How Muons Are Reconstructed in Different Regions of ICAL

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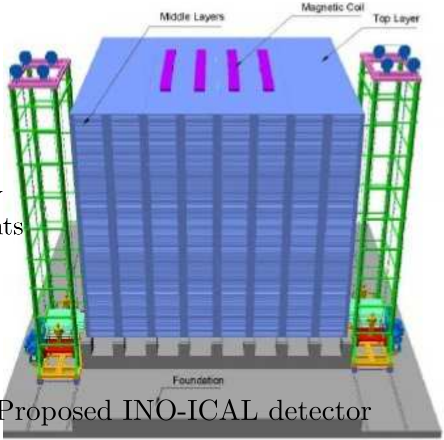
Contents

Introduction

- India-based Neutrino Observatory (INO): Proposed underground facility at Bodi West hills of Theni District of Tamil Nadu, with rock cover of approx 1200 m, which is desirable to study atmospheric muon neutrinos
- Iron CALorimeter (ICAL): Magnetised, aims to determine neutrino oscillation parameters precisely with atmospheric muon neutrinos, matter effect in oscillations and the sign of Δm^2_{32} using matter effect
- Other proposed expts. such as neutrinoless double beta decay expts and dark matter experiments will also be supported in INO



Proposed INO-ICAL detector

ICAL detector specifications

ICAL	Dimensions
No. of modules	3
Module dimension	16 m $\times$ 16m $\times$ 14.4m
Detector dimension	48 m $\times$ 16m $\times$ 14.4m
No. of layers	150
Iron plate thickness	5.6 cm
Gap for RPC trays	4 cm
Magnetic field	1.3 T
RPC	Dimensions
RPC unit dimension	1.84m $\times$ 1.84 m $\times$ 24 mm
Read out strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no. of RPC units	28800
No. of electronic readout channels	$\sim 3.7 \times 10^6$

Motivation

- One of the main aim of ICAL is to determine the mass hierarchy, using the different oscillation signatures for neutrinos vs anti-neutrinos in presence of matter effects
- Matter effects become important in few GeV energy region; sensitive to $E, \cos\theta$ (through path length travelled) of neutrinos
- Reconstruction of E and $\cos\theta$ depends on the energy and direction of muons and hadrons produced

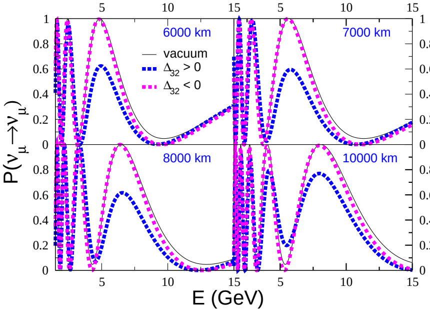


Figure 1: Muon neutrino survival probability in vacuum and matter.
Source: INO Report 2006

Motivation, Cont'd...

- Survival probability of ν_μ in matter is:

$$
\begin{aligned}
P^m_{\mu\mu} &\approx 1 - \sin^2 2\theta_{23}\ \left[\sin^2\theta^m_{13}\sin^2\Delta^m_{21} + \cos^2\theta^m_{13}\sin^2\Delta^m_{32}\right] \\
&\qquad - \sin^4\theta_{23}\sin^2 2\theta^m_{13}\sin^2\Delta^m_{31} \\
&\equiv P^{(2)}_{\mu\mu} - \sin^2\theta_{13} \times \\
&\quad \left[\frac{A}{\Delta - A}T_1 + \left(\frac{\Delta}{\Delta - A}\right)^2 \left(T_2 \sin^2[(\Delta - A)x] + T_3\right)\right],
\end{aligned}
$$

