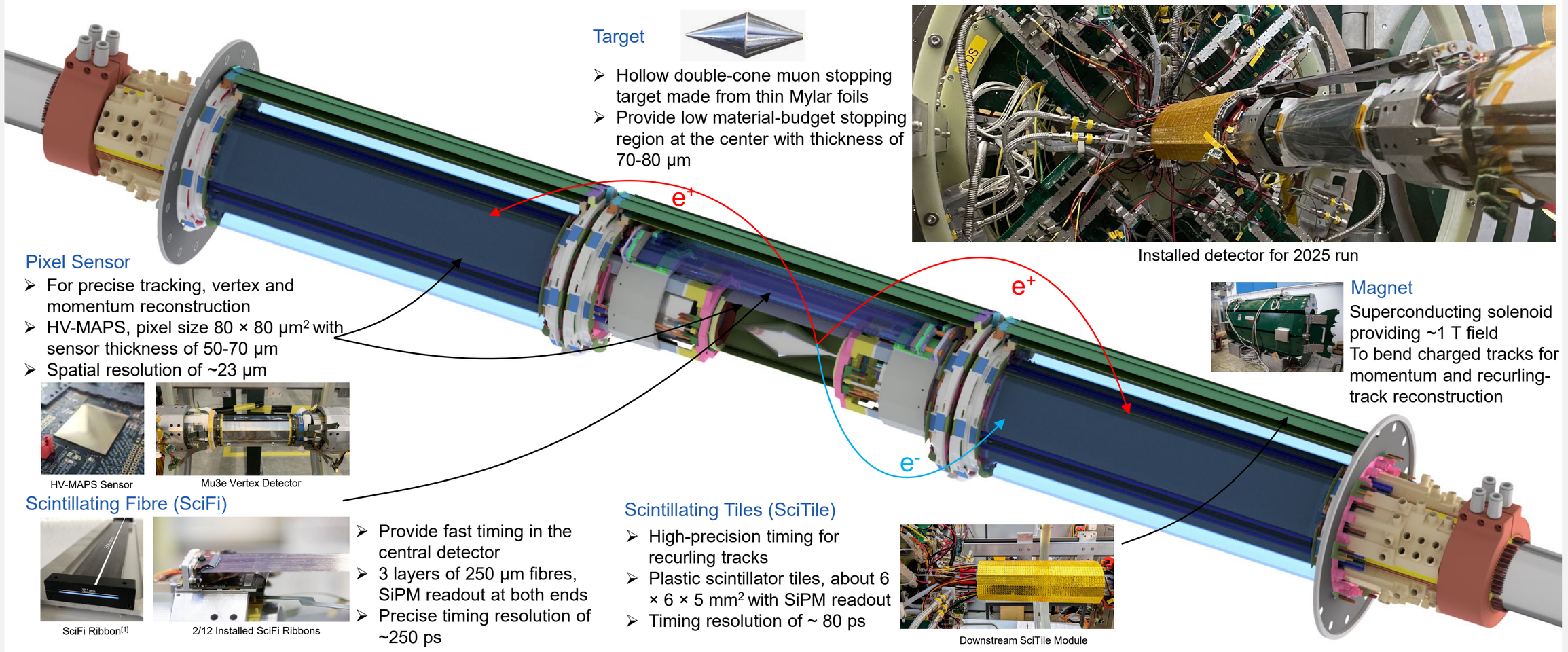
Mu3e Online Event Selection on GPU

Chen Xie[1)] for the Mu3e collaboration[2)]
1) Institute for Particle Physics and Astrophysics, ETH Zürich;
2) Paul Scherrer Institute (PSI), University of Bristol, Université de Genève, Universität Heidelberg, KIT Karlsruhe, University of Liverpool, UCL London, JGU Mainz, University of Oxford, ETH Zürich, Uni Zürich

1 Mu3e Experiment

The Mu3e experiment searches for the Charged Lepton Flavor Violation decay $\mu^+ \to e^+e^-e^+$, aiming for a branching-ratio sensitivity of 10^{-15} at the PSI πE5 beamline in Phase I. To handle a muon rate of 10^8/s (equivalent to ~100 Gbps raw data rate), a triggerless, GPU-based online event selection algorithm is implemented to reconstruct the full kinematics of three tracks and their common vertex, enabling Mu3e signal identification and background suppression while reducing the data rate by two orders of magnitude.

