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Tracking

UPPSALA UNIVERSITET

2025 Belle II Physics week
October 9th, 2025

OUTLINE

Event reconstruction at HEP

Belle II tracking detectors & challenges

Belle II tracking procedures

Tracking performance

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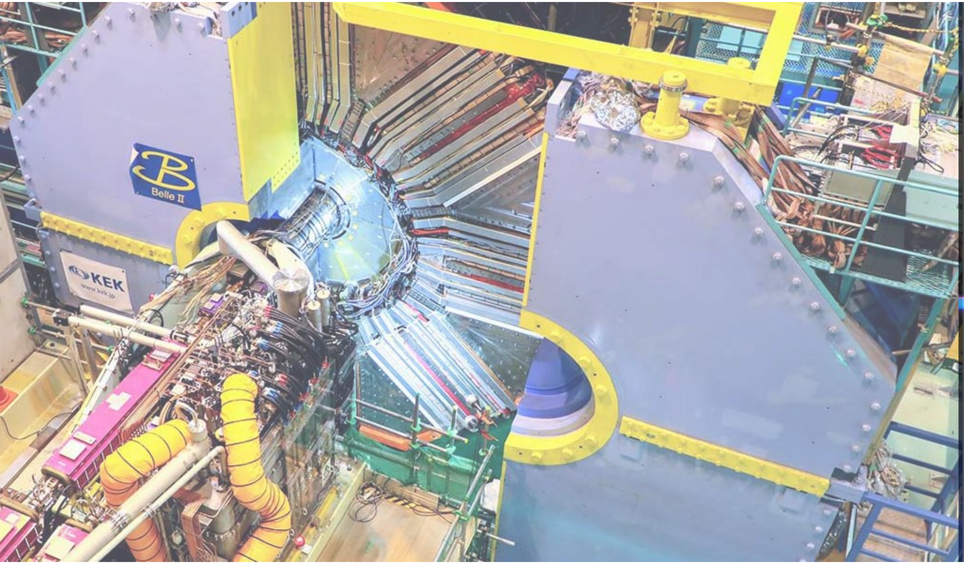
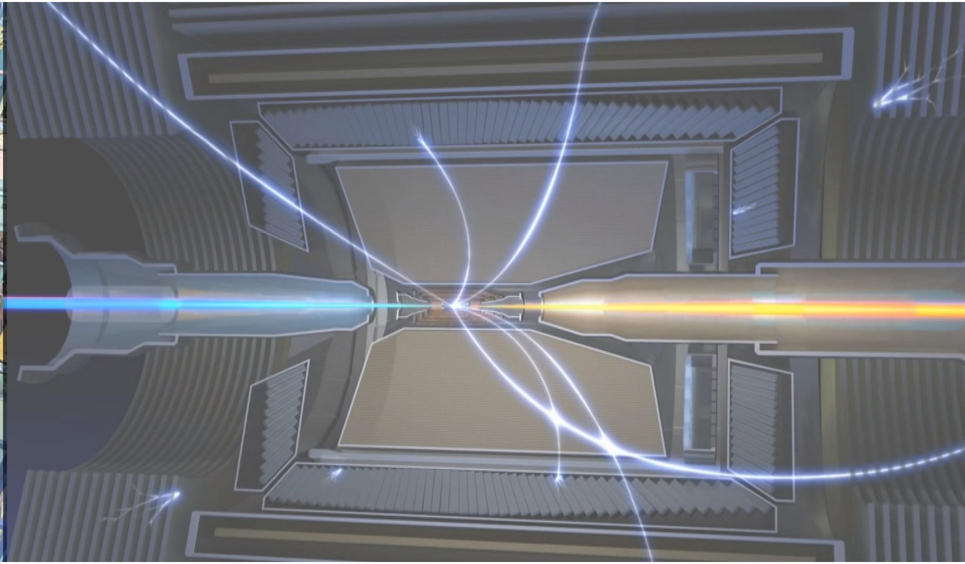
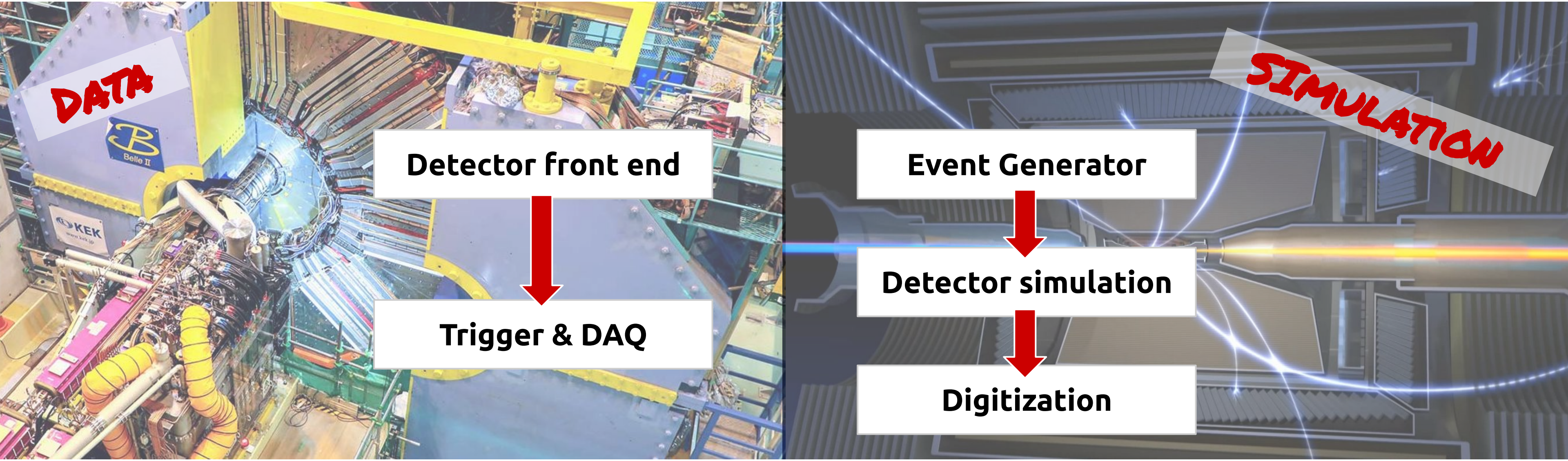




Event reconstruction at HEP



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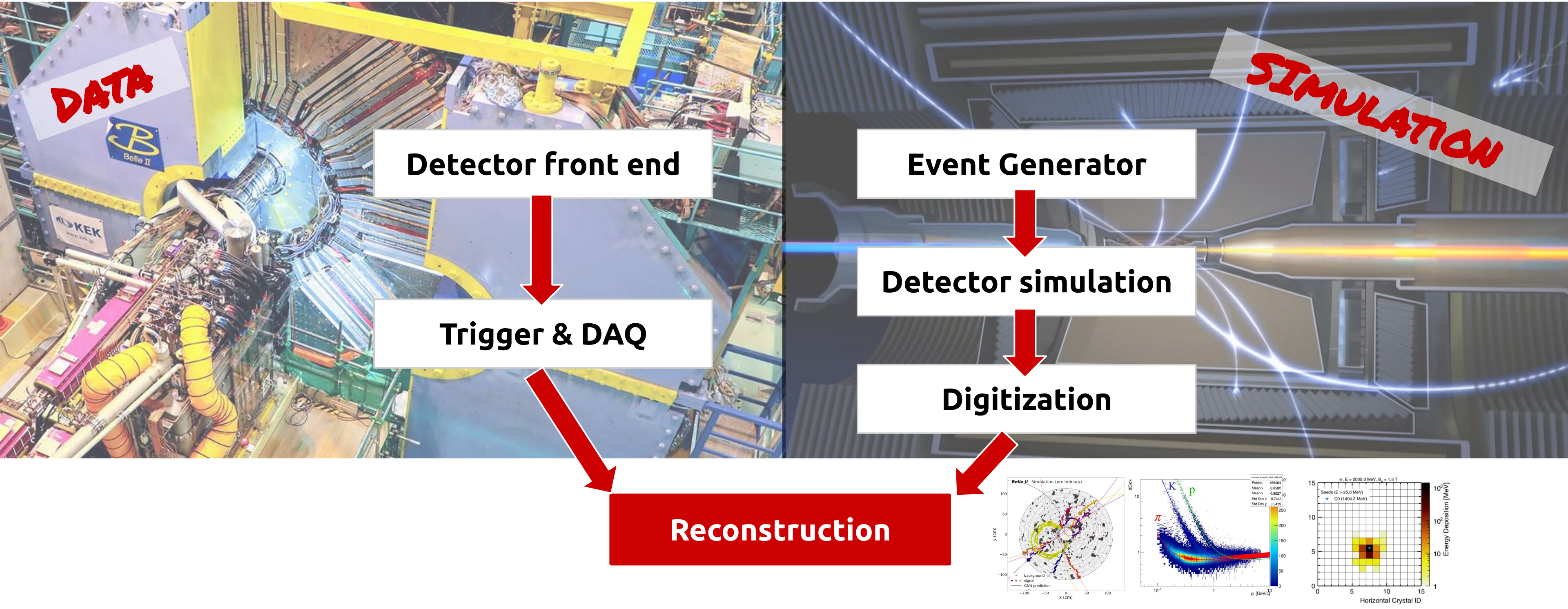

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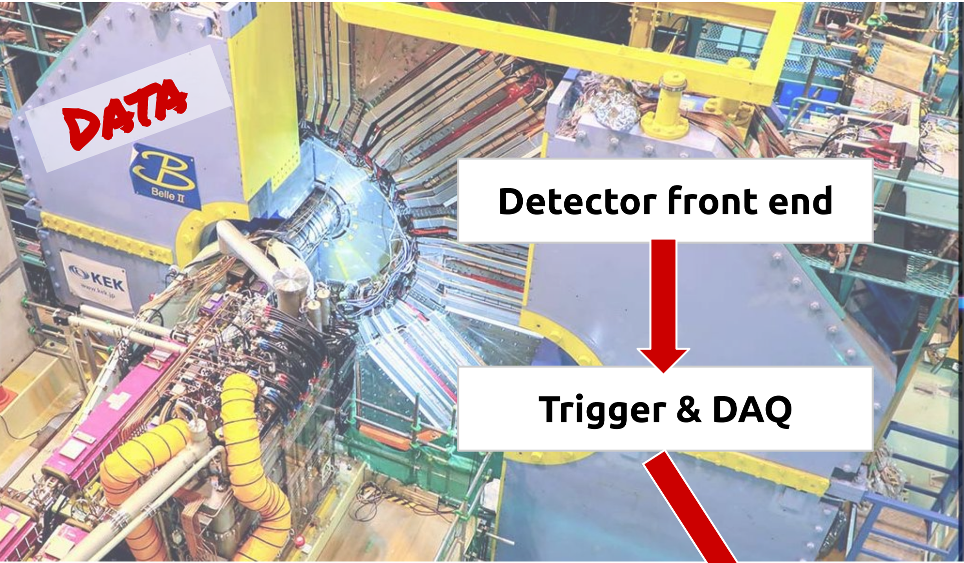
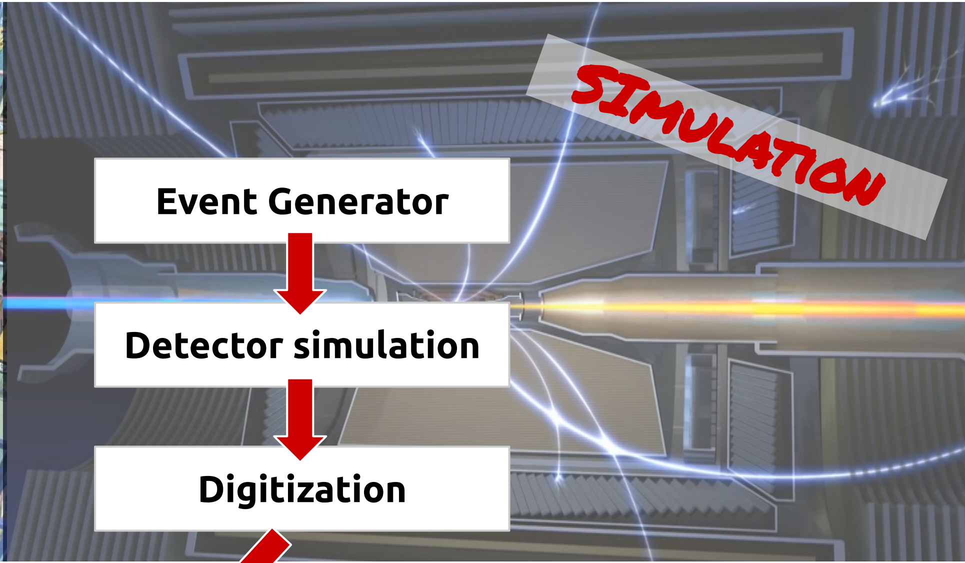


Detector front end

Trigger & DAQ



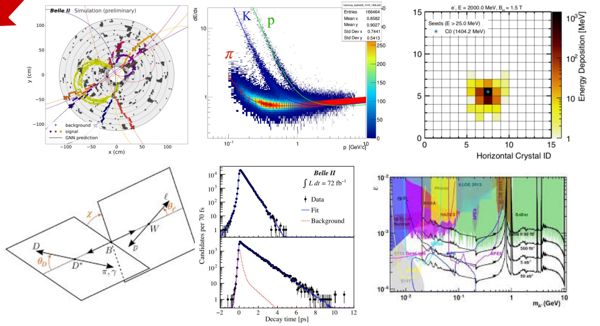
Event Generator

Detector simulation

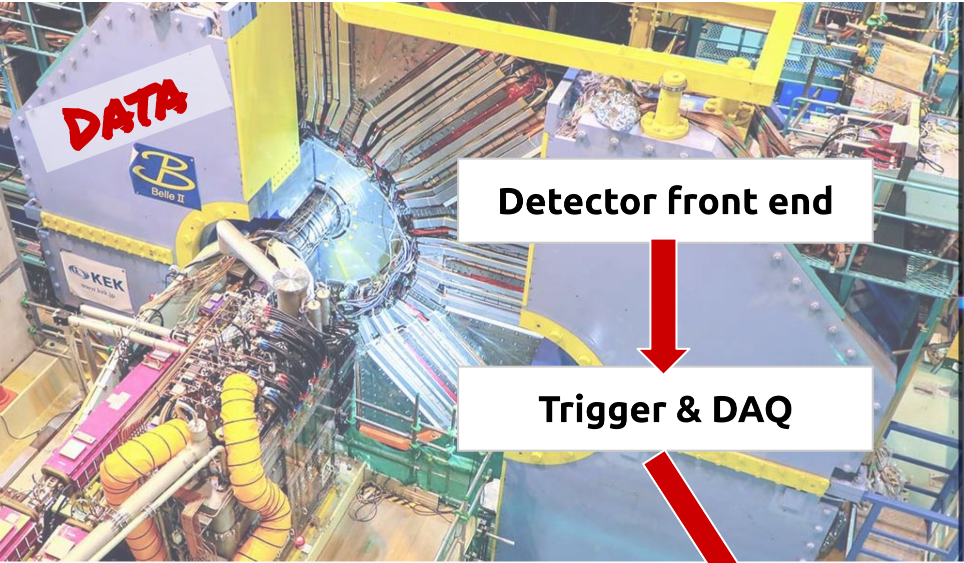
Digitization

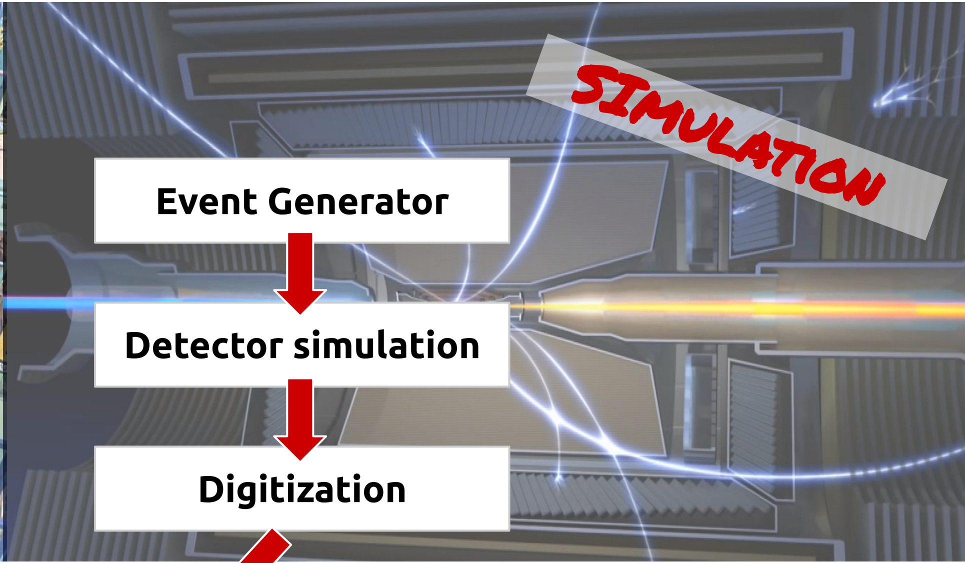
Reconstruction

Analysis



Event reconstruction at HEP



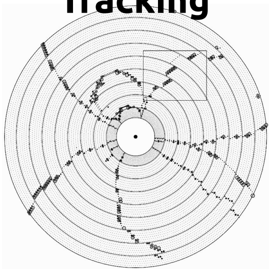


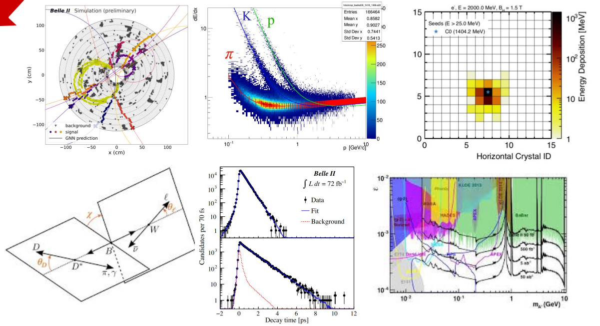
Detector front end → Trigger & DAQ → Reconstruction

Event Generator → Detector simulation → Digitization → Reconstruction

Reconstruction → Analysis

Tracking





What do we need tracking for

- **Tracking: part of the reconstruction stack for reconstructing the trajectories of charged particles starting from signals left by the particles in the tracking detector**

- The majority of HEP experiments rely on the **precise measurement** of a particle's **trajectory** in order 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
  - **Assign hits** to particles (and from the hits measure the energy loss)
  - **Connect** the particles between detectors (across the boundaries)

How does tracking work

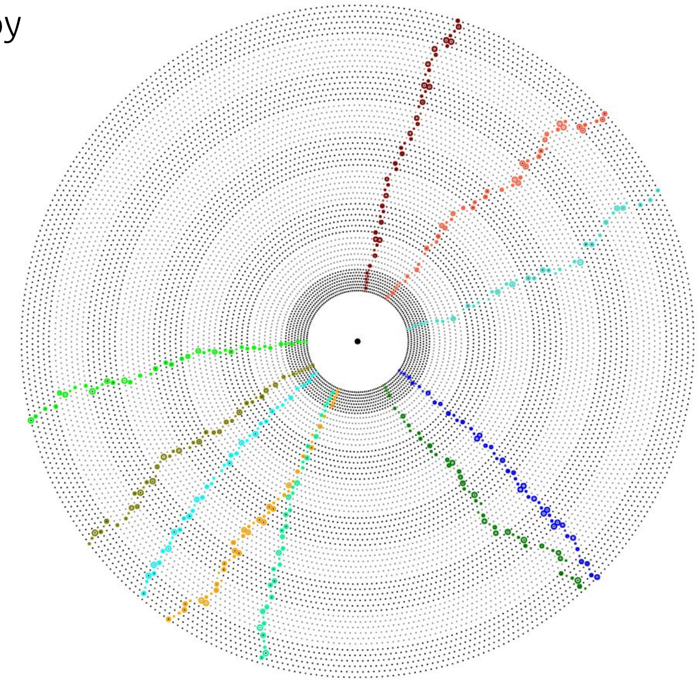
- **Principle:** the main idea is to estimate a particle's trajectory by **multiple point measurements along its flight path**

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

$$p_t \,[\mathrm{GeV/c}] = 0.3 \cdot q \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

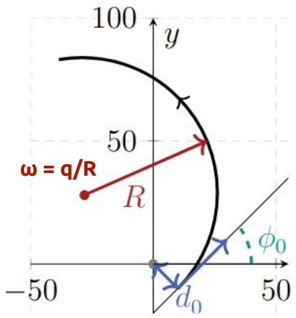
  with the radius R, the charge q and the magnetic field B

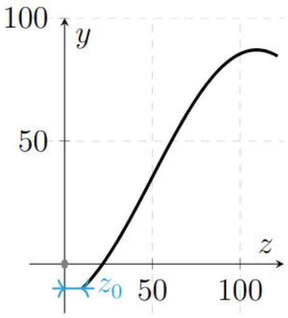
- Detector material and non-homogeneous B-field make things more complicated

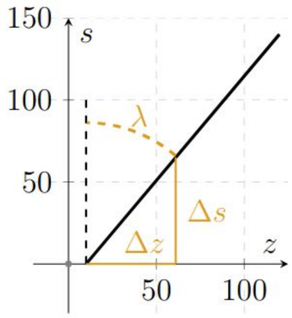


Track parametrization

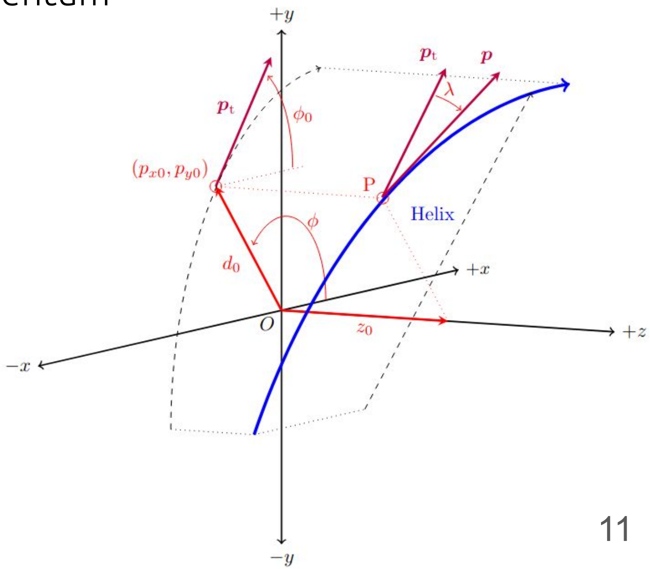
- **Helix description: 5 parameters** computed at the point of closest approach to the z axis (**POCA**)
  - **d_0 ∈ [-∞, +∞]:** signed distance of the POCA on transverse plane
  - **z_0 ∈ [-∞, +∞]:** signed distance of the POCA on z plane
  - **Φ_0 ∈ [-π, +π]:** angle defined by the transverse momentum at the POCA and the x axis
  - **ω ∈ [-∞, +∞]:** inverse of the curvature radius, signed with the fitted charge
  - **tanλ ∈ [-∞, +∞]:** tangent of the angle defined by the momentum at the POCA and the transverse plane







s: path of the helix on xy plane



What is tracking (simplified)

- **Three main components** are needed to get trajectory information
  - the **tracking detectors** (hardware)
  - the **track finder** (software, partly online and offline)
  - the **track fitter** (software, online and offline)

- The actual design of the (software) tracking procedure strongly depends on the details of the experiment and the working point

- Need to **balance high performance** and **usage of computing resources**

- At Belle II, all these components consist of many modules and are under heavy development by many working groups all over the world!

