

Study of Angular Distribution of Cosmic Ray Muons using INO-ICAL Prototype Detector at TIFR

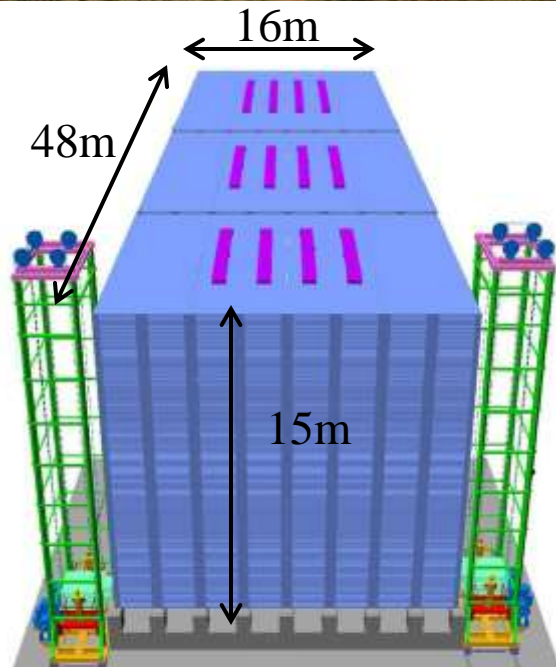
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RPC2012, INFN - LNF, 7/2/2012
Rome, Italy, (5-10 Feb., 2012)



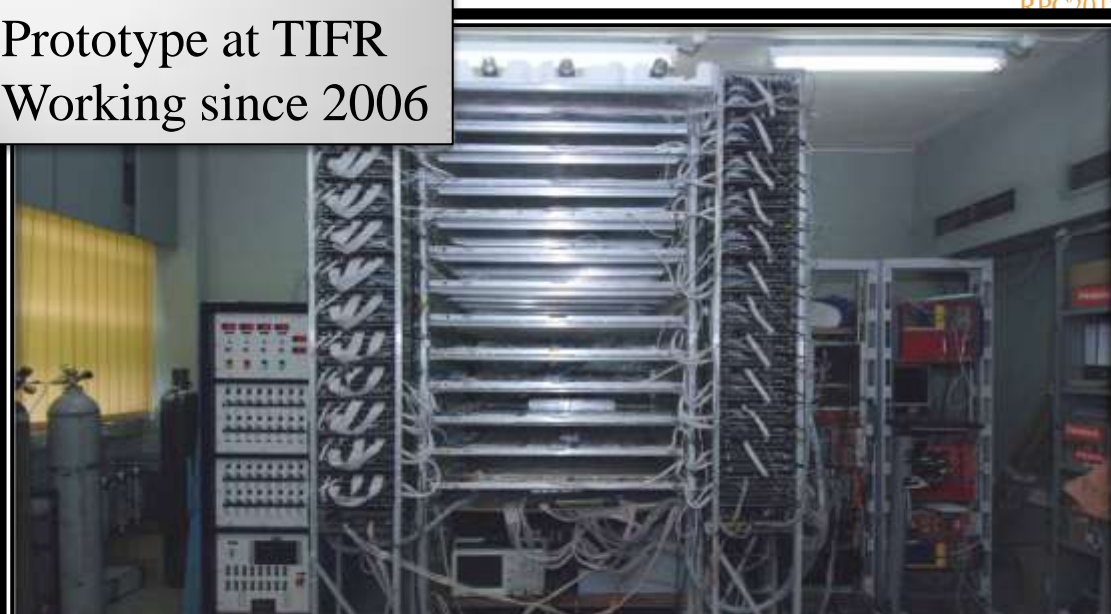
INO site, located at South India



Schematic of ICAL detector

- **India based Neutrino Observatory (INO)**, an underground laboratory facility coming up in India.
- 1st phase goal : confirm neutrino oscillation, mass ordering in neutrino sector etc.
- Proposed detector is a **IronCALorimeter (ICAL)** with **50kton** of Iron as target mass.
- **28,800 Resistive Plate Chambers (2m x 2m)** will be the active detectors in ICAL.
- R&D is going on for RPCs, electronics, gas mixing & its purification, the electromagnet etc..

1m x 1m RPC
Prototype at TIFR
Working since 2006



RPC2012 INFN - LNF, Rome, Italy (5-10 Feb. 2012) 7/2/2012

2m x 2m RPC
Prototype at TIFR
working since 2009



1m x 1m RPC
Prototype with Magnet
at VECC, Kolkata.
Working since 2011

Prototypes status

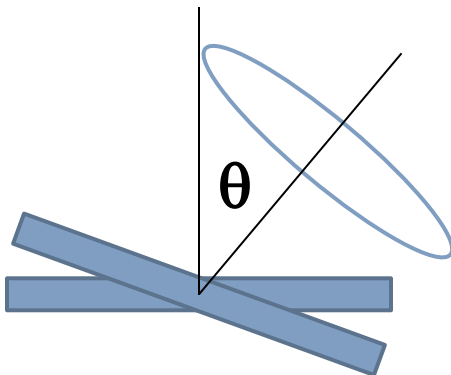
- All prototypes are performing well.
- Noise rate, detector current etc. are stable with respect to temperature, humidity etc.
- No ageing effect observed in any detector.
- Industrial interface is going on to make large number of RPCs for ICAL.
- Some references for detector working status:
 - Ref1
 - Ref2

Today's topic

- Physics Results from 1m x 1m RPC prototype stack at TIFR
- Cosmic Muon angular distribution at sea level and the vertical integrated Muon Flux

Primary cosmic radiation is isotropic at top of the atmosphere

- Primary cosmic rays \Rightarrow Pions \Rightarrow Muons
- Interaction & decay of Pions : a competition between two while reaching Earth's surface.
- Vertical direction Pions decay probability less, so less number of Muons.
- Inclined direction Pions decay rate is more, but to cover more atmospheric length than vertical, incident energy should also be higher. Primary cosmic muon flux falls off at higher energy.
- So, on the average number of Muons reaching Earth's surface is isotropic.



