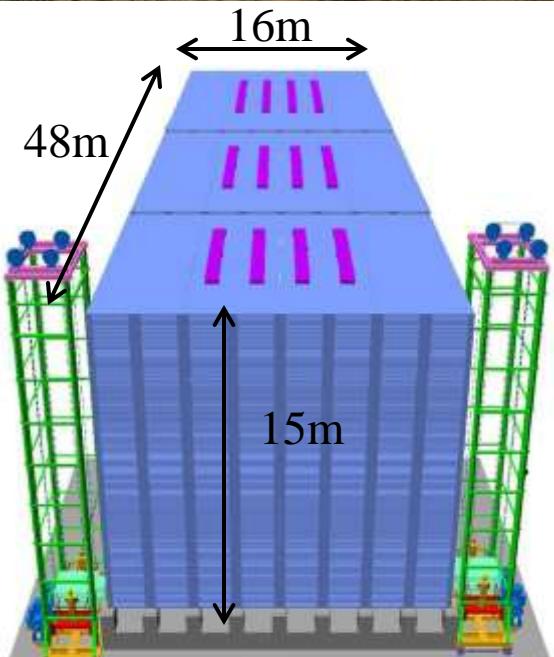
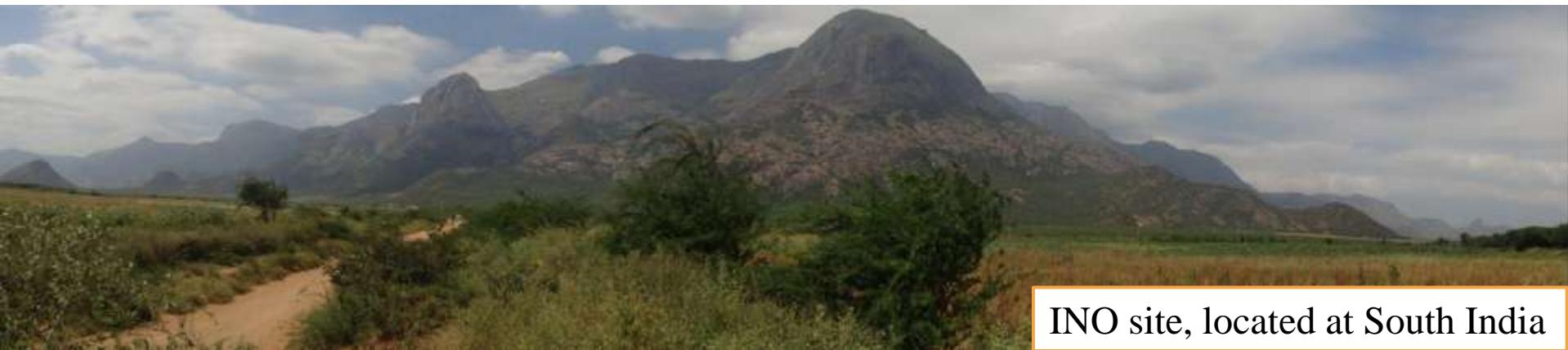


# Study of Angular Distribution of Cosmic Ray Muons using INO-ICAL Prototype Detector at TIFR

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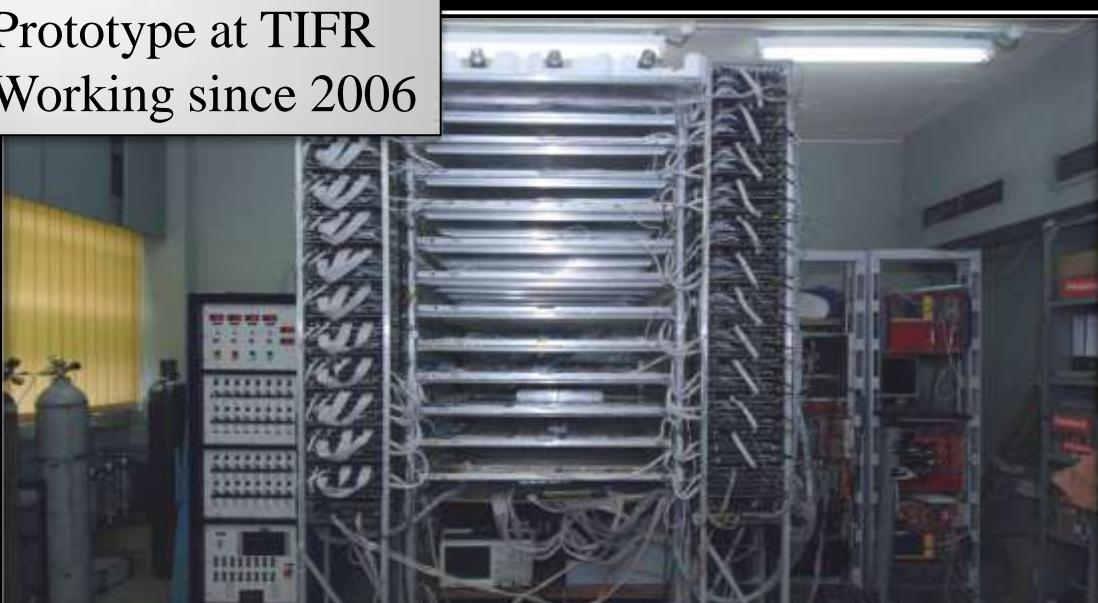
RPC2012, INFN - LNF, 7/2/2012  
Rome, Italy, (5-10 Feb., 2012)



