

Status of the Muon-ID code

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- 1) Evolution in the calculation of $\Delta p_T = f(Bz)$ term
- 2) Input
- 3) μ Detection efficiency and hadron separation in jets with the new Δp_T term
- 4) Resolution of the Low momentum term
- 5) The Kalman filter
 - a) The principle
 - b) The propagation matrix with the new Δp_T term
 - c) The effect on angular resolution on low momenta singles.
- 6) Implementation of the code into LCIO
- 7) Outlook

Evolution of the $\Delta p_T = f(B_z)$

At the momenta we were interested on in the Muon detector ($p \geq 3\text{GeV}$), the expression below was a valid approximation.

$$\Delta p_T / \Delta t \sim dp/dt \sim \alpha \tilde{p} \times \tilde{B}; \quad \text{with } \alpha = 0.3 \cdot q \cdot (1/E_n) \cdot c \cdot \text{light} \cdot dt_{\text{of}}$$

Below $\sim 3\text{GeV}$, this does not represent properly the curling of low momenta tracks. We have to calculate the integral of $\alpha \tilde{v} \times \tilde{B}$ on dt

Using the mean value theorem to integrate, one gets a term

$$\delta = 1 + 0.25 \cdot \alpha^2 \cdot B^2; \quad \eta = 0.5 \cdot \alpha^2 \cdot B^2;$$

and the magnetic field term is now.

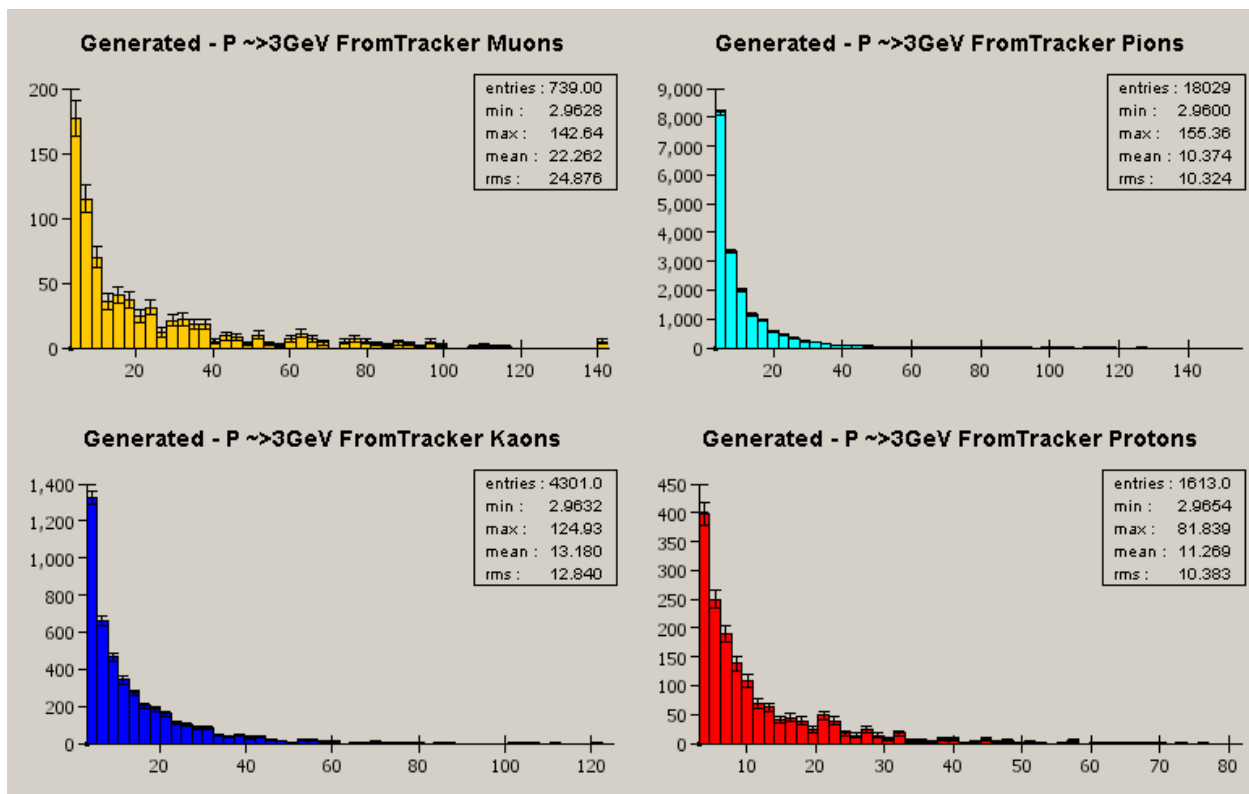
$$\begin{aligned} \Delta p_x^B &= (\alpha/\delta) \cdot p_y \cdot B_z - \eta \cdot p_x; & \text{The } -\eta \cdot p_i; i=x, y \text{ is a friction term} \\ \Delta p_y^B &= (\alpha/\delta) \cdot p_x \cdot B_z - \eta \cdot p_y; & \text{It is in the diagonal in the Transport} \\ \Delta p_z^B &= 0. & \text{Matrix of the Kalman filter} \end{aligned}$$

$$\Delta p_i^{\text{Matter}} = (dE/dx) \cdot (E(n)/p(n)) \cdot (p_i(n)/p(n)) \cdot ds; \quad i=x, y, z$$

Input

- With the improved software we will analyze 10000 b-b_bar jets events
- We will then look at the angular distribution of singles
- This will be compared to the same distributions with the Kalman filter
- The General Algorithm:
 - a) We start with reconstructed and well fitted tracks from the tracker
 - b) An energy deposit in EMCAL and HDCAL within a (θ, φ) road
2 bins = $2 * (\pi/840)$ in EMCAL, 3 bins = $3 * (\pi/600)$ HDCAL,
in each case $\Delta\theta = \Delta\varphi$
 - c) In the Muon Detector 12Hits/12 Layers within a (θ, φ) road
2 bins = $2 * (\pi/150)$ in MUDet. For tracks below 10 GeV a $(1/p)$
dependant bin has been chosen.
 - d) A rejection for each particle without signal in the last 5 layers of HDCAL in
a 3 bins (θ, φ) road.

