Belle II as an Example

TRACKING IN PARTICLE PHYSICS EXPERIMENTS

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1.

WHAT IS TRACKING?

WHAT DO WE NEED TRACKING FOR?

Overview

Tracking is part of the data analysis and reconstruction stack for transforming the detector measurements into physically meaningful results.

Many high energy physics experiments rely on the precise measurement of a particle's trajectory to:

- Measure the charge and the momentum (three spatial components by using the applied magnetic field).
- Reconstruct the production point (vertex) of a set of secondary particles.
- Measure the energy loss in the detector material (by using the deposited energy in the sensor region).
- Connect the particles between detectors (across the boundaries)

HOW DOES TRACKING WORK?

Principle

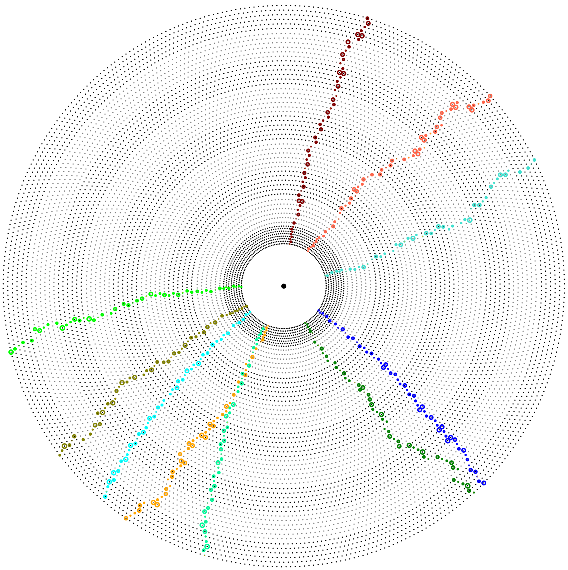
The main idea is to estimate a particle's trajectory by multiple point measurements along its flight path.

Because of the Lorentz force in the applied magnetic field, the trajectory of the charged particles can be described by a helical path:

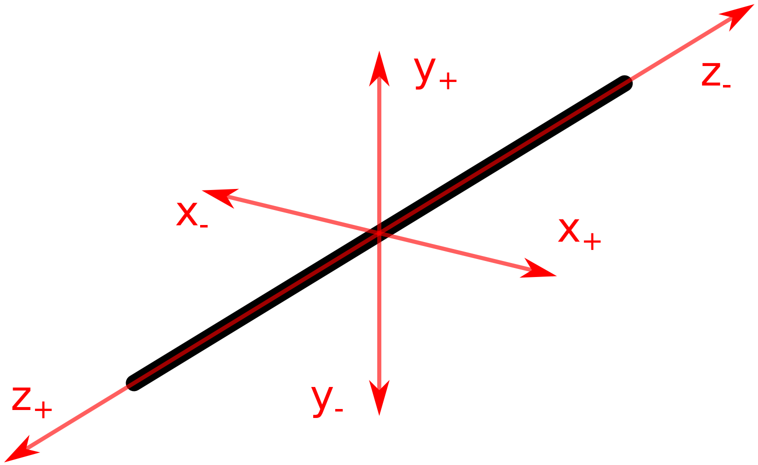
$$|\vec{p}_T| = qBR \qquad |\vec{p}_T| = |\vec{p}|\cos(\theta)$$

with the radius R, the charge q and the magnetic field B.

HOW DOES TRACKING WORK?



COORDINATE SYSTEM



HOW DOES TRACKING WORK?

In most of the cases, we are interested in the 5 parameters of the helix describing the trajectory of the charge particles:

- d_0: the distance to the perigee in two dimensions $\sqrt{x^2 + y^2}$.
- ω: the signed curvature of the track $\propto q/|\vec{p}_T|$.
- ϕ: the direction of the transverse momentum at the perigee $\arctan(p_y/p_x)$.
- z_0: the distance to the perigee in z-direction.
- $\tan\lambda$: the slope of the track in the rz-plane $\arctan(p_z/|\vec{p}_T|)$.

WHAT IS TRACKING (SIMPLIFIED)?

