Belle II track finding and hit filtering using precise timing information

Christian Wessel (DESY)
on behalf of the Belle II Tracking and Vertexing group

Connecting the Dots
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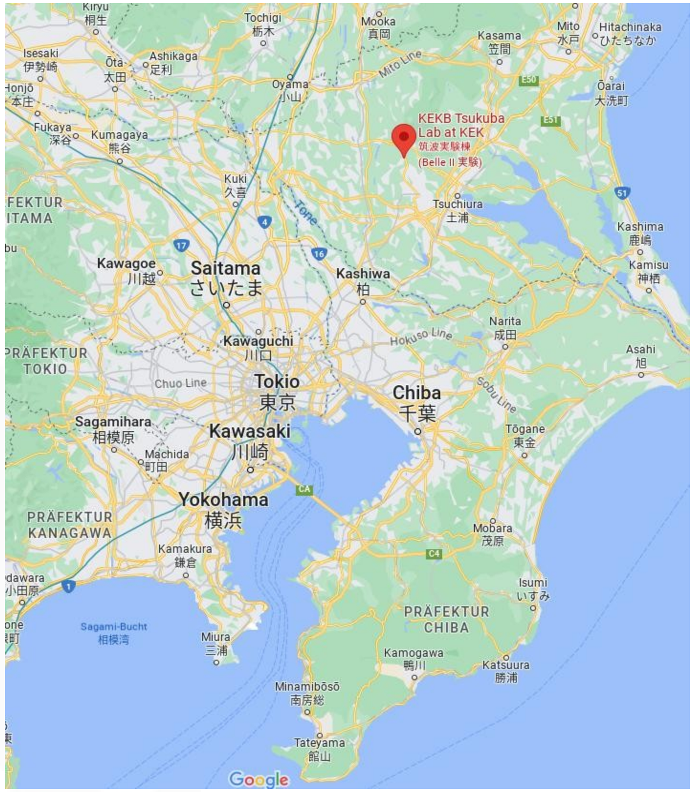
christian.wessel@desy.de

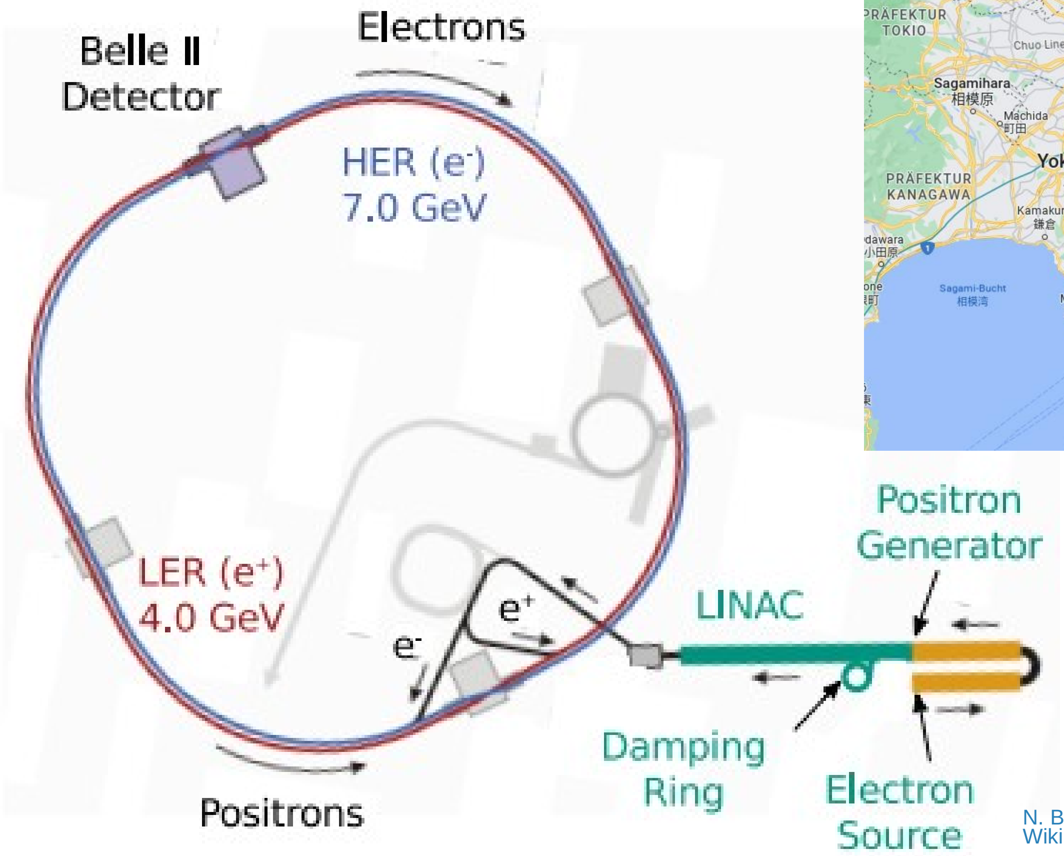
HELMHOLTZ

The Experimental Setup

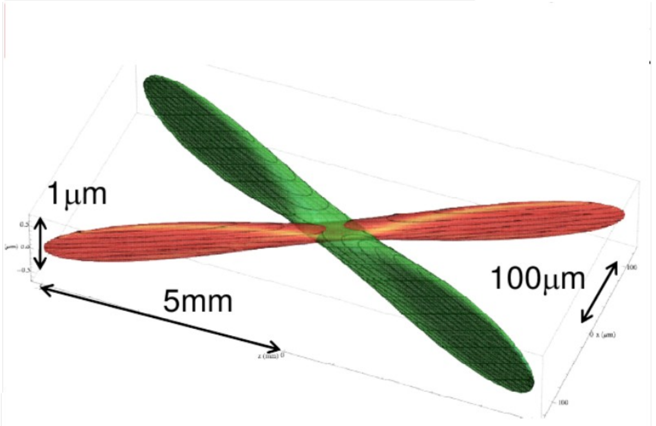
SuperKEKB B-Factory

- Located at KEK, Tsukuba, Japan
- Asymmetric e^+e^- (4 / 7 GeV) collider at $\sqrt{s}$ = 10.58 GeV corresponding to $m_{\Upsilon(4S)}$
  - Also significant $c\bar{c}$ and $\tau^+\tau^-$ production
- Aiming for $\mathscr{L} = 6 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$
  - Nano beam scheme
- Current WR: $\mathscr{L} = 4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- Collected 424 $\mathrm{fb^{-1}}$ since 2019
- Goal: $\int \mathscr{L}\ dt = 50\ \mathrm{ab^{-1}}$
- Currently in long shutdown 1





