# Machine learning for track reconstruction using ACTS

Corentin Allaire
on behalf of
the Acts ML community

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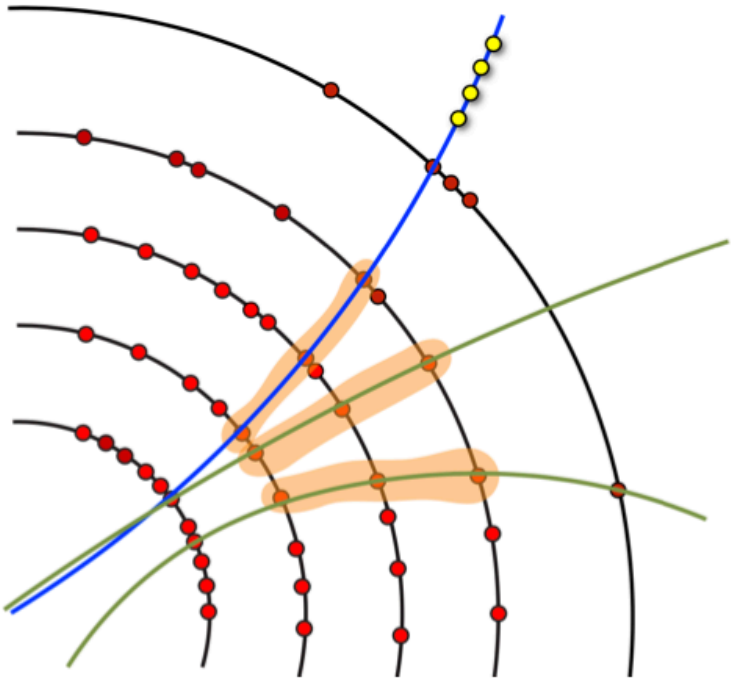
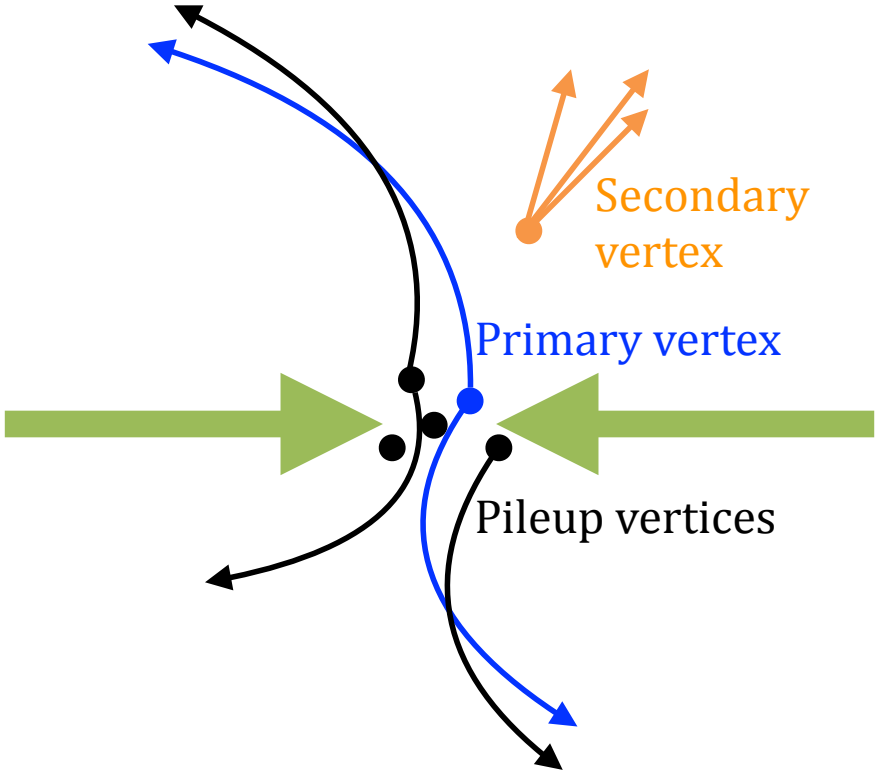
# Track Reconstruction

