Electron-Muon Ranger (EMR) Step I Paper

François Drielsma

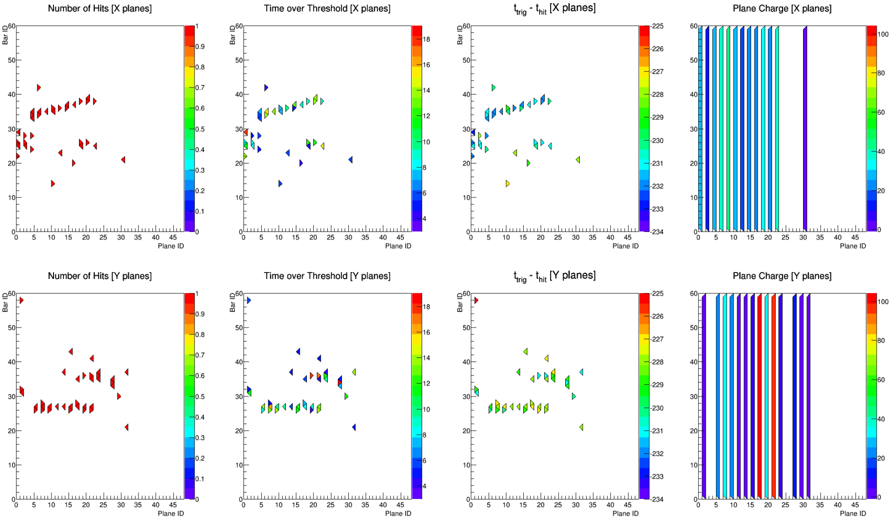
University of Geneva

March 5, 2015

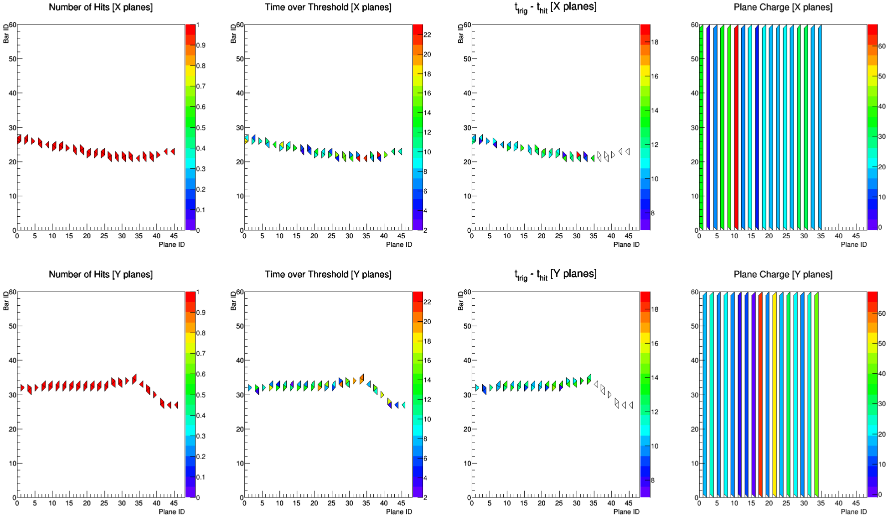
Structure of the EMR Step I paper after CM41

1. Introduction
   - Ionization Cooling, MICE ✓
   - Purpose of the EMR ✓
2. Electron-Muon Ranger
   - Structure of the detector ✓
3. Performance in the MICE Beam
   - TOF selection and particle tagging → Extensive plot updates
   - Correction for the energy loss in TOF2 and KL ✓
   - Useful variables for PID ✓
   - Efficiency of a simple test statistic ✓
   - Momentum reconstruction from the range → Revision and study
4. Conclusions

New event display: Electron shower (450 MeV/c @D2)



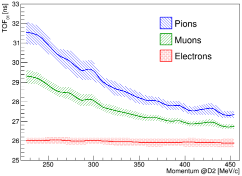
New event display: Muon decay (250 MeV/c @TOF$_2$)