Detection Efficiency and Hadron Rejection in jets



Muons and Hadrons
 From the Tracker
 Above 3 GeV/c
 For 739 Muons there
 Are
 18029 Pions
 4301 Kaons
 1613 Protons

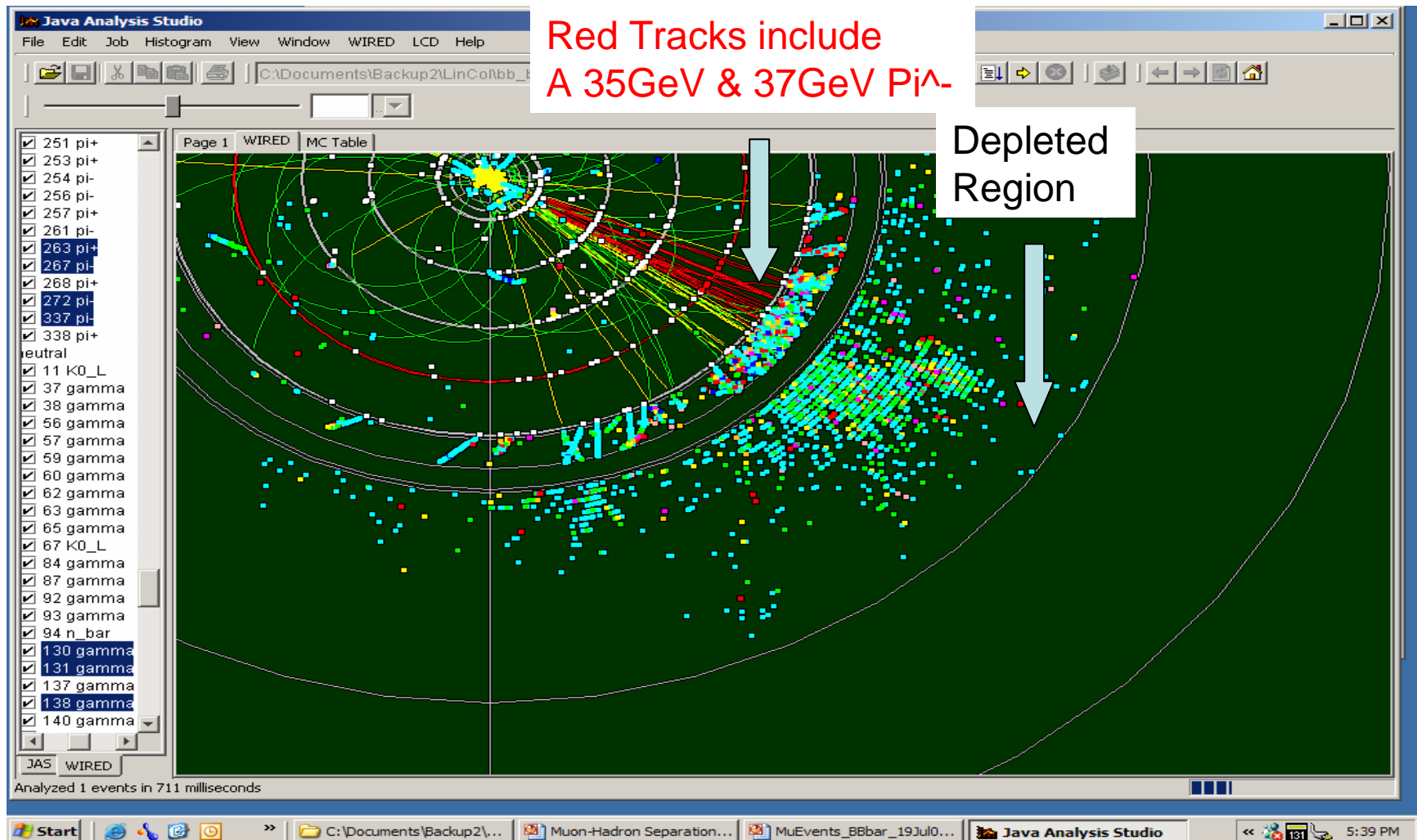
Detected are
668 Muons/739~90%
 427 Pions,
 141 Kaons
 43 protons
 pass the algorithm

