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MINOS

Underground Astrophysics with MINOS

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Outline

I. Muon Astrophysics
   A. Cosmic Muons in MACRO and MINOS
      a. Zenith/Azimuth distributions
      b. Right Ascension/Declination distributions
   B. Shadow of the Moon and Sun
   C. Cosmic Muon Sources
   D. Seasonal Modulations
   E. Compton-Getting Effect/Solar Diurnal Modulations
II. Neutrino Astrophysics

I. Muon Astrophysics

- In a few years (3-5?), the full MINOS detector will record a set of cosmics equal to MACRO's complete data set
- Many analyses can be repeated to optimize MINOS far detector hardware/software
- New physics possible with the MINOS μ^+/μ^- separation capability

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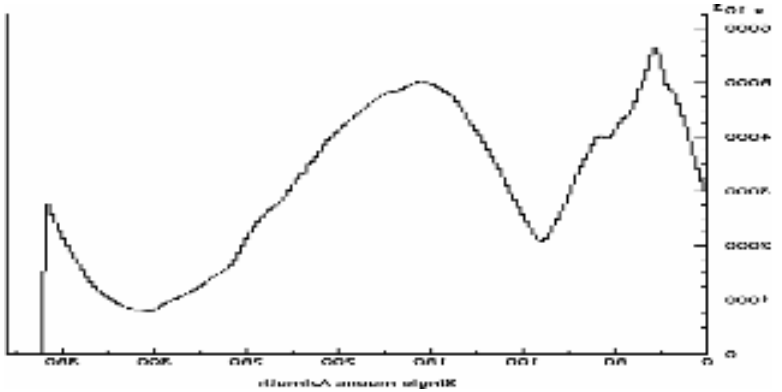
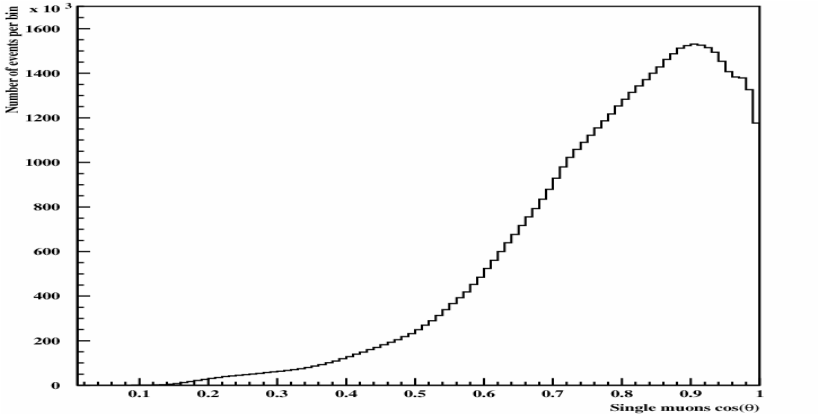
A. Cosmic Muons – MACRO

Zenith/Azimuth distributions

1. MACRO Muon Data
   a. MACRO operational from 1989-2001
   b. > 60 million muons recorded, $E_{th} \approx 25$ TeV
   c. 45-50 million pass cuts (depending on analysis)
   d. Rate ≈ 0.25 Hz
2. Muon Distributions
   a. Azimuth distribution dominated by Gran Sasso overburden
   b. Zenith angle distribution dominated by (mountain + solid angle) effects





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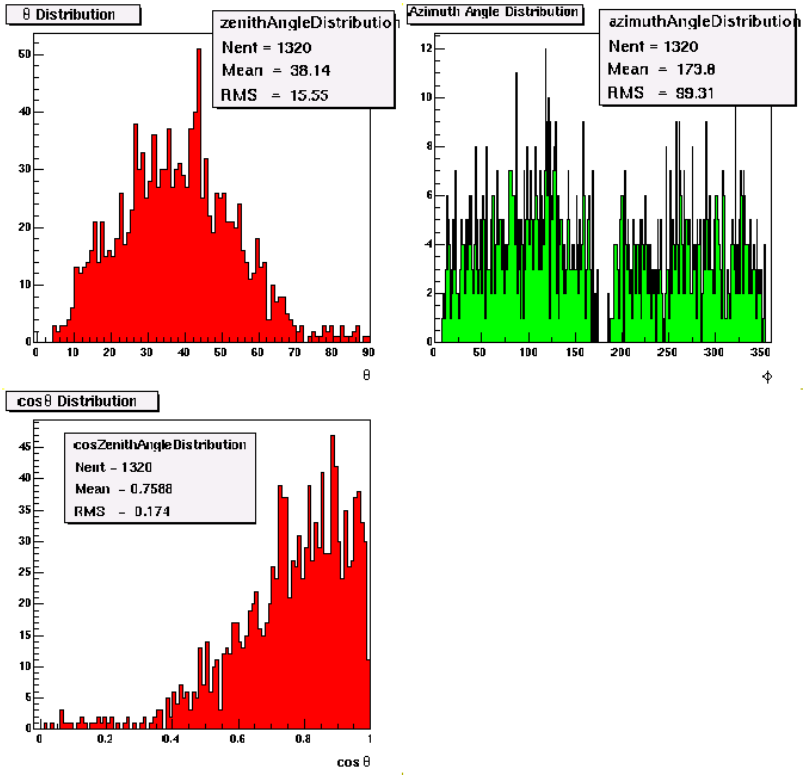
A. Cosmic Muons – MINOS

