# Track Reconstruction and Performance at Belle II

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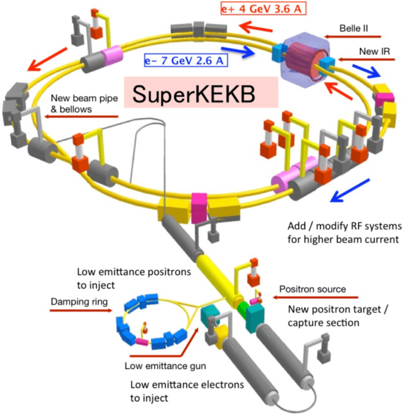
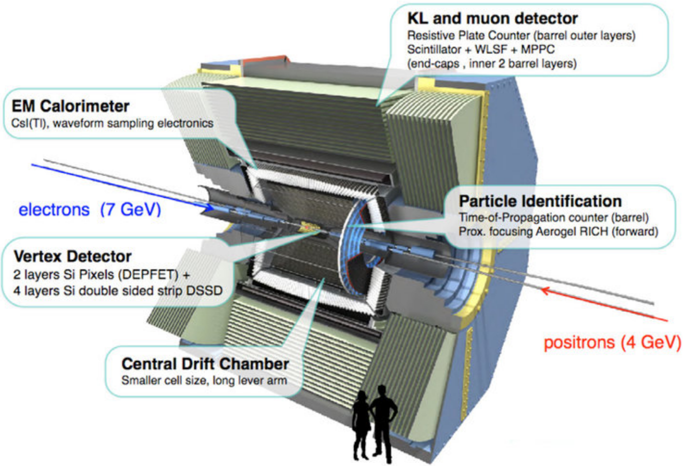
# SuperKEKB

- asymmetric $e^+e^-$ collider in Tsukuba (Japan)
- 7GeV electrons on 4GeV positrons
- B-factory:
  - center of mass energy of 10.58GeV
  - produce $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - design luminosity $6 \times 10^{35} cm^{-2}s^{-1}$
  - current world record inst. luminosity: $\mathcal{L} = 4.7 \times 10^{34} cm^{-2}s^{-1}$



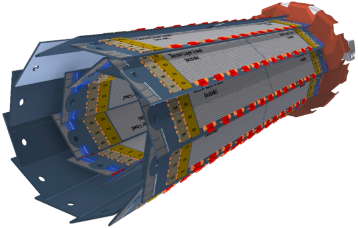
# Belle II

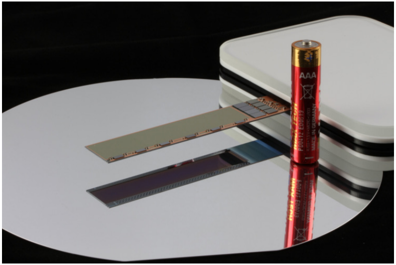



- Run 1: $424fb^{-1}$ (2019-2022); Run 2 started end of 2023
- Goal to collect $50fb^{-1}$

# Pixel Detector (PXD)

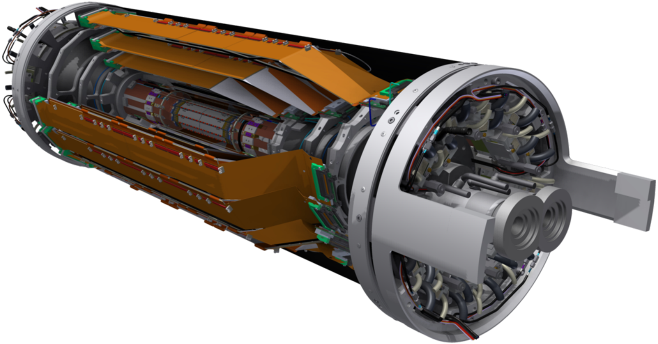
- 2 layers of DEPFET silicon pixel sensors (r = 14, 22 mm)
- pixel sizes 50x (55-85) $\mu m$
- 40 sensors arranged in ladders
- in total 7.7 million pixels
- 20 $\mu s$ integration time
- 0.2% $X_0$ per layer





