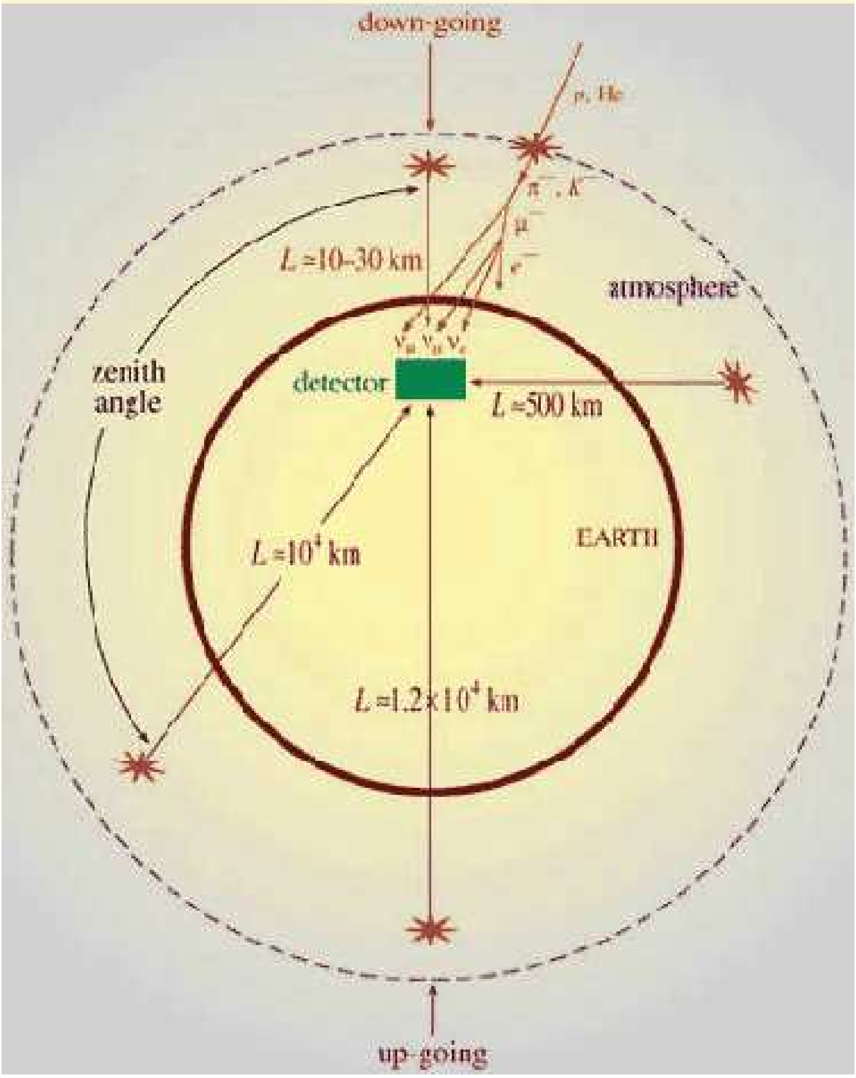
Status of the ICAL detector simulation and reconstruction

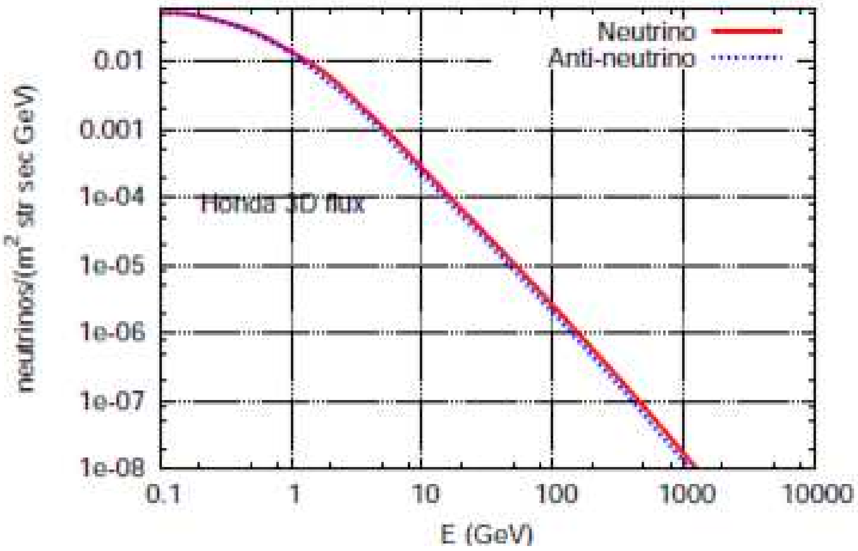
Outline

- Introduction
- Event Generator
- Detector geometry
- Digitisation
- Track Finder/Fitter Algorithm
- Hadronic/EM shower
- Event Display
- Framework
- Conclusion

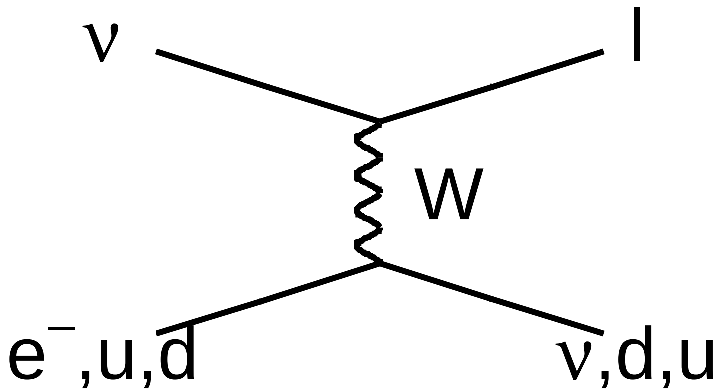
Neutrino interactions, flux and cross sections

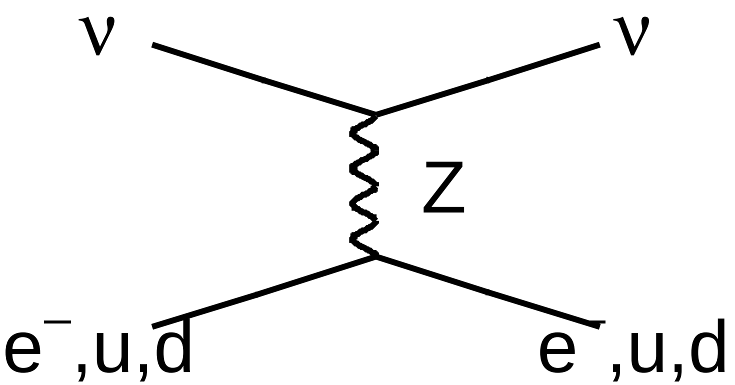
Figure 4

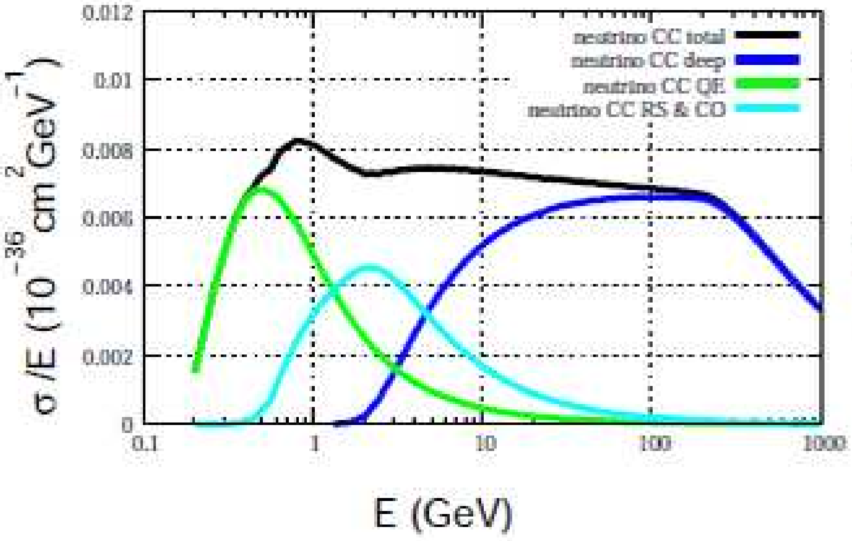


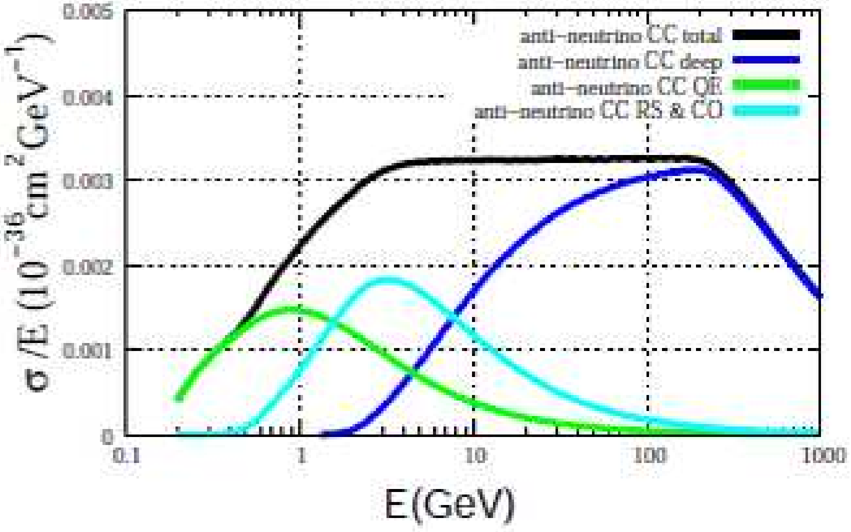


Neutrino interactions, flux and cross sections



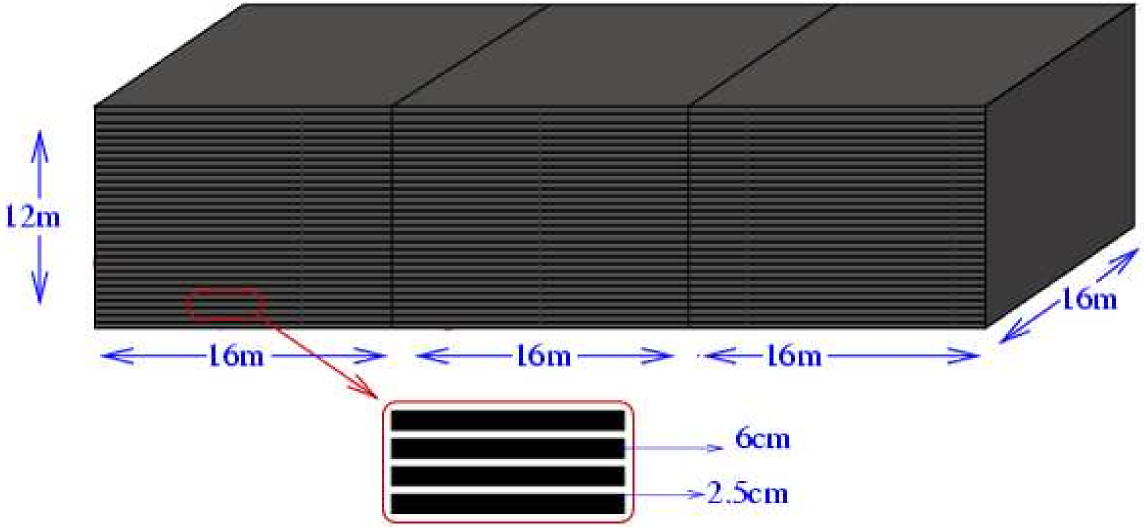




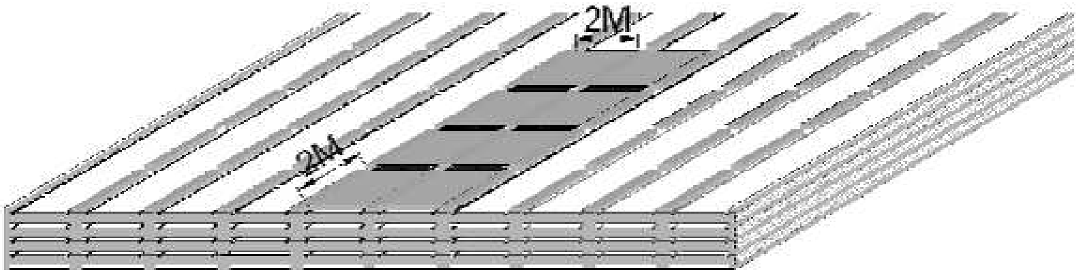


Focus on low energy neutrino/muon, $\sim$ 1GeV.

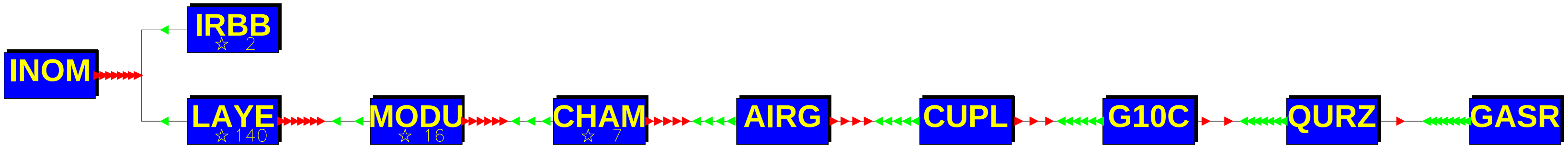
Basic ICAL geometry in simulation (Interim report)



Electronics and available IRON sheets forces us to use dimension 16m × 48m × 12.8m with iron thickness 5.6cm

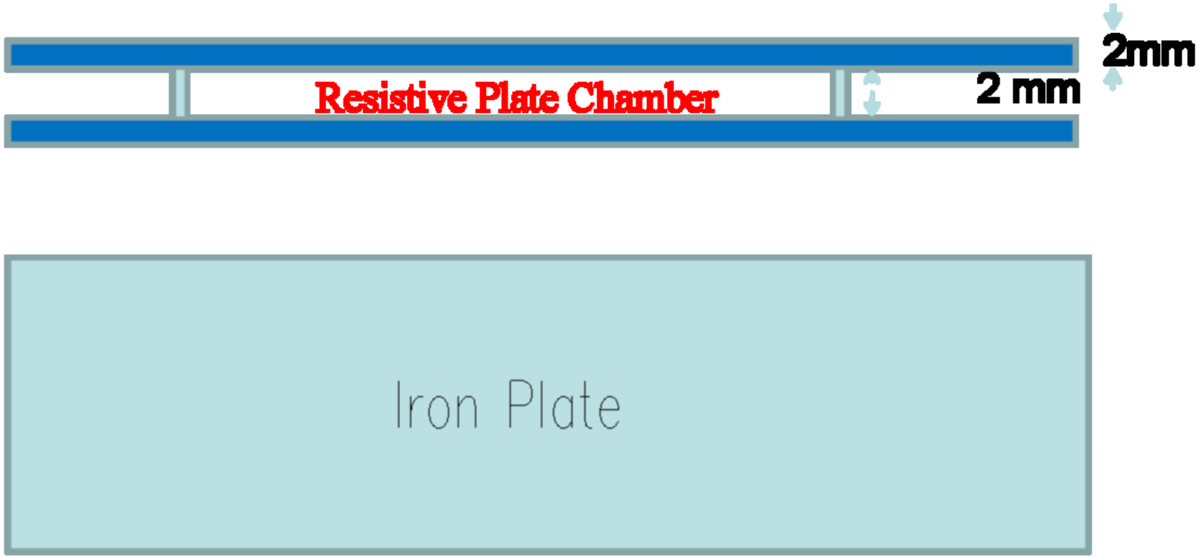


We had started with very simple geometry/code and now move from FORTRAN code to object oriented C++.


INOM
IRBB ☆ 2
LAYE ☆ 140
MODU ☆ 16
CHAM ☆ 7
AIRG
CUPL
G10C
QURZ
GASR

Event generation

- Neutrinos are originated at some source. → Flux
- It will undergo oscillate/decay before it reaches our detector. → Probability
- It will interact in the detector to produce a lepton + X. → Event generation



NUANCE, which can do all these was developed for SK. Necessary modifications were done for ICAL detector shape and its material.

Generate events in one unit of this volume and then randomly distributed over all RPC.
But, this software is not updated properly (last in 7 year back)

GINIE (Generates Events for Neutrino Interaction Experiments) is one of the best generator which we may use in future.

Event generation

NUANCE output for format for detector simulation (as input)

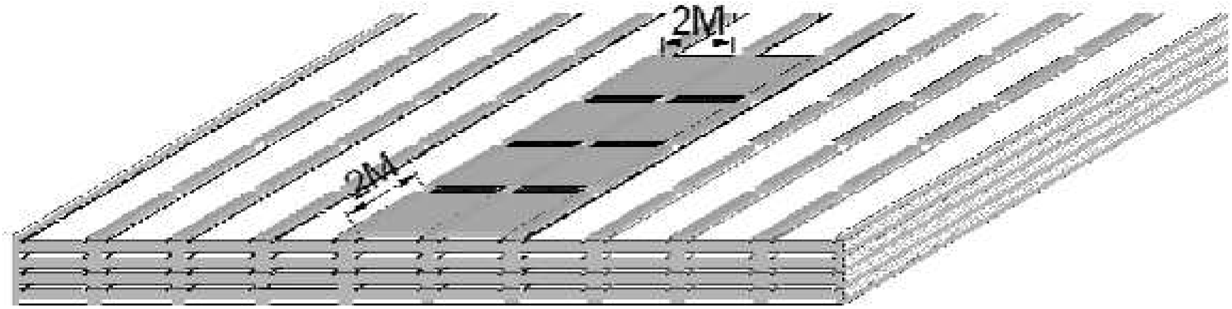
```
2   9    14  1135.1   318.30  -593.85   27.872    0.583  -24.703 0.211118E+05
2   1    13  1135.1   318.30  -593.85    5.386    0.767   -4.284 0.211118E+05
2   2   111  1135.1   318.30  -593.85   11.447   -0.456  -10.314 0.211118E+05
2   3    22  1135.1   318.30  -593.85    0.003    0.001    0.001 0.211118E+05
2   4  -211  1135.1   318.30  -593.85    3.090   -0.318   -2.721 0.211118E+05
2   5   211  1135.1   318.30  -593.85    6.025    0.427   -5.375 0.211118E+05
2   6   211  1135.1   318.30  -593.85    0.632   -0.147   -0.294 0.211118E+05
2   7  2212  1135.1   318.30  -593.85    0.423    0.424   -0.415 0.211118E+05
2   8  -211  1135.1   318.30  -593.85    0.107   -0.036   -0.098 0.211118E+05
2   9   310  1135.1   318.30  -593.85    0.761   -0.078   -1.203 0.211118E+05
```

Now we using both ascii as well as root format as input, eventually only root/Event structure.

