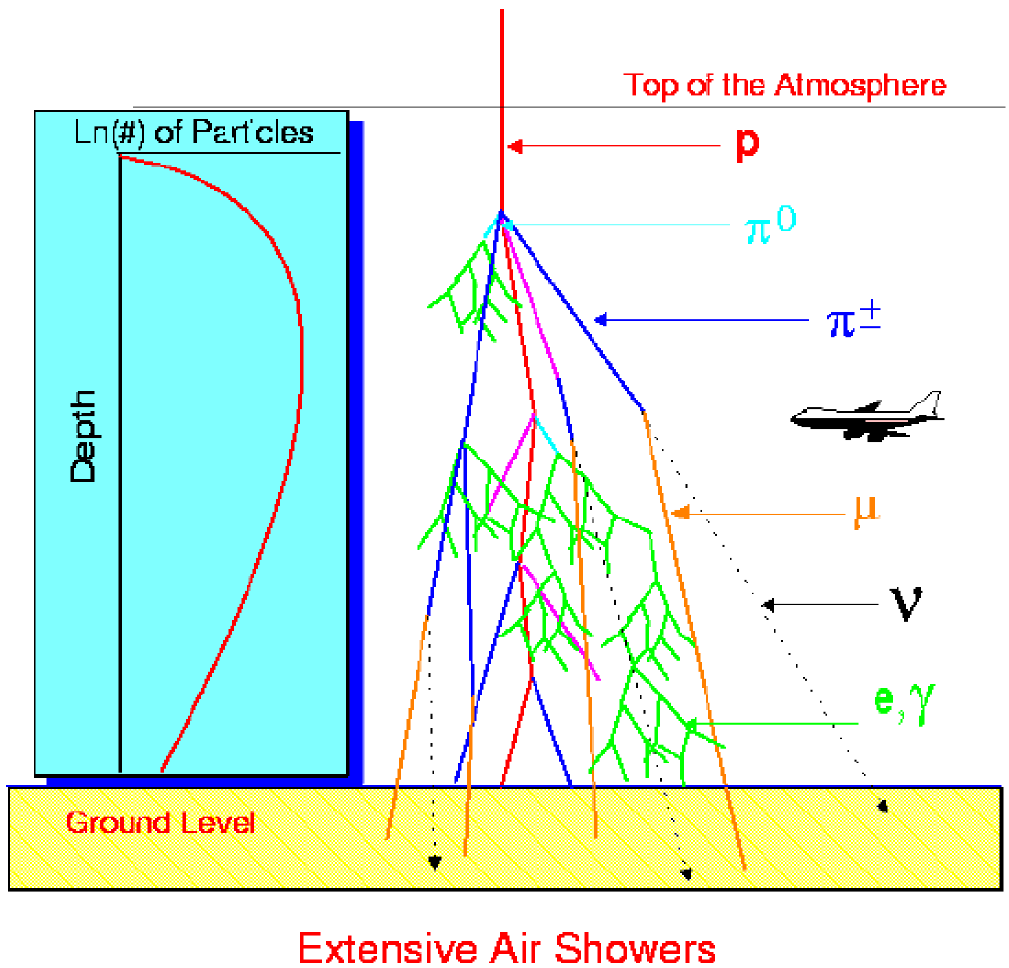
Allen I. Mincer, NYU
(for the Milagro Collaboration)
γ2001 April 2001

Gamma Ray Astronomy with Air Shower Arrays



TeV Gamma-Ray Astrophysics

- Study sources of TeV Gamma Rays
  - Neutron stars and pulsars

    Crab is the "Standard candle"

    Other sources including Vela and PSR 1706−44
  - AGN

    Variability on time scale of hours and longer observed.

    Some of the sources include Mrk 421 (Z=0.031), Mrk 501 (Z=0.033), 1ES 2344+514 (Z=0.044)
  - Galactic plane
  - Gamma Ray Bursts
  - Primordial Black Holes?
  - WIMPS collected by the sun?
  - ???
- Study medium between source and observer.

  Loss due to infrared background.

$$\lambda = \frac{2.7\,\mathrm{Mpc}}{\rho[\mathrm{ptls/cm^3}]f(\beta)}$$

  where $\beta = \sqrt{1 - m^2/k'^2}$, k' is the cm photon momentum,

$$f(\beta) = (1-\beta^2)\cdot[(3-\beta^4)\ln(\frac{1+\beta}{1-\beta}) + 2\beta(\beta^2-2)]$$

  $0 \le f(\beta) \le 1.4$, and $f(\beta)$ is maximum at $\beta \sim 0.7$ For a 1 TeV γ threshold for a head-on collision is with a ~ 0.5 eV γ.
- Background is $\sim$ isotropic cosmic rays, but can study:
  - Moon shadow → detector resolution, earth's B field effects.
  - Shadowing by the sun → solar $B_\perp$
  - Solar energetic particles.
  - Cosmic ray composition.

"First Generation" Pointing Air Shower Experiments:

- Cygnus Experiment
  - April 1986 to ~ 1997.
  - Energy ≥ 10 TeV, median energy ~ 40 TeV
  - Angular resolution $\sim 0^\circ.75$
  - First observation of sun and moon shadowing.
- CASA
  - Began operation early 1990, complete station 1991.
  - Energy ≥ 100 TeV
  - Angular resolution $\sim 0^\circ.8$ for cores on array.
  - Observation of sun and moon shadowing.
- Tibet Air Shower Array
  - Began operation January 1990.
  - Energy ≥ 3 TeV, peak ~ 7 TeV.
  - Angular resolution $\sim 0^\circ.6$ if 2D Gaussian assumed.
  - Observation of sun and moon shadowing.
- Unconfirmed episodic observations reported in 1980s by various experiments.

Goals and Requirements

Study VHE photons from ground based observatory by measuring the atmospheric particle shower that the primary photons produce.

- Large angular acceptance and 24-7 Operation.
  - Study particles surviving to detector altitude, thus allowing daytime operation, and even viewing of the sun!
  - Use particle arrival time lateral distribution to determine primary incidence angle. Angular acceptance determined by atmospheric depth which increases as $1/cos\theta$ from the vertical.
  - Use signal size distribution to measure primary energy.
- Lower energy threshold - conventional air shower arrays become sensitive at ∼50 TeV, since we are looking at "Calorimeter punch-through".
  - Maximize altitude.
  - Maximize active area.
  - Sensitivity to shower photons, not just charged particles.
- Look for gamma signal over large, isotropic nuclear cosmic-ray background.
  - Angular resolution.
  - Gamma - Hadron separation.
  - Where possible, time/space search region defined by other observations.
- Healthy Mistrust of Monte Carlo.
  - Particle physics mostly understood (CORSIKA) but still some nuclear physics questions.
  - Main uncertainties at these energies are due to the details of detector properties.

The Milagro Collaboration

Robert Ellsworth

George Mason University

Galen Gisler, Todd Haines, Cyrus Hoffman, Frank Samuelson, Gus Sinnis

Los Alamos National Laboratory

Lazar Fleysher, Roman Fleysher, Allen Mincer, Peter Nemethy

New York University

Scott Delay, Isabel Leonor, Anthony Shoup, Gaurang Yodh

University of California, Irvine

Ben Shen, Tumay Tumer, Kelin Wang, Morgan Wascko

University of California, Riverside

Wystan Benbow, Don Coyne, David Dorfan, Linda Kelley, Joe McCullough, Miguel Morales, Michael Schneider, Stefan Westerhoff, David Williams

University of California, Santa Cruz

David Berley, Erik Blaufuss, Javier Bussons-Gordo, Jordan Goodman, Elizabeth Hays, David Noyes, Andy Smith, Greg Sullivan

University of Maryland

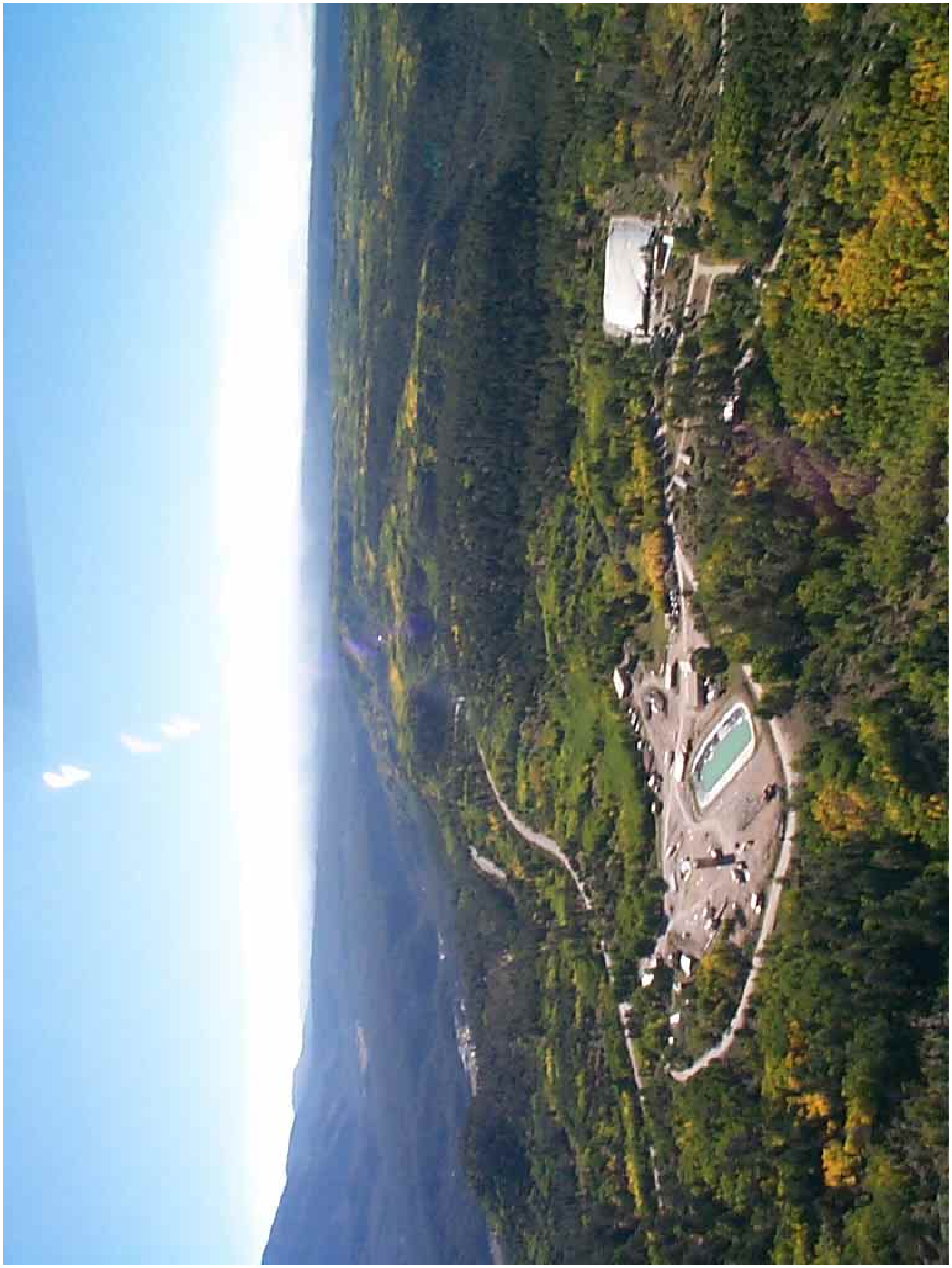
Abe Falcone, Richard Miller, Jim Ryan

University of New Hampshire

Robert Atkins, Brenda Dingus, Julie McEnery

University of Wisconsin

The Milagro Site



The Milagro Method

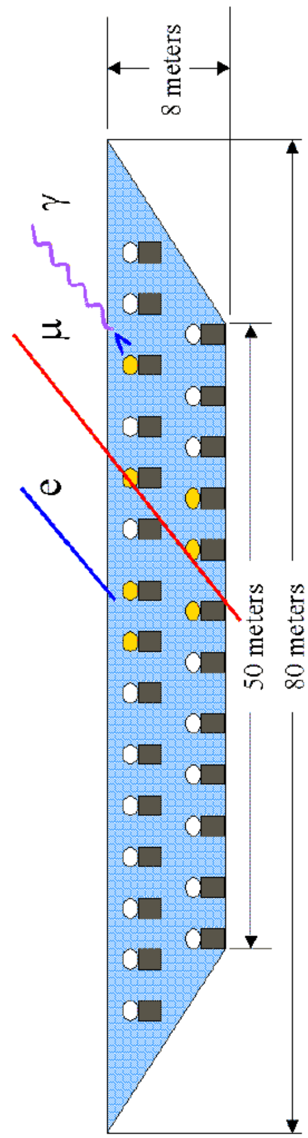
This transparency will be a multi-layer one that shows how:

gamma ray hits the top of the atmosphere

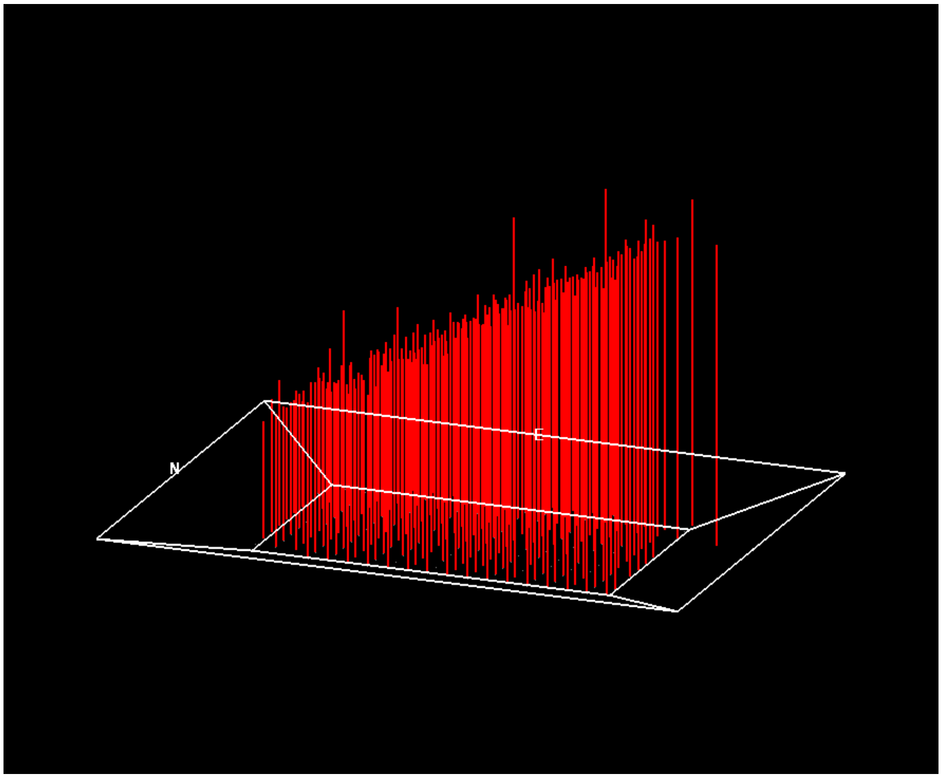
EAS develops

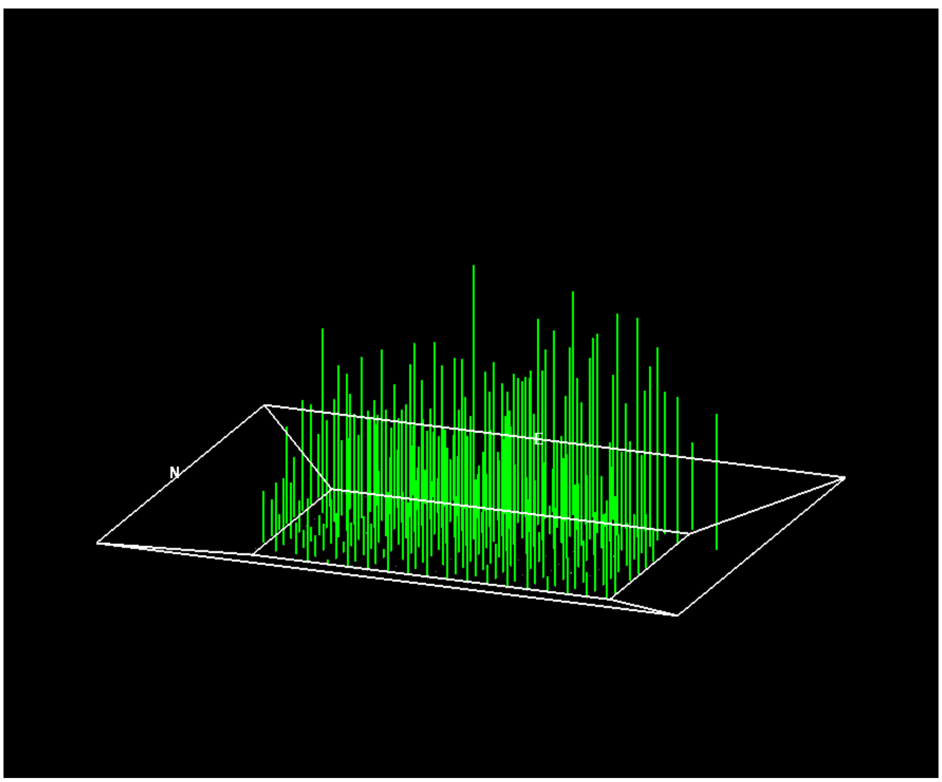
particles hit the pond and PMTs

Shower plane is reconstructed



A Milagrito Event Showing PMT Times and Pulse Heights





A summary of the Milagrito prototype of Milagro

- Specifications
  - 228 PMTs, 8”-diameter, on a 2.8 m, 19x12 grid.
  - February 8, 1997 to May 7, 1998. Live time 79.5% with down time mainly due to power outages (∼11.5%), calibrations (∼3%) and maintenance and construction (∼3%). Rest hardware or software errors.
  - A total of 8.9×10^9 events for PMTs at depths of 0.9 m (300Hz, 5.3×10^9 events), 1.5 m (340Hz, 1.1×10^9 events), and 2m (400Hz, 2.5×10^9 events).
- Behavior:
  - For crab-like ($E^{-2.5}$) spectrum, peak energy ~ 1 TeV if overhead ~ 1.5 TeV for the Crab.
  - Angular resolution depends on $\mathrm{N_{FIT}}$, about 1 degree.
  - Effective area ∼ geometric area at about 500 GeV for protons and γ.
- Some checks of technique and lessons learned:
  - Optimize water depth for angular resolution.
  - Baffles to get rid of late light.
  - Test of monte carlo

    Cosmic ray trigger rate: For $\delta_{\mathrm{Mrk501}} = 39^{\circ}.8$, 1 degree radius bin, measure 2420 ± 80 events per day, calculate 2460^{+160}_{-90} from cosmic rays.

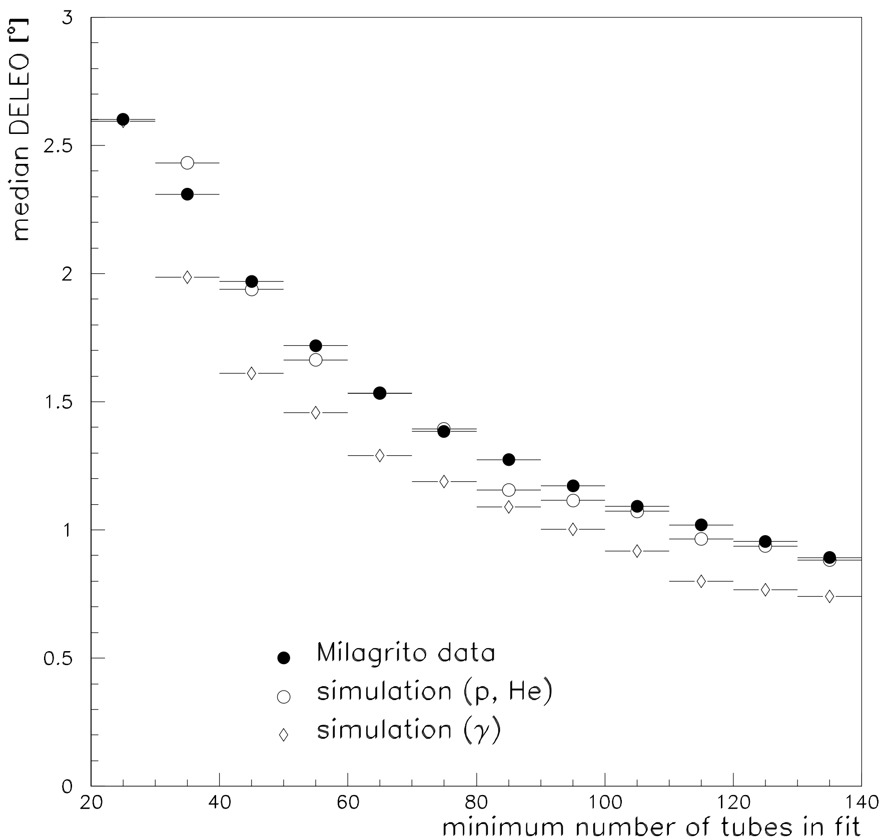
    Zenith angle distribution.

    Angular resolution as tested with Δ_{EO}.

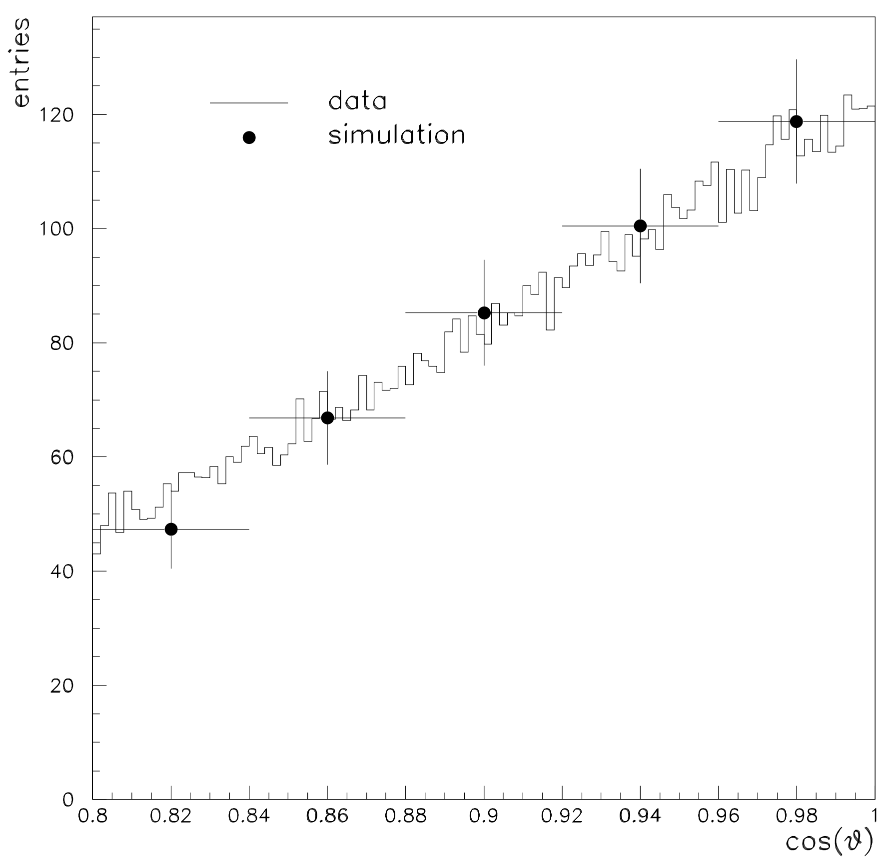
    Moon shadow versus point spread function.

Milagrito Data Monte-Carlo Comparisons:

Δ_{EO}



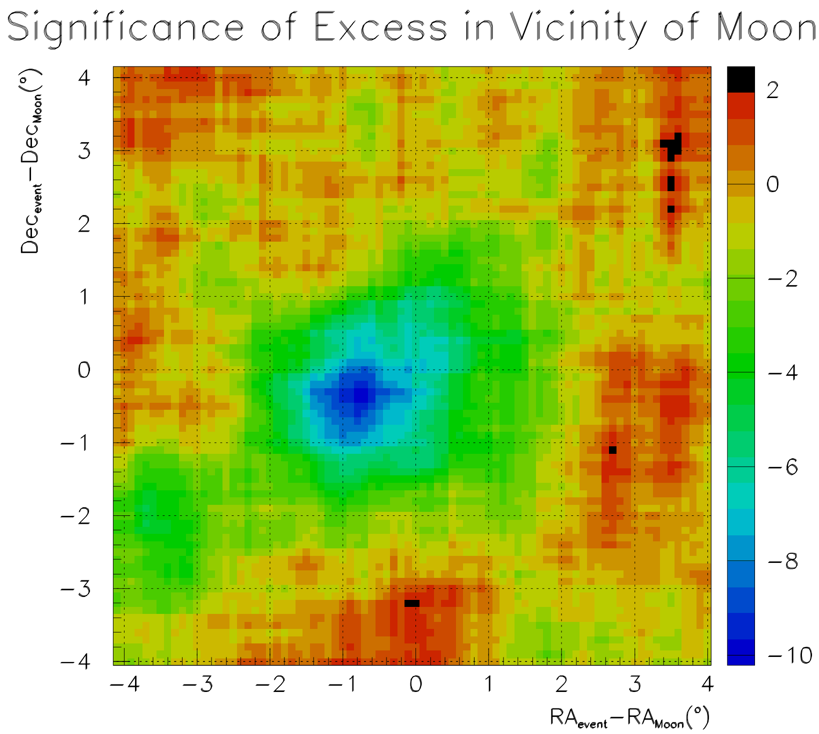
θ
ZENITH



Milagrito Physics, Completed or On-going:

- Moon Shadow, anti-proton search.
- Sun Shadow.
- SEP Event.
- Mrk 501.
- GRB 970417a.
- All-sky source search.
- Untriggered GRB search.
- Some additional source studies in progress.
- Some additional analyses which are possible will be not be performed because Milagro data is available.

