CACTUS

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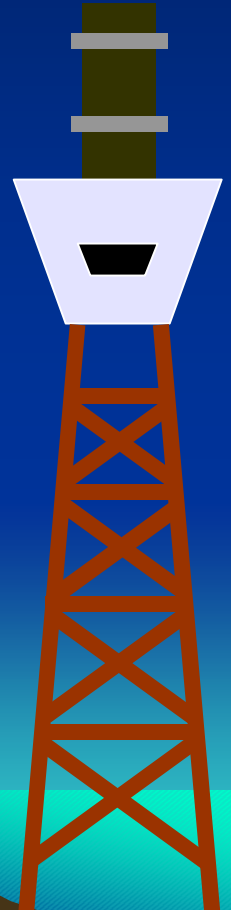
Sho Maruyama

Mani Tripathi

John Stilley

Senior Engineer: Britt Holbrook

Junior Specialist: Tiffany Landry.

Undergrads: John Felde, Cherie Williams, Sasha Laundy, Emily Rostel.

Technical Assistants: John Linn, Joe Trad.

Mani Tripathi, C2CR, Prague, Sept 9, 2005.

Outline

- Solar Two facility and CACTUS.

- Instrument:
  -250 channel (effective) camera.

- Simulations and Calibrations
  -optics & noise

  -energy response

  -Crab

- The Dark Matter problem & Draco

  -Data & Preliminary analysis.

  Future prospects - Dwarf spheroid survey.

The Solar 2 Heliostat Array

Located 15 miles outside Barstow, CA

Over 1,900 42m² heliostats. The largest array in the world.

We have ~160 heliostats in the FOV of our camera.

Collection area ~64,000 m².

Mani Tripathi, UC-Davis

Air Cherenkov

Heliostat arrays offer large collection areas that are not possible with imaging telescopes. Solar Two is the only field large enough to contain the entire Cherenkov light pool.

Utilizing existing arrays is a highly cost-effective method of constructing large area telescopes.

Solar Two was abandoned in 1998 after a successful run as a pilot plant/technology demonstration project.


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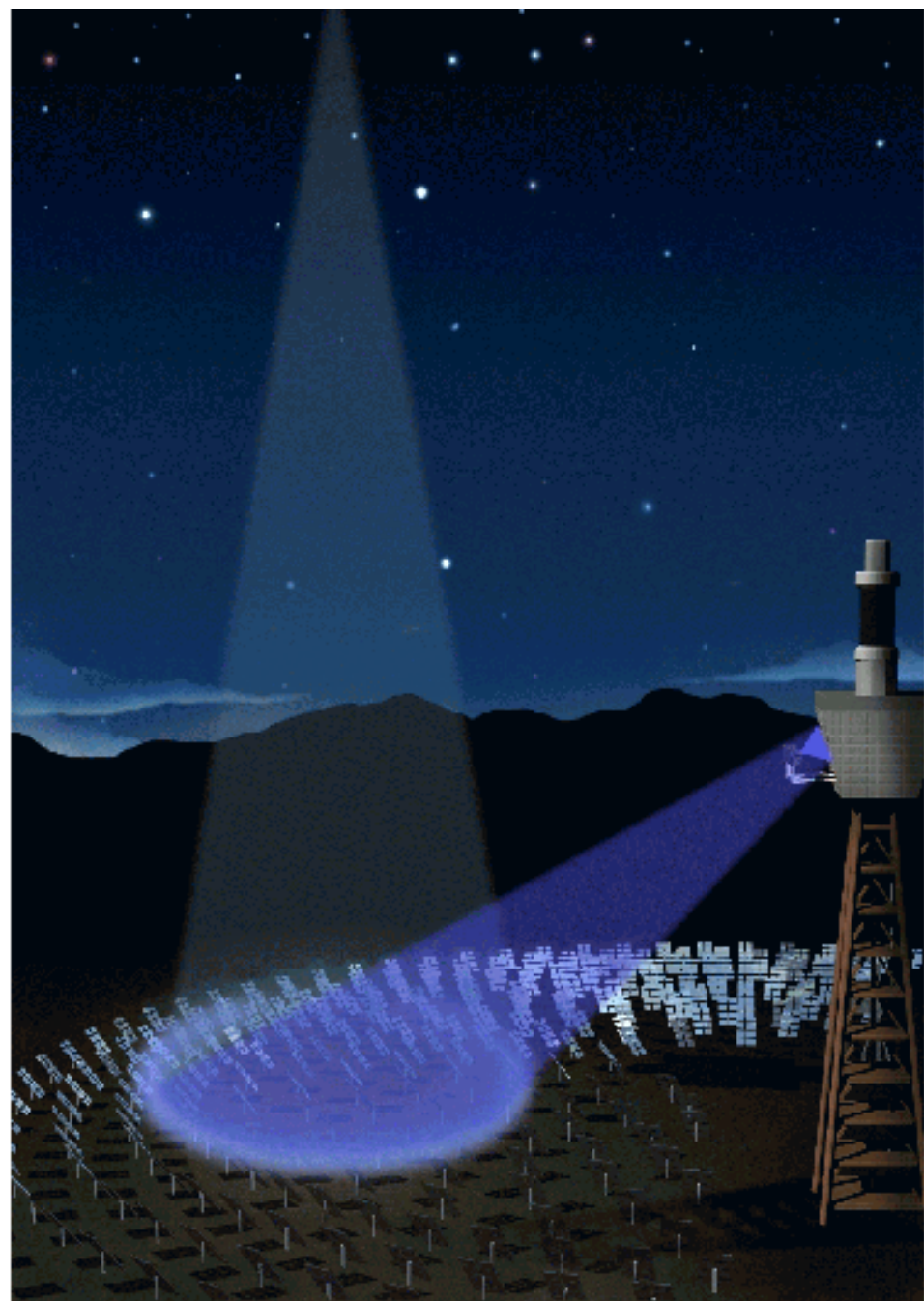
Detection Technique

Electromagnetic showers produce a coherent and compact ring-like Cerenkov wavefront.
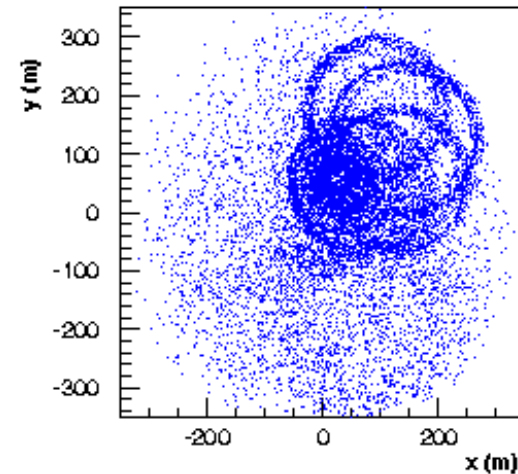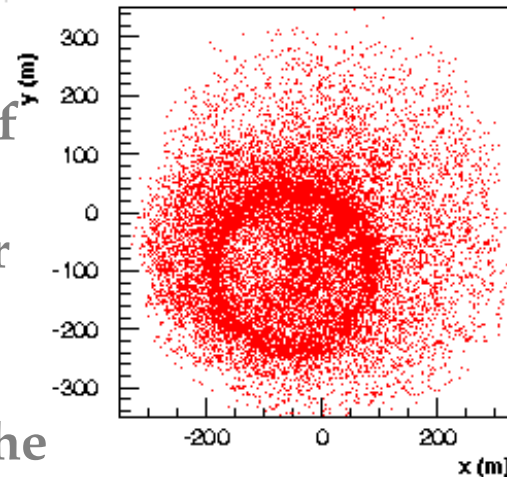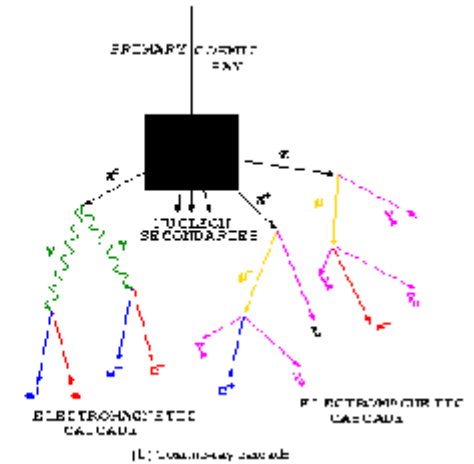
Proton showers consist of EM sub-showers due to neutral pions and/or individual rings due to muons.

Core diameter of the light pool is nearly independent of the primary particle energy (refractive index in the upper atmosphere is very close to unity and the radiating particles rapidly fall below the Cerenkov threshold).


Gamma
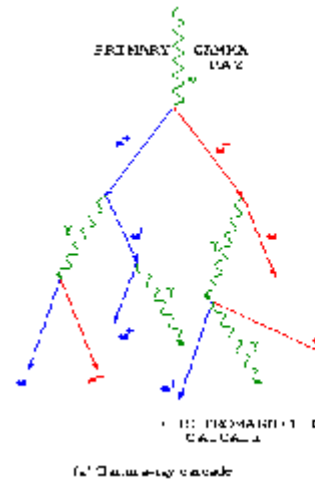
Proton

Detecting the Cherenkov Light

Ground based telescopes attempt to sample a fraction of the core light pool which is ~ 200 - 250 m in diameter.

Good energy resolution demands a high photon detection efficiency. Night-sky background is in the range of ~3-6 x 10^{12} photons/m^2/s/sr.

Temporal coherence (~ 3-5 ns) of the Cerenkov wavefront allows for sharp coincidences between camera elements.

CACTUS can exploit differences in time-structure between gamma and proton showers.

Mani Tripathi, UC-Davis
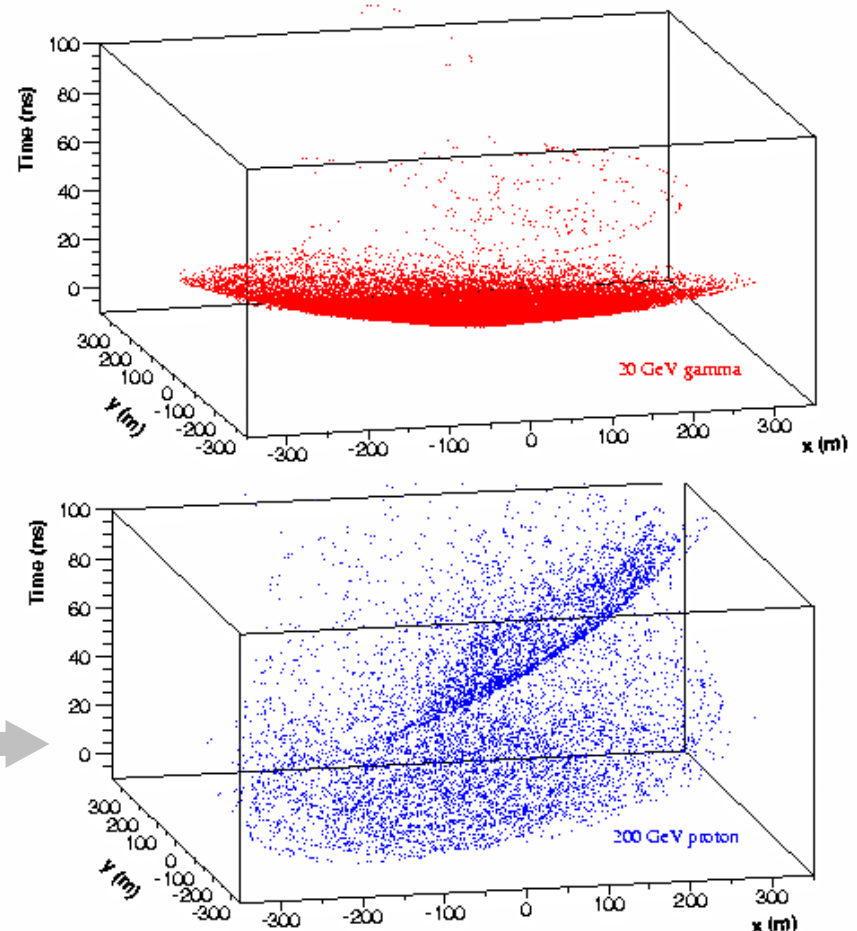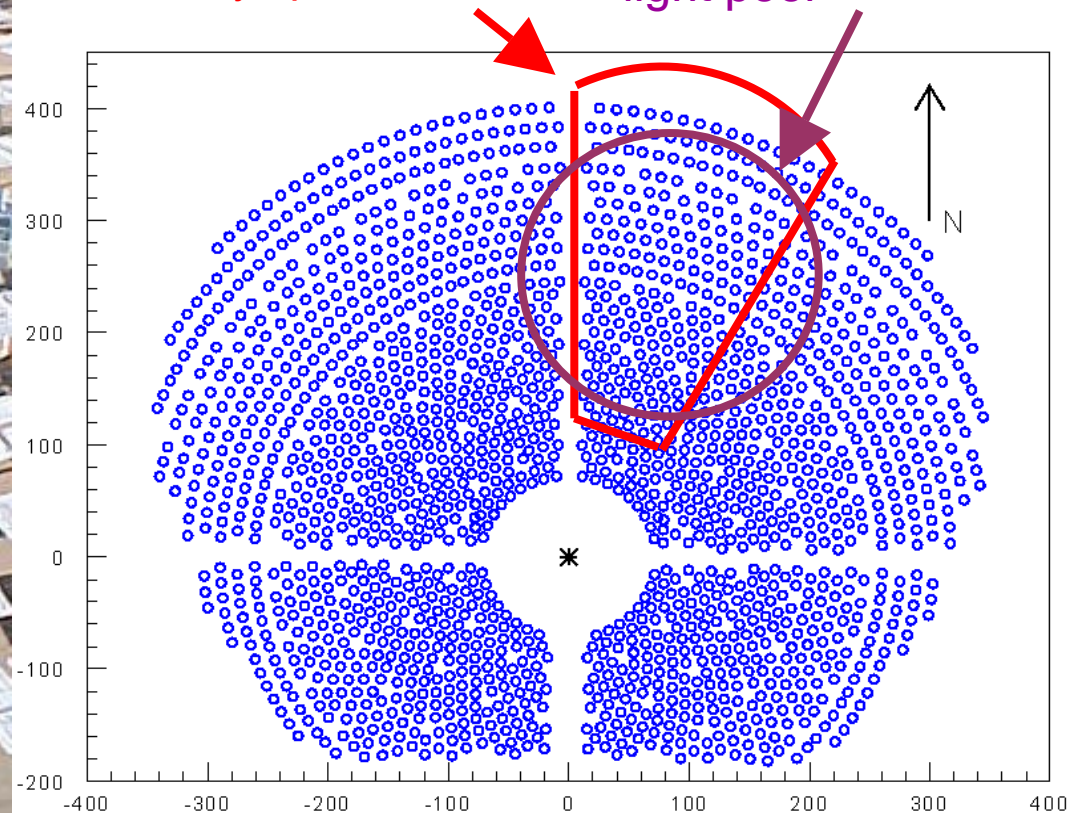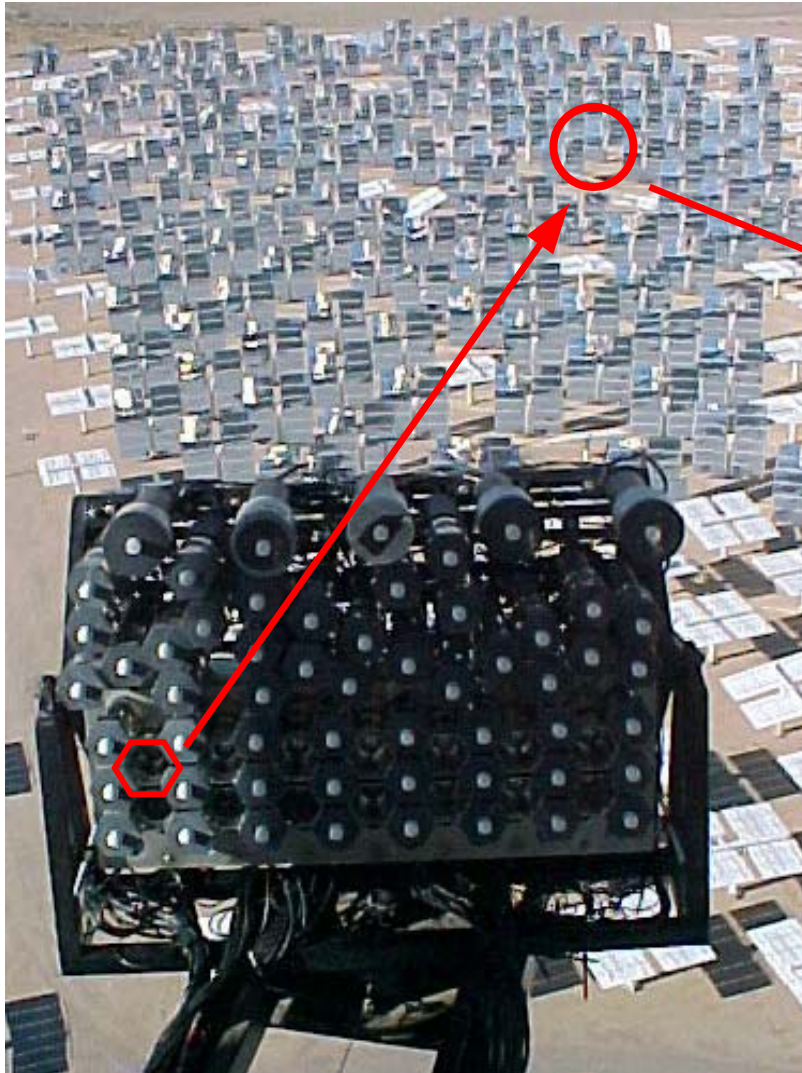
80 channel camera

Heliostat Field

Part of the field being used. 160 heliostats* available. 140 used in this campaign.

*limited by aperture

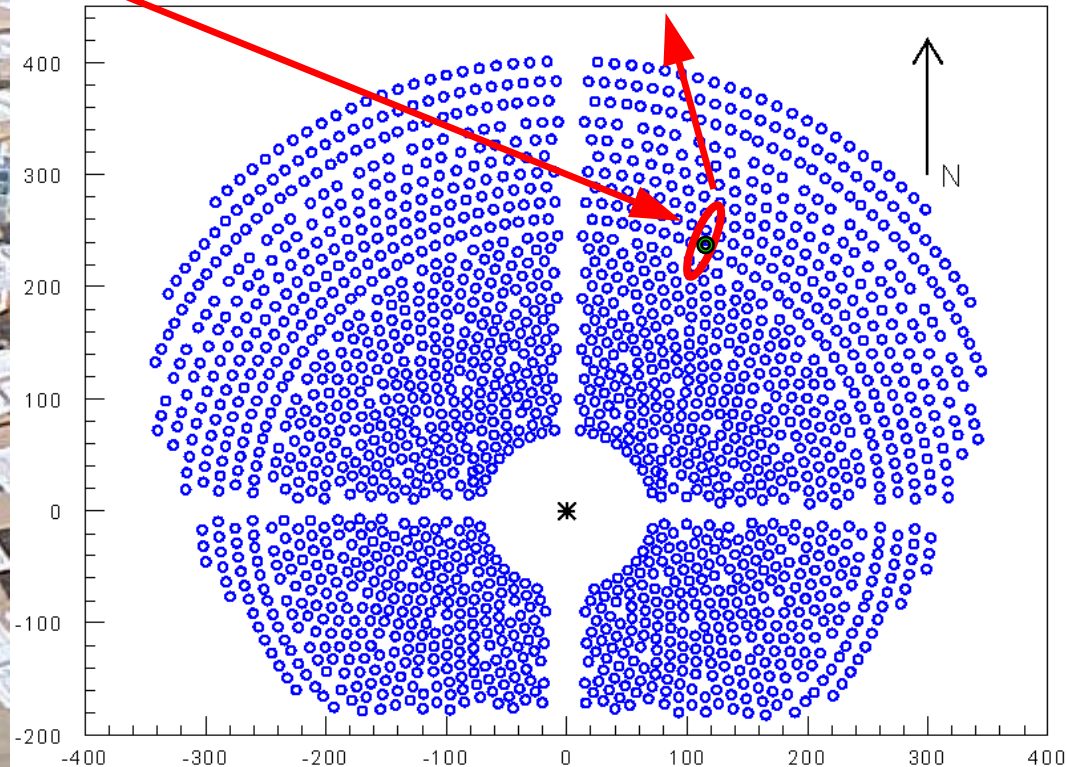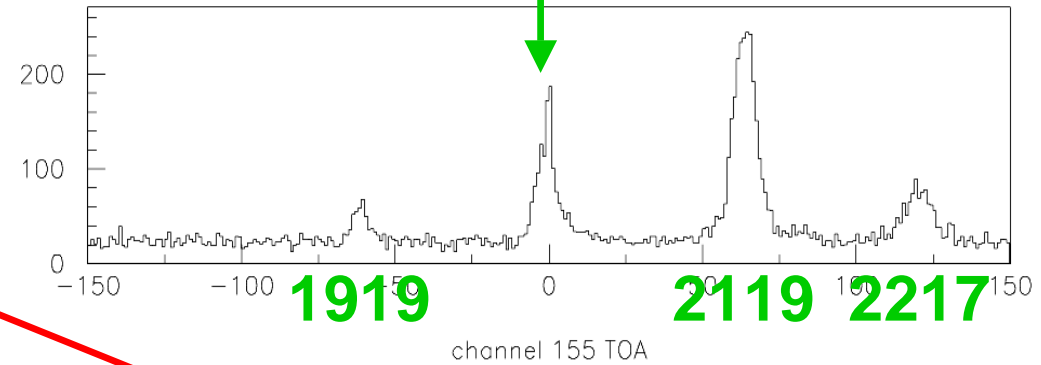CACTUS is capable of collecting nearly the entire Cherenkov light pool

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80 channel camera

Heliostat Field

channel 155 TOA

1919   **2119 2217**

N

Mani Tripathi, UC-Davis

Channel Multiplicity

Mani Tripathi, UC-Davis
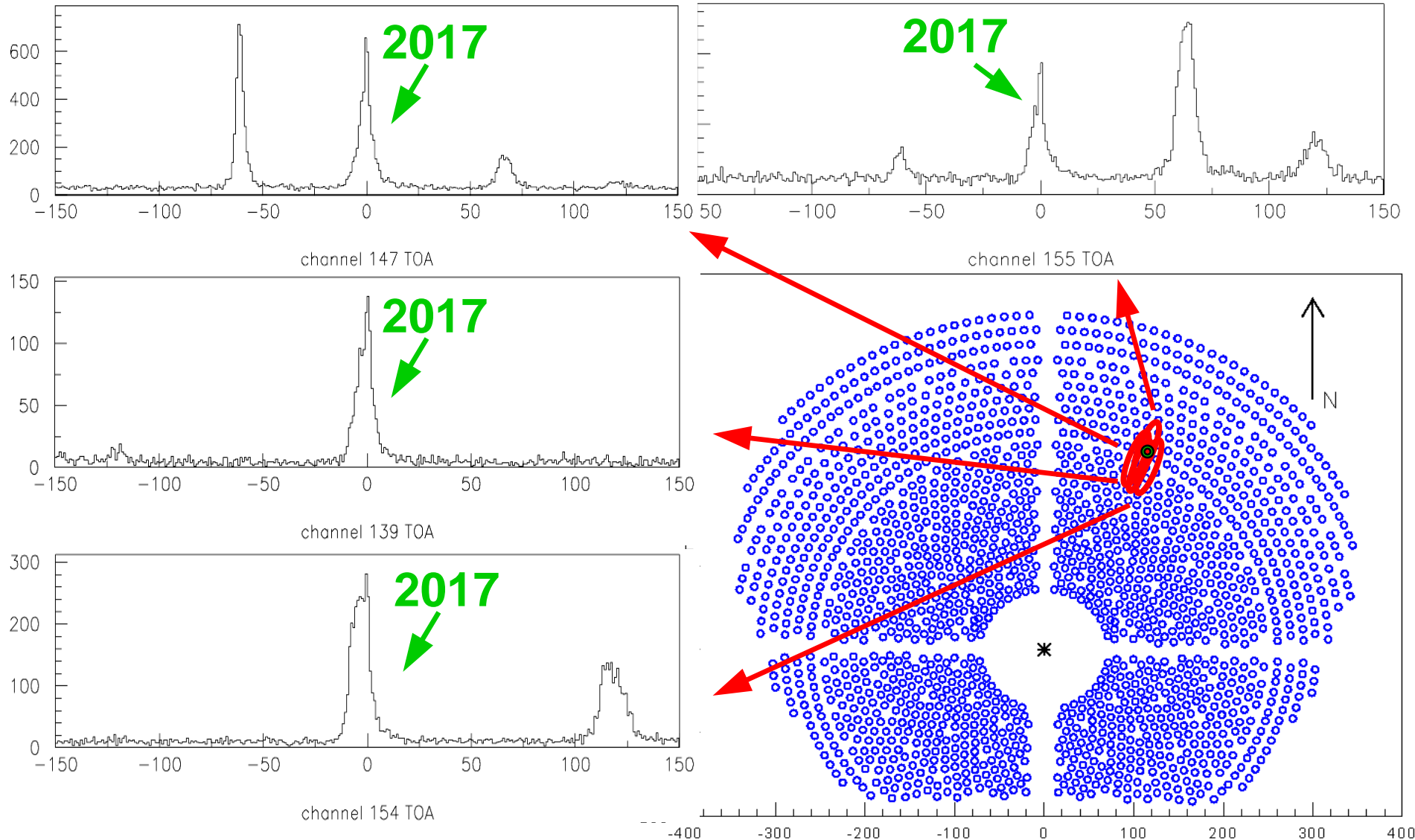
Heliostat Multiplicity

