Constraints on very high energy emission from GRBs with the ARGO-YBJ experiment in shower mode

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***Abstract*. With a large sensitive area, full coverage, high altitude, large field of view ($\sim 2sr$) and high duty cycle ($> 90\%$), the ARGO-YBJ detector is well suited for GRB surveying. Using Monte Carlo simulation, the sensitivity of the ARGO-YBJ experiment for GRB detection in shower mode is estimated. Since June 2006 the central 130 clusters have been taking data, and more than 30 GRBs detected by satellites occurred within the field of view of ARGO-YBJ. Even if no significant excess was found during the prompt phase and 1 hour around the trigger time, the fluence upper limits to 10 GeV - 1 TeV prompt emission from these GRBs are set with 99% confidence level. In addition, the GRBs detected by the LAT instrument onboard the Fermi satellite are studied with special attention.**

***Keywords*: Gamma ray bursts, Gamma ray, Extensive air showers, ARGO-YBJ**

I. INTRODUCTION

Gamma Ray Bursts (GRBs) have been an enigma since their discovery forty years ago. Even if thoroughly investigated in the keV-MeV energy range with thousands of GRBs detected by satellites, the acceleration mechanisms and the emission processes are still in debate today. A deeper understanding could be gained with the detection of a clear signal or the evaluation of stringent upper limits in the Very High Energy (VHE) region. Because of the much lower gamma ray fluxes, only ground-based experiments have areas large enough to detect VHE emission from GRBs. In this paper, we report on the constraints on VHE emissions from 30 GRBs with the ARGO-YBJ experiment in shower mode. In addition, the LAT instrument onboard the Fermi satellite has detected emission at GeV energies from several GRBs with a rate of about one per month, so these GRBs are studied with special attention.

The ARGO-YBJ experiment, a collaboration among Chinese and Italian institutions, is designed for VHE γ-astronomy and cosmic ray observations and located in Tibet, China at an altitude of $4300m$ a.s.l.. The detector consists of a single layer of RPCs, operated in streamer mode, with a modular configuration 12 RPCs are grouped as a cluster. The RPCs are equipped with pick-up strips ($6.75 \times 61.80cm^2$) and the fast-OR signal of 8 strips constitutes the logical pixel (named pad) for triggering and timing purposes. This central carpet, $5600m^2$ with coverage of $\sim 93\%$, is surrounded by 23 additional clusters to improve the core location reconstruction. The total area of the array is $110 \times 100m^2$. The RPC carpet is connected to two independent data acquisition systems, corresponding to the shower and scaler operation modes. With the scaler mode, HE emission from GRBs could be investigated without direction information [1]. In shower mode, the high granularity of the apparatus permits a detailed spatial-temporal reconstruction of the shower with an angular resolution of 0.2° for showers with energy above 10 TeV and 2.5° at approximately 100 GeV [2].

TABLE I: N_{hit} ranges and corresponding angular window sizes for gamma rays.

E_{cut}	N_{hit}	ϕ_{70}
100 GeV	20-60	3.8°
1000 GeV	20-500	2.6°

II. EFFECTIVE AREA AND SENSITIVITY

The effective area of the ARGO-YBJ experiment for detecting gamma ray showers is estimated by using a full Monte Carlo simulation driven by CORSIKA 6.502 [3] and GEANT3-based code (ARGO-G). Five zenith angles ($\theta = 0°$, $10°$, $20°$, $30°$ and $40°$) are chosen in the simulation and the sampling area is $300 \times 300m^2$ around the carpet center. The threshold multiplicity of hits (N_{hit}) which triggers ARGO-YBJ is 20. In order to avoid strong absorption of VHE photons by the EBL, two models of GRB emission with sharp cutoff of their spectra at 100 GeV and 1 TeV are investigated. Since the multiplicity of hits N_{hit} in an event is related to the shower primary energy, the optimization of the ARGO-YBJ sensitivity can be done by choosing a corresponding cutoff on N_{hit}. As results of the optimization, ranges of N_{hit} are found corresponding to the two E_{cut} models as reported in Table 1. Given the ranges of N_{hit}, the corresponding optimal opening angle radii ϕ_{70}, inside which 70% of the signal events is included, are reported in Table 1. This result is almost independent of the zenith angle.

