Belle II Track Reconstruction and Results from First Collisions

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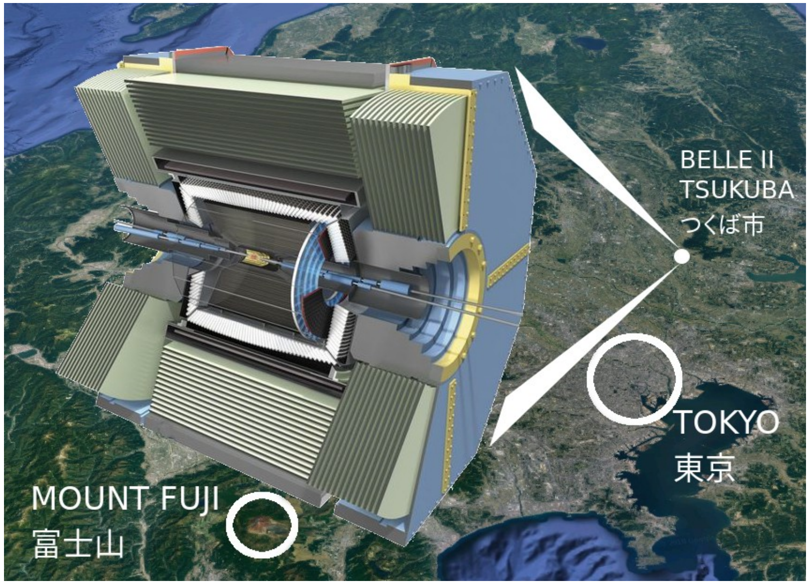
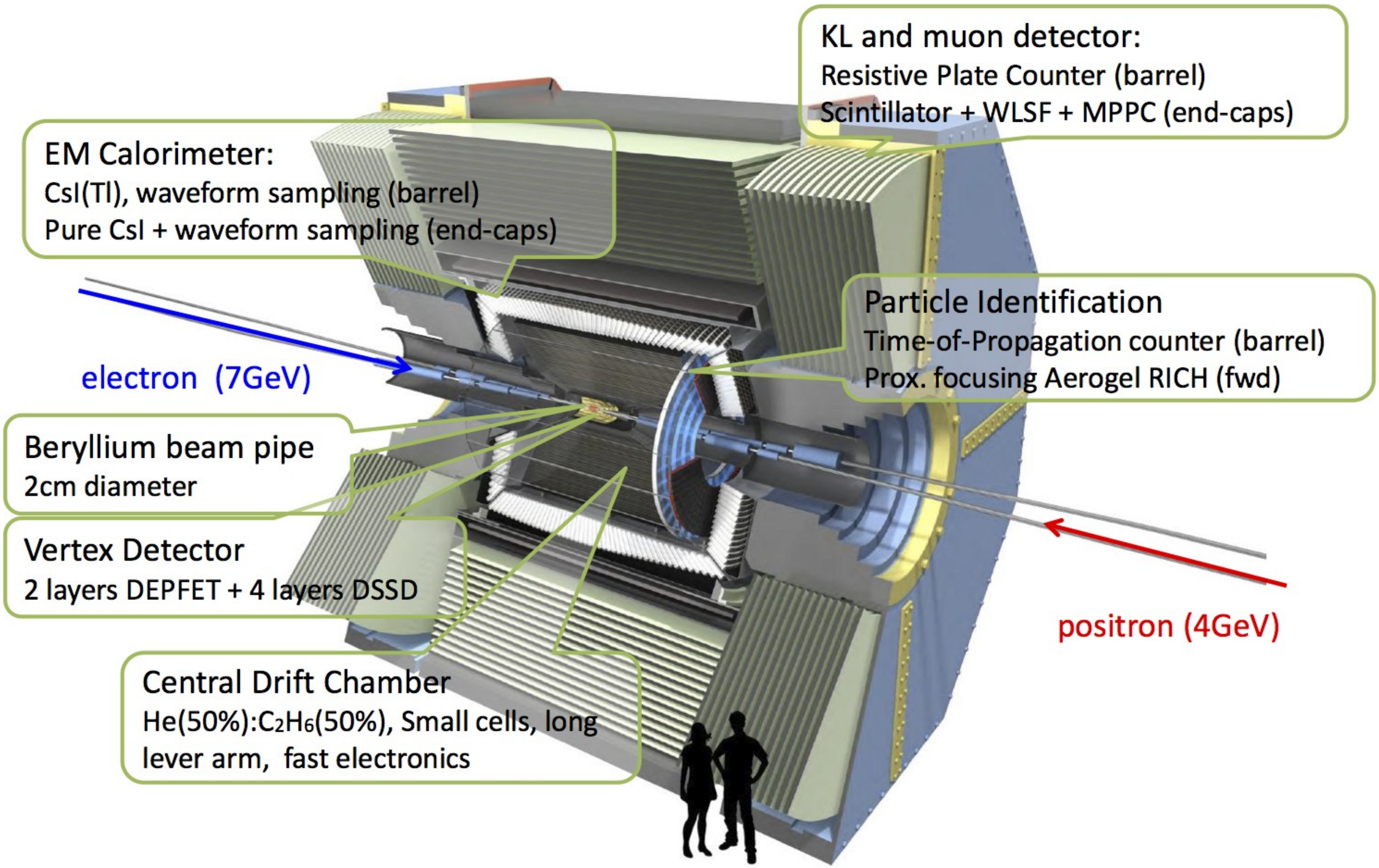
The Belle II Experiment and its Goal

- KEKB was an electron-positron collider at KEK in Tsukuba/Japan which studied the decay of B mesons at the Y(4S) resonance
- Nobel Prize in Physics 2008 to Kobayashi and Maskawa
- The SuperKEKB collider and the Belle II detector will build on the previous success:
  - Study B meson system in far greater precision
  - Probe for new physics in a wide range of interesting topologies
- The Belle II Collaboration: more than 700 scientists from 100 institutes in 25 countries !



