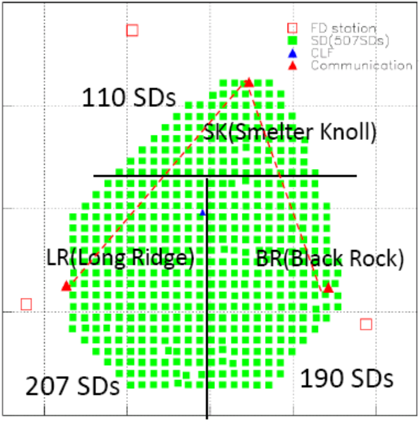
Search for ultra-high energy photons using Telescope Array surface detector

Grigory I. Rubtsov for TA Collaboration

Quarks'2010, Kolomna
June 9, 2010

Institute for Nuclear Research of the Russian Academy of Sciences

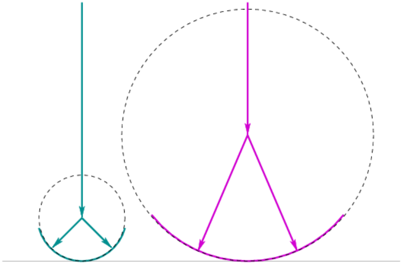


- 507 SD's, 3 m^2 each
- Event-by-event method
- Shower front curvature as an observable

We obtain limit on photon integral flux at $E > 10^{19}$ eV

Shower front curvature

deep shower maximum = curved front



- We use Linsley's shower front curvature parameter *"a"* as a composition sensitive parameter

Event reconstruction

- Joint fit of LDF and shower front profile
- 7-parameters:
  - x_{core}, y_{core} – shower core location at the ground level
  - θ, ϕ – zenith and azimuthal angles of primary arrival direction
  - S_{800} – normalization factor for LDF (corresponds to scintillation signal density at 800 meters)
  - t_0 – arrival time for the shower core
  - a – dimensionless Linsley's curvature parameter

$$t(r) = t_0 + t_{plane}(r) + a\, t_L(r)$$

$$t_L(r) = (r/39m)^{1.5}\, LDF(r,\theta)^{-0.5}$$

$$S(r) = S_{800}\, LDF(r,\theta), \;\; LDF(800\text{m},\theta) = 1$$

$LDF(r)$ – modified AGASA function
r – core distance in shower plane

Dataset

Dataset:

- Data collected by SD from 2008-05-11 to 2009-10-08
- Geometrical exposure for $\theta \in [\theta_1, \theta_2]$:

$$A_{geom} = 2346 \times (\sin^2\theta_2 - \sin^2\theta_1)\ \text{km}^2\ \text{sr yr}$$

Cuts for photon search:

- Number of detectors triggered is 7 or more
- Shower core distance to array boundary is larger than 1 separation unit (1200 m)
- $\chi^2/\text{d.o.f.} < 5$

Photon Monte-Carlo set

- CORSIKA with QGSJET-II, FLUKA and EGS4. PRESHOWER for geomagnetic field cascading
- Thinning with weight optimisation ($\varepsilon = 10^{-6}$)

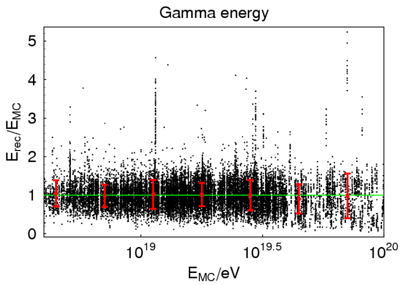
  Kobal, Astropart.Phys.15:259-273,2001
- Dethinning procedure is used

  Stokes et al, ICRC'09
- Detector response is calculated with GEANT sampler
- $E \in [10^{18.4}, 10^{20.5}]\ eV$, $\theta \in [0^\circ, 60^\circ]$
- Exactly same cuts applied to data and Monte-Carlo sets