The Muon detection efficiency in jets is ~90%, it almost doubled to 62% at 3GeV

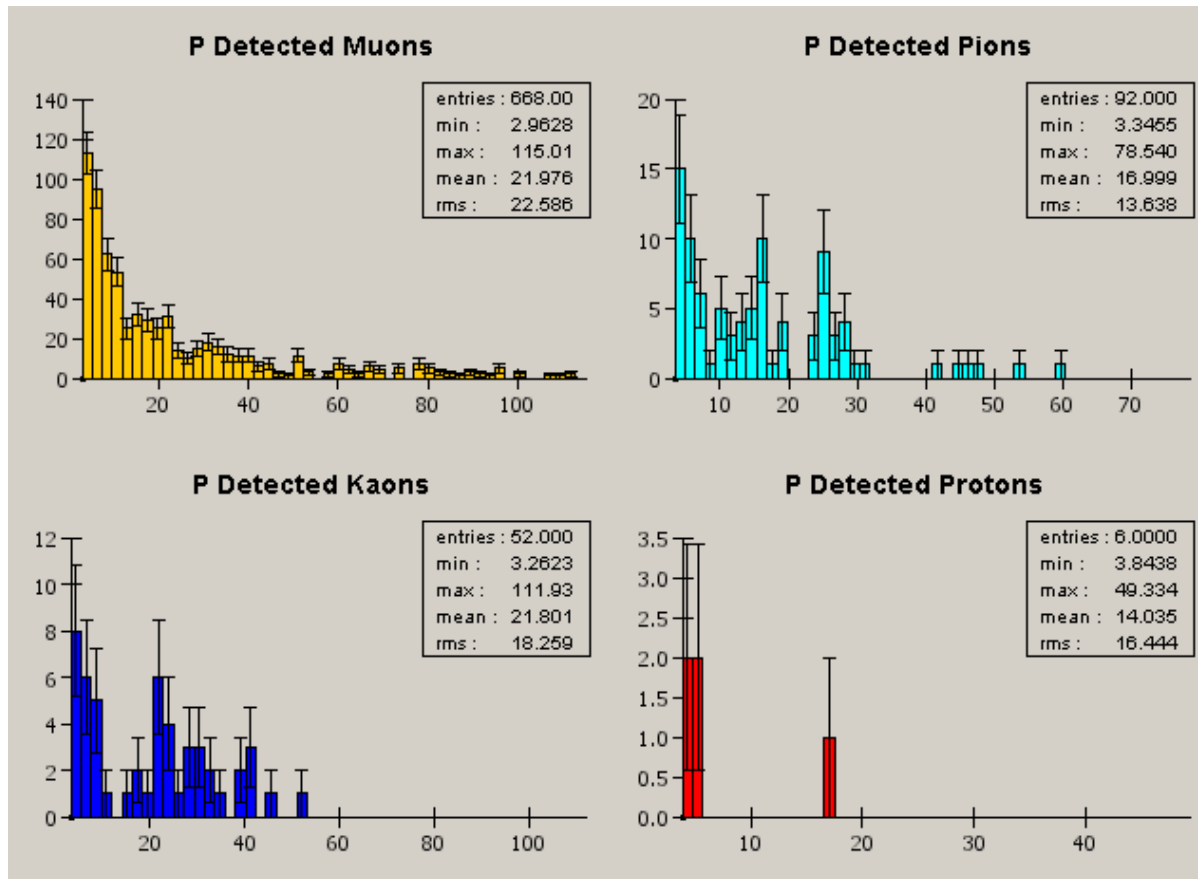
Hadrons Rejection in b-bbar jets

- More muons got reconstructed, 668 versus 657 before the integration of the v^B term, but more hadrons as well
Again we apply the HDCal rejection cut.
- When a hadron interacts the signal spreads out and a hit depletion appears in the path.
- Using the 5 last layers of the hadron calorimeter as an extension of the Muon detector which has a finer grain, this allows to discard part of the hadrons. Therefore, 2 to 4 sensitive planes with a finer grain, located between the coil and the muon detector would have been very useful.

2c-B-Bbar Event



Hadrons Rejection In Jets



The number of
Pions : 92/427
Kaons: 52/141
Protons: 6/43

Hadron Rejection Efficiency In b-bbar Jets

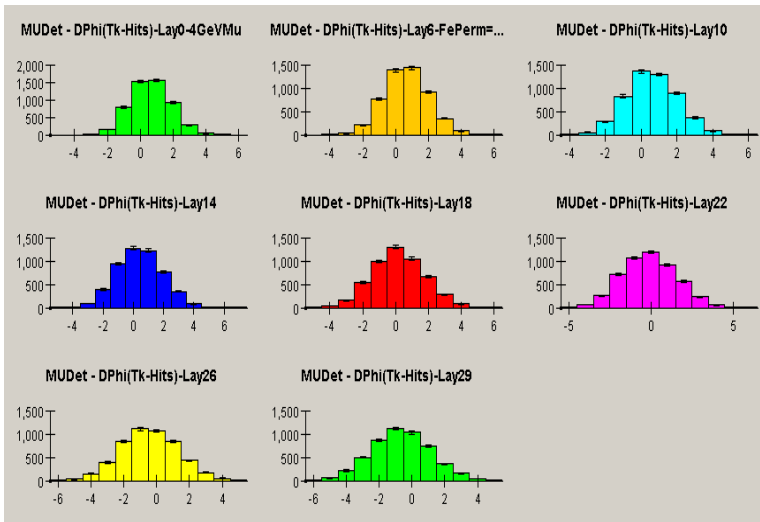
	Pion BG	K BG	Proton BG
TotalFromTracker above.>3 Gev	47585 18029	7777 4301	2768 1613
Detected	92	52	6
Rejection Efficiency	1 / 196	1 / 83	1 / 268

•Generated Particles
above >2.96 GeV used
To calculate the
Rejection Efficiencies.

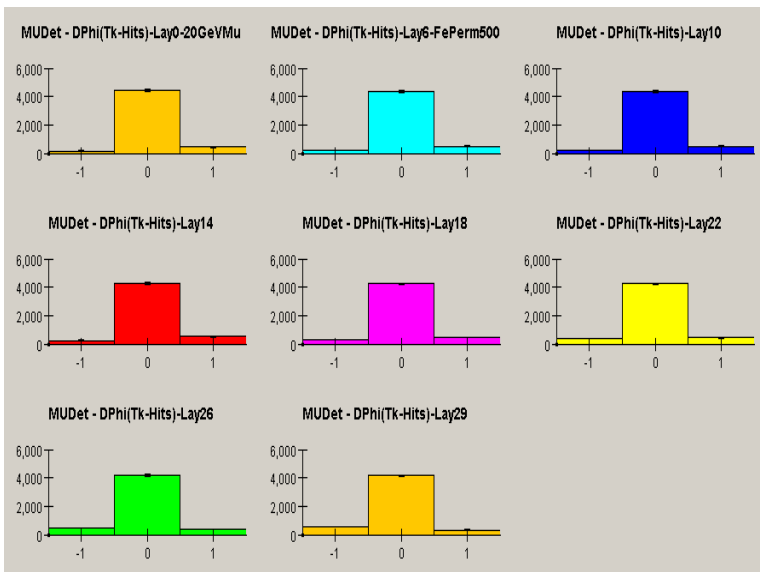
Stepper+Integrated
Field term
668 Muons/739 From
The tracker

The rejection efficiency
Is ~ 70% to 80% of the
Values reached before.

Angular resolution $\Delta\Phi = f(\text{Layer Num})$ 4GeV/20 GeV Muon in MUDET-right



$\Delta\phi(\text{Track-Hit})$ at different radii (layer number)
In Mudet for a 4 GeV Muon



$\Delta\phi(\text{Track-Hit})$ at different radii (layer number)
In Mudet for a 20 GeV Muon

One would like to define a (θ, ϕ) road as sharp
As possible. This will provide a good rejection
Efficiency in jets as well as a better efficiency.
We would like to have the same angular
Resolution at 4 GeV than at 20 GeV.

The Kalman Filter

- Kalman filtering allows to define for each radius a θ , Φ , dynamic road in which are collected the hits left by the particle in the various parts of the detector. It addresses the reconstruction of the low momenta particles in a high magnetic field and the random processes, e.g. Multiple scattering, Bremsstrahlung, etc.
- This is done by the Kalman Gain Matrix which use a weighting procedure which accounts also for the measurements in the active material.
- It should provide a well define separation between tracks inside jets and get rid of miss-identified particles
- The tracks are extrapolated using the same analytical form than in the stepper, translated into a transport Matrix. It accounts now for the integrated vXB term of the magnetic field and for the losses by dE/dx in the material as before.
By transporting the covariant matrix as well, the random processes are now taken into account, e.g multiple scattering .
- This allows to improve further low momenta angular resolution, the information being also more complete since it includes random processes in a realistic way.