Zenith/Azimuth distributions

1. Early MINOS Muon Data
   a. Runs 1740 + 1779
      - 70 planes (~1 p.e. thresh.?)
      - 5^h 40^m run length
      - Rebel DeMuxer, Lee fitter
      - Rate(full det.) ≈ 0.5 Hz
2. Muon Distributions
   a. Distributions consistent with flat overburden
   b. MINOS: smaller than MACRO but shallower



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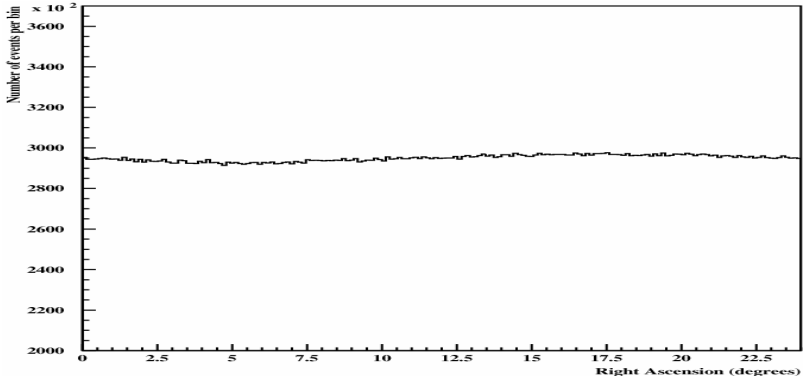
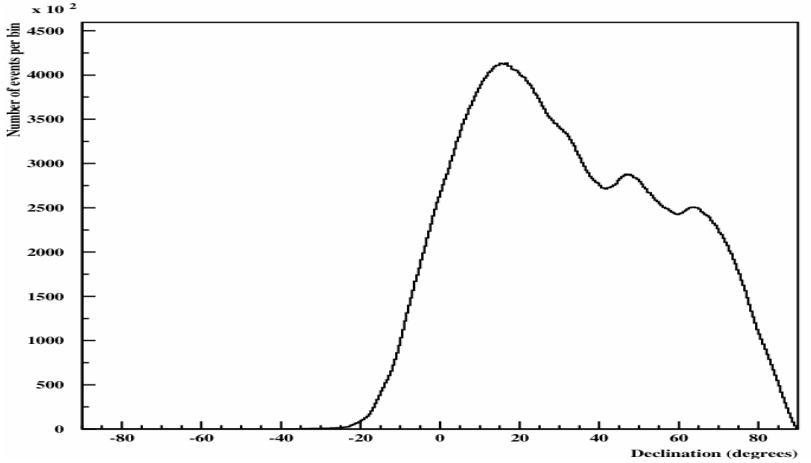
A. Cosmic Muons –MACRO

Right Ascension/Declination distributions

1. MACRO coordinates:
   - longitude = 13° 34’ 28” E
   - latitude = 42° 27’ 09” N
2. Right ascension distribution:
   - no evidence for point sources
3. Declination distribution:
   - Maximum response displaced from vertical by mountain overburden
   - MACRO effective latitude:

$$\lambda_{eff} \approx 30^{o}$$





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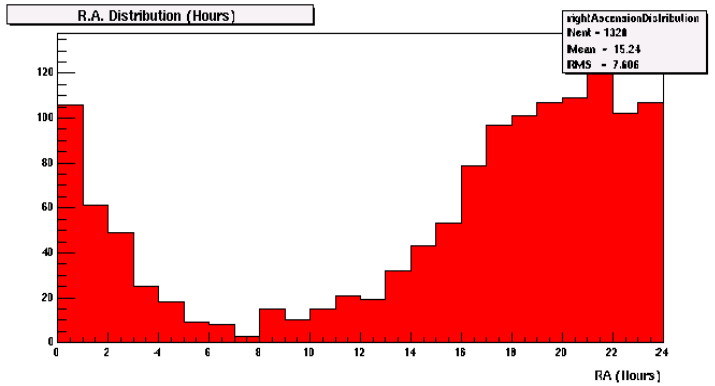
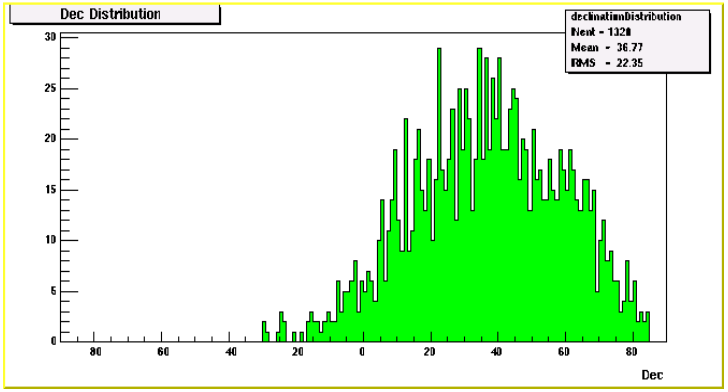
A. Cosmic Muons –MINOS