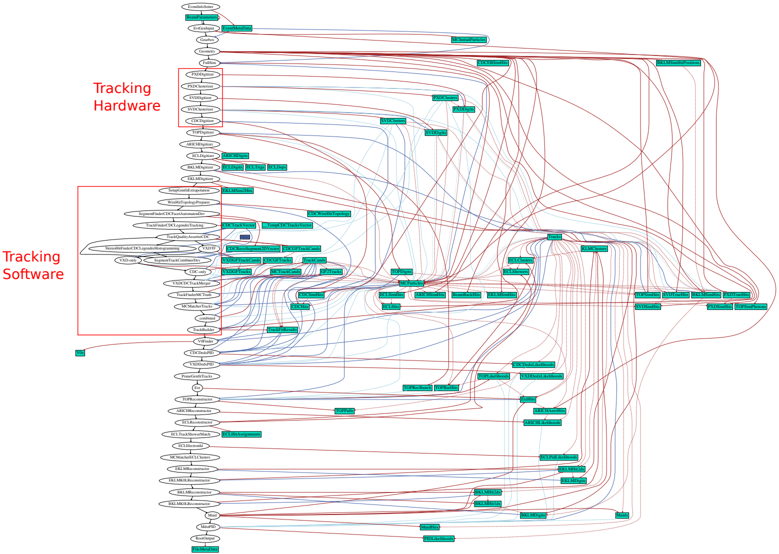
The three components

To get these information, we need three main components:

- the tracking detectors (hardware)
- the track finder (software, partly online and offline)
- the track fitter (software, mostly offline)

All these components consist of many submodules and are under heavy development by many working groups all over the world!

WHAT IS TRACKING (REAL CASE)?



2.

WHY IS TRACKING DIFFICULT?

BACKGROUND

Synchrotron Radiation Electron and positron bunches emit synchrotron radiation because of their bent trajectories.

Beam-Gas Scattering Interactions of the beam particles with residual gas in the beam pipe (bremsstrahlung and Coulomb scattering) leads to momentum changes of the electrons and positrons. As the deflection in the bending magnets is momentum dependent, these particles can then hit the wall of the vacuum chambers and magnets.

Touchek Scattering Intra-bunch scattering can lead to the same momentum changes.

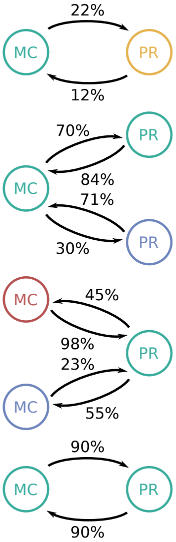
Radiative Bhabha Scattering Colliding electron and positron do not create an Y(4S)-resonance, but rather interact via Bhabba scattering. Photons and the electron–positron-pair can lead to secondary particle showers.

Electron–Positron Pair Production Low momentum electron–positron-pair background produced via $\mathrm{e^+e^-} \to \mathrm{e^+e^-e^+e^-}$ can lead to up to 14000 $\mathrm{e^-e^+}$-pairs in each event in the first PXD layer.

DIFFICULTIES

- Deviations from the typical trajectory shape (helix) because of
    - multiple scattering
    - energy loss
    - radiation
    - secondaries, decay in flight
- Secondaries not coming from the IP
- Inefficiencies in the detector
- Background hits
- Wrong/inefficient algorithms

WRONG TRACKS



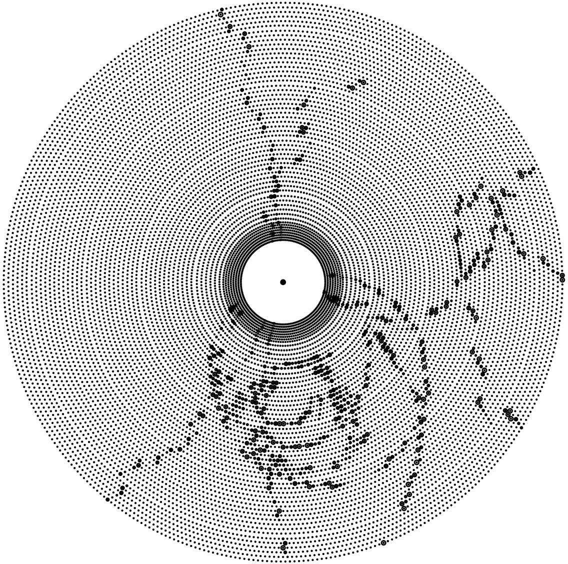
Background: The track finder only/mostly picked up background hits.

Clone: Two tracks describe one real track and should be merged.

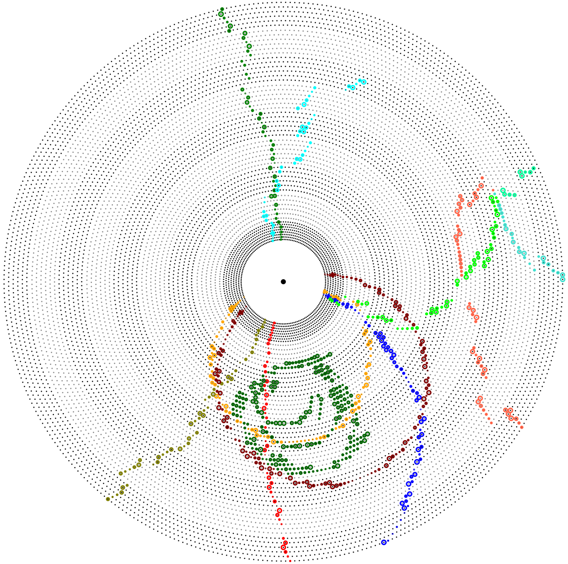
Fake: One track mixes more than one real track and does not describe one good enough.