Event reconstruction at HEP

Belle II tracking detectors & challenges

Belle II tracking procedures

Tracking performance

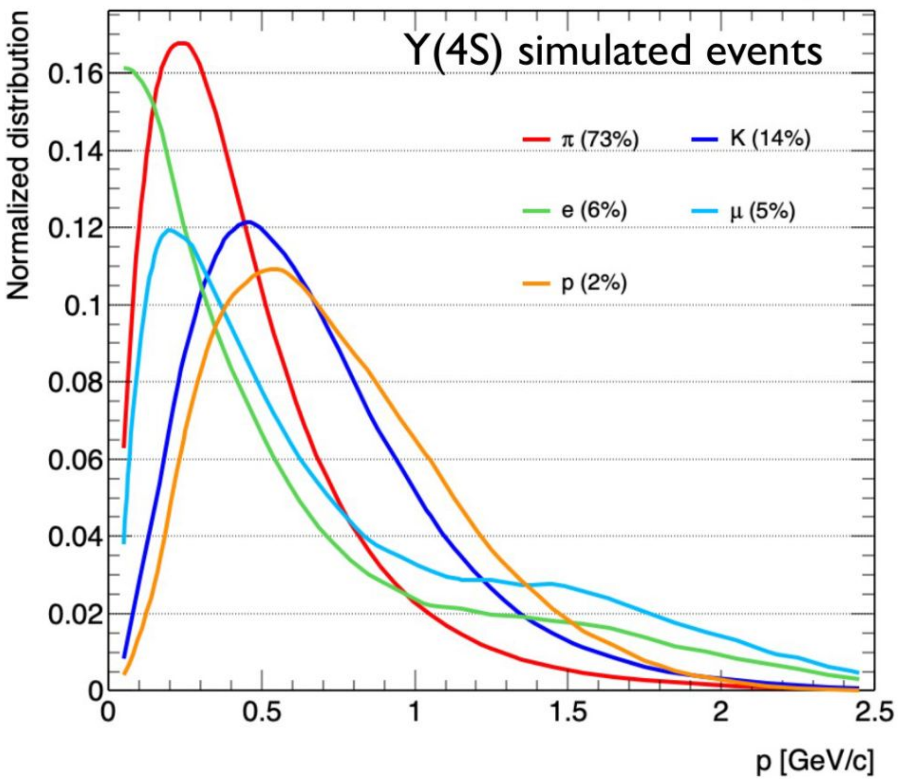
Belle II typical Υ(4S) event

- Typical **Υ(4S) event** at Belle II:
  7 GeV e^- on 4 GeV e^+ , $\beta\gamma = 0.28$

- Average multiplicities:
  - **11 charged tracks**
  - **5 neutral pions**
  - **1 neutral kaon**

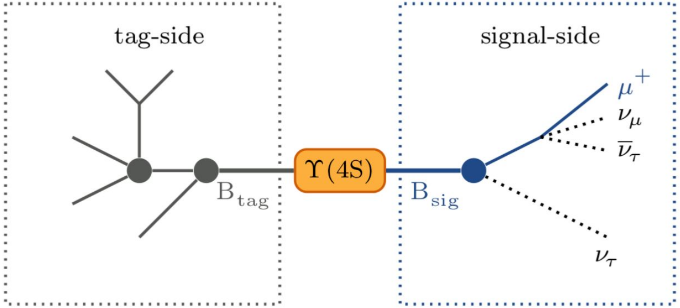
- **Soft momentum spectrum of charged tracks**
  → effect of multiple scattering not negligible
  (especially for very low momentum tracks)

- p_t < 40 MeV/c → tracks do **not reach CDC**
- $p_t \in [40, 250]$ MeV/c: **curling in CDC**



Requirements for tracking @ Belle II

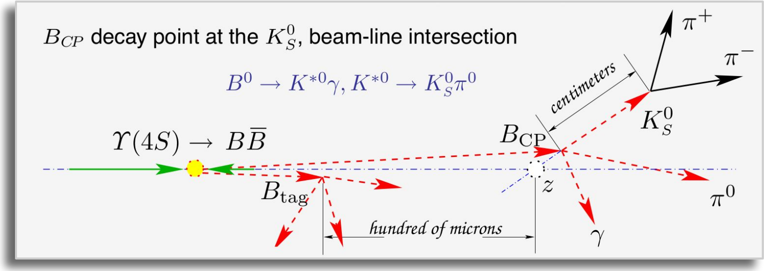
The **requirements** to tracking:



- **High track finding efficiency**
  - Important for every analysis ($\rightarrow$ reconstruction efficiency)
  - Also for analysis with missing energy or using the Full Event Interpretation

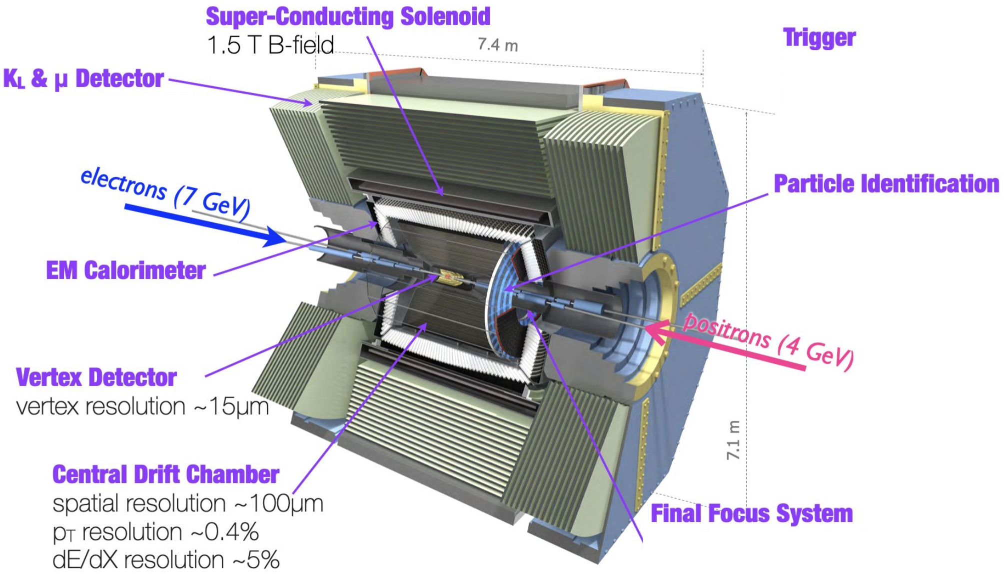
- **Low fake rate**
  - Fake tracks: real but from background, real but duplicates, from random combination
  - Hits from beam background dominate in the inner detector

- **Good vertex position resolution**
  - Much better than 100 μm: average vertices distance ~130 μm for B pairs
  - Crucial for time-dependent analysis



The Belle II detector

- Pixel Detector (PXD)
- Silicon Vertex Detector (SVD)
- Central Drift Chamber (CDC)
- Electromagnetic Calorimeter (ECL)
- Aerogel Ring-Imaging Cherenkov (ARICH)
- Time-of-Propagation (TOP)
- KL and mu detection (KLM)



Tracking subdetectors

- **Pixel Detector (PXD)**
- **Silicon Vertex Detector (SVD)**
- **Central Drift Chamber (CDC)**
- Electromagnetic Calorimeter (ECL)
- Aerogel Ring-Imaging Cherenkov (ARICH)
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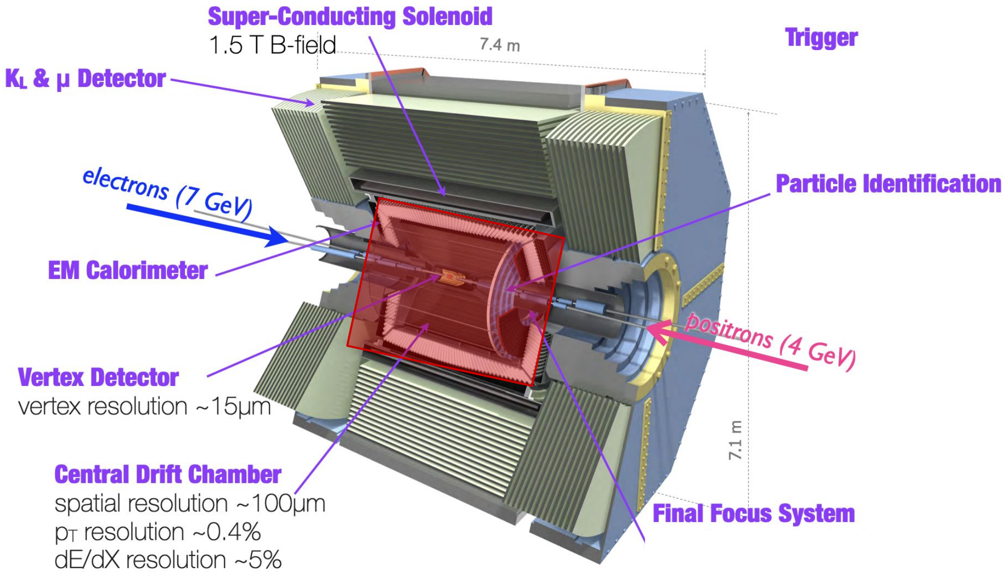
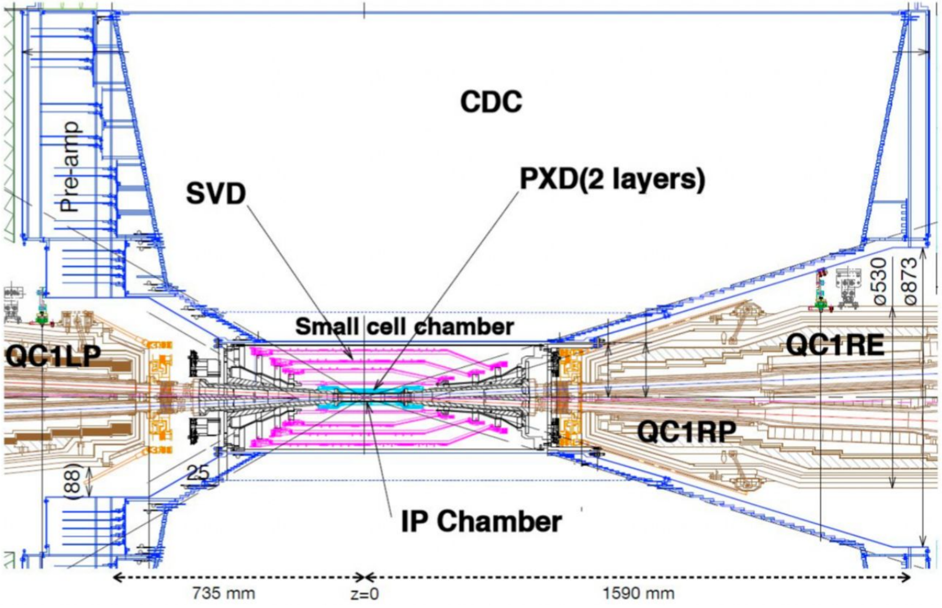


Tracking subdetectors

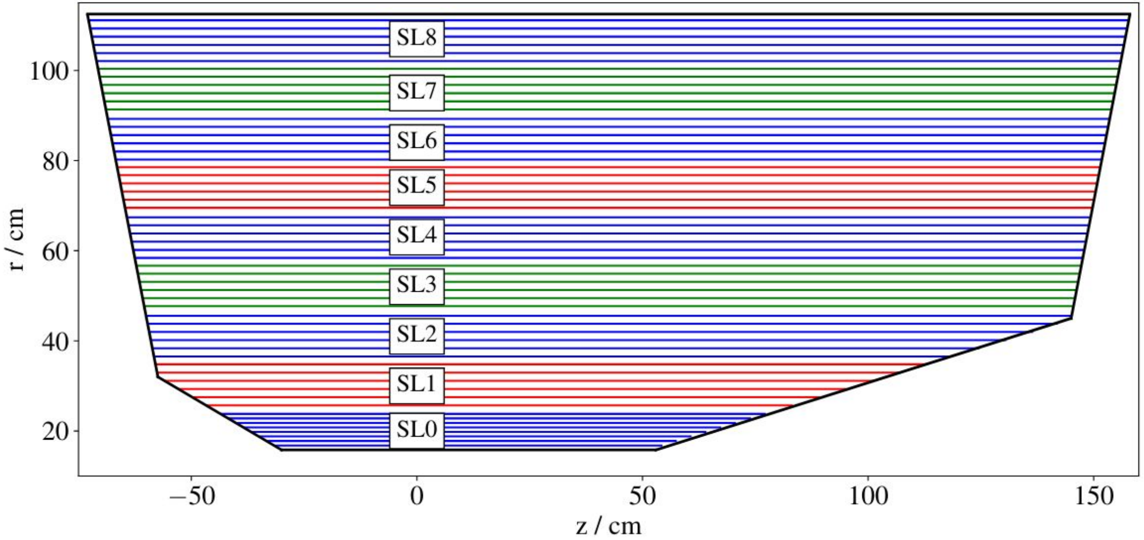
- **Pixel Detector (PXD)**
- **Silicon Vertex Detector (SVD)**
- **Central Drift Chamber (CDC)**
  - Large radius of CDC:
    → **Good p_t resolution**
  - Silicon detectors at the inner region:
    → **Precise vertex resolution**
  - Inside **1.5 T magnetic field** provided by the superconducting solenoid
    → Homogeneous field
    (less than 1% variations in tracking volume)

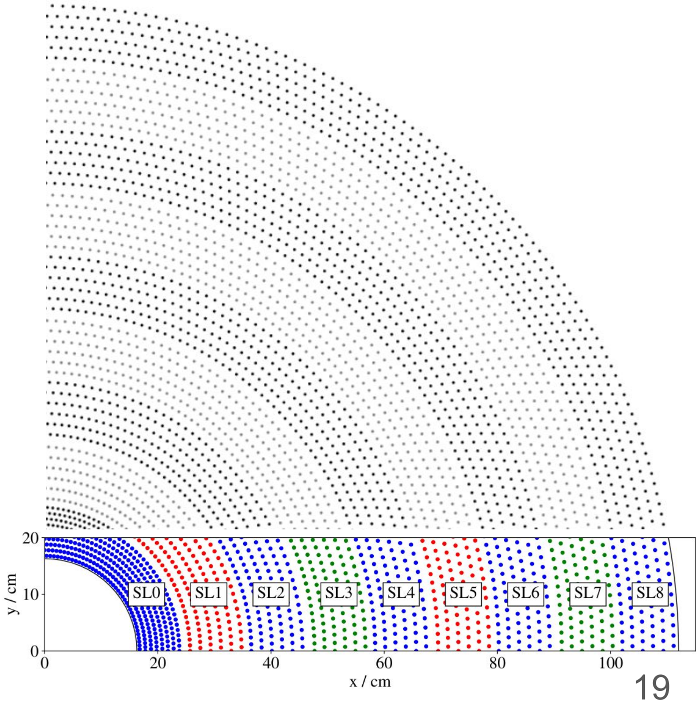


Central Drift Chamber (CDC)

- **CDC:** large multi-wire drift chamber
  - **Tracking, Trigger, PID**

- 56 layers in total
- 9 super-layers : **5 axial** + **4 stereo** (**2U**+**2V**)





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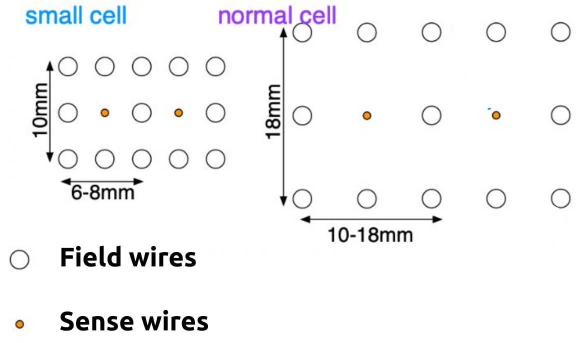
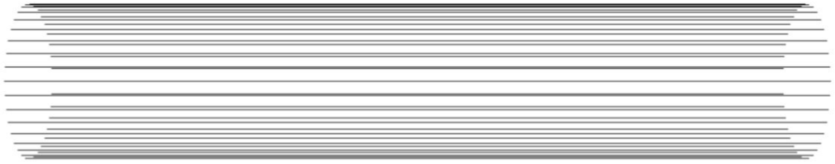
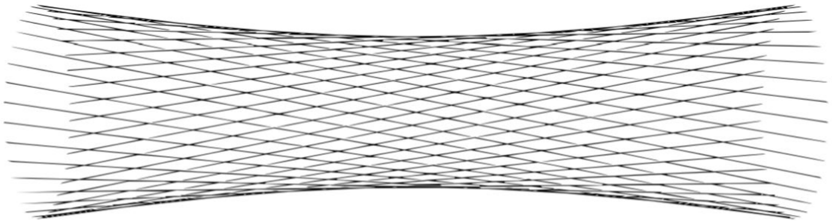


