The Crab Nebula and Mkn 421 High-Energy γ-ray Spectra Above 50 GeV From CELESTE Observations In 1999-2000

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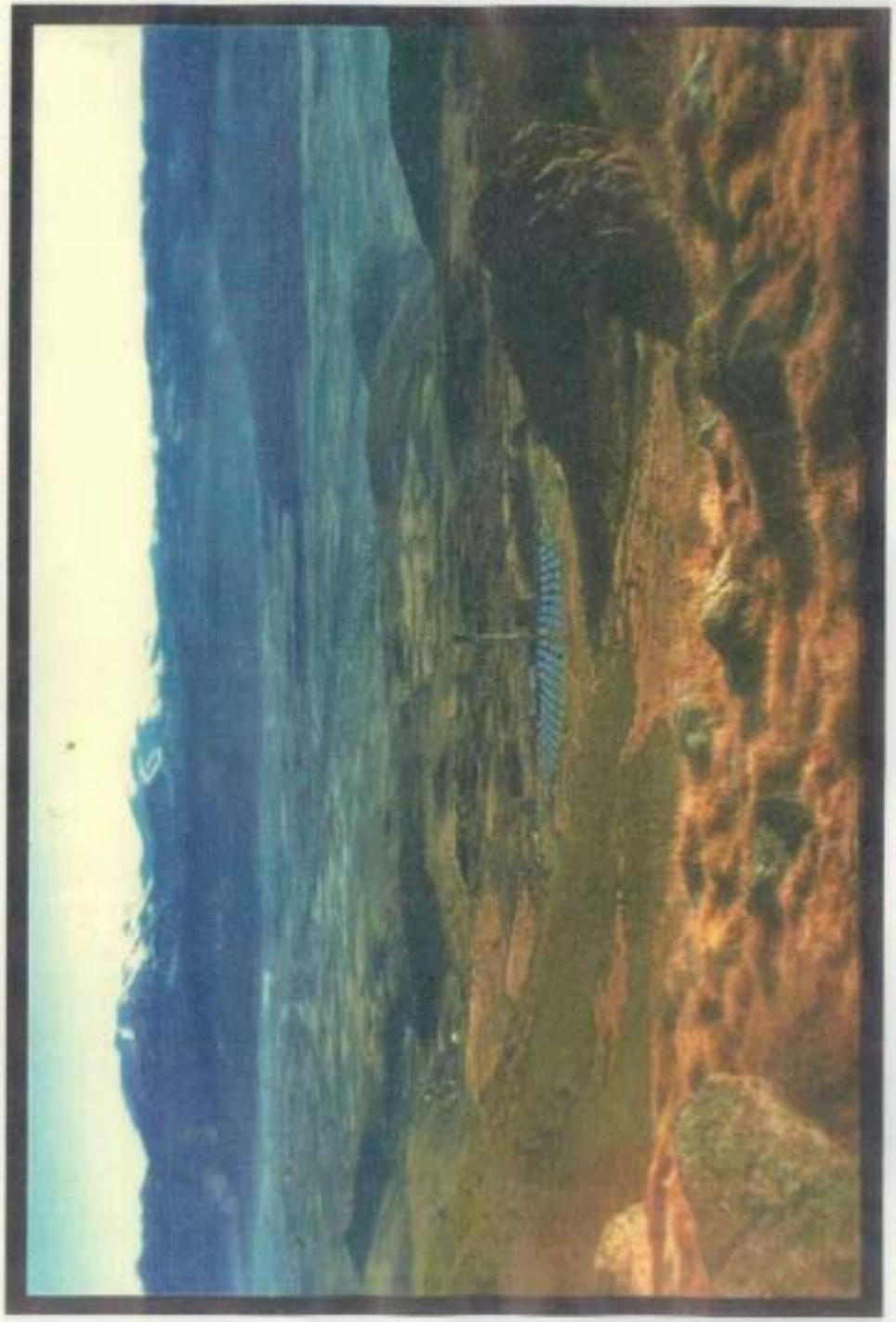

OUTLINE

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II SPECTRA RECONSTRUCTION

1/ Method

2/ Results on Simulations

III THE CRAB NEBULA AND Mkn 421 SPECTRA *

1/ Differential Spectra

2/ Systematic errors

3/ Broad Band H.E. SPECTRA

(*) = PRELIMINARY RESULTS

I ENERGY MEASUREMENT: METHOD

P_m = measured impact parameter
("injection point" at 11km/cos θ_z) $\sigma_p \simeq 15m$

