EDWARD MOYSE

(WITH THANKS TO A. SALZBURGER, R. LANGENBERG + MANY OTHERS)

TRACKING IN ATLAS

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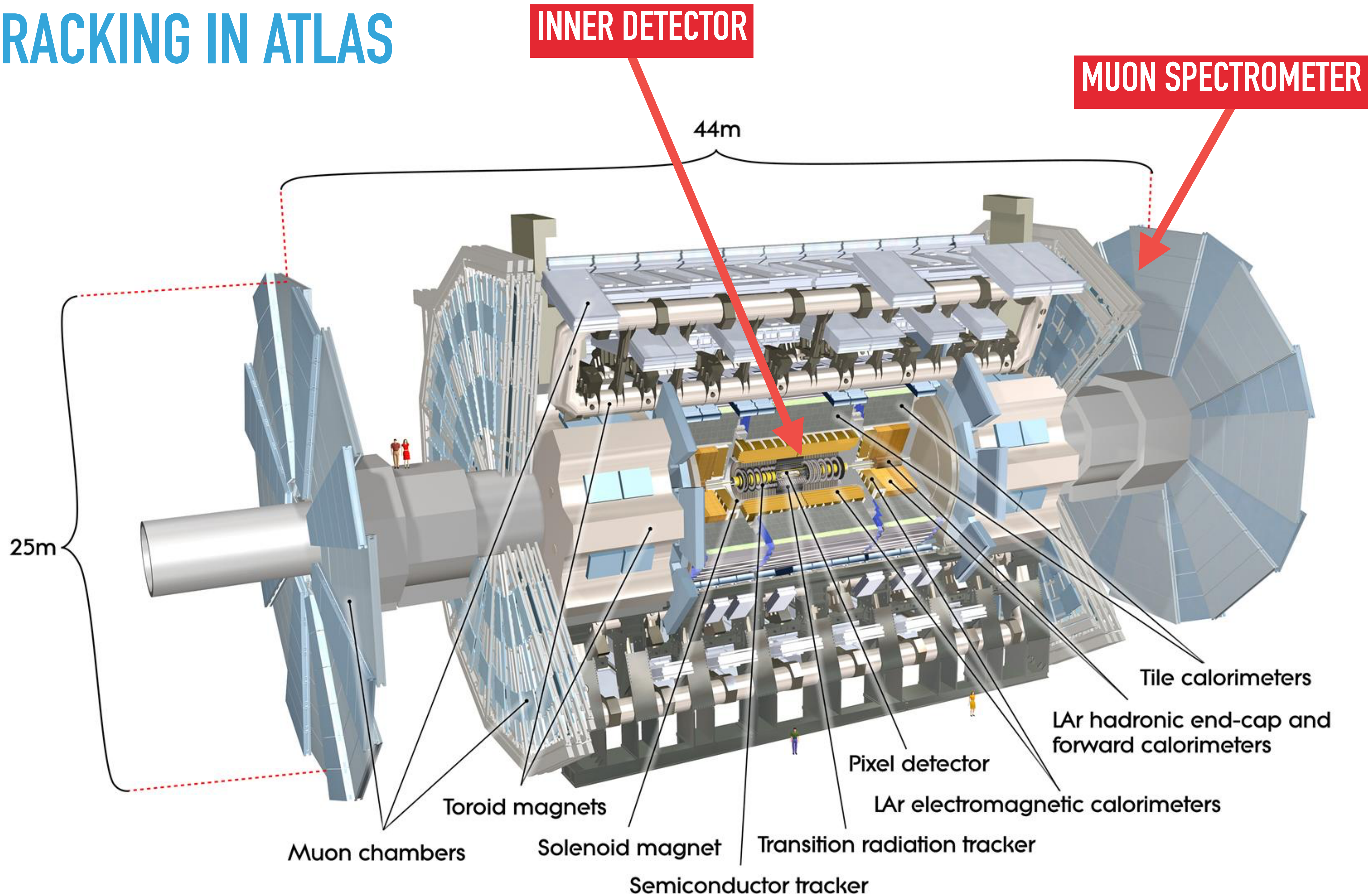
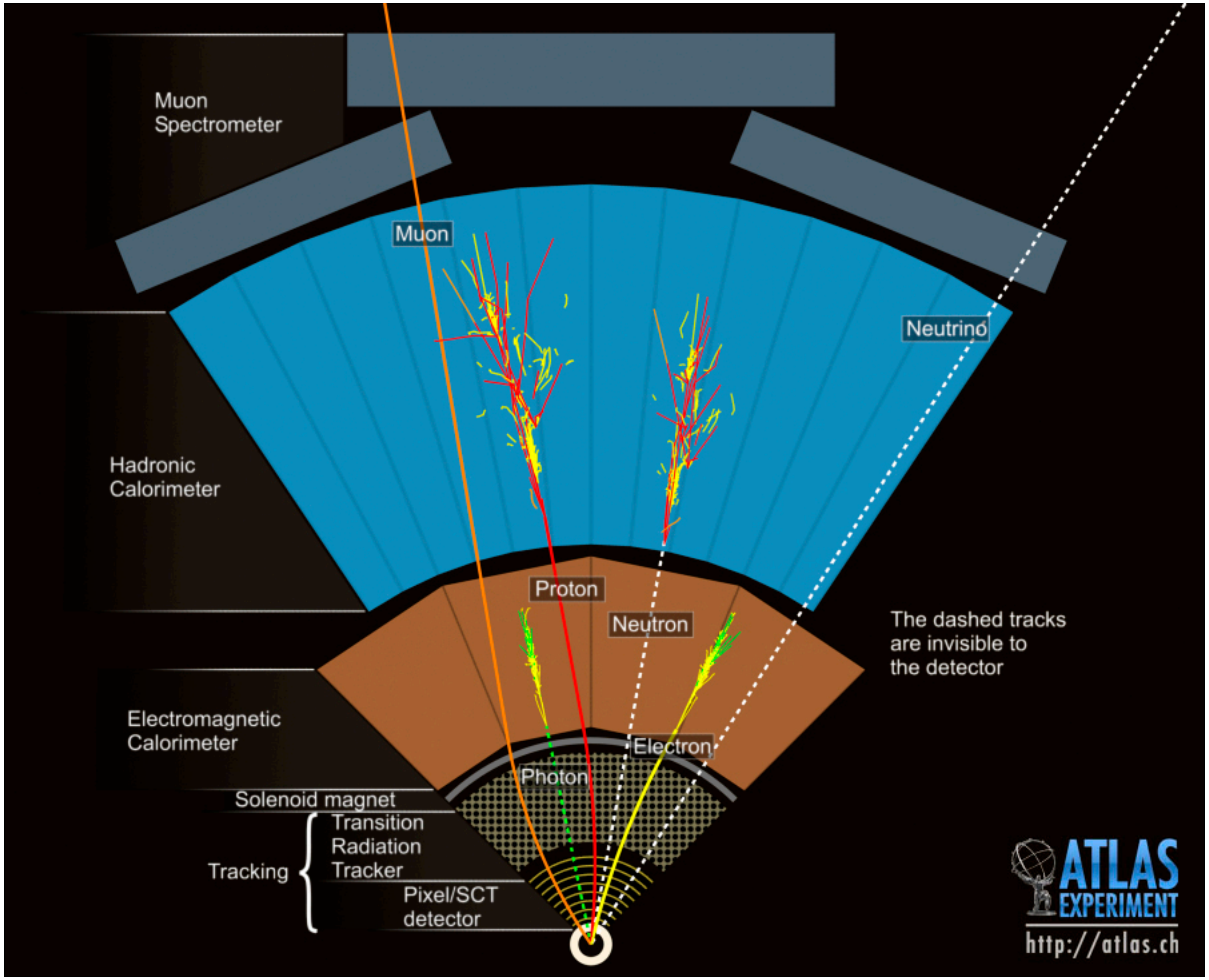


TRACKING IN ATLAS



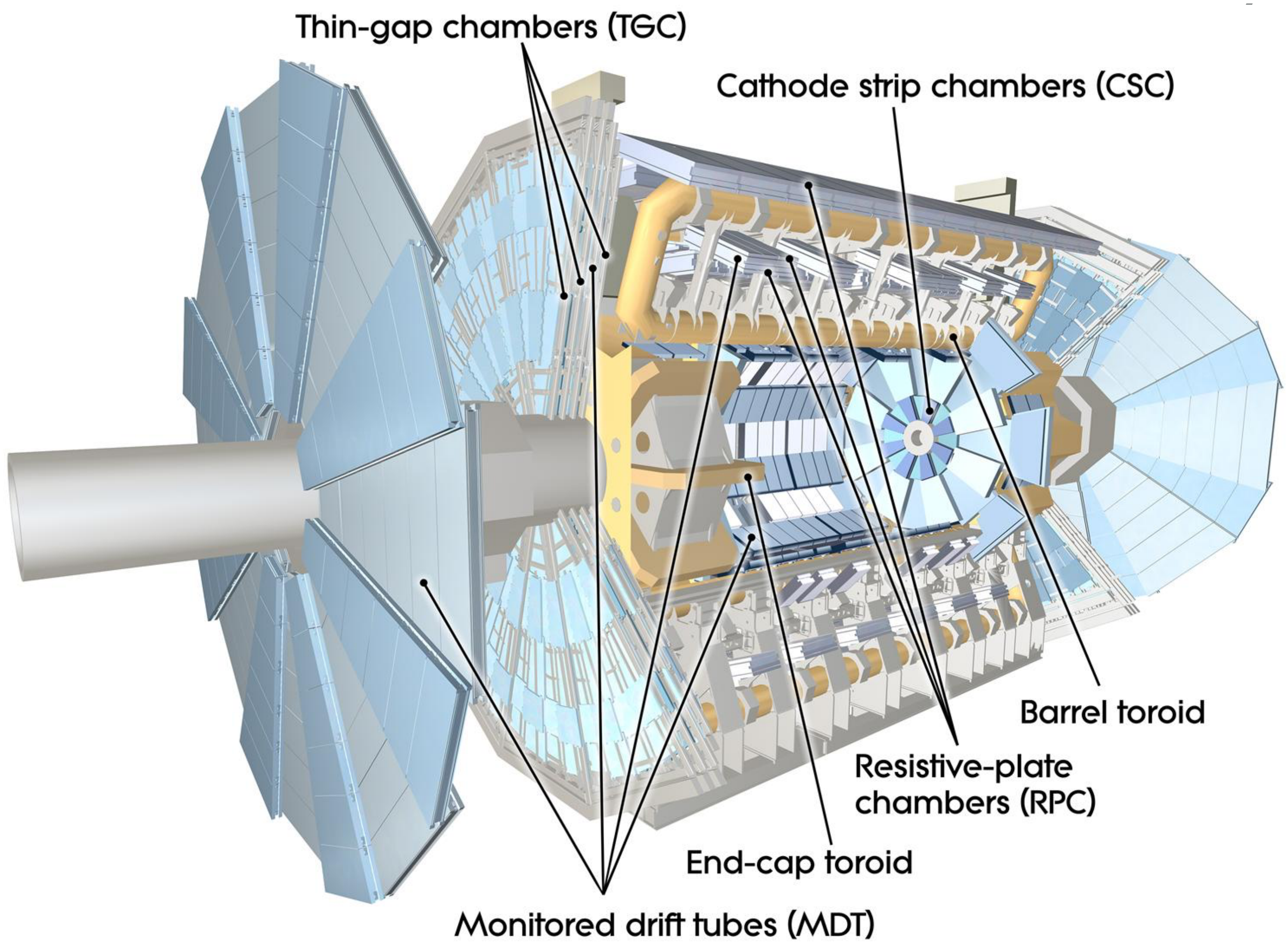
- Like most particle detectors, ATLAS is composed of multiple layers of sub-detectors with different purposes

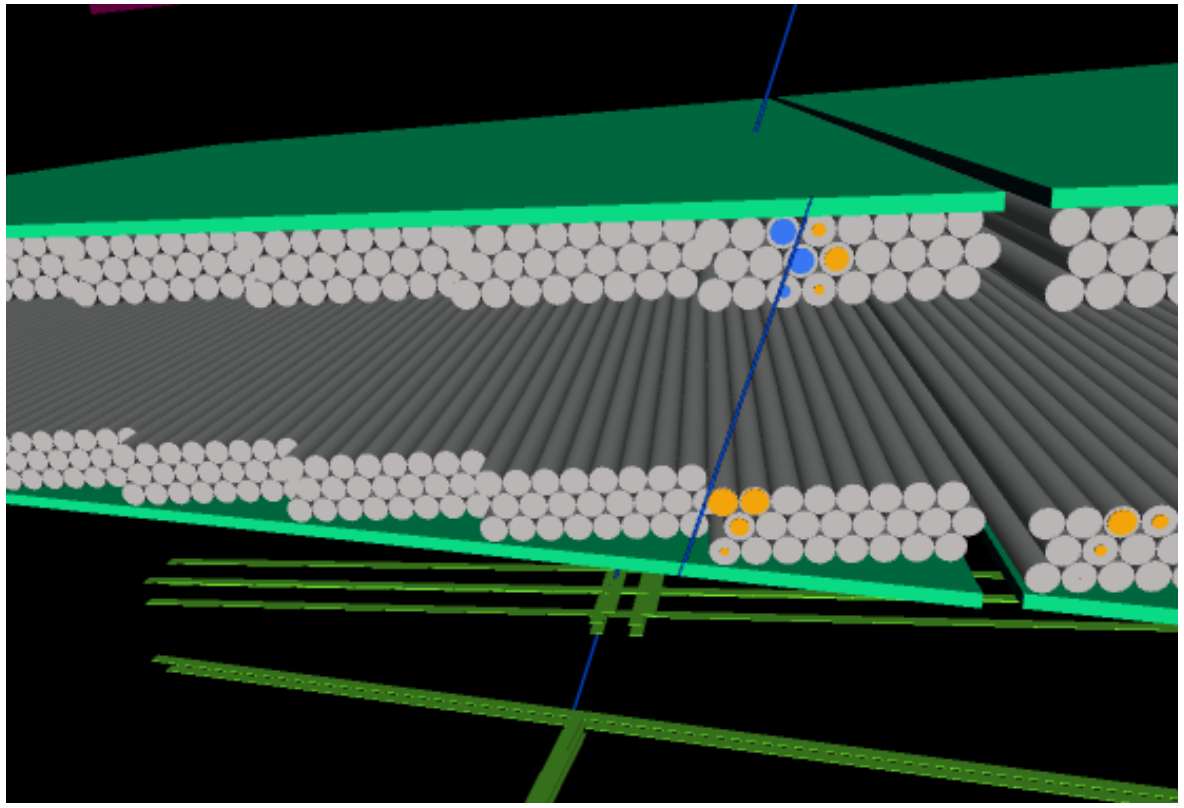
$$\eta = -\ln\tan(\theta/2)$$

- Trackers are :
  - Innermost Inner Detector - η <2.5
  - Outermost Muon Spectrometer - η < 2.7
- Has two magnet systems:
  - Inner tracking detector surrounded by a thin superconducting solenoid providing a 2T axial magnetic field
  - The muon spectrometer surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each.
  - The field integral of the toroids is 2.0-6.0 Tm across most of the detector.

MUON SPECTROMETER

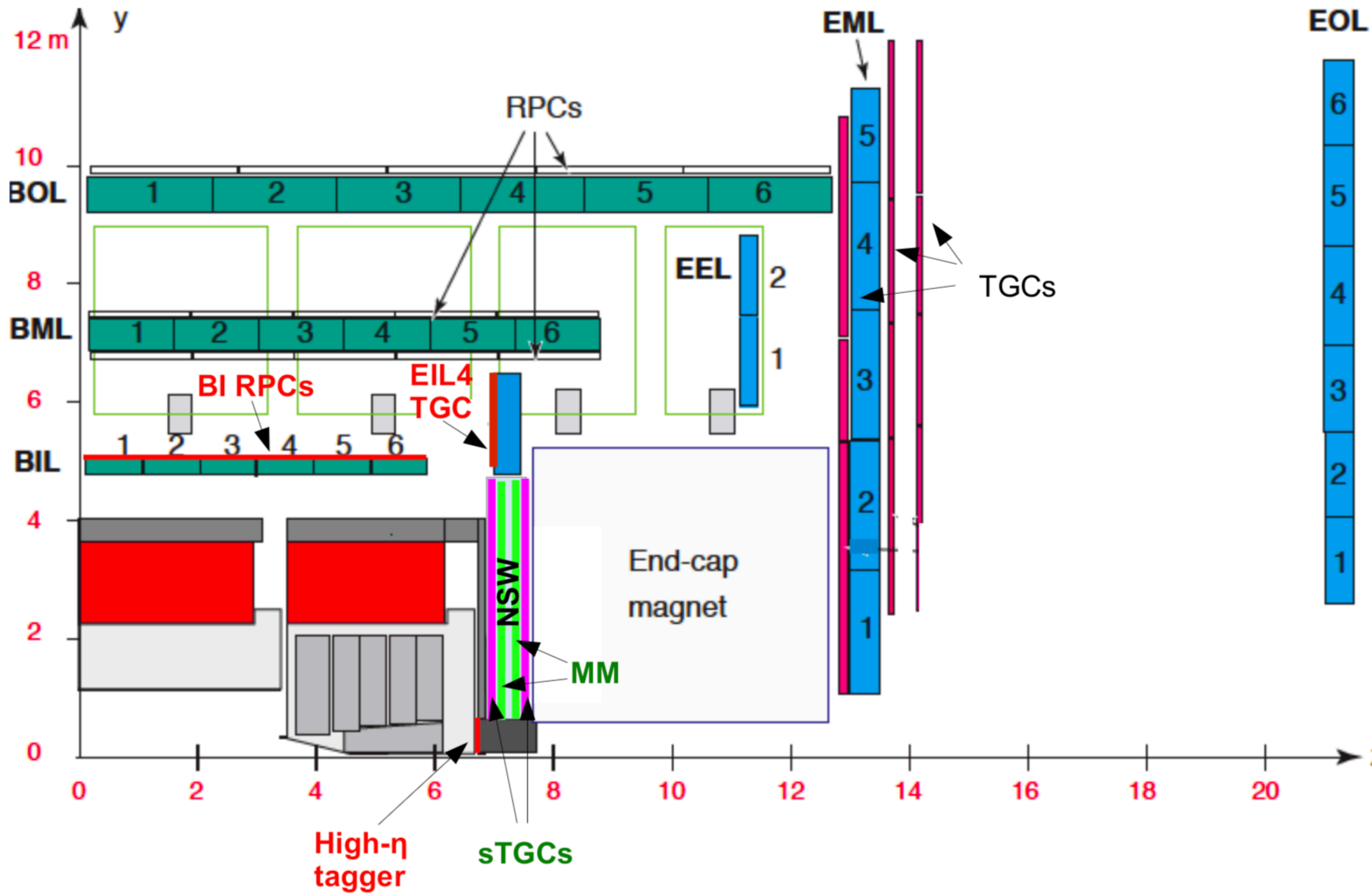
- The Muon Spectrometer forms the outermost layer of ATLAS and is designed to detect tracks in the region 0 < | η | < 2.7.
- It consists of a barrel section and two endcaps, all made up of three layers of chambers fitted around toroidal magnets.
- Currently four types of chamber technologies are used:
    - **Monitored Drift Tubes** (MDT)-precision measurements (80um per tube) in the bending plane
    - **Cathode Strips Chambers** (CSC) - used in the forward regions (2<|η|<2.7) with a resolution of ~60um in the bending (η) plane , and 5mm in the transverse plane (ϕ).
    - **Resistive Plate Chambers** (RPC) and Thin Gap Chambers (TGC)-used by the trigger and provide η and ϕ measurements with a resolution of ~1cm each
- By 2020 will add MicroMegas and sTGC detectors (replacing CSCs)