- **Heliostat 2017 is covered by 4 PMTS**

- **This allows us to record multiple hits on each heliostat with full two-pulse resolution**

2017

2017

channel 147 TOA

channel 155 TOA

2017

channel 139 TOA

2017

channel 154 TOA
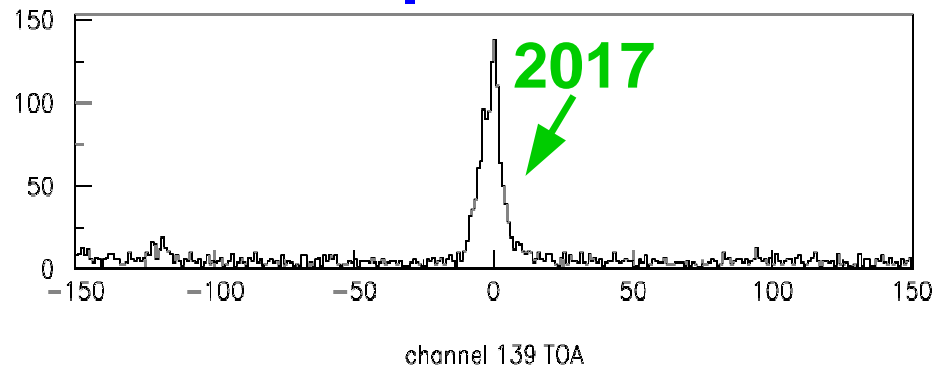
Heliostat Multiplicity
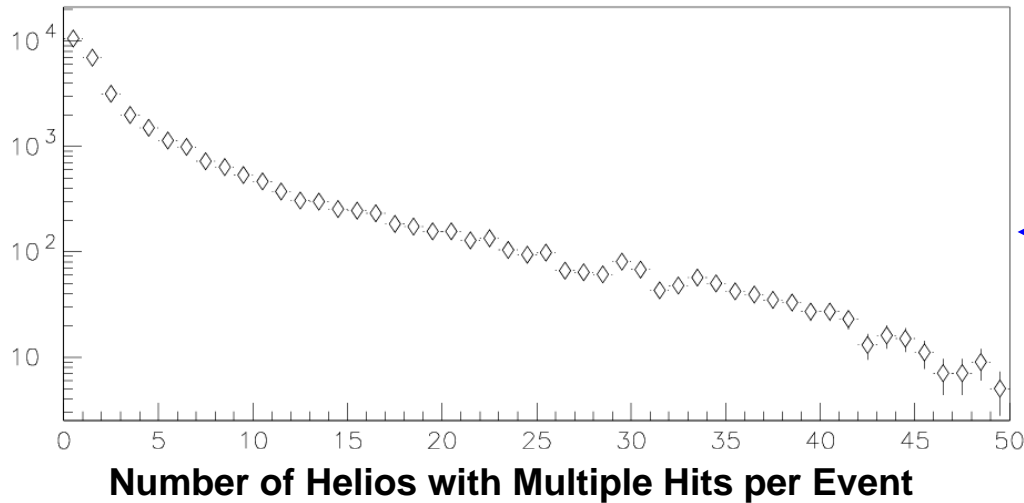
Most events contain multiple hits in each heliostat.
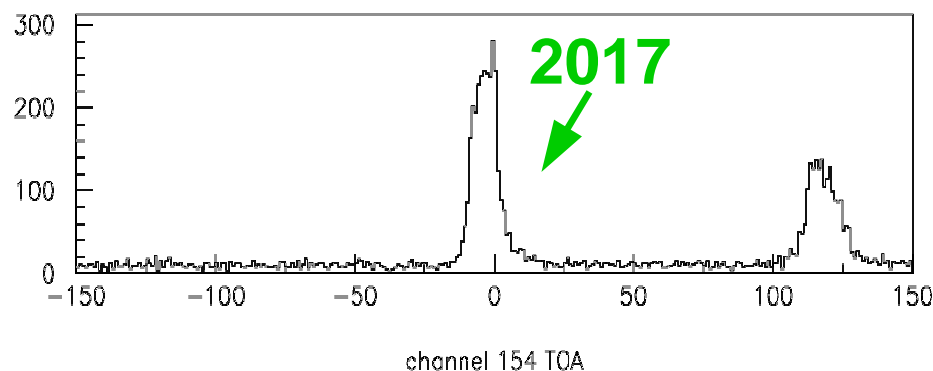
Number of Helios with Multiple Hits per Event
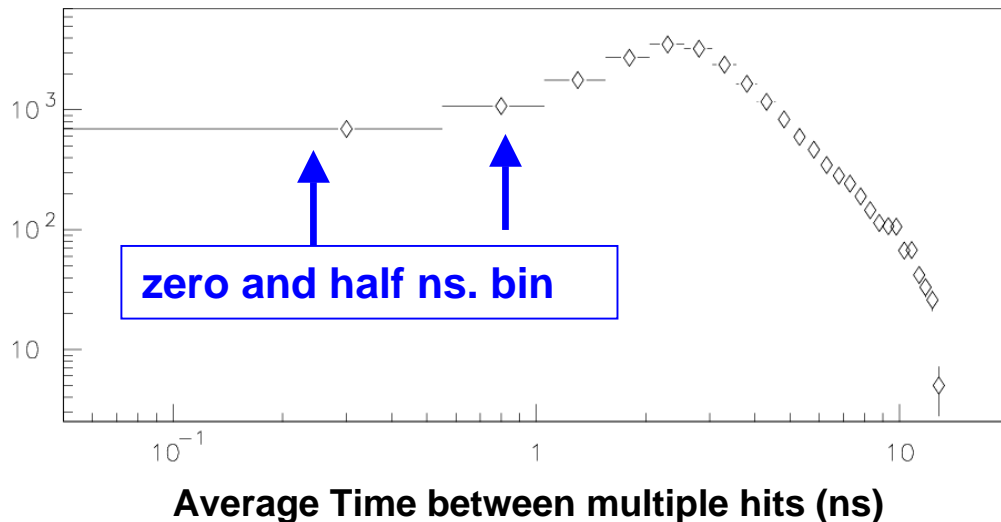
We can record multiple hits with 0.5 ns resolution without any pile-up.

zero and half ns. bin

Average Time between multiple hits (ns)

Mani Tripathi, UC-Davis
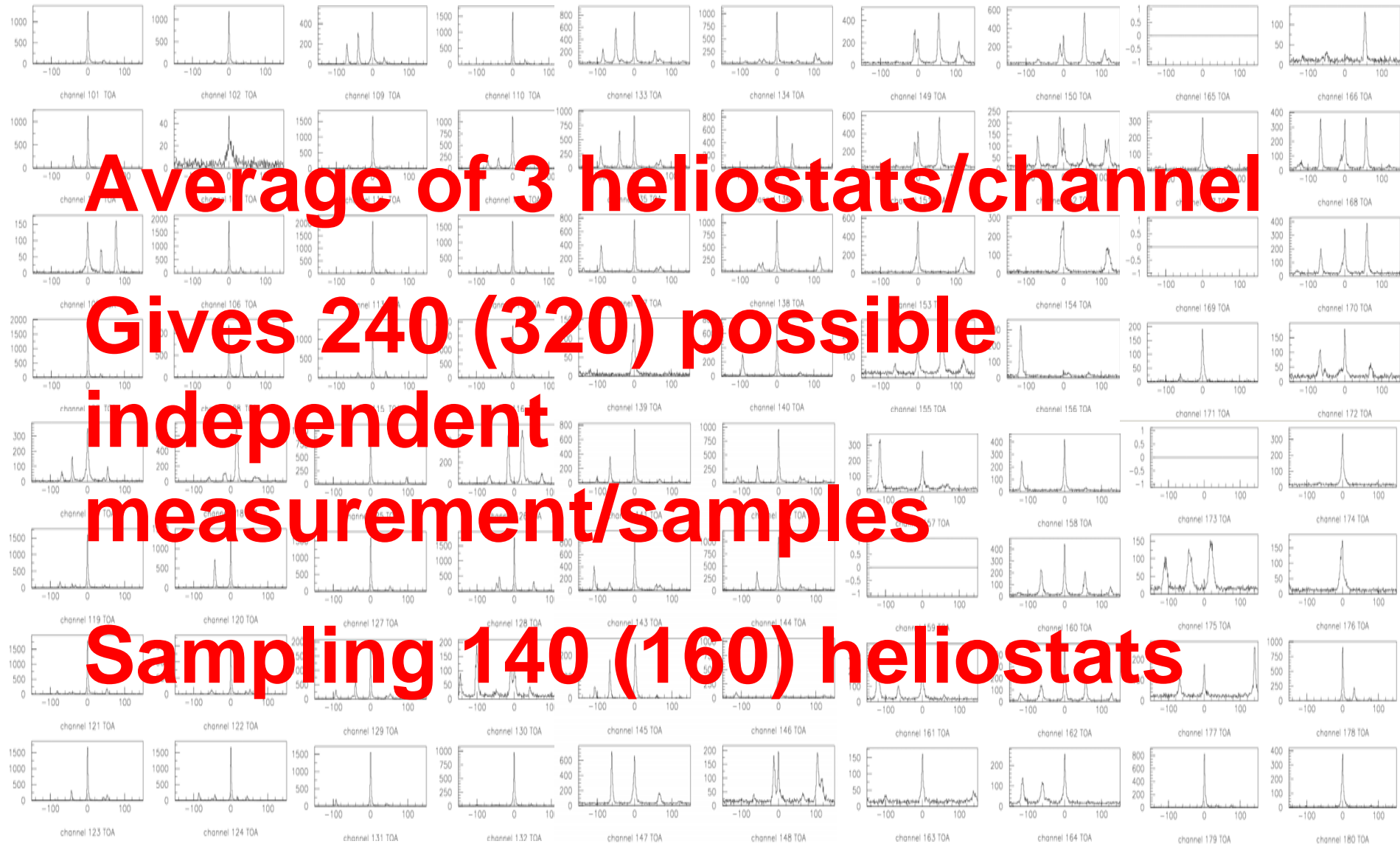
Average of 3 heliostats/channel

Gives 240 (320) possible independent measurement/samples

Sampling 140 (160) heliostats

Heliostat Multiplicity

Dynamic range if 80 channels mapped to 80 heliostats.

Dynamic range gained by using more than 80 heliostats.

Dynamic range using heliostat multiplicity.

Heliostat Alignment and MC Calibration

The heliostats are aligned using a sunspot projected on the tower face.
An infrared CCD camera is used to measure the sun spot and maximize the brightness at the core.
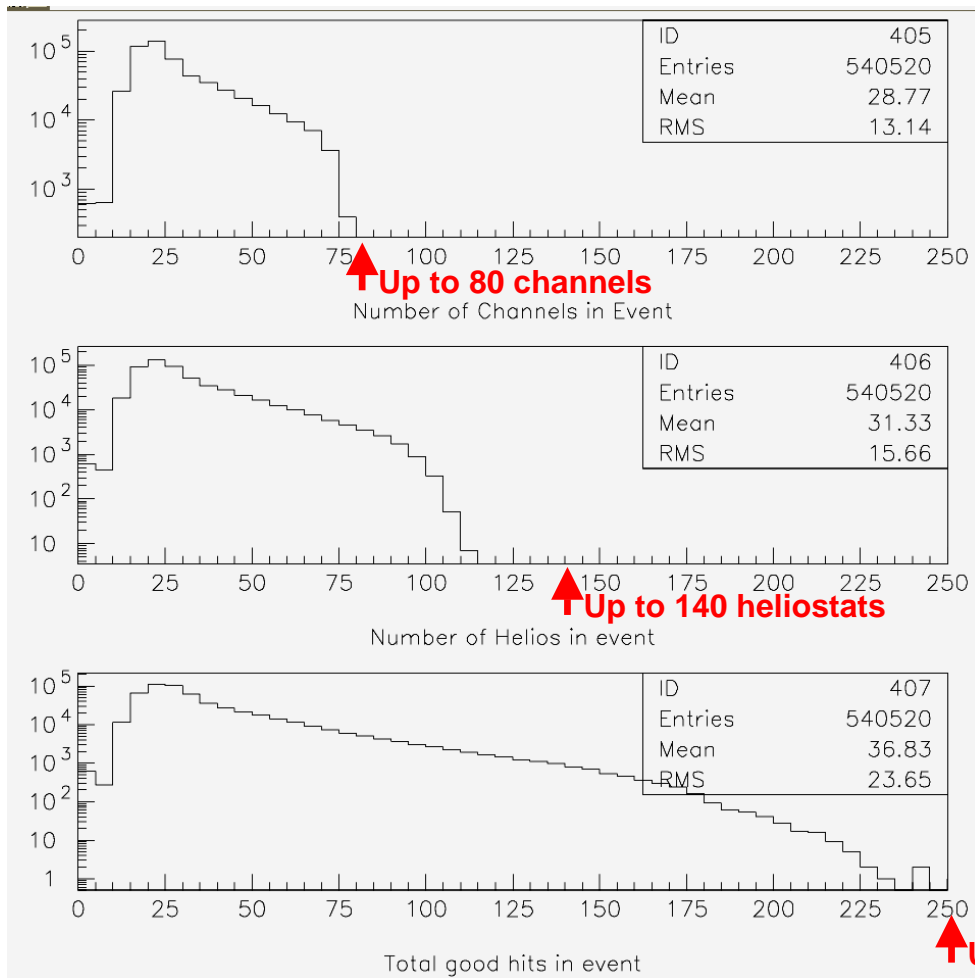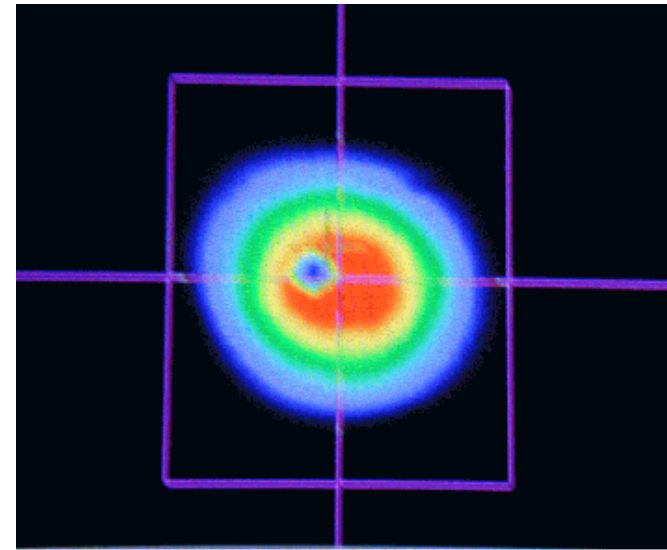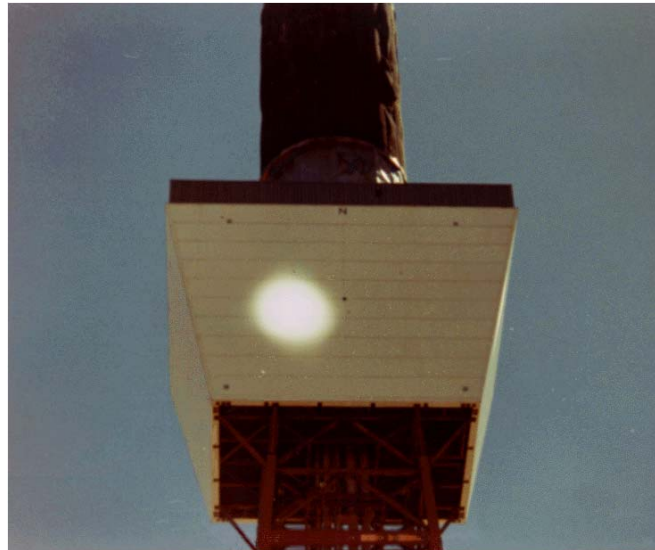

Simulated Sunspots

Heliostat facet parameters were optimized to match the CCD images

heliostat 1609 sunspotz .06 meter horizontal slice from centerz .1 m. bins

ID	300
Entries	10265
Mean	-0.4369E-01
RMS	0.5945
χ^2/ndf	704.4 / 28
Constant	690.8
Mean	-0.5809E-01
Sigma	0.5555

Sunspot contour on door for heliostat 1609 (sun at el70 az180)

ID	300
ENTRIES	277345
0.00	0.00	0.00
0.00	0.277E+06	0.00
0.00	0.00	0.00

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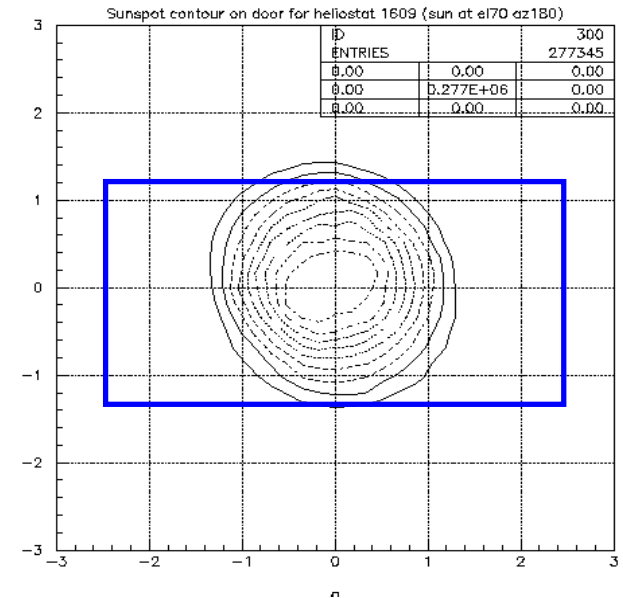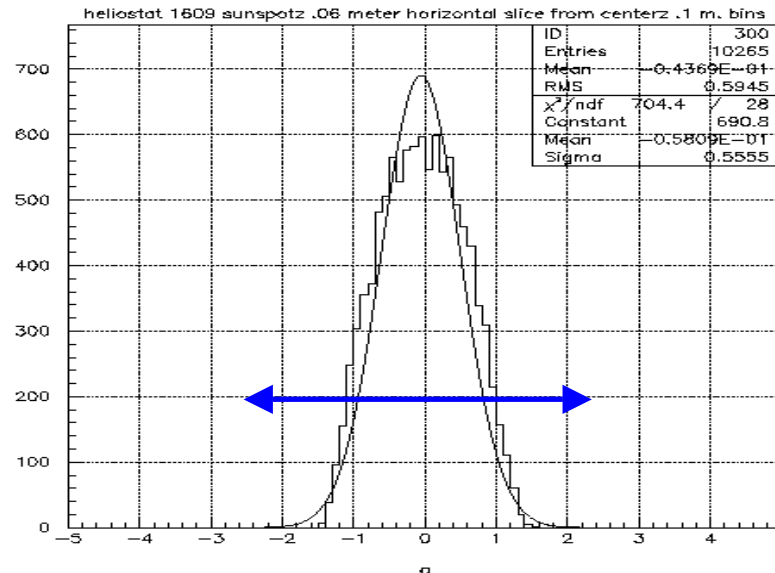
Calibrations and Simulation

Calibrating with starlight: Drift scan of Sirius

Drift scan of Sirius across one heliostat compared with a detailed simulation of all the optical elements involved.

Data

ID	201
Entries	3349
Mean	−0.3613E−01
RMS	0.2073

Sirius 500 Helio 2311 (Drift Scan)

Simulation

ID	300
Entries	24203
Mean	−0.1718E−01
RMS	0.1909

Simulated data 3 arcmin FOV slice source at el60 az236 (no facet jitter)
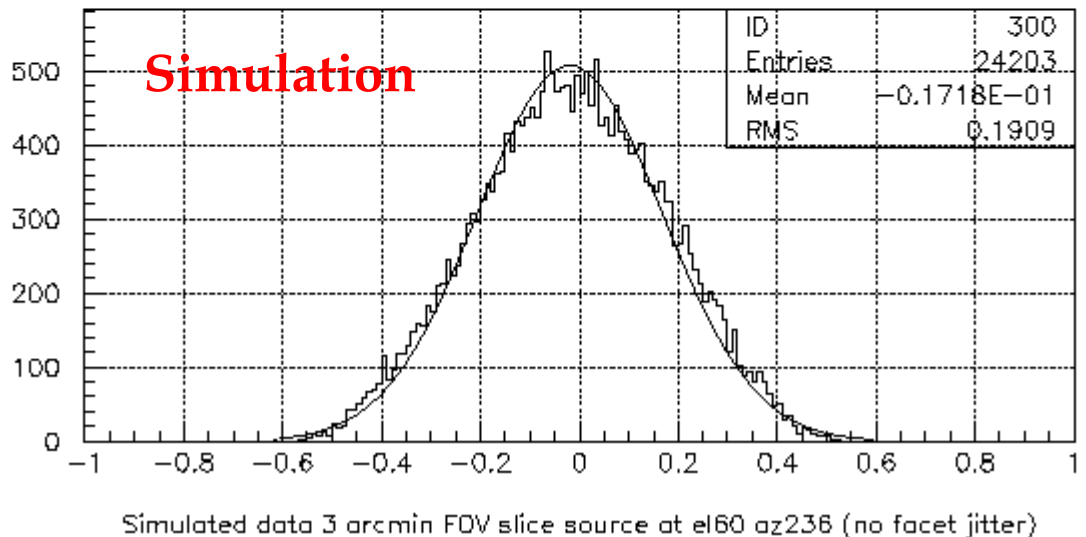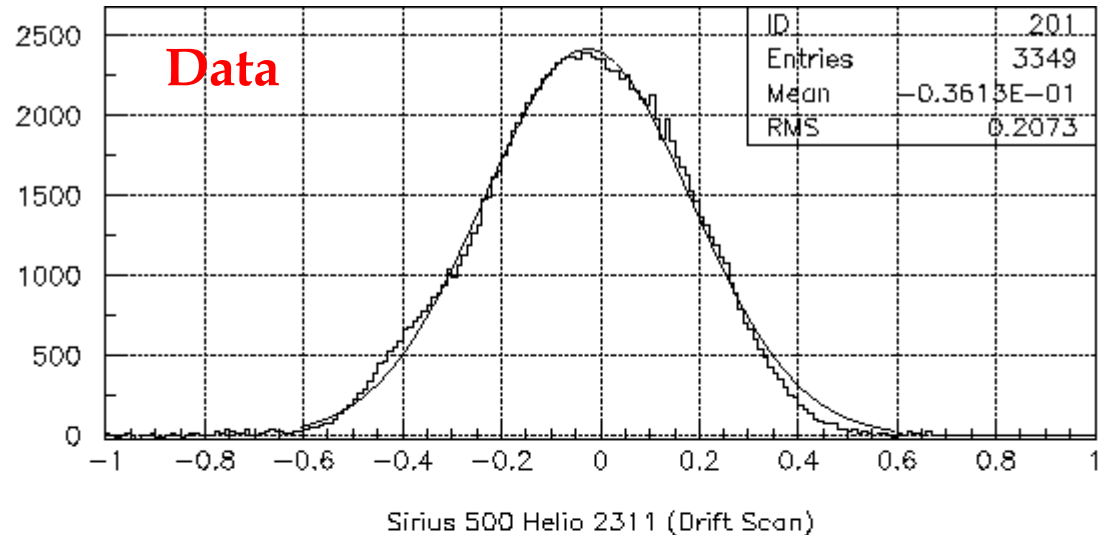
Almeisan Noise Drift Scan