The Kalman Filter- The principle

The Kalman filter basic ideas:

The Phase Space point has been chosen as the state vector point. Here too the effect of the magnetic field, the dE/dx and now the multiple scattering will be translated, into a change in px py , pz ..

$$\left\{ \begin{array}{l} x_{k-1}(-) \\ y_{k-1}(-) \\ z_{k-1}(-) \\ px_{k-1}(-) \\ py_{k-1}(-) \\ pz_{k-1}(-) \end{array} \right\}$$

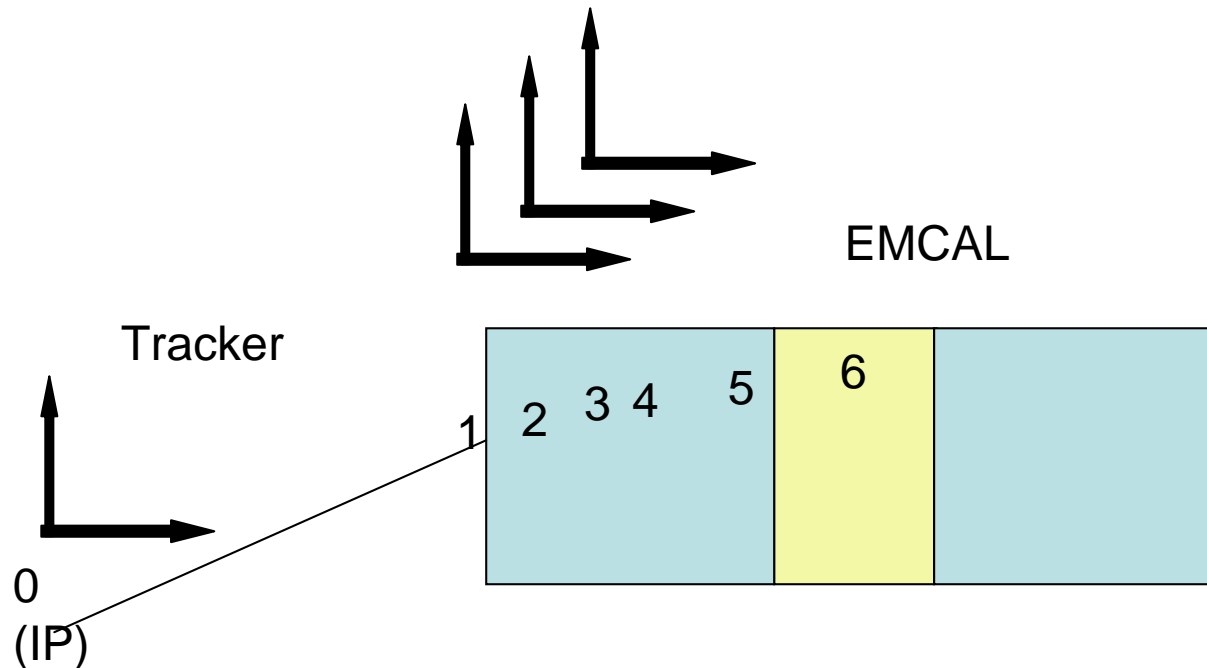
The state vector at location $k-1$, is propagated using the propagation matrix, to location k . The choice of the state vector as the phase space point allows to use the stepper algorithm translated into a propagation matrix.

This will be done a number of times in the dense material of the absorber whereas the multiple Scattering is transported with the covariant matrix.

Then, In the active material the Kalman filter weighting procedure is applied using the estimate at point k : $x_k(-)$ & the actual measurement at k , z_k and at that point the the state vector get calculated anew by a weighting procedure which combines the extrapolation and measurement & produces the vector $x_k(+)$.

Remark: in $x_k(-)$ and $x_k(+)$ the $(-)$ indicates the extrapolation, the $(+)$ the Kalman weighting.

b-Track Intersections with the Material



- The Change in the vector state accounts for the dE/dx and B_z and is taken into account in the propagation Matrix (step 1,2,3,4,5) in the passive material. The covariant matrix accounts for the Multiple Scattering in (1,2,3,4,5)
- The change in the vector state which includes the Kalman Weighting as a result of all the above, takes place when the hit is recorded in the active material (step 6)

c-Muon Code Implementation of the Filter

Propagation In Passive material

$$\left\{ \begin{array}{l} \vec{x}_k(-) = \Phi_{k-1} \cdot \vec{x}_{k-1}(-) \\ P_k(-) = \Phi_{k-1} \cdot P_{k-1}(-) \cdot \Phi_{k-1}^T + Q_{k-1} \end{array} \right\} \quad (1)$$

Kalman Filter in Scintillator after Measurement of the signal

$$\left\{ \begin{array}{l} \vec{x}_k(+) = \vec{x}_k(-) + K_k \cdot [\vec{z}_k - H_k \cdot \vec{x}_k(-)] \\ P_k(+) = [1 - K_k \cdot H_k] \cdot P_k(-) \end{array} \right\} \quad (2)$$

Kalman Gain Matrix

$$K_k = P_k(-) \cdot H_k^T \cdot [H_k \cdot P_k(-) \cdot H_k^T + R_k]^{-1} \quad (3)$$

$Q_{k-1} = |\vec{p}| \cdot \Theta_0 \cdot \mathbf{I}$; is [3x3] lower corner of Q_{k-1} ; $\vec{p} = \text{Momentum}$

Q_k is the noise from Multiple scattering- a [6x6] Matrix ; [3x3] lower corner $\neq 0$

R_k = Measurement Error, dx, dy, dz - a [3x3] Matrix

H_k = Measurement Matrix - a [3x6] Matrix

Φ_k = Propagation Matrix, applied in passive material- [6x6] Matrix

$X_k(-)$ is the extrapolated vector state (x, y, z, px, py, pz) -[6x1] “

Z_k is the measured quantities (r,θ,φ) translated into (x,y,z)-[3x1] Matrix

$X_k(+)$ = the state vector after applying the Kalman filter-[6x1] Matrix

K_k = The Kalman Gain Matrix - [6x3] Matrix

d-The Propagation Matrix

$$\begin{Bmatrix} x_k(-) \\ y_k(-) \\ z_k(-) \\ px_k(-) \\ py_k(-) \\ pz_k(-) \end{Bmatrix} = \left(dT * \begin{pmatrix} aa & ab \\ ba & bb \end{pmatrix} + I \right) * \begin{Bmatrix} x_{k-1}(+/-) \\ y_{k-1}(+/-) \\ z_{k-1}(+/-) \\ px_{k-1}(+/-) \\ py_{k-1}(+/-) \\ pz_{k-1}(+/-) \end{Bmatrix}; \phi = dT * \begin{pmatrix} aa & ab \\ ba & bb \end{pmatrix} + I$$