Axial wires

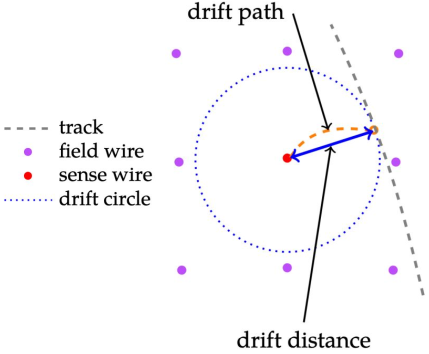


Stereo wires



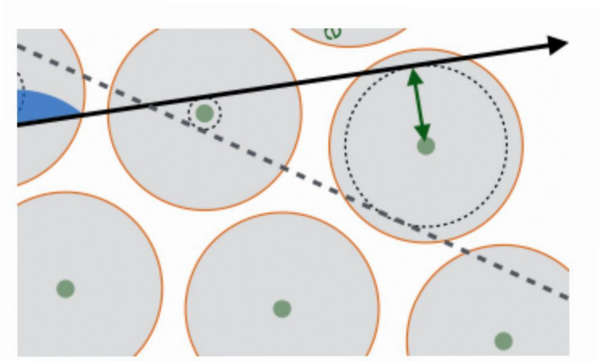
Gas mixture	Helium, ethane
Radius [mm]	**160 - 1130**
Acceptance [degree]	17-150
Layers/ Super Layers	**56 / 9**
Stereo and axial wires	14336
Length (Z) [mm]	**2325**
Radiation Length	680 m
Stereo angle [mrad] Inner -> outer	(U) 45.4-45.8 (V) -55.3 - -64.3 (U) 63.1 - 70.0 (V) -68.5 - -74.0

Central Drift Chamber (CDC)



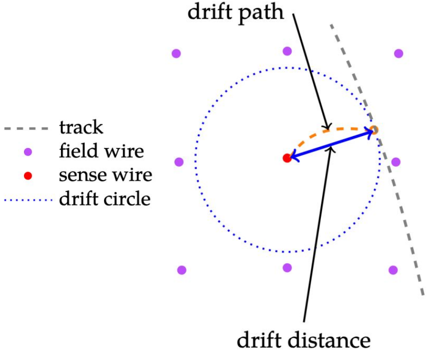
- **Charged particle** passing through the **CDC volume**
  - The gas mixture is **ionised**
  - The electrons **drift** towards the sense wires and cause **avalanches** when they arrive near the wire, detected as a current on the wire

- **Measurements:**
  - **Time of arrival:** time of the arrival of the signal (1 ns resolution) to derive the drift distance (x-t relation) → a circle to represent the CDC hit → Left/right ambiguity
  - **Signal amplitude (ADC):** used for background suppression and determination of the energy loss for PID



➢ **Provide a measurement with spatial resolution of 120 μm on average**

Central Drift Chamber (CDC)



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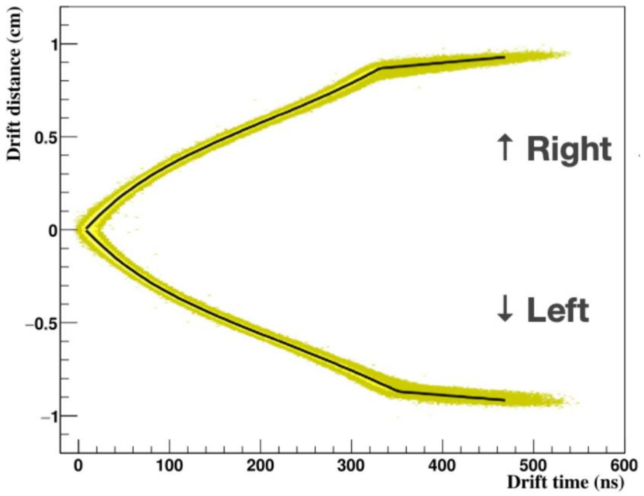

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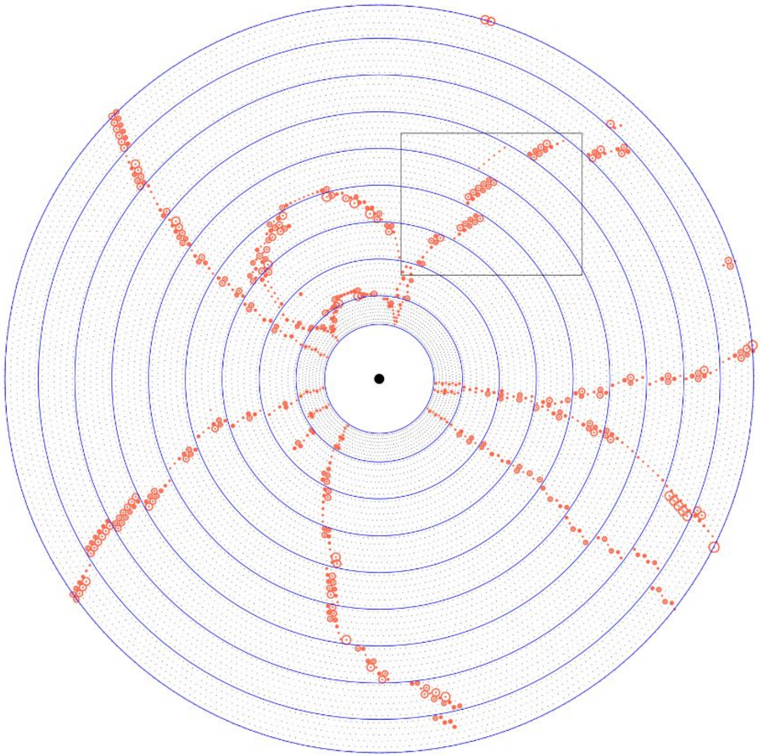
Central Drift Chamber (CDC)

- **CDC SpacePoints** (xy) of a typical Υ(4S) event (no beam background)



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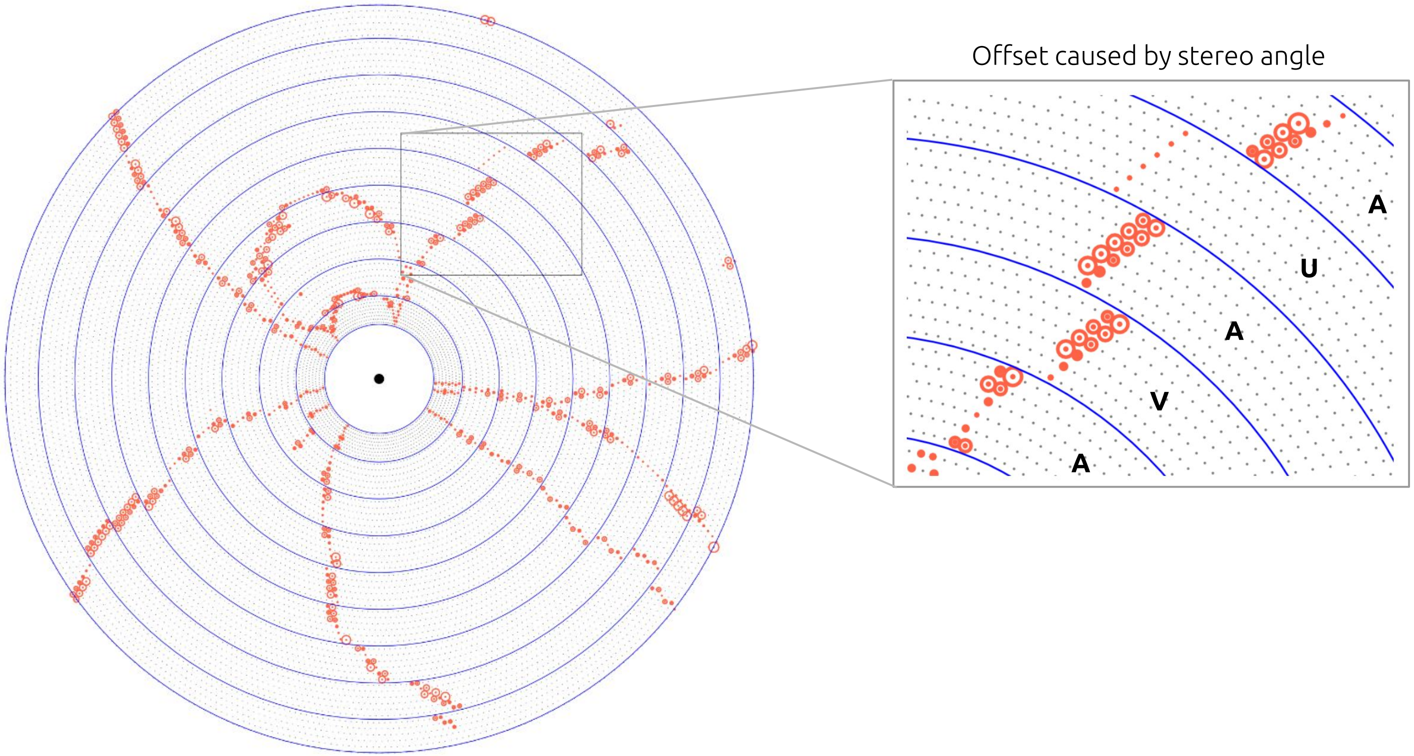
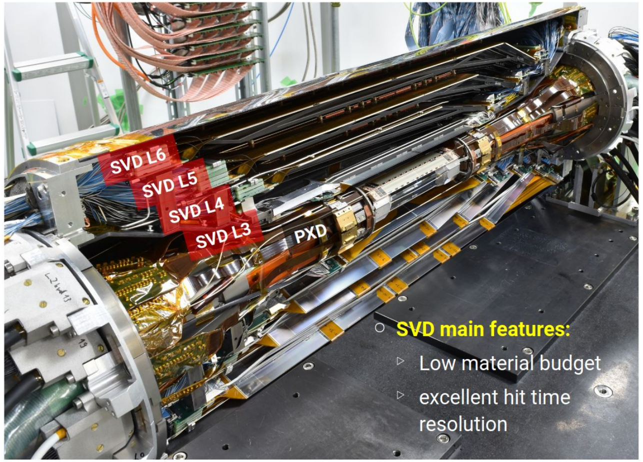
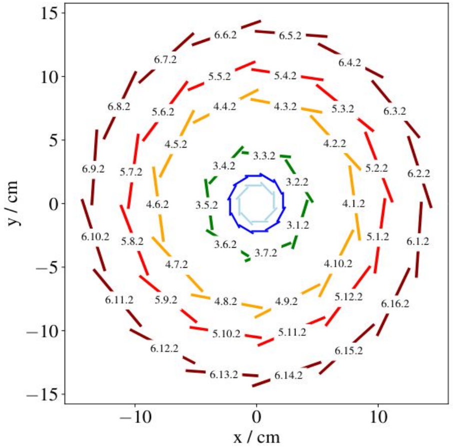
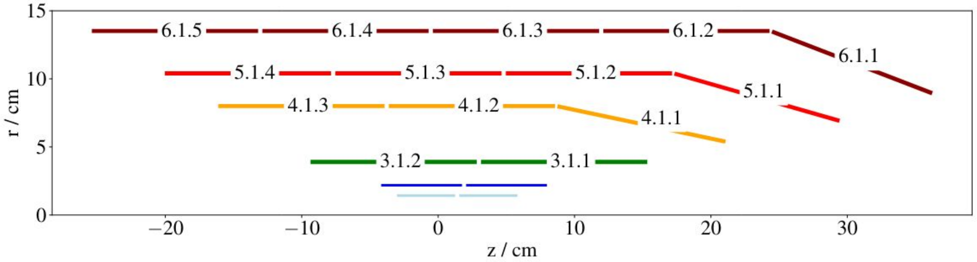


Silicon Vertex Detector (SVD)

- Four layers of **double-sided silicon strip detectors**
- Rectangular sensors in barrel and backward region and trapezoidal sensors in the forward section to **increase** the angular coverage and **minimise** the material
    - U: perpendicular to the beam; V: parallel to the beam
    - Pitch size in U/V: 50-75 um, 160-240 um







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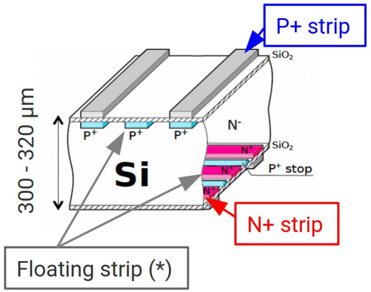
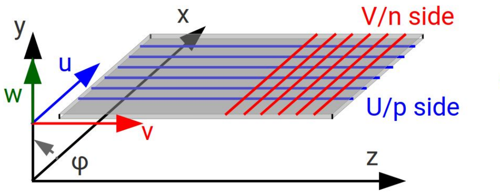
  - U: perpendicular to the beam; V: parallel to the beam
  - Pitch size in U/V: 50-75 μm, 160-240 μm
- **Double-sided readout:** combination of measurement on U and V
  - Wrong combination: **ghost hits**

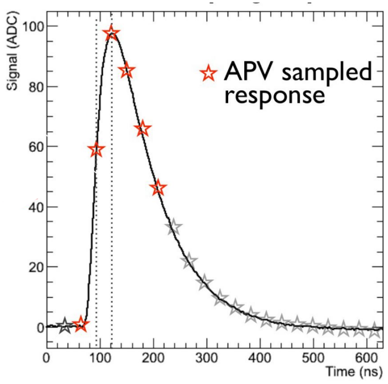
➤ **Position resolution on U: 7-12 μm**
V: 15-25 μm

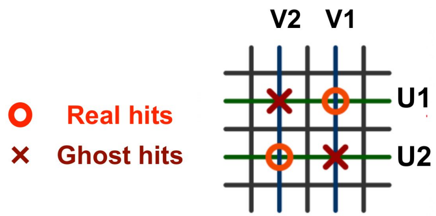
➤ **Time resolution : 3-4 ns**





- u-v coordinates are used on each sensor
  - p-strips: u (r-φ) information
  - n-strips: v (z) information

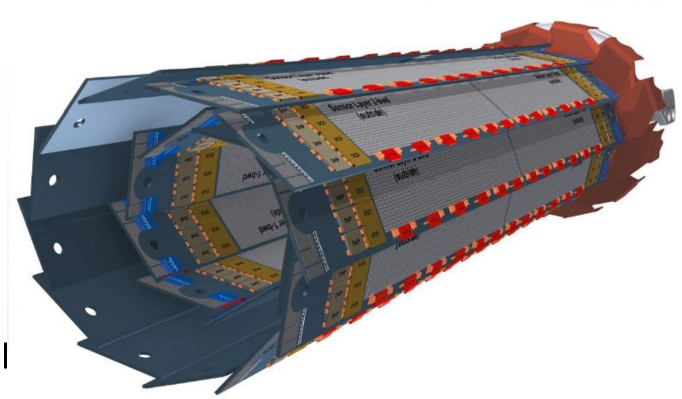


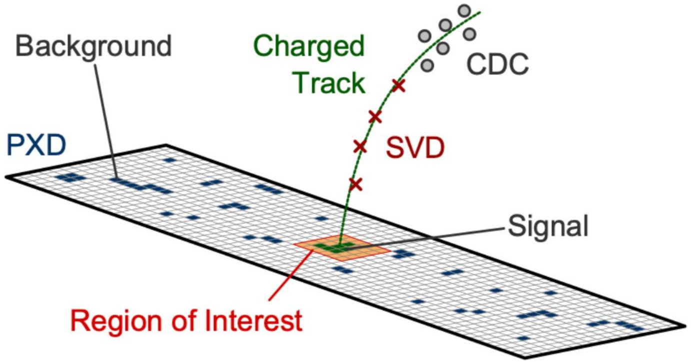


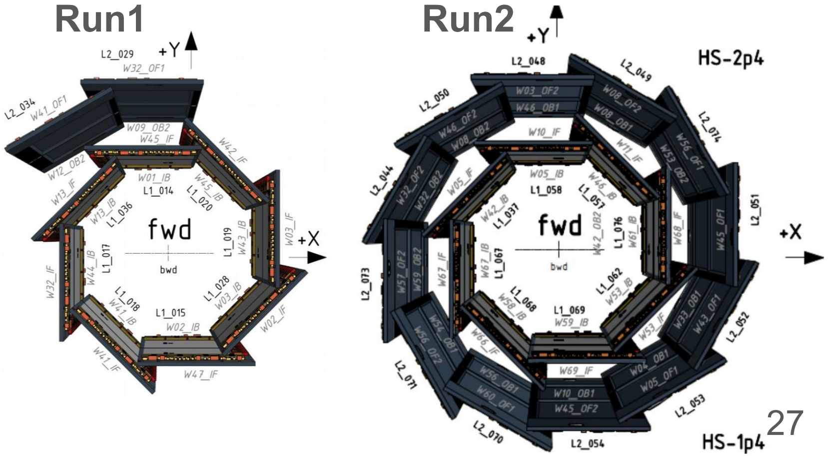
PiXel Detector (PXD)

- The innermost 2-layer silicon pixel detector
  - Not involved in track finding but big **improvement** to the **track quality**

- High Level Trigger **ROIs** (region of Interest): **extrapolate** the tracks to PXD sensor planes and define a ROI
  - **Reduce the PXD data size** (as the data size is too large and dominated by beam background)







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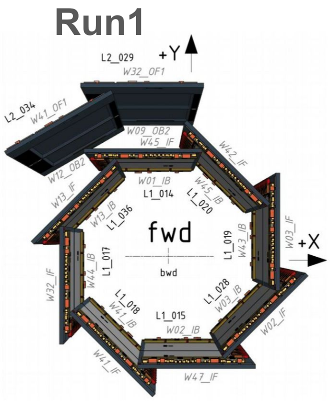
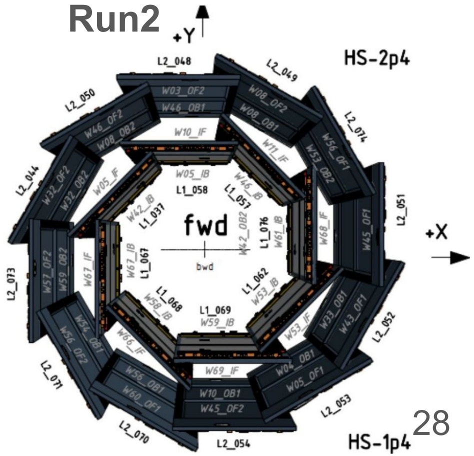
➢ **Accurate 3D SpacePoint with resolution ~10 µm (rphi, z)**

	Layer 1	Layer 2
Radius (mm)	14	22
# Ladders / modules	8 / 16	12 / 24
Sensitive thickness (um)	75	75
Pixels per module	768 x 250	768 x 250
Pixel size (um)	55x50 and 60x50	70x50 and 85x50
Total number of pixels	3.072×10^6	4.608×10^6





Challenges for tracking @ Belle II

1. Multiple scattering
    - Many low momentum tracks

2. Significant **machine background**
    - Beam background
        - Touscheck scattering
        - Beam-gas scattering
        - Synchrotron radiation
        - Beam-beam interaction
    - Luminosity Background
        - Radiative Bhabha
        - two-photon processes
    - Injection background
        - L1 trigger veto when injection bunch is close to IP

Detector occupancy(*) @ nominal luminosity: 6 x 10^{35} cm^{-2} s^{-1}

	L1 occupancy	L3 occupancy
Y(4S)	5 x 10^{-6}	0.02%
beam background	3%	3%

(*) Occupancy: fraction of pixel/strips above threshold

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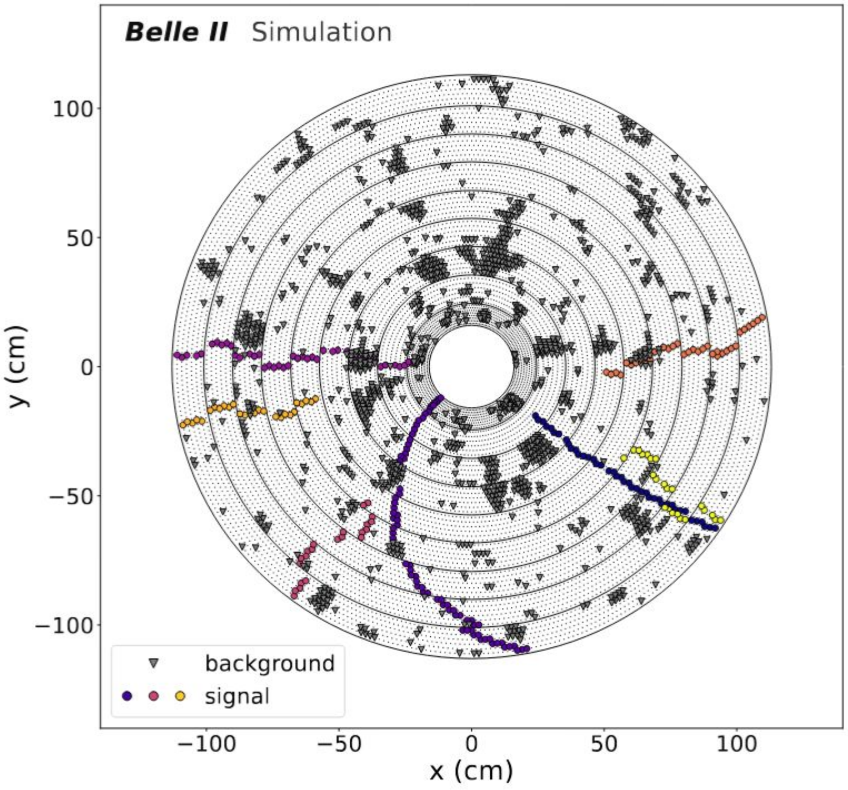


