Electron-Muon Ranger (EMR) performance report

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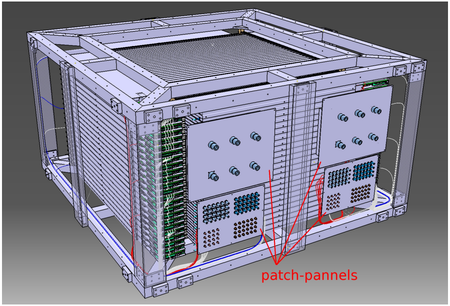
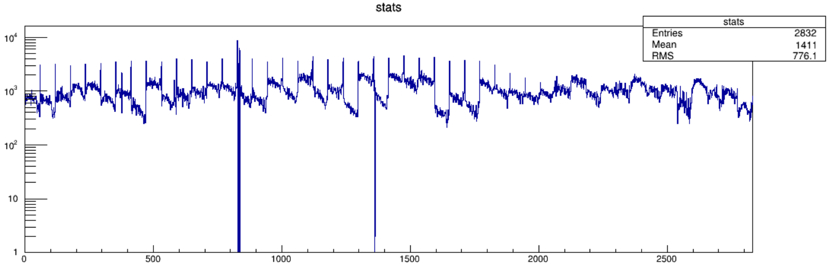
Hardware and DAQ

EMR hardware:

* 48 planes of 59 scintillator bars in an XY arrangement
* 1 SAPMT per plane (charge integration), 1 MAPMT channel per bar (ToT)

→ 2880 readout channels, 6 dead MAPMT channels (0.2 %), must run a new calibration.





Battery of tests

A selection of runs (summarized below) were taken from the 2017/01 ISIS user cycle to test the performance of the EMR in multiple ways:

- Raw efficiency of the hardware at in the MA and SAPMTs;
- Efficiency of the reconstruction at different levels;
- Beam profiles at different momenta;
- PID variable reconstruction;
- Muon and pion decay matching.

Setting	Run ID	TOF1 triggers	EMR events	EMR tracks
140 MeV/c	9401	100032	1694	300
170 MeV/c	9400	150042	7385	5894
200 MeV/c	9398	150000	5555	4879
240 MeV/c	9386	264564	6949	6195
300 MeV/c	9367	273335	31158	28572
400 MeV/c	9370	190757	29581	27850

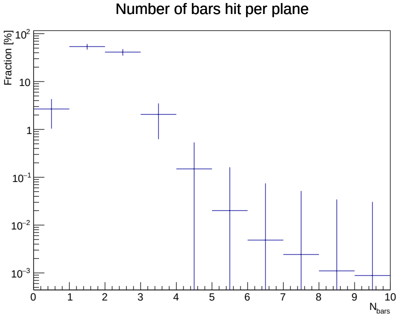
Hardware efficiency: raw MAPMT hits

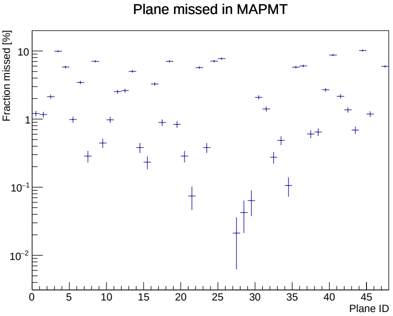
Highest momentum setting (run 9370) is used to investigate the amount of bars hit per plane on average (the muons punch through)

- → **97.33±1.63% global digit efficiency** (1 % decrease in 2 years)
- → One bar hit ∼49% of the time, 2 bars ∼47% of the time

On a plane to plane basis

- → Levels of inefficiencies increased since last study, still reliable to reconstruct full tracks as probability of missing track is extremely low





Hardware efficiency: raw SAPMT charge

Highest momentum setting (run 9370) is used to investigate the amount of charge deposited in each plane (the muons punch through)

