

GAMMA RAY ASTRONOMY AT PEV ENERGIES – A SIMULATION STUDY

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Discussion

- ▣ Motivation
- ▣ Detection
- ▣ Simulation Study

MOTIVATION

A Timeline History of High-Energy Cosmic Rays

1912 Hess discovered cosmic rays – hot air balloon

1927 Cosmic rays seen in cloud chamber

1932 Anderson discovered antimatter (positron); Debate over cosmic rays

1937 Discovery of muon

1938 Auger discovered extensive air showers

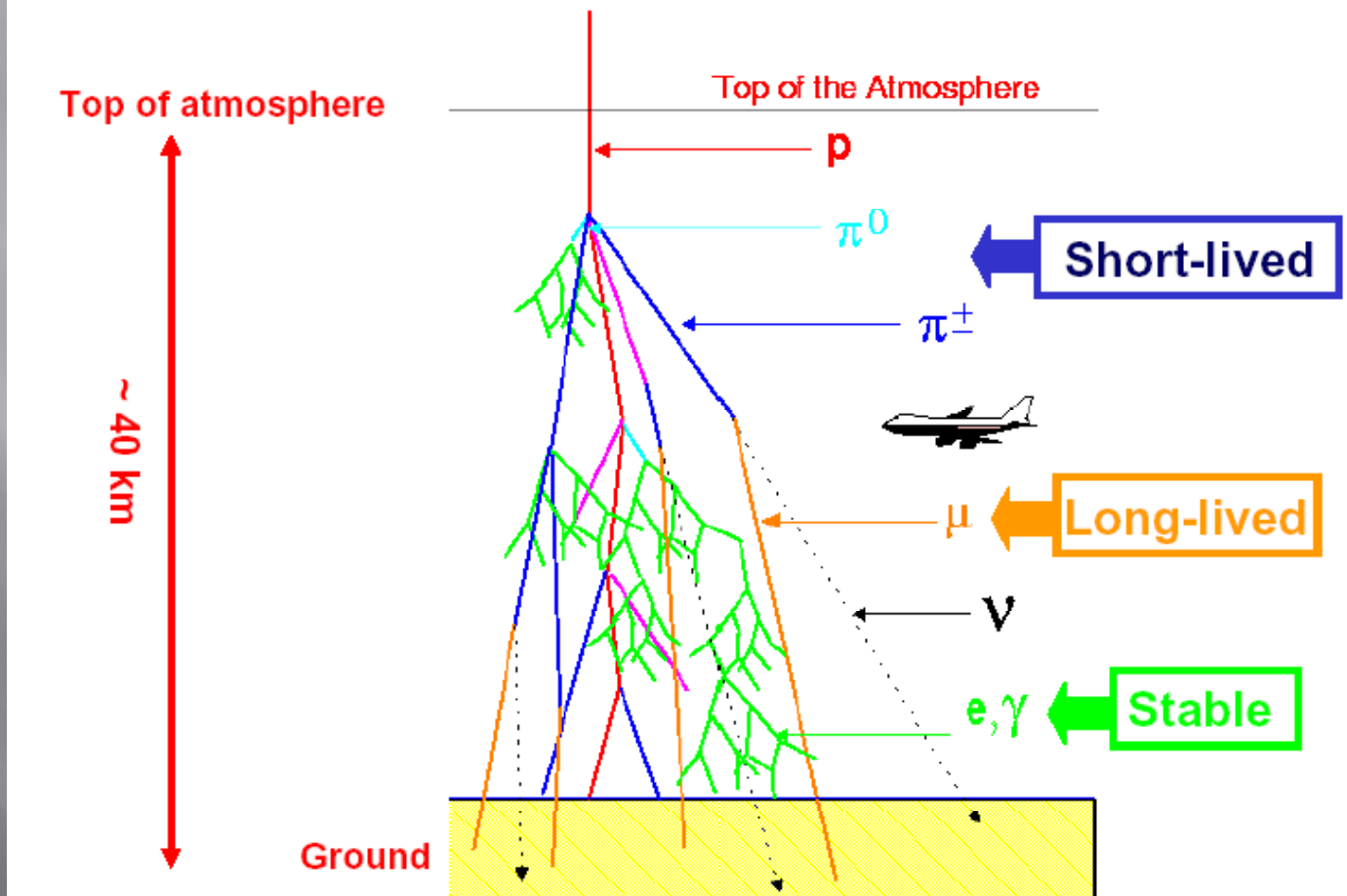
1946 First air shower experiments; Discovery of pion and kaons