Found: This is the only category we are interested in!

EVENT DISPLAY



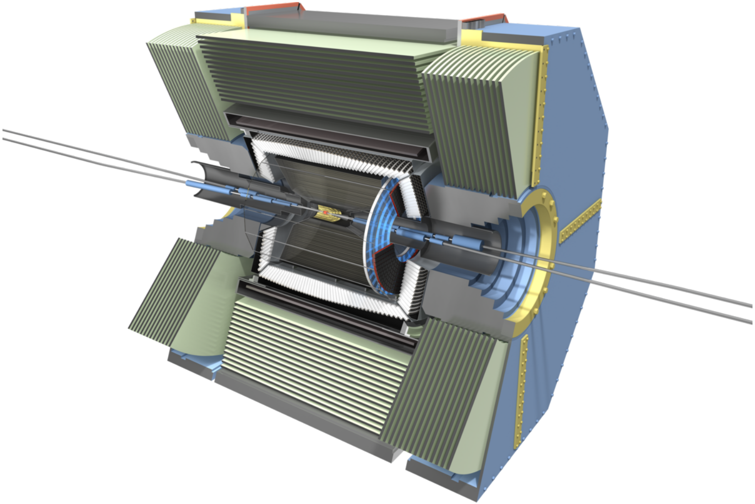
EVENT DISPLAY



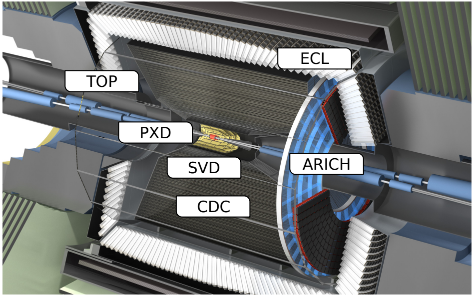
3.

TRACKING DETECTORS

THE BELLE II DETECTOR



THE BELLE II DETECTOR

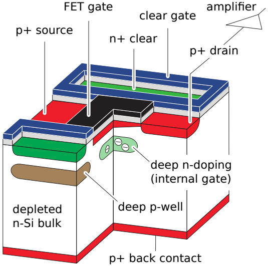


The tracking detectors in Belle II are:

- PXD (PiXel Detector)
- SVD (Silicon Vertex Detector)
- CDC (Central Drift Chamber)

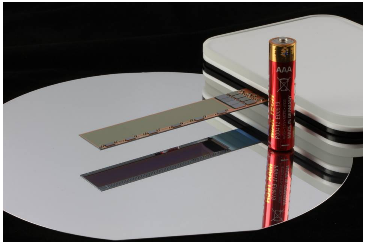
SILICON BASED DETECTORS

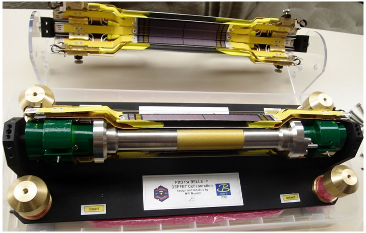
- Incident charged particles generate electron-hole pairs in the depleted region of the semiconductors. They are very thin to reduce multiple scattering.
- The charges are collected by readout electronics (amplifier and analog-digital converter).
- Vertex detectors must cope with a high occupancy and high background rates.

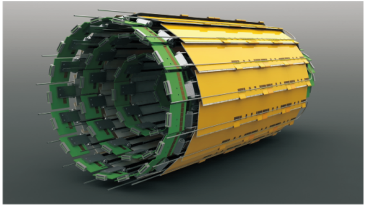


DEPFET pixel in the PXD detector as an example for a silicon based detector.

THE SVD AND PXD - PICTURES

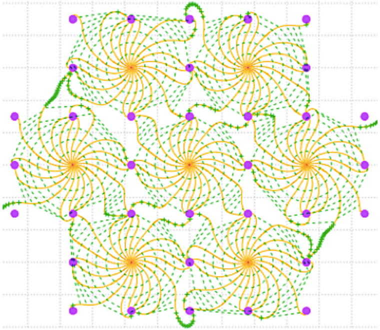




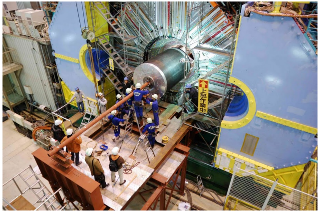


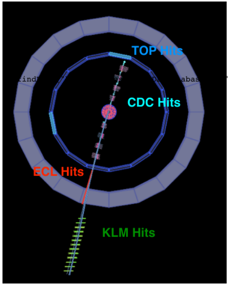
THE CDC - WORKING PRINCIPLE

- Multi-wire proportional chamber with 14336 sense wires arranged in 56 layers grouped in 9 superlayers.
- Sense wires and (larger number of) field wires strained mostly parallel to the beam axis.
- Gas mixture of 50 % helium and 50 % ethane.