$$ab = \begin{pmatrix} (cdedx) & f(Bz) & 0 \\ -f(Bz) & (cdedx) & 0 \\ 0 & 0 & (cdedx) \end{pmatrix}; bb = \begin{pmatrix} dxyz & 0 & 0 \\ 0 & dxyz & 0 \\ 0 & 0 & dxyz \end{pmatrix}; cdedx = dE/dx \cdot 100 * c/Pabs$$

$$R_0 = \begin{pmatrix} dx & 0 & 0 \\ 0 & dy & 0 \\ 0 & 0 & dz \end{pmatrix}; \Theta_0 = (13.6MeV / P \cdot \beta c) \sqrt{x / X0} \cdot (1 + 0.038 \cdot \ln(x / X0)); \beta = c = 1$$

$$x = r \cdot \sin \Phi; y = r \cdot \cos \Phi; z = r \cdot ctg \Theta$$

$$dxyz = 100 * clight / E_n; f(Bz) = 0.3 * q * \frac{p_x(n)}{E(n)} * clight * B_z$$

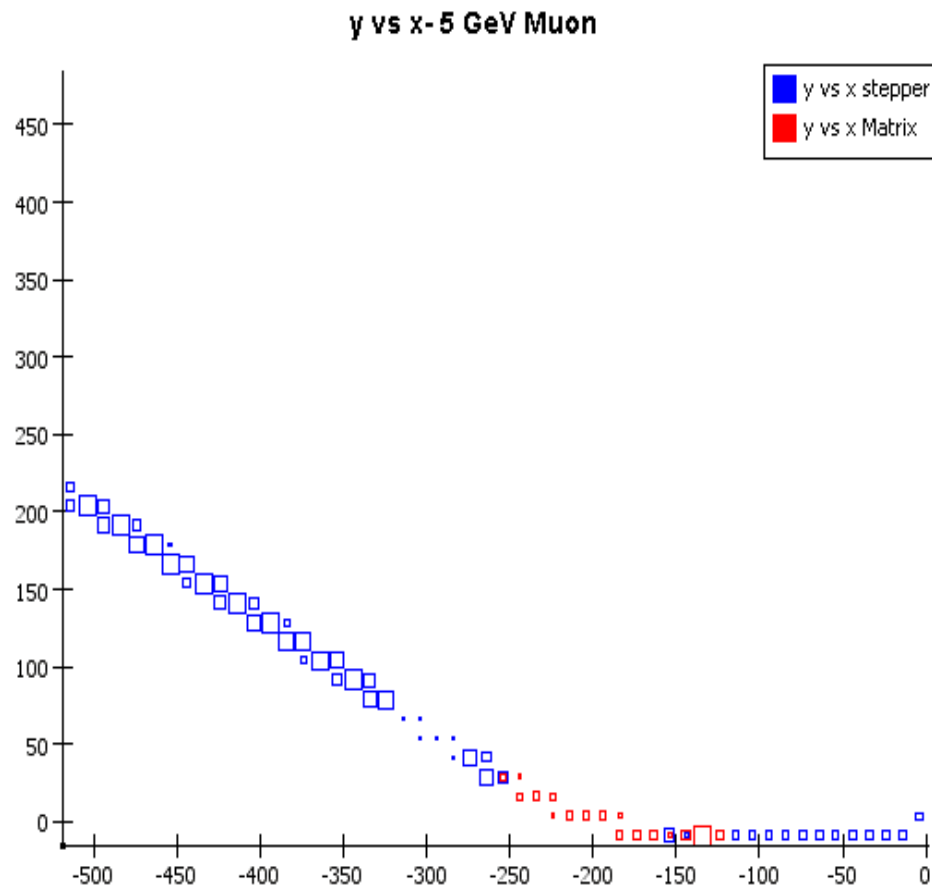
Examples of Transport and Covariance Matrices, P_{k+} and Φ_{k+}

- Matrix Φ_k
- 1.0000 0.0000 0.0000 0.0064 0.0000 0.0000
- 0.0000 1.0000 0.0000 0.0000 0.0064 0.0000
- 0.0000 0.0000 1.0000 0.0000 0.0000 0.0064
- 0.0000 0.0000 0.0000 0.9998 0.0001 0.0000
- 0.0000 0.0000 0.0000 -0.0001 0.9998 0.0000
- 0.0000 0.0000 0.0000 0.0000 0.0000 0.9998

- New x, y, z=101.165cm -77.099cm 0.0130cm
- New px, py, pz=2.51 GeV -3.119 GeV 4.072E-4 GeV
- del_x=0.0161 del_y=-0.02003 del_z=2.6154E-6

- Matrix P_k
- 0.0008 0.0000 0.0000 0.0184 -0.00001 0.0000
- 0.0000 0.0008 0.0000 0.00001 0.0184 0.0000
- 0.0000 0.0000 0.0001 0.0000 0.0000 0.0027
- 0.0184 0.00001 0.0000 0.4222 -0.0000 0.0000
- -0.00001 0.0184 0.0000 0.0000 0.4222 0.0000
- 0.0000 0.0000 0.0027 0.0000 0.0000 0.0730