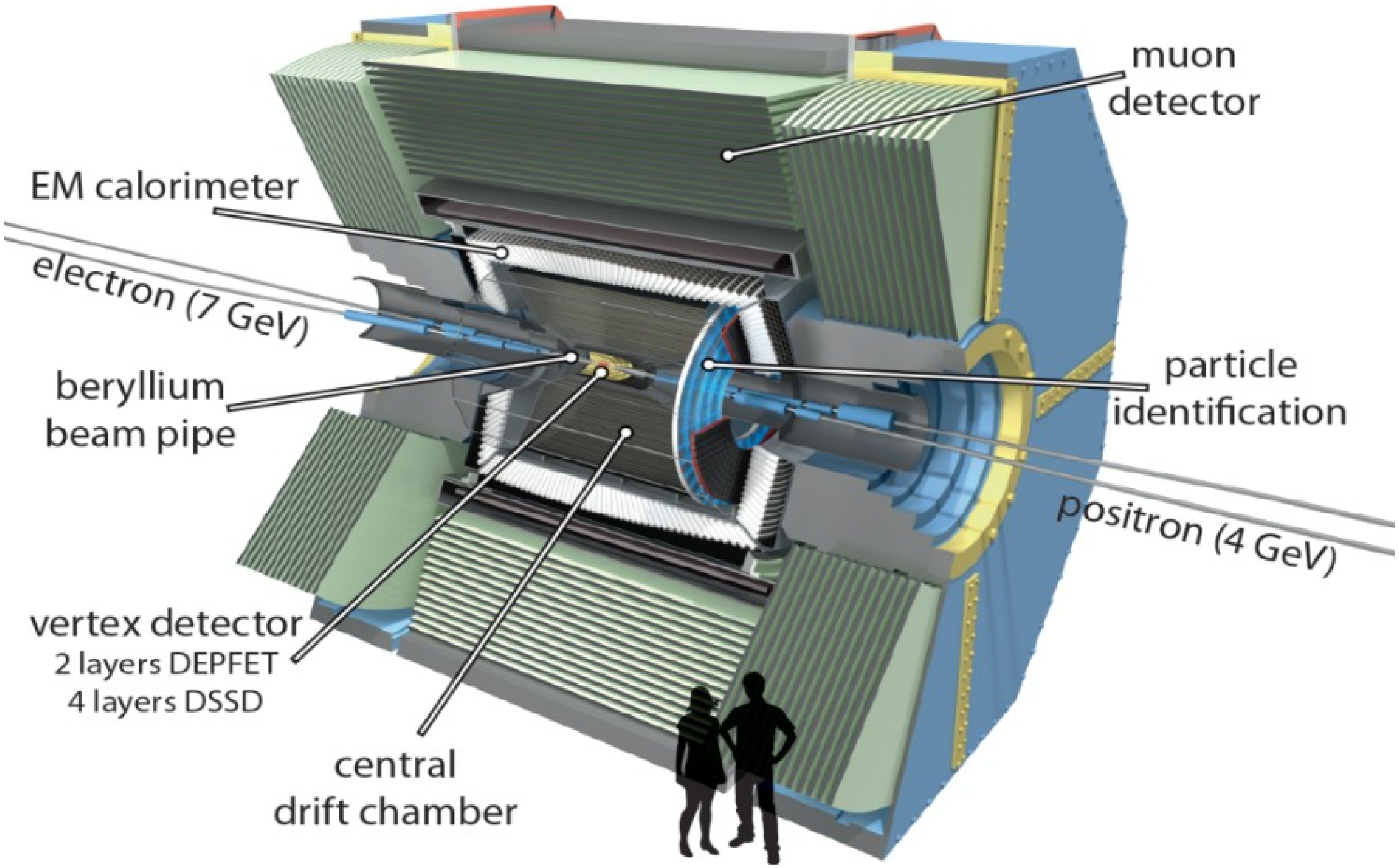
N. Braun, adapted from Wikipedia/KEKB



The Experimental Setup

Belle II

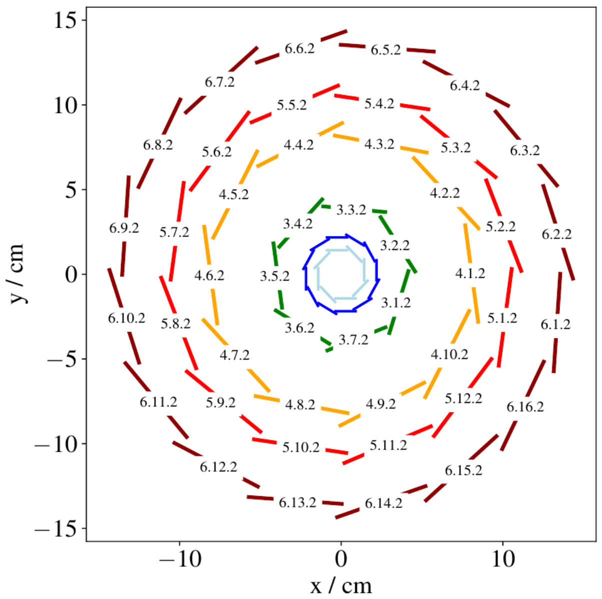
- Multi purpose, near 4π detector
- Roughly 7x7x7 m^3
- 2 DEPFET pixel layers
- 4 double sided silicon strip layers
- Central drift chamber
- Particle identification:
  Time of Propagation (barrel) and
  Aerogel Ring Imaging Cherenkov
  (forward) detectors
- Electromagnetic calorimeter
- 1.5 T magnetic field
- K^0_L and muon detector

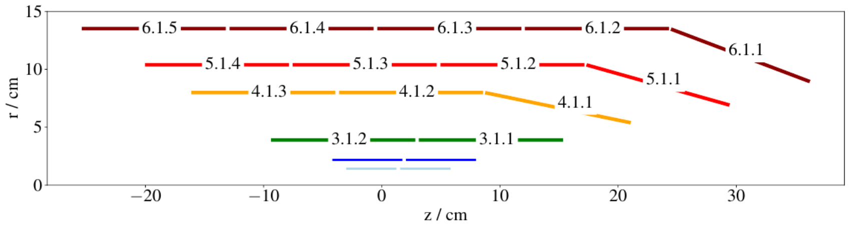


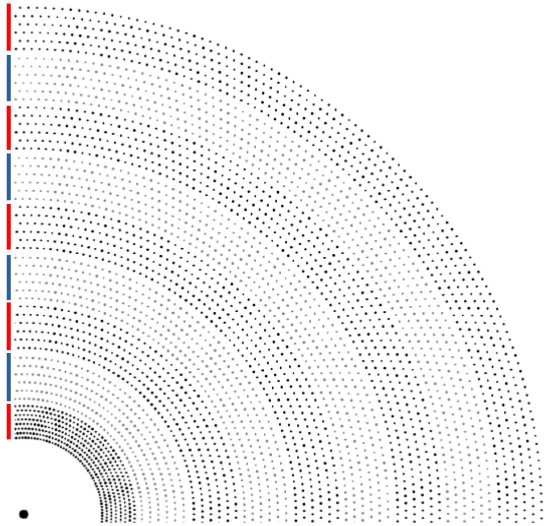
The Experimental Setup

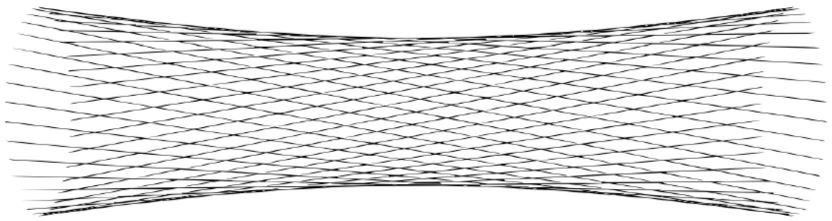
Belle II tracking and vertexing detectors

- 2 DEPFET pixel layers
  - r = 14, 22 mm
  - 7.68M pixel
  - Pixel size 50 x (55 – 85) µm²
  - 20 µs integration time
  - 0.2% X_0 per layer
- 4 double sided silicon strip layers
  - Up to r = 135 mm
  - 223k strips
  - Strip pitch 50 / 75 (r-φ), 160 / 240 µm (z)
  - < 1% X_0 per layer
- Central drift chamber
  - Up to r = 112 cm
  - 14.3k wires in 9 super layers
  - 5 axial and 4 stereo super layers
  - Drift cell size: ~1 cm up to ~2 cm
- Coverage in θ: 17° to 150°









Physics at Belle II

Precision

- Probing the standard model with high precision measurements
  - Search for rare processes
  - Branching fraction measurements
  - Time dependent CP violation
  - Tests of lepton flavour universality
  - Standard model parameters
  - Dark sector searches
  - …

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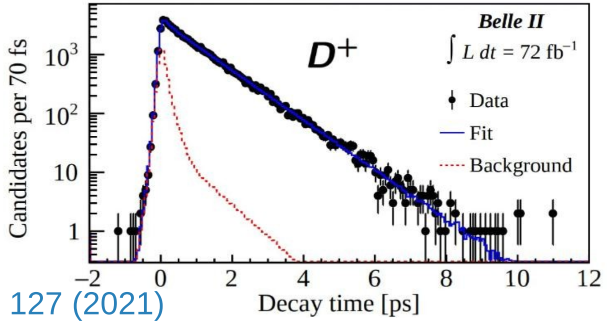
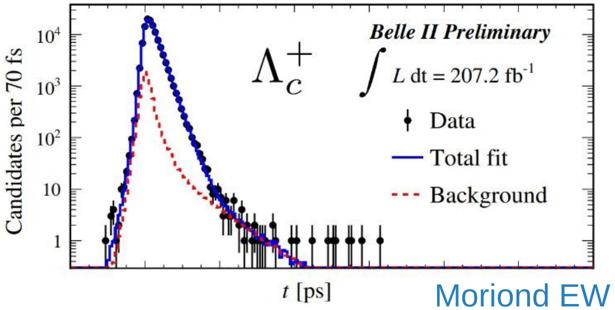
  - …
- Physics results relying on excellent tracking and vertexing performance

PDG	$\tau(D^+) = 1040.0 \pm 7.0$ fs	$\tau(\Lambda_c^+) = 202.4 \pm 3.1$ fs
Belle II	$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs	$\tau(\Lambda_c^+) = 203.2 \pm 0.9 \pm 0.8$ fs

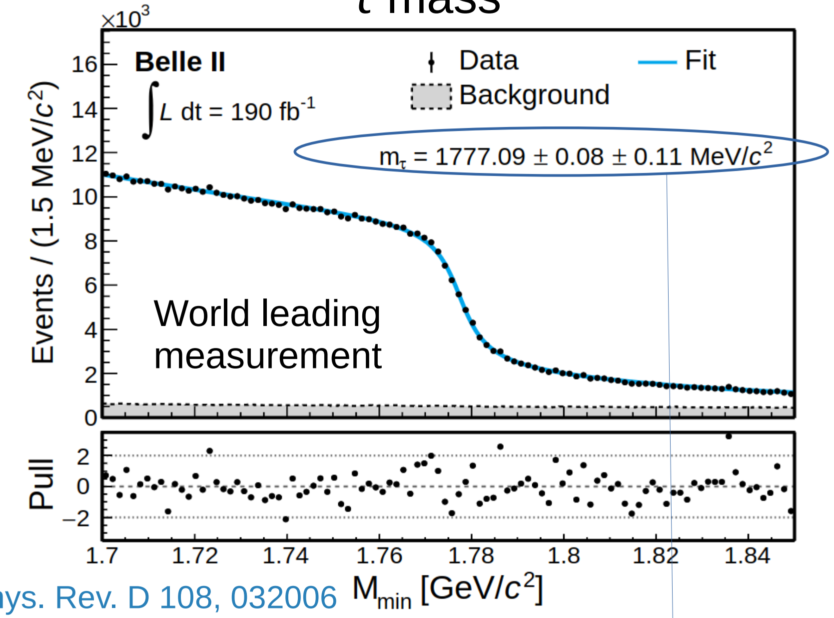


Phys. Rev. Lett. 127 (2021)