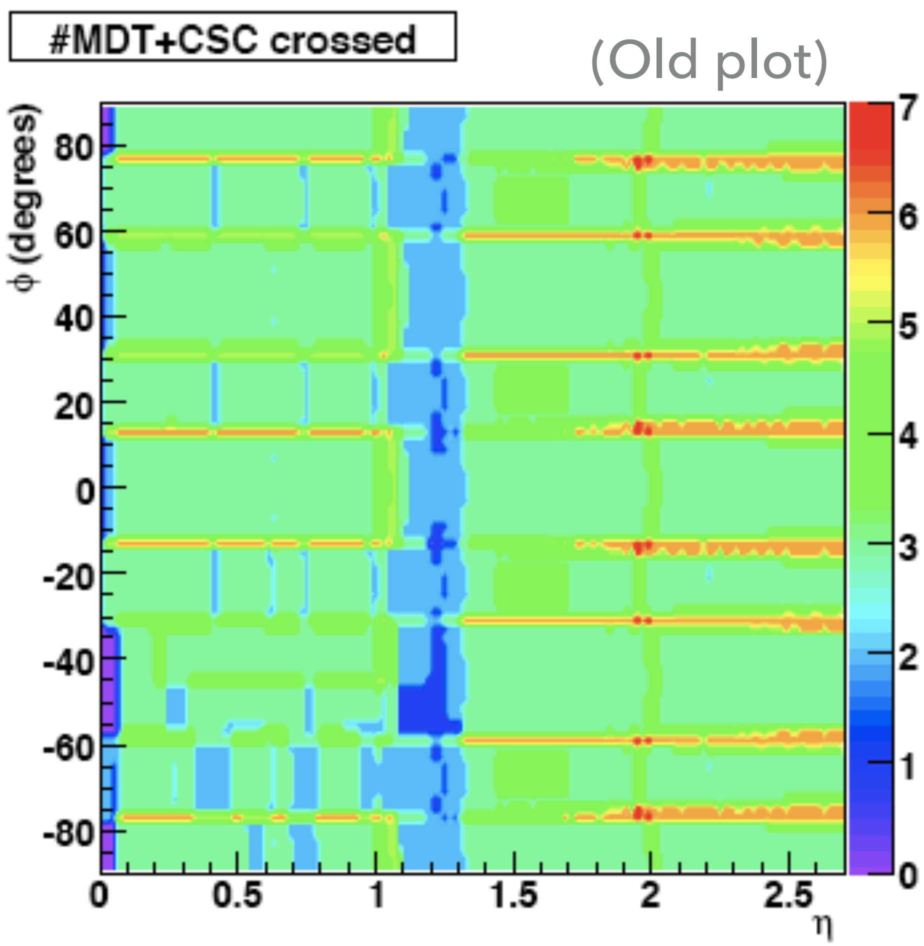


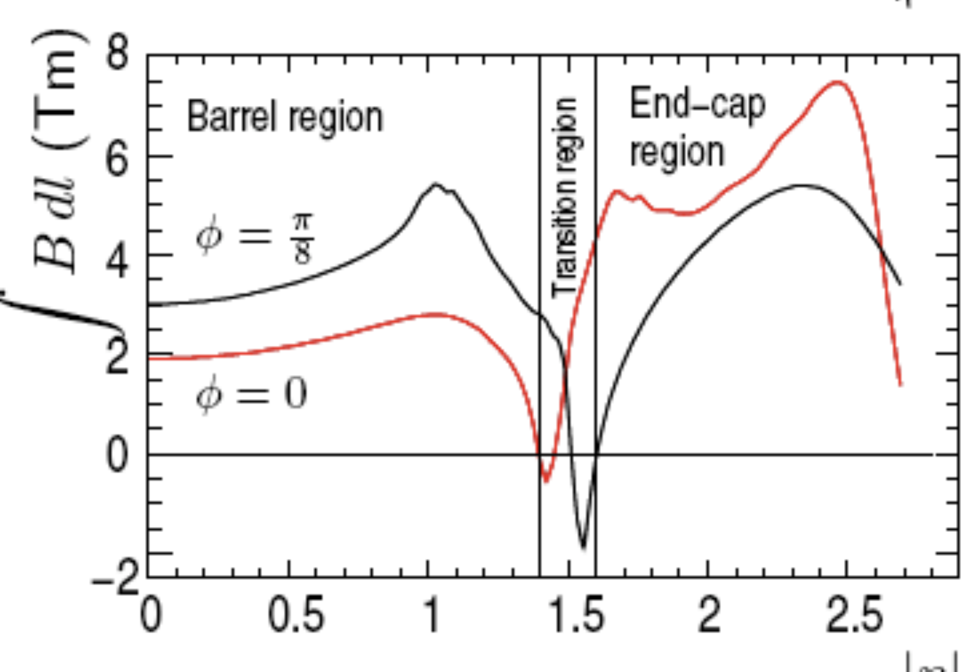
MUON SPECTROMETER (2)

Slice through the MS system, showing NSW.



MUON SPECTROMETER – MAIN CHALLENGES

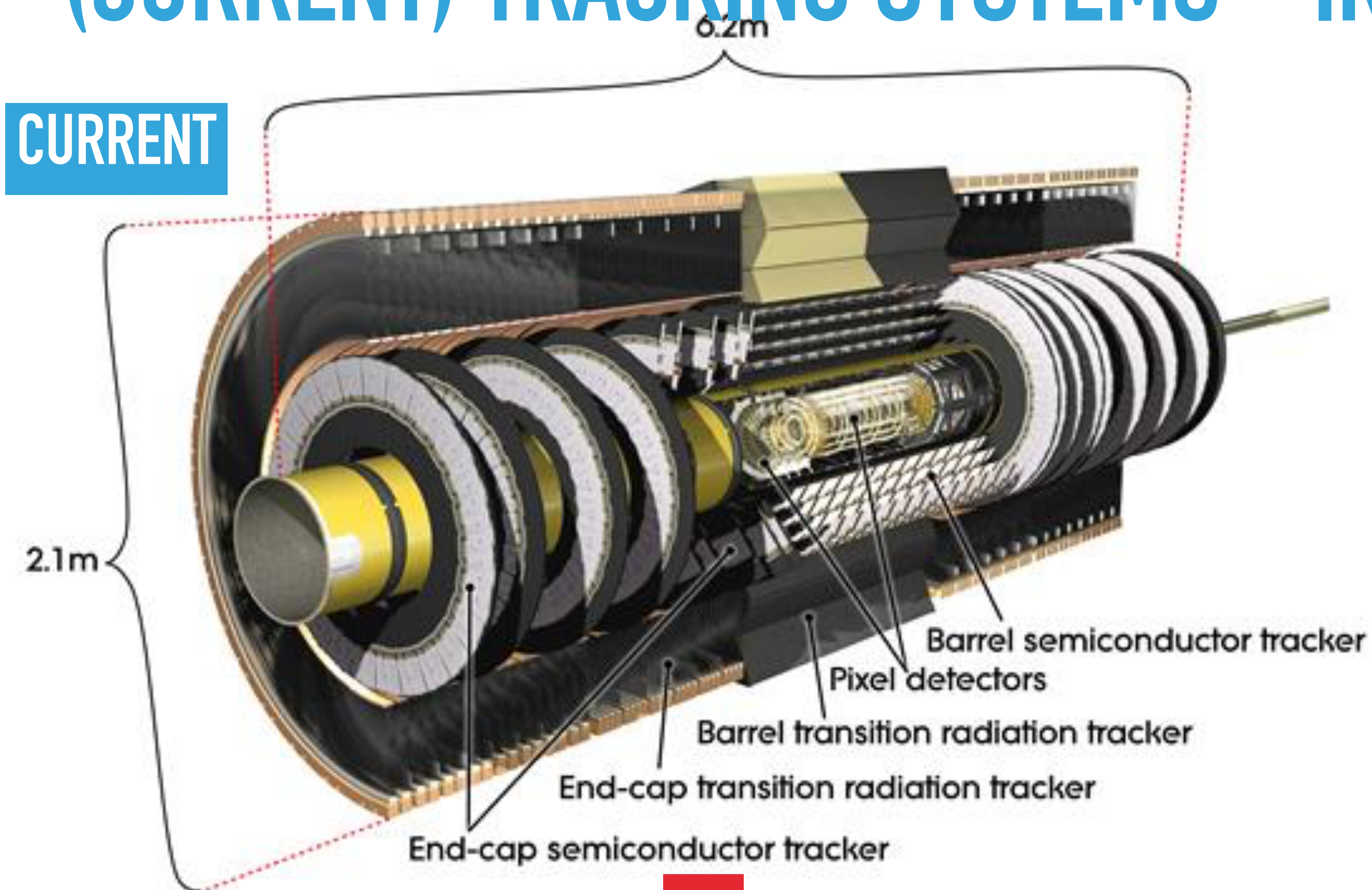


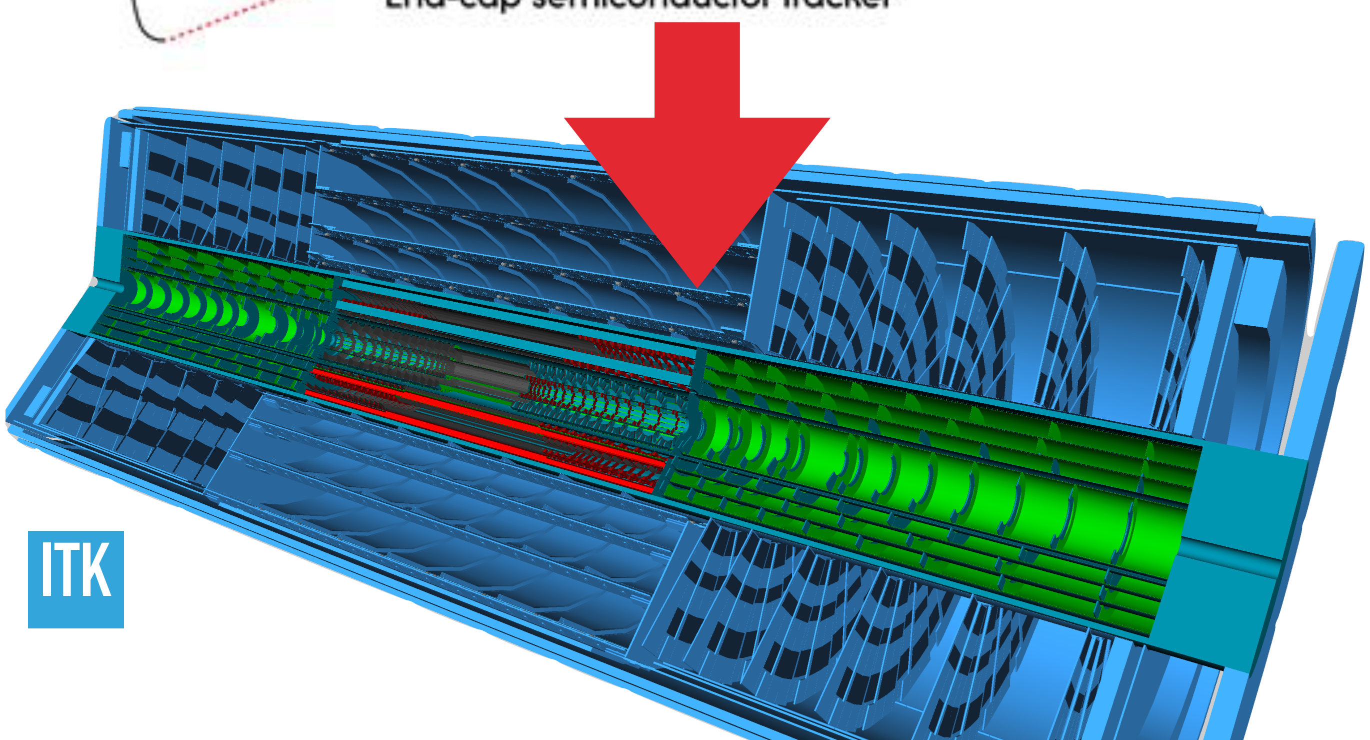


- There are some challenges to reconstructing muons with the Muon Spectrometer alone:
  - High background level present in the ATLAS experimental hall which yields high single tube occupancy may spoil or mask muon hits and create fake track segments from combinatorial hit associations
  - Large variety of the muon chambers and the complexity of the layout
  - The large distances between measuring stations (+ large amount of dead material) causes significant extrapolation uncertainties
  - There are regions where we have limited numbers of measurements: $|\eta| \approx 1.2$, $|\eta| \approx 0.0$ and near the feet (much improved though)
  - … and regions where the B field integral is small ($|\eta| \approx 1.5$)
    - The high inhomogeneity of the magnetic field and dead material prevents the use of simple analytical shapes for muon tracks of these chambers
  - Alignment
- Typically we combine MS with measurements from Inner Detector and Calorimeter

(CURRENT) TRACKING SYSTEMS – INNER DETECTOR

CURRENT





ITK

- Solenoidal magnetic field (2T) in the central region (η<2)
- **Pixel Detector**
  - ~100 million read-out channels
  - Pixel size 50 μm x 250 μm .
  - Resolution 14 x 115μm2
- **Semiconductor Tracker**
  - 6 million read-out channels
  - 80 μm x 12 cm
- **TRT**
  - 350,000 read-out channels
- Space resolution: ~ 15 μm (in the azimuthal direction)
- TRT will be replaced by silicon in all new Inner Tracker (ITK) by ~2030)

DATA MODEL AND DATA FLOW

ID/MS DATAFLOW

- At fundamental level, both ID and MS have same approach:
  - **BS→RDO**
    - Raw data from detector ('bytestream') turned into simple objects
  - **RDO→PRD**
    - Calibration and clustering applied - correct for e.g. misalignments, voltages, gas mixture effects
  - **Reco→Tracks**
    - Various techniques are applied to find Tracks and Segments, which represent charged particles

RECONSTRUCTION

CHARGED PARTICLES

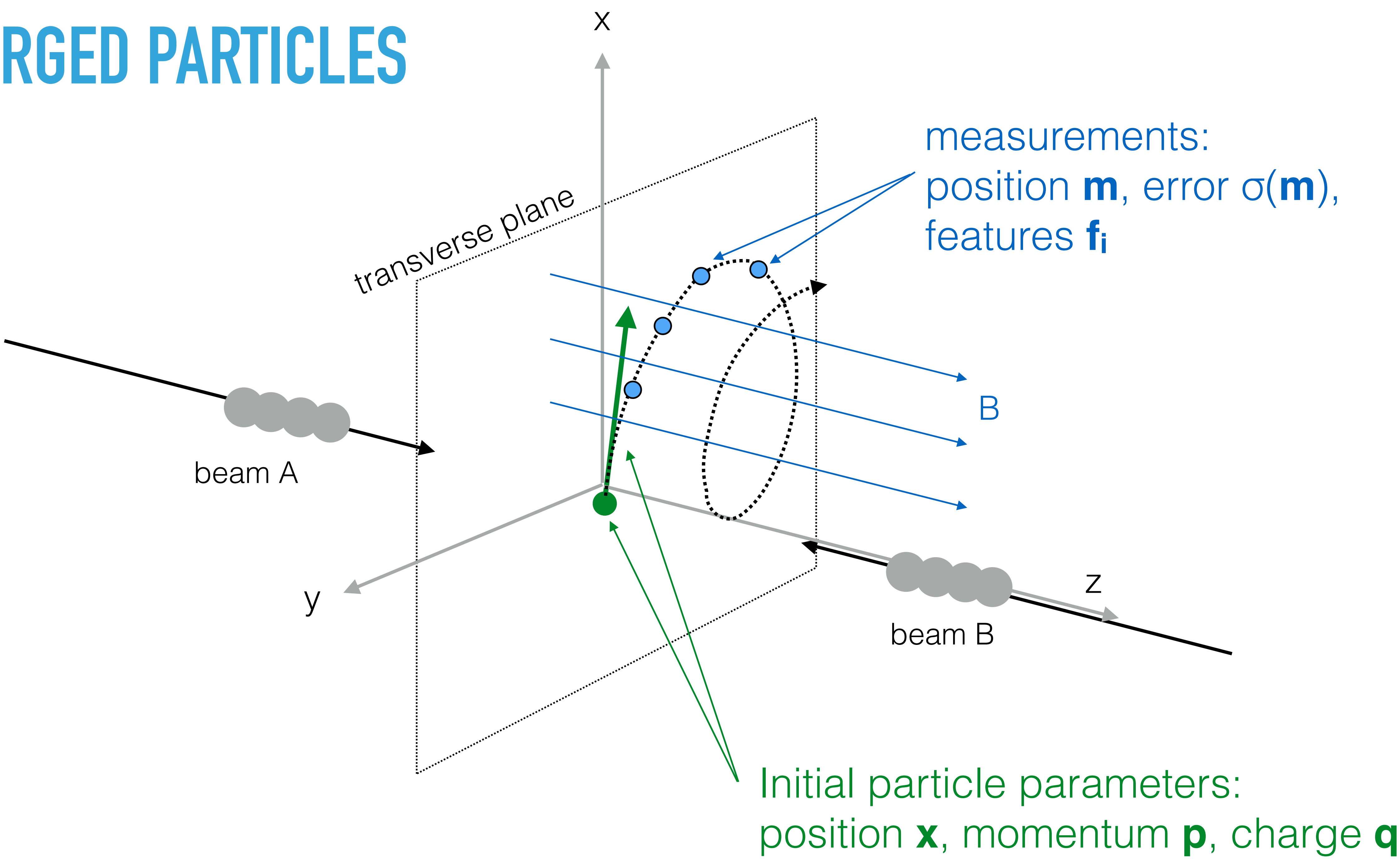
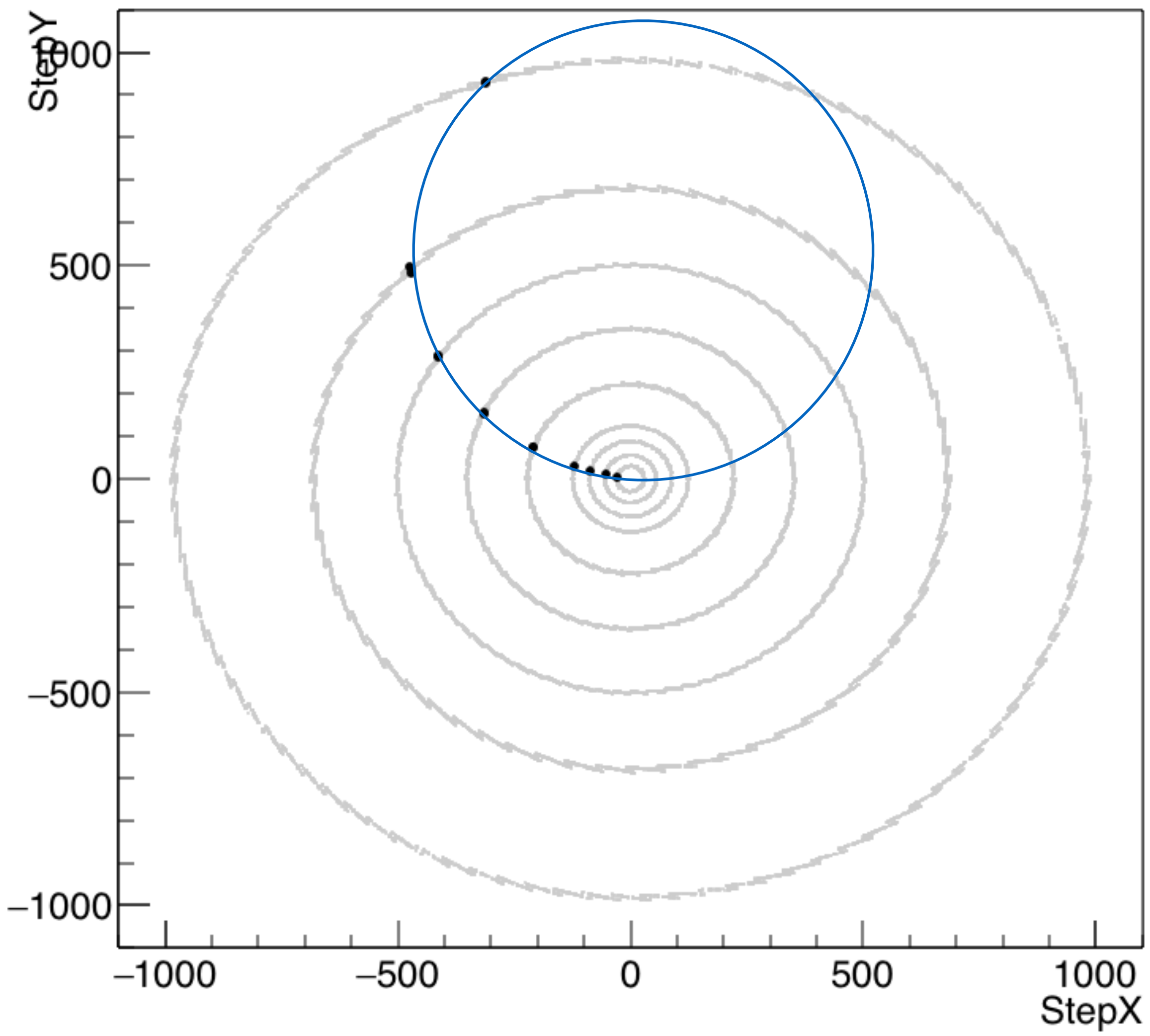
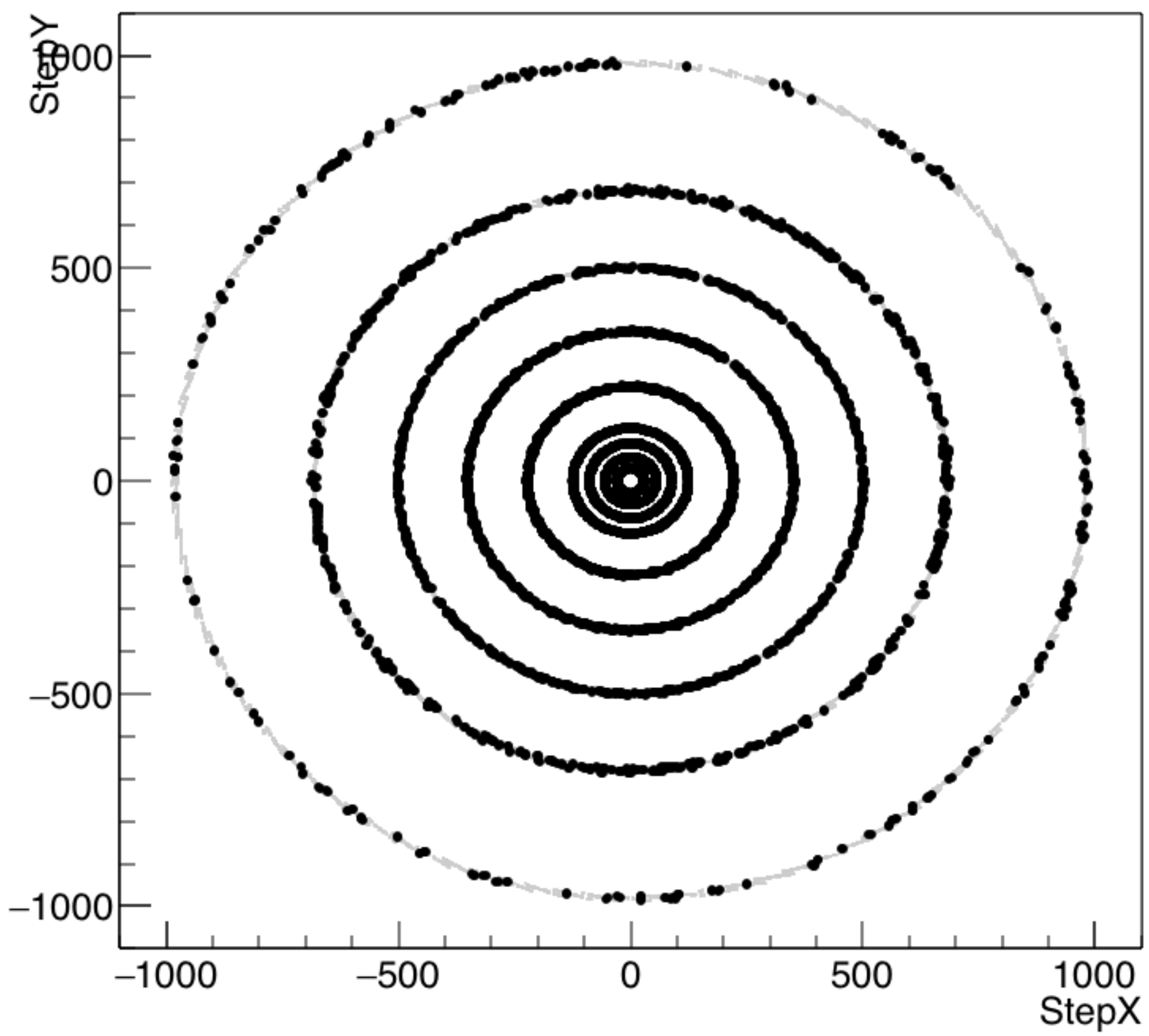


