Revised PID analysis for the EMR paper

François Drielsma

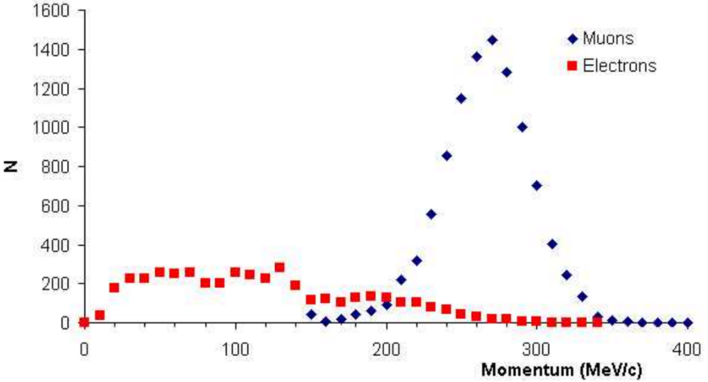
University of Geneva

December 11, 2014

1. Electron-Muon Ranger

The EMR is fully active scintillator tracker calorimeter

- Pupose of the EMR in the MICE beam
    - measure the range of muons, rejecting the muons that decayed inside the cooling channel and their decay products
    - Keep the contamination downstream the CC below 1%

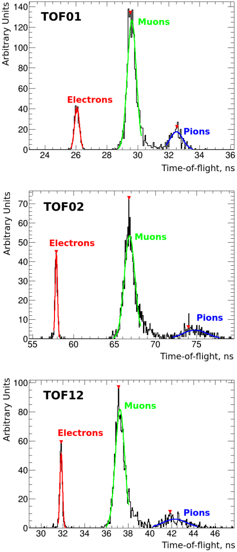


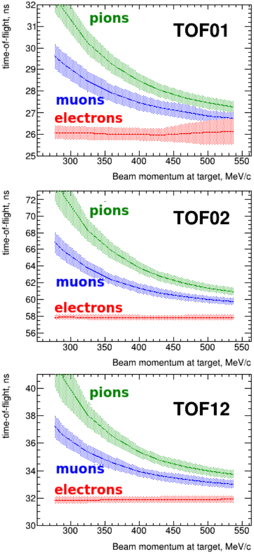
2. TOF selection system

- Only the tracks with one TOF spacepoint are selected
- The TOF measurement between station 1 and 2 is used to tag the **particle ID** and **momentum** at the entrance of the EMR

left TOF @277 MeV/c

right TOF measurement as a function of the momentum at target

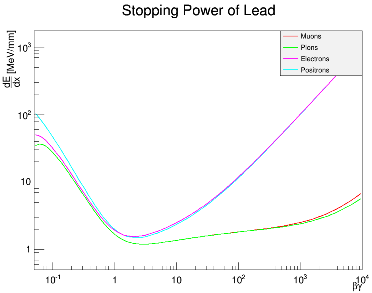


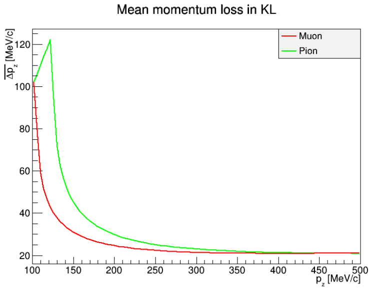


3. Energy loss in KL (1)

Characteristics of the energy loss:

- $X_0 \simeq$ 0.5 cm in Pb
- **MIP particles** loose $\sim$ 20 MeV/c in KL (muons and pions with $p_z > 2m_i c$)
- **Low energy muons and pions** ($p_z < m_i c$) can potentially stop in the detector if $p_\mu < 100 MeV/c$ or $p_\pi < 120 MeV/c$
- The **electrons** are all ultra-relativistic ($\beta\gamma > 100$) and will shower in the lead of KL ($3X_0$)
- **Pions** can hadronize in KL and loose substantially more energy on occasions ($0.1\lambda_I$)

