# Online Track Reconstruction and Calibration for the Mu3e Experiment

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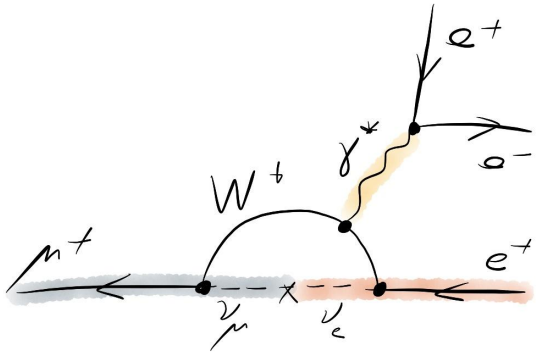
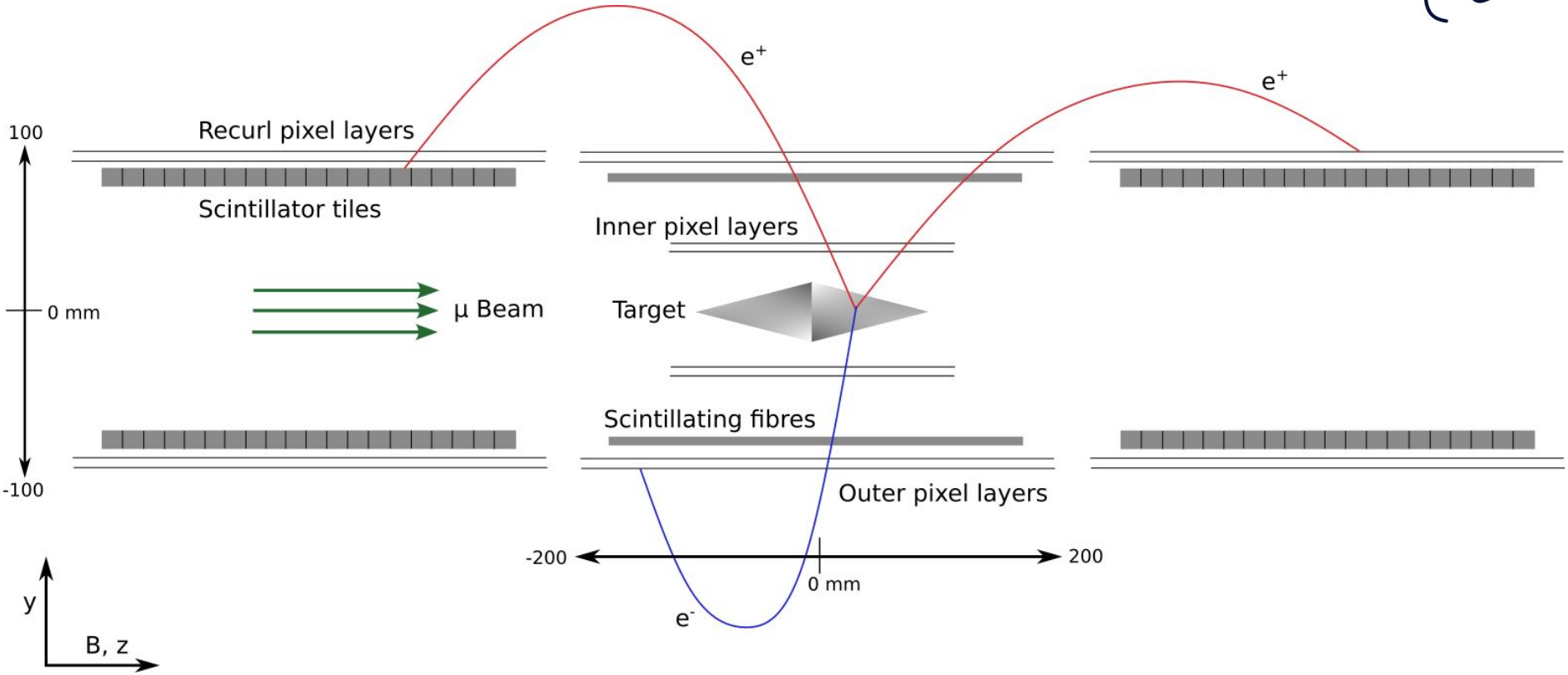
***G.A. 858199***

# Mu3e Experiment



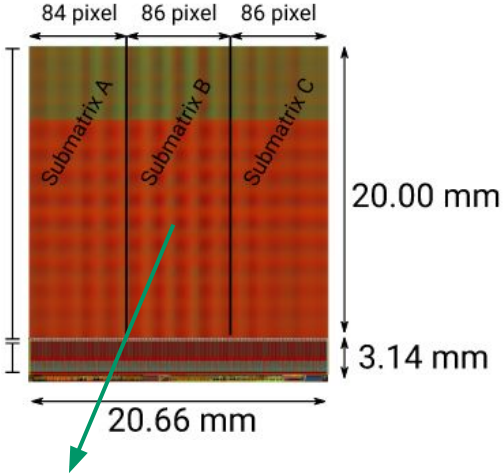

- We aim to observe or exclude the decay of a positive muon to two positrons and an electron.
- In standard model, possible via neutrino mixing but suppressed to unobservable level (Br < $10^{-54}$).
- Observation would be a violation of the lepton flavour conservation.
- SINDRUM limit the sensitivity to Br < $10^{-12}$ (1988) PSI.
- Phase I - muon rate of $1x10^{8}$ $s^{-1}$ and Br < $2x10^{-15}$.

# Mu3e Detector



# Detector Subsystems

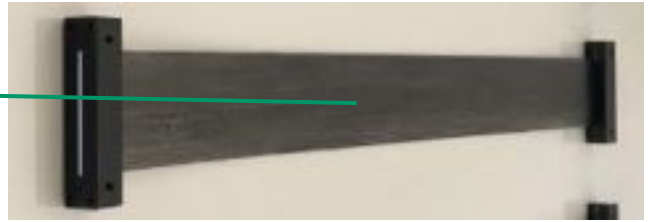
## Tracking detector

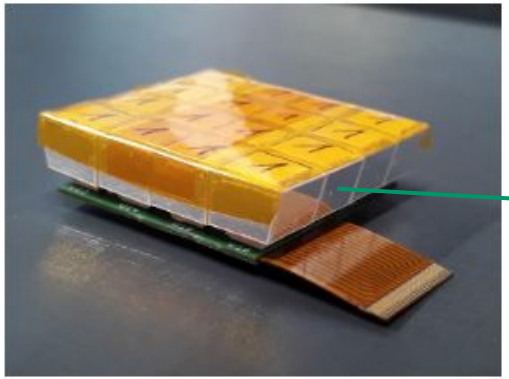



MuPIX: High Voltage Active Pixel Sensors, pixels and the detector electronics are integrated into the same chip

## Timing detector

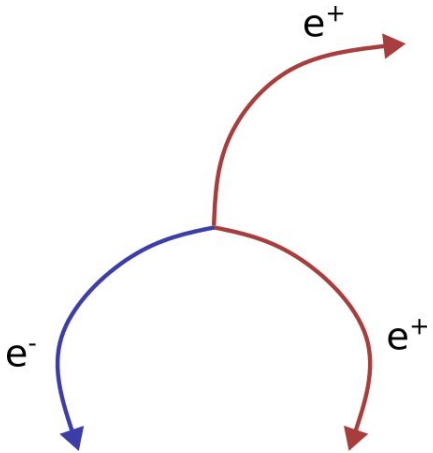
Scintillation fiber:
timing resolution is ~1 ns