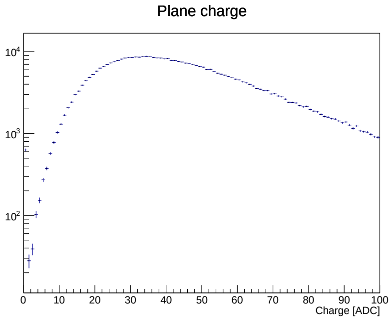
$\rightarrow$ **99.861% global SAPMT efficiency**

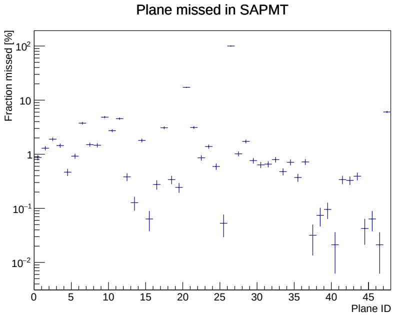
$\rightarrow$ Need a pedestal study for a more accurate statement

On a plane to plane basis

$\rightarrow$ Two planes inefficient at the level of $\sim 10\%$, need to investigate

$\rightarrow$ Plane 26 off at the time of data taking (tripped) but fixed





First level of reconstruction: plane hits

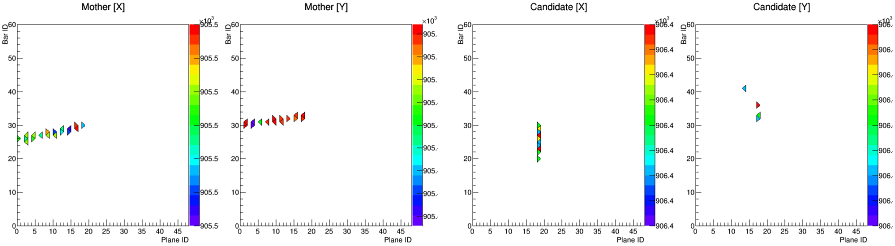
EMR readout

- Bar time-over-threshold and TDC recorded for each hit above threshold, stored **for the entire spill** in 48 DBBs
- Charge in each plane (ADC) integrated when **fADC triggered**

Plane hit reconstruction

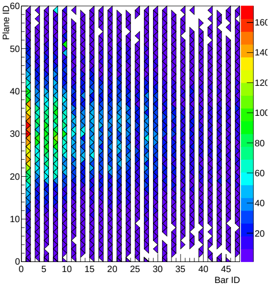
→ DBB hits and corresponding fADC charge are matched by their temporal proximity ($\Delta t \sim 500$ ns) and create a plane hit

→ Leftover bar hits are bunched in time and form decay candidates

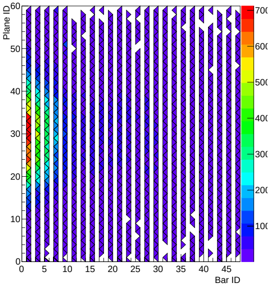


Occupancy (bar hits)

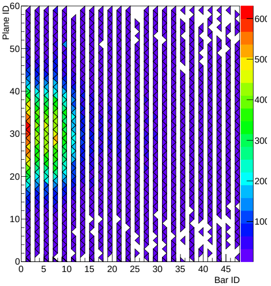
yz projection (140 MeV/c)



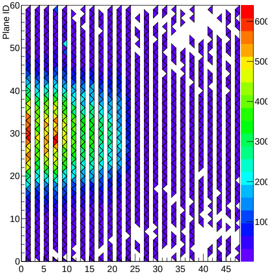
yz projection (170 MeV/c)



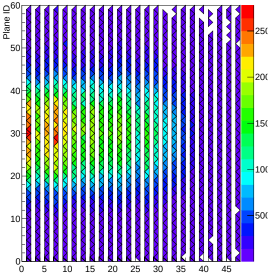
yz projection (200 MeV/c)