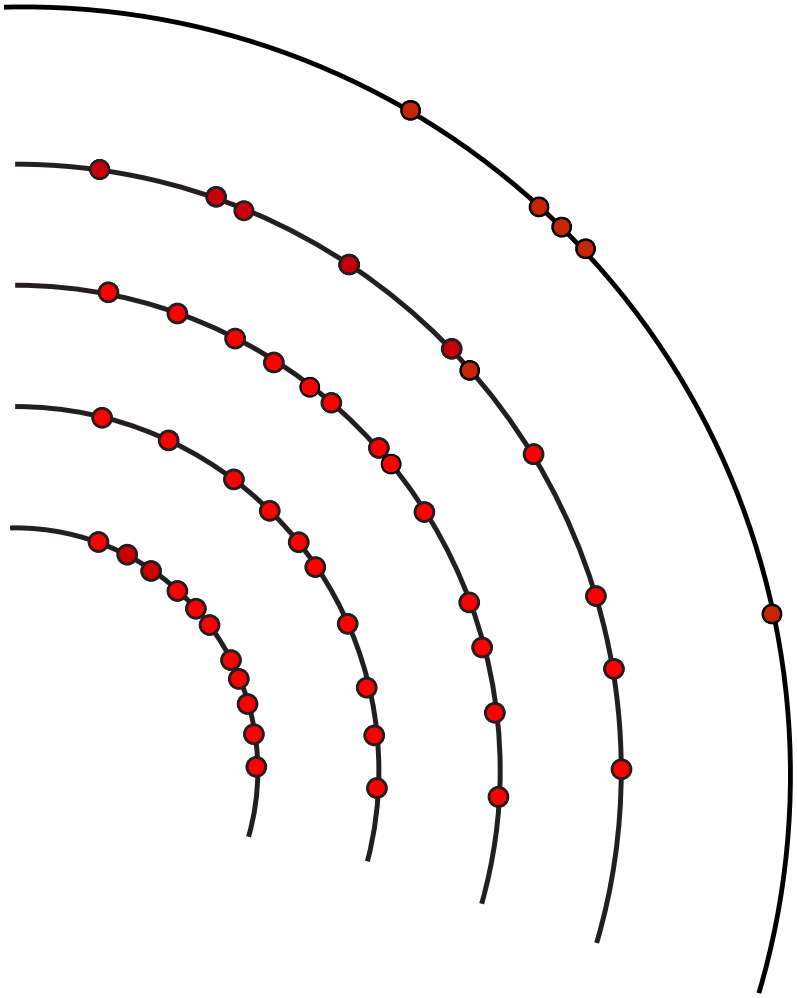





- Reconstruct the trajectory of (charged) particles in detectors based on the hits in the sensors
- Extract track parameters from their reconstructed trajectory
- Reconstruct the interaction vertices

# Track Reconstruction

Space point formation
Clustering



- Hits in the detector are collected to create measurement (space) points

# Track Reconstruction

Space point formation
Clustering

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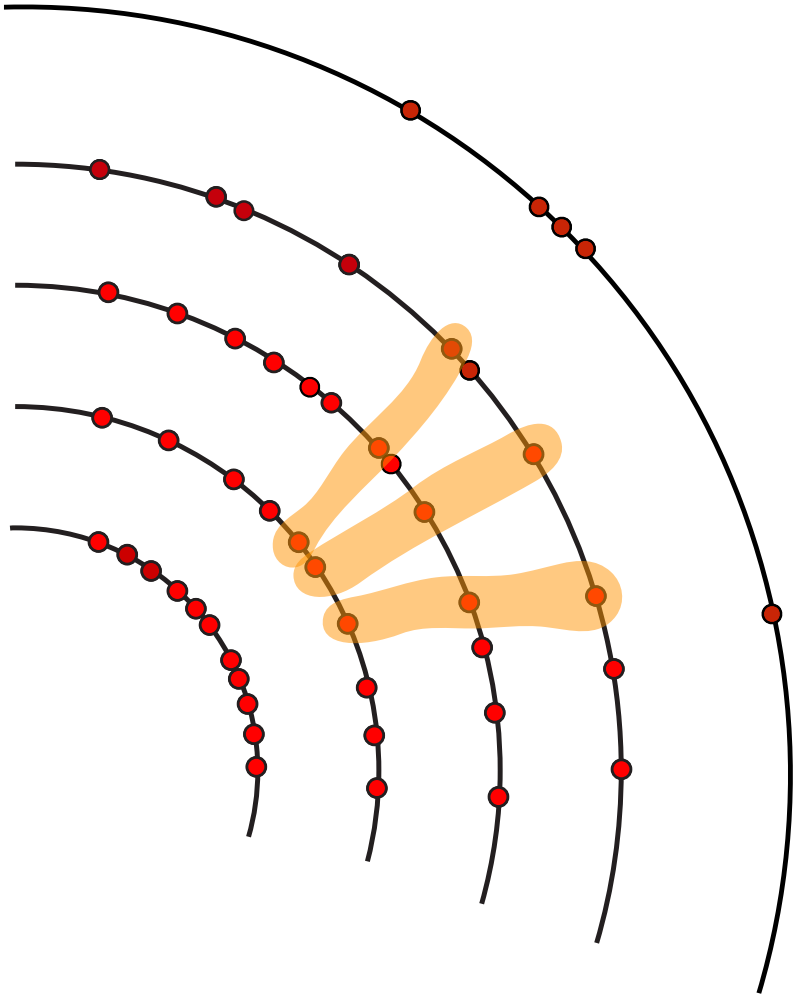
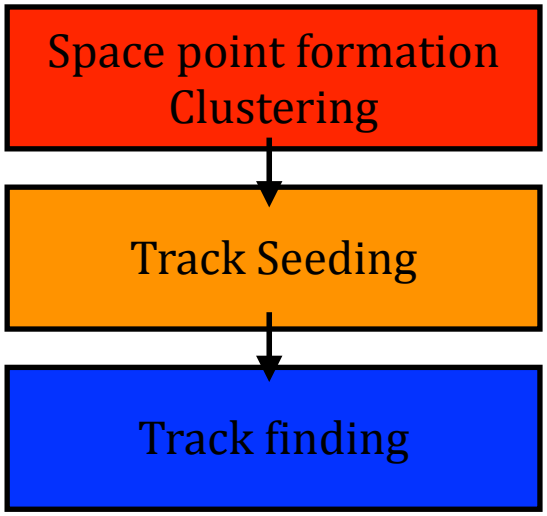
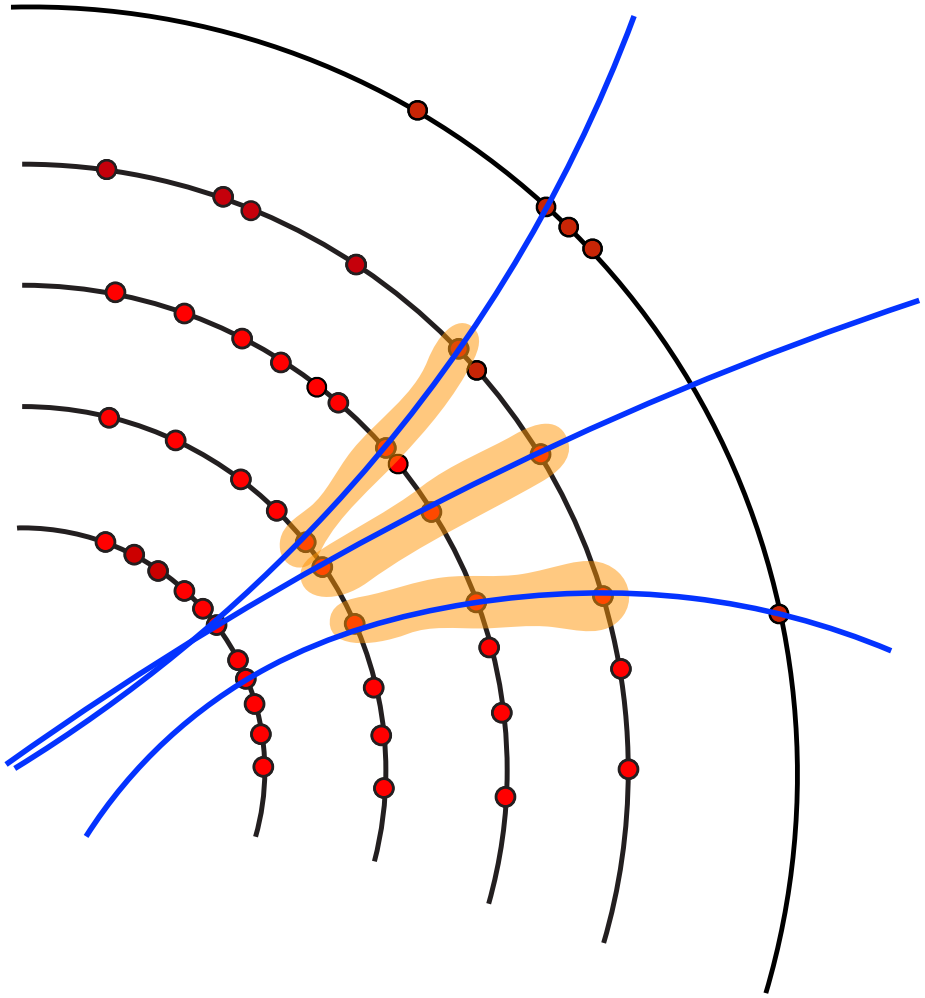
Track Seeding