Schematic of ICAL detector

- India based **Neutrino Observatory (INO)**, an underground laboratory facility coming up in India.
- 1<sup>st</sup> 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

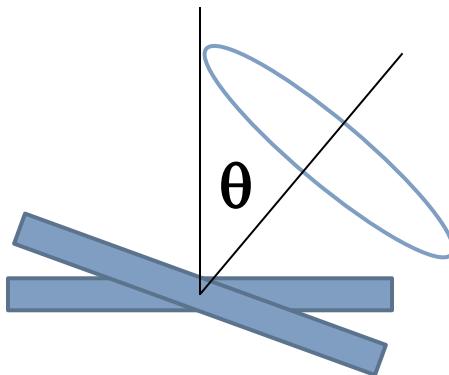
- All prototypes are performing well.
- Noise rate, detector current etc. are stable with respect to temperature, humidity etc.
- No ageing effect observed in any detector.
- Industrial interface is going on to make large number of RPCs for ICAL.
- Some references for detector working status:
  - [Ref1](#)
  - [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 ( $\text{cm}^{-2} \text{ sec}^{-1} \text{ str}^{-1}$  )

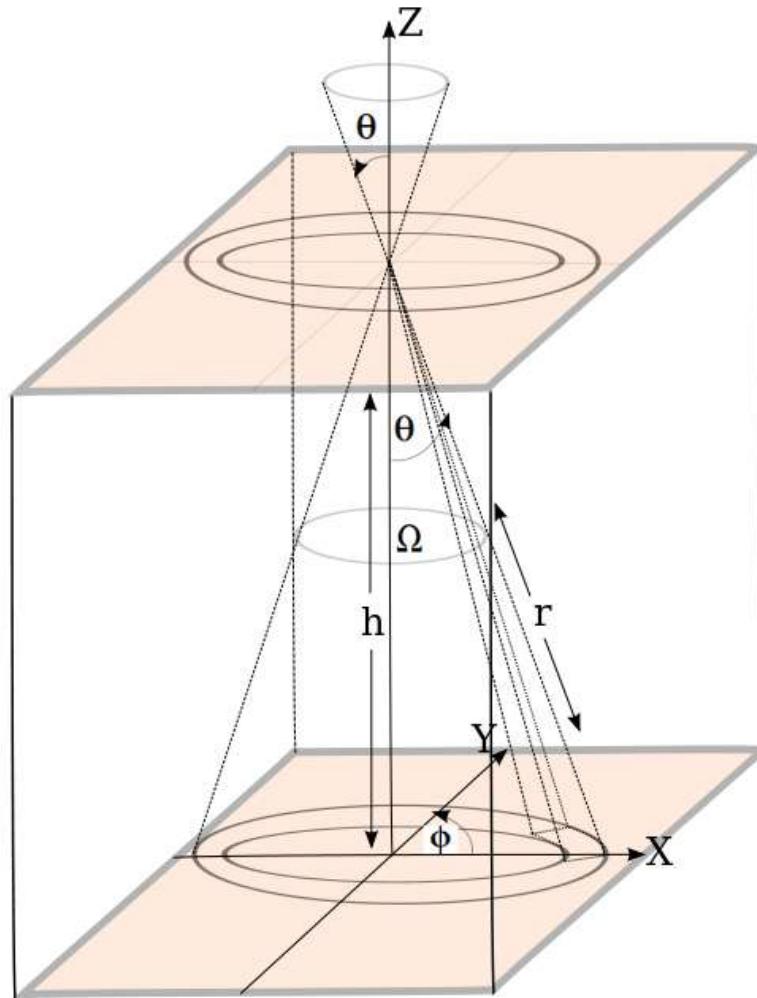
Goal : Estimate  $I_0$  &  $n$

# What the detector observes :

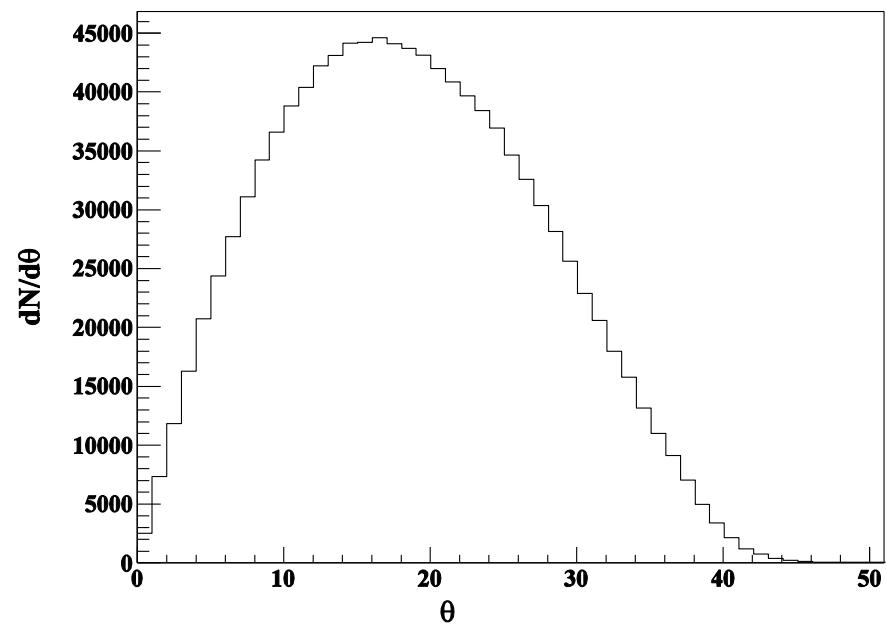


- Incident Muons falling on the top surface of the detector,  $I_0 \text{Cos}^n \theta$
- Trigger finally decides the detector geometrical acceptance,  $\omega(\theta)$ .
- Finally we see an observed angular spectrum of cosmic ray muons.