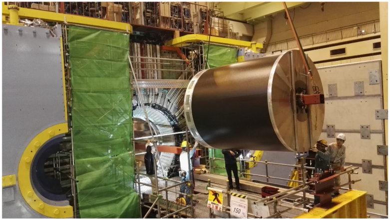
# Silicon Vertex Detector (SVD)

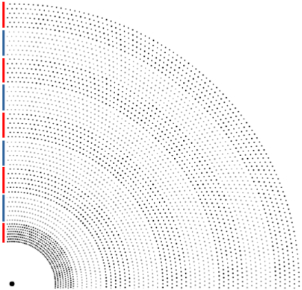
- 4 layers of double-sided silicon strip sensors (r=39, 80, 104, 135mm)
- 172 sensors, 220k readout strips
- slanted sensors in forward direction
- strip distance between 50 and 240 $\mu m$
- strips are arranged perpendicular to get 2D information
- $< 1\%$ $X_0$ per layer

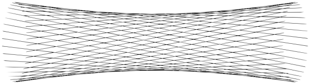


# Central Drift Chamber (CDC)

- 14.2k wires in 56 layers radius 168 - 1111 mm
- arranged into 9 super layers of axial and stereo wires
- stereo wires skewed w.r.t. axial wires to get z information
- drift cell sizes from $\approx 1cm$ to $\approx 2cm$

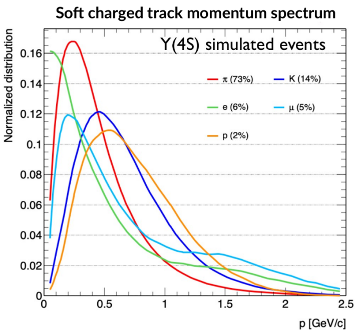






# Tracking environment at Belle II

- on average 11 tracks per BB event
- soft momentum spectrum
  - multiple scattering is significant
- tracks with $p_T < 0.25 GeV$ loop inside the detector

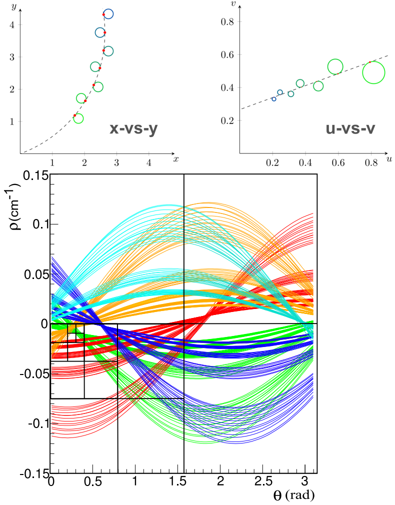



**Detector occupancy at nominal luminosity: $6 \times 10^{35} cm^{-2} s^{-1}$**

| | layer 1 | | layer 3 | |
|---|---|---|---|---|
| | # of hits | occupancy | # of hits | occupancy |
| Υ(4S) | 11 | $5 \times 10^{-6}$ | 11 | 0.02% |
| beam bkg | 50000 | 3% | 3200 | 3% |

# Global CDC track finder

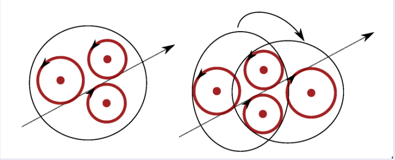
- tracks coming from IP
- conformal mapping:
  $u = \frac{x}{x^2+y^2}$; $v = \frac{y}{x^2+y^2}$
- Legendre transformation for Hough space:
    - parameter space representing all tangents to a drift circle
    - $\rho = x_0 \sin(\theta) + y_0 \cos(\theta) \pm R_{Drift}$
- Quad-Tree-Search for finding track parameters in Hough space