Q_m = $\langle$ collected charge $\rangle_{\text{4o heliostats}}$

* AT FIXED P_m : $\text{Log}(Q_m) = p_1 + p_2 \text{Log}(E_t)$

⇒ Choose a typical value of P_m : 50m

$E_{m1} = \alpha (Q_m)^\beta$ unbiased if $P_m = 50m$

* AT FIXED E_t : $\frac{E_{m1}}{E_t} = p_3 + p_4 (P_m - 50)$, $p_3 \simeq 1$
for intermediate values of P_m

⇒ Select events in a given range of P_m :

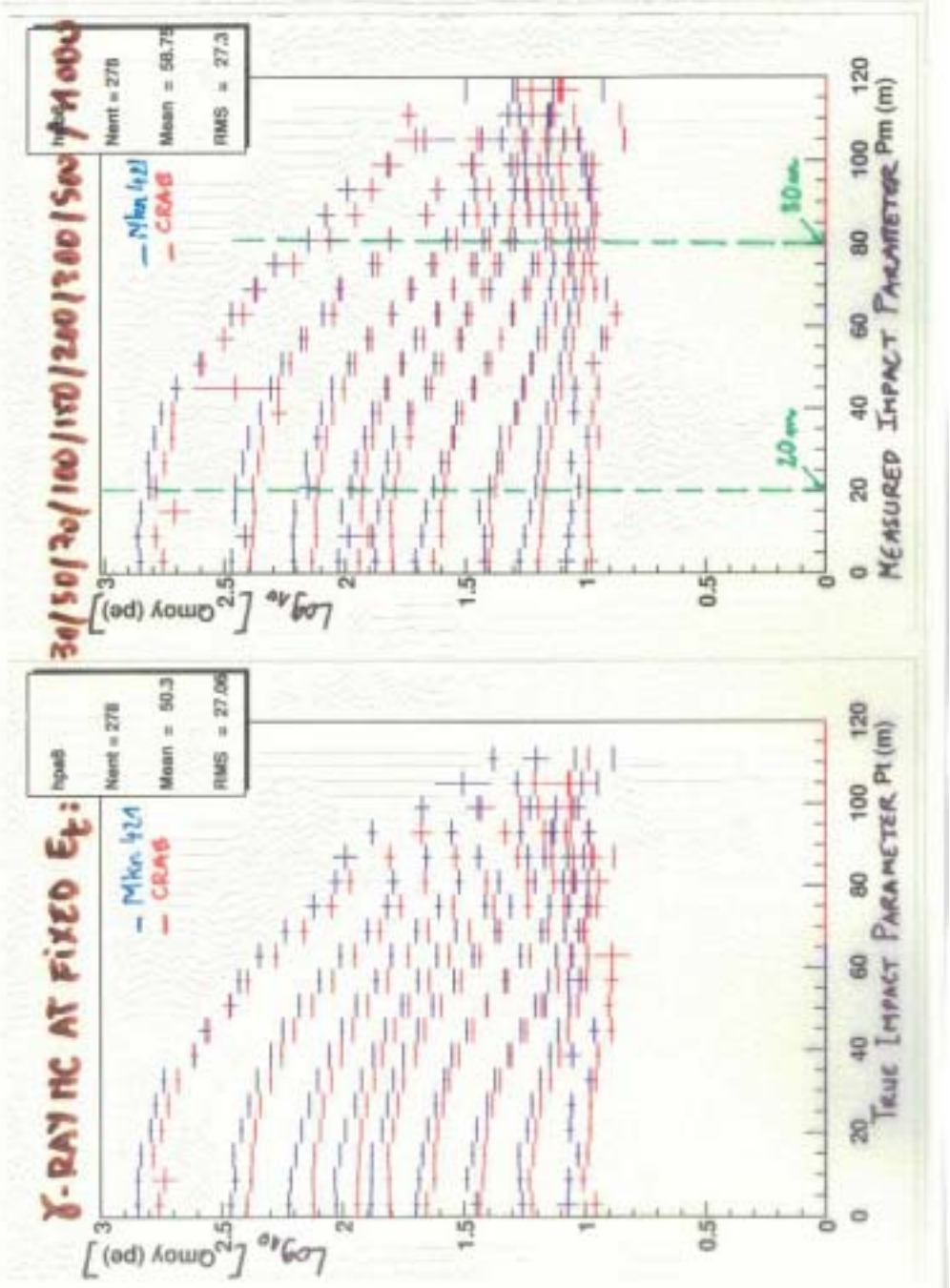
$20m < P_m < 80m$ ($\varepsilon_\gamma \sim 77\% \to 85\%$)

⇒ Fit $\frac{E_{m1}}{E_t} = 1 + \text{slope}\ \delta P$, $\delta P = P_m - 50$

* MIRACLE ! slope $= a/E_t - b$

⇒ $E_m = \frac{\alpha Q_m^\beta - a\delta P}{1 - b\delta P}$

$\delta P = P_m - 50$



II SPECTRA RECONSTRUCTION: Method

* **CHOOSE LARGE ENERGY BINS** to separate energy resolution effects and acceptance corrections:

$E_t \in [50 \cdot 100], [100 \cdot 200], [200 \cdot 400]$ GeV

* **ESTIMATE THE TRUE MEAN ENERGY $\widetilde{\langle E_t \rangle}^i$**

BY A MAXIMUM LIKELIHOOD METHOD

$$\text{p.d.f.} \propto \int dE_t \left(\frac{dS}{dE_t}\right)_{cuts} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(E_m - E_t)^2}{2\sigma^2}\right]$$

$$\left(\frac{dS}{dE_t}\right)_{cuts} \propto e^{-E_t/x_0} \quad \text{OK above threshold}$$

$$\Rightarrow \text{p.d.f. } f(x_j/x_0, \sigma) = \frac{1}{2x_0} e^{\sigma^2/2x_0^2 - x_j/x_0} \operatorname{erfc}(Q)$$

with $x_j = E_m^i$ and $Q = \frac{1}{\sqrt{2}}\left(\frac{\sigma}{x_0} - \frac{x_j}{\sigma}\right)$

$$\Rightarrow -\log \mathcal{L} = \sum_j -\log f(x_j | x_0, \sigma)$$

EXPECTED VALUE: $\widetilde{\langle E_t \rangle}^i = x_0$

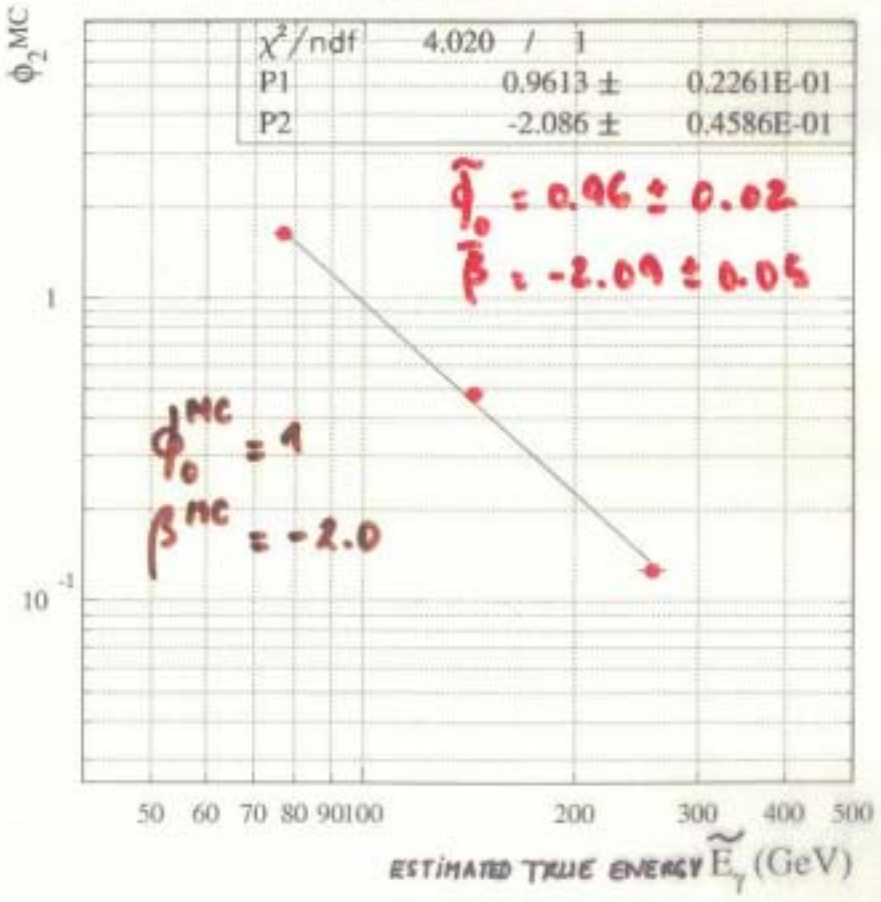
(Yost, G.P. 1984, NIM 234, 485)

* **ESTIMATE THE DIFF. FLUX Φ_i IN $[a_i, b_i]$**

$$\widetilde{\Phi}_i = \frac{(ON \cdot OFF)_i}{(b_i - a_i)\, T_{obs}} \cdot \frac{1}{A_i}$$

with $A_i = \dfrac{\int_{a_i}^{b_i} A(E) E^\beta dE}{\int_{a_i}^{b_i} E^\beta dE} = f(\beta) \Rightarrow$ **ITERATIVE PROCEDURE**