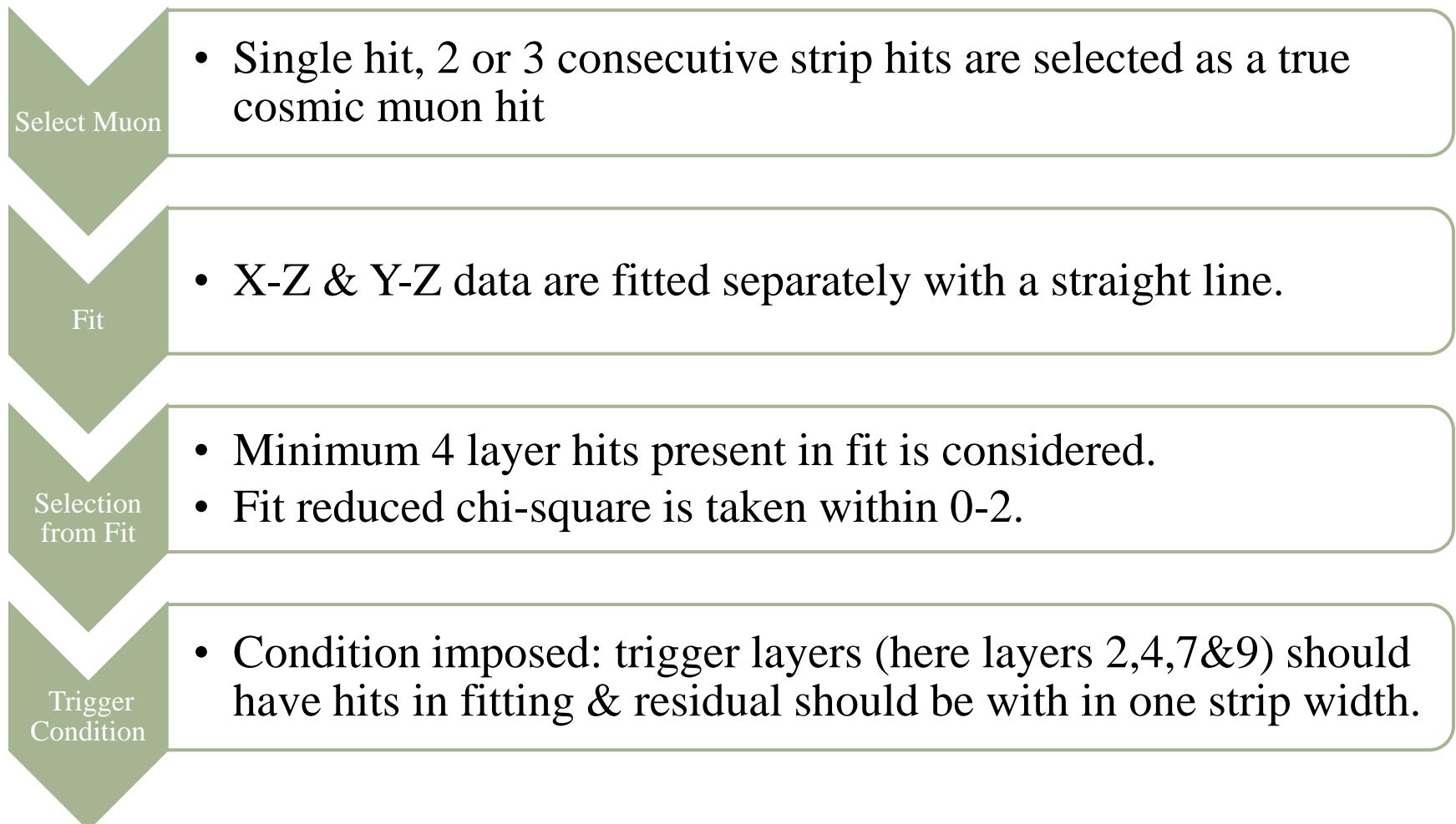
# What the detector see



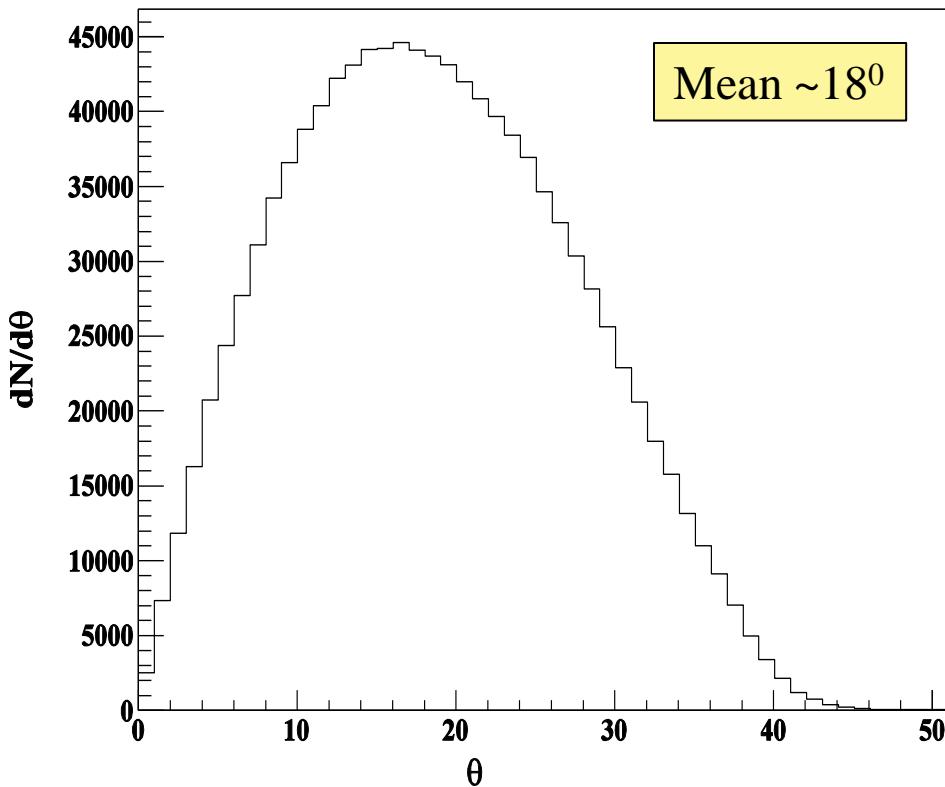
$$N_{\theta_1 \rightarrow \theta_2} = \int_{\theta_1}^{\theta_2} N(\theta) d\theta = \int_{\theta_1}^{\theta_2} I(\theta) \omega(\theta) d\Omega$$



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



# Observed zenith angle distribution of muons



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

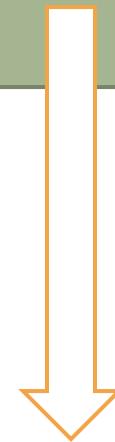
$$\theta = \cos^{-1}\left(\frac{h}{l}\right)$$

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

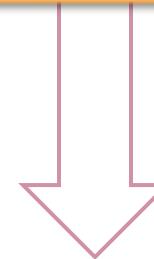
$$N_{\theta_1 \rightarrow \theta_2} = \int_{\theta_1}^{\theta_2} N(\theta) d\theta = \int_{\theta_1}^{\theta_2} I(\theta) \omega(\theta) d\Omega$$