After using the events selection listed in Table 1, the corresponding effective areas for different energy ranges can be obtained. As an example, the effective areas suited for $20 < N_{hit} < 500$ and the corresponding ϕ_{70} at the three zenith angles $\theta = 0°$, $20°$ and $40°$ are shown in Fig.1. Using these results, the average effective areas $\langle A \rangle$ over the energy ranges from 10 GeV to 100 GeV

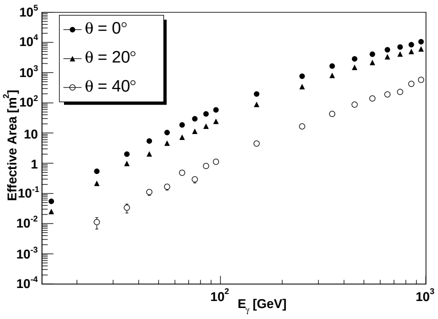

Fig. 1: Effective areas of ARGO-YBJ for gamma rays with N_{hit} inside the range $[20, 500]$ and opening angle $2.6°$. Different symbols stand for three zenith angles $\theta = 0°$, $20°$ and $40°$.

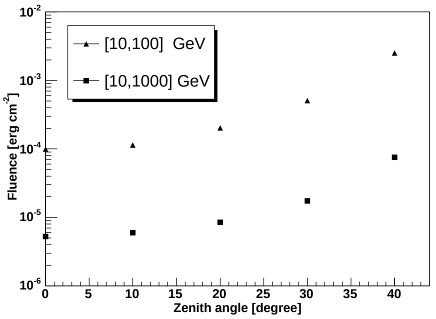

Fig. 2: The 5σ minimum detectable fluences for GRBs with a duration T=12 s in the two energy ranges [10,100] GeV and [10,1000] GeV for different incident zenith angles. The spectrum index α is fixed to -2.0 in this calculation.

and from 10 GeV to 1 TeV with a differential spectral index α are calculated as functions of the zenith angle θ. They fit a functional form $A_0 \cos^n \theta$ and with these functions the average effective areas at any zenith can be obtained. For $\theta = 20°$ and $\alpha = -2.0$, the effective area of the ARGO-YBJ detector is about $1.8m^2$ above 10 GeV if the cutoff energy E_{cut} of the GRB spectrum is chosen as 100 GeV. On the other hand, it is $64.3m^2$ if E_{cut}=1000 GeV.

Using measured cosmic ray data, the background event rate is estimated according to the selected N_{hit} ranges reported in Table 1. Combining this with the average effective area $\langle A \rangle$ and assuming a spectral index $\alpha = -2.0$, the minimum detectable fluences for GRBs requiring a 5σ excess are estimated and shown in Fig.2. The sensitivity worsens with the increase of the zenith angle. The GRB time duration in this figure is fixed at $T = 12$ s and the fluence scales with $T^{1/2}$. We find that the ARGO-YBJ detector has a sensitivity of $10^{-5} erg/cm^2$ in the energy range [10,1000] GeV for GRBs with a duration of 12 s at $\theta = 20°$.

Since its launch in June 2008, LAT onboard Fermi has detected 7 GRBs with high energy emission up to about 10 GeV. Their high energy emissions are consistent with the power law spectrum measured in the MeV energy region [4]. If the power law spectrum could also be extrapolated to 1 TeV, the VHE emission could be detected by ARGO-YBJ if GRBs were inside the FOV. Fig.3 shows the number of events N_{exp} expected by ARGO-YBJ as a function of the GRB angle. The other two GRBs are measured with a exponential cutoff around MeV, so they are excluded and only 5 GRBs are in the Fig.3. For comparison, the numbers have been normalized using their duration $T_{90}^{1/2}$. So, if the energy spectra are not steeper than $\beta = -2.2$, they will reach ARGO-YBJ sensitivity with a naive extension from GeV to TeV without taking into account the absorption by Extragalactic Background Light (EBL).

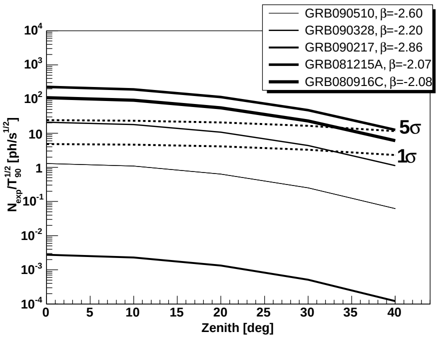

Fig. 3: The number of events N_{exp} expected by ARGO-YBJ with a naive extension of the power law spectrum measured at MeV energies. The numbers N_{exp} have been normalized using their T_{90} time for comparison. The 5 curves stand for different GRBs detected both by Fermi GBM and LAT, and β is the high energy power law index in the Band function. The dotted lines are the number of events needed for a 5σ and 1σ excess respectively.