Event reconstruction at HEP

Belle II tracking detectors & challenges

Belle II tracking procedures

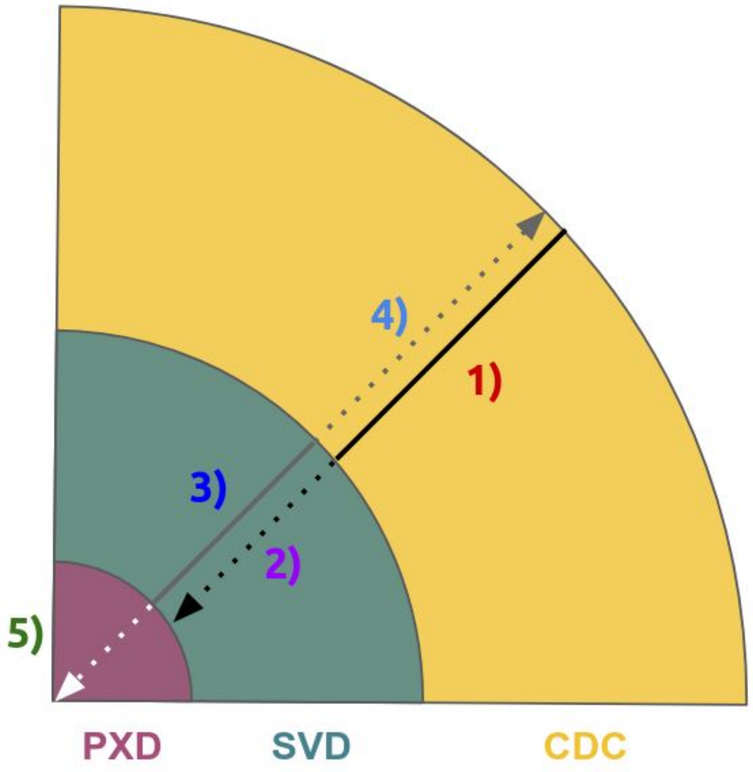
Tracking performance

Summary

Tracking procedure @ Belle II

Track finding at Belle II

CKF: Combinatorial Kalman Filter



1) CDC tracking with
   I) Global Legendre approach
   II) Local approach (off by default)
   III) Merge

2) Extrapolation to SVD with CKF

3) SVD standalone tracking

4) extrapolate SVD standalone tracks to CDC

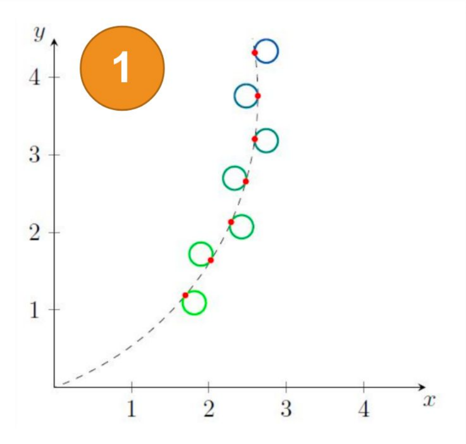
5) Combine and attach PXD hits

- Heavy relying on filters trained on simulated events (MVAs, SectorMaps)

- Not mentioned, but important: **hit filtering**

Global CDC track finder

- Start with **axial** wires (**r-Φ plane**)
- Add **z** information in the end using hits in the **stereo** layers
- Hit positions are approximated by **drift circles**



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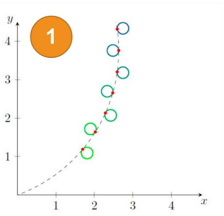
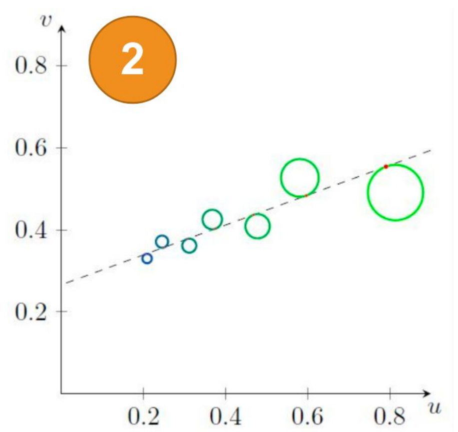
  - circular trajectory through origin → straight line
  - drift circle → circle
- Simplified problem: find common tangent for set of circles





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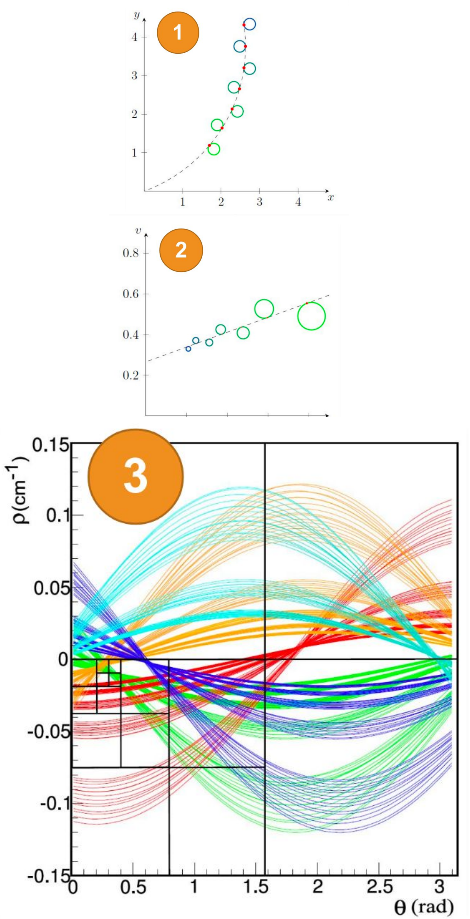
- Use **Legendre functions** to describe tangents to drift circles

  $$\boldsymbol{\rho = x_0 \sin(\theta) + y_0 \cos(\theta) \pm R_{Drift}} \quad \text{(Hough transformation)}$$

- Determine **point of maximum density** (→ 2D binary search)
- Efficient implementation: dedicated Quad-tree search for finding track parameters in Hough space, ‘sliding bins’



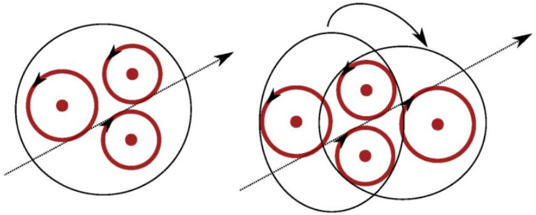
Local CDC track finder

Use local track finder for **short** and **displaced tracks** based on
Cellular Automaton: computational model with discrete cells updated synchronously

- Usage for **track finding**:
  - Solve longest path problem on a directed acyclic graph
  - Fast: O(n) instead of O(n!) (for general graphs)

Local CDC track finder

Use local track finder for **short** and **displaced tracks** based on
Cellular Automaton: computational model with discrete cells updated synchronously



- Cellular automaton for **segment building** in CDC
  - Segments: shorter track pieces (usually within one super layer)
  - Start combining triplets of hits assuming straight trajectory

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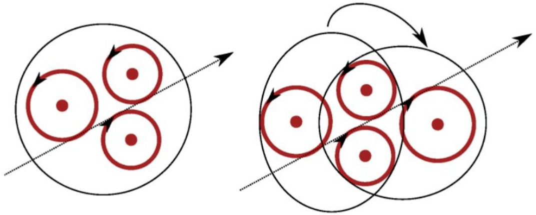
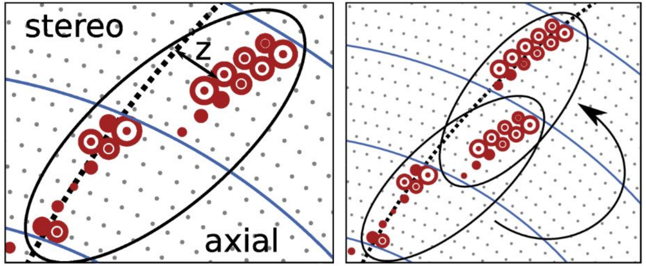


- Cellular automaton for **track building** in CDC
  - Cell: pair of axial + stereo wire segments
  - Combining cells into tracks starting from a seed, by selecting longest path



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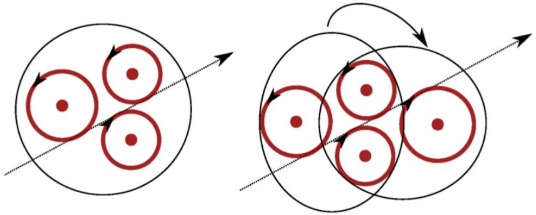

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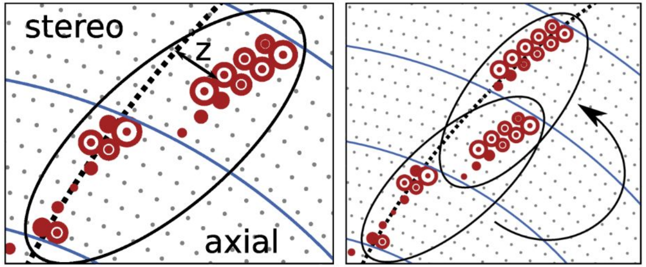
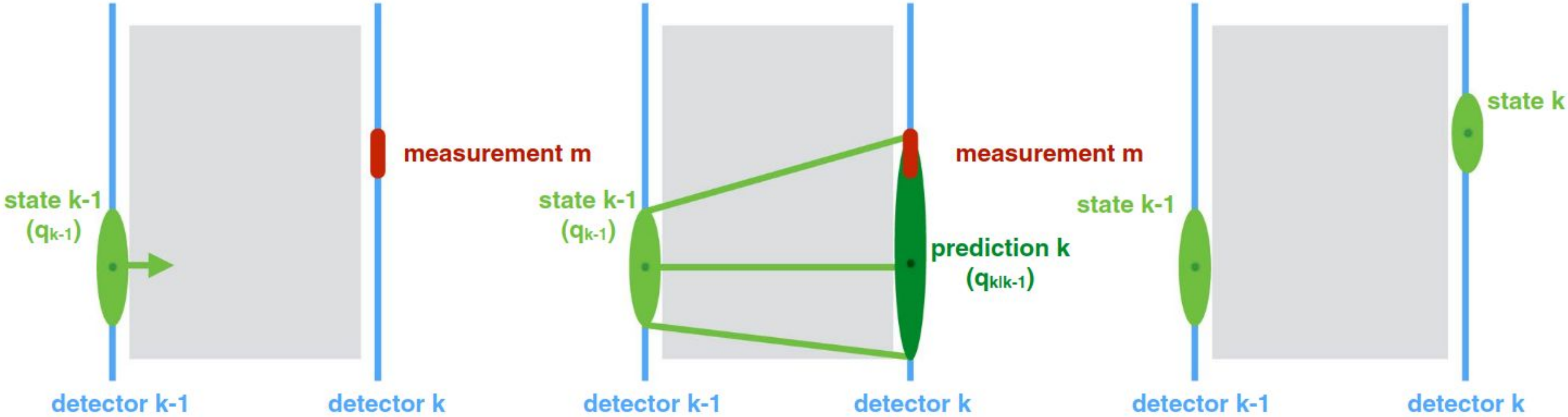


➤ Currently **not used** as a standalone algorithm due to **non-negligible fake rate**

Intermezzo: Kalman Filter

- A famous method for **track fitting**:
  - Progressively perform a least square fit
  - Extrapolate from k-1 to k: prediction + filtering
    - Prediction: extrapolate the state to next detector plane
    - Filtering: update the predicted state with the measurement



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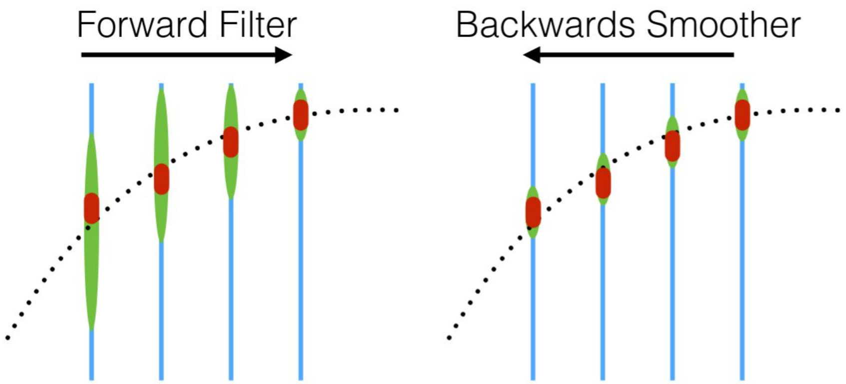
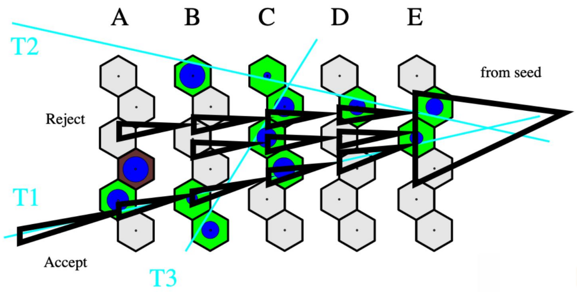
  - **Backward smoothing** to update all the states when forward filtering is done
  - **Propagate** in inhomogeneous **magnetic field** (Runge-Kutta-Nystrom method)
  - Material effects included



CDC to SVD using CKF

- **CKF** (Combinatorial Kalman Filter)
  → Perform a **full combinatorial exploration** when there are **multiple next-hit candidates**
  - **duplicate** the track candidate and treat as different tracks
  - **select best** candidate



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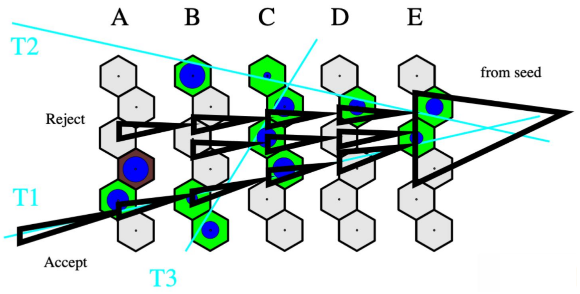
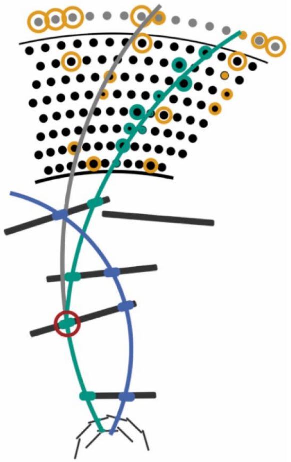


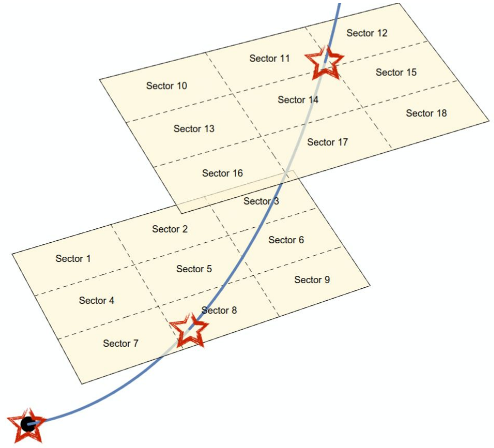
- Reach out to SVD hits using CKF:
  1. CKF:
     - Extrapolate to SVD in both directions:
       low momentum tracks curl and can pass SVD multiple times
     - MVA-based filter to attach the signal SVD cluster

  2. Combined CDC-SVD track **refitted** with full material effects included



SVD standalone track finding

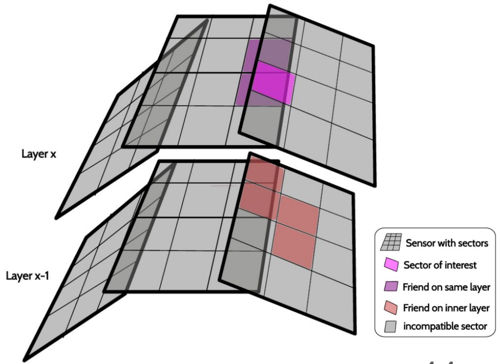
- VXDTF2: **SVD standalone** pattern recognition algorithm
    1. **Sector map** filters: reduce the combinations
    2. **Cellular automaton**: identify track candidates
    3. **Best candidate** selection



1. **Sector map**
    - Data structure holds information about the relations and filters of the space points in different region(sector)

How to **build** the sector map:

- Sub-divide sensors into virtual Sectors (3x3)
- 'Friends sectors': two sectors connected by one track
- **Training**: use MC events to learn which sectors are friend
    - Training samples: Y(4S) events, Bhabha
- **Store** the possible 'friendships' into a so called "Sector Map"



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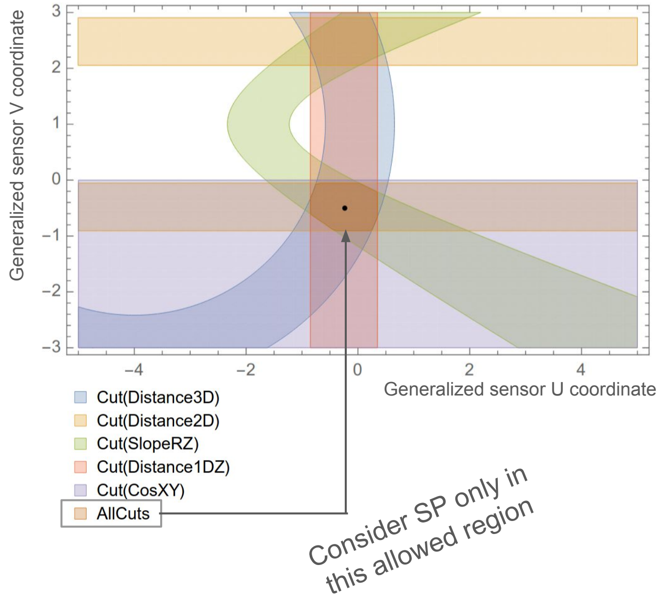

1. Sector map

Also **holds** selection criteria (**filters**) on the space points on friend sectors to reduce the number of combinations of hits

- Filters: defined individually for each sector combination (2- or 3- hits filters)
  - Geometrical quantities (distance, ϕ, θ-direction)
  - SVD timing information
  - Trained with same MC samples

  e.g. combination of filters' effects with a given space point on another sensor

➢ Capable of **adapting** to different detector conditions (defects, misalignments, ..)