A Timeline History of High-Energy Cosmic Rays

- 1949 Fermi's theory of cosmic rays
- 1962 First 10^{20} eV cosmic ray detected
- 1966 Proposal of GZK cut-off energy for cosmic rays
- 1991 Fly's Eye detected highest-energy cosmic ray
 - 1994 AGASA high-energy event
 - 1995 Pierre Auger Project begun
- 2002 HiRes and AGASA Debate the GZK cut-off

An Energy Shower

Cosmic ray air shower



Some Types of Cosmic Particles

- ▣ Atomic nuclei: protons and neutrons. E.g., ^{12}C is composed of 6 p and 6 n.
- ▣ Protons: the hydrogen atom is 1 p and 1 e⁻
- ▣ Neutrons: decay into a proton via the reaction
$$n \rightarrow p + e^- + \bar{\nu}_e$$
with a lifetime $\sim 10^3$ sec.
- ▣ Electrons and positrons: e⁻ and e⁺ .
- ▣ Quanta of light: photons or gammas

Cosmic Ray Energies

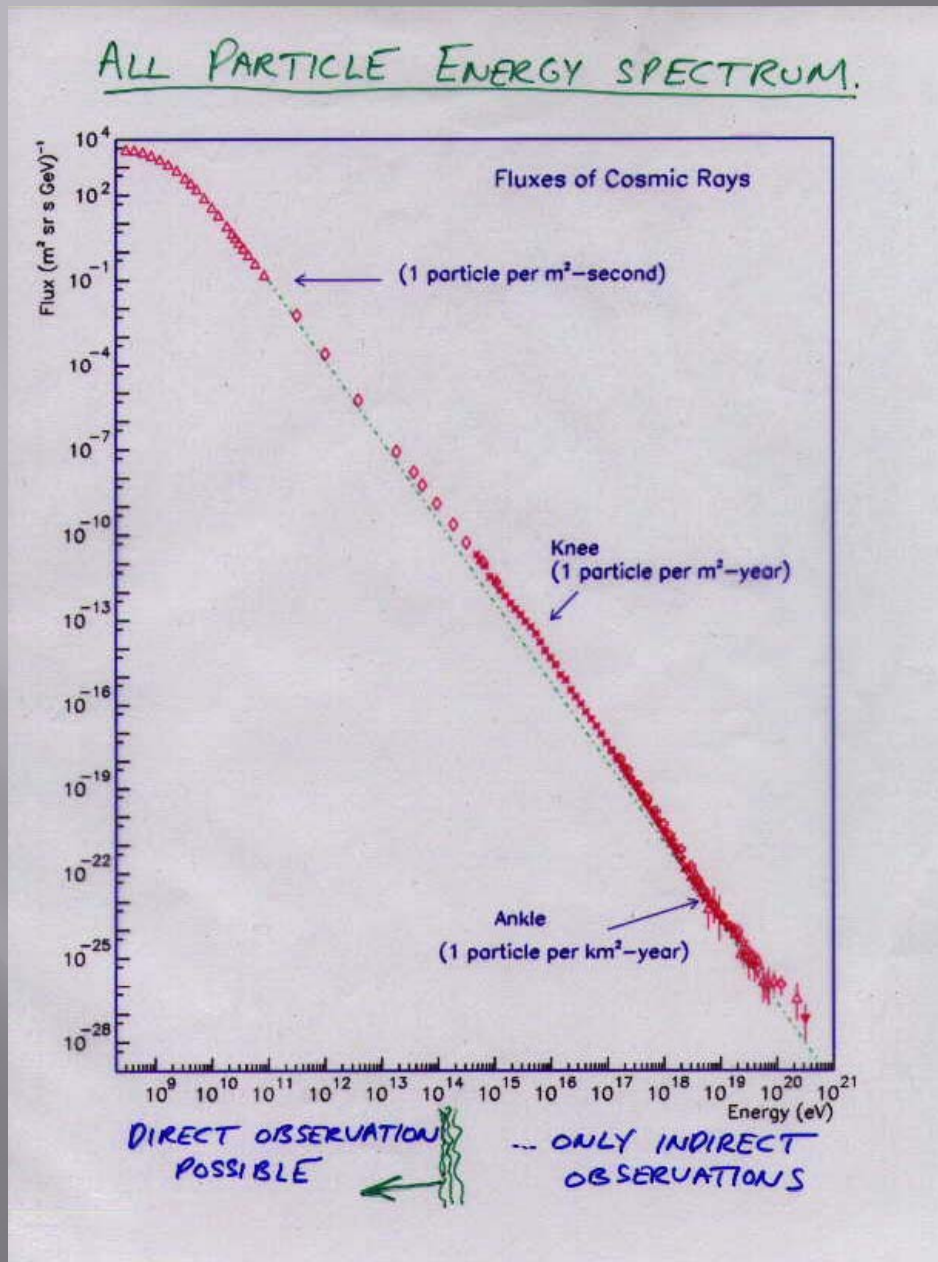
- ▣ A standard unit for elementary particle energies is the “electron Volt” – eV.
- ▣ 1 eV is the kinetic energy of 1 electron moved through a potential of 1 Volt.
- ▣ *Ultra-high energy cosmic particles* have energies greater than $\sim 10^{19}$ eV.
- ▣ 1 MeV = 1 Mega eV = 10^6 eV
- ▣ 1 GeV = 1 Giga eV = 10^9 eV
- ▣ 1 TeV = 1 Tera eV = 10^{12} eV