III. DATA ANALYSIS

In an angular window surrounding the GRB with aperture given in Table 1, the N_{on} events that fall in N_{hit} ranges are taken as on-source. Among these, the contribution from the cosmic ray background, N_b, is estimated by integrating all the events over two hours around the GRB trigger time, referred as "direct integral method" in the literature [5]. The significance of any excess in the on-source events is calculated using Eq. 17 of Li & Ma [6].

As widely discussed, the acceleration mechanism for VHE emission could be different from that at low energies, so that it could be in a different time scale. Even if the duration of every burst detected by satellite is known, the duration of VHE emission is still unknown. It is believed that (a) the most probable emission is still in the prompt phase; (b) the emission may be delayed even by hours, like in the case of the 18 GeV photon in GRB940217, detected 1.5 hr after the prompt emission [7]; (c) the high energy emission could be produced earlier according to some models [8]. The

GRB counterpart is first searched in a window T_{90}, which is defined as the time in which 90% of the GRB photons is released. If no signal is found, we continue the search from one hour before to one hour after the GRB. Time intervals of 1 s, 6 s, 12 s, 24 s, 48 s and 96 s are used in this search with steps 1 s, 2 s, 3 s, 6 s,12 s and 24 s, respectively. If no signal is found, we set an upper limit to the fluence in T_{90}.

Given the observed N_{on} and the expected background N_b in T_{90}, the upper limits for the number of events, N_{UL}, with confidence level of 99% is calculated with Helene's method (Eq.10 in [9]). Using the effective area and assuming a differential power law photon spectrum, the upper limit to the fluence of a GRB in the VHE range is obtained. Guided by the average spectrum of the four brightest bursts observed by EGRET, where a power law index of -1.95 ± 0.25 was found over the energy range from 30 MeV to 10 GeV [10], an energy spectrum $dN/dE = CE^{-2}$ is assumed. At first, the normalization constant C is calculated by solving the equation $N_{UL} = \int A(E)(dN/dE)e^{-\tau_{EBL}}dE$. Then the total fluences can be obtained by integrating $\int E(dN/dE)dE$ from 10 GeV to 100 GeV and to 1 TeV. The τ_{EBL} is the optical depth due to EBL absorption, and the optical depths predicted by A. Franceschini [11] are used in this work. According to our estimation, the EBL effect for gamma rays below 100 GeV is almost negligible, however it could be substantial for farther GRBs in the range [10,1000] GeV.

IV. RESULTS

The data used in this work were collected by the ARGO-YBJ experiment in the period from July 2006 to April 2009, during which the DAQ was turned off from July 2007 to November 2007 for detector maintenance. 30 GRBs detected by satellites were within the FOV ($\theta < 45°$) of the detector array while it was on. The GRBs detected by Fermi GBM are excluded in this paper for their large position uncertainty. Angular resolution, pointing accuracy and stability of the ARGO-YBJ detector were thoroughly tested by measuring the Moon shadow in cosmic rays over all observational periods [12]. The Crab Nebula and flares of Mrk421 in years 2006 and 2008 were successfully detected [13].

No significant excess was observed for any of the 30 GRBs, neither as prompt nor prior/delayed emission (see Fig.4). Upper limits to fluences in the VHE range are listed in Table II. The upper limits for the 7 GRBs with redshift information have been corrected for EBL absorption, while the others will increase by a factor about 1.4 (for 10-100 GeV) and 30 (for 10-1000 GeV) assuming z= 1.0. The fluences in keV bands measured by the satellite experiments are also listed in Table II. To improve the detector sensitivity, 30 GRBs are added up as one source, that is a stacked analysis method. Even if no excess is found up to now, the ARGO-YBJ sensitivity will increase with the number of GRBs inside the FOV.

