Time resolution of the ATLAS Tile calorimeter and its performance for a measurement of heavy stable particles

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Abstract

Time resolution of the ATLAS Tile calorimeter modules has been measured using the test beam data. The resolution depends on the energy deposited in a given cell and is equal to about 1.5 ns at $E = 1\ GeV$, 270 ps at $E = 25\ GeV$ (high gain), 700 ps at $E = 25\ GeV$ (low gain) and 170 ps at $E = 150\ GeV$. These values have to be compared to the time of flight of relativistic particles to reach the first samples of Tile calorimeter (from 8.3 ns to 20 ns). Time-Of-Flight measurements using Tile Calorimeter can be used to identify and, combined with momentum measurements by the ATLAS inner detector, measure the mass of exotic heavy stable particles. The results are compared to a previous analysis using the ATLAS muon spectrometer[1].

1 ATLAS Tile calorimeter

The ATLAS [?] Tile Calorimeter [3] is a large hadronic sampling calorimeter which makes use of steel as the absorber material and scintillating plates read out by wavelength shifting (WLS) fibers as the active medium. The new feature of its design is the orientation of the scintillating tiles which are placed in plane perpendicular to the colliding beams and are staggered in depth.

The Tile Calorimeter consists of a cylindrical structure with an inner radius of 2280 mm and an outer radius of 4230 mm. It is subdivided into a 5640 mm long central barrel and two 2910 mm extended barrels. The scintillating tiles lie in the $r - \phi$ (radius-azimuthal angle) plane and span the width of the module in the ϕ direction. WLS fibers running radially collect the light from the tiles along their two open edges. Readout cells are then defined by grouping together a set of fibers into a photomultiplier (PMT), to obtain a three dimensional segmentation. In total there is 4928 readout cells. Radially, the calorimeter is segmented into three layers, approximately 1.4, 3.9 and 1.8 interaction lengths thick at pseudorapidity $\eta = 0$; the $\Delta\eta$x $\Delta\phi$ segmentation is 0.1x0.1.

Each cell of the Tile Calorimeter is read-out by two PMTs in order to provide redundancy in the light read-out and improve spatial uniformity. The conversion of the light signal from the fiber bundles to electrical charge is done by the photomultipliers in the PMT blocks.

The output of the PMT block is a shaped electronic signal which is subsequently digitized by electronics inside the superdrawer (see Fig. 1). Two linear outputs (high and low gain) are used for each channel, differing in gain by a factor of 64.

2 Tile calorimetry time measurement

For the purpose of this analysis, test beam data of Tile calorimeter modules taken in 2002 and 2003 have been used. Tile calorimeter production modules have been irradiated by 180 GeV beam of negative pions at different pseudorapidities. The beam contained also muons, its contamination by electrons was very low. No special requirements have been imposed on the particle trajectory. For each PMT the time and energy are evaluated with the fit method [4], i.e. as the peak position and height of the shaped signal fit to the digitized pulse samples.

For a given cell (readout by two PMTs called *e*ven and *o*dd) and a given interval of energies deposited in that cell the distribution of $\Delta t = (t_e - t_o)/2$ is plotted and its sigma is estimated by a gaussian fit. For relativistic particles the time of flight varies from approximately 8.3 ns for the cell A-1 to about 20 ns for the cell D-8 of the extended barrel. A particle that moves slower than relativistic particles and which interacts electromagnetically and/or hadronically will give the response delayed with respect to that of relativistic particles. In case of no correlations between the two time measurements t_e and t_o, the value of $\sigma_{\Delta t}$ is the best estimator of σ_t of a variable $t = (t_e + t_o)/2$. In ATLAS this variable t could serve as a measurement of the time of flight of particles with electromagnetic and/or hadronic interactions. Examples of Δt distributions are plotted on Fig. 2 and Fig. 3 for high gain and low gain respectively.

On Fig. 4 time resolutions for low gain and high gain of the same cell are compared for two different test beam runs. More distributions [10] showing a comparison of resolution curves for different cells in the same module are in Fig. 5 and Fig. 6. The resolution has been parametrized by a quadratic sum of statistical (proportional to $1/\sqrt{E}$) and noise (proportional to $1/E$) terms (E is in GeV):

$$\sigma_t\left(E\right) = \frac{p_0}{\sqrt{E}} \oplus \frac{p_1}{E} = \sqrt{\left(\frac{p_0}{\sqrt{E}}\right)^2 + \left(\frac{p_1}{E}\right)^2} \tag{1}$$

As indicated on Fig. 4-6, the resolution curves are quite similar for different cells, moreover in the ATLAS environment these curves could eventually be obtained for each Tile cell. For further analysis we took the parametrization of the time resolution for the cell A-6 (see Fig. 5) with following values of parameters:

High Gain $p_0 = 1.45$ ns $\cdot GeV^{1/2}$, $p_1 = 0.38$ ns $\cdot GeV$
Low Gain $p_0 = 1.7$ ns $\cdot GeV^{1/2}$, $p_1 = 17.2$ ns $\cdot GeV$.

3 Detection of heavy stable particles with Tile calorimeter and Inner detector

There are different theories predicting an existence of heavy particles stable enough to be detected prior to their decay. For recent references see e.g. [5]. A possibility to measure such particles in ATLAS using time of flight measurement performed by the muon system has been thoroughly discussed in [1].