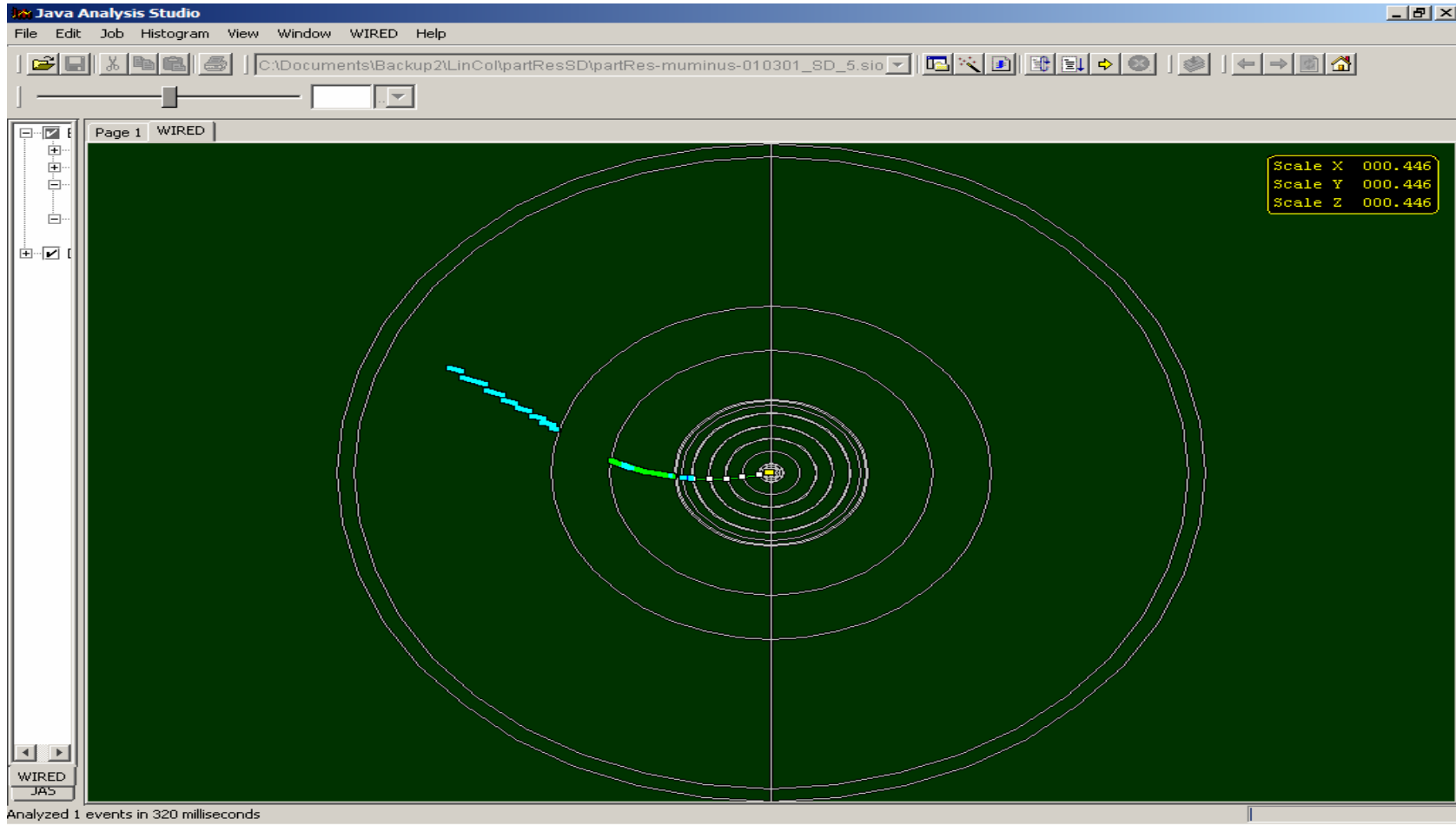
The propagation Matrix (cont)



-In red the propagation Matrix in EMCAL && HCAL-

-In blue the stepper elsewhere

Track Single Event Display (By WIRED)



Assumptions

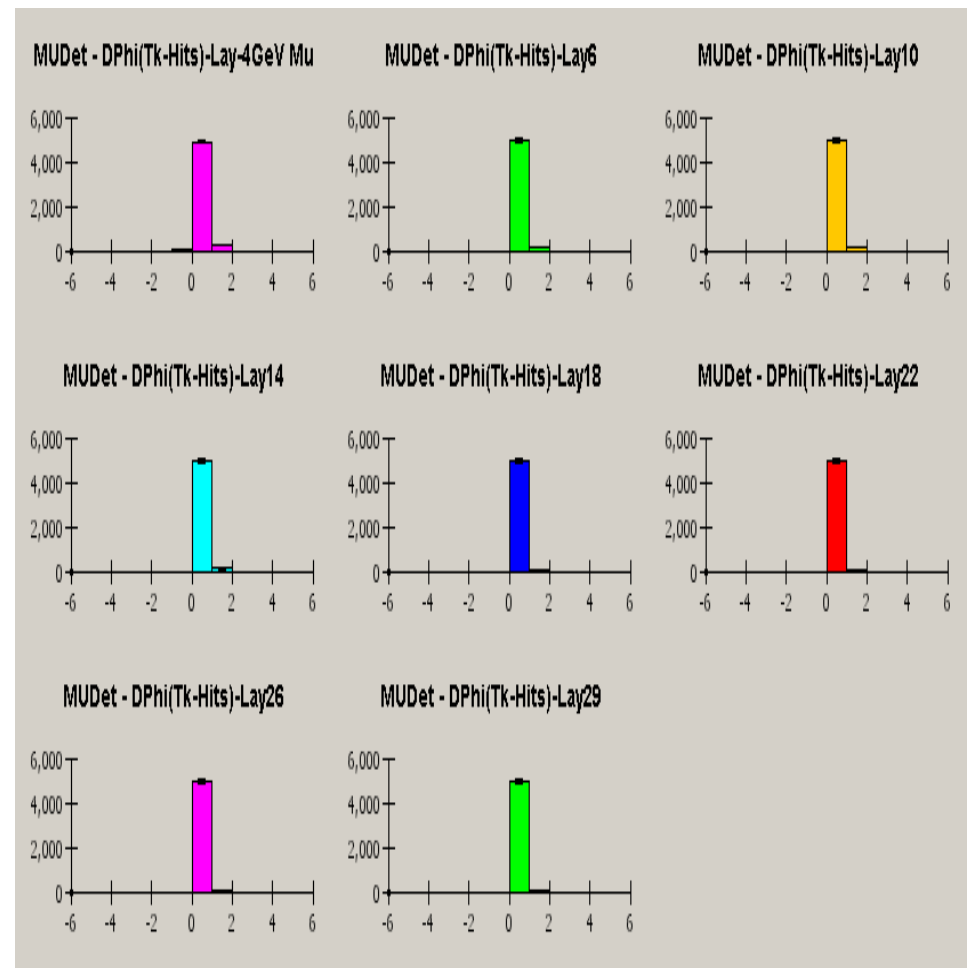
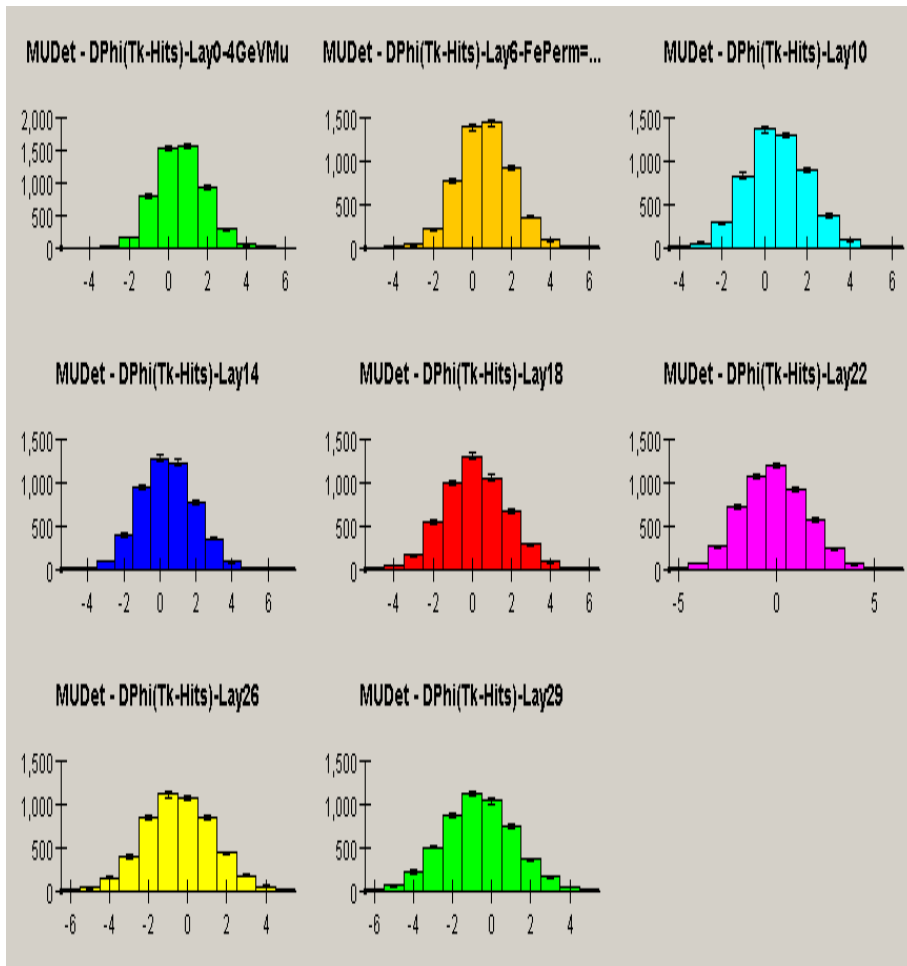
- For now: In the tracker one uses the stepper(200 steps)
- The covariance Matrix P_k got “started” at the entry of EMCAL, it is zero everywhere except the lower right 3x3 region.
I have chosen the cell size at the Entry of ECAL as the sigma
- In Q_k has zeros everywhere, except in the Lower right where $\Theta_0 p_{abs}$ is the term in the diagonal.
- H is the measurement matrix.
- First result of low energy single muons are showing a real improvement. The width of the distribution is ~ constant and of the order of the detector detection accuracy, the size of the angles bin.

