The Cosmic Ray Background as a Tool for Relative Calibration of Atmospheric Cherenkov Telescopes

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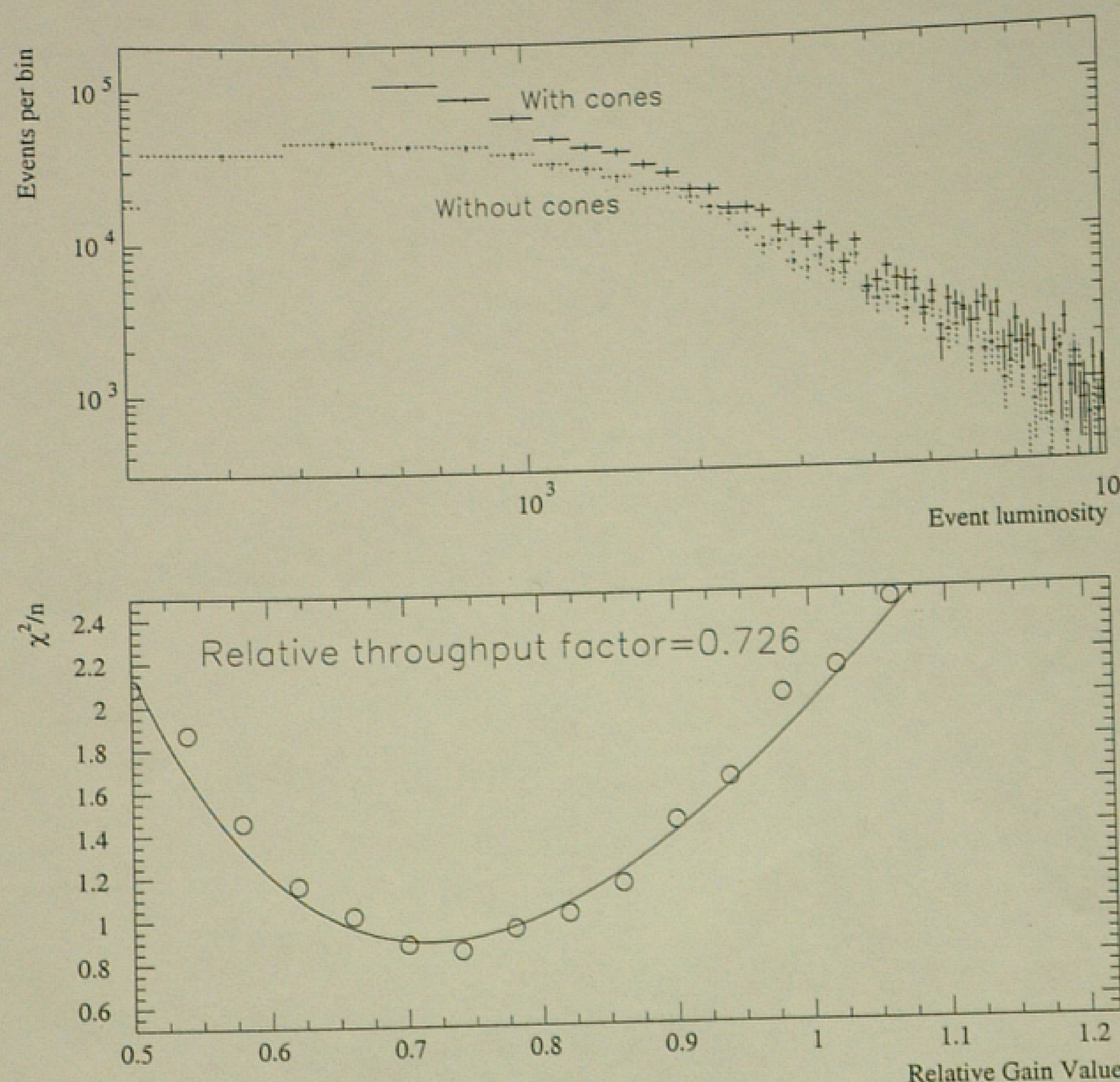
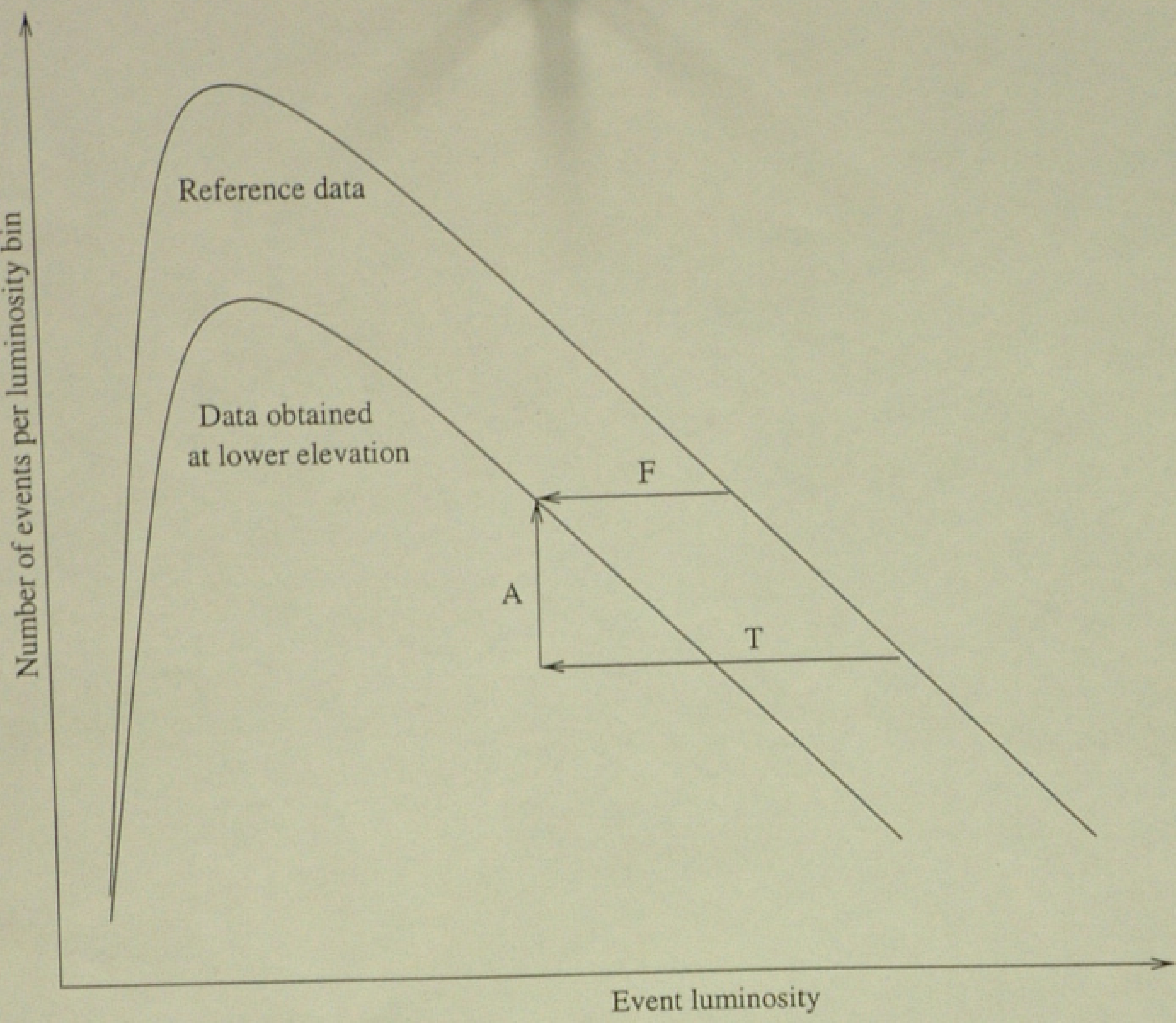
Abstract

