Online Track Reconstruction for the Mu3e Experiment

Haris Murugan

for the Mu3e-Collaboration

DPG Spring Meeting, 2024
T 94.6
7th March, 2024

Institute of Nuclear Physics,
Johannes Gutenberg-Universität Mainz

European Commission

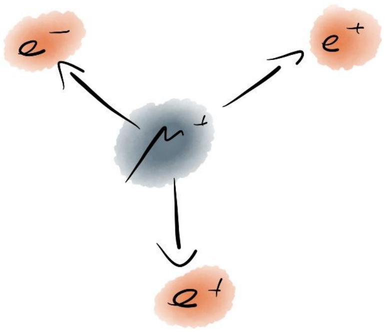
Intense

H2020 MSCA ITN
G.A. 858199

Overview

- Mu3e Experiment
  - Mu3e Detector
  - Detector Subsystems
  - Signal and Background processes
  - Readout System
- Online Event Selection
  - Filter Farm
  - Track Reconstruction
  - Vertex Selection
  - Parallel computing on GPU
  - Performance
- Misalignment Studies
  - Misalignment Modes
  - Misalignment on Simulations
  - Effect on Efficiency
  - Track based Alignment
- Conclusion

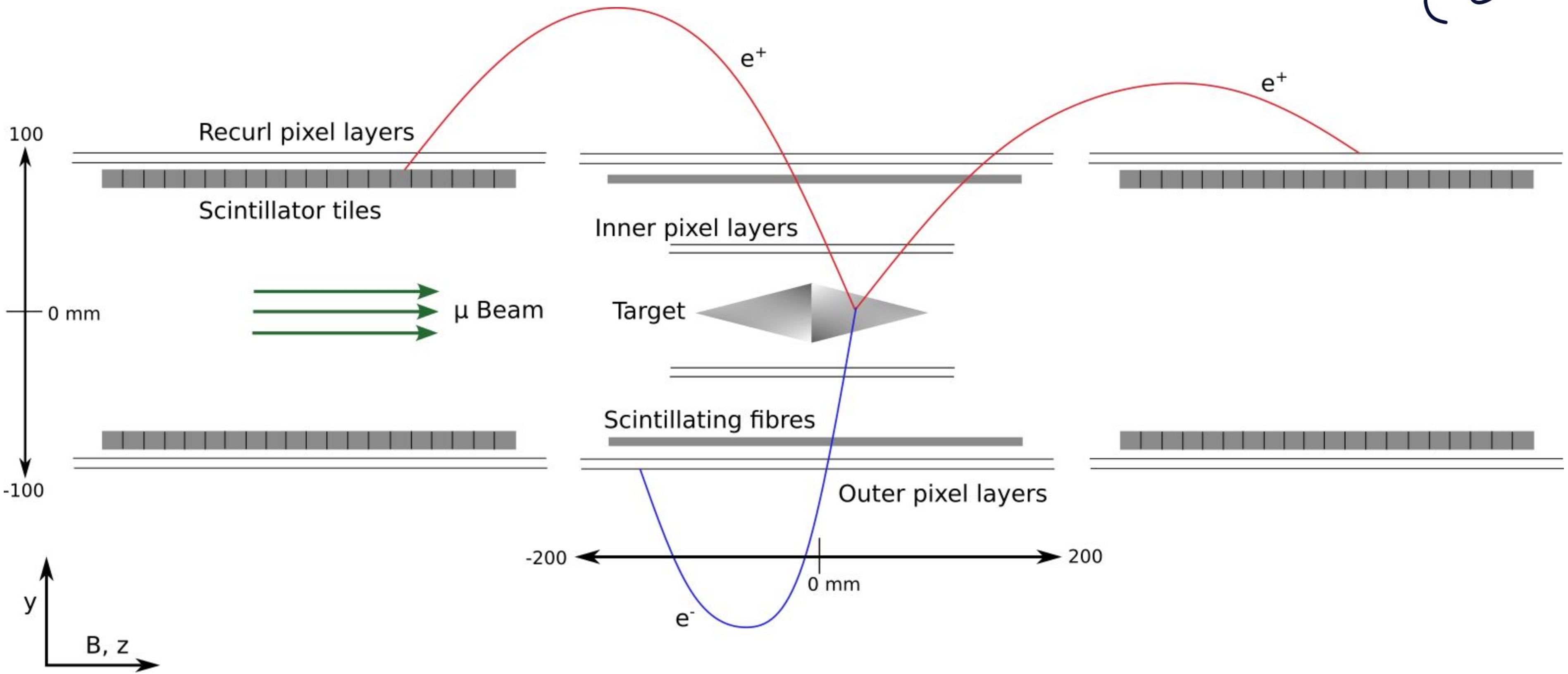
Mu3e Experiment




Paul Scherrer Institute, Villigen

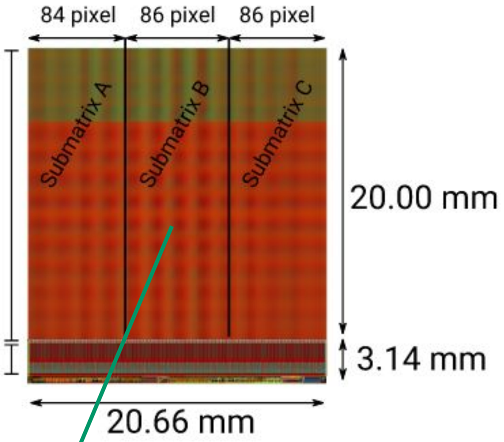
- We aim to observe or exclude the decay of a positive muon to two positrons and an electron.
- If observed, would indicate Physics beyond The Standard Model.
- SINDRUM limit the sensitivity to Br < 10^{-12} (1988), PSI.
- Phase I - muon rate of $1x10^{8}$ s^{-1}
- Phase II - muon rate of $2x10^{8}$ s^{-1}