Milagrito Moon and Sun Shadows



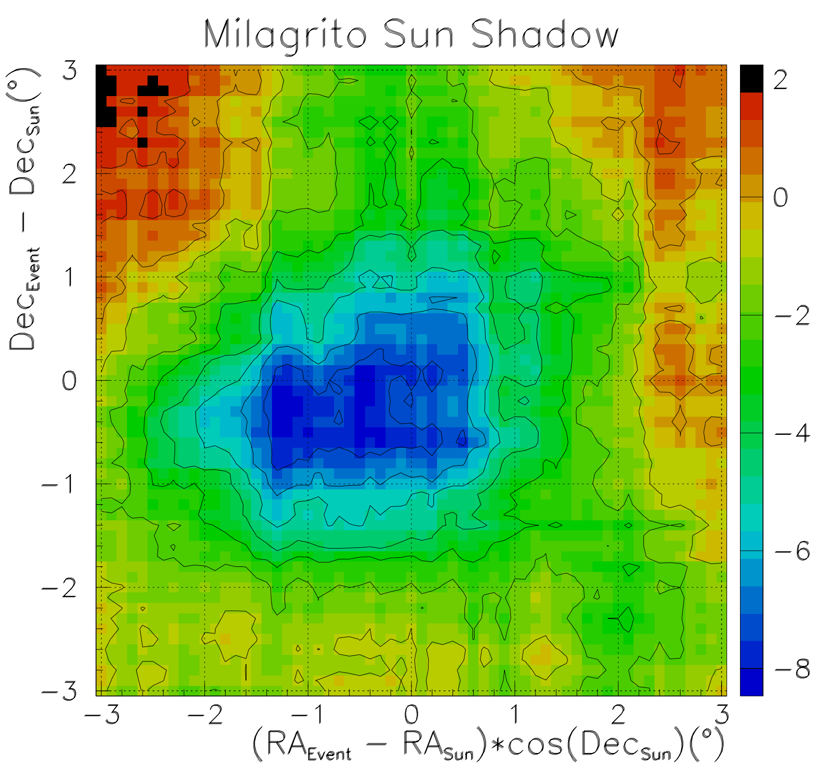
1°.7 square bins

Moon signal is 10.2 σ

Median energy 2.7 TeV

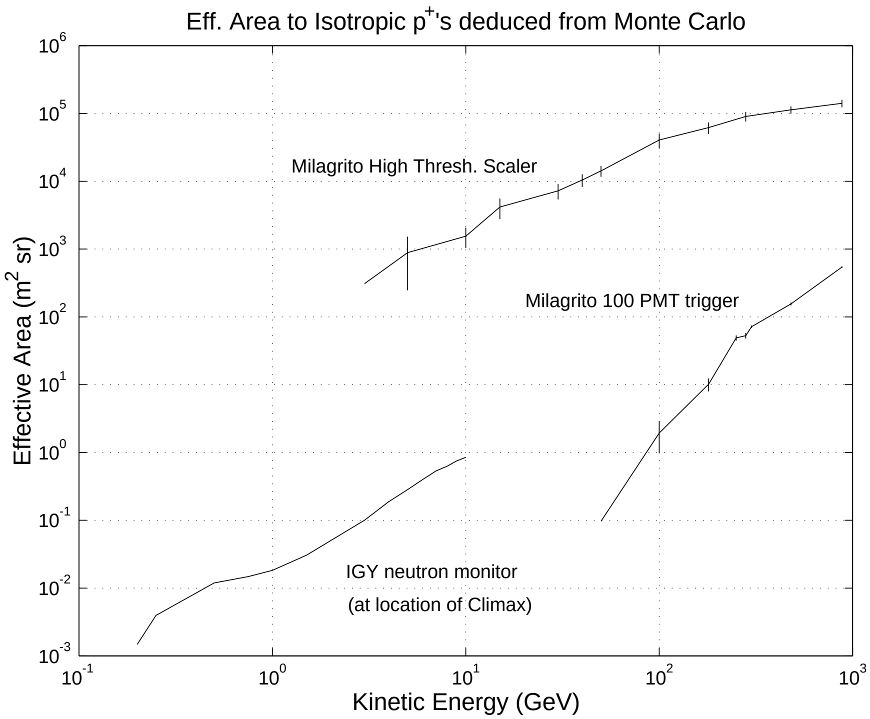
$\bar{p}/p$ 95% limit =17%

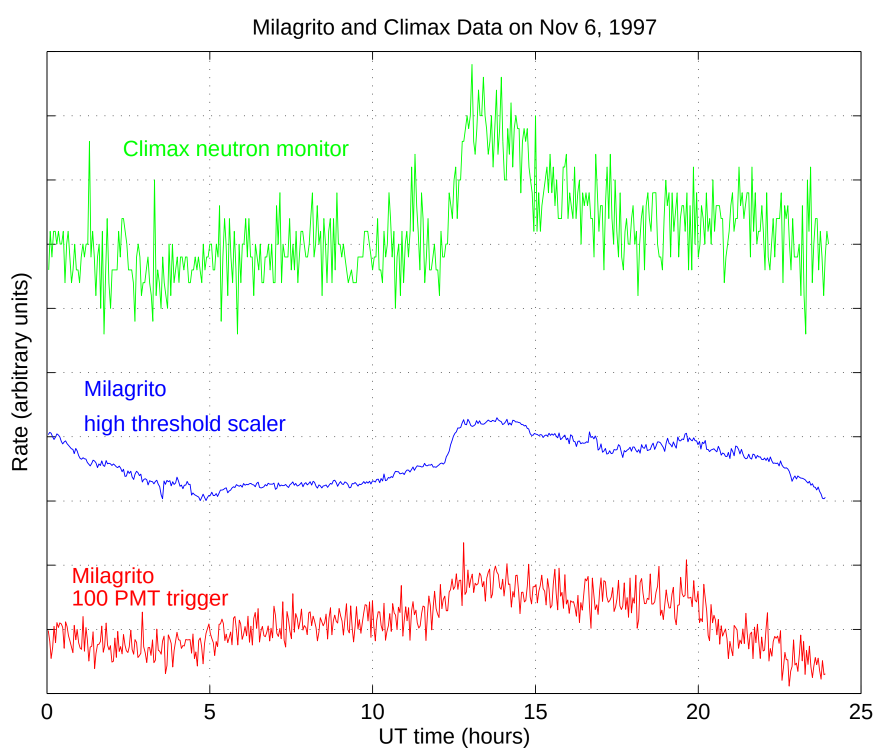
Significance of Excess in Vicinity of Sun



Sun signal is 10.1 σ

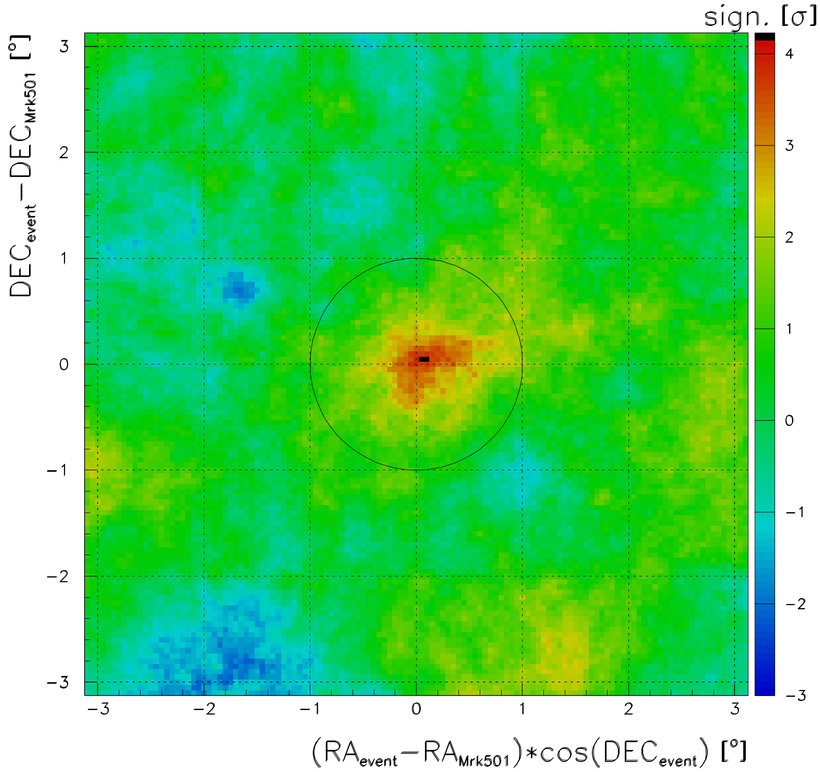
Solar Energetic Particles from 6 Nov. 1997 Event





Probability of background fluctuation $< 2 \times 10^{-4}$

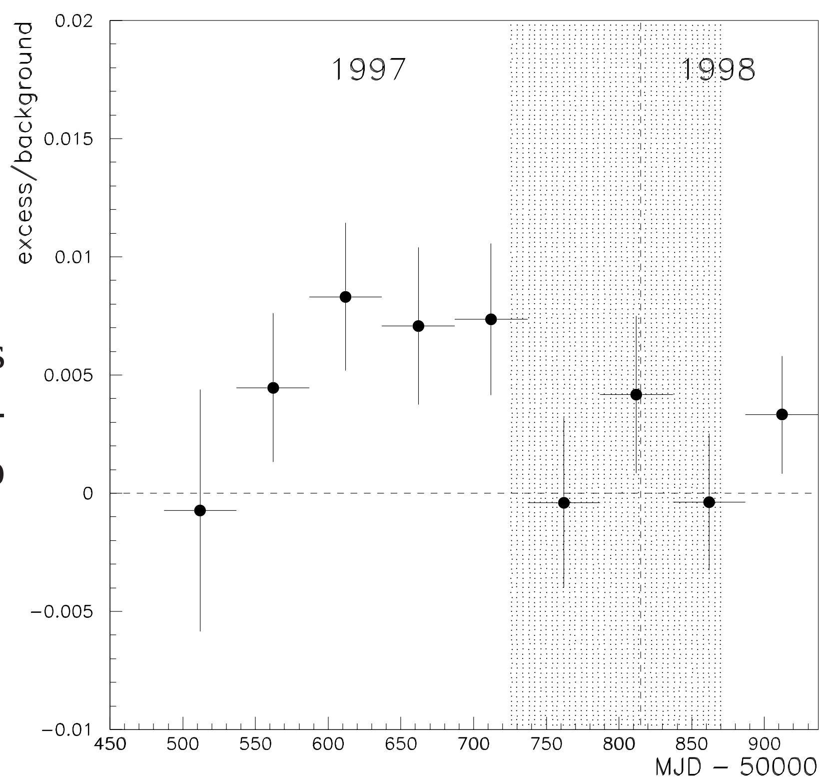
Milagrito Markarian 501 Results



Observed 918954 events in 1 degree radius bin.

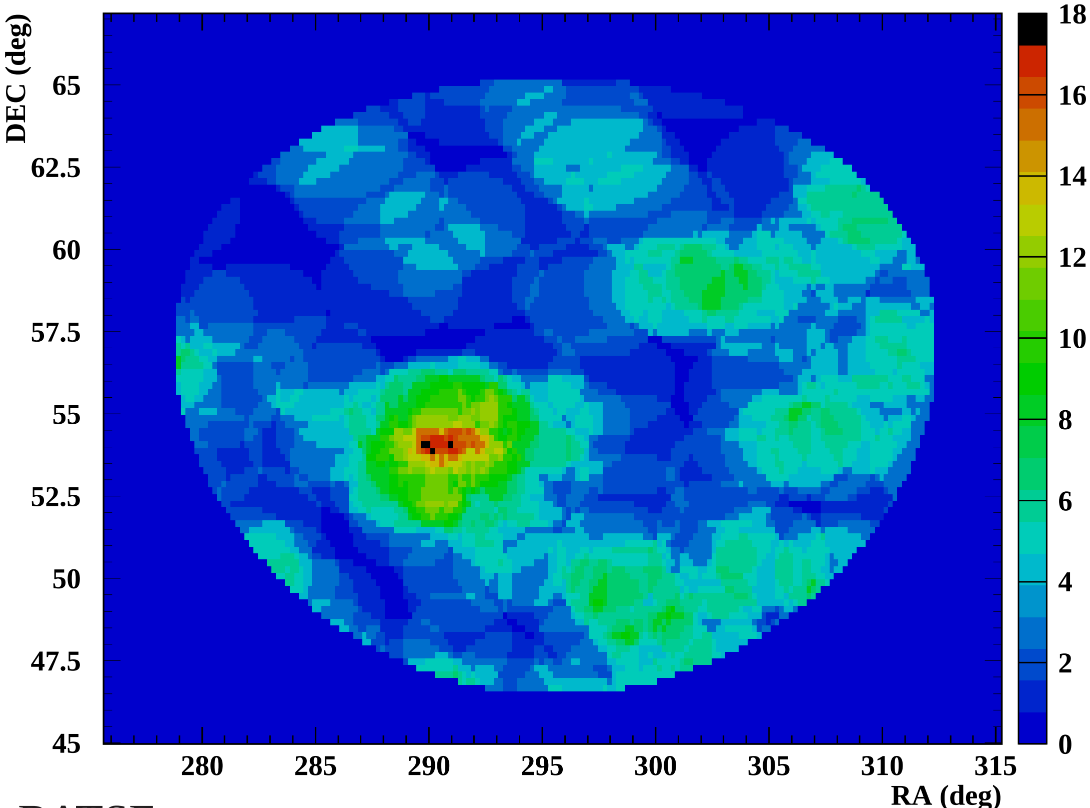
Average expected 915330 ± 250

Excess is $3624 \pm 990 = 3.7\sigma$



Shaded region has Mrk 501 visible during the day, so no ACT data.