THE CDC - PICTURES





THE CDC - WORKING PRINCIPLE

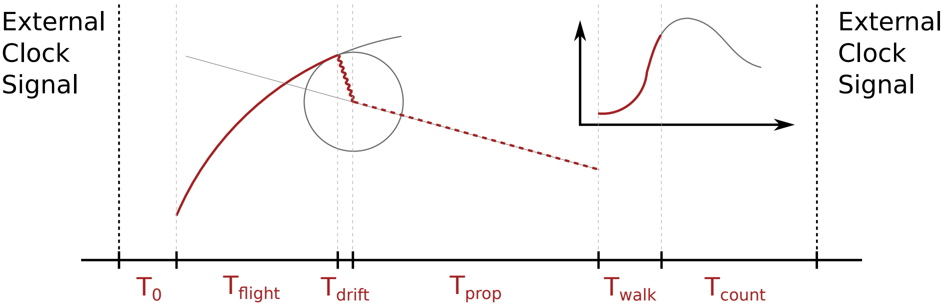
The charged particles can ionize the helium atoms. The energy deposition is described by the Bethe formula

$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = Kz^2 \frac{Z}{A\beta^2} \left(\frac{1}{2} \frac{2m_e c^2 \beta^2 \gamma^2 E_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right) .$$

Because of the small ionization energy of helium ($\approx$ 20 eV), electrons are released very easily. They get accelerated in the artificial electric field and can ionize helium atoms by themselves, which creates a cascade of free electrons. The drift however can take up to 500 ns.

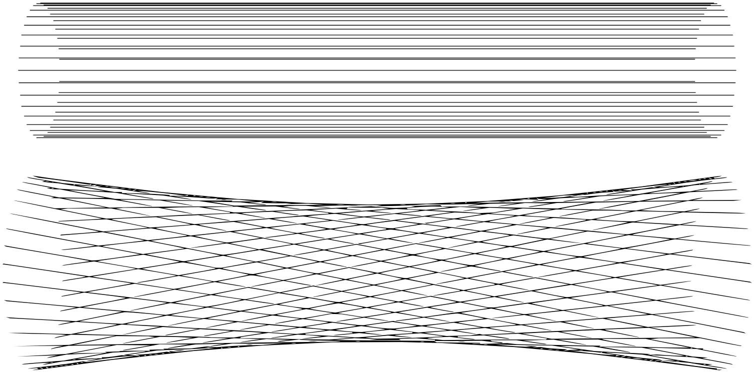
The additional ethane ensures the cascading ionization is localized in the sense wire region.

EVENT TIME



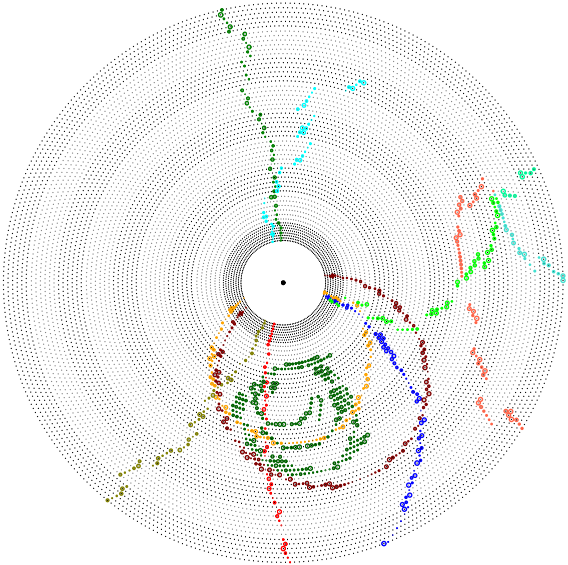
External Clock Signal
External Clock Signal
T_0
T_{flight}
T_{drift}
T_{prop}
T_{walk}
T_{count}

THE CDC - AXIAL AND STEREO LAYERS



Stereo wires are needed for a z-information in the CDC, but give alone no information at all.

THE CDC - EVENT DISPLAY



SOME NUMBERS

Thickness of PXD sensors	75 $\mu\mathrm{m}$
Number of PXD sensors	over 8 million
PXD radii	14 mm and 22 mm
Thickness of SVD sensors	300 $\mu\mathrm{m}$
Size of PXD	50 $\mu\mathrm{m}$ $\times$ 50 $\mu\mathrm{m}$
Number of SVD sensors	187
SVD radii	38 mm to 140 mm
Pitch size of SVD	50 mm on p-side
Expected resolution of CDC	100 $\mu\mathrm{m}$ in xy and $\leq$ 2.2 mm in z
Acceptance region of all detectors	17 $^\circ$ - 150 $^\circ$

4.