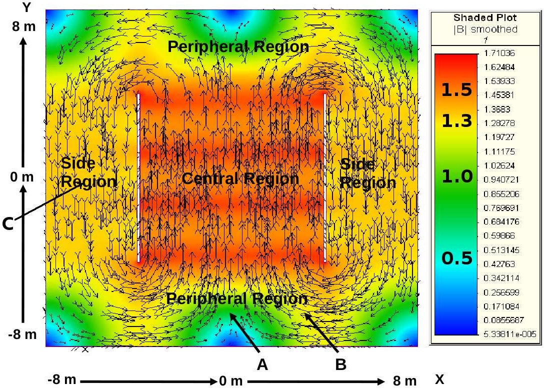
  where $A = 7.6 \times 10^{-5}\rho(\text{gm/cc})\,E(\text{GeV})$, and $\Delta = (m_3^2 - m_2^2)$; A is positive for ν and negative for $\bar{\nu}$

- ν interacts in ICAL to give μ^- and $\bar{\nu}$ gives μ^+; hence, charge identification (cid) is important for measurement of the mass hierarchy. Note that ICAL has cid possibility because of magnetic field

- In addition, we need to measure E and $\cos\theta$ of muons; hence, muon resolution studies are crucial

Magnetic Field Mapping

- Central Region: Uniform magnetic field
- Side Region: Uniform magnetic field but smaller (15% less) and opposite to central region; acceptance effects are an issue
- Peripheral Region: Changing magnetic field, smaller in magnitude but both B_x and B_y components; also acceptance effects



Peripheral A: $(x = 0, y = -650)$ cm; B: $(x = 300, y = -650)$ cm

Side "C": $(x = -2270, y = 0)$ cm

(13, 17, 18)

Methodology

- In ICAL, muons are reconstructed according to INO-ICAL code through a Kalman filter algorithm that returns both the magnitude and direction of the muon momentum
- Muon momentum can be reconstructed through the curvature of their track, closest to the vertex whereas hadron energy is calculated using the hit information from hadron shower (refer posters by Daljeet and Lakshmi on hadron resolution)
- In addition, direction of curvature gives charge of muon
- So, we have analysed behaviour of muons in different regions of ICAL
- Results on muon momentum and angular resolution, reconstruction and charge identification efficiencies are presented here

Definitions

- Momentum resolution:
$$R = \frac{\sigma}{P_{\rm in}} \ ,$$
where $(\delta R/R)^2 = (\delta\sigma/\sigma)^2$
- Angular resolution: $\cos\theta$ is studied, where θ is both the polar and zenith angle
- Reconstruction efficiency: is the ratio of total no. of reconstructed events $n_{\rm rec}$ (irrespective of charge) to the total no. of events, $N_{\rm total}$
$$\epsilon_{\rm rec} = \frac{n_{\rm rec}}{N_{\rm total}} \ , \delta\epsilon_{\rm rec} = \frac{\sqrt{r}(1-r)}{N_{\rm total}} \ ; r = n_{\rm rec}/N_{\rm total} \ .$$
- Relative charge identification efficiency: is ratio of number of events with correct charge identification, $n_{\rm cid}$, to the total number of reconstructed events
$$\epsilon_{\rm cid} = \frac{n_{\rm cid} \pm \delta n_{\rm cid}}{n_{\rm rec} \pm \delta n_{\rm rec}} \ ,$$
where $\delta n_{\rm cid}$ and $\delta n_{\rm rec}$ are inter-dependent so the error is $\sqrt{r}(1-r)/n_{\rm rec}$; $r = n_{\rm cid}/n_{\rm rec}$