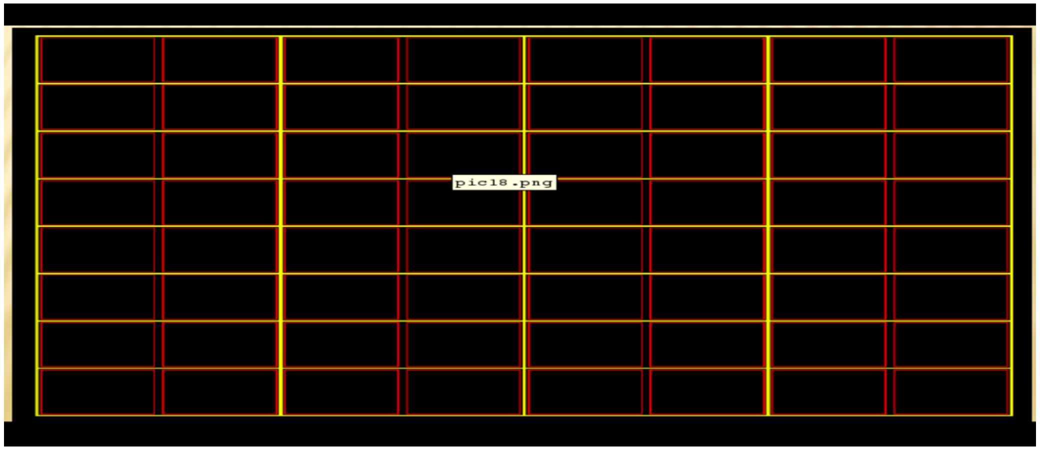
GEANT4 Simulation

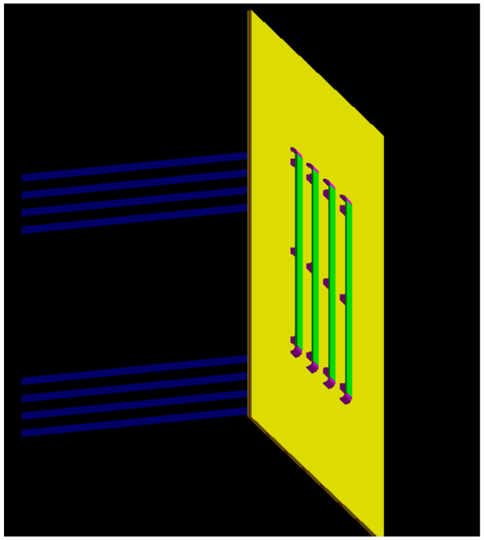
Basic features :

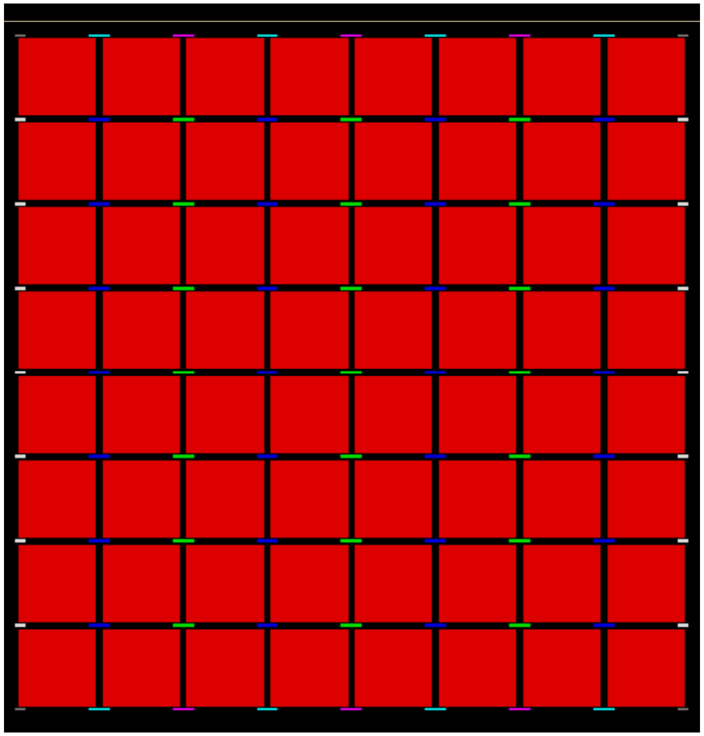
- Detector dimension : $48m \times 16m \times 14.4m$
- Number of modules : 3
- Module dimension: $16m \times 16m \times 14.4m$
- Number of RPC layers per module: 150
- Dimension of RPC: $1.84m \times 1.84m \times 24mm$
- Number of iron layers per module: 151
- Dimension of iron plate: $4m \times 2m \times 56mm$
- Gap for inserting RPC between two iron plates: 40mm

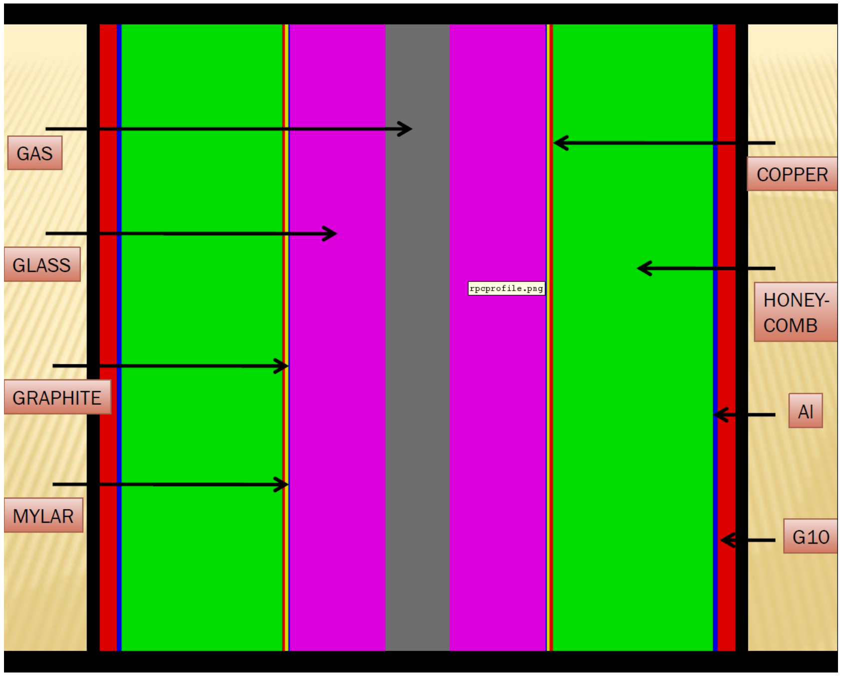


GEANT4 Simulation

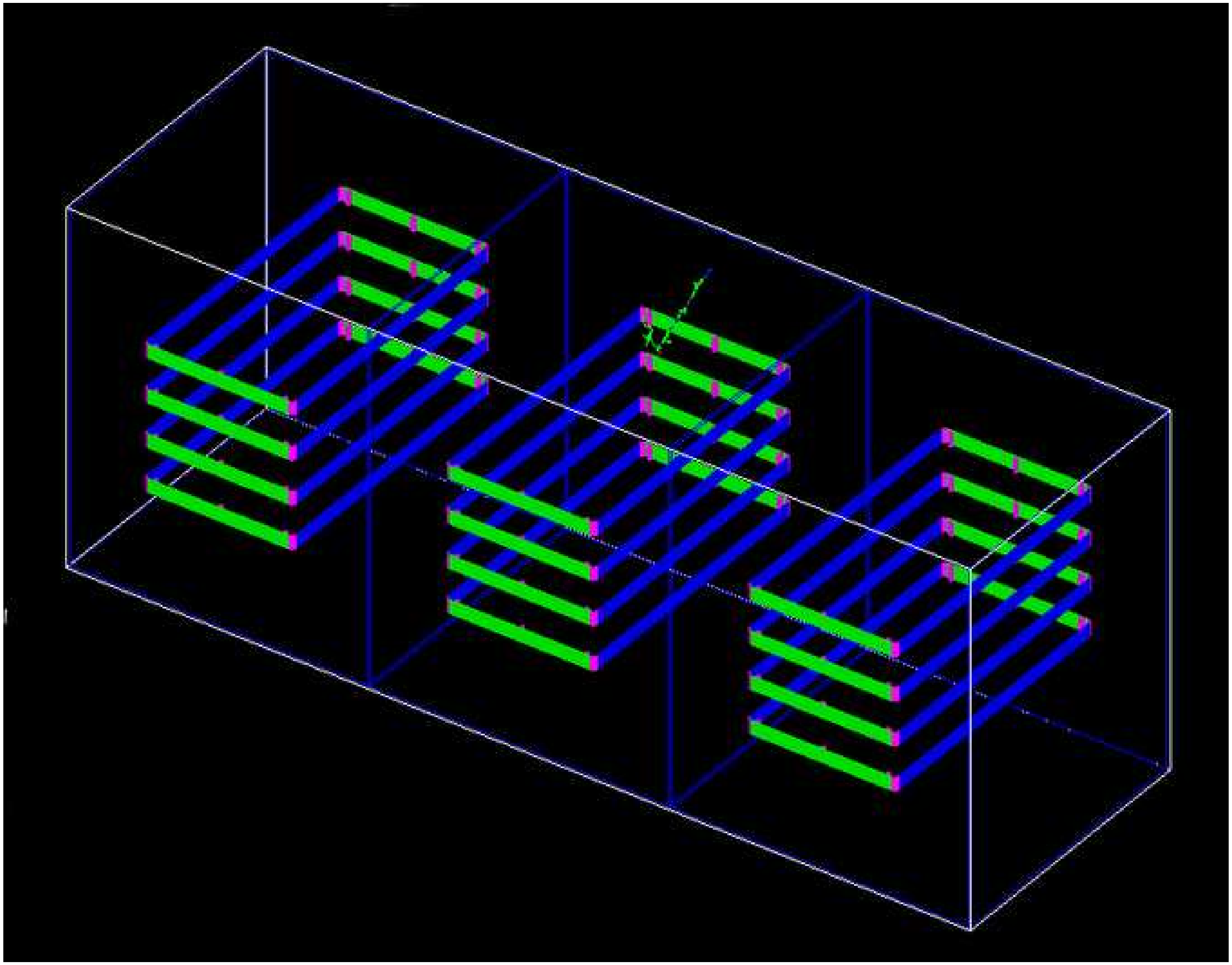








Present detector with magnetic coils

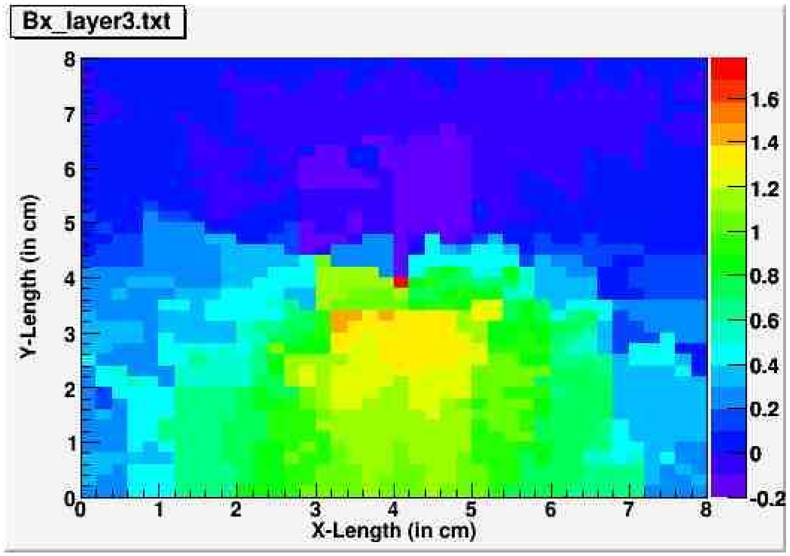


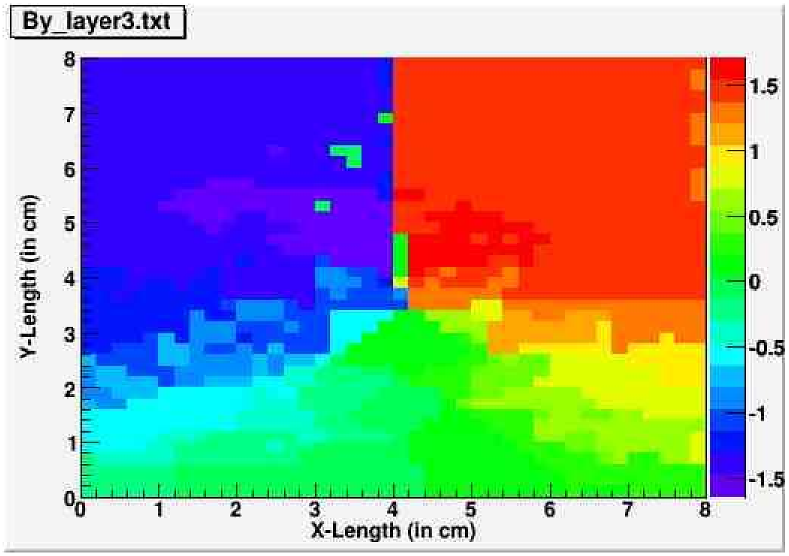
Y-direction : Outside board

Gap 9.6cm with 5.6cm iron

Magnetic field map

- Magnetic field is highly non uniform, sharp change in directions
- Have components of field in 3-D grid points
- Use 3-D non-linear extrapolation to extract field in each point.
- Extrapolation near edge (and change in field direction) has large error.





This is not final map, but trying to develop code using this old design

- Exact field will depend on the quality of iron, which may not be uniform
- Using probe, one can measure field in air, but what about inside iron ?

Simulation

- Detector parameters are put as member variables of a class. Same parameters are also used in digitisation and track reconstruction code. Will be extracted from Database.
- Magnetic field : Not implemented yet due to problem of interpolation function, but field in an arbitrary direction e.g. (1.0, 0.5, 0.0) or any function of position.
- At present, input kinematics from single/multi particle(s) and from Nunace Generator only. GINIE in future ?
- Store X-strip and Y-strip informations, which is our observable in real data. Strip informations are not included in GEANT4 simulation due to memory problem, strip number (ID) is calculated from the local co-ordinate of in RPC.

Standard softwares : GEANT4, root, CLHEP, QT

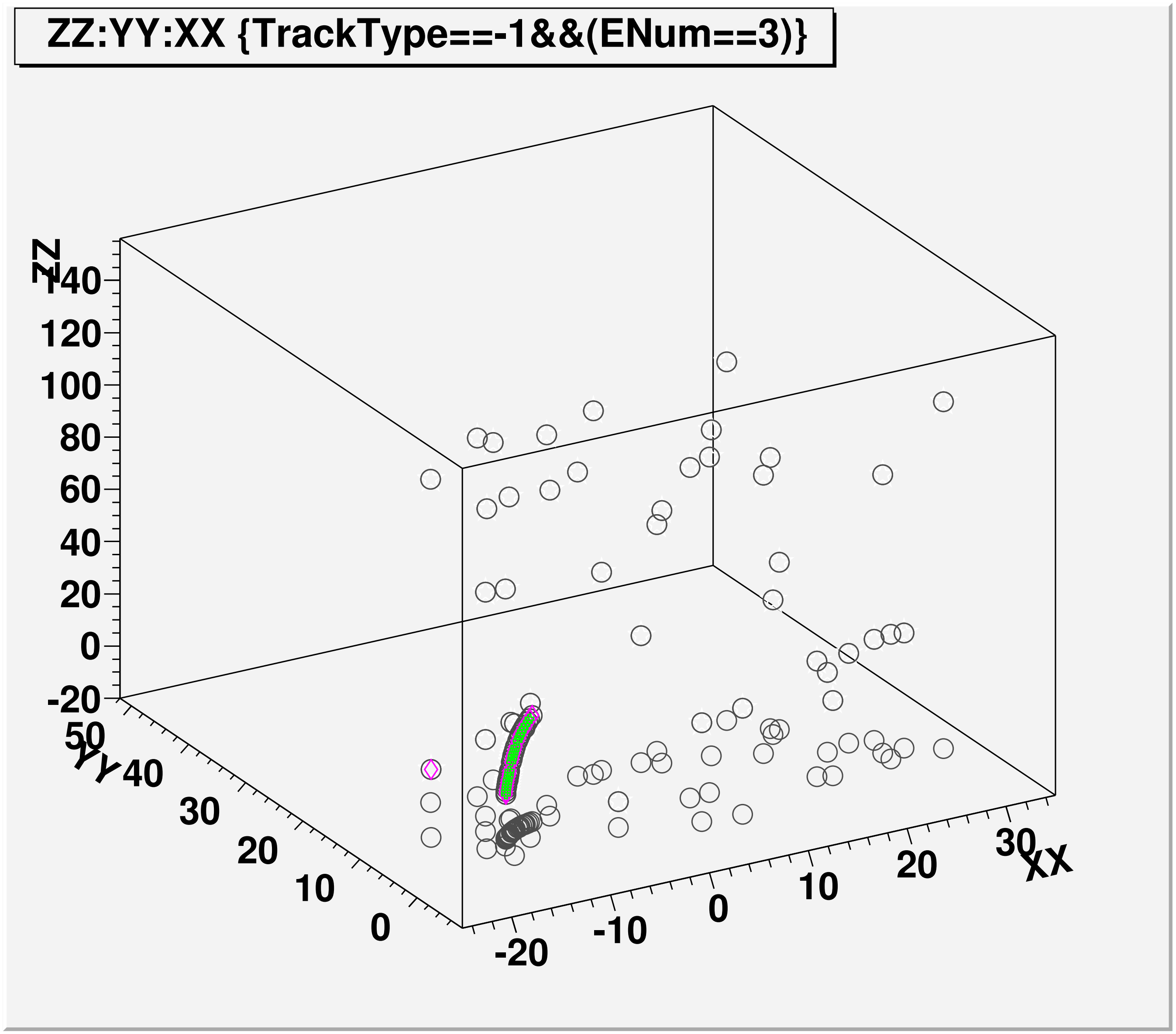
Digitisation

- Use threshold energy (minimum energy requires to produce electron-ion pair) to consider signal in a strip.
- Add inefficiency in strips though random number, e.g., 10%
- Noise in strips, add noisy strip (in the moment it is arbitrary, will put number according to real RPC)
- Convert Strip number to physics co-ordinate through database (what is used in detector construction)
- On the average, multiplicity of RPC hits is ~ 1.2
- At most we can have energy in three strips (from data).
- Combined X and Y strips for a 2D hit (position of traverse particle).
- Check timing information of strips to form a hit (window depends on background rate).

