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

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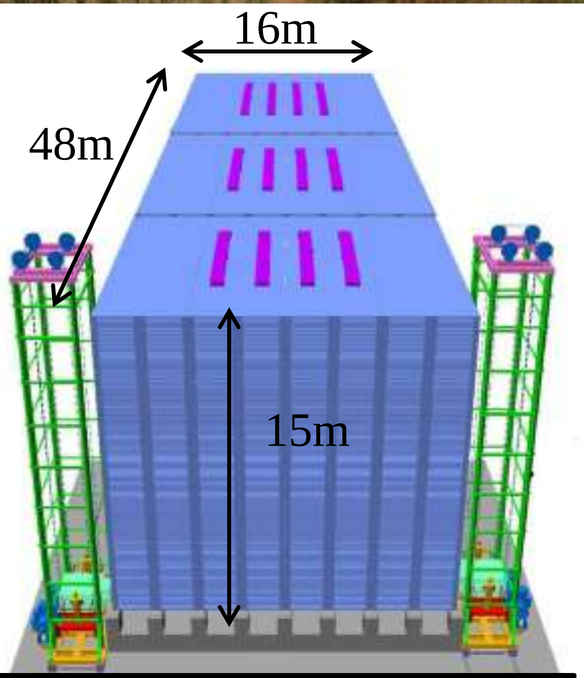
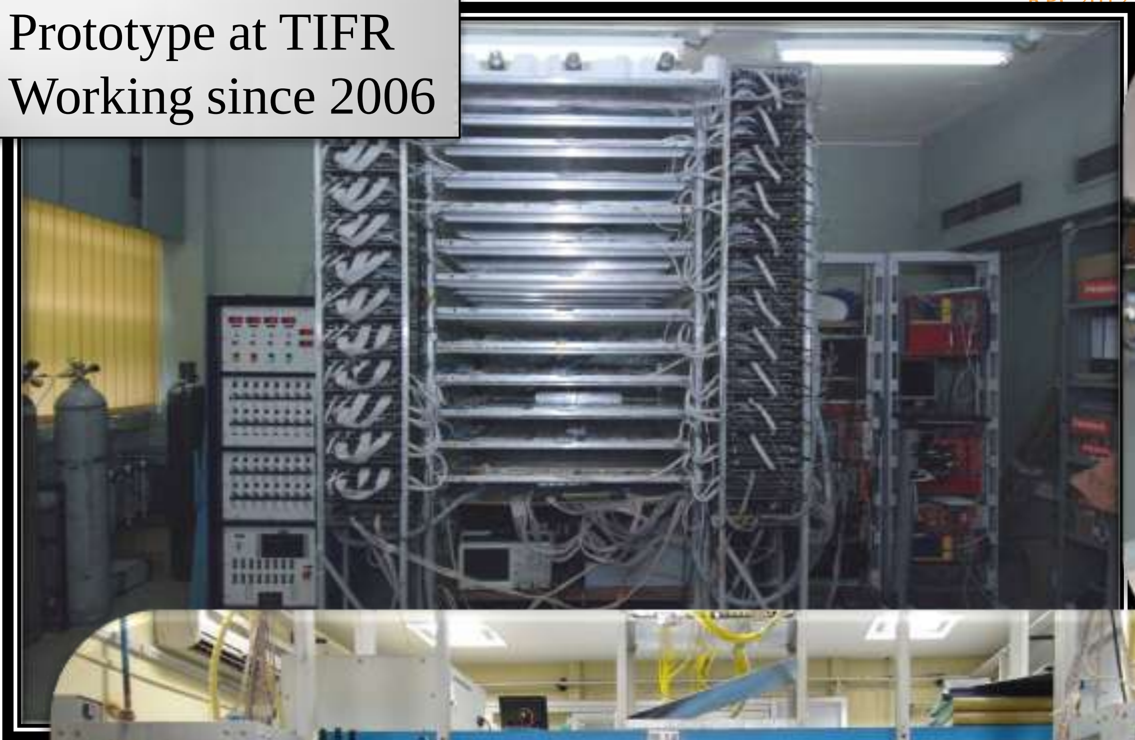
INO site, located at South India