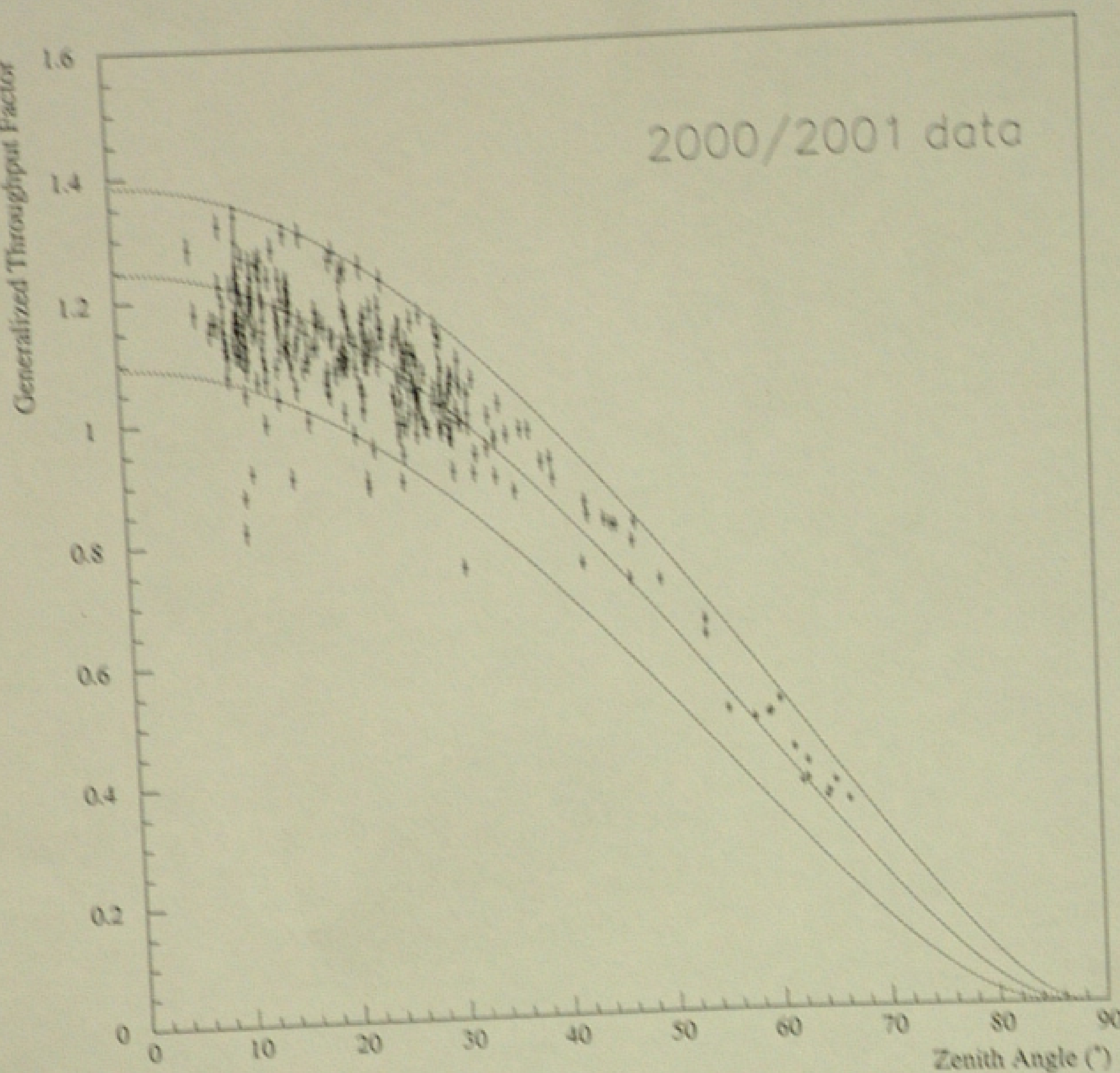
The atmosphere is an intrinsic part of any ground based Cherenkov γ-ray telescope, and the telescope response is therefore sensitive to unpredictable changes in the atmospheric transparency which are difficult to measure and interpret in the absence of a calibrated beam of high energy γ-rays. In this paper, we use the detector response to Cherenkov emission from cosmic ray initiated air showers to obtain a relative calibration for data obtained under different instrumental and atmospheric conditions as well as over a range of source angles to the zenith. We show that such a relative calibration is useful and efficient for data selection, for correcting the measured γ-ray rate and for inter-calibration between the elements of an array of Cherenkov telescopes.



