Electron-Muon Ranger (EMR) software

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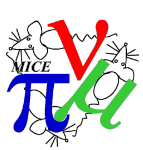


Massive structural changes and upgrade

EMREvent
($\vec{V}$, Δs, Δt, θ_{D}, φ_{D})

↪ **EMREventTrackArray** (*mother+daughter*)
(ρ_P^{MA}, ρ_P^{SA}, Q^{MA}, Q^{SA}, ϕ^{MA}, ϕ^{SA}, TDC, type, track ID)

↪ **EMRPlaneHitArray**
(Q, TDC, Δt, samples, plane ID)

↪ **EMRBarHitArray**
(ToT, TDC, Δt, channel ID)

↪ **EMRSpacePointArray**
($\vec{q}$, $\vec{q}_G$, $\vec{\sigma}$, Q_i^{MA}, Q_i^{SA}, TDC, Δt, channel ID)

↪ **EMRTrack**
($\vec{a}^x$, $\vec{a}^y$, $\vec{O}$, θ, φ, $\hat{\chi}^2$, R, $|\vec{p}|$)

↪ **EMRTrackPointArray**
($\vec{q}$, $\vec{q}_G$, $\vec{\sigma}$, res_x, res_y, χ^2, channel ID)

EMR data at the Spill level

Spill

- ↪ **DAQData**
  - ↪ **EMRDaq**
    - ↪ **DBBHitArray**
    - ↪ **V1731HitArray**
- ↪ **ReconEventArray**
  - ↪ **EMREvent**
- ↪ **MCEventArray**
  - ↪ **EMRHitArray**
- ↪ **EMRSpillData**
  - ↪ **EMRBarHitArray**
  - ↪ **EMREventTrackArray** (1 per candidate)

EMREvent

Contains two EMREventTrack

→ One for the mother particle (μ, π, e)

→ One for the daughter e if there is one

If a daughter is found, additional information

→ The coordinate of the **vertex** $\vec{V}$ where the decay took place and the uncertainty on its measurement

→ The **distance** Δs between the mother and its decay, measures the degree of belief that the matching was correct

→ The **time difference** Δt between the mother and its decay

→ The **polar angle** θ_D between the mother and its decay

$\theta_D \in [0, \pi]$, angle with respect to the zenith $\vec{e}_z$

→ The **azimuthal angle** φ_D between the mother and its decay

$\varphi_D \in [-\pi, \pi]$, angle with respect to $\vec{e}_x$ in the xy plane

EMREventTrack

Contains the following for a single particle (EventTrack)

- → **EMRPlaneHitArray**
- → **EMRSpacePointArray**
- → **EMRTrack**

and a series of **additional variables** for PID and such

- → The **plane density** $\rho_{\mathrm{P}}^{\mathrm{MA}}$, $\rho_{\mathrm{P}}^{\mathrm{SA}}$ [1]
- → The **total charge** Q^{MA}, Q^{SA}
- → The **charge ratio** ϕ^{MA}, ϕ^{SA}
- → The **global time** TDC, time stamp of the EventTrack
- → The **type** of EventTrack: *mother, daughter, candidate*
- → The **track ID** (useful to identify candidates)

[1] The superscripts MA, SA signify which PMT was used to reconstruct the variable, MA = multi-anode, SA = single-anode.

EMRPlaneHit

Each EMRPlaneHit (plane that **recorded something**) contains

- → **Integrated charge** in ADC counts
- → **Time stamp** TDC provided by the DBB
- → **Time between the trigger and the pulse** Δt (time selection)
- → **Sampled pulse shape** (output of the fADC)
- → **Plane ID** which refers to one of the 48 planes of the EMR
- → An array of EMRBarHit
  - → **Time-over-threshold** provided by the FEB (proportional to charge)
  - → **Time stamp** TDC provided by the DBB
  - → **Time between the trigger and the hit** Δt (time selection)
  - → **Channel ID** which refers to one of the 2880 channels of the EMR

EMRSpacePoint

For each EMRBarHit one space point is reconstructed

- → 3-vector of **local coordinates** of the interaction $\vec{q}$
- → 3-vector of **global coordinates** of the interaction $\vec{q_G}$
- → 3-vector of **uncertainty** on the coordinates $\vec{\sigma}$
- → Corrected **SAPMT charge** Q_i^{SA} corresponding to the channel
  - The ADC charge is corrected for fibre attenuation and calibration
- → Reconstructed **MAPMT charge** Q_i^{MA} corresponding to the channel
  - Reconstructed from the time-over-threshold: $Q = \exp(a\mathrm{ToT} + b) + c$
- → **Time stamp** TDC provided by the DBB
- → **Time between the trigger and the hit** Δt (time selection)
- → **Channel ID** of the EMRBarHit

EMRTrack

With a set of space points, a **polynomial track is fitted** in xz and yz

- → Array of **parameters** $\vec{a}^x$ in the xz proj. $P_x(z) = \sum_0^n a_p^x z^p$
- → Array of **parameters** $\vec{a}^y$ in the yz proj. $P_y(z) = \sum_0^n a_p^y z^p$
- → Coordinates of the **origin** $\vec{O}$ of the track at the entrance of the EMR
- → **Polar angle** θ at the entrance
- → **Azimuthal angle** φ at the entrance
- → **Normalised chi squared** $\hat{\chi}^2$ of the polynomial fit
- → **Range** R of the particle in PS
- → **Total momentum** $|\vec{p}|$ of the particle
- → An array of EMRTrackPoint
  - → $\vec{q}$, $\vec{q_G}$, $\vec{\sigma}$ similarly to the space points
  - → **Residual** with respect to the space point in the two proj. res_x, res_y
  - → **Local chi squared** χ^2 for this track point, $\chi^2 = \Delta s_i^2 / \sigma_i^2$
  - → **Channel ID** of the EMRSpacePoint