A flat detector of surface area 'A' will see Muon spectrum as

$$\int I_0 (A \cos \theta) \sin \theta d\theta d\phi = I_0 \cos^2 \theta$$

The General Angular Distribution of Cosmic ray Muons

$$I_{\theta} = I_0 \cos^n \theta$$

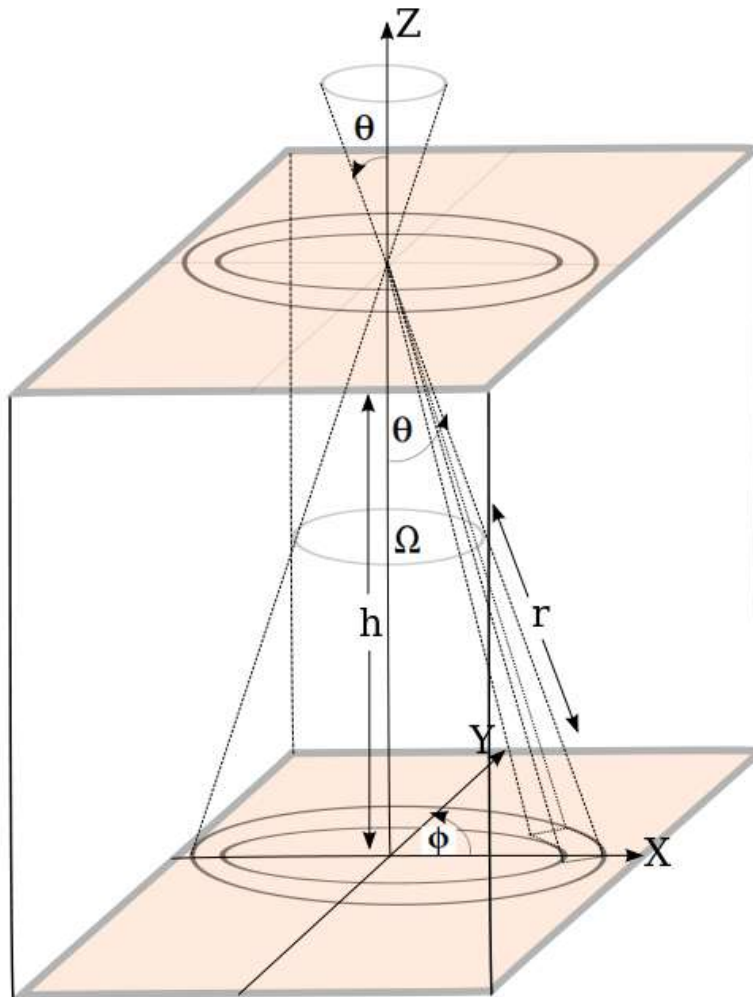
- The exponent, $n = 2$, is based up on an approximation.
- It depends on **Energy**, **Latitude**, **Altitude/Depth** etc.
- I_0 is the vertical flux ($\text{cm}^{-2} \text{ sec}^{-1} \text{ str}^{-1}$)

Goal : Estimate I_0 & n

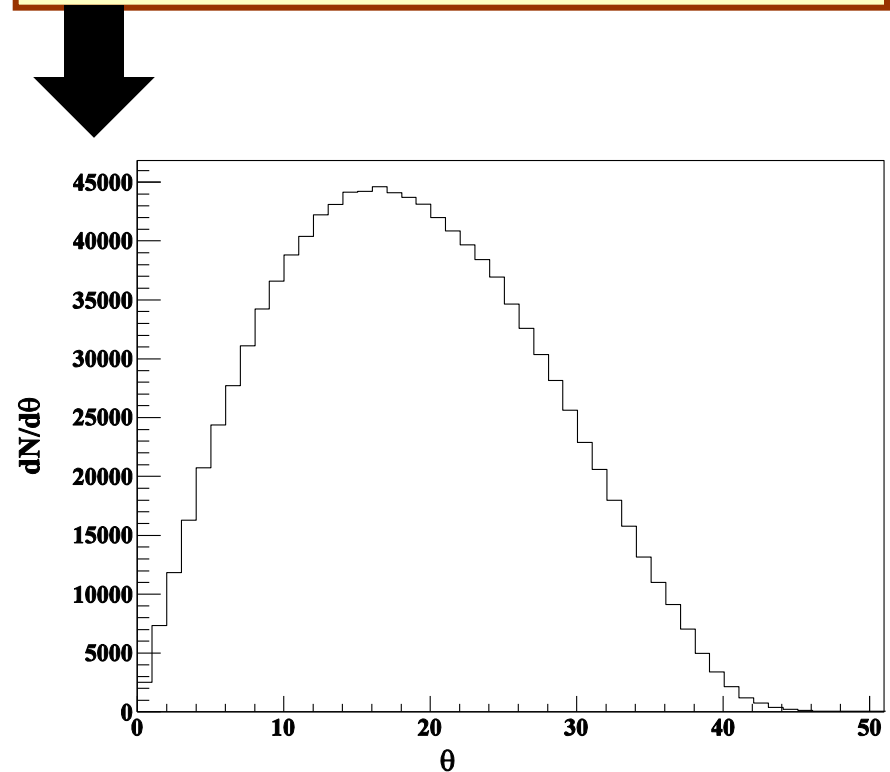
What the detector observes :

- Incident Muons falling on the top surface of the detector, $I_0 \cos^n \theta$
- Trigger finally decides the detector geometrical acceptance, $\omega(\theta)$.
- Finally we see an observed angular spectrum of cosmic ray muons.