The event luminosity distributions obtained with and without light collecting cones are shown at the top. The χ^2 is calculated by comparing the distribution obtained without the cones with the distribution obtained with the cones and rescaled by a test value for the throughput factor F. The minimum occurs for $g = 0.73 \pm 0.03$ indicating a 27% contribution by the cones to the light collection efficiency.



Factor T measures the horizontal shift in the distribution caused by changes in the light collection efficiency which result from changes in the instrument and atmospheric conditions as well as from differences in zenith angle. Factor A measures the vertical shift (a change in the number of showers observed with a given luminosity) caused by changes in the effective γ-ray collection area due to different source zenith angles. Only the factor F can be directly measured from the event luminosity distributions. As the radius of the Cherenkov light pool is defined only by the atmospheric density profile and source zenith angle, factors T and A should show the same zenith angle dependence for both γ-ray and cosmic-ray initiated showers as long as most of the Cherenkov light is emitted from the core of the shower. This allows us to use a generalized throughput factor in our analysis of γ-ray signals.



The reference data was taken at $\theta_z \sim 30°$ from zenith and so F is close to one at this point. It can be shown that if the atmospheric density profile is assumed isothermal, the area of the Cherenkov light pool is proportional to $\frac{1}{\cos^2 \theta_z}$ (see appendix). Using this, for a luminosity distribution of differential power law index $-\Gamma$, the throughput factor is expected to vary as

$$F \propto (\cos \theta_z)^{2(\frac{\Gamma-1}{\Gamma})} \times e^{-\frac{K}{\cos \theta_z}} \qquad (1)$$

where the exponential term is used to describe the atmospheric attenuation of Cherenkov light. For our observed $\Gamma = 2.3$ we have

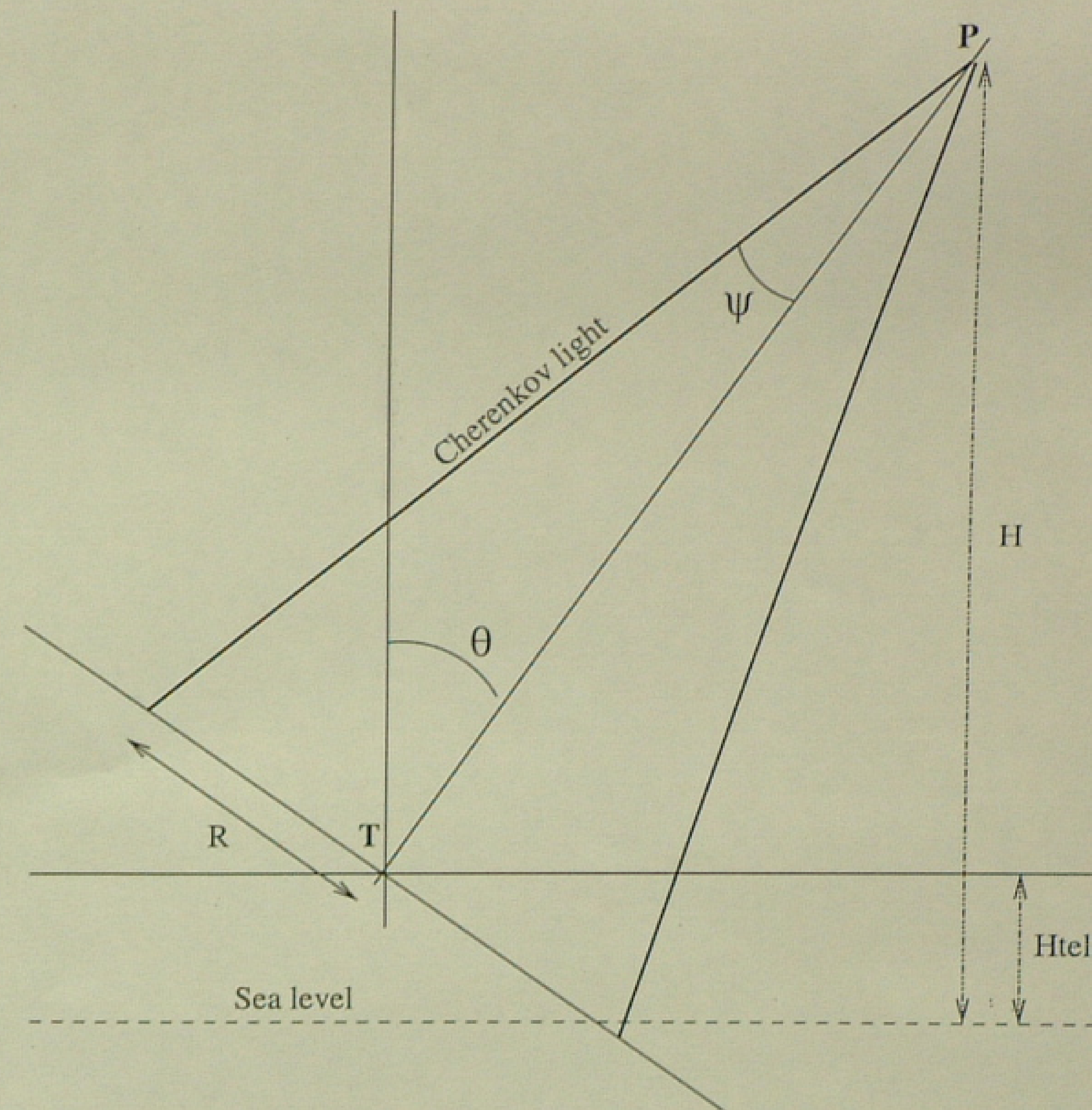
$$F \propto (\cos \theta_z)^{1.13} \times e^{-\frac{K}{\cos \theta_z}} \qquad (2)$$