Reconstruction: MapCppEMRPlaneHits

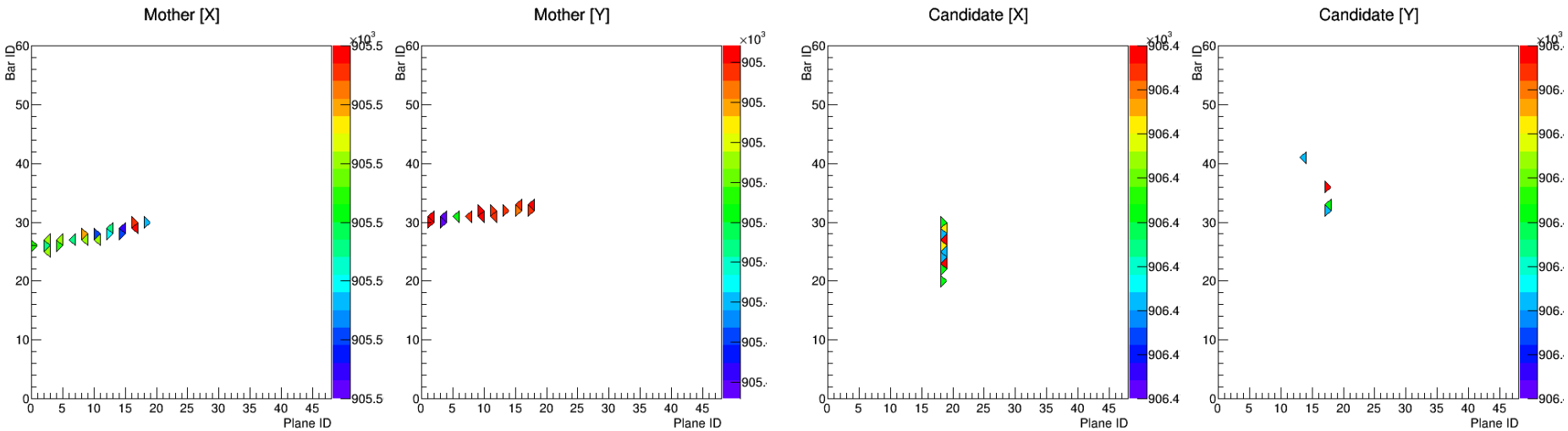
EMR readout

- 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**

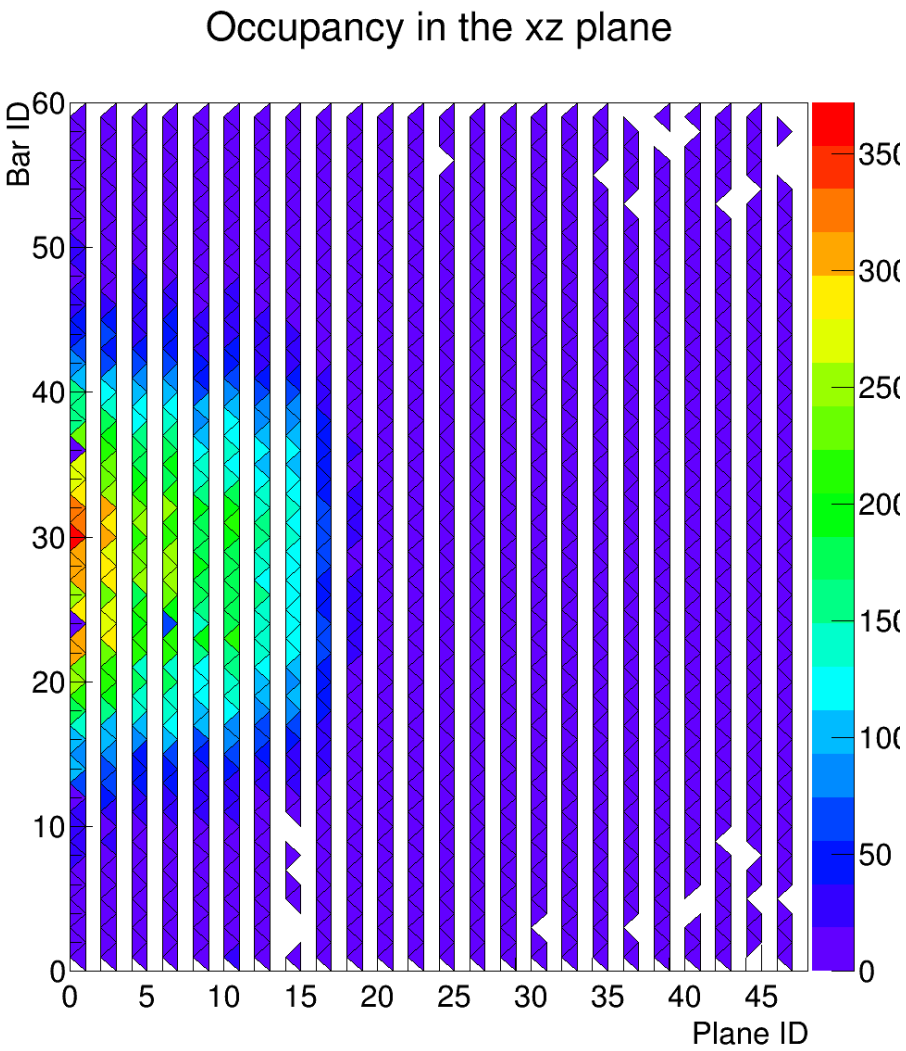
Plane hit reconstruction

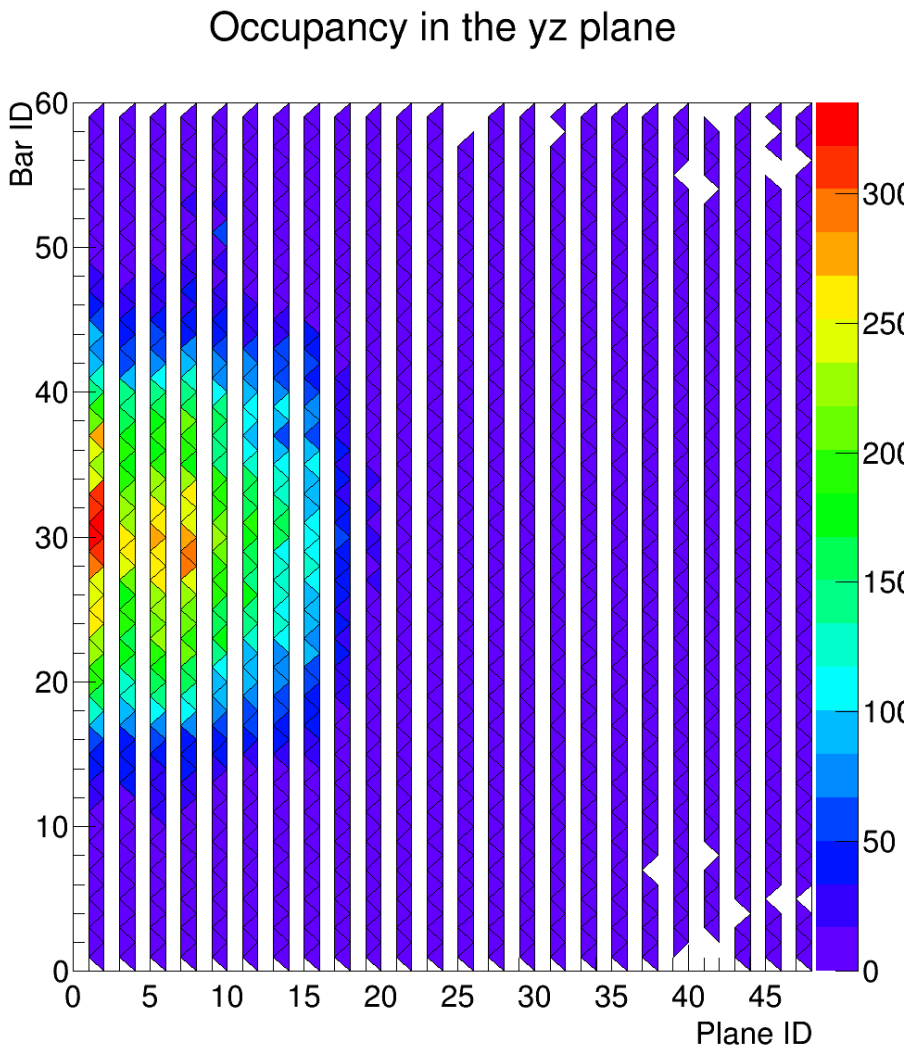
→ DBB hits and corresponding fADC charge are matched by their temporal proximity ($\Delta t \sim 200\,\text{ns}$) and create a plane hit