MC SPECTRUM $\beta^{MC} = -2.0$ @ CRAB TRANSIT



$\tilde{\phi}_0 = 0.96 \pm 0.02$

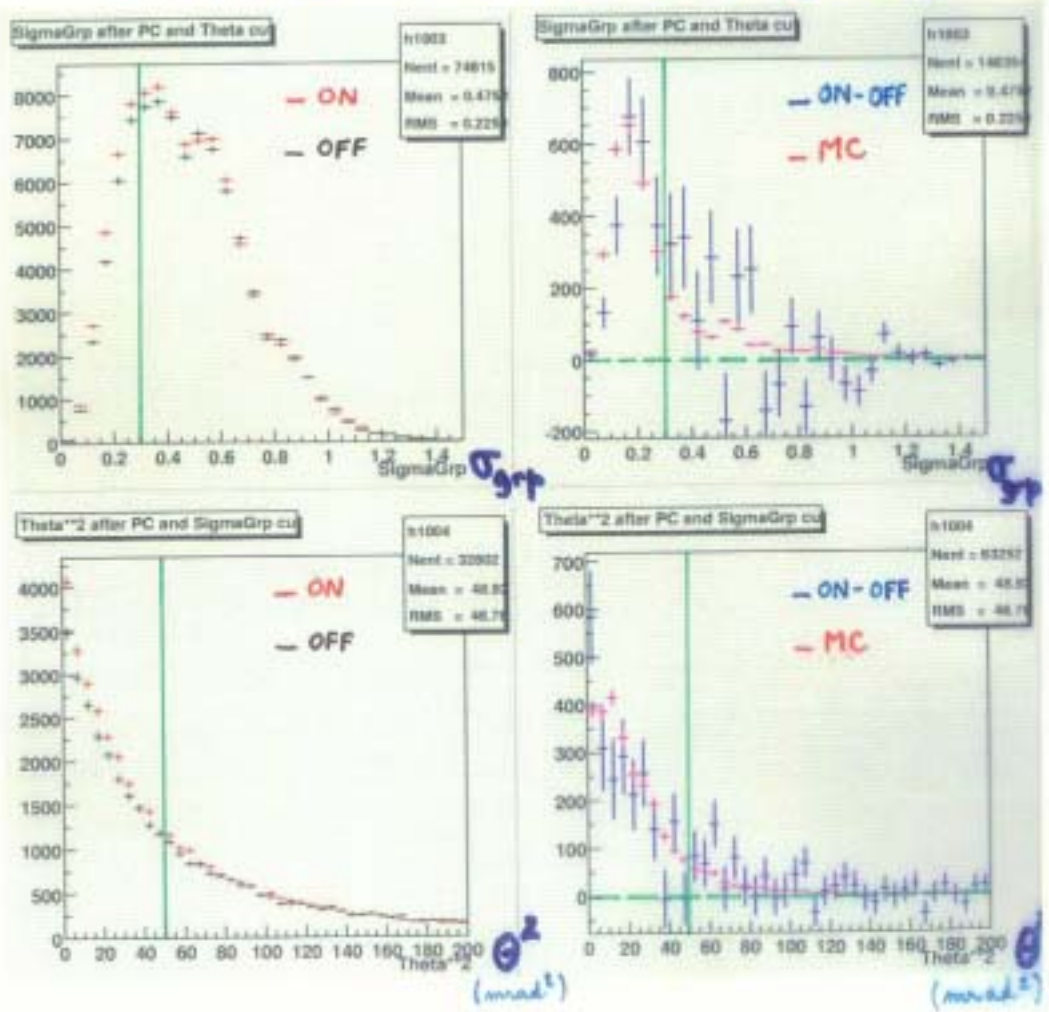
$\tilde{\beta} = -2.09 \pm 0.05$

$\phi_0^{MC} = 1$

$\beta^{MC} = -2.0$

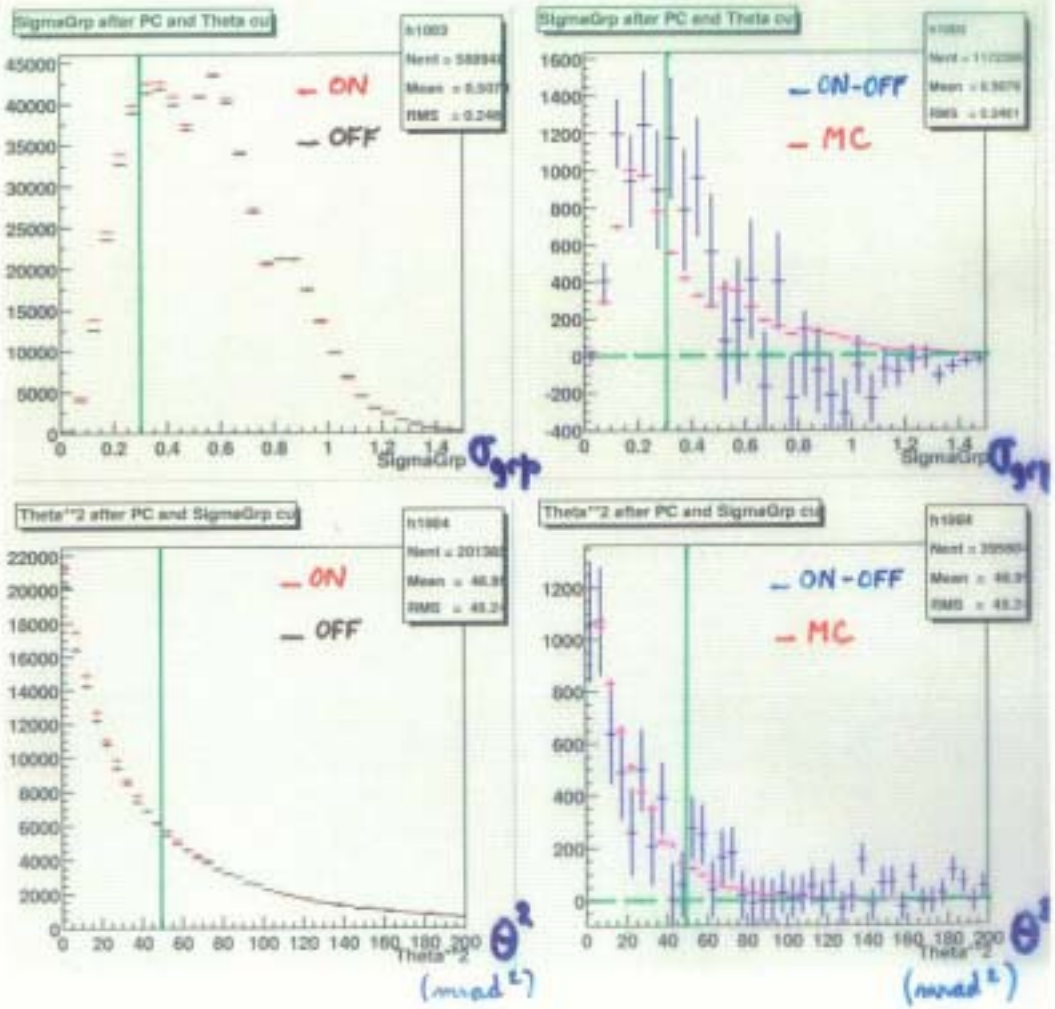
CRAB SAMPLE

$T_{obs} = 3.5^h$ $S = 1411 \pm 169$ $N_\sigma = 8.3$

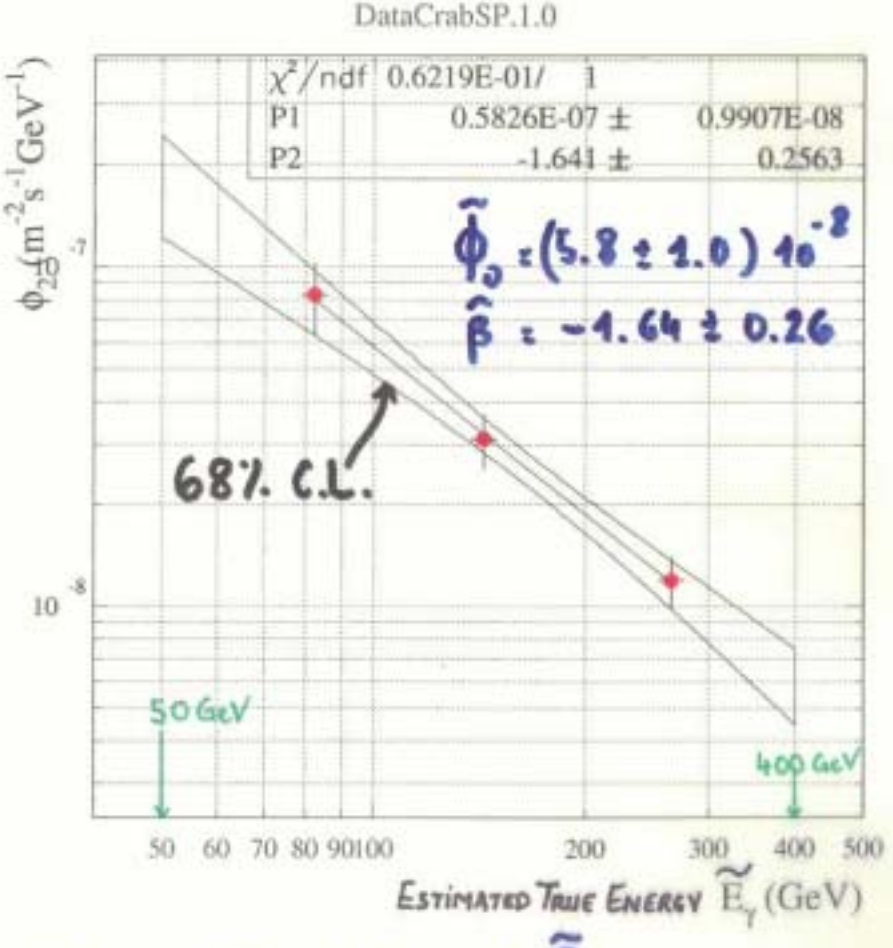


MKN 421 SAMPLE

$T_{OBS} = 22.1^h$ $S = 3277 \pm 427$ $N_\sigma = 7.7$