DETECTION

Some Terminology

- ▣ *Flux*: the amount of something arriving in one unit of area (e.g., 1 m^2) in one unit of time (e.g., 1 sec).
- ▣ *Spectrum*: A plot showing the amount of something, as a function of energy. In the next slide, the “something” is the number of particles in one bin of energy.

Cosmic Ray Energy Spectrum



- In this spectrum, the Log of the flux in one unit of angle (sr) is plotted versus the Log of the energy. A sphere has 4π steradian.
- The CR spectrum falls rapidly as energy increases: $dN/dE \sim E^{-3}$

Cosmic Rays

High energy particles from space are divided into two classes:

- i) Photons (gamma rays)
- ii) matter particles (protons, neutrons, nuclei etc.).

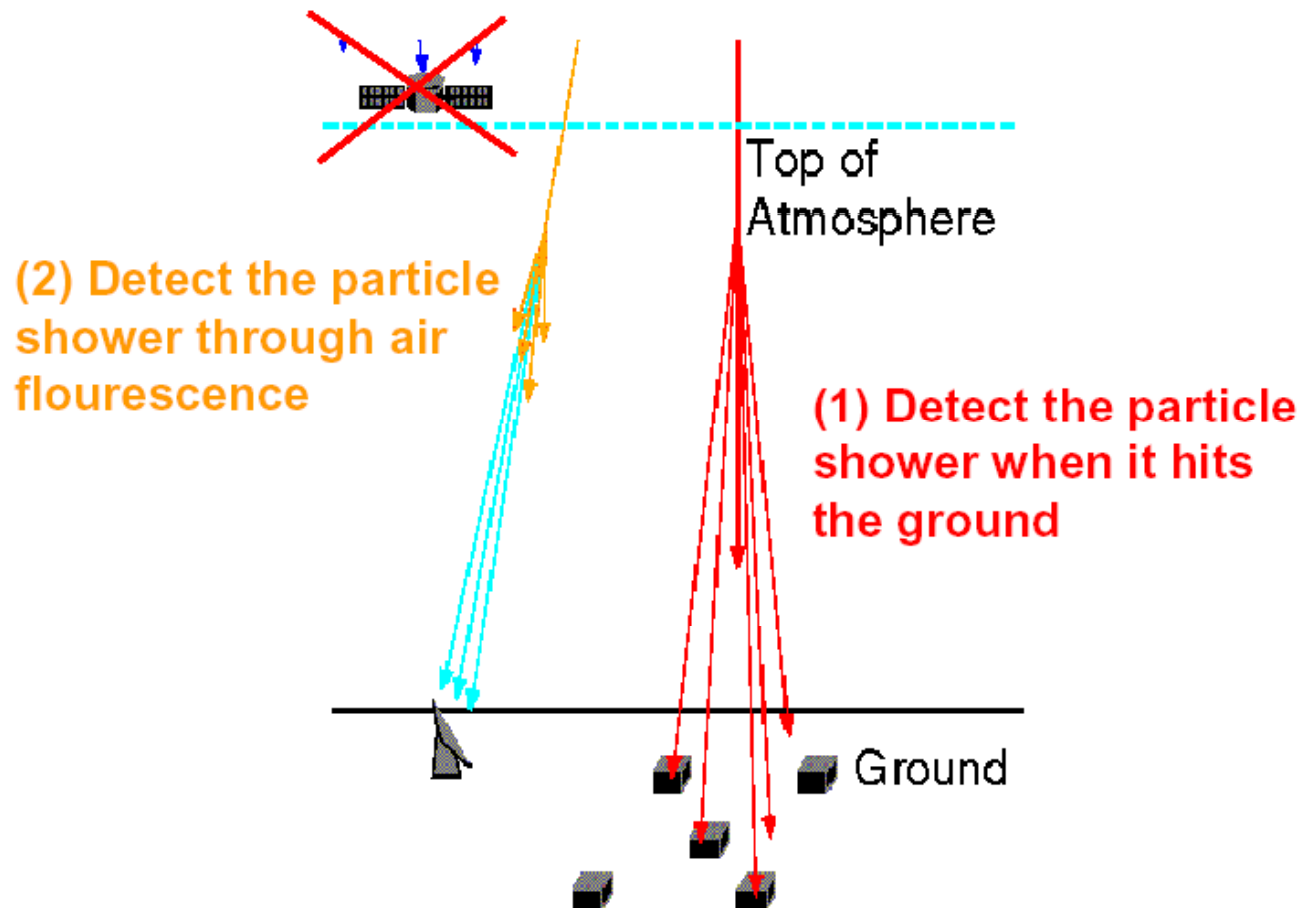
High Energy Gamma ray photons travel unscattered and practically unabsorbed through great lengths of galactic and intergalactic space.