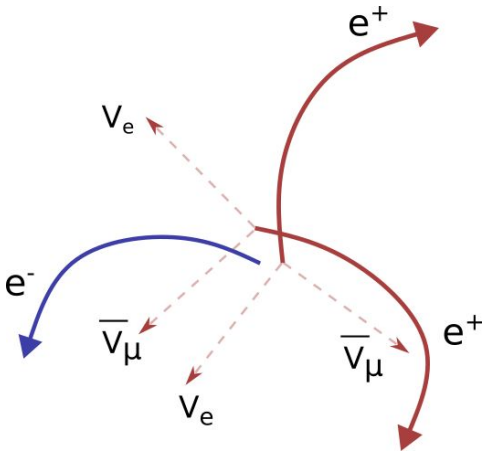


Scintillation Tiles: timing resolution about 70 ps

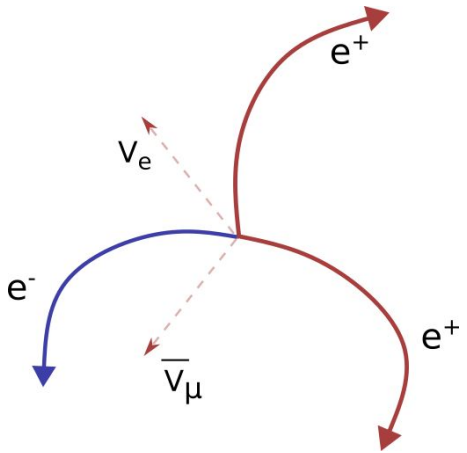
# Signal and Background processes




Signal

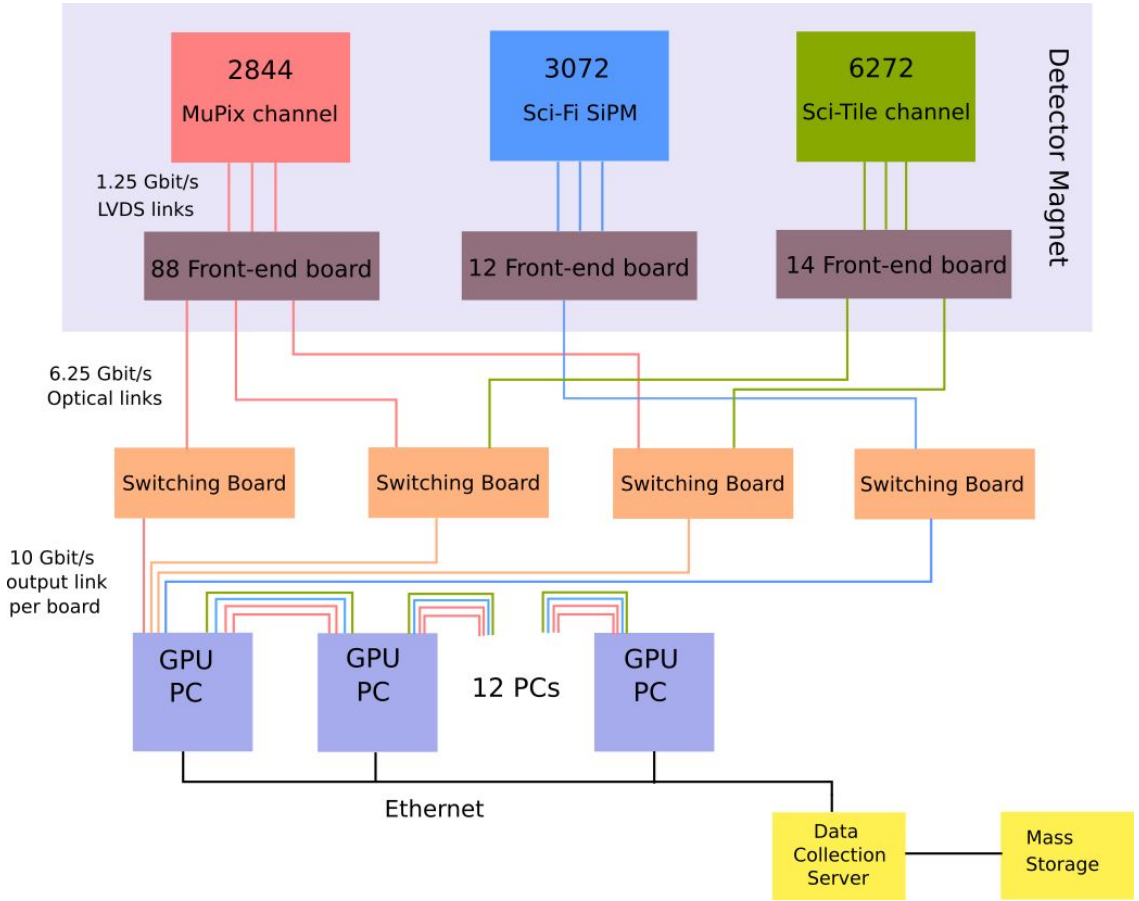



Combinatorial Background




Internal photon conversion
(Br = $3.4 \times 10^{-5}$)

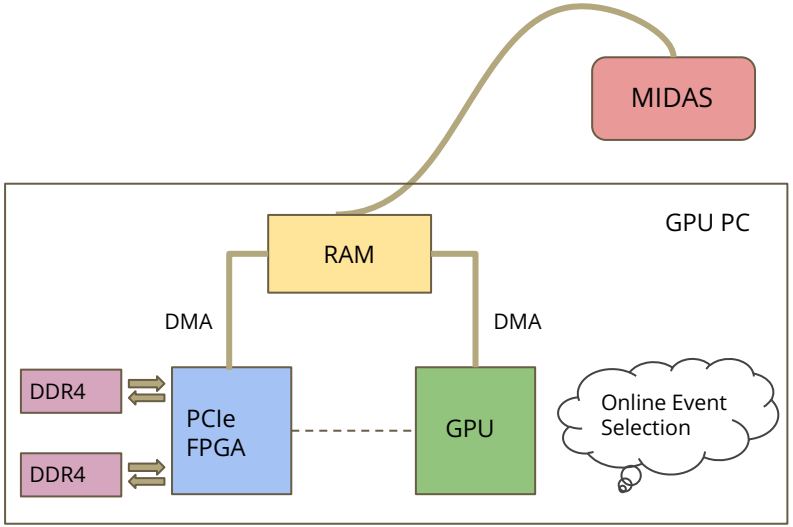
# Readout System

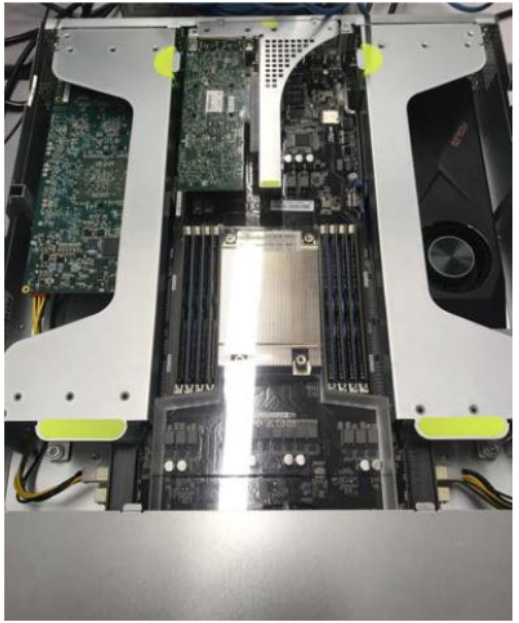



| Detector | Rate (Gbit/s) |
|---|---|
| Pixel sensors | 56 |
| Fibers | 28 |
| Tiles | 17 |
| Total | 101 |

# Filter Farm

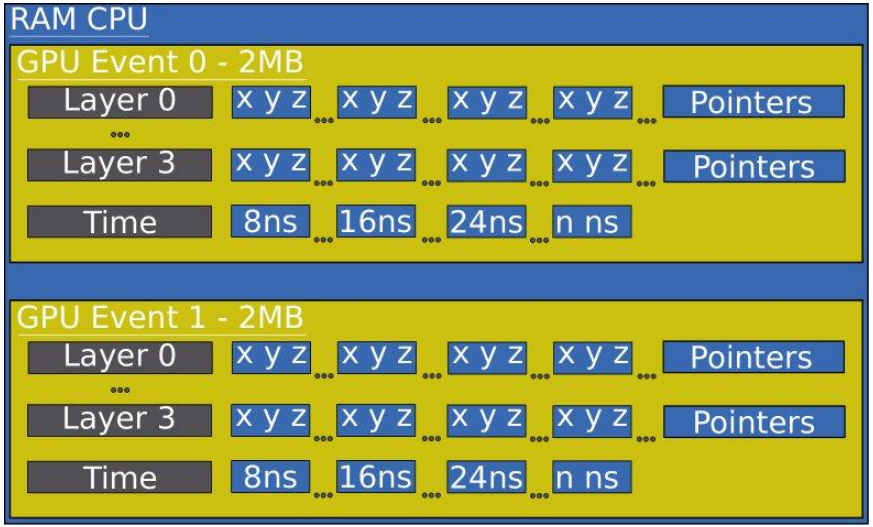
- Objective - select signal candidate events by reconstruction of tracks and vertices. To reduce data rate by a factor of 100.