Illustration:
A schematic view of a particle in a magnetic field.

CHARGED PARTICLES



hits from 1 particle

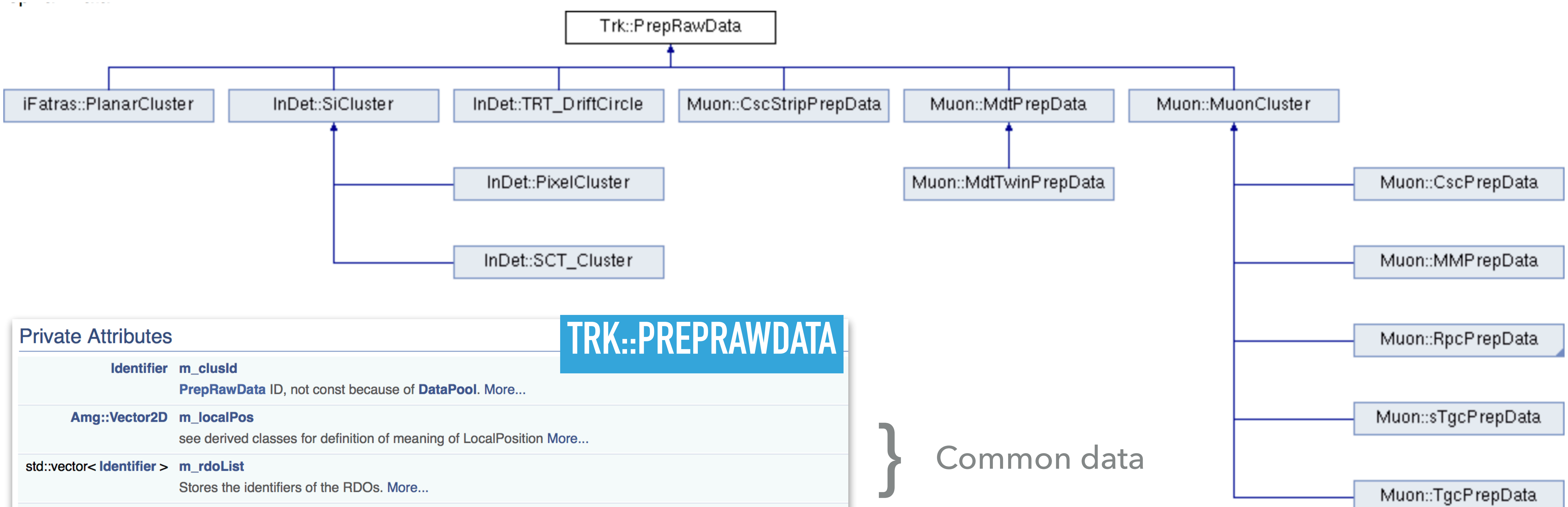


fraction of hits
from particles
in 200 pile-up events

Andreas Salzburger

EVENT DATA MODEL: PREP RAW DATA

- Common 'Transient' data model is shared between detectors, which gives a good level of abstraction:
  - Much of tracking is purely mathematical - can re-use fitters between ID and MS
  - However we overdid this - costs of many virtual calls was not understood/ considered significant



TRK::PREPRAWDATA

Private Attributes

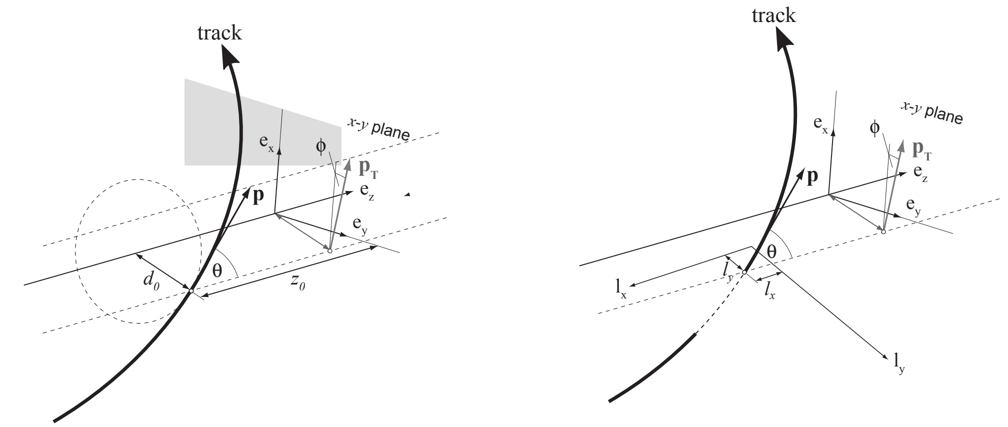
Identifier	**m_clusId** PrepRawData ID, not const because of DataPool. More...
Amg::Vector2D	**m_localPos** see derived classes for definition of meaning of LocalPosition More...
std::vector< Identifier >	**m_rdoList** Stores the identifiers of the RDOs. More...
const Amg::MatrixX *	**m_localCovariance** See derived classes for definition of ErrorMatrix. More...
IdentContIndex	**m_indexAndHash** Stores its own position (index) in collection plus the hash id for the collection (needed for the EL to IDC) More...

} Common data

EVENT DATA MODEL: TRACK

- **Track** class is even more complex
  - Vectors of track parameters, vectors of measurement
  - Very poor data locality & thread hostile constructs e.g. lazy initialisation of data
- But this is primarily an OUTPUT class….

Track Parameters



Global track parameters e.g. wrt. perigee

$$\left({\color{blue}d_0}, {\color{blue}z_0}, \phi, \theta, \frac{q}{p} \right)$$

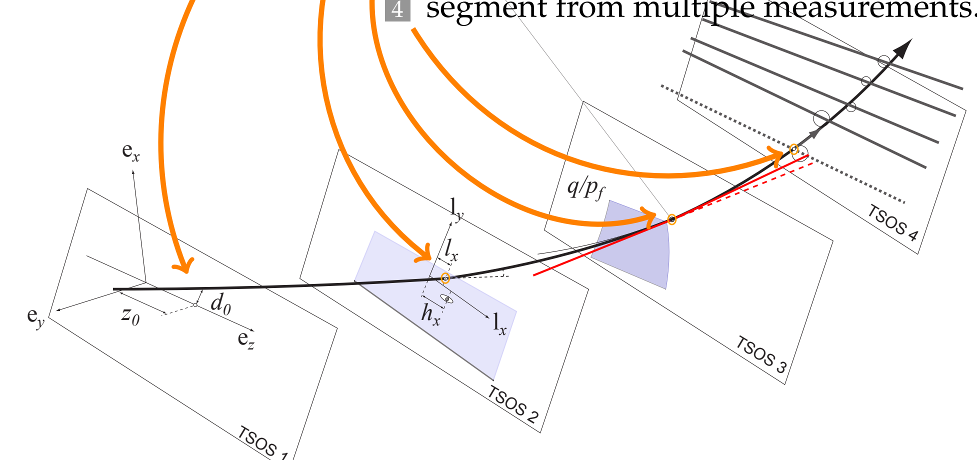
Track parameters in **local** coordinates e.g. detector modul

$$\left({\color{red}l_x}, {\color{red}l_y}, \phi, \theta, \frac{q}{p} \right)$$

Trk::Track (ESD)

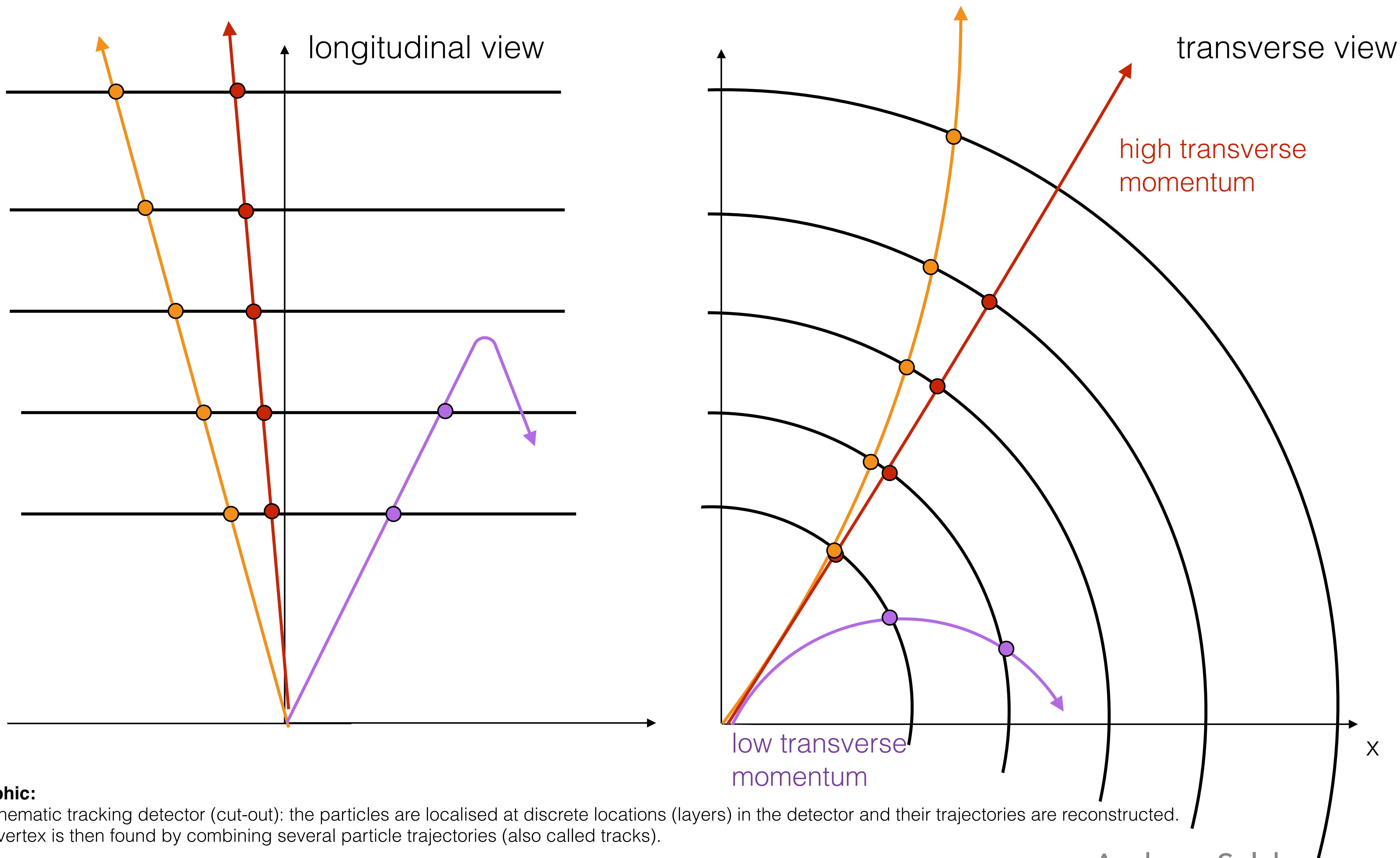
contains inputs for fitting and fit results, mostly contained in list of TrackStatesOnSurfaces(→git, lxr) e.g.

1. Track defining parameters
2. measurement and track parameters at surface of measurement
3. material effects e.g. kinks,
4. segment from multiple measurements.



Introduction Charged particles in the detector

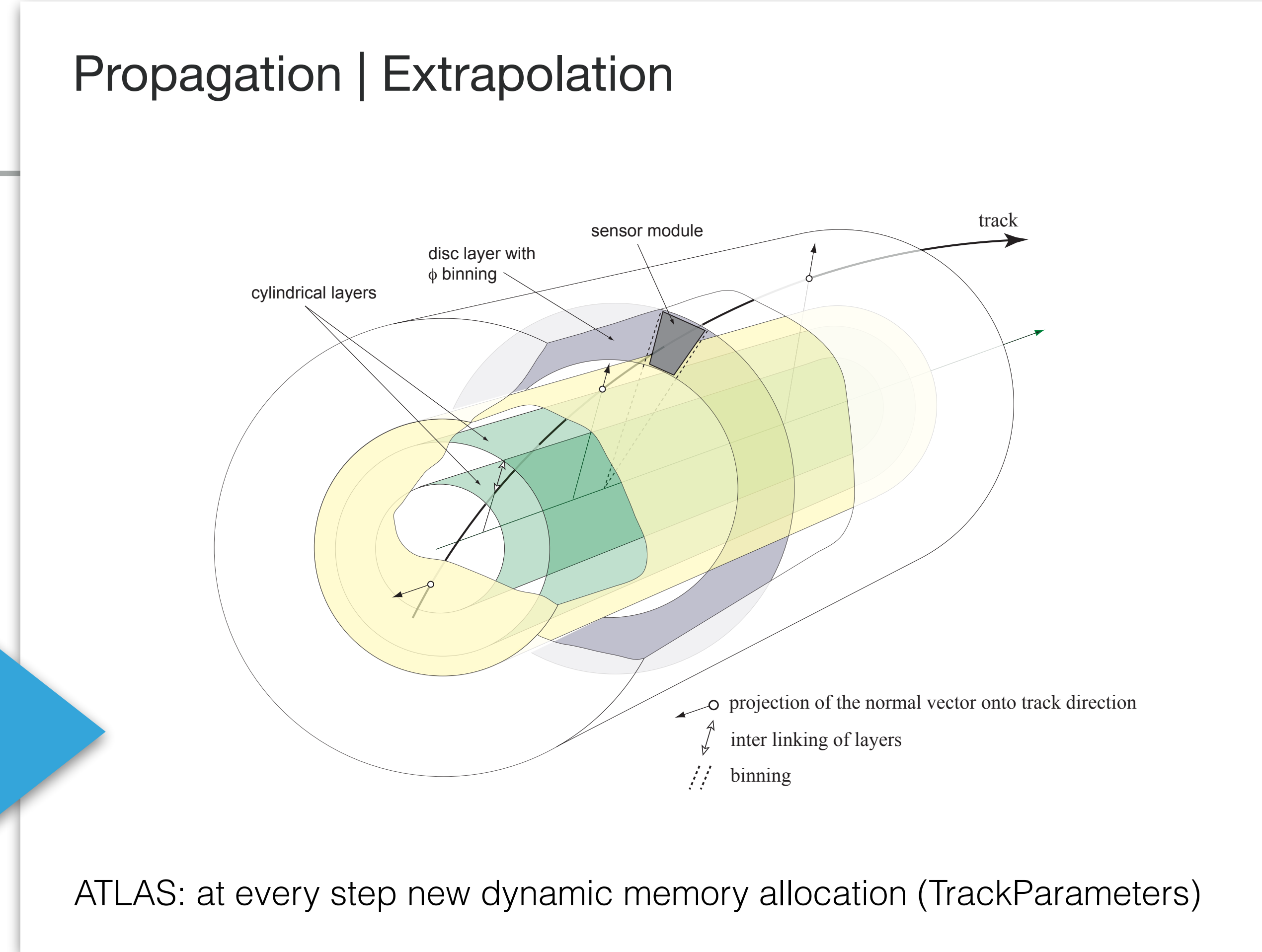
Particle trajectories can not be directly measured and have to be reconstructed from localisations.