Right Ascension/Declination distributions

1. MINOS coordinates:
   - longitude = 92° 14’ 29” E
   - latitude = 47° 49’ 11” N
2. Right ascension distribution:
   - Reflects run time
3. Declination distribution:
   - Maximum response ≈ latitude, as expected for flat overburden





B. Moon and Sun Shadow

- Moon shadow used to estimate the angular resolution and systematic pointing accuracy for the MACRO detector
- Moon/Sun shadow analysis provides information about the solar magnetic field, the Geomagnetic (GMF) and the Interplanetary (IMF) magnetic fields
- Displacement of the sun shadow can be used to establish an upper limit on the antiproton/proton flux

- *Moon/Sun analyses based on single and double muon events recorded by MACRO*

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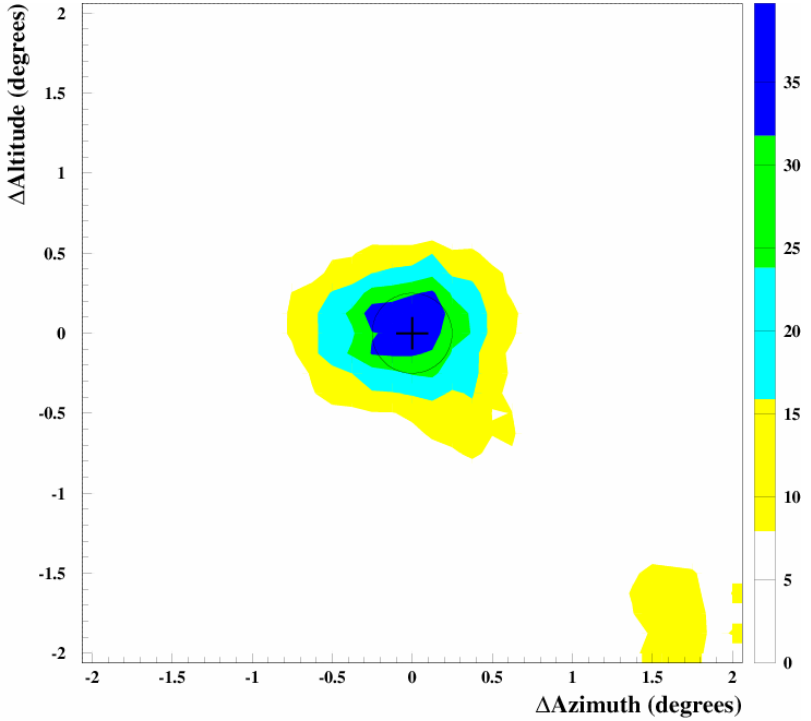
B. Moon Shadow

- Analysis:
  - Includes all muons with distance < 10^o from Moon
  - Likelihood function to establish significance of distribution

$$\lambda = 2\sum\left[N_i^{ex} - N_i^{obs} + N_i^{obs} \ln\left(\frac{N_i^{obs}}{N_i^{ex}}\right)\right]$$

  - χ^2/DoF = 39.7/36 at position (0^o, $+0.1^o$)
  - ➔ MACRO points accurately and its angular resolution better than 1^0



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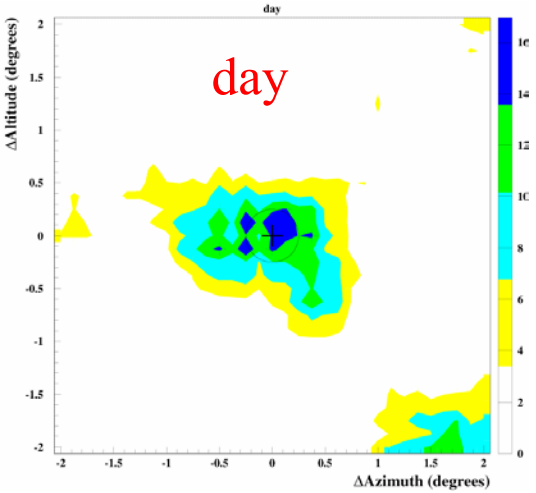
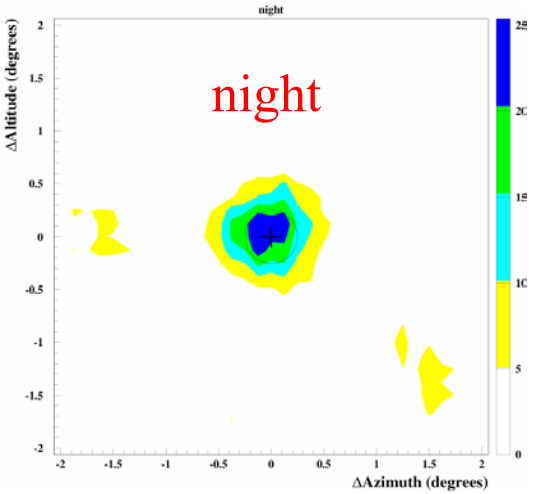
B. Moon Shadow:

"Day" and "Night" Samples

- Moon sample divided in 2
  - "day" sample: moon < 90° from sun
  - "night" sample: moon>90° from the sun
- Results:
  - Maximum χ^2 for "day" sample at: $\Delta = (-0.25^o, 0^o)$
  - Maximum χ^2 for "night" sample at: $\Delta = (0^o, 0^o)$
- Due to different shape of GMF on day/night side of magnetosphere
  - Consistent with deflection of primaries with $E_{pri} > 15$ TeV

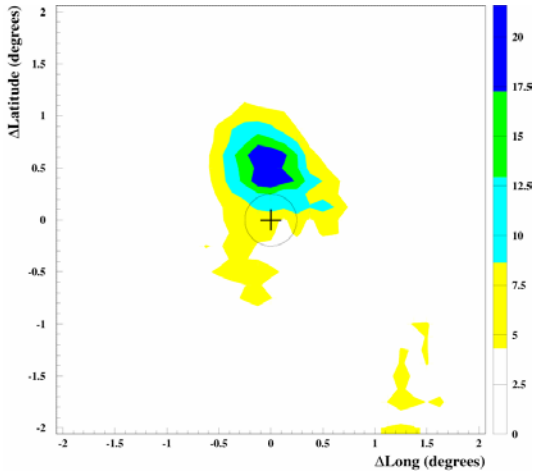


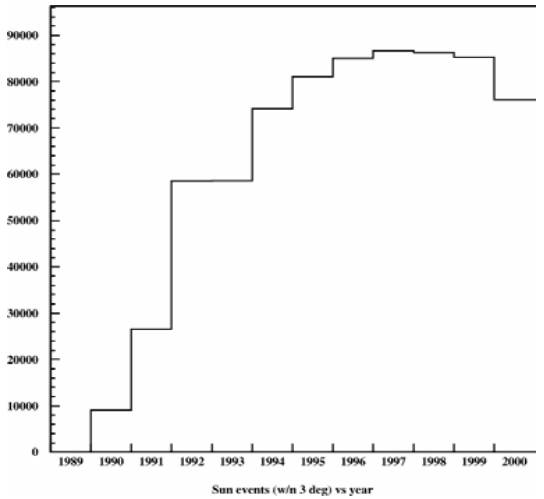


B. Sun Shadow

- Analysis repeated with events from direction of the sun
  - Deficit expected to be variable & displaced due to
    - Sun's B field
    - IMF
    - GMF
  - Maximum χ^2 at $\Delta = (-0.25^o, 0^o)$
    - Data too sparse for yearly map
- Displacement of sun shadow symmetric wrt to protons/antiprotons
  - No antiproton shadow $\Rightarrow$

$$flux(\bar{p}) / flux(p) \leq 0.22$$





C. Cosmic Muon Sources

- The search for cosmic muon sources has been motivated mainly by the report of detections of cosmic muons from Cyg X3 by Soudan 1 and NUSEX
- Unambiguous detection of muons from point sources would have a tremendous impact on particle physics and astrophysics
  - Cosmic muons from Cyg X3 are anomalous – charged particles cannot propagate 10 kpc in a straight line through the Galactic magnetic field to Earth
  - Low probability for UHE γ's to produce TeV muons able to reach underground detectors
  - Cygnets??
- In the end, astounding physics requires convincing evidence