What the detector see



$$N_{\theta_1 \rightarrow \theta_2} = \int_{\theta_1}^{\theta_2} N(\theta) d\theta = \int_{\theta_1}^{\theta_2} I(\theta) \omega(\theta) d\Omega$$



Experimentally observed spectrum ($N(\theta)$)

Select Muon

- Single hit, 2 or 3 consecutive strip hits are selected as a true cosmic muon hit

Fit

- X-Z & Y-Z data are fitted separately with a straight line.

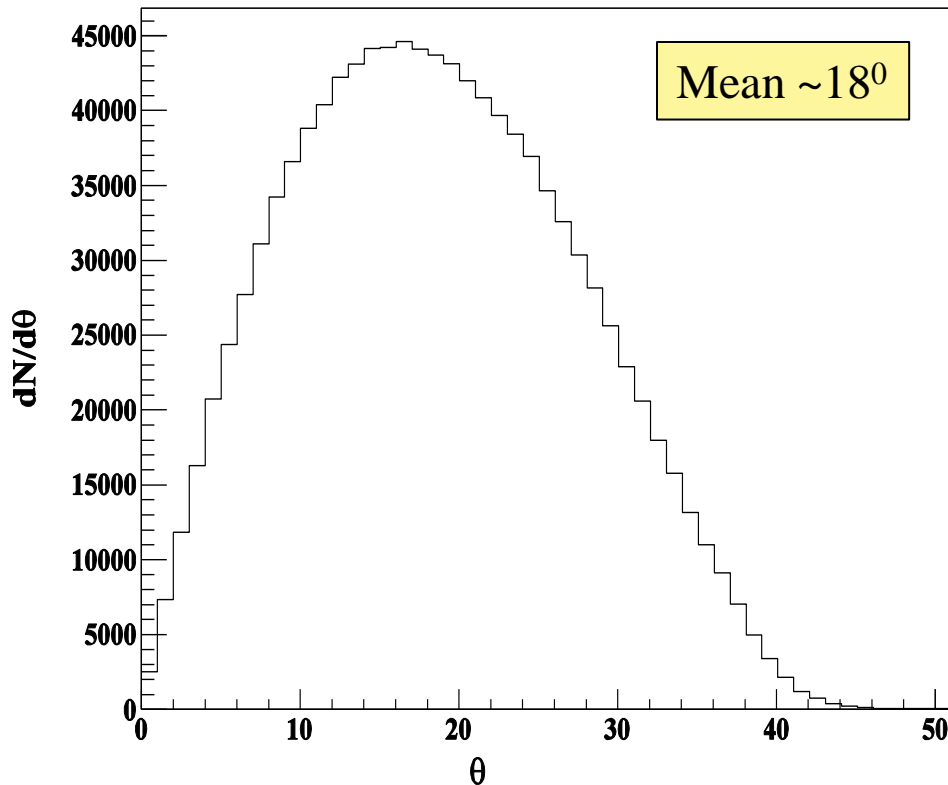
Selection
from Fit

- Minimum 4 layer hits present in fit is considered.
- Fit reduced chi-square is taken within 0-2.

Trigger
Condition

- Condition imposed: trigger layers (here layers 2,4,7&9) should have hits in fitting & residual should be within one strip width.

Observed zenith angle distribution of muons



- Slope and intercept are used to calculate zenith angle of incident cosmic muons.

$$\theta = \cos^{-1} \left(\frac{h}{l} \right)$$

- h is vertical height of the detector stack & l is the corresponding track length of muons.

$$N_{\theta_1 \rightarrow \theta_2} = \int_{\theta_1}^{\theta_2} N(\theta) d\theta = \int_{\theta_1}^{\theta_2} I(\theta) \omega(\theta) d\Omega$$

Experimentally Measured Data

Want to Reproduce this well known distribution

Detector Acceptance has to be calculated

Detector geometrical acceptance ($\omega(\theta)$)

- Generate a point randomly on top trigger layer (x_0, y_0)
- θ is generated uniformly over the solid angle using random number. ϕ is generated uniformly over the azimuthal angle (0 to 2π).
- Hit point at the bottom layer (x_2, y_2) is generated and also for the other layers.
- Smearing of these hits are done on the basis of :
 - Layer residual effect (seen in real data)
 - Hit multiplicity effect.