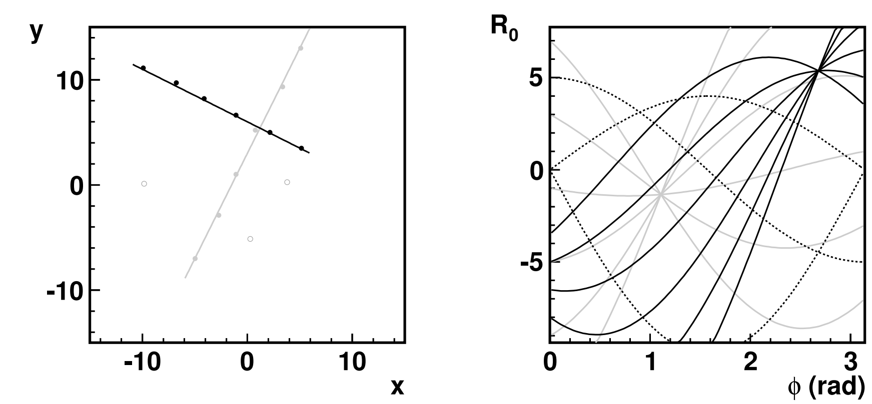


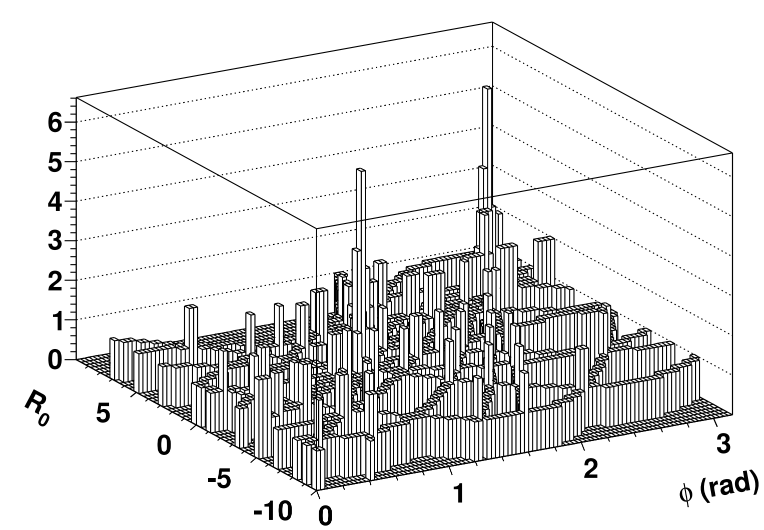
Graphic:
A schematic tracking detector (cut-out): the particles are localised at discrete locations (layers) in the detector and their trajectories are reconstructed.
The vertex is then found by combining several particle trajectories (also called tracks).

TOOLS

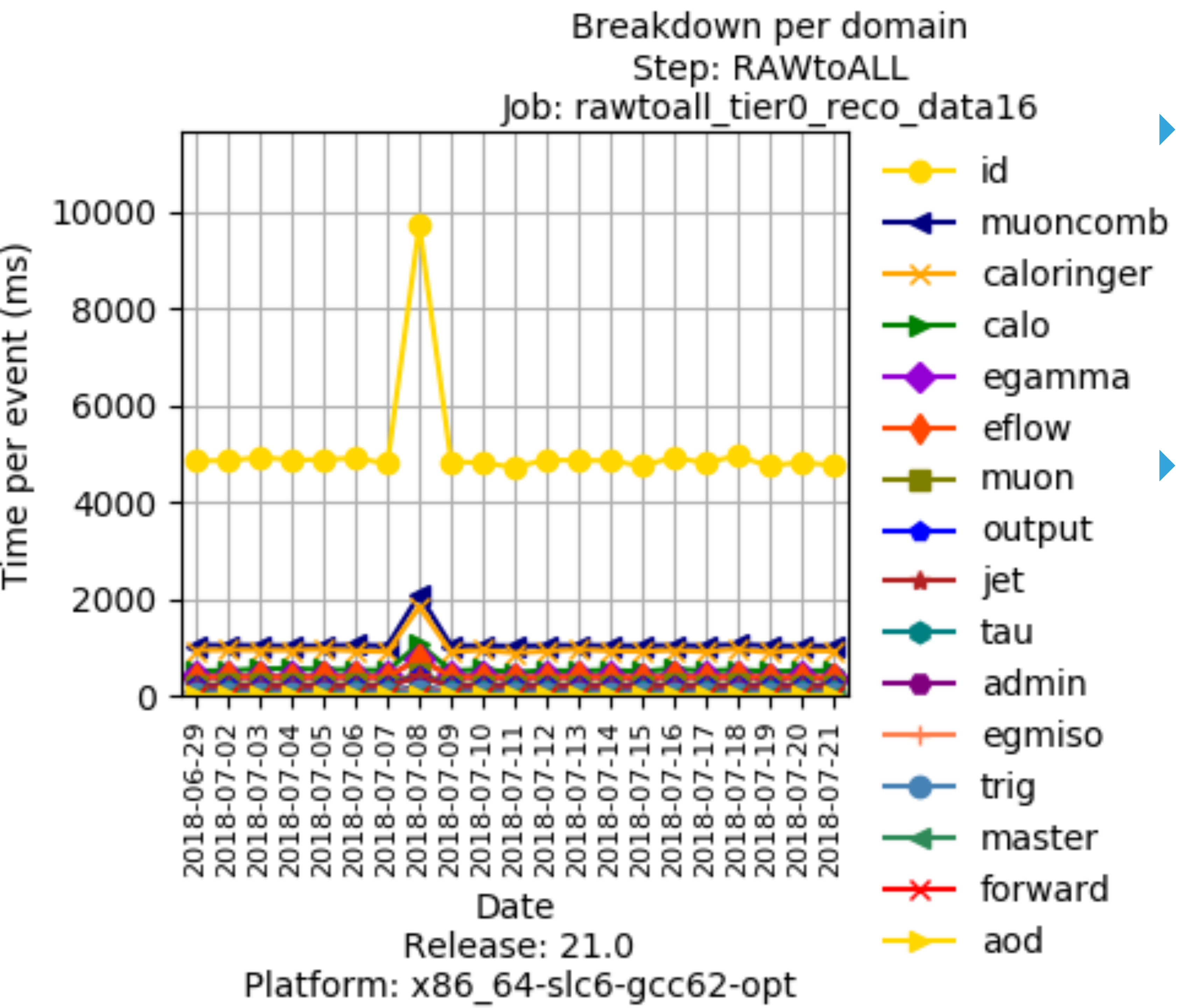
- Propagation / extrapolation
    - Needs to understand geometry, magnetic field etc
- Pattern recognition
    - Many techniques, including conformal mapping (e.g. hough transform)
- Fitters
    - e.g. Kalman filter, Global chi2
- Will focus on ID in following slides …







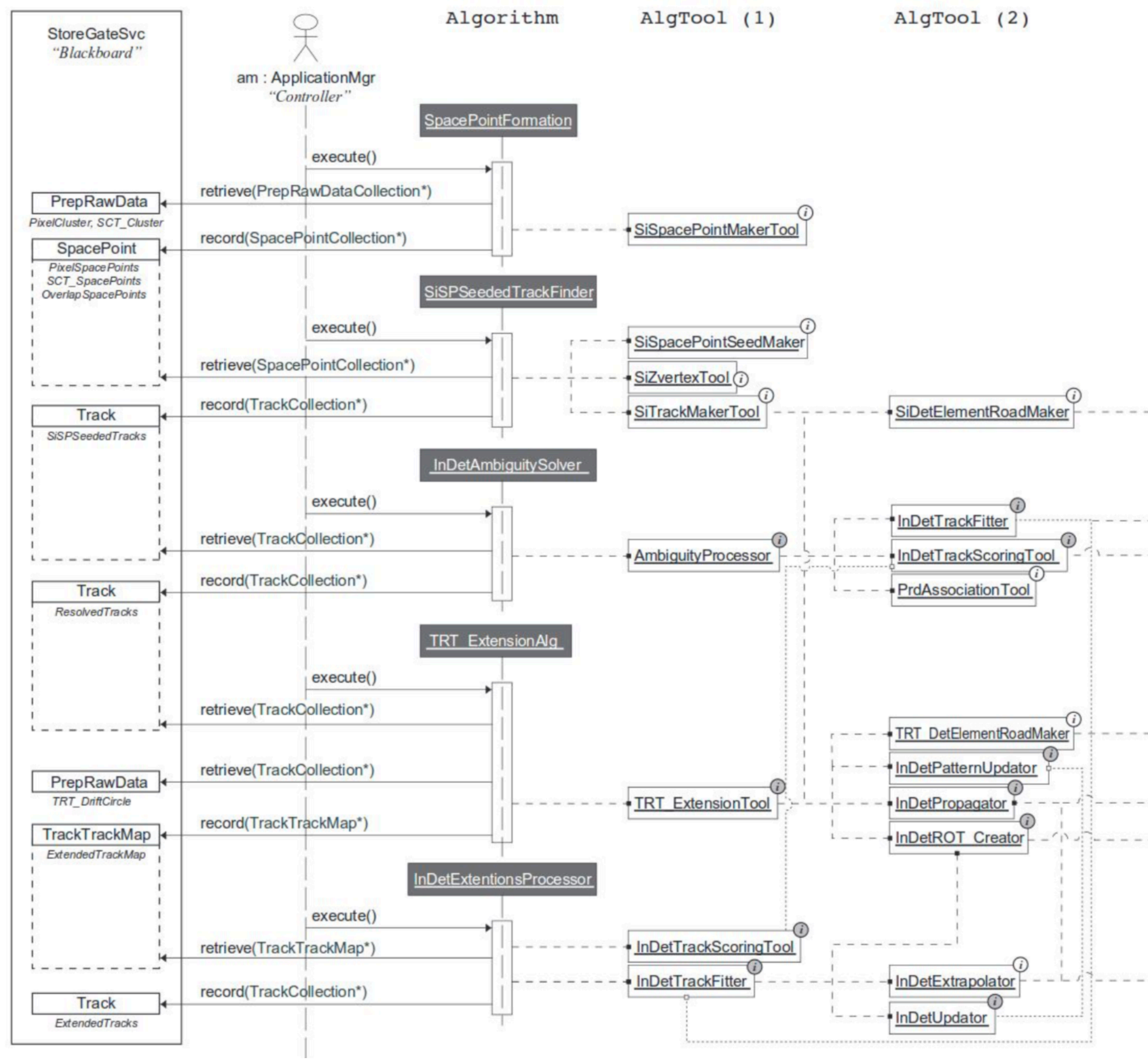
CPU CONSUMPTION

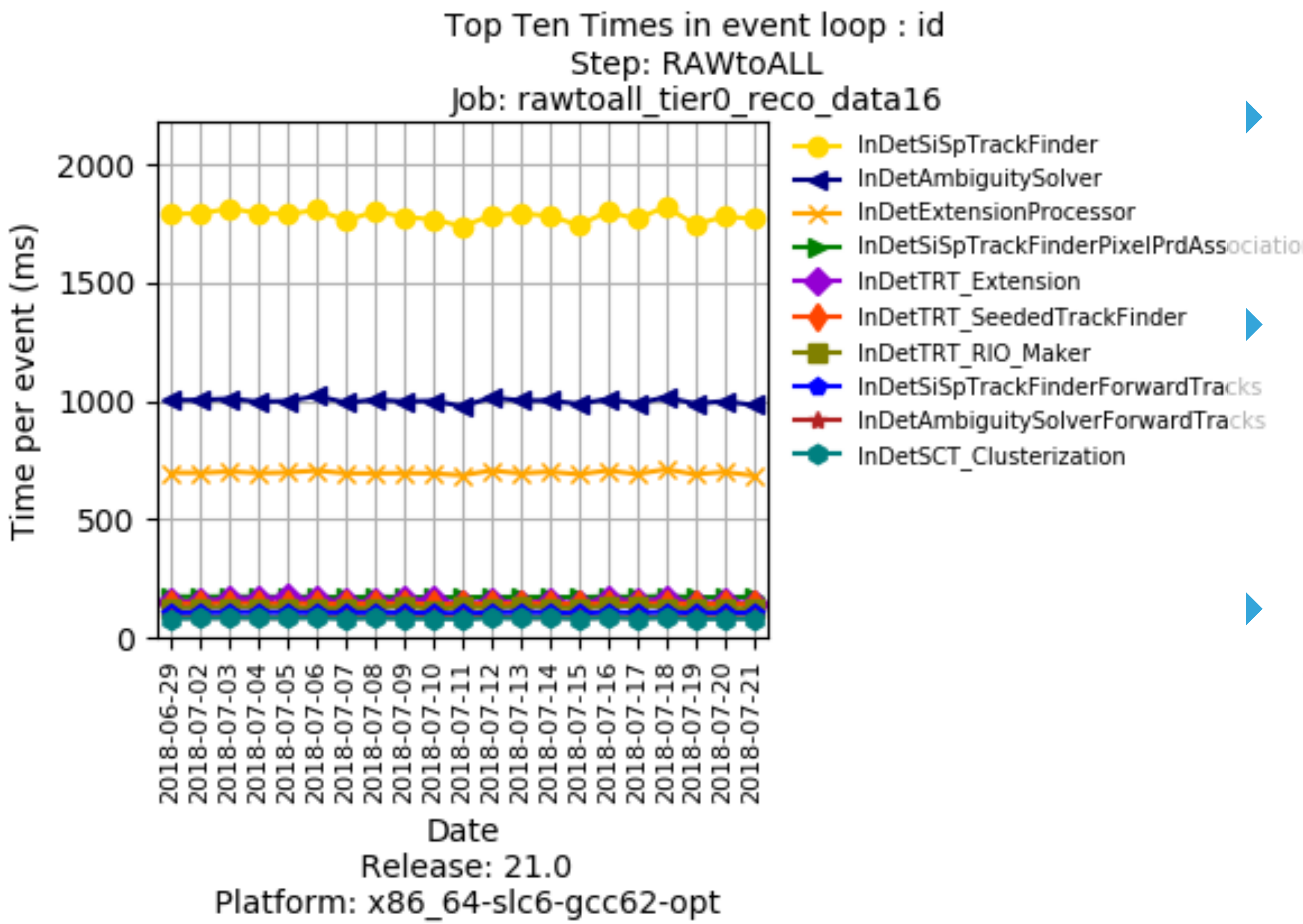


- InnerDetector is the dominant CPU consumer in our RAW to ALL workflow
- For other workflows, e.g. trigger, muons become significant too

INDET: ALGORITHMIC FLOW

- Storegate used as a ‘blackboard’ to which algorithms read from and write to
- Algorithms call Tools (which can call further tools)
- MT-hostile wrinkle:
  - we currently update existing EDM objects later on (we add decorations)
- GPU-hostile wrinkle:
  - We don’t just need event data for algorithms - a large amount of related (‘conditions’) data is needed too

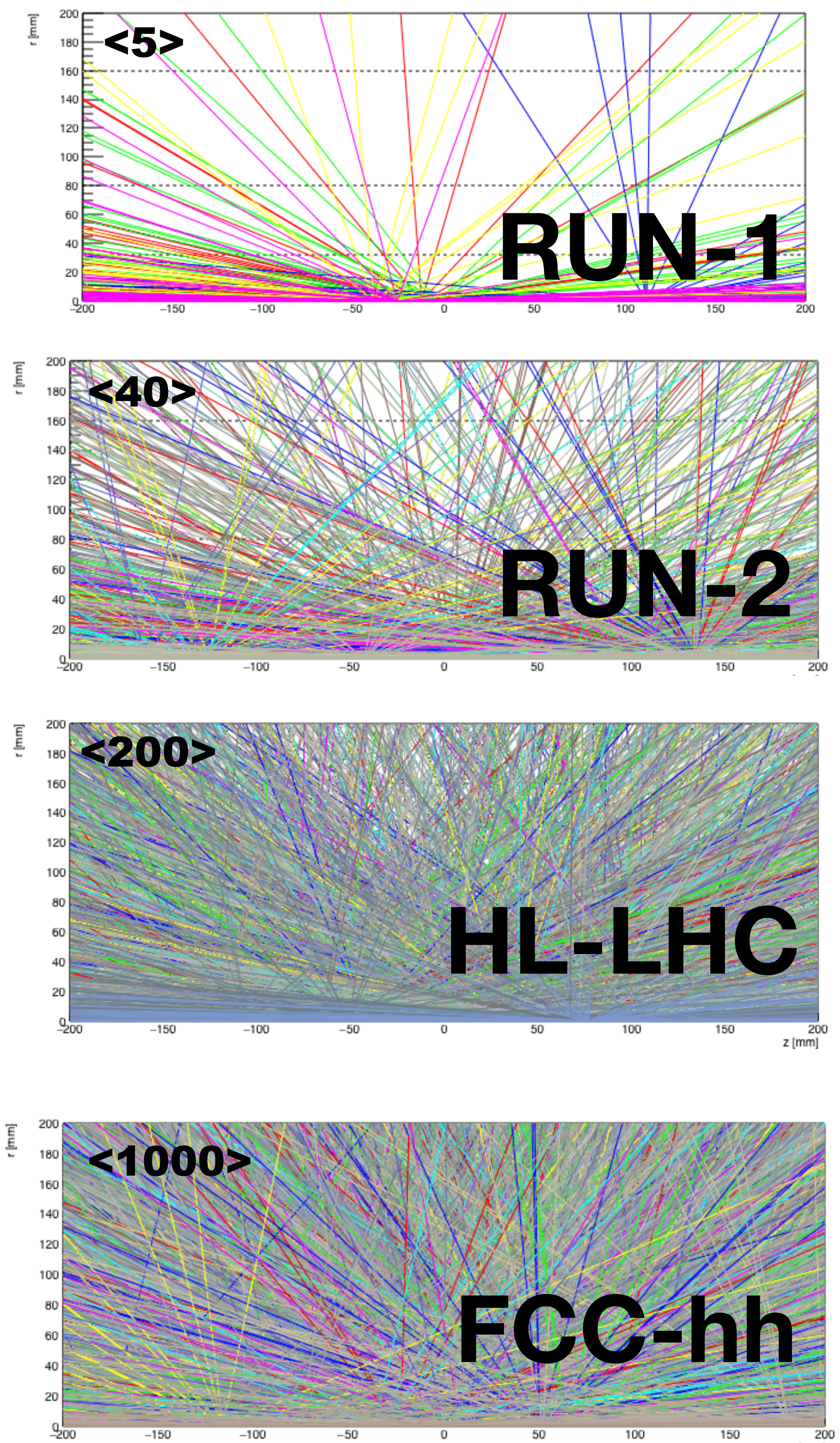


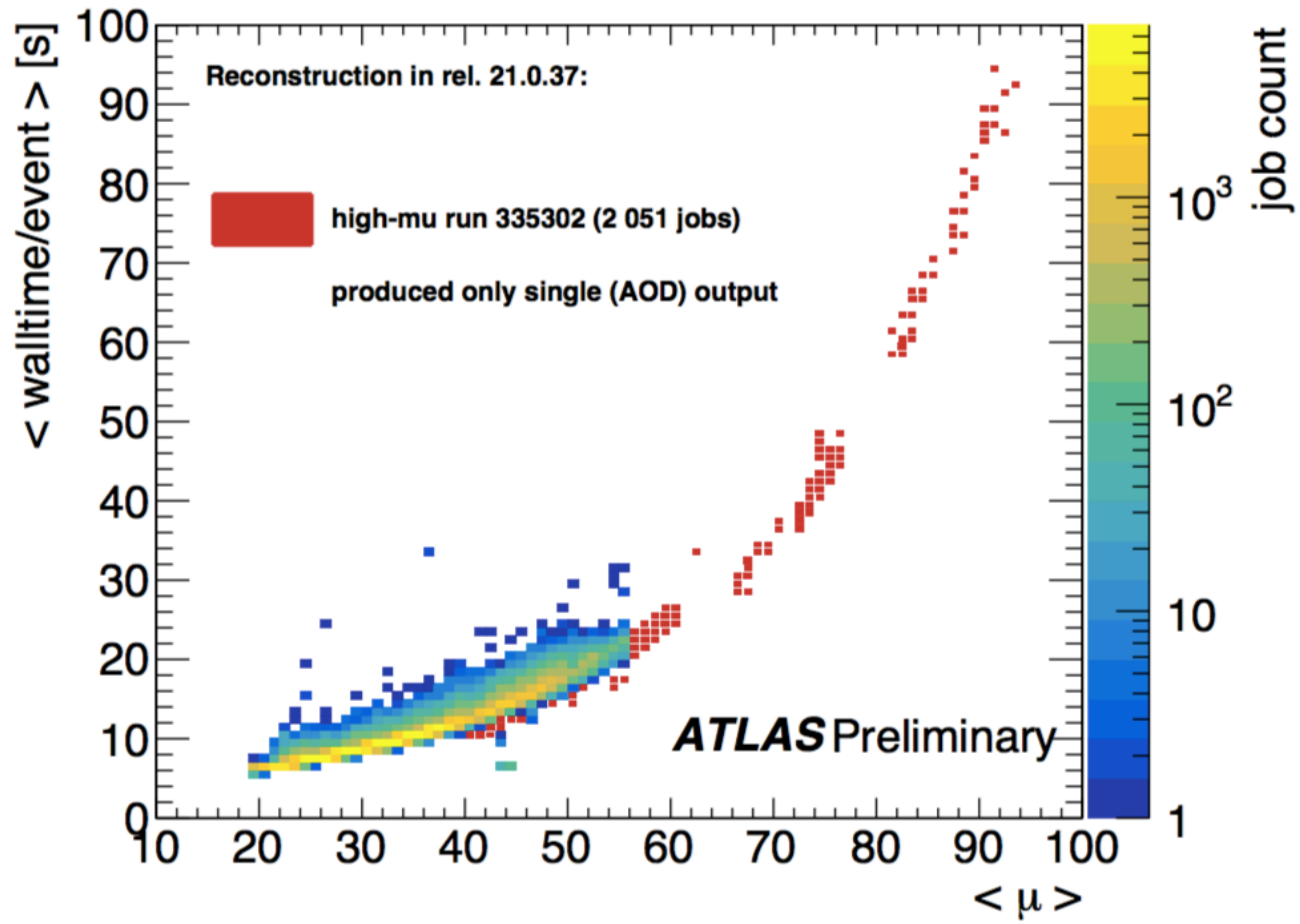


- InDetSiSpTrackFinder dominant within ID
- ~30 % of overall total reco time is spent here(!)
- Will focus on this in the next few slides

ASIDE: SITUATION WILL GET WORSE IN THE FUTURE!