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C. Cosmic Muon Sources

All-Sky Survey

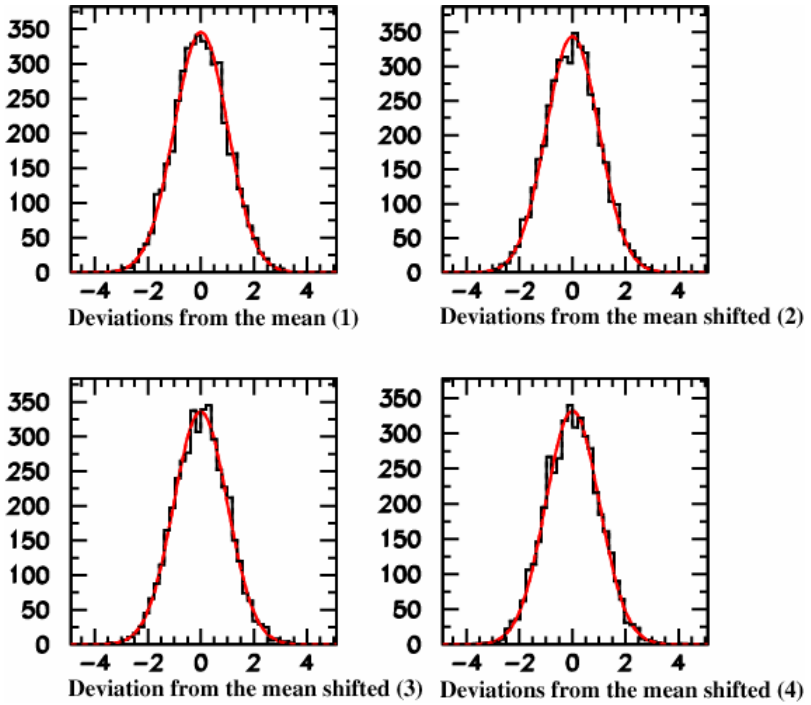
- All-Sky survey is the unbiased way to search for sources when a new window opens on the sky
- Events binned in

$$\left(\Delta\alpha = 3^0, \Delta \sin\,\delta = 0.04\right)$$

- In each bin, compute

$$\left(N^{obs} - N^{ex}\right)/\sqrt{N^{ex}}$$

- **No evidence for point sources**



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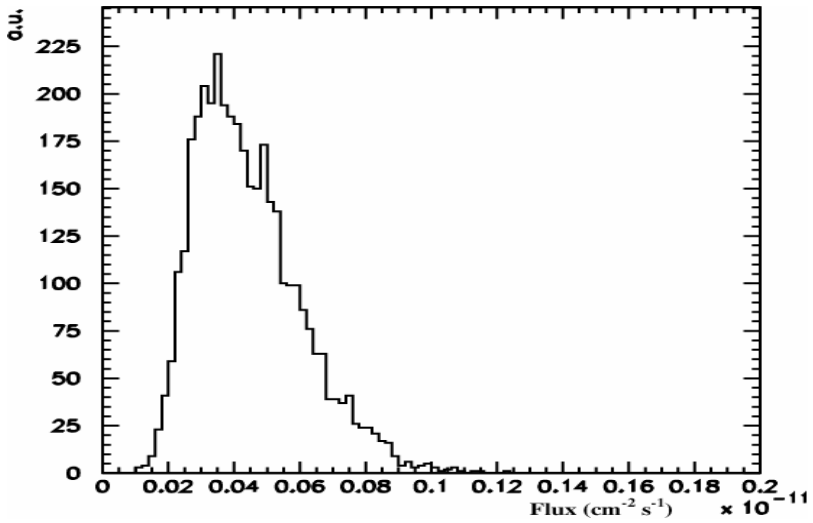
C. Cosmic Muon Sources

All-Sky Survey

- 95% C.L. to the muon flux, $J_\mu(95\%)$, computed from

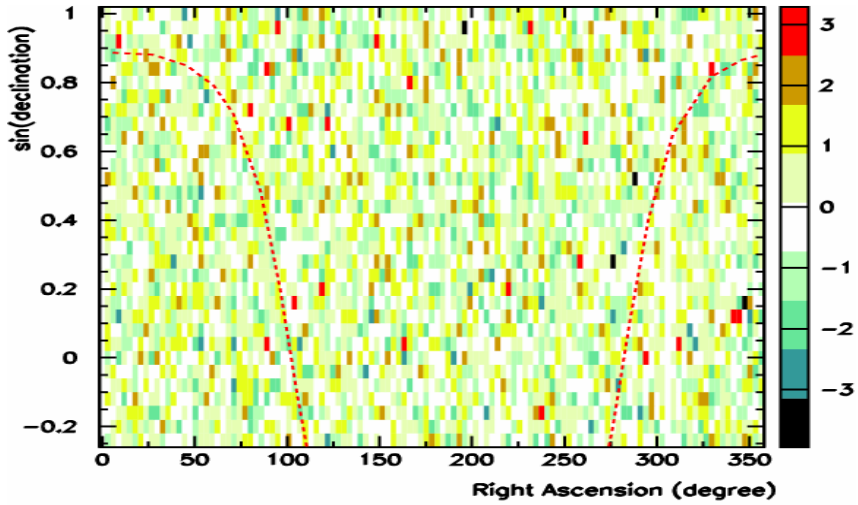
$$J_\mu(95\,\%) \le \frac{N_\mu(95\,\%)}{0.78\,\bar{\varepsilon} A_{eff}\, t_{\exp}} cm^{-2} s^{-1}$$