Two Types of Cosmic Ray Detectors

- ▣ Ground Shower Array (AGASA, Auger, GRAPES3)
 - Large area because of low flux ($1 / \text{km}^2 / \text{century} > 10^{20} \text{eV}$)
 - Collects data day and night, any weather
 - Measures direction by arrival times across array
 - Relies on modelling of shower to infer energy and primary type
- ▣ Air Fluorescence (Hires, Auger)
 - 10% duty cycle (clear, moonless nights...)
 - Difficult to calibrate and Insensitive to shower details

Detection

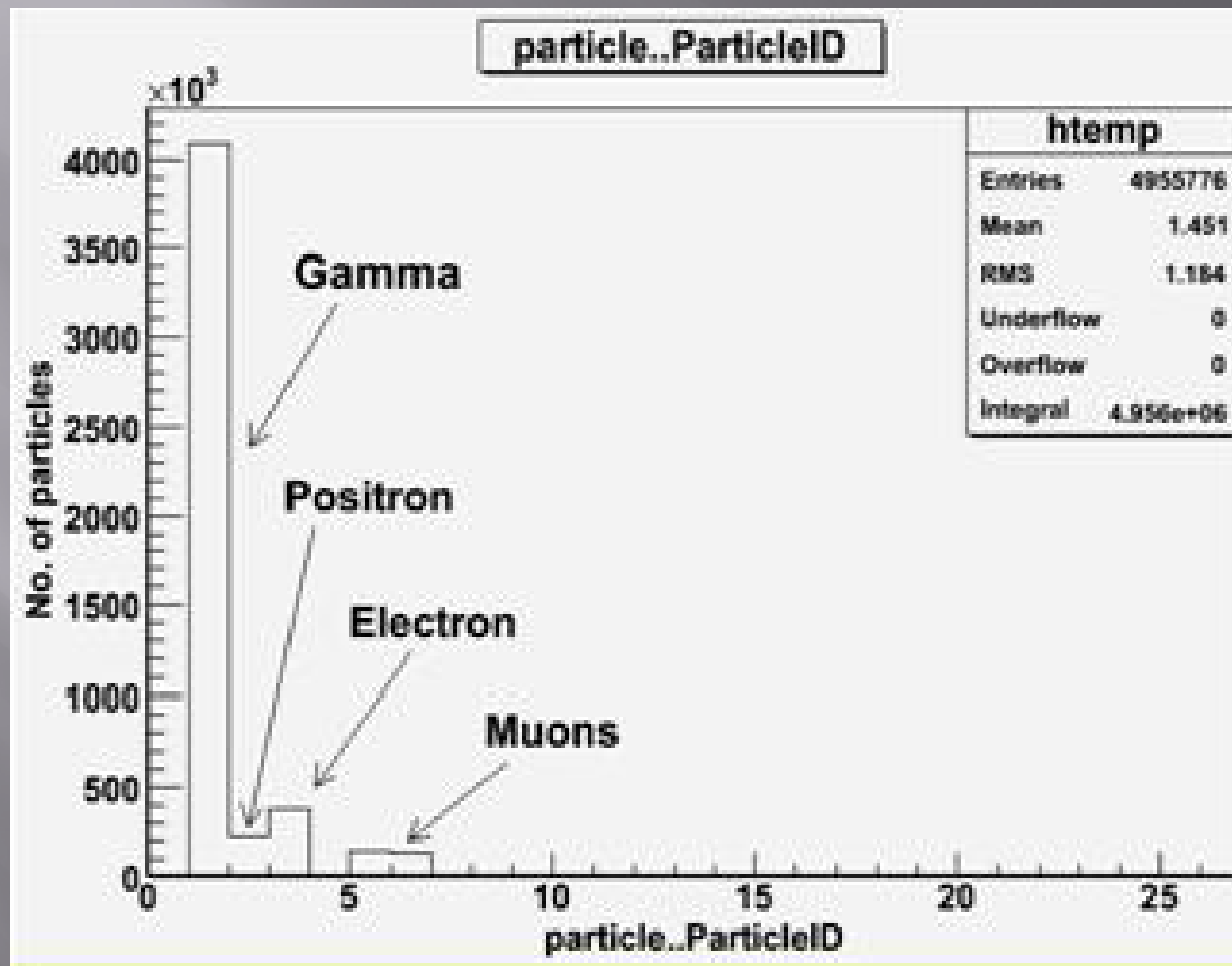
Detecting cosmic ray air showers



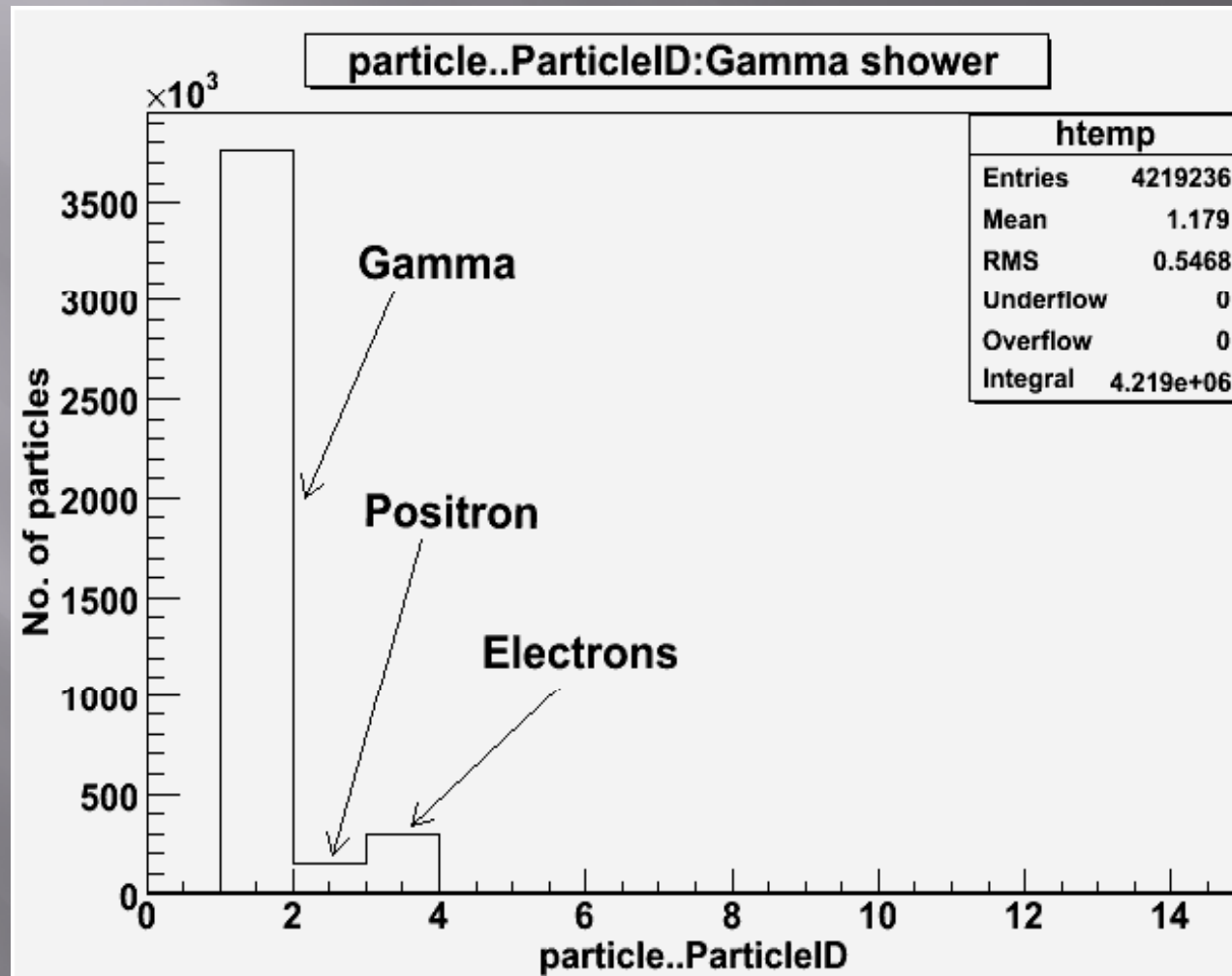
SIMULATION STUDY

- ▣ The simulation of air showers for particular energy ranges was done using CORSIKA with hadronic model SYBILL and electromagnetic model EGS4. The muon content in the proton generated shower is $\sim 10\%$.

Muon content in a proton shower