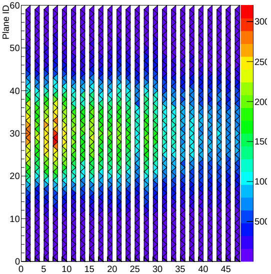
yz projection (240 MeV/c)



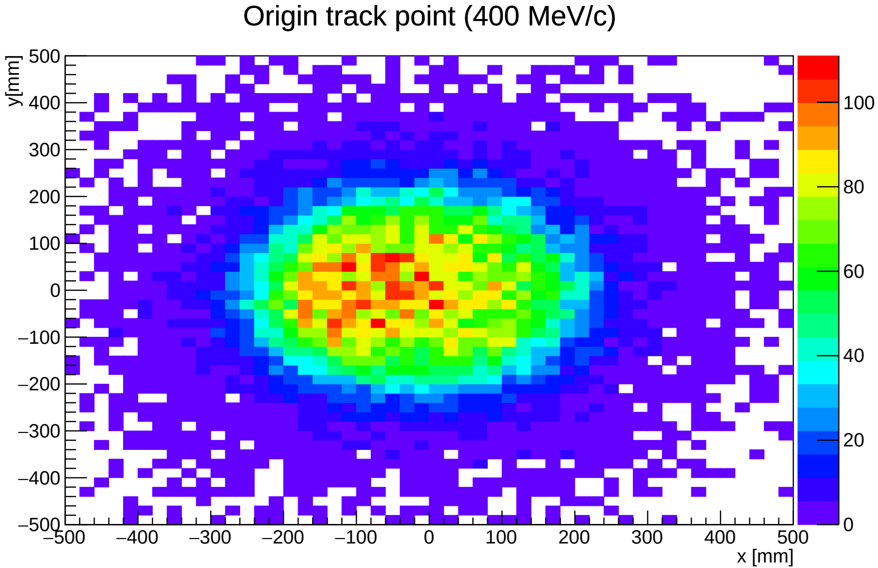
yz projection (300 MeV/c)



yz projection (400 MeV/c)



Beam profile at the entrance of the EMR



Detector efficiency and acceptance

Efficiency*Acceptance for a 400 MeV/c muon beam (run 09370)

→ Select events with SP in TOF2

→ $\alpha E_{\mathrm{PH}} = 97.3\,\%$ (**stable**)

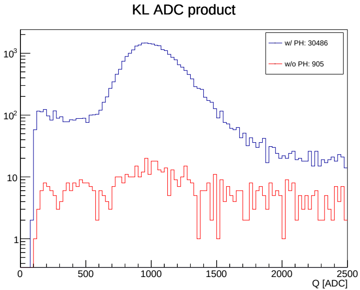
Sources of "inefficiency"

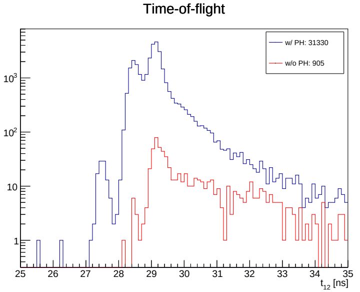
- Particles that scatter out of the EMR fiducial volume
- Particles that stop in the KL ($2.5X_0$ in KL + magnet bore)
- Real detector inefficiency?

Select fast particles (muons):

→ $\alpha E_{\mathrm{PH}} =$ **99.9 %**

→ **No real inefficiency**





Higher level of the reconstruction

Space point reconstruction

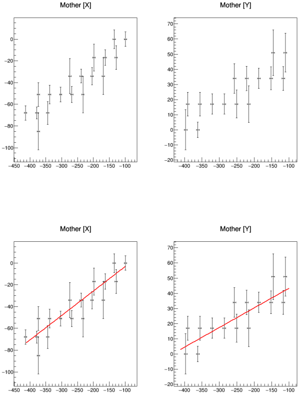
- → XT rejection (keep highest ToT bunch)
- → One SP per bar with $\sigma_i = \sigma_q \sqrt{Q_P / Q_i}$
- → Corrects the hit charge for attenuation