# Local CDC track finder using Cellular Automaton (CA)

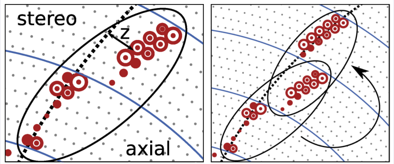
## Cellular automaton for segment building in CDC

- segments: shorter track pieces (usually within one super layer)
- start combining triplets of hits assuming straight trajectory



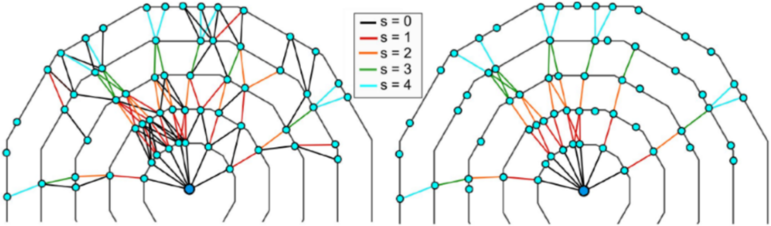
## Cellular automaton for track building in CDC

- cell: pair of axial + stereo wire segments
- combining cells into tracks starting from a seed, by selecting longest path



# SVD Standalone track finder (VXDTF2)

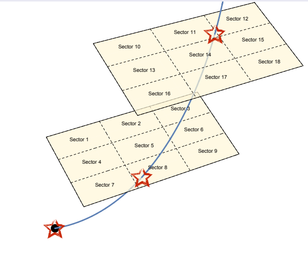
- local algorithm utilizing Cellular Automaton
- segments (cell): connection between hits on neighboring sensors
- connections of segments are filtered using simple requirements
- Cellular automaton collects longest paths
- start from outer - most hits due to less background



# SVD track finder: Hit Filtering

- filter hits during CA step
- divide sensor into rectangular sectors (4x4 sectors per sensor)
- only hits on related sectors: reduces combinatorics
- selection of hit combinations:
  - consider 2-hit and 3-hit combinations of sectors
  - simple geometric quantities (angles, distances, radii) and hit times
  - individual cut values for each sector combination
- training on MC samples:
  - learn relations between sectors
  - learn cut values for each sector combination
  - use 13 mio MC events (mostly BB and some $e^+e^-$ and $\mu^+\mu^-$)

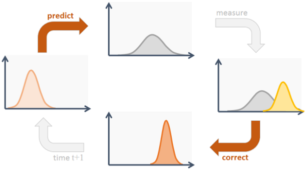
**Illustration of the sector concept**



# Combinatorial Kalman Filtering (CKF) in Belle II tracking

## Track Finding

- use found track as seed track
- extrapolate track into other sub-detector to look for hits
- from CDC to SVD and vice versa
- PXD hits only via CKF




Object-Tracking-Kalman-Filter-with-Ease

## Track Merging

- tracks from one particle are found by different subdetectors / track finders ⇒ need merging
- use one track as seed
- use CKF to update seed track with hits from other track

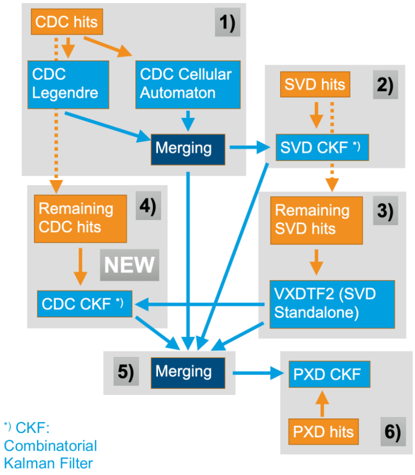
# Track Fitting

## Deterministic Annealing Filter

- implentation: Genfit2 package
- iterate Kalman filtering for track candidate
- reject hits farthest away from track in each iteration
- on average 3-5 passes till convergence
- material effects are taken into account