GRB 970417a



BATSE:

$\mathrm{RA} = 295^\circ.7$, $\delta = 55^\circ.8$, uncertainty $\sim 6^\circ.2$, $T_{90} = 7.9$ sec.

Fluence (20 to 300 KeV) 1.5×10^{-7}ergs/cm^2

Milagrito

Search $9^\circ.4$ radius area with $1^\circ.6$ radius bins, $0^\circ.2$ spacing.

18 events with avg background 3.46, probability 2.8×10^{-5}

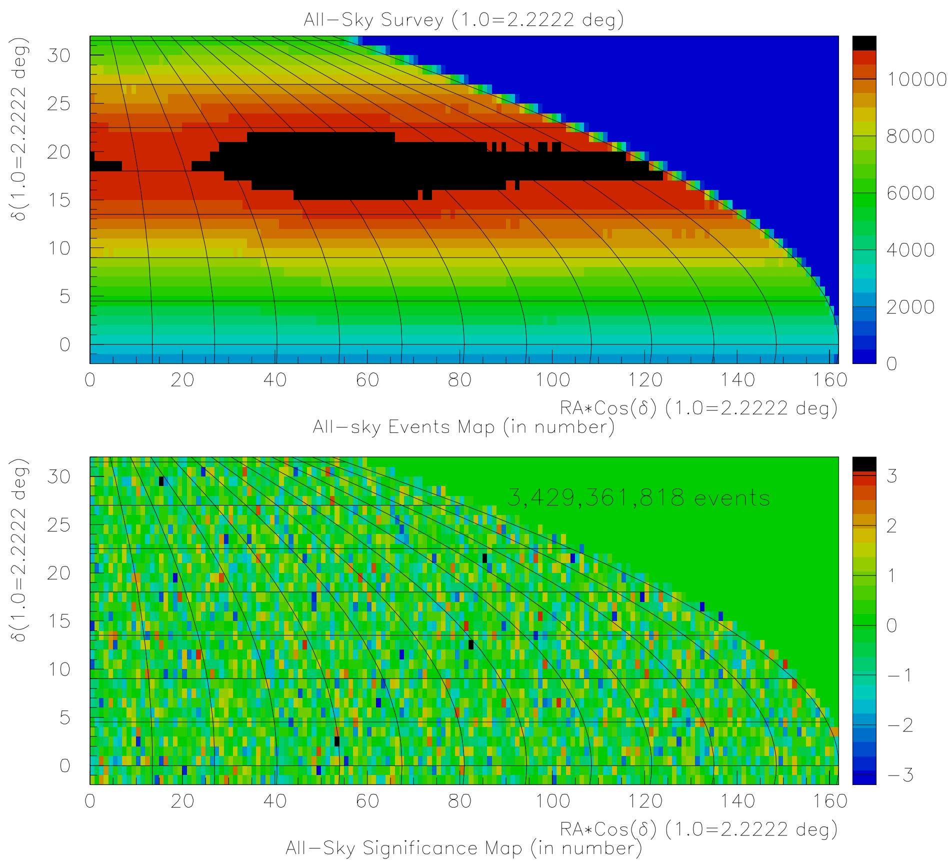
$\mathrm{RA} = 289^\circ.9$ $\delta = 54^\circ.0$ uncertainty $\sim \pm 0^\circ.5$

Probability of Background fluctuation is 10^{-3}

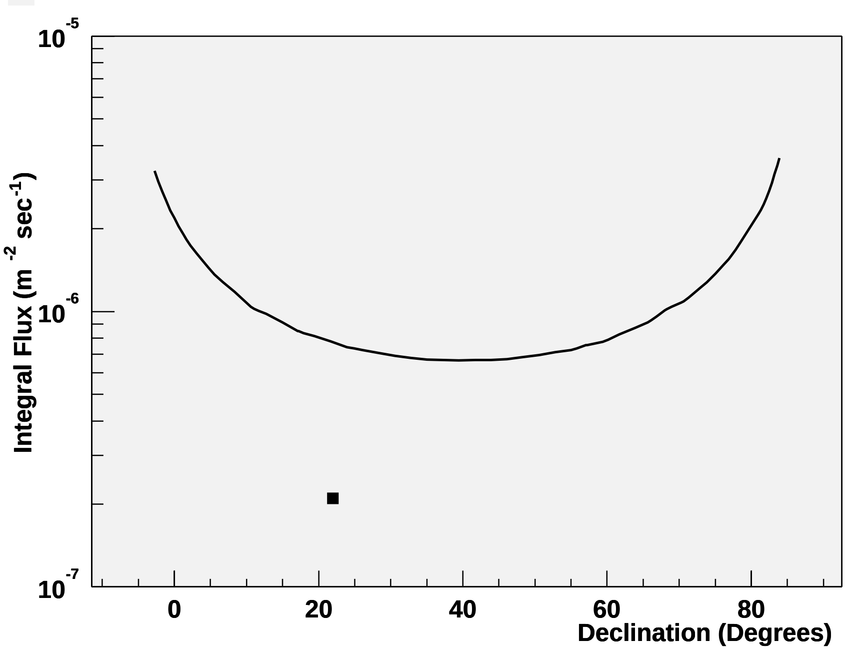
Fluence calculation:

- Depends on assumed spectrum, $\frac{dN}{dE} = AE^{-\gamma}$ for $E < E_{\mathrm{C}}$.
- $\int A_{eff}(E)\Phi(E)dE =$ observed number of events $\rightarrow A$.
- Scalar rate sets a limit on low energy particle flux.
- Can exclude $\gamma > 2.8$, $E_{\mathrm{C}} < 700GeV$. Typical fluence above 1 TeV $\sim$ order of magnitude $>$ at BATSE energy.

Milagrito All-Sky Source Search



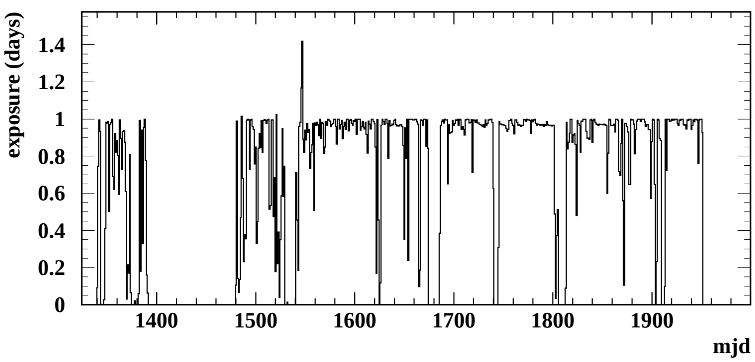
δ:
$2.2222°$ bins
RA:
$2.2222°/cos\delta$ bins

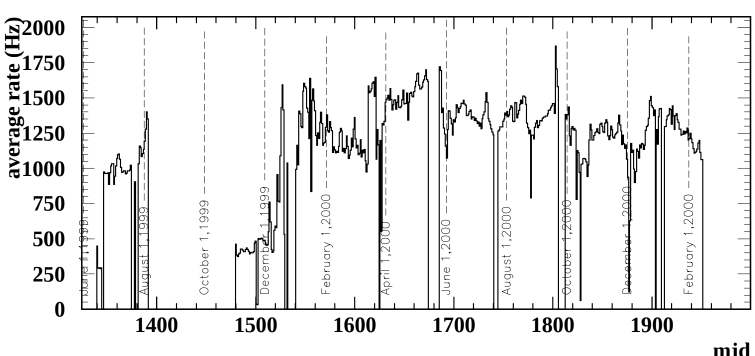


Typical upper limit compared with the Crab flux.

Milagro Design and Operation

- High altitude and large active area, photon sensitivity.
  - Altitude is 2650m (750 g/cm^2).
  - PMTs provide full area coverage.
  - Photons pair produce or Compton scatter in 1.4m of water above the PMT, giving rise to energetic charged particles.
- History:
  - Engineering run started July 1999.
  - Physics run started December 1999.
- Behavior:
  - Excluding Los Alamos fire, > 95% duty cycle.
  - Data Rate $\sim$1.5 kHz





  - Sensitive to about 200 GeV to 50 TeV.
  - Resolution $\sim$0.75 degrees.
- Monte-Carlo Data comparisons in progress.

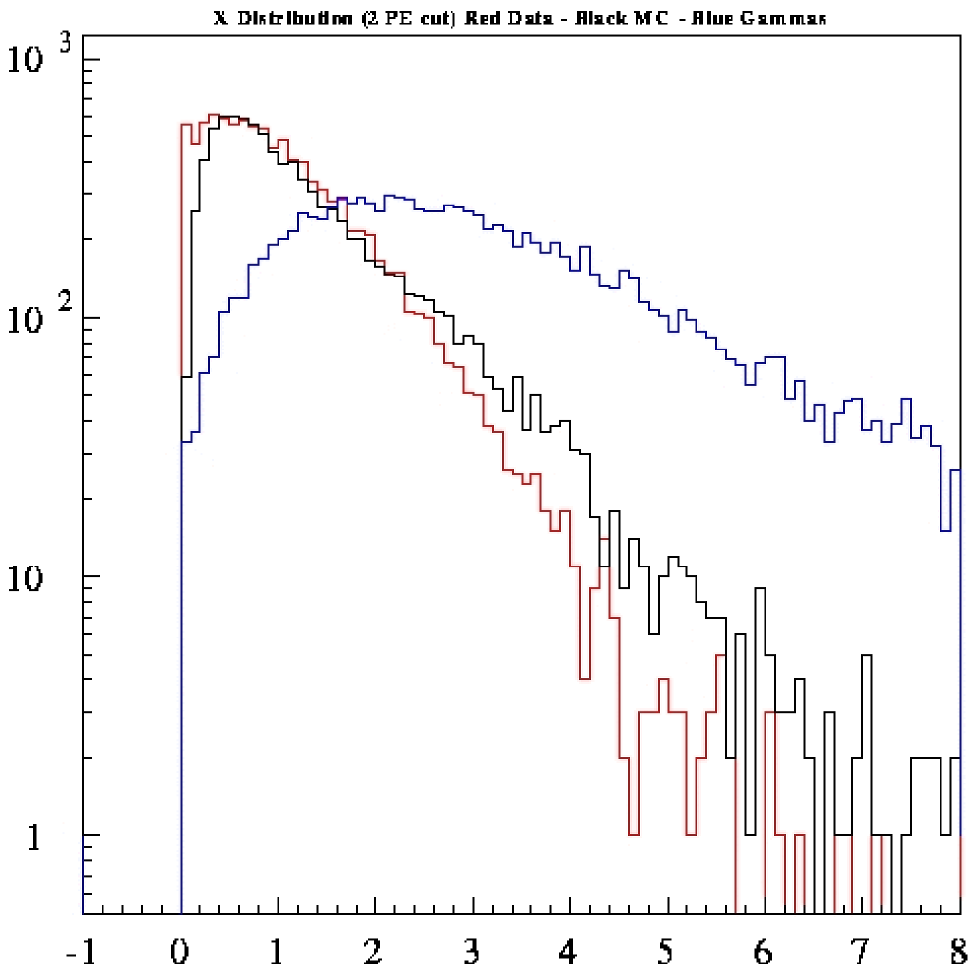
- Gamma - Hadron separation
  - Multi-layer measurements.