Tracking at LHC, HL-LHC and FCC-hh





Pattern recognition is due to its combinatorial behavior the main CPU driver

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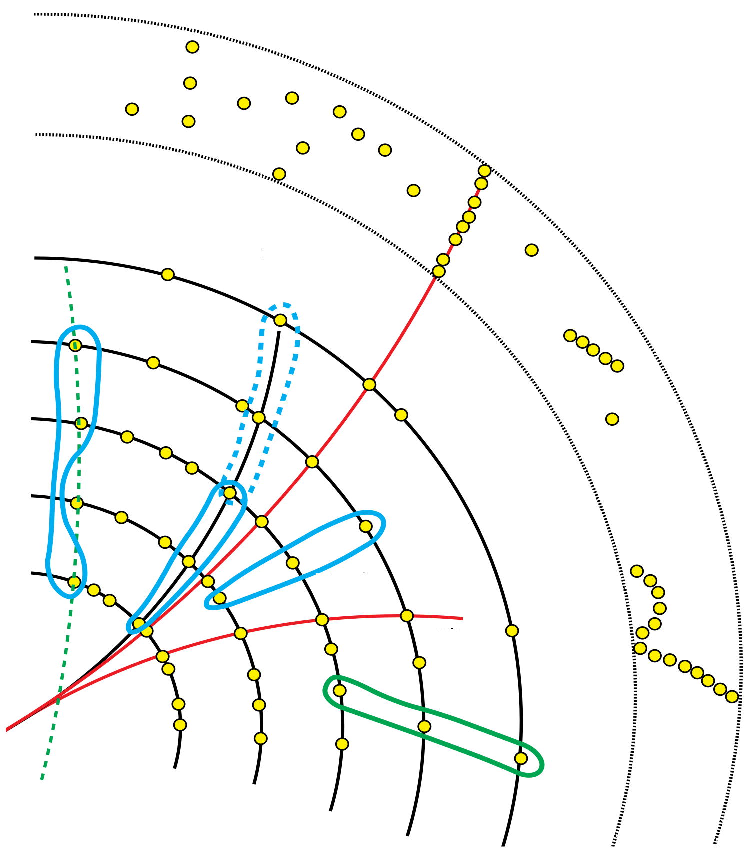
SISPSEEDEDTRACKFINDER

Robert Langenberg

Seeding goals

- Provide an initial direction ("seed") to the trackfinder where to look for a particle track
- Do not miss particles
  - A particle track for which no seed exists cannot be found
- Provide as few seeds as possible
  - Do not provide many seeds for the same track
  - Avoid creating seeds where there is no track (fakes)
- Use pattern recognition to find combinations of measurements (SpacePoints) that could stem from the same particle
  - Then use combination to localize search of trackfinder



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https://indico.cern.ch/event/742347/contributions/3065742/attachments/1682641/2703814/Acts_Review_-_Seeding.pdf

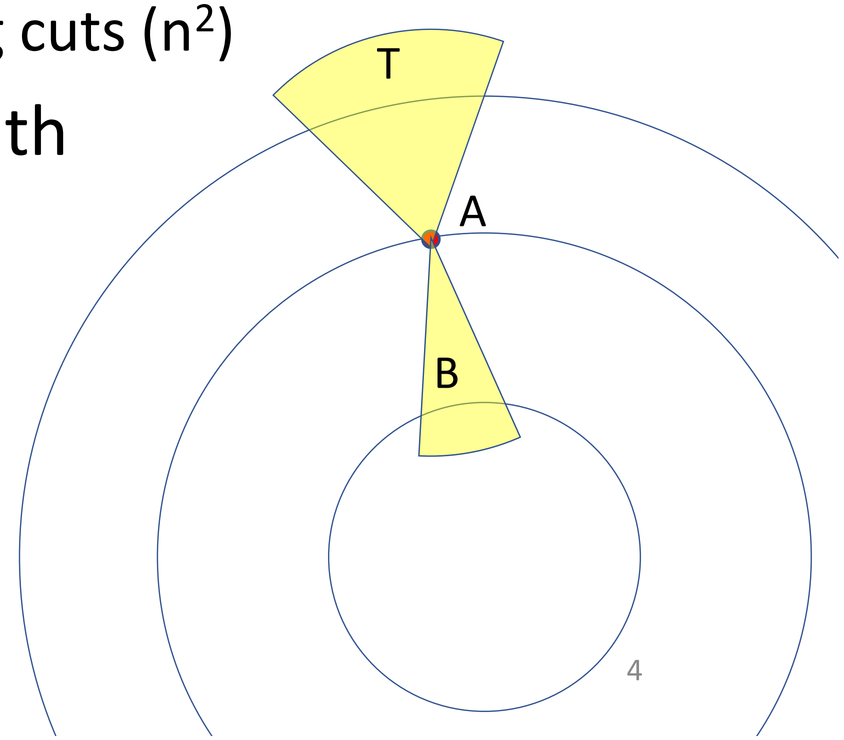
SISPSEEDEDTRACKFINDER

Robert Langenberg

The ATLAS Seedfinder - A game of cutting

- ATLAS Seedfinder: finds SpacePoint triplets (n^3 complexity)

1. Iterate over each SpacePoint (SP) A: Assume A is middle of triplet
2. Collect SP "B" closer to interaction region that satisfy cuts (n^2)
   - Then collect SP "T" further from interaction satisfying cuts (n^2)
3. Iterate over all B and attempt to form triplet with A and all T for each SP in B (n^3)
   - Apply cuts for each triplet
4. After creating all triplets for A, apply more cuts



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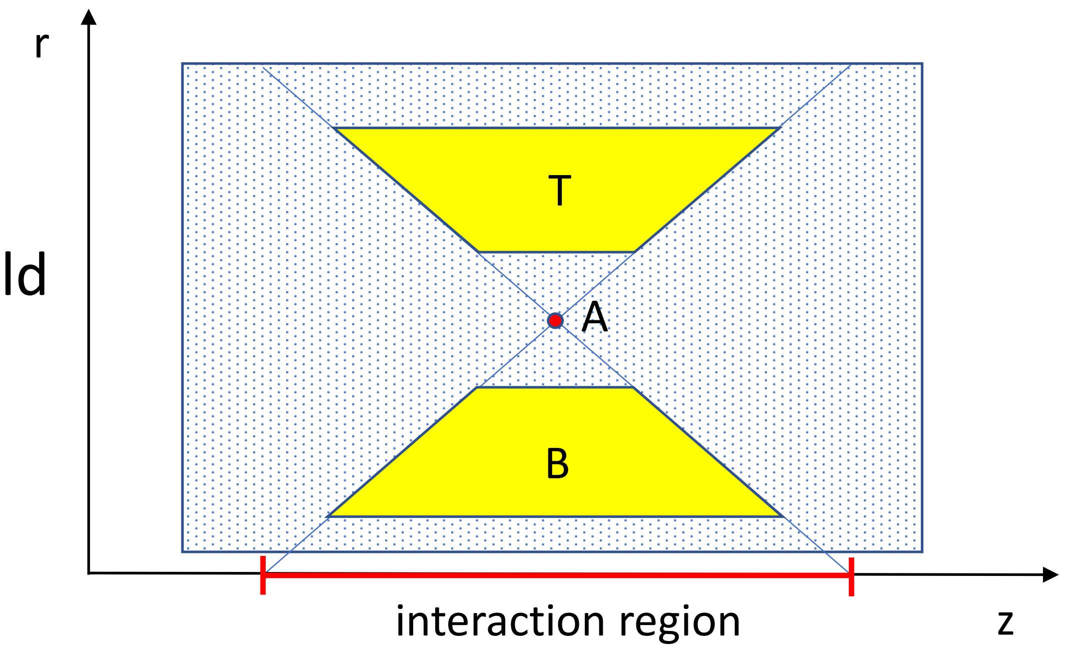
SISPSEEDEDTRACKFINDER

Robert Langenberg

What are Cuts?

- Criteria if a seed should be created
- Selection of cuts:
  - Compatibility of SP with helix in magnetic field
  - Maximum seed angle with beam line (η)
  - Difference in η within one seed
  - σ measurement errors
  - σ multiple scattering
- "Soft" cuts: Seed weight
  - Limit number of combinations per SP, only accept highest weights
  - Weight: d_0, number of compatible seeds, …



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(Closest approach in the x-y plane)

https://indico.cern.ch/event/742347/contributions/3065742/attachments/1682641/2703814/Acts_Review_-_Seeding.pdf

SISPSEEDEDTRACKFINDER: SUMMARY

- Current seedfinder is very efficient at finding tracks and has low fake rate. Is also highly optimised for serial processing, and so is fast (in that context)
    - Hopefully scope for MT gains here, because it doesn't a priori need to be serial
- However it is complex code, "fortran-like" in design, and is very hard to maintain
    - Intrinsically not thread-safe
    - Hard-coded cuts / numbers

```
if      (!(*r)->spacepoint->clusterList().second) {if(i < 20) ibl = true;}
```

```
if(Z>0.) {
  Z< 250.?z=5:Z< 450.?z=6:Z< 925.?z=7:Z< 1400.?z=8:Z< 2500.?z=9:z=10;
}
else     {
  Z>-250.?z=5:Z>-450.?z=4:Z>-925.?z=3:Z>-1400.?z=2:Z>-2500.?z=1:z= 0;
```

- Re-design being discussed as part of a new 'external' tracking toolkit: ACTS (see later)

CONDITIONS ACCESS WITHIN TRACKING

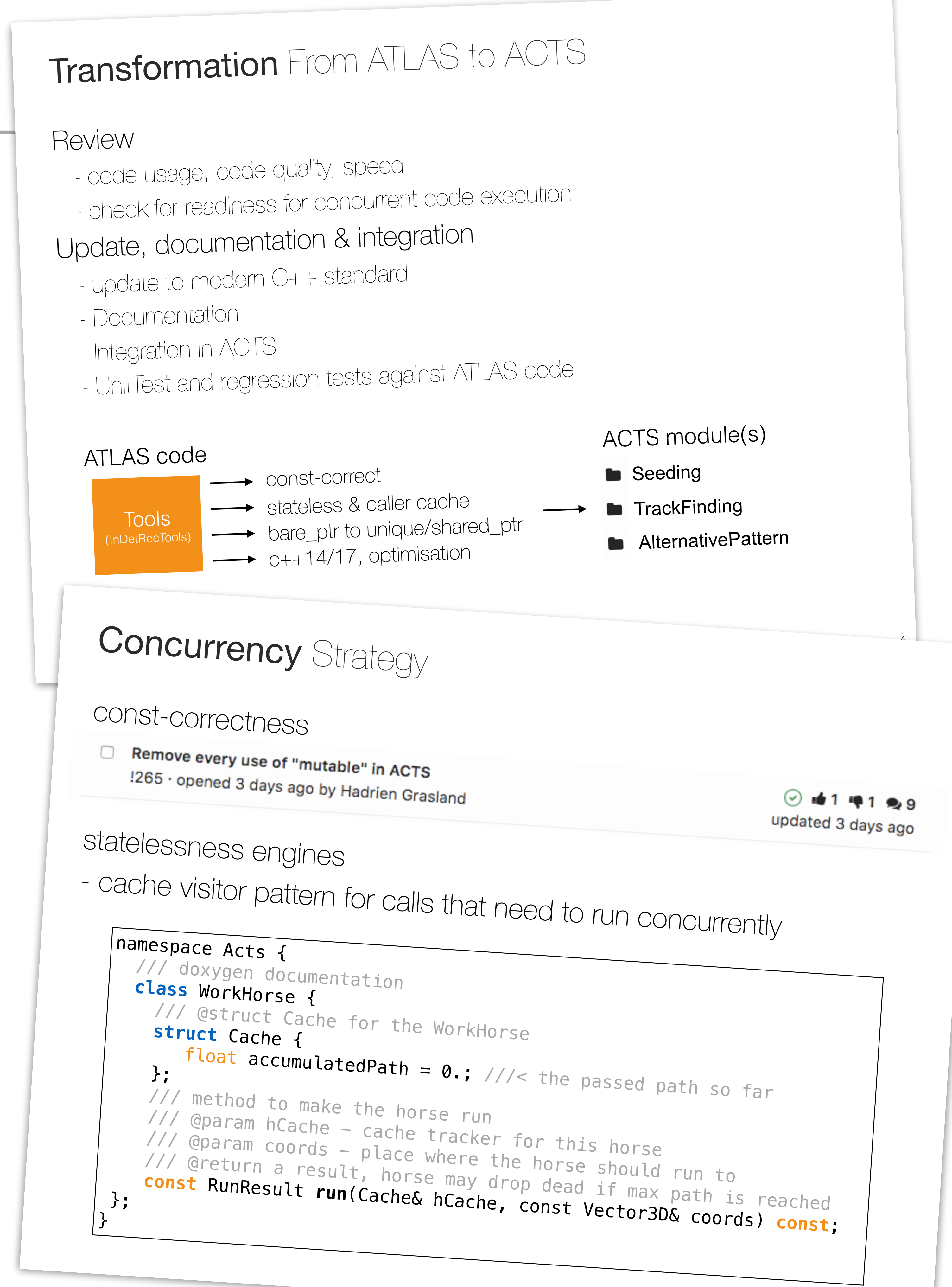
- To process ATLAS data we don't just need event data - need also conditions data
- Examples of conditions
  - Alignment, RT relations, detector status
  - Magnetic field (~120 Mb on disk, more in memory)
- Conditions typically change infrequently but some, such as alignment, can change at any time, and can have significant size
  - (See Scott's talk for technical details)

MT HOSTILE CONSTRUCTS / FUTURE DEVELOPMENTS

- ‘Tools’ which are used to share data / which have state
- Tools are called from all over the place - not always a clear dataflow
- EDM was designed for clarity - but overly complex
  - Many algorithms user simpler internal representations - expose
- Conditions access will remain a big problem

ACTS

- ACTS is track reconstruction software, based on ATLAS's, but made detector agnostic and multithreaded
- Currently under review, but likely that ATLAS will make use of this in run-3 (2020)
  - (at least for parts of ID)



ACTS (2)

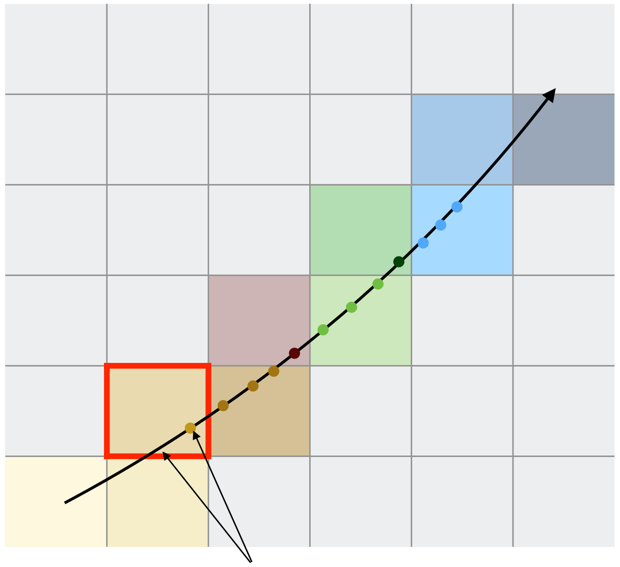
- Improve data locality / thread safety by e.g. caching magnetic field around a track

Magnetic field field caching

Magnetic field caching found to reduce CPU time in
- Simulation (up to 20%)
- Reconstruction (around few %)

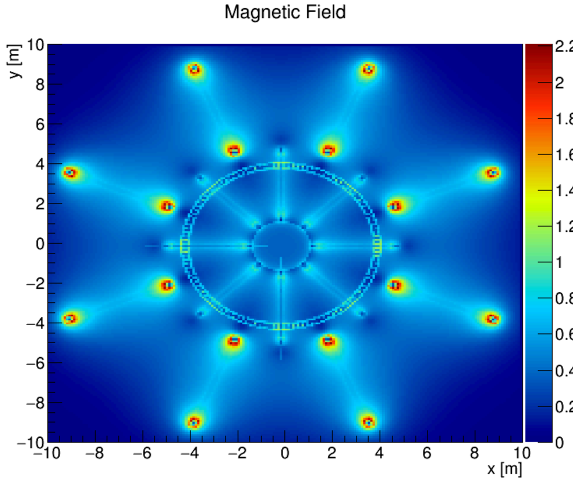
ATLAS locks the field cell in the magnetic field service
- not ideal for concurrent usage

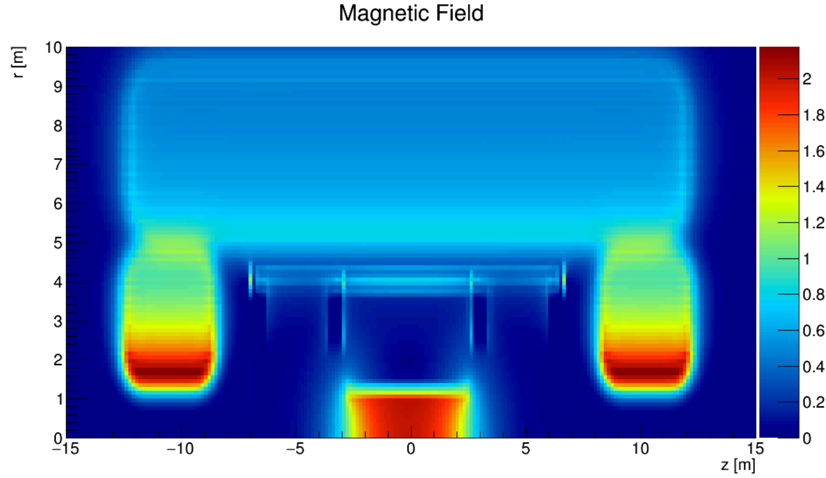
ACTS field service provides a field cell to be cached by the caller (see propagation)
- AnyCell<> concept