Moriond EW 2022

τ mass



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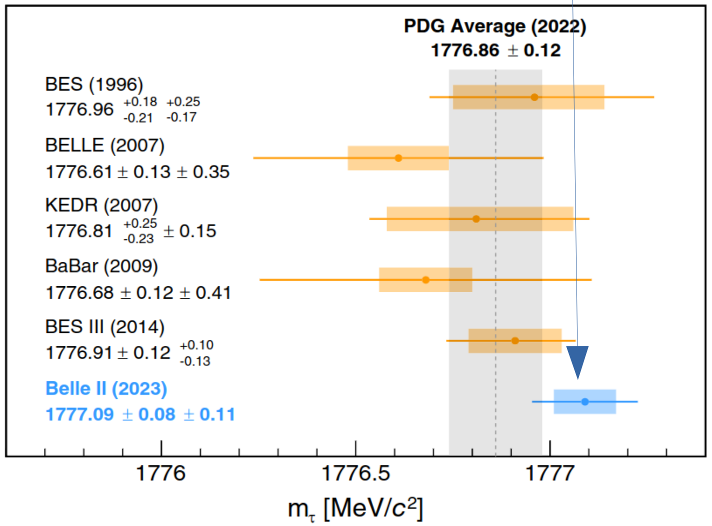
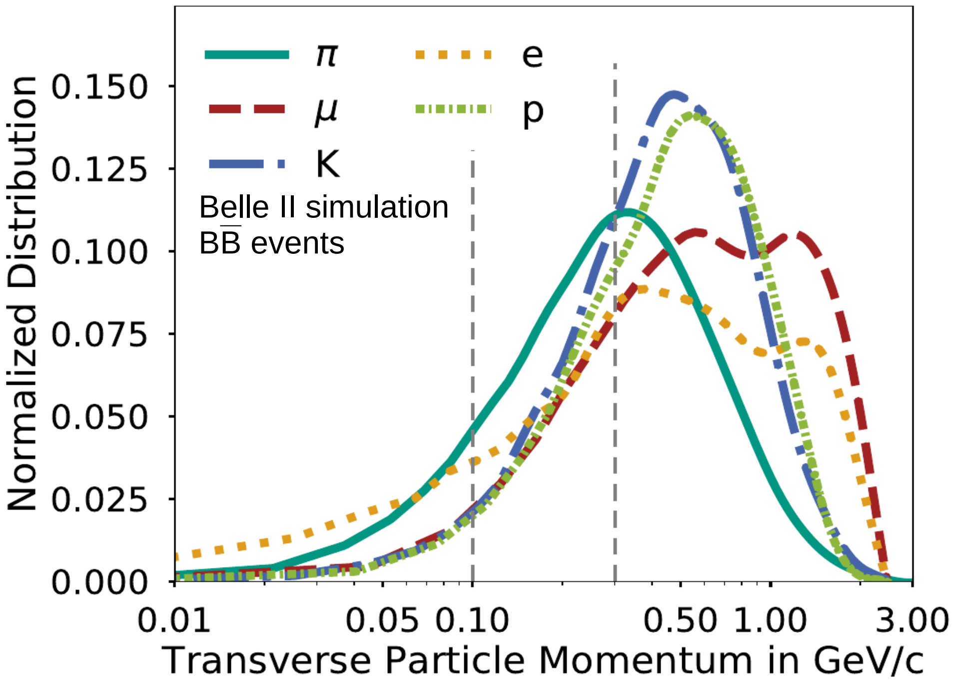


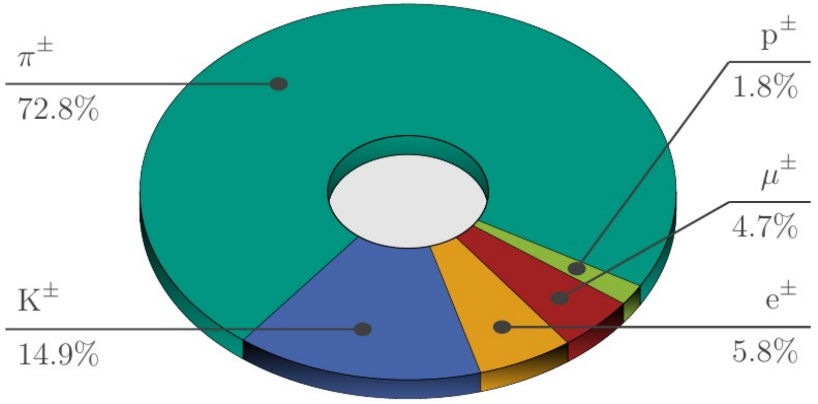
The Tracking Environment

Tracking

- Clean environment with well known initial state: $\Upsilon(4S)$
  - Can calibrate beam spot using precise vertexing
- Soft momentum spectrum
  - Mean p_t at 400 MeV/c – multiple scattering is an issue
- Around 10 tracks per hadronic event in fiducial volume
- Majority of events Bhabha or two photon scattering
- Used on High Level Trigger: need fast track finding algorithms with **high efficiency** and **low fake** rate down to **p_t = 50 MeV/c**
  - Bunch crossings every 4 ns → high probability of background tracks from previous bunch crossing being reconstructed in triggered event
- Tiny signal fraction among silicon hits at target luminosity
  - O(0.1%) of hits in PXD
  - < 10% of hits in SVD

→ Use precise timing information from SVD to reject fake hits in future





The Tracking Environment

Tracking data flow

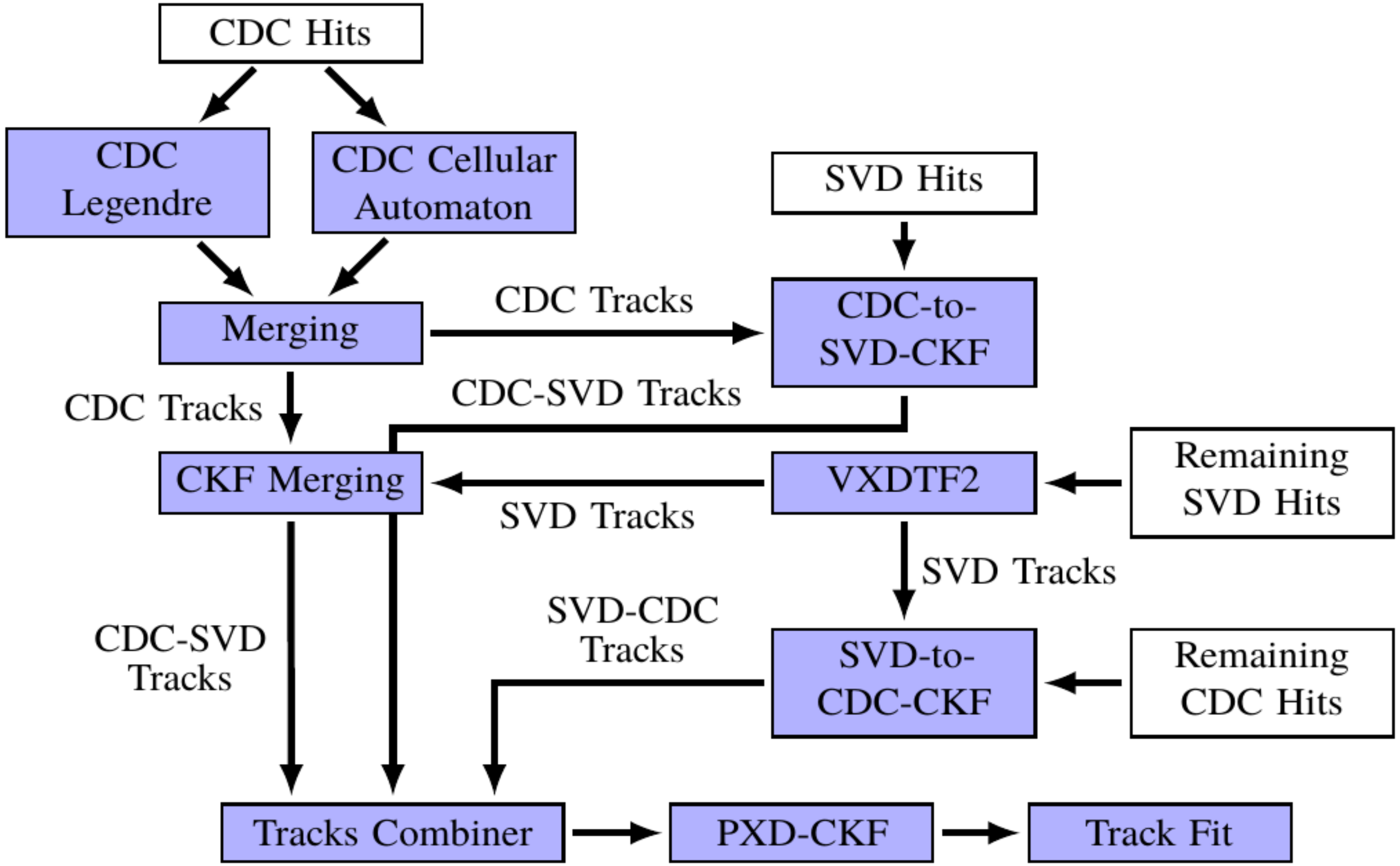
- Employ a combination of global and local tracking algorithms (paper)
- Track fits performed with GenFit's Deterministic Annealing Filter (DAF) (paper, github)
- Same software (basf2, paper, github) used **online (high level trigger)** and offline