	KEKB	Super KEKB	Factor
Instantaneous Luminosity	$2 * 10^{34}$ cm^{-2}s^{-1}	$8 * 10^{35}$ cm^{-2}s^{-1}	40
Integrated Luminosity	1 ab^{-1}	50 ab^{-1} (projected)	50
Runtime	1998 to 2010	start in 2017	
Detector	Belle	Belle II	
Raw Data	1 PB	100 PB (projected)	100

Belle II Detector

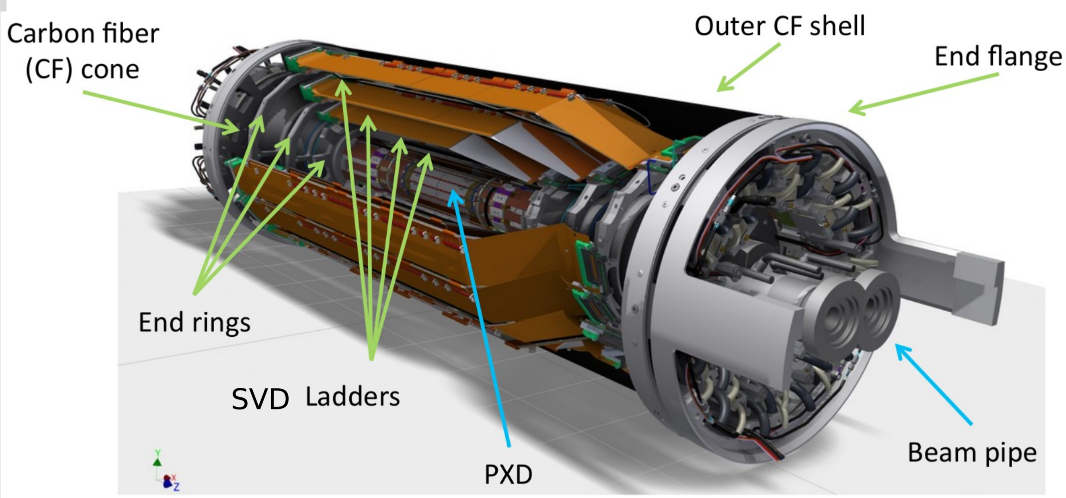


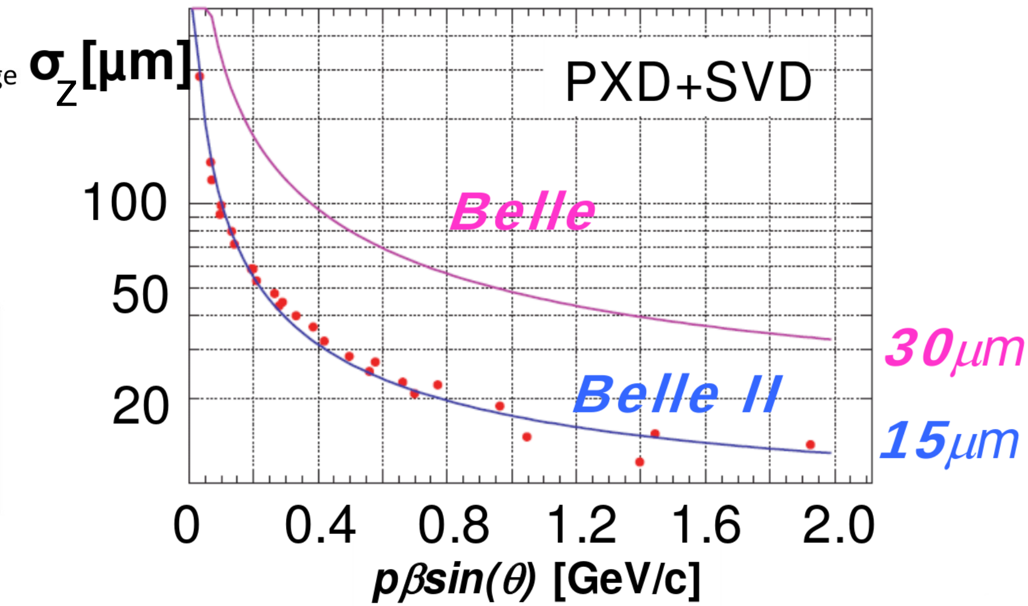
Tracking Detectors - VXD

The Belle II **V**erte**X** **D**etector (VXD) is formed by

- 2 inner DEPFET Pixel Layer (**P**i**X**el **D**etector) : PXD
- 4 outer Silicon Strip Layers (**S**ilicon **V**ertex **D**etector) : SVD

- Very light mechanical structure: ~0.5% X/X_0 per SVD layer
- DEPFET technology - pixel internal amplification allows for very low material budged in PXD layers: ~0.19% X/X_0 per layer
- Compared to Belle: factor 1.5 improvement of the impact parameter over a wide range with the new inner tracking sysem