In this paper we discuss a possibility to detect such particles and measure their mass using the time measurement performed by the Tile calorimeter combined with the momentum measurement using ATLAS inner detector (ID).

The velocity of a particle that deposits energy in the Tile calorimeter cell i located at a distance L_i from the interaction piont could be measured as follows:

$\beta_{tile} = \frac{L_i/c}{t_{tile,i} - t_{rel,i} + L_i/c}$

where for a given cell i the variable $t_{tile,i} = \frac{t_e + t_o}{2}$ is the time measured in a given event, while $t_{rel,i} = \langle \frac{t_e + t_o}{2} \rangle$ is the mean value of the time measured over all events in a given cell. The latter is the time of flight of the relativistic particle.

The precision in measurement of β is given by a formula:

$\sigma_\beta = \beta^2 \frac{\sigma_{t_{tile}} \oplus \sigma_{t_{rel}} \oplus \frac{t_{tile} - t_{rel}}{L_i/c} \sigma_{L_i/c}}{L_i/c}$

Dominant contribution to the velocity uncertainty is due to the first term. The precision of the mean value over many events $\sigma_{t_{rel}}$ is certainly much better. Also the third term contributes very little to the overall velocity resolution.

In general the particle deposits the energy in couple of Tile calorimeter cells. The particle's velocity could be evaluated for each cell and the measurements could be combined with weights proportional to $1/\sigma_\beta^2$.

When the particle's momentum p and velocity β are measured, the mass of the particle could be evaluated as follows:

$$M = \frac{p}{\beta\gamma} = p\frac{\sqrt{1-\beta^2}}{\beta} \quad (2)$$

The mass resolution is then given:

$$\sigma_M = \partial_p M \sigma_p \oplus \partial_\beta M \sigma_\beta = \sqrt{(\partial_p M \sigma_p)^2 + (\partial_\beta M \sigma_\beta)^2} \quad (3)$$

To estimate the mass resolution, the following assumptions about momentum and velocity resolutions and particles energy losses in the Tile calorimeter have been made:

- To get a conservative estimate we assume that particle's velocity is measured by the closest to the ATLAS interaction point Tile calorimeter cell A-1. Then $\beta_{tile} = \frac{8.3ns}{t_{tile}}$ and consequently $\sigma_{\beta_{tile}} = \beta^2 \frac{\sigma_t(E_{tile})}{8.3ns}$, where $\sigma_t\left(E_{tile}\right)$ is given by formula (1) with quadratically added constant time resolution term of 70 ps. This term is caused by the time spread of the primary interaction due to finite lengths of the LHC proton bunches. The primary interaction could appear anytime within a time window of $\frac{L_{bunch}}{30cmns^{-1}}$, i.e. the time of the primary interaction has a dispersion of $\frac{L_{bunch}}{30cmns^{-1}}\frac{1}{\sqrt{12}}$ which equals to 70ps for $L_{bunch} = 7cm$.

- Purely hadronic losses of heavy stable particles have been parametrized using results of [6]. For 1 m of iron they are roughly equal to 4% and 1.2% of kinetic energy for the mass M=100 and 600 GeV respectively[6]. Because the thickness of the Tile calorimeter is more than 1.5 m, the values of the slopes have been rescaled accordingly.

- Ionization losses in TileCal have been parametrized as $\Delta E_{ioniz} = 2.2GeV/\beta^2$ using a measured value of the most probable muon losses (2.2 GeV) in the Tile calorimeter at small pseudorapidities. Energy losses up to kinetic energy of the particle have been allowed. The particles with the mass of 200 (1000) GeV and a momentum smaller than about 80 (260) GeV are stopped at the Tile calorimeter.

- $\sigma_{p_{id}}\left(p_{id}\right) = 3.6 \cdot 10^{-4}\ p_{id}^2 \oplus 3.6 \cdot 10^{-2}$ (all values in GeV) - approximate precision of the momentum measurement with the ATLAS inner detector at the investigated momentum region [8];

- $\sigma_{p_\mu}\left(p_\mu\right) = 1.3 \cdot 10^{-4}\ p_\mu^2$ - approximate precision of the momentum measurement with the ATLAS muon spectrometer at the region of interest [9];

- $\sigma_{\beta_\mu}\left(\beta_\mu\right) = 0.067\beta_\mu^2$ - anticipated precision of the velocity measurement using the muon system [1];

On Fig. 7,8 and 9 the mass resolution σ_M/M for three different masses (200, 500 and 1000 GeV) of particles are plotted as a function of a momentum at pseudorapidity close to η =0. The resolution of Tile+ID is compared with that of the muon system.

4 Discussion of results and conclusions

For particles of low mass the results of Tile+ID are compatible with an anticipated precision of the muon spectrometer, for the case of hadronic losses it is even better. For masses around 500 GeV Tile+ID precision is worse than that of the muon spectrometer, but it still could improve the muon measurements. For the highest masses the Tile+ID precision is significantly worse than that of the muon spectrometer, however with Tile calorimeter being closer to the interaction point, a possible range of measurements of the muon spectrometer can be extended. This feature is indicated on Fig. 7-9 by limits which correspond to a limit of $\beta > 0.5$ required for a correct reconstruction of the track in muon system [1] and to a limit of $\beta > 8.3ns/(8.3 + 25)ns = 0.25$ ensuring the signal in the first cells of the Tile is seen within a correct bunch crossing.