We can see that $R = \frac{H-H_{tel}}{\cos\theta}\tan\psi$. The Cherenkov angle ψ is given by $\cos\psi = 1/n$ where n is the atmospheric refraction index at altitude H. In a standard isothermal atmosphere $n = 1 + 273 \times 10^{-6}e^{-H/8.5}$ where H is expressed in km. Using the first order small angles approximation for ψ one finds $R = \frac{H-H_{tel}}{\cos\theta}\sqrt{(546 \times 10^{-6}e^{-H/8.5})}$.

For small values of H, R increases with H while for large values of H, R decreases with H. Therefore R must take a maximum of value R_{max} which corresponds to the rim of the Cherenkov light pool. By solving $\frac{dR}{dH} = 0$ for R one finds: $R_{max} = \frac{17}{\cos\theta}\sqrt{546 \times 10^{-6}e^{-(17+H_{tel})/8.5}}$ which, for $H_{tel} = 2km$, gives $R_{max} \sim \frac{130m}{\cos\theta}$. From this it results that the effective collection area should scale as $\frac{1}{\cos^2\theta}$.

When we consider cosmic rays which are incident at an angle to the vertical the air shower develops in less dense atmosphere, where the Cherenkov emission per unit of track length is lower. The total track length is longer by an amount which compensates for this and consequently the total quantity of Cherenkov light produced by the shower does not depend on the zenith angle θ. However, as the Cherenkov light pool on the ground extends over a larger radius, the light is more diluted and Q, the measured luminosity of a shower, scales as $\cos^2\theta$.

In the generalized throughput calculation we compare luminosity distributions obtained under different elevations. The content of a specific luminosity bin will be affected by a factor $\frac{1}{\cos^2\theta}$, corresponding to the change in collection area, and by a factor $\cos^{2\Gamma}\theta$, corresponding to the event luminosity scaled for a power law luminosity distribution of spectral index $\Gamma = 2.3$ as measured in the case of the Whipple telescope. By combining those two factors raised to the $1/\Gamma$, one expects the throughput factor to scale as $F \propto (\cos\theta_z)^{2(\frac{\Gamma-1}{\Gamma})}$.