The Goal

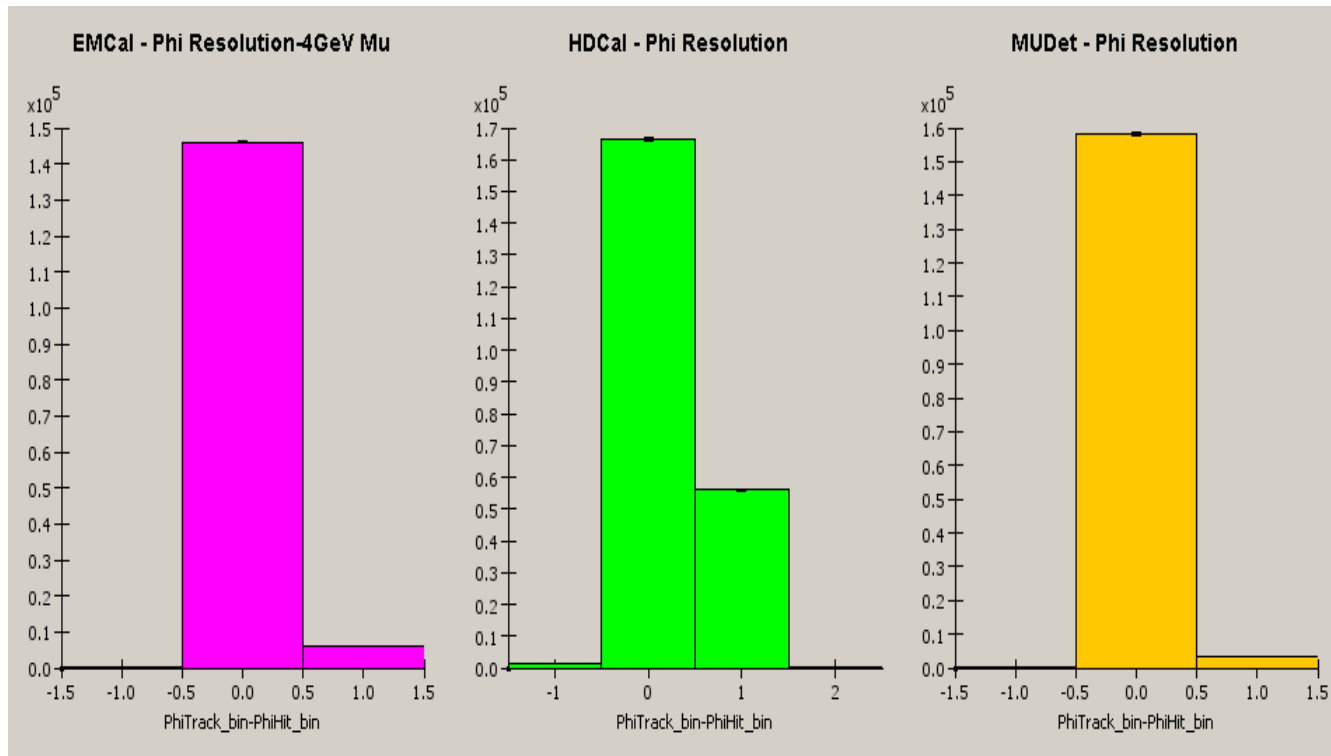
- The goal is to include the random terms and by having a dynamic path to reach at low energy, e.g. 5 GeV and below the angular resolution reached at 20 GeV, namely better than 0.5 bin, 1 bin $\sim 5\text{mrd}$ in HDCal and $\sim 21\text{mrd}$ in MUDet.
- In the next two transparencies are the values obtained with the stepper at different radii (different layer number) for the Muon Detector where there is room for improvement.