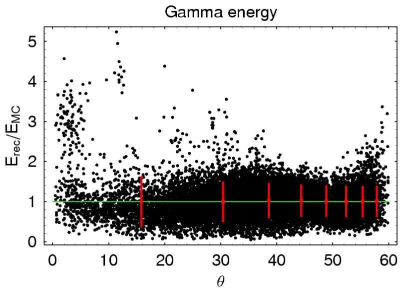
Photon energy reconstruction

- **We estimate $E_\gamma(S_{800}, \theta)$ using photon MC**
- Plots below made with photon MC (E^{-2} spectrum)

Energy dependence

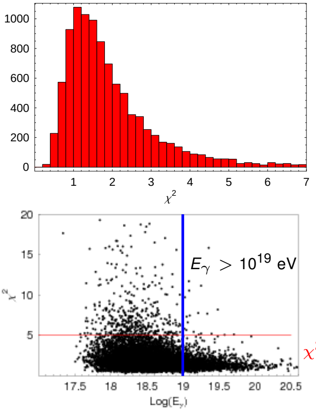


Zenith angle dependence



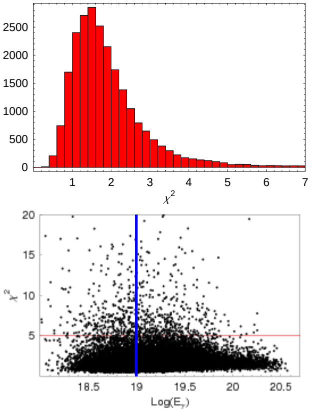
Reconstruction: χ^2/d.o.f. cut

Data

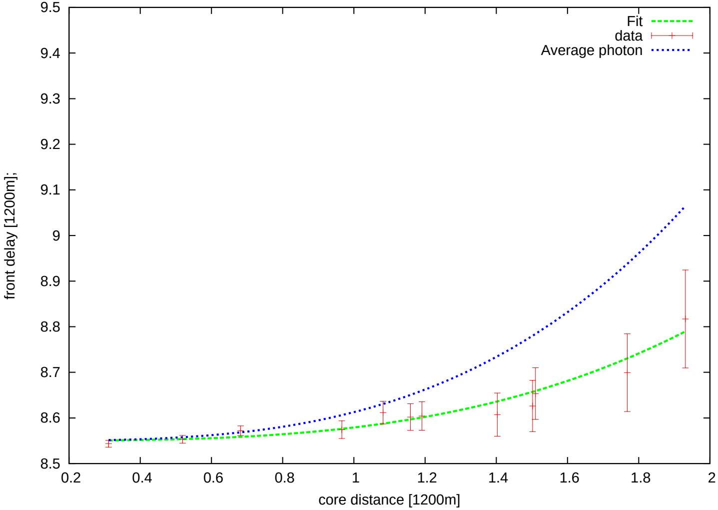


χ^2/d.o.f < 5

Photon MC ($f \sim E^{-2}$)