TRACK FINDING ALGORITHMS

GLOBAL OR LOCAL?

A track finding algorithm has the task to sort all detector hits into sets of hits, which origin from the same particle.

Global

- Uses all hits at the same time (e.g. with a mathematical transformation).
- Needs strict assumptions on the trajectories.
- Fast.
- Can cope with missing hits.

Legendre Algorithm (CDC)

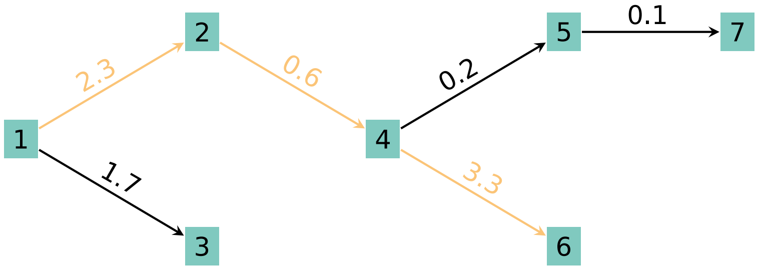
Local

- Uses the relation among neighboring hits.
- Does not depend on the form of the trajectory.
- Can be slow because of high combinatorics.
- Missing hits can make the algorithm fail.

Cellular Automaton (CDC)

CELLULAR AUTOMATON

- Cellular Automaton is a concept from computer science.
- Each "item" is represented by a node, the relations by edges (which can have weights). This transforms the problem into a directed acyclic graph.
- The goal is to find the longest (or heaviest), non-cyclic, directed path.
- There are many algorithms for this problem; the task for tracking developer is to match the physical objects to the edges and nodes.

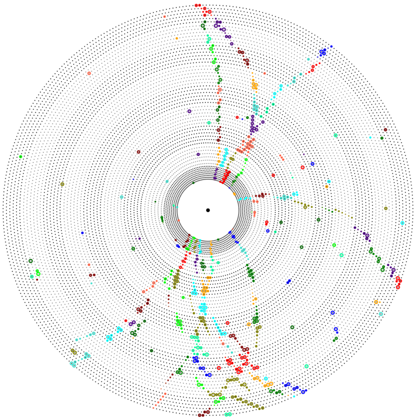


CA - WORKING PRINCIPLE

(1) Clusterize the hits into groups and create segments out of these clusters.
   - A segment is a smaller part of a track limited by the superlayer bounds of the CDC.
   - The selection of segments is done using a cellular automaton.

(2) Use these superlayer segments and combine them into track candidates.
   - This is also done using another cellular automaton.
   - This step combines stereo and axial segments, which is very difficult.

CA - TRACKING ALGORITHM



A cluster of hits is defined as the largest set of directly adjacent hits in a single superlayer. This condition can also be weakened to allow for one-cell-wide gaps in the clusters.

CA - TRACKING ALGORITHM

Instead of using each hit separately as a node in the first step, filtered groups of three hits (facets) with a direction information are used.

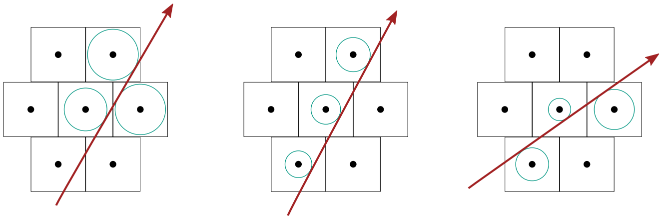


Figure: Examples for facets in the process of building segments.

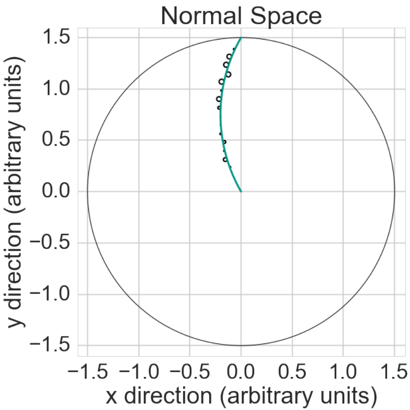
In the second step, groups of two or three segments are used as an input.