    450 Shower layer PMTs under 1.4 m of water.

    273 Muon layer under 6 m of water.
  - Currently using:

    Clumpy hadron showers give few PMTs with large signals.

$$X_2 \equiv \frac{\text{Number bottom PMTs} > \text{2PE pulse height}}{\text{Max bottom layer pulse height}} > 2.5$$

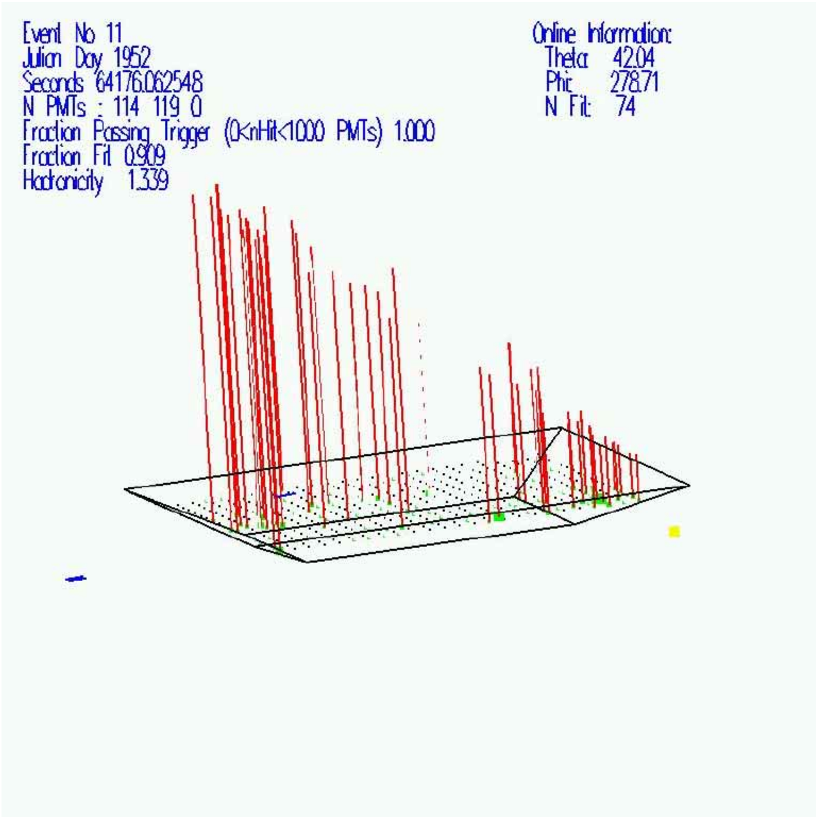


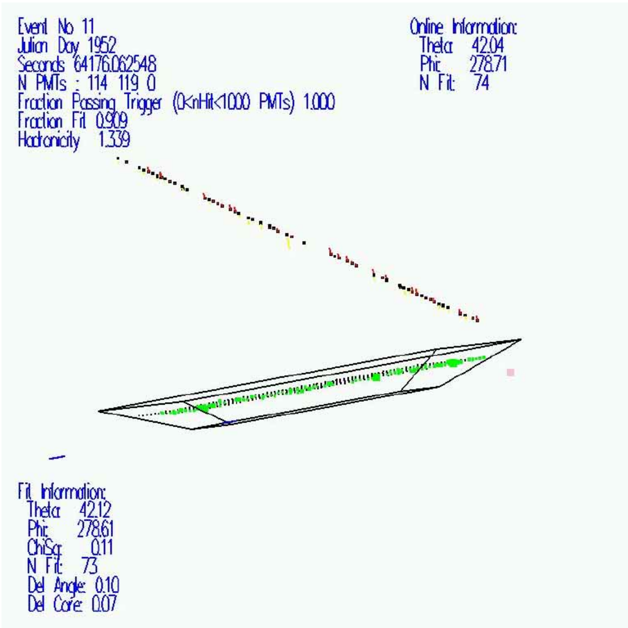
Cut $X_2 > 2.5$ retain 54% of γ reject 91% of hadrons

$$Q \equiv \frac{S_{CUT}/\sqrt{B_{CUT}}}{S/\sqrt{B}}$$

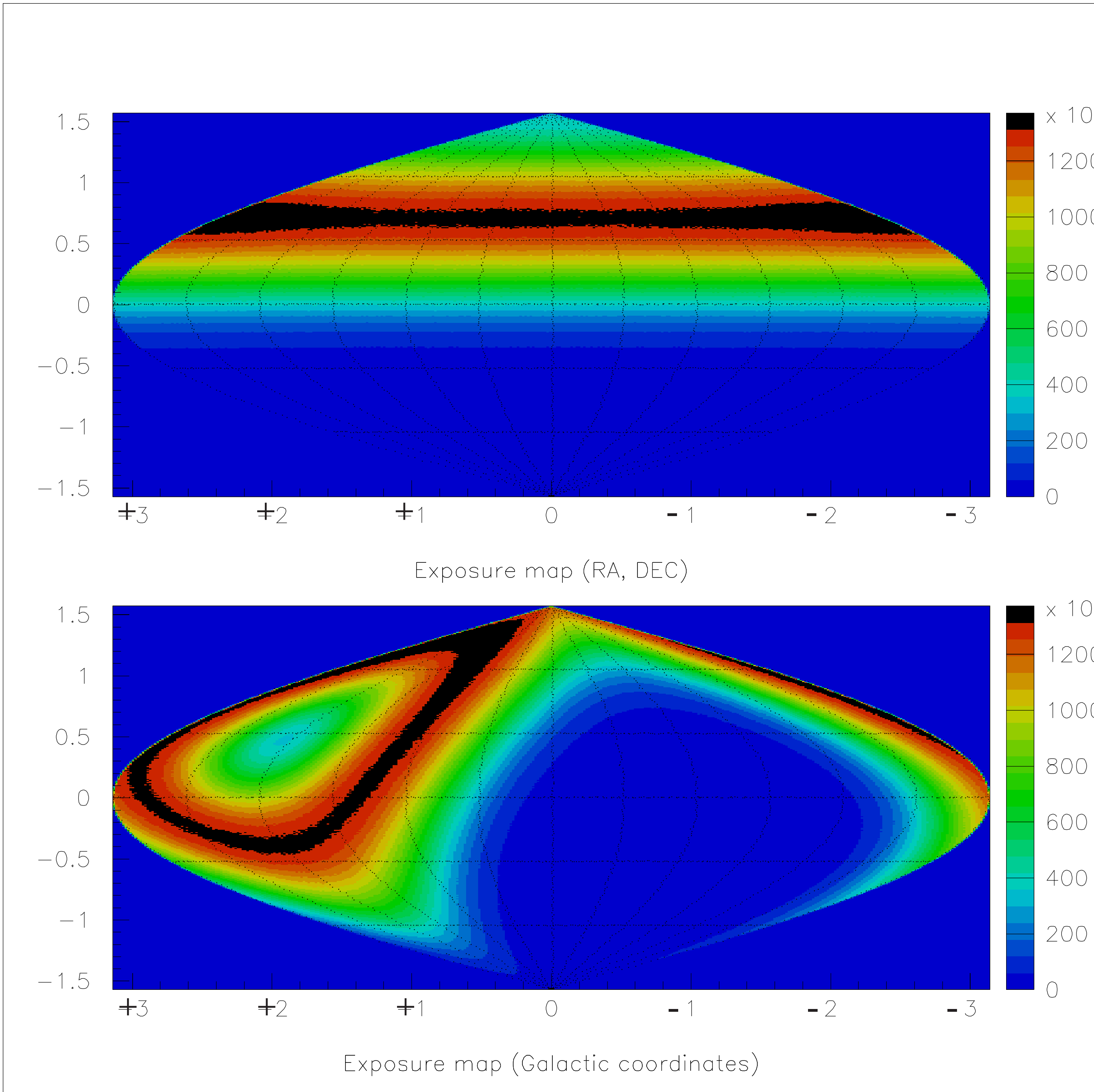
$Q = 1.8$

A Milagro Event Showing PMT Times and Fit Plane





Milagro Exposure, 60 Days of Data

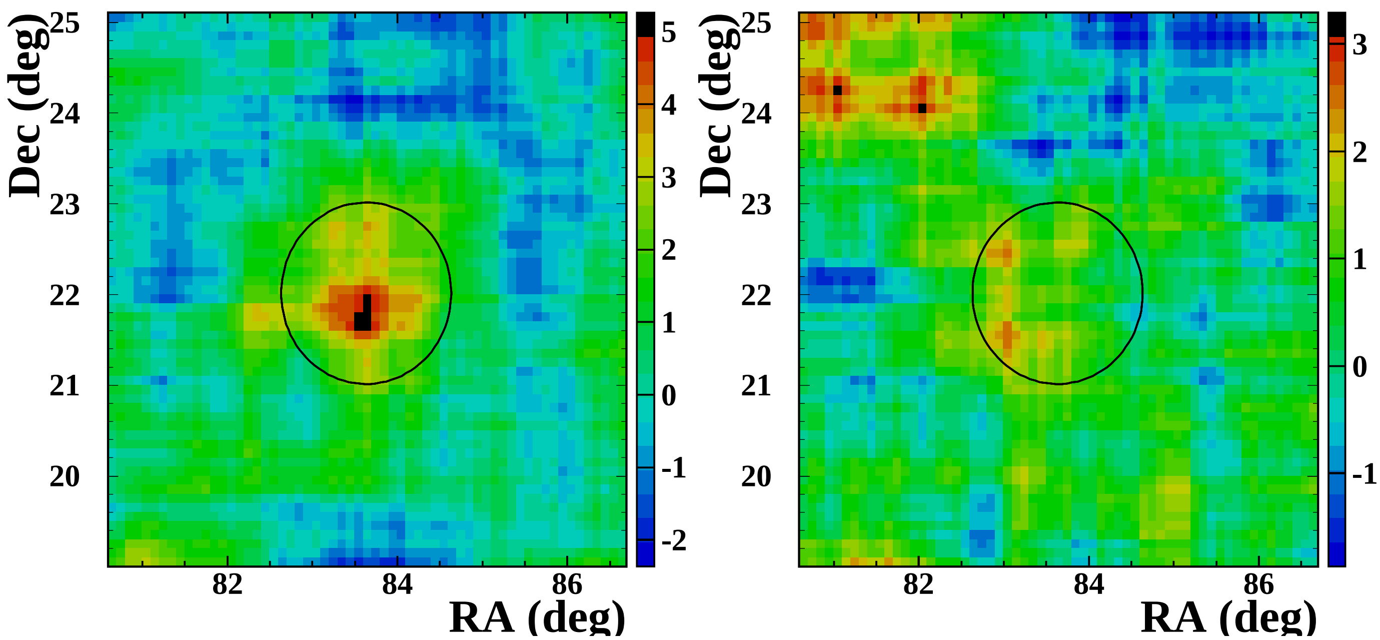


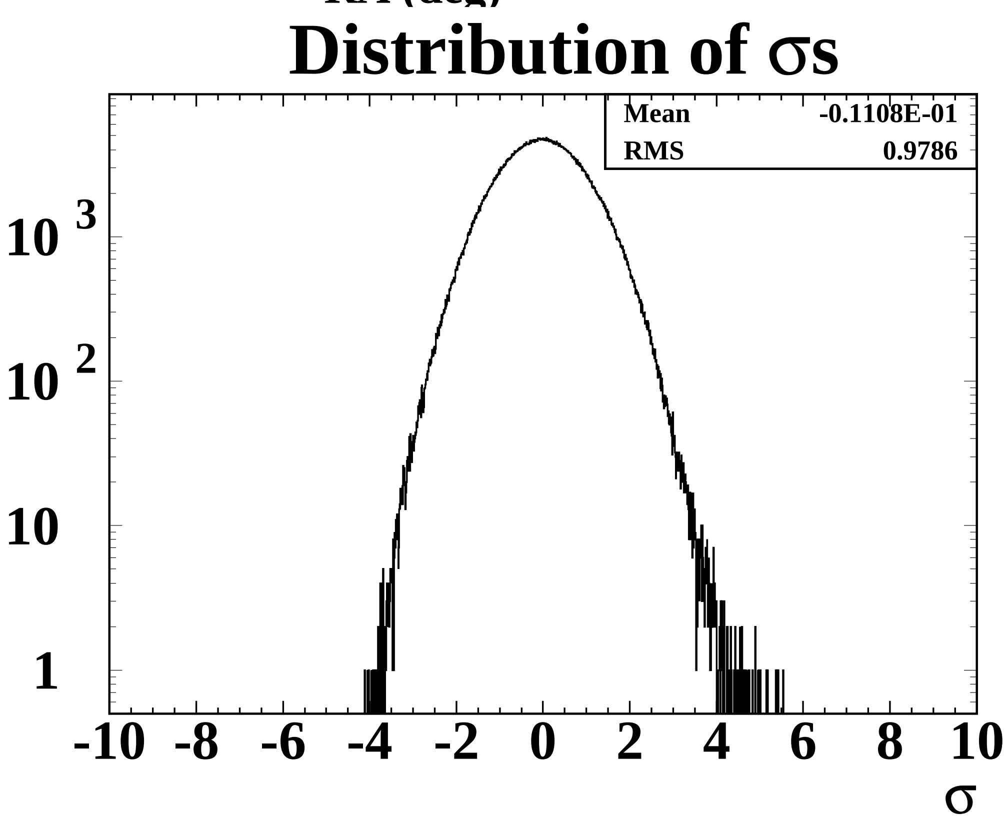
Bins are $0^{\circ}.5$ in δ by $1^{\circ}.0$ in RA$\times cos\delta$

Ongoing Milagro Studies

- Crab
- AGNs
- Moon Shadow
- Sun shadow
- Neutralinos
- Galaxy
- Surviving single hadrons
- Keep looking for GRBs...