A sample event generated in ICAL detector

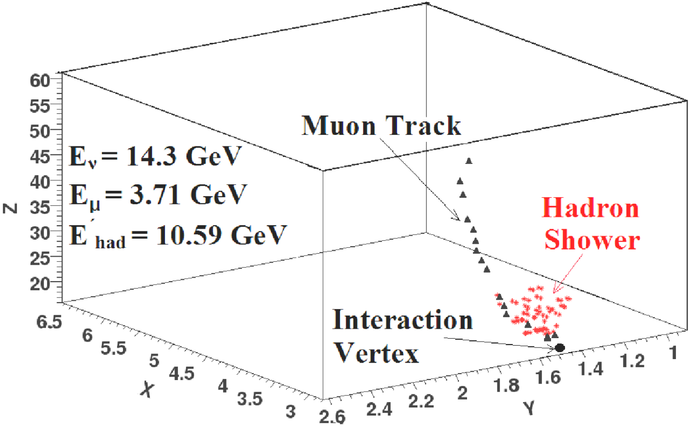
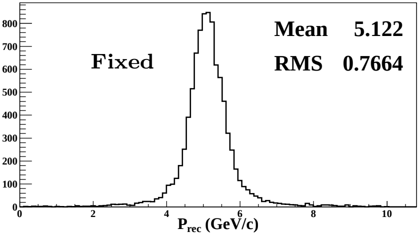
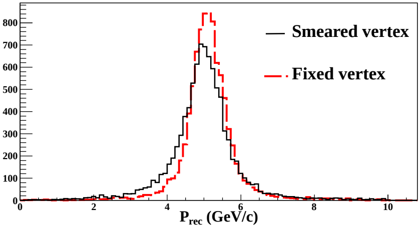


Figure 2: A sample event generated in ICAL showing muon track and hadron shower

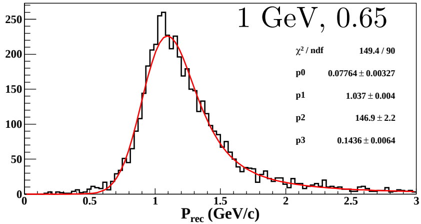
Muons in Central Region

- Fixed and Smeared vertex muons: Example, for $(E, \cos\theta) = (5\text{ GeV}, 0.65)$



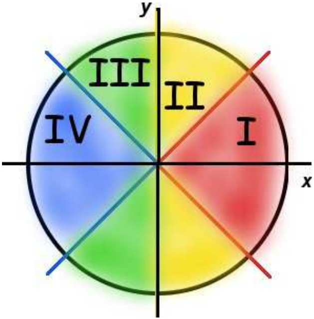


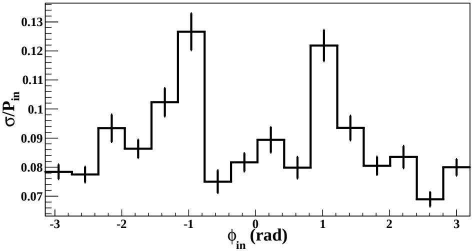
- Low energy muons: Landau convoluted Gaussian fits for $E \leq 2$ GeV; gaussian fits for $E > 2$ GeV



Azimuthal dependence

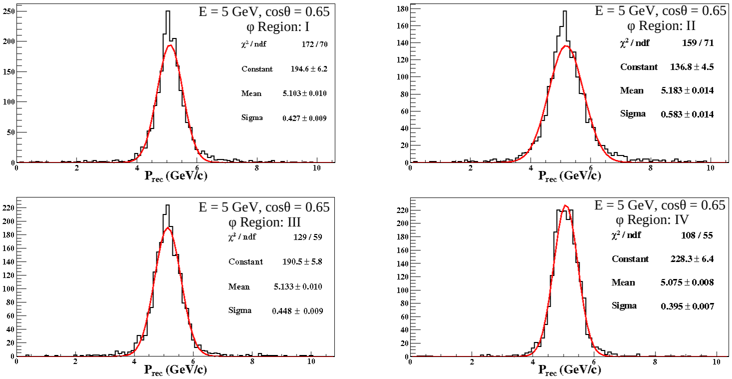
- Muons with different ϕ have different detector response.
- So muon sample is divided into four regions: I: $|\phi| < \pi/4$,II: $\pi/4 \leq |\phi| < \pi/2$,III: $\pi/2 \leq |\phi| < 3\pi/4$,IV: $|\phi| \geq 3\pi/4$



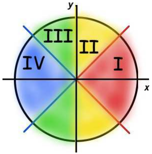


- Momentum resolution for μ^- with $(E, \cos\theta) = (5\text{ GeV}, 0.65)$, plotted in bins of ϕ.
- Notice resolutions are symmetric in ϕ; worse when the muon momentum is parallel to the magnetic field (y-axis)