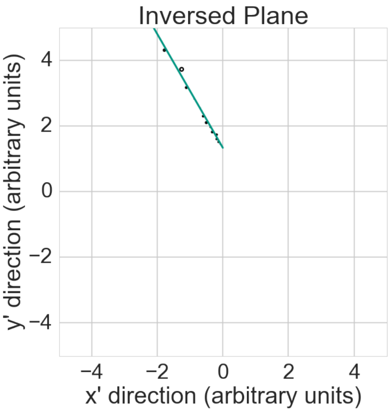
LEGENDRE ALGORITHM

- Extended Hough algorithm.
- All (axial) hit positions with their drift circle information are transformed with a mathematical function into the Legendre space.
- In this space it is much easier to find all hits created by the same track/connected by the same trajectory.

FROM CIRCLES TO LINES...

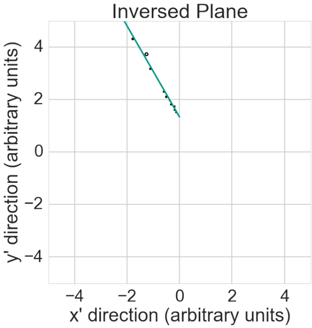
$$x' = \frac{2x}{x^2 + y^2 - d^2} \qquad y' = \frac{2y}{x^2 + y^2 - d^2} \qquad d' = \frac{2d}{x^2 + y^2 - d^2}$$

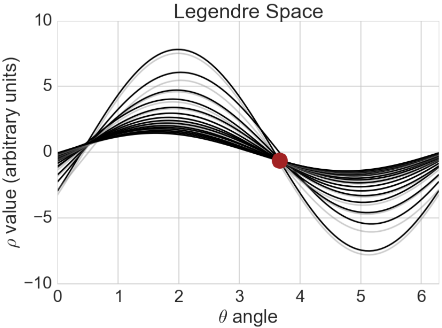




...FROM LINES TO SINOGRAMS.

$$\rho(\theta) = x' \cos(\theta) + y' \sin(\theta) \pm d'$$





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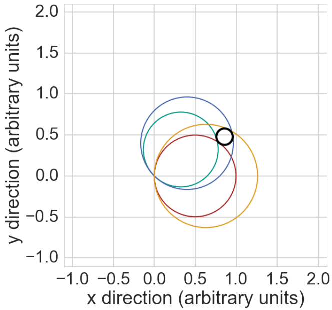
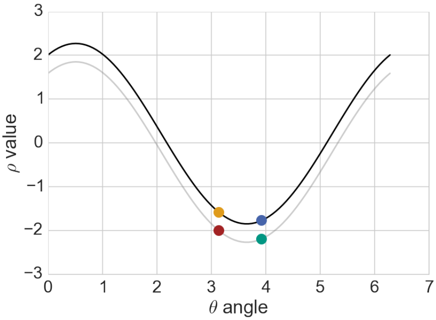
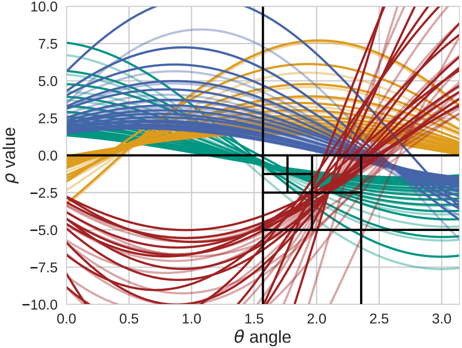




THE QUAD TREE



- In the Legendre space, points with a large number of intersections must be found.
- To do this fast, a quad tree structure is used which is transversed recursively to find the intersection point.

THE LEGENDRE ALGORITHM

- The presented algorithm is only the most simple form.
- In practice, the algorithm is applied many times with different parameters, hit deletion, track post-processing, etc.
- Many extensions are possible and under development:
  - Use clusters/facets/segments instead of single hits.
  - Use overlapping bins, other bin shapes, parameter-dependent levels.
  - Combine VXD and CDC information in one quad tree run.
  - ...

STEREO FINDER

Problem

The Legendre algorithm needs a fixed x–y position, so it can **not** be used for stereo wires!

Solution

Stereo hits are added in a second step. After collecting all axial hits of a track, the x–y position of the stereo hits can be calculated.

POST-PROCESSING

Because of inefficiencies and difficulties (energy loss, multiple scattering, secondaries), heavy post-processing routines after finding a track must be applied, including:

- Reassignment of hits.
- Deletion of whole tracks.
- Merging of tracks.
- Splitting of tracks.

These routines have a large impact on the quality of the tracks and on the physic analyses!

BDTs IN TRACK FINDING?

Because of the large data samples in high energy physics, the tracking software must run fully automated.
However, many crucial but complex decisions need to be taken, e.g.

- if a hit belongs to a track.
- if two tracks should be merged.
- if a hit is background or noise.
- if a track is fake/clone.

All these decisions are hard to implement using simple cuts.

BDTS IN TRACK FINDING?

Multivariate Techniques (BDTs in our case) are much better here!