Mu3e Detector



Detector Subsystems

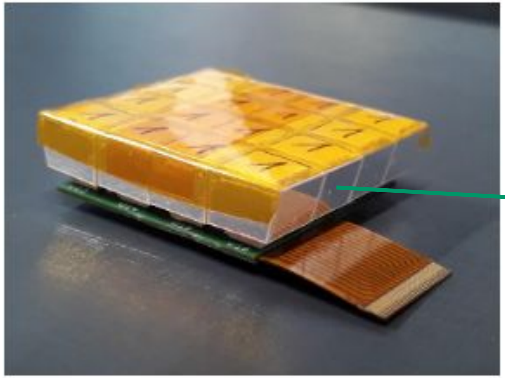
Tracking detector



MuPIX: High Voltage Monolithic Active Pixel Sensors, pixels and the detector electronics are integrated into the same chip

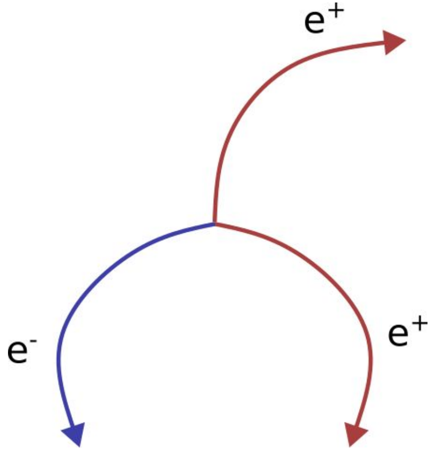
Timing detector

Scintillation fiber:
timing resolution is 0.5 ns

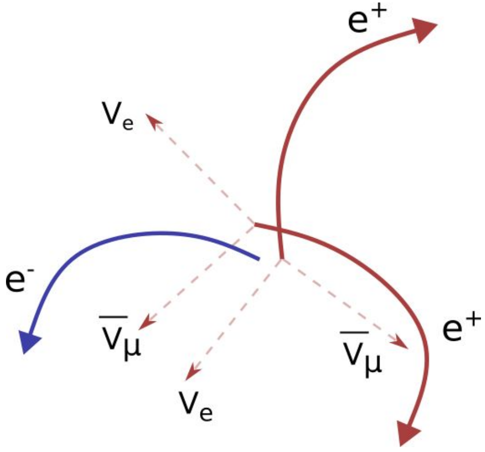


Scintillation Tiles: timing resolution about 70 ps

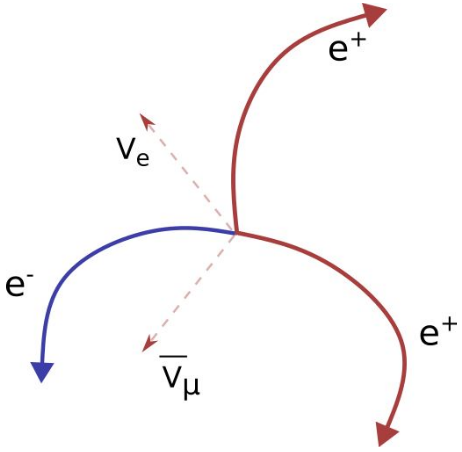
Signal and Background processes