- Flux limits in the range

$$J_\mu(95\%) = 10^{-13} - 10^{-12}\, cm^{-2} s^{-1}$$

- No significant clustering of excesses



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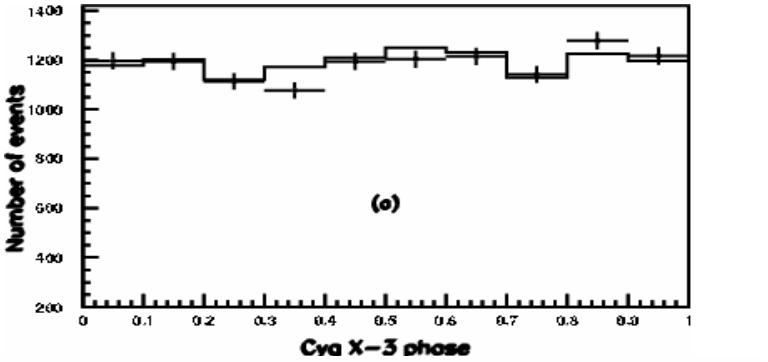
C. Cosmic Muon Sources

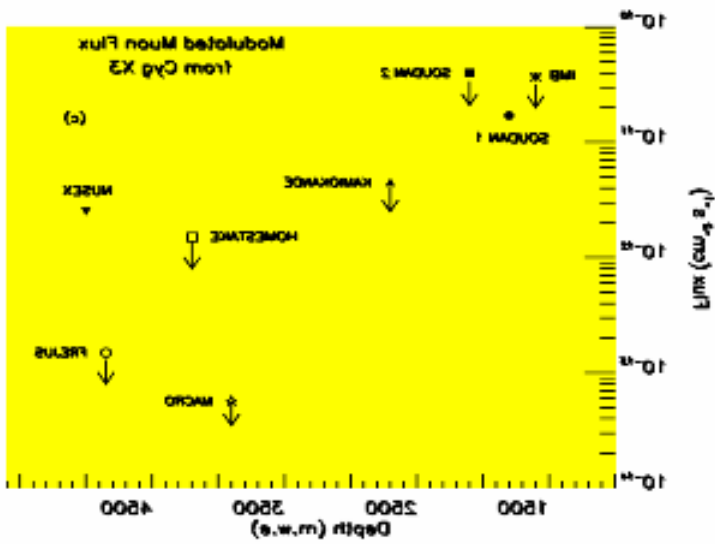
Modulated Muon Signals from Cyg X3

- Searches made for modulated signals from sources with claimed detections
  - Periodicity searches improve signal-to-noise
- Cyg X3 historically most often claimed as detection
  - Largest positive deviation in phase bin $0.8 \leq \Phi \leq 0.9$
    - 1.48σ
  - Limit to modulated flux $\leq 10^{-15}$ cm^{-2} s^{-1}

No evidence for modulated signal

- Similar results hold for Her X1





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C. Cosmic Muon Sources

Flaring Activity from Mrk 421

(a) Daily fluctuations in expected muon rate

$$P = 1 - \sum_{n=0}^{(N^{obs}-1)} \frac{\alpha^n}{(1+\alpha)^{n+N^{ex}+1}} \frac{(n+N^{ex})!}{n!\,N^{ex}!}$$

where P = probability to observe a burst at least as large as N^{obs}

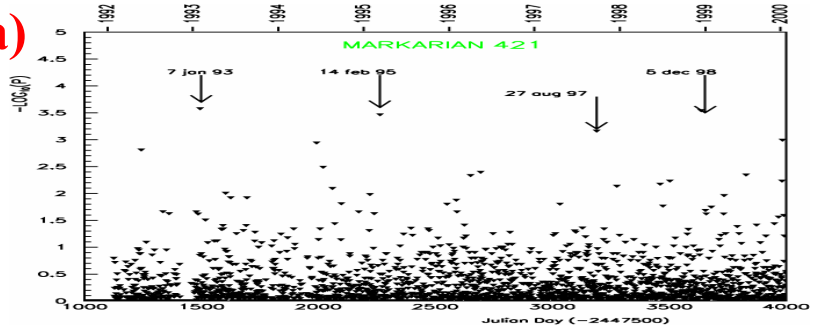
(b) Progressive accumulation of observed excesses above computed background during MACRO life

$$\Delta = (N^{obs} - N^{ex}) / \sqrt{N^{ex}}$$

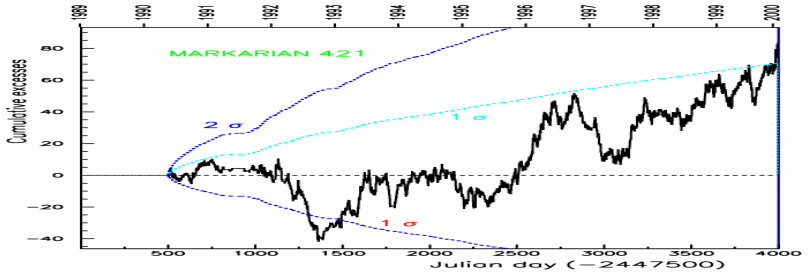
(c) Cumulative frequency dist. for –log P. For Poissonian process, slope = -1

No evidence for bursting behavior!