Benefit

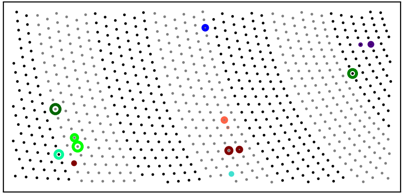
- Work most of the times out of the box.
- We can implement “as much as we can”.
- Changing environments are much easier to handle.
- The result is a real number in $[0, 1]$.
- One filter concept for all decisions in the software.

Disadvantage

The result of a MVA is often a “black box”.

BACKGROUND **HIT FINDER - CONCEPT**

Before doing track finding, many background hits can be dismissed to increase the performance and reduce the fake rate. This is done using a MC-trained BDT on each cluster of hits.



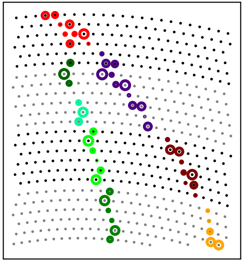
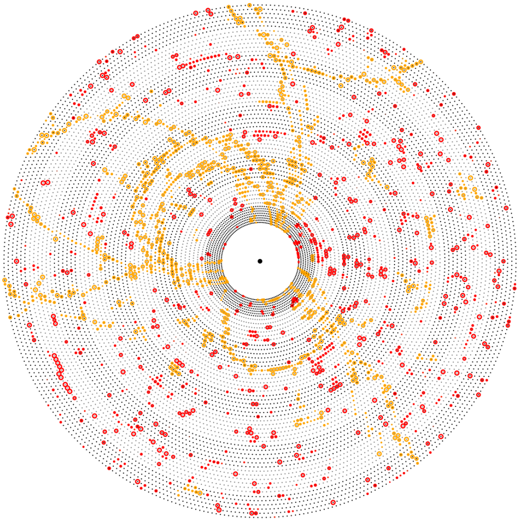
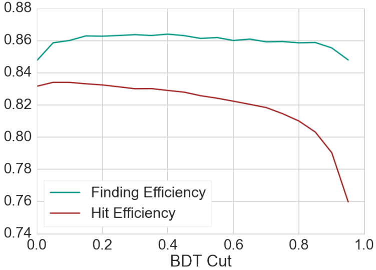


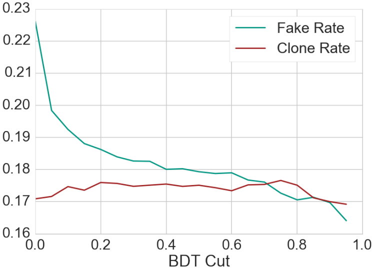
Figure: Background (left) and signal (right) cluster in the background hit finder.

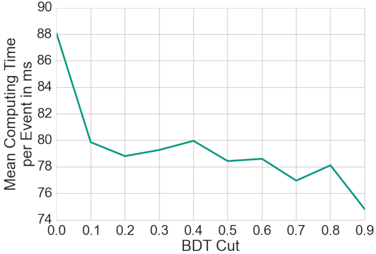
BACKGROUND HIT FINDER - CONCEPT



BACKGROUND HIT FINDER - RESULTS







5.

TRACK FITTING ALGORITHMS

WHY FIT THE TRACKS?

- We are interested in the particles parameters (e.g. momentum, vertex position, energy loss) and not in its hits (except hit pattern analyses).
- After finding all hits corresponding to one particle, we want to extract the parameters by fitting a trajectory model to the hits.
- Idea: Start with the parameters given by the track finder and refine them until a perfect match between hits and trajectory model is given.
- Input: hits, energy loss in VXD, geometry of the detector, (ECL energy), (photons), etc.

THE KALMAN FILTER - PRINCIPLE

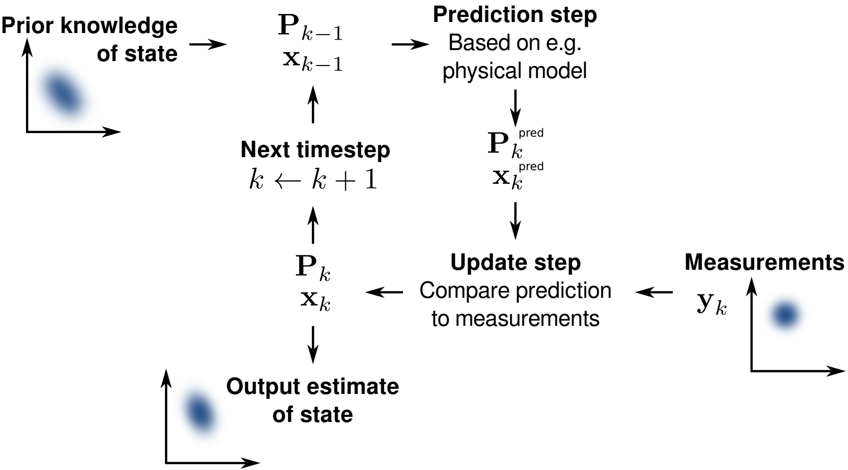


Figure: ”Basic concept of Kalman filtering” by Petteri Aimonen

THE KALMAN FILTER - PRINCIPLE

$$x_k^{\text{pred}} = \mathbf{A}_k x_{k-1} \qquad \mathbf{P}_k^{\text{pred}} = \mathbf{A}\mathbf{P}_{k-1}\mathbf{A}^T$$