CKF: Combinatorial Kalman Filter

- Used for inter-detector reconstruction

VXDTF2: Vertex Detector Track Finder 2

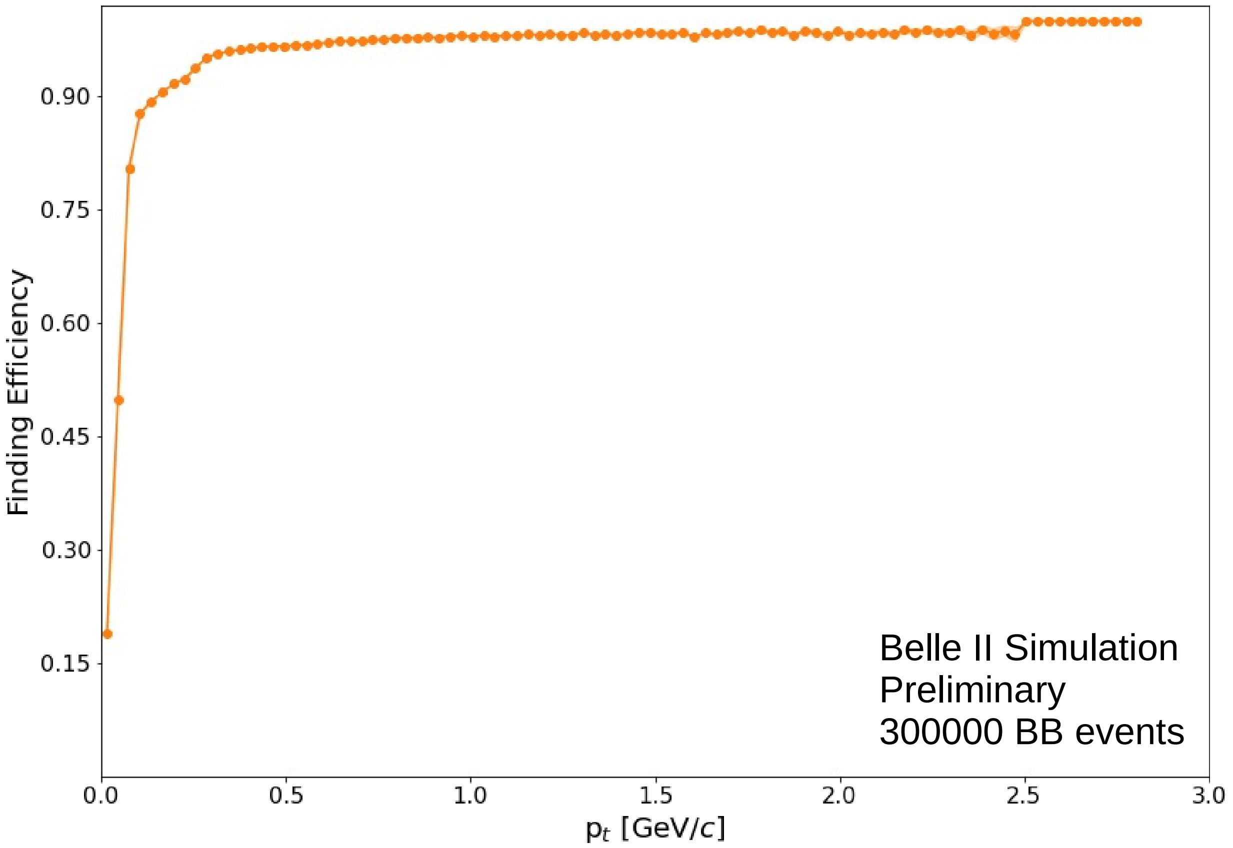
- Silicon only track finding in SVD
- Sector map concept using "Sectors on Sensors" (paper)
- Applies geometrical and timing cuts between hits learned during training

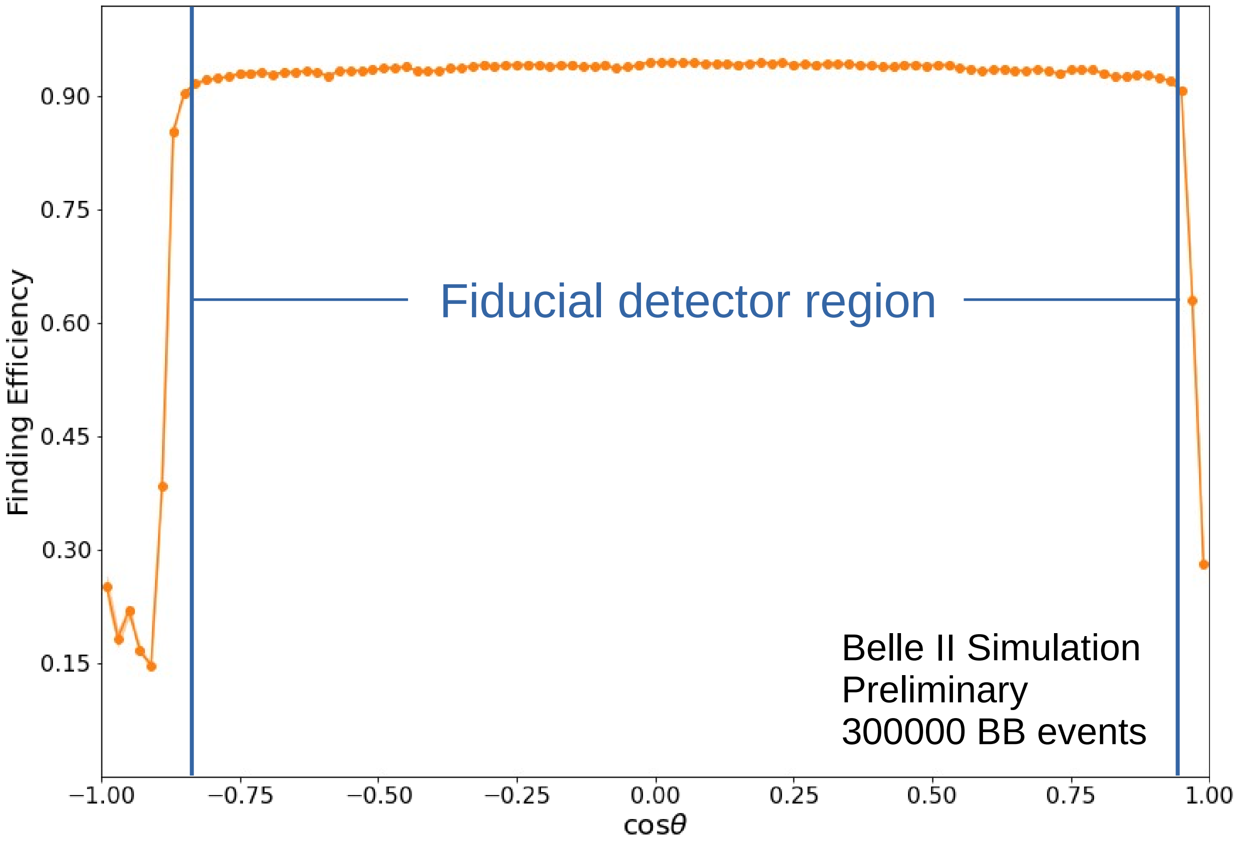


Tracking Performance

Tracking performance

- Track finding efficiency vs p_t and cosθ
- Above 90 % for most of the phase space covered by Belle II detector
  - 93.6 % efficiency on average