$(E, \cos\theta) = (5\text{ GeV}, 0.65)$: ϕ Analysis



- Region IV has the best resolution since we are studying up-going μ^- in the central region and the magnetic field is in the $+y$ direction (See page 7)



More details in poster: A Simulations Study of the Response of ICAL Detector to Muons

Fixed Vertex Muon Resolution

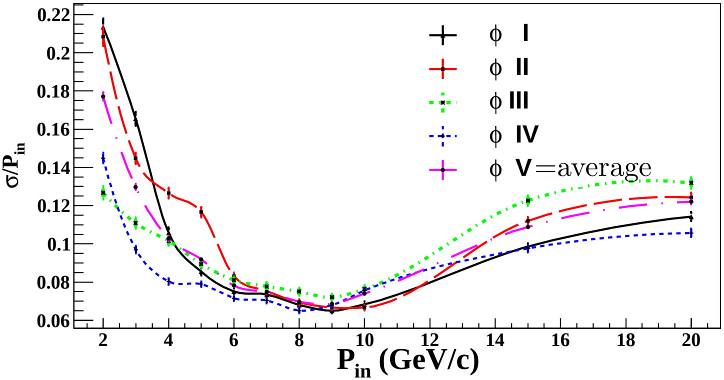
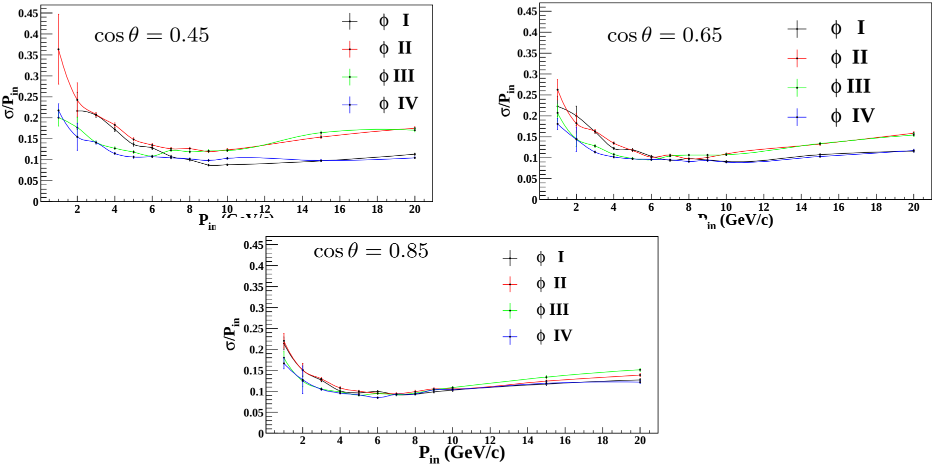


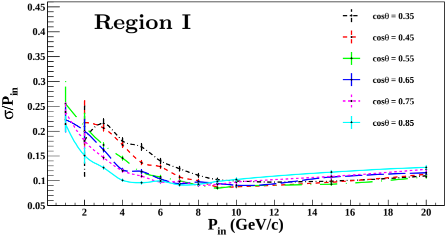
Figure 3: Momentum resolution for fixed vertex muons as a function of energy for different ϕ regions and at $\cos\theta = 0.65$ (Note: V : ϕ averaged)