Signal

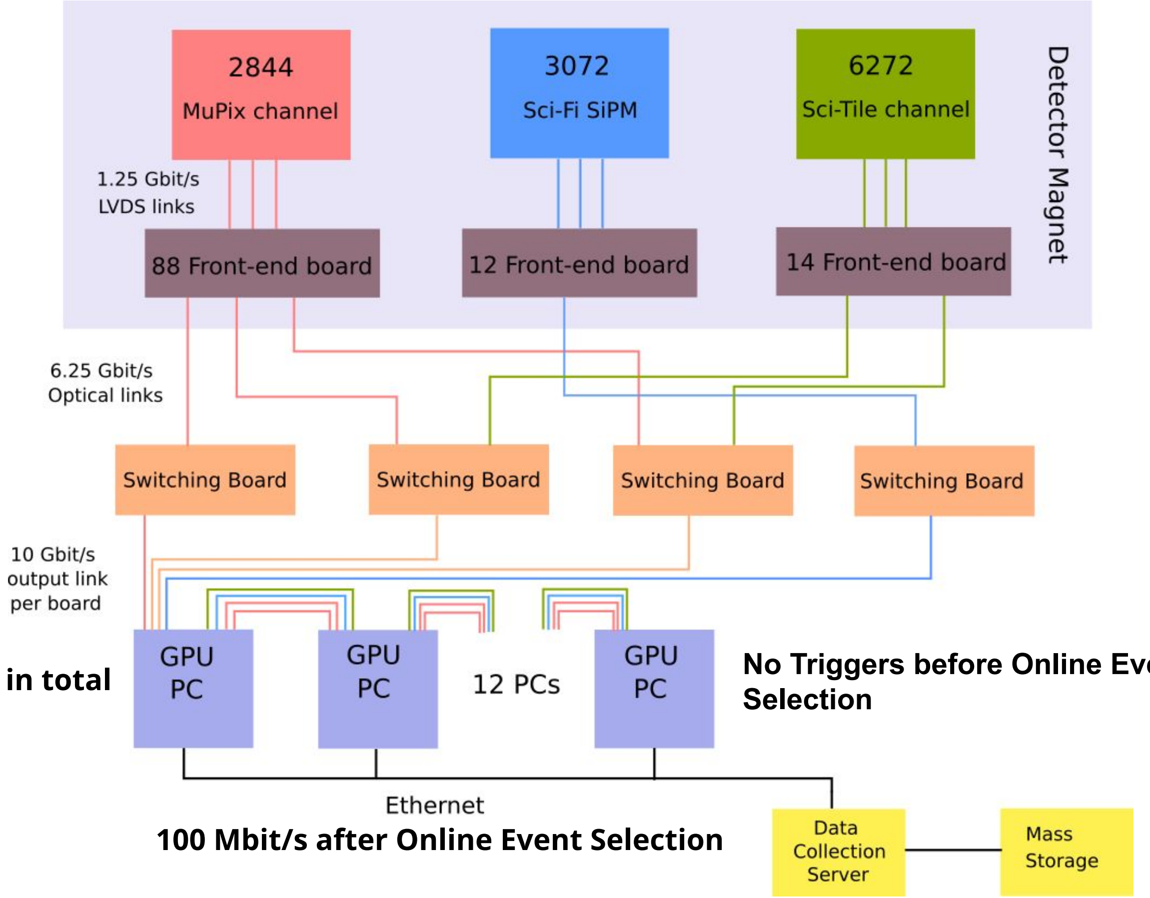


Combinatorial Background



Internal photon conversion
(Br = 3.4×10^{-5})

Readout System



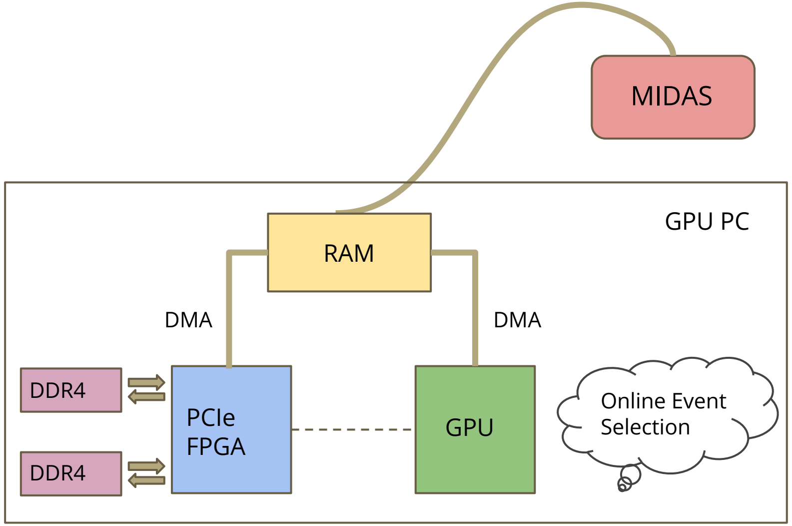
101 Gbit/s in total

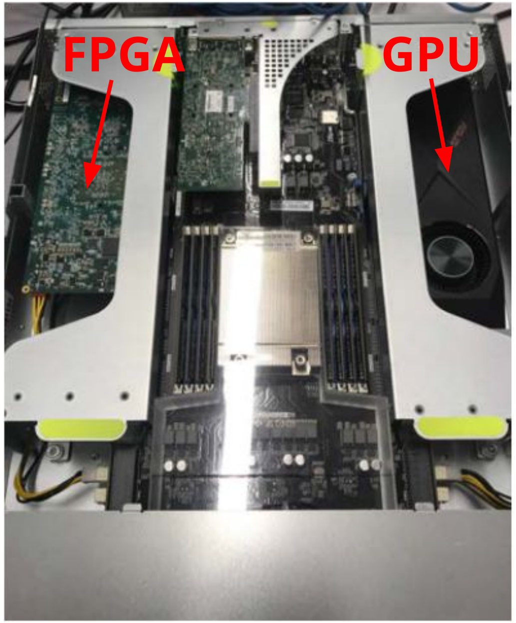
No Triggers before Online Event Selection

100 Mbit/s after Online Event Selection

Filter Farm

- Objective - select signal candidate events by reconstruction of tracks and vertices. To reduce data rate by a factor of 100.