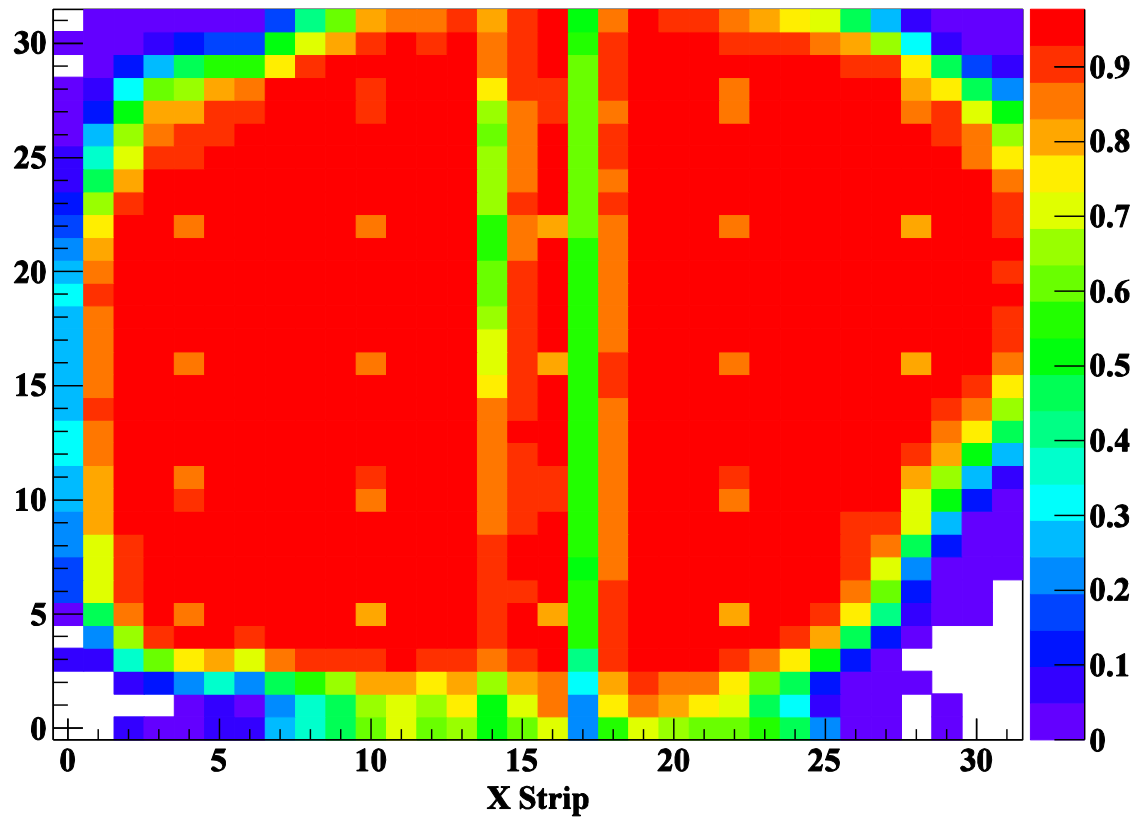
Contd.

- At this stage a hit point in this Monte-Carlo based calculation is still accepted with 100% efficiency where ever it is, either central region of the RPC or at the corner.
- As the hit point generation use uniform random number this 100% efficiency is obvious.
- In reality, there is a variation of this efficiency over the RPC area.

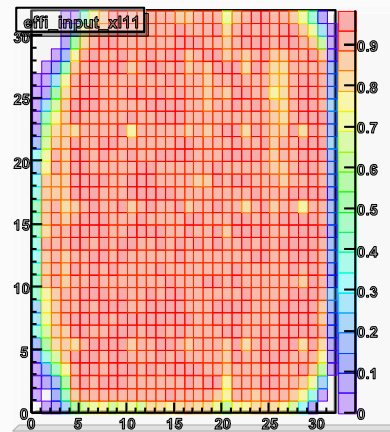
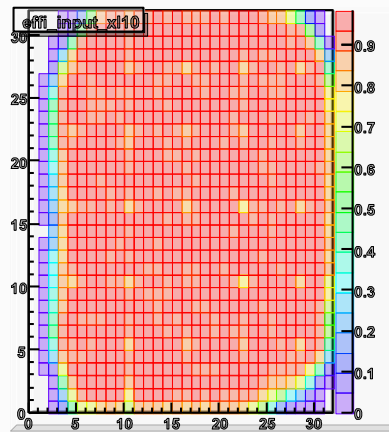