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



Occupancy (bar hits)





Reconstruction: MapCppEMRSpacePoints

Crosstalk Cleaning

→ Only the bunch of hits with the highest charge is kept each plane

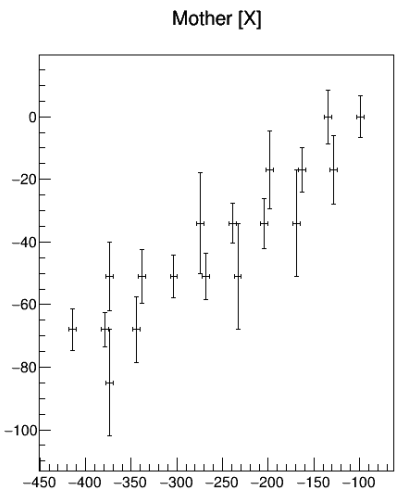
Space point formation

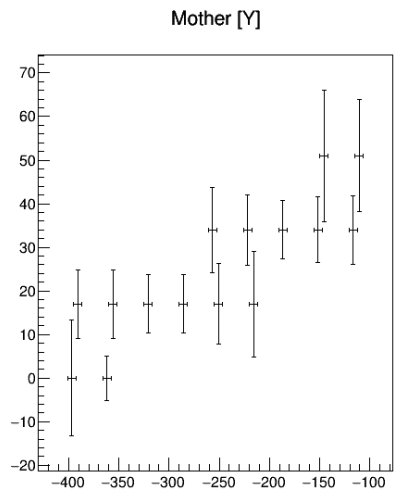
→ We need to make a space point per hit, not per plane (decays)

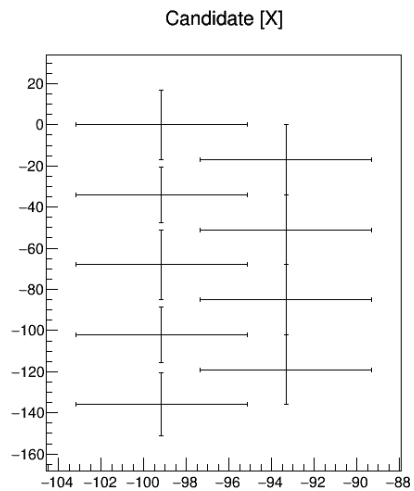
→ The space point position is the barycentre of the bar

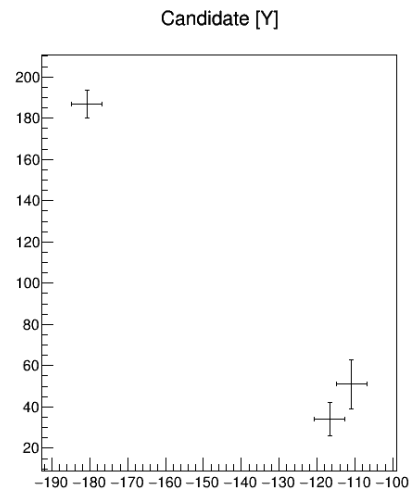
→ The want the error bar to represent the charge weighted average

$$\sigma_i = \sigma_q \sqrt{\frac{Q_\mathrm{P}}{Q_i}} \rightarrow \hat{q} = \frac{1}{\sum_i 1/\sigma_i^2} \sum_i \frac{q_i}{\sigma_i^2} = \frac{1}{Q_P} \sum_i q_i Q_i \qquad (1)$$