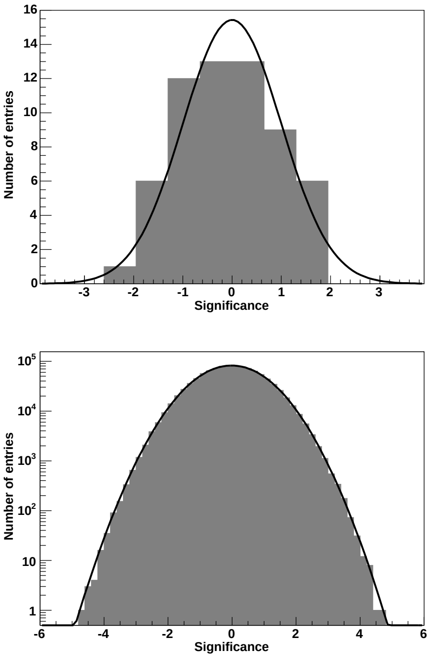

Fig. 4: Top: Distribution of the statistical significance of the 30 GRBs with data available during their prompt phase using both events selections of Table 1. Bottom: Distribution of the statistical significance derived from two hours of observations around the 30 GRBs analysed with different time durations. The solid curves are normal Gaussian functions given for comparison.

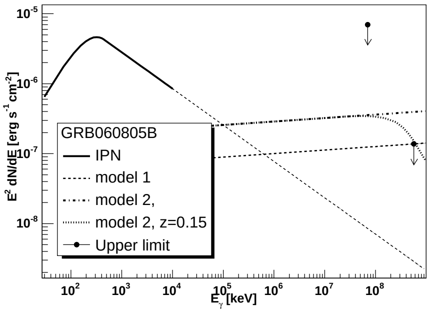

Fig. 5: The spectrum of GRB060805B and the upper limits obtained by ARGO-YBJ. The solid curve is the result of fitting the IPN data with the Band function and the dotted line is a simple extrapolation. The upper limits are located at the mean energies of gamma ray events. For details about model 1 and model 2 see text.

V. DISCUSSION

It is known that GRB spectra can be well fitted with a Band function with a break at energy E_0 mostly between 100 keV and 1 MeV, and the average index α below the break is ~ -1 and the average index β above the break is ~ -2.3 [14]. Most GRBs observed by Swift do not have such a clear spectral structure with a break since its effective energy range is often lower than the

TABLE II: List of GRBs in the FOV ($\theta < 45°$) of ARGO-YBJ and 99% C.L. fluence upper limits

GRB	Satellite	Redshift	T90	θ	keV fluence	10-100 GeV	10-1000 GeV
			s	deg	$erg * cm^{-2}$(keV range)	$erg * cm^{-2}$	$erg * cm^{-2}$
060714	Swift	2.71	115	42.8	2.9E-6 (15-150)	2.10E-2	3.11E-2
060805B	IPN	...	8	29.1	1.1E-4 (30-10000)	1.29E-4	5.08E-6
060807	Swift	...	43.3	12.4	8.5E-7 (15-150)	7.32E-5	4.23E-6
060927	Swift	5.47	22.6	31.6	1.2E-6 (15-150)	6.63E-3	1.56E-2
061028	Swift	...	106	42.5	9.7E-7 (15-150)	6.23E-3	1.08E-4
061110A	Swift	0.76	41	37.3	1.1E-6 (15-150)	1.23E-3	5.32E-4
061122	Integral	...	18	33.5	2.3E-5 (20-2000)	4.27E-4	8.45E-6
070306	Swift	1.50	210	19.9	5.5E-6 (15-150)	5.86E-4	9.63E-4
070531	Swift	...	44	44.3	1.1E-6 (15-150)	3.09E-3	7.82E-5
070615	Integral	...	30	37.6	...	1.42E-3	3.93E-5
071112C	Swift	0.82	15	22.1	3.0E-6 (15-150)	2.02E-4	1.04E-4
080207	Swift	...	340	27.7	6.1E-6 (15-150)	8.95E-4	3.31E-5
080324	Integral	...	13.6	14.6	...	8.52E-5	5.19E-6
080328	Swift	...	90.6	37.2	9.4E-6 (15-150)	1.60E-3	4.79E-5
080602	Swift	...	74	42.0	3.2E-6(15-150)	3.31E-3	1.32E-4
080613B	Swift	...	105	39.2	5.8E-6(15-150)	2.49E-3	7.32E-5
080726	AGILE	...	125	36.7	...	2.38E-3	5.21E-5
080727C	Swift	...	79.7	34.5	5.3E-6(15-150)	8.15E-4	3.18E-5
080822B	Swift	...	64	40.4	1.7E-7(15-150)	2.55e-3	9.46E-5
080903	Swift	...	66	21.5	1.5E-6(15-150)	1.73e-4	7.03e-6
081025	Swift	...	23	30.5	1.9E-6(15-150)	3.75E-4	1.56E-5
081028	Swift	3.04	250	29.9	3.7E-6(15-150)	7.72E-3	1.25E-2
081105	Swift	...	10	36.7	...	4.09E-4	1.30E-5
081128	Swift	...	101.7	31.7	2.5E-6(15-150)	6.21E-4	2.05E-5
090107	Swift	...	12.2	40.1	2.3E-7(15-150)	7.38E-4	3.21E-5
090118	Swift	...	16	13.4	4.0E-7(15-150)	6.68E-5	3.68E-6
090301A	Swift	...	41	14.1	2.3E-5(15-150)	8.34E-5	4.34E-6
090306B	Swift	...	20.4	38.5	3.1E-6(15-150)	1.30E-3	1.95E-5
090407	Swift	...	310	45.0	1.1E-6(15-150)	1.02E-2	2.46E-4
090417B	Swift	0.345	260	37.2	2.3E-6(15-150)	4.58E-3	6.13E-4