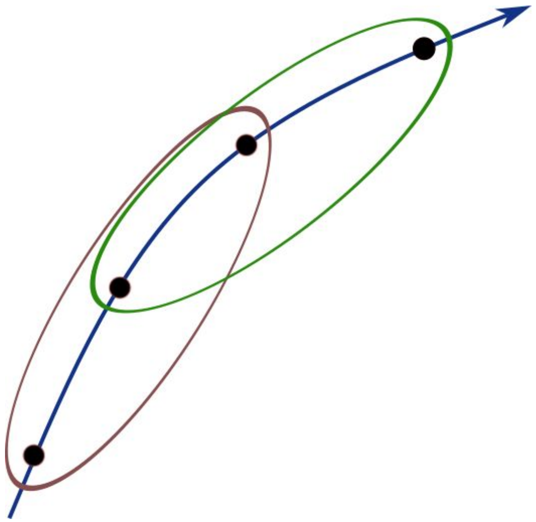




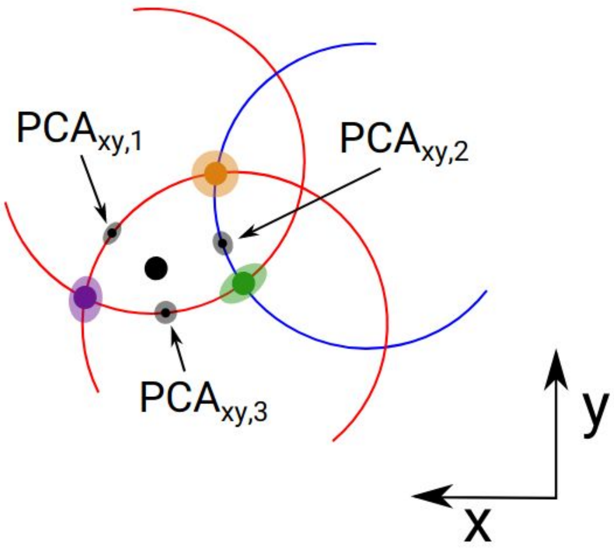
- NVIDIA GeForce RTX 3080 Ti.
- DE5a-NET FPGA card by Terasic.

Track Reconstruction

- 3D Multiple Scattering (MS) fit.
- Finds the curvature, minimising the MS angles for each triplet.
- Fits the triplets from first 3 layers after preselection.
- Helix trajectory is propagated to the 4th layer and the closest hit is found.
- The global curvature from both helix is used to find the track parameters.

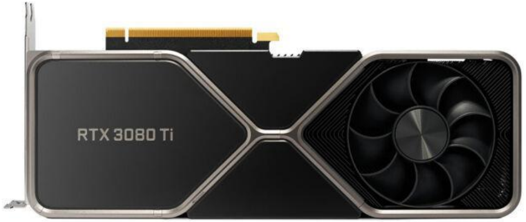


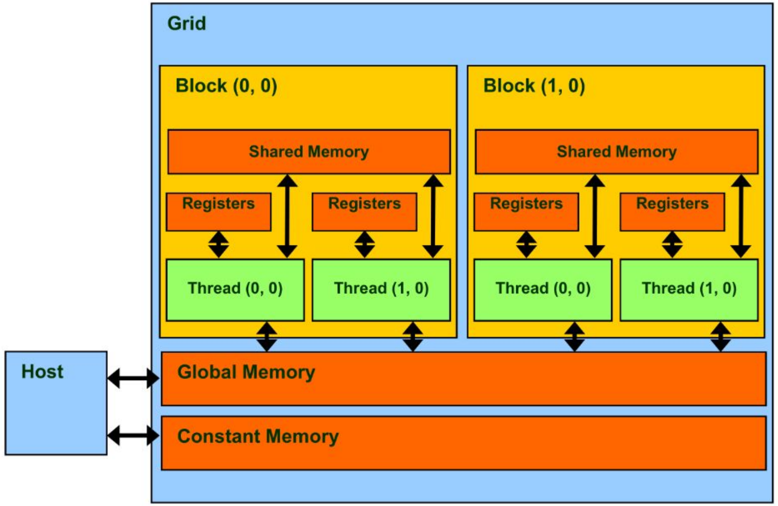
Vertex Selection



- With curvature the e^- and e^+ can be identified.
- Only when all three tracks intersect in the transverse plane then the weights are calculated.
- The weights are from the MS in the first detector plane and due to the pixel size.
- The total energy of all particles, must match the muons rest mass and total momentum is zero.
- Frames with signal vertices are kept.