In overlapping regions, the Tile+ID and muon measurements can be combined in order to improve the resolution. This is true for charged exotic particles measured both by Tile and muon spectrometer.

For the case of hadronically interacting particles, there are following possibilities in addition:

- In case of neutral particles with hadron interactions, the Tile calorimeter time of flight measurement can identify these particles giving, however, only lower limit of their mass.
- In the case of charged particles which are converted to neutral within Tiles, only Tile measurements will be available.
- In the case when particle is neutral, in Tile it interacts hadronically and converts to charged particle, muon measurements of its mass can be improved using the time of flight measurements performed by the Tile calorimeter.

An important question arises what deterioration of the time measurement is expected due to the pile-up effect. On Fig. 10,11 and 12 the contributions to the mass resolution due to momentum and time precisions are plot. For the particles with mass of 200 GeV, the Tile calorimeter time uncertainty dominates the errors, while the dominant contribution to the mass resolution for particles with mass larger than 500 GeV is due to uncertainty in the momentum measurement of the ID.

The results obtained in this analysis are encouraging and indicate a very good potential of ATLAS to measure heavy stable exotic particles with electromagnetic and/or hadronic interactions.

Acknowledgement

Authors are indebted A. Kraan and her colleagues for their work on the ATLAS muon spectrometer performance for R-hadrons searches. These works served as an inspiration for current analysis. The results, of course, would not be possible to obtain without an excellent work of the ATLAS Tile and TDAQ communities and CERN SPS accelerator group during the test beams.

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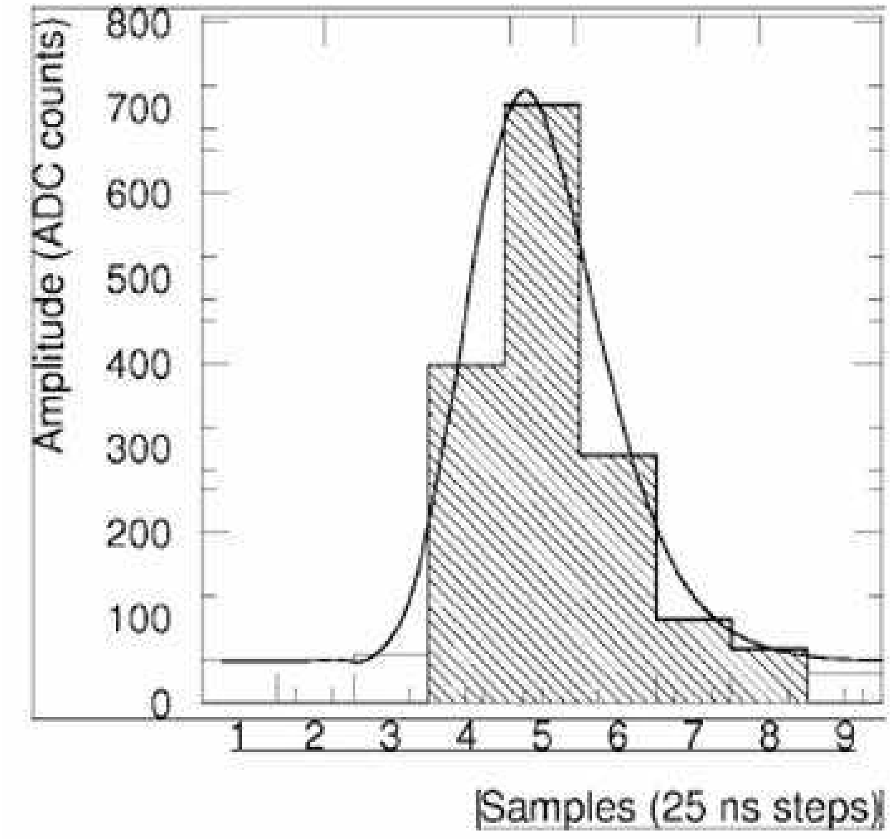

Figure 1: Shaped Tile signal and digitized samples.