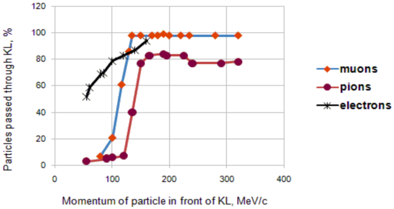

Stopping Power of Lead


Mean momentum loss in KL

Energy loss in KL (2)

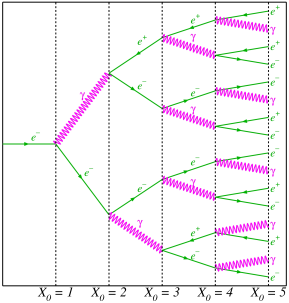
Survival of **muons** and **pions** after KL:

- In the 2010 PID detectors run, TAG counters were placed behind KL to see what comes out of it
- The theoretical suspicions are confirmed, muons and pions are killed under a certain threshold

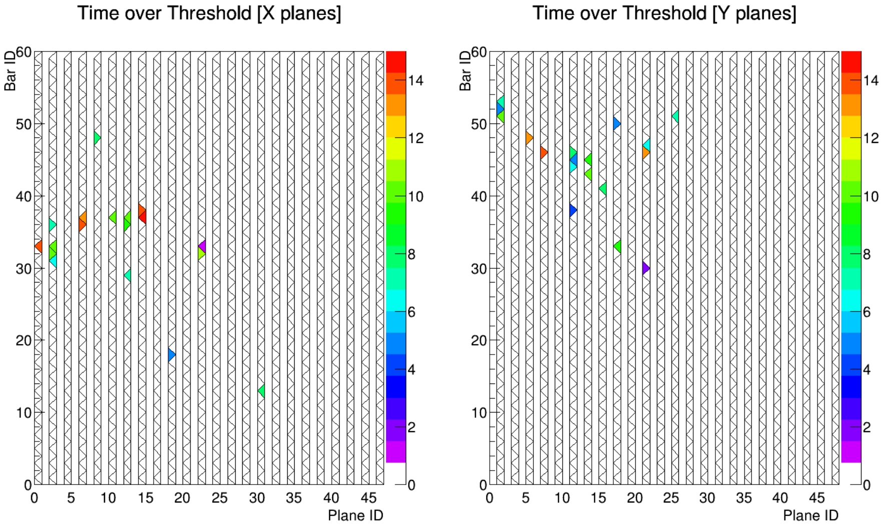


Electromagnetic **showers**:

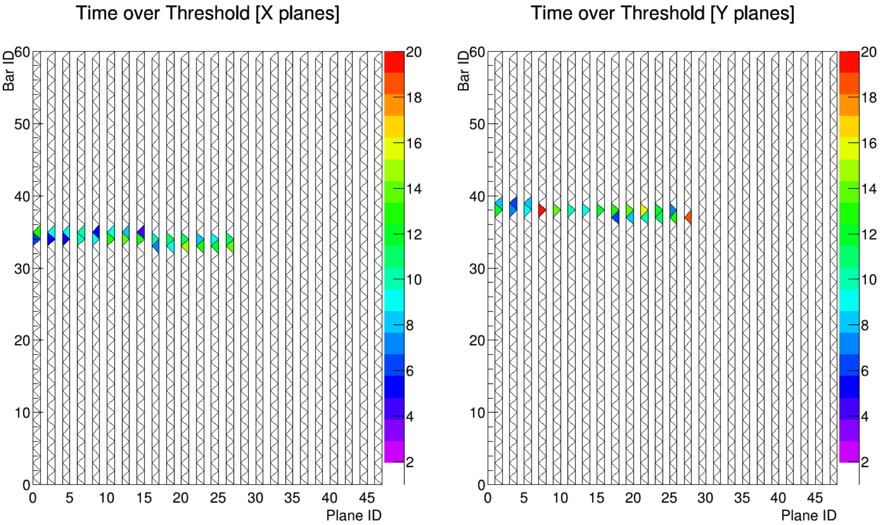
- Electrons radiate in KL and create several secondary γ, e^- and e^+
- e^- and e^+ come out with very low momentum ($\sim p_z/2^3$)
- Photons go through the EMR with low probability of interacting with the scintillating material (hits rare)