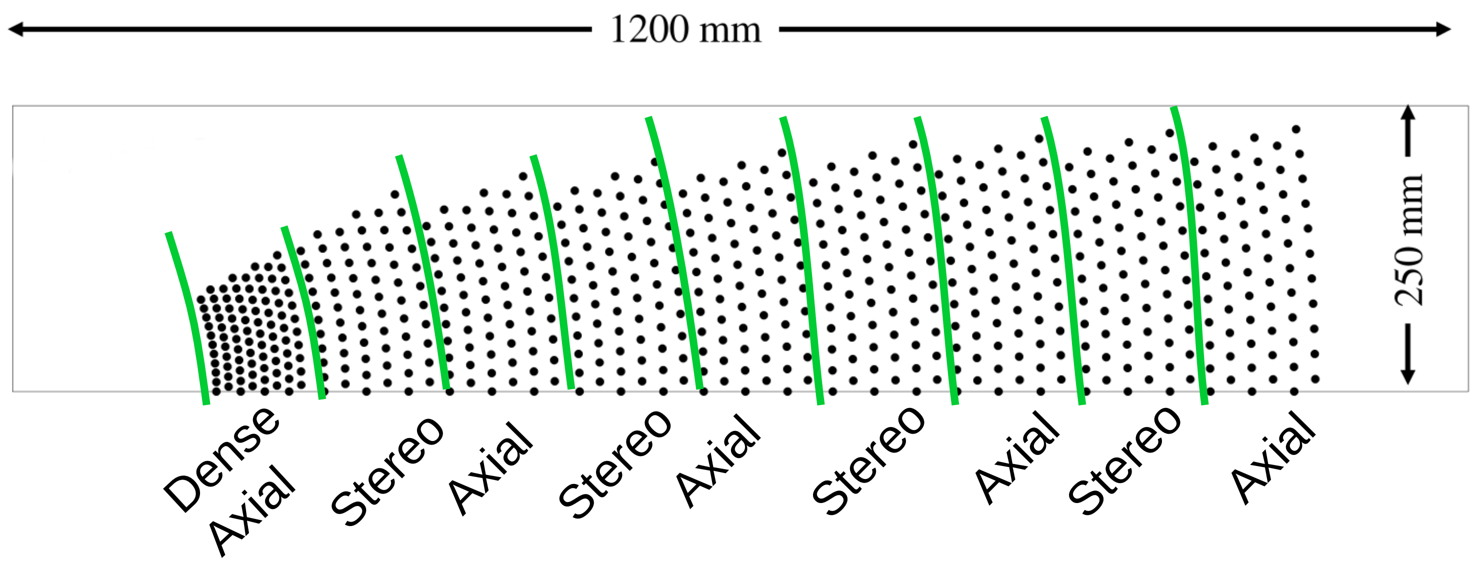


Tracking Detectors - CDC

- The Belle II Central Drift Chamber is a significant upgrade compared to the drift chamber of the Belle detector

	Belle	Belle II
Radius of inner cylinder (mm)	77	160
Radius of outer cylinder (mm)	880	1130
Radius of innermost sense wire (mm)	88	168
Radius of outermost sense wire (mm)	863	1111.4
Number of layers	50	56
Number of sense wires	8,400	14,336
Gas	He–C_2H_6	He–C_2H_6
Diameter of sense wire (μm)	30	30

- Larger lever arm for precise momentum estimation
- z-component measurement with stereo layers with wires shifted by 2.6 to 4.2 degrees



Tracking Environment & Challenges

- The most widely used event categories for analysis are Y(4S) ⟶ BBar decays
- On average: 11 primary tracks / per event (but additional background hits)
- Here: almost all of the beam energy is converted into the B-Meson pair
- If all visible decay products of the two B-Meson decays can be reconstructed:
  - Very clean topolgies with well-known kinematics
  - Search for rare decays by assigning all tracks to a particle candidate

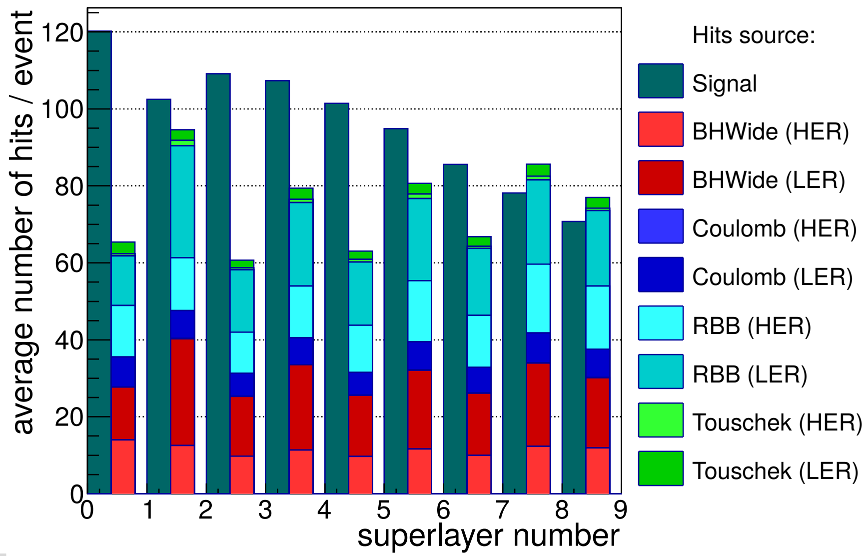
Challenges for Tracking Hard & Software:

- Reconstruct **all** tracks, also down to very low-pt regions
- Cope with the huge contribution of background hits
- Low fake rate

SVD Signal & Background Cluster

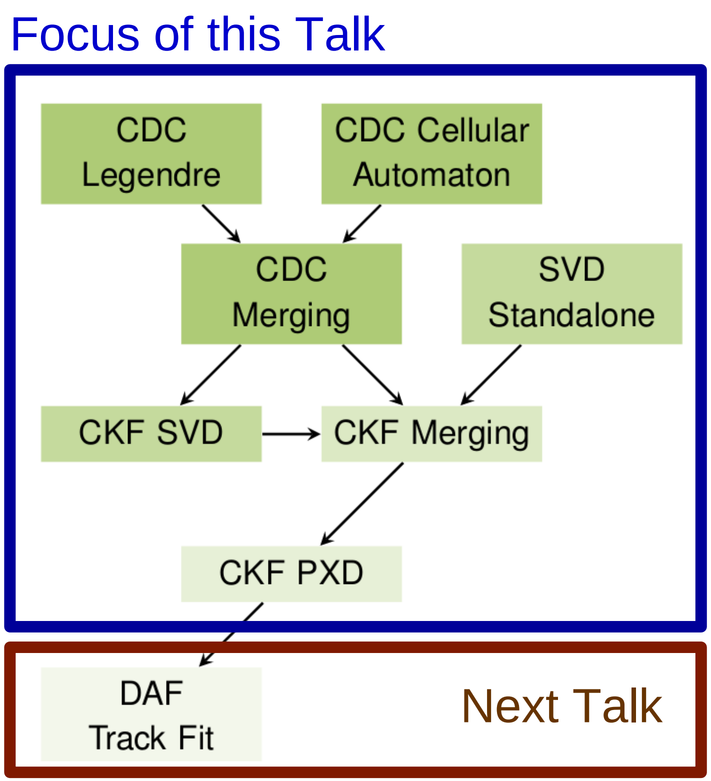
Case	$\Upsilon(4S)$-only	BG-only	$\Upsilon(4S)$ + BG
Average strips/layer u/v	164.3/122.8	159.4/81.7	200.1/112.3
Total clusters u/v	49.2/48.7	146.0/131.3	194.4/179.6
Total SpacePoints	84.8	534.6	721.3
	Signal	Noise	Combined

CDC Signal & Background Hits



Belle II Modular Tracking

- The Software Framework of Belle II (`basf2`) allows to implement processing steps in a so-called Modules which are not coupled and exchange input and output data via a `DataStore`
- Due to the very different nature of the two major tracking systems (silicon-based and drift chamber), two different track finders were implemented
- All stages of the Belle II Tracking software are implemented in independent framework modules which:
  - fits well with our (geographically) distributed development model
  - allows to re-arrange parts of the tracking software for different use cases (online / offline / beamtest scenarios)
- A common exchange format class (*RecoTrack*) is used to transfer pattern recognition and fit results between modules
- While the earlier Module (for example VXD Track Finder) are specifically developed for specific hardware, all downstream modules (like TrackFitting) can operate on the common *RecoTrack*



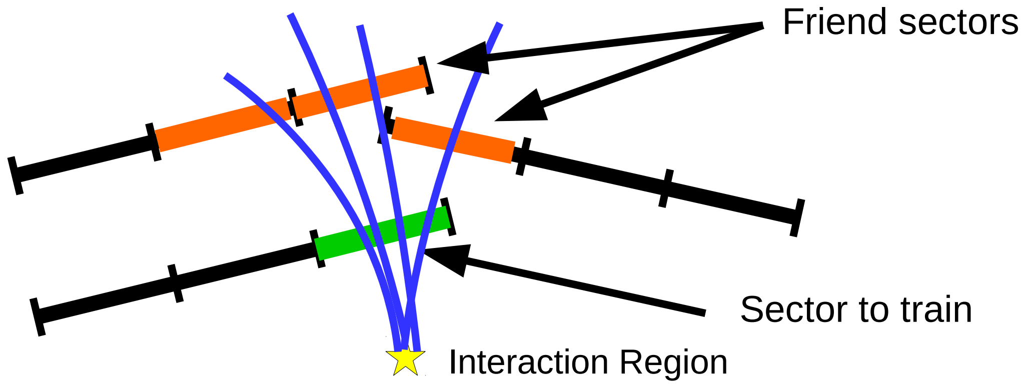
CKF = Combinatorial Kalman Filter

Belle II VXD Tracking

- Primary Task: Reconstruct tracks in the 4-layer SVD detector (PXD hits are assigned via CKF later)
- Very large combinatorics, due to huge number of background hits, especially in the innermost layers & ghost hits in the SVD

SectorMap – Concept to reduce combinatorics

- Each sensor is split into sectors (~10 per sensor)
- Using tracks from simulated Monte Carlo events, the possibility to hit the next sector is evaluated
- Connections between sectors are stored up to 4 sectors deep
- The SectorMap also stores cut values for two and three-hit filter combinations and is depending on different Pt values