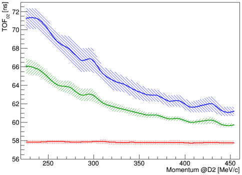


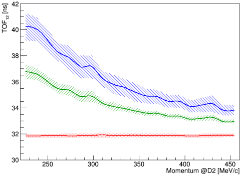
New beam characterisation plots

After CM41, the need to remake all the test beam characterisation plots arose from the fact that they were made in terms of the momentum at target instead of the more sensible momentum set at D2. The following plots were reprocessed:

- TOF_{01}, TOF_{02} and TOF_{12} vs momentum ✓
- Momentum loss fraction vs momentum ✓
- Momentum @TOF_1 vs momentum ✓
- Rate and events @EMR vs momentum ✓
- Momentum reconstructed at TOF_{ij} vs momentum @D2 ✗
- Beam particle composition vs momentum ✓

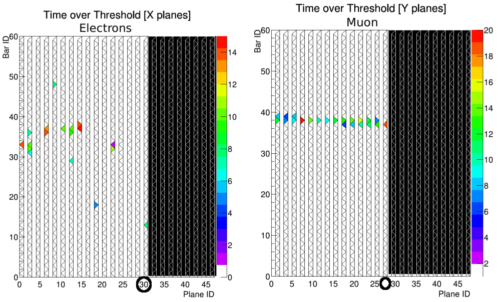






Definition of the Range R

The range $R = \Delta_Z/(\cos\theta_X \cos\theta_Y)$ is defined as the distance the particles travels through the EMR before it stops. It is expressed in metric.
$\rightarrow$ For μ it corresponds beautifully to the range as their path is more or less straight forward in PS;
$\rightarrow$ for e it gives us an idea of the range of the electromagnetic shower but is much less precise as there are multiple particles



Electrons: the last hit is in plane 30, $R \simeq 520mm$;

Muons: the muon stopped in plane 27, $R \simeq 460mm$.

Electromagnetic shower range

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 strong way to reject electrons

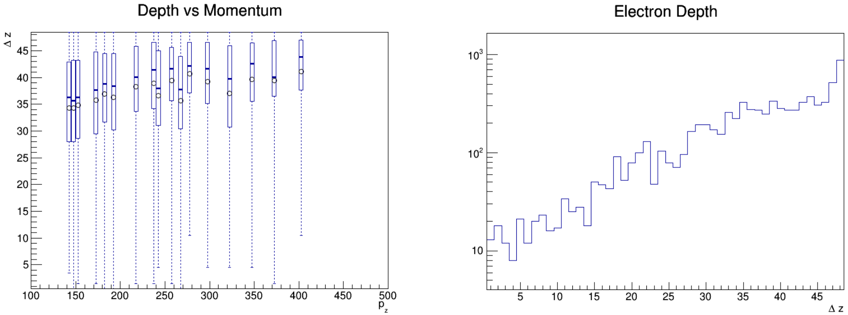


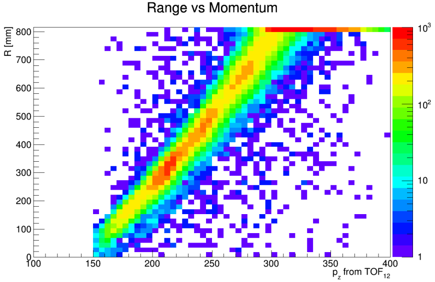
Figure: The momentum is inferred at Q9 from the beam setting

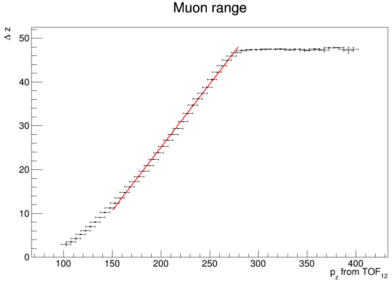
Muon range in the EMR

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, for $150MeV/c < p_z < 280MeV/c$:

$$R_\mu(p_z) \simeq (0.29 \times p_z - 32.13)\texttt{planes}\,, \quad (1)$$

$$R_\mu(p_z) \simeq (0.49 \times p_z - 54.62)\texttt{cm}\,. \quad (2)$$





→ Can we do better than that ?