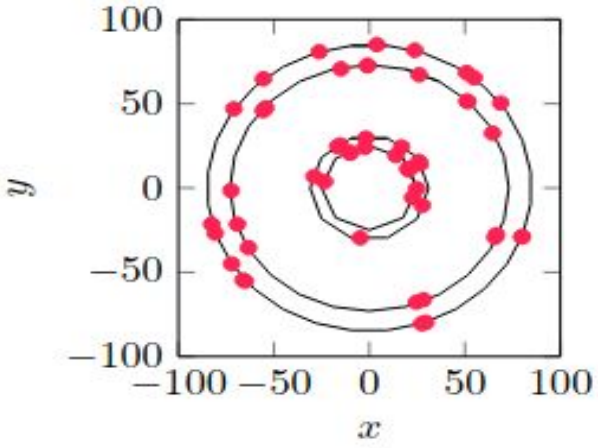
- NVIDIA GeForce RTX 3080 Ti.
- DE5a-NET FPGA card by Terasic.

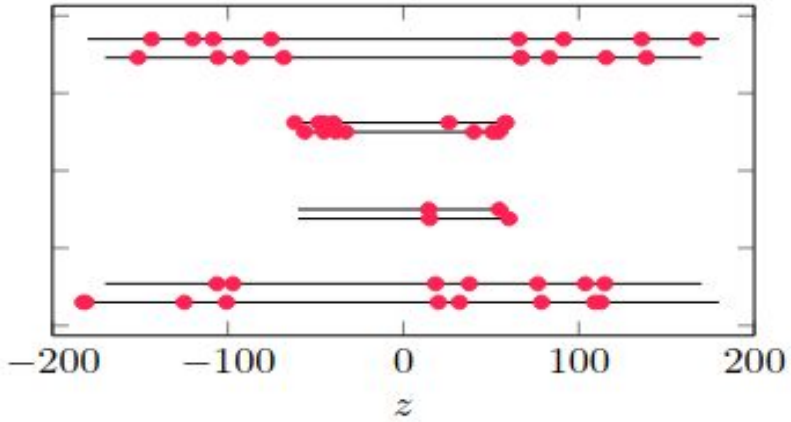
# Memory Data Layout



# Frames - Time Slices

- Each frame is a snapshot of 64ns. Needs to be discussed and finalized.
- Threshold performance - $1.5625 \times 10^7$ frames per second.

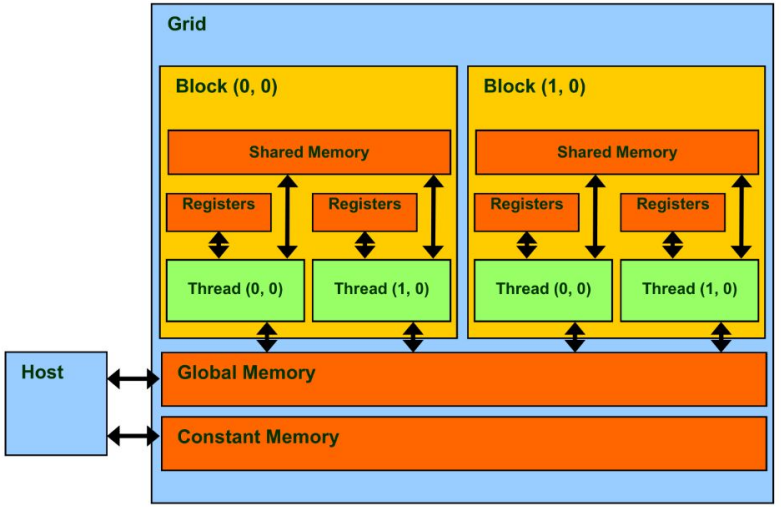


# Online Event Selection

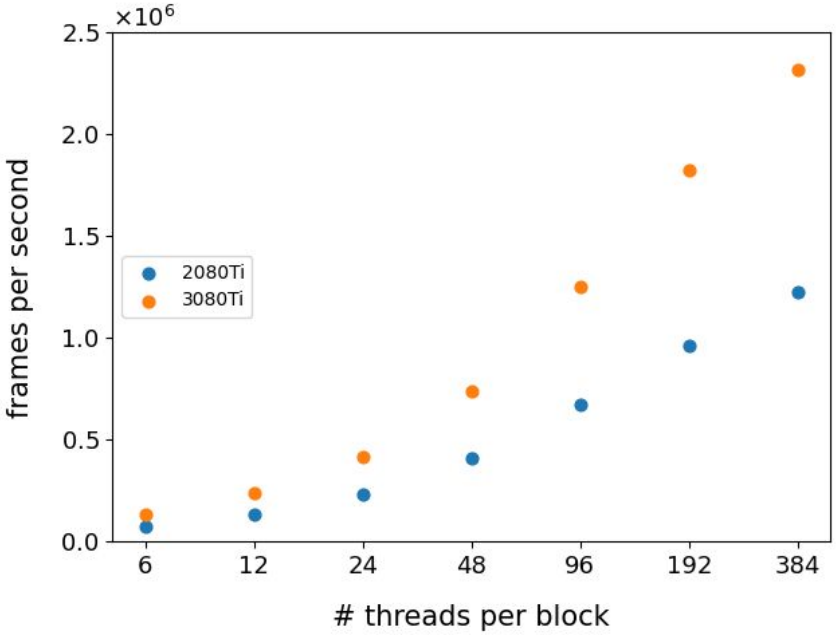
- Selection Cuts: Geometric cuts.
- Track Reconstruction: Hit triplet-based reconstruction.
- Vertex Selection: Reconstruction of possible event vertices.