2b-MUDET-Angular resolution

$\Delta\Phi = f(\text{Layer Num})$ - 4GeV-Kalman right

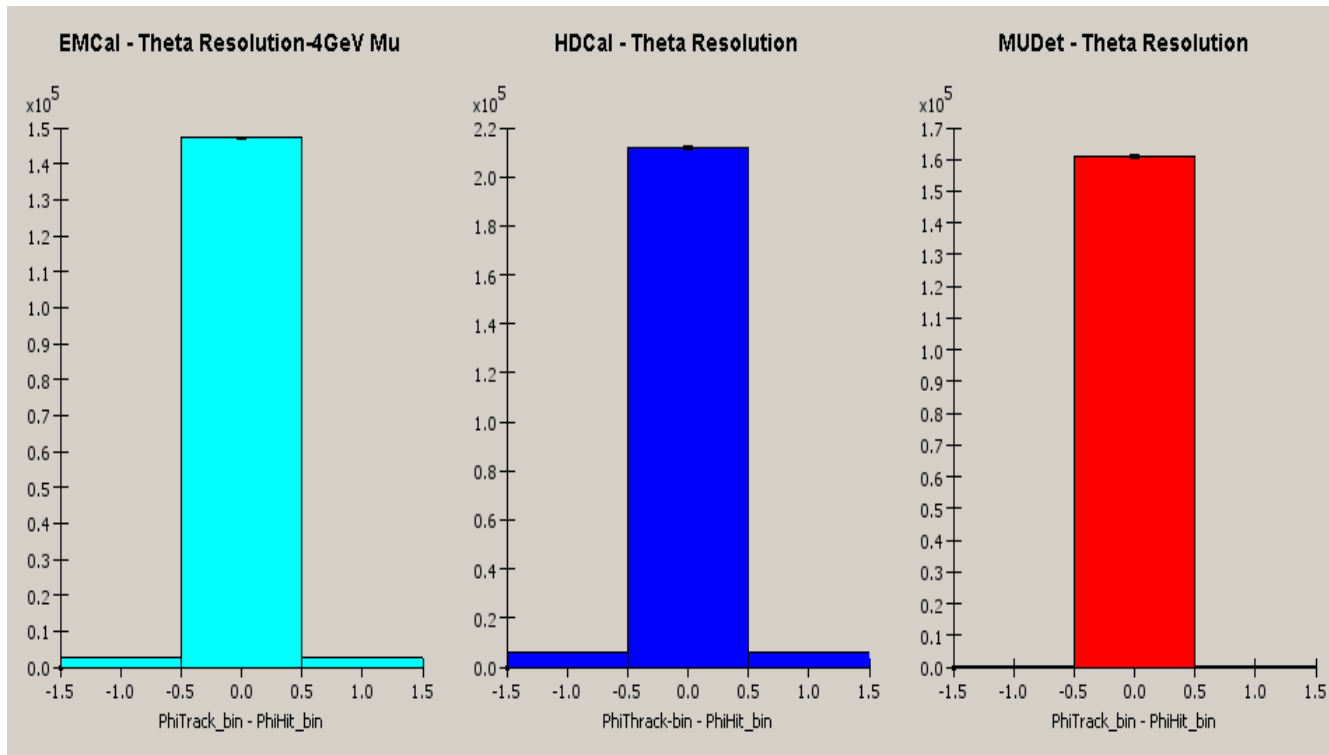


Resolution in Φ - EMCaI- HDCaI-MUDet Running 5000 Muons at 4 GeV



- The resolution is better than 0.5 bin in each detector component, a bin being in EMCaI(~ 3.8 mrd), in HDCaI(~ 5 mrd), in MUDet(~ 21 mrd)

Resolution in θ - EMCaI- HDCaI-MUDet Running 5000 Muons at 4 GeV



- The resolution better ~ 0.5 bin in each detector component, the bin being EMCaI(~ 3.8 mrd), HDCaI(~ 5 mrd), MUDet(~ 21 mrd)

Implementation in LCIO

- The stepper code has been imported to LCIO with the help of G. Lima and T. Johnson. Some more implementation to the new format is being done.
- Then the Kalman filter code will be transported as well.

Outlook

- The Kalman filter has been implemented in the Muon code and has to be brought to LCIO format .
- It includes the multiple scattering, the integrated vxB term from the magnetic field and the dE/dx . The error at starting point has been chosen to be the angle bin size in the calorimeter EMCAL. Up to the entry of EMCAL the stepper is used.
- The Kalman filter applies a realistic propagation at each step and allows hits to be collected in a narrower kinematical band. The “direction” taken by the band get dynamically implemented using information from the data.
- Next to be done
 - a) Transfer to LCIO format
 - b) Study of the Kalman filter in jets
 - c) Implementation of a driver which redirect in a transparent way to the stepper, which is more rapid, for particles > 10 GeV and the Kalman filter below.
- I am Thankful for very useful suggestions and comments from Gene Fisk, and I want to thank Adam Para and Harry Weerts for their comments . My thanks are also due to Tony Johnson and Guilherme Lima for their valuable help with LCIO.

The SiD

Amount of Material in front of MuCal

EMCAL $22X0 - 0.87 \Lambda - 190\text{MeV}$ lost by dE/dx

HDCAL $39.5X0 - 4.08 \Lambda - 800\text{MeV}$ lost by dE/dx

The Coil $5.6 X0 - 1.27 \Lambda - 218\text{MeV}$ lost by dE/dx

Total = $67 X0 - 6.22 \Lambda - 1200\text{MeV}$ lost by dE/dx

A Magnetic Field of 5 Tesla

Instr MuCal $91 X0 - 9.6 \Lambda - 1600\text{MeV}$ lost by dE/dx

MuCal:

Outer_Radius 660.5cm(up to 550cm Instrumented)

Inner_Radius 348.5cm

A Total 312 cm(202cm instrumented)

The Unit: Fe 5cm + Gap 1.5cm scintillator
48 Layers /32 Layers Instrumented
80cm Fe = 16 planes

d-The Propagation Matrix

- The term $(cdedx)$ is now replaced by $(cdedx) - \eta \cdot p_i$; $i=x,y,z$
- The term $f(Bz)$ is now replaced by $f(Bz)/\delta$

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