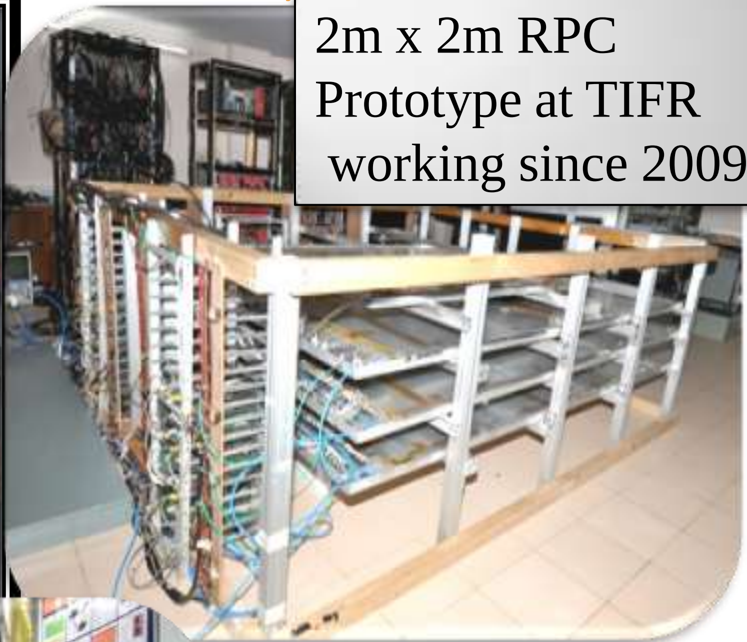


Schematic of ICAL detector

- **I**ndia based **N**eutrino **O**bservatory (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 **I**ron**CAL**orimeter (ICAL) with **50kton** of Iron as target mass.
- **28,800 R**esistive **P**late **C**hambers **(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



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 existing references for detector working status:
  - Ref1 : V. M. Datar, et al., NIMA 602 (2009) 744.
  - Ref2 : A. Behere et al., NIMA 602 (2009), p. 784.
  - Ref3 : RPC 2010 proceedings.

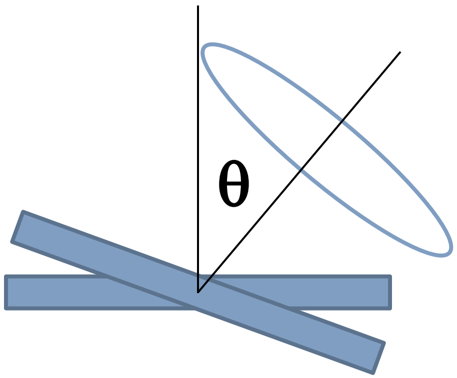
Today's topic

- 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 ⇨ Pions ⇨ 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, if it assumed an isotropic muon flux is reaching the Earth’s surface what a flat detector will observe?

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 ($cm^{-2}\ sec^{-1}\ str^{-1}$)

Goal : Estimate I_0 & n

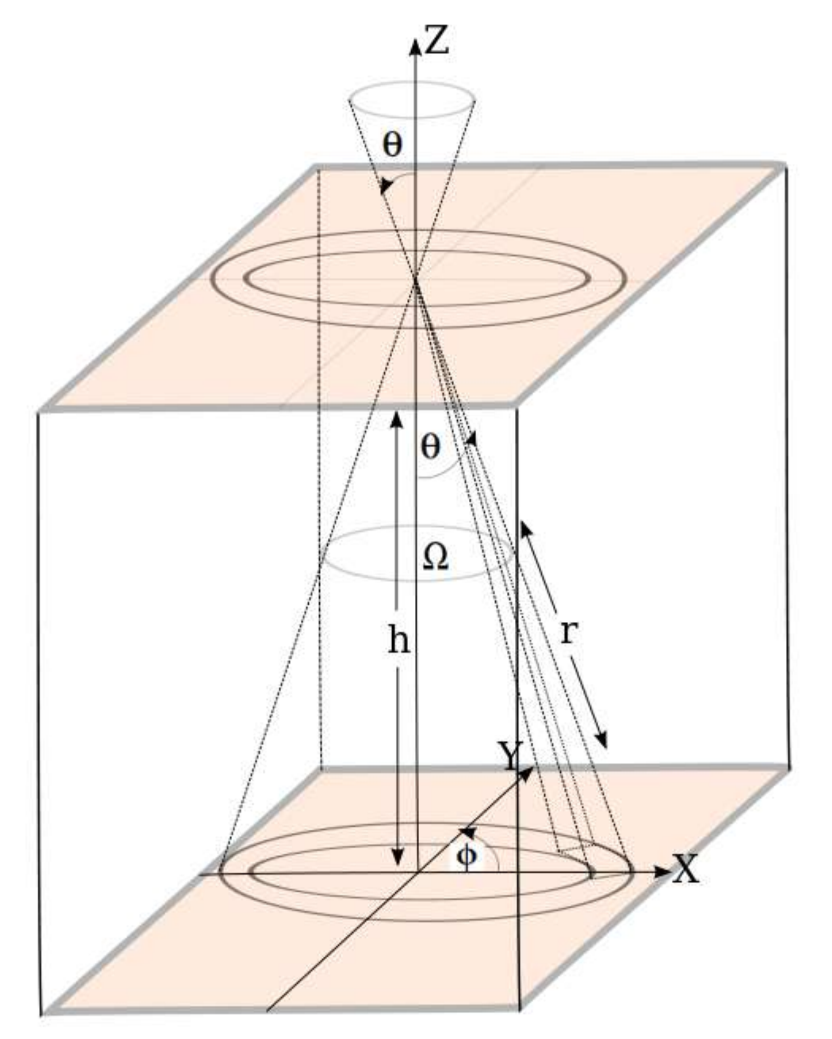
What the detector observes :