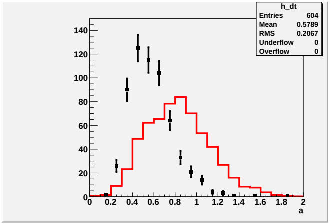


Front curvature example

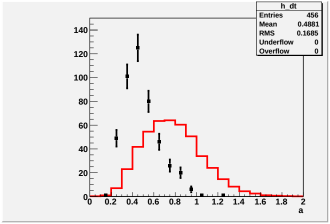


Linsley curvature “a”: data vs photon MC

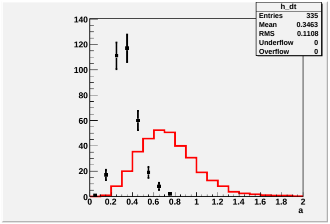
$0° - 30°$



$30° - 45°$



$45° - 60°$



$E_\gamma > 10^{19}$ eV

data
photon MC, E^{-2} spectrum

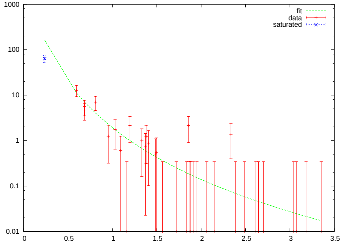
Event-by-event method

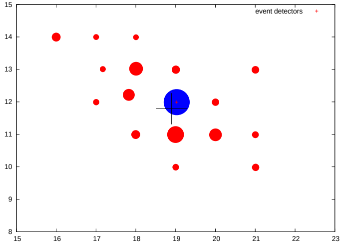
- For each event with curvature a_{obs} we select photon MC events compatible by arrival direction and S_{800}.
- We calculate curvature distribution function $f_\gamma(a)$ for MC photons
- Let's define

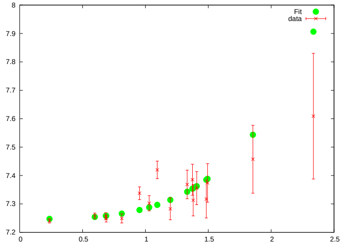
$$\mathcal{C} = \int_{-\infty}^{a_{obs}} f_\gamma(a) da$$

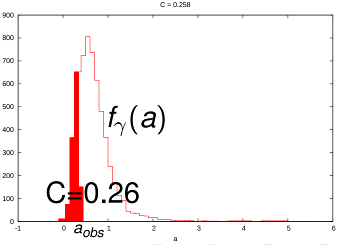
- $\mathcal{C}$ is defined event-by-event
- For gamma events, $\mathcal{C}$ is uniformly distributed between 0 and 1 (independently of the photon primary spectrum).