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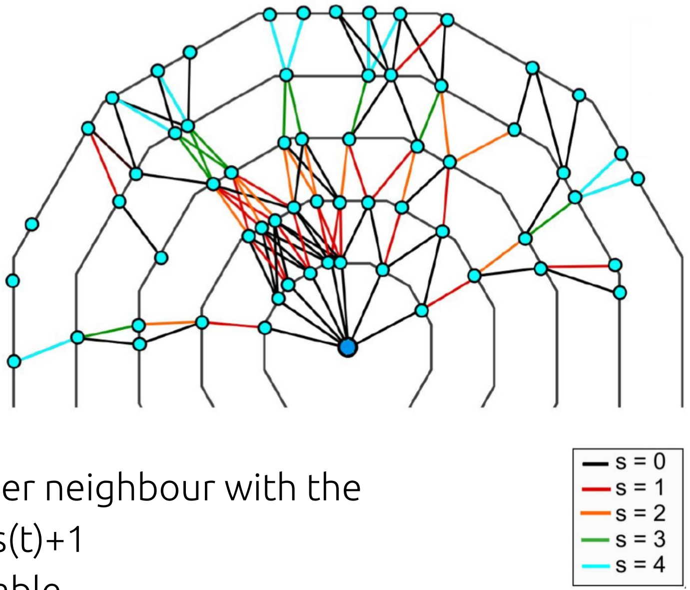


2. Cellular Automaton (helps to gather the longest path):
Beginning with the nodes on the outermost layers

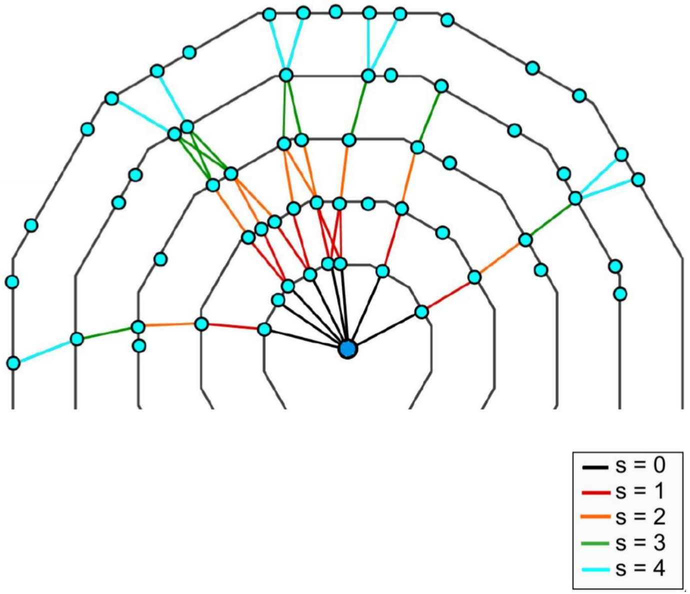
- **Cell**: segments (pairs of hits)
- **Rules**:
  - Check step: for each cell if there is at least one inner neighbour with the same state; if yes increase the state by 1: s(t+1) = s(t)+1
  - Repeated until all states of all the cells became stable

➢ **Final situation**: outer cell with higher states and inner Segment with lower states

SVD standalone track finding

- VXDTF2: **SVD standalone** pattern recognition algorithm
  1. **Sector map** filters: reduce the combinations
  2. **Cellular automaton**: identify track candidates
  3. **Best candidate** selection

2. **Cellular Automaton** (helps to gather the longest path):
Select the the **outermost cells** that have a
state **larger** than a threshold (=3 in this case)
and collect the next inner neighbour if the state
is s-1 iteratively



SVD standalone track finding

- VXDTF2: **SVD standalone** pattern recognition algorithm
    1. **Sector map** filters: reduce the combinations
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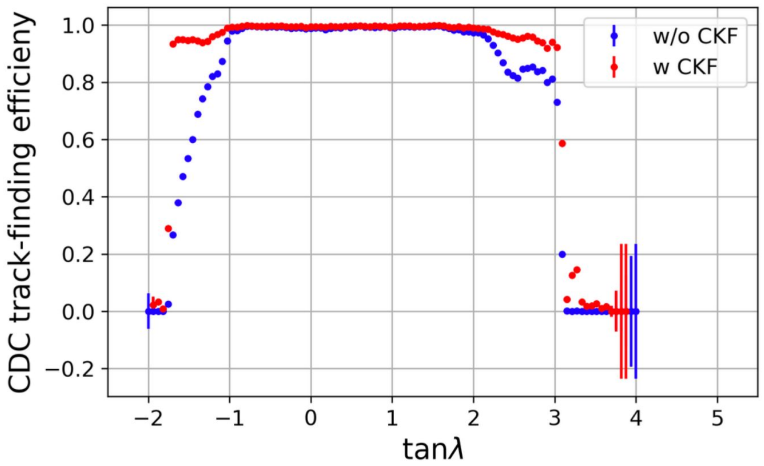
    3. **Best candidate** selection

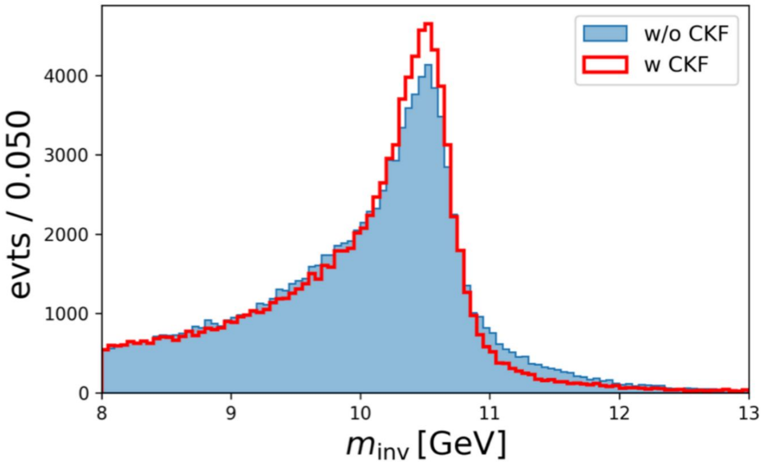
3. **Best path selection**:
    - Quality for each track estimated by a fast fit
    - Tracks are sorted and picked according to their **qualities**; tracks selected after are required not to have any SVD cluster shared with the tracks picked before

SVD standalone to CDC using CKF

- Use **CKF** to extrapolate **SVD (standalone) tracks into CDC**
  → attach CDC hits (remaining ones)
  - **Improves** the **finding efficiency** of CDC hits
  - Significant **improvement** at **large |tan λ|**
  - Improves the **momentum resolution** of the full track

2-track events (data), $\lambda \equiv \frac{\pi}{2} - \theta$





CDC-SVD tracks

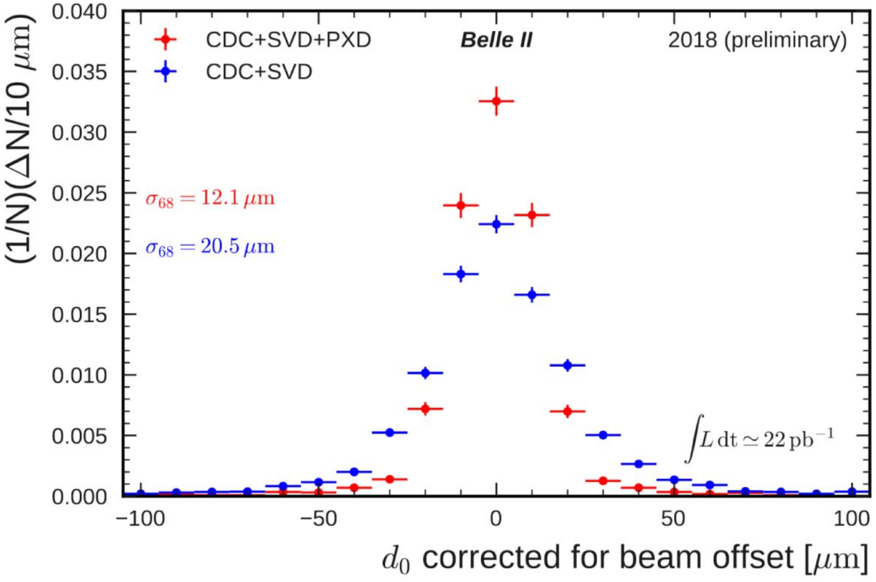
- **Merging step w/ CKF**
  - CDC - SVD tracks

CDC-SVD tracks to PXD

- **Merging step w/ CKF**
  - CDC - SVD tracks

- Use **CKF** to **add PXD hits**
  - Improve **position resolution** significantly e.g. the impact parameter: d_0

Belle II early data
Bhabha events



CDC-SVD tracks to PXD

- **Merging step w/ CKF**
  - CDC - SVD tracks

- Use **CKF** to **add PXD hits**
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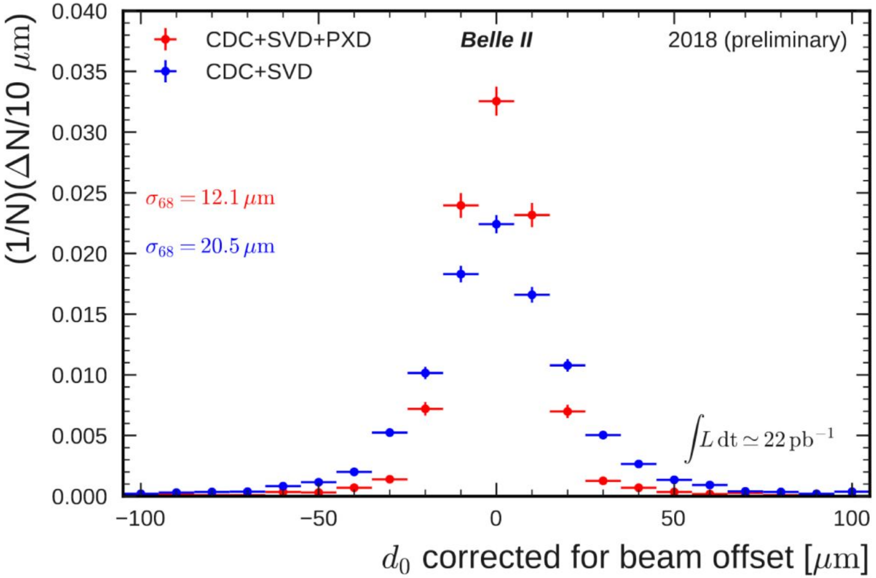
➤ **Track finding complete!**

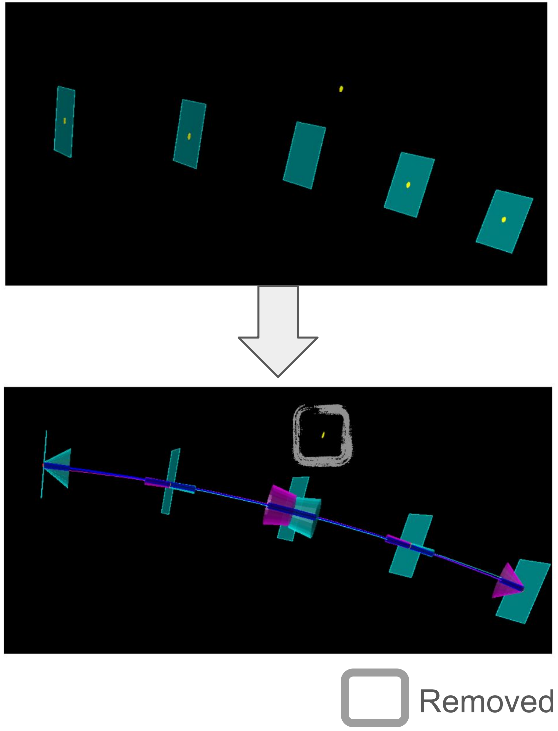
Belle II early data
Bhabha events



Track Fitting

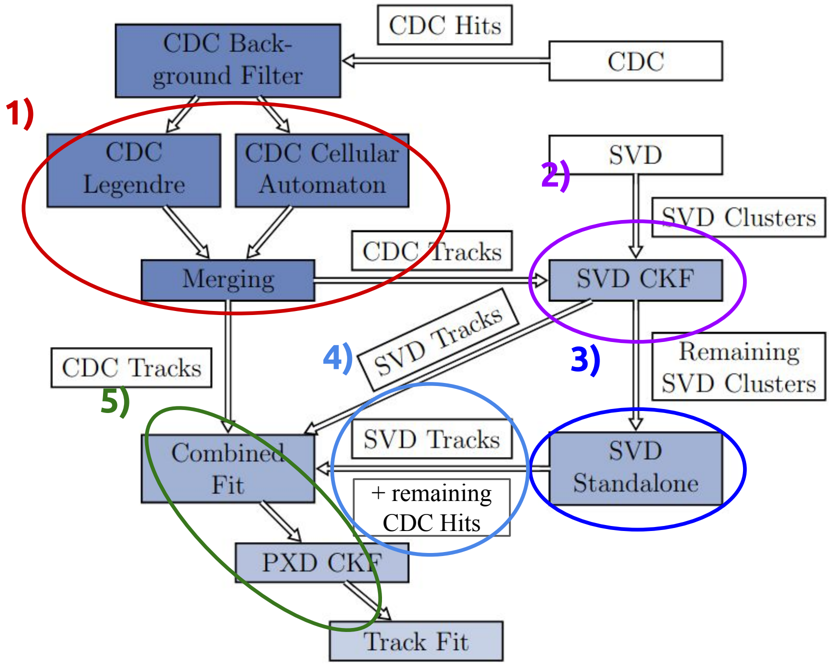
- **GENFIT**: experiment-independent framework for track reconstruction → Widely used in different experiments

- **DAF** (Deterministic Annealing Filter)
  - **Iterative Kalman Filter** with reweighted observations Designed for **track fitting in presence of outlier** and **background hits**
  - Capable of **outlier rejection**, L/R ambiguity resolution
    - **Outliers**: wrongly assigned hits (background hit found during track finding step) Hits are **weighted** according to their **residual** to the smoothed track
  - At most 5 iterations per track
  - **Fit with three different mass hypotheses (π, K, p)**



Tracking procedure @ Belle II: summary

CKF: Combinatorial Kalman Filter



Track finding at Belle II

1) CDC tracking with
   - I) Global Legendre approach
   - II) Local approach (off by default)
   - III) Merge

2) Extrapolation to SVD with CKF

3) SVD standalone tracking

4) extrapolate SVD standalone tracks to CDC

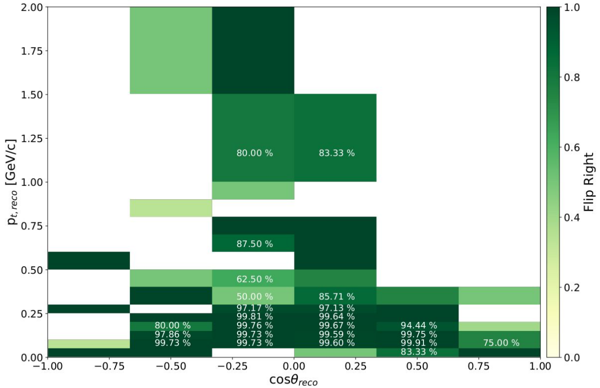
5) Combine and attach PXD hits

- Heavy relying on filters trained on simulated events (MVAs, SectorMaps)
- Not mentioned, but important: **hit filtering**

Refining step: flip & refit

- Significant **charge asymmetry** observed for low momentum tracks in the transverse plane
  - Found to be related with the **mis-assignment of direction** for low p_t tracks in transverse plane

- **Refining step** added to **mitigate** the mis-assignment as much as possible
  - Two MVA involved
  - Low level information + fit results of same track with different direction
  - Correct **~50% of the charge mis-assignment** with high efficiency (99%) and less than 1% (of the total tracks) refitted

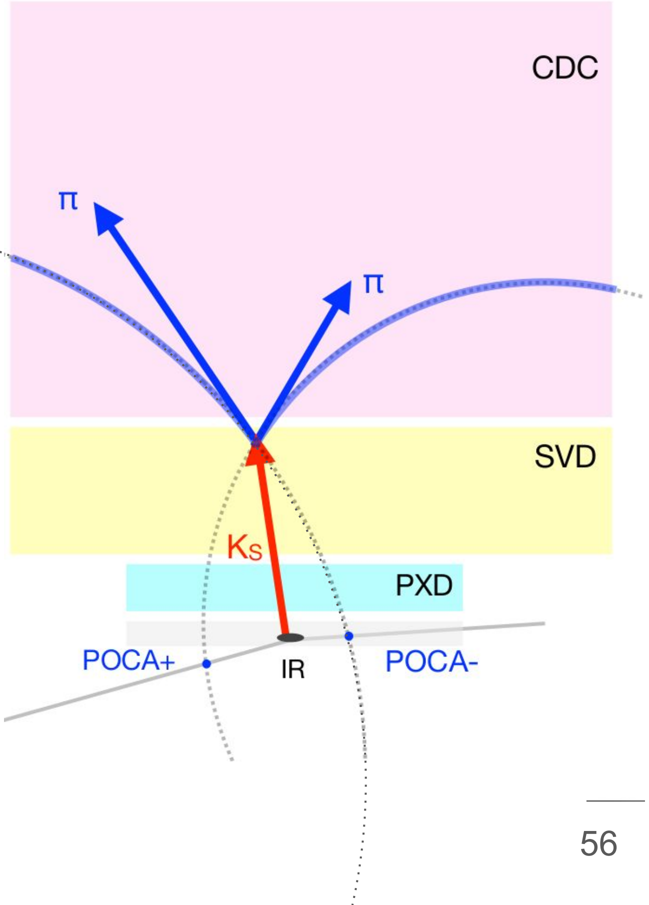


➢ **Increase** the **charge finding efficiency** and **partially cure** the **charge asymmetry**

Refining step: V0Finder

- V0s are K_s , Λ and converted Photons which have **displaced vertices** located outside the beam pipe
- By default, in files for analysts (mdst) we store the **track parameters** extrapolated to **POCA**
- **Includes** the correction for **material effects** and **energy loss**
- **Not true** for the daughters of V0s, since they are not produced at the POCA

➢ Special Treatment needed: **V0Finder**

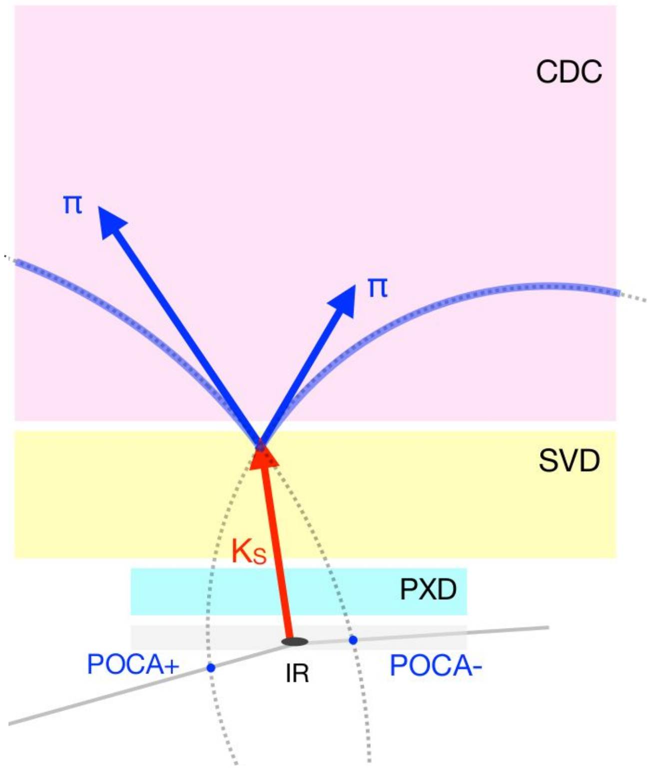


Refining step: V0Finder

- **V0Finder**: pairs up all positive and negative tracks and tries to find vertices between them during tracking (mDST):
  - **Re-fitting needed**:
    Need geometry material, magnetic field map, hits attached to tracks (not available at analysis level)

- Returns V0s **outside** of the **beam pipe**
  - Contain the **references to two tracks** and **fitResults** with the parameters of the helix at the **decay vertex position**
    (*basf2:* stdV0s.stdKshorts, stdV0s.stdLambdas)

- “Standard” reconstruction for V0s inside the beam pipe
  - Merged list available for analisis



Event reconstruction at HEP

Belle II tracking detectors & challenges

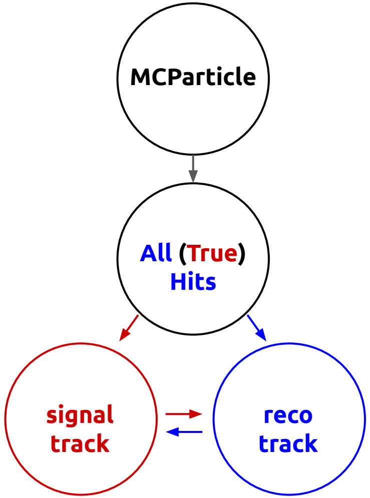
Belle II tracking procedures

Tracking performance

Tracking performance in MC

- Track Finding **FOM definition** provided by comparing **signal** with **reconstructed (reco)** tracks
  - From truth: Generator → Geant4 → True hits → MC track finder → **signal tracks**
    (ideal tracks, only limited by detector acceptance, hit efficiency and resolution)