Track reconstruction

- → A line is fitted to the set of space point (least squares)
- → χ^2/N, parameters, track points, etc.
- → Reconstructs the total charge

Range, Momentum

- → Range recon: $\int_0^{z_{\max}} \sqrt{1 + (\partial P_x / \partial z)^2 + (\partial P_y / \partial z)^2} \mathrm{d}z$
- → Momentum unfolding (CSDA): $R = \int_{p_0/m_i c}^{0} \frac{\mathrm{d}p}{\langle \mathrm{d}E/\mathrm{d}x \rangle} \beta m_i c^2$



Reconstruction efficiencies

Efficiency of the space point reconstruction provided PHs

→ Events that do not record at least one hit in each projection don't allow for SP recon

- Electron/Positron showers
- Very shallow tracks

→ Noisy SAPMT without MAPMT hits (common)

→ $E_{\mathrm{SP}} = 94.10\,\%$

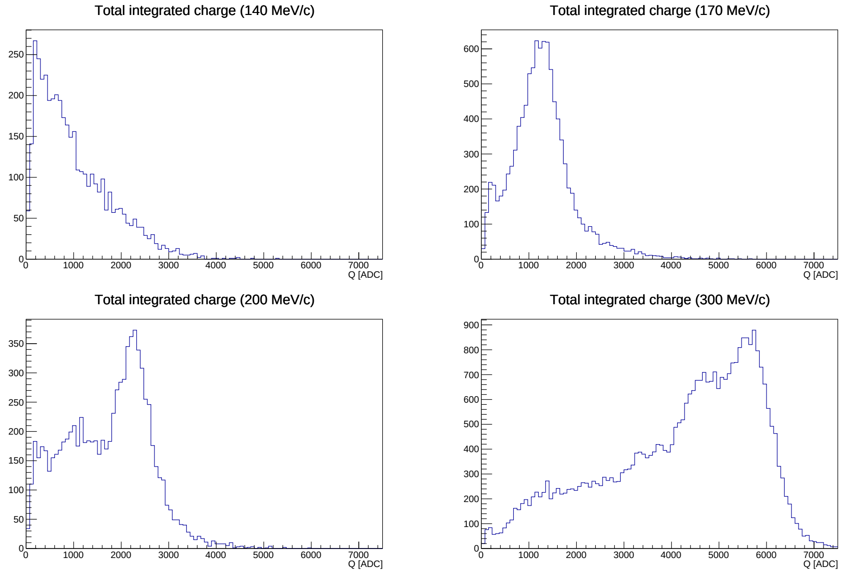
- With the same criterion as for PH, we get $E_{\mathrm{SP}} = \mathbf{99.7\,\%}$

Efficiency of the track fitting provided SPs

→ Can never fail because there is no selection on the goodness of fit (electrons are likely to badly fit a line, which is a PID criterion)