Digitisation

- Accept hits with only single strips too (which reduces inefficiency of hits).
- Combined nearby hits to form a cluster, basic elements for track finder algorithm. Here also looked for hits within certain time window.
- To reject hadronic shower/noisy RPC in track finder algorithm, special algorithm is used, which uses total hits in that RPC modules.
- Error in cluster, just Strip Width/$\sqrt{12}$, which is not true for the cases, where cluster contains more than one layer of strips.
- Smear timing information of hit by 1.5ns.
- Use 100ps as least count of TDC
- Smeared RPC positions for reconstructed cluster position (misalignment of a chamber in all three directions).

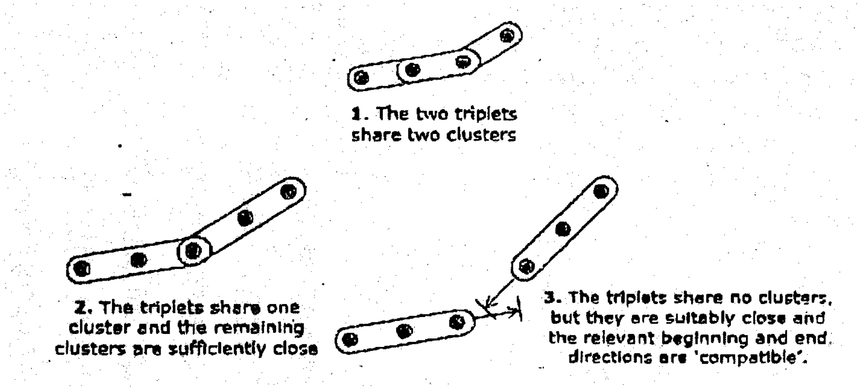
Track Finder Algorithm



Track fit algorithm is a CPU intensive job. Finder's job is to collect sets of hits, which could belongs to different track track

Track Finder Algorithm

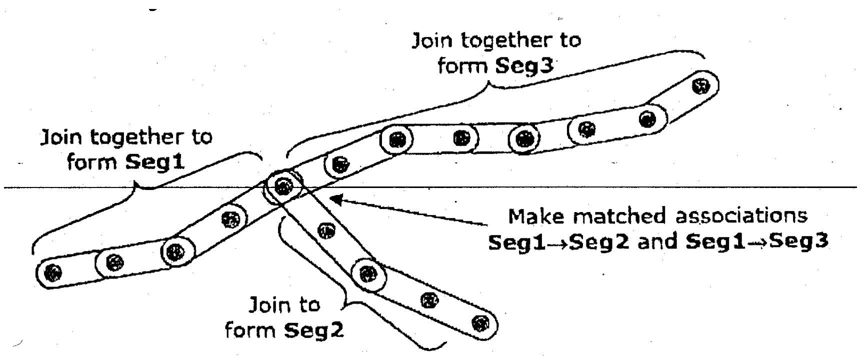
- Assumption: tracks are nearly straight
- Triplet : Formation (allowed maximum gap of two layers), join them in a chain, sort out the best choice as track candidate

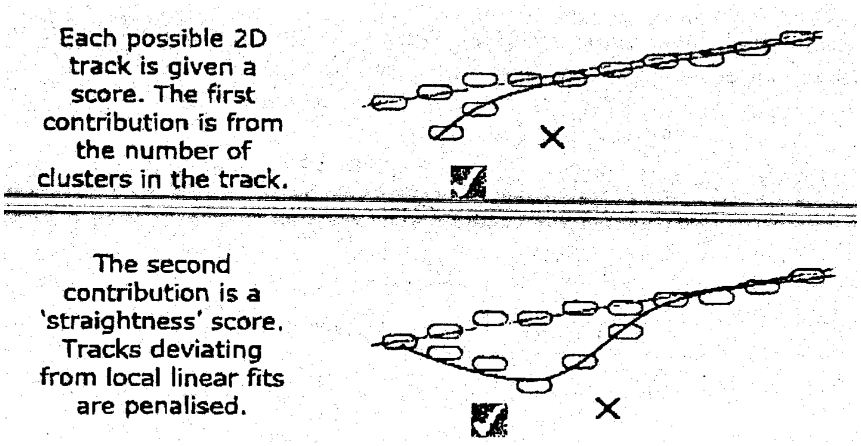


1. The two triplets share two clusters

2. The triplets share one cluster and the remaining clusters are sufficiently close

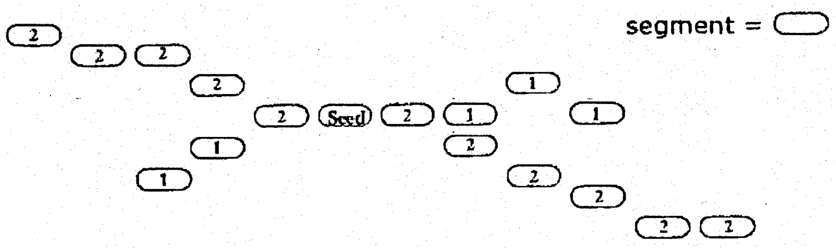
3. The triplets share no clusters, but they are suitably close and the relevant beginning and end directions are 'compatible'.





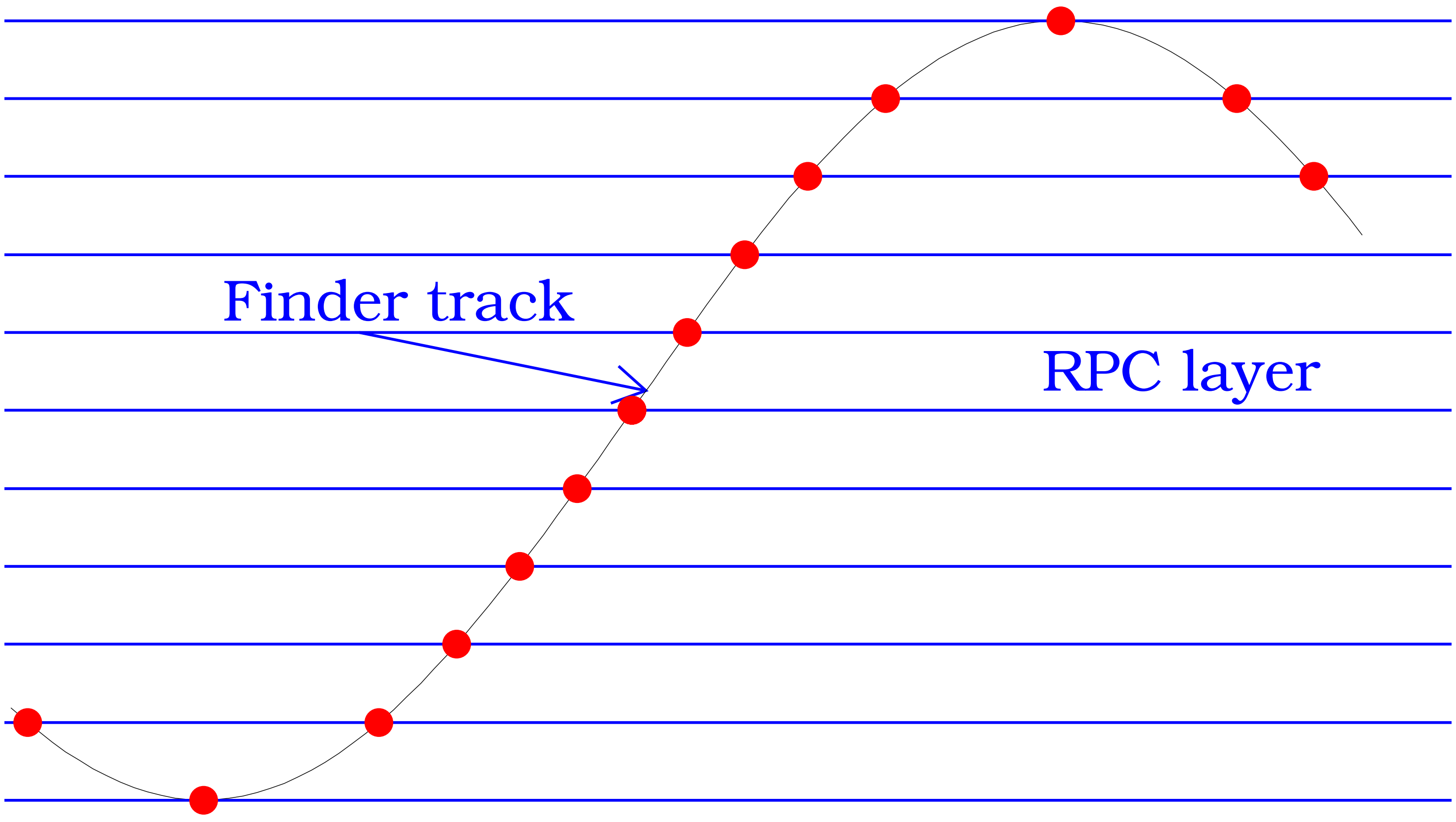
Each possible 2D track is given a score. The first contribution is from the number of clusters in the track.

The second contribution is a 'straightness' score. Tracks deviating from local linear fits are penalised.

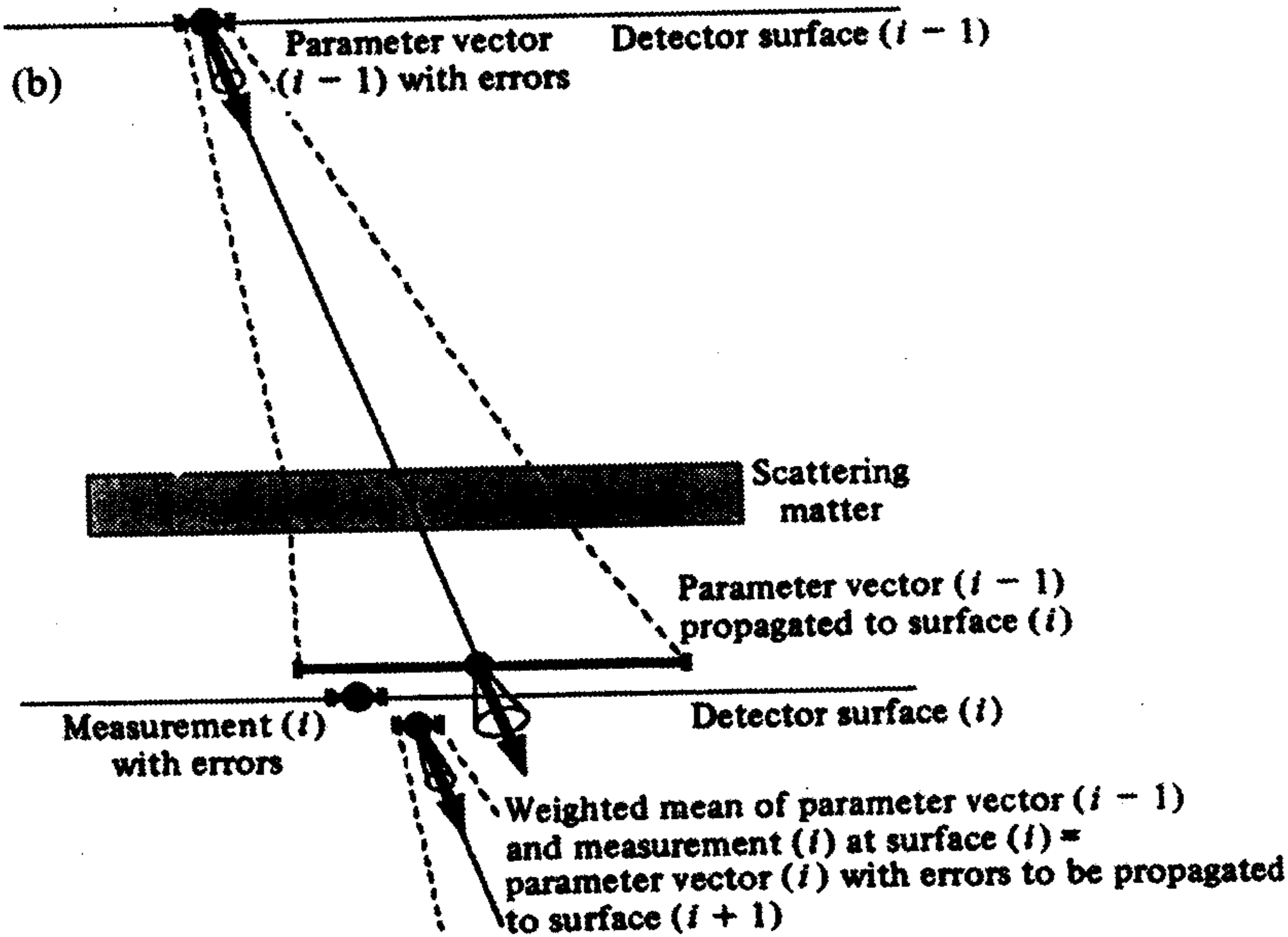


Track Finder Algorithm

- Large bending at tail, recovered using simple curve fitting.
- Gap between hits in two RPC is $\sim$ 16cm, special care taken to join in gaps, similarly in three ICAL modules.
- All these need optimisation (signal to background)

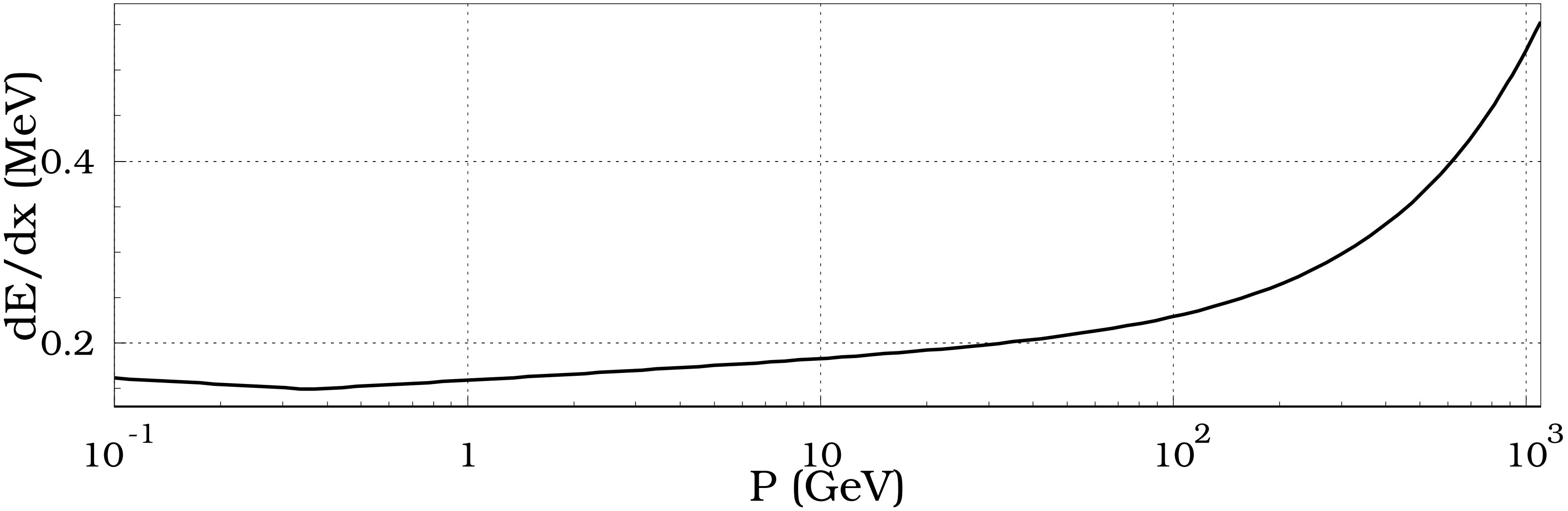


Fitting algorithm (Kalman technique)