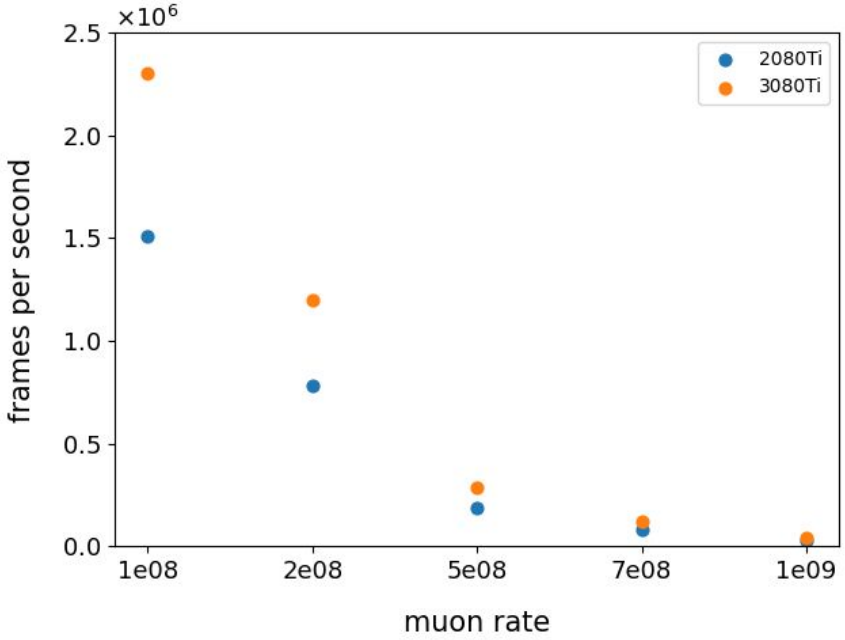
# Parallel computing on GPU

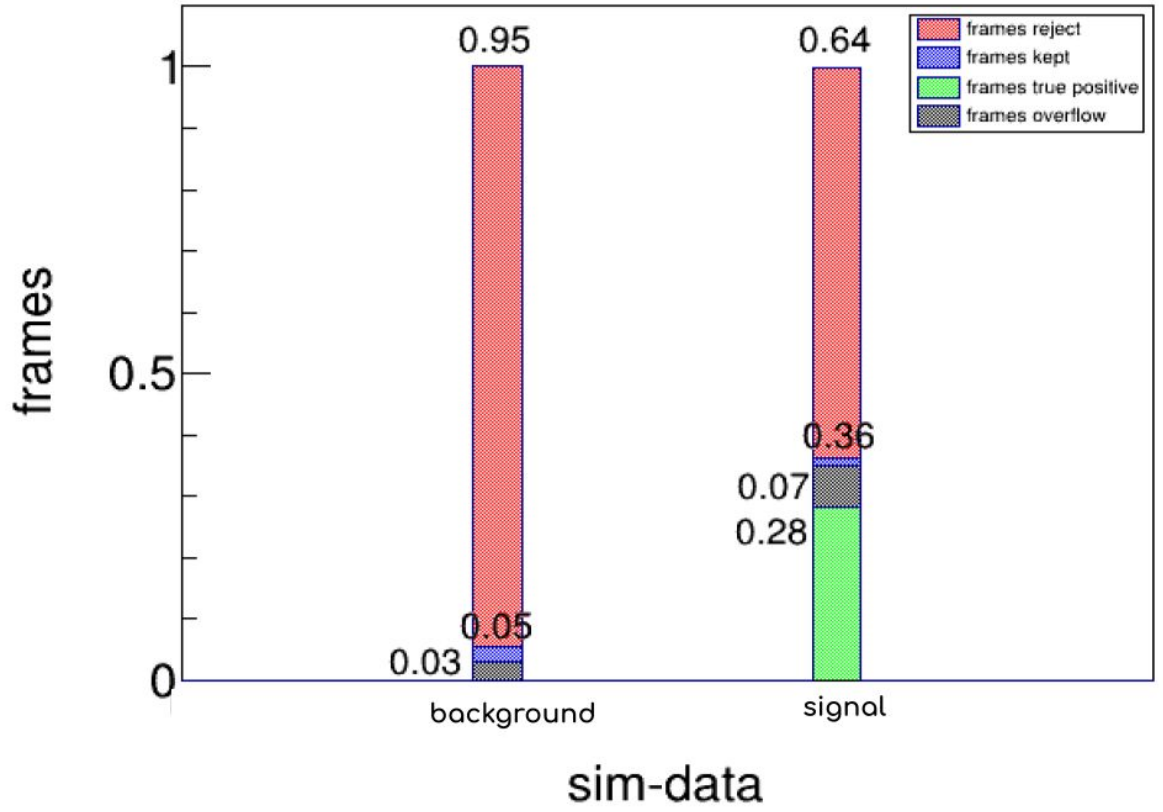

- Each SM consists of 64 CUDA cores in 2080Ti and 128 CUDA cores in 3080Ti.
- Warps of 32 threads execute at once in streaming multiprocessors (SM)

# Performance



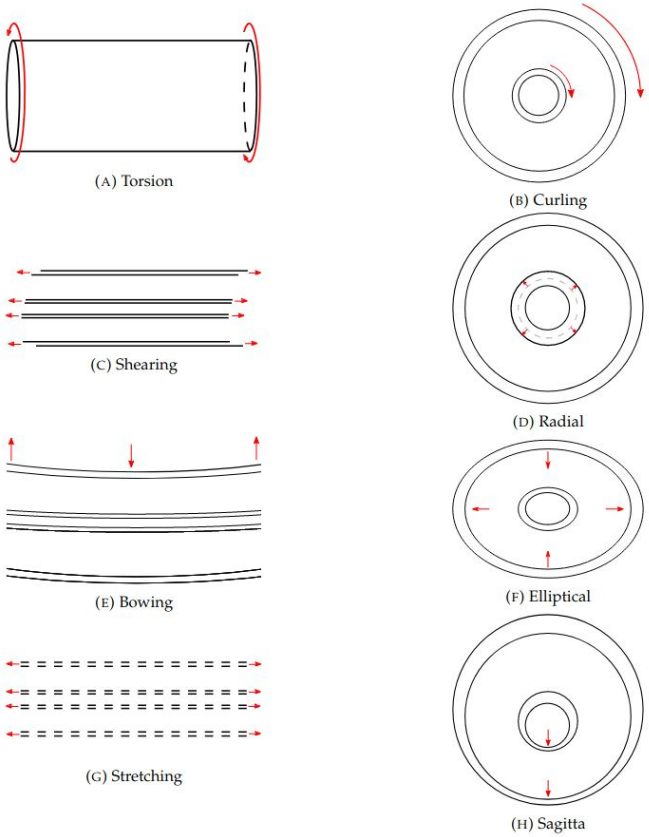



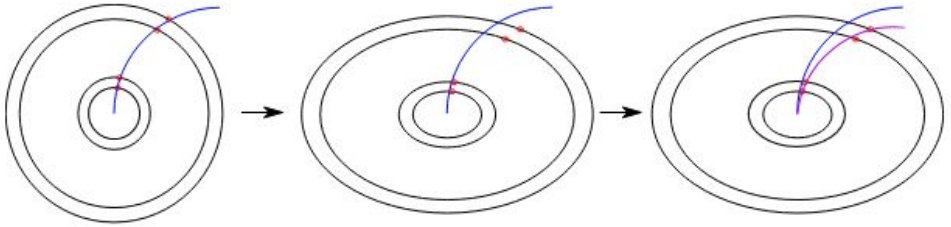
# Efficiency


frames reject
frames kept
frames true positive
frames overflow
0.95
0.64
0.36
0.07
0.28
0.05
0.03
1
0.5
0
frames
background
signal
sim-data

# Camera System for Calibration

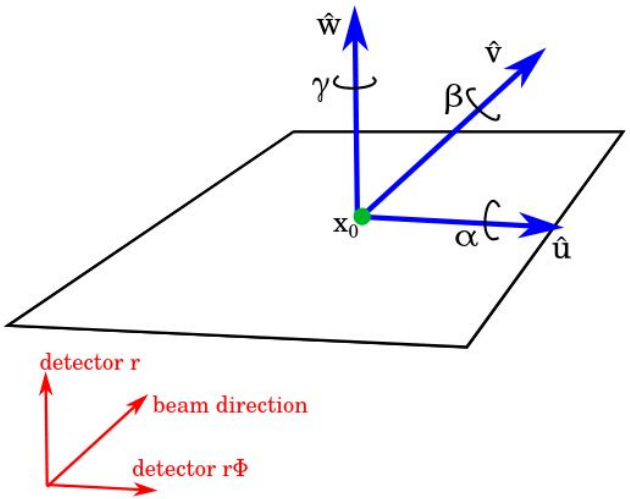
# Weak Modes



- In blue, the true track is depicted.
- If the barrel is deformed elliptically, the blue track will have a worse $\chi^2$ than without the deformation.
- Purple track can be reconstructed with the same $\chi^2$ as the original blue one.