- 5 track parameter (Runge Kutta representation) at interaction point are stored
- three particle hypotheses fitted and stored:
  - $\pi$, $K$, $p$
  - track fit hypothesis with closest mass provided to analysts
- dedicated V0 ($K_S$, $\gamma \rightarrow e^+e^-$, $\Lambda$) finder/fitter for off IP vertices: store separate track fit results

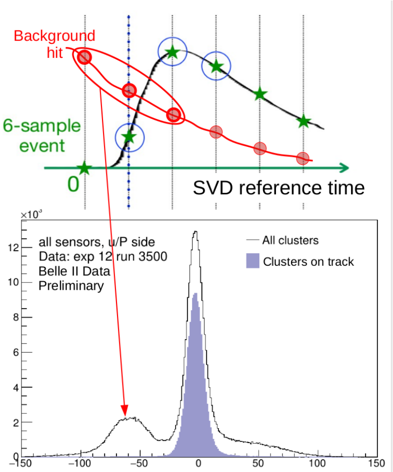
# Bringing it all together




- 2 different tracking algorithms for CDC
- one stand alone algorithm for SVD
- have to combine tracks found in different detectors
- attach PXD hits to tracks

# Usage of SVD time in track finding

- beam background is an issue
- use precise SVD time to reduce beam background:
  - APV25 chip for readout developed for CMS
  - shaping time of 50 ns
  - 6 samples recorded after trigger
  - sample every 31.44 ns
  - fit shaping function to 3 most relevant hits: $f(t) = \frac{t}{\tau} \exp\left(-\frac{t}{\tau}\right)$
  - resolution of few ns
- most beam background hits are off-time
- signal hits peak at 0



# Usage of SVD time in track finding

- time information at the moment only for SVD track finding
- both SVD - standalone algorithm and CKF use space points as input

**Space Point**

- global 3D coordinates of hit
- SVD space point: combine positions of perpendicular Clusters (u,v)

- filter by time during space point creation:
  - absolute time for single hits: $|t_{u,v}| < 50ns$
  - time difference between u- and v-Clusters on same sensor: $|t_u - t_v| < 20ns$
- time filters applied during CA step of SVD track finding
  - time difference between u- and v-Clusters same sensor
  - time difference between Clusters from different sensors
  - cut values learned during training phase
  - individual cuts for different combination of sectors

# Other and future applications of SVD time

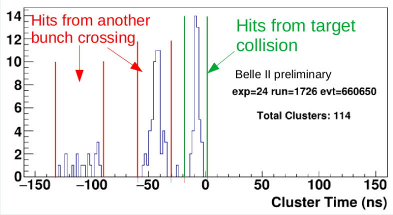
- SVD time for Event T0 estimation
  - estimate Event T0 from time associated to SVD hits attached to tracks
  - only track candidates with $p_t > 250 MeV$ to avoid curling particles
  - on average less than 1 ns resolution on data
  - previous method based on CDC hits: 2000 x slower
- provide track time information to analysts in future
  - included in new release
  - not yet used in MC production or data reprocessing
- replace time cuts by hit time grouping
  - currently cut on times for space point selection
  - grouping of SVD hit times promises improvement
- SVD hit times for CDC to SVD CKF hit selection
  - work in progress

# New idea: SVD hit time grouping

- finding efficiency for tracks normalized to MC based track finder (ideal track finder)
- fake rate: fraction of fake tracks and tracks from beam background
- clone rate: fraction of multiple tracks reconstructed per single particle (e.g. looper)
- selection on hit time grouping reduces fake rate by 50%

**SVD hit time grouping**

- identify groups in hit time
- chose hits from group closest in time to collision



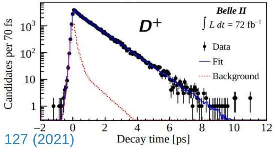

| | Hit time grouping | | Rel. difference |
|---|---|---|---|
| | off | on | |
| Track finding eff. | $93.67 \pm 0.24$ % | $93.69 \pm 0.24$ % | +0.02 % |
| Fake rate | $9.55 \pm 0.29$ % | $4.37 \pm 0.20$ % | -54.26 % |
| Clone rate | $3.81 \pm 0.19$ % | $3.56 \pm 0.18$ % | -6.62 % |