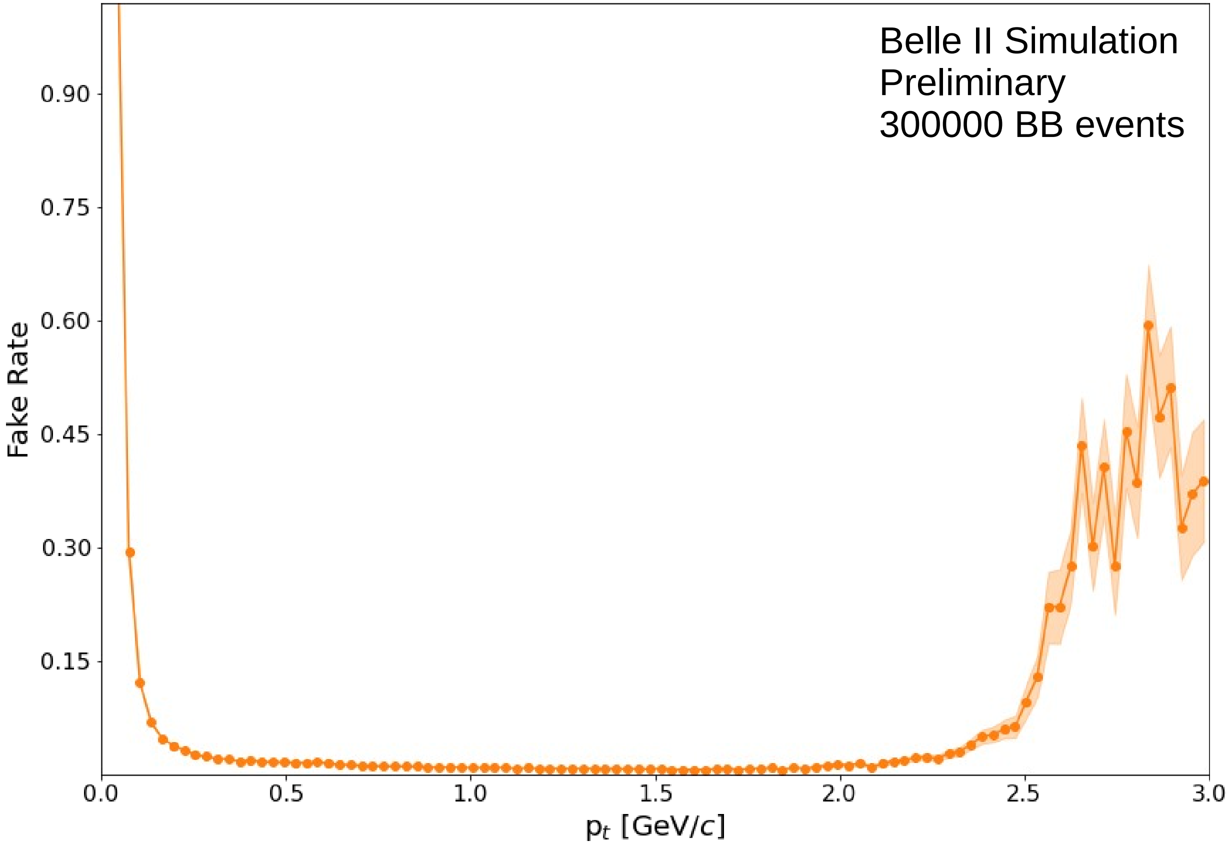


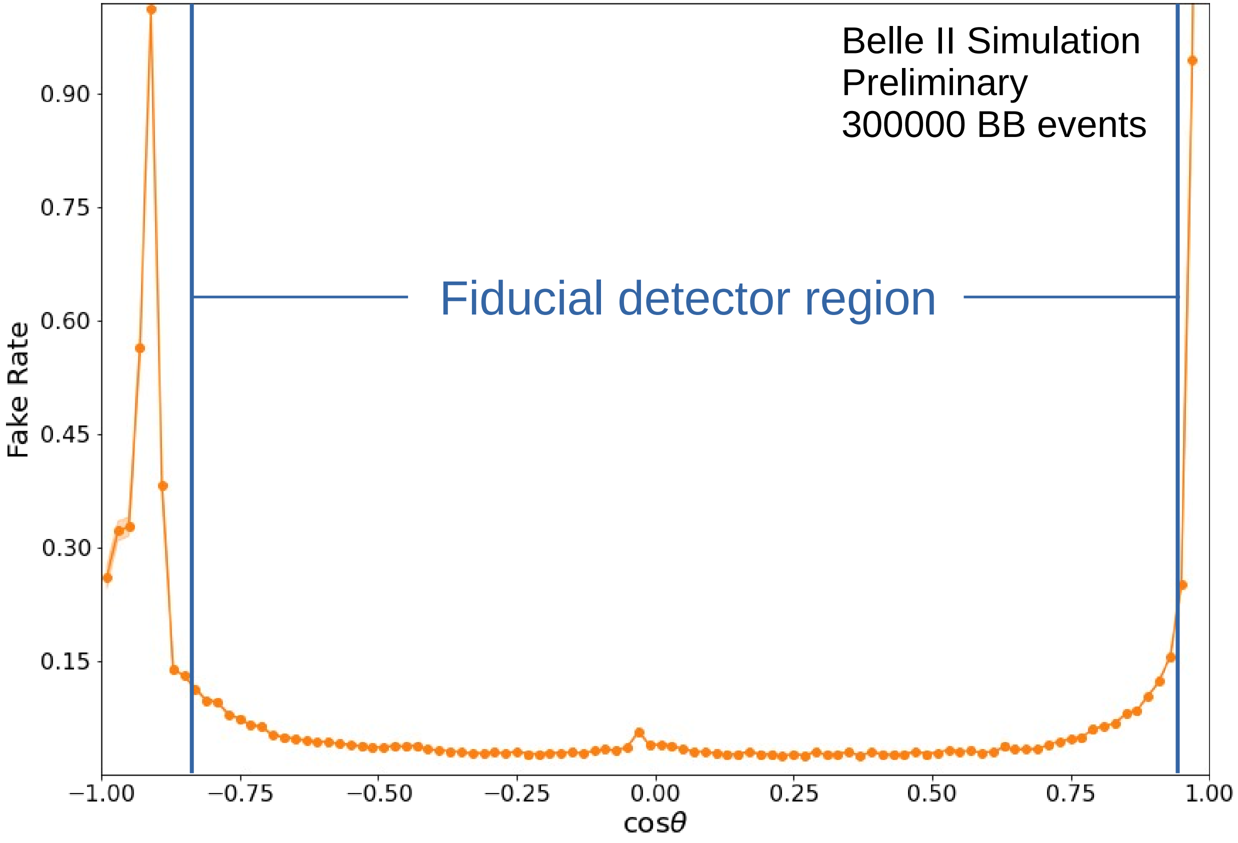


Tracking Performance

Tracking performance

- Increased rate of fake and beam background tracks for low and high values of p_t and $\cos\theta$
  - More small angle $e^+e^- \rightarrow e^+e^- (\gamma)$ scattering and $e^+e^- \rightarrow e^+e^- f\bar{f}$ (two photon process) with low p_t and in very forward and backward directions → actual tracks from physis backgrounds
  - At high p_t: random combinations of hits and low number of tracks from BB events



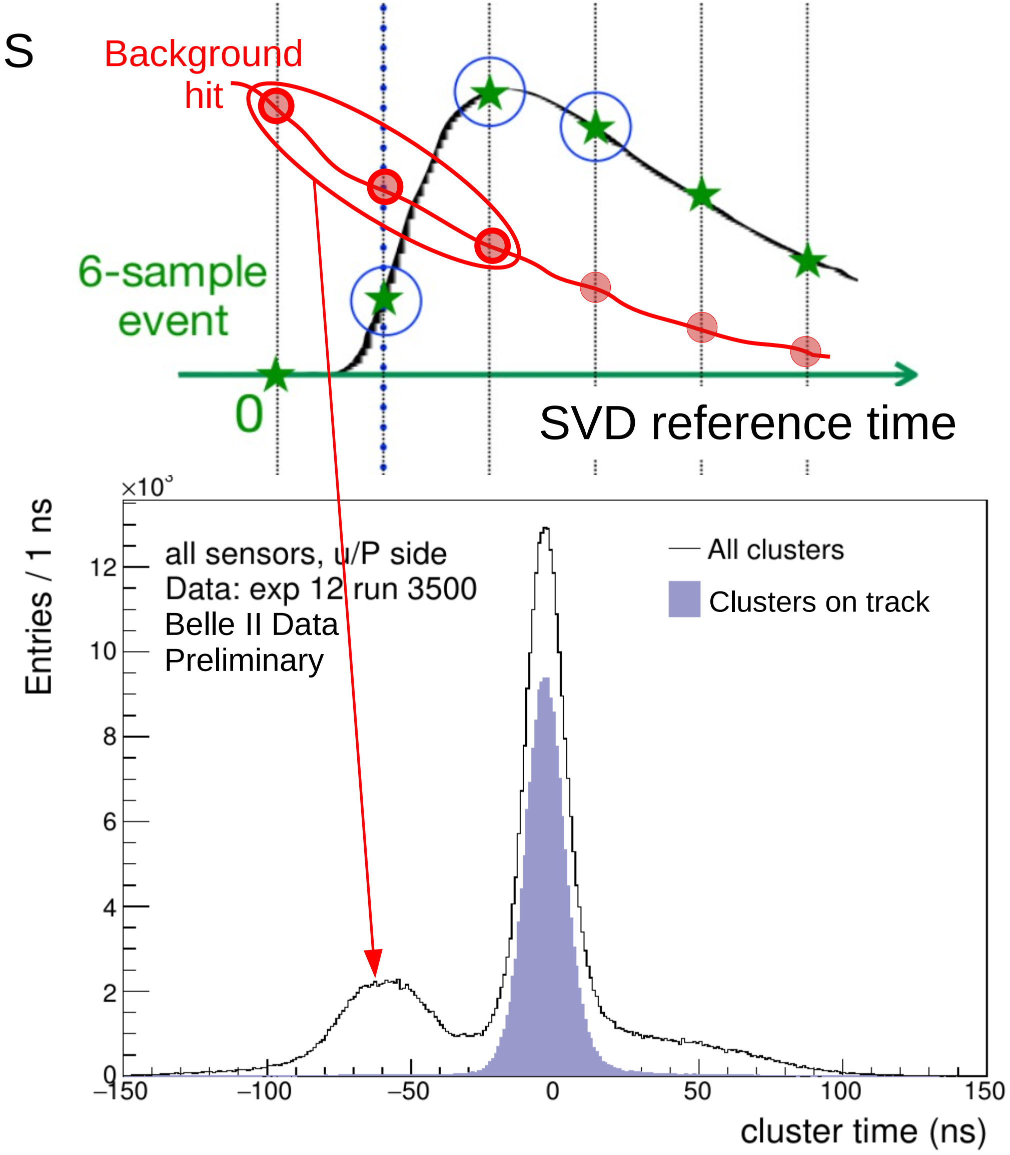


Precise SVD timing

SVD data reconstruction

- SVD analogue signal shaped with APV25 chip developed for CMS
- One sample each 31.44 ns
- 6 samples collected per strip after trigger
- Shaping function $f(t) \propto \frac{t}{\tau} \cdot e^{-\frac{t}{\tau}}$

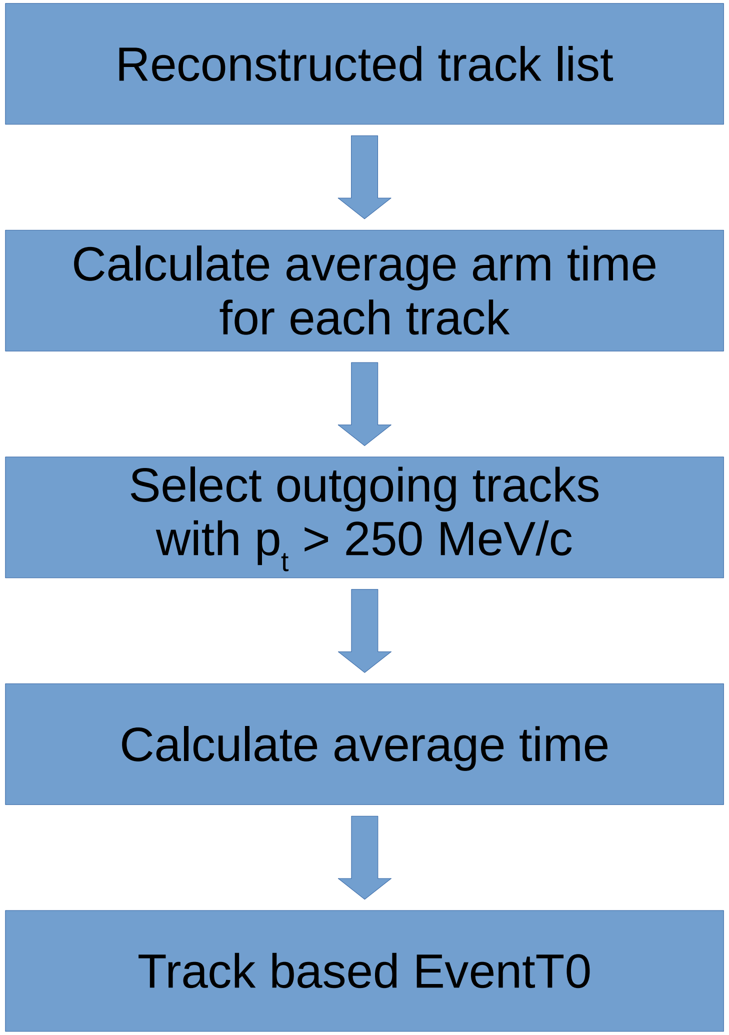
  with shaping time τ = 50 ns
- Estimate cluster time with ns precision
  - Use samples with highest information density
- Hit time more difficult to estimate correctly if hit time ≪ 0
  - Missing rising edge of shaping function
- Signal hits centered around 0
  - Usually signal clusters within 50 ns from the collision time