Average Noise Rate vs. Time (Almeisan)

Rate (kHz)

RA (degrees)

Almeisan 99.704 RA

Normal operating noise rate
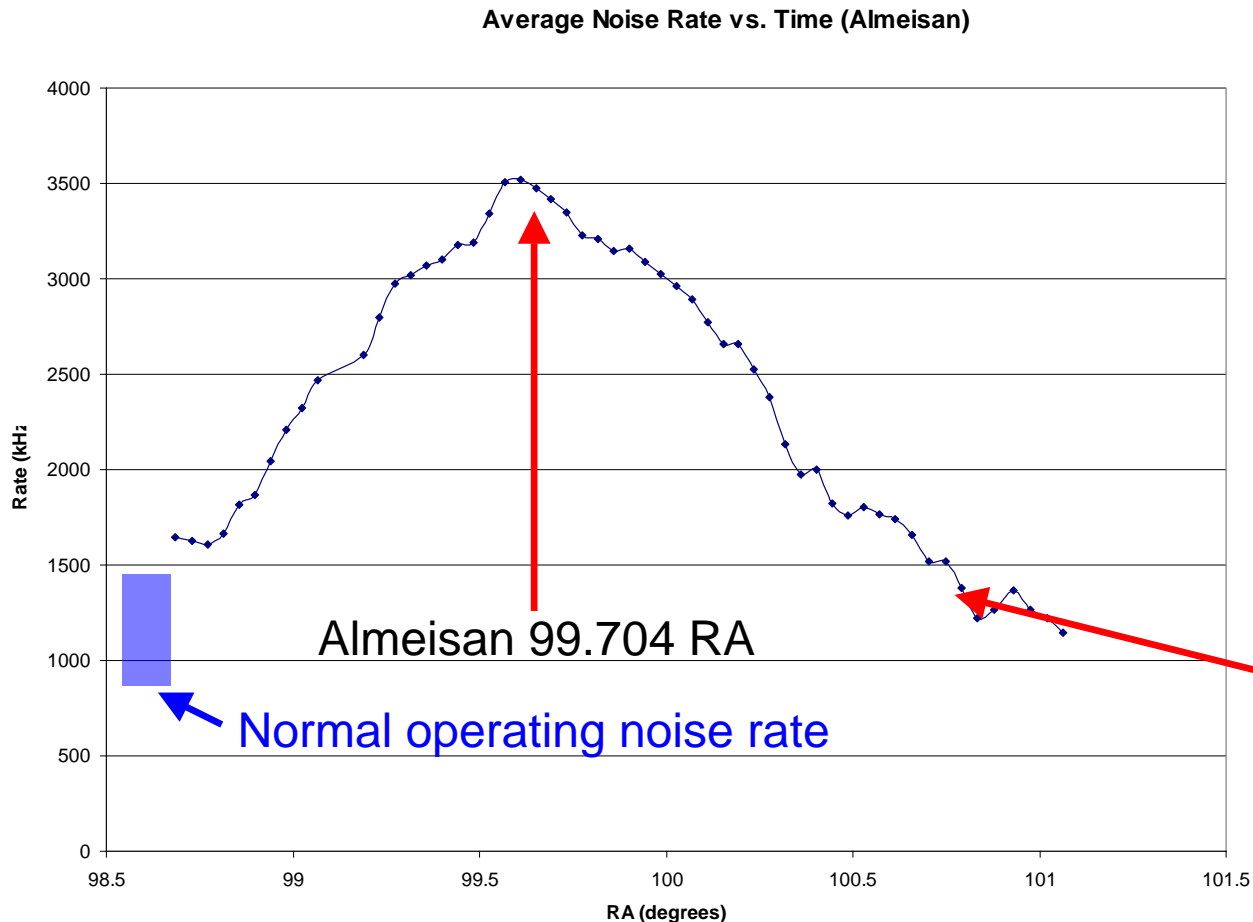
Background Noise Rates as the star Almeisan drifts across our field of view.

Rates are calculated from noise regions of 2 µsec tdc window.

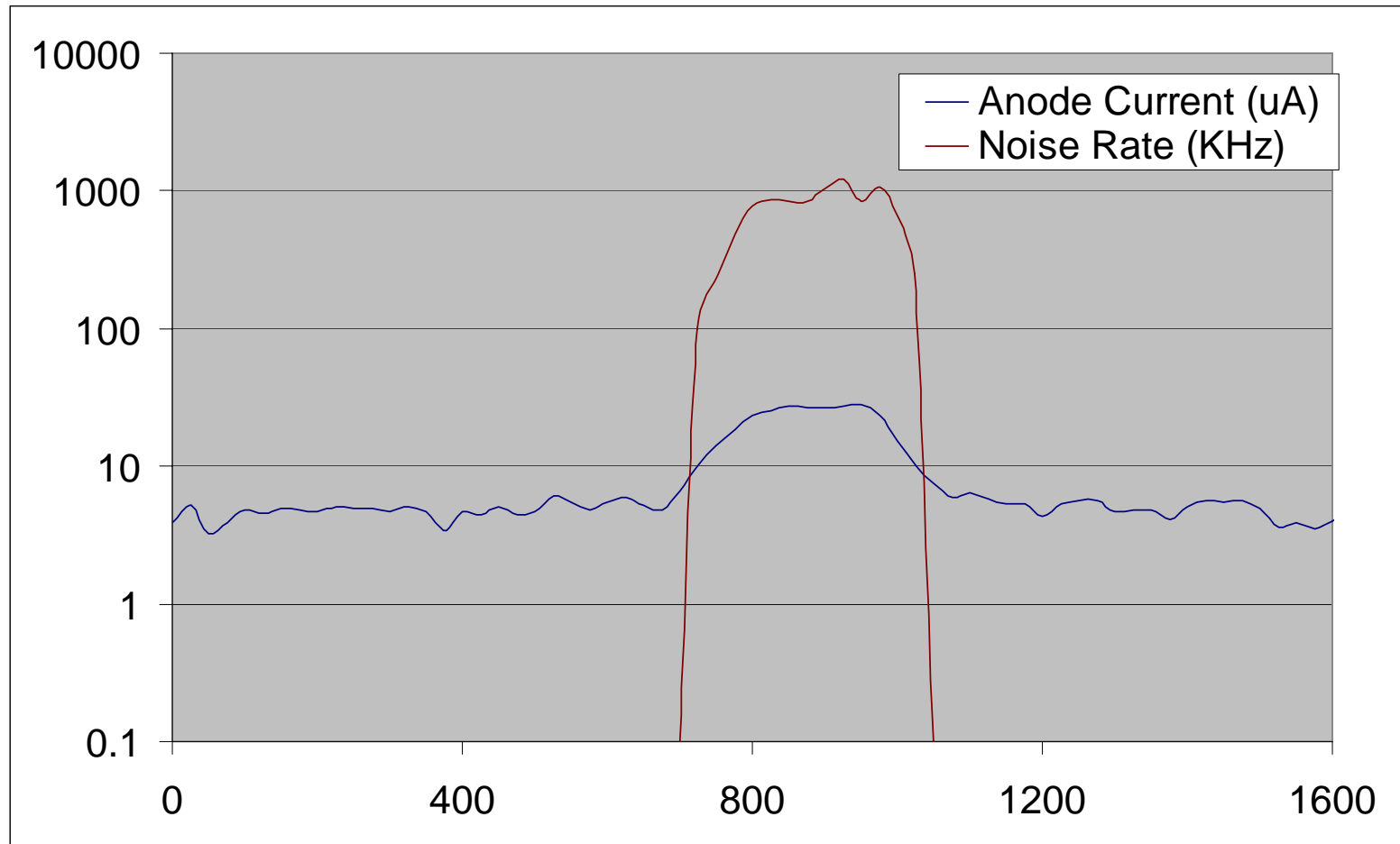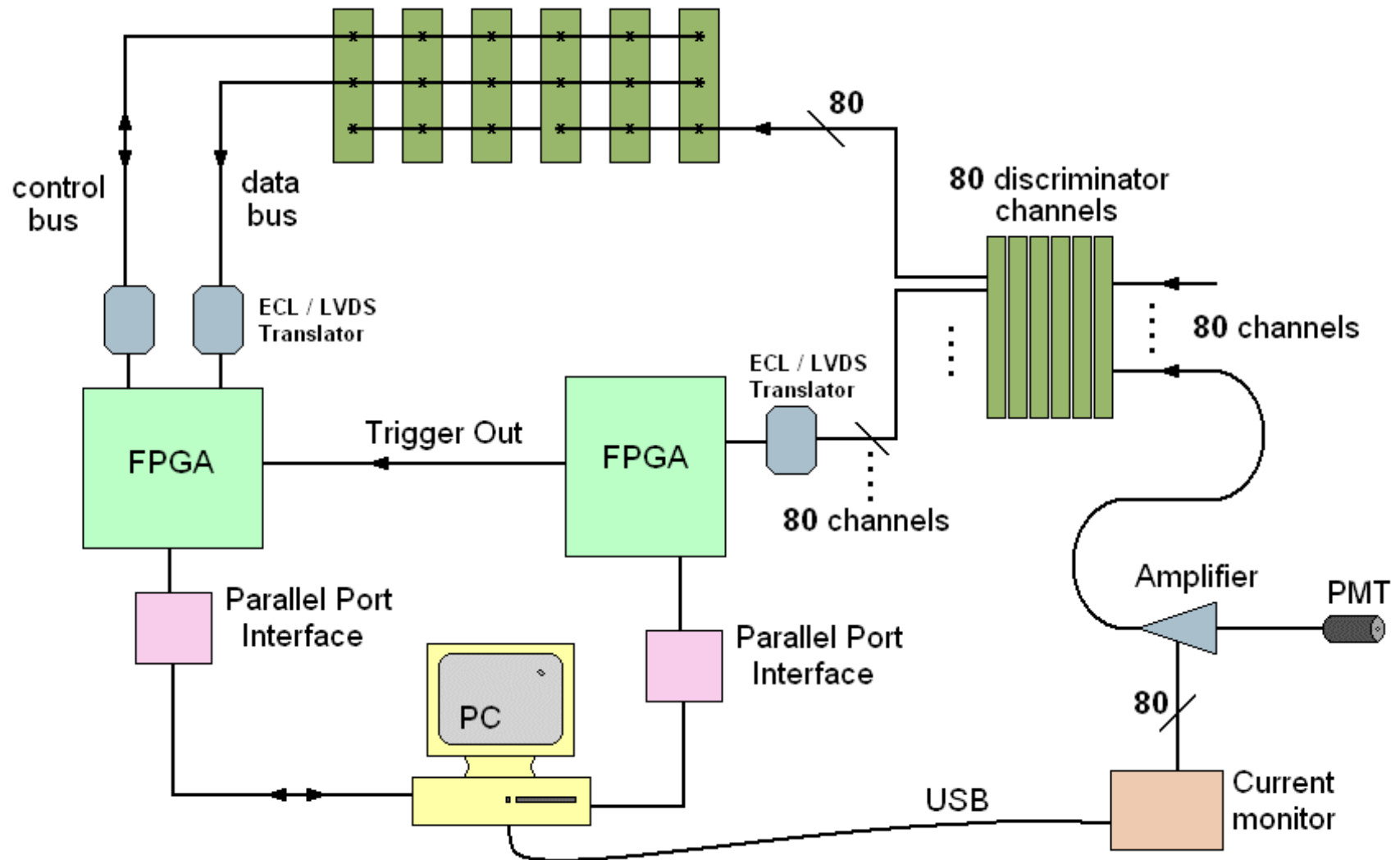We are within normal noise rates 1 degree from a neighboring star.
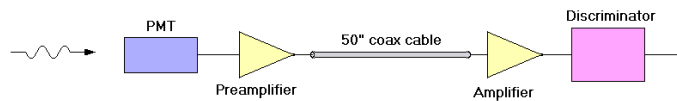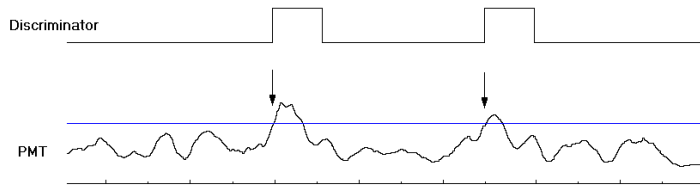
(Almeisan is magnitude 7)

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Altair Scan
RA = 305.05   Dec = 40.36

Legend:
- Anode Current (uA)
- Noise Rate (KHz)

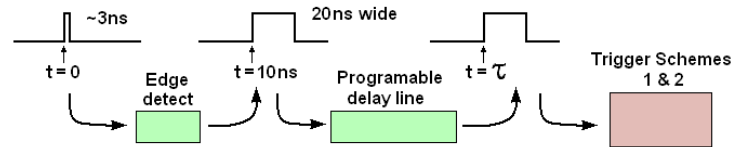Mani Tripathi, UC-Davis

Electronics Chain

Mani Tripathi, UC-Davis .

Electronics Chain and Trigger

Analog input stage

Trigger Scheme 1: Add all 80 channels and triggers at a given coinsidence level.

Trigger Scheme 2: Add all 80 channels and look for a pattern of one central peak with two side peaks, then it ask for a coinsidence level to trigger.

Data this season was taken with trigger scheme 1, a simple sum of 80 channels.

We have also implemented a 3-tap scheme to bring more heliostats into the trigger

Discriminated signals after delays

Coinsidence level and peaks constrain

Trigger Out
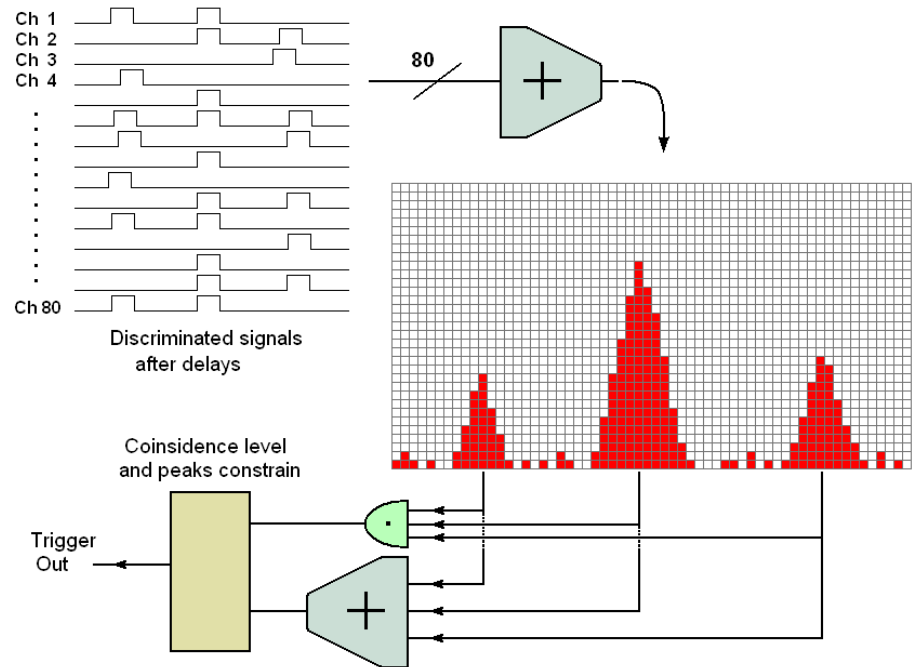
Trigger decision schemes. An FPGA based system allows us to implement several types of trigger.

Data are recorded in multi-hit TDCs with a time-of-arrival resolution of 0.5 ns. The signal to noise ratio for Cherenkov wavefront detection is excellent.
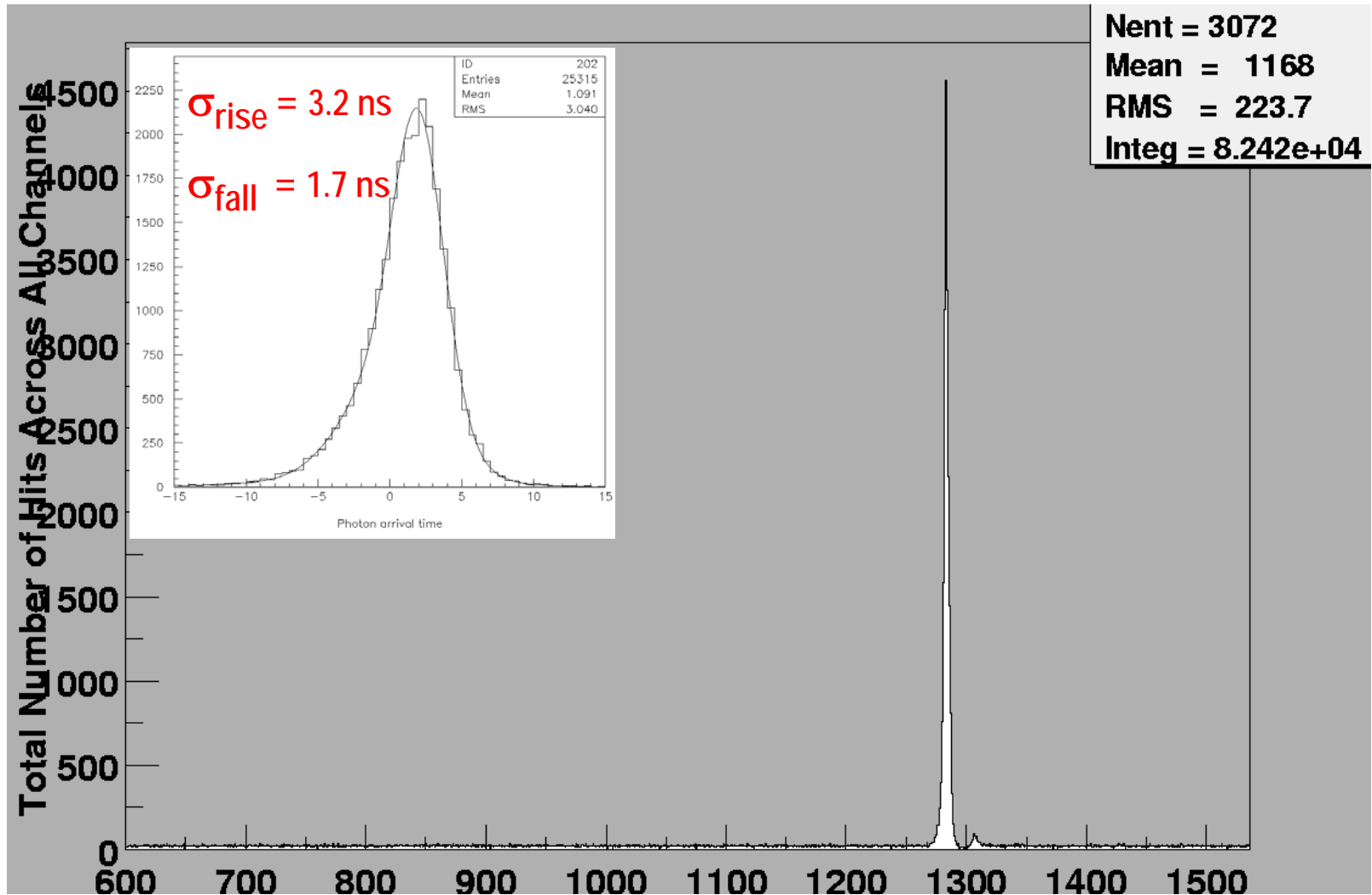
Simulation of Electronic Response

1. Background starlight is simulated by random insertion of photoelectrons. Each p.e. is ascribed a pulse shape based on measurements and with appropriate gain variations.
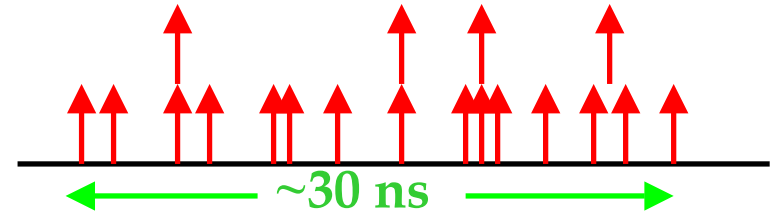
2. The a.c. component of the piled up p.e.'s is then used as background noise. The agreement with measured noise is excellent.
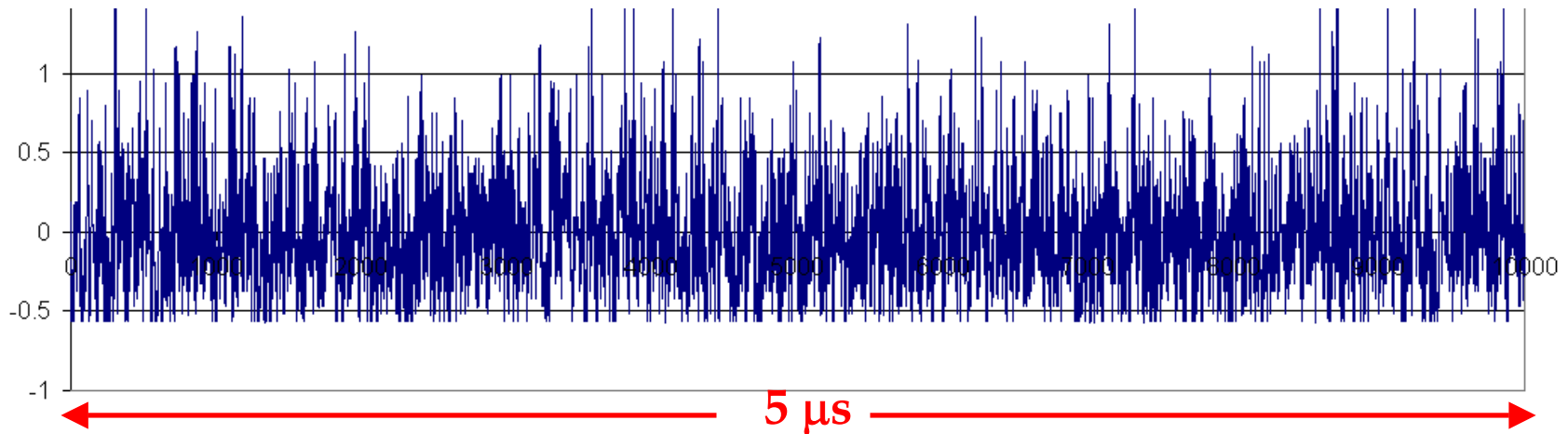
3. A threshold is applied and digital signals are recorded for comparison with measured rates.

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Understanding the NSB

Several simulations were created to understand noise response of our system. Optical and electrical noise were input into a simulated channel and the response was compared to actual data.

… by changing Noise and Gain, we can also match simulated TOT to TOT taken from data.

Data indicates that our NSB is between 0.3 and 0.6 P.E./ns

Figure 1. Five typical channels are being fit to different noise curves

...ting data noise to simulated ...ise. The plot on the left is pure ...mulated noise, and the plot on ...e right is noise plus real showers. For TOT fitting purposes, only the peak at ~3ns needs to be tuned.