Incident Flux
- Incident Muons falling on the top surface of the detector, $I_0 Cos^n\ \theta$

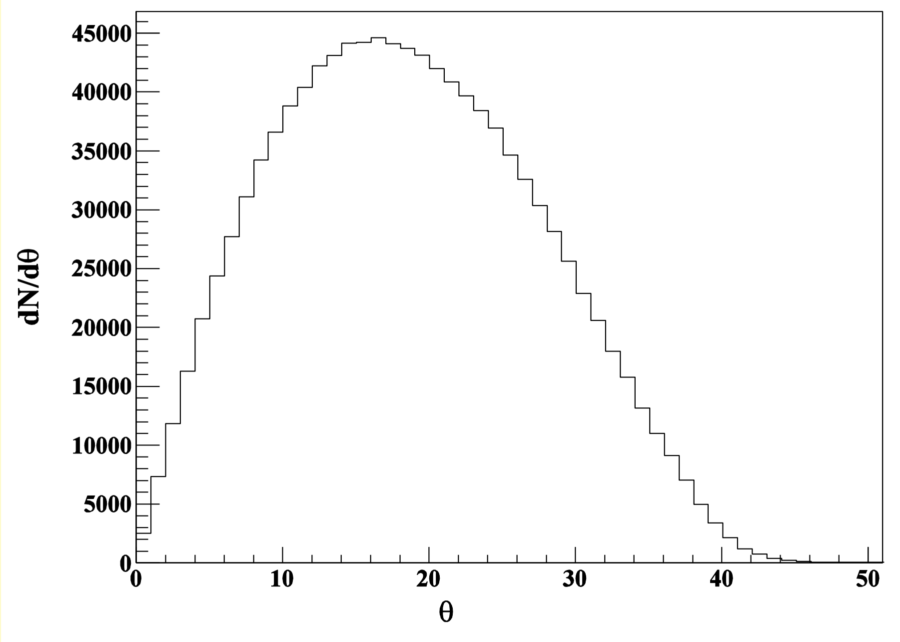
Acceptance
- Trigger finally decides the detector geometrical acceptance, $\omega(\theta)$.

Observed
- Finally we see an observed angular spectrum of cosmic ray muons.

What the detector see



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



Experimentally observed spectrum (N(θ))