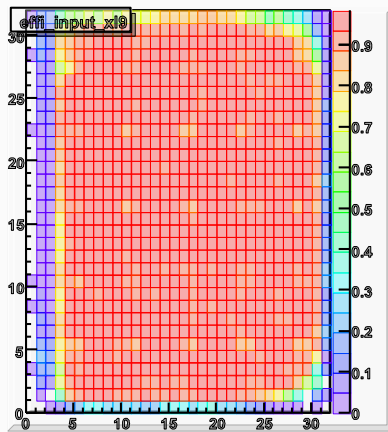
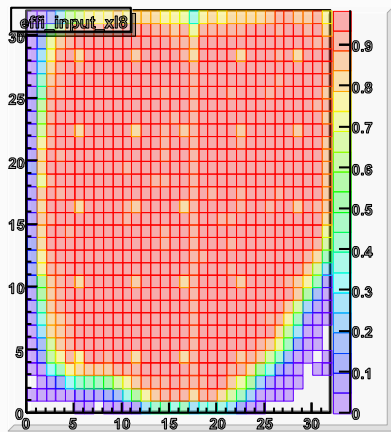
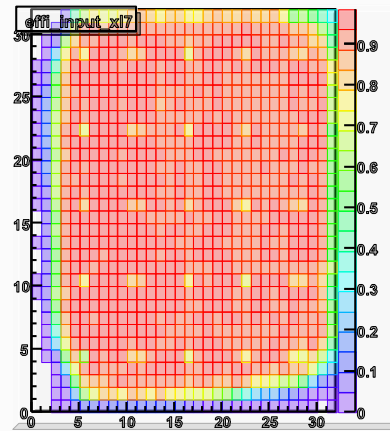
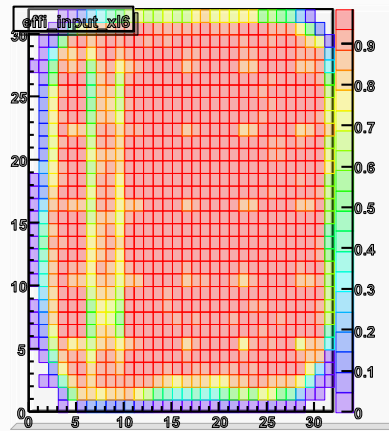
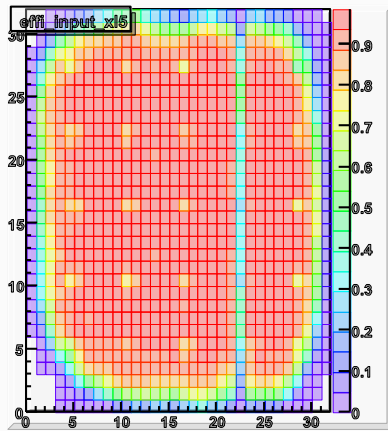
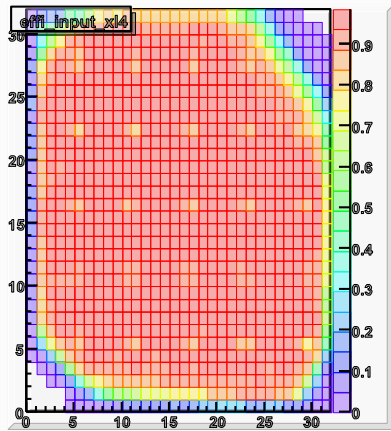
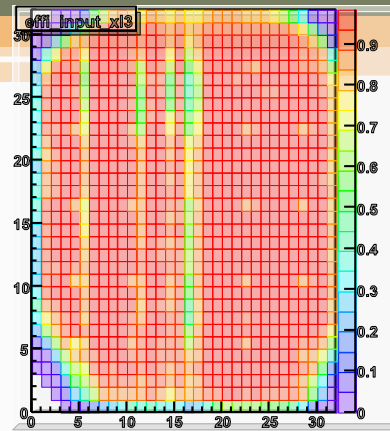
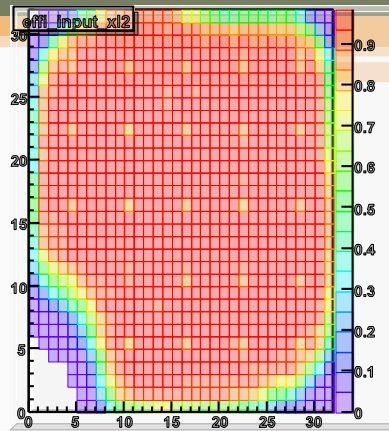
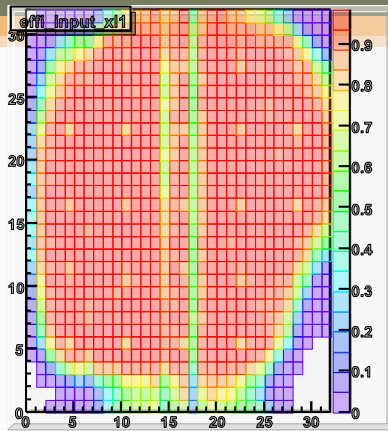
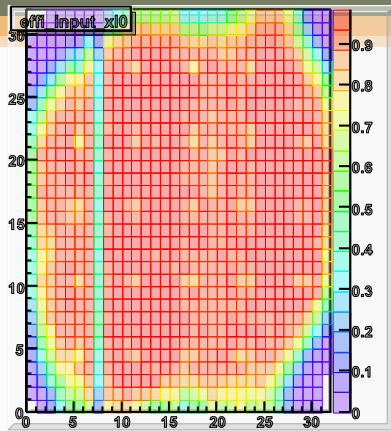
Pixel wise tracking efficiency for layer 1(x side)