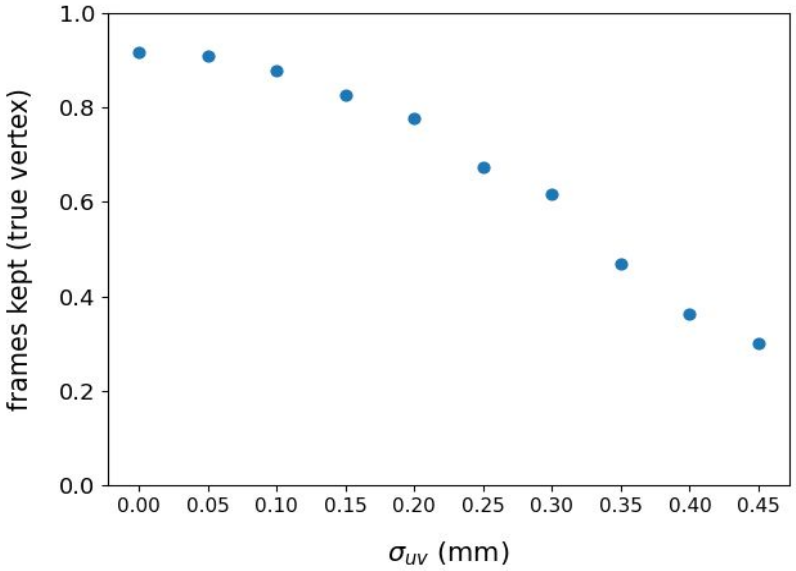
# Misalignment

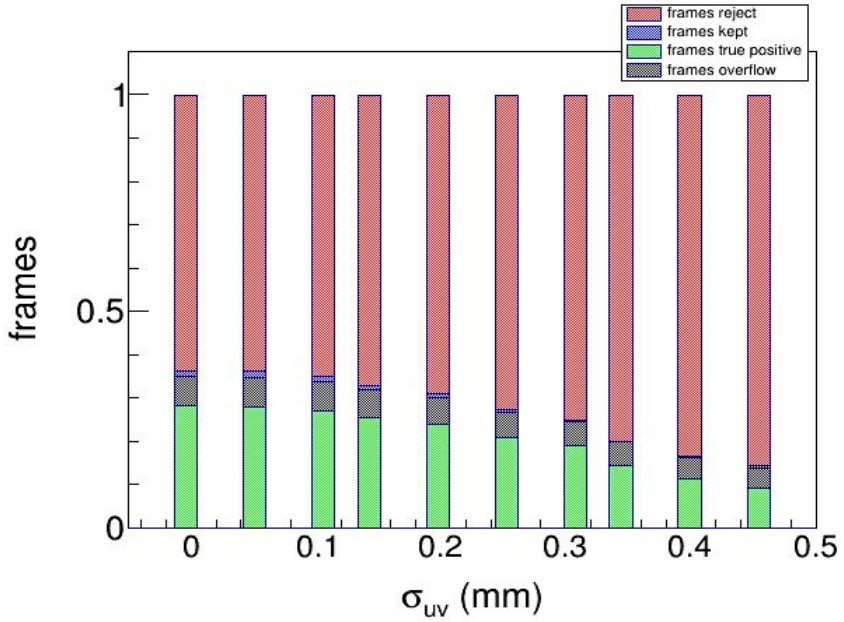



| $\sigma_{off,\ u,v}$ (mm) | $\sigma_{rot,\ \alpha,\beta}$ (mm) | $\sigma_{off,\ w}$ (mm) | $\sigma_{rot,\ \gamma}$ (mm) |
|---|---|---|---|
| 0.05 (0.45) | 5 (10) | 0.005 (0.1) | 5 (10) |

- Deviations of more than 400 μm corresponding to 5 times the pixel pitch (pixel-size) are expected.

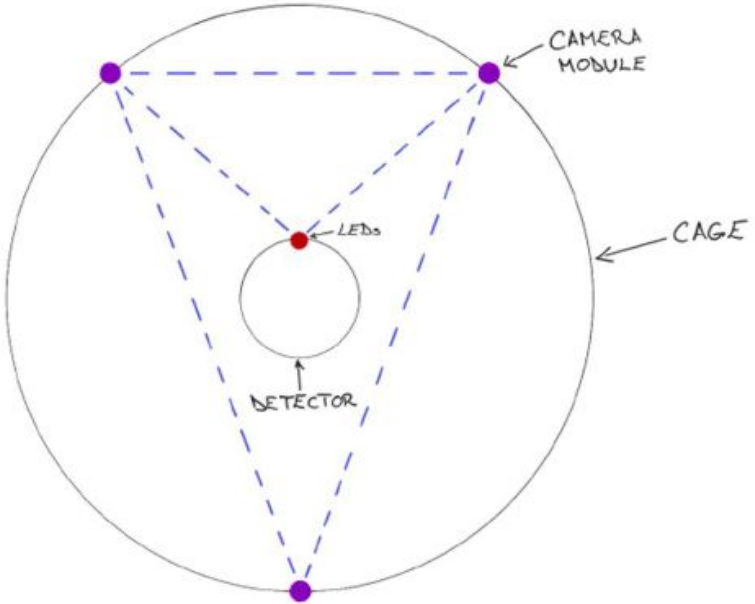
# Online Efficiency

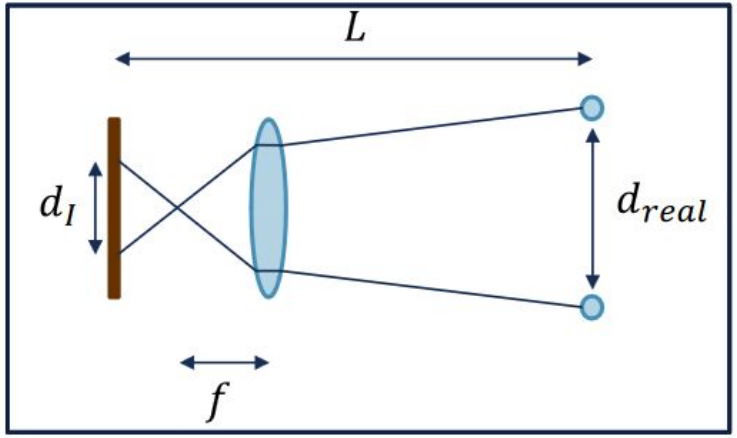



- $\sigma_{off,w}$ = 0.1 mm and $\sigma_{rot,\alpha,\beta,\gamma}$ = 10 mRad were applied in all steps.
- Efficiency of Online Event Selection is compared with Monte Carlo truths.