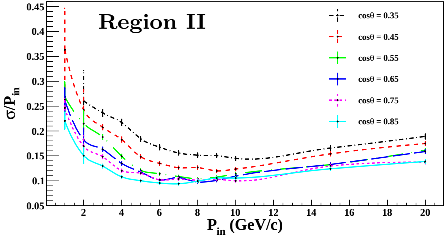
Smeared Vertex Muon Resolution

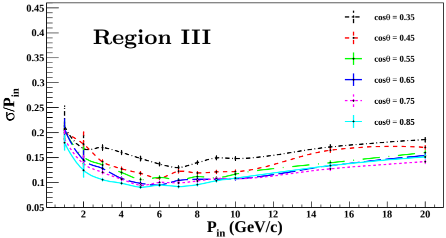


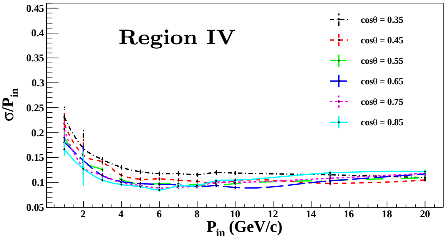
- Resolution improves with increasing $\cos\theta$ for the same E
- Resolutions worse in ϕ regions II and III where v_y component is large (esp at large E)
- Resolution in ϕ region IV best, as before

Resolution in Different ϕ Regions

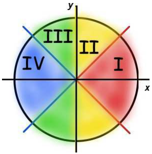




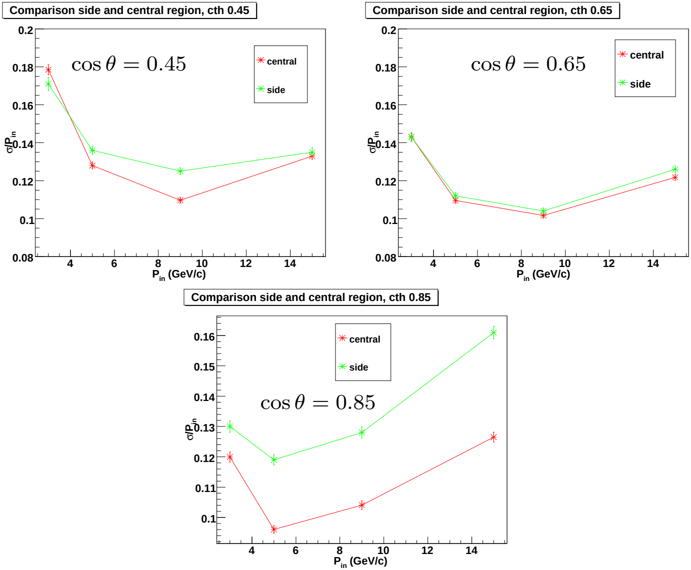




- Region IV has the best resolution
- Region II is the worst
- Generic behavior (E dep) same for all



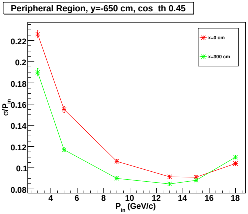
Comparison of Resolutions in Side vs Central Region

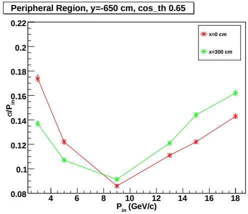


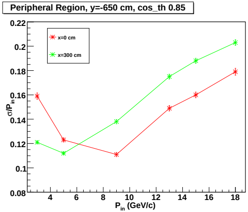
- Central systematically better because larger **B** (See page 7)

Resolutions in Peripheral Regions (A and B)

- Cuts: Either the track is completely contained or else it must have nhits > 20 for B or nhits > 30 for A