- **Seeds** are groups of **three measurements** compatible with basic track hypothesis
- Will be extended to create the tracks candidate

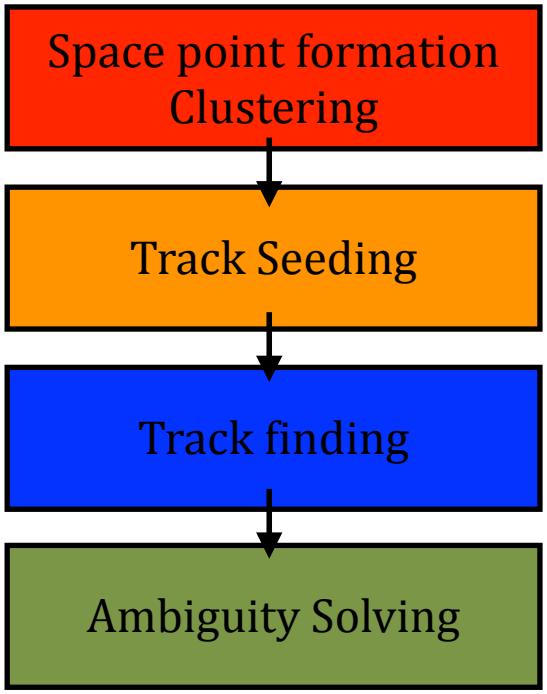
# Track Reconstruction

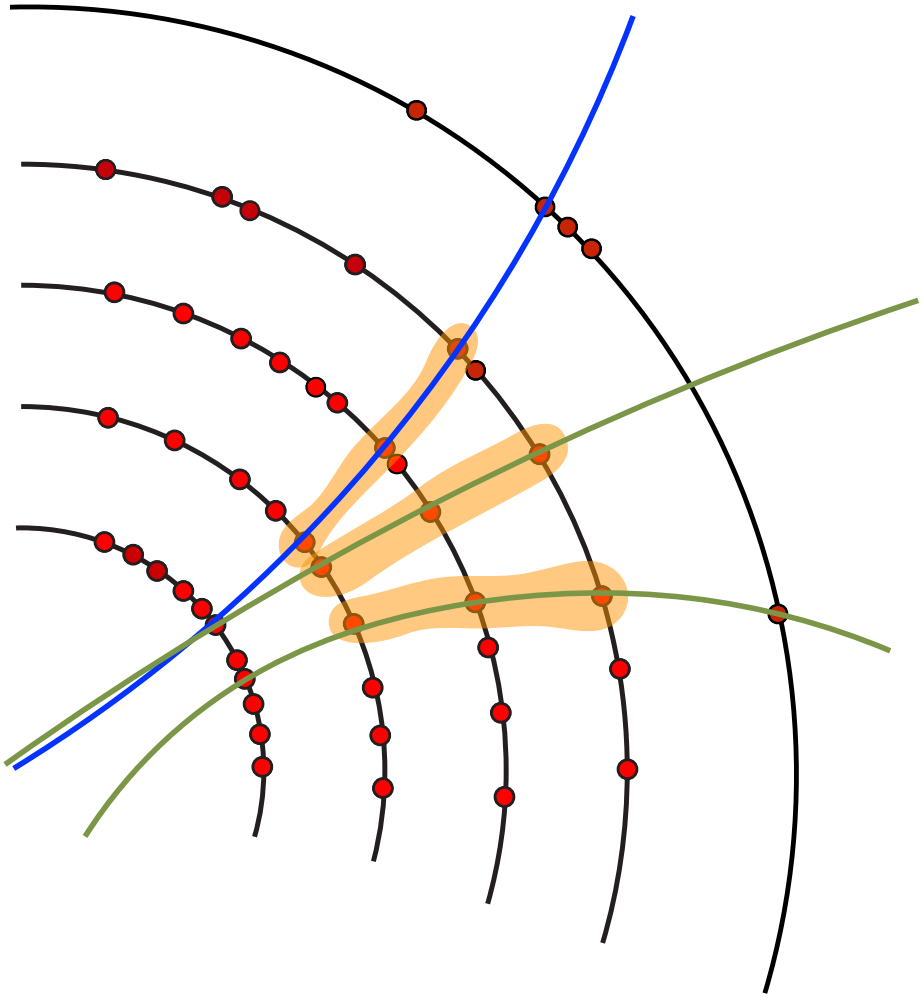


- A combinatorial Kalman filter is then used to build track candidates from the seed
- Compatible measurement are added to the track seed
- More than one **track candidate** can be built from a seed if multiple paths are possible