❖ Trigger with layers 0,1,3,4 are used to get the efficiency for layer 6 to 11.

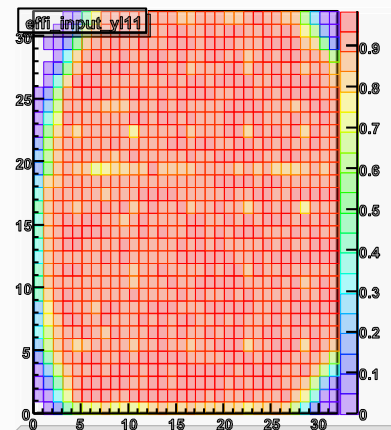
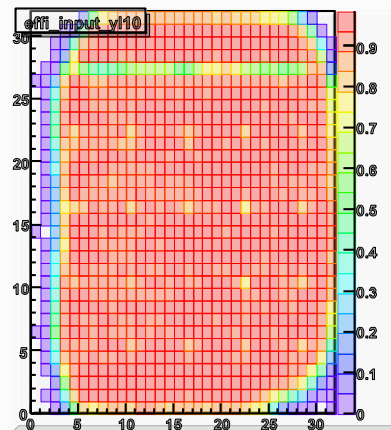
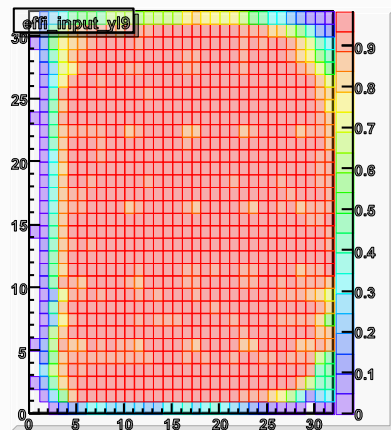
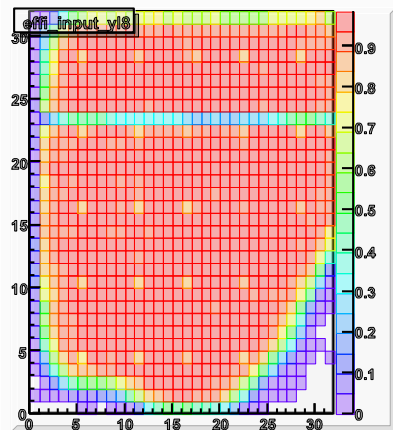
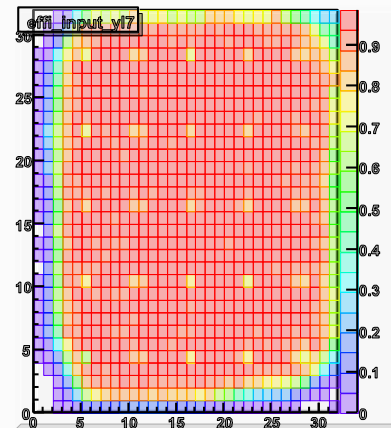
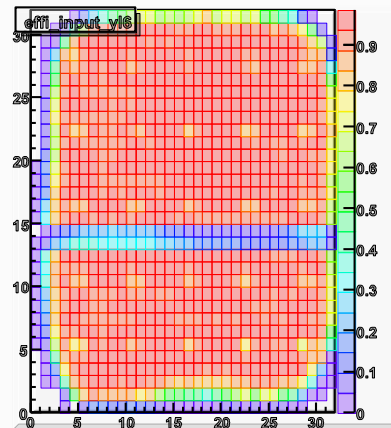
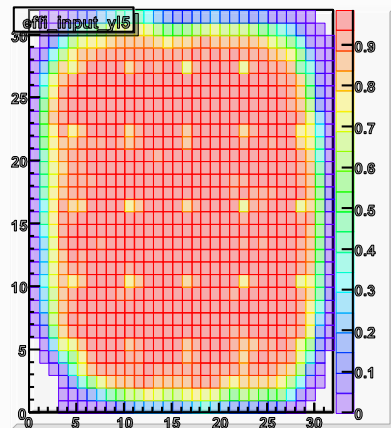
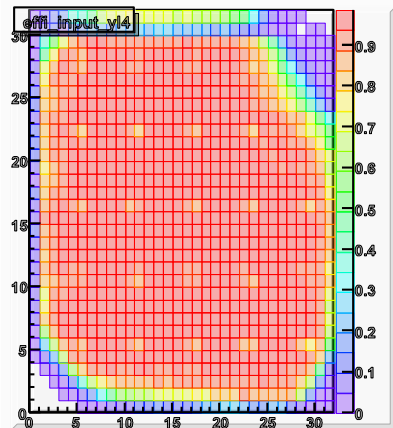
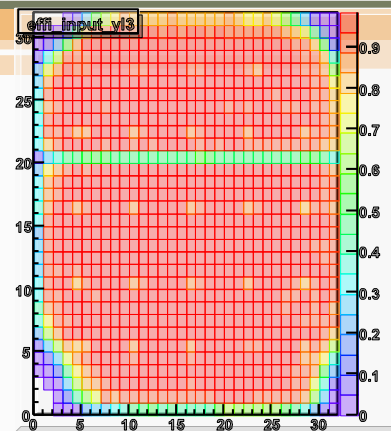
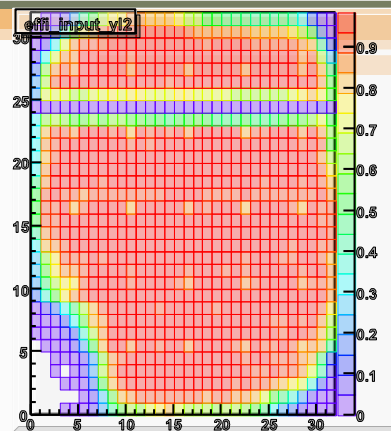
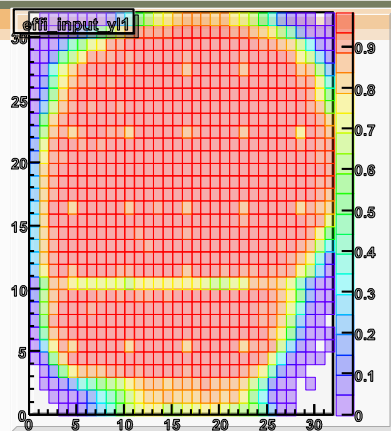
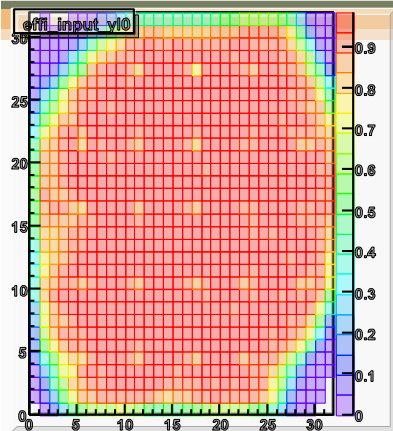
❖ Trigger with layers 7,8,10,11 are used to get efficiency for layers 0 to 5.