# Camera System

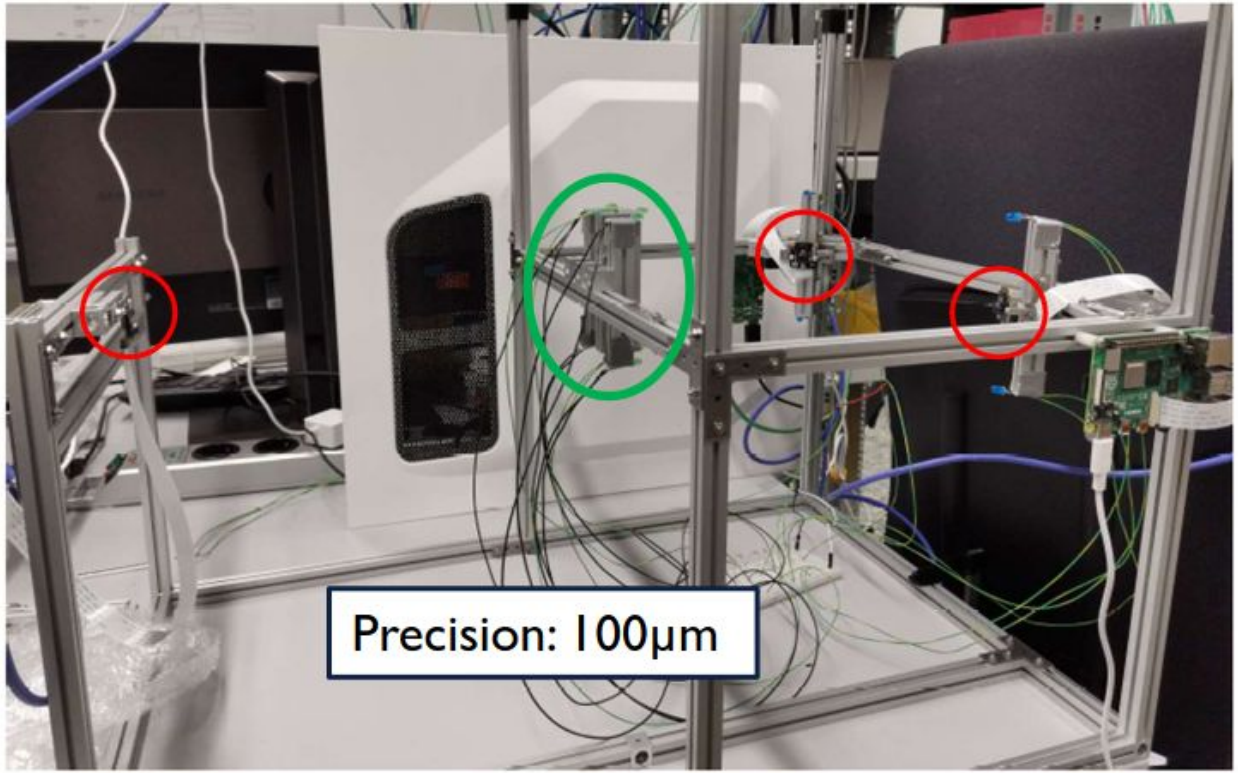



$$\frac{d_I}{d_{real}} = M = \frac{f}{f - L}$$

# Lab setup

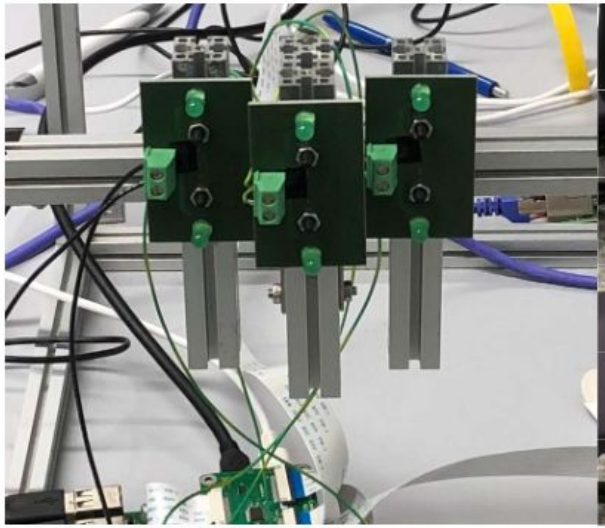
Main Camera

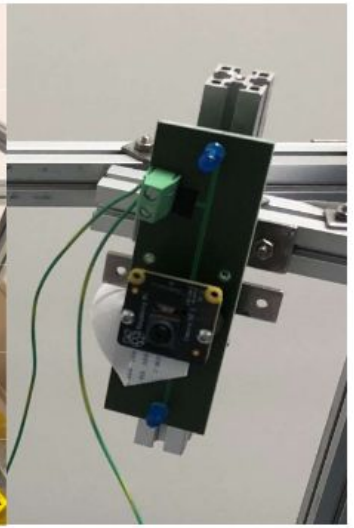


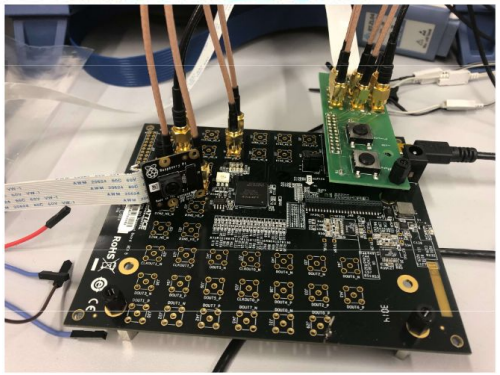

2 cameras with LED’s

LED’s on the detector

# Updation







- **MachXO3L DSI breakout board.**
- **Adapter card.**

# Tooling balls

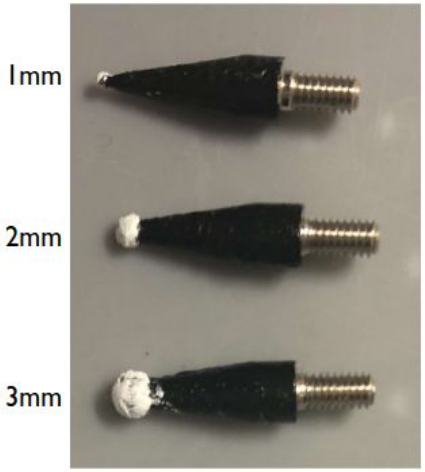
3 sizes tested

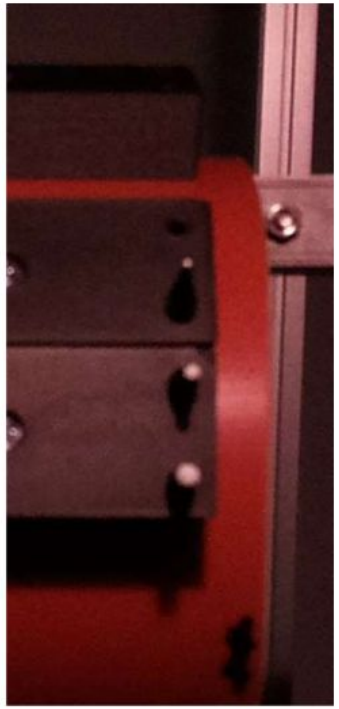

Double reflections due to 2 light sources

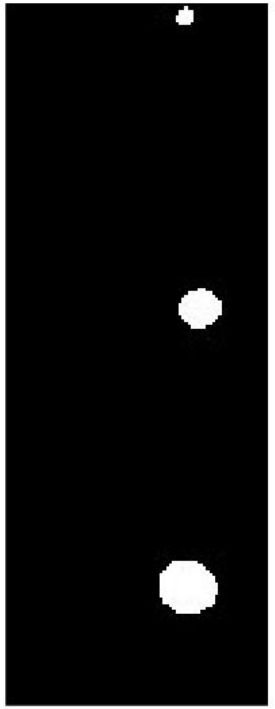
Diffuse reflection

# Tooling balls

3 sizes tested



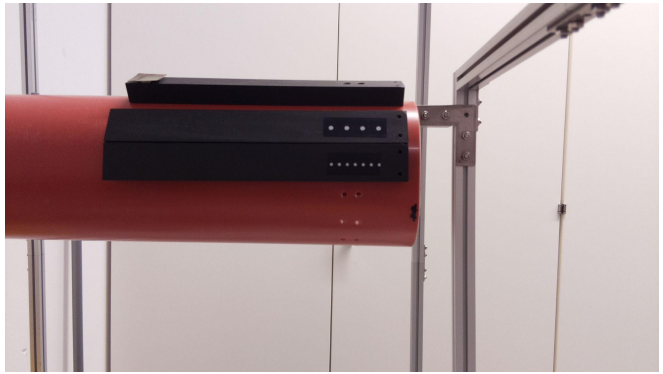



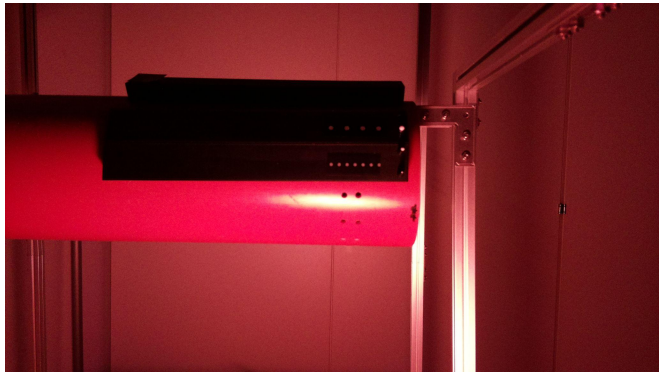


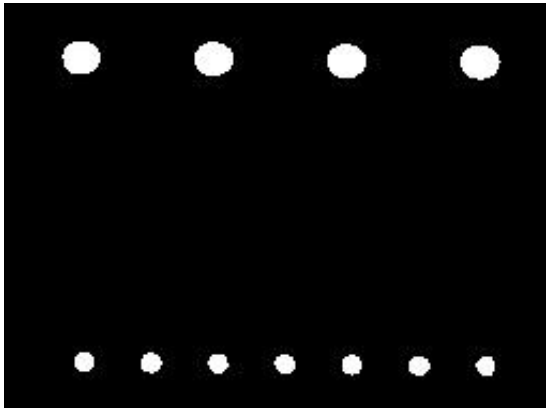
**Estimated distance from camera:**

**410.483 mm**

# Reflective Strips





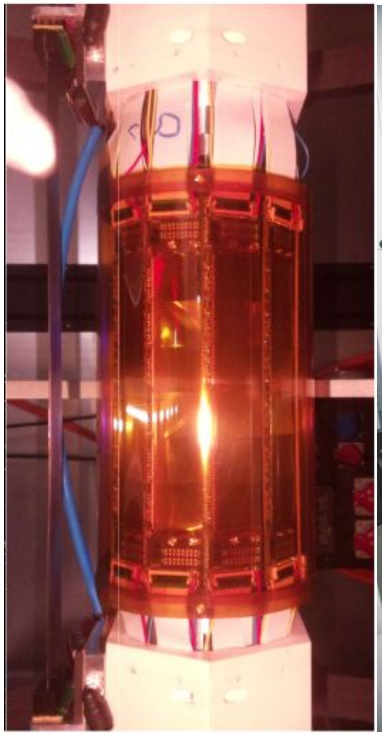


- Reflective tapes are visible and is a better option over tooling balls since they lay flat on the surface of the detector.

- Can see the contrast difference between tapes and tooling balls.

# Conclusion

- Implement new data memory layout for to load frames for the online reconstruction.