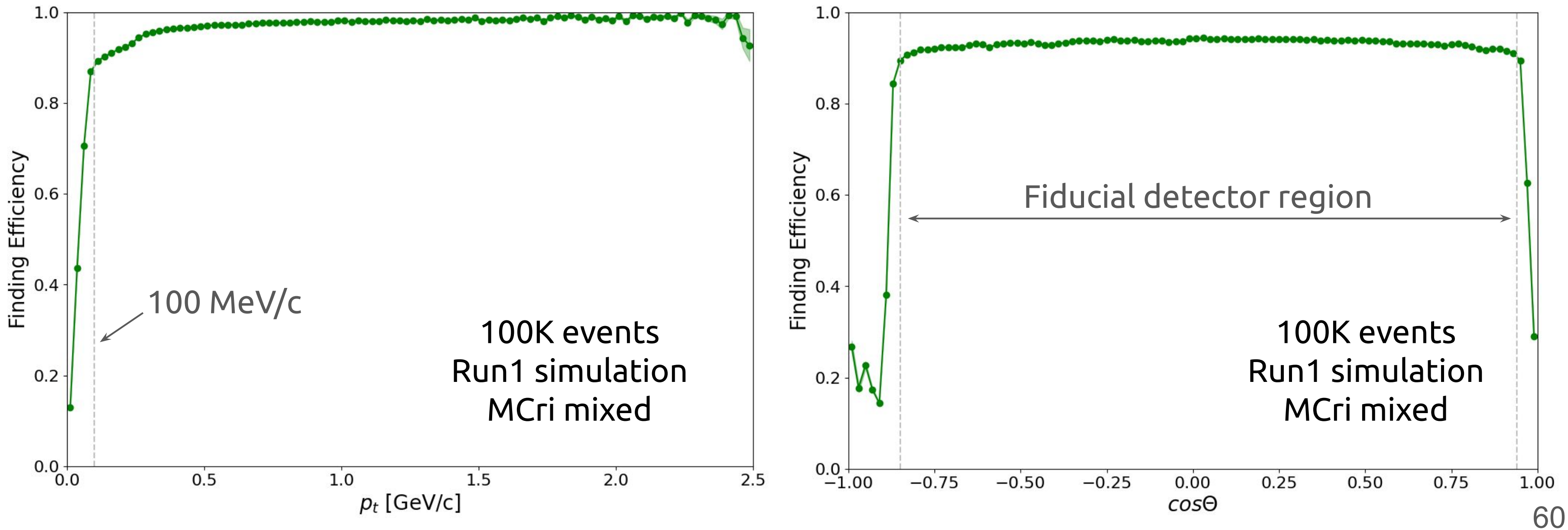
  - From Pattern Recognition: … → Track Finding → (pattern recognition) **reco tracks**



- **Hit efficiency:** fraction of signal hits contained in corresponding reco track
- **Hit purity:** fraction of hits in reco track contained in corresponding signal track
- **Matched:** hit purity > 66% and hit efficiency > 5%
- **Finding efficiency:** fraction of matched reco tracks over all signal tracks
- **Fake rate:** reco tracks not coming from the triggered collision
- **Clone rate:** fraction of reco tracks matched to an already matched signal track

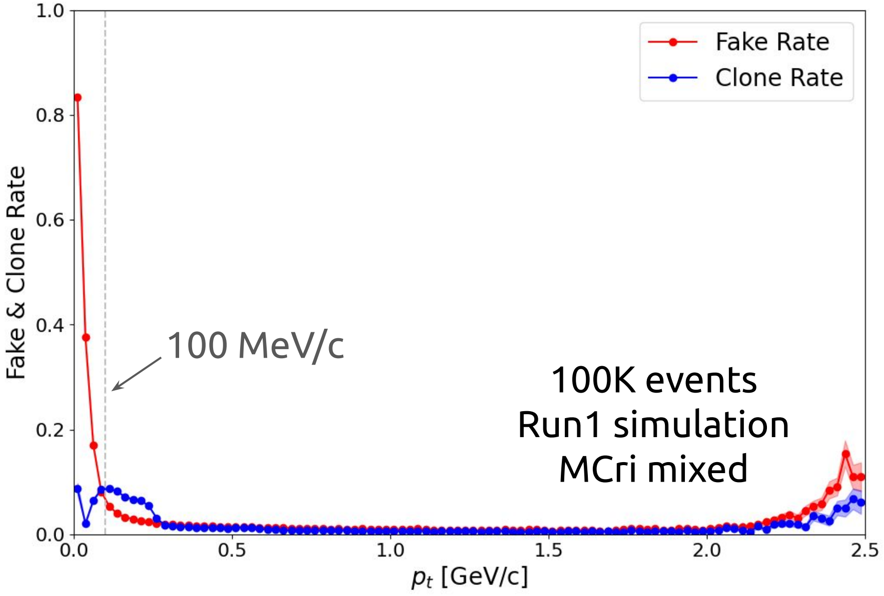
Tracking performance in MC

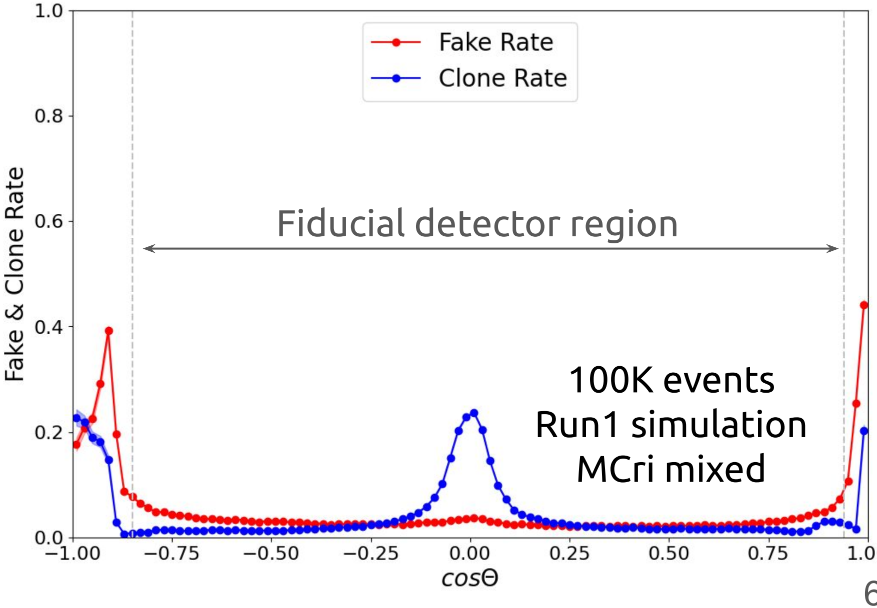
- **Finding efficiency** vs p_t and cosθ (not including detector acceptance)
  - Above 90% for most of the phase space covered by the detector (**average: 92%**)
  - **Drop** for low pt (<100 MeV/c) → small number of hits, larger multiple scattering, ..



Tracking performance in MC

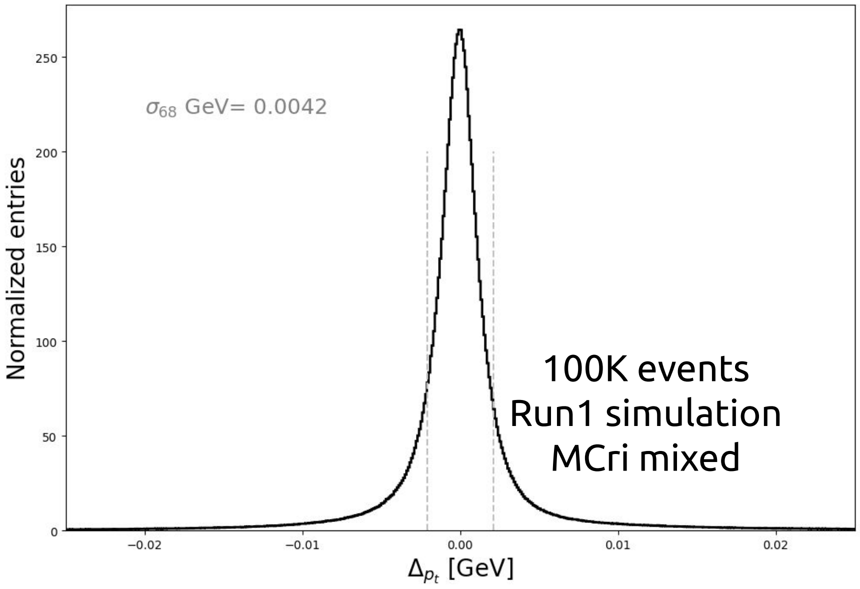
- **Fake Rate** and **Clone Rate** vs p_t and cosθ
  - Fake rate: average ~3.4%. Note: beam background tracks are also classified as fakes
  - Clone rate: average ~3.5%, increase at low p_t & in the proximity of cosθ=0 → curlers

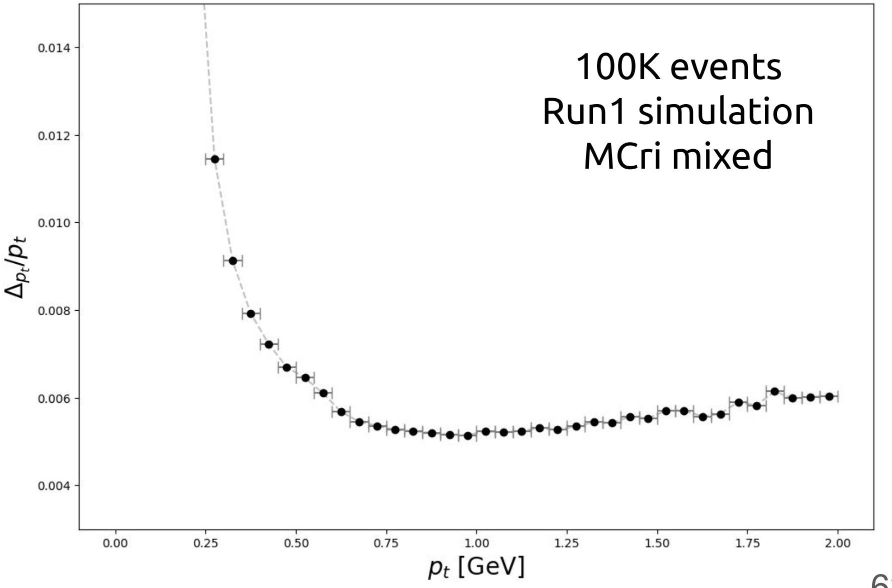




Tracking performance in MC

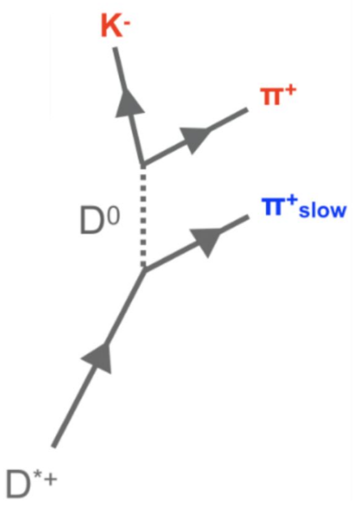
- **p_t resolution** ($\Delta p_t = p_{t,reco} - p_{t,MC}$)
  - Integrated over all p_t values: σ_{68} ~ 0.0042 GeV
  - $\Delta p_t/p_t$ plotted as a function of p_t





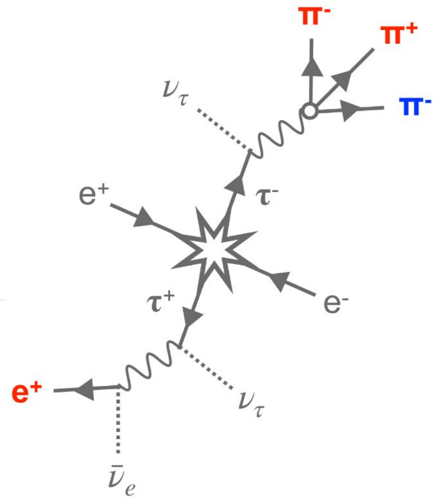
Tracking performance in data

- Validation with data
  - **Tag** and **probe** studies focusing on a many of final states to cover a **large** momentum **spectrum**



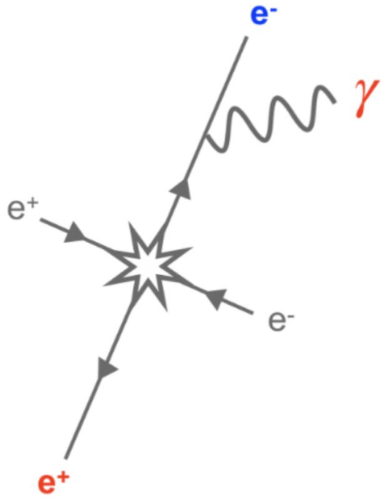
$p_t \lesssim 200$ MeV

$D^{*+} \rightarrow D^0\pi^+_{slow}$



200 MeV $\lesssim p_t \lesssim$ 2 GeV

$e^+e^- \rightarrow \tau^+\tau^-$



$p_t \gtrsim 2$ GeV

$e^+e^- \rightarrow e^+e^-\gamma$

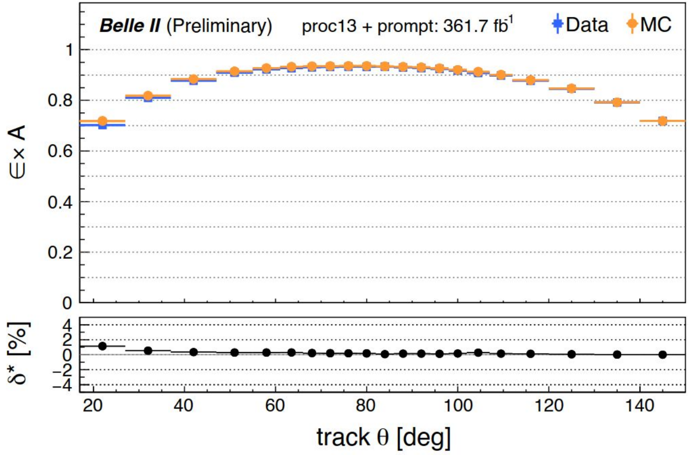
Tracking performance in data

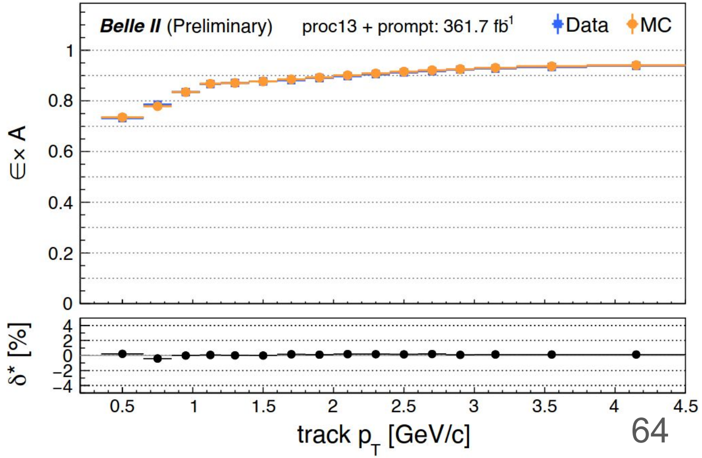
$$\delta^* = 1 - \frac{\epsilon^*_{Data}}{\epsilon^*_{MC}} = 1/k \cdot \left(1 - \frac{\epsilon^{Data}_{meas}}{\epsilon^{MC}_{meas}}\right)$$

- Validation with data
  - **Tag** and **probe** studies
  - $e^+ e^- \rightarrow \tau^+ \tau^-$ with one τ decays to 1 single charged particle and the other decays into **3 charged particles**
  - **Tagging**: 3 good quality tracks, total charge of ±1
  - **Probing**: the fourth track
  - **Tracking finding efficiency ε**

$$\epsilon \cdot A = \frac{N_4}{N_3 + N_4}$$

A: detector acceptance
N4 (N3): # of events where 4 (3) tracks were found





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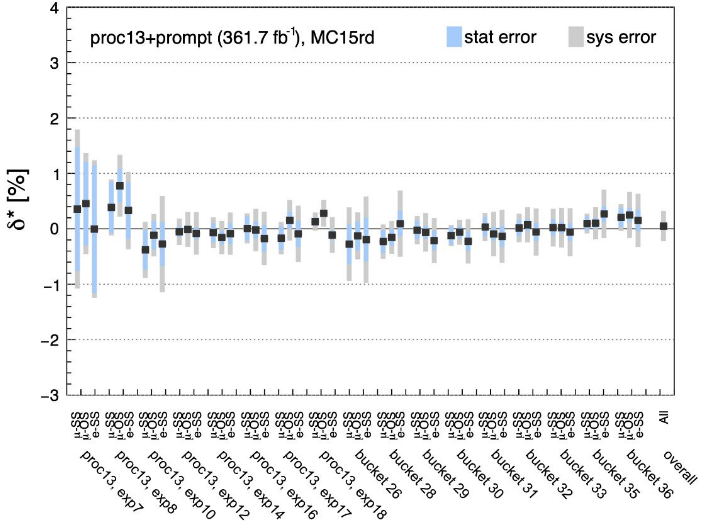
  - **Tagging**: 3 good quality tracks, total charge of ±1
  - **Probing**: the fourth track

➤ **Result from 2024 (Run1)**

$$\delta^*_{\text{overall}} = 0.049 \ \pm \ 0.019 \ (\text{stat}) \ \pm \ 0.268 \ (\text{sys}) \ \%$$

$$\delta^* = 1 - \frac{\epsilon^*_{Data}}{\epsilon^*_{MC}} = 1/k \cdot \left(1 - \frac{\epsilon^{Data}_{meas}}{\epsilon^{MC}_{meas}}\right)$$



Tracking performance in data

- Validation with data
  - **Tag** and **probe** studies

  - **$e^+ e^- \rightarrow \tau^+ \tau^-$** with one τ decays to 1 single charged particle and the other decays into **3 charged particles**

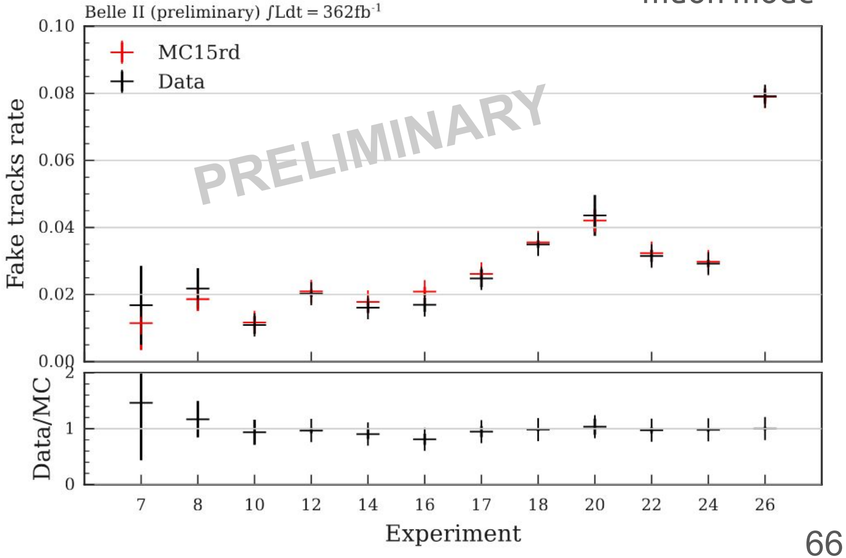
  - **Tagging**: 4 good quality tracks
  - **Probing**: one additional track

  - **Fake rate r_{fake}**

$$r_{fake} = \frac{N_5}{N_4 + N_5}$$

N4 (N5): # of events where 4 (5) tracks were found

muon mode



Corrections & Systematics

- The tracking group provides **corrections & systematics** to the analysts for some known effects

1. Slow pion efficiency
2. Fast track efficiency
3. Ks efficiency

Account for the **differences in reconstruction efficiency** between data and MC

4. Momentum scale & energy loss

Account for **imperfect map of the (real) B-field**, and incorrect energy loss correction in the track fit (data & MC)

5. Alignment

Accounts for **residual misalignment** in the data (no correction, only systematic)

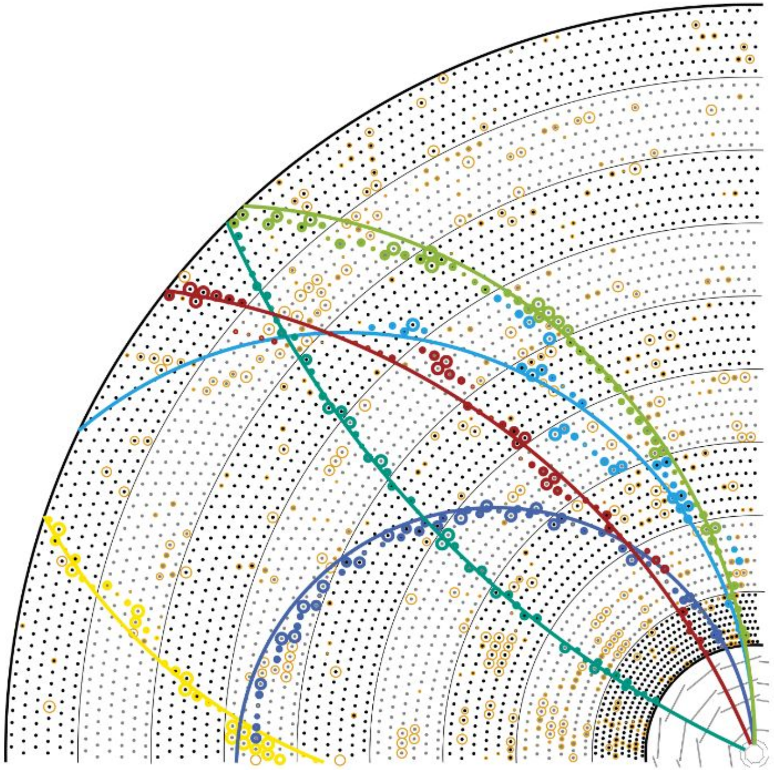
Summary

- Tracking @ Belle II in a nutshell

- Just an introduction, many topics not covered
  - *Some* of them in the backup (definitely not all)