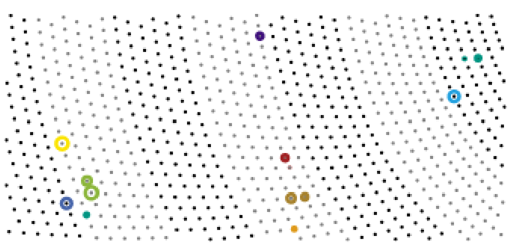


Cellular Automaton – Graph search for connected Hits

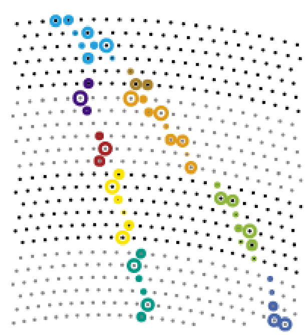
- A Cellular Automaton (CA) is used to explore the possible combinations of hits to form track candidates
- Quality of the these track candidates is evaluated with a fast fitting method

Belle II CDC Tracking: Background Treatment

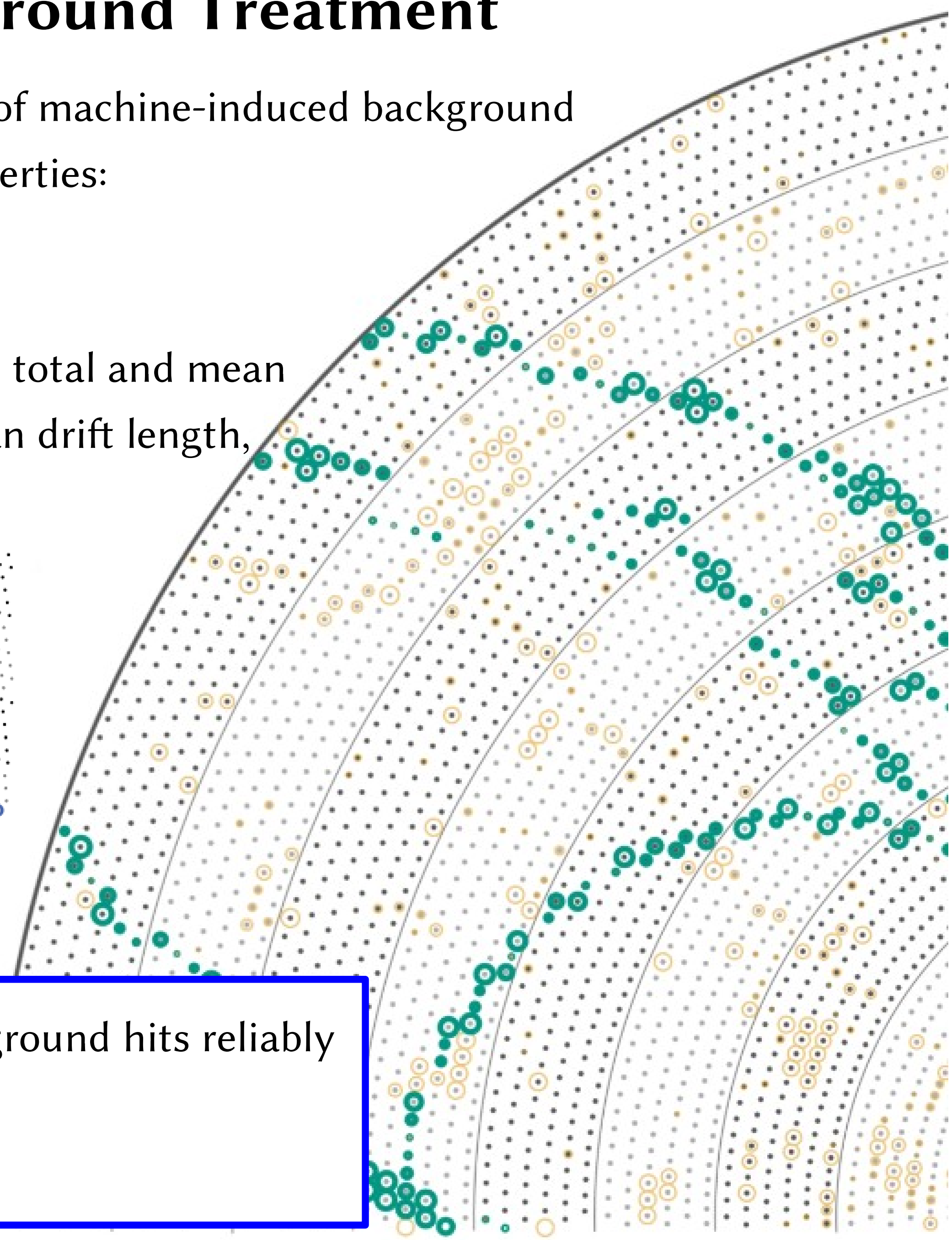
- Around 40 percent of all CDC hits are results of machine-induced background
- Background hits have distinctly different properties:
  - Isolated
  - Don't form larger clusters
- A boosted decision tree classifier is trained on: total and mean number of neighboring clusters, total and mean drift length, super-layer number