Magnetic field

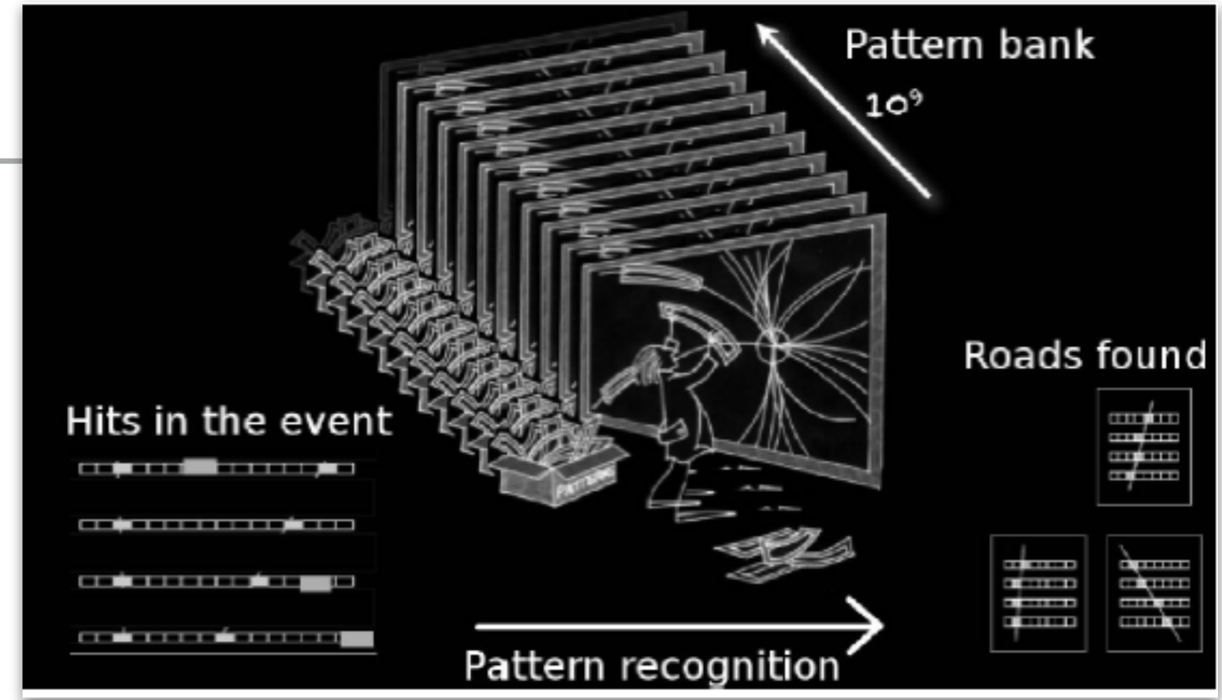
Tests using different magnetic field inputs within ACTS
- ATLAS map (currently converted from ATLAS root file), direct use of ATLAS MagneticFieldSvc possible (template parameter)
- FCC-hh field map



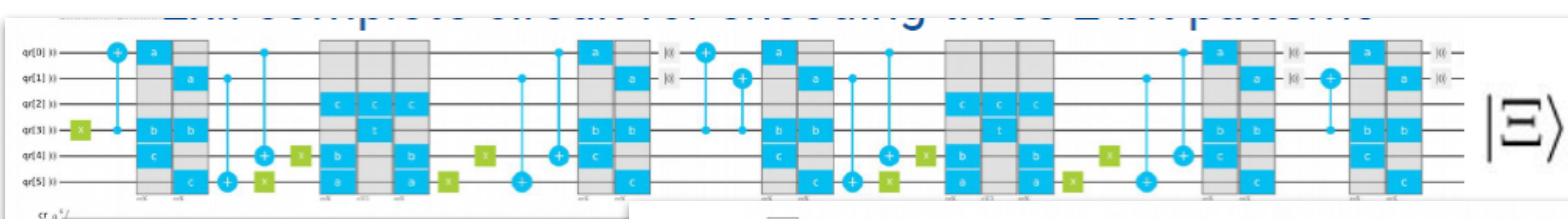


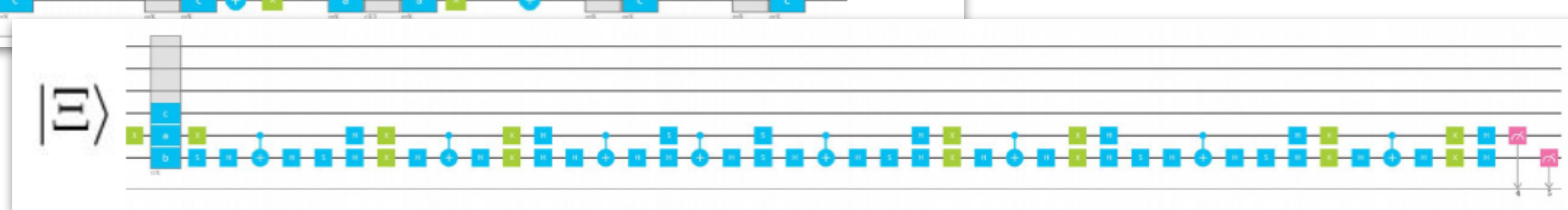
PARALLEL(LIZABLE) ALGORITHMS

ATLAS FAST TRACKER

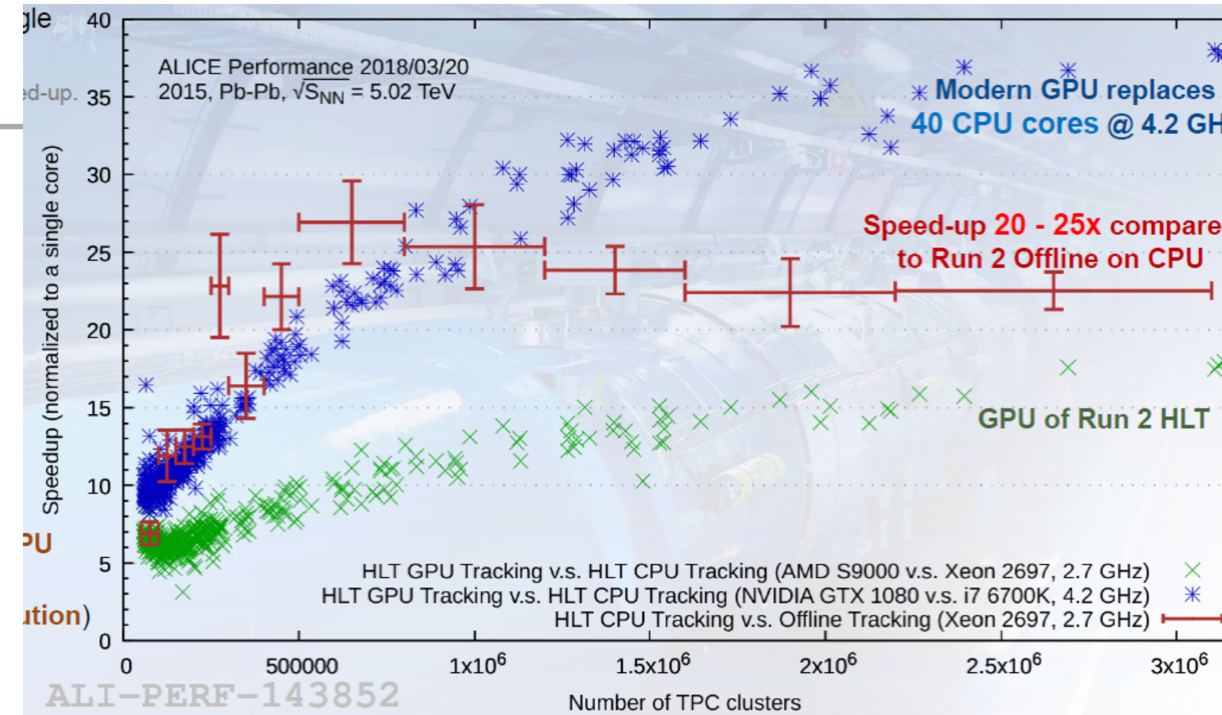


- Constant-time track finding using associative memory lookup
    - Trading off speed for memory footprint (offline-simulation requires >20GB in Run 2 conditions).
        - Memory size (5×10^9 pattern bank) limits resolution, hence purity
- Followed by traditional extrapolation, χ^2 selection, parameter fitting
- 13K ASIC+3K FPGA implementation runs in microseconds
- Data Parallel (geometrical segmentation, multiple candidates)





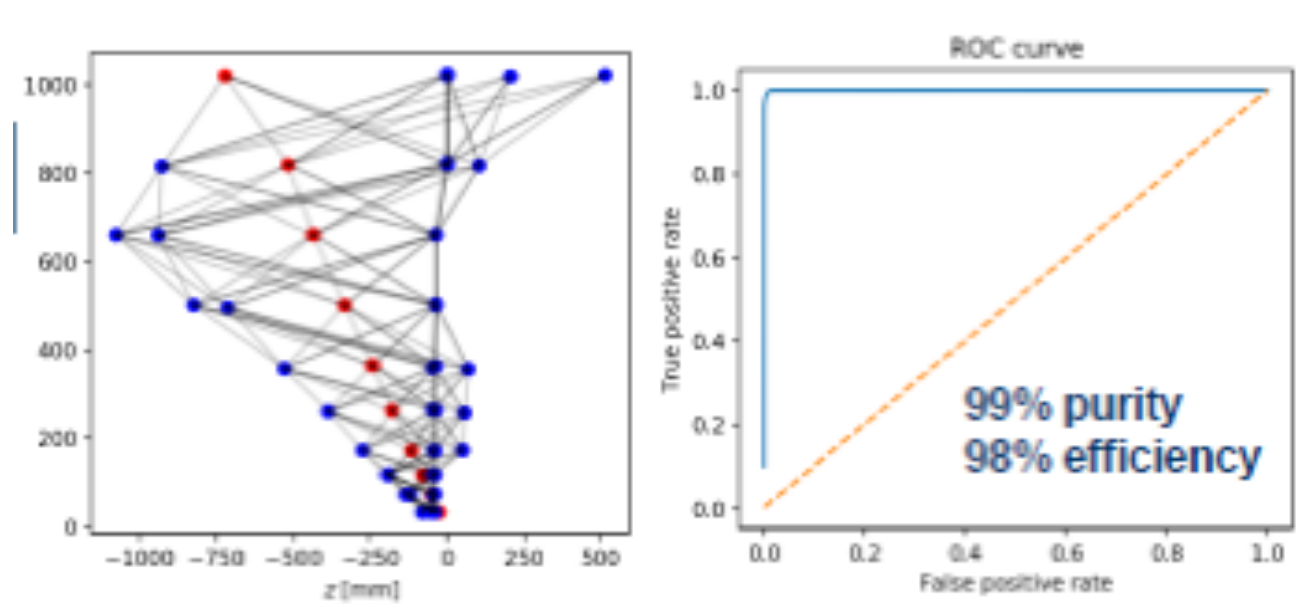
SIMD SEEDING



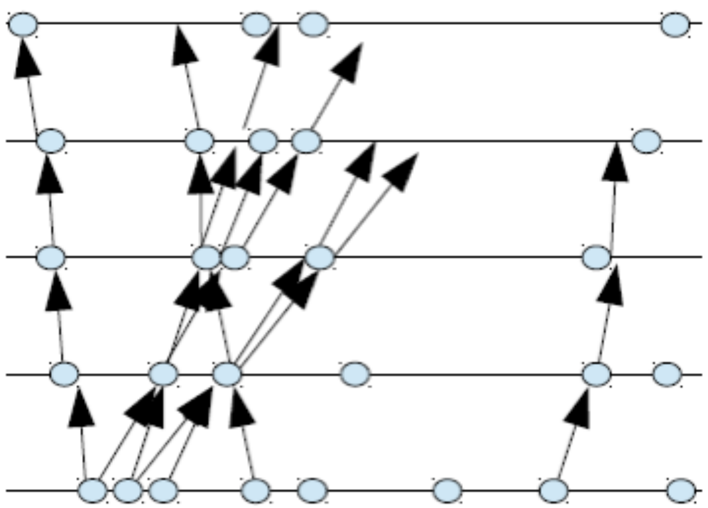
- Early focus on seed creation and filtering. Targeting accelerators

1. Seeding loop parallelization (ATLAS HLT)

2. Cellular automata (CMS, ALICE)
3. GNN seed classifier (HEP.TrkX)



PARALLEL TRACK FINDING



$$
\begin{aligned}
x_k^{k-1} &= \mathbf{F}_{k-1} x_{k-1} \\
\mathbf{C}_k^{k-1} &= \mathbf{F}_{k-1} \mathbf{C}_{k-1} \mathbf{F}_{k-1}^T + \mathbf{Q}_{k-1} \\
r_k^{k-1} &= m_k - \mathbf{H}_k x_k^{k-1} \\
\mathbf{R}_k^{k-1} &= \mathbf{V}_k + \mathbf{H}_k \mathbf{C}_k^{k-1} \mathbf{H}_k^T \\
\mathbf{K}_k &= \mathbf{C}_k^{k-1} \mathbf{H}_k^T \left(\mathbf{R}_k^{k-1}\right)^{-1} \\
x_k &= x_k^{k-1} + \mathbf{K}_k r_k^{k-1} \\
\mathbf{C}_k &= (\mathbf{I} - \mathbf{K}_k \mathbf{H}_k) \mathbf{C}_k^{k-1} \\
\chi_+^2 &= r_k^{k-1T} \left(\mathbf{R}_k^{k-1}\right)^{-1} r_k^{k-1} \\
\chi_k^2 &= \chi_{k-1}^2 + \chi_+^2
\end{aligned}
$$

- CMS parallel Kalman Filter (mkFit)
  - Parallelizes and vectorized nicely on CPU
    - Matriplex data structure optimized to vectorize small matrix linear algebra
  - Poor performance on GPUs so far
    - Memory cache bandwidth
- TrackML: track finding Kaggle challenge
  - 561 entries so far, two weeks to go. 85% “efficiency” achieved.
- HEP.TrkX: RNN Gaussian predictors (filter+regression)
- BM@N GEM combined track finding NN (classifier+regression)

CONCLUSION

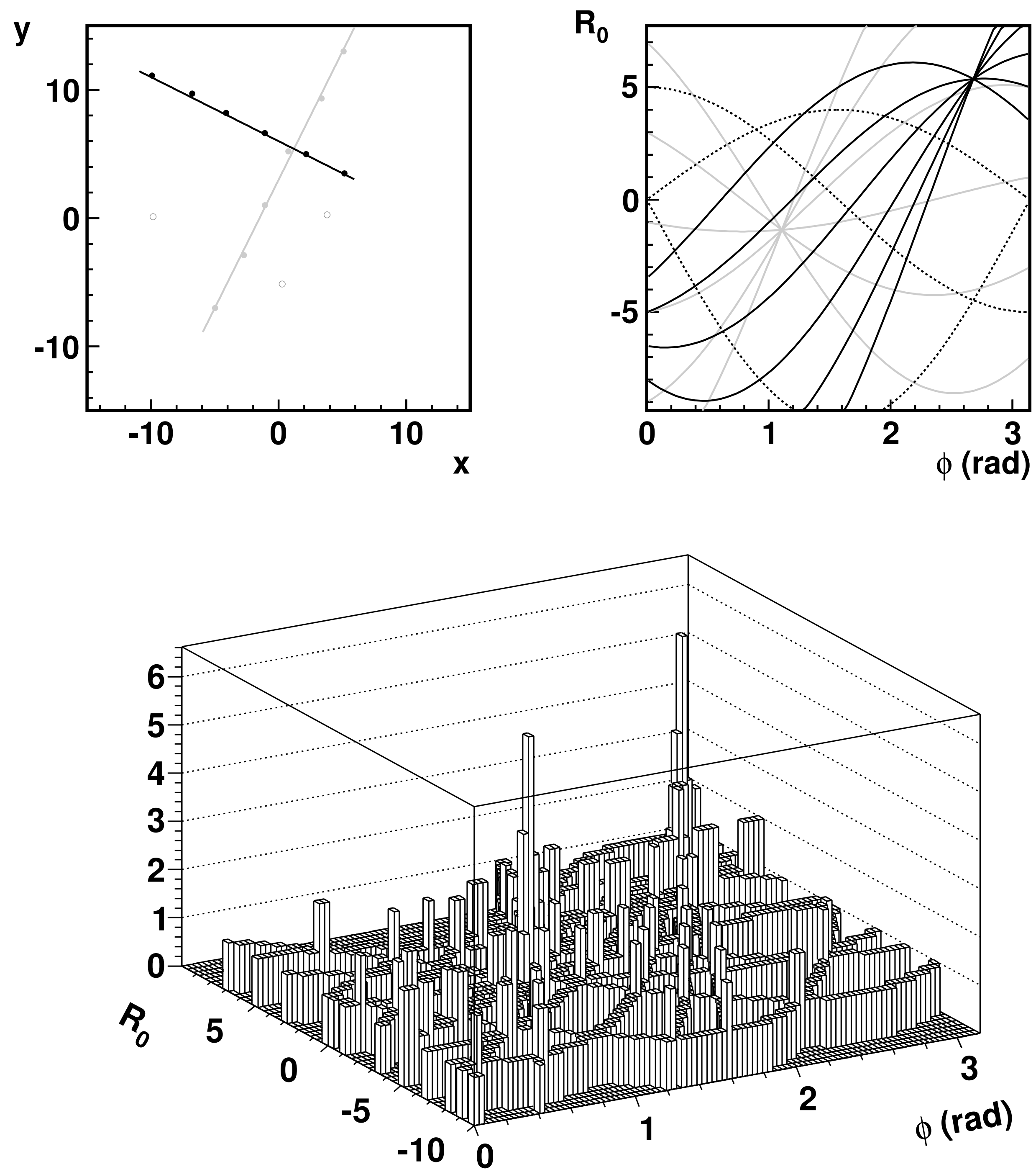
- ATLAS Tracking is highly physically performant and (we believe!) well optimised for serial processing
- Migrating to work in MT will be a significant challenge
  - Some thread-hostile design, lots of thread-hostile implementation
  - Limited person-power to radically re-think algorithms (which is likely necessary)
- "Externals" like ACTS looks like promising options to explore
- Also interesting work happening in the community with parallelizable algorithms

BACKUP

https://indico.cern.ch/event/394320/contribution/2/attachments/789437/1082040/MuonRecoOverview.pdf