Theoretical range of muons in the EMR

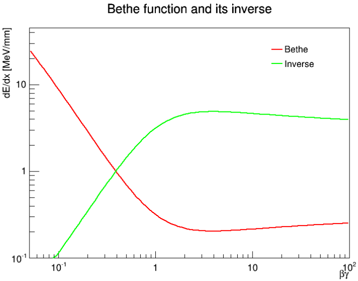
Although the EMR is a complex piece of technology, to muons it is essentially a bloc of polystyrene a little over 80 cm deep

$\rightarrow$ the energy loss of muons of $\beta\gamma \in [0.05, 100]$ is dictated by Bethe

$$-<\frac{dE}{dx}>= K\frac{\rho Z}{A}\frac{1}{\beta^2}\left(\frac{1}{2}\ln\left(\frac{2m_e\beta^2\gamma^2T_{max}}{I^2}\right)-\beta^2-\frac{\delta(\beta\gamma)}{2}\right) \quad (3)$$

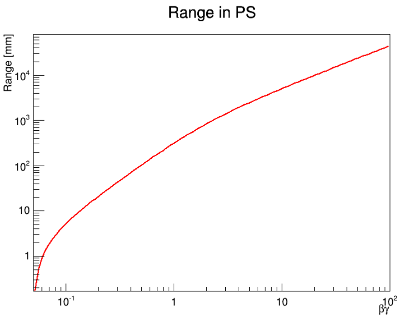
$\rightarrow$ the expected range in PS for impinging momentum p_0 is:

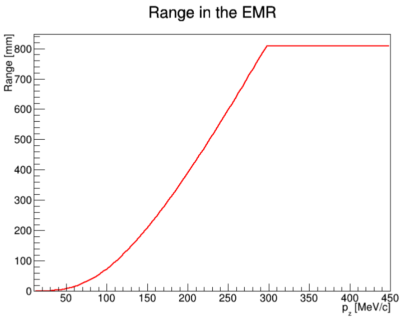
$$\begin{aligned} R &= \int_{E_0}^{0}\frac{dE}{dE/dx} = \int_{p_0}^{0}\frac{dp}{dp/dx}\frac{dE}{dp} \\ &= \int_{p_0}^{0}\frac{dp}{dp/dx}\frac{p/m_\mu}{\sqrt{(p/m_\mu)^2+1}} \quad (4) \end{aligned}$$



Let us make some observations about the theoretical range:

- It is the solution of a complex integral and has no analytical formula
- The maximum range observable in the EMR is a hit in the last plane, i.e. $\sim$ 800 mm. Any particle with a higher range will have that maximal value R_{max}
- The momenta reconstructed from the TOFs had a $\beta\gamma \in [1, 4]$
- The range can be linear for certain regimes of momenta but only in the upper part of our data sample



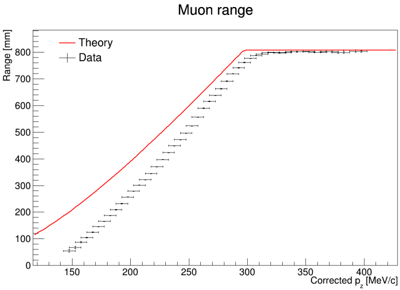


Comparaison with the momentum from TOF_{12}

If we don't apply any correction, we observe:

- The measured range is grossly underestimated for all momenta, we aren't within any acceptable interval from the theory
- The discrepancy increases as low momenta

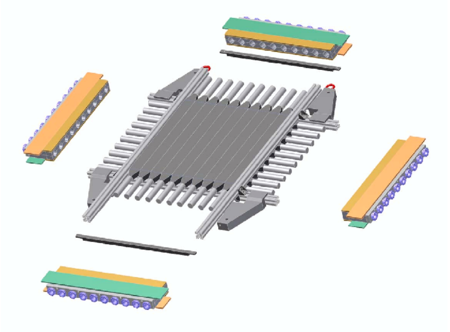
$\rightarrow$ The momentum of the particles between TOF_1 and TOF_2 needs to be corrected for the **energy loss in TOF and KL** !