Background

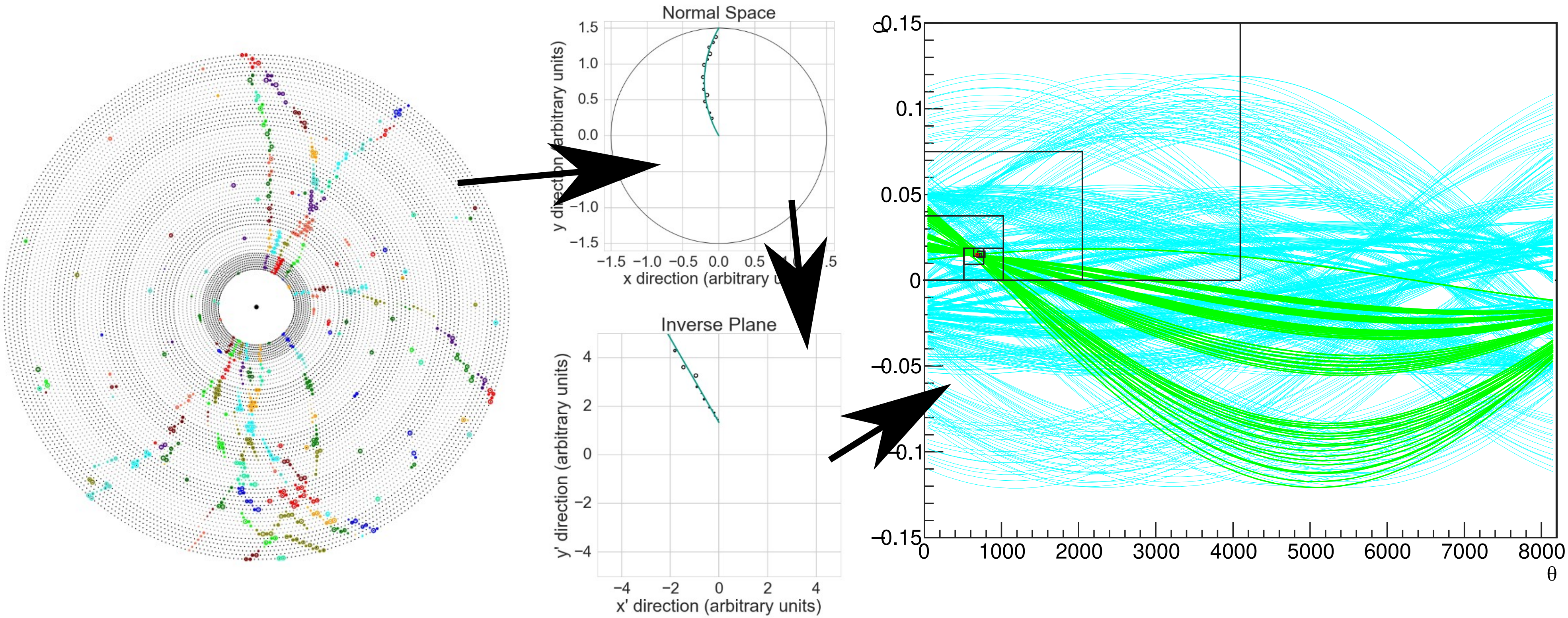


Signal



- The background filter is able to classify background hits reliably
- Reduction of fake rate by 25% and increase of finding efficiency by 2%

Legendre-based Finder

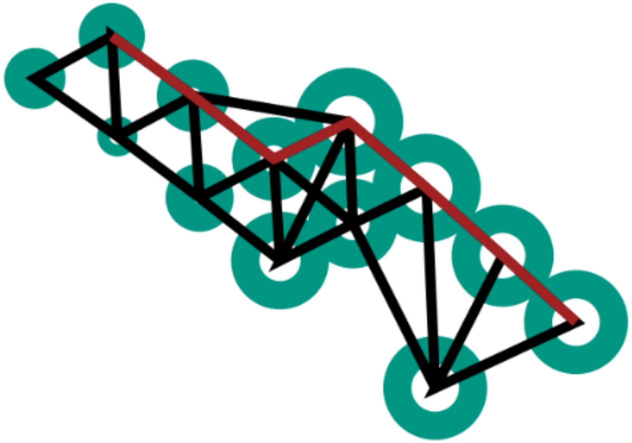


- All axial CDC Hits are transformed to Legendre-space where each forms a sinusoidal curve
- Fast iterative quad tree algorithm is used to search for areas of high curve densities ⟶ parameters shared by one track
- Takes the drift length and the left/right ambiguity into account
- **Legendre-based search is a track finder targeting complete tracks originating from the interaction point**

Local Finder

- **Build segments from individual hits in each super layer**
  - A graph of hits in one CDC super-layer is created
  - Graph search algorithm: cellular automaton searches for connected entries (hits) in the graph which can belong to one track segment
  - All found track segments are fitted with a fast circle fit
- **Build tracks from connected segments**
  - A graph of segments is build
  - Neighboring segment pairs are connected in the graph
  - Loose feasibility cuts first, then judge compatibility by combined $\chi 2$ of the trajectories

Local Finder does not rely on any track origin: designed for displaced tracks and short tracks



Combinatorial Kalman Filter (CKF)

- Very versatile tool which can operate on hits of all tracking detectors: PXD, SVD and CDC
- Implemented using the eigen vectorized library, fast analytical track extrapolations
- Used for multiple improvements of the tracks found by the previous algorithms

Improve SVD Hit Efficiency

Search for compatible hits in the SVD detector for tracks which have only CDC hits at the moment

Search for PXD Hits

Due to the high occupancy of the two innermost PXD sensors, existing SVD/CDC tracks are used for PXD hit assignment

In Development: Assign CDC hits to SVD tracks

Some track segments in the CDC are very short and cannot be found by CDC standalone tracking. Existing SVD tracks can be used to assign these hits to the proper track

First Collisions !