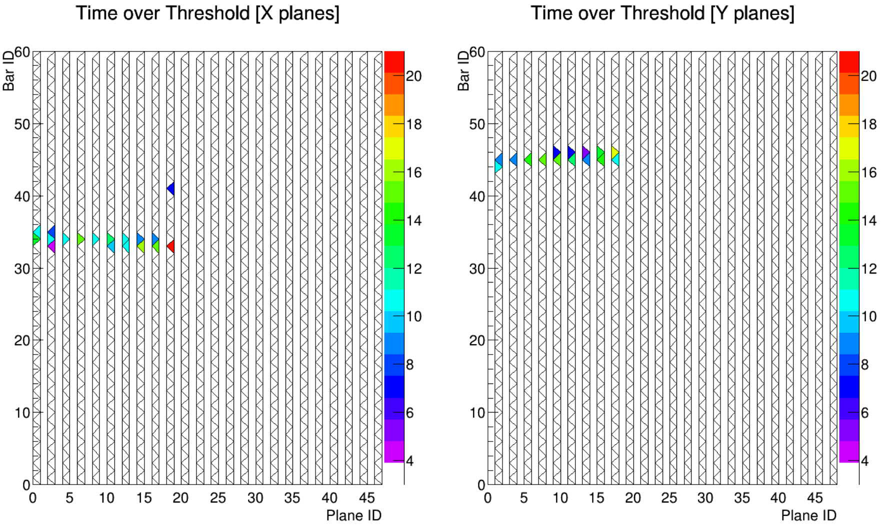
Electron event (shower in KL, no clear track)



Muon event (~ 250 MeV/c)



Pion event (~ 250 MeV/c)



4. Useful variables to discriminate electrons

For each beam setting (i.e. **momentum**) and each **event**, we measure:

1. Plane **density** ρ_p
2. Average bar **multiplicity** $\overline{N}_b$
3. *(Bar multiplicty in the first plane* $N_{b,1}$*)*
4. **Depth** Δz (i.e. range)
5. *(Spread in terms of* χ^2 *in the two projections)*

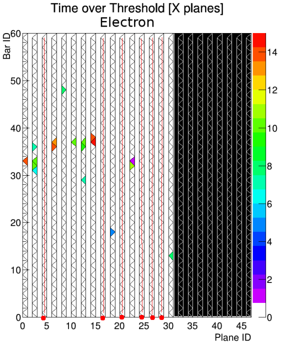
→ A rudimentary cut on some of these variables will prove to be a strong tool to reject electrons and tag real muons in the detector as we will see in the following sections

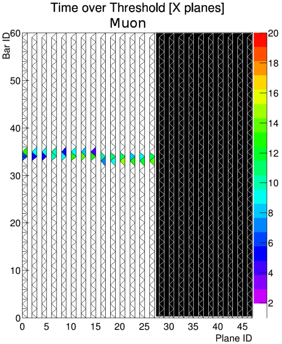
Plane Density ρ_p

The plane density is defined as the percentage of the planes that record a signal on the path of the particle or its shower, i.e.

$$\rho_p = \frac{number\,of\,planes\,hit}{\Delta z} \tag{1}$$

with Δz the depth of the particle expressed in number of planes.