- Merge the online software to the MIDAS frontend.
- Use MIDAS frontend to view online histograms for QA.
- Develop Online Track Alignment for GPU selection.
- Use Camera Calibration inputs for the Online Track Alignment.
- Need to finalize the decision on reflective tapes.



# PhD Requirements:

- Completed the teaching assistantship of Advanced Practical course on Balmer series for the mandatory three semesters.

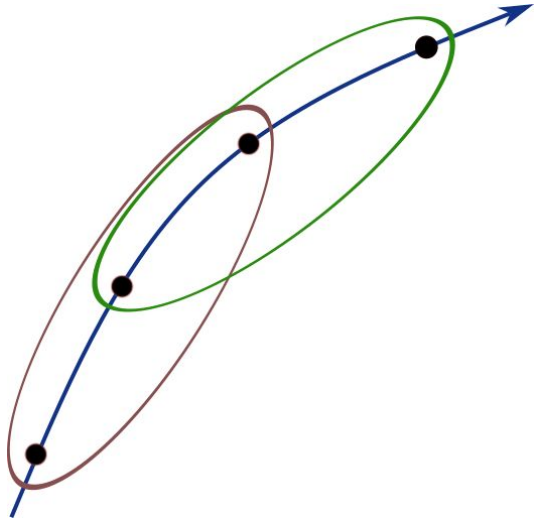
# Workshops and Conferences

- “Mu3e Collaboration Meeting”, (Villigen, April 28-29, 2022) workshop held at Paul Scherrer Institute;
- “EPT Summer Camp for Physics TAs”, (Zuoz, August 12-14, 2022) engaging physics tutoring summer camp organised by ETH Zürich;
- “Paul Scherrer Institute Particle Physics Summer School – Vision and Precision”, (Zuoz, August 14-20, 2022) lectures and talks organised by Paul Scherrer Institute.
- “PRISMA+ Cluster of Excellence” (Geisenheim, September 19-21, 2022) gave a talk about my dissertation.
- “DPG Conference”, (Dreden, March 20-24, 2023) held and organized by Deutsche Physikalische Gesellschaft e.V.; gave a talk.
- “Mu3e Collaboration Meeting”, (Wengen, March 28-31, 2023) presented works.