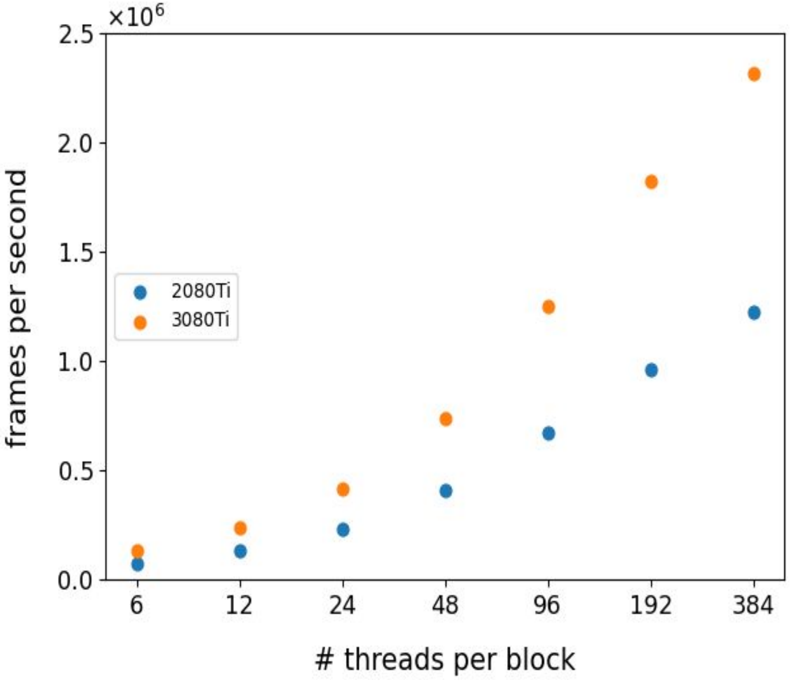
Parallel computing on GPU

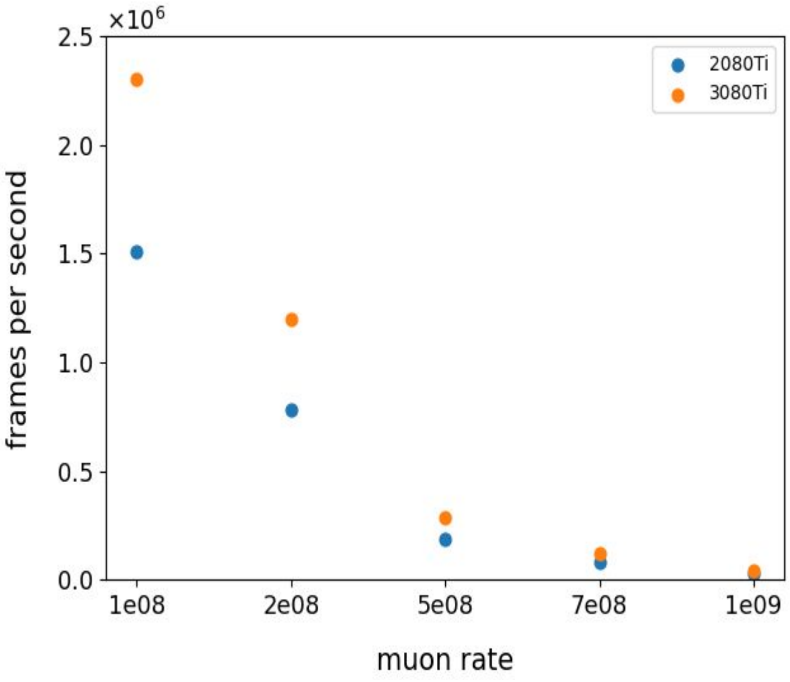




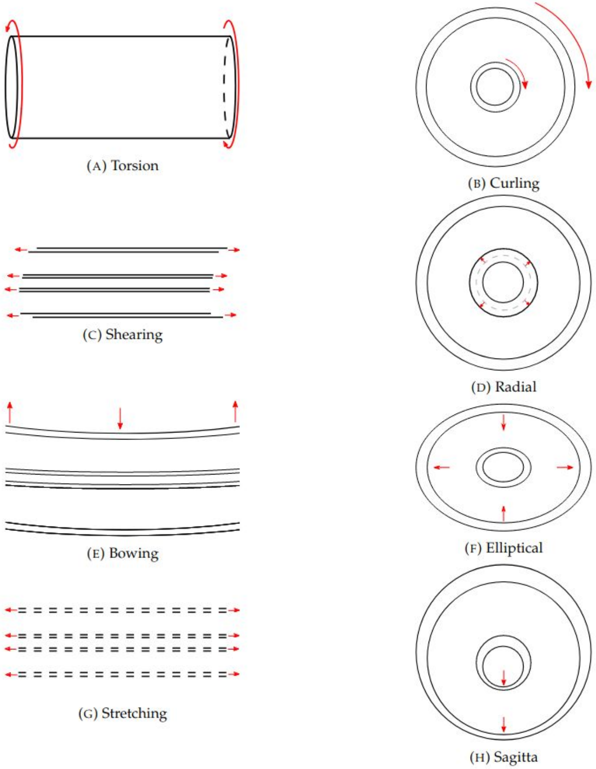
- Each SM consists of 64 CUDA cores in 2080Ti and 128 CUDA cores in 3080Ti.
- Warps of 32 threads execute at once in streaming multiprocessors (SM)

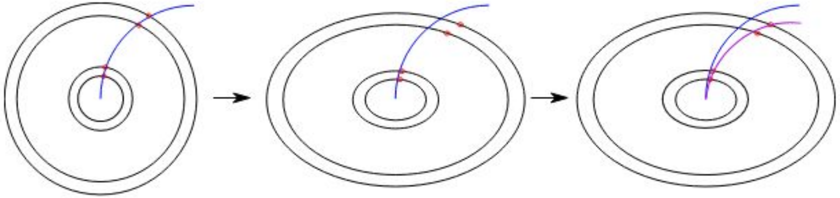
Performance





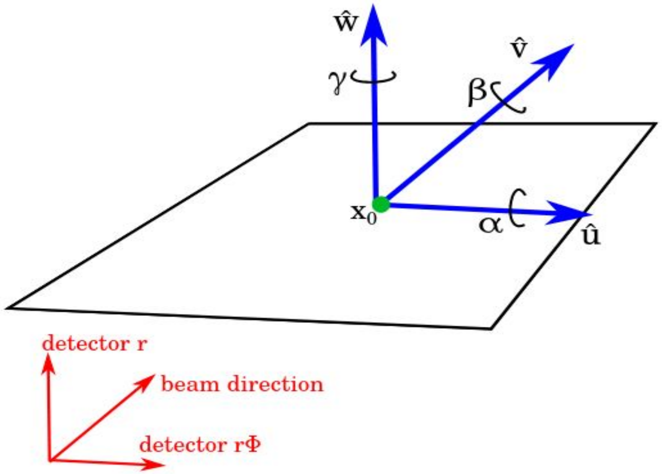
Misalignment Modes





- Blue track is fitted with hits from ideal detector.
- When the detector is deformed elliptically, the blue track would have worse χ^2 , compared to purple track.
- Track fitting needs to account for such deformations and needs to identify true tracks.