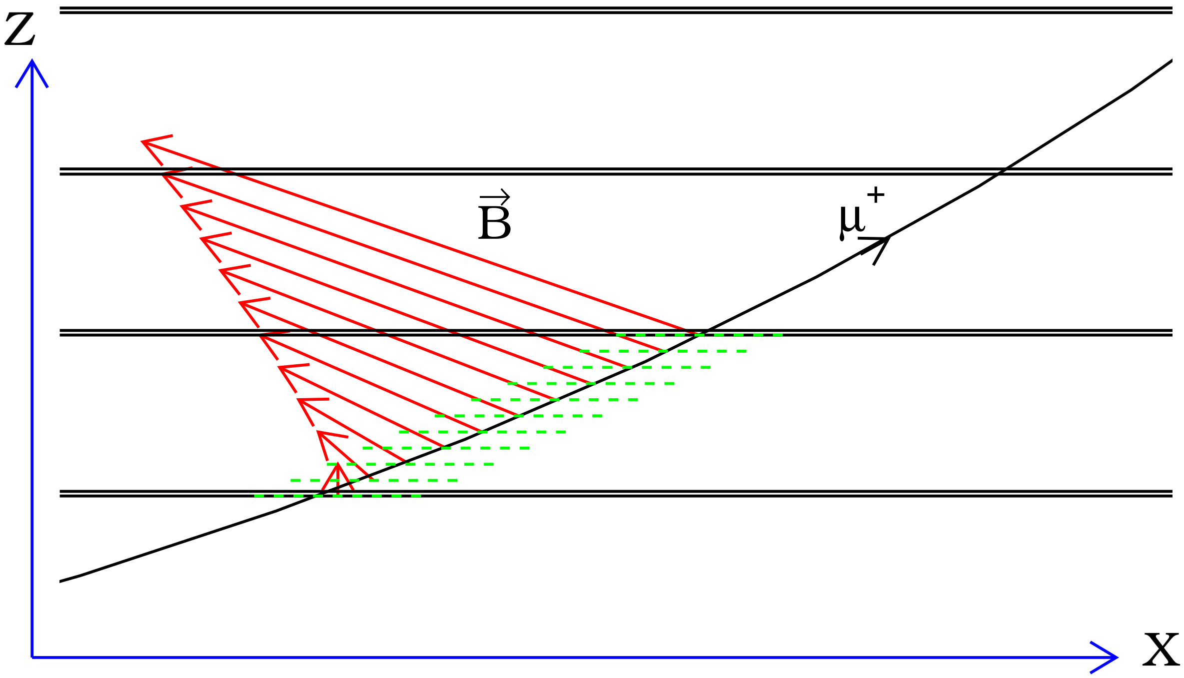
Steps in track fitting algorithm

- Basic assumption, large bending is expected only in tail part, but not in neutrino interaction point.
- start with cluster from Track finder
- Calculate direction from the timing informations.
- Option to fit for both directions, to check how precisely Kalman fit able to choose right direction. Also useful, in case of insufficient/improper timing information
- Initial track direction/position is taken from only first two layers (in straight section) with q/p=0, whereas track has five parameters (x,y,dx/dz,dy/dz,q/p)
- Extrapolation to next layer, irrespective of that has hits from track finder.



Extrapolation

- Transform co-ordinate system such that magnetic field is along Z' axis
- Get distance to the crossing point of helix and plane
- Get the track parameters at the crossing point
- Return back to ICAL co-ordinate system
- Step size is 5mm, need optimisation of CPU time and performance
- Use density of different material by hand (not exactly from database, but with the same parameters in detector construction).



Alternate,
Runge-Kutta Method,
it is under test

Updating track parameter

Five different scenarios :

- Track did not find any extrapolated point (low momentum, almost parallel to plane, lost due to ionisation energy loss)
- Track P_Z did not change sign
  - Exists cluster from finder/previous steps : Update track parameter with Kalman filter
  - Does not find cluster from finder/previous steps : Use extrapolated track as for track parameters
- Track parameter changes sign of P_z
  Use extrapolated track as for track parameters, irrespective of (a) having cluster from finder/previous iteration or (b) not

The Propagation Matrix

- $$F_{k-1} = \begin{pmatrix} 1 & 0 & \delta z & 0 & \frac{1}{2}B_y(\delta z)^2 \\ 0 & 1 & 0 & \delta z & \frac{1}{2}B_x(\delta z)^2 \\ 0 & 0 & 1 & 0 & B_y\delta z \\ 0 & 0 & 0 & 1 & B_x\delta z \\ 0 & 0 & 0 & 0 & 1+\epsilon \end{pmatrix}$$

  is an simplified form of propagation with the assumption that particle is going almost along Z-direction, which is not true for large inclination angle and can not applicable at all for track, which change direction in Z.

  – Will move for general solution of it.

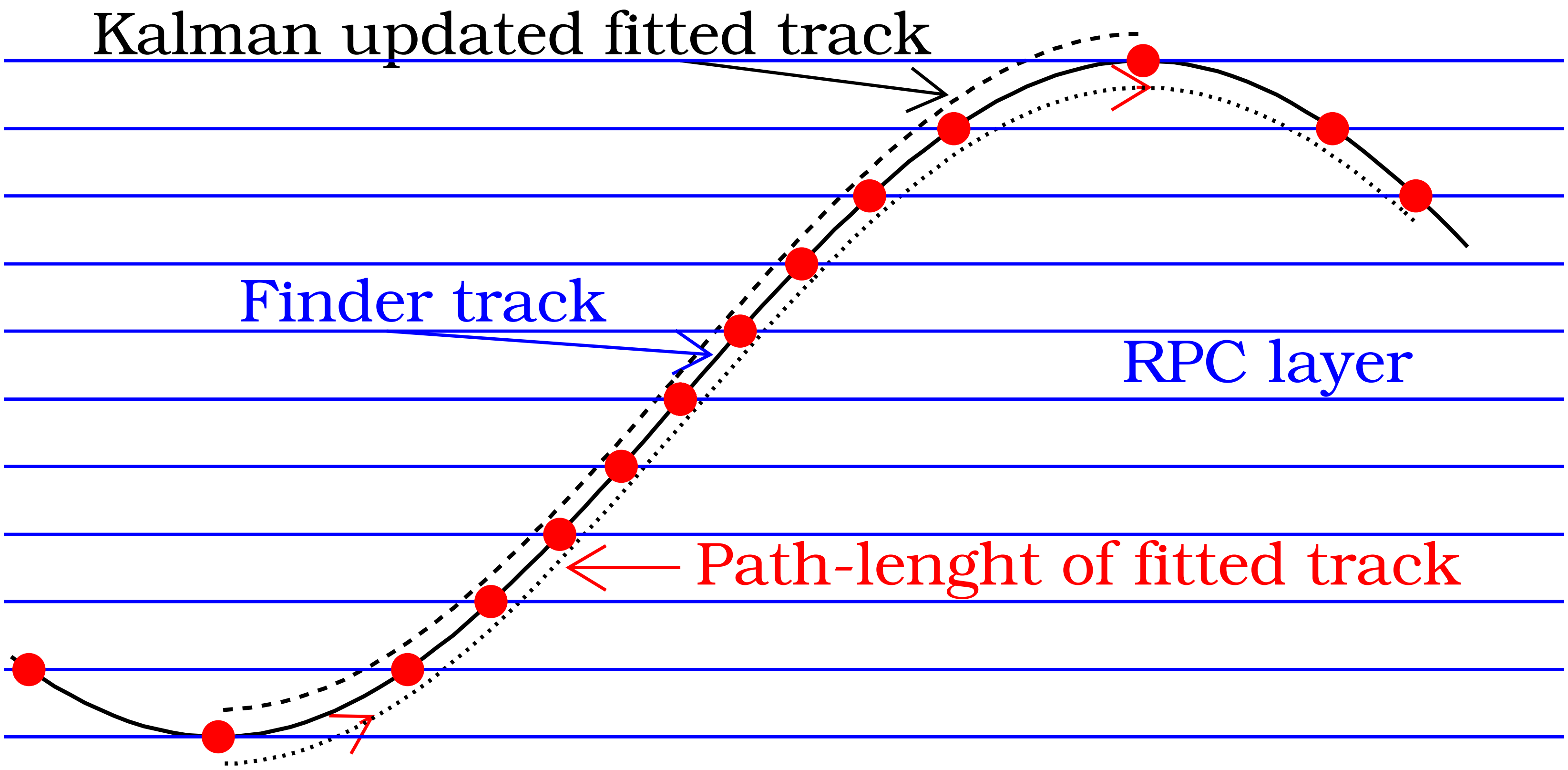
  – But for the time being, update track parameter till it does not change the sign of P_z.

  – Expect such large being mainly for low momentum at tail, fully confined track, where track momentum is measured from track length.

- Propagate track in the forward direction, then backward and calculate track parameter in each layer.
- Update cluster lists (finder track information) in different layer by comparing fitter track parameters with all clusters in that layer.

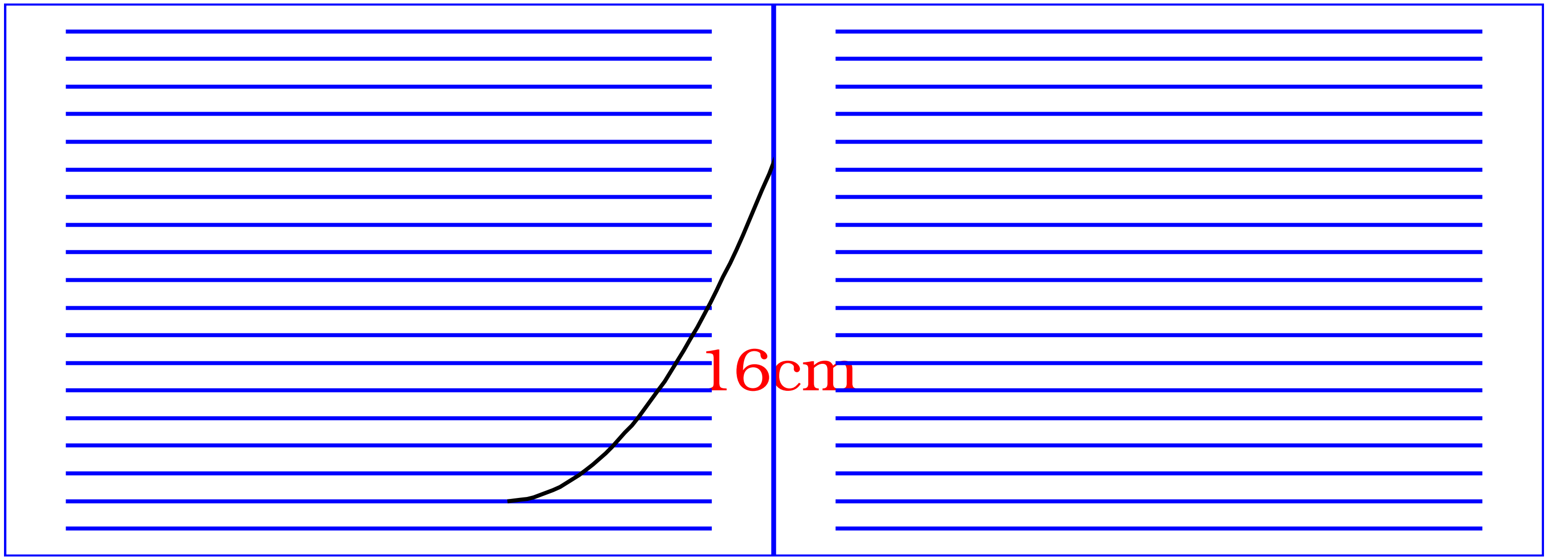
Fitted track

- Loop until, difference in χ^2 and ndf the present fit and previous fit are less than 0.01 and 1
- In general, fit is terminated within 2-3 iteration.
- At the end: interpolate tracks to another half layer to get track parameter. muons vertex is anywhere in between two layers.



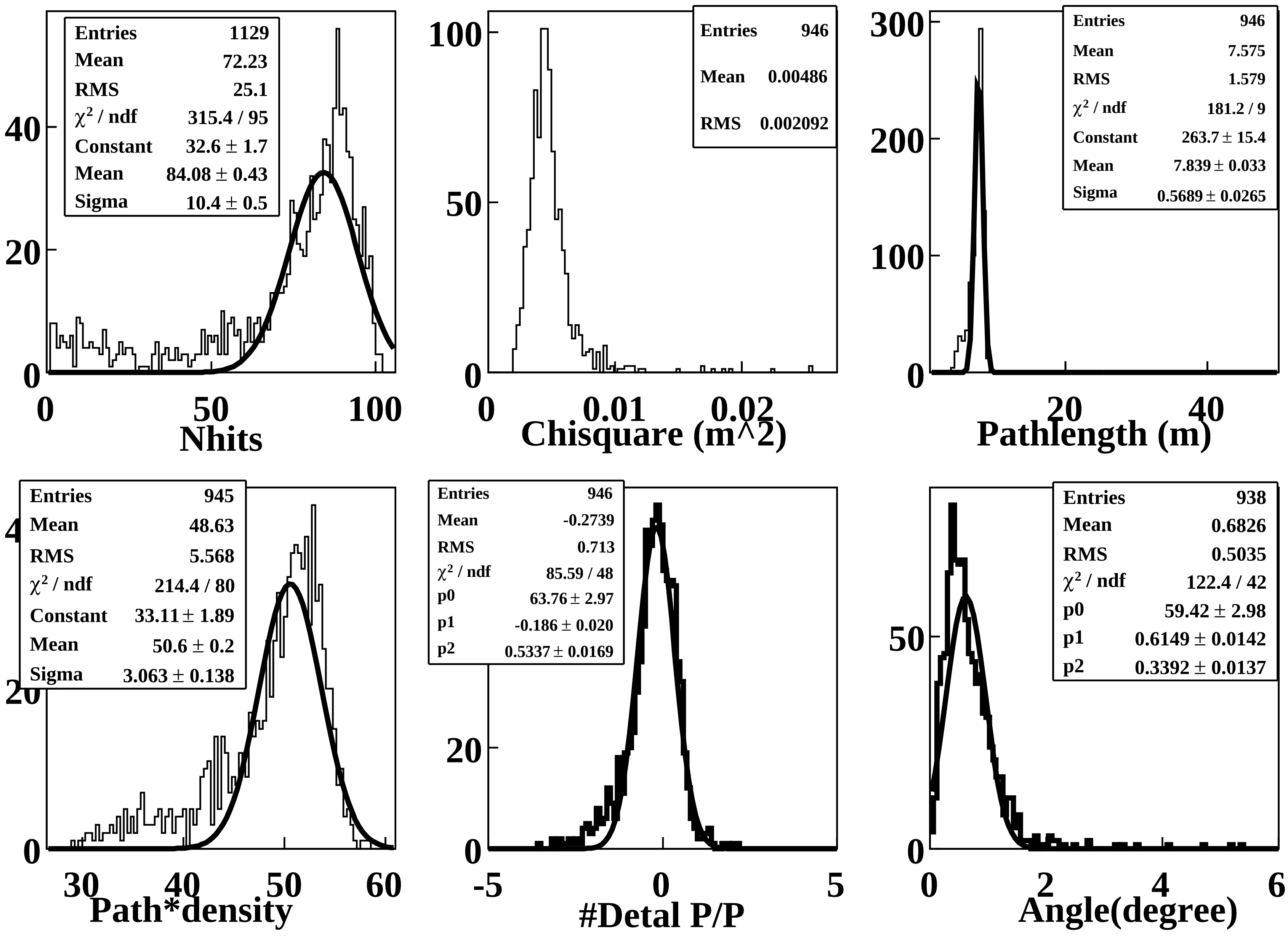
Further optimisations/improvements

- Give less weight on hit points, if the hits belongs to a shower, mainly in the vertex point, where muon is associated with other pions etc.
- Optimisation of Showerlike (hadronic shower from $\pi^{\pm}$ or electromagnetic shower from π^{0}) and Tracklike clusters
- Track Propagate through shower
- ....
- Many more, e.g., Track momentum, pathlenght vs curve fit