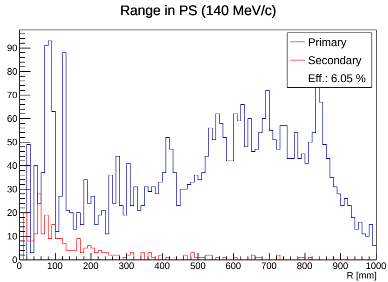
→ $E_{\mathrm{T}} = 100\,\%$

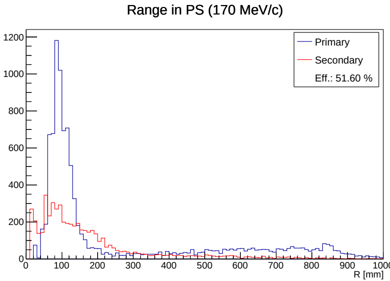
Total reconstructed charge

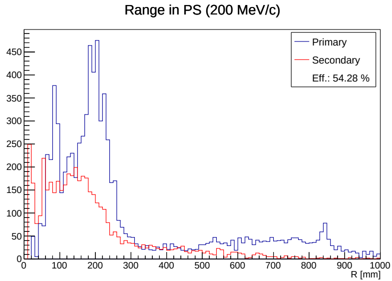


Range reconstruction for low momentum beams

- **140 MeV/**c: Mostly positron cloud, broad large range dist.
- **170 MeV/**c: Muons make it to the EMR, single mother peak
- **200 MeV/**c: Pion and muon peak distinguishable



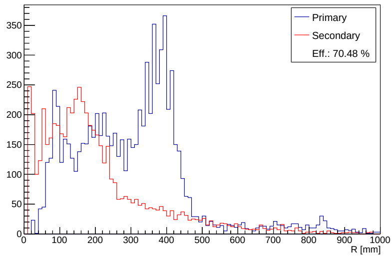




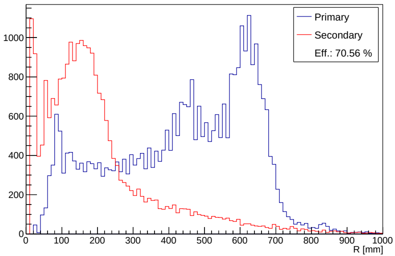
Range reconstruction for high momentum beams

- **240 MeV/**c: Matching efficiency reaches a maximum
- **300 MeV/**c: Muons start to reach the edge of the detector
- **400 MeV/**c: Muons and pions cross the entire detector

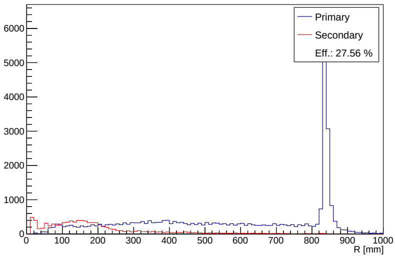
Range in PS (240 MeV/c)



Range in PS (300 MeV/c)



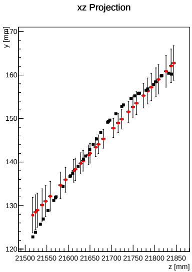
Range in PS (400 MeV/c)

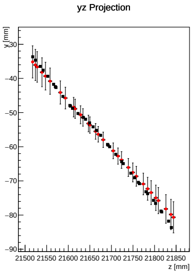


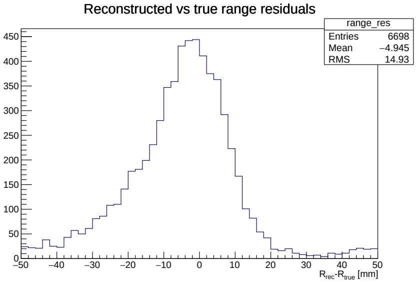
Momentum resolution (MC)

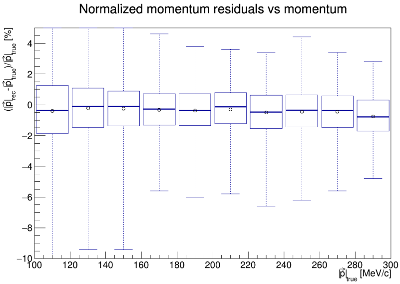
Compare MC truth/recon

- $\rightarrow$ Range resolution $\sim$ 1.5 cm
- $\rightarrow$ Momentum resolution $\sim$ 1.5 % for $100 < |\vec{p}| < 300$ MeV/c
- $\rightarrow$ Linear fit reliable, minor muon straggling introduces a very small bias on range