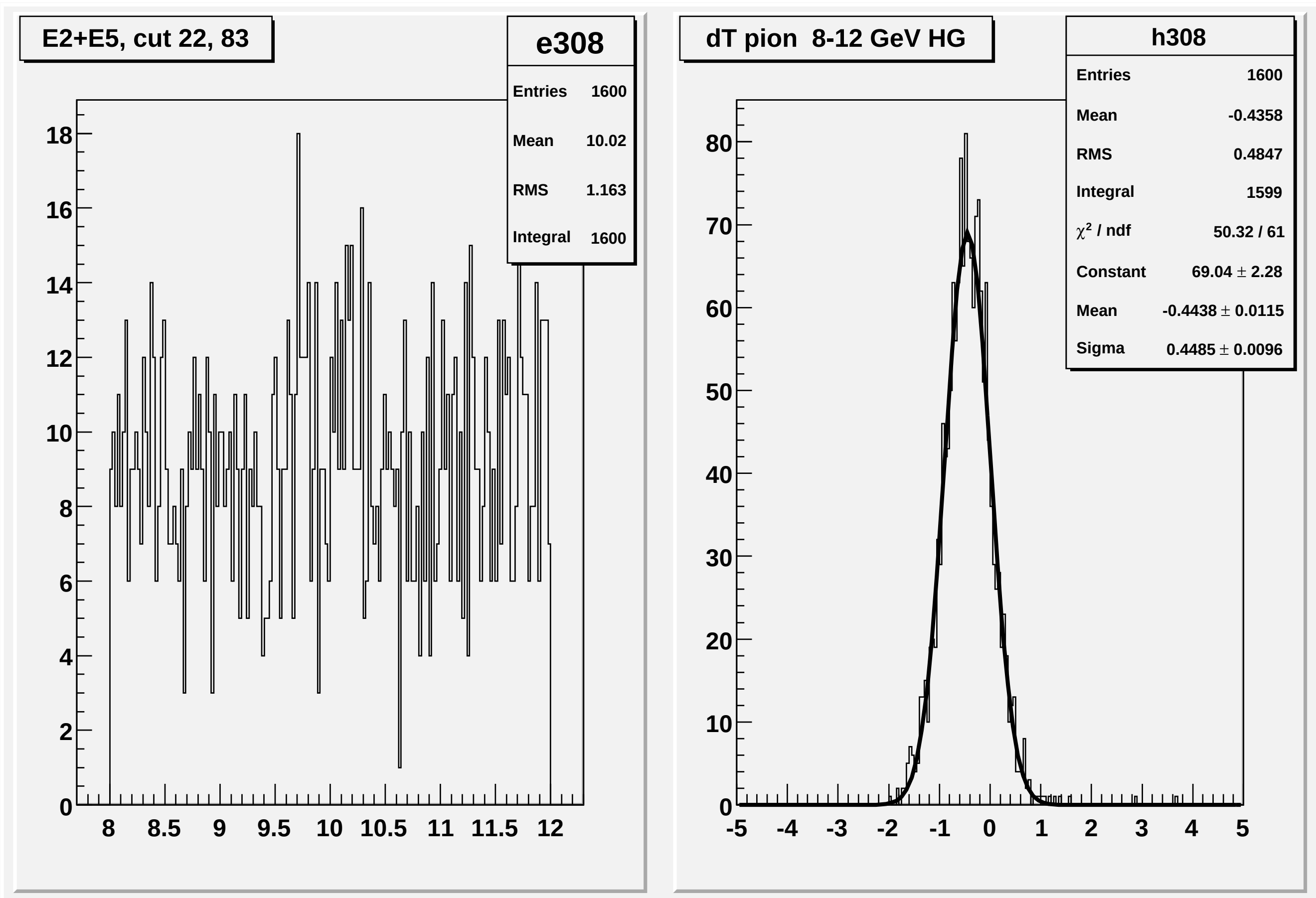

Figure 2: Left - Energy distribution in the interval 8-12 GeV. Right - Distribution of $\Delta t = (t_e - t_o)/2$ in the range from -5 ns to 5 ns and gaussian fit with $\sigma_{\Delta t} = 0.45$ ns.