X side efficiency



Y side efficiency

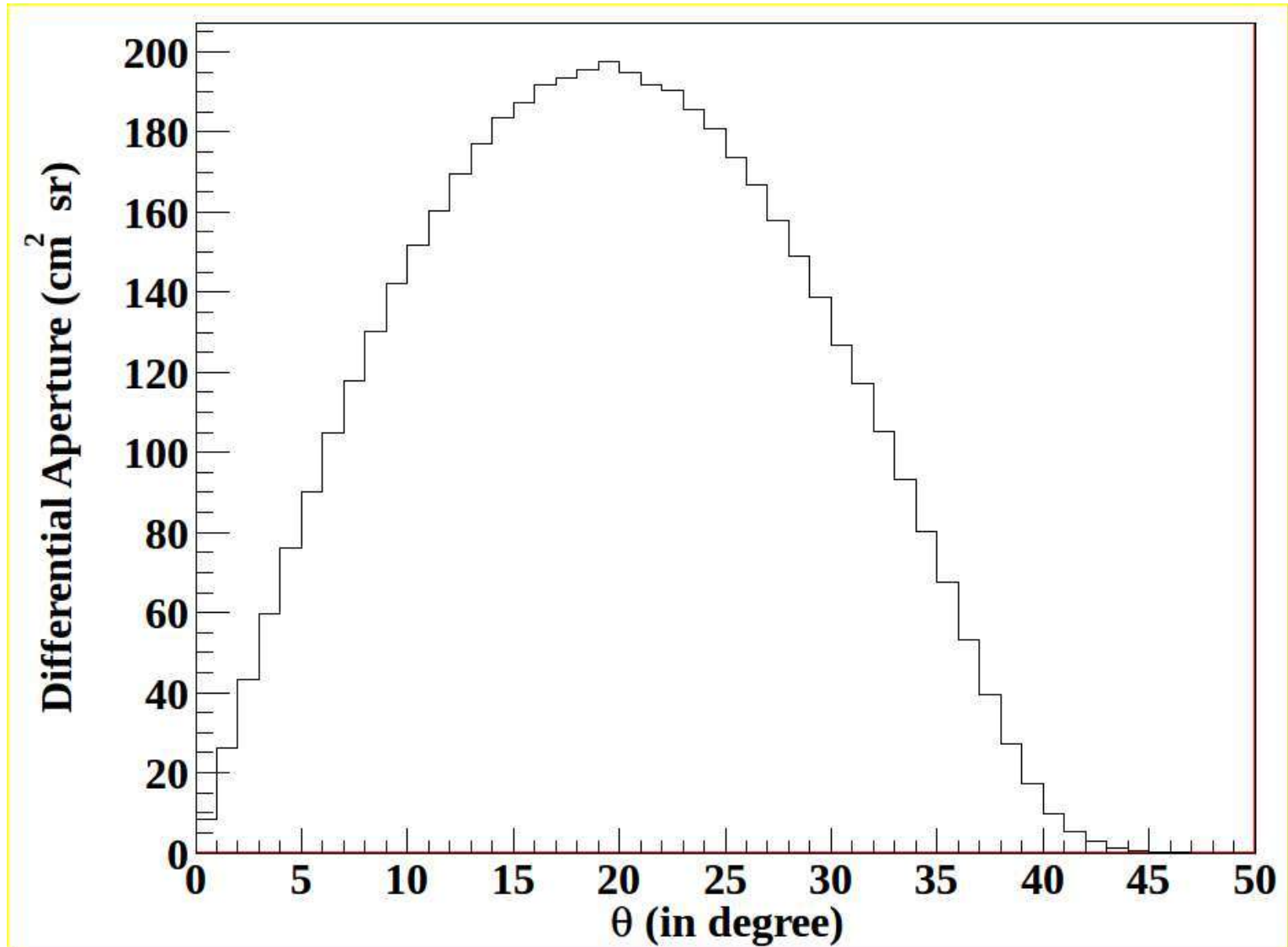


Detector acceptance

- This pixel wise efficiency profile is taken into consideration while selecting a hit point in Monte-Carlo process for detector acceptance.
- Finally selected hits are fitted with a straight line, exactly same as data.
- The angular distribution here in MC gives detector acceptance profile as $I(\theta)$ effect is absent in MC.

$$N^{MC}_{\theta_1 \rightarrow \theta_2} = \int_{\theta_1}^{\theta_2} N^{MC}(\theta) d\theta = \int_{\theta_1}^{\theta_2} \cancel{I(\theta)} \omega(\theta) d\Omega$$