Phase II Started in February 2018 till July 2018

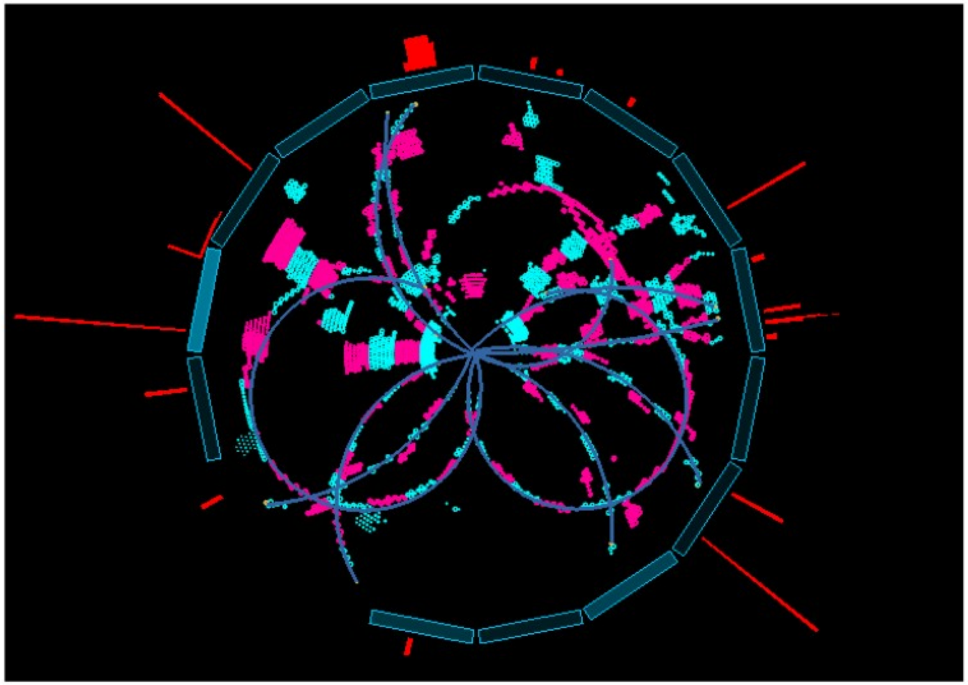
Belle II detector, only one segment of the inner-most silicon-based tracking system

Primary goals: Quantify accelerator background and commission Belle II detector and associated systems

Phase III Start in February 2019

Complete Belle II detector

Goals: Continuous physics run at peak instantaneous luminosity



One of the first hadronic events recorded with the Belle II Detector at 2:27 a.m. JST on the 26th April 2018

Tracking with First Data

Track Finding and Fitting is executed during data-taking on the

- High-Level Trigger farm (for event filtering, not done in Phase II, SVD&CDC tracking only)
- ExpressReconstruction for live event display and data quality monitoring (Full Reconstruction)

Furthermore, multiple offline processings of the Phase II dataset have been completed successfully.

During initial commissioning of the SuperKEKB collider, detector occupancy could vary widely and was sometimes over the background rates expected from simulation.

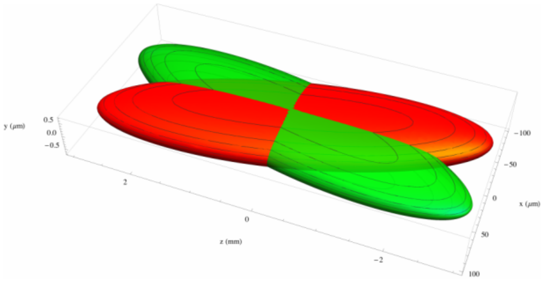
- For CDC track finding, the background filters worked excellent and the event reconstruction could be completed
- For SVD and CKF track finders, we put local combinatorial limits in place which prevent overly high resource consumption (in case of "hot sensors" etc.)

  This limits will not affect the reconstruction of regular detector signals

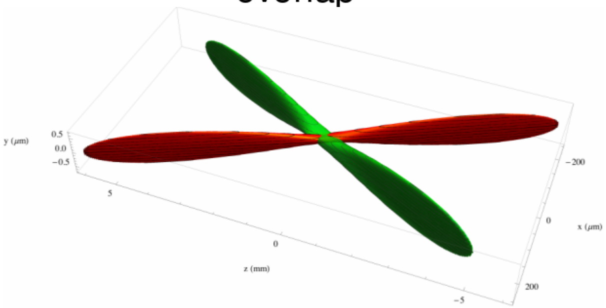
"Study of the collision point properties.," BELLE2-NOTE-PL-2018-008
May 2018. https://docs.belle2.org/record/888?ln=en