Simulating Night Sky Background

Simulations indicate that our threshold is 4.0 PE

Two levels of noise caused by number of helios entering the channel. The first 32 are nearly 1 to 1 and the rest are close packed
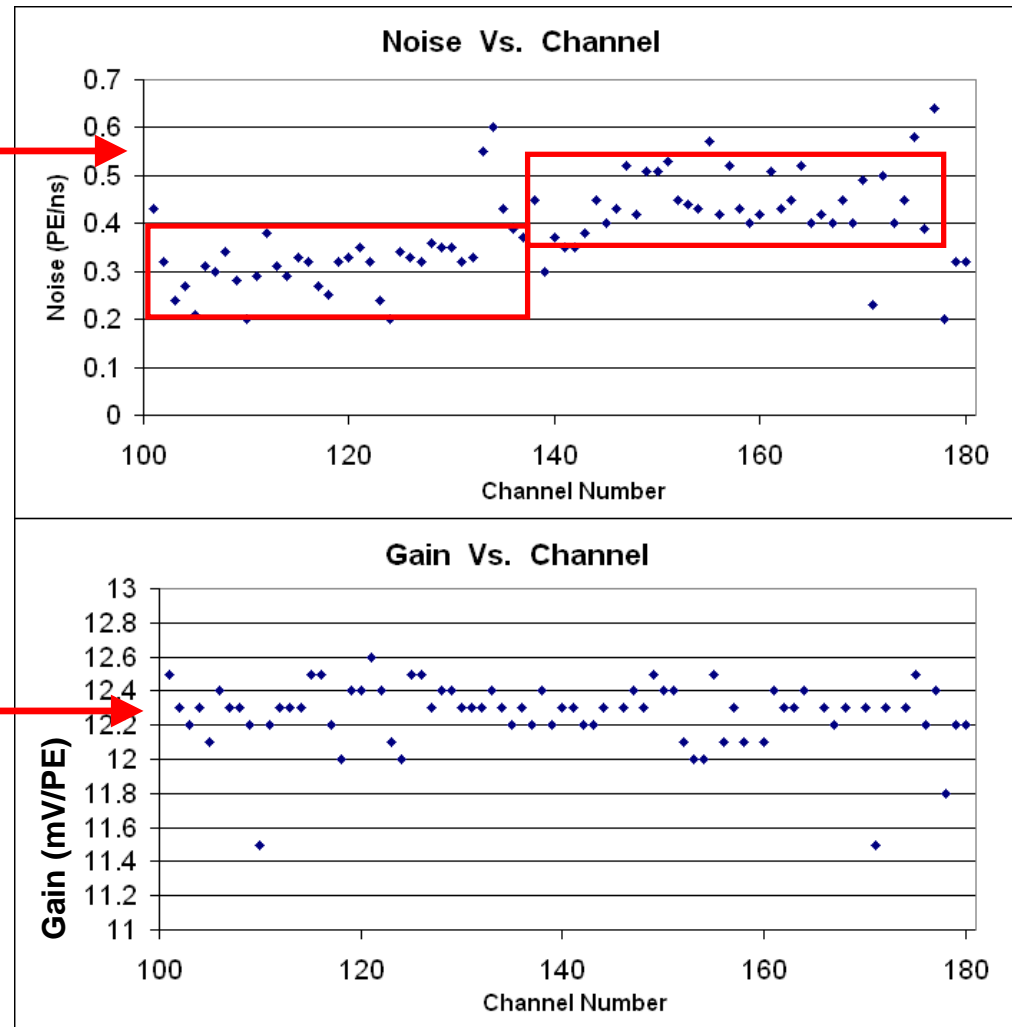
Gains are stable

Fit is to Mkn 421 background which is low compared to the Crab NSB

Noise Vs. Channel

Gain Vs. Channel

Time Over Threshold Calibration

Pulse Height as Measured by Time-over Threshold

$y = -0.0535x + 12.366$
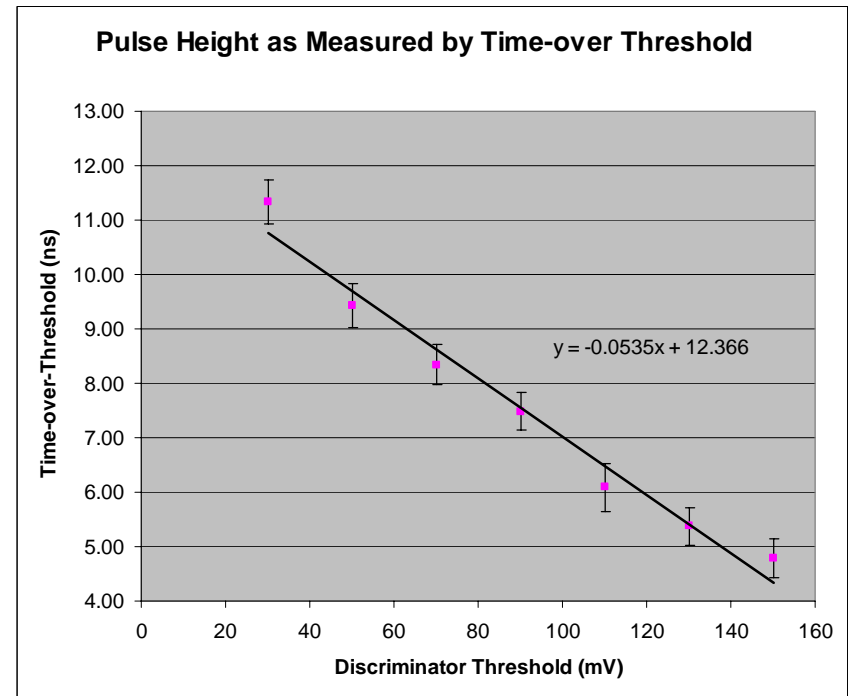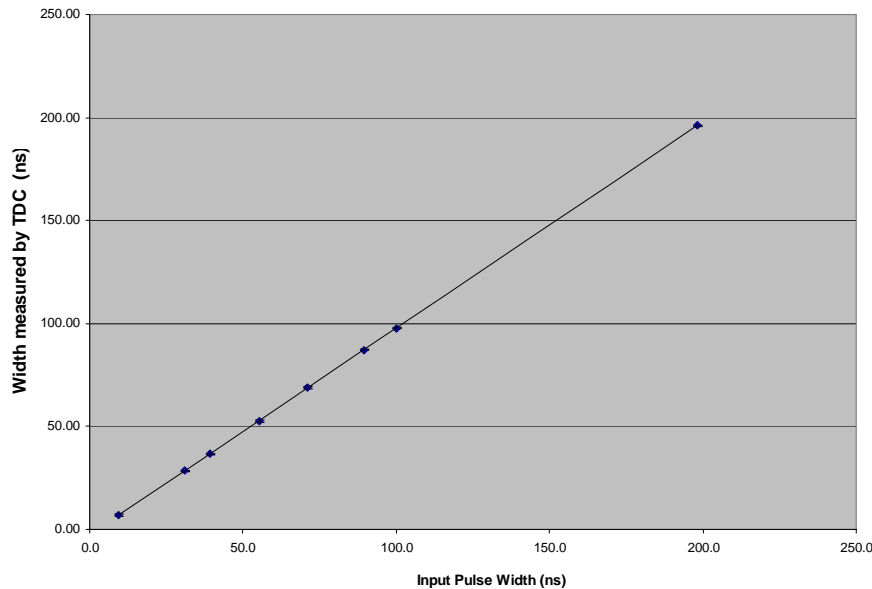
Average Pulse-width (100 samples) measurements on a 12 ns pulse as a function of discriminator threshold.

Effective resolution is
~50 ps/mV. Hence,
For a 0.5 ns TDC resolution on each edge an effective ToT resolution of ~0.7 ns is achieved.

For a 1V dynamic range, this provides a 6-bit digitization.

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Typical events with a fitted wavefront overlaid on the hits.

Overlay #Run9328 #Shower ID 113
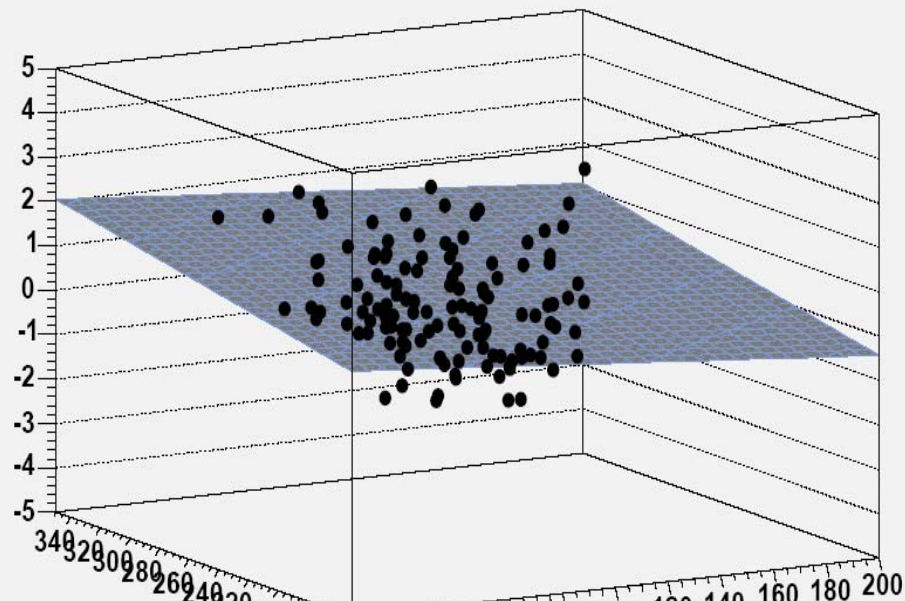
Overlay #Run9328 #Shower ID 261

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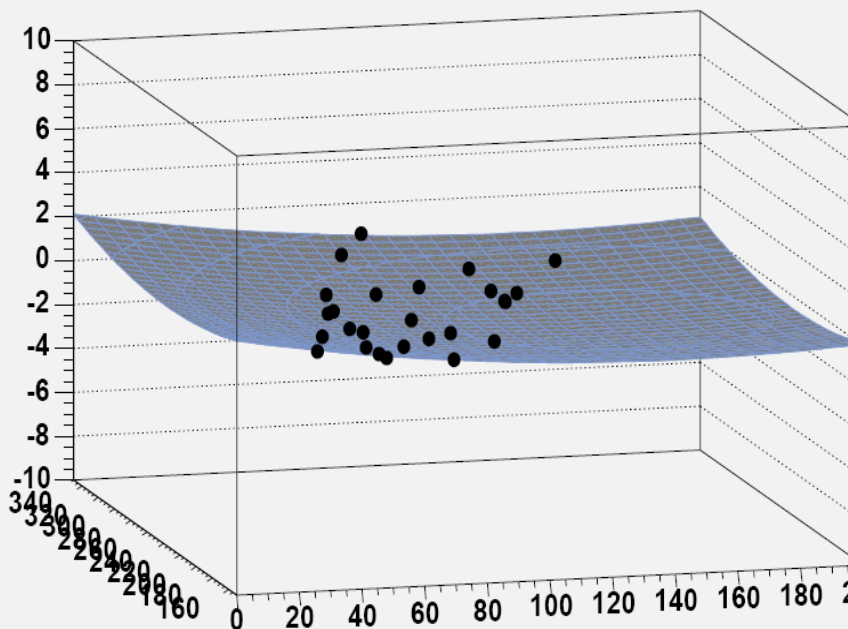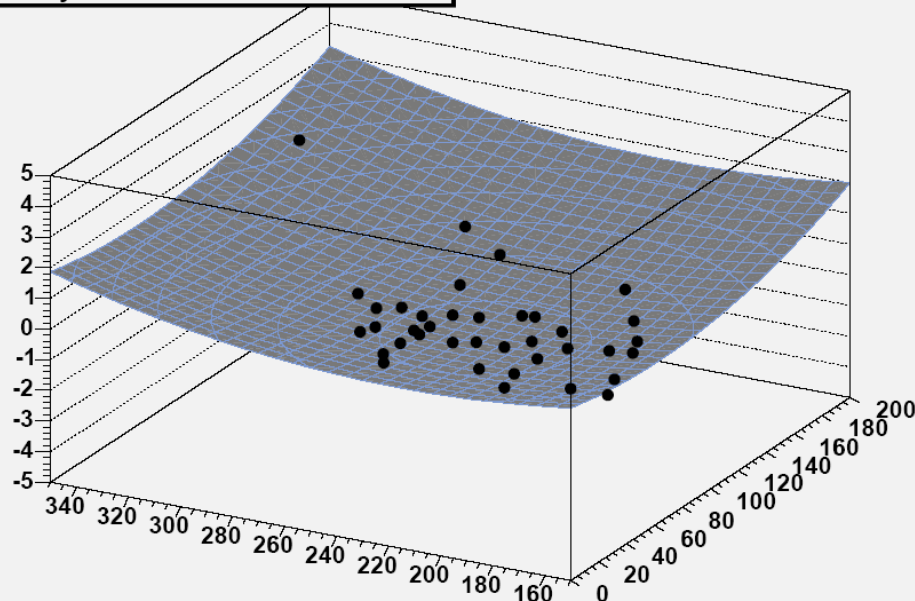
Time Projection Reconstruction

Time Projection Reconstruction

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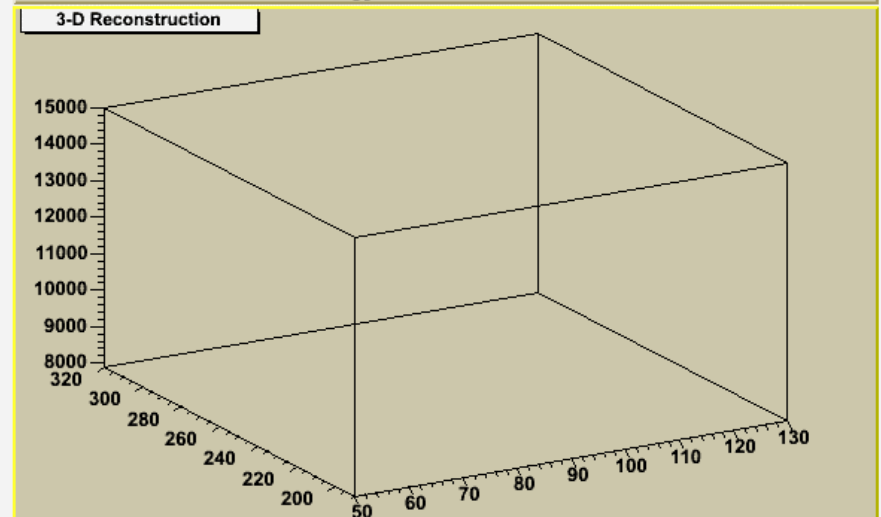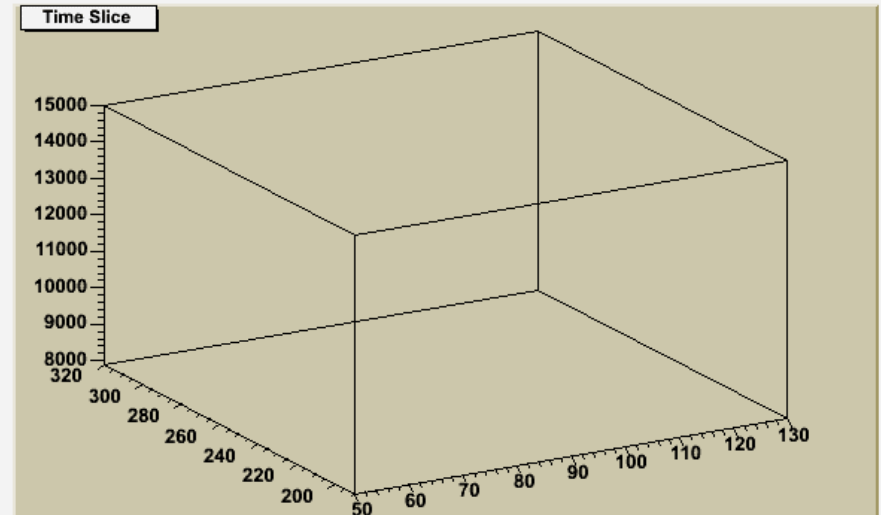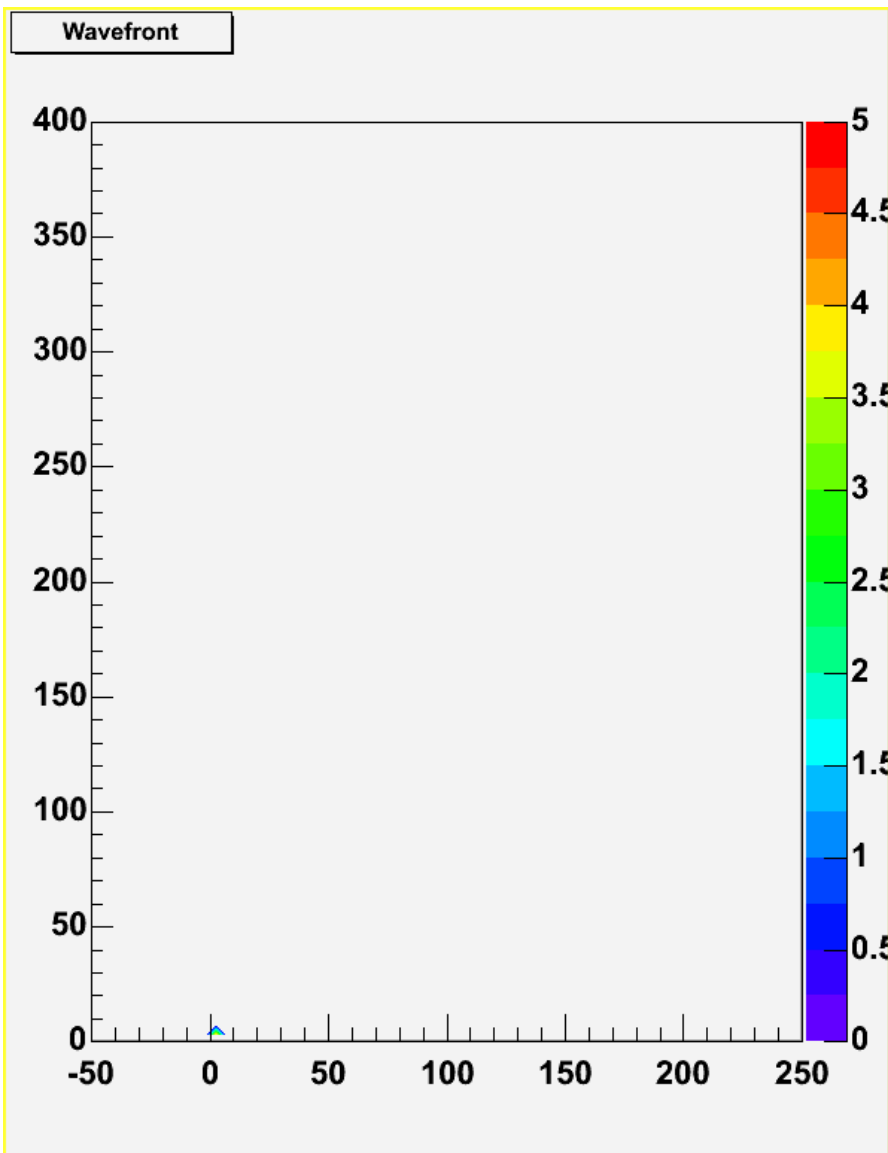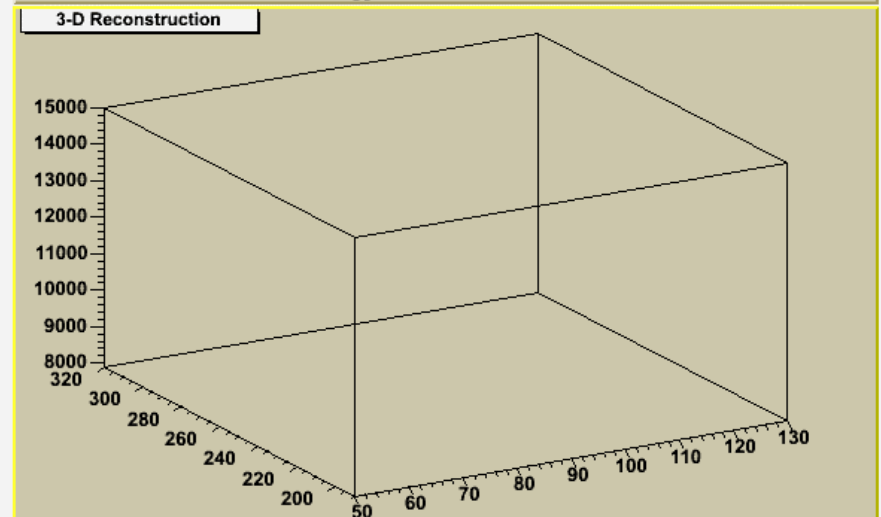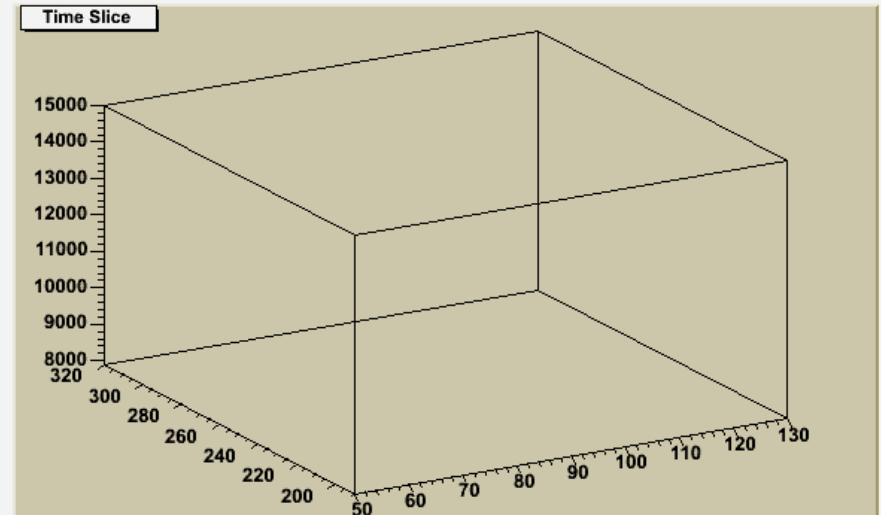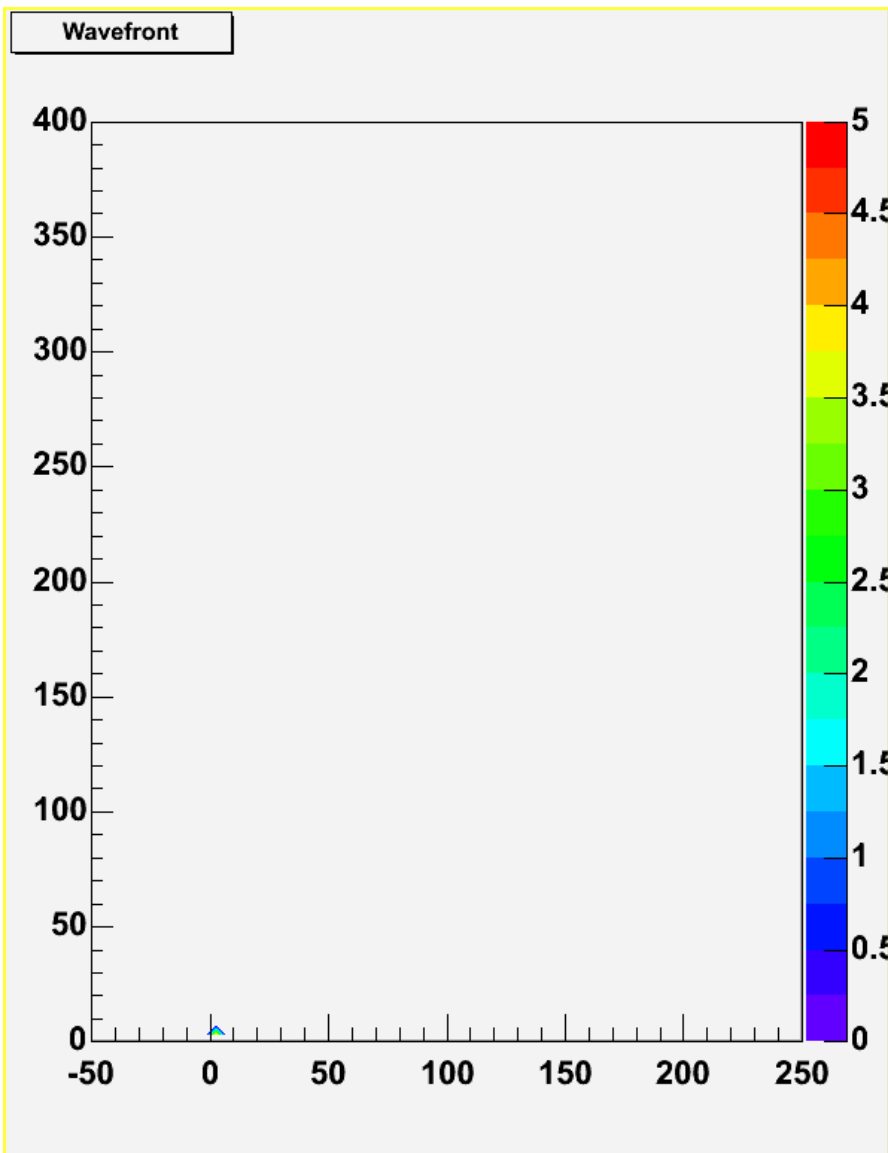
Calibrations using the Crab Nebula

The standard candle of gamma-ray astrophysics, the Crab has been studied extensively and is now believed to have a well known and stable spectrum above ~300 GeV.