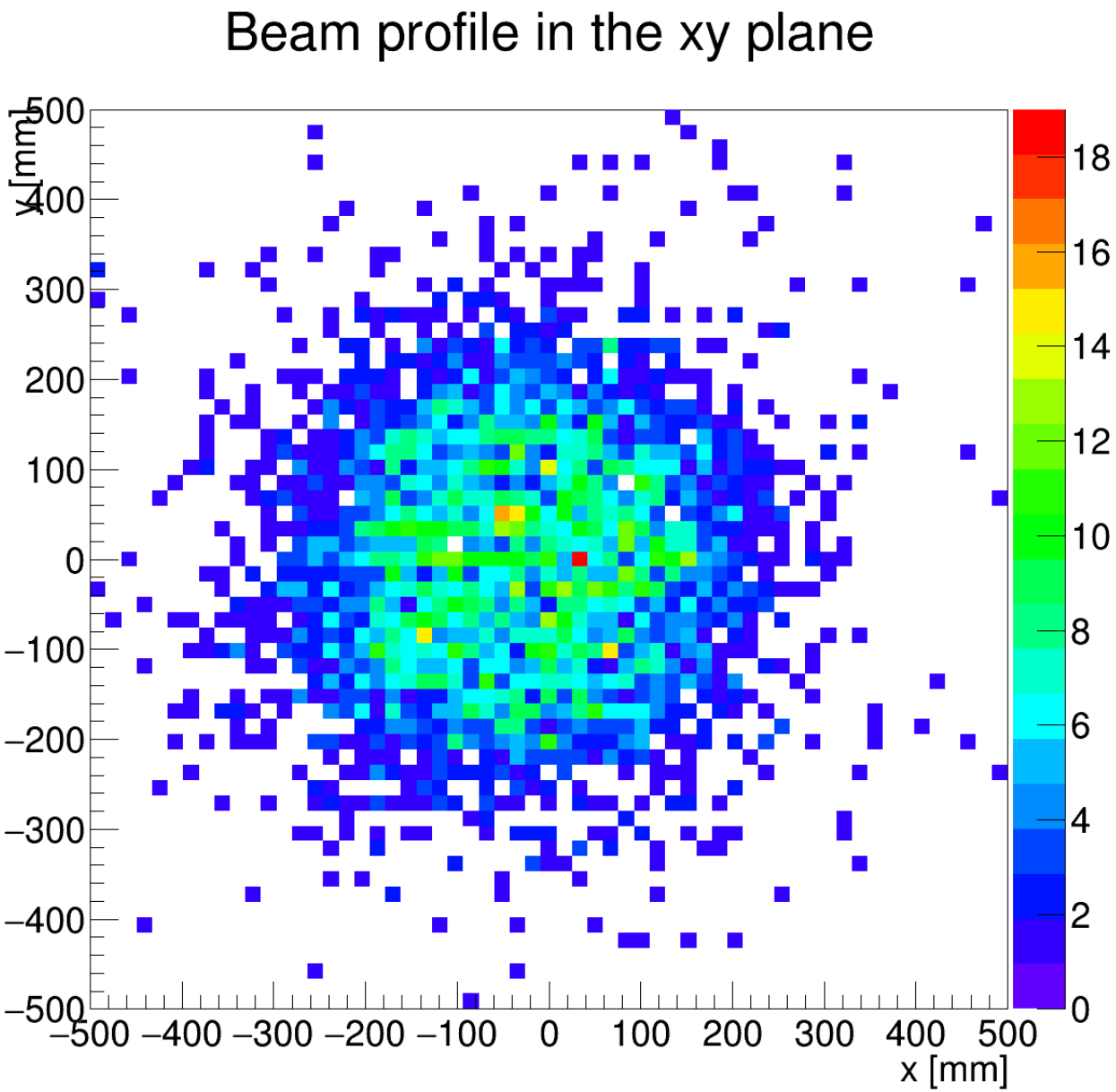








Muon beam profile at the entrance of the EMR

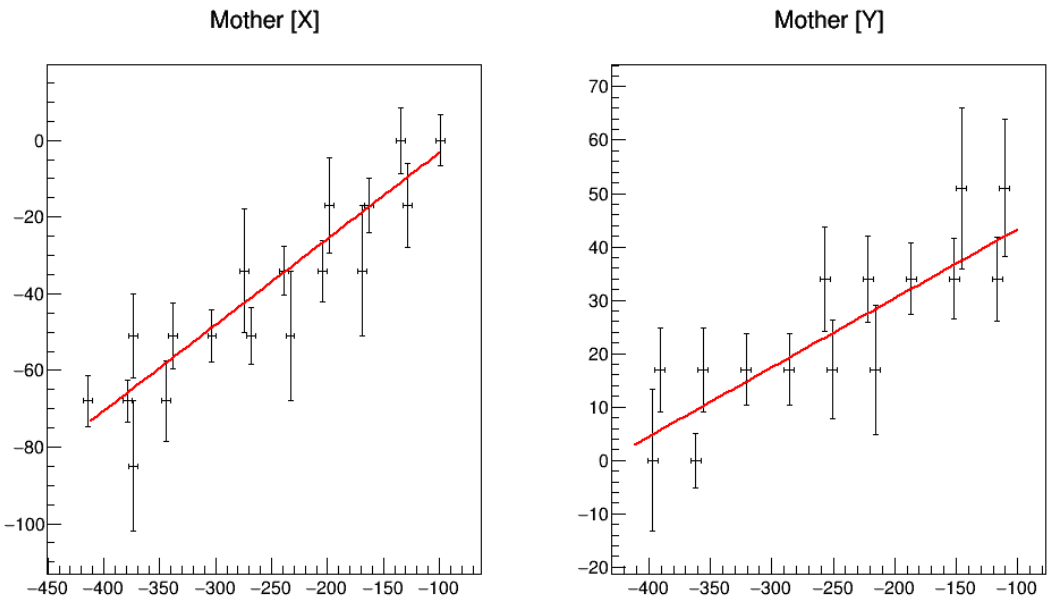


MapCppEMRRecon: Track fitting

For an array of space points, a polynomial is fitted using a least squares algorithm separately in the two projections. This produces two array of parameters $\vec{a}^x, \vec{a}^y$ for two polynomials $P_x(z), P_y(z)$
When a polynomial is fitted to the space points, their coordinates are corrected by pushing them radially to the closest point on the track

$$z_i' = \min_{z \in [z_{\min}, z_{\max}]} \sqrt{(z - z_i)^2 + (P(z) - q_i)^2}\,, \tag{2}$$

which creates as many track points as there was space points.



MapCppEMRRecon: range and total momentum $|\vec{p}|$

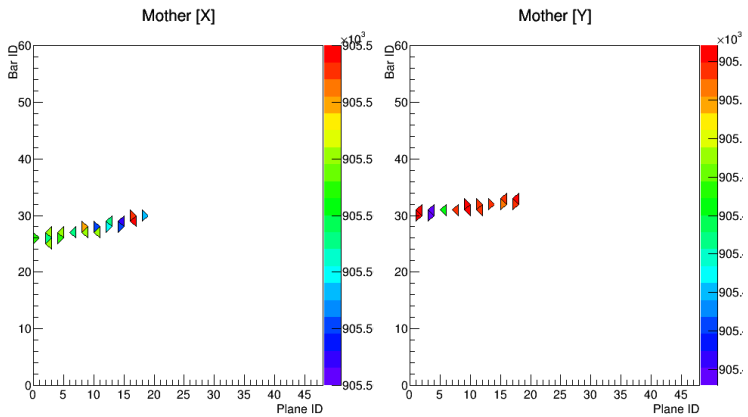
- The **range** is reconstructed from the track fitting parameters

$$R = \int_{z_{\min}}^{z_{\max}} \sqrt{1 + \left(\frac{\partial P_x(z)}{\partial z}\right)^2 + \left(\frac{\partial P_y(z)}{\partial z}\right)^2}\,\mathrm{d}z \tag{3}$$

NB: For $n = 1$ (line fit): $R = \int_{z_{\min}}^{z_{\max}} \sqrt{1 + a_{x,1}^2 + a_{y,1}^2}\,\mathrm{d}z$.