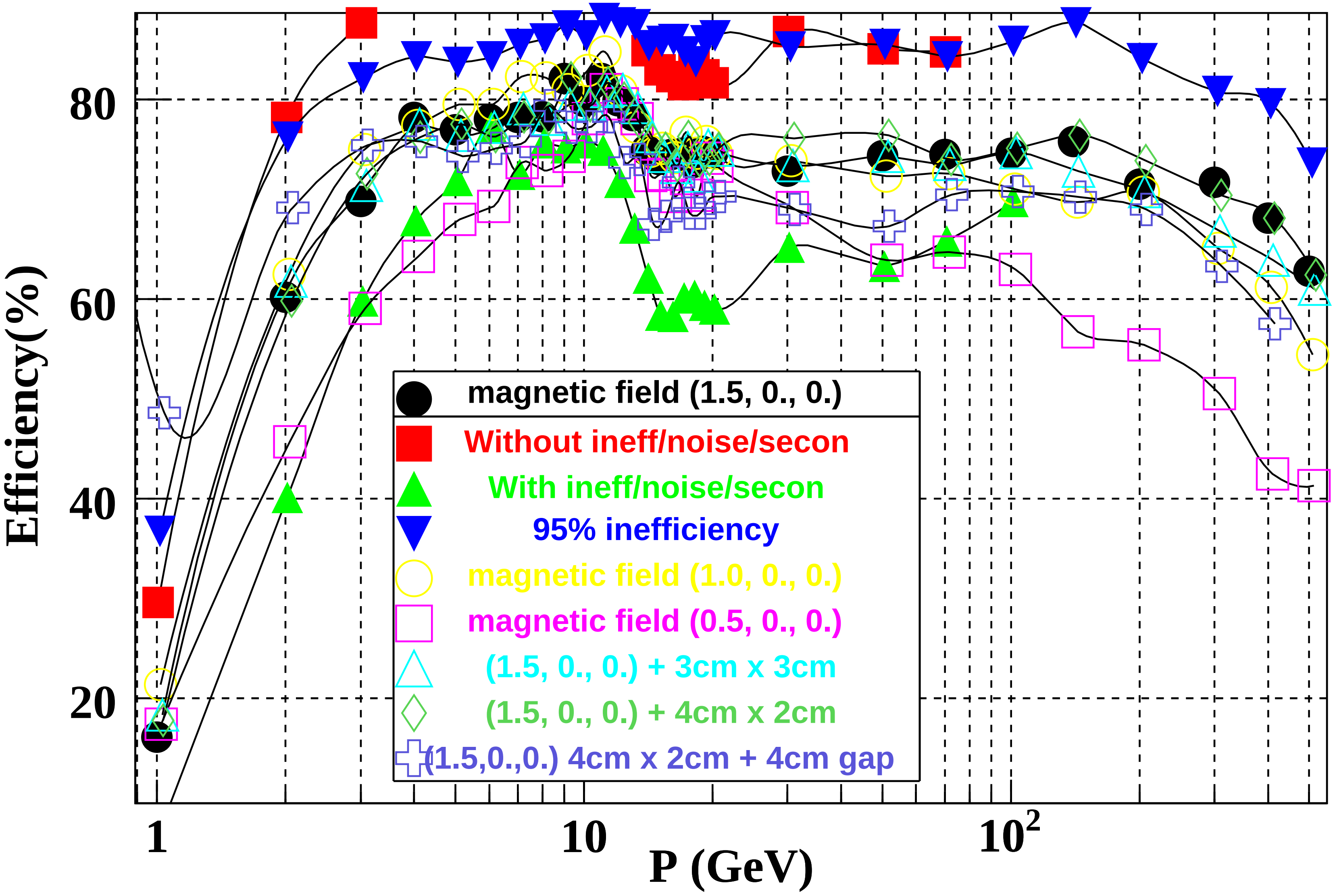
Large part of it outside the sensitive region

Reconstructed track parameters with ineff: P_{Gen}=10 GeV

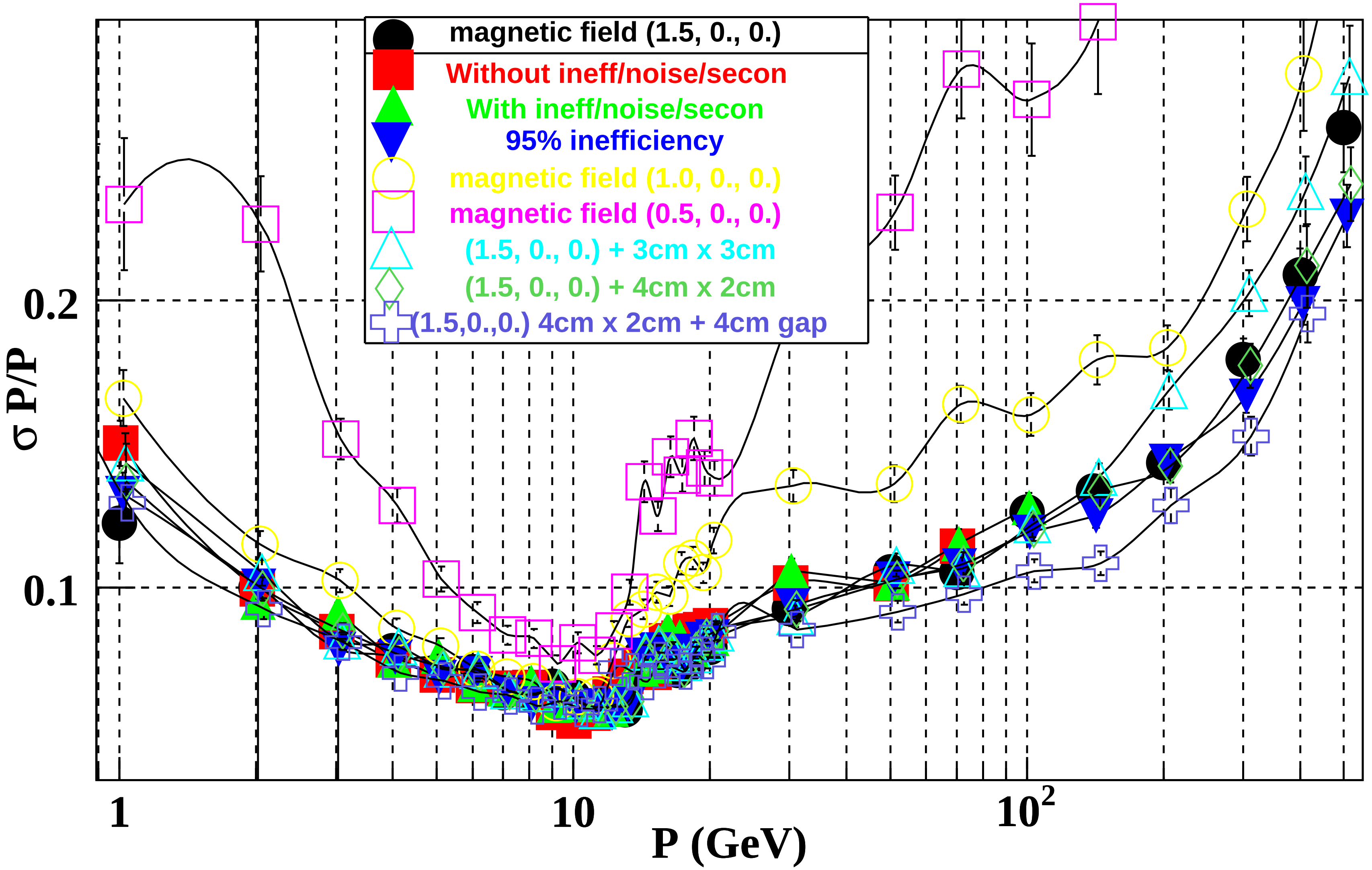


Efficiency of track fitter, after all steps

Performances with single muon simulation, where muons passed vertically upward with a smearing of 100 mrad in polar angle and 2π in azimuthal angle.



Momentum resolution of fitted tracks



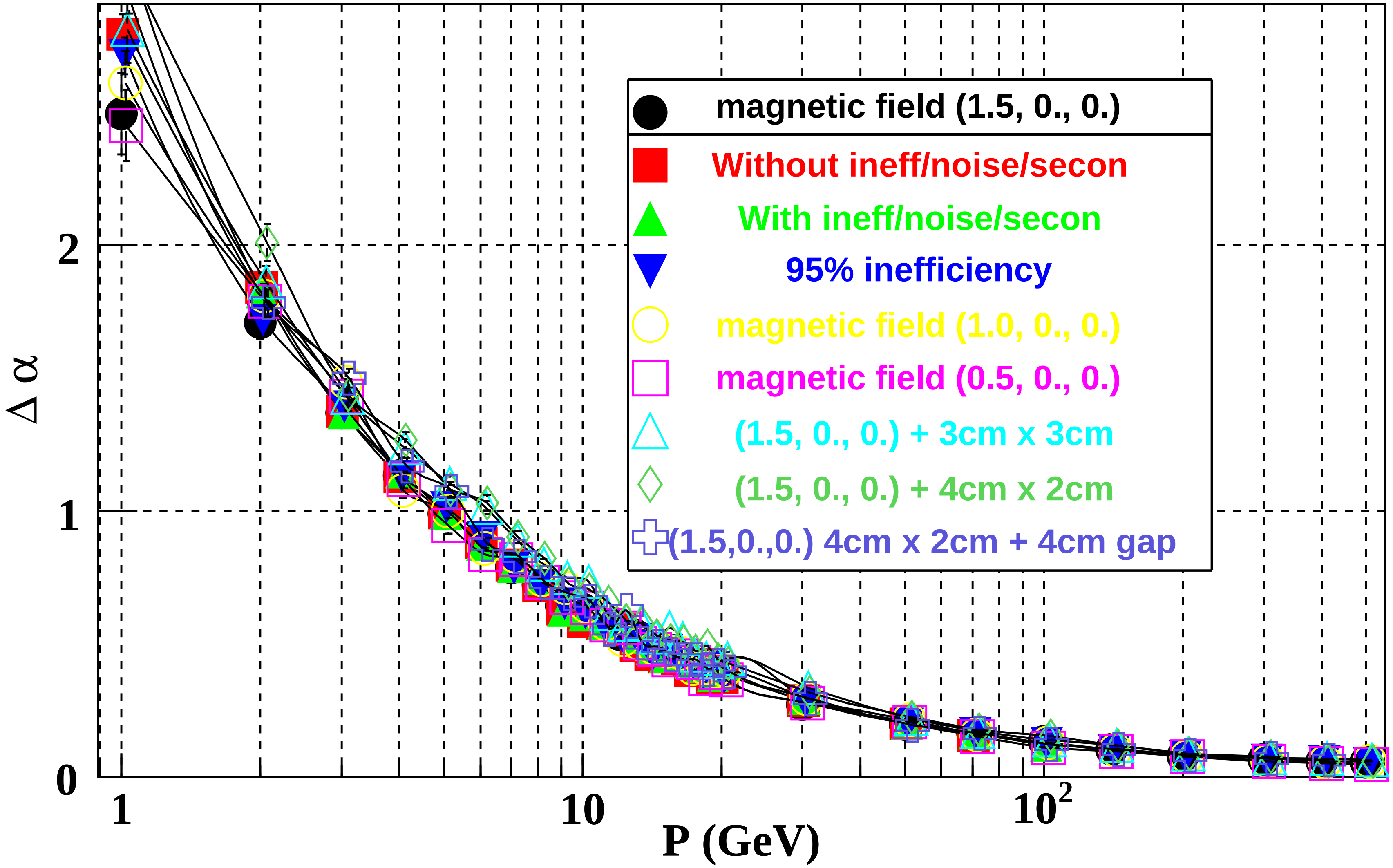
0.5 tesla magnetic field is distinctly poorer than others, not acceptable

Not much difference with strip widths !!!

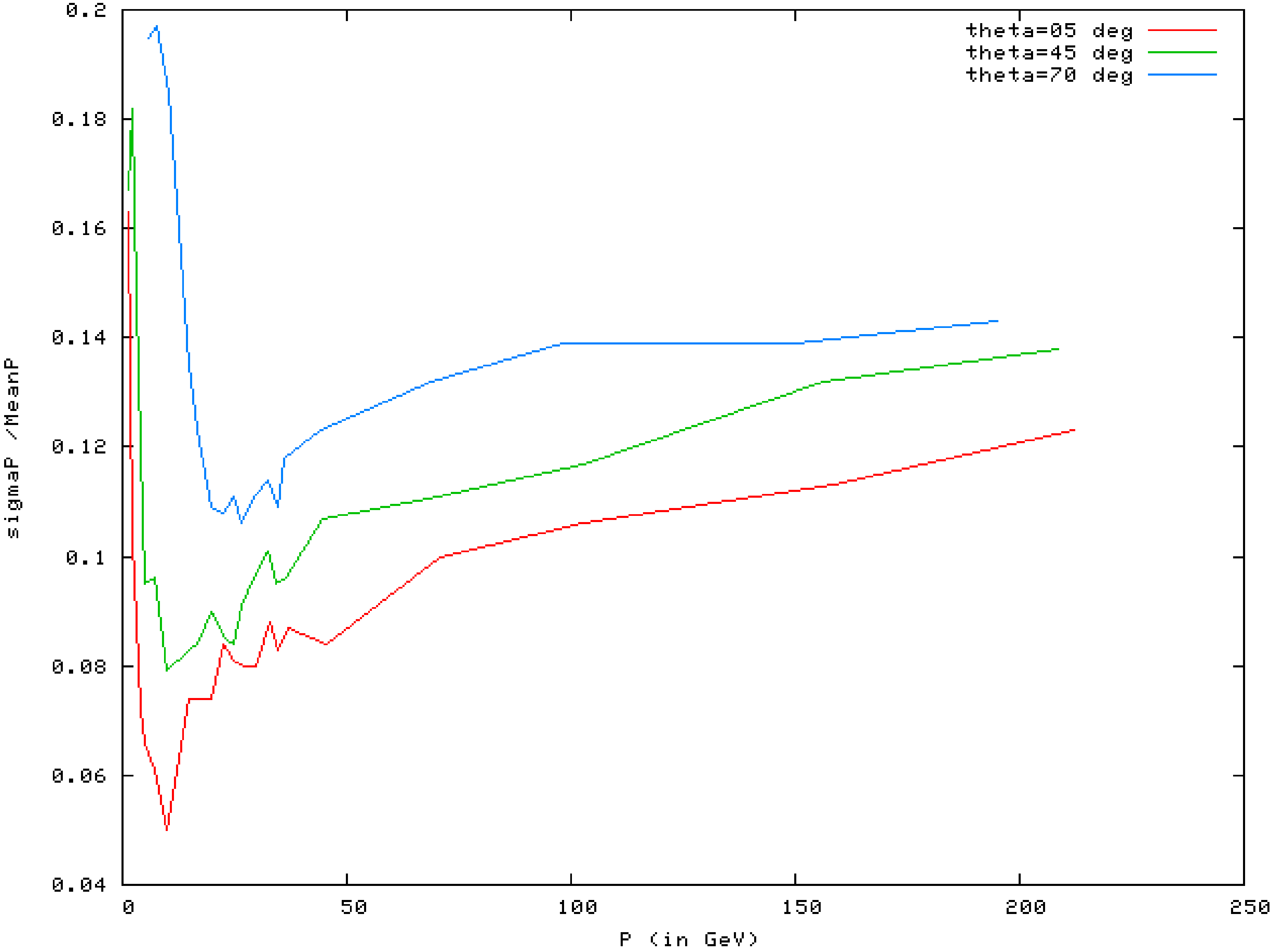
Angular resolution looks same for all cases ($< 3^\circ$ at 1GeV and $< 1^\circ$ at 10 GeV).

Average shift in angle

It is a combination of two Gaussian function, do not expect peak at zero !!!!

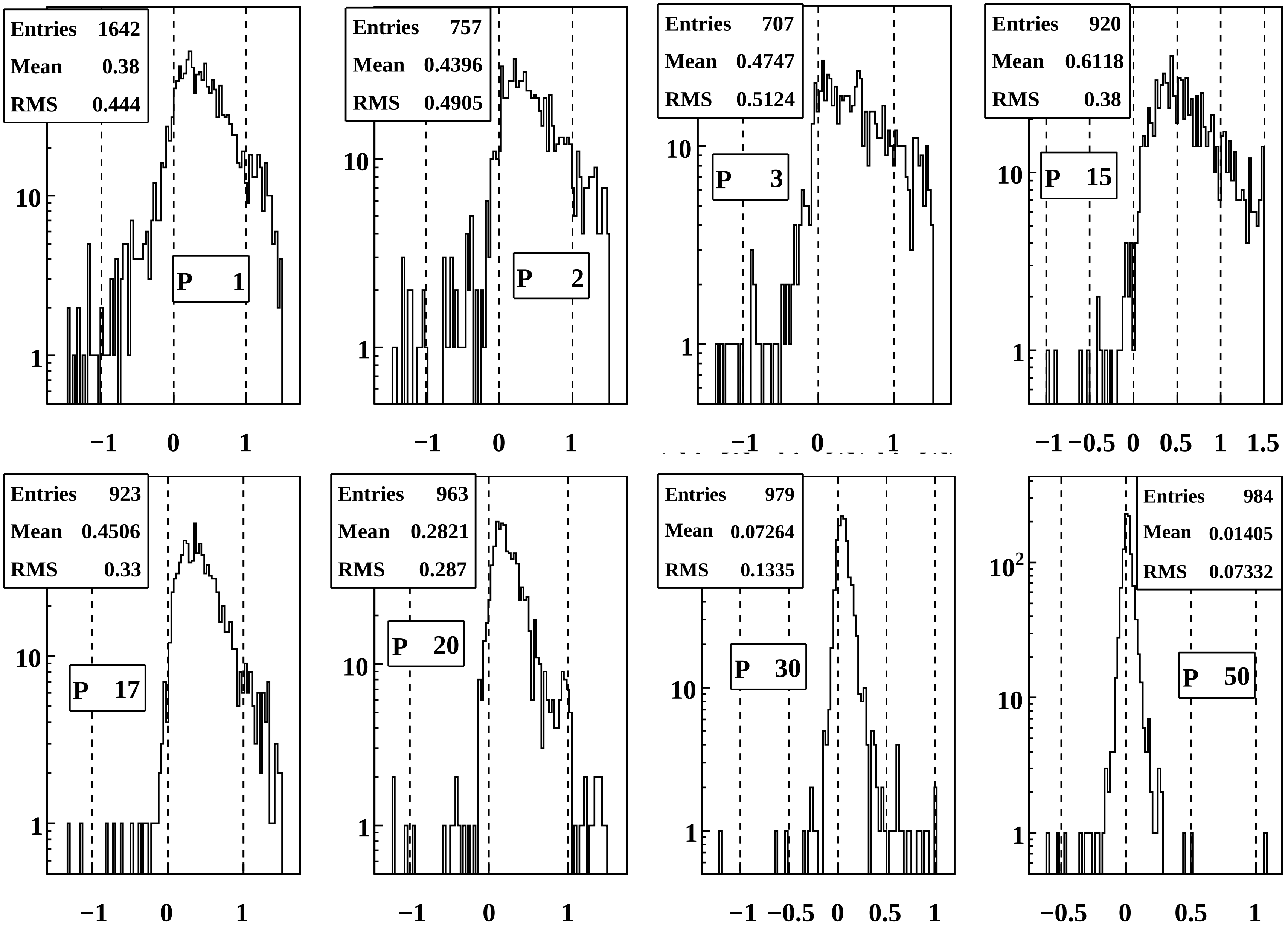


Effect due to inclination angle



Performances is deteriorated with inclination angle, which is expected due to the effect of more multiple scattering.