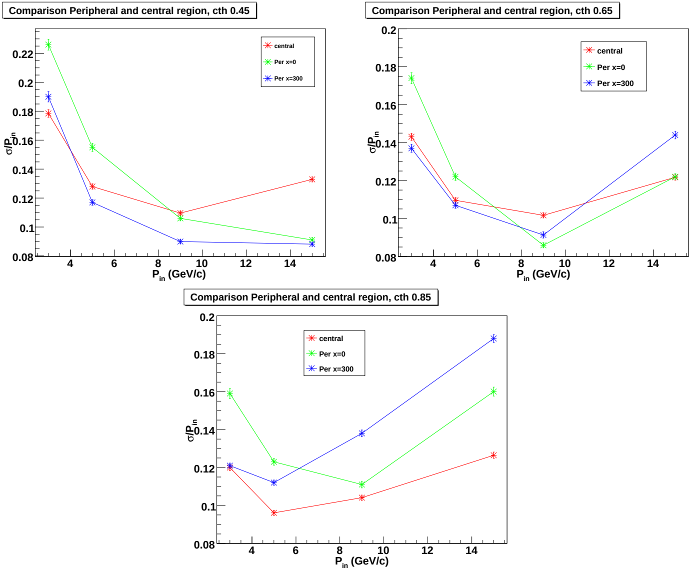






- At cosθ=0.45, B is better since it has both (B_x, B_y) (Page 7)
- At vertical angles, B is better in low energies as most of the events are inside the detector but at high energies events goes out of detector

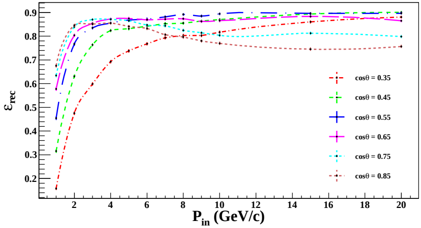
Comparison of Peripheral A, B, vs Central



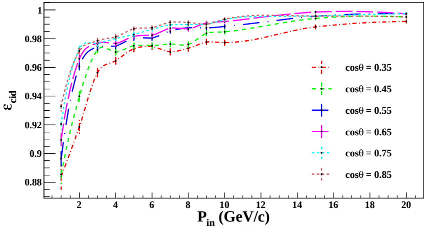
- Comparison more complicated because of different **B** as well as edge effects

Efficiencies in Central Region

- Reconstruction Efficiency

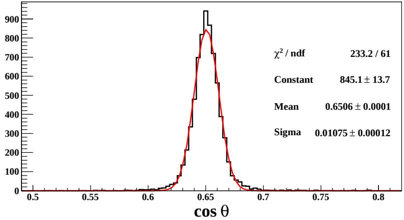


- Cid Efficiency

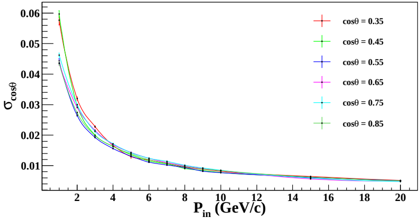


$\cos\theta$ Resolution in Central Region

- Reconstructed cosθ distribution for (E,cosθ) = (5 GeV, 0.65)



- Cosθ resolution as a function of E



Discussion and Summary

- ICAL is optimised for studying matter effects so the best energy resolution is at $E \sim 6$–8 GeV
- The resolution (esp at smaller E) improves as $\cos\theta$ increases
- The resolution worsens somewhat when the muon vertices are smeared over a larger volume
- Muon response in different ϕ regions is different due to different response to B field
- In the central region, the best resolution is $\sim 7\%$ at $E \sim 6$–8 GeV. Worsens to 10% for smeared muons. Worsens marginally $\sim 11\%$ in side region where $\mathbf{B}$ is smaller
- Resolution more complicated in peripheral region because of presence of both B_x and B_y; can be better or worse than central region, depending on location and $\cos\theta$ value
- In all regions, angular resolution of muons is very good, better than a degree for $E >$ few GeV
- In all regions, the cid is very good, 98-99%
- Understood muon response in whole ICAL region

References and Acknowledgements

This work is done in collaboration with:
A. Chatterjee, T. Thakore, V. Bhatnagar, R. Gandhi,
D. Indumathi, N.K. Mondal, N. Sinha.

INO Web-site: http://www.ino.tifr.res.in/ino/

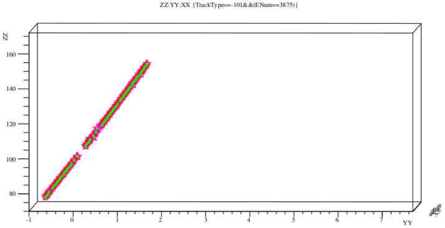
Acknowledgement: Thanks to INO collaboration,
DAE/DST and NUFACT for support.