Experimentally Measured Data



Want to Reproduce this well known distribution



Detector Acceptance has to be calculated

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

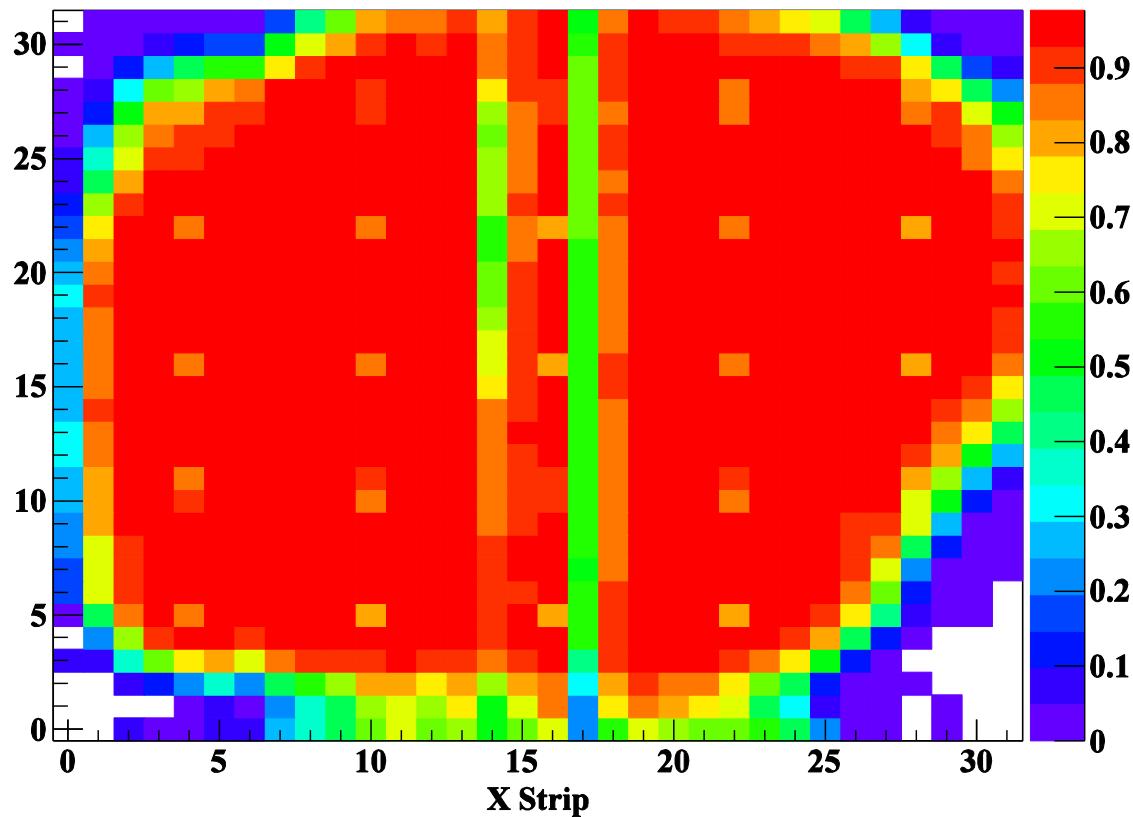
- Generate a point randomly on top trigger layer ( $x_9, y_9$ )
- $\theta$  is generated uniformly over the solid angle using random number.  $\phi$  is generated uniformly over the azimuthal angle (0 to  $2\pi$ ).
- Hit point at the bottom layer ( $x_2, y_2$ ) is generated and also for the other layers.