Select Muon

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

Fit

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

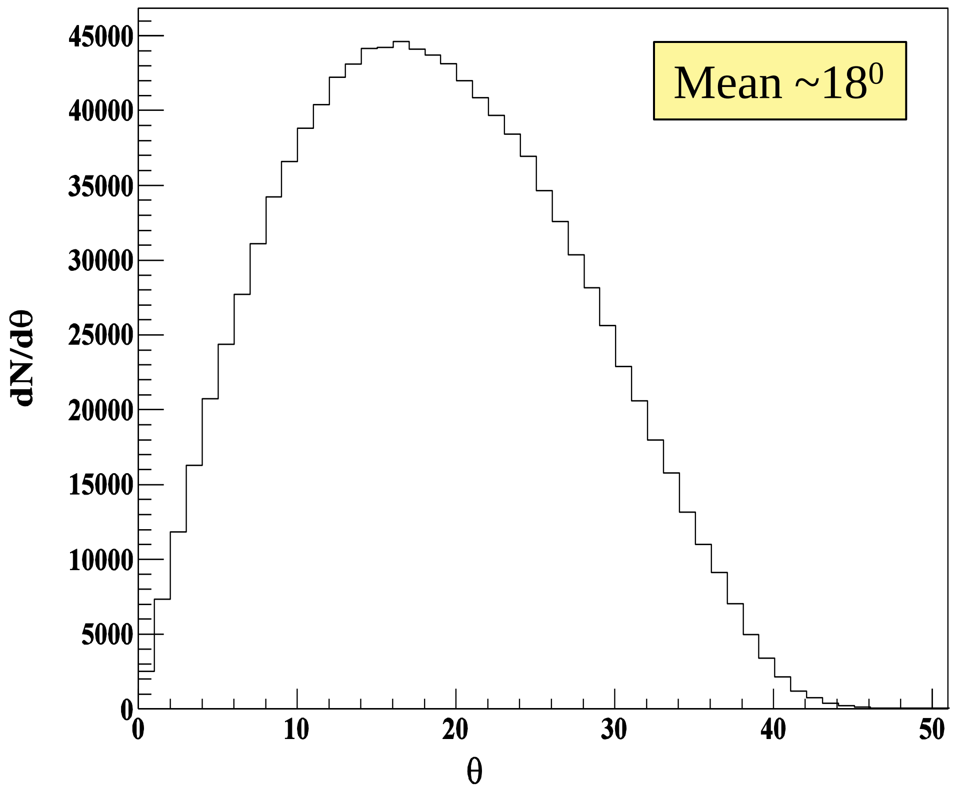
Selection from Fit

- Minimum 4 layer hits present in fit is considered whereas total number of layers is 12.
- 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 with in one strip width.

Observed zenith angle distribution of muons



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

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

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

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

Experimentally Measured Data

Want to Reproduce this well known distribution

Detector Acceptance has to be calculated

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

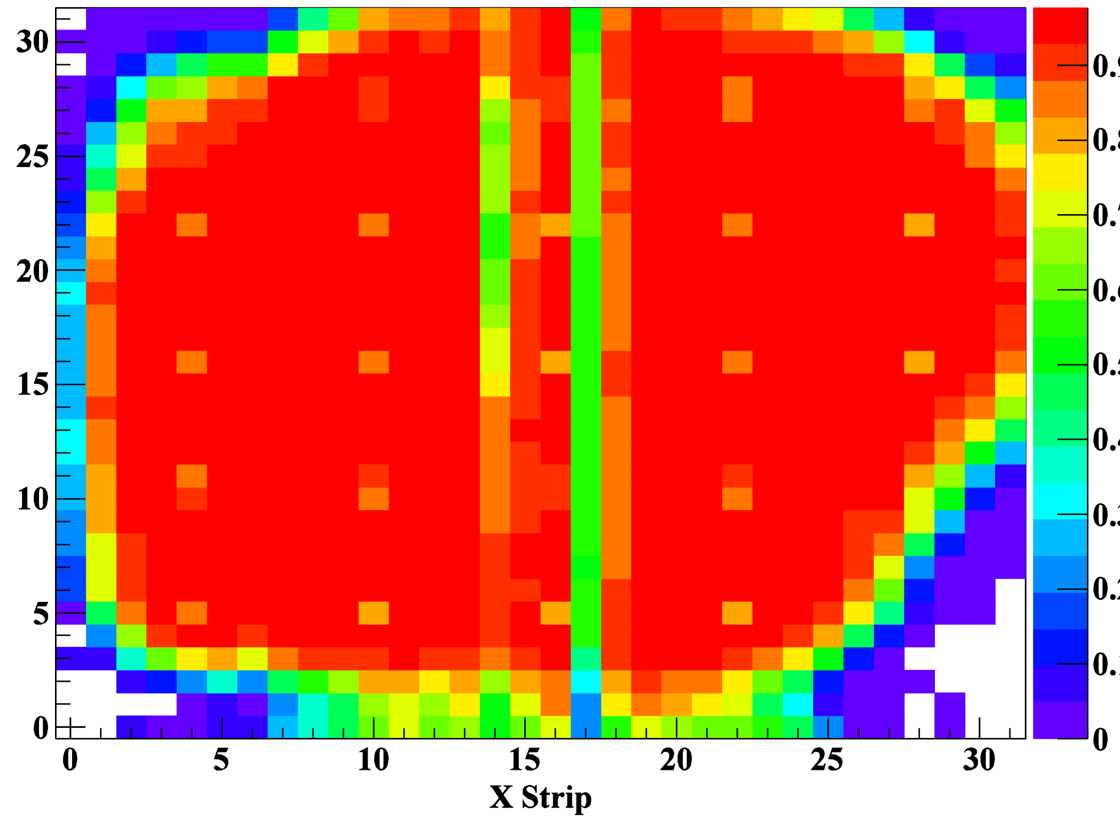
- Generate a point randomly on top trigger layer (x_9,y_9)
- θ is generated uniformly over the solid angle using random number. ϕ is generated uniformly over the azimuthal angle (0 to 2π).
- Hit point at the bottom layer (x_2,y_2) is generated and also for the other layers.
- Smearing of these hits are 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.