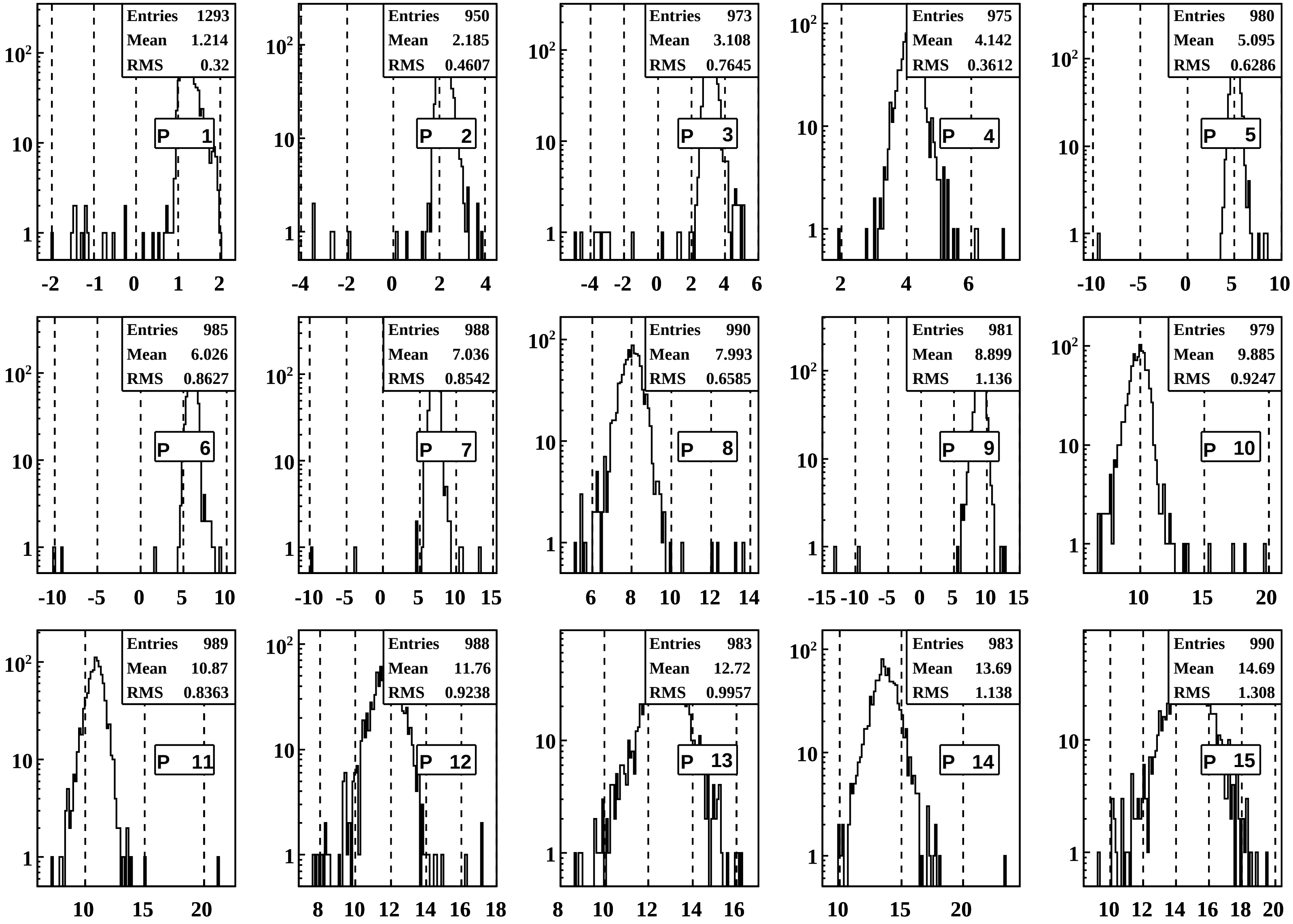
$\Delta\chi^2/ndf(m^2)$ for wrong and true direction



Not possible at all with track momentum greater than 20 GeV.

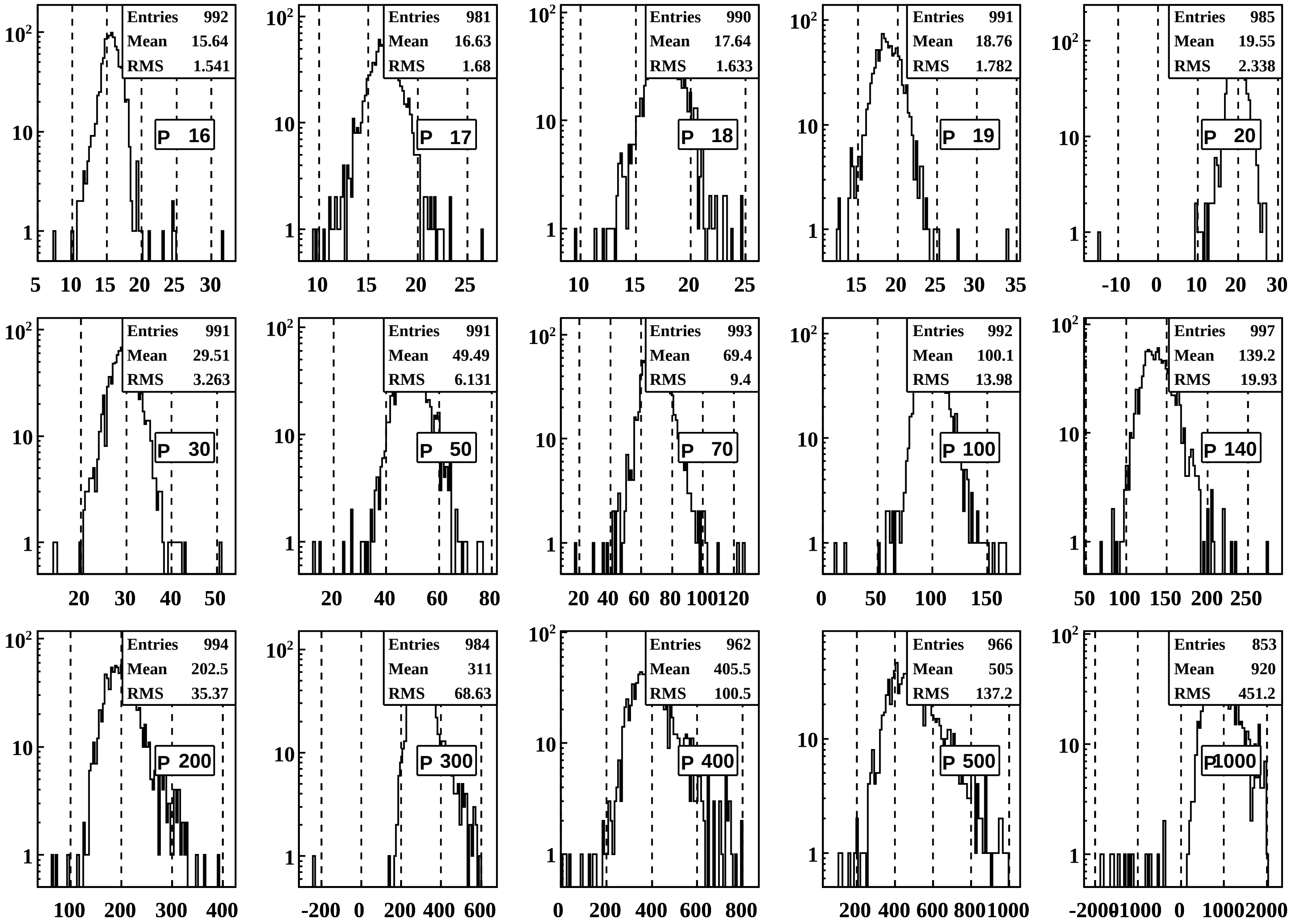
Charge mis-identifications : Measured momentum

Input tracks are μ^+.



Except very low momentum (multiple scattering) there is no charge confusion

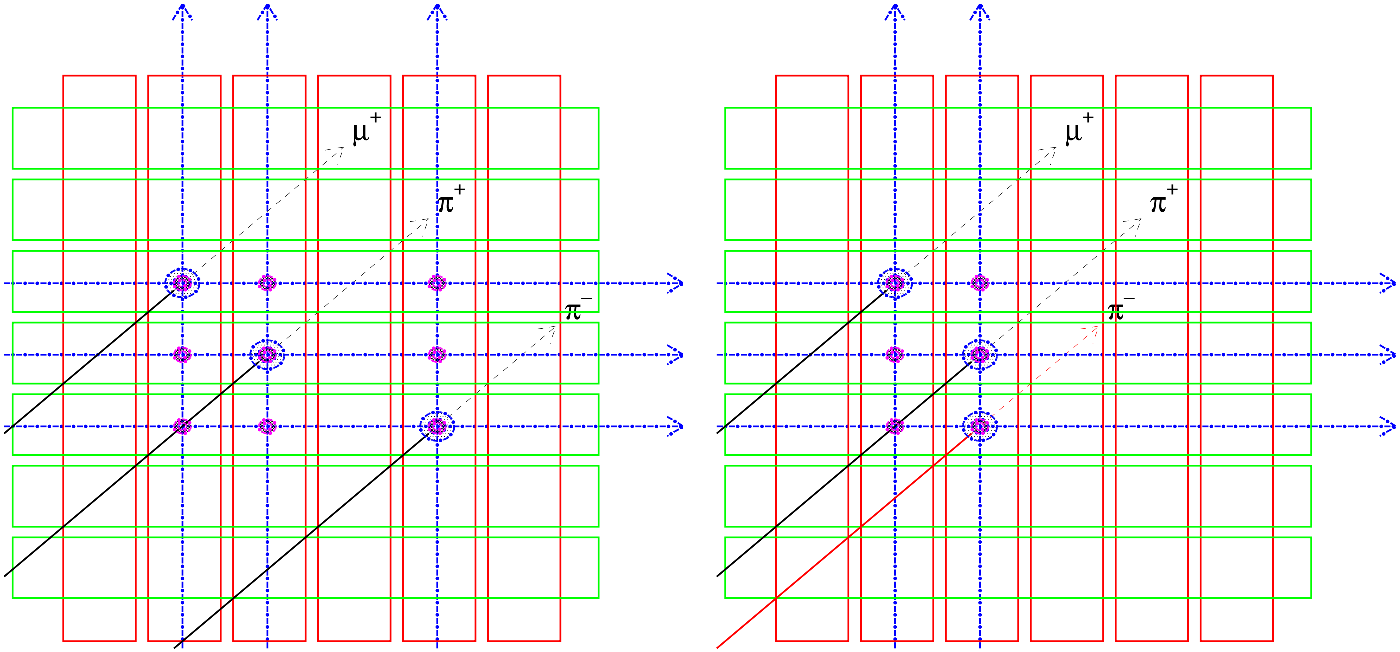
Charge mis-identifications : Measured momentum



Not any charge confusion, keep in mind that all these track has passed through at least 70 layers

Energy of hadronic shower

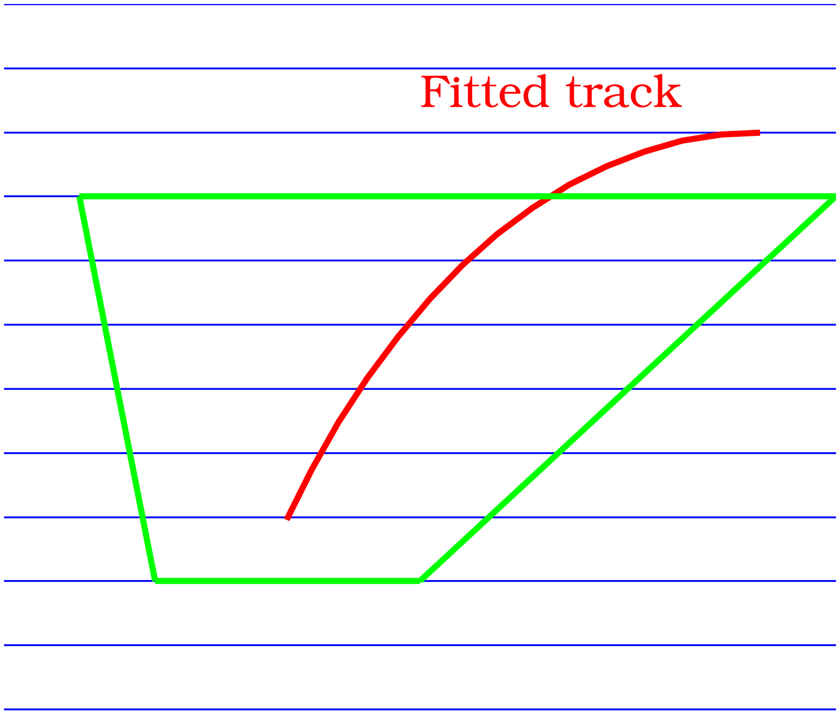
- Hadronic shower resolution, $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 9\%$



- Signal in 3×3, a fluctuation of more than 100%
- Number of strips is better choice than number of cluster/hits
- Experience from previous experiment (e.g., 5cm thick iron with ∼3cm strip width) : energy measurement is not useful, but there were no specific physics goal for hadronic energy measurement (or there were alternate solution). But, let us try again
- Store cluster/strip informations which are close to track vertex, how close ?

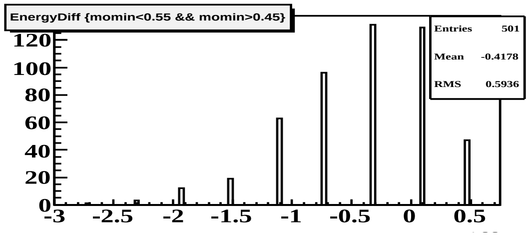
Energy of hadronic shower

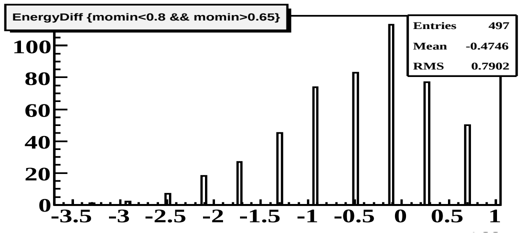
Again needs optimisation.

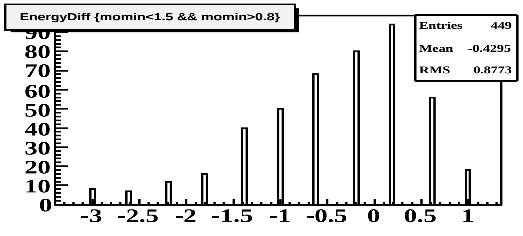


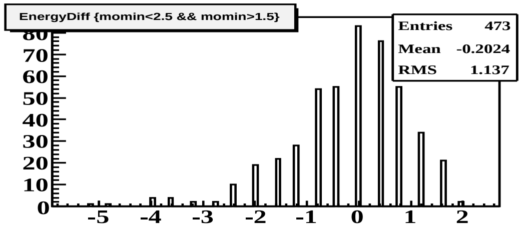
- Base window = 10cm
- angle of cone wrt to track direction = 45°
- looked from -1 to 5th layer wrt track vertex

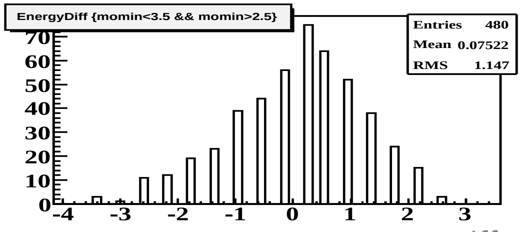
Energy of hadronic shower, long way to go