THE ASTROPHYSICAL JOURNAL, 503:744–759, 1998 August 20

HILLAS ET AL.

○ Method 1 1988−9
✢ Method 1 1995−6
★ Method 2 1988−9

—— Power−law fit
···· Quadratic fit
- - - - Vacanti et al. 1991

$E^2 * Flux (TeV m^{-2} s^{-1})$

E (TeV)

Mani Tripathi, UC-Davis
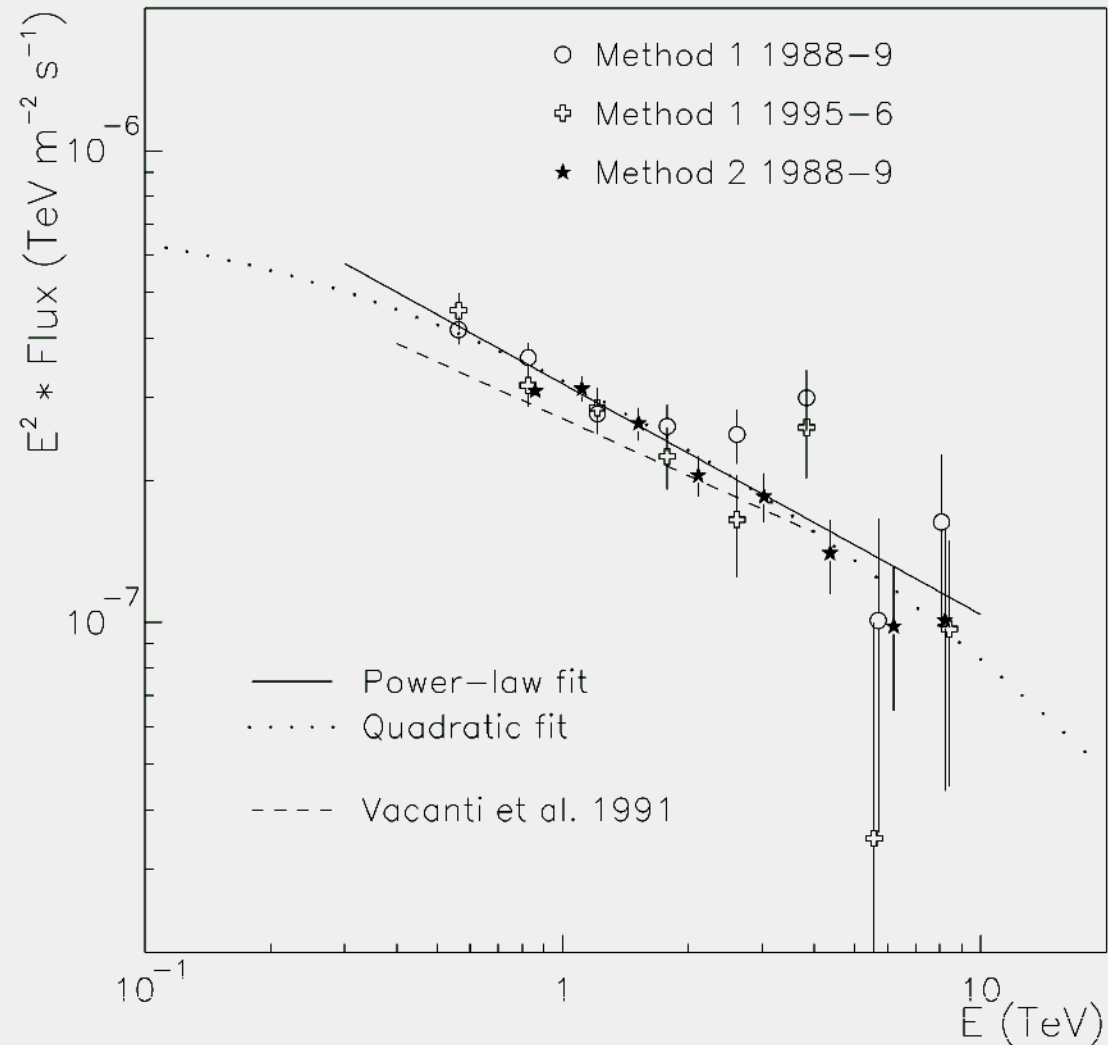
Crab Spectrum: The spectrum has not been established in the 10-100 GeV region, thus making it difficult to use the Crab as a standard candle in this regime. We have to rely on simulations.
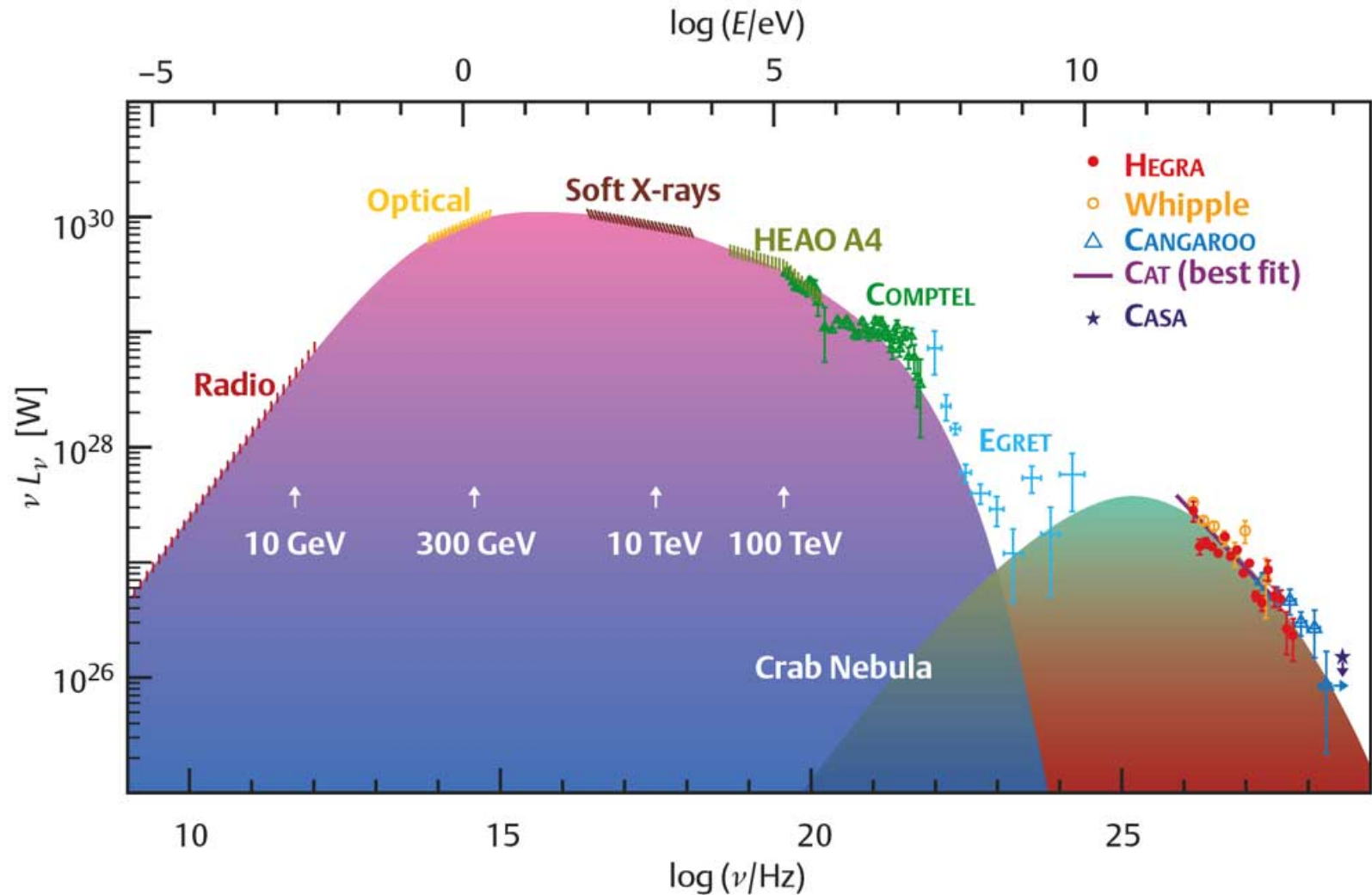
CRAB: The observed distribution in Total Pulse-Height.

Data are recorded in ON-source (heliostats track the Crab) and OFF-source (heliostats revert and track a point 30 mins away from the Crab) pairs of 28 minute duration each.

We require >20 channels in a 13 ns window for the event to be considered in our offline sample.

Further fiducial cuts are applied on the measured centroid and angle to restrict the sample to well contained events (next slide).

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CACTUS Preliminary

ID	1101
Entries	21996
Mean	319.8
RMS	268.8

ON

Total Pulse Height –– On–source

ID	1102
Entries	19673
Mean	311.2
RMS	263.8

OFF

Total Pulse Height –– Off–source
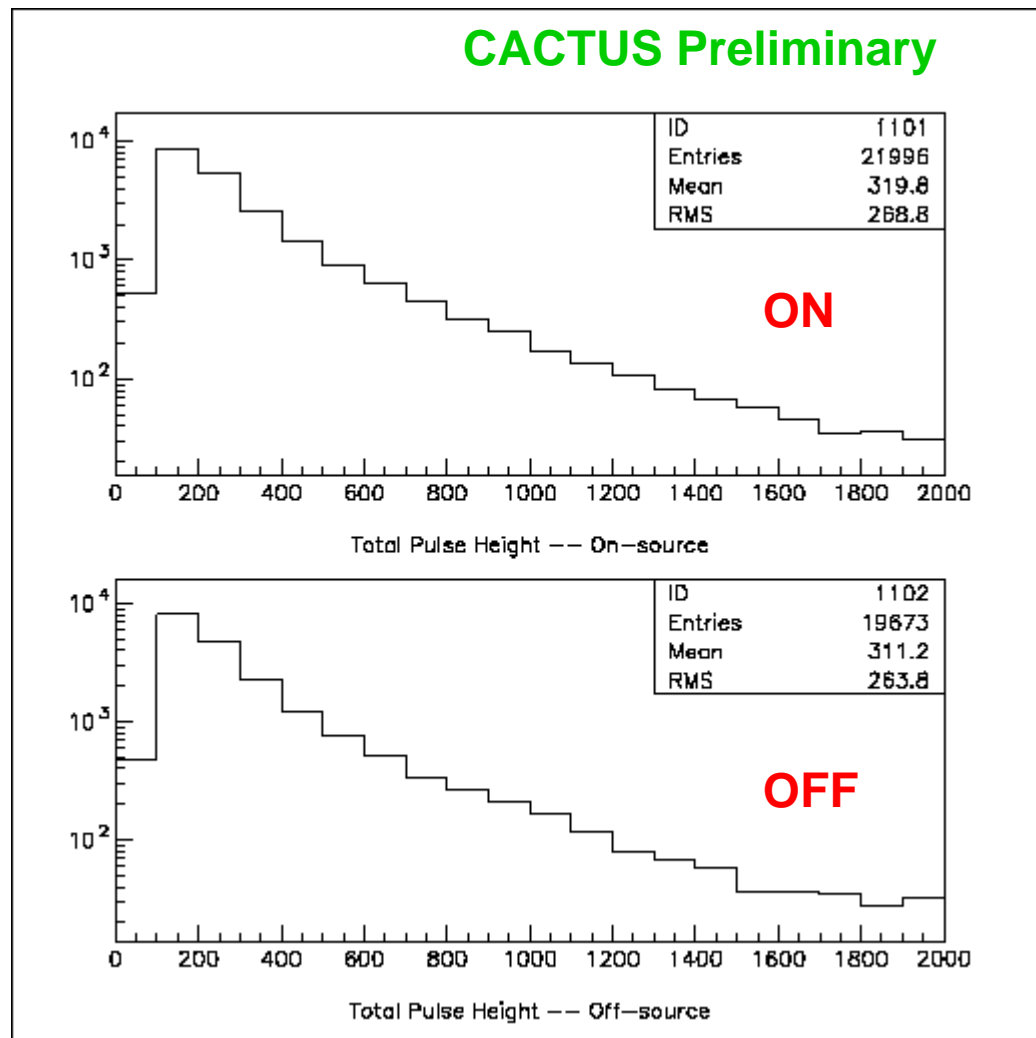
Fiducial Cuts

First Planar Angle Fit

X/Y Shower Centroids
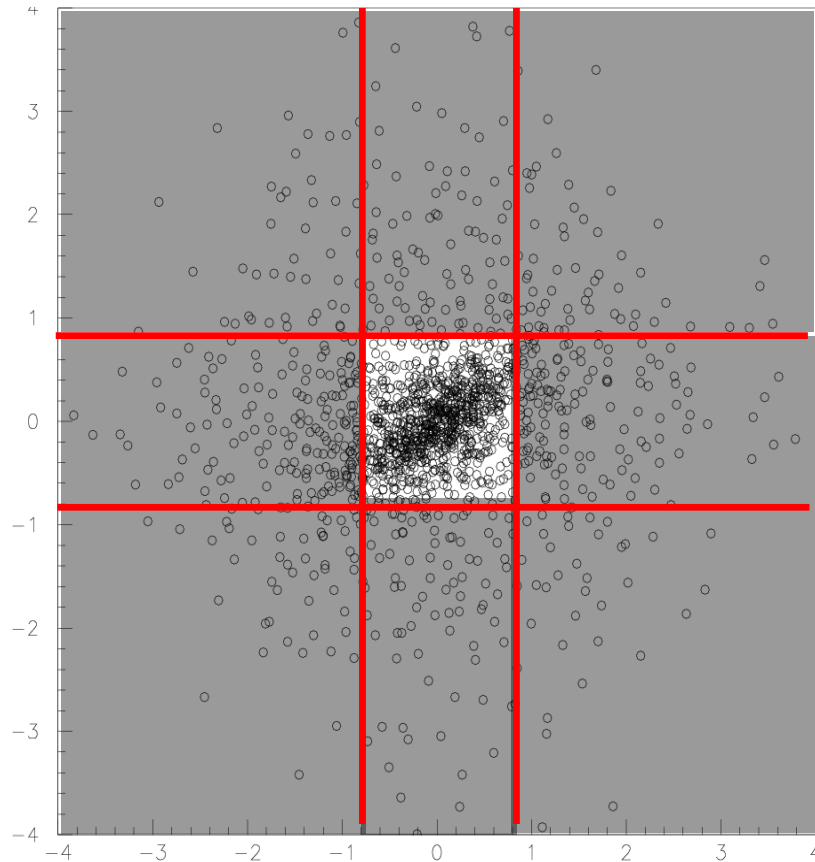
Y ang vs X ang —— Triggered —— On-Source
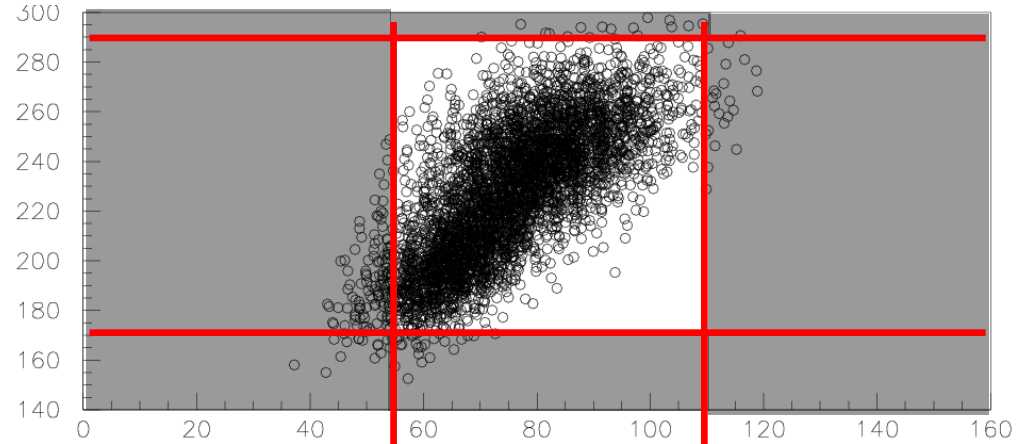
Centroid —— Triggered —— On-Source
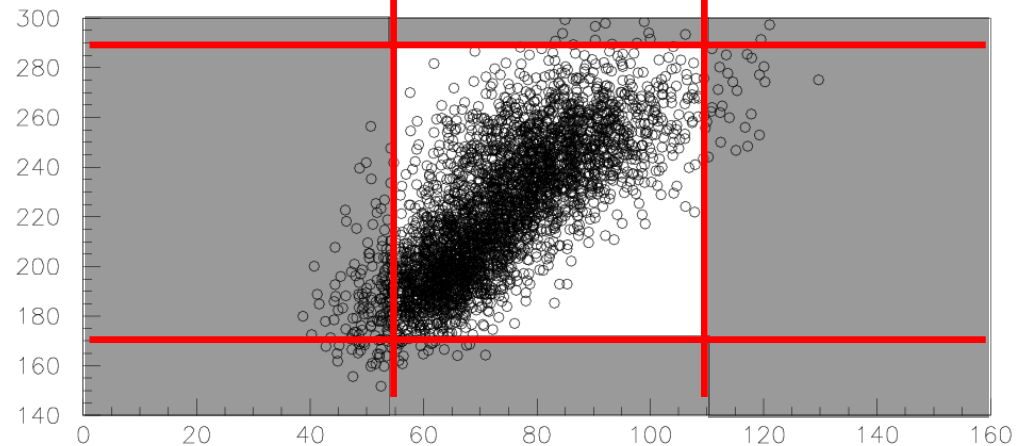
Centroid —— Triggered —— Off-Source

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Efficiency and Effective Area

Input spectrum = k*E$^{-2.4}$
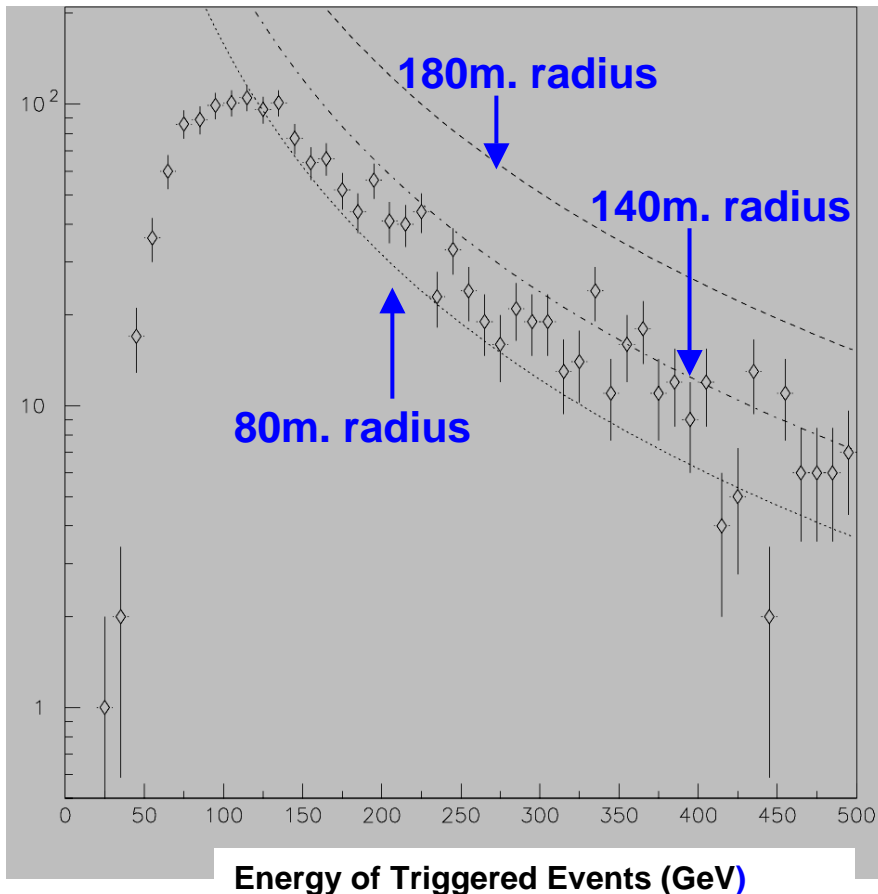
Simulations indicate an effective area of ~140m radius for energy > 500 GeV.

180m. radius

140m. radius

80m. radius

Energy of Triggered Events (GeV)

60,000 m^2

Effective area for 100% efficiency

Energy of Triggered Events (GeV)
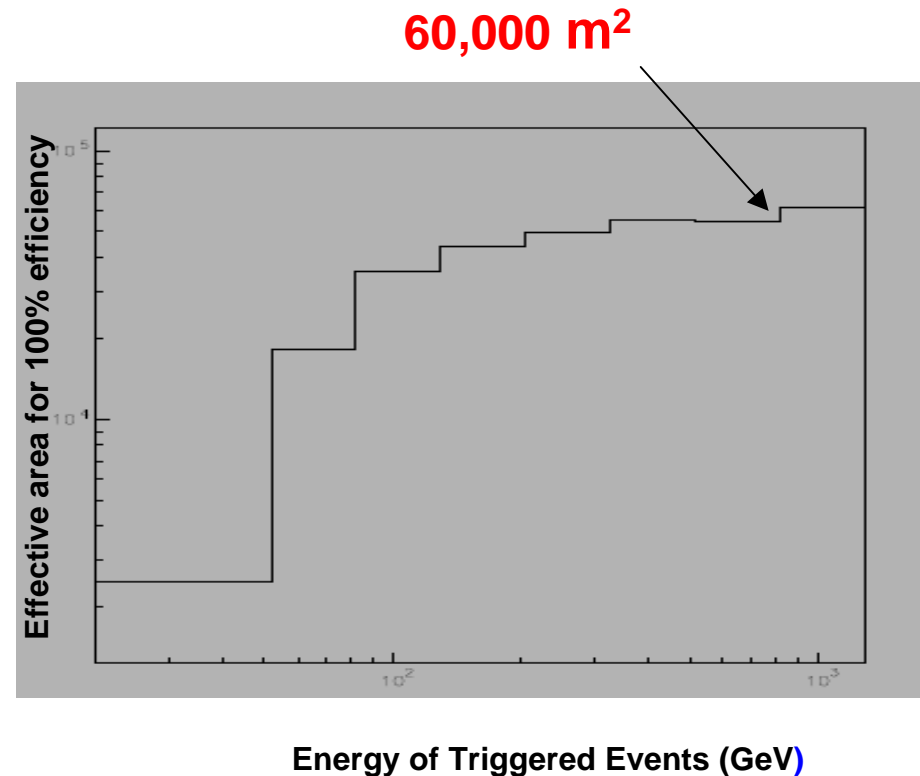
Preliminary analysis of pulse-height and energy calibration from simulations.

This is a difficult region to calibrate because we rely on the Crab spectrum. However, Crab spectrum below 100 GeV is not known.

More detailed simulations are in progress.