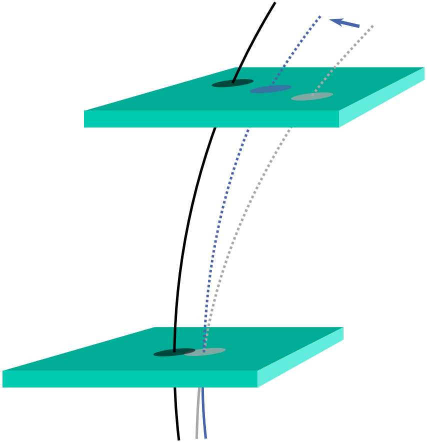
$$x_k = x_k^{\text{pred}} + \left(\mathbf{P}_k^{\text{pred}}\mathbf{H}_k^T \left(\mathbf{H}_k\mathbf{P}_k^{\text{pred}}\mathbf{H}_k^T + \mathbf{V}_k\right)^{-1}\right)\left(y_k - \mathbf{H}_k x_k^{\text{pred}}\right)$$

with

- x_k the state at measurement k.
- $\mathbf{P}_k$ the state error matrix at measurement k.
- $\mathbf{A}_k$ the state transport matrix (must be implemented) projecting onto a plane perpendicular to the measurement k.
- y_k the measurement k.
- $\mathbf{V}_k$ its error matrix.
- $\mathbf{H}_k$ the measurement matrix, which relates the state vector to the measurement.

THE KALMAN FILTER IN TRACKING

- The state vector is $(q/p, u, v, \mathrm{d}u/\mathrm{d}s, \mathrm{d}v/\mathrm{d}s)$.
- u and v are the local coordinates defined on the plane perpendicular to the measurements.
- The measurements are given by the detector.
- A includes the whole geometry and is in practice often solved approximately.
- The whole process is repeated many times forward and backward with all measurements.



THE DETERMINISTIC ANNEALING FILTER (DAF)

Problem

Every measurement influences the final state, including wrong hits!

Solution

An annealing scheme combined with the Kalman filter is applied:

- Set the weights of all hits to 1.
- Fit the track with a Kalman fitter taking into account the weights.
- Recalculate the weights with the distance of the hit to the current trajectory hypothesis.
- Dismiss hits with a weight below a certain threshold.
- Repeat with (2).

WHY ANNEALING?

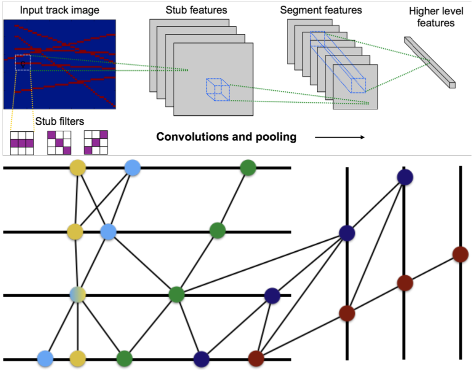
Problem

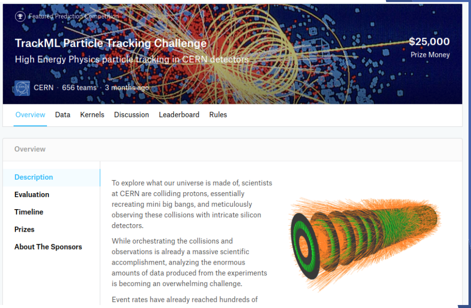
Because of wrong starting parameters, most of the hits can be dismissed in the first iteration!

Solution

Each weight is transformed with a Maxwell-Boltzmann distribution depending on a decreasing “temperature” T. In the first iteration, only hits with a very large distance from the trajectory are deleted. In the last iteration, also hits with a small deviation are dismissed.

NEWEST RESULTS





7.

SUMMARY

SUMMARY

This talk should give you a brief overview on:

- The importance of tracking for high energy physics.
- How tracking detector works.
- How track finding and track fitting works.
- Which problems tracking software has to face.
- How large the influence of tracking on physic analyses can be.

BIBLIOGRAPHY

Most of the figures are taken from

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- T. Abe et al., “Belle II Technical Design Report”, 2010.