# Impact parameter resolution

- excellent resolution due to PXD: $\approx 2\times$ improvement
- down to $10\mu m$ for $d_0$ for high momentum
- still around $40\mu m$ to $50\mu m$ at $p_T \approx 0.5 GeV$

## Resulted in most precise $D^+$ life time measurement:

- $\tau_{PDG} = 1040.0 \pm 7.0 fs$
- $\tau_{BelleII} = 1030.4 \pm 4.7 \pm 3.1 fs$

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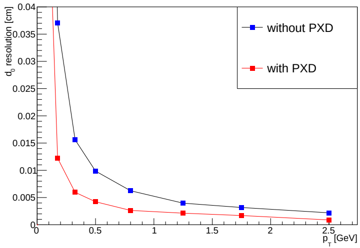
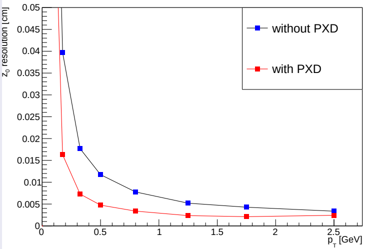
## $d_0$ resolution on MC




## $z_0$ resolution on MC

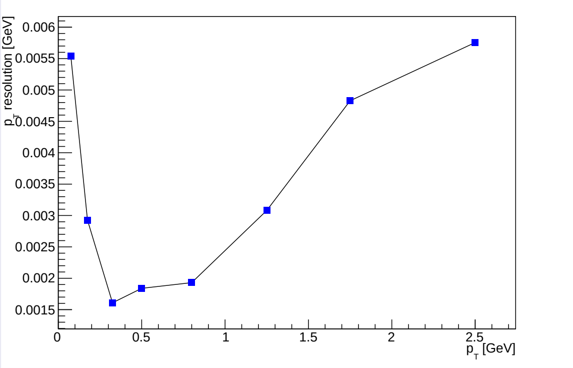


# Momentum resolution

- ranges between 0.2% for high $p_T$ and $\approx 5\%$ at $p_T = 0.1 GeV$
- majority of tracks in BB events $p_T \approx 0.5 GeV \Rightarrow \approx 0.4\%$ resolution

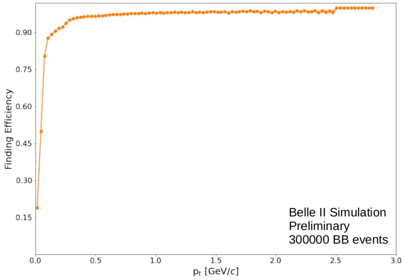
## Transverse momentum resolution

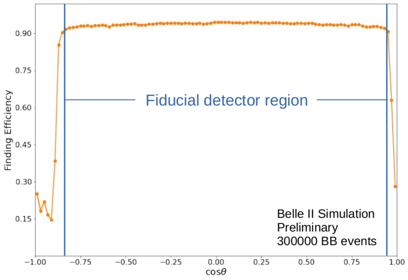
- estimated on 5000 simulated BB events at nominal luminosity



# Track finding performance

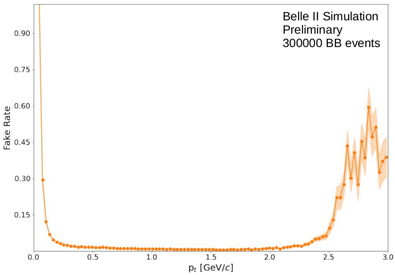
- track finding efficiency as function of $p_T$ and $\cos(\theta)$
- above 90% for most of the phase space covered by Belle II
- on average 93.6% efficiency

