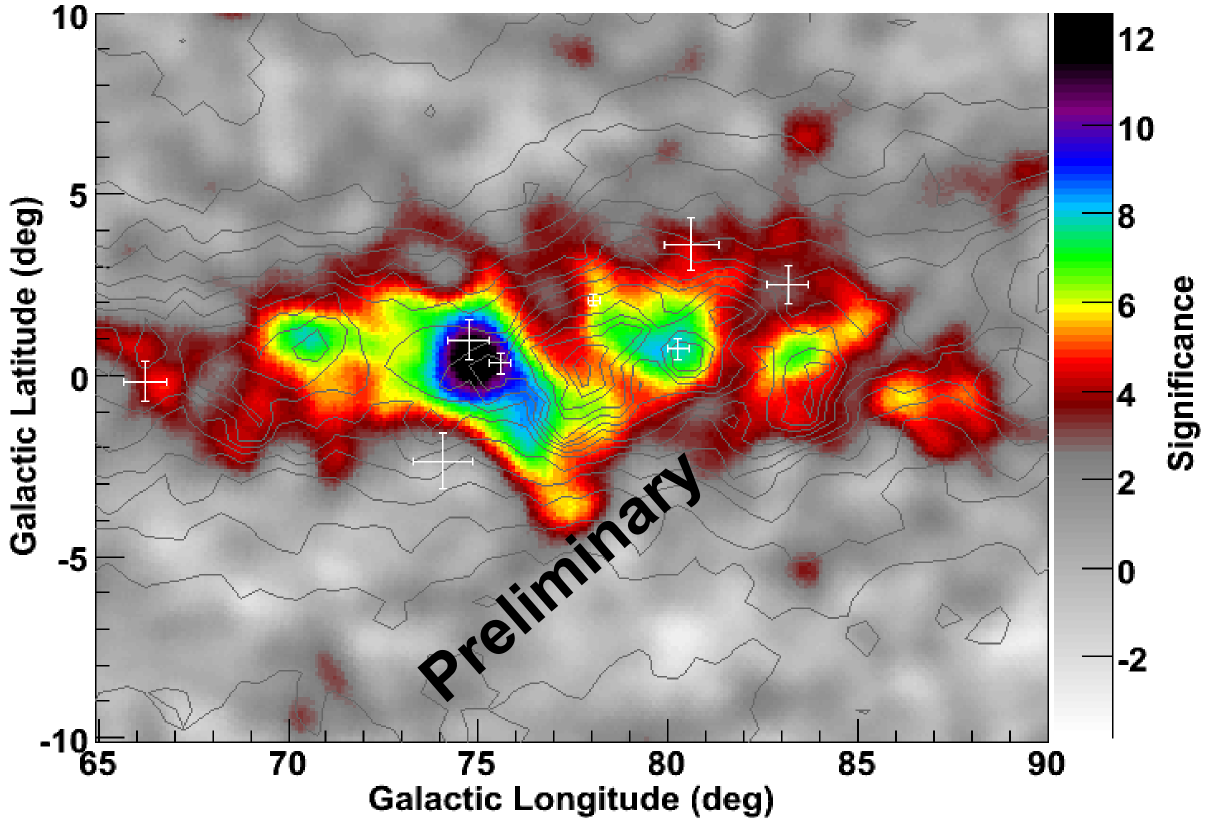



- GP diffuse excess clearly visible from l=25° to l=90°
- Cygnus Region shows extended excess
- $F_{Cygnus} \sim 2 \times F_{crab}$
  120 square degrees
  l (65,85), b (-3,3)


Cygnus Region
Canadian Galactic Plane Survey - Far IR

# Cygnus Region Spatial Morphology

- Crosses are EGRET sources
- Contours are EGRET diffuse model
- TeV/matter correlation good in Galactic latitude
- Brightest TeV Region
  - Coincident with 2 EGRET sources (unidentified) 3EG J2016+3657 3EG J2021+3716
- *Hot Spot: 0.38+/- 0.17 degrees*
- *Analysis in progress*