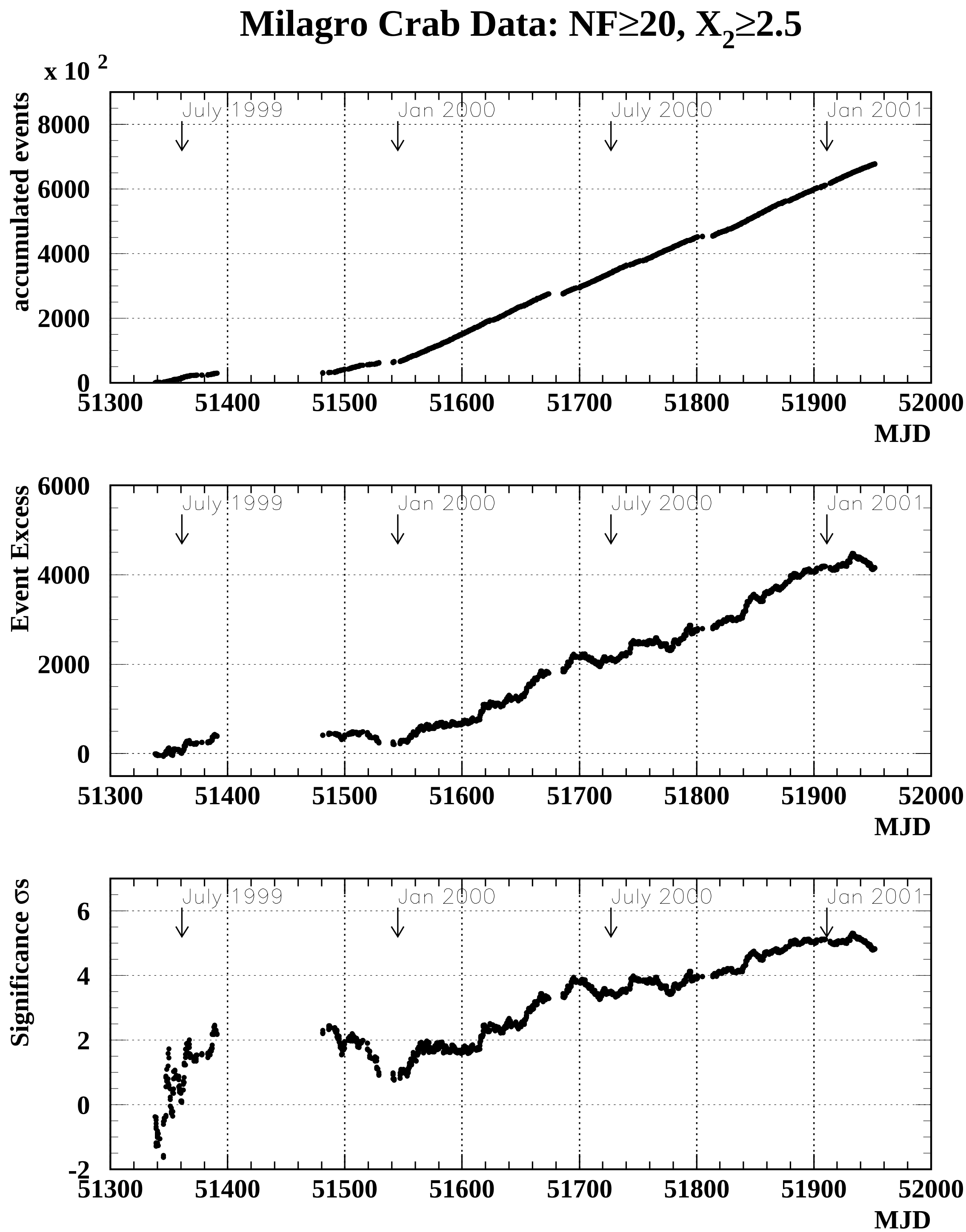
Milagro Crab Signal





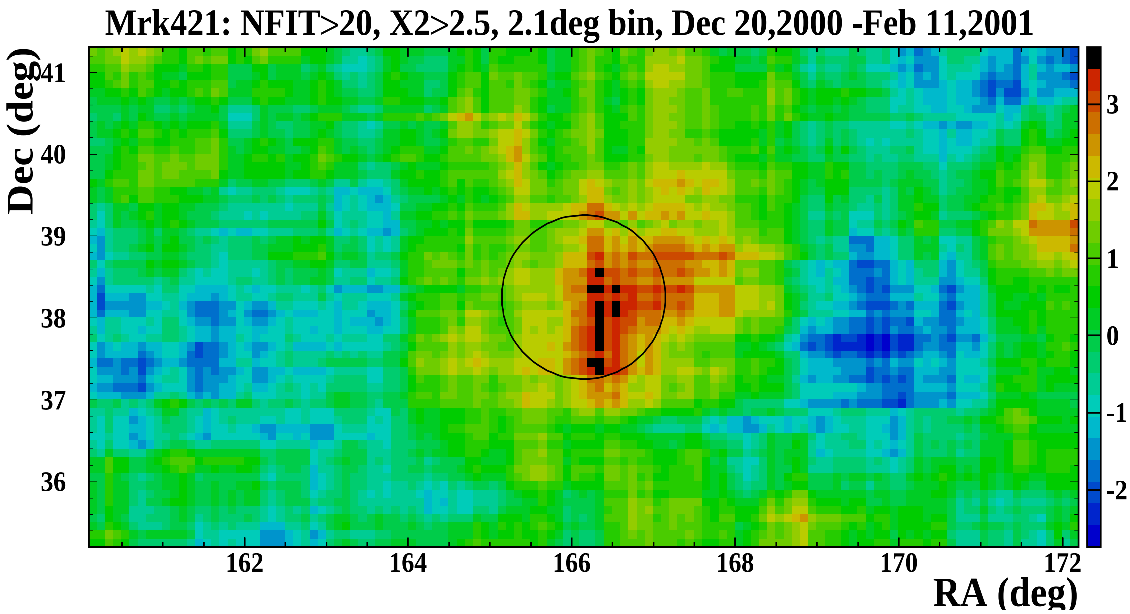
	Number events	Expected BG	Significance
No X_2 Cut	6,739,156	6,735,122	1.6 σ
$X_2 > 2.5$	622,536	618,766	4.8 σ

Milagro Crab Signal Accumulation



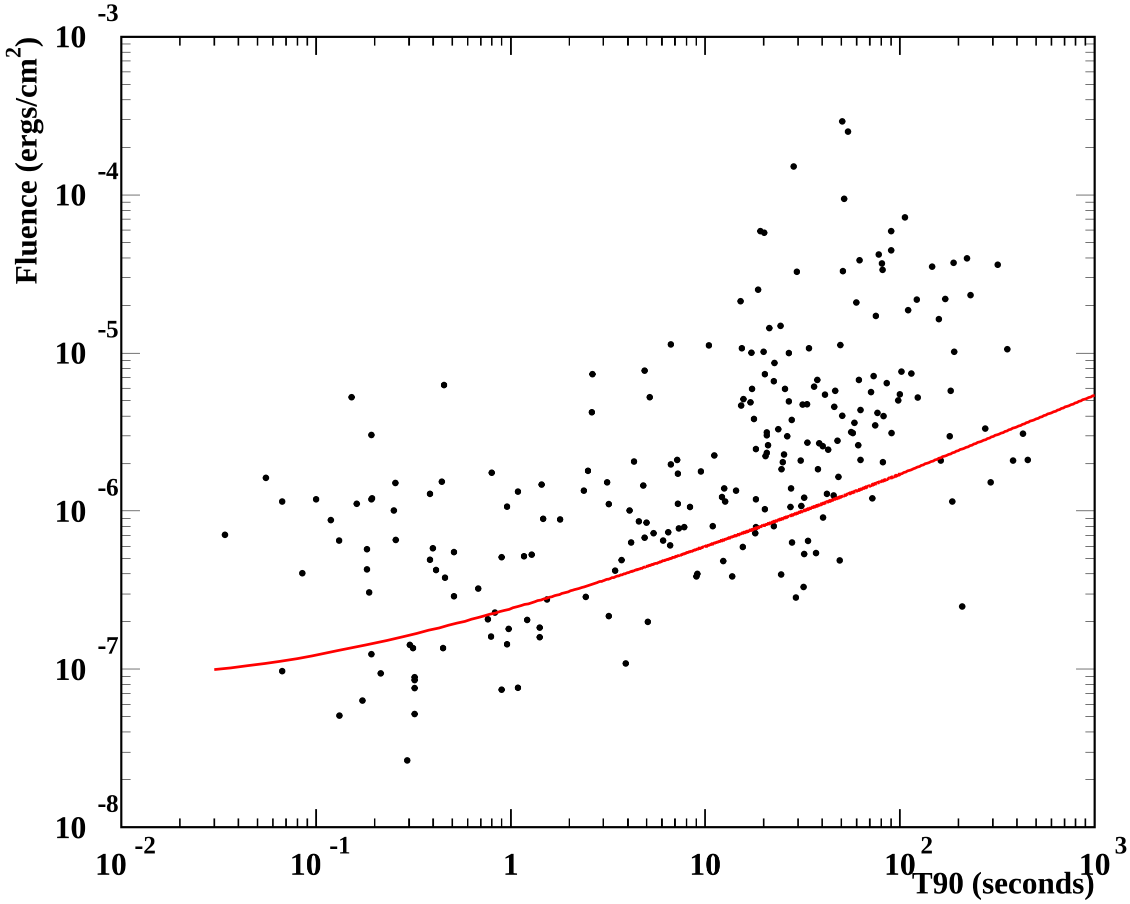
Milagro accumulates about 10 Crab photons per day.

Milagro Markarian 421



- Data recorded December 15, 2000 to March 1, 2001
- 154,391 on source events
- Expected BG 153,281
- Signal significance $\sim 2.95\sigma$

Milagro GRB Sensitivity



- Dots: BATSE GRB summed fluence vs. T_{90}.
- Curve: Milagro sensitivity for fluence above 1 TeV vs. T_{90} for a triggered burst.

  Does not include γ/hadron separation (For current X_2 cut, this would lower threshold by ~ 2.)

  Does not include outriggers, which would lower threshold by ~ 2.

The Milagro Future

- Improve Gamma - Hadron separation

  ACT breakthrough with 1989 Whipple γ/hadron cut.

  Milagro currently using:

  – X_2

  Additional parameters:

  – Nhit_{bottom}

  – Shower signal rise time for muon elimination and γ/hadron separation.

  – Lateral signal distribution.

- Building Outriggers

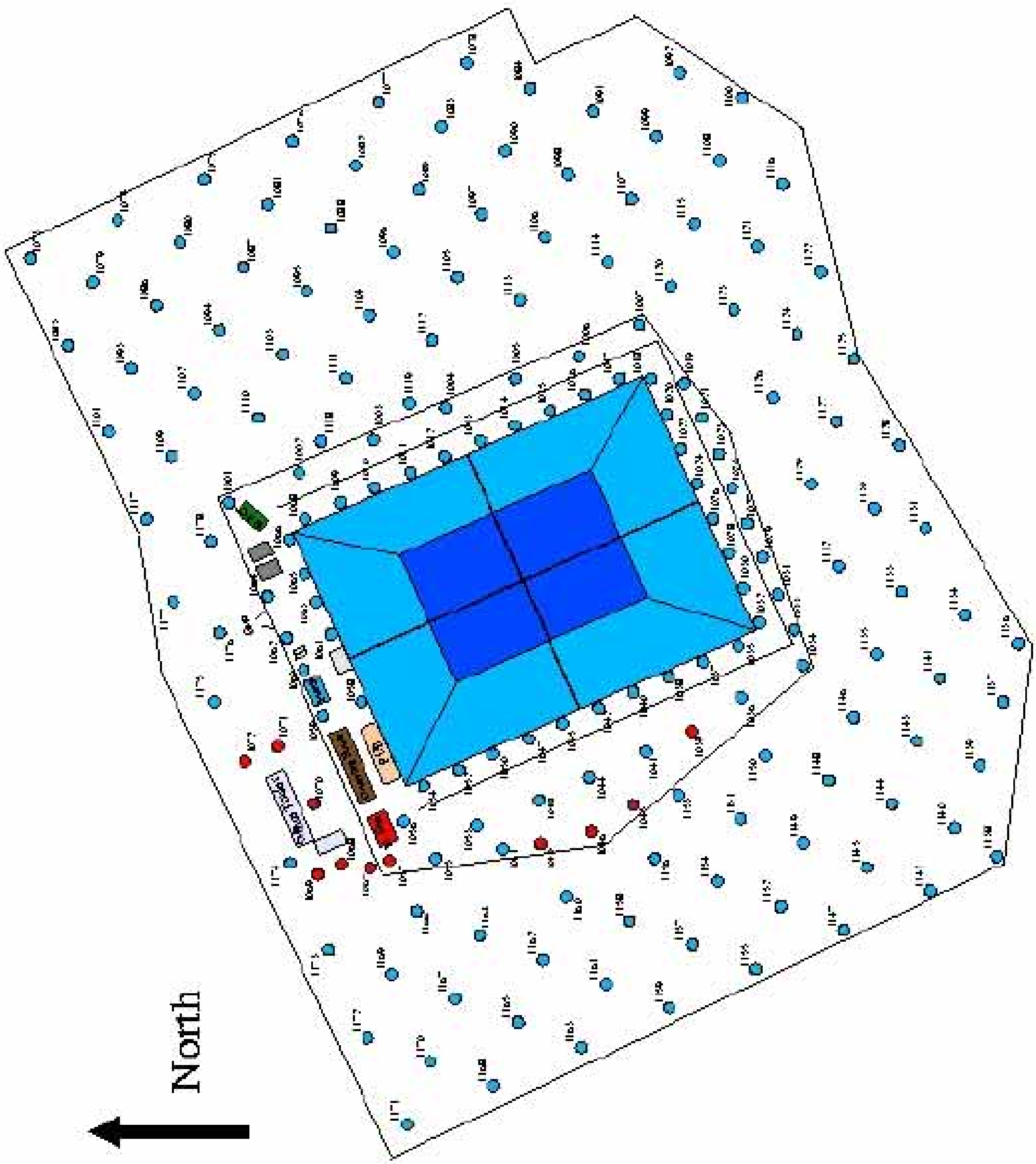
  Contain EAS, area ∼10 times Milagro.