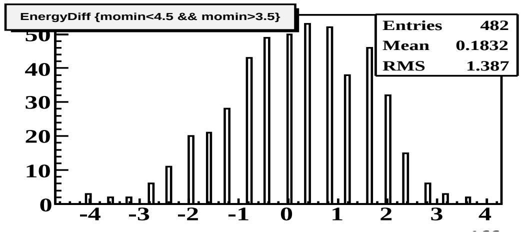


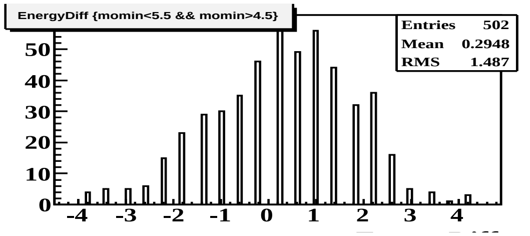


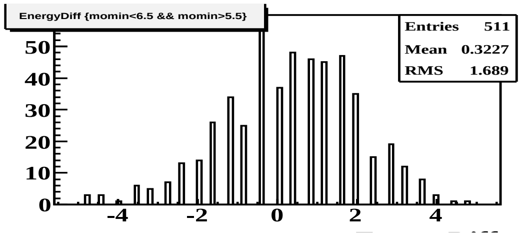


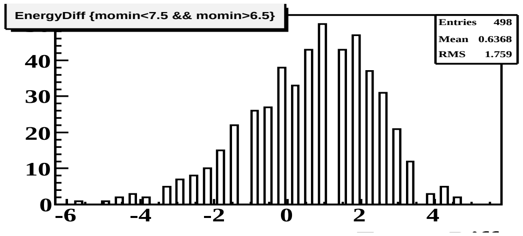


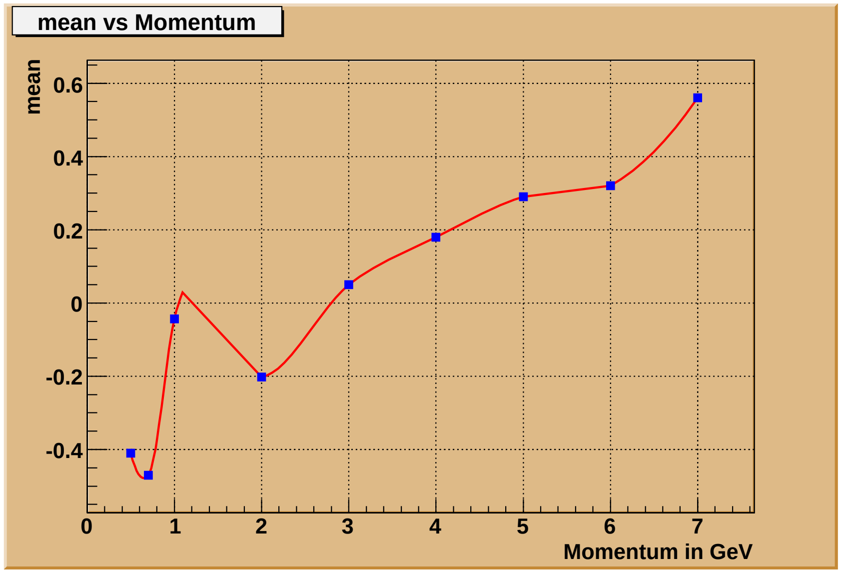


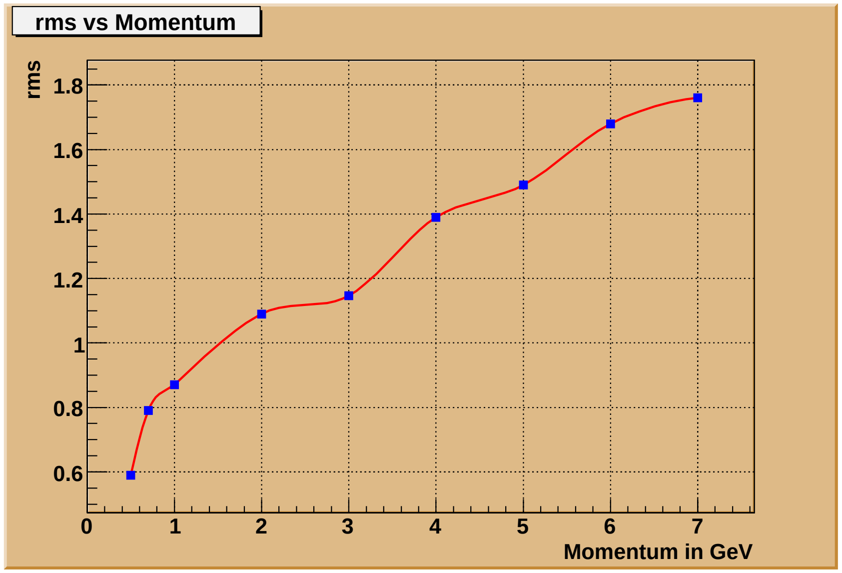






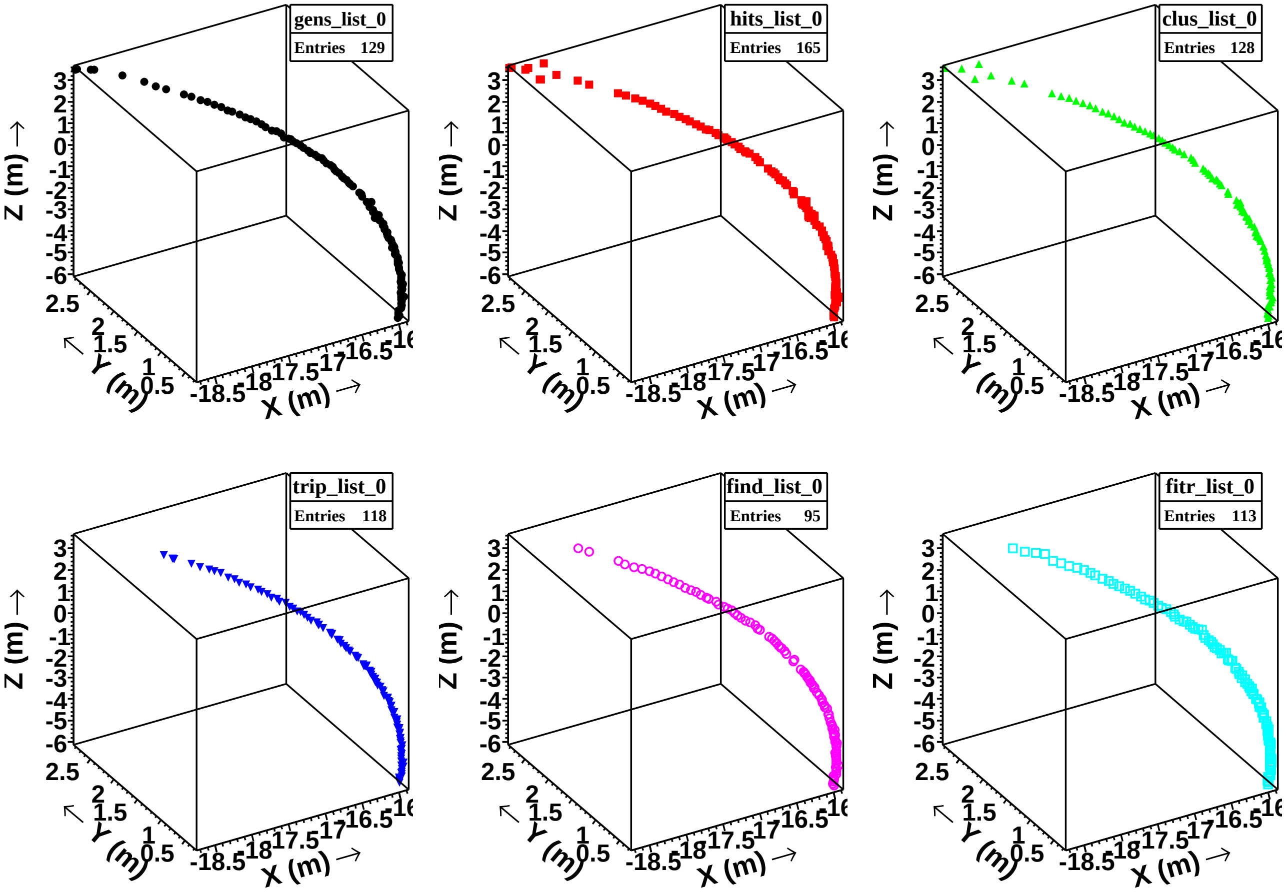






A crude event display (3D hist): 12 GeV muon

Use simple root for event display

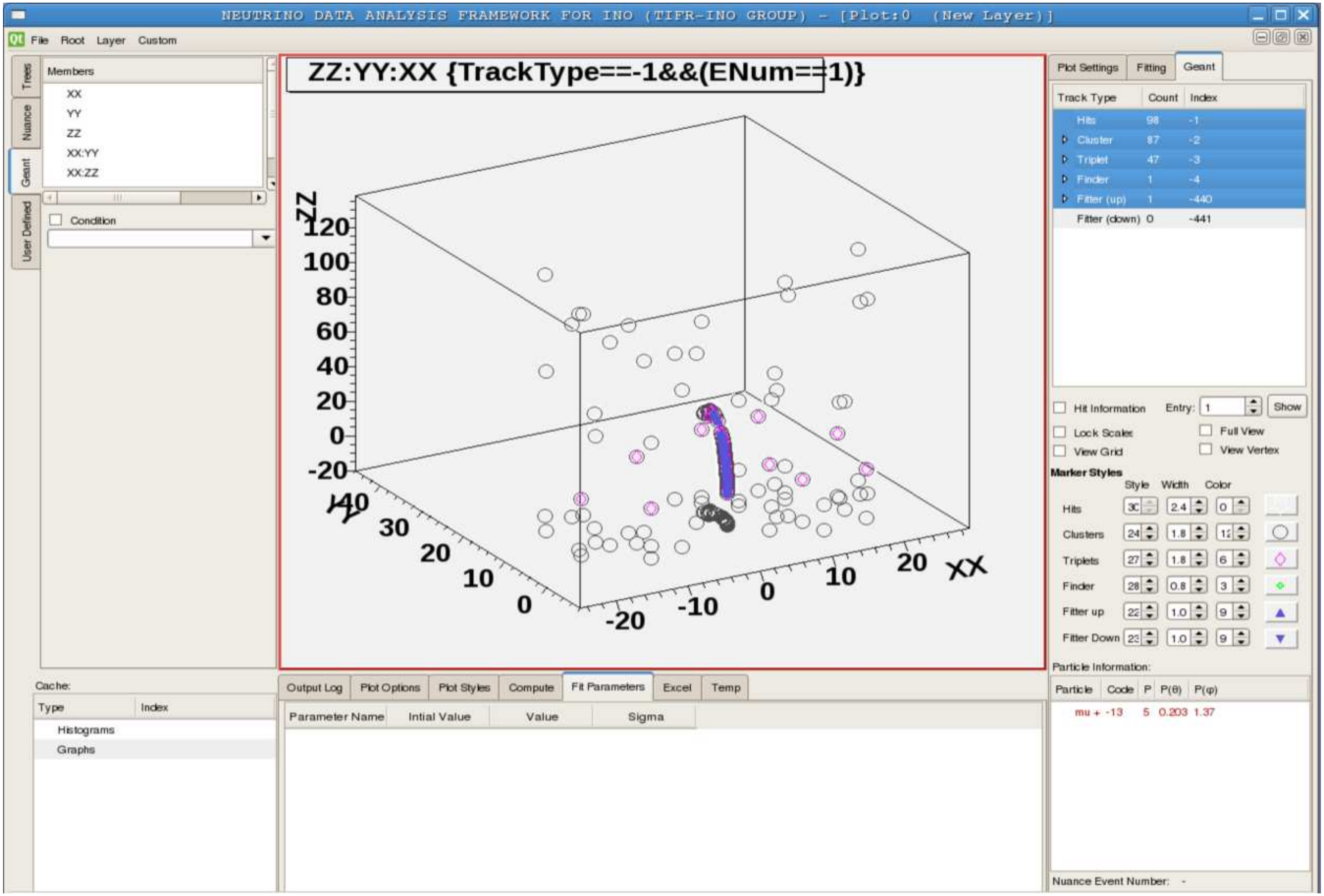


Trajectory hit Hits from strip Clusters

Track segment cls in Finder track cls in Fitted track

An example of fit, where it did able to join clusters at tail

QT based event display



NEUTRINO DATA ANALYSIS FRAMEWORK FOR INO (TIFR-INO GROUP) - [Plot:0 (New Layer)]

Track Type	Count	Index
Hits	98	-1
Cluster	87	-2
Triplet	47	-3
Finder	1	-4
Fitter (up)	1	-440
Fitter (down)	0	-441

☐ Hit Information   Entry: 1

☐ Lock Scales   ☐ Full View

☐ View Grid   ☐ View Vertex

Marker Styles

	Style	Width	Color	
Hits	30	2.4	0	
Clusters	24	1.8	1	○
Triplets	27	1.8	6	◇
Finder	28	0.8	3	◆
Fitter up	22	1.0	9	▲
Fitter Down	23	1.0	9	▼

Particle Information:

Particle	Code	P	P(θ)	P(φ)
mu +	-13	5	0.203	1.37

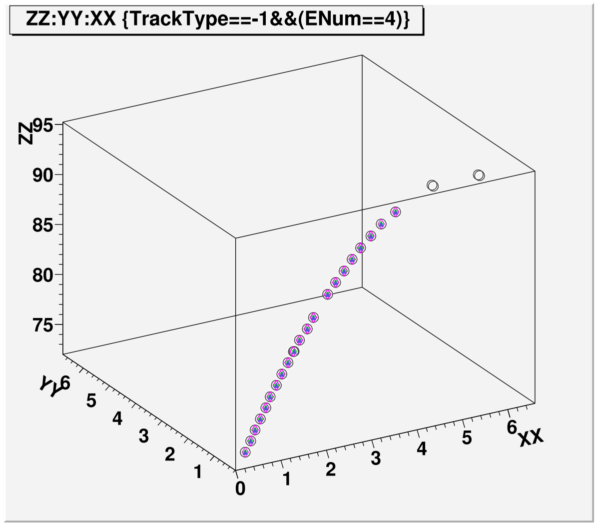
Nuance Event Number: -

Type	Index
Histograms	
Graphs	

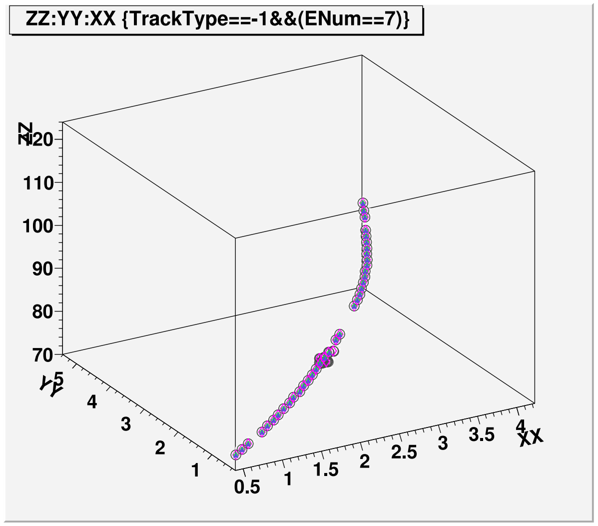
Parameter Name	Intial Value	Value	Sigma

Plots from physics analysis are also developed using this interactive graphics tools

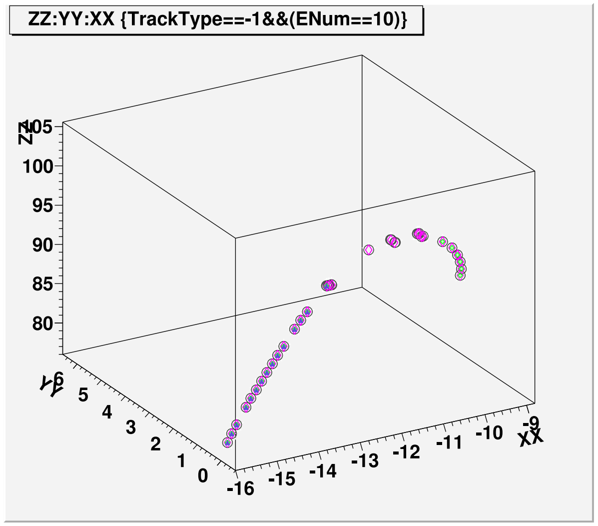
QT based event display



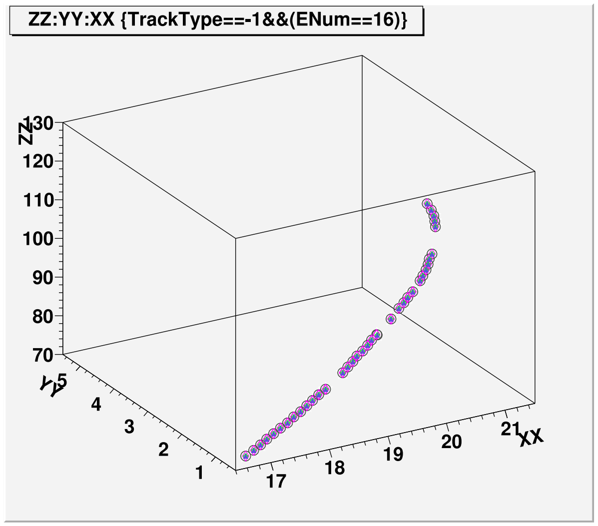
ZZ:YY:XX {TrackType==-1&&(ENum==4)}



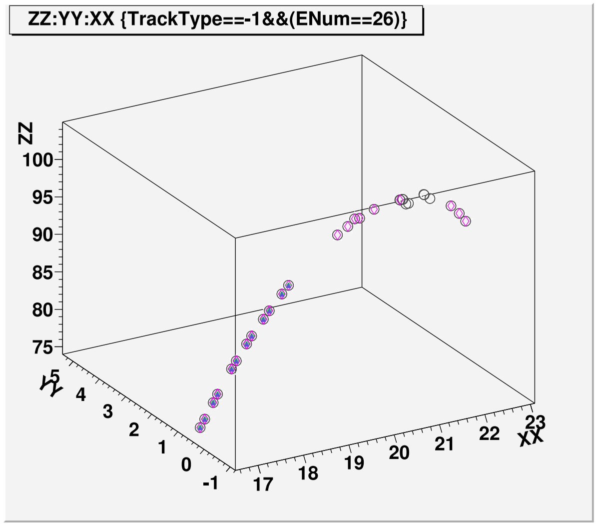
ZZ:YY:XX {TrackType==-1&&(ENum==7)}



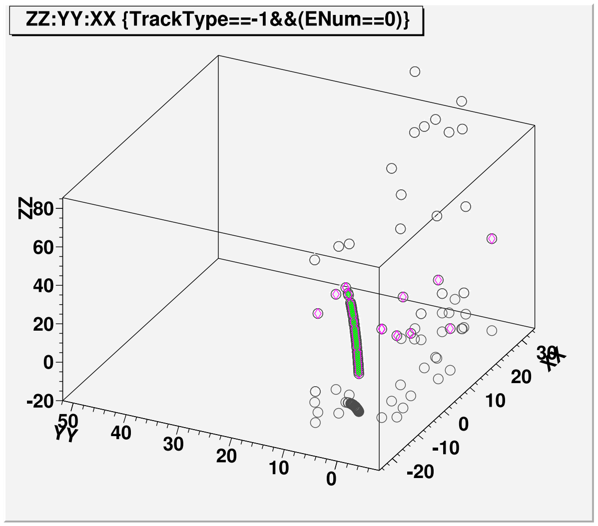
ZZ:YY:XX {TrackType==-1&&(ENum==10)}



ZZ:YY:XX {TrackType==-1&&(ENum==16)}



ZZ:YY:XX {TrackType==-1&&(ENum==26)}



ZZ:YY:XX {TrackType==-1&&(ENum==0)}

Clearly visible, where and how do we miss cluster in track finder/fitter algorithms

Modular code

Modular code, move any point to any next points of $\underline{\mathrm{GEN} \rightarrow \mathrm{SIM} \rightarrow \mathrm{DIGI} \rightarrow \mathrm{RECO}}$ chain. Have output root files for

GEN : Informations of neutrino generator (4-momenta, 3-vertex and PDGID of particles from neutrino interaction)

SIM : Generator + Simulated energy deposit in each point (sum up in $2\,cm \times 2\,cm/1\,cm \times 1\,cm$ area

DIGI : Generator + Digitised strip informations with time (also includes strips due to noise and reject due to inefficiency)

RECO : Generator + List of fitted tracks (with its properties) + Shower informations (developing)

At present it is in simple root format, but in future will convert it standard event tree, code is already developed.