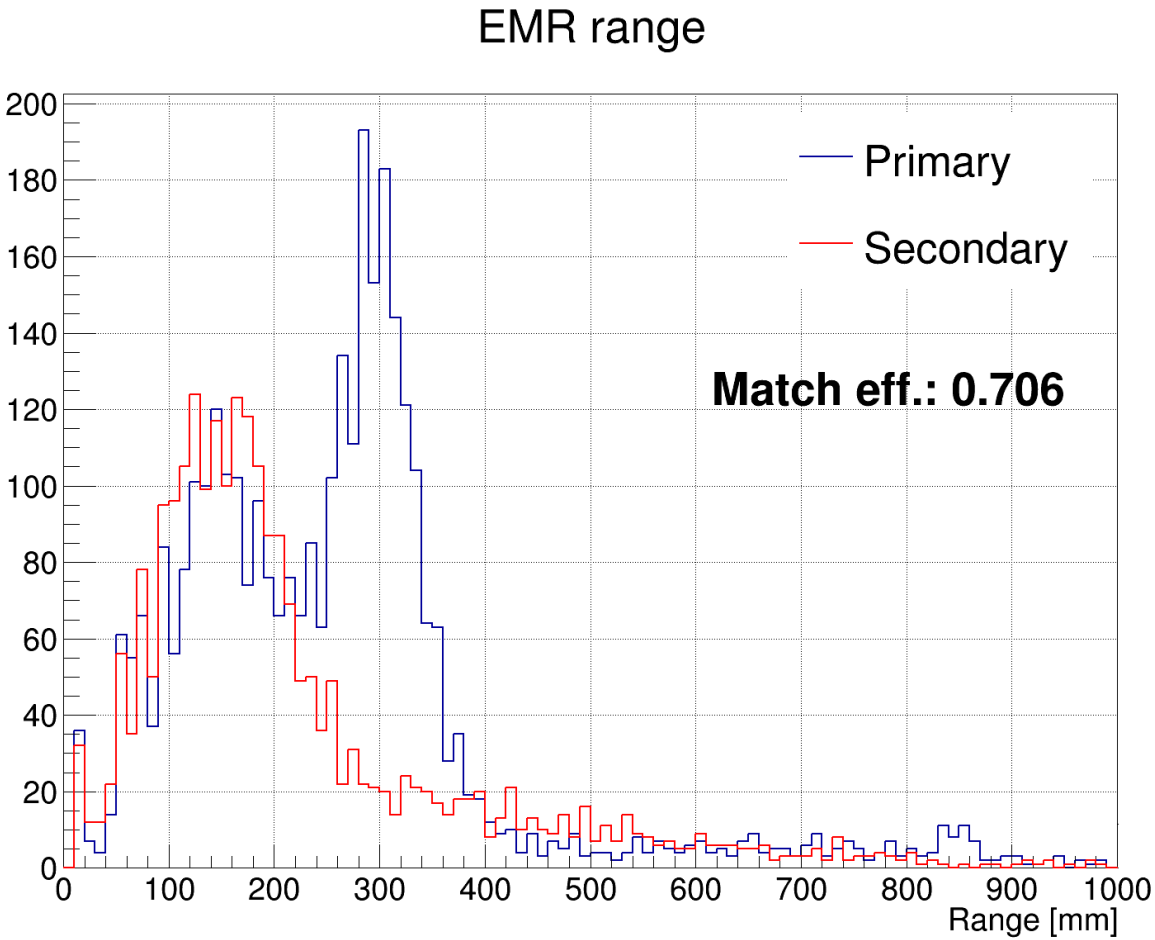
- The **momentum** is unfolded from the CSDA range, assuming PID

$$R = \int_{E_0}^{0} \frac{\mathrm{d}E}{\langle \mathrm{d}E/\mathrm{d}x \rangle} = \int_{p_0/m_i c}^{0} \frac{\mathrm{d}p}{\langle \mathrm{d}E/\mathrm{d}x \rangle} \beta m_i c^2 \tag{4}$$



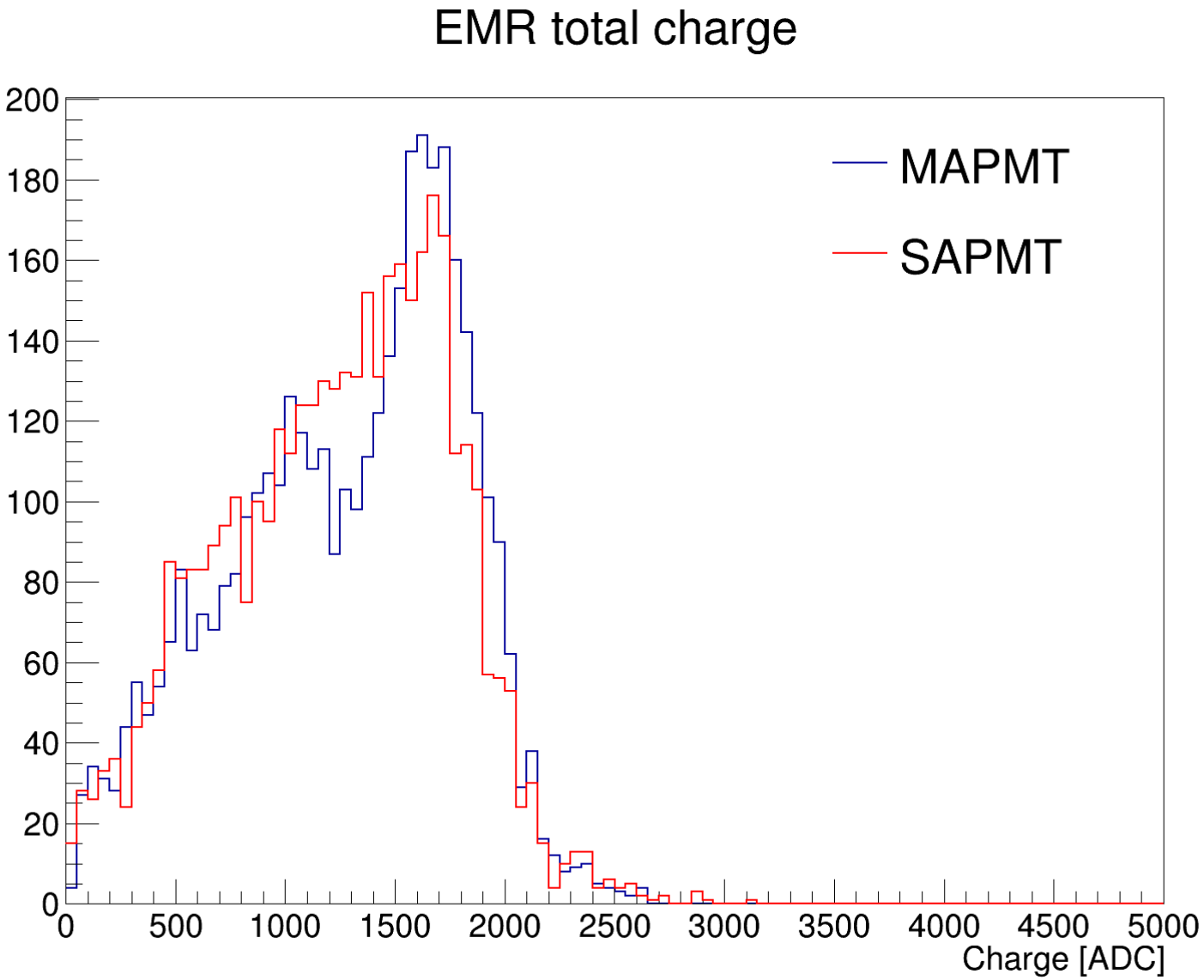
$\rightarrow \boxed{R_\mu \sim 332\,\mathrm{mm}} \rightarrow \boxed{|\vec{p}| \sim 185\,\mathrm{MeV}/c}$