- Smearing of these hits are done on the basis of :
  - Layer residual effect (seen in real data)
  - Hit multiplicity effect.

# Contd.

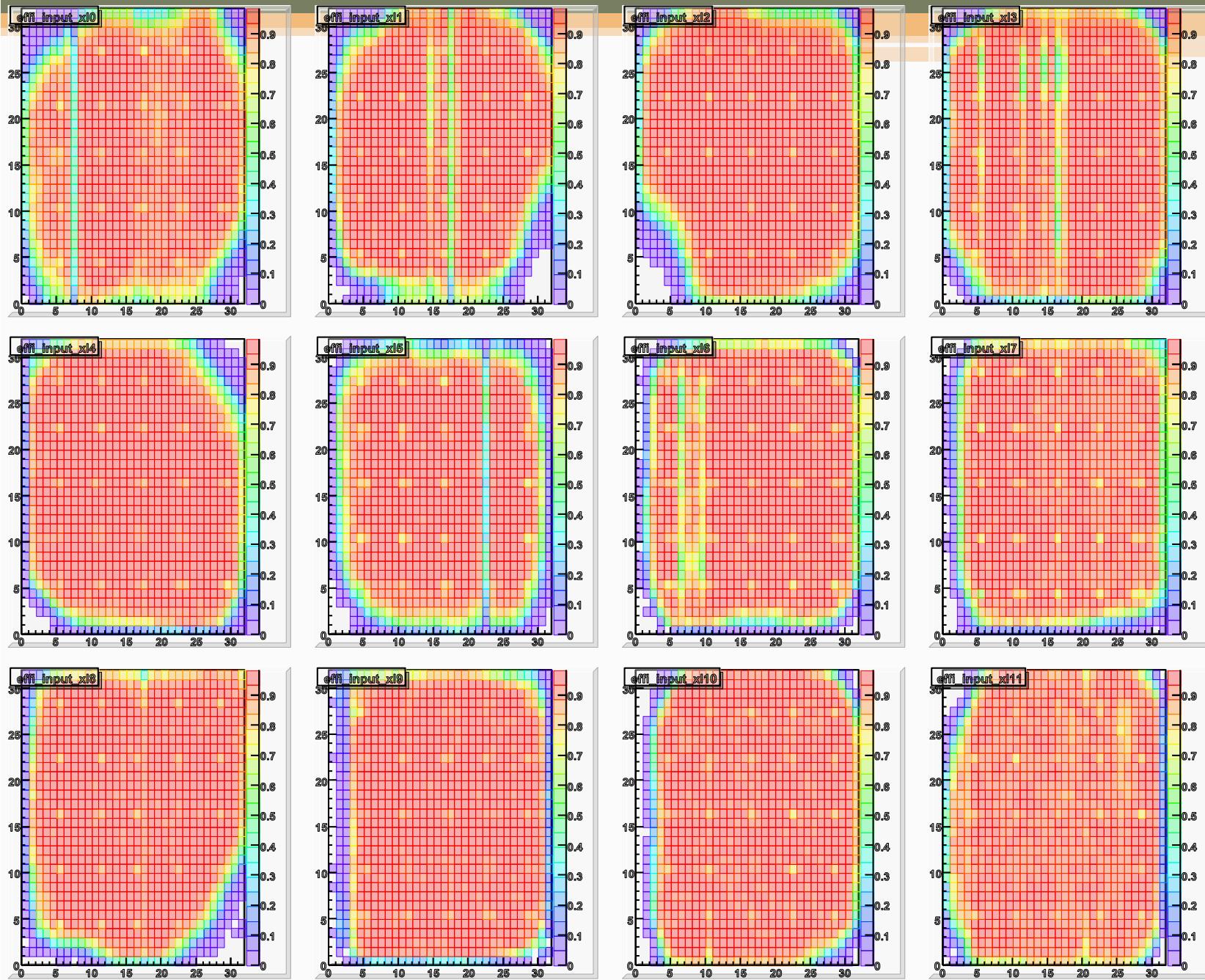
- At this stage a hit point in this Monte-Carlo based calculation is still accepted with 100% efficiency where ever it is, either central region of the RPC or at the corner.
- As the hit point generation use uniform random number this 100% efficiency is obvious.
- In reality, there is a variation of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