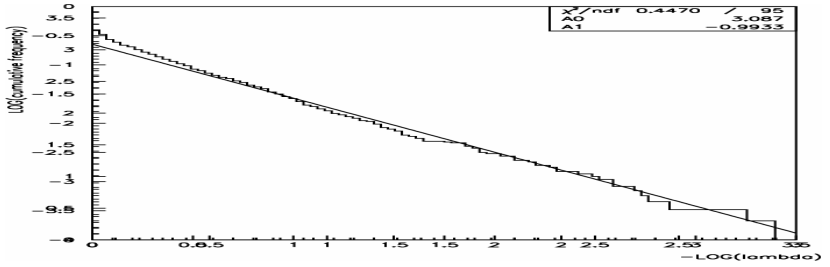
(a)



(b)



(c)



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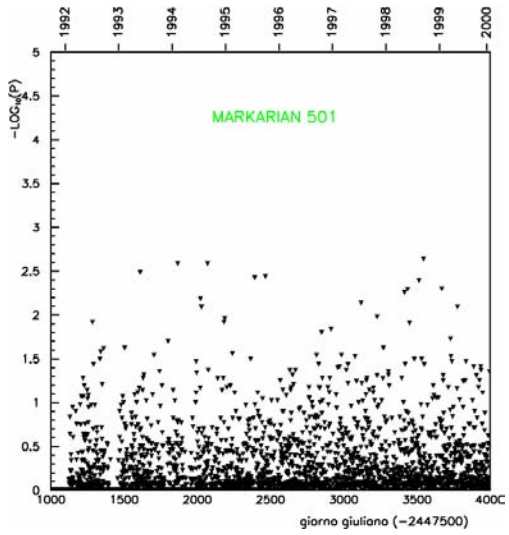
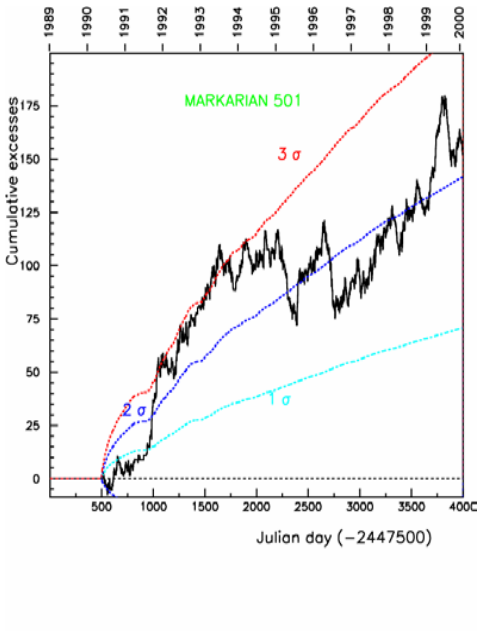
Cosmic Muon Sources

Flaring Activity from Mrk 501

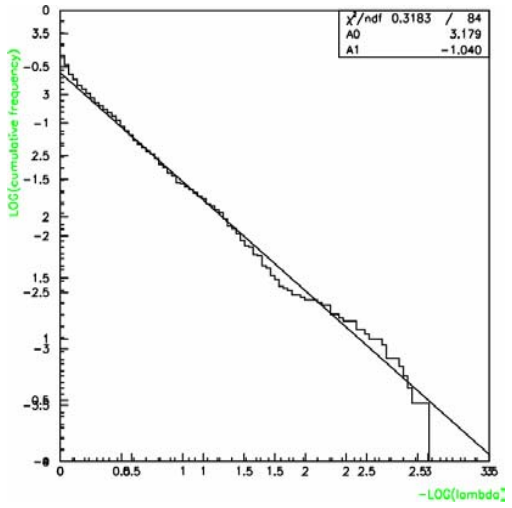
(a)



(b)



(c)



No evidence for bursting behavior!