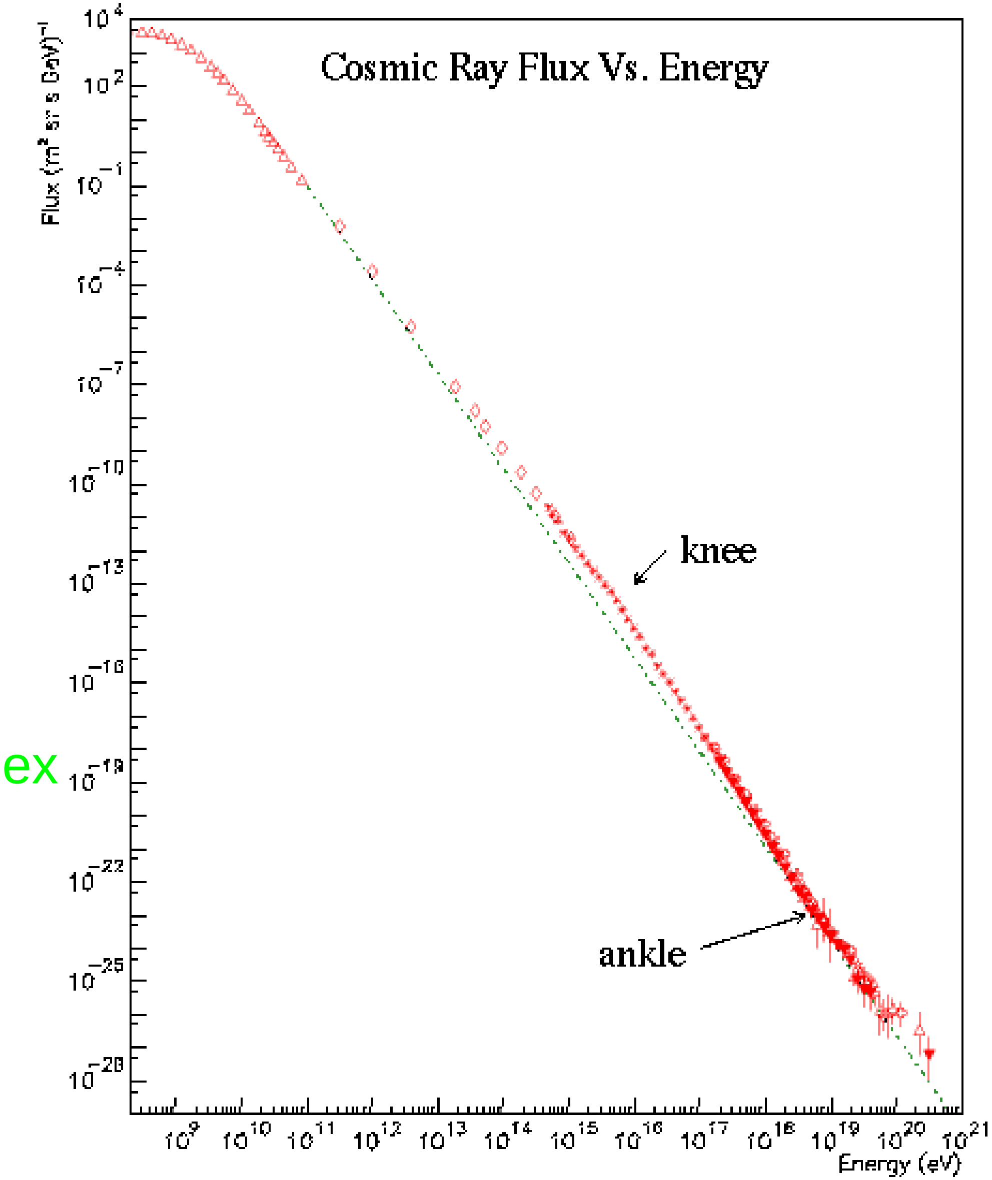
# Spectral Determination

Energy Spectrum for cosmic rays follows a simple power law over large energy range