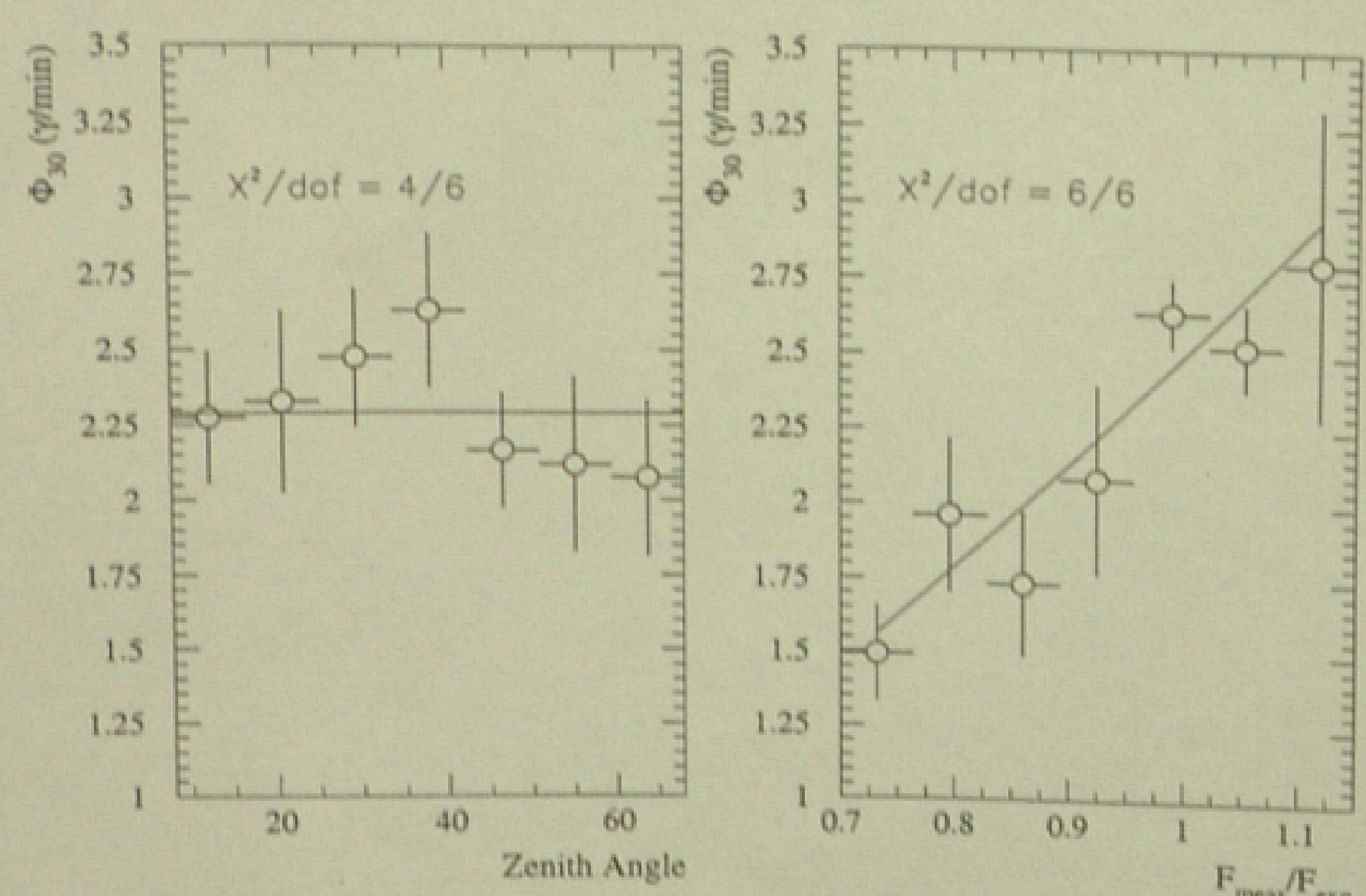


To apply the throughput correction we first calculate the expected throughput factor, F_{exp}, normalized to a zenith angle of 30° (because the measured throughput factor F_{meas} has been calculated with reference to an observation taken at a zenith angle of 30°) such that :