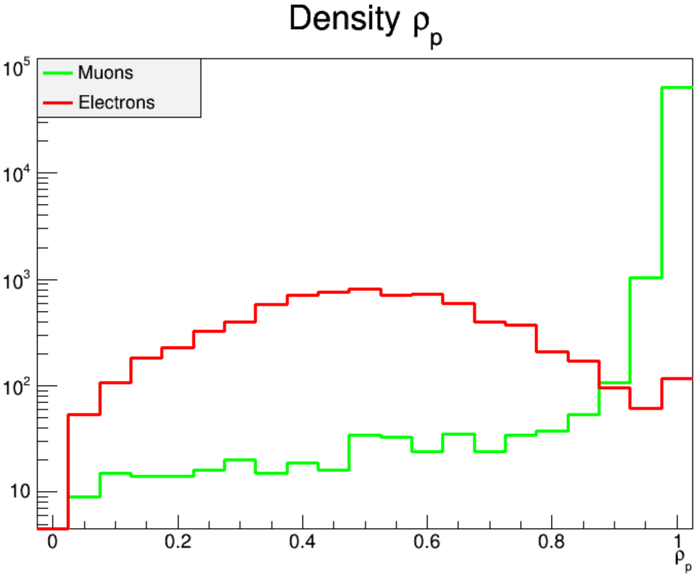




Electrons: 9 planes hit over a span of 15, $\rho_p = 60\%$;

Muons: 14 planes hit over a span of 14, $\rho_p = 100\%$.

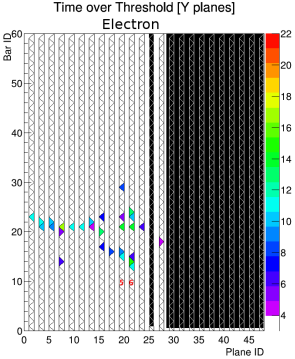
Muon vs electron: Density

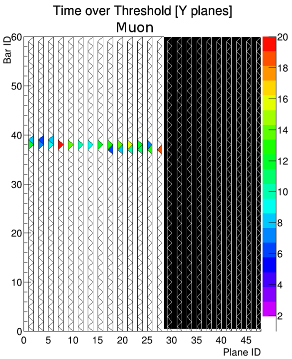


Average bar multiplicity $\overline{N}_b$

The bar multiplicity $N_{b,i}$ is defined as the amount of bars hit in a given plane i. Subsequently, if N planes recorded hits, the average reads

$$\overline{N}_b = \frac{1}{N}\sum_{i=1}^{N} N_{b,i} = \frac{1}{\rho_p \Delta z}\sum_{i=1}^{N} N_{b,i}\,. \tag{2}$$



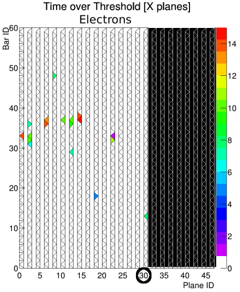


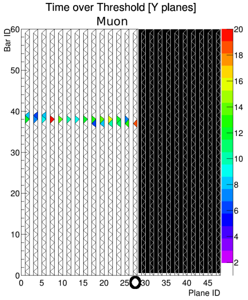
Electrons: 12 planes with up to 6 hits, $\overline{N}_b \simeq 2.42$;

Muons: 14 planes with *2 hits or less*, $\overline{N}_b \simeq 1.57$.

Depth Δz

The depth Δz is defined as the distance the particles travels through the EMR before it stops. It can be expressed in number of planes or cm (1 plane = 1.7cm).
→ For μ and π it roughly corresponds to the range as their path is more or less straight forward along the BL;
→ for e it gives us an idea of the range of the electromagnetic shower but is much less precise.



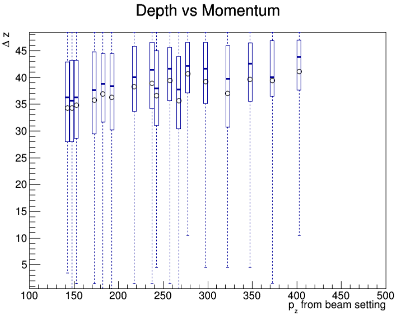


Electrons: the last hit is in plane 30, $\Delta z = 30$;

Muons: the muon stopped in plane 27, $\Delta z = 27$.