Misalignment on Simulation

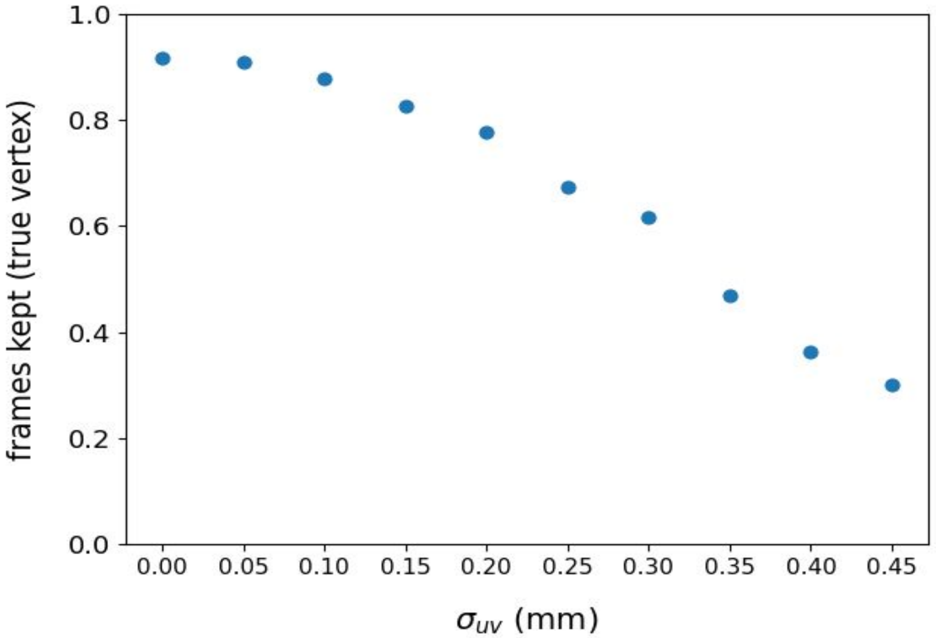


Offsets and Rotations

$\sigma_{off,u,v}$(mm)	$\sigma_{rot,\alpha,\beta}$(mRad)	$\sigma_{off,w}$(mm)	$\sigma_{rot,\gamma}$(mRad)
0.05 (0.45)	5 (10)	0.005 (0.1)	5 (10)

- Modification to the nominal (simulated) geometry by random Gaussian distributed values which reflect realistic misalignment errors.
- Deviations of more than 400 μm (0.4 mm) corresponding to 5 times the pixel pitch (pixel-size) are expected.

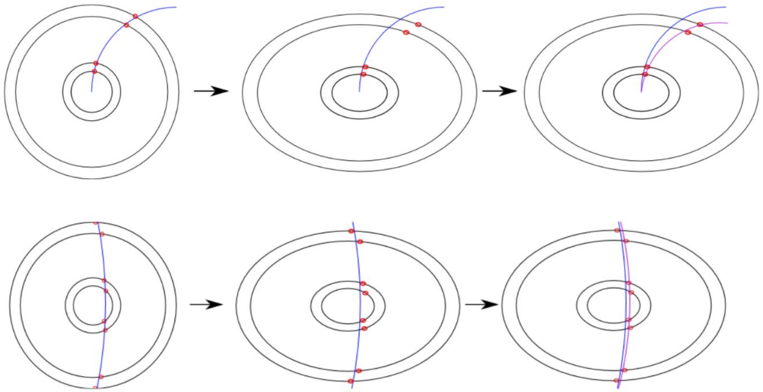
Effect on Efficiency

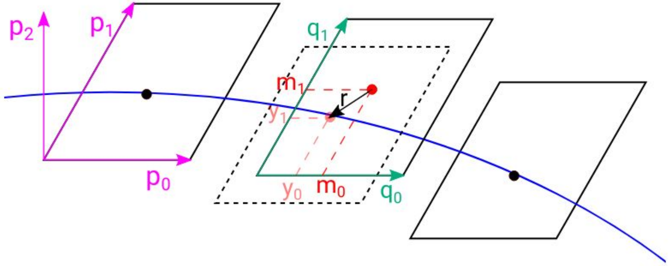


- $\sigma_{off,w}$ = 0.1 mm and $\sigma_{rot,\alpha,\beta,\gamma}$ = 10 mRad were applied in all steps.
- Efficiency of Online Event Selection is compared with Monte Carlo truths.

Track-based Alignment

- Misalignments affect the efficiency of online track reconstruction.
- Weak modes of the detector misalignment causes track-based alignment software to fit deformed tracks.
- Track-based alignment needs constraints from global parameters. Which can be provided by the camera system.
- Precise position measurement of the detector segments using camera system would provide additional information regarding the detector geometry.