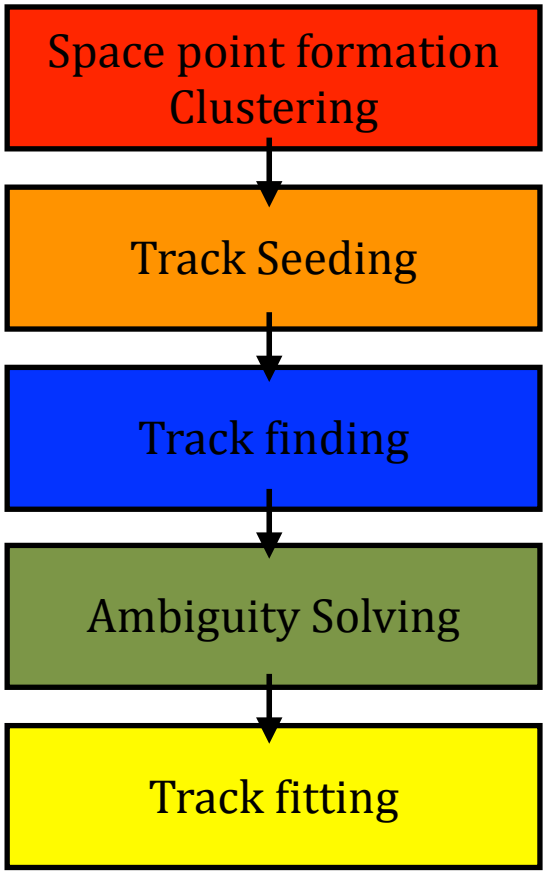
# Track Reconstruction

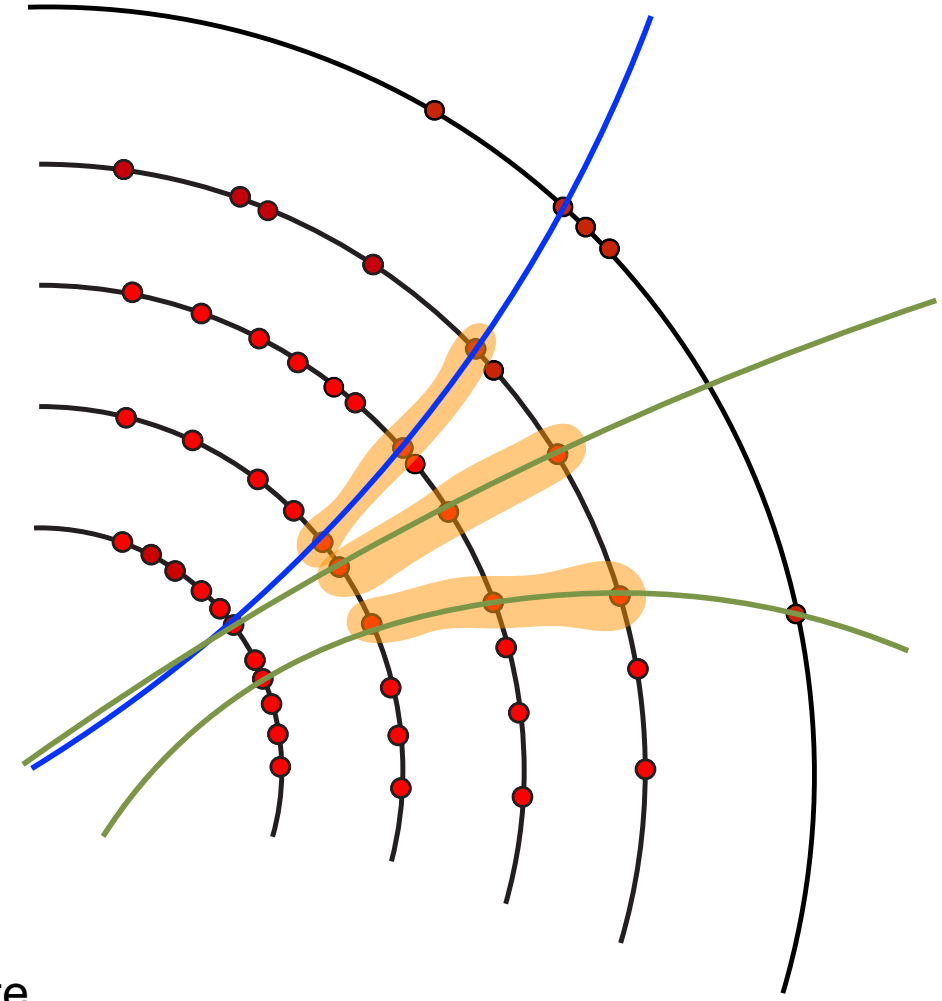


- A score is then associated to each track candidate
- To resolve ambiguity the reconstructed track are kept in descending order of a track score