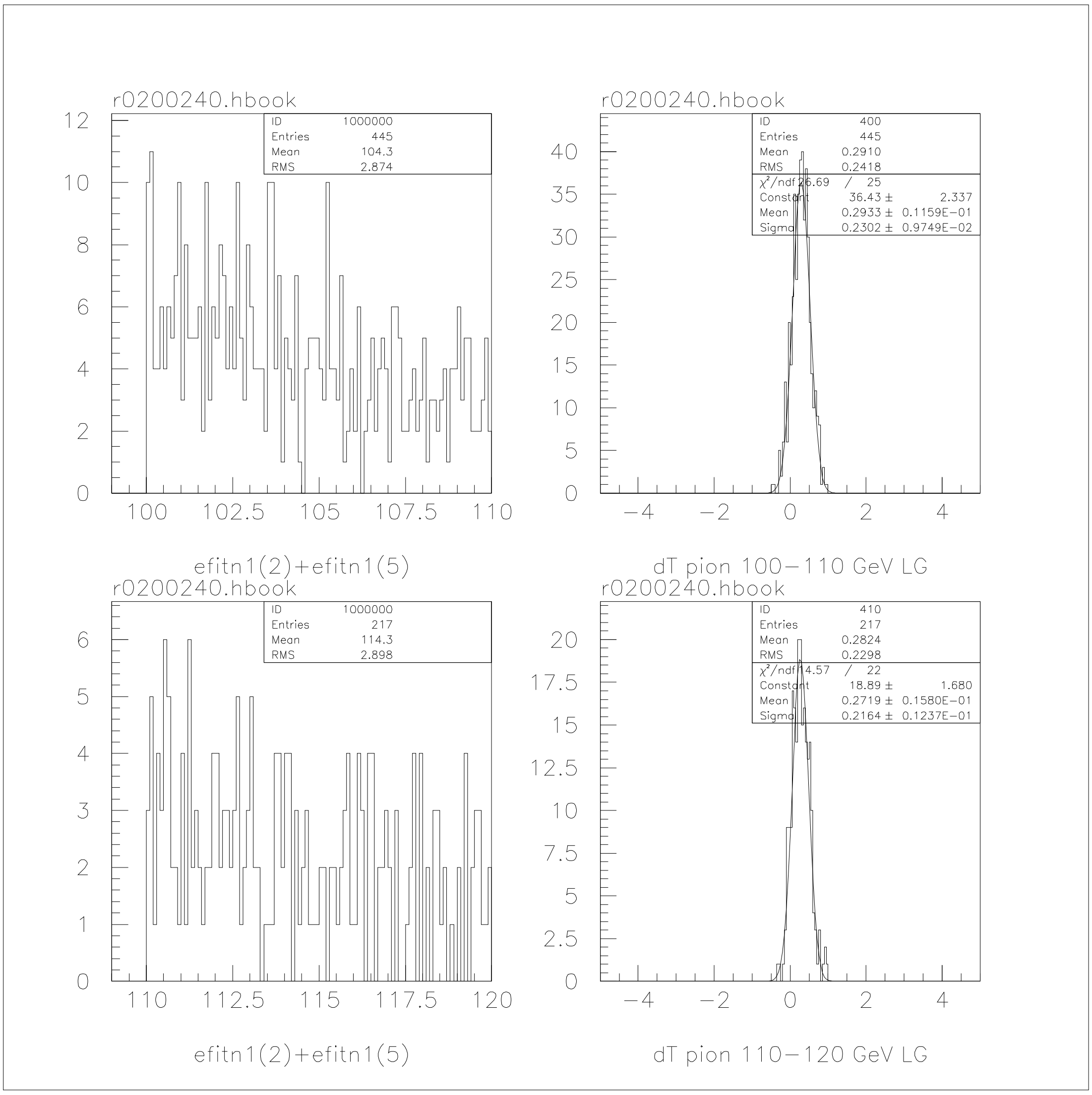

Figure 3: Left plots - Energy distribution in the interval 100-110 GeV and 110-120 GeV for cell A-1. Right plots - Distribution of $\Delta t = (t_e - t_o)/2$ in the range from -5 ns to 5 ns and gaussian fits with $\sigma_{\Delta t} = 0.230$ and 0.216 ns respectively.

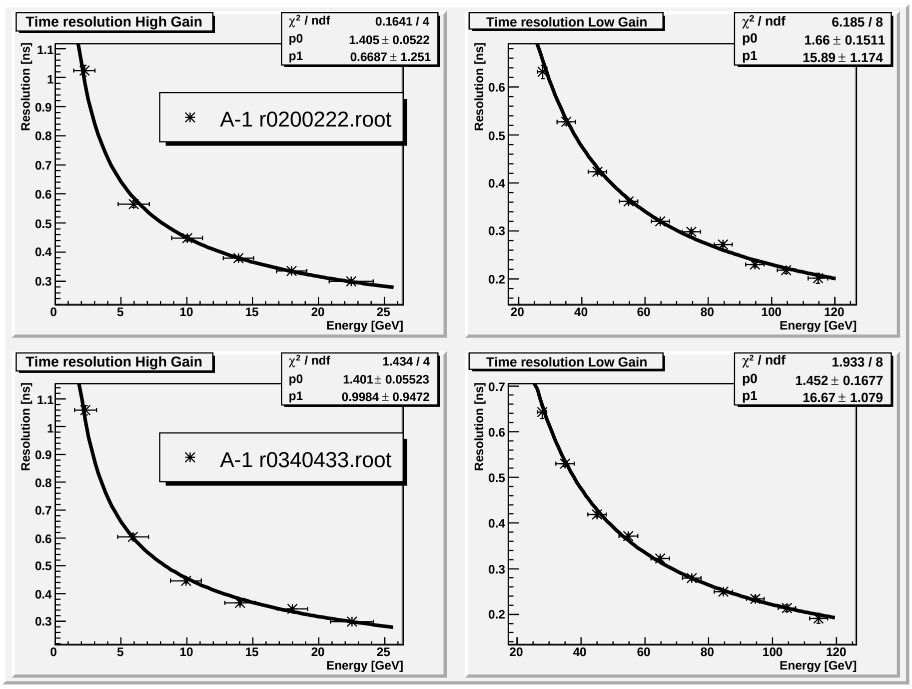

Figure 4: Time resolution in the first Tile calorimeter sampling cell A-1 for two different Tile calorimeter modules.