Range reconstruction for a 'calibration' beam (π, μ, e)

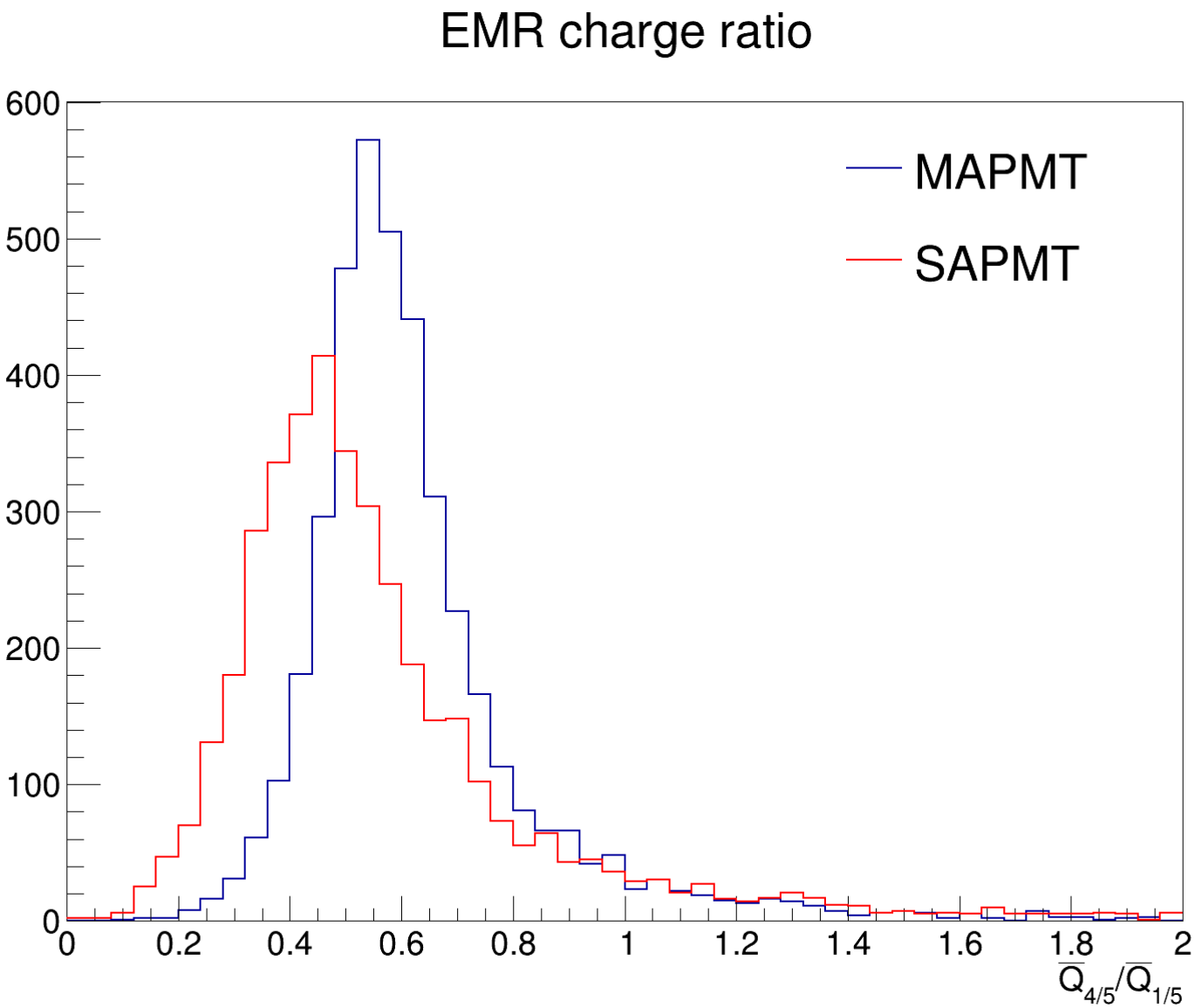


$\rightarrow$ Very sharp **muon** peak (blue right), distinct **pion** peak (blue left) and clean **Michel electron** distribution (red).