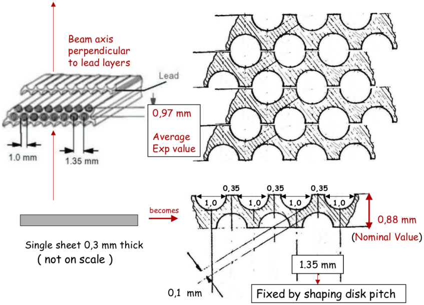


Energy loss before entering the EMR

After tagging, a particle goes through TOF2 and KL before the EMR:

- Composition of TOF2:
  - 2" ($\sim$ 5cm) of PVT (Polyvinyl Toluene) scintillator bars
- Composition of KL:
  - 4 cm calorimeter made of Pb and PS scintillating fibres
  - $V_{PS}/V_{Pb} \simeq 2$
  - On average $\sim 2.2X_0$ and $\sim 0.1\lambda_I$



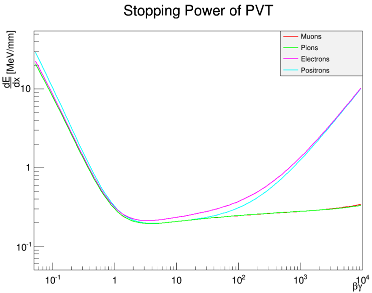


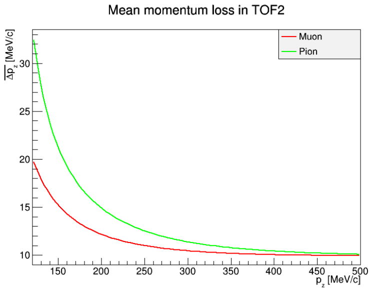
Energy loss in TOF2

Characteristics of the energy loss:

- $X_0 \simeq 42.6$ cm in PVT
- **MIP particles** loose ~ 10 MeV/c in TOF (muons and pions with $p_z > 2m_i c$)
- **Low energy muons and pions** ($p_z < m_i c$) will experience higher energy loss. At 120 MeV/c, a pion looses 20 MeV/c on average
- The **electrons** are all ultra-relativistic ($\beta\gamma > 100$). Due to the high X_0, they are unlikely to shower in TOF2 (0.1 X_0)

$\rightarrow$ For μ and π, the shift in energy is only significant at low energies

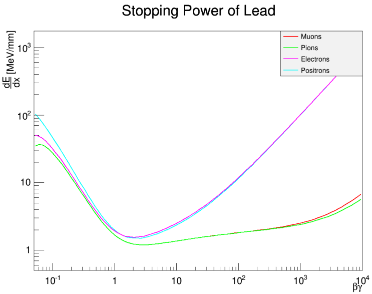


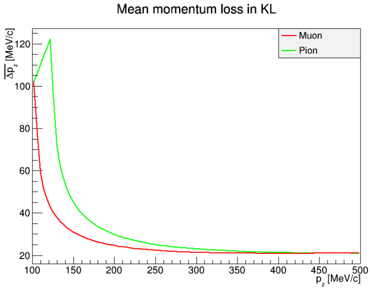


Energy loss in KL

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 ($2.2X_0$)
- **Pions** can hadronize in KL and loose substantially more energy on occasions ($0.1\lambda_I$)



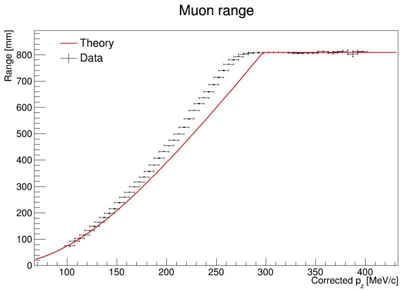


Comparaison with the momentum after Eloss

After correcting the momentum for the energy loss in TOF2 and KL

- The measured range now fits nicely to the expected value at low energy but drifts slowly significantly at higher energies
- The theoretical range is still not at this stage an acceptable estimator