# Track Reconstruction



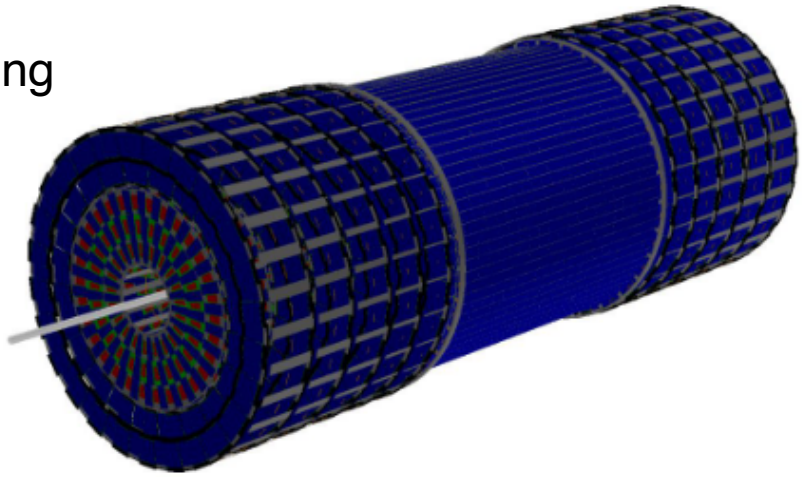
- The tracks are **fitted** using the full detector geometry and the appropriate material -> track parameters

# Acts : A Common Tracking Software

- Open source tracking software : https://github.com/acts-project/acts
- Experiment independent toolkit :
  - ATLAS
  - ALICE
  - BVG
  - FASER
  - LDMX
  - sPHENIX
  - ePIC (EIC)
  - …
- Developed with modern C++
- Features :
  - Tracking geometry description
  - Simple event data model
  - Most track reconstruction algorithms
  - Example framework with python bindings
  - Performance evaluation algorithms

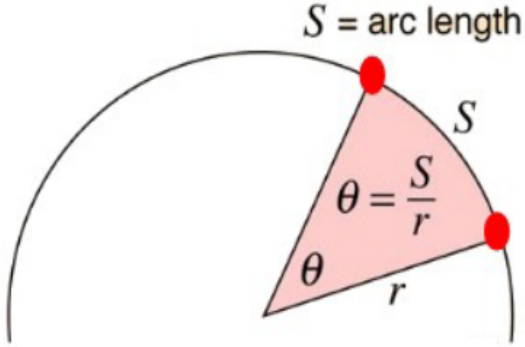
# Acts : A Common Tracking Software

- Provides a testing environment for new tracking algorithms
- Open Data Detector (ODD) :
  - Virtual detector implemented for testing purposes
  - Based on the Track ML challenge
  - Full silicon design (similar to ATLAS ITk)
- Offers a full tracking chain -> Used to evaluate the performances of our algorithms
- Great environment for developing and testing new machine learning based tracking algorithm



# Hashing for hits selection

- Track finding : Combinatorial problem -> scales quadratically with the pileup (PU)
- Hashing : perform the reconstruction on subsets of hits (buckets) -> reduce the PU dependency
- Buckets created using Approximate nearest neighbours search (Annoy)
- For a given metric, return the nearest neighbours
- Metric : angular distances
- Other metric possible : Metric learning ?

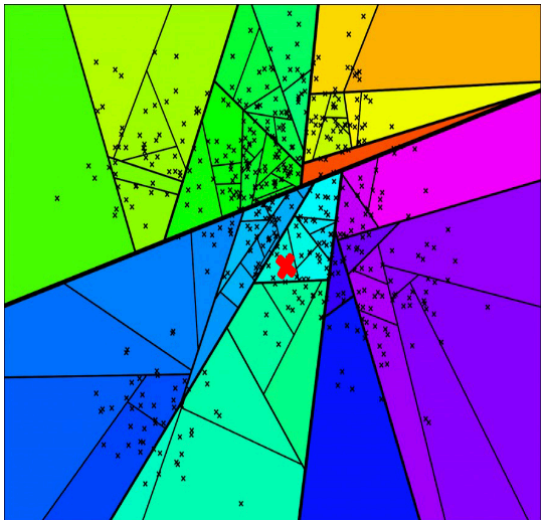



$$\theta = \frac{S}{R}$$

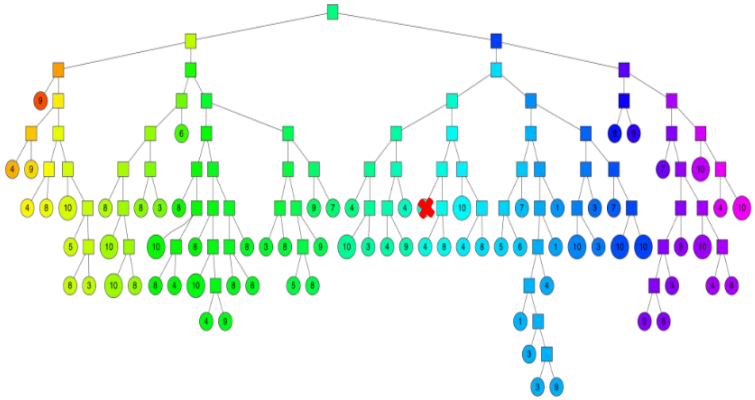
S = Distance travelled (on the arc)

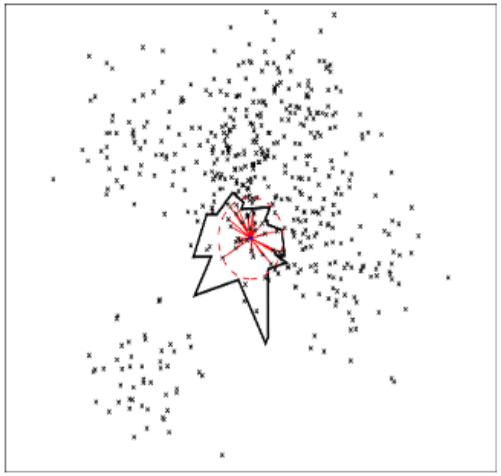
R = Radius of the circle

# Hashing for hits selection



- Annoy : Build trees by dividing the space
- Collect hits in the same leaf and check leaf from close split
- Perform in parallel the search in many trees and get the union
- Finds nearest neighbours