Muon content in a gamma shower



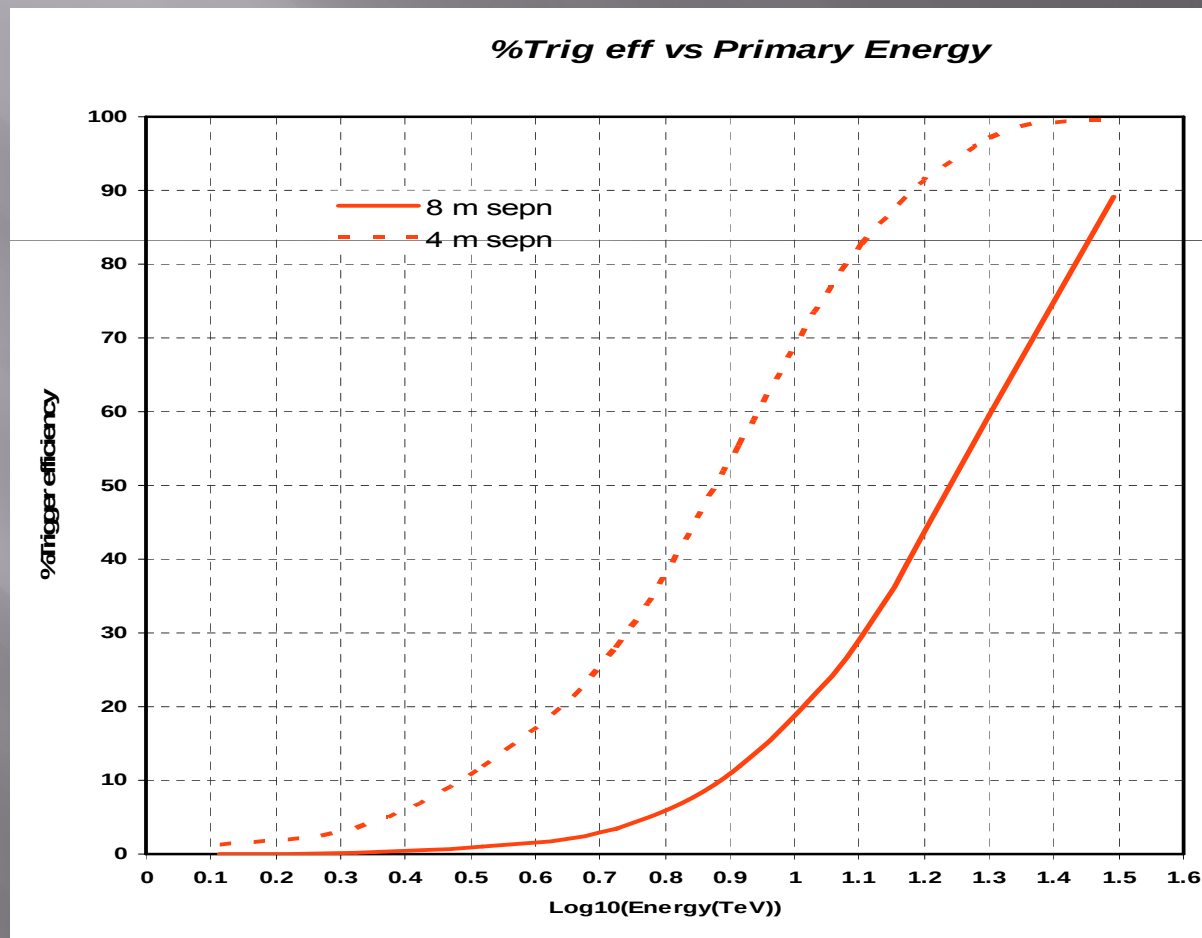
Trigger Efficiency and Angular Resolution

- ▣ Trigger efficiency =
$$\frac{\text{No. of showers of particular energy detected}}{\text{Total no. of showers that fell in the trigger area of the array}}$$
- ▣ Angular resolution : This measures the accuracy with which a source of a primary gamma ray can be located by reconstruction of the shower.