→ A discrepancy function of the momentum points towards a bad reconstruction of the momentum for the TOF



Correction of the reconstructed momentum

The distance between the TOFs was assumed to be 9.48 m but the distance seemed to be in fact 9.387 m, which has two consequences:

- Overestimation as we use a longer distance, $\delta_D = -0.093$ m (1%)
- Underestimation as the calibration is biased, $\delta_t = -0.680$ ps (2%)

$$
\begin{aligned}
p_z(t+\delta_t,\, D+\delta_D) &\simeq p_z(t,\, D) + \delta_t \frac{dp}{dt} + \delta_D \frac{dp}{dD} \\
&\simeq p_z + \frac{m_\mu c^3 t}{D^2}\left(\left(\frac{ct}{D}\right)^2 - 1\right)^{-3/2}\left[\delta_D \frac{t}{c} - \delta_t\right] \quad (5)
\end{aligned}
$$

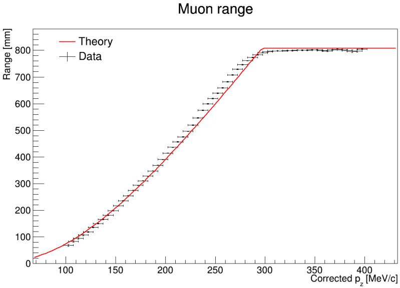
Comparaison with the momentum after corrections

After correcting the momentum for a new distance between the two TOFs

- The measured range now fits nicely for all momenta. We still have small shift for the highest momenta but the TOF correction needs refinement and recalibration

→ This is so sensitive to the distance between the TOFs that we could use it to infer the distance between TOF1 and TOF2 !

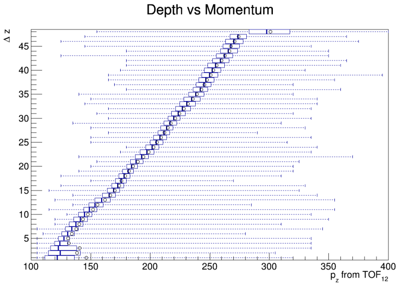
→ The range measurement could be used to reconstruct the momentum by numerically inverting the relation. But with what accuray?

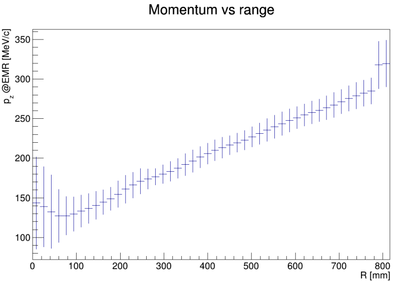


Resolution on the muon momentum

We can get a feel of the resolution in momentum of the EMR by looking at the distribution of momenta in each bin. For a range $R \in [200, 780]$ mm, the RMS of the distribution of momenta is always around 10 MeV/c
This spread comes from 3 sources:

- The uncertainty from the time-of-flight σ_{TOF} ($\sigma_t \sim$ 70 ps)
- The momentum loss uncertainty from the energy loss in KL σ_{KL}
- The uncertainty due to the EMR resolution σ_{EMR} ($\sigma_R \sim$ 8.5 mm)





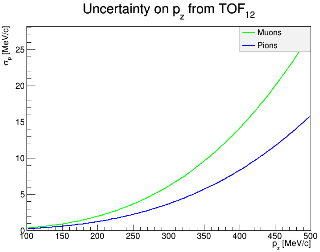
Uncertainty on the momentum measurement from TOF_{12}

The source of the momentum measurements in the test beam is reconstructed (provided TOF PID) from the time of flight $t \equiv TOF_{12}$:

$$|\overrightarrow{p}| \equiv p = \frac{m_i c}{\sqrt{(\frac{ct}{D})^2 - 1}} \tag{6}$$