$$\frac{dN}{dE} = AE^{-\alpha}$$

Spectral Index

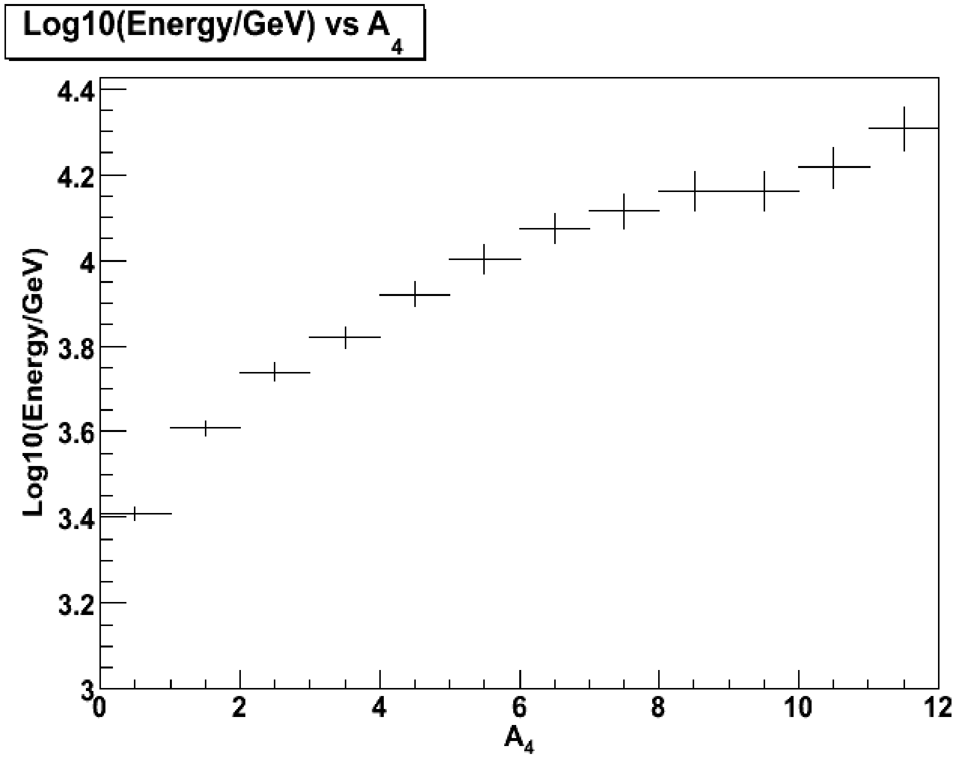
Differential flux



# Spectral Determination (Cont'd)

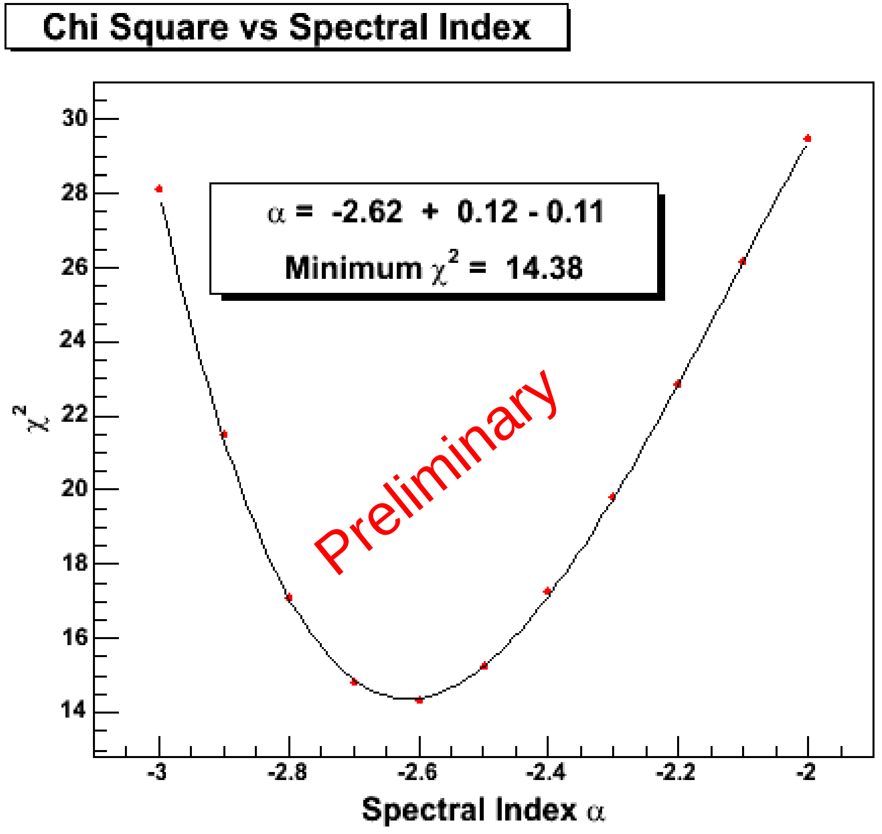
- $A_4$ is related to Energy
- 2-20 TeV useful range

- Bin Excess from data in $A_4$: Differentially
- Bin Gamma MC in $A_4$ for different spectral indices
- Fit differential excess from data to the different gamma MC distributions
- Calculate Chi Square for each fit
- Minimum Chi Square corresponds to Spectral Index of source



# Crab Nebula Spectral Determination

- Minimum Chi Square/ndf = 14.38/10
  - ➔ Alpha Crab = -2.62 + (0.12 – 0.11)$^{(stat)}$
- Results from other experiments in the same energy range:
  - HEGRA: -2.59 +/- 0.03 +- 0.05
  - Tibet: -2.62 +/- 0.17
  - Whipple: -2.49 +/- 0.06 +- 0.04



# Conclusions

- The Muon layer of the Milagro detector is an imaging calorimeter that can be used to measure the lateral distribution of energy deposited in Milagro
- A simple algorithm to differentiate hadronic showers from gamma-ray showers has been developed. This simple cut, based on the $A_4$ parameter improves the sensitivity of Milagro by a factor of 2.
- All-sky survey has lead to significant discoveries
  - Diffuse TeV gamma-ray emission from the Galactic plane
  - Extended source in the Cygnus region at 12 $\sigma$ in TeV gamma-rays
  - Diffuse emission from Cygnus region
  - Given the diffuse nature of the detected region, the "Cygnus Region" is the most luminous source of TeV gamma-rays in the northern sky