Tracking with First Data

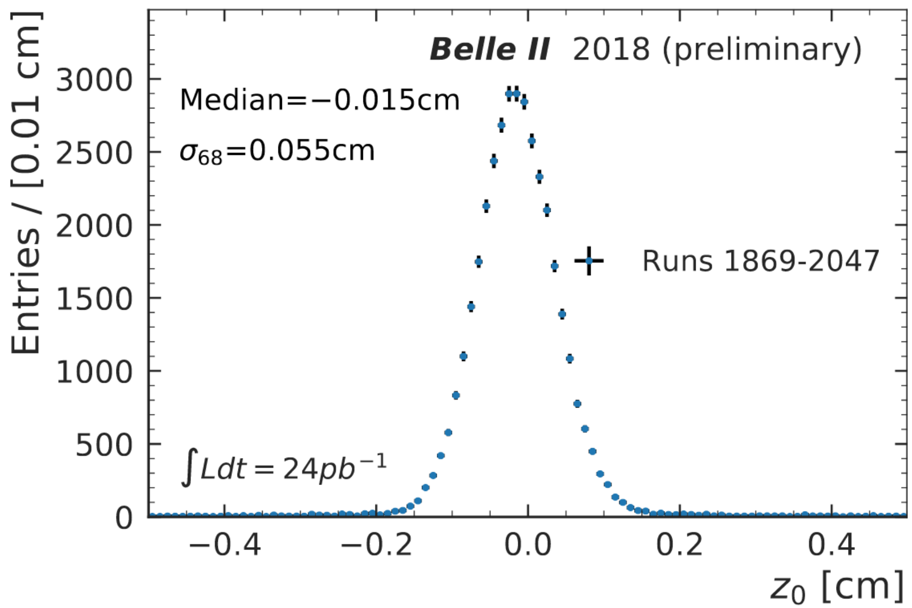
- Fast feedback to the SuperKEKB-Accelerator group is important during the early commissioning phase of the accelerator.
- One novel feature to achieve the 40 times higher luminosity is the nano-beam scheme which allows for a very strong focusing at the beam interaction point up to 10 µm (20 times smaller than KEKB)



KEKB Interaction region beam overlap



SuperKEKB Interaction region beam overlap



Longitudinal component of the interaction vertex estimated using single tracks originating from the interaction vertex in early Belle II events.

Within days of first collisions, Belle II Track Reconstruction and Fitting was used for feedback to the accelerator groups.
→ Here: Confirm the nano-beam scheme works !

Conclusion

- The Belle II Pattern Recognition Software supports and integrates two quite distinct detectors:
  - Silicon-based PXD & SVD
  - Central Drift Chamber
- Modular structure of the track finding and fitting algorithms allows for easy replacement and improvement of existing code
- All components of the pattern recognition chain have been successfully used to reconstruct the first collisions of SuperKEKB with the Belle II detector

The work has just started:

- Data recorded during Phase II (ending in 5 days) is very valuable to further tune the algorithms for Phase III next year
- Studies of tracking efficiencies using data only are being done right now.

Thank you for your attention !

Backup

Belle II CDC Tracking: Background Treatment

- Around 40 percent of all CDC hits are results of machine-induced background
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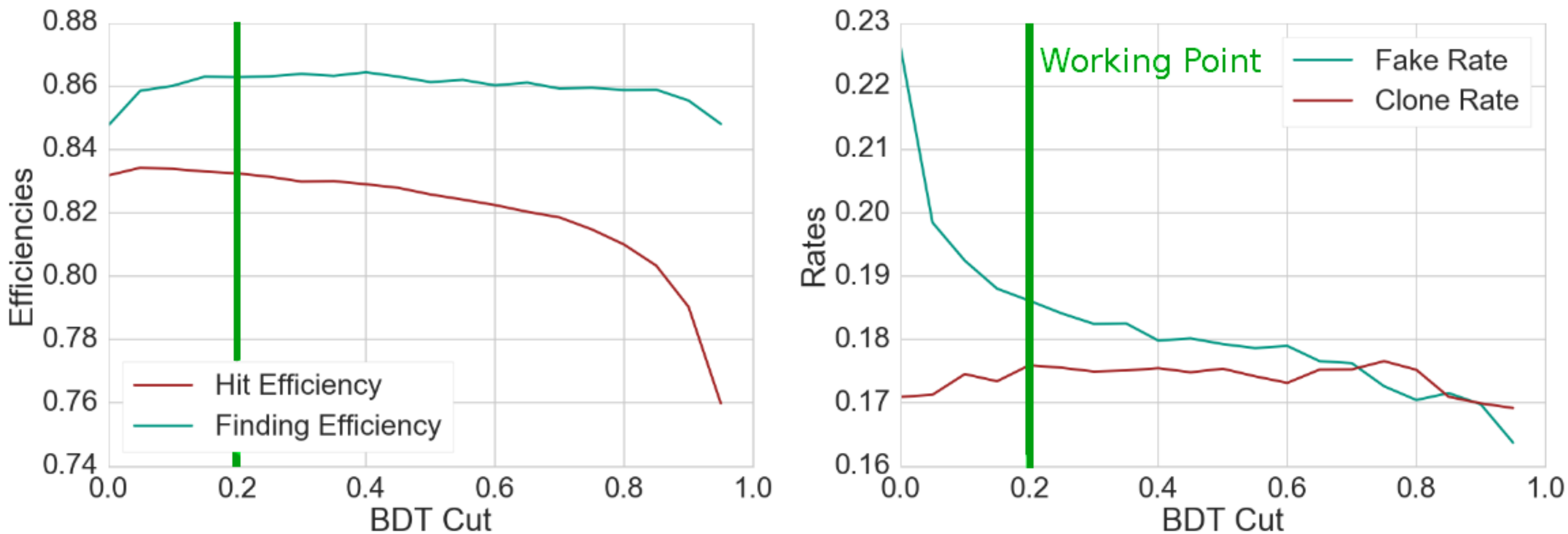

- The background filter is able to classify background hits reliably
- With the chosen cut value of 0.2, the finding efficiency and the fake rate can be improved
- Only very small loss in track hit efficiency observed