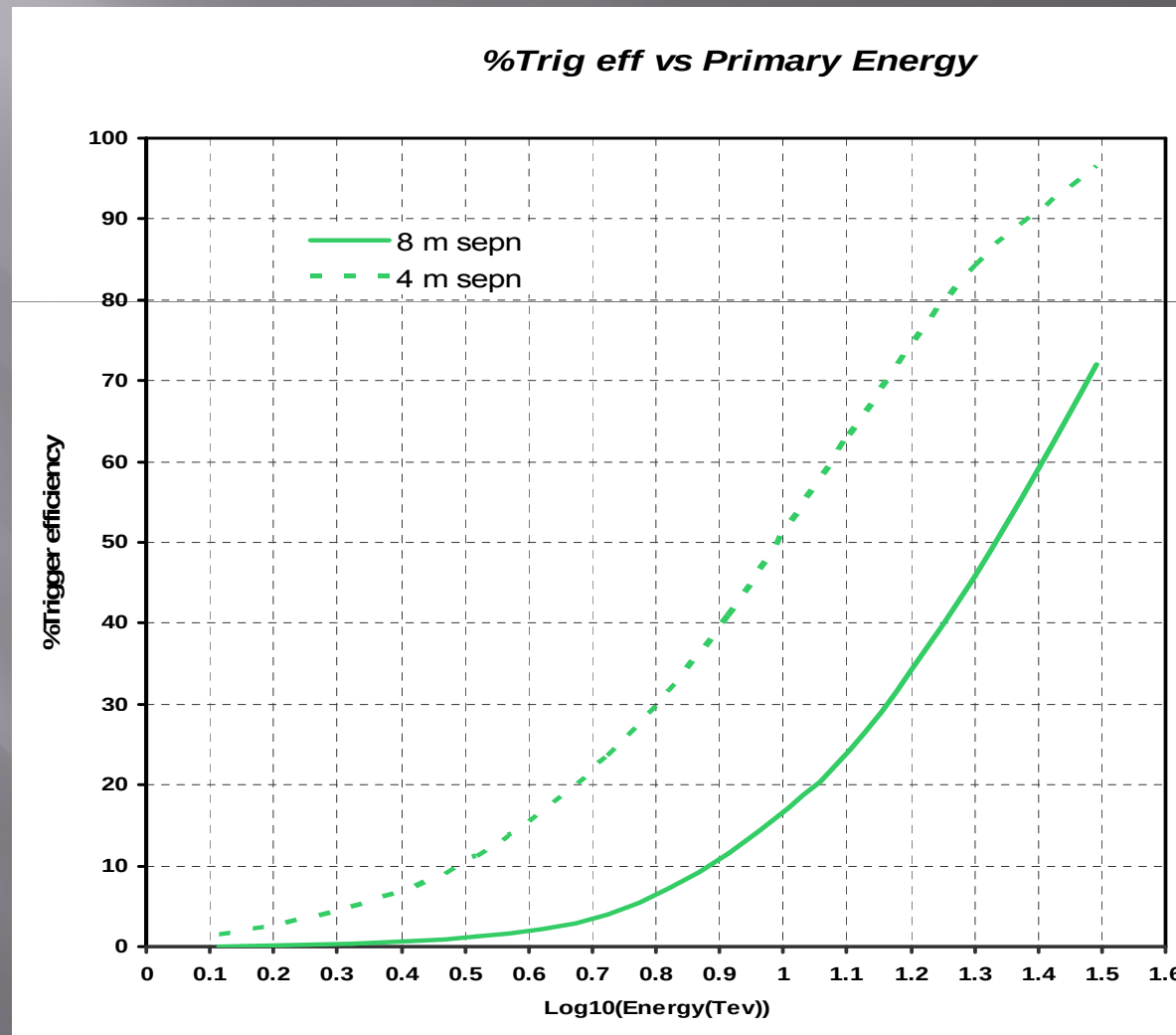
Study of the variation in Trigger efficiency and Angular resolution