Shower Energy (GeV) vs **Pulse Height (arb units)**
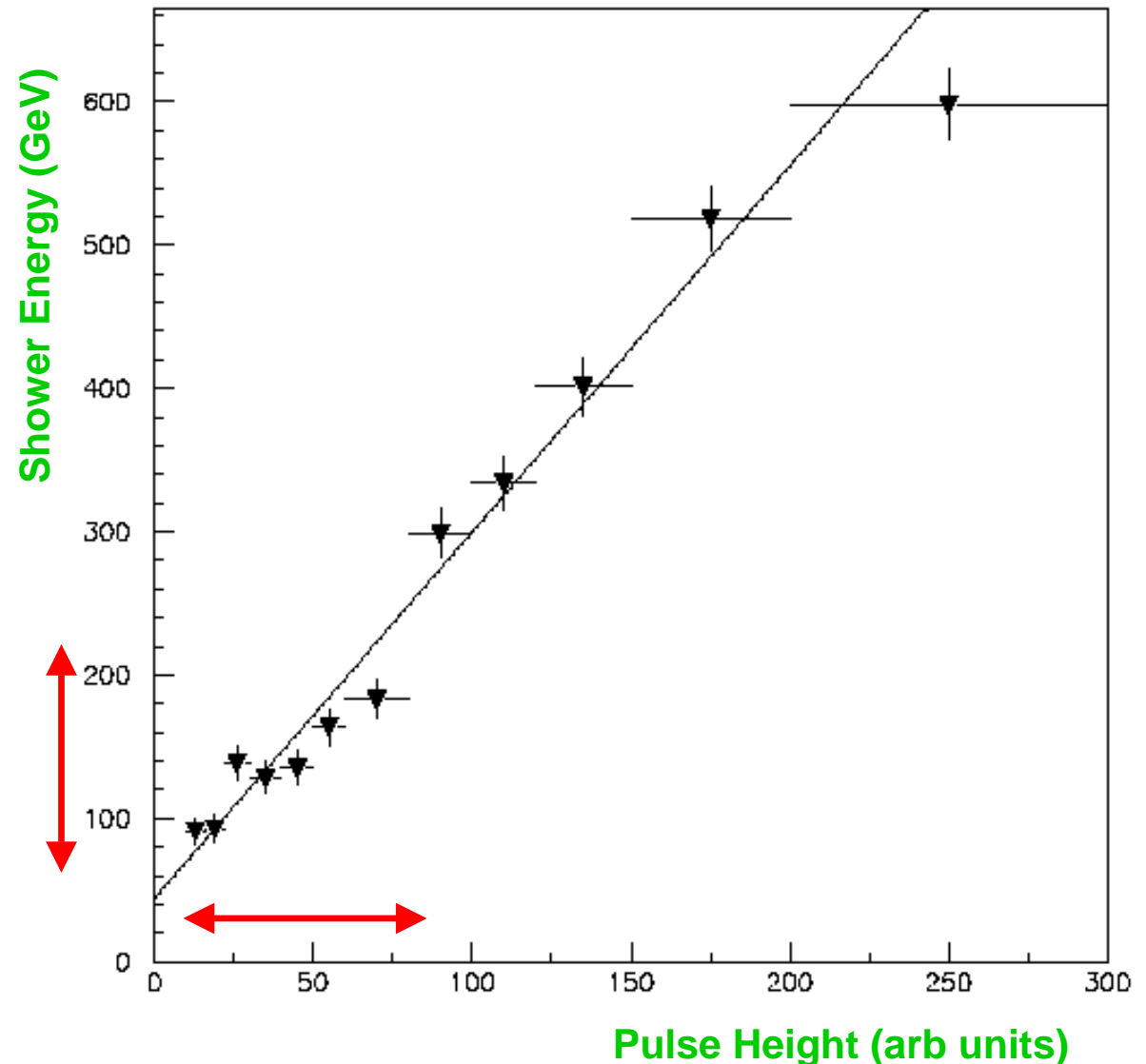
CRAB: Measured excess for "high energy" events

This sample from the Crab represents an excess rate of 12/min.

The horizontal scale is "total measured pulse height" which is closely related to the incoming energy.

The range of measurements here represent an energy range of ~ 50-2000 GeV.

CACTUS Preliminary

Total Pulse Height –– Excess with Nhelio gt. 20.
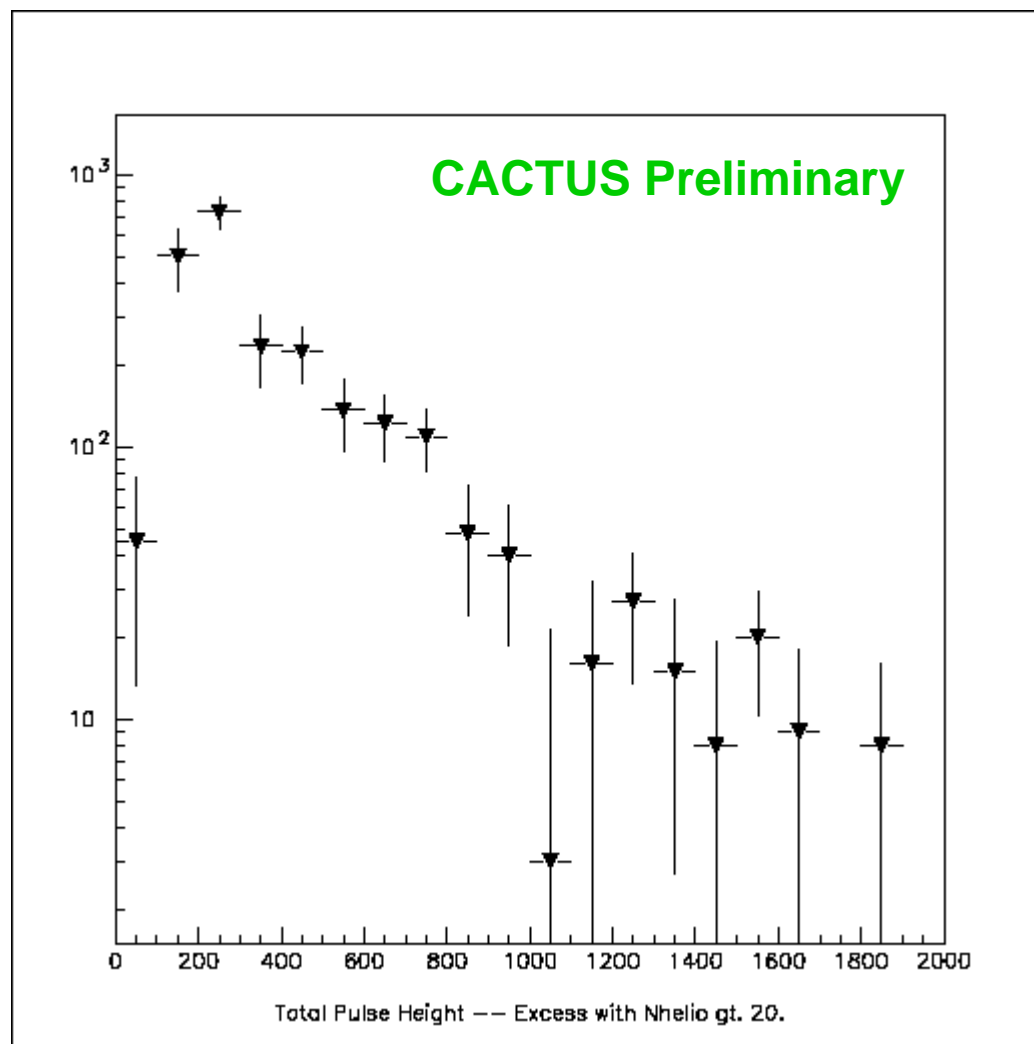
CRAB: Attempt at understanding the low energy regime

Lower the requirement for Number of channels in the trigger (>15).

Same fiducial cuts as before.

Restrict the data set to one on/off pair (28 mins) to avoid weather related differences.

Observed excess of events after cuts = **42/min**.

ID	f103
Entries	4340
Mean	191.5
RMS	85.41

ON

Total Pulse Height –– On–source

ID	1104
Entries	3176
Mean	198.5
RMS	81.66

OFF

Total Pulse Height –– Off–source
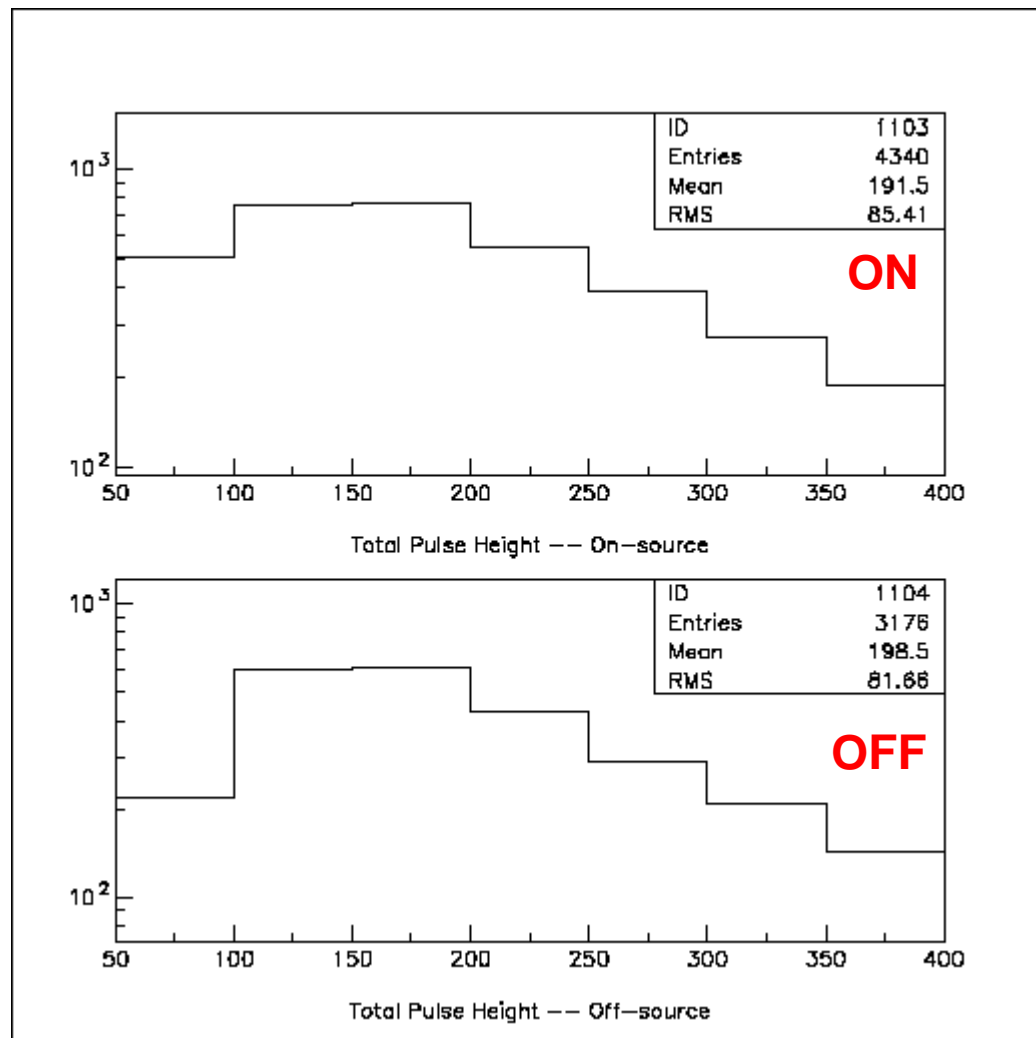
CRAB: Measured excess for "low energy" events

Crab low energy excess: Rate of ~ 42/min!

CACTUS Preliminary

Pulse Height —— Excess with 15 Helio cut
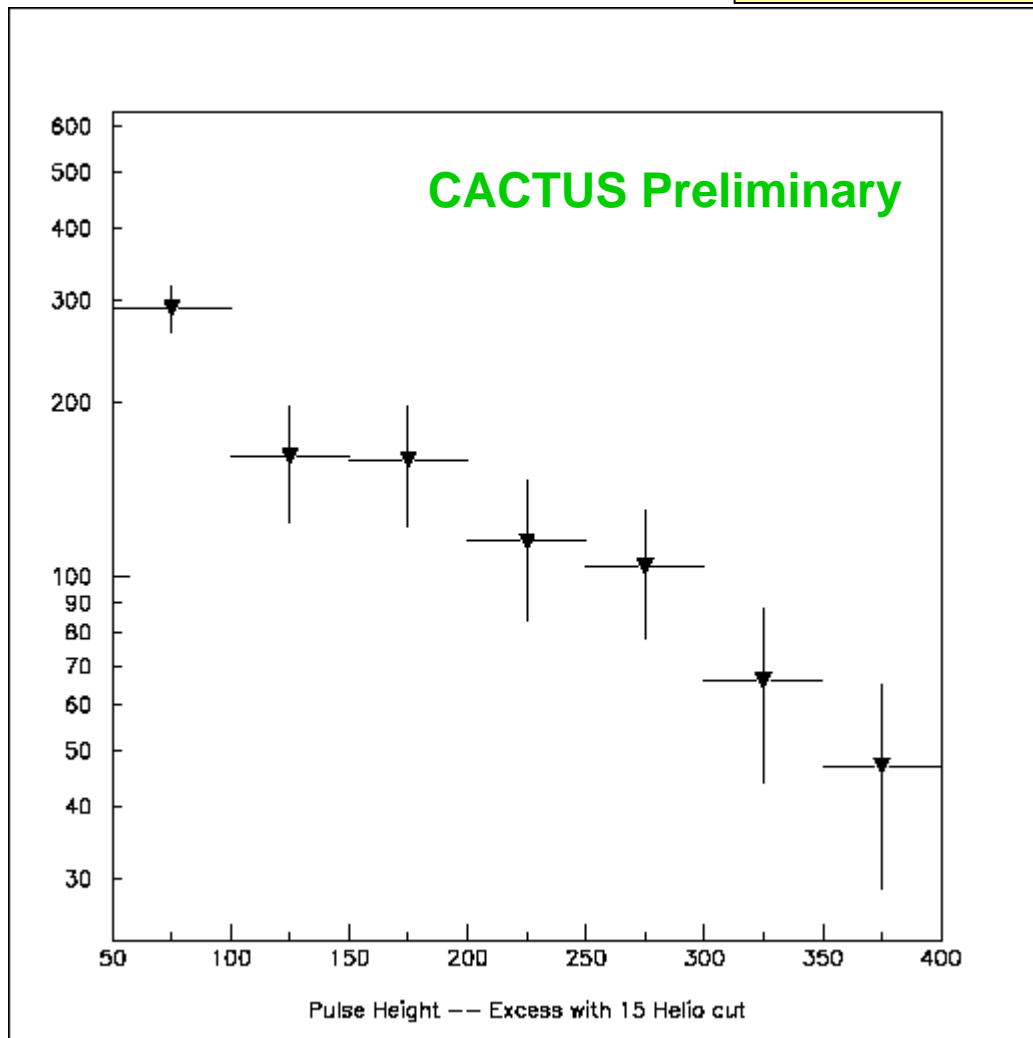
The significance of this detection of Crab in 28 mins is 13 σ .

Much work remains to be done before a final flux measurement can be extracted.

Recent Measurements of the Crab

Observations of the Crab nebula with the MAGIC telescope

R. M. Wagner[a], M. Lopez[b], K. Mase[a,f], E. Domingo–Santamaria[c], F. Goebel[a], J. Flix[c], P. Majumdar[a], D.Mazin[b], A. Moralejo[d], D. Paneque[a], J. Rico[c], and T. Schweizer[e] on behalf of the MAGIC collaboration

The lowest data point is at ~130 GeV with a flux of ~5x10^{-8} GeV^{-1} m^{-2} s^{-1}. This is a good calibration point.

Crab Nebula · Differential Spectrum, 5.50 + 7.05 hrs

$$\frac{dF}{dE} = (1.50 \pm 0.18)\ 10^{-3} \left(\frac{E}{GeV}\right)^{-2.58 \pm 0.16} \left[\frac{ph}{cm^2\ s\ TeV}\right]$$

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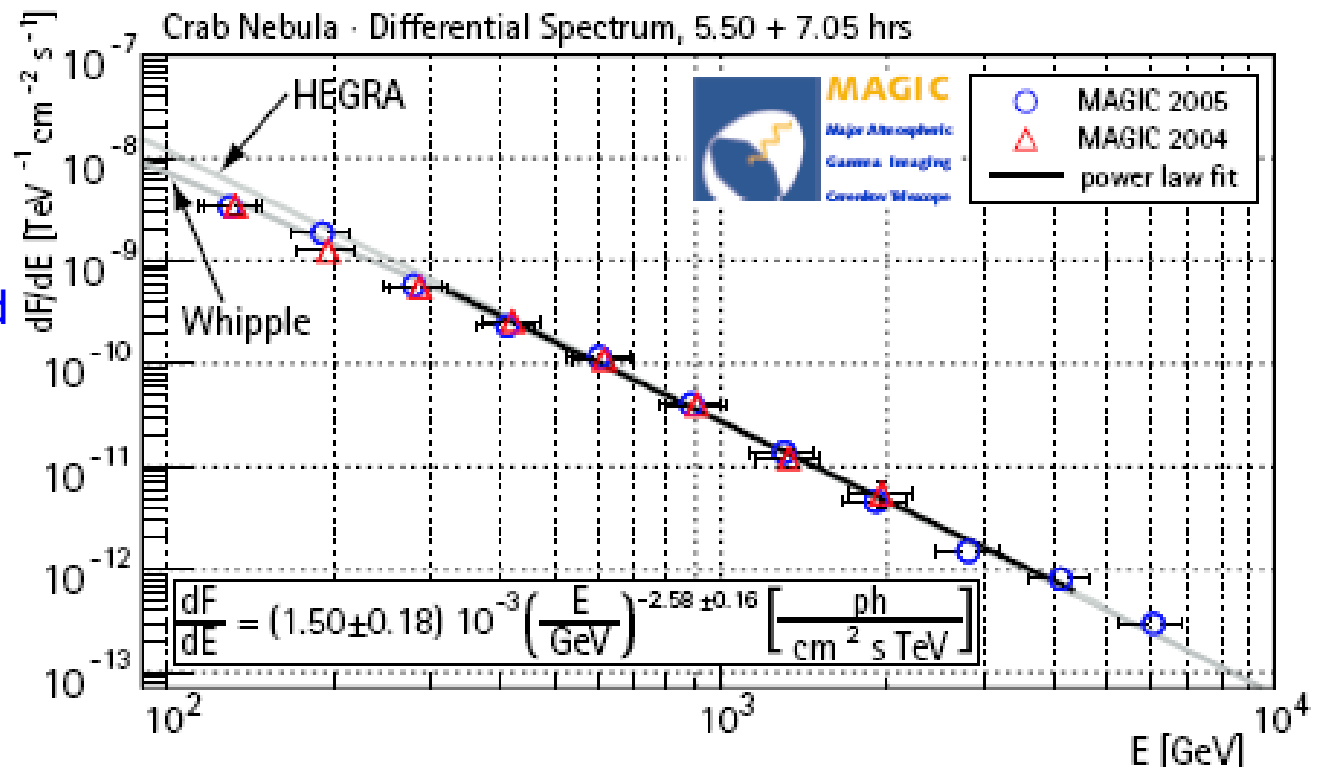
CACTUS Measurement of the Crab Spectrum

Using a shower wavefront fitting technique, we are able to improve our energy resolution, albeit with some loss in efficiency.

Our measured Flux at low energies seem to be in agreement with an extraloplation of the MAGIC fit.

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Flux (GeV⁻¹ m⁻² s⁻¹)

MAGIC

Energy (GeV)

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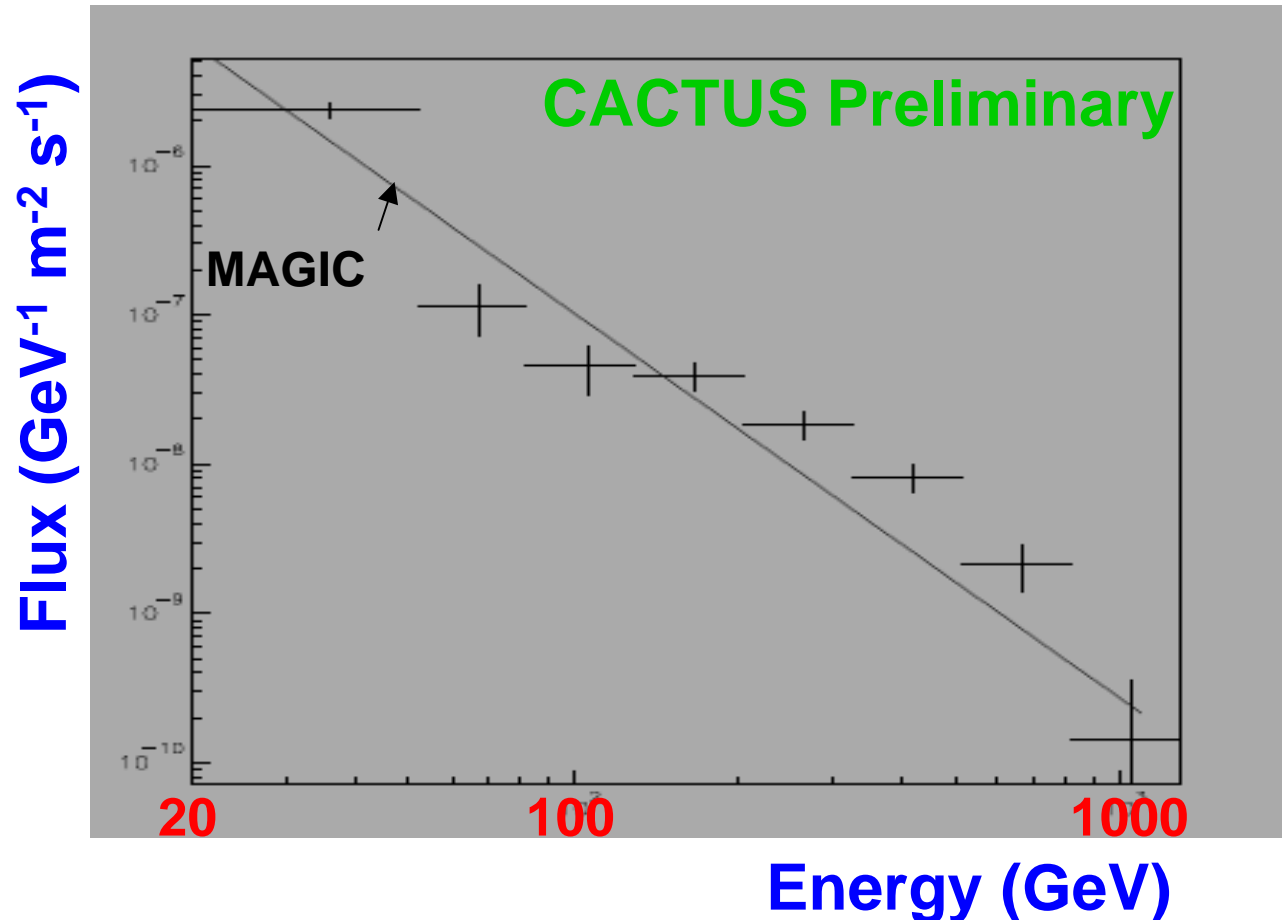
Draco and Dark Matter

Draco is a dwarf spheroidal galaxy in the vicinity of the milky way. Its estimated total mass of is ~0.3 - 8 x 10^7solar masses and, given the low luminosity of ~2 x 10^5 Lsolar, the global mass-to-light ratio anywhere in the 10-100 range. This requires that Draco contain a dominant dark matter component.
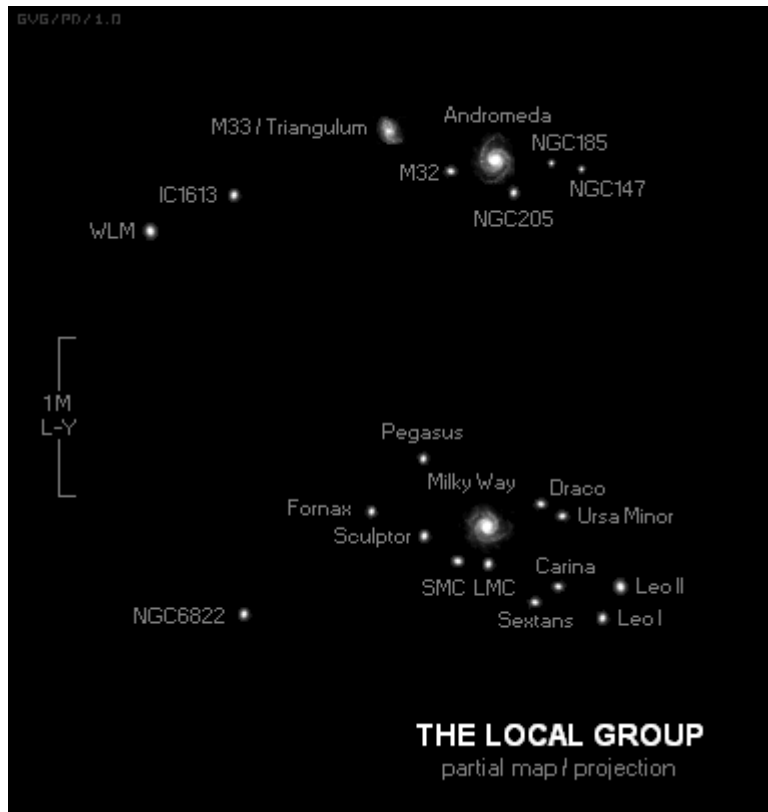
Draco is about 0.5 degrees across. It is very faint in the optical.