# Pixel wise tracking efficiency for layer 1(X side)

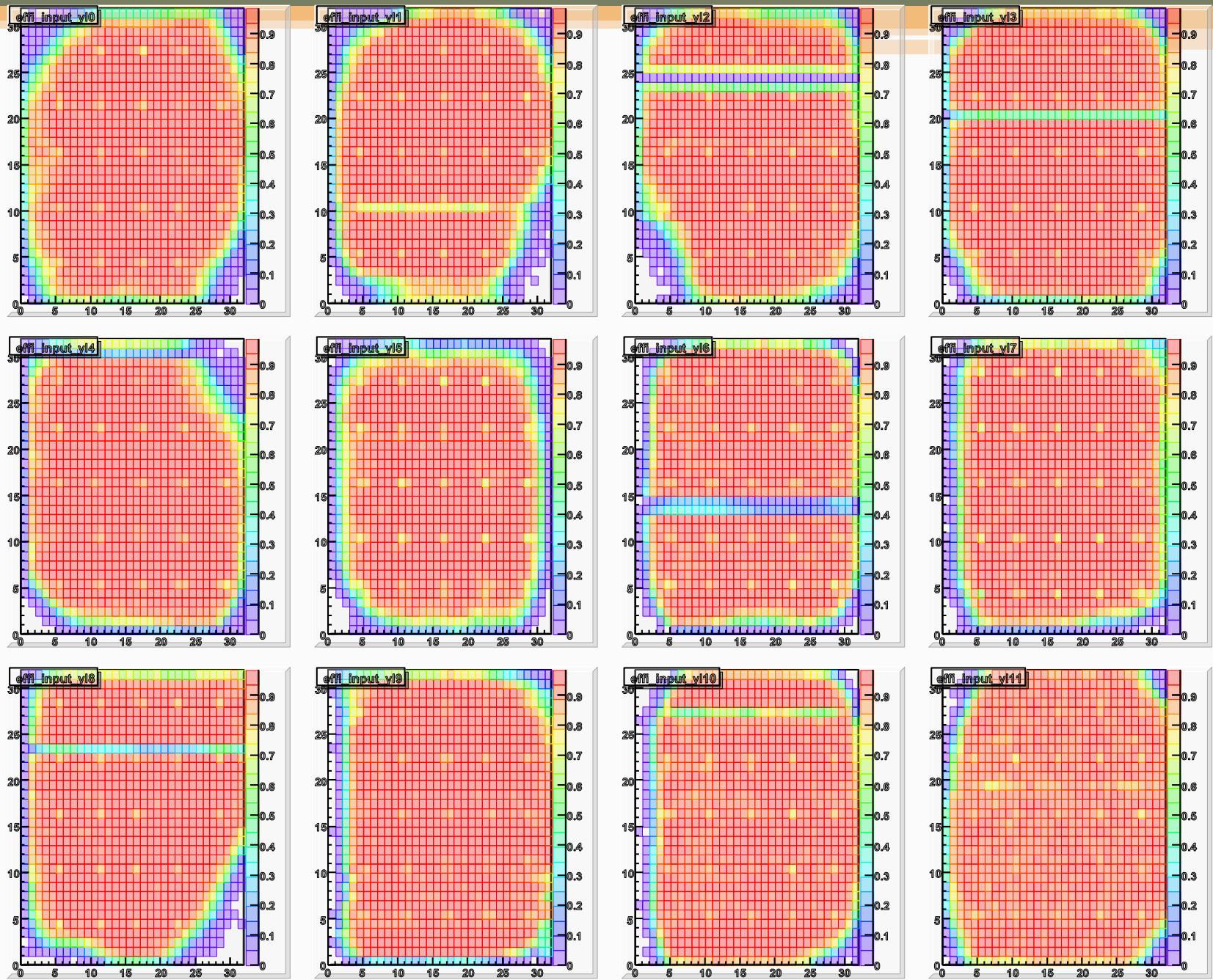
- ❖ Trigger with layers 0,1,3,4 are used to get the efficiency for layer 6 to 11.
- ❖ Trigger with layers 7,8,10,11 are used to get efficiency for layers 0 to 5.