break energy. GRB060805B was detected by the IPN from 30 keV to 10 MeV and the result of fitting the data with the Band function ($\alpha = -0.66$, $\beta = -2.52$ and $E_0 = 240$ keV) is shown in Fig.5 (solid curve). If this GRB spectrum extends to TeV energies only following the Band function, it will be compatible with the upper limits obtained by ARGO-YBJ. However, the spectrum might not extend with a simple power law ($\beta = -2.52$) above 100 MeV. It might turn to $\beta = -1.95$ like the four brightest bursts detected by EGRET observations [10]. If EBL absorption is negligible, the limit found by this work implies that the transition energy should be above 620 MeV (see model 1 in Fig.5). Another possibility is that if the transition energy is 100 MeV for this burst, the source should be farther than z=0.15 (see model 2 in Fig.5). In addition, if the SSC mechanism used by Finke et al. [15] to interpret the spectrum of GRB 940217 also works on GRB060805B, the limit found by this work will provide a strong constraint.

VI. CONCLUSIONS

We have investigated 30 GRBs in the FOV of ARGO-YBJ in about two years in the GeV-TeV energy range searching for prompt, delayed or prior emission. Since no significant excess is found, we have set upper limits to fluences for these GRBs. These limits are compatible with a naive extension of the power law spectrum. The Fermi LAT instrument detected GeV emission from GRBs about once per month until now, and two GRBs will be expected inside ARGO-YBJ FOV per year. With a effective area about 100 times larger than Fermi LAT at 100GeV, a stringent upper limit or some excess for these GRBs will be gained by ARGO-YBJ in the future.

VII. ACKNOWLEDGEMENTS

This work is supported in China by the National Natural Science Foundation of China (NSFC) under the grant 10120130794, the Chinese Ministry of Science and Technology, the Chinese Academy of Sciences (CAS), the Key Laboratory of Particle Astrophysics, Institute of High Energy Physics (IHEP), and in Italy by the Istituto Nazionale di Fisica Nucleare (INFN). Thanks to Qiang Yuan for his help in the EBL absorption calculation.

REFERENCES

[1] G. Aielli et al., Astropart. Phys. 30 (2008) 85.
[2] G. Di Sciascio et al., 30th ICRC 4 (2007) 123-126.
[3] J.N. Capdevielle et al., KfK Report (1992) No. 4998.
[4] A.A. Abdo et al., Science 323 (2009) 1688 press.
[5] R. Fleysher et al., Astrophys. J. 603 (2004) 355.
[6] T.P. Li & Y.Q. Ma, Astrophys. J. 272 (1983) 317.
[7] K. Hurley et al., Nature 372 (1994) 652.
[8] X.H. Ma et al., HEP & NP 27 (2003) 973 (in Chinese).
[9] O. Helene, Nucl. Instr. and Meth. 212 (1983) 319.
[10] B.L. Dingus, AIP Conf. Proc 558 (2001) 383.
[11] A. Franceschini et al, A & A 487 (2008) 837-852.
[12] B. Wang et al., 30th ICRC 4 (2007) 107-110.
[13] G. D'Alì Staiti et al., Nucl. Instr. and Meth. A 588 (2008) 7.
[14] R. D. Preece et al., Astrophys. J. S. 126 (2000) 19.
[15] J.D. Finke et al., arXiv:0802.1537v1 [astro-ph].