Electromagnetic shower depth

We can't infer the electron momentum from the TOF information as they are all ultra-relativistic. Even if we could, the showering in KL is such that there is no strong correlation between initial momentum and shower depth.
→ The **whole** electron sample must be rejected to prove efficiency
→ The range **is not** a relevant way to reject electrons



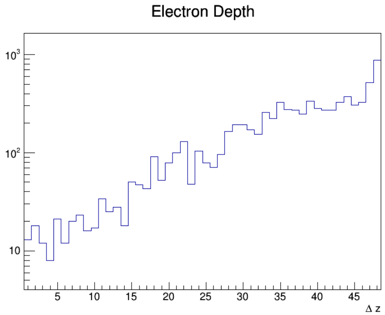


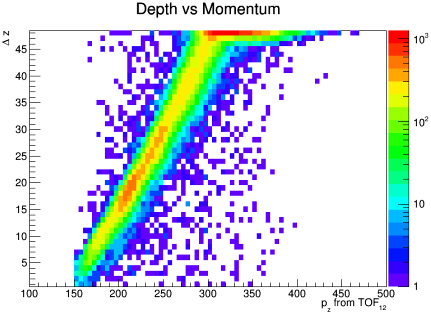
Figure: The momentum is inferred at Q9 from the beam setting

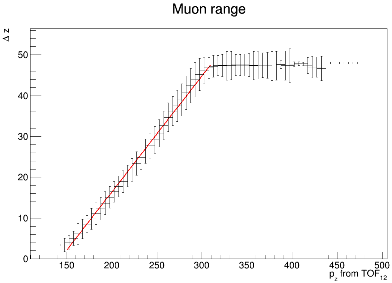
Muon range in the EMR

Unlike the electrons, the muons don't shower in KL. They loose energy in the EMR until they stop or cross the whole detector before stopping.
A simple linear fit yields the formulas:

$$R_\mu(p_z) \simeq (0.3 \times p_z - 40.6)\texttt{planes}\,, \tag{3}$$

$$R_\mu(p_z) \simeq (0.5 \times p_z - 68)\texttt{cm}\,. \tag{4}$$

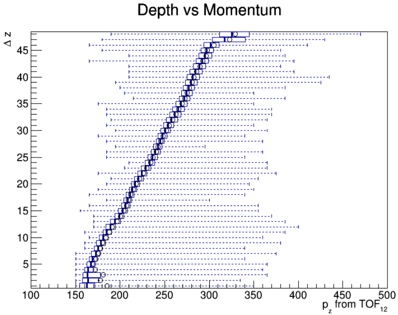

Depth vs Momentum

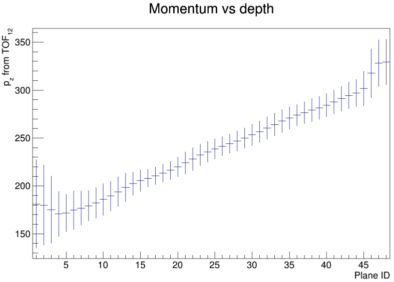

Muon range

Resolution on the muon momentum

We can also inverse this relation to get an estimation of the momentum of the muon as a function of the range measured in the EMR. The **uncertainty** on the reconstructed momentum is about **10 MeV/c** for every range between 5 and 45 planes (NB: uncertainty on p_z from TOF)
Inverting the relation yields:

$$p_z(R_\mu) \simeq ([3.5 \times R_\mu - 142.7] \pm 10) MeV/c\,. \tag{5}$$



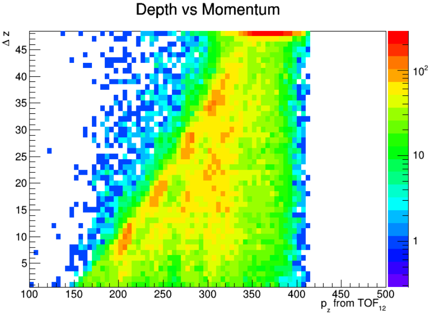


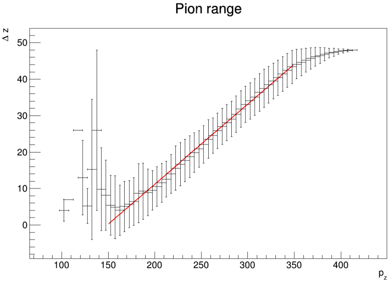
Pion range in the EMR

Due to hadronic interactions in lead, pions can reach the EMR with significantly lower energy than before KL. As a result, even though they loose their energy in the same fashion as the muons, their impinging momentum is **distributed** from 0 to an upper limit, i.e.

$$R_\pi(p_z) \leq (0.2 \times p_z - 32.8)\texttt{planes}\,, \tag{6}$$

$$R_\pi(p_z) \leq (0.4 \times p_z - 55.8)\texttt{cm}\,. \tag{7}$$





5. First selection attempt

At first glance, the most efficient variable to reject the electrons at all momenta is the plane density ρ_p. Provided that the average bar multiplicity $\overline{N}_b$ increases with density for the electrons, the combination of the two should yield promising results.

Hypothesis testing :

- H_0 is the null hypothesis, the particle X is a muon. H_1 is the alternative, i.e. X is an electron.
- $\alpha = p(X \in w|H_0)$ is the **loss**, the probability that X is tagged as an electron, given that X is a muon (w the critical region)
- $\beta = p(X \in (W - w)|H_1)$ is the **contamination**, the probability that X is tagged as a muon, given that X is an electron (W the space)

→ We want to define w such that $1 - \beta$ is maximized without losing too much of the initial sample (minimize α)
→ The real contamination is in fact $R_e\beta$ with R_e the abundance of electrons in the beam, i.e. $R_e = N_e/N_\mu$ (= 11.7% in the test beam)

Average Multiplicity vs Density

Two simple but carefully chosen cuts are applied on both the electron and the muon samples:

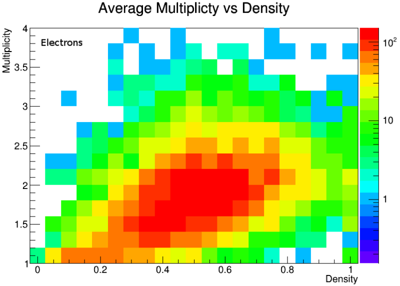
- $\rho_p > .95$
- $\overline{N}_b < 2.2$

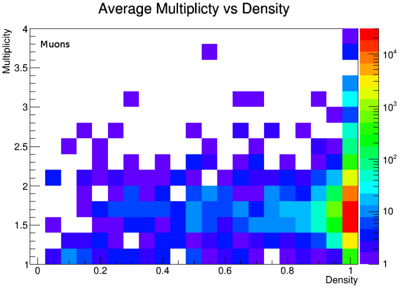
This yields the values:

- $\alpha \simeq 1.8\%$
- $\beta \simeq 1.3\%$

As a result, given that the abundance of electrons is 11.7%, the purity of the muon sample reaches

$$\boxed{1 - R_e\beta = 99.85\%} \qquad (8)$$





Conclusions

What will stay **unchanged** in the final EMR Step I paper:

- Introduction, presentation of MICE and the role of the EMR
- Technical description of the detector and its features
- TOF analysis to extract the momentum between TOF1 and TOF2

What will be **added** or **replaced** in the paper:

- Energy loss correction of the muon and pion impinging momentum after going through **TOF2** and **KL**
- New variables to tag muons, reject electrons (density, multi, range) → **New PID efficiency analysis**
- Lower limit given for the purity provided downstream the CC by the EMR ($>$ **99.85 % for now**)