Integrated magnitude ~11 making it an ideal candidate for ACT observations.

Draco Dwarf DDO 208
APQ 130mm f-7.7
CCD ST10-XME hires.
composition 30 5 min. exp.

by Bernhard Häusler + Ralf Mündlein
Observatory Mündlein, Germany

Neutralinos: Previous attempts at understanding Draco.

Neutralinos are the lowest mass supersymmetric particles in the Minimum SUSY Model. Since they are stable, they are a popular candidate for Cold Dark Matter.

Neutralinos can annihilate into quark and anti-quark pairs. The resulting hadron jets will contain gammas from neutral pion decays.

The rate will depend on ρ^2, where $\rho \sim r^{-\gamma}$ is the density profile of the neutralinos.

Particle dark matter constraints from the Draco dwarf galaxy

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(Received 18 March 2002; published 3 July 2002)

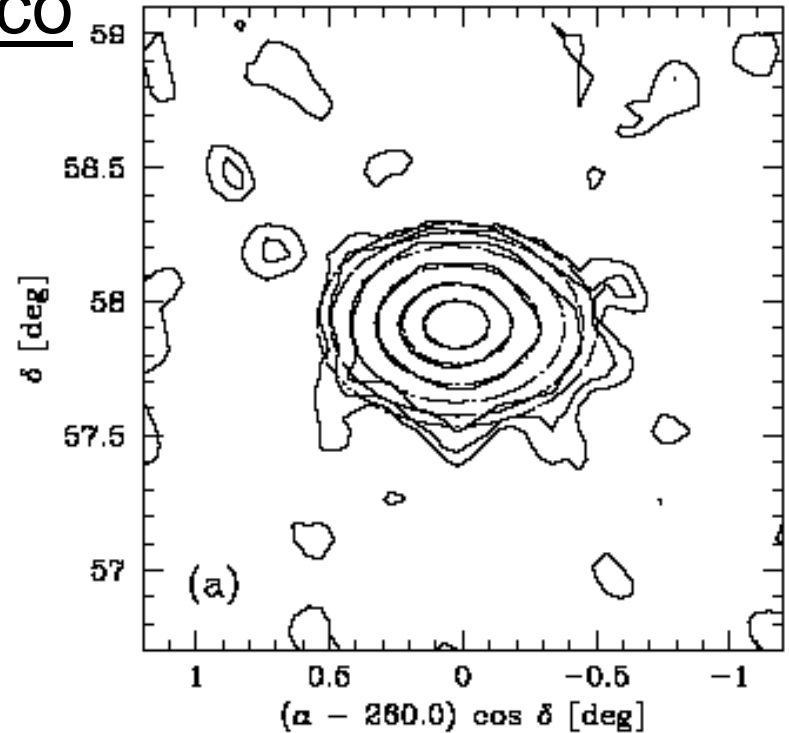Mani Tripathi, UC-Davis

CACTUS Observations of Draco

- Drift scans: +- 2 degrees in RA.

- Background check using Draco minus 1 degree in Dec.

4 degrees in RA

~1 deg in Dec

0.5 deg in Dec

1 deg in RA

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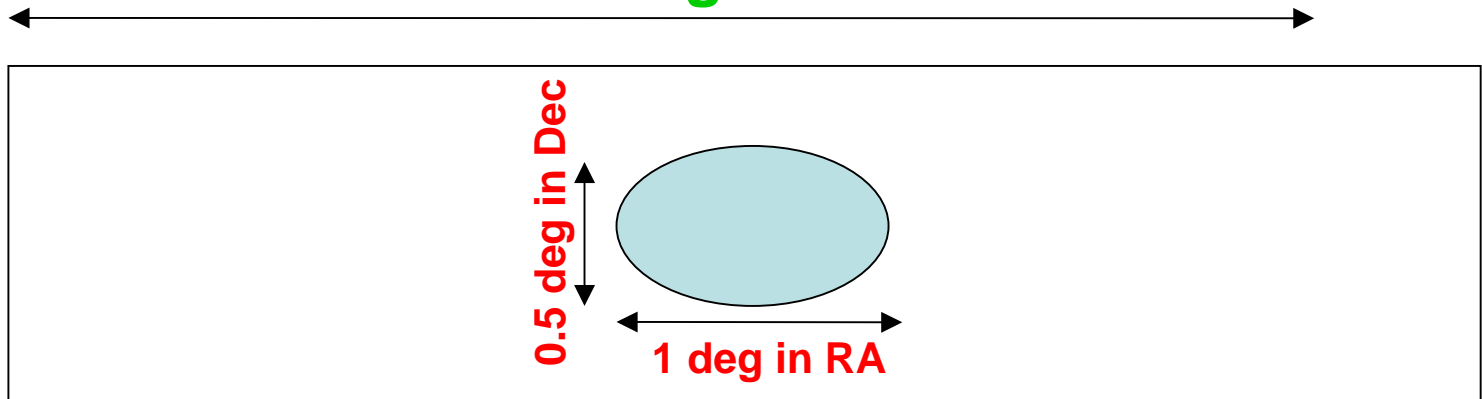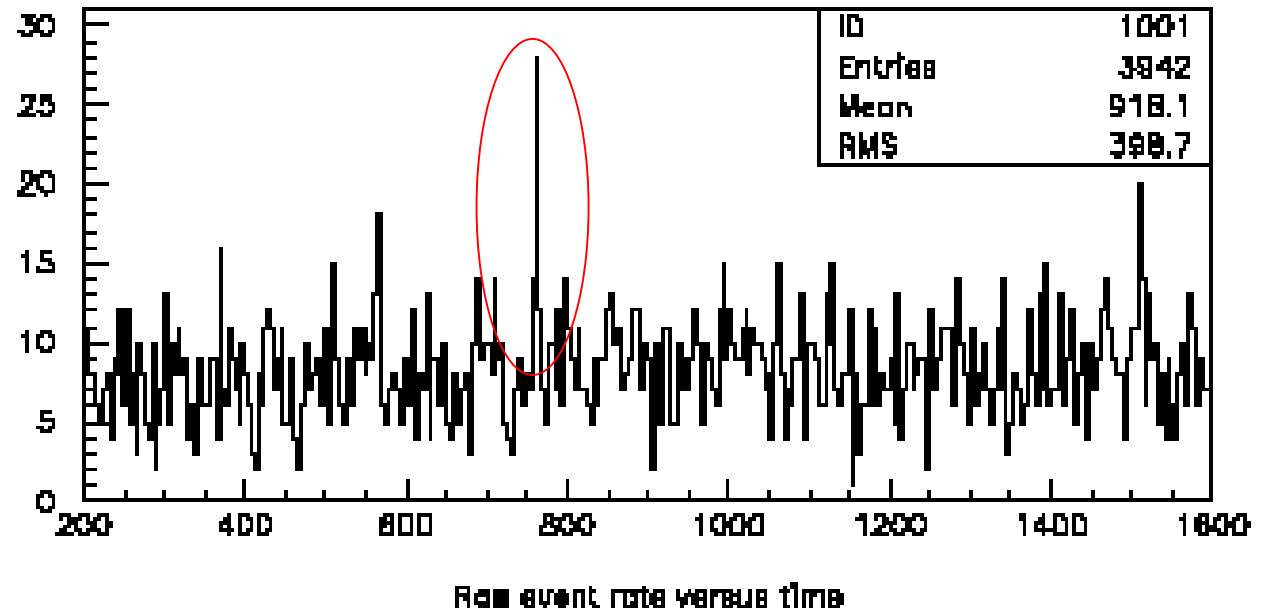
Typical Scan lasting 30 minutes

The data-acquision consists of recording time of arrival and pulse heights for each channel. In addition, background noise rates are recorded for 1 microsecond preceding the triggering event.

Noise spikes due to fluctuations and/or meteorites, airplanes etc can be tracked in the background noise rate which is otherwise very stable.

Raw event rate versus time

ID		1001
Entries		3942
Mean		918.1
RMS		399.7

Noise Coinc rate versus time

ID		1005
ENTRIES		3942
0.00	4.00	0.00
422.	0.290E+04	801.
5.00	74.0	0.00

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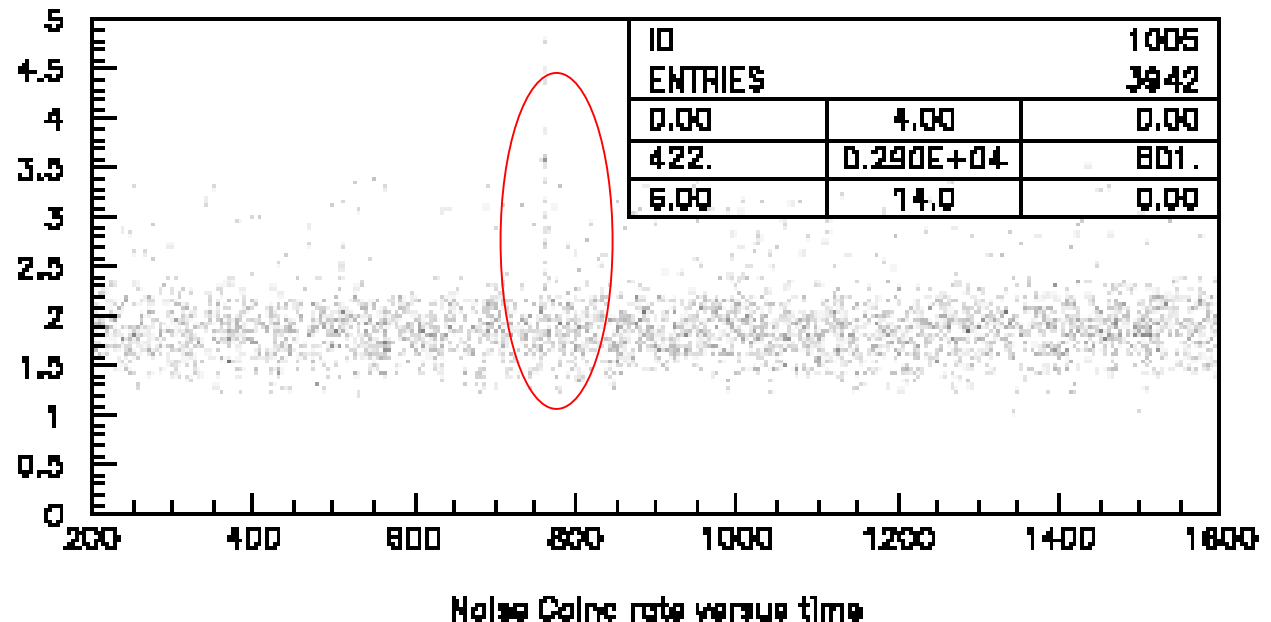
Integral of 44 scans

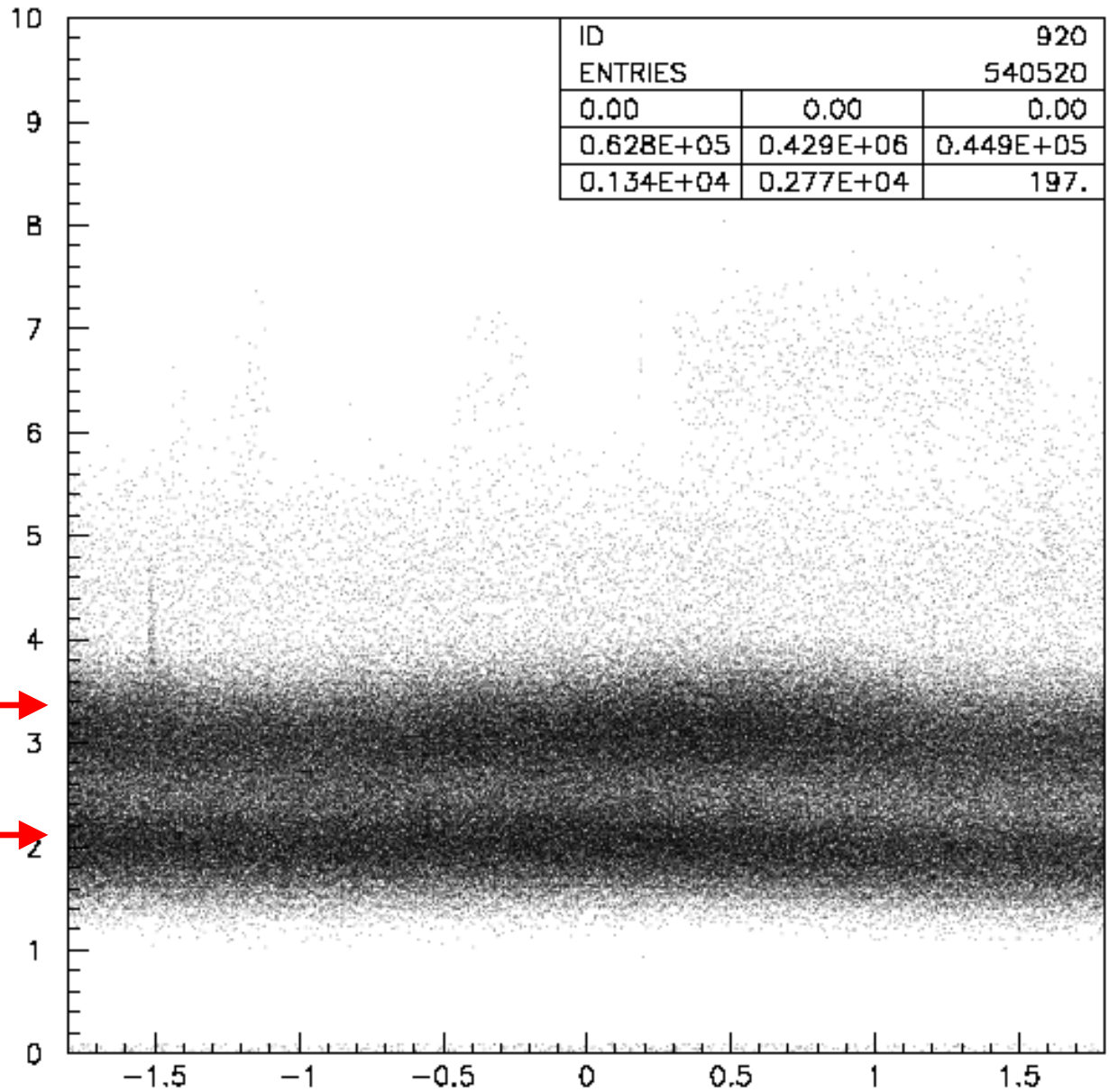**During the 10 days of observing the night sky had a small shift in transparency. The noise coincidence rate went up and the trigger was adjusted to accommodate this change.**

Trigger on >13 channel coincidence →

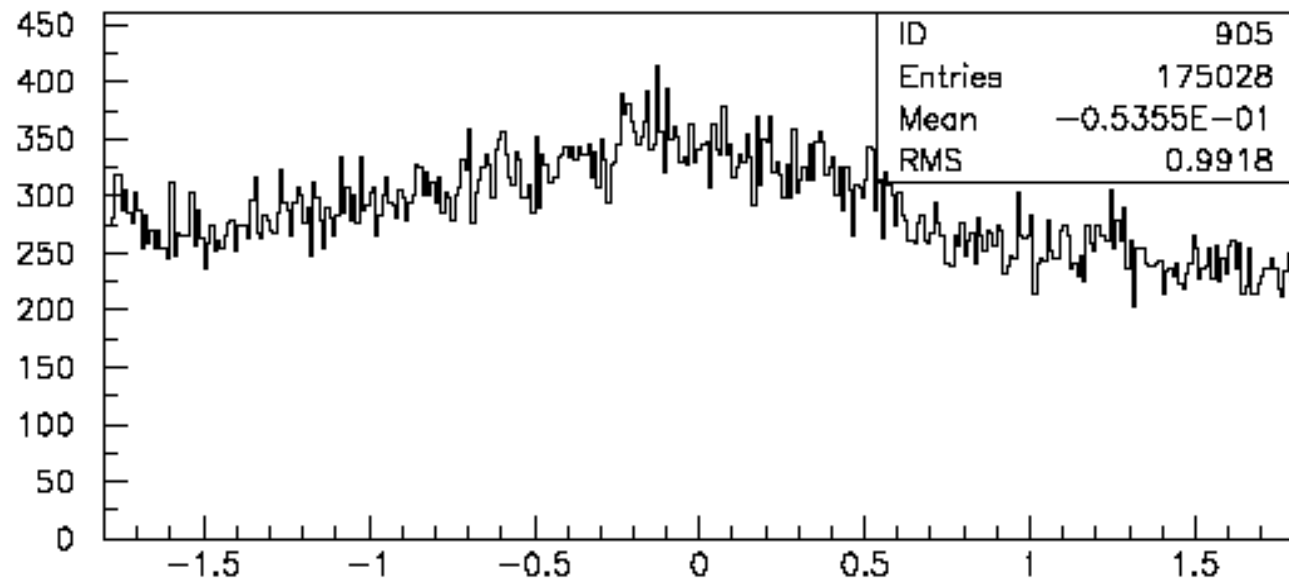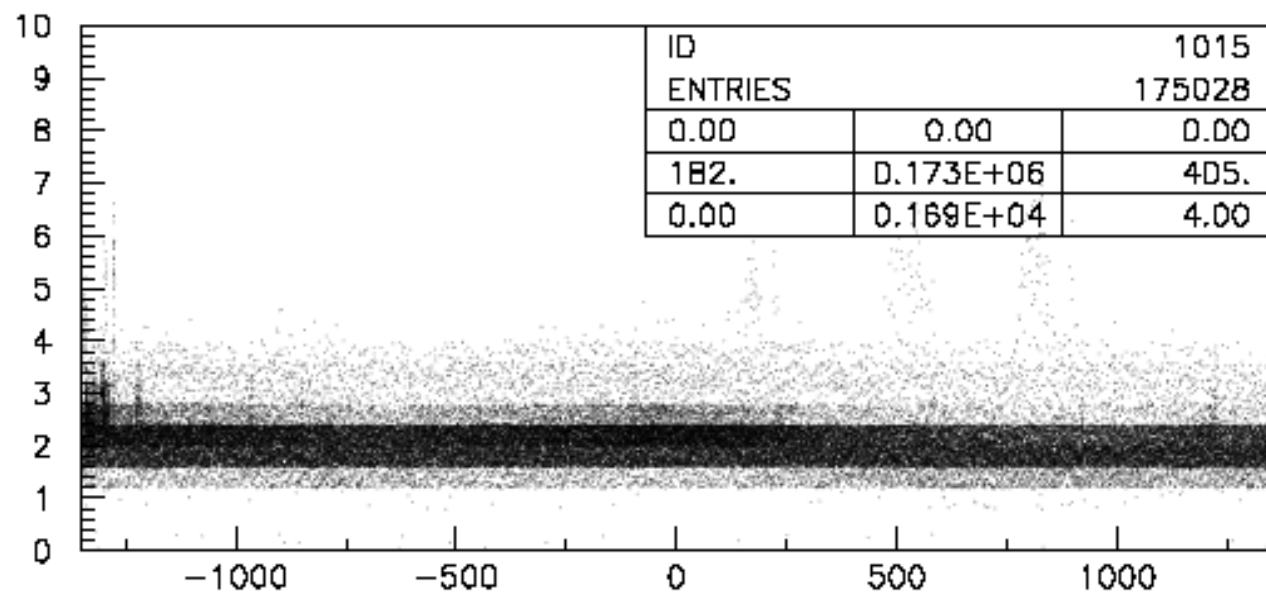**Trigger on >11 channel coincidence** →

ID		920
ENTRIES		540520
0.00	0.00	0.00
0.628E+05	0.429E+06	0.449E+05
0.134E+04	0.277E+04	197.

Row Noise Coincidence versus RA —— 0.01 degree bins

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Sum of 7 scans taken during low background rate conditions.

The background is stable, while the scan data show a feature.

ID		905
Entries		175028
Mean		−0.5355E−01
RMS		0.9918

Raw events versus RA −− 0.01 degree bins

ID		1015
ENTRIES		175028
0.00	0.00	0.00
1B2.	0.173E+06	4D5.
0.00	0.169E+04	4.00

Raw Noise Coincidence rate per 4s versus time

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Integral of 44 scans

Placing cuts on the total Pulse Height in the event (~energy) reveals that the excess is not visible above about 150, which is ~150 GeV.

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ID	904
Entries	486031
Mean	−0.1779E−01
RMS	1.005