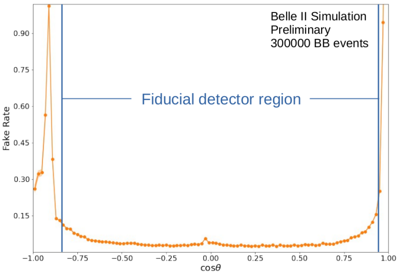


# Tracking Performance

- fake rate: beam background particles or random combination of hits
- at low $p_T$ dominated by two photon processes: $e^+e^- \rightarrow e^+e^- f\overline{f}$
- forward and backward direction BhaBha events: $e^+e^- \rightarrow e^+e^-(\gamma)$
- at high $p_T$: random combination of hits and low statistics (kinematics BB events)

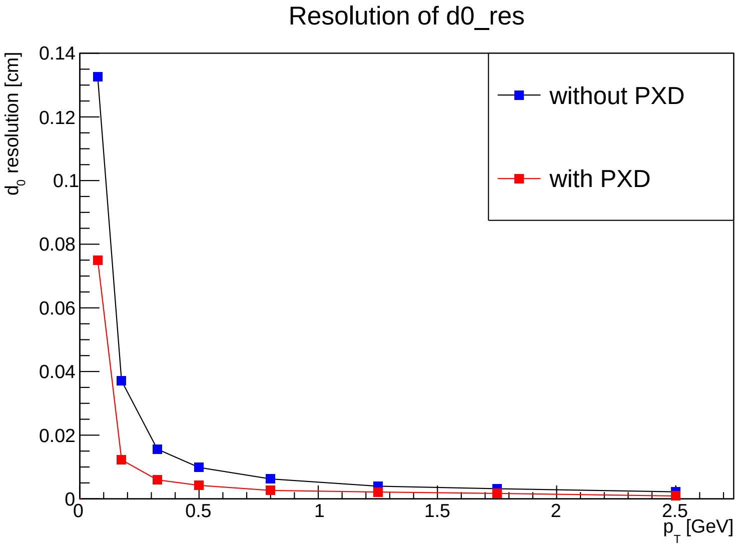


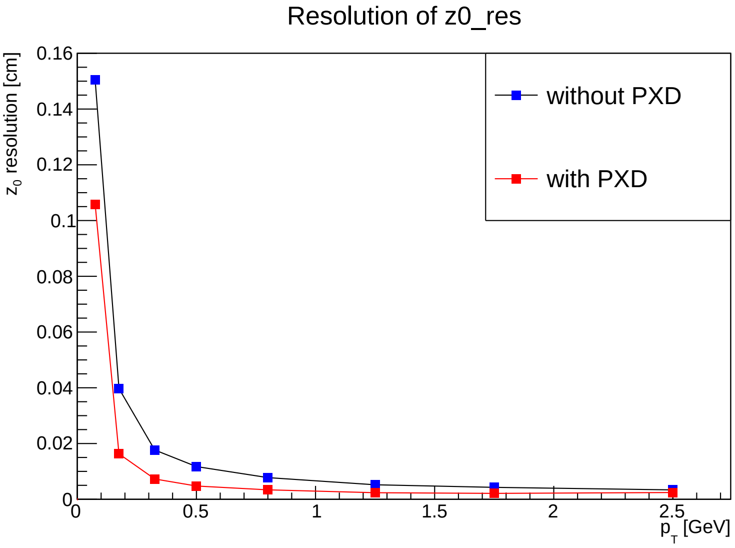
# Summary

- introduction to Belle II track finding
- usage of SVD hit time during Belle II track finding:
  - hit filtering before track finding
  - filtering of hit combinations during track finding
  - Event T0 estimation
- SVD hit time information powerful tool to reject beam background
- SuperKEKB constantly increases luminosity
  - beam background will become more important in future
- Belle II track finding performed well so far, contributing to competitive physics results
- new approaches investigated: GNN track finding for CDC

# Appendix



Resolution of d0_res
d0 resolution [cm]
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
pT [GeV]
without PXD
with PXD


Resolution of z0_res
$z_0$ resolution [cm]
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
$p_T$ [GeV]
without PXD
with PXD