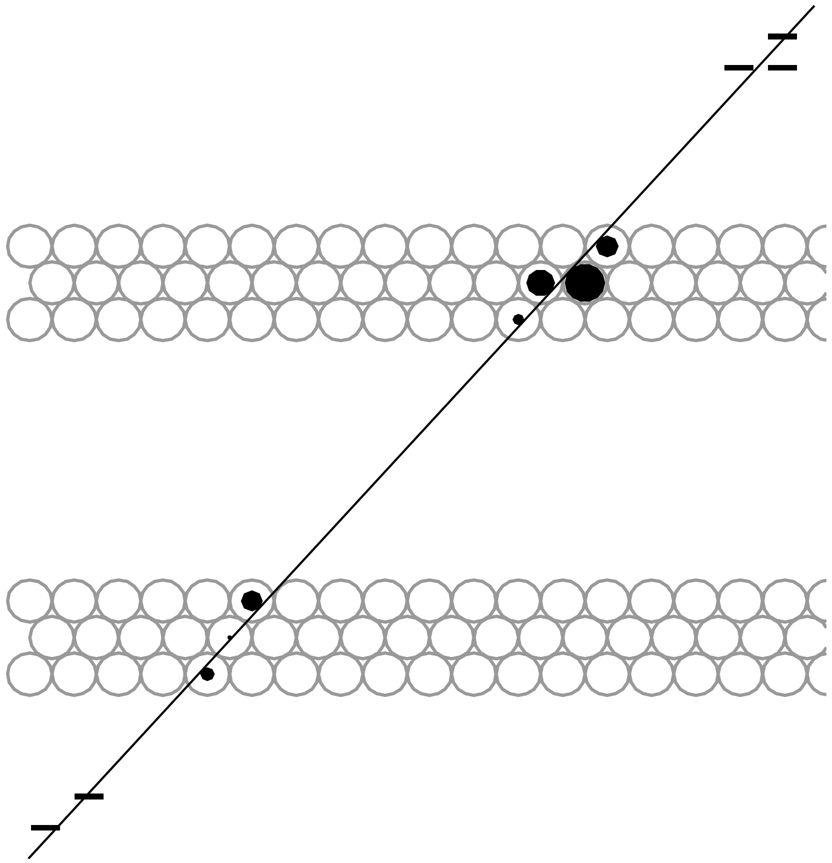
Hits pattern finding

- **Use 2D Hough transform using (R0,φ)**
- **The Hough transform**
  - transforms points in the x,y space into lines in R0,φ
  - straight lines in the xy plane are points in the Hough space
    - the lines of all hits from a given line cross in one point in the Hough space
    - when combined with a histogramming technique the problem reduces to finding the bins with the highest value in the histogram
- **Advantages of the method**
  - very good background rejection properties
  - complexity almost linear with number of hits



Segment finding (MDT)

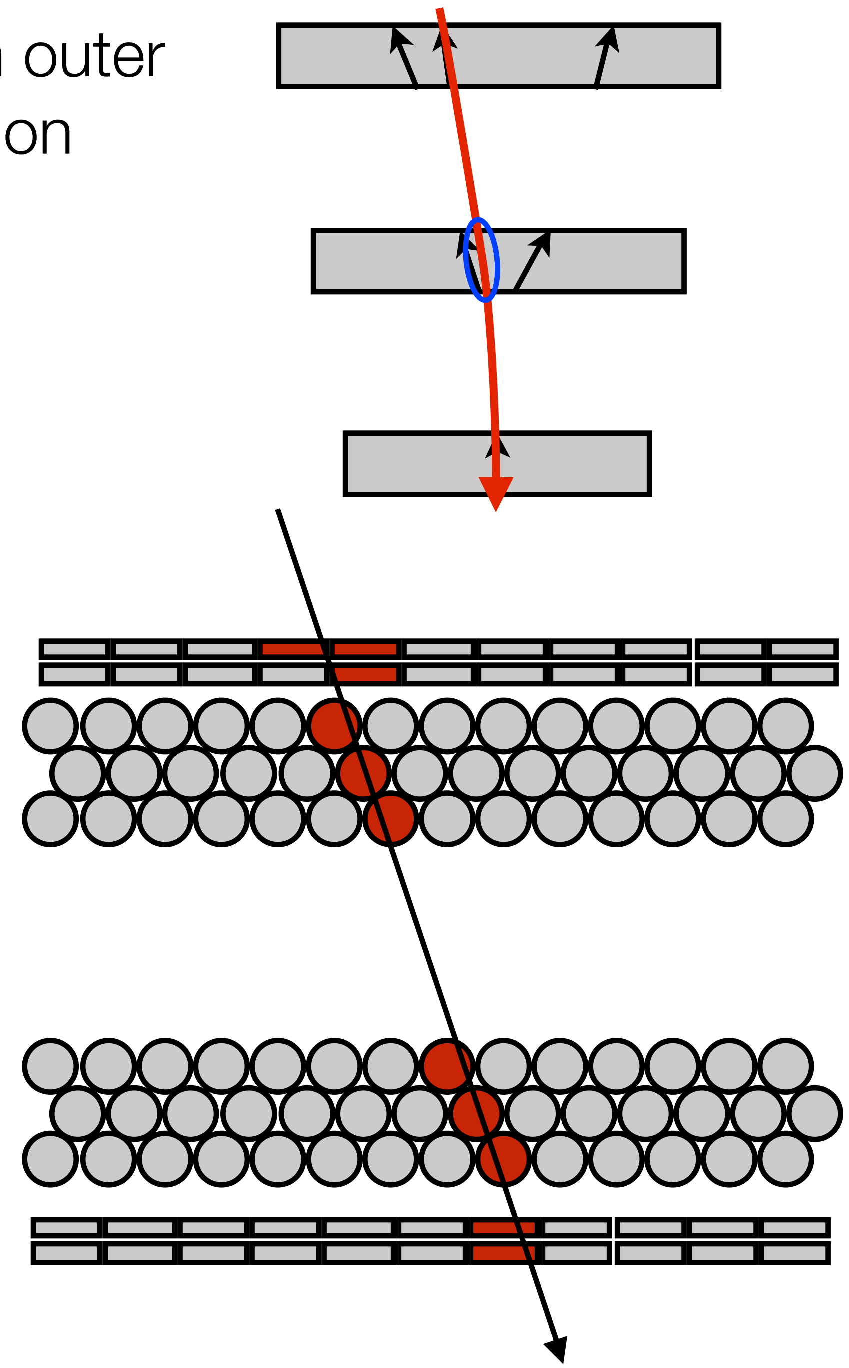
- Local segment finding in the individual MDT stations offers a powerful way of reducing combinatorics
  - the bending of muons above p = 3 GeV is sufficiently small: their trajectory can be approximated by a straight line
  - MDTs provide a very high precision measurement of the trajectory of the muon (80µm average resolution) -> good background rejection
  - trigger confirmation can be used to reduce out-of-time background



Track finding

- **Four stage track reconstruction**
  - Select high quality seed segment
  - Look for chambers crossed by the track without hits
  - Calculate track intersection with the chamber
    - Search for hits in a road around the intersection
  - Add hits to the track
    - First add trigger hits (if any) and refit
    - Run MDT segment finding if more than three MDT hits are within the road
  - Rerun hole search if any hits were added
  - Add crossed channels without hits to the track as holes

Seed in outer station



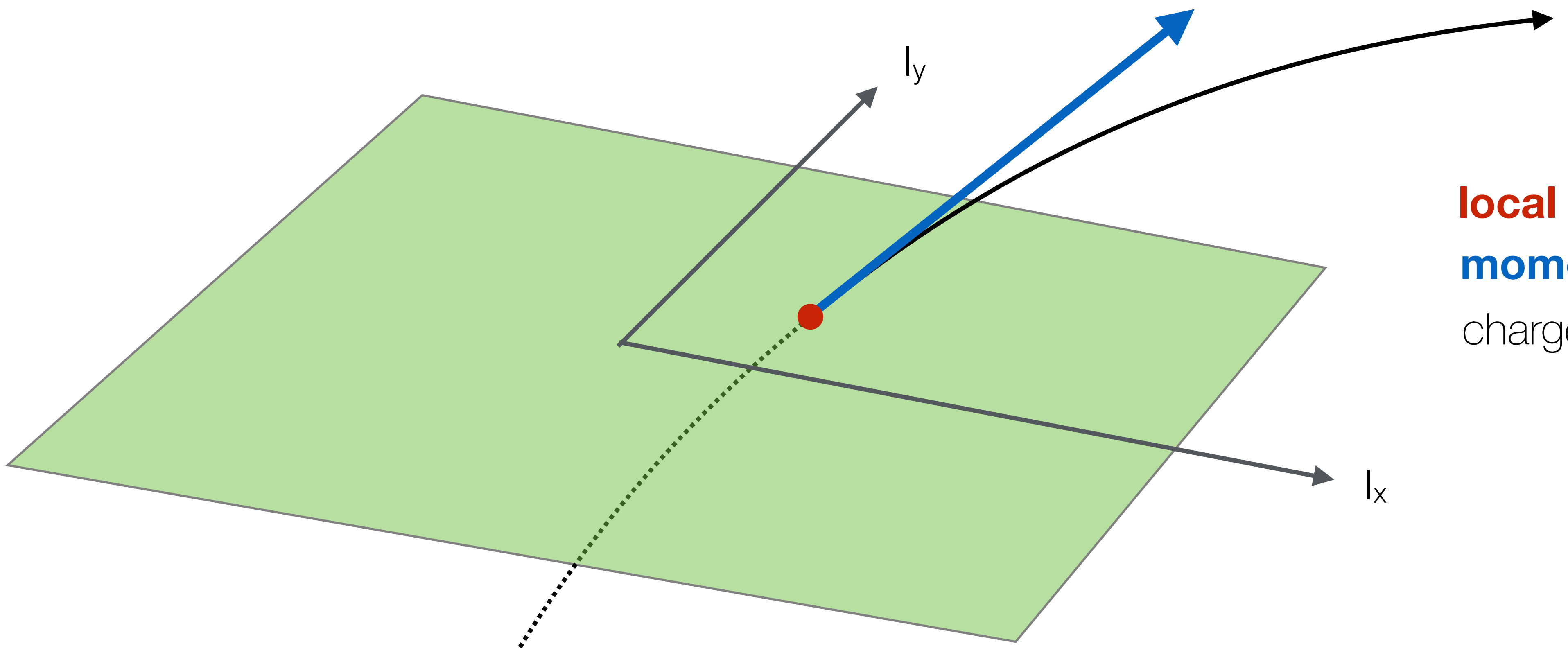
Muon reconstruction

- Final stage is combination (not covering in any detail here):
  - Combined muons - ID + MS hits, full refit
    - Can also be ID seeded - i.e. extrapolate ID track to MS and start reconstruction in that road
  - Standalone muons - no ID track, so just MS
  - Segment tagged muons - ID track + matching segment
  - Calo tgged muons - ID track + matching calorimeter energy deposit
- Code is already highly optimised
  - Competition between competing software chains, and various software reviews
  - Code used in trigger, where performance is very important
  - Recently largely re-written
  - LOTS of details in summary talk from Niels here:
    - https://indico.cern.ch/event/279845/session/0/contribution/1/attachments/512634/707448/TrackingLectureMuons.pdf

Definitions Track parameterisation

Charged particle trajectory parameterisation

- five parameters needed to describe a trajectory localisation on a surface



local position on surface

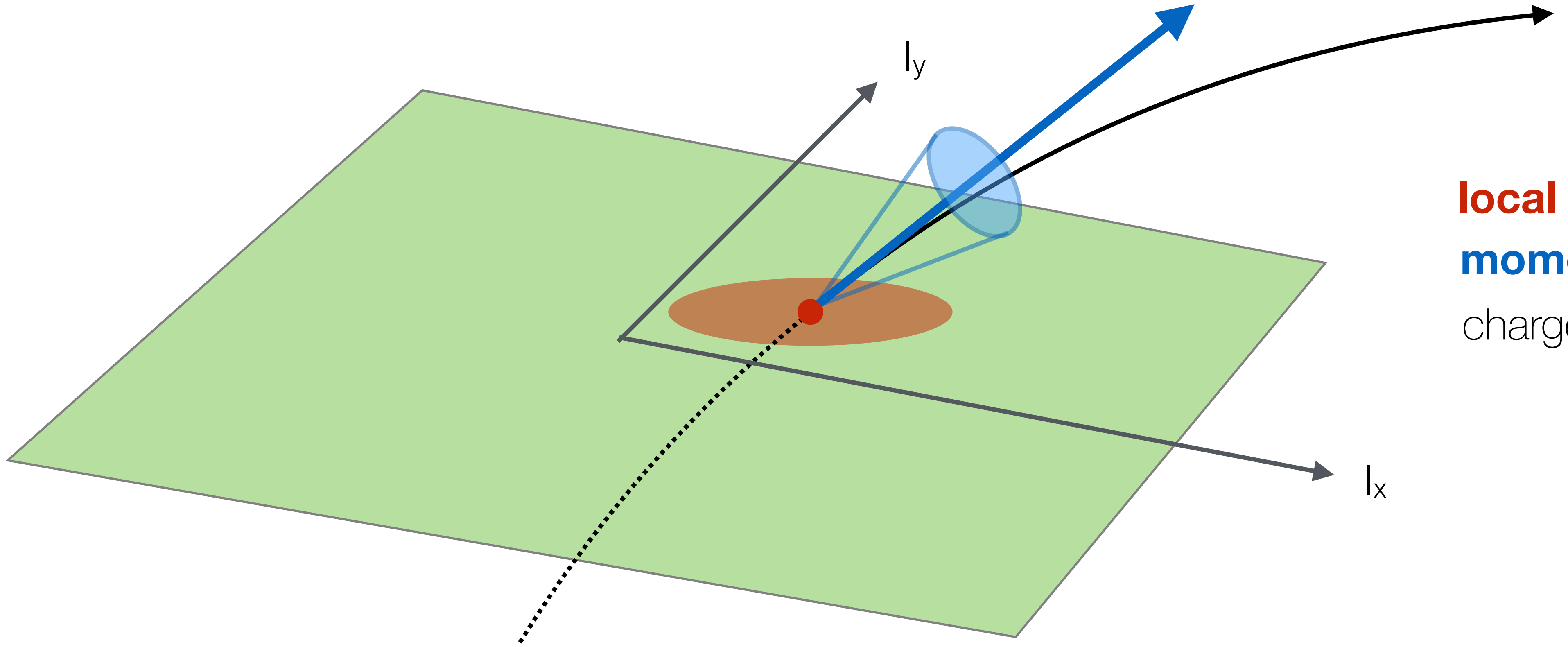
momentum

charge

$$\mathbf{q} = (l_1, l_2, \phi, \theta, q/p)$$

Definition Track parameterisation

Obviously, every measurement has associated errors



$$\mathbf{q} = (l_1, l_2, \phi, \theta, q/p)$$

$$\mathbf{C} = \begin{pmatrix} \sigma^2(l_1) & cov(l_1,l_2) & cov(l_1,\phi) & cov(l_1,\theta) & cov(l_1,q/p) \\ . & \sigma^2(l_2) & cov(l_2,\phi) & cov(l_2,\theta) & cov(l_2,q/p) \\ . & . & \sigma^2(\phi) & cov(\phi,\theta) & cov(\phi,q/p) \\ . & . & . & \sigma^2(\theta) & cov(\theta,q/p) \\ . & . & . & . & \sigma^2(q/p) \end{pmatrix}$$

Introduction Tracking detectors - pixel detector

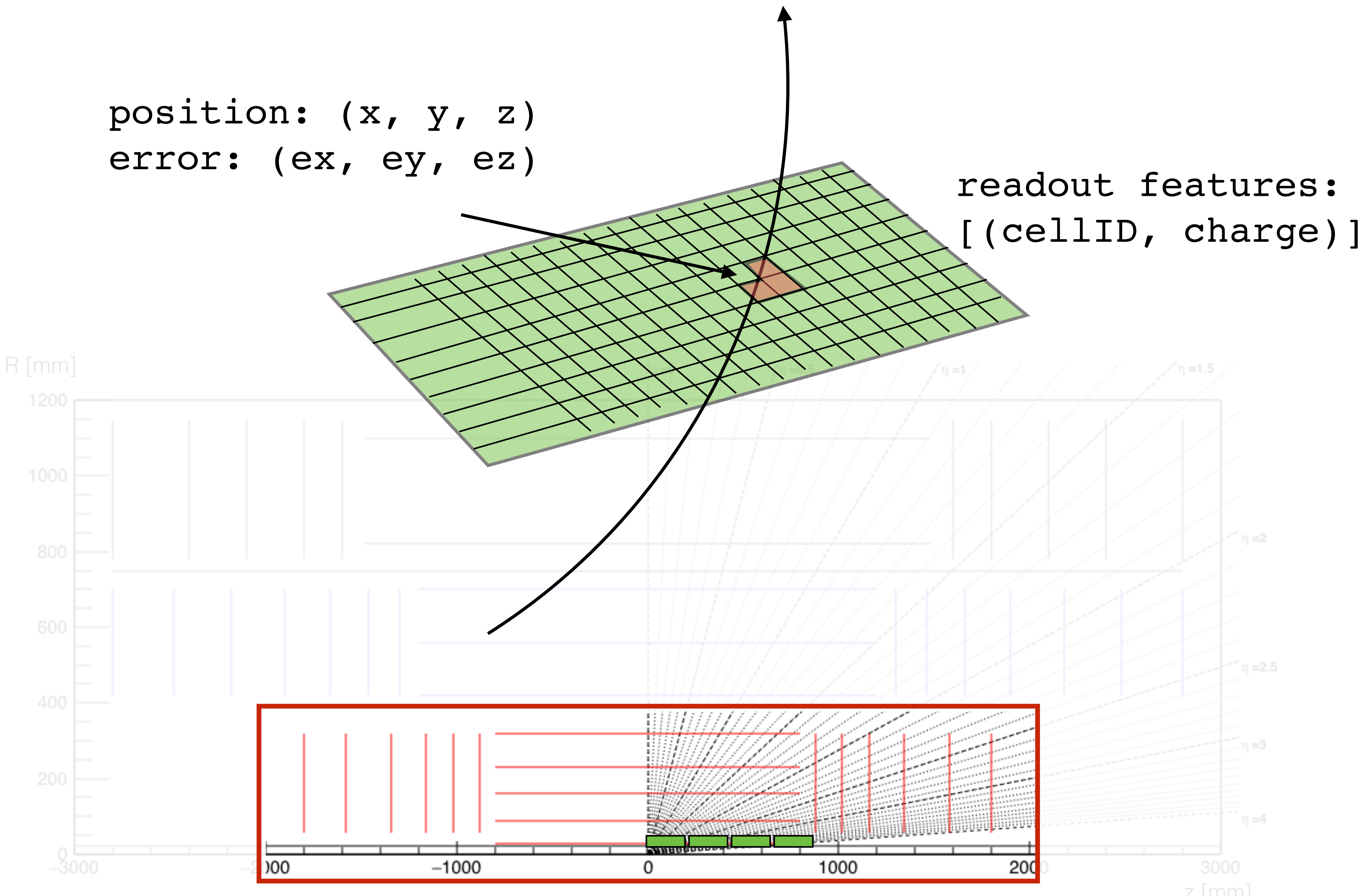


Illustration:
Longitudinal view of a schematic Tracking detector with a central barrel and endcap system.