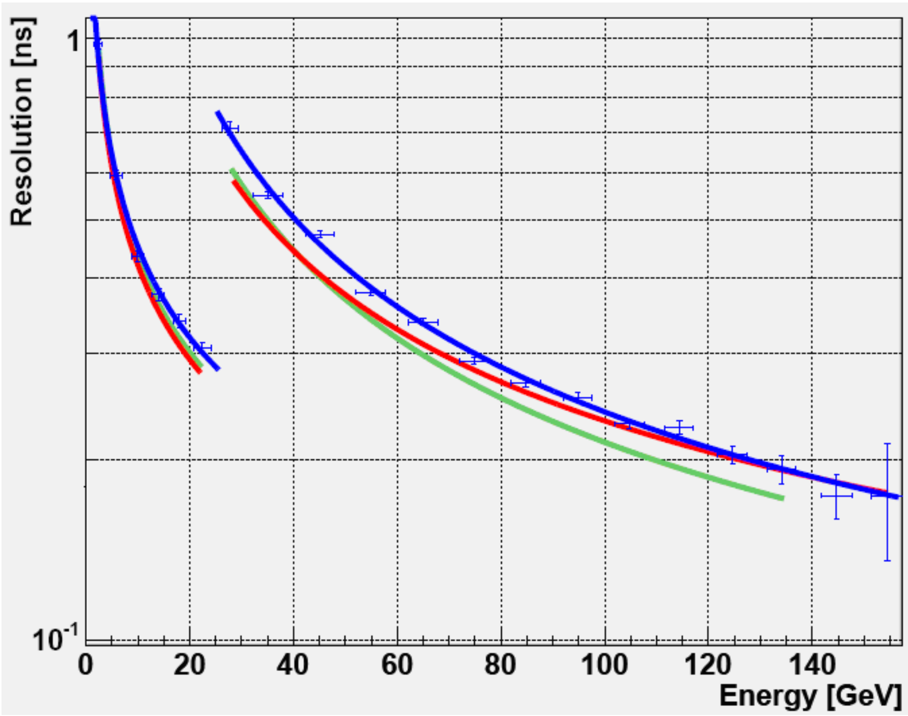

Figure 5: Time resolution in different A cells (A-1 (the best resolution), A-3, A-6(with data points)).

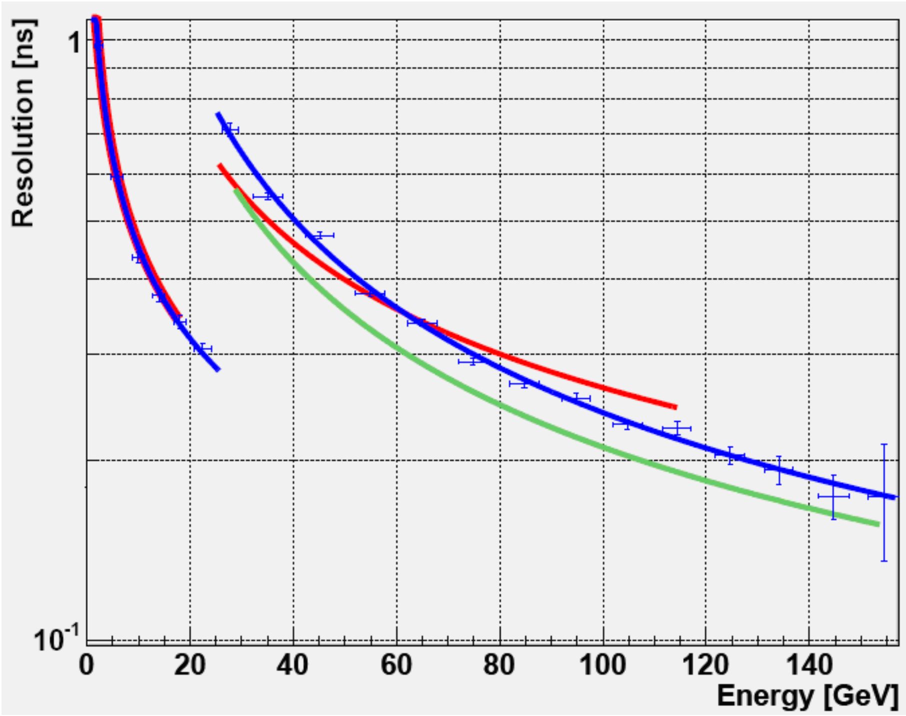

Figure 6: Time resolution in cells at different depths (A-6(with data points), B-6(the best resolution), D-3).

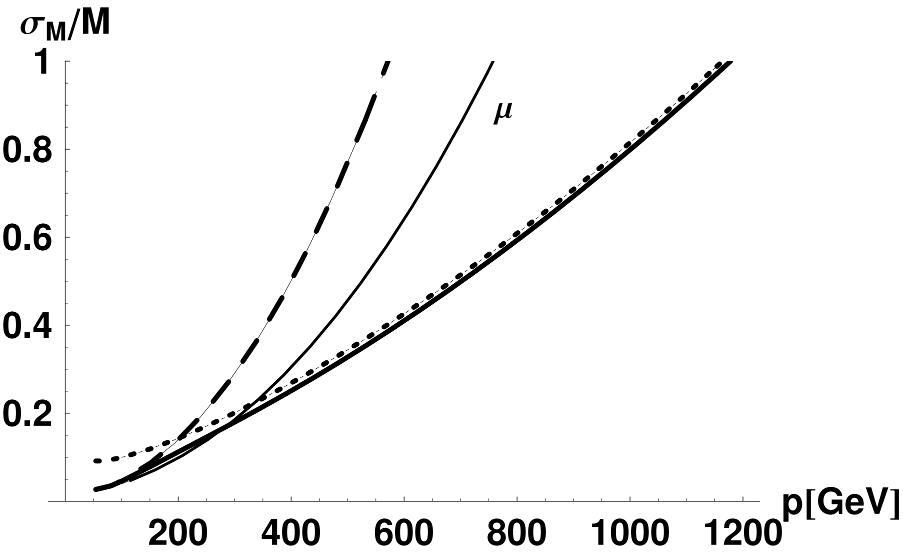

Figure 7: Mass resolution σ_M/M for exotic heavy stable charged particle with mass M=200 GeV as a function of its momentum. The curve with μ is for the muon spectrometer, the other three curves are for the Tile calorimeter and ID combined measurement. Dashed, dotted and solid lines correspond to only ionization energy losses, purely hadronic and ionization plus hadronic energy losses of the particle respectively. Thick parts of all curves indicate the region where $\beta > 0.5$ for muon sepctrometer and $\beta > 0.25$ for the Tile calorimeter (see details in the text).