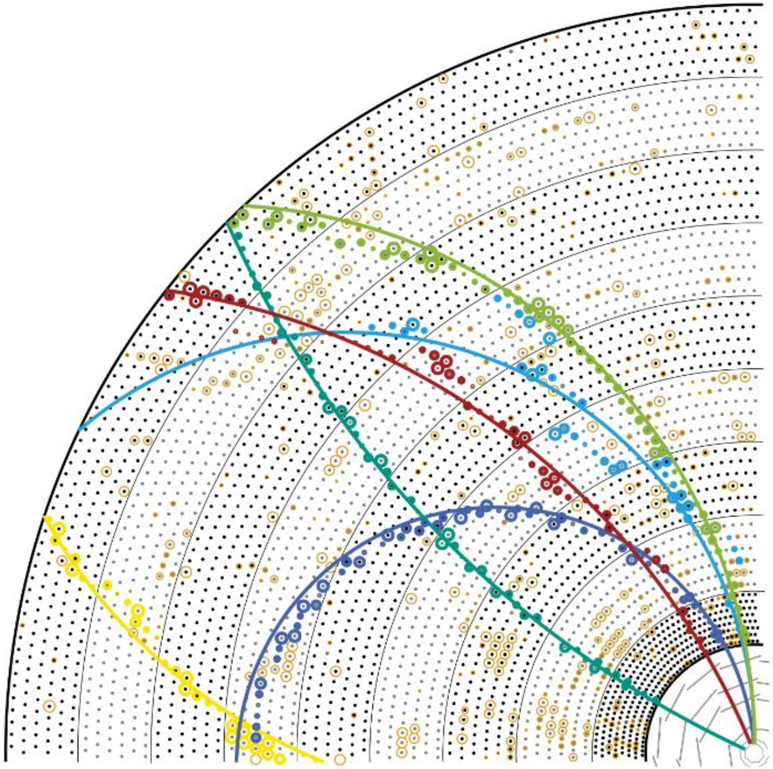
- Belle II tracking works, very good performance
  - However, *"the devil is in the details"*

- Two picks readings (many more in the backup):
  - *Track finding at Belle II*
  - *End-to-End Multi-Track Reconstruction using Graph Neural Networks at Belle II*
    (not covered today, not yet in the default chain)



Acknowedgments

My travel to KEK was supported
by the Scandinavia-Japan Sasakawa Foundation
https://sjsf.se/



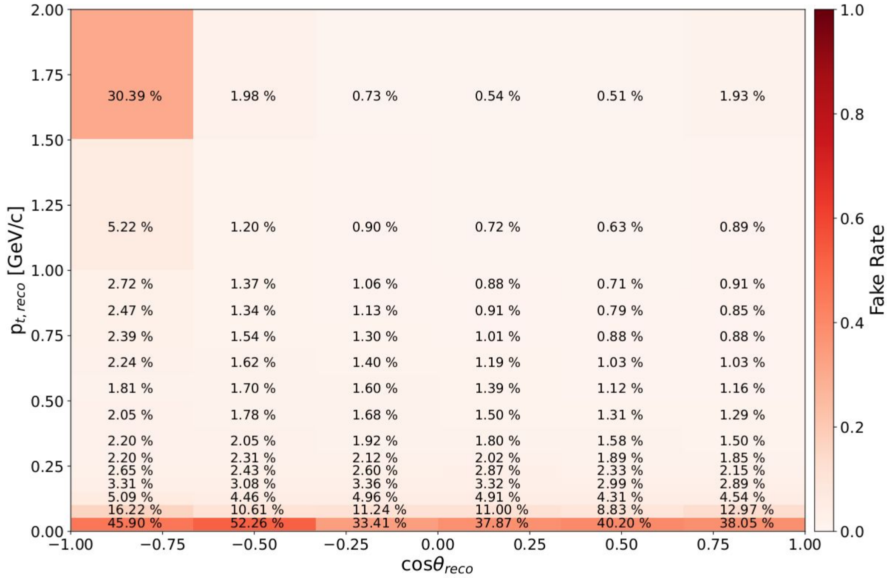
BACKUP SLIDES

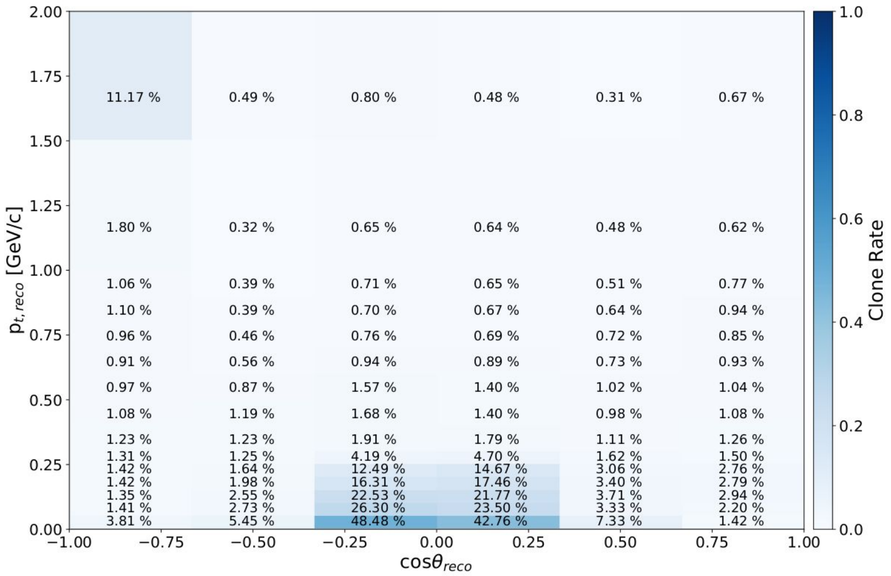
Bibliography

- V. Bertacchi et al., *Track finding at Belle II*
- L Reuter et al., *End-to-End Multi-Track Reconstruction using Graph Neural Networks at Belle II*
- O. Frost, *A Local Tracking Algorithm for the Central Drift Chamber of Belle II* (Diploma thesis, KIT, 2013)
- N. Braun, *Momentum Estimation of Slow Pions and Improvements on the Track Finding in the Central Drift Chamber for the Belle II Experiment* (Masters thesis, KIT, 2015)
- C. Wessel, *Optimisation of the Data Reduction for the Belle II Pixel Detector and Development of a new Track Finding Algorithm using the Belle II Vertex Detector* (PhD thesis, Bonn, 2022)
- T. Abe et al., *Belle II Technical Design Report*

Tracking performance in MC

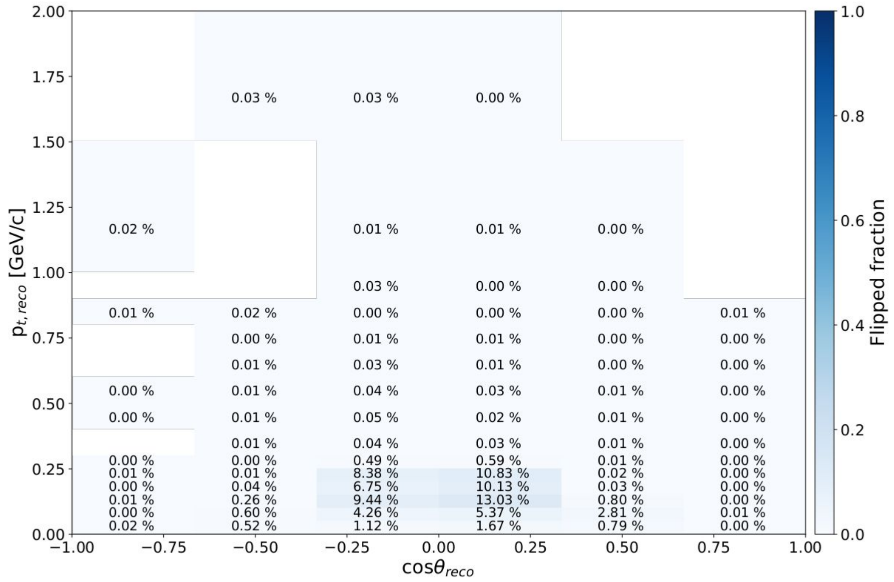
100K events
Run1 simulation
MCri mixed

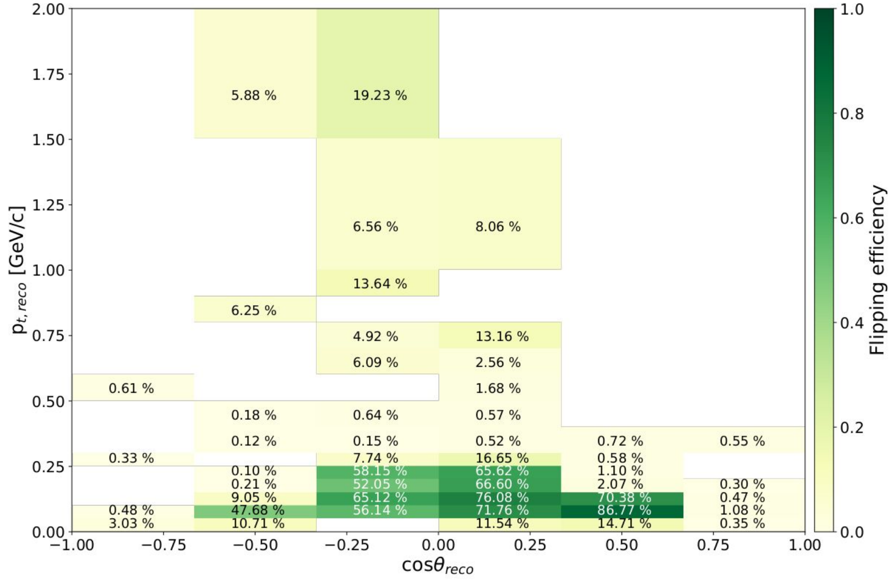




Tracking performance in MC

100K events
Run1 simulation
MCri mixed





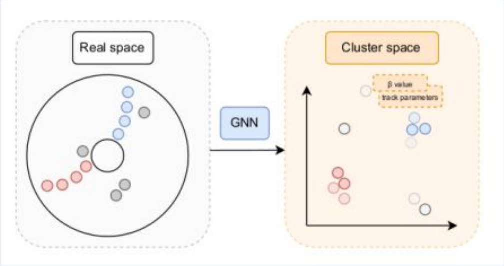
Use of AI in tracking

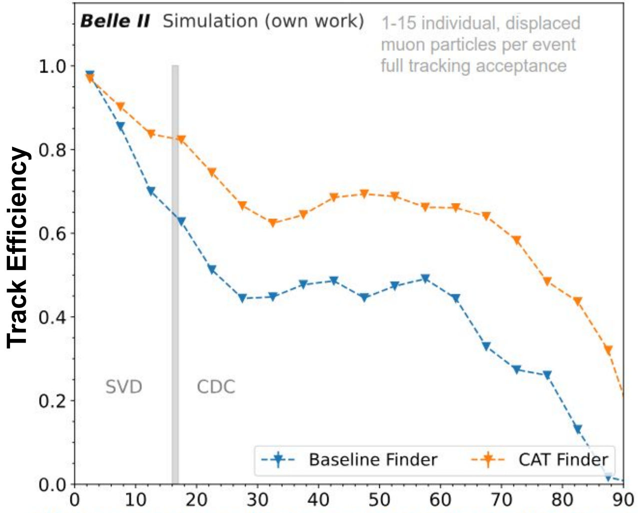
- use MVA for hit filtering
- MVA for track quality assessment (not provided to analysts yet)

New approach with Graph Neural Network (GNN) for CDC tracking

- developed by KIT group
- employ GNN to do object condensation
- prototype exists:
  - promising results partially outperforming current CDC algorithm
- soon to be published: Belle II Document 4224
- full integration into basf2 needs more time (after rel-10)

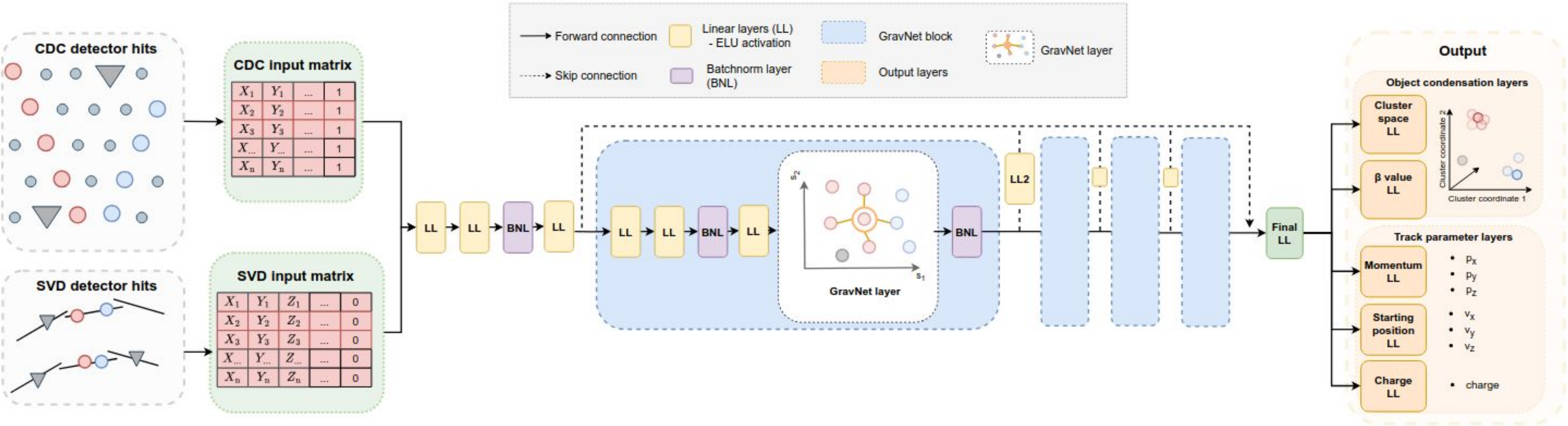
"CAT Finder"





Distance from collision point to track starting position (cm)

CAT Finder



Forward connection
Skip connection
Linear layers (LL) - ELU activation
Batchnorm layer (BNL)
GravNet block
Output layers
GravNet layer
CDC detector hits
SVD detector hits
CDC input matrix
SVD input matrix
LL
BNL
LL2
GravNet layer
Final LL
Output
Object condensation layers
Cluster space LL
β value LL
Cluster coordinate 1
Cluster coordinate 2
Track parameter layers
Momentum LL
Starting position LL
Charge LL
charge

Kink finder

- **kink:** the topological signature of a charged particle in-flight decay or scattering in the detector material, appearing as a sudden change in the direction of the trajectory
- The Kink Finder algorithm handles two general cases of kinks:
  - Both mother and daughter tracks are found individually
    → reconstruct the geometry and kinematics of the kink and stores the information
  - Hits left by mother and daughter tracks are reconstructed as one combined track
    → Identify such a track, splits it into two tracks, and repeats the procedure of the first case

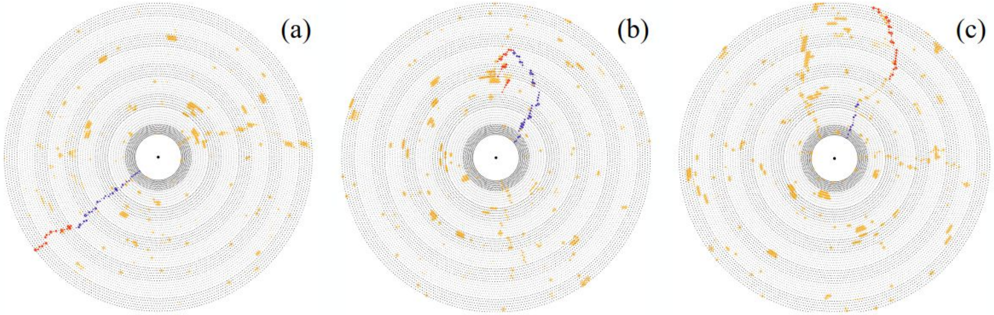


Figure 1: CDC event display of three MC simulation events with kinks (a)–(c). Blue and red hits represent reconstructed mother and daughter tracks from the kink, respectively. All remaining hits in the CDC are yellow.

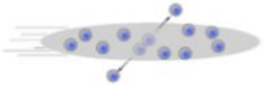
Belle II beam backgrounds

Beam background

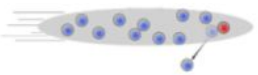
- particles that deviate from the nominal orbit are lost by hitting the beam pipe or other machine apparatus
- The generated shower particles might reach the detector and increase the hit rate
- Real Tracks but not belong to the triggered collision
- Deteriorate the detector’s physics performance and damage the sensors

Beam background type:

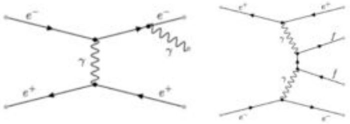
Touschek scattering:



Beam-gas scattering:



Luminosity background:



Synchrotron radiation:

Injection background
Large beam loss accidents

Other none-physic factor: noise hits, cross talk …

https://browse.arxiv.org/pdf/2302.01566.pdf

Belle II beam backgrounds

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.

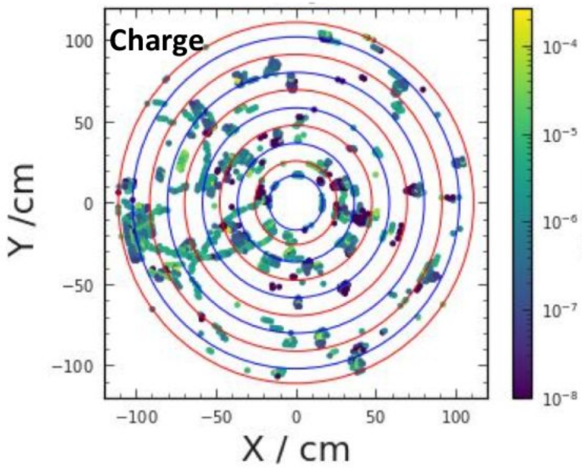
Radiative Bhabha Scattering Colliding electron and positron do not create an Y(4S)-resonance, but rather interact via Bhabba scattering. Photons and the electron–positron-pair can lead to secondary particle showers.

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

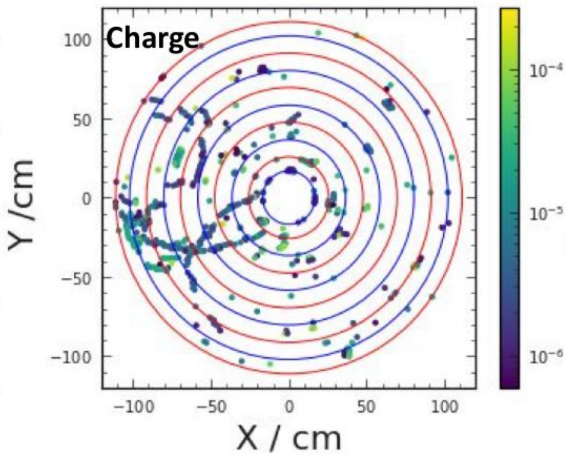
CDC background filter

- CDC Hits component: 500 vs 3000 (signal hits vs background hits @full lumi)
- Main background hits: beam background + cross talk
- Filters: ADC counts + ASIC cross talk filters
  - ASIC cross talk: ASICs sharing same connector with the one which has signal hits fired with low ADC
  - Can be suppressed by the Time&ADC information/relations

➡ Background hits and hits from cross-talk are reduced



All Hits



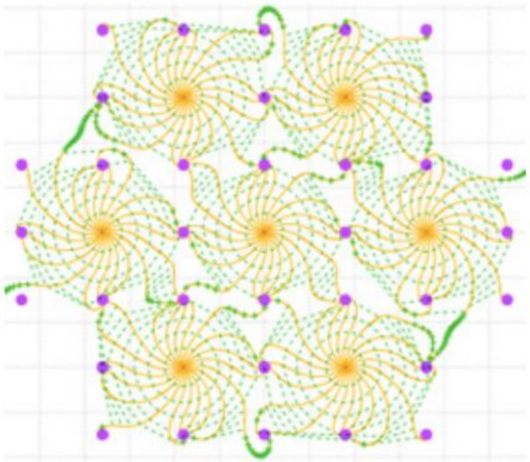
Hits after ADC+ASIC cuts

	ADC > 18	ADC > 18 and ASIC filter
Signal	95.4%	**93.2%**
Background	54.1%	**31.1%**

DESY.