Typical event 1. $\theta = 59.9$, $E_\gamma = 31.71$ EeV, $\mathcal{C}$=0.258

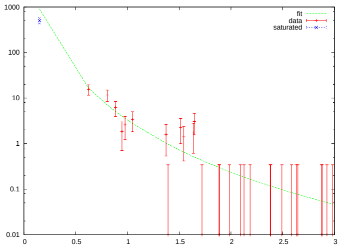


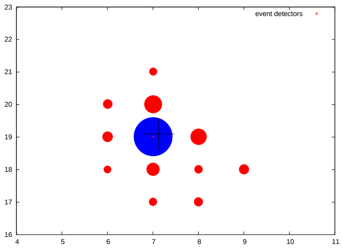


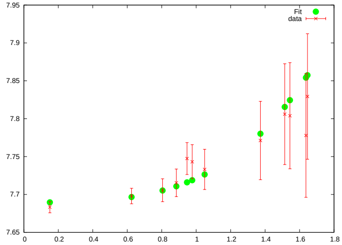


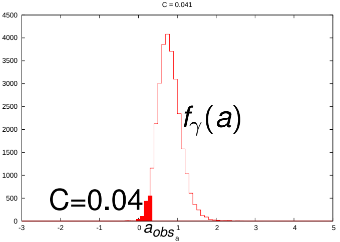


Typical event 2: $\theta = 49.3$, $E_\gamma = 10.63$ EeV, $\mathcal{C}$=0.041



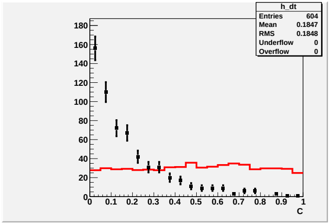




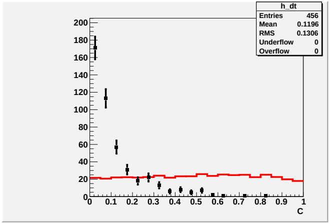


$\mathcal{C}$: data vs photon MC

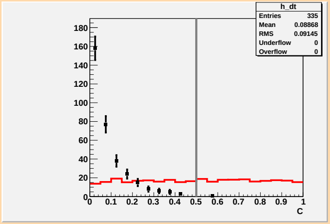
$0° - 30°$



$30° - 45°$



$45° - 60°$



$E_\gamma > 10^{19}$ eV

data

photon MC, E^{-2} spectrum

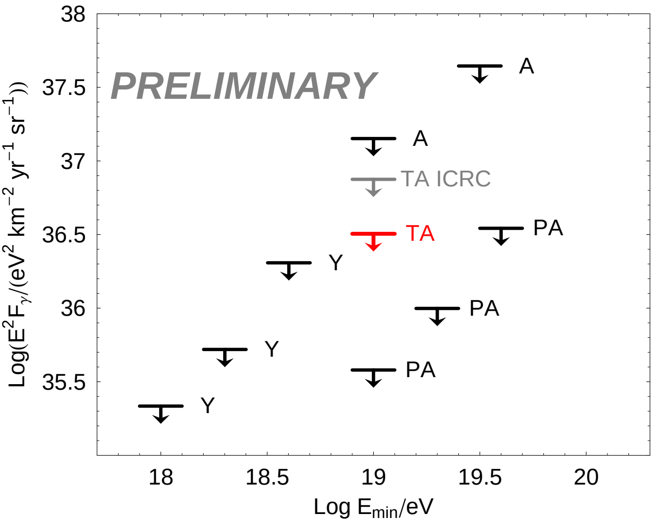
Search region:

- $E_{gamma} > 10^{19}\ eV$ — 1395 events
- $45^\circ < \theta < 60^\circ$ — 335 events
- $\mathcal{C} > 0.5$ — **1 event**
- Poisson 95% upper limit: — $\leq$ **5.14 events**

- Total exposure: $A_{total} = 158$ km^2 sr yr

- $F_\gamma < 3.3 \cdot 10^{-2}$ km^{-2}sr^{-1}yr^{-1} (95% CL) */PRELIMINARY/*

Photon flux limits



Exposure calculation with photon MC

- We take MC photon set with $E_{mc} > 10^{19}$ eV conservatively assuming E^{-3} spectrum.
- We calculate the fraction of photons entering the search region.

- Geomertical exposure $45° < \theta < 60°$:
  $A_{geom} = 587$ km^2 sr yr **100%**
- $n_{det} \geq 7$ **71%**
- χ^2/d.o.f < 5 **69%**
- S_{800} cut **54%**
- $\mathcal{C} > 0.5$ **27%**

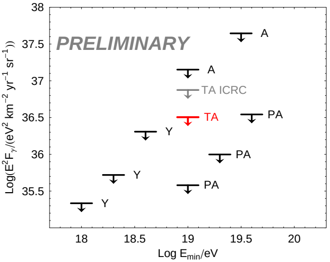
$$A_{total} = 0.27 \times A_{geom} = 158 \text{ km}^2 \text{ sr yr}$$

Conclusion: TA SD photon limit

- Event-by-event method is implemented for photon search
- We present upper limit for photon flux above 10^{19} eV
- Calculation based only on photon simulations

  $\Rightarrow$ no hadronic generator uncertainty

$F_\gamma < 3.3 \cdot 10^{-2}\ \mathrm{km}^{-2}\mathrm{sr}^{-1}\mathrm{yr}^{-1}$ (95% CL) */PRELIMINARY/*



Backup slides

Reconstruction: fit functions

- Joint 7-parametric fit: x_{core}, y_{core}, θ, ϕ, S_{800}, t_0, a

$$f(r) = \left(\frac{r}{R_m}\right)^{-1.2}\left(1+\frac{r}{R_m}\right)^{-(\eta-1.2)}\left(1+\frac{r^2}{R_1^2}\right)^{-0.6}$$

$$LDF(r) = f(r)/f(800\text{ m})$$

$$S(r) = S_{800} \times LDF(r)$$

$$t_0(r) = t_0 + t_{plane} + a \times 0.67\,(1+r/R_L)^{1.5}LDF(r)^{-0.5}$$

$$R_m = 90.0\text{ m},\ R_1 = 1000\text{ m},\ R_L = 30\text{ m}$$

$$\eta = \max[3.97 - 1.79(\sec(\theta)-1), 3.0]$$