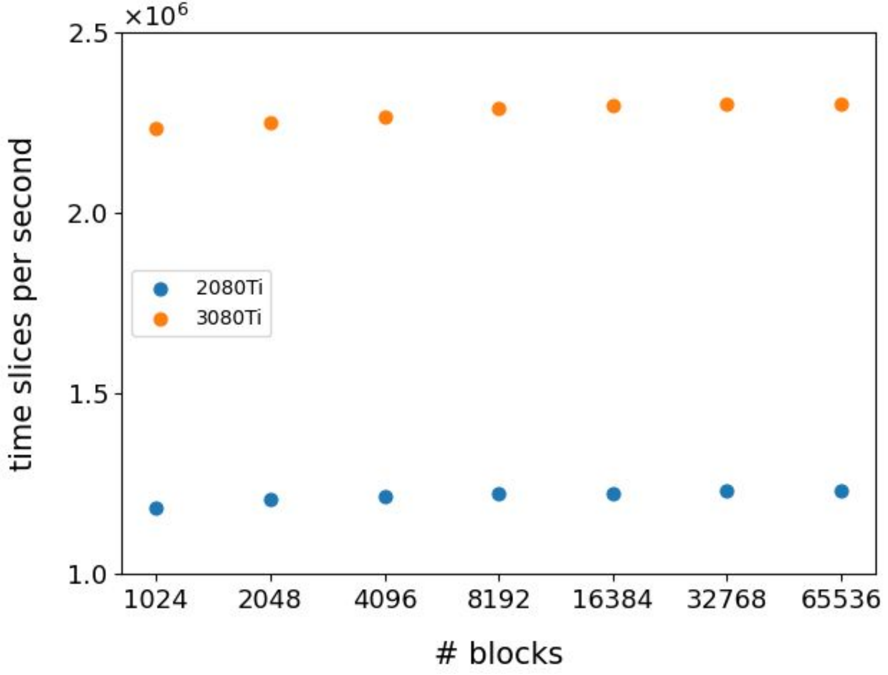


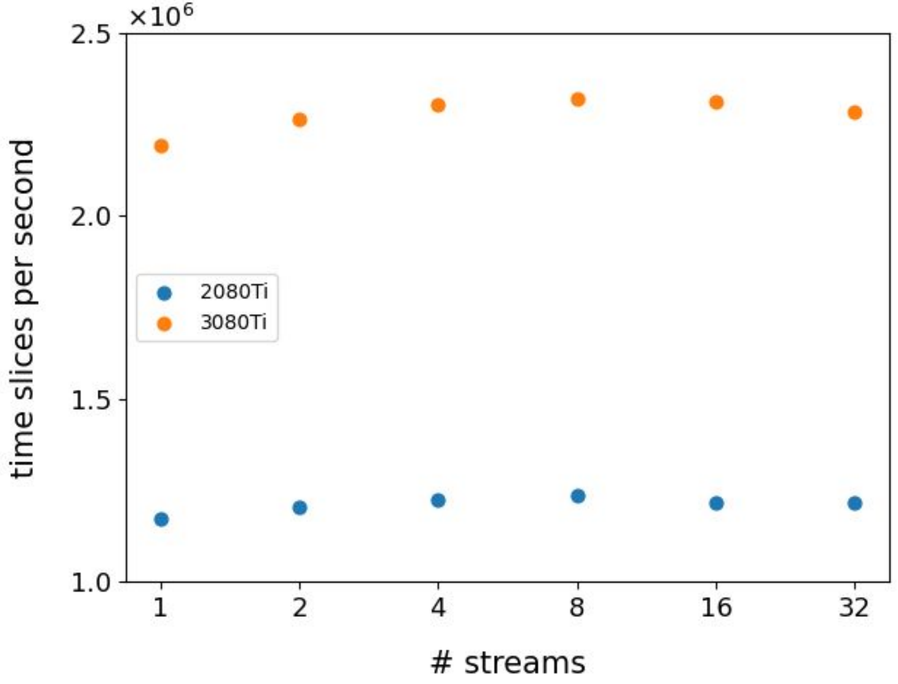
Conclusion

- Online track reconstruction achieves a peak performance of 2.3×10^6 frames per sec.
- We aim to commission the filter farm and start data acquisition by the end of this year.
- Therefore, Phase I needs just 7 GPU farms with NVIDIA Geforce RTX 3080Ti. (Will be receiving the latest RTX 4090 soon)
- Misalignment in the detector geometry greater than 100 µm significantly affects the efficiency of the online track reconstruction.
- Track-based alignment must be integrated to Online track reconstruction to overcome such limitations.