Energy interval	Mean Energy	log of Energy	Trig eff (gamma shower)		Trig eff (proton shower)		Angular resolution (degrees)	
(TeV)	(TeV)		8 m sepn	4 m sepn	8 m sepn	4 m sepn	8 m sepn	4 m sepn
1-1.6	1.3	0.1139	0.06	1.14	0.07	1.49	--	1.99
1.6-2.6	2.1	0.3222	0.12	3.37	0.28	4.79	1.27	1.94
2.6-4.1	3.3	0.5185	0.99	11.86	1.3	11.24	1.93	1.65 ?
4.1-6.6	5.3	0.7242	3.53	27.9	3.9	23.6	1.56	1.73
6.6-10	8.2	0.9138	11.9	55.4	11.5	41	1.76	1.69
10-15.9	12.7	1.1038	29.7	82.8	24.4	63.3	1.85	1.62
15.9-25.1	20	1.3010	59.5	97	45.8	84.3	1.66	1.58
25.1-39.8	31.1	1.4927	89.1	99.9	72.1	96.5	1.64	

Plot for the trigger eff. Vs primary energy (gamma shower)



Plot for the trigger eff. Vs primary energy (proton shower)



Observations

- ▣ At 4 meter detector separation the trigger efficiency reaches 90% at almost half of the 'energy threshold with 8 meters detector separation', for both gamma and proton generated showers.

Variation in Trigger efficiency

Detector separation (meters)	Trigger efficiency (%)
8	59.5
7.5	61.2
7	63.3
6.5	74
6	83
5.5	84.6
5	89.7
4.5	93.2
4	97

Observations

- ▣ For energies greater than 6 TeV we get an improvement in angular resolution while going from 8 meters to 4 meters detector separation.
- ▣ For 4 meter detector separation angular resolution shows a trend of decreasing with increase in the energy as expected, whereas for 8 meters detector separation we don't see any particular trend of angular resolution with energy (surprising!).

Observations

- ▣ When detector separation decreases from 8 m to 4 m, the number of detectors increases by a factor of about 4. This implies that statistically the angular resolution should decrease by a factor of $\sqrt{4} = 2$, but this is not observed. A possible solution on this is to use the number of detectors hit during a shower of particular energy range.
- ▣ The angular resolution is always $< 2^\circ$.

Crude Approximation of Significance from Crab-like spectrum

$$\square \text{ Significance(s)} = \frac{\text{No. of signal events}}{\text{Sqrt}(\text{total no. of events})}$$

Significance

- ▣ The integral flux is

500TeV

- ▣
$$N(>E) = \sum_{1\text{TeV}} \varepsilon(E) * dN/dE(E)$$

- ▣ where $\varepsilon(E)$ is the trigger efficiency at primary energy E and $dN/dE(E)$ is the differential flux at an energy E . We have calculated $\varepsilon(E)$ only up to ~ 30 TeV, and to calculate integral flux we need $\varepsilon(E)$ up to 500 TeV. Hence the data were extrapolated using cubic spline extrapolation method

Significance

- ▣ The differential spectrum of gamma showers from Crab nebula as observed by HESS is given by
- ▣ $dN_{\gamma}/dE (E) = 3.45 * 10^{-11} E^{-2.63} (\text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1})$
- ▣ proton differential spectrum was taken to be the cosmic ray spectrum found by GRAPES-2 is given by
- ▣ $dN_p/dE (E) = 1.057 * 10^{-5} * E^{-2.76} (\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{TeV}^{-1})$

Improvement in the Significance from Crab-like spectrum

>E (TeV)	Integral flux		Detected showers				Significance		Improvement by factor
	Gamma	Proton	Gamma		Proton				
			4m	8m	4m	8m			
>1	12305	24,89,510	470	107	76433	14978	1.69	0.87	1.94252874
>5	497	78901	261	92	32551	11766	1.44	0.84	1.71428571
>10	147	21327	129	70	15429	8052	1.04	0.78	1.33333333
>15	74	10134	72	51	8852	5695	0.76	0.68	1.11764706
>20	45	6011	45	38	5662	4204	0.6	0.59	1.01694915
>25	31	4016	31	29	3916	3197	0.5	0.51	0.98039216
>30	23	2891	23	22	2865	2489	0.43	0.45	0.95555556

Inferences

- ▣ As we increase the lower limit of energy for integral flux calculation, the improvement in significance (σ) reduces. If all energies above 1 TeV are considered the improvement is by a factor of ~ 2 .

THANKS

- ▣ ICCGF Organizers
- ▣ GRAPES Collaboration and CRL, Ooty Team where the experiment runs.