Detector geometrical acceptance profile

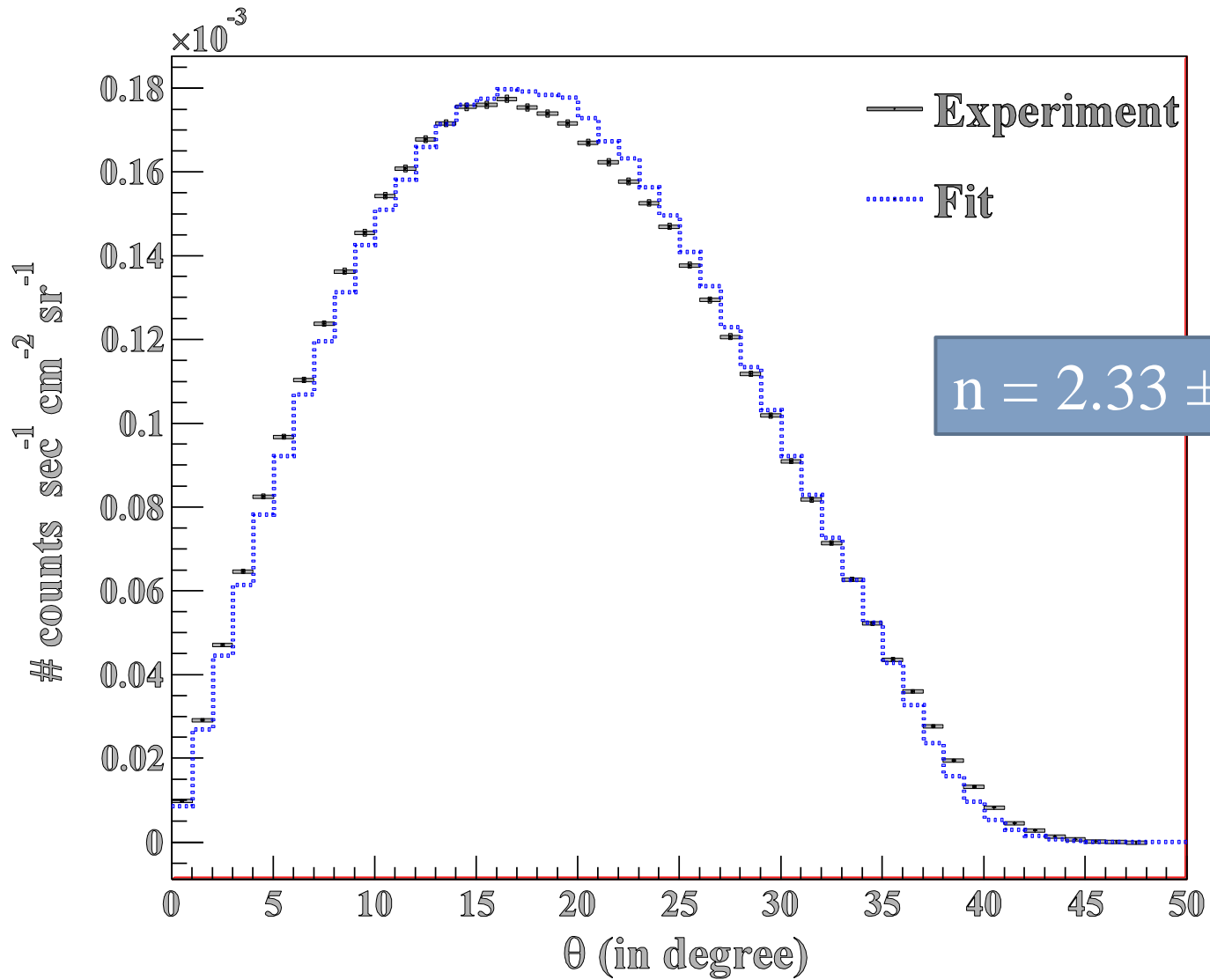


Chi-square definition to get I_0 & n

$$\chi^2 = \sum_{\theta=0}^{\theta_{max}} \frac{\left(N_{\theta}^{Exp} - p(0)\cos\theta^{p(1)}w(\theta) \right)^2}{N_{\theta}^{Exp}}$$

- $I_0 : p(0)$
- $n : p(1)$
- $w(\theta) : \text{weight factor per } \theta \text{ bin from detector acceptance plot}$

Flux Distribution



Vertical Flux calculation

- To get the shape of this cosmic muon flux distribution, a uniform flux incident up on the top layer of the detector was assumed in MC while estimating detector geometrical acceptance.
 - Remember θ is generated uniformly over the solid angle, i.e., $\int \sin \theta d\theta$
 - Now to get back the vertical flux θ has to be generated through $\int \cos^{2.33} \theta \sin \theta d\theta$

Contd.

$$\frac{I_0^{fit}}{Time \times \varepsilon_{trigger} \times \varepsilon_{tracking} \times \Omega}$$

- Time : total time through which data is collected with dead time correction
- ε are efficiency correction to get the actual number fallen on top of the detector
- Ω is the solid angular correction

$$I_0 = (6.050 \pm 0.001) \times 10^{-3} \text{ cm}^{-2} \text{ sec}^{-1} \text{ str}^{-1}$$

Comparison of vertical integral muon flux

Authors	Geomagnetic		Altitude (m)	Momentum (GeV/c)	Flux $\times 10^{-3}$ (cm ⁻² sec ⁻¹ Str ⁻¹)
	Lat. (°N)	P _c (GV)			
Allkofer et al. ¹	9	14.1	S.L	≥ 0.32	7.25 ± 0.1
Karmakar et al. ²	16	15.0	122	≥ 0.353	8.99 ± 0.05
				≥ 1.0	6.85 ± 0.04
Gokhale ³	19	--	--	≥ 0.32	7.3 ± 0.1
Fukui et al. ⁴	24	12.6	S.L.	≥ 0.34	7.35 ± 0.2
<i>Present Data</i>	<i>18</i>	<i>--</i>	<i>S.L.</i>	<i>≥ 0.287</i>	<i>6.050 ± 0.001</i>
Rossi ⁵	≥ 50	~ 1.8	S.L.	≥ 0.32	8.3
Greisen ⁶	54	1.5	S.L.	≥ 0.33	8.3 ± 0.1
Crookes & Rastin ⁷	53	2.2	40	≥ 0.35	9.13 ± 0.12

List of References:

1. Allkofer et al., Canadian Journal of Physics, 1968, 46: (10) S301-S305, 10.1139/p68-233.
2. N.L.Karmakar et al., Nuovo Cimento B 17, 173 (1973).
3. G.S.Gokhale, Private Communication (1953) (after Allkofer et al. 1968*).
4. S.Fukui et al., J.Phys.Soc. Japan 12, p.854 (1957)* .
5. DOI : 10.1103/RevModPhys.20.537.
6. Greisen, Phys. Rev. 61, 212 (1942), Phys. Rev. 63, 323 (1943), Phys. Rev. 62, 316 (1942).
7. Crrokes & Rastin, Nucl. Phys. B 39(1972) 493-508.
8. Cosmic Rays at Earth, Researchers' Reference Manual and Data Book, Peter K.F.Greider, Elsevier.

More Contributions in RPC2012:

- Electronics and Data Acquisition systems for the RPC based INO ICAL detector by Dr. B. Satyanarayana, TIFR (7th Feb., Poster Session).
- Preliminary results on optimization of gas flow rate for RPCs, by S.D.Kalmani, TIFR (8th Feb).
- Proposed Trigger Scheme for the ICAL detector of INO, by Sudeshna Dasgupta, TIFR (9th Feb).