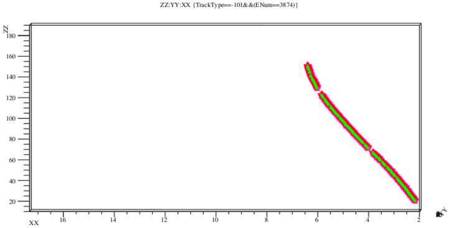
THANK YOU

B A C K - U P S L I D E S

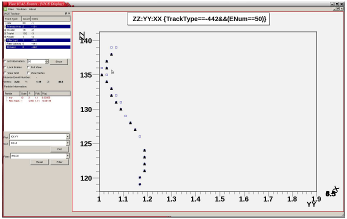
Back-up Slides 1

- Muon discontinuous track in ICAL due to support structure giving multi-tracks; (E, cosθ) (16 GeV,0.95), event=(3875, 3874)



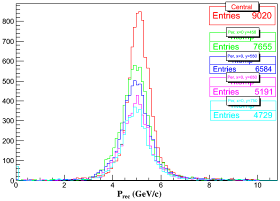


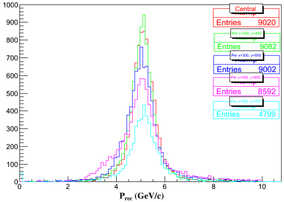
- (E, cosθ) = (3 GeV,0.95)



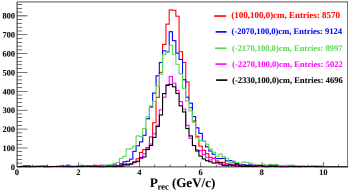
Back-up Slides 2

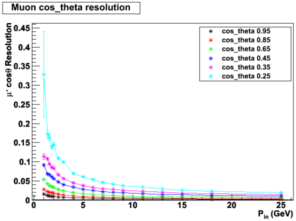
- Momentum distribution at x=0, 300 and y=-450, -550, -650, -750





- Left: Momentum distribution at x=-2070, -2170, -2270, -2330 and y=100 cm. Right: $\sigma/\cos\theta$ resolution in peripheral region (x=0)





Back-up Slides 3

- Inputs taken:

Softwares used	Geant 4.9.4.p02, inoical0_20112011
Events generated for μ^-	10000
Energy Range	1 - 20 GeV
Cosθ values	0.95, 0.85, 0.75, 0.65, 0.45, 0.35, 0.25, 0.15
ϕ smeared	0 - 2π

- Regions analysed:

Region	Vertex (cm)	smearing (cm)
Central	(100,100,0), (0,0,0)	(10,10,10),(400,400,600)
Peripheral	(0,y,0) (300,y,0) y= -650	(10,10,10)
Side	(x,0,0) x= -2270	(10,10,10)

- Cuts Taken:

Central	E <= 2 GeV	0-3 P_{in} , nhits[0] > 0, χ^2 / (2*nhits[0]-5) < 10, ntrkt[0]==1, poszin[0] <= 400
Central	E > 2 GeV	0-2 P_{in} , nhits[0] > 0, χ^2 / (2*nhits[0]-5) < 10, ntrkt[0]==1, poszin[0] <= 400
Peripheral x=0	E > 2 GeV	0-2 P_{in} , χ^2 / (2*nhits[0]-5) < 10, ntrkt[0]==1, ((abs(posyend[0]) <= 750 && nhits[0] > 0) || (abs(posyend[0]) > 750 && nhits[0] > 30))
Peripheral x = 300	E > 2 GeV	0-2 P_{in} , χ^2 / (2*nhits[0]-5) < 10, ntrkt[0]==1, ((abs(posyend[0]) <= 750 && nhits[0] > 0) || (abs(posyend[0]) > 750 && nhits[0] > 20))
Side	E > 2 GeV	0-2 P_{in} , χ^2 / (2*nhits[0]-5) < 10, ntrkt[0]==1, ((abs(posxend[0]) <= 2370 && nhits[0] > 0) || (abs(posxend[0]) > 2370 && nhits[0] > 20))