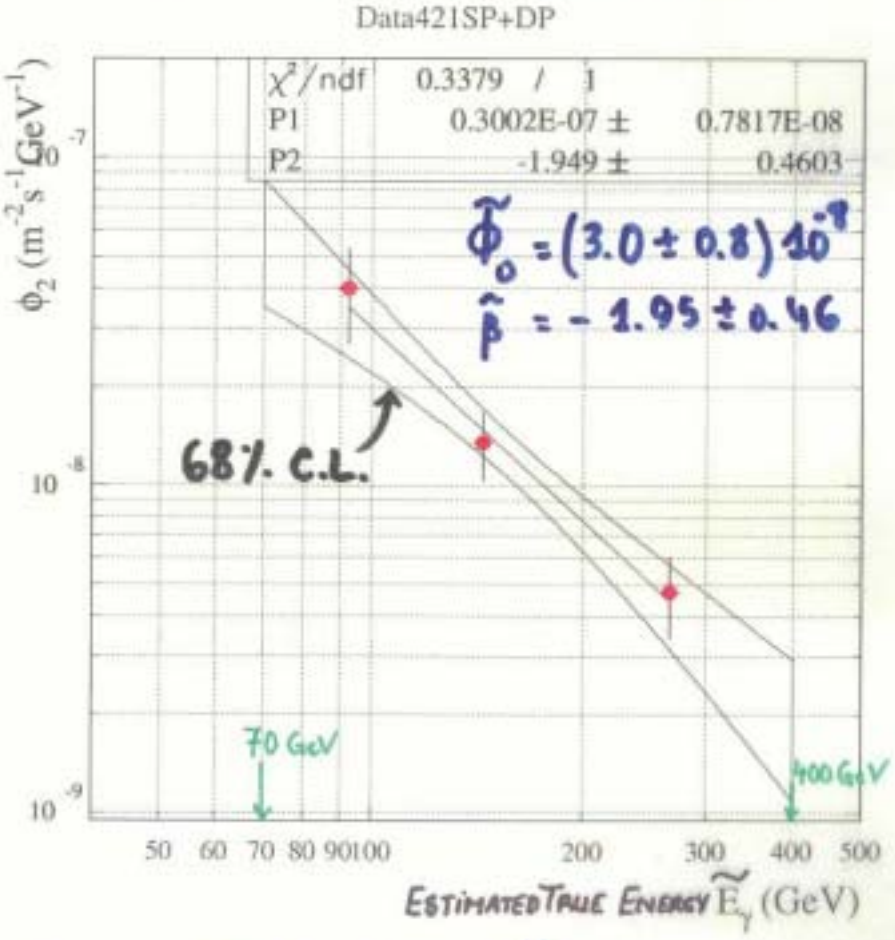
THE CRAB NEBULA DIFF. SPECTRUM



$$\phi(E) = \tilde{\phi}_0 \left(\frac{E}{100\ \text{GeV}}\right)^{\tilde{\beta}}$$

[$m^{-2}\ s^{-1}\ GeV^{-1}$

MKN 421 DIFF. SPECTRUM



$$\phi(E) = \tilde{\phi}_0 \left(\frac{E}{100\,\text{GeV}}\right)^{\hat{\beta}}$$

$\tilde{\phi}_0$ in $m^{-2}\,s^{-1}\,GeV^{-1}$

III THE CRAB NEBULA & MKN 421 SPECTRA

* SYSTEMATIC ERRORS:

① MC SPECTRA RECONSTRUCTION:

$$\delta\tilde{\phi}_0 / \tilde{\phi}_0 = \binom{+0}{-10}\,\% \qquad \delta\tilde{\beta} = \binom{+0}{-0{,}15}$$

② $\langle \tilde{E}_\gamma \rangle \pm \delta\langle \tilde{E}_\gamma \rangle$:

$$\delta\tilde{\phi}_0 / \tilde{\phi}_0 = \begin{vmatrix} -5\,\% \\ +5\,\% \end{vmatrix} \text{ and } \delta\tilde{\beta} = \begin{vmatrix} +0{,}10 \\ -0{,}13 \end{vmatrix}$$