  Improve angular resolution for core not on pond.

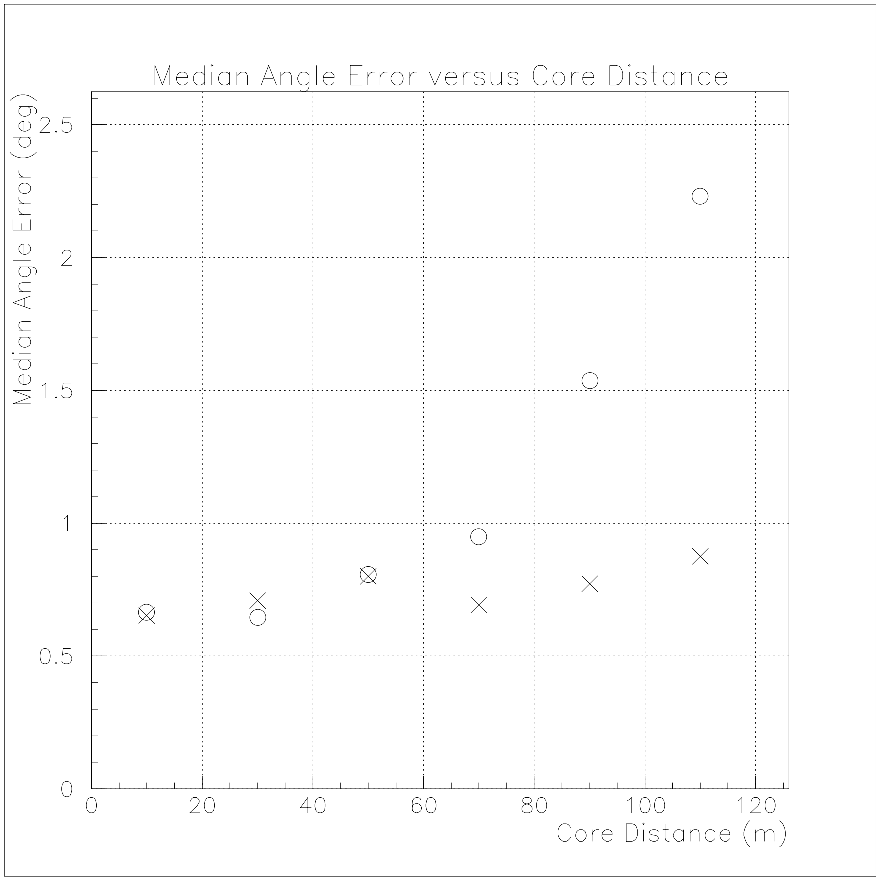
  Energy resolution ~ 50% using Lateral distribution fit.

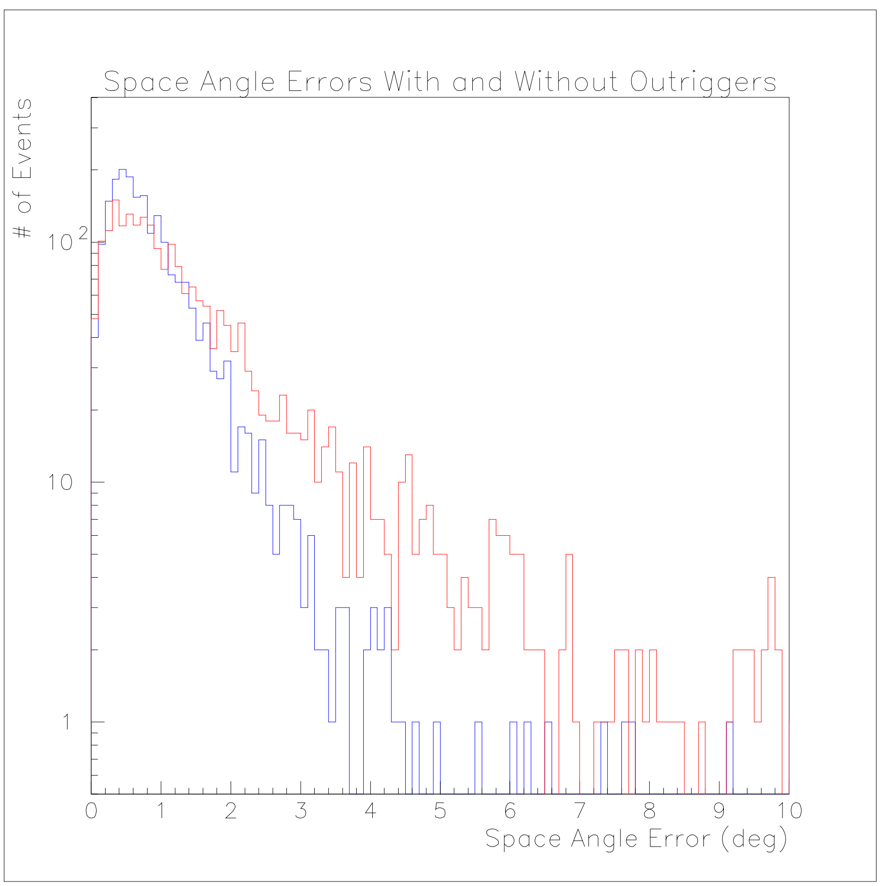
  Allows lowering energy threshold by vetoing isolated muons.