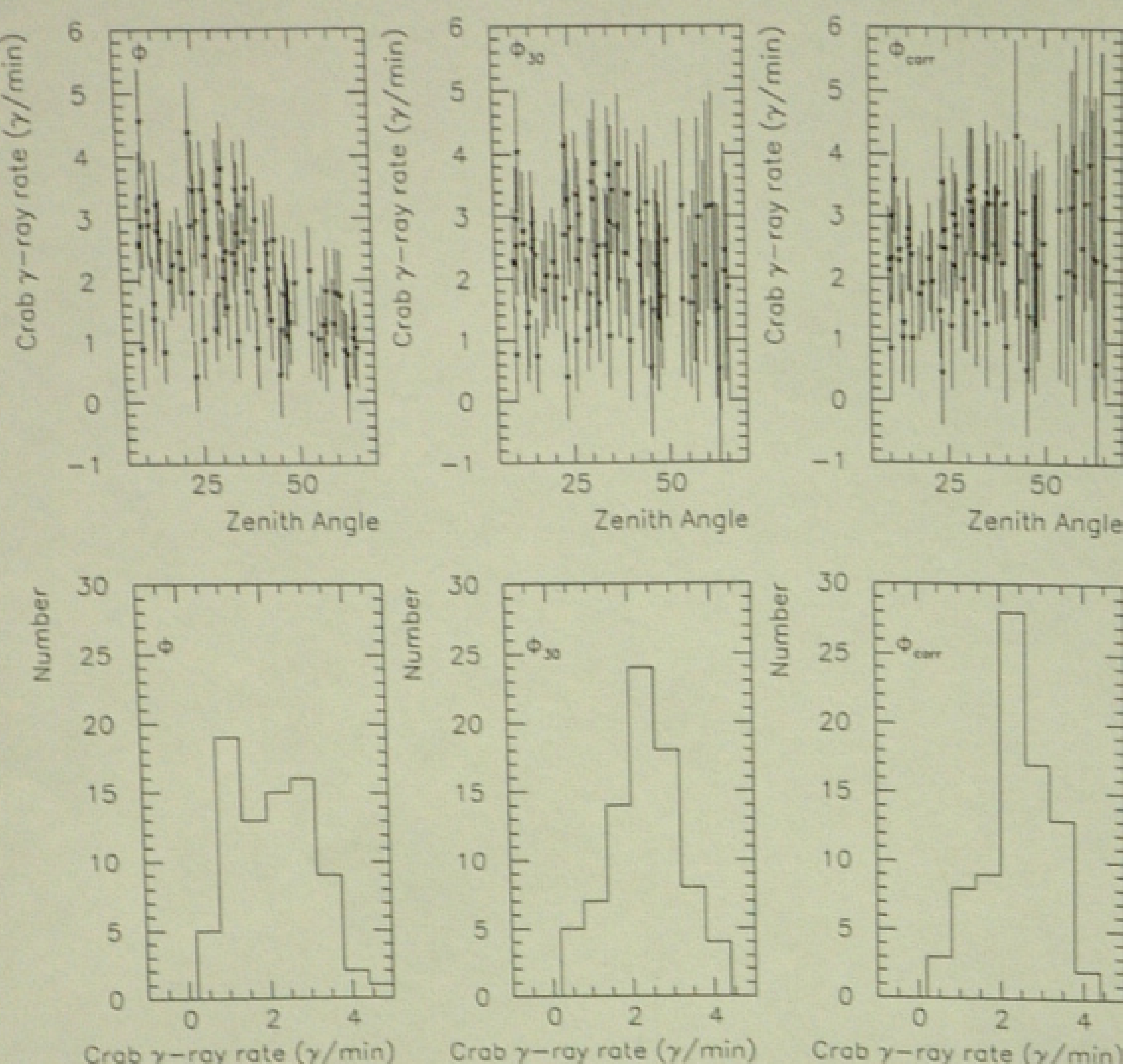
$$F_{exp} = (\frac{\cos\theta_z}{\cos 30^\circ})^{1.13} \tag{3}$$

This is equivalent to equation 2 but without atmospheric attenuation. The effects of atmospheric attenuation are automatically incorporated in the throughput correction , which we use to calculate the corrected rate as follows:

$$\Phi_{corr} = \frac{\Phi_{30}}{(F_{meas}/F_{exp})^{\alpha}} \tag{4}$$



The averaged Crab nebula γ-ray rate after correction for the zenith angle as a function of zenith angle (left) and F_{meas}/F_{exp} (right).



The effect of the elevation and throughput corrections to the Crab Nebula γ-ray rate. The upper plots show the rate as a function of the zenith angle. Each point represents a 28 minute observation (with statistical errors) showing the uncorrected rate (Φ), the rate corrected to a fixed zenith angle (Φ_{30}) and the rate corrected for zenith angle and throughput (Φ_{corr}). The lower plots are histograms showing the distribution of the three rates.