With uncertainty:

$$\begin{aligned} \sigma_{TOF} &= \left.\frac{\partial p}{\partial t}\right|_{\bar{t},\overline{D}} \sigma_t \oplus \left.\frac{\partial p}{\partial D}\right|_{\bar{t},\overline{D}} \sigma_D \\ &= \frac{m_i c^3 t}{D^2}\left[(\frac{ct}{D})^2 - 1\right]^{-3/2} \sigma_t \\ &\oplus \frac{m_i c^3 t^2}{D^3}\left[(\frac{ct}{D})^2 - 1\right]^{-3/2} \sigma_D \end{aligned} \tag{7}$$



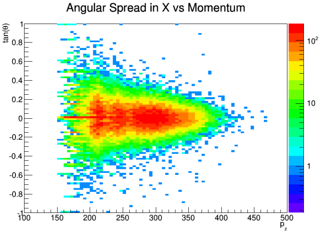
with $\sigma_t \sim 70$ ps and $\sigma_D \sim 8$ mm.

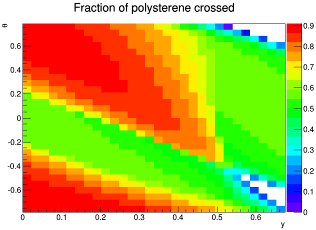
The other main source of error on the reconstructed momentum at the entrance of the EMR is the correction for the energy loss in KL. A simplified model has been developed to simulate the spread in EL:

- KL is made out of PS fibres threaded through sheets of Pb ($V_{PS}/V_{Pb} \sim 2$)
- We reduce to the smallest repeatable lattice element and define the function:

$$\Delta x(PS)/\Delta x \equiv f(y_0, \theta) \qquad (8)$$

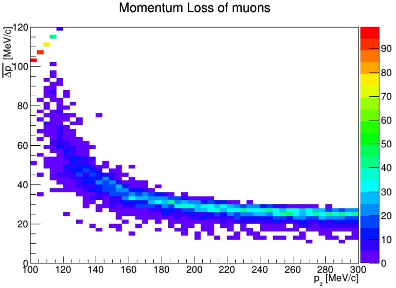
→ The proportion of PS the track goes through in this element.
→ Small angles are favoured (see data).

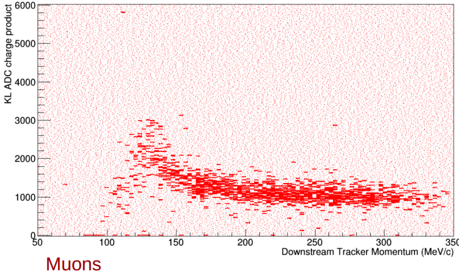




Given the angular distribution (0 ± 0.13 radians) and a uniform distribution in y_0 (no favored initial position), we can simulate the EL.

- → Beautiful agreement between simulation and data
- → Offset of 15 MeV/c of the peak, energy loss in TOF2 !
- → For MIP particles, $\overline{\Delta p_z} \simeq (28 \pm 3)$ Mev/c is a good approximation





Simulated p loss **Real KL ADC product**

In fine, for muons @200Mev/c (MIP particles), uncertainty of **2MeV/c** from 200Mev/c and **5MeV/c** from 200Mev/c. It increases at low p_z because of KL EL and at high p_z because of TOF.

Conclusions

EMR Paper: Status

Task	Person	Timescale
Plots post CM42 comments	François Drielsma	< 1 week
Improvements to range-momentum analysis	Francois Drielsma, (Alain Blondel)	~ 3 weeks
Write up long form (MICE Note) version of new analysis	François Drielsma	~ 3 weeks
MICE Note → Wise People	François Drielsma	< 1 week
MICE Note digested	Alan Bross, Ludovico Tortora	~ 2 weeks
MICE Note comments received and implemented → return to Wise People. Publish MICE Note (on wiki/notes page/arXiv(?))	FD, AB, LT	Iterative
Paper drafted	François Drielsma	~ 4 weeks
Paper → Wise People	Alan Bross, Ludovico Tortora	~ 2 weeks
Comments received and acted on.	François Drielsma	Iterative
Paper → Collaboration	François Drielsma	2 * 1 week iterations
Paper → Publish, reviewer comments, etc.	François Drielsma	...