All Data

P.H.>100

P.H.>125

P.H.>150

P.H.>200

Draco

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Scan of Draco -1 in Dec

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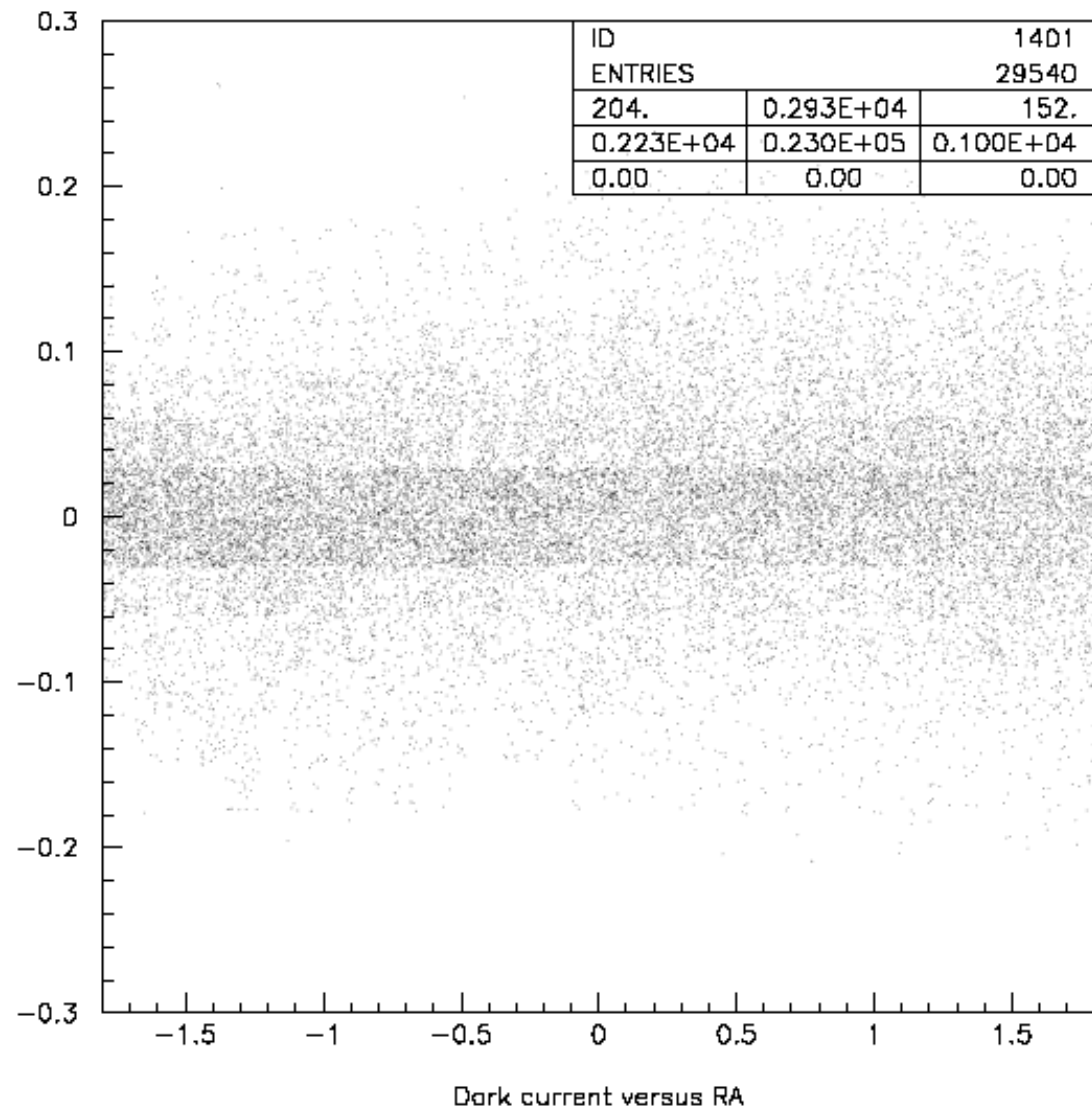| ID	904
Entries	111245
Mean	−0.4782E−01
RMS	1.034
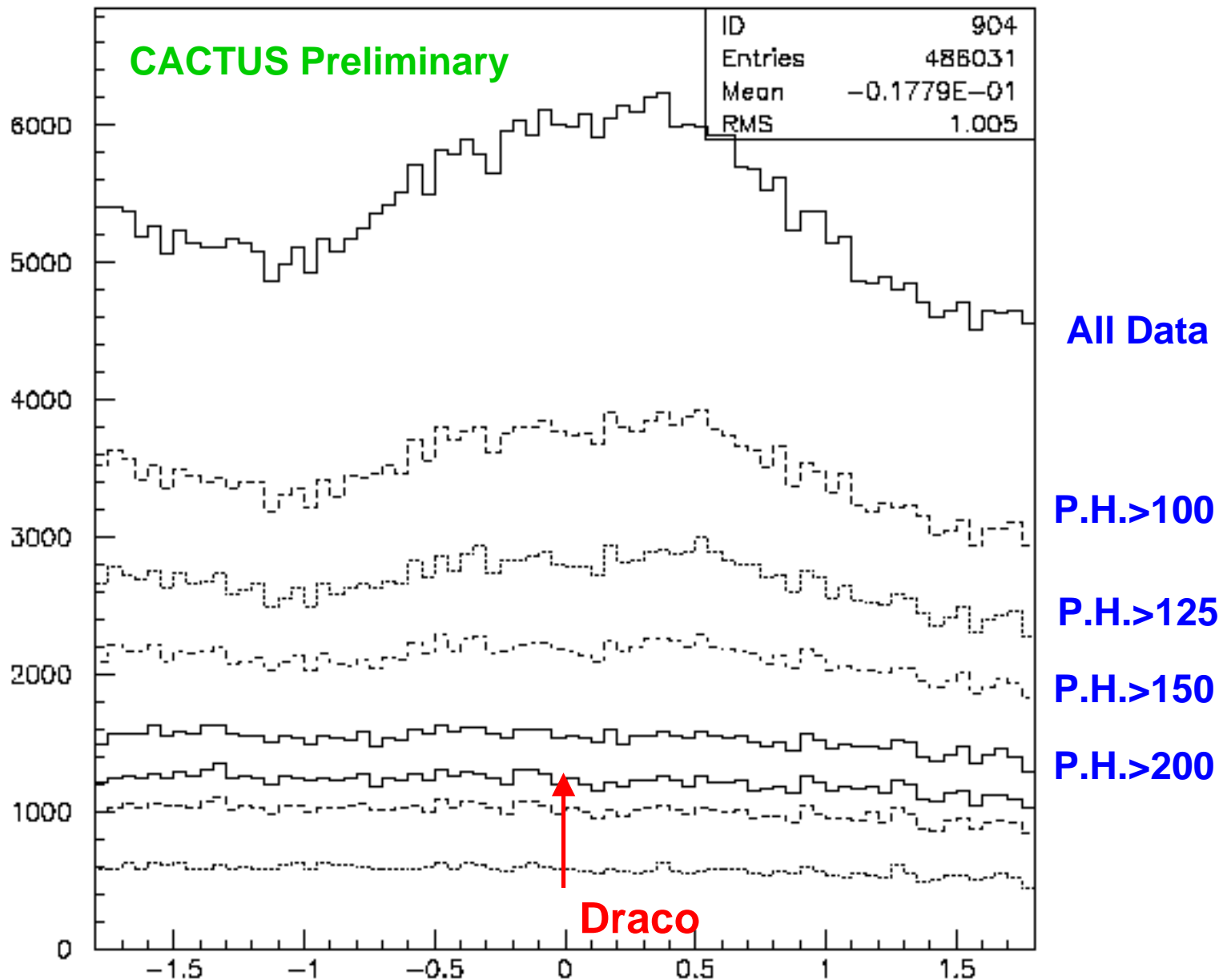
A similar set of scans in RA but offset by 1 degree in Dec show flat distributions in all energy bins.

A total of 10 scans are integrated here. The scaled rates agree with the background in 44 Draco scans.

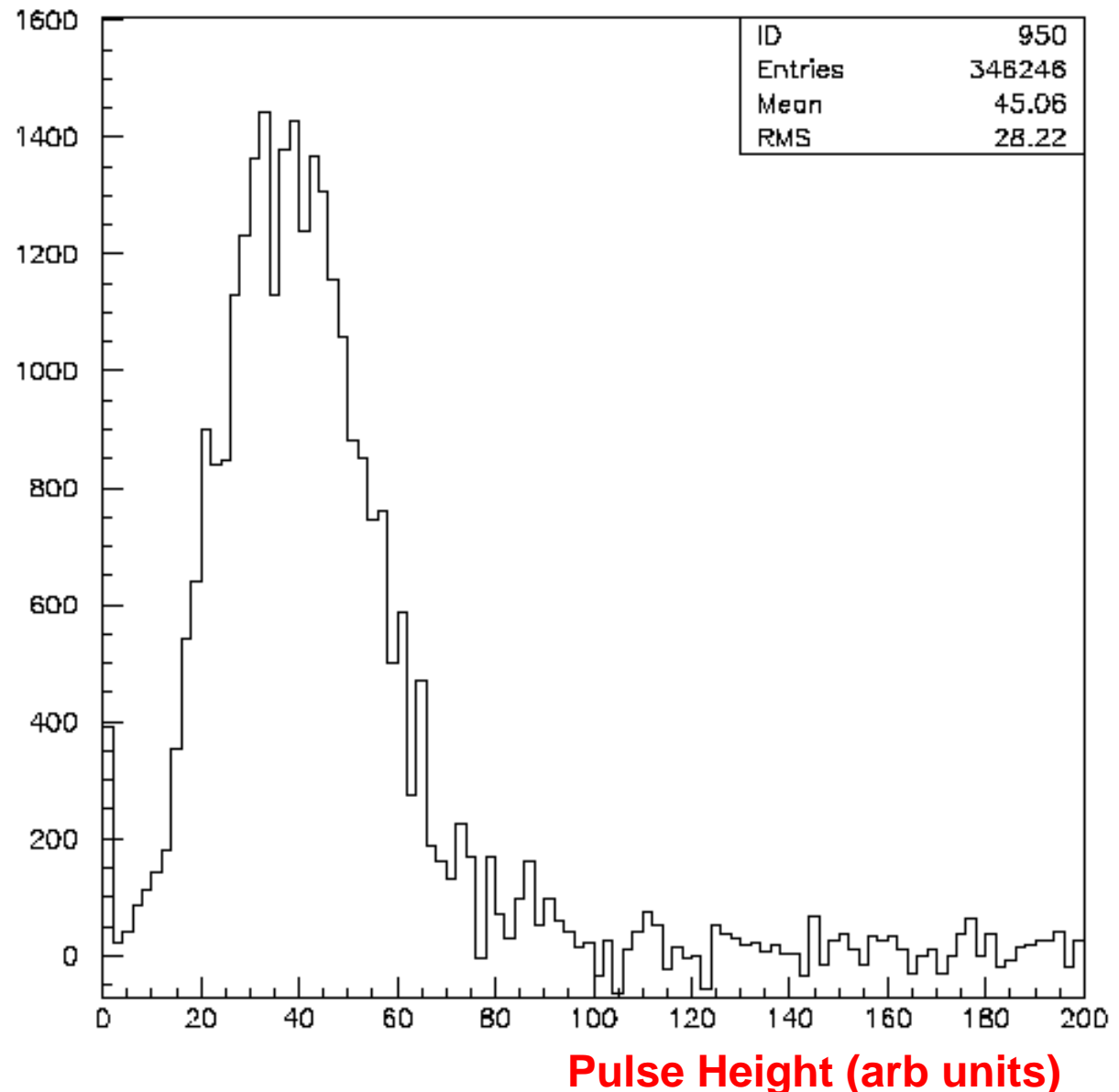Mani Tripathi, UC-Davis
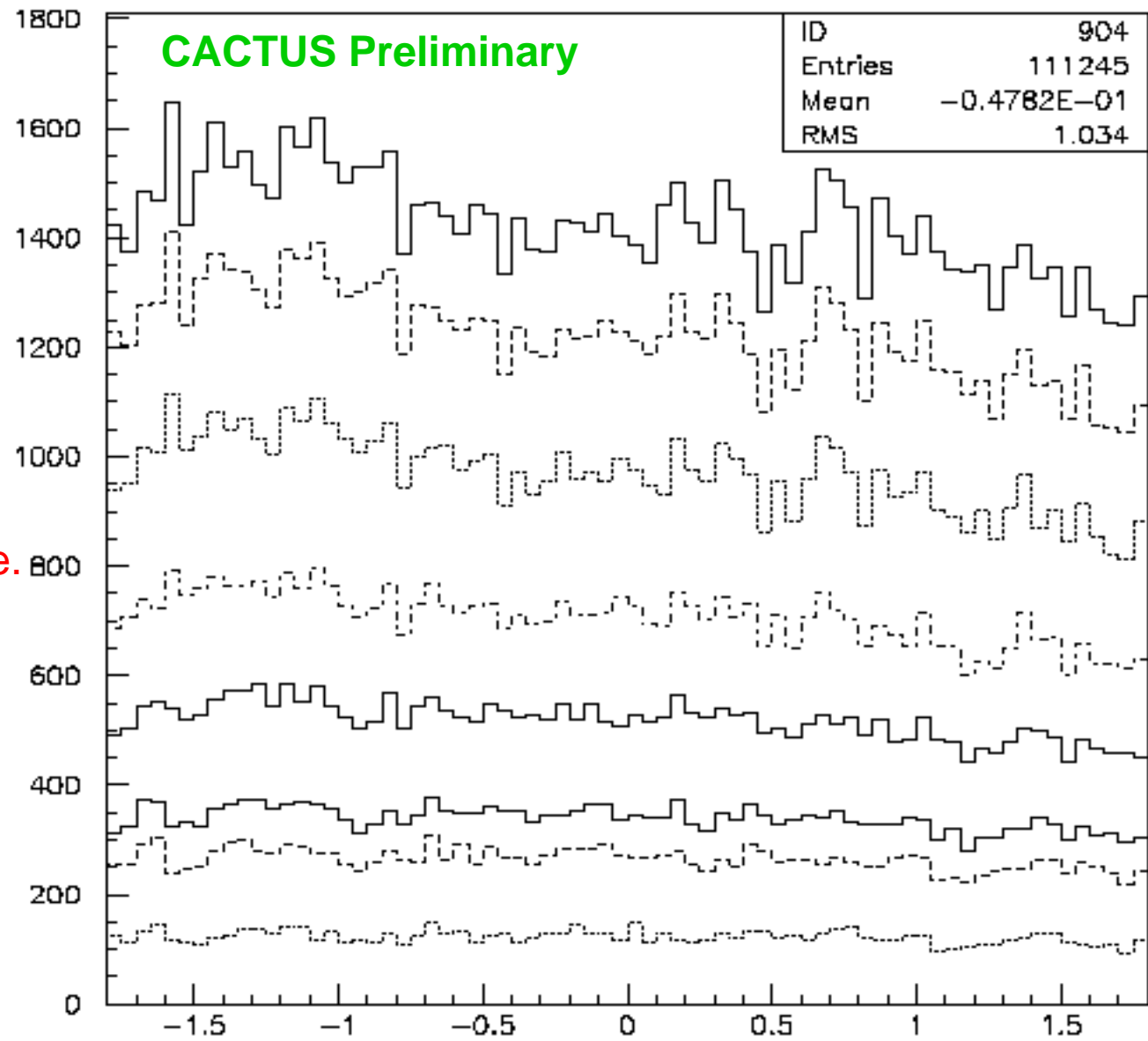
Dark Currents were also quite stable for the duration of the scans.

Shown here is the deviation from the baseline average dark currents recorded during 1 minute prior to the scan.

ID		1401
ENTRIES		29540
204.	0.293E+04	152.
0.223E+04	0.230E+05	0.100E+04
0.00	0.00	0.00

Dark current versus RA

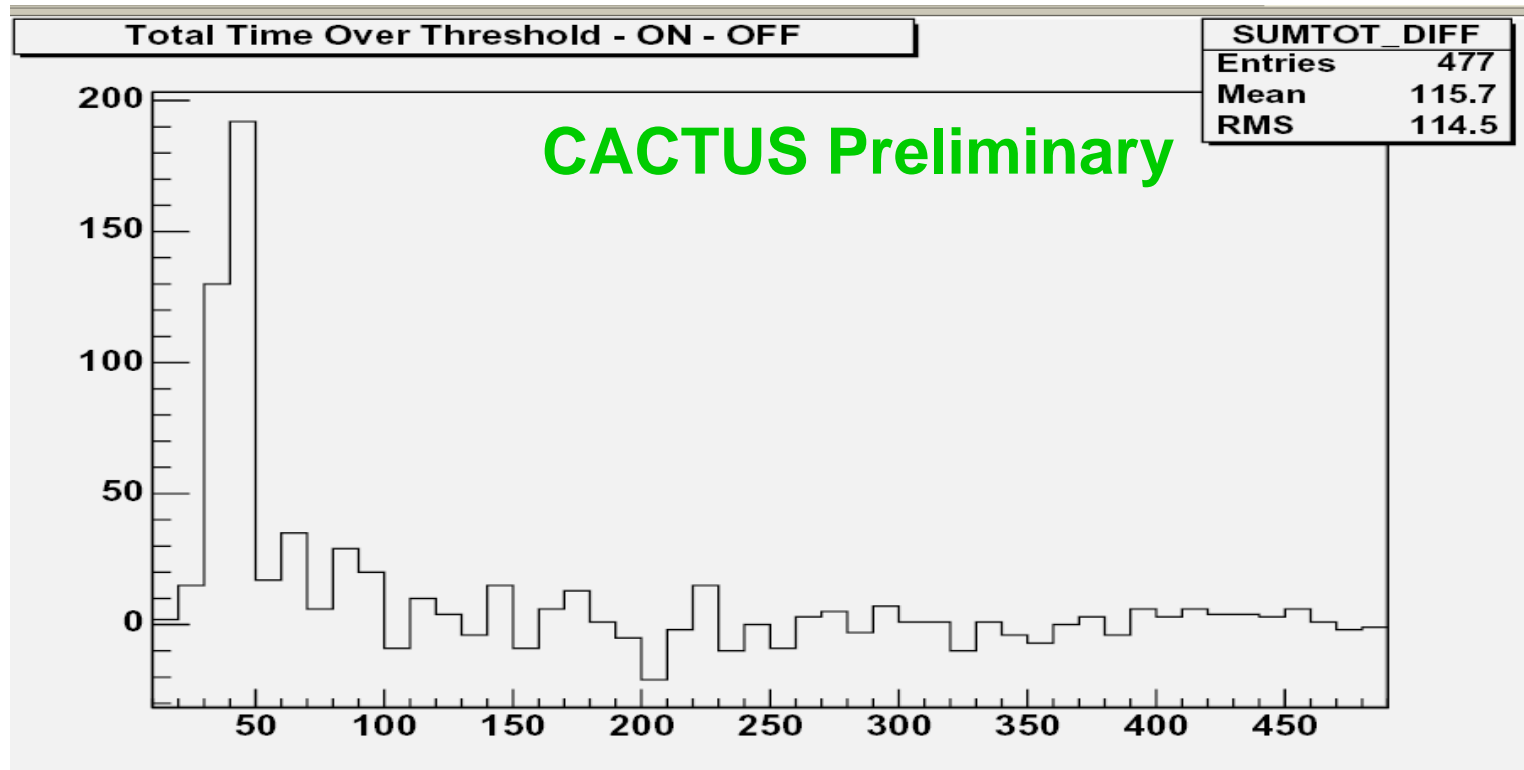Mani Tripathi, UC-Davis

Energy Distribution of the Excess

As an estimator of the energy spectrum of the excess in the Draco region, the pulse height distributions in the central region (|RA| < 0.8) minus the side-bands (1.0<|RA|<1.8) is plotted.

The peaked structure is mostly due to the detector resolution. At the present level of analysis it is difficult to distinguish a line-shape from an end-point Jacobian.


ID	950
Entries	346246
Mean	45.06
RMS	28.22

Pulse Height (arb units)

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Improved energy definition using the shower-fitting method.

Example for one scan only.

Total Time Over Threshold - ON - OFF

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SUMTOT_DIFF	
Entries	477
Mean	115.7
RMS	114.5

Dwarf Spheroid Survey

Our future plans include a survey of Sextans dwarf and a return to Draco in March 2006 to confirm the excess seen in this observing period.
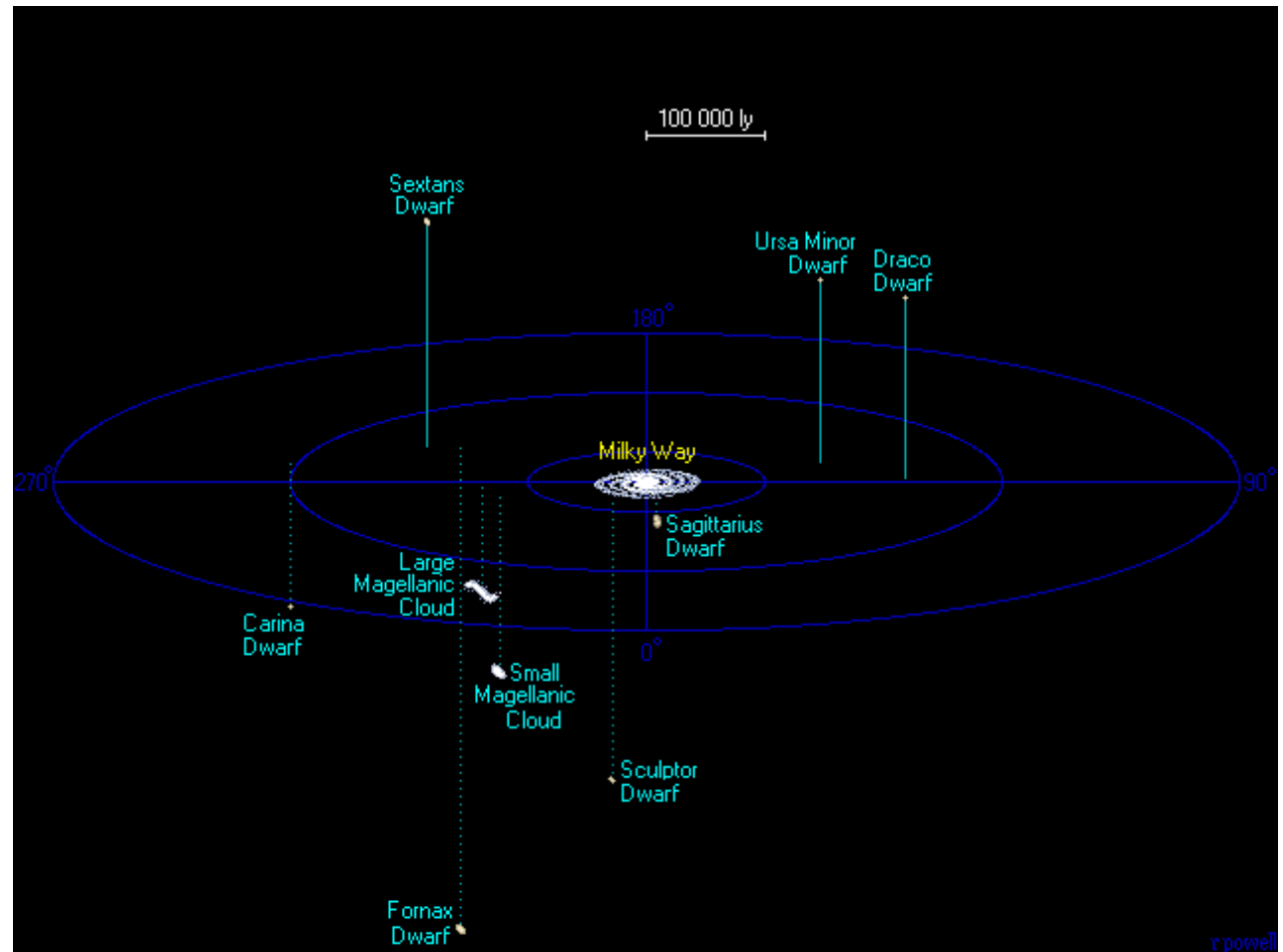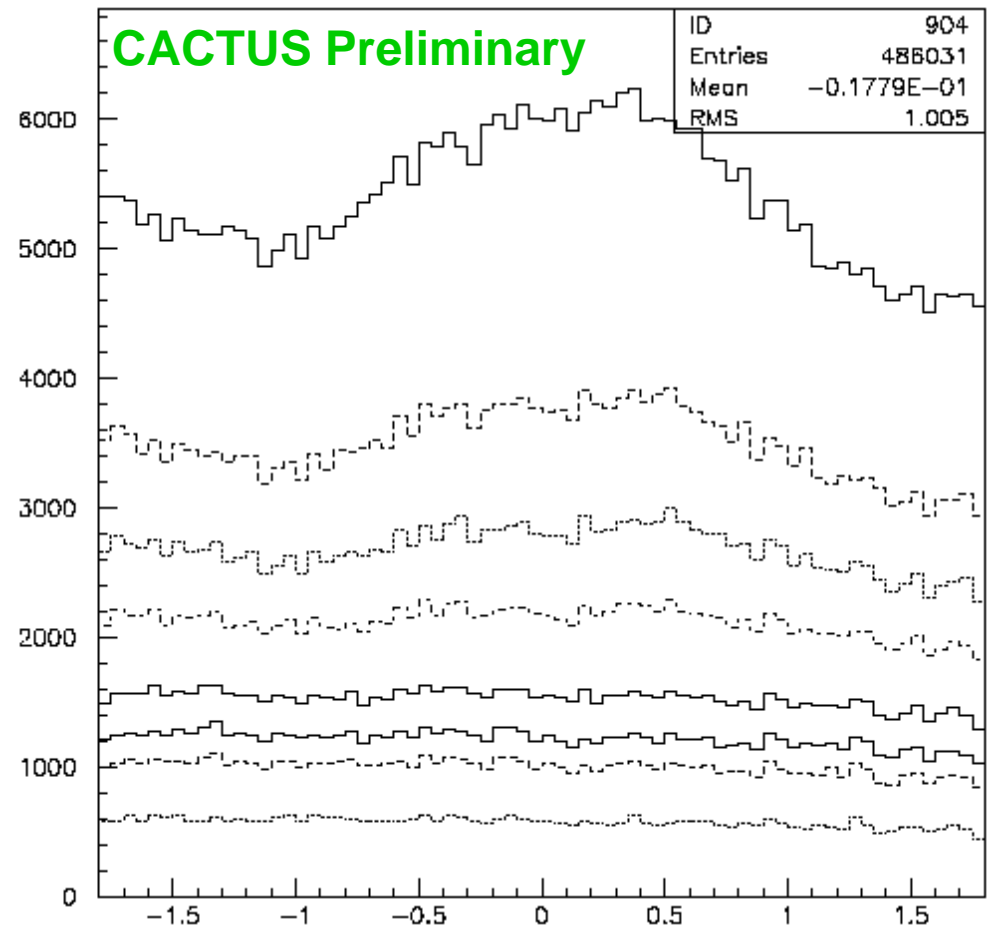
Summary

We have observed an excess of showers from Draco. We have to test the robustness of the excess. Work to be done:

1. Full shower fit analysis.

2. More detailed energy scale simulations and comparisons with world data on Crab.

3. Trigger threshold analysis.

Observe Sextans in the Fall.

Return to the Crab in the Fall for further calibration.

Implement time-imaging technique for improved gamma/cosmic ray discrimination.

CACTUS Preliminary

ID	904
Entries	486031
Mean	−0.1779E−01
RMS	1.005

Further update and published results expected by year end.

We welcome collaborators.

Mani Tripathi, UC-Davis

Acknowledgements

Time-Projection Imaging

CACTUS records multiple hits and pulse-heights per Heliostat. The time-of arrival difference between these pulses can be correlated to height of emission.

$\Delta h \sim c \, \Delta T/(n-1)$

For, $|1-\beta| \sim |n-1| \sim 10^{-3}$

$\Delta T = 16$ ns => $\Delta h \sim 5$ Km

Canting Targets

Pulse-heights are time-projected back on to the sky.

~5Km

~16 ns

Times of arrivals and Pulse heights measured by CACTUS.

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