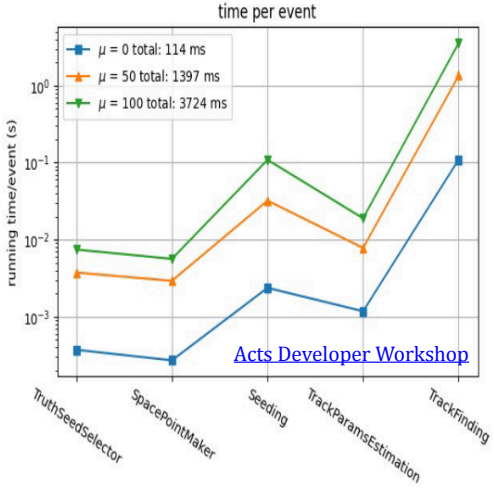


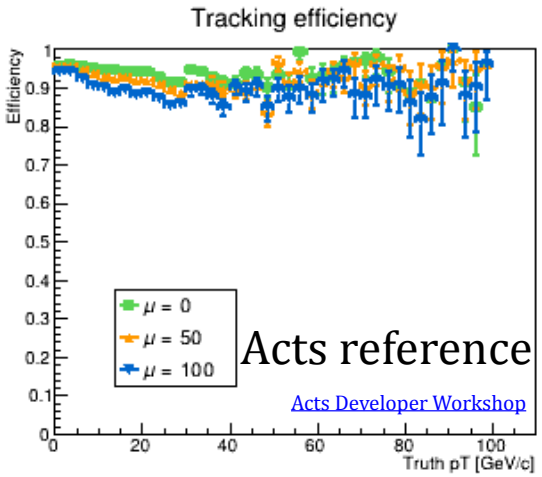


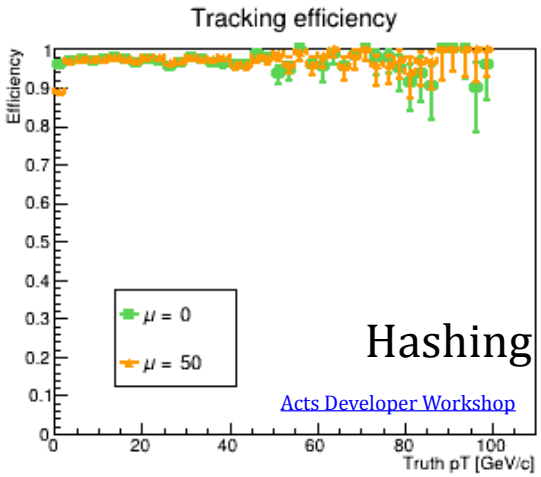
# Hashing for hits selection

- Similar performances to the CKF can be achieved with hashing (some issue at low pt -> larger bucket?)
- Creates a lot of seeds -> slow down the seeding
- More work needed to improve the chain

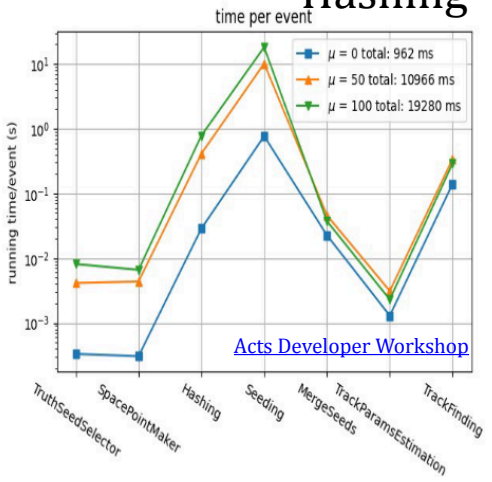
Acts reference




Hashing



# Parameter auto-tuning

- Most track reconstruction algorithm use multiple parameters to account for experimental condition :
  - Detector geometry
  - Material Configuration
  - Pile-up
  - Center-of-mass energy
  - Many other factors

- Currently -> Hand-tuned :
  - Time-consuming (need expert)
  - Need to be retuned when condition change

- Idea -> Auto-tuning :
  - Less time-consuming (trade CPU time for human time)
  - Easy retuning
  - Allow more granular tuning

- Tried different optimisation :
  - Oríon: Black box optimisation framework with different optimisation techniques
  - Optuna: Open source software for automatic hyper-parameter search
  - Many others …

Oríon

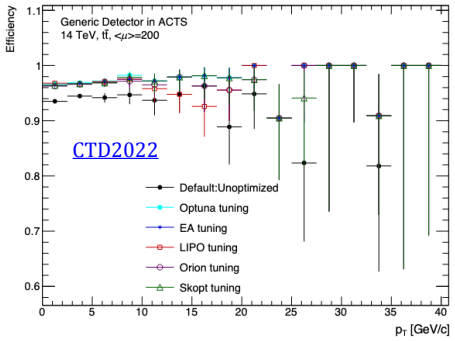
OPTUNA

# Parameter auto-tuning

- Seeding goals : efficiency and the track duplication rate (slow the reconstruction)
- Performance evaluated after the track finding

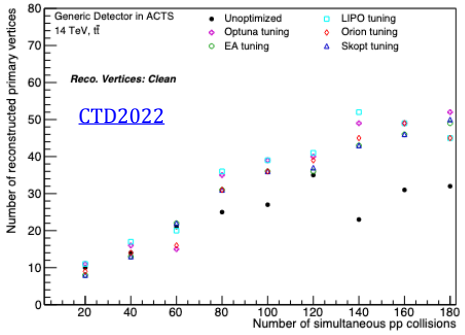
$$\text{Score Function} = \textit{Efficiency} - \left(\textit{FakeRate} + \frac{\textit{DuplicateRate}}{K} + \frac{\textit{RunTime}}{K}\right),$$

(K = 7 for all algorithms)