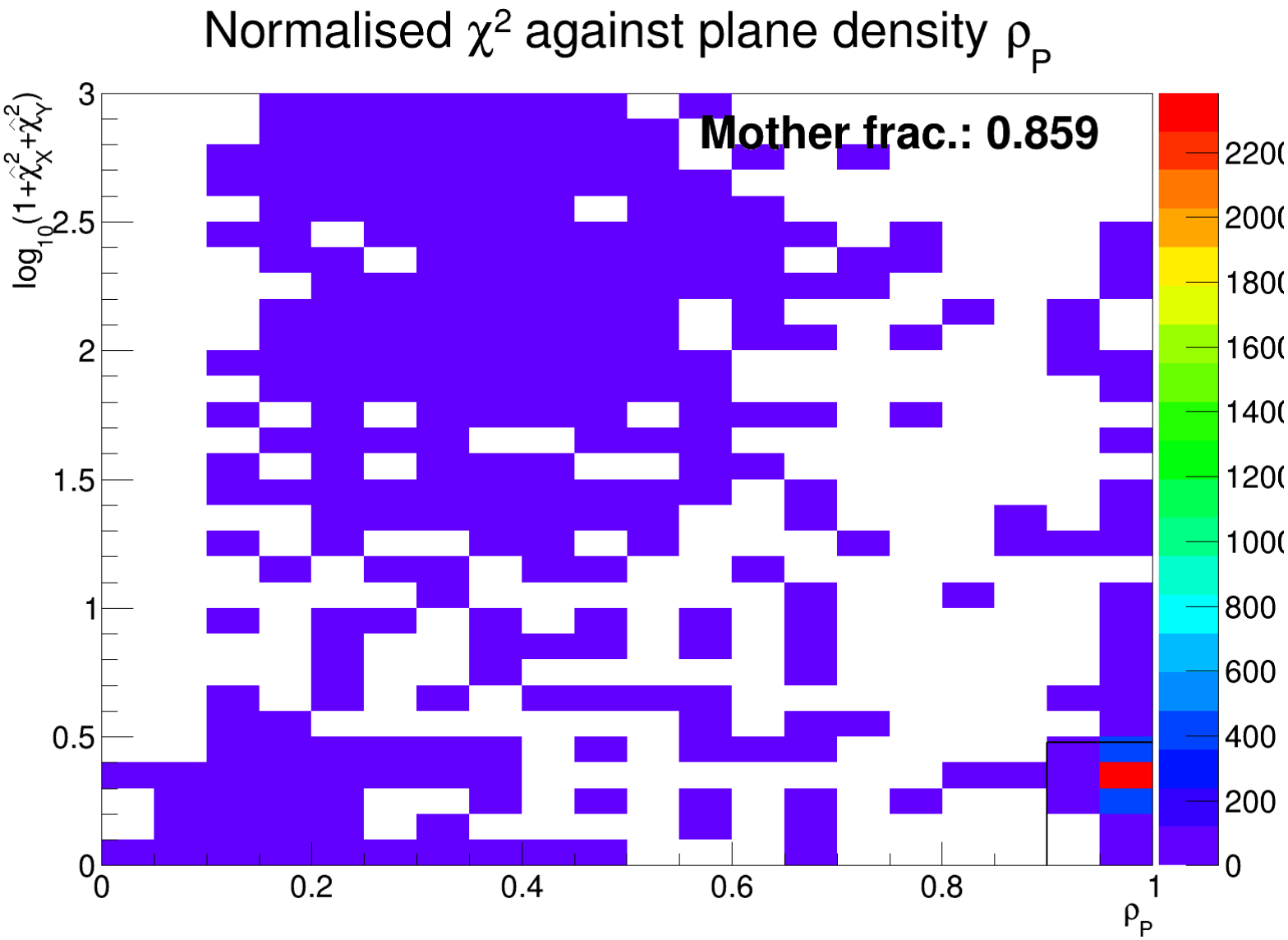
MapCppEMRRecon: Total charge Q^{MA}, Q^{SA}



MapCppEMRRecon: Charge ratio ϕ^{MA}, ϕ^{SA}



MapCppEMRRecon: PID variables $\hat{\chi}^2$ and ρ_P



MapCppEMRRecon: track matching

Track matching **procedure**

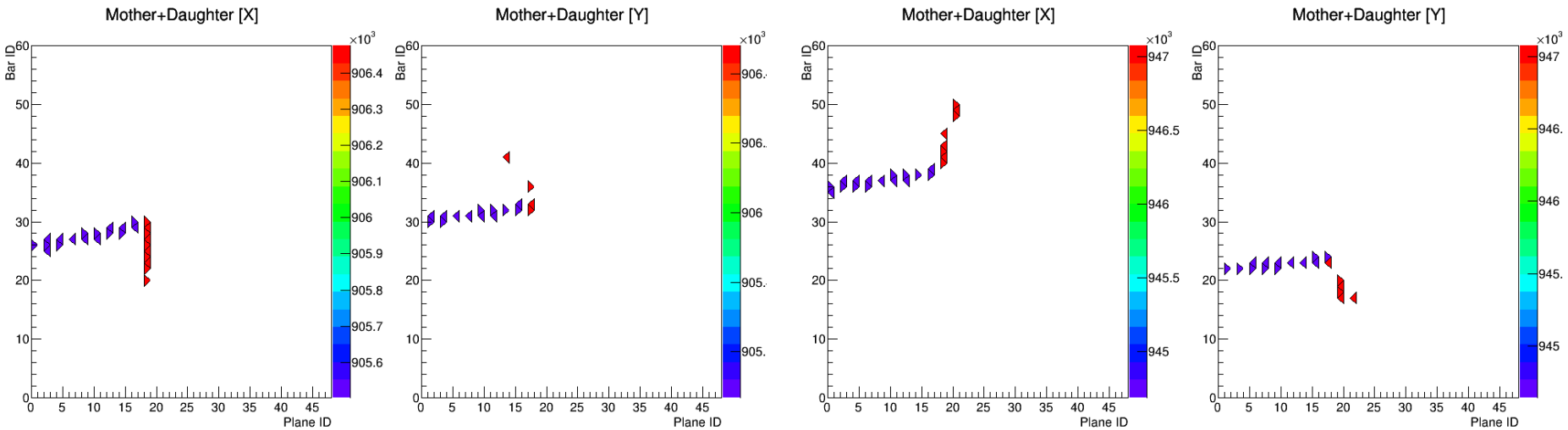
→ Find candidates that are within 10 τ_μ of the mother