## X side efficiency



## Y side efficiency

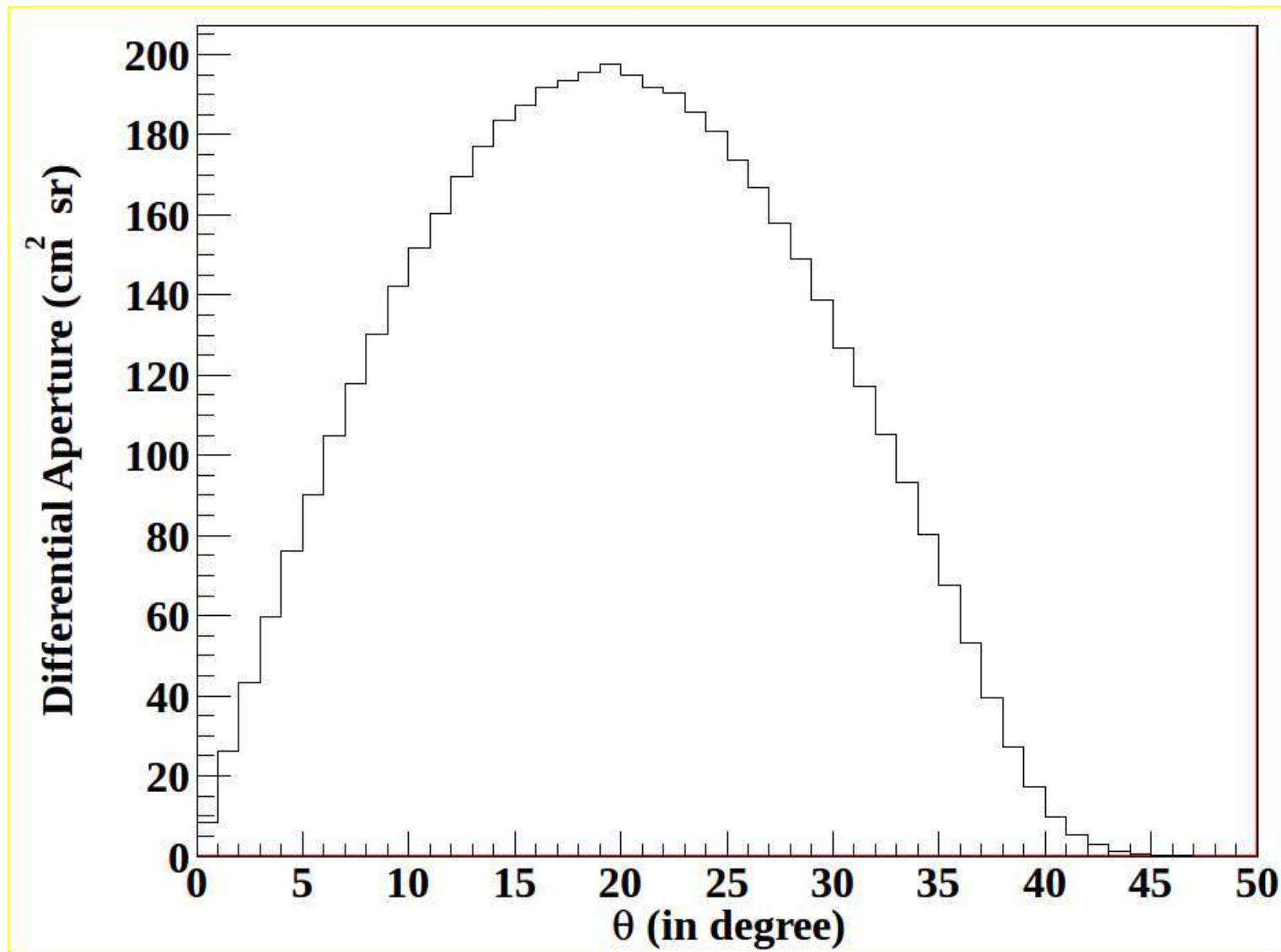


# Detector acceptance

- 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.