EventT0 and Track Time Estimation

From hit times to track times

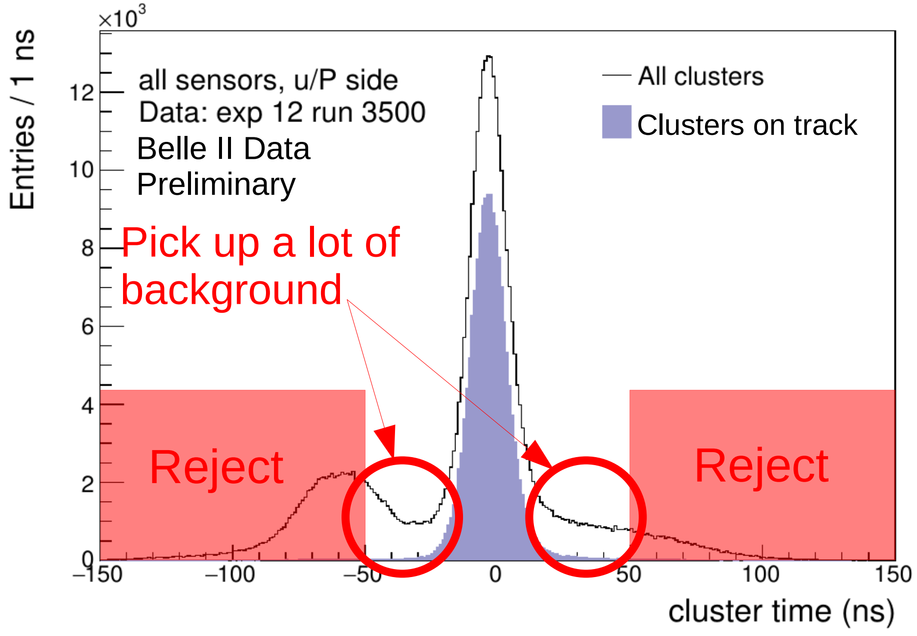
- In the past: used CDC based EventT0 estimation
  - Multiple iterations of GenFit DAF with full CDC information of track → long execution time
- Superseded by EventT0 determination with SVD
  - Calculate track time as average of time of clusters associated to the outgoing track-arm
  - EventT0 = Average of all SVD cluster times of clusters in all tracks for p_t > 250 MeV/c to avoid curling tracks
  - If no tracks with p_t > 250 MeV/c and sufficient number of SVD hits are present, EventT0 is based on ECL information
  - 2000 x faster than CDC method
  - Less than 1 ns resolution on data
- Relative track time
  - Difference between average of all SVD cluster times within a track and EventT0
  - Will be provided to analysts in the future



SVD time grouping

Concept

- Before: cuts on absolute SVD cluster time helpful
  - $|t_{u,v}| < 50$ ns for single cluster
  - $|t_u - t_v| < 20$ ns for space point creation
- Many background clusters per event survive
  - Number will increase with increasing luminosity



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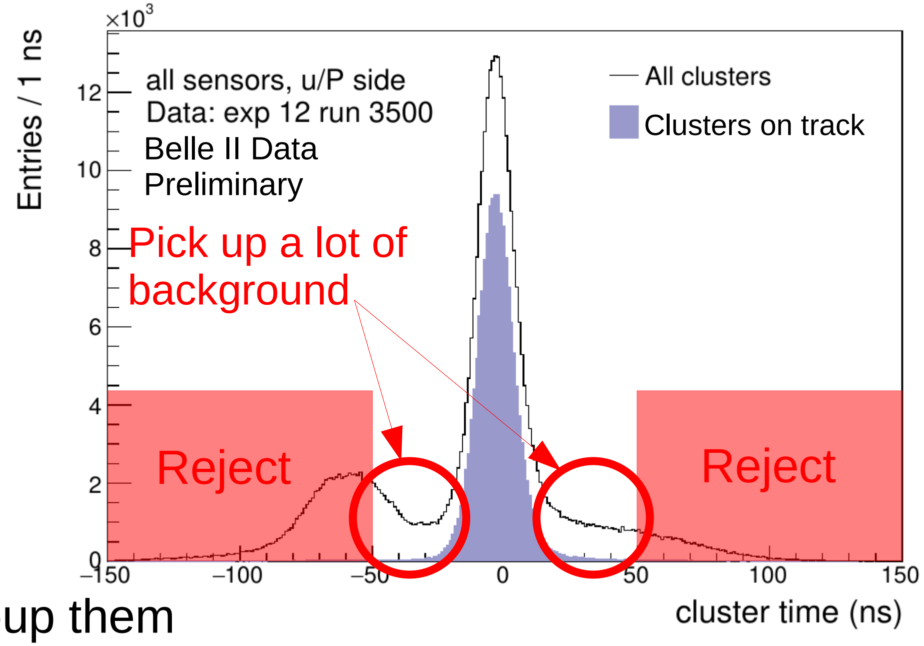
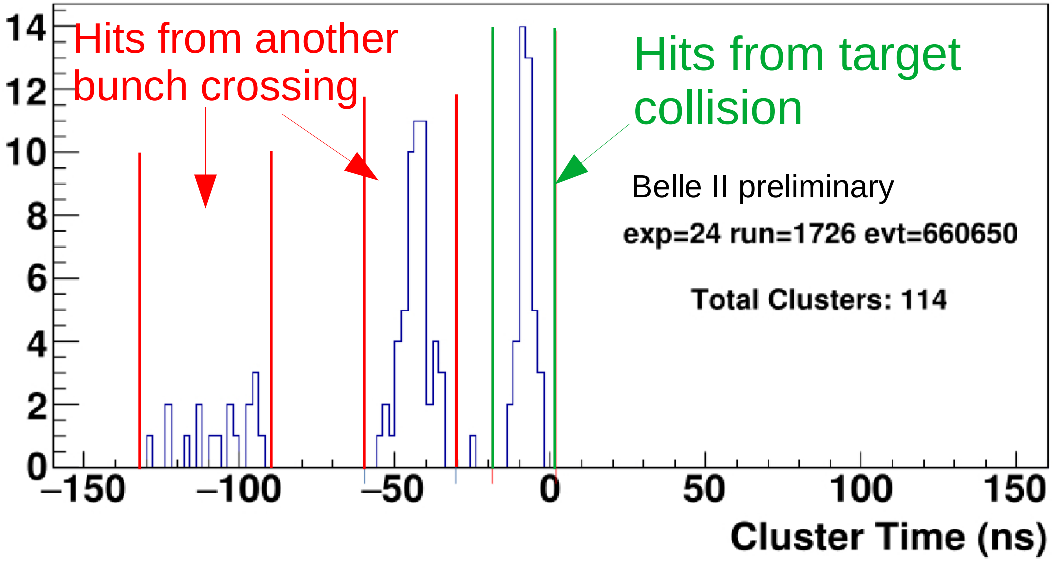


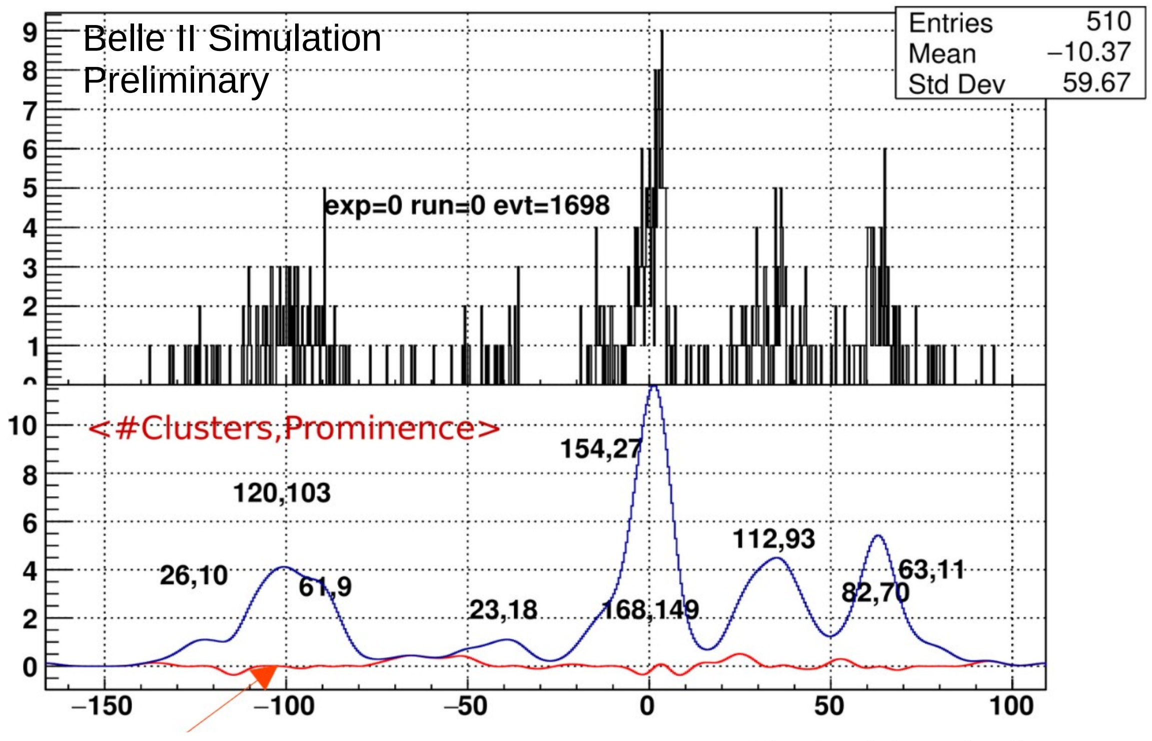
- New idea: Check individual cluster times per triggered event and group them
  - Signal clusters from same bunch crossing close in time
  - Histogram hits and fit with Gaussian
  - If cluster time > 3σ away from group → new group
  - Group closest to 0 and with highest number of clusters is priority group
- Only form 3D space points from clusters from priority group
  - Reduce number of reconstructed background tracks