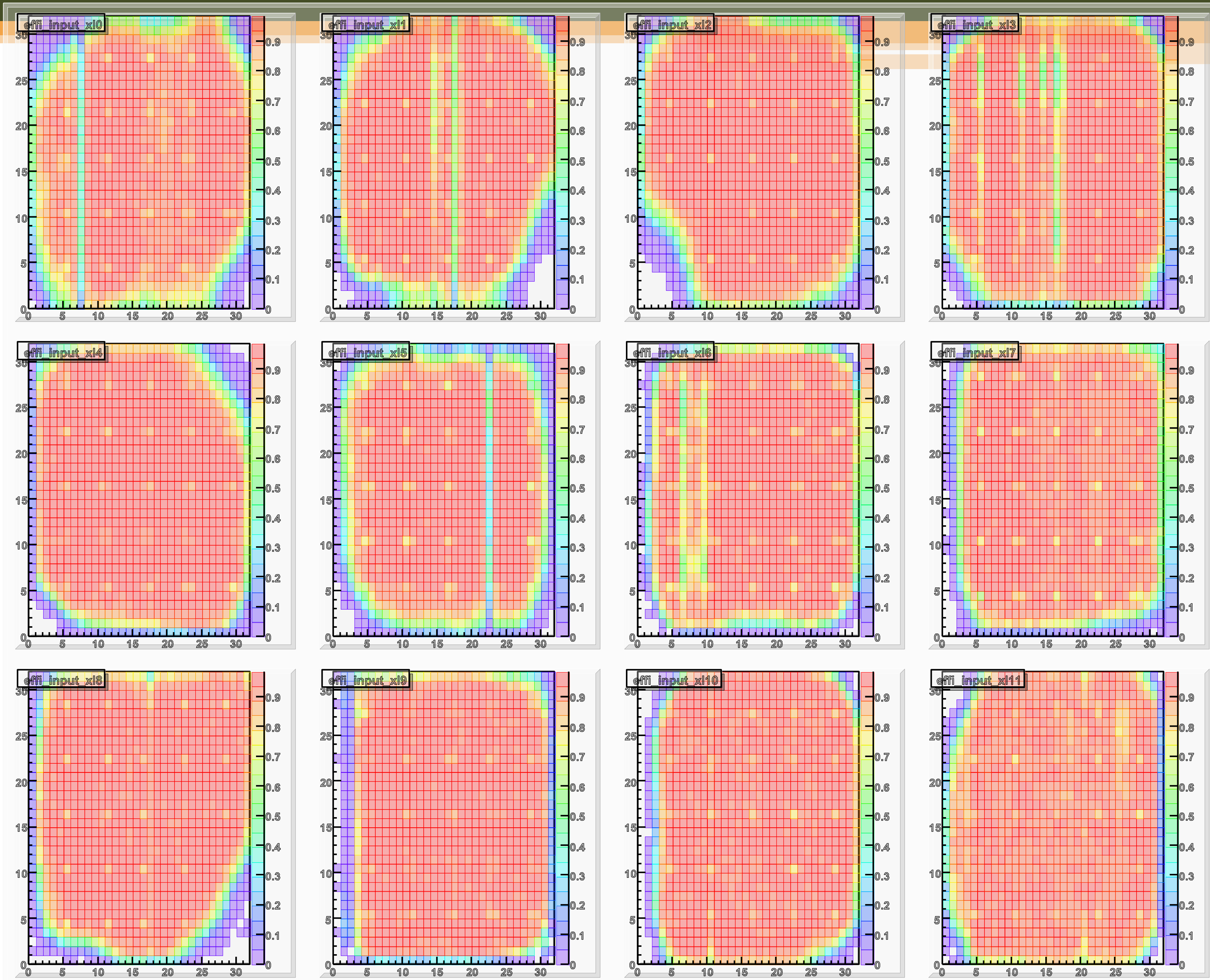
Pixel wise tracking efficiency for layer 1(X side)

- ❖Trigger with layers 0,1,3,4 are used to get the efficiency for layer 6 to 11.
- ❖Trigger with layers 7,8,10,11are used to get efficiency for layers 0 to 5.