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


# Detector geometrical acceptance profile

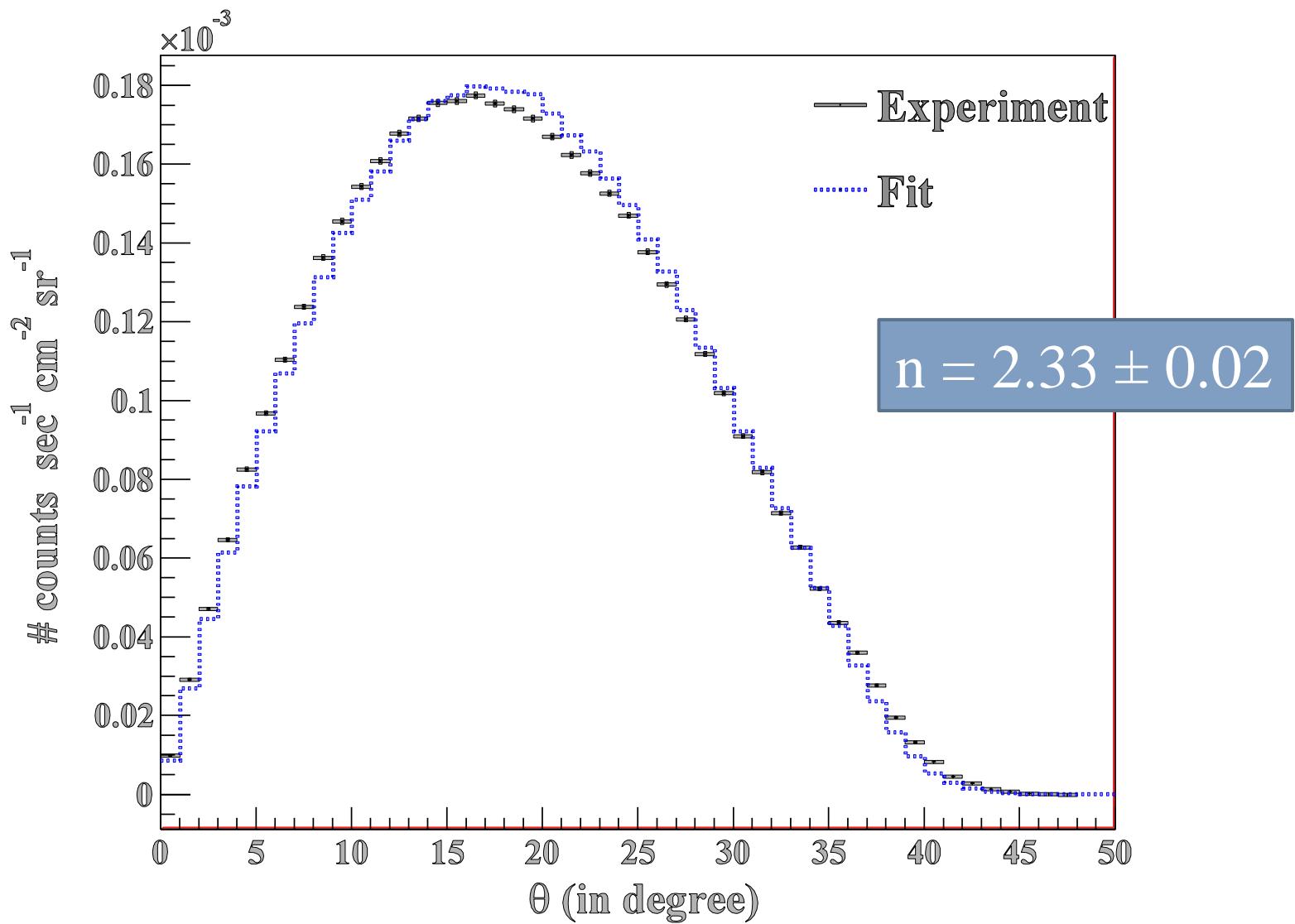


# Chi-square definition to get $I_0$ & $n$

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

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

# 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  $\theta$  is generated uniformly over the solid angle, i.e.,  $\int \sin \theta d\theta$
  - Now to get back the vertical flux  $\theta$  has to be generated through  $\int \cos^{2.33} \theta \sin \theta d\theta$

## Contd.

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

- Time : total time through which data is collected with dead time correction
- $\epsilon$  are efficiency correction to get the actual number fallen on top of the detector
- $\Omega$  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	Momentum	Flux $\times 10^{-3}$
	Lat. ( $^{\circ}$ N)	$P_c$ (GV)	(m)	(GeV/c)	( $\text{cm}^{-2} \text{ sec}^{-1} \text{ Str}^{-1}$ )
Allkofer et al. <sup>1</sup>	9	14.1	S.L.	$\geq 0.32$	$7.25 \pm 0.1$
Karmakar et al. <sup>2</sup>	16	15.0	122	$\geq 0.353$	$8.99 \pm 0.05$
				$\geq 1.0$	$6.85 \pm 0.04$
Gokhale <sup>3</sup>	19	--	--	$\geq 0.32$	$7.3 \pm 0.1$
Fukui et al. <sup>4</sup>	24	12.6	S.L.	$\geq 0.34$	$7.35 \pm 0.2$
<b>Present Data</b>	<b>18</b>	<b>--</b>	<b>S.L.</b>	<b><math>\geq 0.287</math></b>	<b><math>6.050 \pm 0.001</math></b>
Rossi <sup>5</sup>	$\geq 50$	$\sim 1.8$	S.L.	$\geq 0.32$	8.3
Greisen <sup>6</sup>	54	1.5	S.L.	$\geq 0.33$	$8.3 \pm 0.1$
Crookes & Rastin <sup>7</sup>	53	2.2	40	$\geq 0.35$	$9.13 \pm 0.12$

# 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. Cruk & 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<sup>th</sup> Feb., Poster Session).
- Preliminary results on optimization of gas flow rate for RPCs, by S.D.Kalmani, TIFR (8<sup>th</sup> Feb).
- Proposed Trigger Scheme for the ICAL detector of INO, by Sudeshna Dasgupta, TIFR (9<sup>th</sup> Feb).



*Thank you*