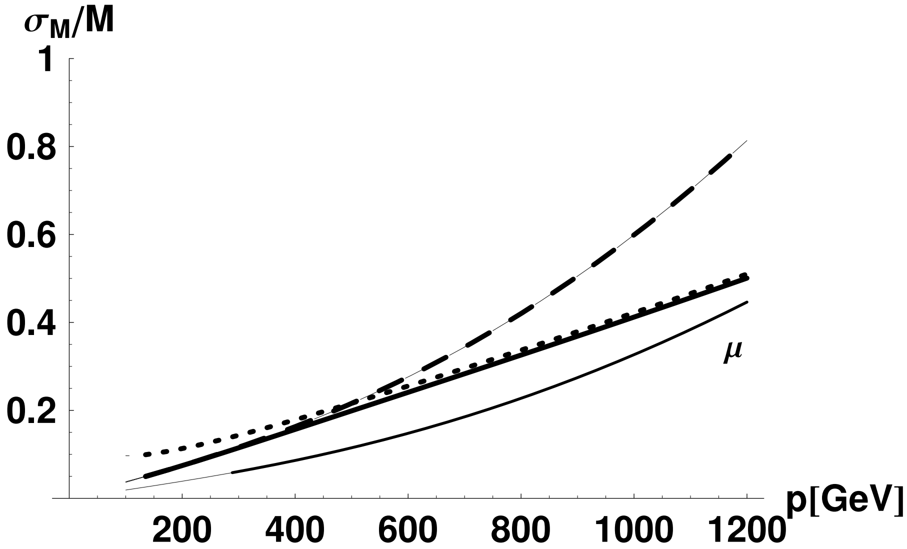

Figure 8: Mass resolution σ_M/M for exotic heavy stable charged particle with mass M=500 GeV as a function of its momentum. The curve with μ is for the muon spectrometer, the other three curves are for the Tile calorimeter and ID combined measurement. Dashed, dotted and solid lines correspond to only ionization energy losses, purely hadronic and ionization plus hadronic energy losses of the particle respectively. Thick parts of all curves indicate the region where $\beta > 0.5$ for muon sepctrometer and $\beta > 0.25$ for the Tile calorimeter (see details in the text).

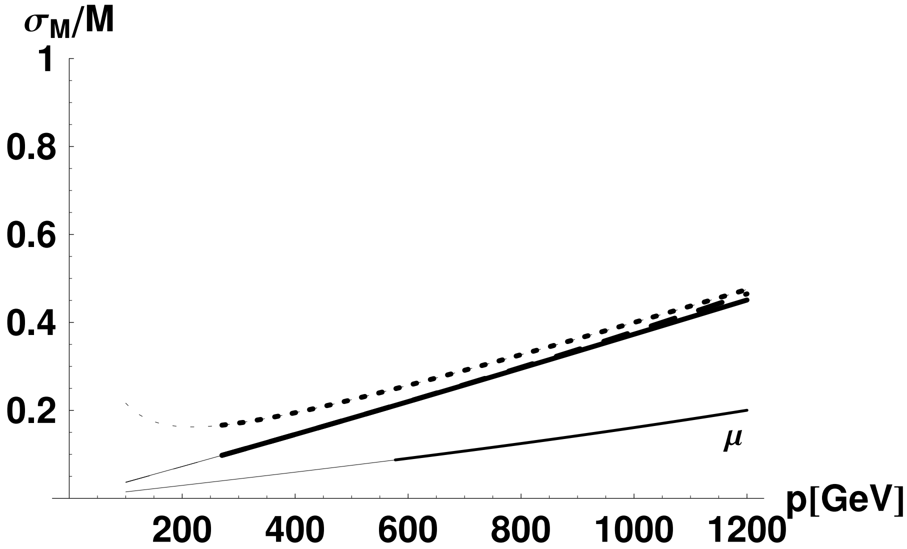

Figure 9: Mass resolution σ_M/M for exotic heavy stable charged particle with mass M=1000 GeV as a function of its momentum. The curve with μ is for the muon spectrometer, the other three curves are for the Tile calorimeter and ID combined measurement. Dashed, dotted and solid lines correspond to only ionization energy losses, purely hadronic and ionization plus hadronic energy losses of the particle respectively. Thick parts of all curves indicate the region where $\beta > 0.5$ for muon sepctrometer and $\beta > 0.25$ for the Tile calorimeter (see details in the text).