2 Mu3e Detector



Target

- Hollow double-cone muon stopping target made from thin Mylar foils
- Provide low material-budget stopping region at the center with thickness of 70-80 μm

Installed detector for 2025 run

Pixel Sensor

- For precise tracking, vertex and momentum reconstruction
- HV-MAPS, pixel size 80 × 80 μm² with sensor thickness of 50-70 μm
- Spatial resolution of ~23 μm

HV-MAPS Sensor

Mu3e Vertex Detector

Magnet

Superconducting solenoid providing ~1 T field
To bend charged tracks for momentum and recurling-track reconstruction

Scintillating Fibre (SciFi)

SciFi Ribbon[1]

2/12 Installed SciFi Ribbons

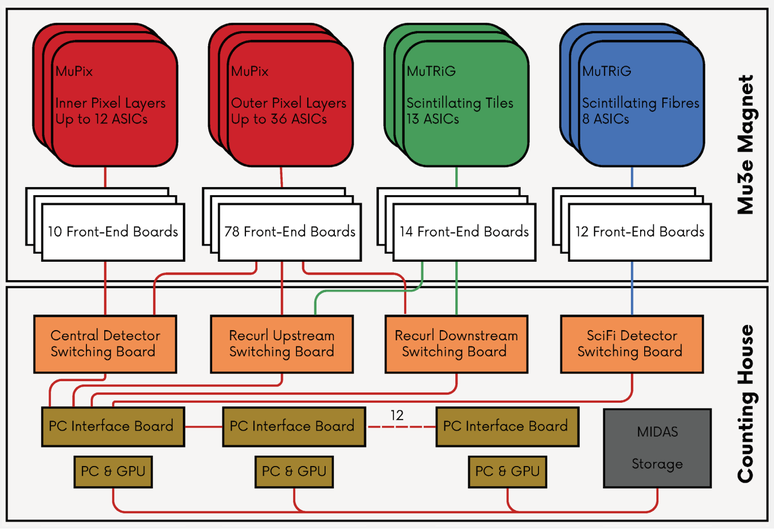
- Provide fast timing in the central detector
- 3 layers of 250 μm fibres, SiPM readout at both ends
- Precise timing resolution of ~250 ps

Scintillating Tiles (SciTile)

- High-precision timing for recurling tracks
- Plastic scintillator tiles, about 6 × 6 × 5 mm² with SiPM readout
- Timing resolution of ~ 80 ps

Downstream SciTile Module

3 Mu3e DAQ



- Continuous triggerless DAQ
- Front-end data are transported and sorted by FPGA switching boards
- Synchronized data slices from all sub-detectors are built on filter PCs
- GPU then performs fast tracking, vertexing, and event selection in real time
- Only selected events are stored, with an output rate of ~100 MB/s (up to 100x reduction)

4 Online Event Selection[2,3]

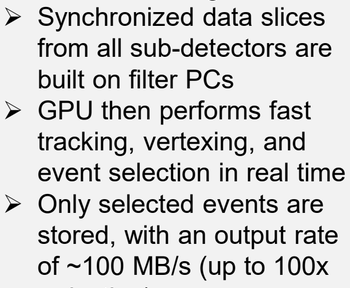
Projected triplet of hits h_0, h_1, h_2 with scattering at h_1

Efficiency of geometric cuts

Triplet Selection:
Triplets are formed from hit combinations in the first 3 layers by applying geometric cuts on angular differences (Φ_{01} , Φ_{12} in the xy-plane; λ in the sz-plane) and on the xy-plane radius R_t

Track Reconstruction:
A preliminary helix from triplets passing the cuts is extrapolated to the 4th layer to predict the hit position, matched to the closest hit to form a second triplet. After a refined fit, tracks are kept with $\chi^2_{\text{global}} < 32$:

$$\chi^2(\kappa) = \frac{\Phi_{MS}(\kappa)^2}{\sigma_\Phi^2} + \frac{\Theta_{MS}(\kappa)^2}{\sigma_\Theta^2};\ \chi^2_{\text{global}}(\kappa) = \sum_t^{n_{triplets}} \chi_t^2(\kappa).$$