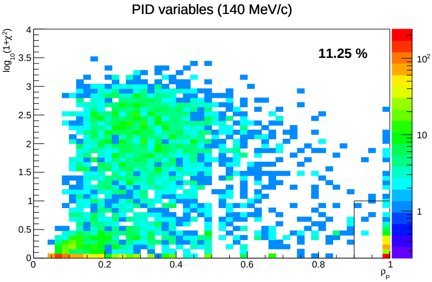
PID variables for positron rejection

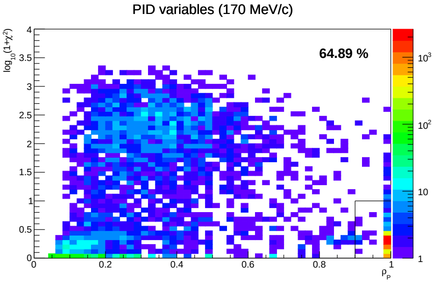
Two main PID variables present in the online reconstruction

- **Density**, ρ_P, i.e. the fraction of the planes hit on the particle path
- Spread, quantified by χ^2/N, i.e. the **dispersion** of hits in the xy plane

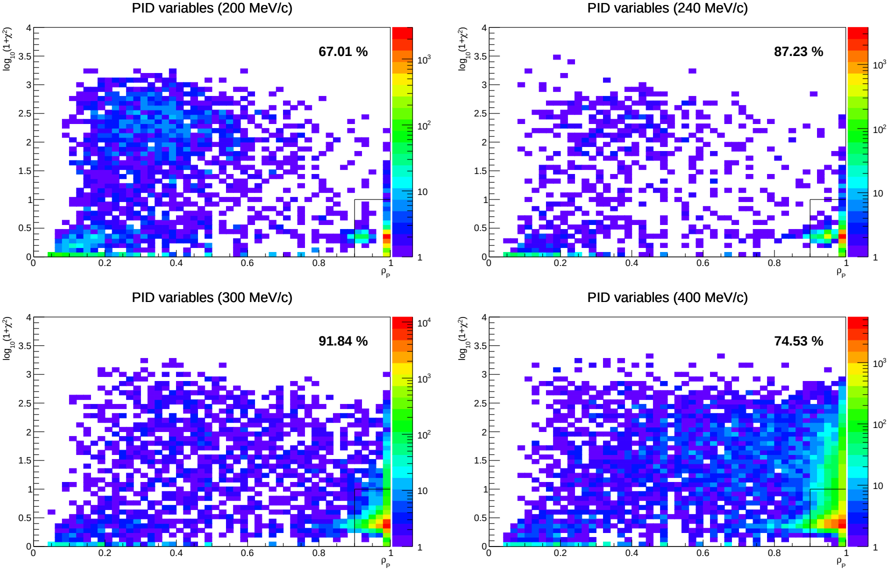
Three main populations in the ρ_P–$\log\hat{\chi}^2$ plot

- Muons and pions, dense and straight (bottom right)
- EM showers, loose and wide (top left cloud)
- Photon deep hits, loose and straight (bottom right line)





PID variables at higher momenta



EMR μ–π separation

With perfect resolution, the EMR should be able to distinguish μ from π

$\rightarrow$ Two separate measurements of **range** and **integrated charge**

$$\left.\begin{array}{c} R \simeq \frac{m}{k^*}\frac{(\gamma-1)^2}{\gamma} = \frac{1}{k^*}\frac{T^2}{E} \\ Q \simeq q^* T \end{array}\right\} \quad \rightarrow m = E - T = \frac{Q_T}{q^*}\left[\frac{Q_T}{k^* q^* R} - 1\right]. \qquad (1)$$

The uncertainty on this measurement is driven by

$$\sigma_m = \frac{1}{k^* q^{*2}}\sqrt{\left[\frac{2Q_t}{R} - k^* q^*\right]^2 + \frac{Q_T^4}{R^4}\sigma_R^2}. \qquad (2)$$

which, for resolutions on the measurements of $\sigma_R = 1.5\,$cm, $\sigma_{Q_T} = 100$, yields a resolution on the mass of $24.7\,$MeV$/c^2$, of **order the splitting**...