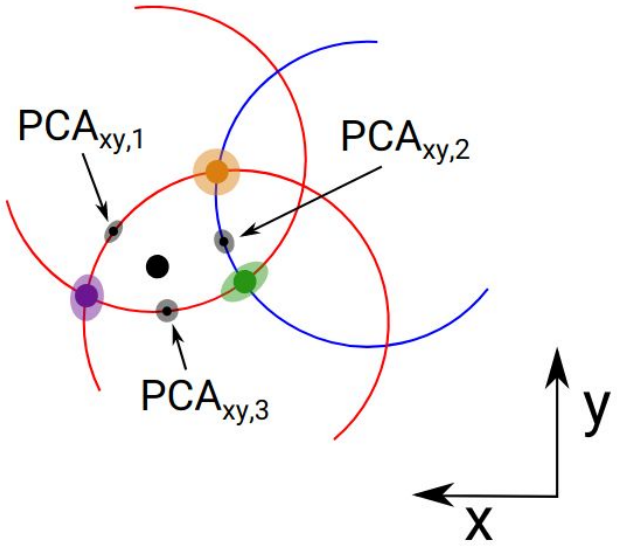
# Backup

# 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 find the track parameters.

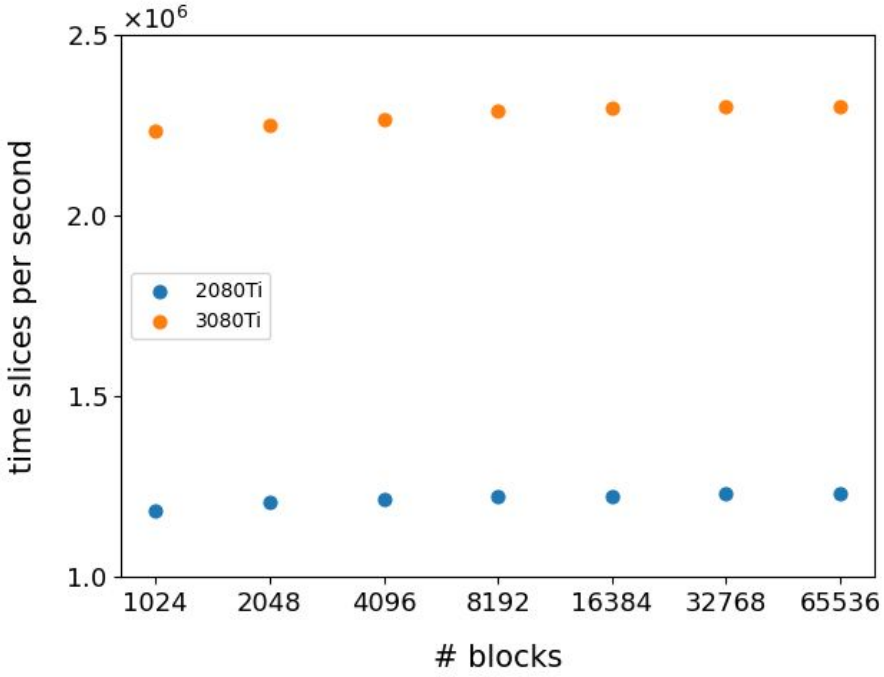


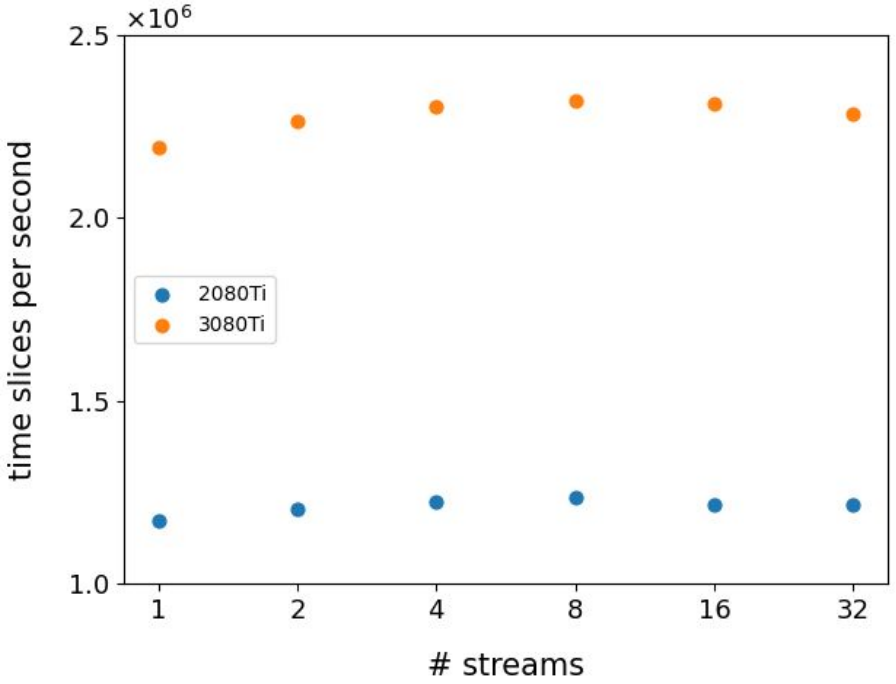
# Vertex Selection




- 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.
- Time slices with signal vertices are kept.

# Performance



# Selection Cuts

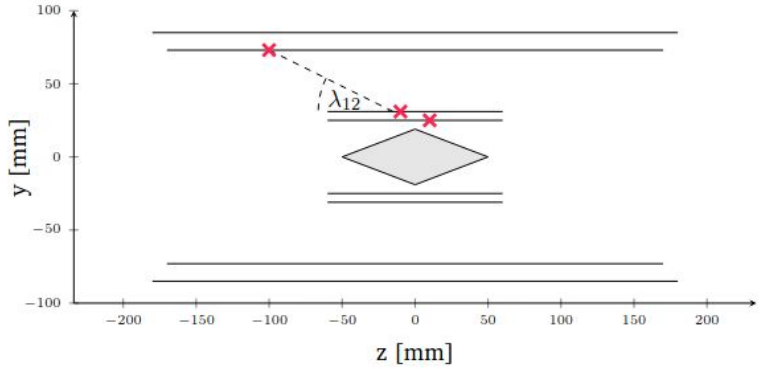
- Slope difference Δz between the slopes of consecutive layer hits in the longitudinal plane.

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

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

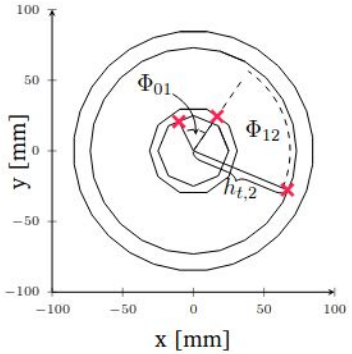
- In transverse plane we observe the angle $\Phi_{ij}$ between hits of two consecutive layers in relation the the origin:

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




- $z_0$ - $z_1$ < 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

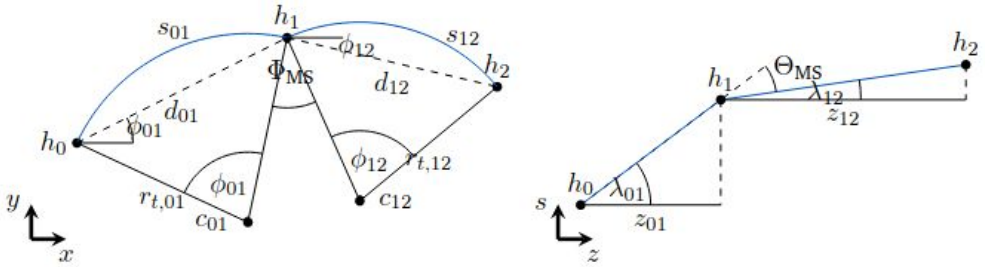
- For reconstruction Triplet fit is used.
- We search for the track minimizing the objective function. Assuming no momentum loss and thus a constant curvature k.

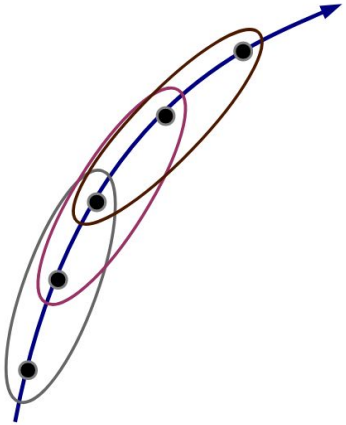
$$\chi^2(\kappa) = \frac{\Phi_{\mathrm{MS}}(\kappa)^2}{\sigma_\Phi^2} + \frac{\Theta_{\mathrm{MS}}(\kappa)^2}{\sigma_\Theta^2}.$$

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

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

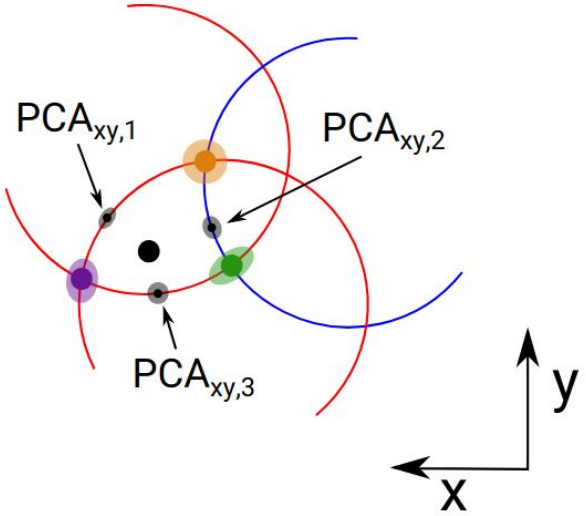
- A global curvature is found for all triplet combinations minimising the MS angles for each triplet.



# Vertex Fit

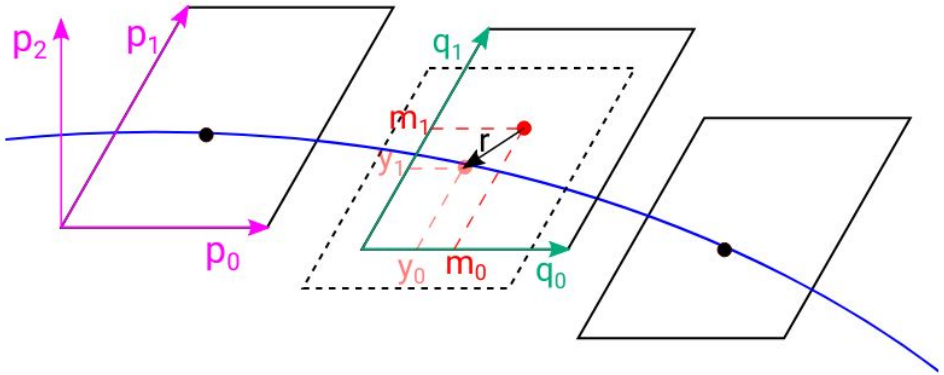
- All combinations of two positrons and one electron are considered within each time slice. We calculate the total energy of all particles in the triplet using their curvature κ.
- The total energy of all particles, must match the muons rest energy.
- The weighted mean is calculated only if all three reconstructed tracks intersect and it is calculated for all combinations of three intersections from three tracks.
- The $\chi^2$ 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.



# Track-based Alignment

$$r_{ij} = m_{ij} - f(\boldsymbol{q}_j, \boldsymbol{p})$$

$$\chi^2(\boldsymbol{q}_j, \boldsymbol{p}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\text{hits}} \left( \frac{r_{ij}}{\sigma_{ij}} \right)^2$$




- We get residuals after fitting individual particle tracks with an adequate track model.
- From these residuals, one can derive geometry corrections.
- These track fits however assume a fixed set of global parameters. As a result, the obtained residuals will be biased in case of shifts in global parameters.