transverse point for an event vertex

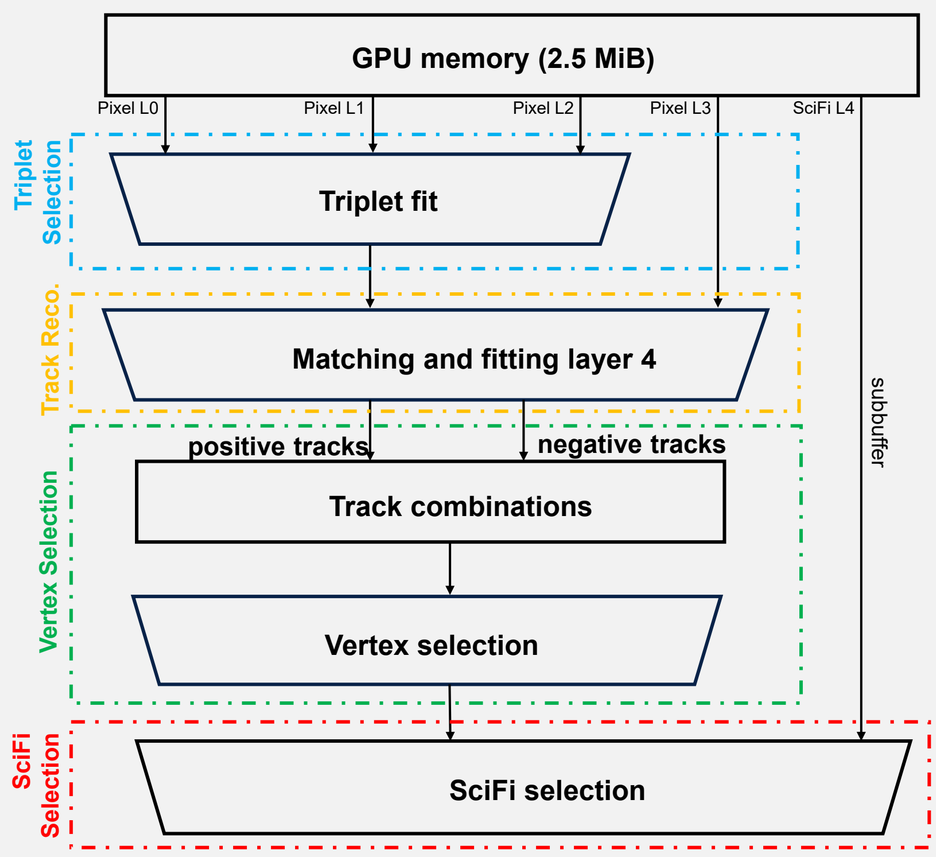
Vertex Selection:
Vertex is defined as the spatial-uncertainty-weighted mean point μ_t of intersection points from all combinations of 2 positive tracks and 1 negative track with the lowest χ^2_t

$$\mu_t = \sum_{i=0}^{3} \frac{p_i}{\sigma_i^2} \Big/ \sum_{i=0}^{3} \frac{1}{\sigma_i^2};\ \chi_t^2 = \sum_{i=0}^{3} \frac{(p_{t,ca,i} - \mu_t)^2}{\sigma_i^2}$$

SciFi Selection
Events with lower χ^2_{SciFi} tend to be accepted further by the SciFi selection as χ^2_{SciFi} is correlated with the distance between the points of close approach (pca) on the SciFi and the three reconstructed tracks.

$$\chi^2_{\text{SciFi}} = \sum_{i=0}^{3} \frac{\left| p_{t,ca,i} - \mu_{\text{SciFi}} \right|^2}{\sigma^2_{\text{SciFi}}}$$

5 Selection Workflow



6 Conclusion

Monte-Carlo studies show that at the targeted muon rate of 10^8 μ/s for Mu3e Phase I, more than 94% of the signal tracks are retained with a reconstruction accuracy of 97%, while the data rate is reduced by a factor of 100[2].
SciFi selection has also been incorporated into the online event selection and successfully tested on the computing farm during the 2025 Mu3e beam time. Further validation is currently in progress.

References:
[1] K. Arndt et al., "Technical design of the phase I Mu3e experiment", Nucl. Instrum. Methods. Phys., A 1014, 165679 (2021).
[2] V.Henkys et al, "Online Event Selection for Mu3e using GPUs", ISPDC 2022, 17-24 (2022).
[3] H. Augustin et al., "The Mu3e Data Acquisition", IEEE Trans. Nucl. Sci., 68, 1833-1840 (2021).