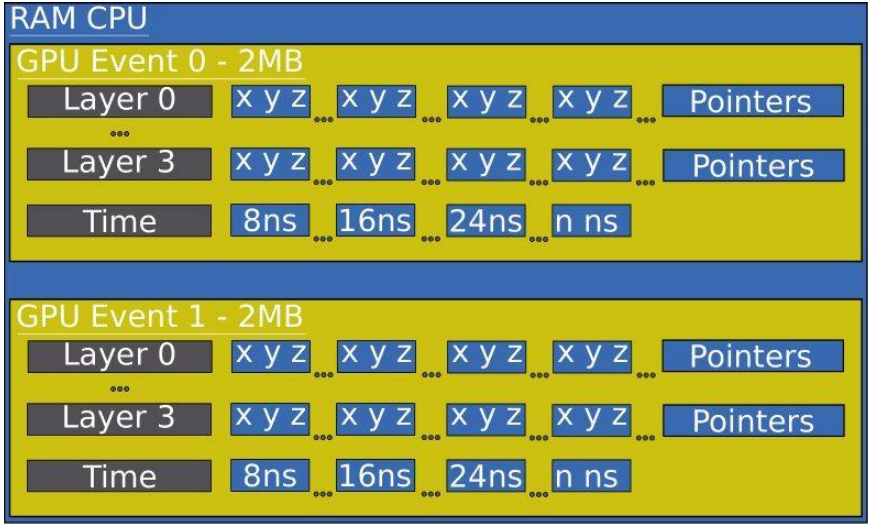
Backup

Performance





Global memory layout

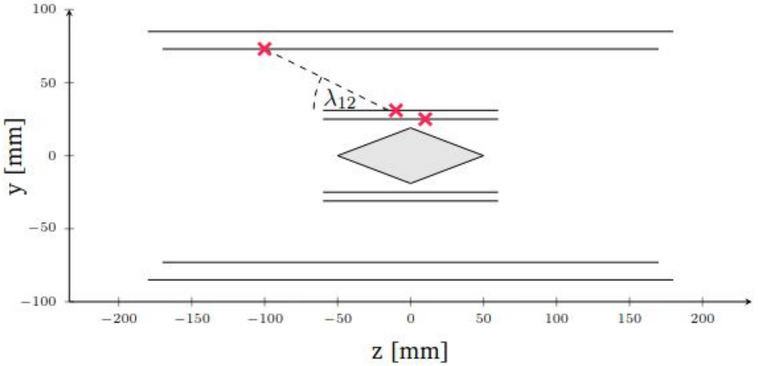


Selection Cuts

- Slope difference Δz between the slopes of consecutive layer hits in the longitudinal plane.

$$\tan \lambda_{ij} = \frac{z_j - z_i}{h_{t,j} - h_{t,i}},$$

$$\Delta\lambda = \tan \lambda_{12} - \tan \lambda_{01}.$$

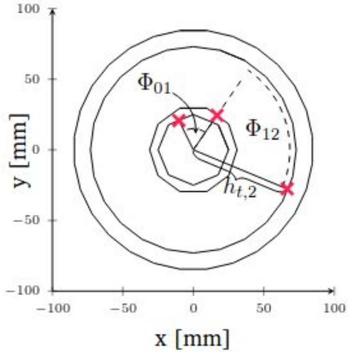


- In transverse plane we observe the angle Φ_{ij} between hits of two consecutive layers in relation the the origin:

$$\cos \Phi_{ij} = \frac{\mathbf{h}_{t,i} \cdot \mathbf{h}_{t,j}}{h_{t,i} h_{t,j}},$$

- $z_0 - z_1 < 30$ mm
- The transverse radius of the circle going through all three hits

$$r_{t,c} = \frac{d_{01} d_{12} d_{20}}{2[(\mathbf{h}_0 - \mathbf{h}_1) \times (\mathbf{h}_2 - \mathbf{h}_1)]_z},$$



Track Reconstruction

- For reconstruction Triplet fit is used.

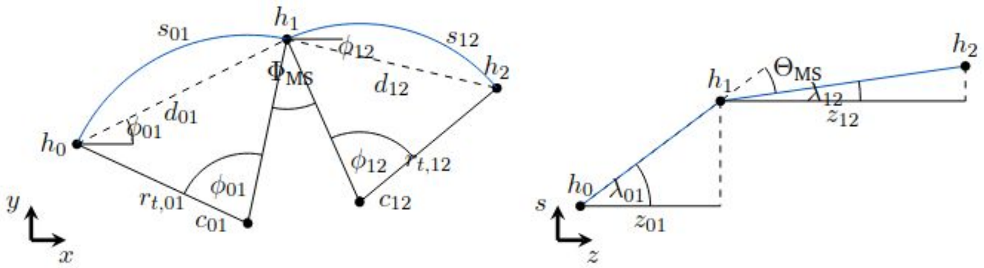
- We search for the track minimizing the objective function. Assuming no momentum loss and thus a constant curvature k.

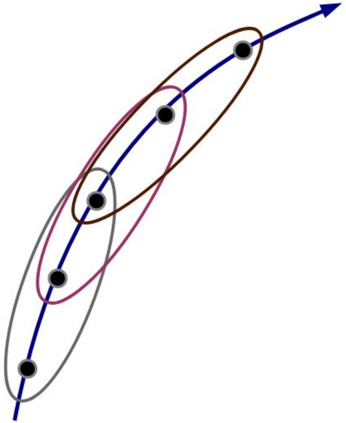
$$\chi^2(\kappa) = \frac{\Phi_{\text{MS}}(\kappa)^2}{\sigma_\Phi^2} + \frac{\Theta_{\text{MS}}(\kappa)^2}{\sigma_\Theta^2}.$$

- More than three hits for a full track fit requires to accommodate for multiple triplets.

$$\chi^2_{\text{global}}(\kappa) = \sum_t^{n_{\text{triplets}}} \chi_t^2(\kappa).$$

- A global curvature is found for all triplet combinations minimising the MS angles for each triplet.





Vertex Fit

- All combinations of two positrons and one electron are considered within each time slice. We calculate the total energy of all particles in the triplet using their curvature κ.

- The total energy of all particles, must match the muons rest energy.

- The weighted mean is calculated only if all three reconstructed tracks intersect and it is calculated for all combinations of three intersections from three tracks.

- The χ^2 for a vertex estimate is computed from the differences between the point of closest approach and the weighted mean both in the transverse plane and in the z-coordinate.