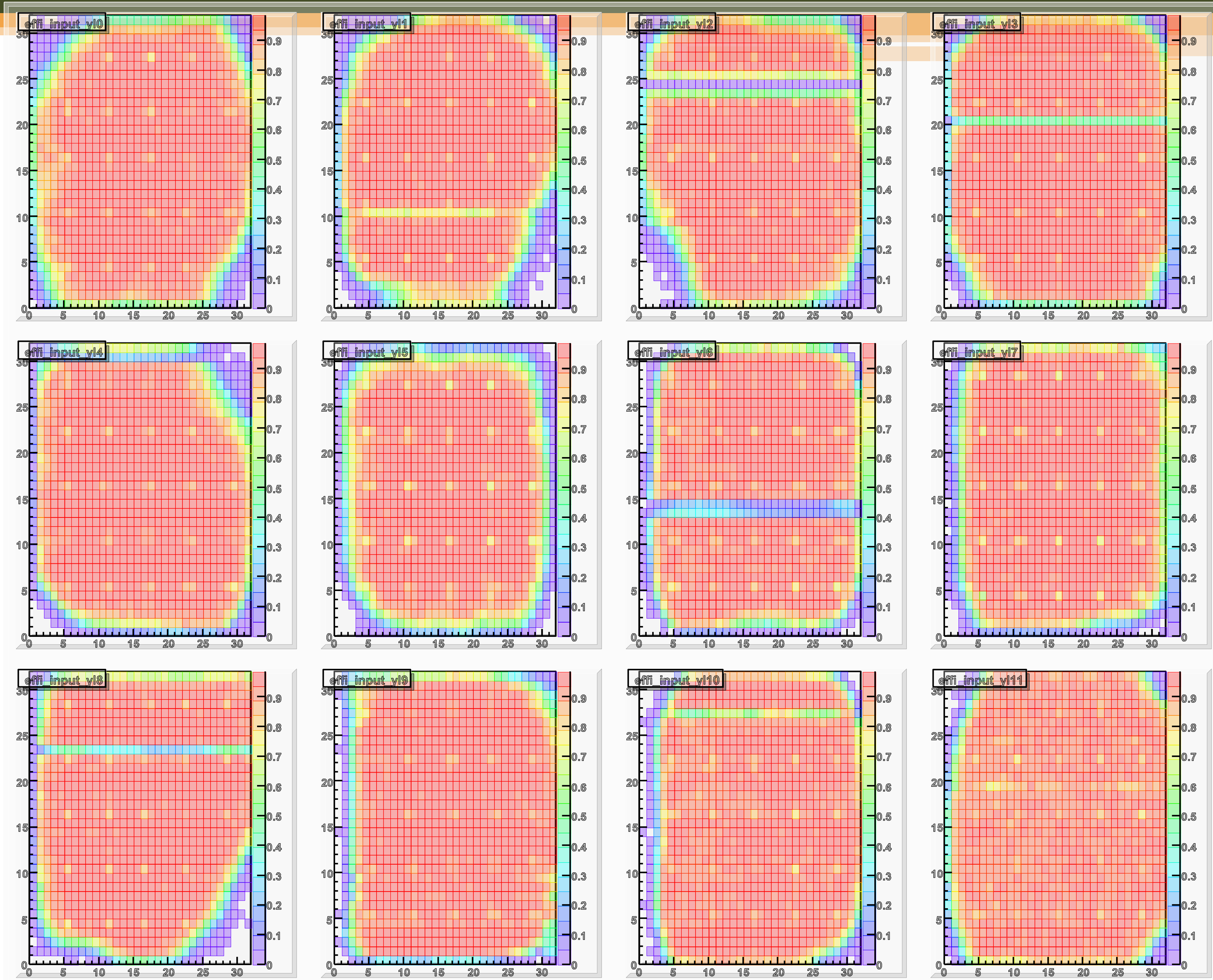


Otherwise, vertically downward muon efficiency may be underestimated

X side efficiency



Y side efficiency