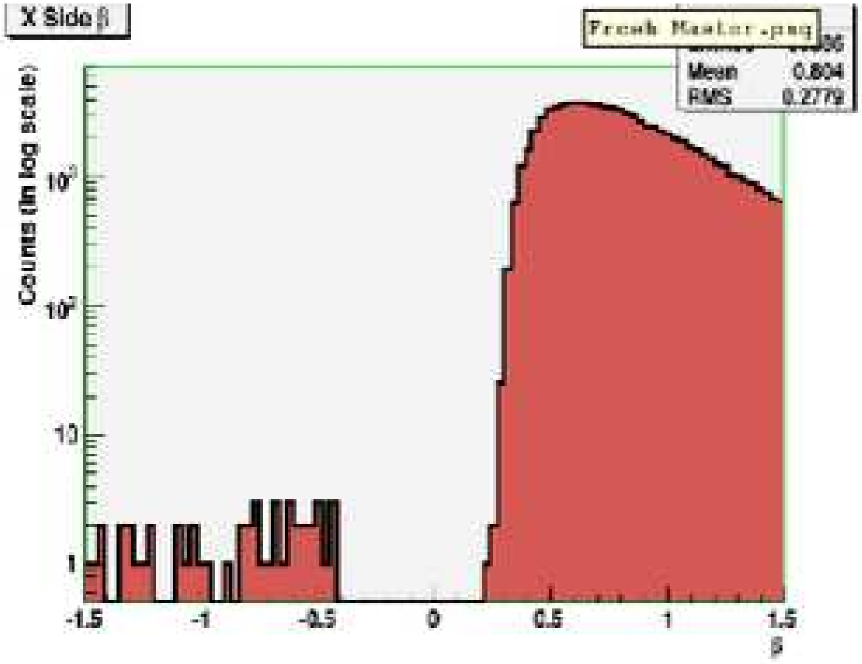
Study of RPC timing to identify muon direction

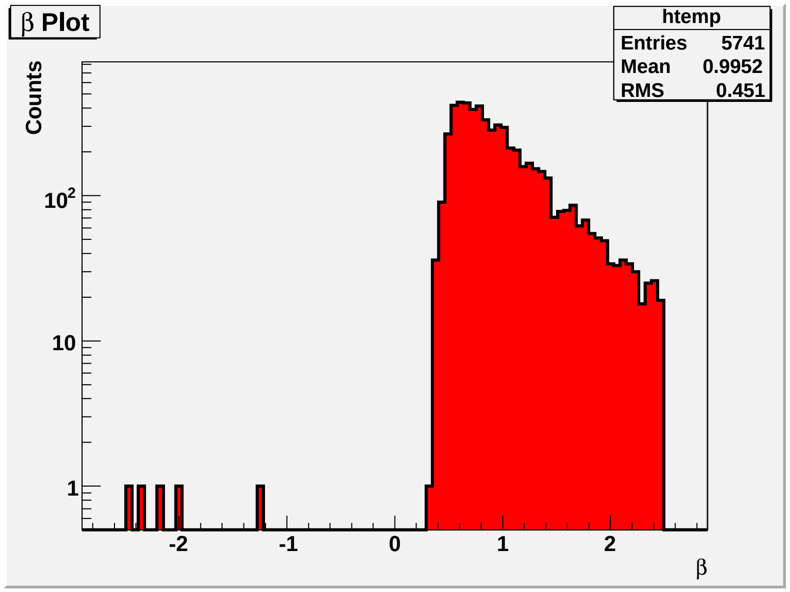
Test with existing RPC setup of dimension $1m \times 1m$. Minimise

$$\chi^2 = \sum_{i=1}^{12} \frac{(\Delta r_i - c \times t_i - shift)^2}{{\sigma_{t_i}}^2}$$

First calibrate TDC (relative timing, no need for absolute value), then look for this events.

We do not expect any up going events, but let see the result.



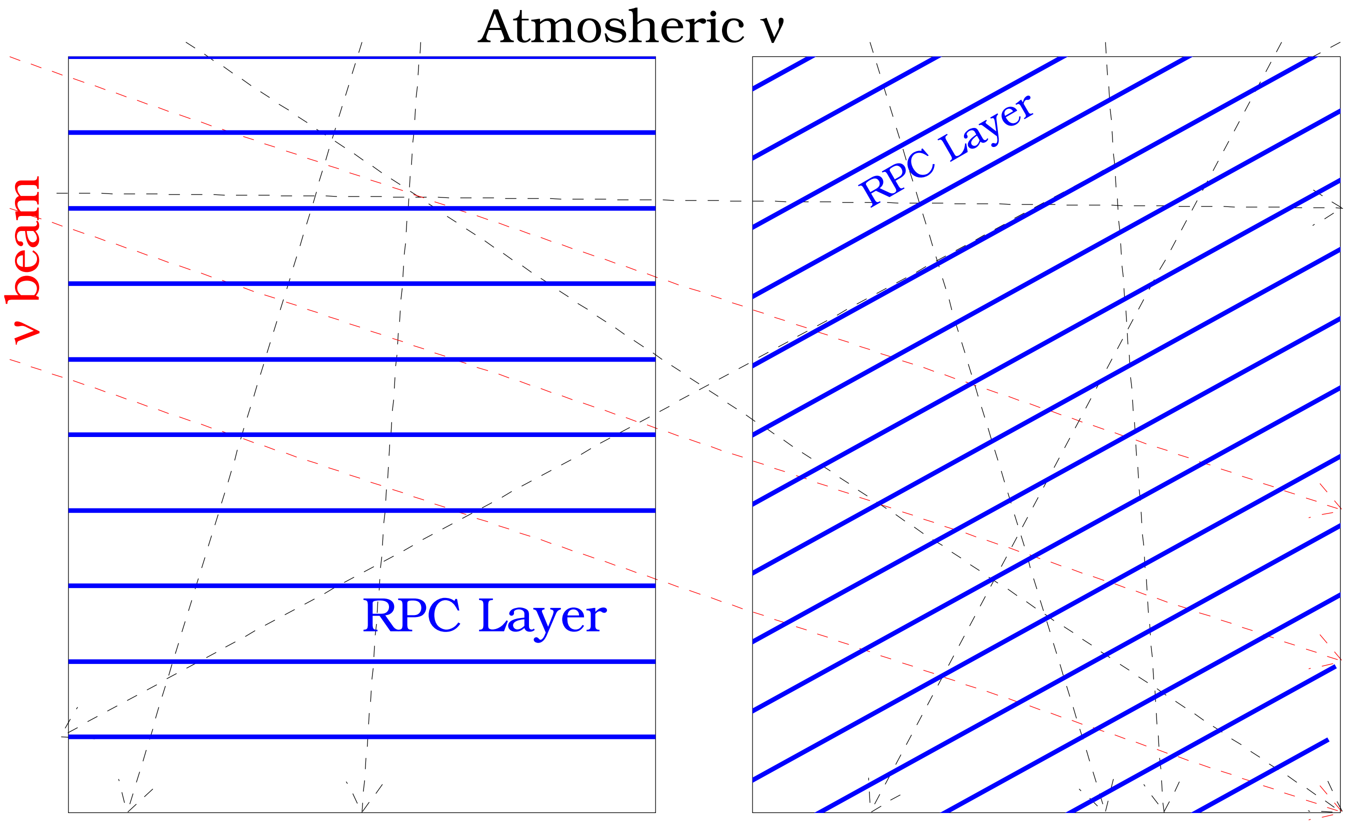


Looking for TDC behaviours for these $-ve\ \beta$, improvement hardware condition/calibration

Study of RPC timing to identify muon direction

- Do not expect any reconstructed events at 90°
- Horizontal RPC layer, only $\sim 30^\circ$ angle with respect to ν-beam $\Longrightarrow$ poor performance.

Can we put detector with an inclination ? Hardware wise, difficult but possible (Optimisation of those two physics goals)



Conclusion

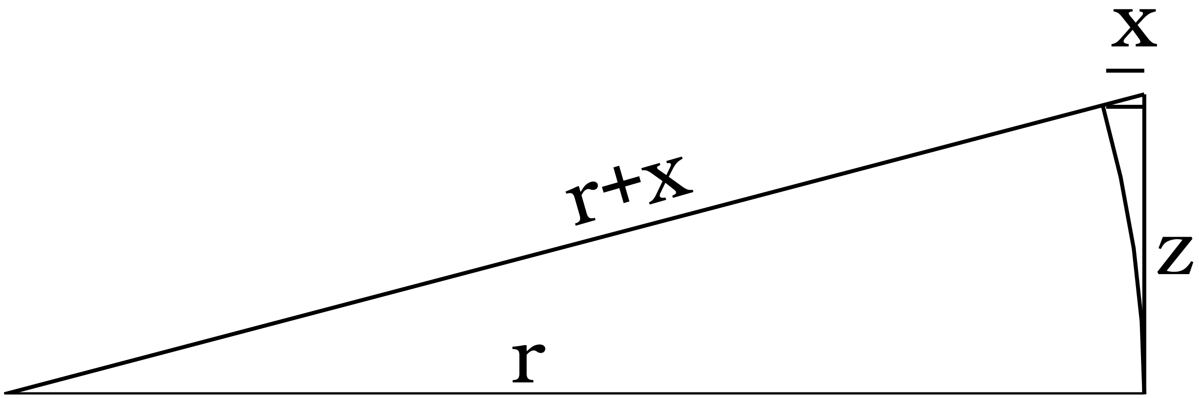
- We have full simulation code, which is working fine, but need some more tune/update
- Event Generator, Continue with Nuance and go for new generator
- Track finder : Cluster-like/track-like hits, weight for cluster-like hits, curvature at tails. All are implemented, but need optimisation
- Track fitter : To include large bending (change in sign of P_Z), change the Kalman gain, change co-ordinate system, error matrix, noise matrix, propagator
- Join two tracks, which are separated by a many layers, but looks part of a single track
- Hadronic shower, not much done in that direction

Trigger simulation is an urgent business! It is definitely important to fix the specification of the electronics.

Shielding ? Fudicial volume, need optimisation of rock background/cosmic ray with signal

Charge identification of high momentum track

e.g. at 1 TeV. Simulation at 1 TeV track does not show any (less than %) charge confusion, surprised all. $P_T = 0.3Br \Longrightarrow x \approx l^2/2r = (l^2 \times 0.3 \times B)/(2 \times 2 \times$



$P_T) \approx 2cm$

whereas position error $=2/\sqrt{12}$ cm, and we had more than 100 measured points in those tracks.

Some questions

Can we detect electron in ICAL detector ? no simulated result, but wild guess, though we can identify μ, hadronic shower and EM shower, we can not measure energy of hadronic/EM shower. Anyhow, we will do this study (simulate $e/\mu/\pi$ separately).

In that context, can we identify the following processes

1. $\nu_\mu + N \rightarrow \mu + \pi_{low\ energy}$
2. $\nu_\mu + N \rightarrow \mu + n\pi$
3. $\nu_\mu + N \rightarrow \mu + \pi^0 + X$
4. $\nu_e + N \rightarrow e + X$
5. $\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + X$

processes 1 & 3 : No distinction at all, if π^0 momentum is low
processes 2 & 3 : very little chance to discriminate
processes 4 & 5 : No distinction at all

Do we need uniform magnetic field ?

Uniform is good, but our result does not effect much (a qualitative argument without any proof) due to the nonuniformity we have at present design. Anyhow, we will study this effect more carefully to have quantitative number.

But, there are concerns about the magnetic field

- Magnetic field is too non-uniform to handle with simple interpolation code
- Exact field will depend on the quality of iron, which may not be uniform
- Using probe, one can measure field in air, but what about inside iron ?

Spacers

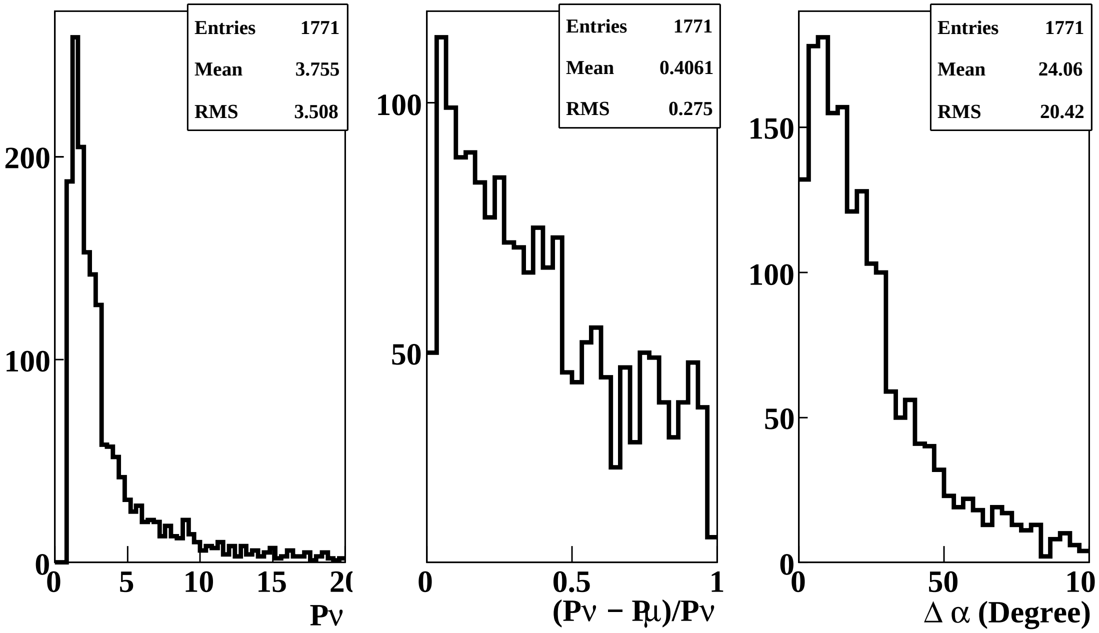
Six types of spacers are there depending on their position and differing in their number and dimensions accordingly.

- Type 1: 4corners($250mm \times 40mm \times 40mm$).
- Type 2: Along one axis, 4+4($500mm \times 80mm \times 40mm$)
- Type 3: Along same axis, at junction of two iron plates, 3+3 ($505mm \times 80mm \times 40mm$).
- Type 4: Intermediate, at junction of iron plates,3×7 ($505mm \times 80mm \times 40mm$).
- Type 5: Intermediate, in between edges of two plates, 4×7 ($500mm \times 80mm \times 40mm$).
- Type 6: Along perpendicular axis, at junction of twoplates, 7+7 ($250mm \times 80mm \times 40mm$).

Smearing of muon momentum

Neutrino rate from NEUGEN : 1GeV MeV threshold : 1year of ICAL : 4733 ev events

	RS		QE		DI		CO		EL	
	CC	NC	CC	NC	CC	NC	CC	NC	CC	NC
ν_e	448	145	277	96	176	66	10	7	0	0
$\nu_{\bar{e}}$	122	53	114	34	37	23	7	3	0	0
ν_μ	713	258	432	135	392	119	13	6	0	1
$\nu_{\bar{\mu}}$	237	115	168	75	93	40	9	6	0	0
ν_τ	14	89	5	59	6	30	0	1	0	0
$\nu_{\bar{\tau}}$	7	45	7	17	3	17	0	2	0	1



About 85% of events has $\cos\theta_{\nu\mu} \geq 0.9(\theta < 13^\circ$ for $P_\nu >$ 1GeV

Neutrino rate from NEUGEN

500 MeV threshold : 1year of ICAL : 6915 events

	RS		QE		DI		CO		EL	
	CC	NC	CC	NC	CC	NC	CC	NC	CC	NC
ν_e	584	187	690	224	187	45	15	9	0	0
$\nu_{\bar{e}}$	154	60	150	64	41	17	27	5	0	1
ν_μ	852	308	985	344	386	118	15	17	0	1
$\nu_{\bar{\mu}}$	237	144	294	132	85	53	15	6	0	0
ν_τ	20	110	9	137	3	31	0	4	0	0
$\nu_{\bar{\tau}}$	7	61	5	54	2	18	0	1	0	1

2 GeV MeV threshold : 1year of ICAL : 2769 events (1 Gev : 4733 evt)

	RS		QE		DI		CO		EL	
	CC	NC	CC	NC	CC	NC	CC	NC	CC	NC
ν_e	206	81	84	21	177	50	6	3	0	0
$\nu_{\bar{e}}$	79	31	44	17	34	12	4	0	0	0
ν_μ	368	151	159	44	393	115	5	2	0	1
$\nu_{\bar{\mu}}$	177	56	74	23	102	44	3	3	0	0
ν_τ	14	54	3	25	11	36	0	0	0	0
$\nu_{\bar{\tau}}$	7	22	2	3	10	12	0	1	0	0