→ Compute the distance between the mother and the candidate

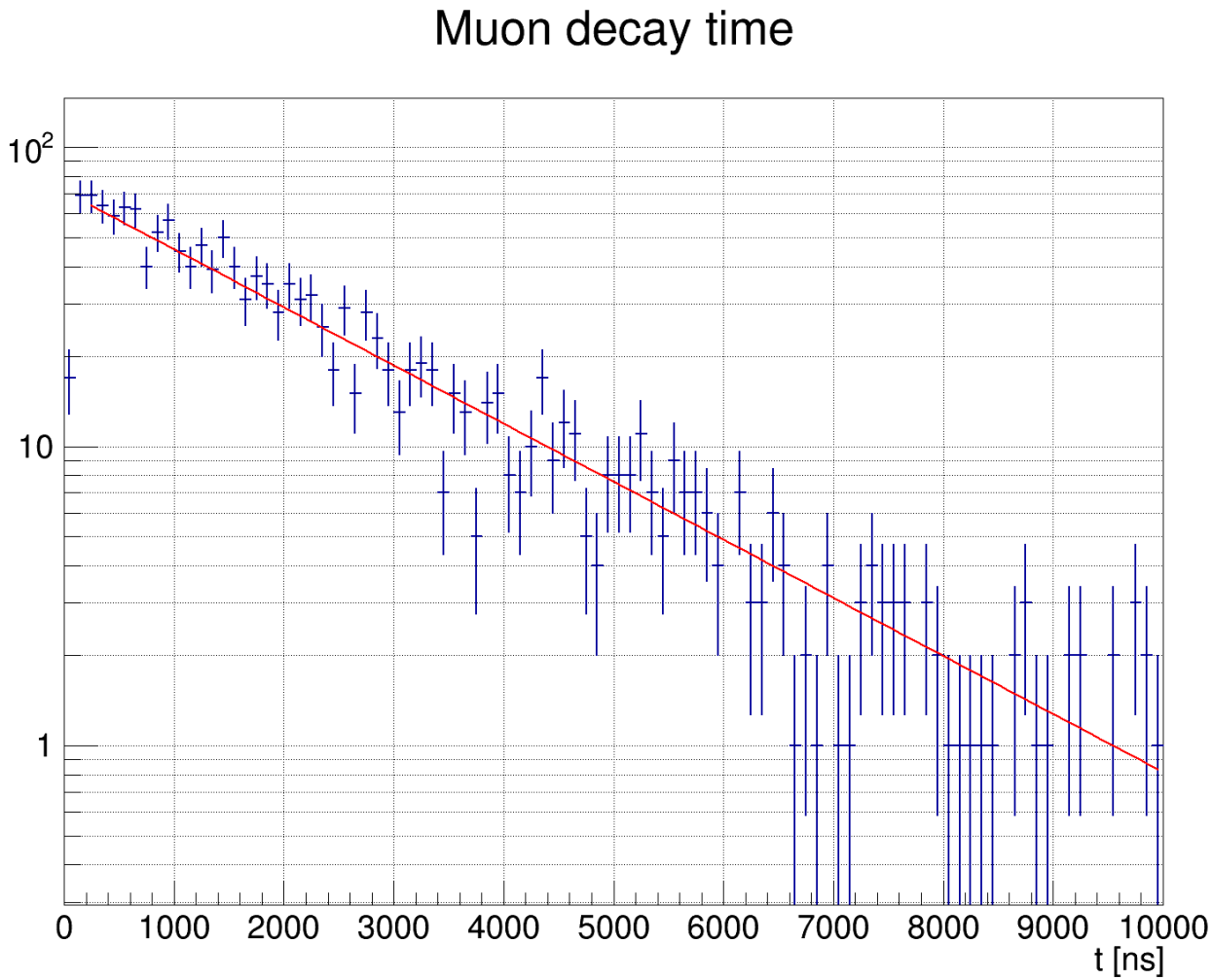
→ Select the closest candidate

Reconstructed **variables**

→ Vertex $\vec{V}$, distance Δs, time diff. Δt, inclination θ_{D}, azimuth φ_{D}



Muon lifetime



$\rightarrow \tau_\mu = 2.218 \pm 0.066 \mu$s !

Other recent and future updates

Additional features and corrections:

- EMR quality flags in python provided to DR
- MC digi. calibrated in energy to match Step IV real data
- 100x faster MapEMRSpacePoint (multiple maps rewritten to make them more efficient), 30x faster MapEMRRecon (reduced the resolution of the momentum reconstruction to 10^{-3})
  - → MapEMRSpacePoint takes $\sim$ 10 ms for a 200 triggers spill (produces an SP for each BarHit)
  - → MapEMRRecon takes $\sim$ 100 ms for a 200 triggers spill (fits a track, reconstruct the pid variables, range, momentum and match daughters)

Future updates:

- Daughter fitting algorithm
- Minor reducer updates
- Fine tune the digitizer

EMR code completion

94	**EMR**			Drielsma	1.0	99	1 Apr 14		1 May 16
95		Particle ID		Drielsma	1.0	100	1 Apr 14		Done
96		Reconstruction		Drielsma	1.0	100	1 Apr 14		Done
97			Hit reconstruction	Drielsma	1.0	100	1 Apr 14		Done
98			Track reconstruction	Drielsma	1.0	100	1 Apr 14		Done
99			Range measurement	Drielsma	1.0	100	1 Apr 14		Done
100			Decay products matching	Drielsma	1.0	100	1 Apr 14		Done
101			Energy measurement	Drielsma	1.0	100	1 Apr 14		Done
102		Calibration		Drielsma	1.0	100	1 Apr 14		Done
103			Take data w cosmics	Drielsma	1.0	100	1 Apr 14		Done
104			Calibrate + validate	Drielsma	1.0	100	1 Apr 14		Done
105		MC		Drielsma	1.0	100	1 Apr 14		Done
106			Physics Process	Drielsma	1.0	100	1 Apr 14		Done
107			Sensitive Detector	Drielsma	1.0	100	1 Apr 14		Done
108			Data structure	Drielsma	1.0	100	1 Apr 14		Done
109		MC Dig		Drielsma	1.0	100	1 Apr 14		Done
110			ADC simulation	Drielsma	1.0	100	1 Apr 14		Done
111			Data structure	Drielsma	1.0	100	1 Apr 14		Done
112		DAQ Dig		Drielsma	1.0	100	1 Apr 14		Done
113		Calibration Interface		Drielsma	1.0	100	1 Apr 14		Done
114		Geometry Interface		Drielsma	1.0	100	1 Apr 14		Done
115		Reducer		Drielsma	1.0	100	1 Apr 14		Done
116		Cartesian Output		Drielsma	1.0	100	15 Apr 15		Done
117		Measurement Error		Drielsma	1.0	100	15 Apr 15		Done
118		Data Quality Flag		Drielsma	1.0	100	15 Apr 15		Done
119		Test		Drielsma	1.0	100	1 Apr 14		Done
120		Doc		Drielsma	1.0	0	1 Apr 14		1 May 16