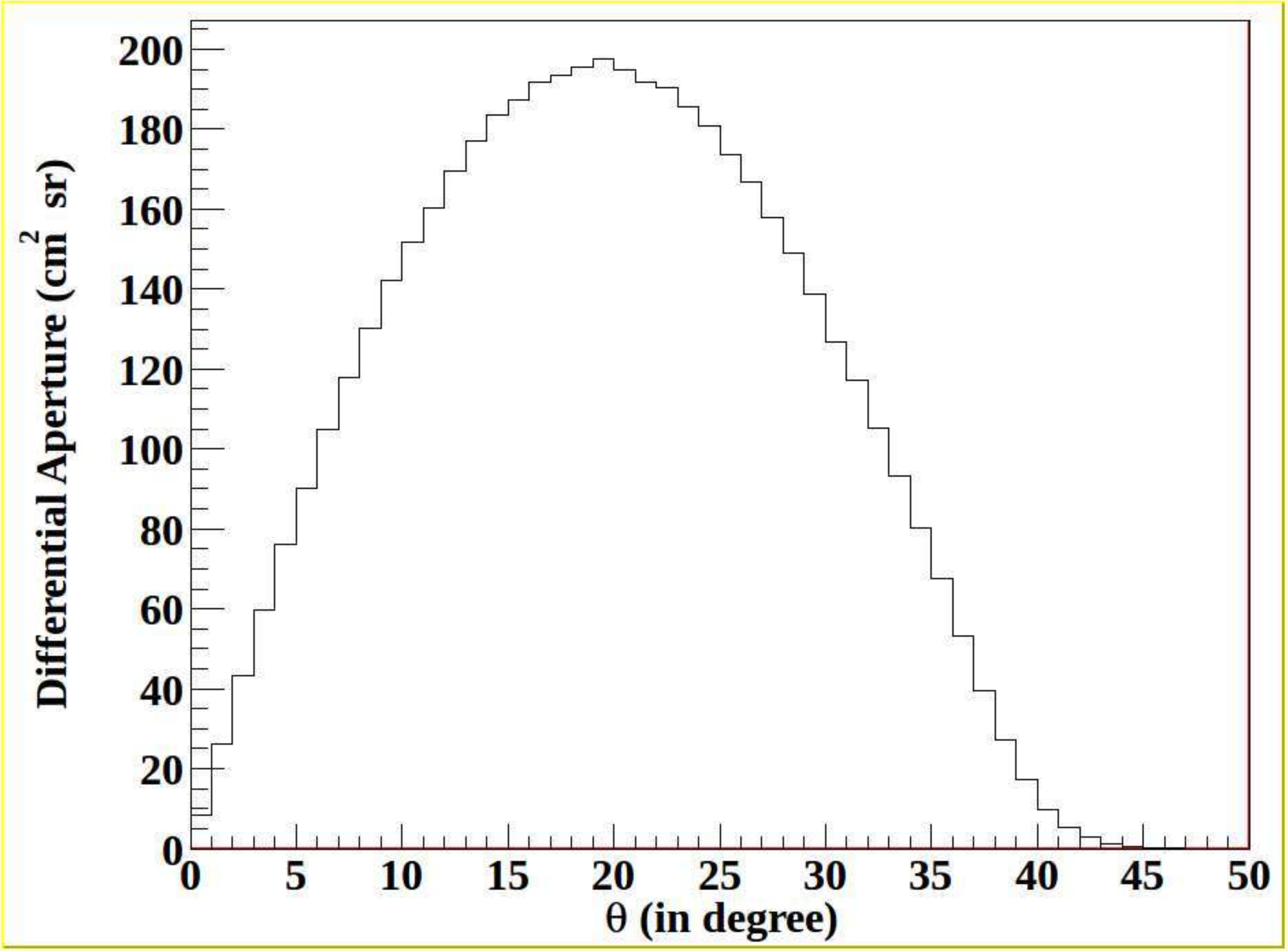


Detector acceptance

- 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(θ) effect is absent in MC.