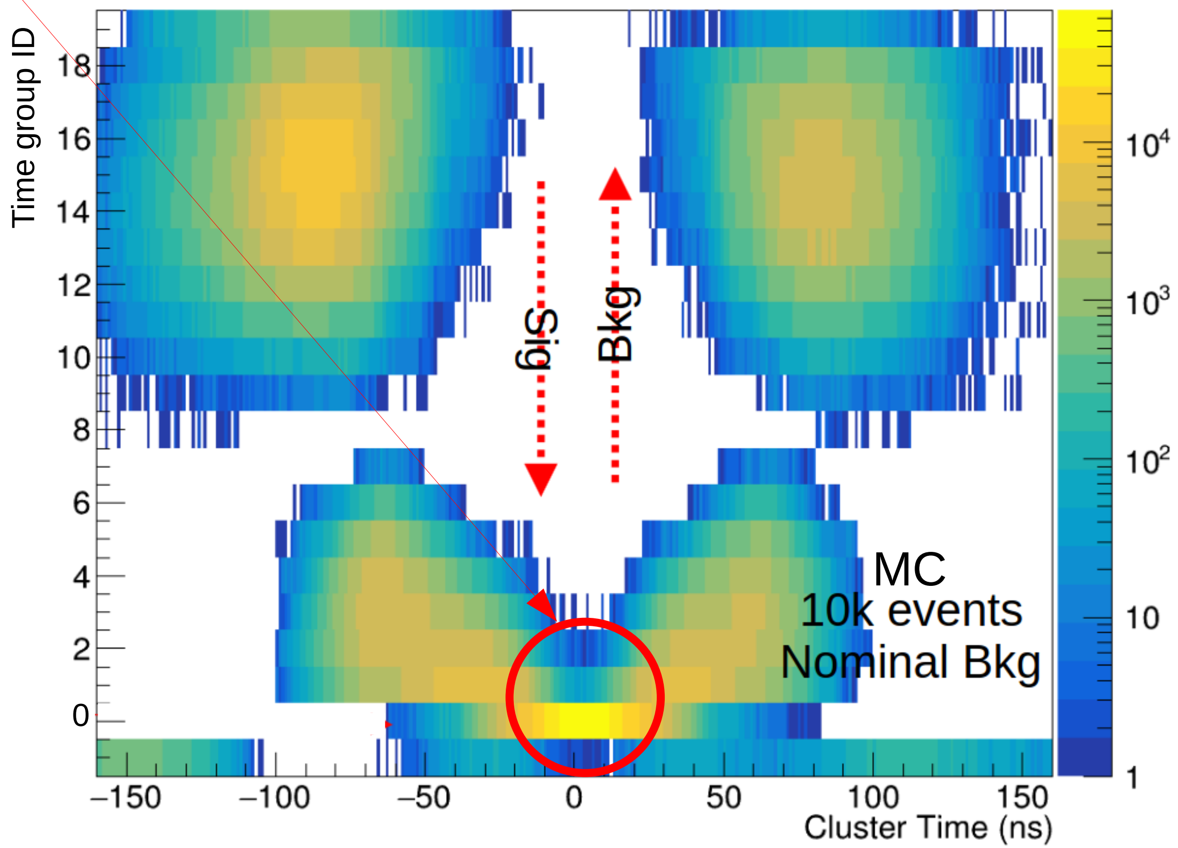
SVD time grouping

Performance

- Background rejection depends on background levels
  - Examples on this slide for **simulated** backgrounds for nominal luminosity
- Priority time group (ID = 0) nicely centered around 0 in cluster time
  - Mostly background free



Clusters below threshold



Tracking performance with SVD time grouping

Performance

- Grouping shows no degradation in track finding efficiency
- Significantly reduces fake rate
  - **50 % less fake tracks and tracks from beam backgrounds**
- Small reduction in clone rate (tracks reconstructed multiple times)
  - Ingoing track arm with time > 0 so hits don't belong to priority group anymore

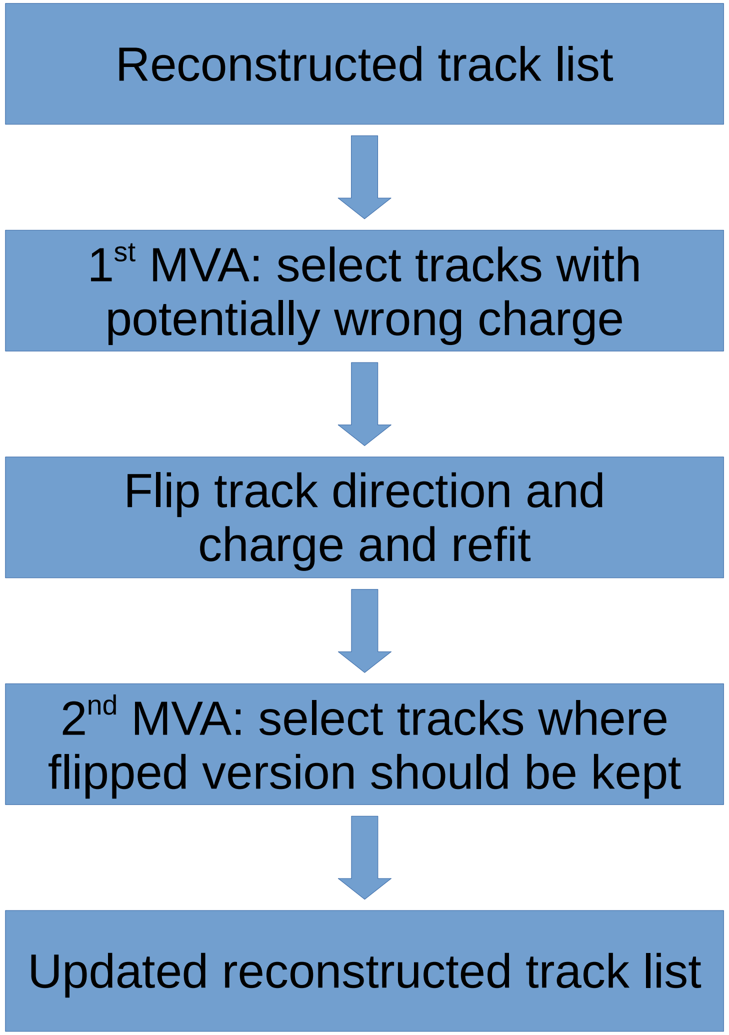
	Hit time grouping off	Hit time grouping on	Relative difference
Track finding efficiency	93.67 ± 0.24 %	93.69 ± 0.24 %	+0.02 %
Charge efficiency	98.68 ± 0.11 %	98.74 ± 0.11 %	+0.06 %
Fake rate	9.55 ± 0.29 %	4.37 ± 0.20 %	-54.26 %
Clone rate	3.81 ± 0.19 %	3.56 ± 0.18 %	-6.62 %

Track Flip-and-Refit

Wrongly assinged track charges

- Found to have a small fraction of tracks with wrongly assigned charge in certain phase space region
  - Low pt curling tracks in the transverse plane