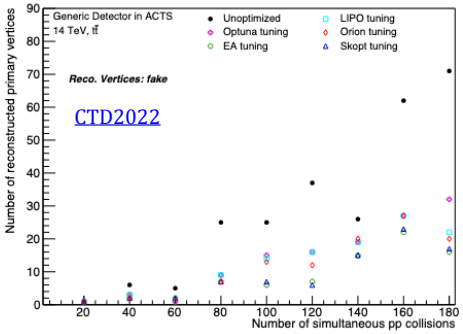



- Vertex reconstruction goals : efficiency and cleanness of the vertex

$$\text{Score Function} = (\textit{Eff}_{Total} + 2\textit{Eff}_{Clean}) - (\textit{Merged} + \textit{Split} + \textit{Fake} + \textit{Resolution})$$

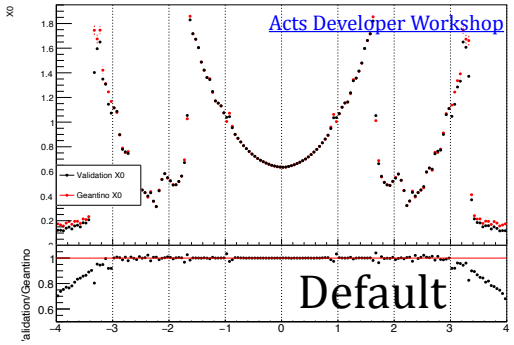


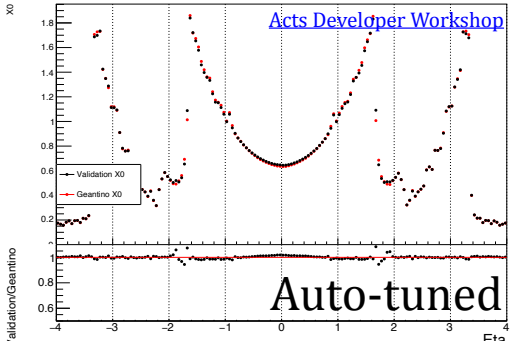

- Both show clear improvements with respect to the unoptimised solution
- Scoring function needs more work
- Available in ACTS, can be used on any detector



# Parameter auto-tuning

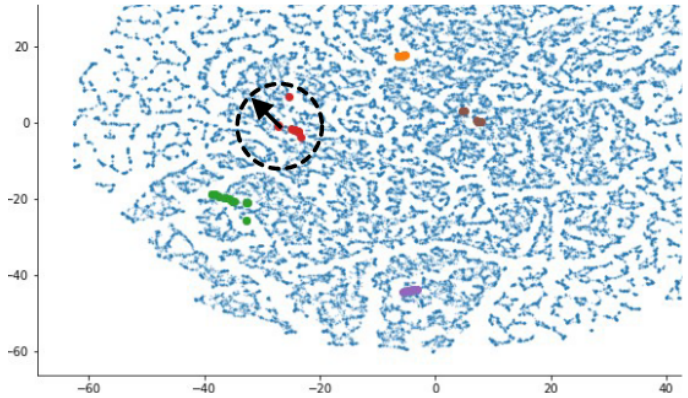
- Material Mapping goals : create a simplified material representation for the navigation
- Approximate effects of detector materials by projecting them onto binned surfaces
- Use Orion to optimise the binning on each surface
- Score : $\frac{1}{Bins}\sum_{bin} variance_{mat} \times (1 + \frac{1}{hits_{bin}})$
- Works great on the ODD, some small issue in the barrel (change the score ?)
- Also available in Acts