Milagro Outrigger Deployment

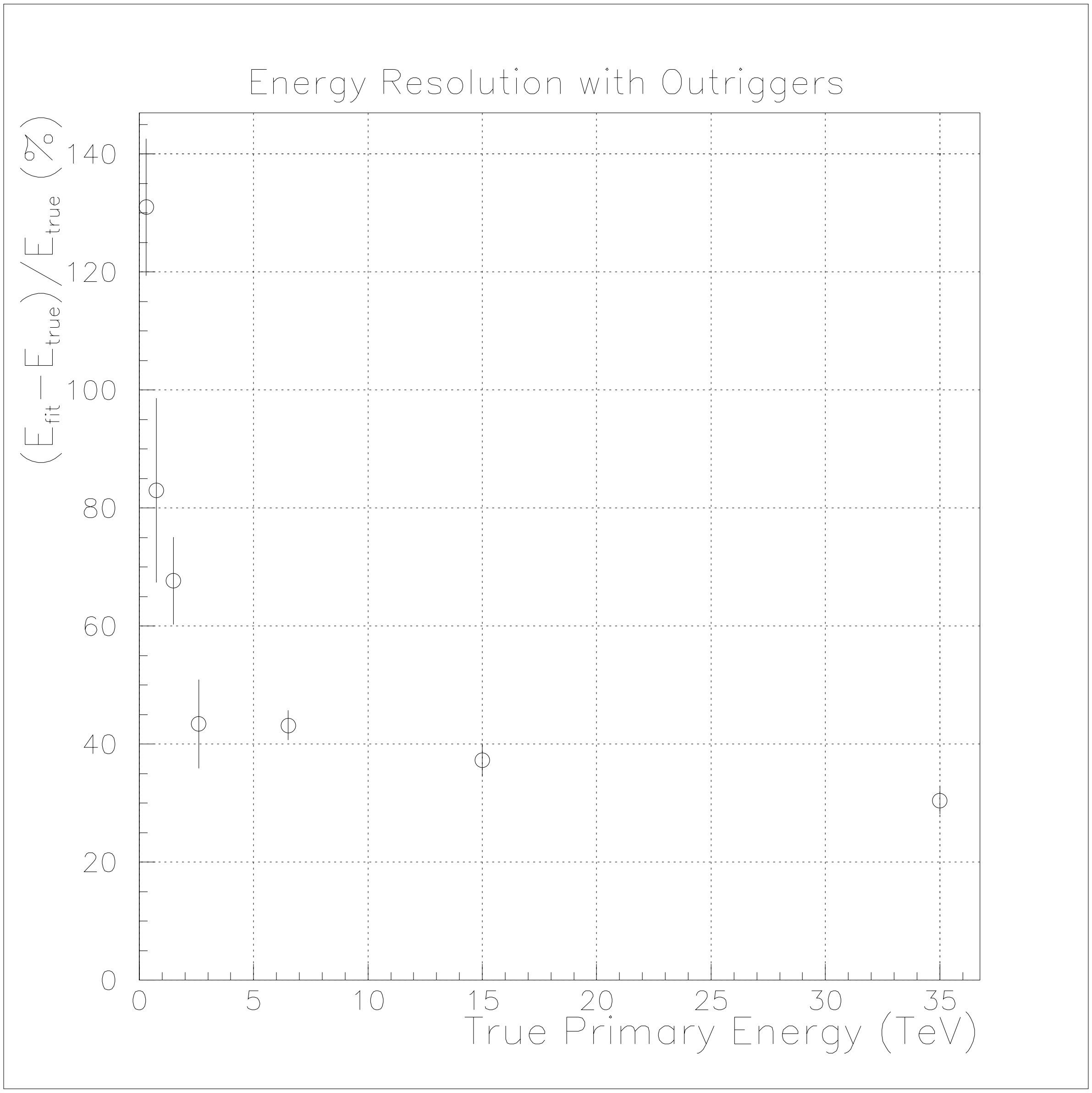


Outrigger Angular Resolution Improvement

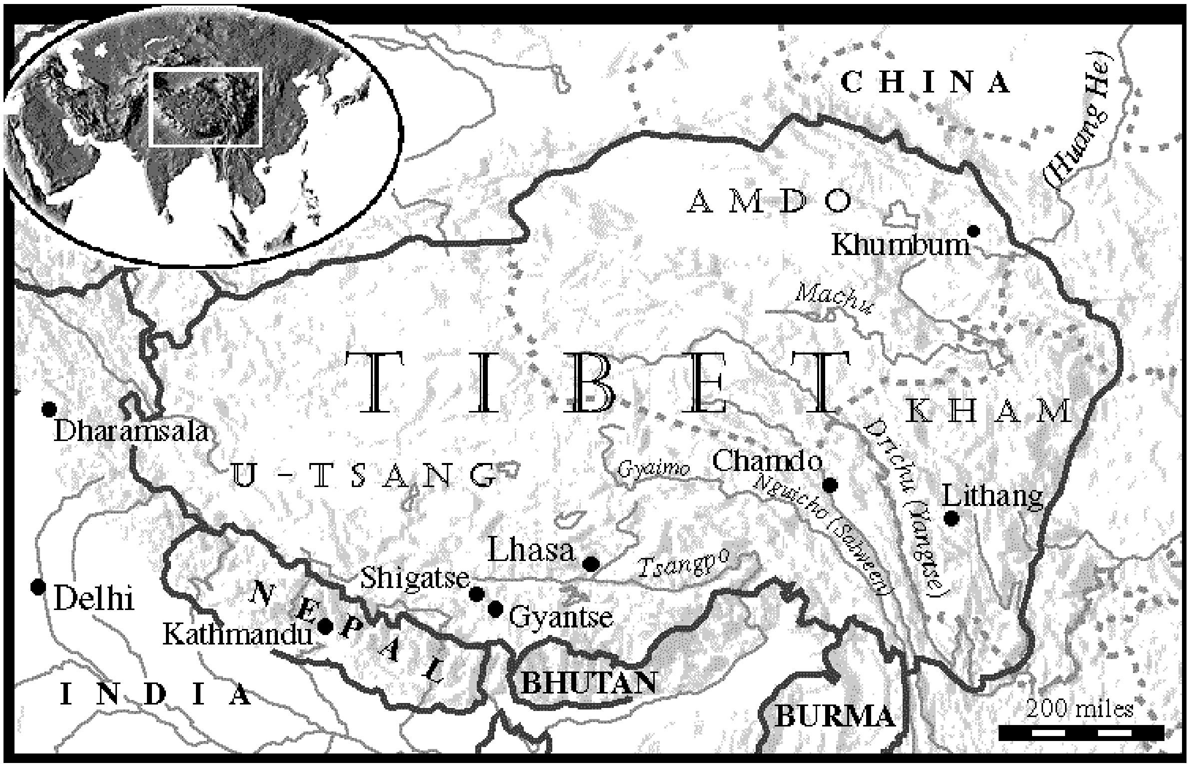


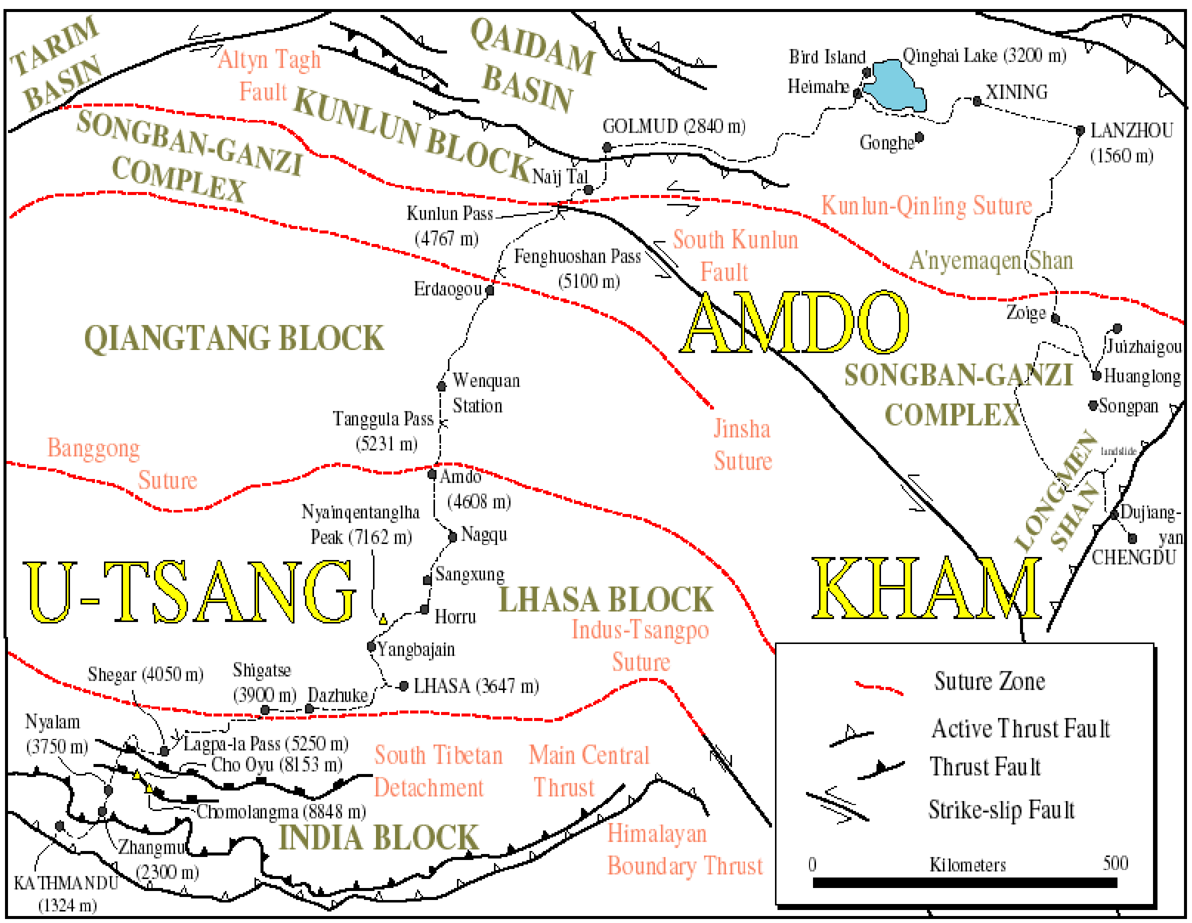


Milagro Energy Resolution with Outriggers

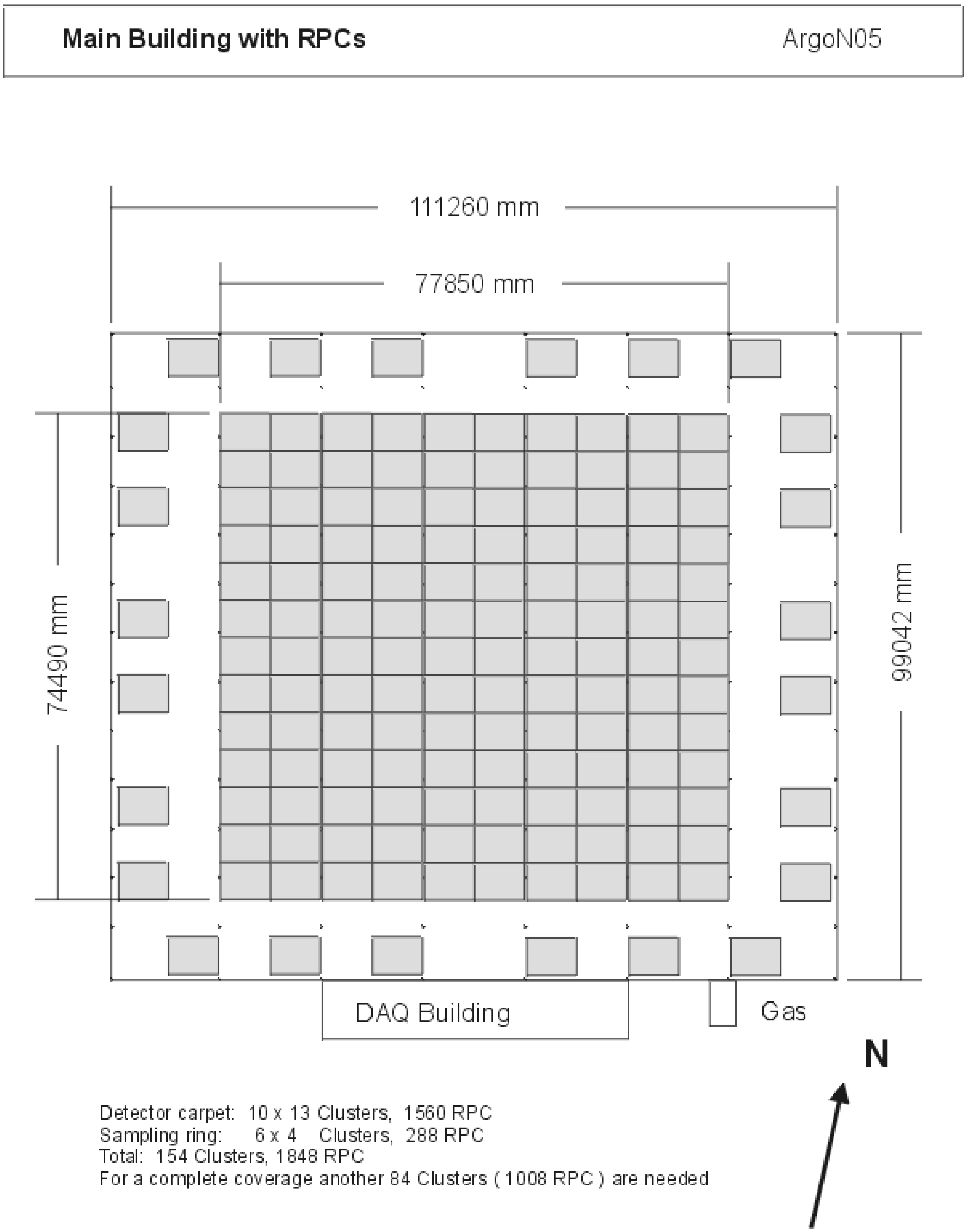


The ARGO-YBJ Experiment Location





The ARGO-YBJ Experiment Layout



The ARGO-YBJ Collaboration

ITALY:

P. Bernardini, C. Bleve, F. Cesaroni, P. Creti, I. De Mitri, G. Mancarella, G. Marsella, D. Martello, D. Orlando, M. Panareo, A. Surdo

INFN and Dipartimento di Fisica dell'Universita', Lecce

A. Aloisio[1] , F. Barone[2] , B. Bartoli, E. Calloni, S. Catalanotti, S. Cavaliere, B. D'Ettorre Piazzoli (Spokesman), T. Di Girolamo, G. Di Sciascio, M. Iacovacci, L. Milano, L. Saggese

INFN and Dipartimento di Fisica dell'Universita', Napoli

G. Aielli, P. Camarri, R. Cardarelli, M. Casolino, A. Cavaliere, V. D'Elia, B. Liberti, A. Morselli, A. Paoloni, R. Santonico

INFN and Dipartimento di Fisica dell'Universita' ”Tor Vergata”, Roma

C. Bacci, S. Bussino, E. Cisbani, M. De Vincenzi, N. Iucci, S.M. Mari, P. Pistilli, C. Stanescu, M. Storini

INFN and Dipartimento di Fisica dell'Universita' ”Roma Tre”, Roma

G. Badino, P. Vallania, S. Vernetto

INFN and Istituto di Cosmogeofisica del CNR, Torino

G. Cusimano, G. D'Ali' Staiti, T. Mineo, L. Nicastro, G. Raso, B. Sacco, L. Scarsi

INFN Sezione di Catania and Istituto di Fisica Cosmica IFCAI/CNR Palermo

G. Liguori

INFN Sezione di Pavia

1. Universita' del Sannio, Benevento
2. Dipartimento di Scienze Farmaceutiche, Universita' di Salerno

The ARGO-YBJ Collaboration

China:

H.H.He, H.H.Kuang, H.Lu, X.H.Ma, Z.R.Peng, P.R.Shen, Y.H. Tan (Spokesman), H.Wang, H.Y.Wang, M.Cha, H.M.Zhang, J.L.Zhang, Q.Q.Zhu

IHEP, Beijing

B.Y.Cao, Y.Fu, F.M.Kong, J.Y.Li, C.R.Wang, N.J.Zhang, X.Y.Zhang

Shandong University, Jinan

Z.Y.Feng, Q.Huang, H.Y.Jai, G.C.Yu

South West Jiaotong University, Chengdu

Danzengluobu, H.W.Guo, Labaciren, X.R.Meng, A.F.Yuan, Zhaxisangzhu, Zhaxiciren

Tibet University, Lhasa

X.Y.Gao, Q.X.Geng, Z.Q.Liu, J.Mu, T.J.Zhang

Yunnan University, Kunming

K.Z. Bao, B.Li, L.R.Sun, S.C.Sun, Y.N.Wei, Q.K.Yao, X.D.Yue

Zhenghou University, Henan

ARGO-YBJ

- Maximize altitude and active area, photon sensitivity.

  Altitude is 4300m (606 g/cm^2).

  Resistive Plate Chambers (RPC) allow large coverage:

  – Each RPC is constructed of 10 pads each 0.60 m x 0.56 m

  – 92% of 78m x 74m

  – Additional 20% of remaining area inside 111m x 99m

  – Total of 6700 m^2 active area.

  0.5 cm Pb on RPCs converts γs.

- Expected Properties:

  Sensitivity 5σ in 1 year for ~1/10 Crab from 100 Gev to 20 TeV.

  Angular resolution $\sim 0^\circ.4$ for 100 pad multiplicity.

  Rates ~ 20 kHz.

- Gamma - Hadron separation

  Proposed neural network approach:

  – Radial distribution of signal, steeper for photons.

  – Local fluctuations in the signal, greater for protons.

  – Yields $Q \sim 1.8$ retaining about 80% of Gammas.

- History:

  Tested 91% coverage of 51 m^2 February to May 1998.

  – 1.3 ns time resolution.

  – $\Delta_{\rm EO} \sim 2^\circ$ for 100 pad multiplicities.

  – Pb decreases $\Delta_{\rm EO}$ from 8° to 5° for ~ 35 pad multiplicity.

  Construction began October 2000; now in progress.

  Expect data taking to begin in 2001 with 800m^2.

  Finish "central carpet" by end of 2003; outer ring during 2004.

Conclusions

- Second generation of detectors coming into their own.
- Milagro
  - Milagrito shows method is understood, and already produced some interesting results.
  - γ/hadron separation in infancy, lots of room for improvement.
  - Many analyses under way.
- ARGO
  - Small scale detector behaved as expected.
  - Should provide interesting data from turn on.
  - More γ/hadron separation possibilities can be studied.
- Third generation detectors? Large area, high altitude, segmented, multiple layers, good timing.