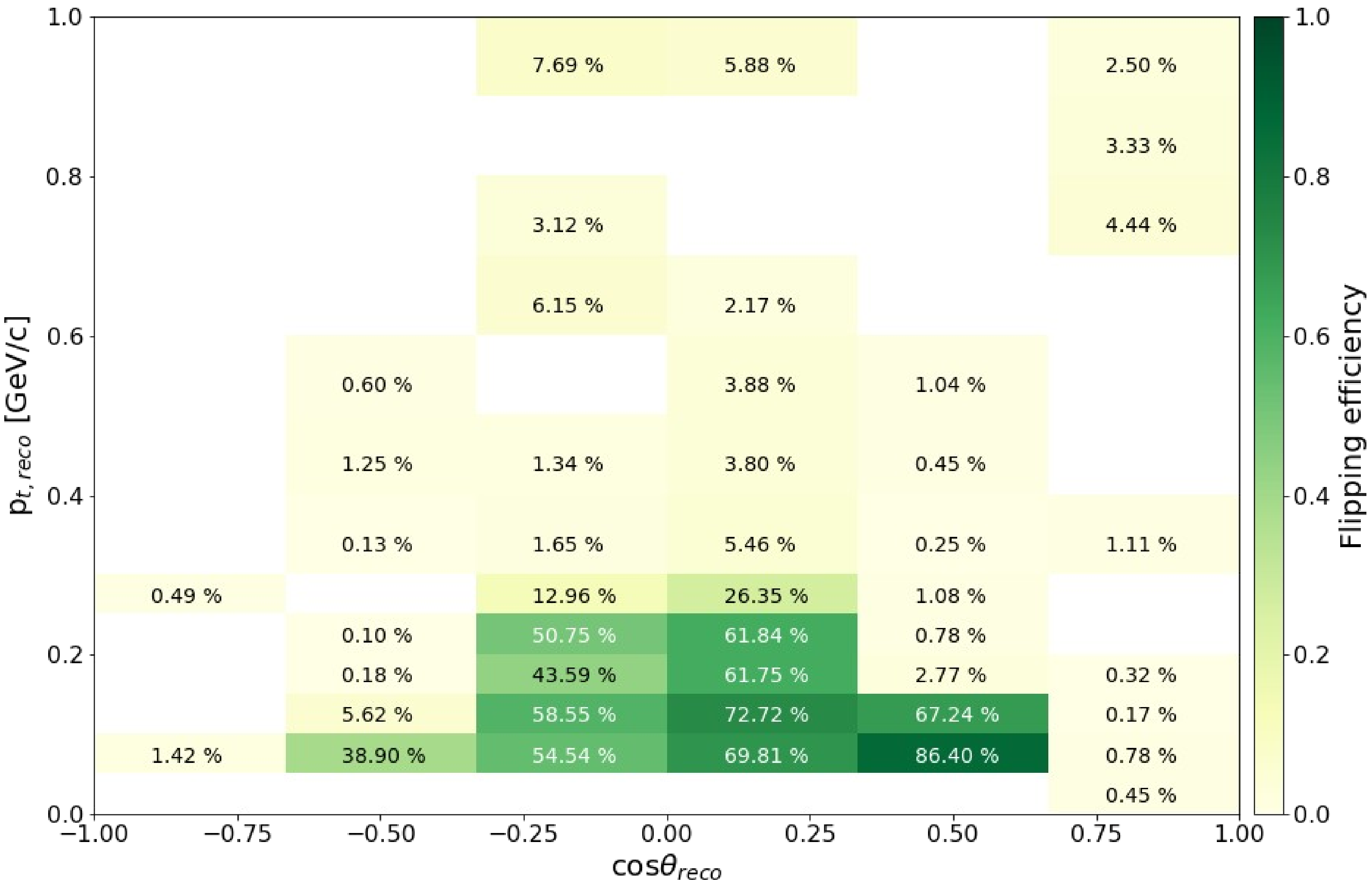
  → Use two BDT based methods to improve situation
- BDTs use track features
  1. Seed information (estimates for momentum, point of closest approach), SVD and CDC hit content, **track time**, …
  2. Fit information of flipped tracks, fit p-value, **track time**, result of first BDT
- High efficiency and purity of selecting and flipping tracks selected
  - Around 1.2 % of all tracks selected
  - Successful correction of charge for **50 % of tracks with wrong** charge assignment



Track Flip-and-Refit

Results and improvements from flip and refit

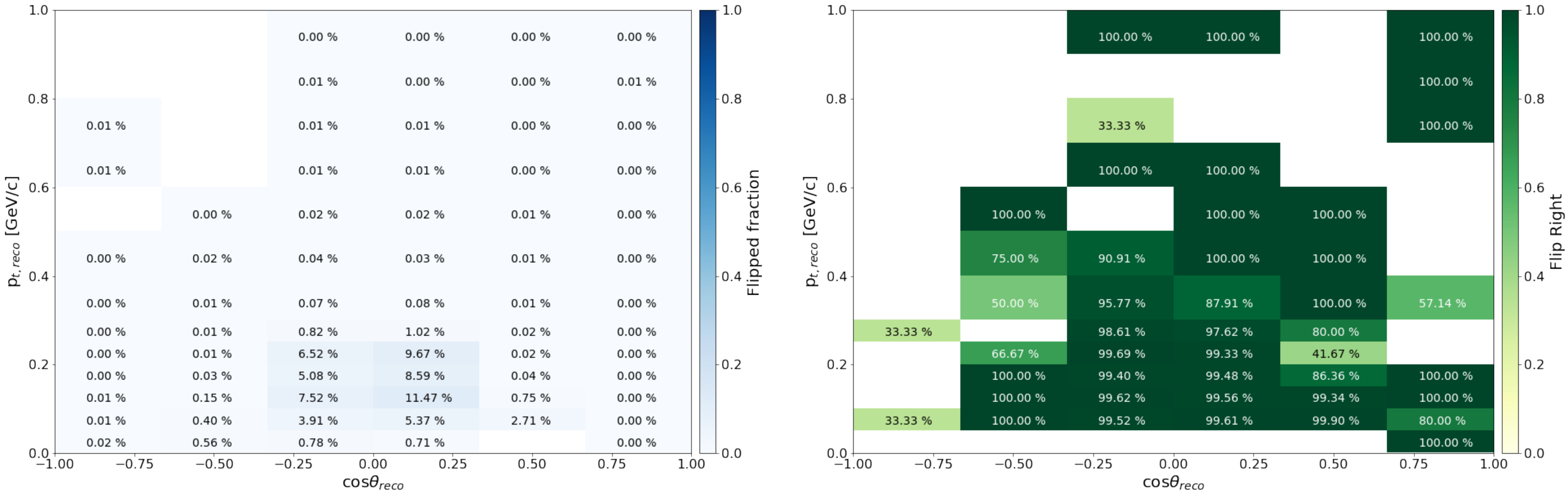
- Succesfully correcting wrongly reconstructed track charges in up to 86 % in certain phase space regions



Track Flip-and-Refit

Results and improvements from flip and refit

- Up to 11.5 % of flipped tracks in certain phase space regions
- Majority of flipped tracks are flipped correctly



Conclusion

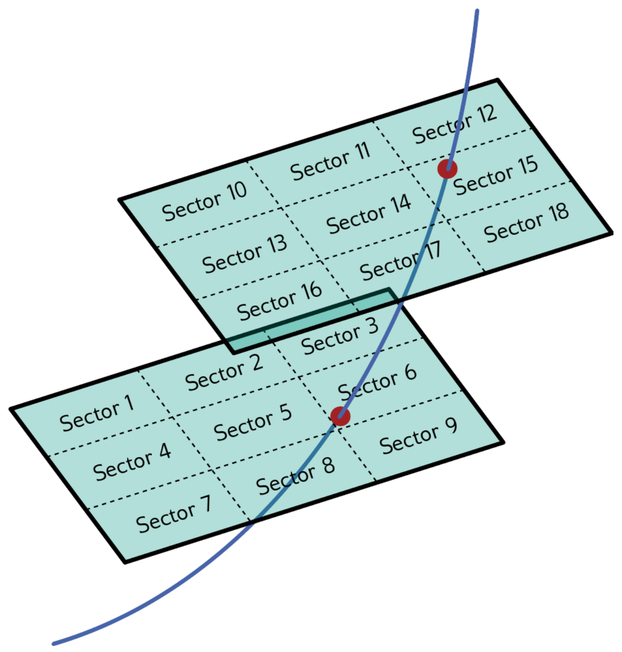
- Belle II tracking works reliably and with high efficiency both online and offline
- Reconstructed tracks are used to produce world leading physics results
  - D^+, D^0, Λ_c lifetimes, τ mass, …
- Precise timing information from SVD in the future
  - Used to calculate EventT0
  - Used to significantly reduce the number of fake tracks from non-triggered collisions by employing time grouping
- Newly developed method of flipping and refitting employing machine learning used to reduce number of tracks with wrongly assigned charge
  - Reduction of up to 50% in certain phase space region
- Positive effect of both methods demonstrated in simulation
  - To be applied during data taking and offline processing in the future – next data taking period starts in spring 2024
- Further improvements on tracking will ensure that Belle II can continue to produce world leading physics results
- Increased beam backgrounds will be a major challenge for operation and reconstruction

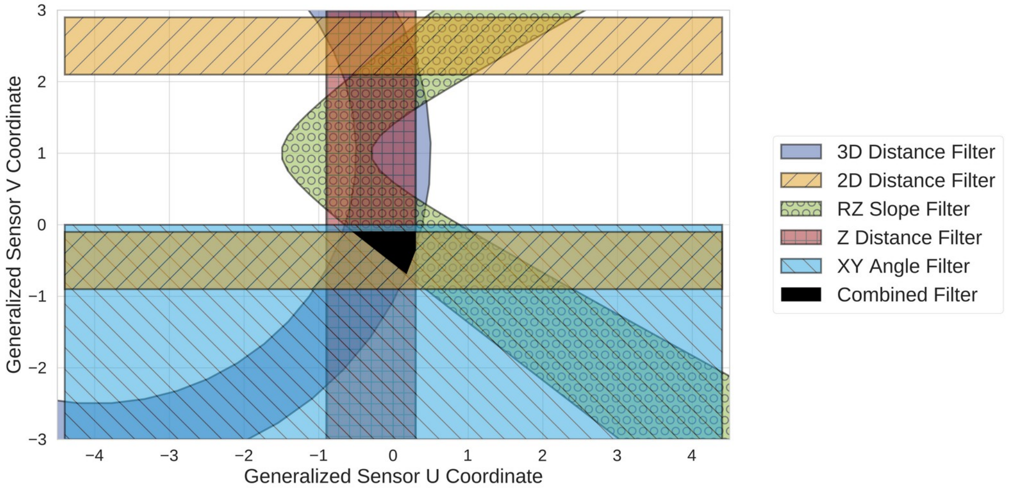
Thank you for your attention!

VXDTF2

SVD only track finding

- 3D space points from combining clusters from both sides of a SVD sensor
- Concept of “Sectors on Sensors” to create sector map
  - Each sensor divided in several sectors
  - Only hits on sectors know to be related are considered
  - Apply selection criteria called “filters”
    - Unique for sector combinations
    - Two-hit or three-hit combinations
    - Based on geometric quantities or timing information
- Requires training with Monte Carlo events to learn the relations and filter selection criteria
  - Usually Υ(4S) events, with additional high momentum muons and Bhabha events
  - Sector map learns the geometry without explicit definition





Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Dr. Christian Wessel
Belle II
christian.wessel@desy.de