Drift chambers in general

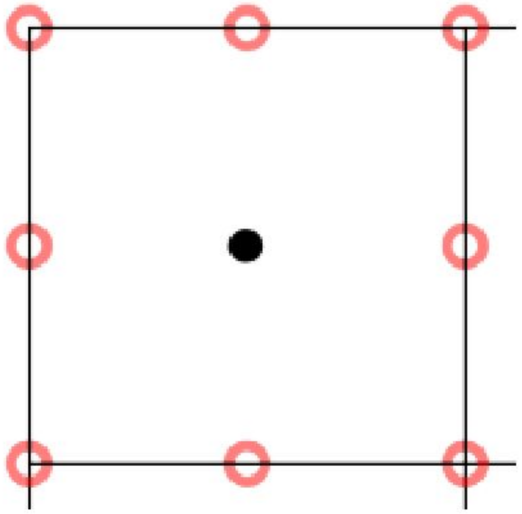
To induce the drift **electric field** is needed.
→ Accelerated electrons create avalanches



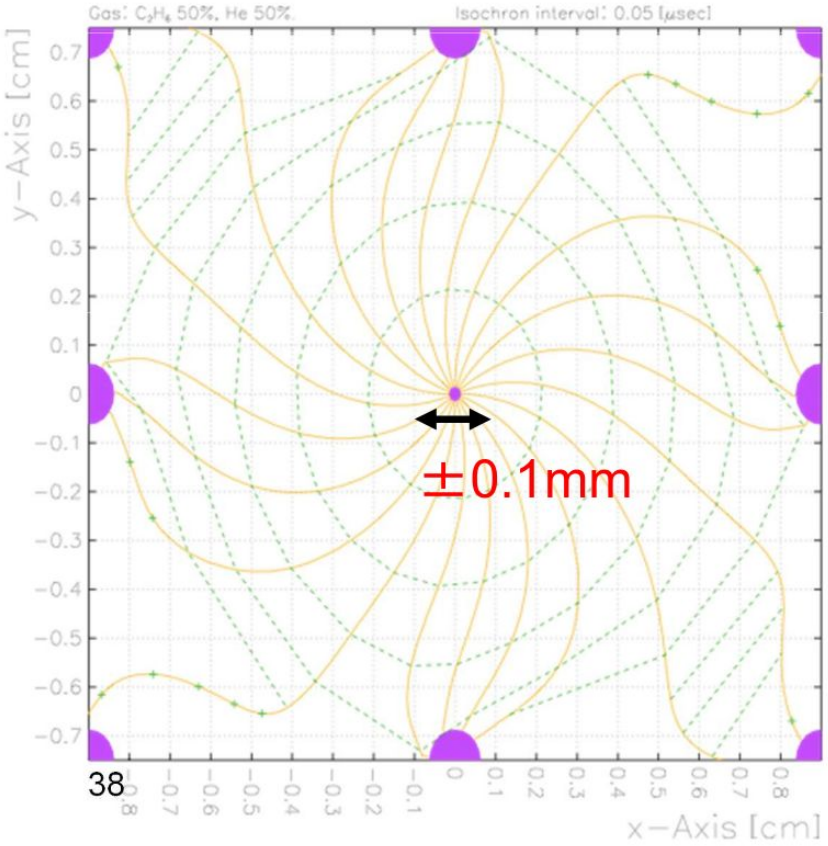
- Field wires generate electric field.
- Sense wires "sense" the signal

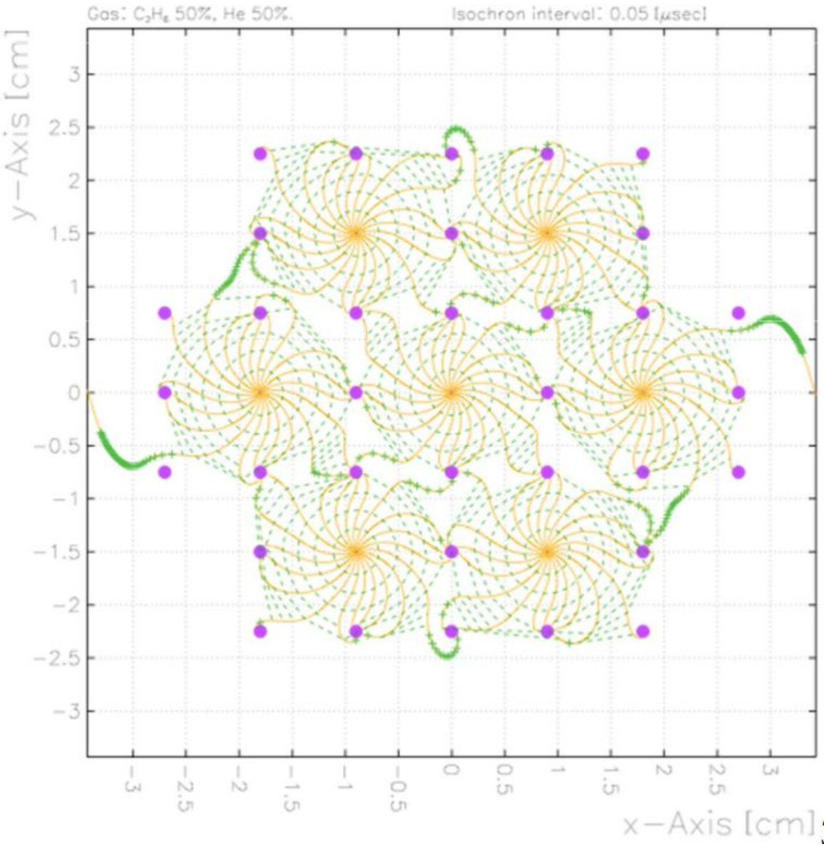
$$E \sim \frac{U}{r} \quad (5)$$

In Belle2:
8 field wires
1 sense wire



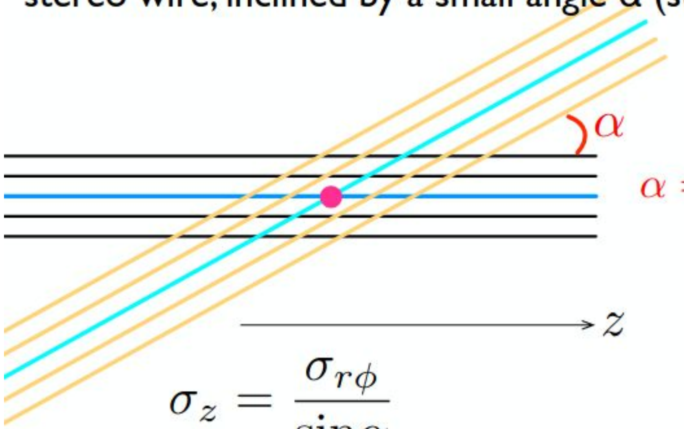
Belle II CDC (simulation using Garfield)



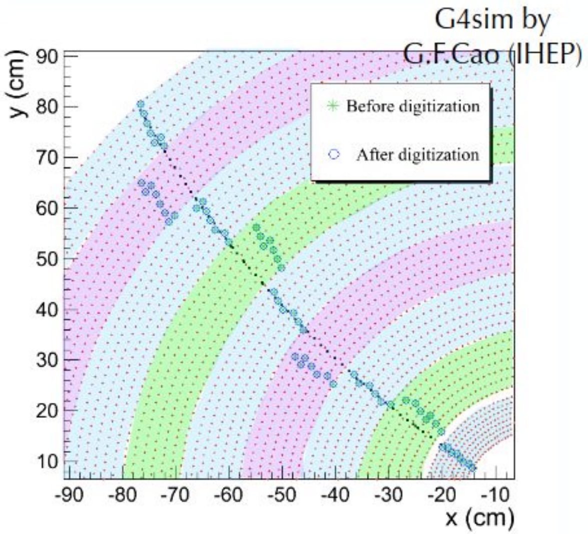


CDC, z position

axial wire; parallel to z-direction
stereo wire; inclined by a small angle α (stereo angle)

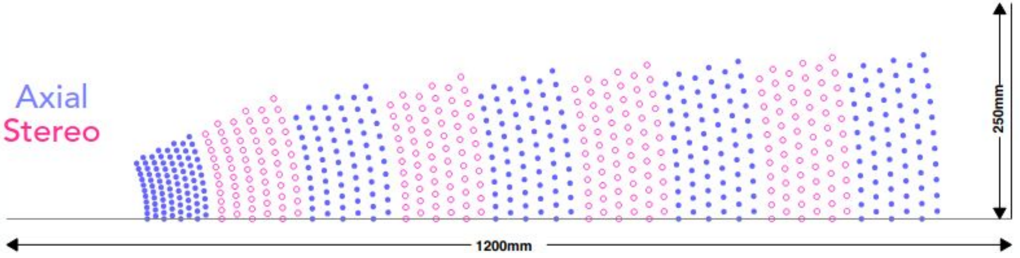


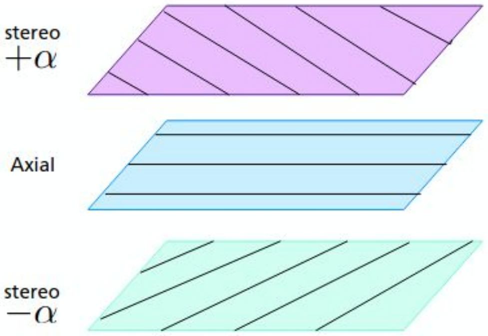
$\alpha = 60 \sim 80\text{mrad}$
(BelleII)



$$\sigma_z = \frac{\sigma_{r\phi}}{\sin\alpha}$$

$$\sigma_z = 1.9 \sim 2.5\text{mm}(\sigma_{r\phi} = 0.15\text{mm})$$





basf2 objects for CDC

Some important quantities that you actually "see" that characterise hits.

- **A**nalog-to-**D**igital-**C**onverter (ADC).

→ related to integrated charge deposited on the wire.

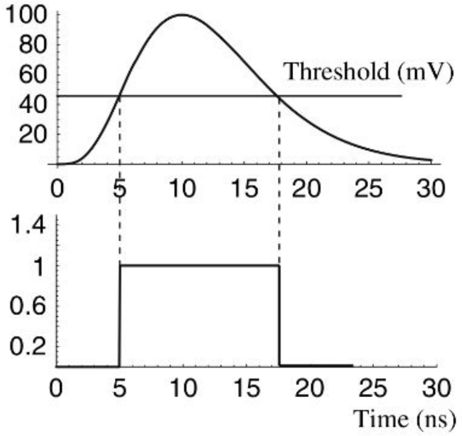
- **T**ime-**o**ver-**T**hreshold (TOT).

→ threshold for a hit to be registered as non-background/noise.

- **T**ime-to-**D**igital-**C**onverter (TDC).

→ related to drift time.

Very important in track reconstruction and correct hit selection!



Kalman filter-based track fit

- A kalman filter is a progressive way of performing a least square fit
- How it works:
  - Estimate starting parameter P0|0
  - Iterate over all hits 1…K
    1. Take P(k-1|k-1) at point k-1
    2. Propagate to point k to get predicted parameter p(k|k-1)
    3. Update predicted parameters with measurement m_k to get p(k|k)
    4. Repeat until reach the last hite

Material effects are included as the error

1. propagate p_{k-1} and its covariance C_{k-1} :

$$q_{k|k-1} = f_{k|k-1}(q_{k-1|k-1})$$

$$C_{k|k-1} = F_{k|k-1} C_{k-1|k-1} F^{T}_{k|k-1} + Q_k$$

with Q_k ~ noise term (M.S.)

2. update prediction to get $q_{k|k}$ and $C_{k|k}$:

$$q_{k|k} = q_{k|k-1} + K_k[m_k - h_k(q_{k|k-1})]$$

$$C_{k|k} = (I - K_k H_k) C_{k|k-1}$$

with K_k ~ gain matrix :

$$K_k = C_{k|k-1} H_k^{T} (G_k + H_k C_{k|k-1} H_k^{T})^{-1}$$

Smoother:

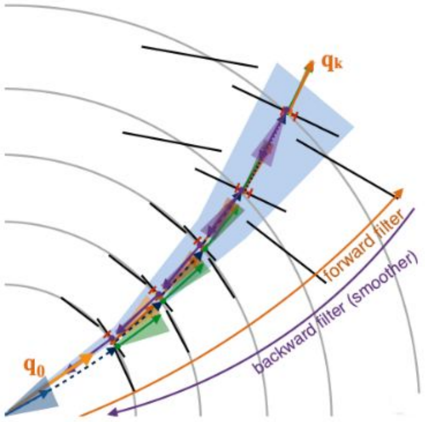
proceeds from layer $k+1$ to layer k :

$$q_{k|n} = q_{k|k} + A_k(q_{k+1|n} - q_{k+1|k})$$

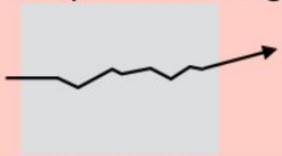
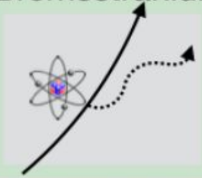
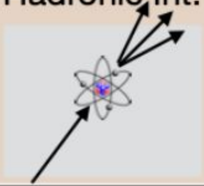
$$C_{k|n} = C_{k|k} - A_k(C_{k+1|k} - C_{k+1|n}) A_k^{T}$$

with A_k ~ smoother gain matrix :

$$A_k = C_{k|k} F^{T}_{k+1|k} (C_{k+1|k})^{-1}$$



Interactions most relevant to tracking

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

Challenges for tracking @ Belle II

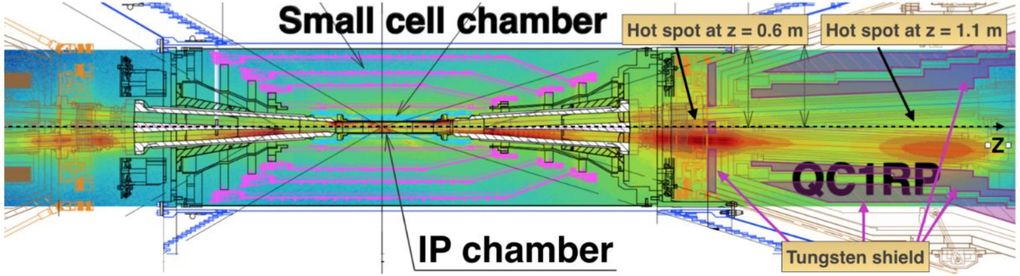
1. Multiple scattering
   - Many low momentum tracks

2. Significant **machine background**
   - Beam background
     - Touscheck scattering
     - Beam-gas scattering
     - Synchrotron radiation
     - Beam-beam interaction
   - Luminosity Background
     - Radiative Bhabha
     - two-photon processes
   - Injection background
     - L1 trigger veto when injection bunch is close to IP

Detector occupancy(*) @ nominal luminosity: 6 x 10^{35} cm^{-2} s^{-1}

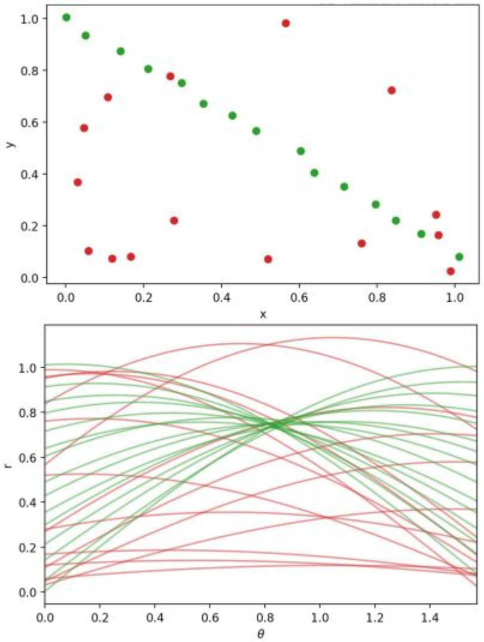
	L1 occupancy	L3 occupancy
Y(4S)	5 x 10^{-6}	0.02%
beam background	3%	3%

(*) Occupancy: fraction of pixel/strips above threshold



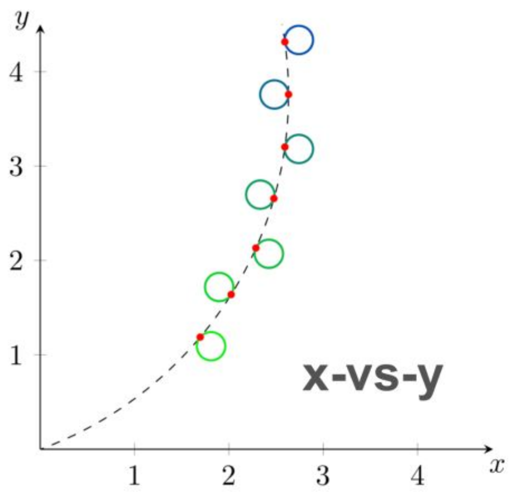
Hough transformation

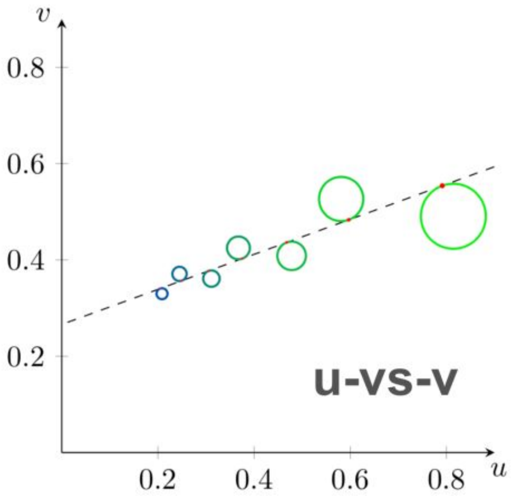
- global finding: start with all position measurements
- How to find a pattern if you know its shape (functional form)?
- Simple example: straight line
  $r = x\cos(\theta) + y\sin(\theta)$
- Go into parameter space (Hough space) by inverting function: For each measurement (x,y) look at all parameters resulting in a line through (x,y).
- Points with high density in Hough space correspond to parameters which fit for many measurements $\Rightarrow$ the parameters for our line



Conformal mapping

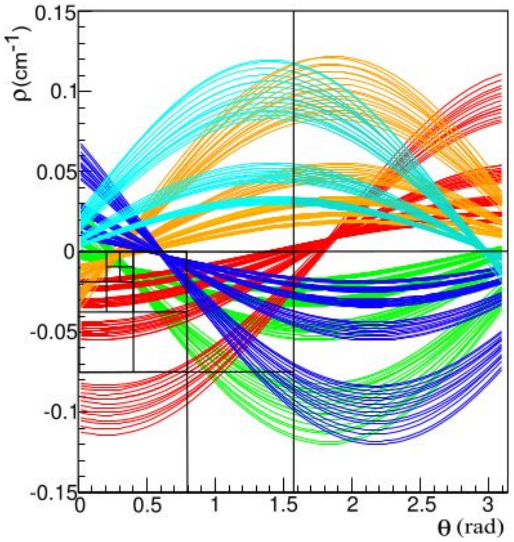
- problems at Belle II:
  - B-field $\Rightarrow$ helix (circle in x-y-plane)
  - in CDC only know distance to hit wire (drift circles) not exact position
- conformal mapping $u = \frac{x}{x^2+y^2}$; $v = \frac{y}{x^2+y^2}$
- properties
  - circles through the origin become straight lines in u - v
  - circles not going through origin stay circles (e.g. drift circles)





CDC case

- use Legendre transformation for Hough space:
  - parameter space representing all tangents to a drift circle
  - $\rho = x_0 \sin(\theta) + y_0 \cos(\theta) \pm R_{Drift}$
- employ fast Quad-Tree-Search for finding high density regions:
  - subdivide parameter space in 4 quadrants
  - pick quadrant with highest density
  - repeat for this quadrant until convergence



Information available to the analysts

- Direct inputs to analysis
  - objects in mdst

mdst

```
MDST_OBJECTS = (
    'ECLClusters',
    'ECLClustersToTracksNamedBremsstrahlung',
    'EventLevelClusteringInfo',
    'EventLevelTrackingInfo',
    'EventLevelTriggerTimeInfo',
    'KLMClusters',
    'Kinks',
    'KlIds',
    'PIDLikelihoods',
    'SoftwareTriggerResult',
    'TrackFitResults',
    'Tracks',
    'TRGSummary',
    'V0s',
)
```

Analysis package

Belle2::Particle
Belle2::ParticleList

anaylsis steering file

- Track+PIDLikelihoods
  ➡ **Charged particles** (π, k, e,μ, p)
- ECL/KLM cluster
  ➡ Neutral particles
- V0s (backup slide)
  ➡ **Ks, Λ, converted photons**