③ ABSOLUTE ENERGY SCALE UNCERTAINTY:

$E_m \times 0.8$: $\delta\tilde{\phi}_0 / \tilde{\phi}_0 = \begin{vmatrix} +20\,\% \\ -20\,\% \end{vmatrix}$ and $\delta\tilde{\beta} = \begin{vmatrix} -0{,}50 \\ +0{,}10 \end{vmatrix}$

$E_m \times 1.2$:

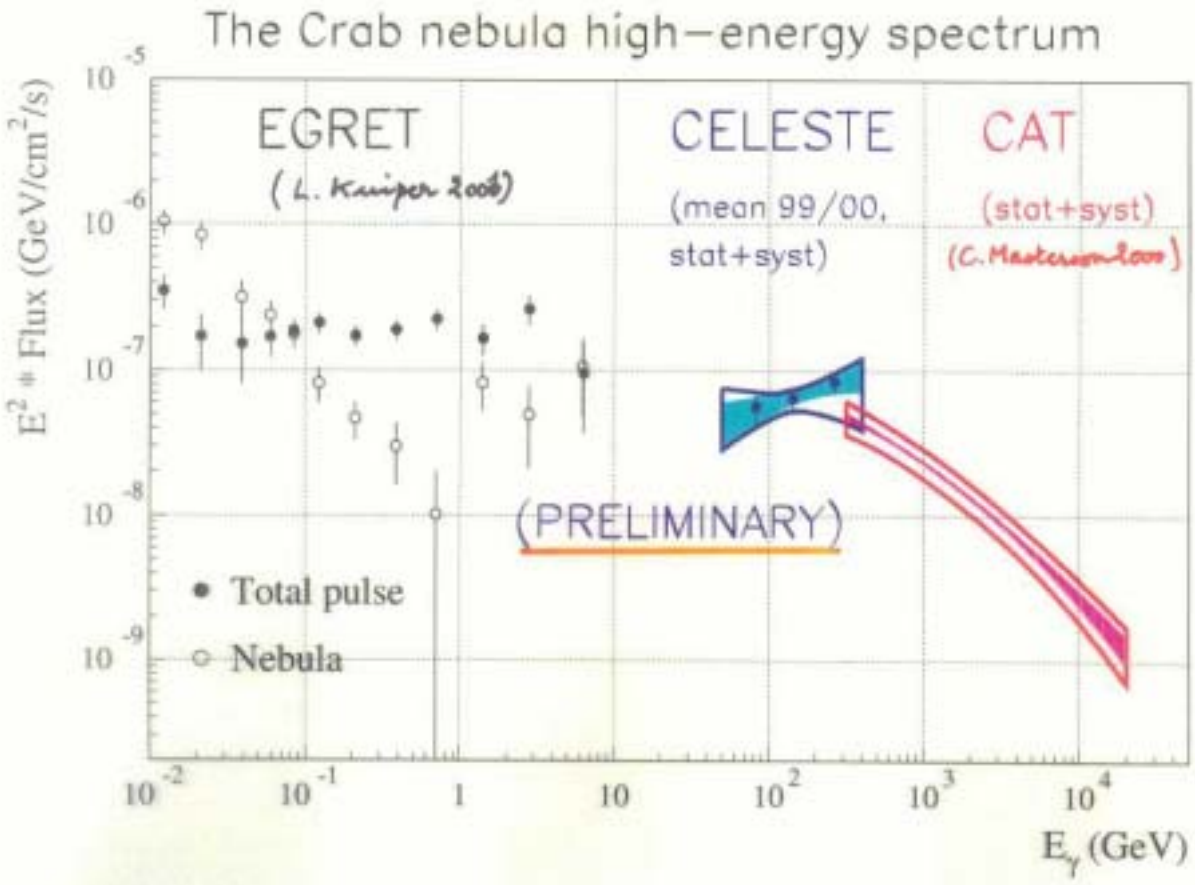
* FINAL (PRELIMINARY) RESULTS:

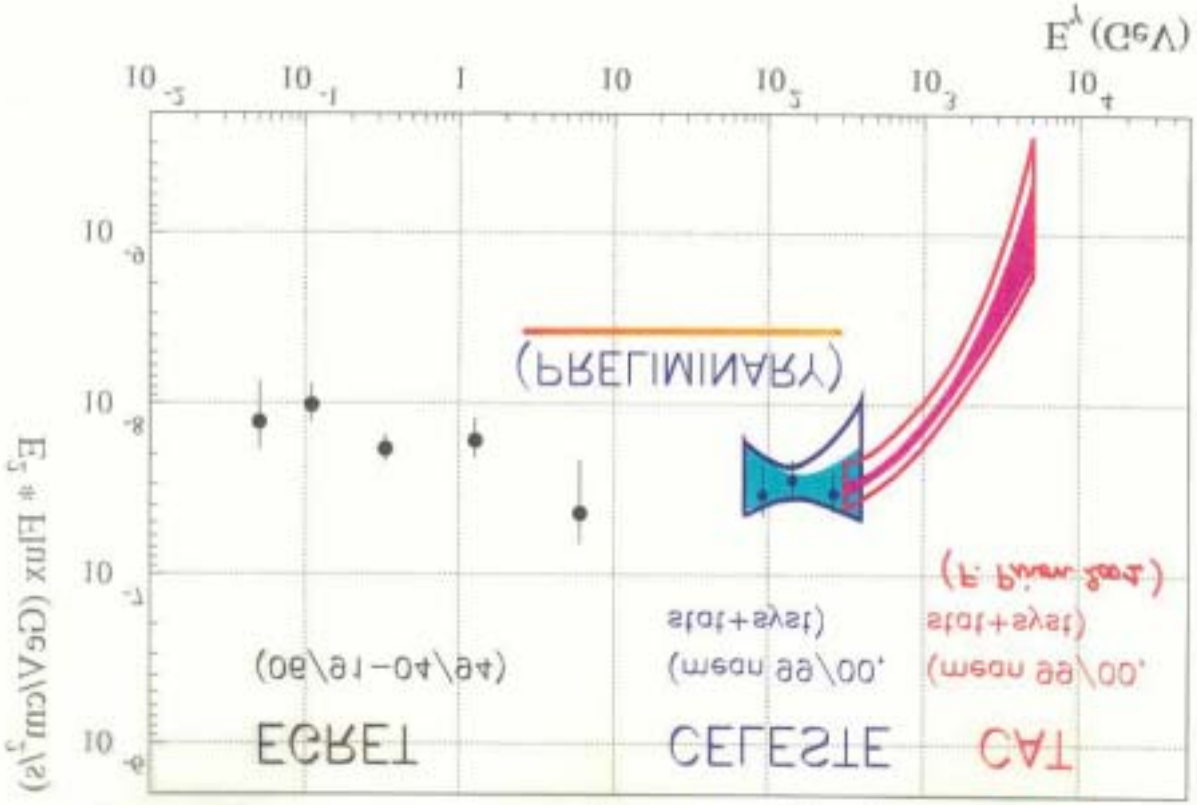
$$\phi(E) = \tilde{\phi}_0 \left(\frac{E}{100\,\text{GeV}}\right)^{\hat{\beta}}$$

$\tilde{\phi}_0$ in $10^{-8}\,m^{-2}\,s^{-1}\,GeV^{-1}$

	E range (GeV)	$\tilde{\phi}_0$	$\hat{\beta}$
CRAB	50 - 400	$5{,}8 \pm 1{,}0_{stat} \pm 1{,}3_{syst}$	$-1{,}64 \pm 0{,}26_{stat} \pm 0{,}54_{syst}$
Mkn 421	70 - 400	$3{,}0 \pm 0{,}8_{stat} \pm 0{,}7_{syst}$	$-1{,}95 \pm 0{,}46_{stat} \pm 0{,}54_{syst}$

REMARK: Systematic errors a bit under-estimated (errors on acceptance / cuts efficiencies assumed negligible)


The Crab nebula high−energy spectrum
EGRET
(L. Kuiper 2008)
CELESTE
(mean 99/00,
stat+syst)
CAT
(stat+syst)
(C. Masterson 2006)
(PRELIMINARY)
Total pulse
Nebula
$E^2 * Flux\ (GeV/cm^2/s)$
E_γ (GeV)


(PRELIMINARY)
EGRET
CELESTE
CAT
(mean 99/00,
stat+syst)
(stat+syst)
(mean 99/00,
stat+syst)
(C. Masterson 2006)
$E^2 * Flux\ (GeV/cm^2/s)$
E_γ (GeV)

CONCLUSIONS

* CELESTE MEASURES γ-RAY ENERGY WITH $12\% < \sigma_E < 24\%$ ABOVE 50 GeV

Note that σ_E = "true" energy resolution = $\sigma\left(\frac{E_m}{E_t} - 1\right)$

No Log scale !

* 1st SPECTRAL MEASUREMENT OF THE CRAB NEBULA & MKN 421 ABOVE 50 GeV 70 GeV

* RESULTS COMPATIBLE WITH CONTEMPORARY MEASUREMENTS ABOVE 300 GeV FROM THE CAT IMAGING TELESCOPE

* STATISTICAL & SYSTEMATIC ERRORS ARE STILL BIG → FUTURE WORK :

① Extend the study to larger data samples (far from transit)

② LIDAR operating on the site since beginning of 2002 (J. B. G.)