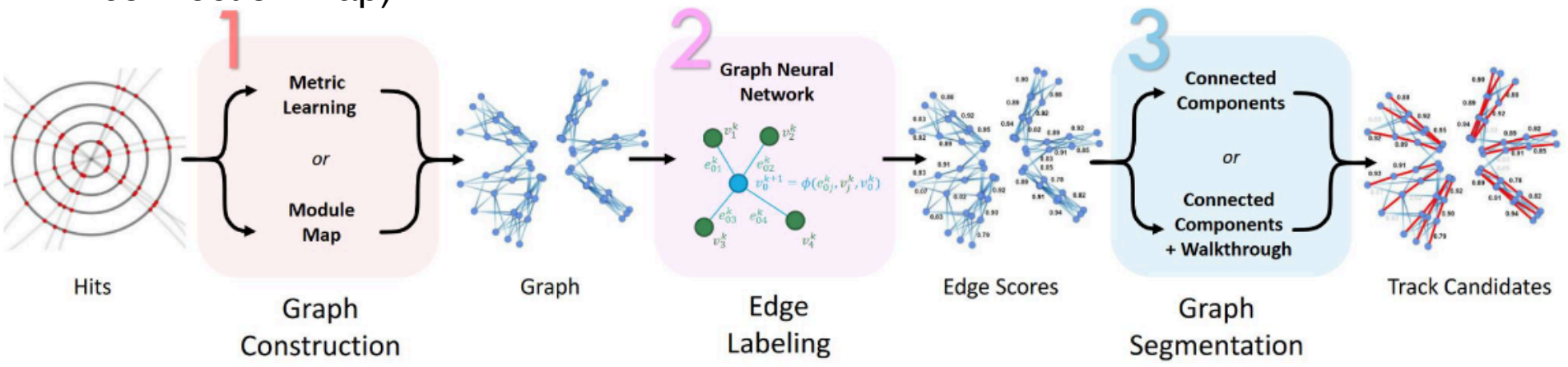



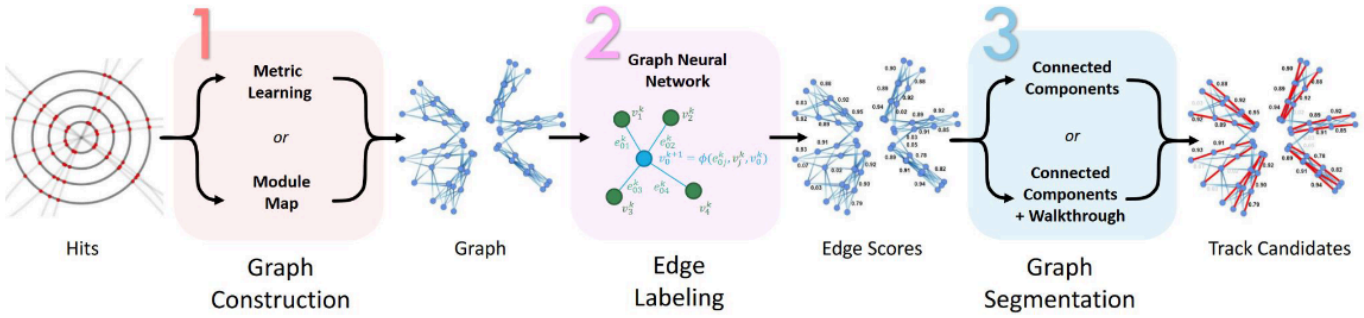
# GNN for track finding

- Track finding scales quadratically with the PU
- Interpret the hits in the detector as a graph -> Use Graph Neutral Network (GNN) to reconstruct tracks
- Embedding : Use all the hits in the detector to build a graph
- Filtering : Neural-Network predicts if nodes should be connected (can also use a connection map)



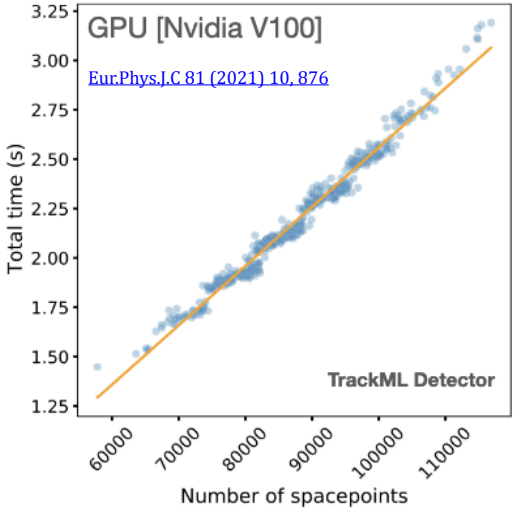
# GNN for track finding

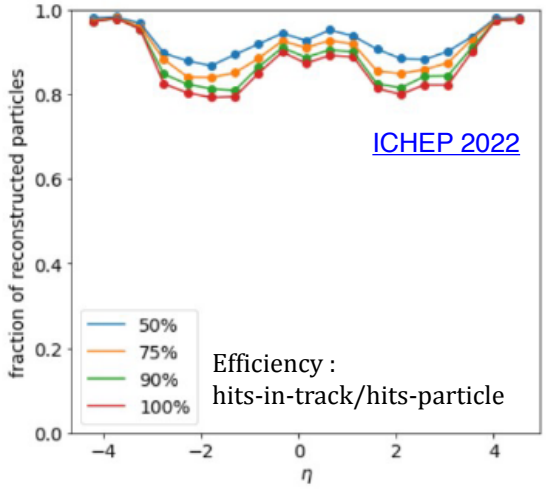


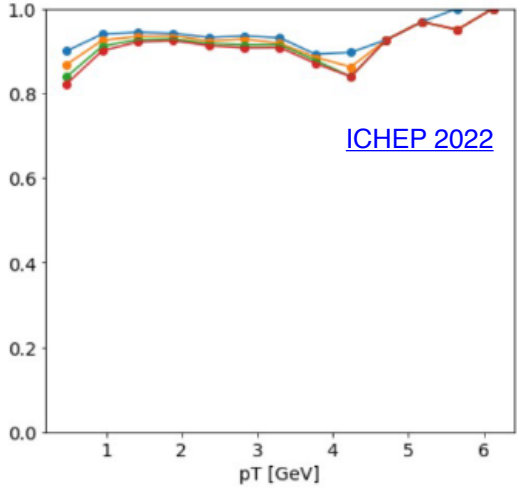

- EDGE labelling : compute a score for each edge
- Message-passing graph neural network : pass variables from nodes to edge then from edges to nodes
- After multiple iteration, compute scores for the edges and use them to remove the bad edges
- Graph Segmentation : track reconstruction from the connected nodes

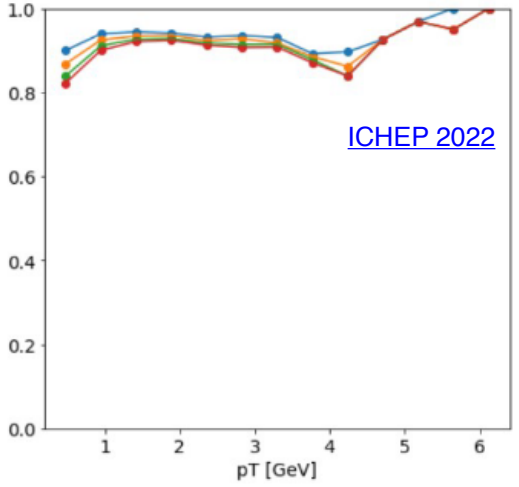
# GNN for track finding

- A good efficiency can be achieved using this method
- Tested and fully implemented in Acts and usable by any experiment
- Computing performance scales linearly with number of hits (and not quadratically)
- Real comparison of computing performance and reconstruction efficiency with standard CKF planned soon



# Conclusion

- ACTS is an Open Source tracking toolkit
- Provides virtual ODD detector to test different algorithm
- Great environment to develop new Machine learning based solution for track reconstruction :
  - Hashing for track reconstruction
  - Parameter auto-tuning for tracking algorithm (available in Acts)
  - GNN for track finding (also available)

# BACKUP