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

Detector geometrical acceptance profile

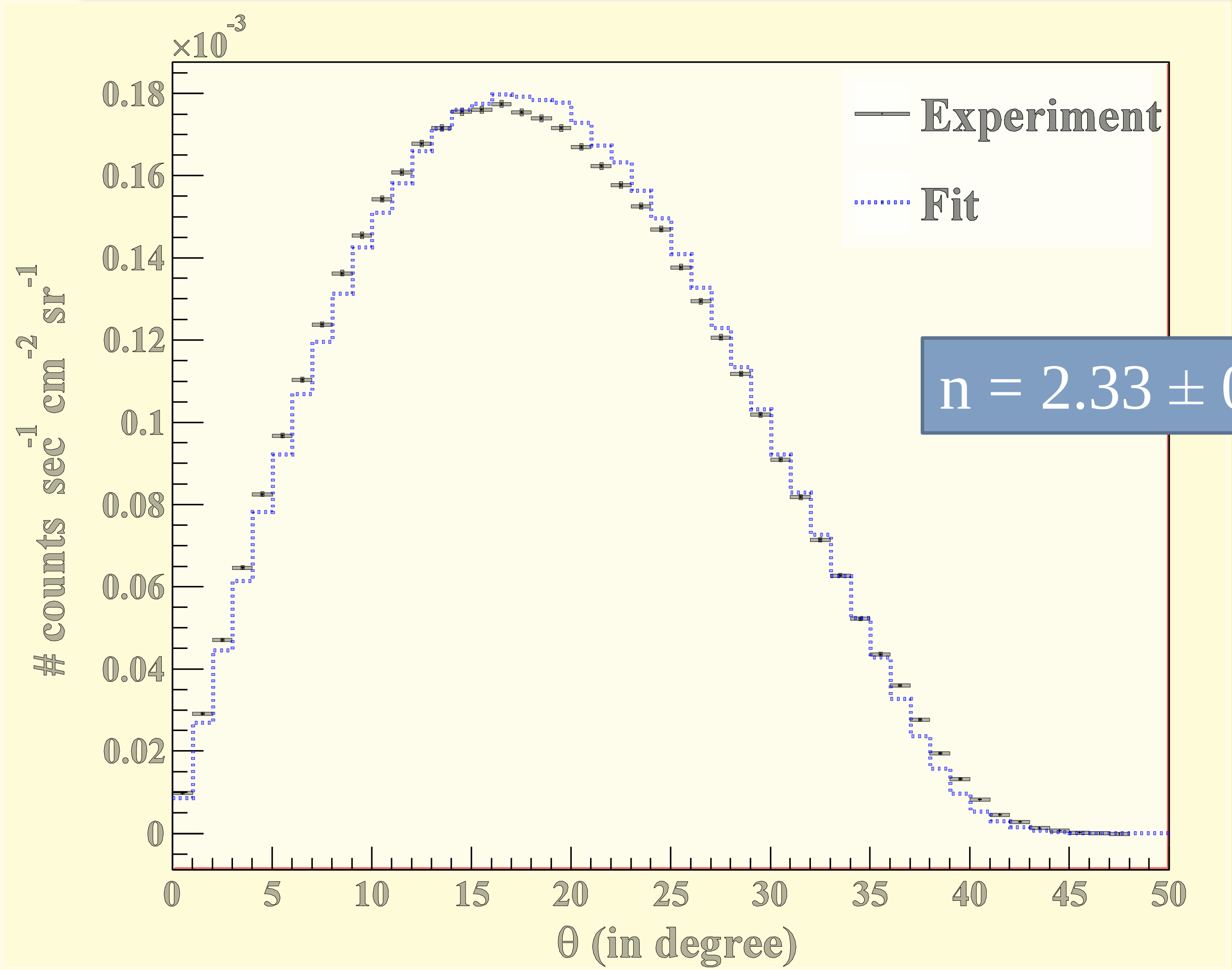


Chi-square definition to get I_0 & n

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

- I_0 : *p(0)*
- n : *p(1)*
- *w(θ)* : weight factor per θ bin from detector acceptance plot

Flux Distribution



n = 2.33 ± 0.02

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

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

Comparison of vertical integral muon flux

Authors	Geomagnetic		Altitude	Momentum	Flux × 10^{-3}
	Lat. (^{0}N)	P_c (GV)	(m)	(GeV/c)	(cm^{-2} sec^{-1} Str^{-1})
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 ≥1.0	8.99 ± 0.05 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
Present Data	***18***	***--***	***S.L.***	***≥0.287***	***6.050 ± 0.001***
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 (7^{th} Feb., Poster Session).
- Preliminary results on optimization of gas flow rate for RPCs, by S.D.Kalmani, TIFR (8^{th} Feb).
- Proposed Trigger Scheme for the ICAL detector of INO, by Sudeshna Dasgupta, TIFR (9^{th} Feb).


Thank you