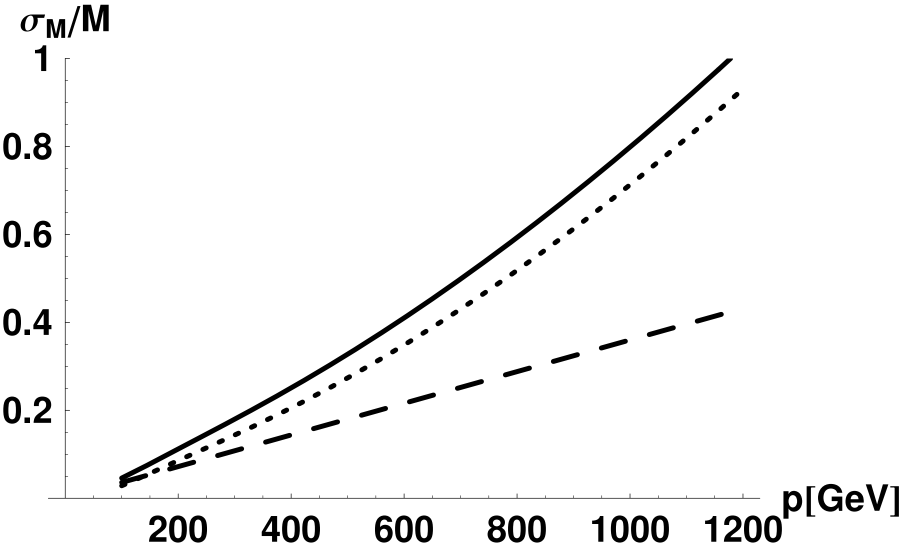

Figure 10: Mass resolution σ_M/M for heavy R-hadron with mass M=200 GeV and both hadronic and ionization interactions are shown by the solid line and the contributions from momentum and time measurements are shown by dashed and dotted lines respectively.

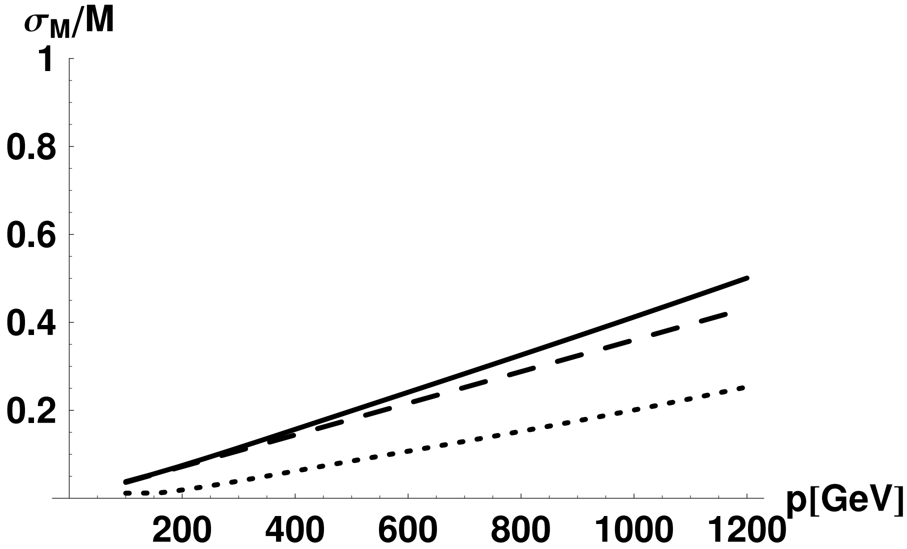

Figure 11: Mass resolution σ_M/M for heavy R-hadron with mass M=500 GeV and both hadronic and ionization interactions are shown by the solid line and the contributions from momentum and time measurements are shown by dashed and dotted lines respectively.

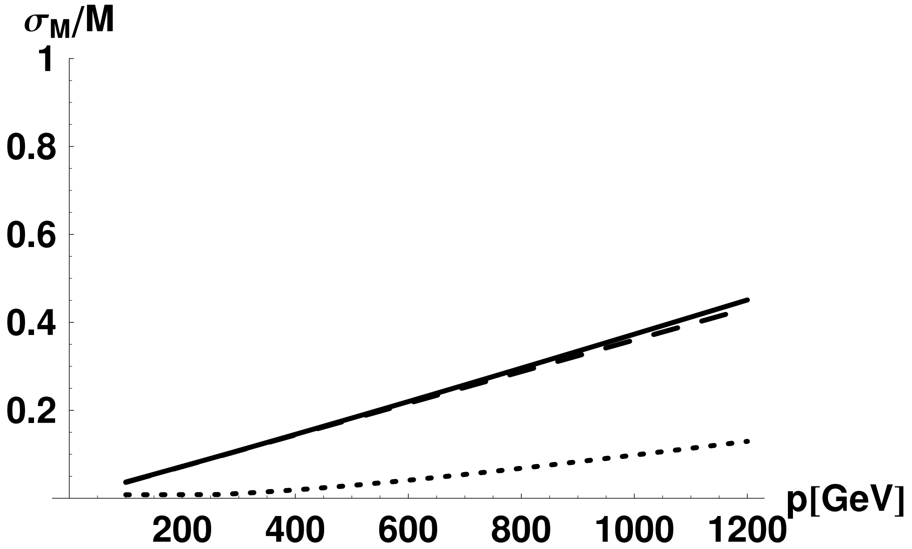

Figure 12: Mass resolution σ_M/M for heavy R-hadron with mass M=1000 GeV and both hadronic and ionization interactions are shown by the solid line and the contributions from momentum and time measurements are shown by dashed and dotted lines respectively.