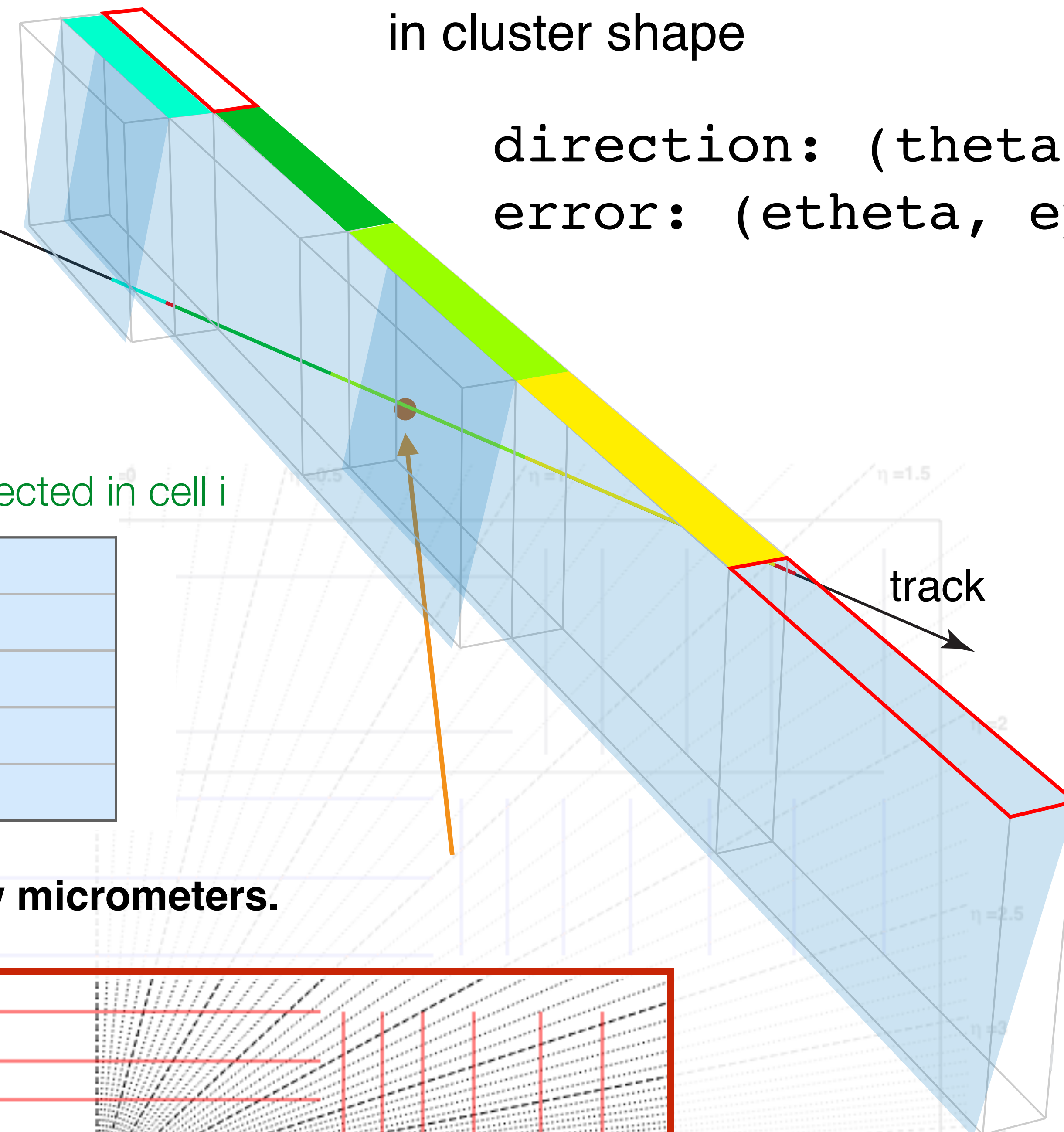
Introduction Tracking detectors - pixel detector

Multiple cells hit can be used to increase measurement precision

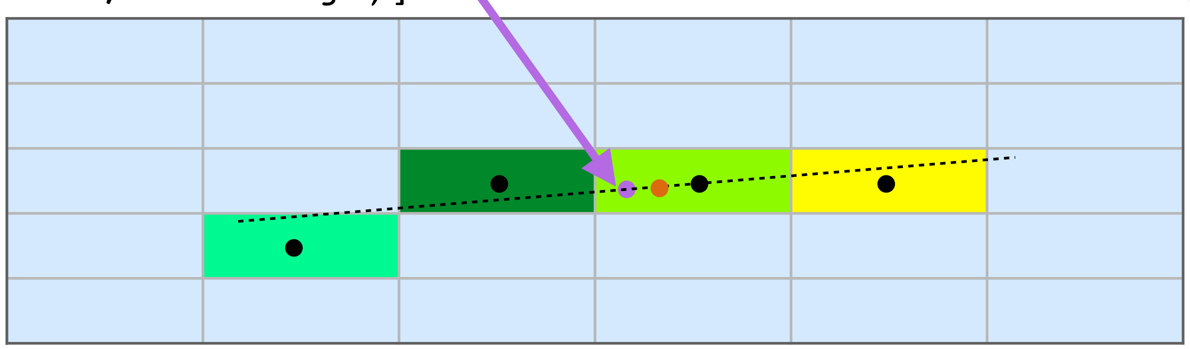
the charge-weighted approach :

$$\mathbf{m} = \frac{1}{\sum_{i=1,N} q_i} \sum_{i=1,N} q_i l_i$$

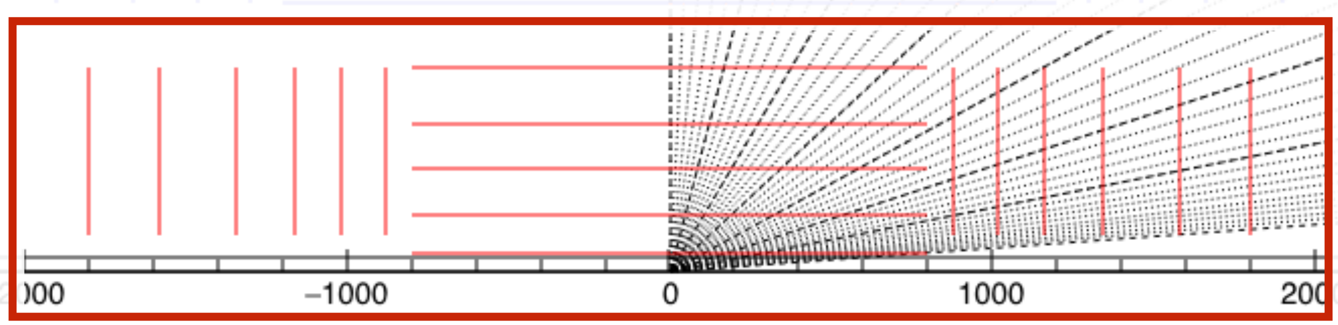
charge collected in cell i



`[(cellID, c. charge)]`



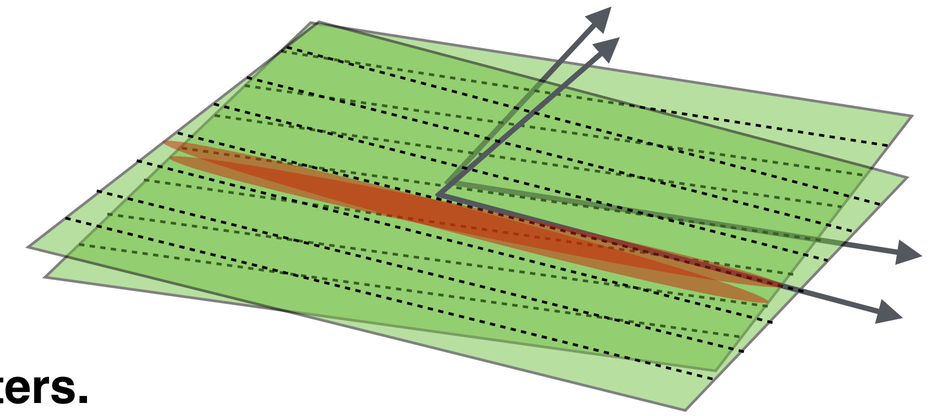
Measurement precision of a **few micrometers.**



Illustrations:
A particle passing through a pixel silicon sensor: it provides a track localisation and some information about the track angle.

Introduction Tracking detectors - strip detector

Strip detector is less precise
- often realised with a double layer structure



Measurement precision of a **few tens of micrometers.**

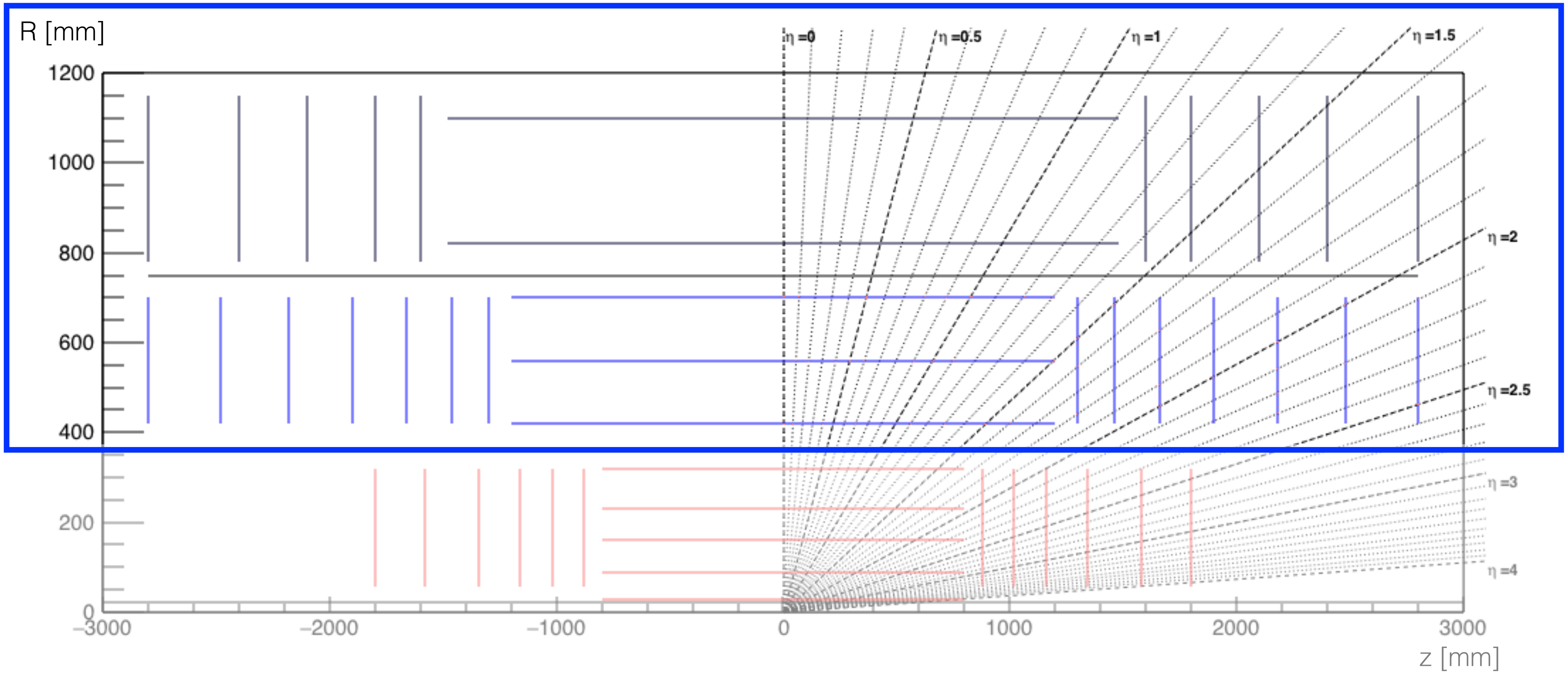
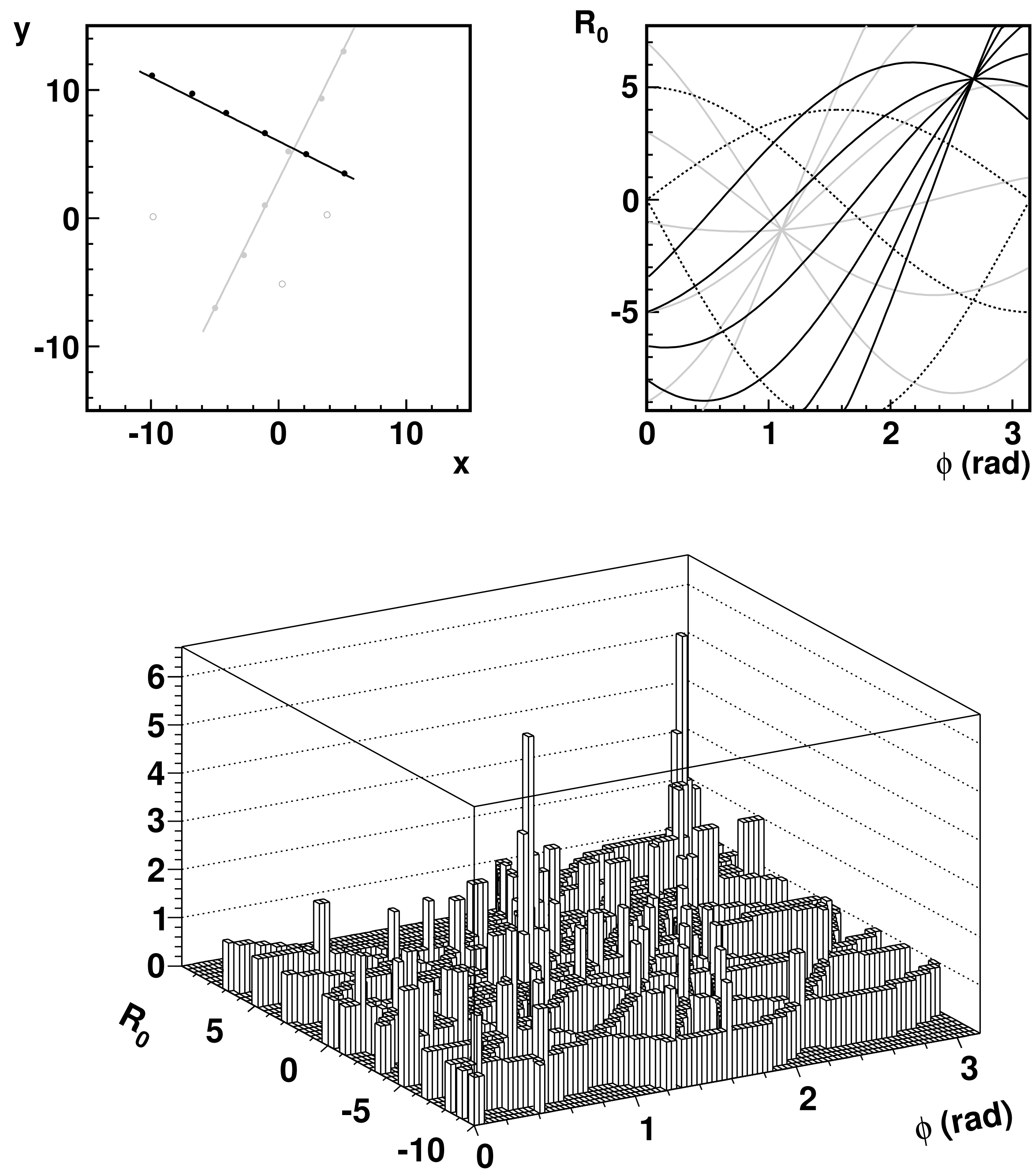


Illustration:
Longitudinal view of a schematic Tracking detector with a central barrel and endcap system.

https://indico.cern.ch/event/394320/contribution/2/attachments/789437/1082040/MuonRecoOverview.pdf

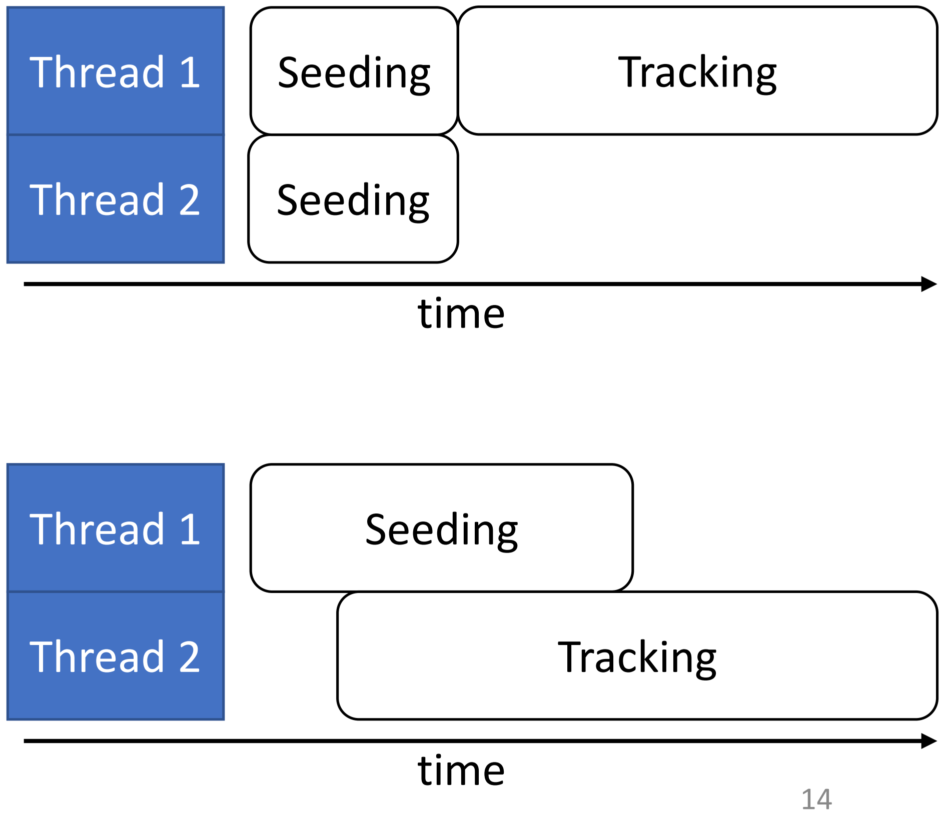
Hits pattern finding

- **Use 2D Hough transform using (R0,φ)**
- **The Hough transform**
  - transforms points in the x,y space into lines in R0,φ
  - straight lines in the xy plane are points in the Hough space
    - the lines of all hits from a given line cross in one point in the Hough space
    - when combined with a histogramming technique the problem reduces to finding the bins with the highest value in the histogram
- **Advantages of the method**
  - very good background rejection properties
  - complexity almost linear with number of hits

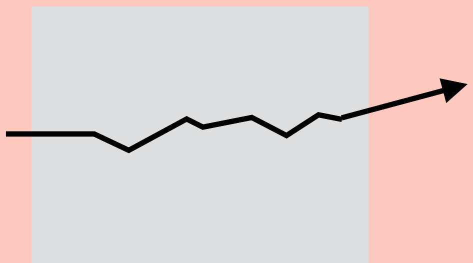
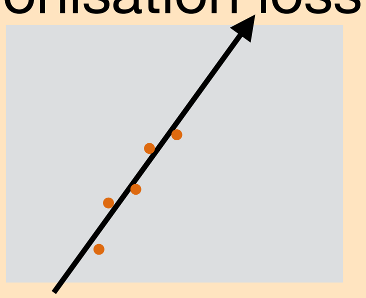
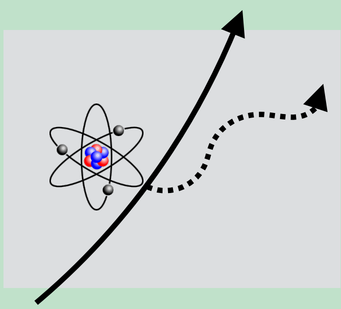
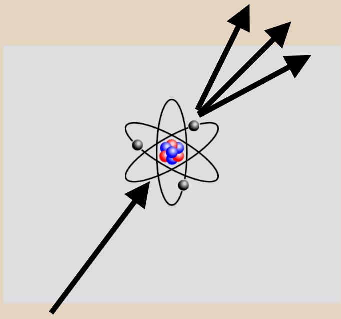


Parallelizability of Rewritten Seedfinder

- Thread Safe
  - All functions const
  - State carried in function arguments
- Parallelizable per SpacePoint
  - Fine-grained parallelism – task size can be configured arbitrarily
  - If SP/Seeds do not carry state – no such state needed for ATLAS Seeding
- Output written to queue – tracking can start while more seeds are still created
  - Limit number of seeds created per call to limit memory usage



Material Effects Summary

Type	particles	fund. parameter	characteristics	effect
Multiple Scattering 	all charged particle	radiation length X_0	almost gaussian average effect 0 depends $\sim 1/\mathrm{p}$	deflects particles, increases measurement uncertainty
Ionisation loss 	all charged particle	effective density $A/Z * \rho$	small effect in tracker, small dependence on p	increases momentum uncertainty
Bremsstrahlung 	all charged particle, dominant for e	radiation length X_0	highly non-gaussian, depends $\sim 1/\mathrm{m}^2$	introduces measurement bias
Hadronic Int. 	all hadronic particles	nuclear interaction length Λ_0	destroys particle, rather constant effect in p	main source of track reconstruction inefficiency