With the help of the TOF measurement, neglecting the straggling in the KL, a better resolution of $4.8\,$MeV$/c^2$ can be achieved (200 MeV$/c$):

$$\sigma_m = m\sqrt{\frac{\sigma_R^2}{R^2} + (1+\gamma)^4\frac{\sigma_t^2}{t^2}}. \qquad (3)$$

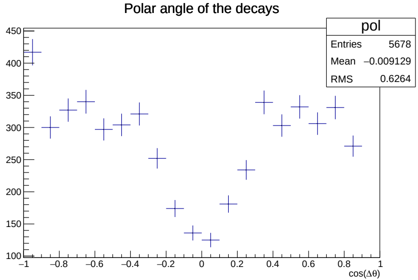
Decay matching

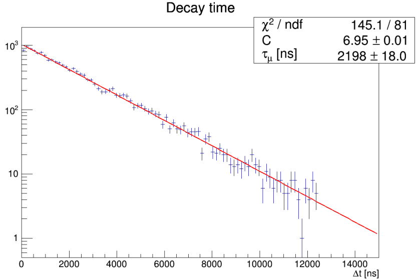
Although a seldom used feature, the EMR matches decays to the mothers (μ, π) by matching **in time** and **in position**.
Reconstructed variables:

$\rightarrow$ Decay time, vertex position, θ and ϕ angles, range and momentum.

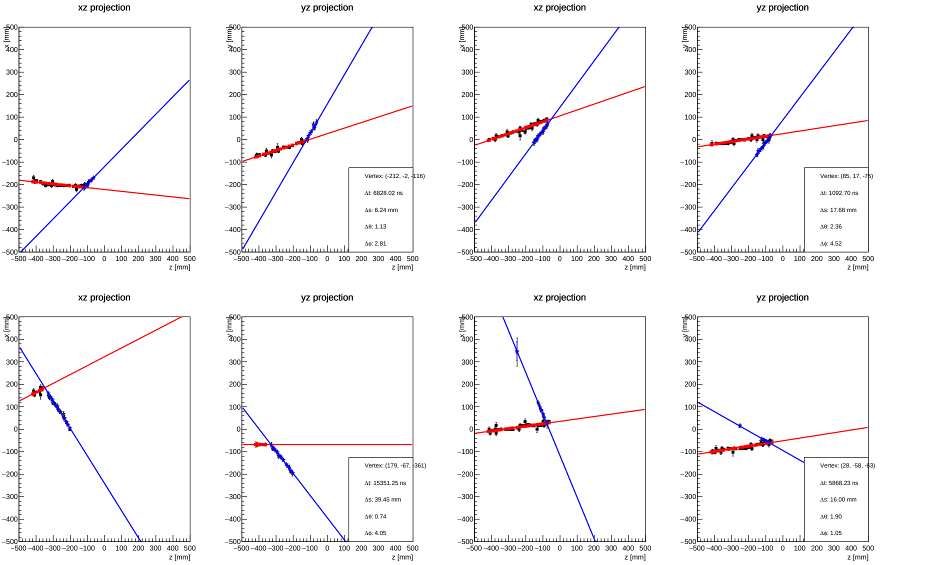
Sources of inefficiency:

- Positrons and electrons do not have decays;
- Low energy decays do not form a track (low end of Michel dist.);
- $\cos\theta = 0$ decays can go through a single plane.





Matched decays



Conclusions

Raw efficiencies

- Slight decrease in efficiency since last analysis
- No dead PMTs, need a new calibration for extensive channel check.

Reconstruction efficiencies

- Have not been altered since last analysis
- For fast muons, the presence of digits in the EMR is virtually guaranteed if they hit TOF2 first
- If a track is present, space points are associated with the hits
- Higher level of reconstruction are guaranteed given SPs

Particle identification

- The EMR is still able to separate muons from positrons
- Does not have the resolution standalone to separate pions from muons