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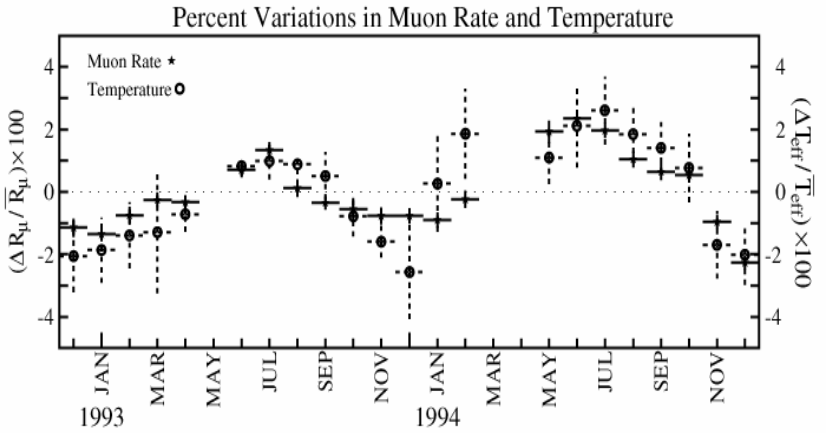
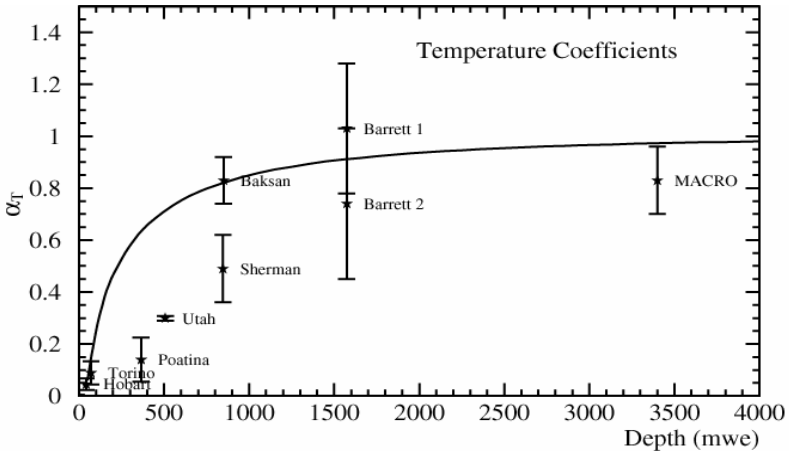
D. Seasonal Modulations

- Known effect with an amplitude of a few percent
  - Density variations at first interaction:
    - When cold, density high and pions fractionally more likely to interact than decay
    - When warm, the opposite occurs
- Expected relation:

$$\frac{\Delta R_\mu}{\overline{R}_\mu} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}}$$





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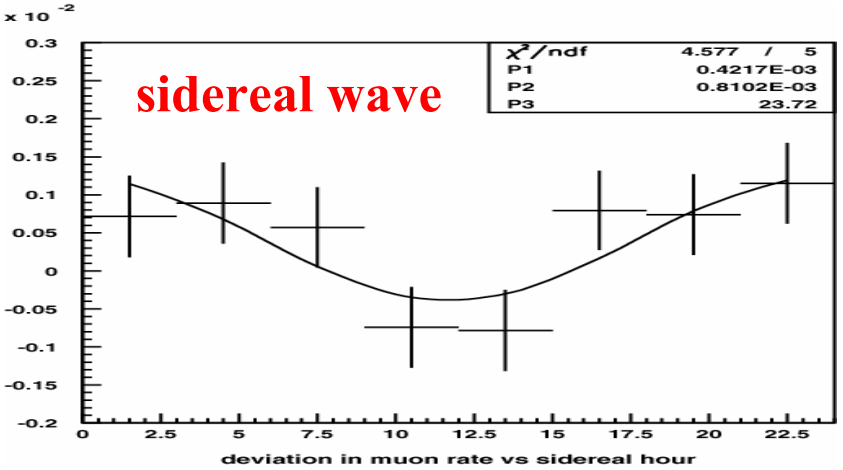
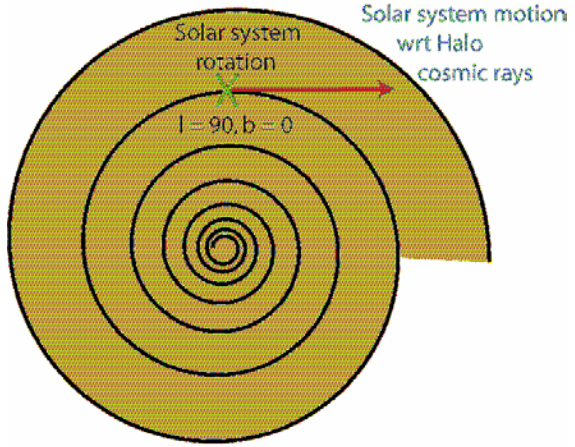
E. Compton-Getting Effect



- An observer moving with velocity **v** relative to the rest frame of a cosmic ray plasma will detect a deviation from the average c.r. rate
  - **Compton-Getting Effect**
  - Events binned in sidereal time; deviations plotted relative to the mean
  - Deviation maximum when observer moving parallel to velocity vector

➔ Results:

  - Amplitude = 0.081%
  - Maximum deviation when moving in direction of Galactic rotation



E. Solar-Diurnal Modulations

- Events binned in solar diurnal time (local solar time) ; events plotted relative to the mean
  - Modulation expected due to processes responsible for seasonal modulations

➔ Results:

  - Amlitude = 0.088%
  - Phase max. = 17.8^{h}

- Compton-Getting effect from Earth's orbital motion has a phase max at 6am local time