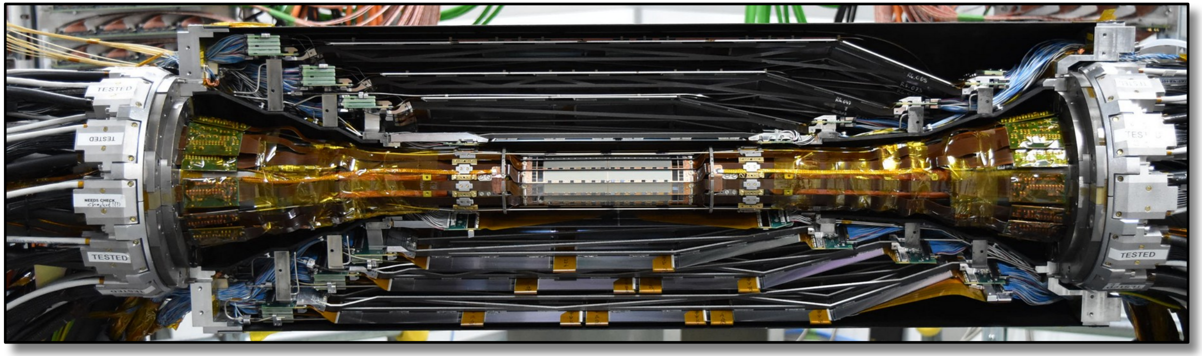

Hit time computed with the Silicon Vertex Detector (SVD) of Belle II

4D Track Reconstruction

May 8th, 2024, online

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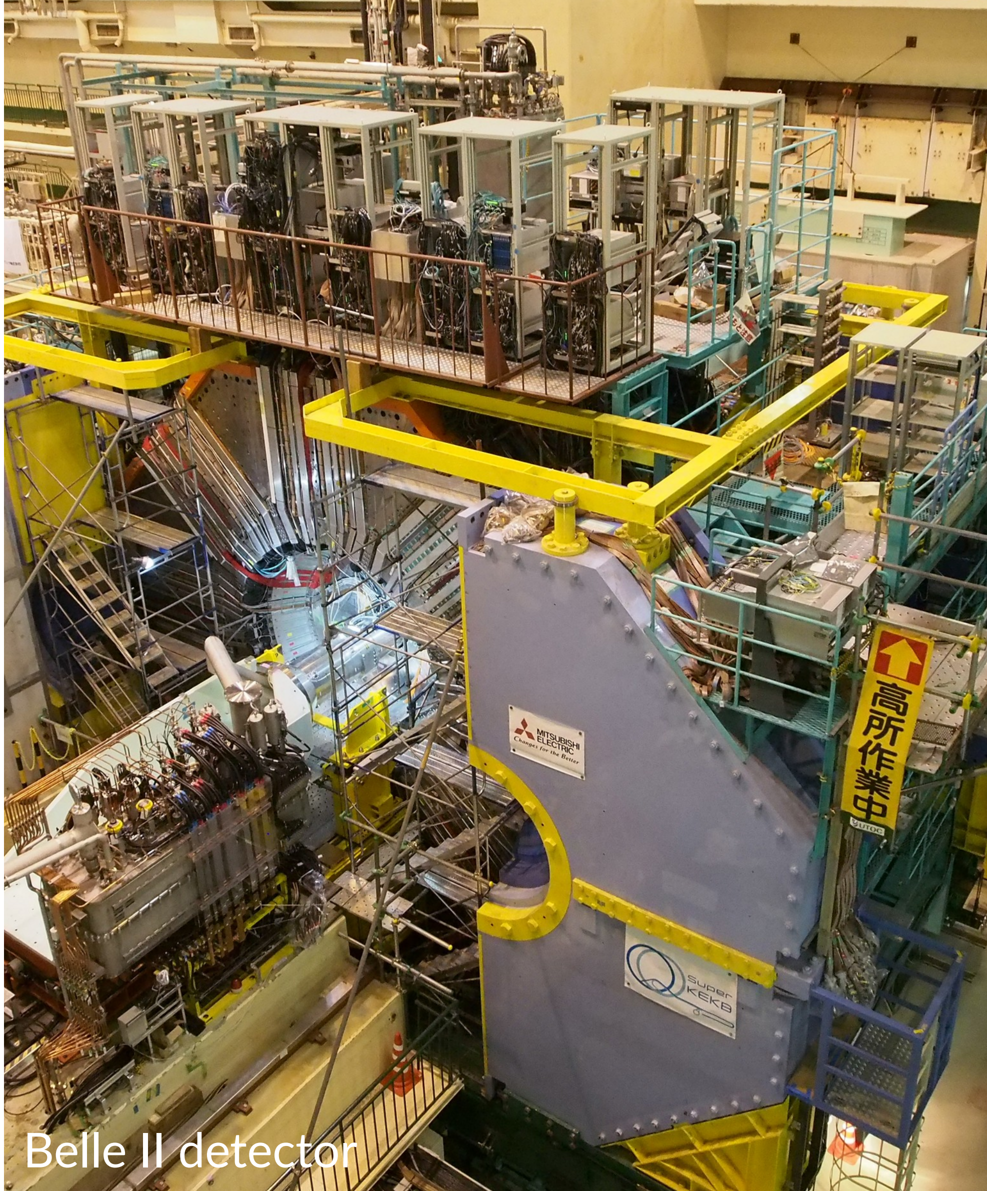
Belle II SVD paper: JINST, 17, 2022

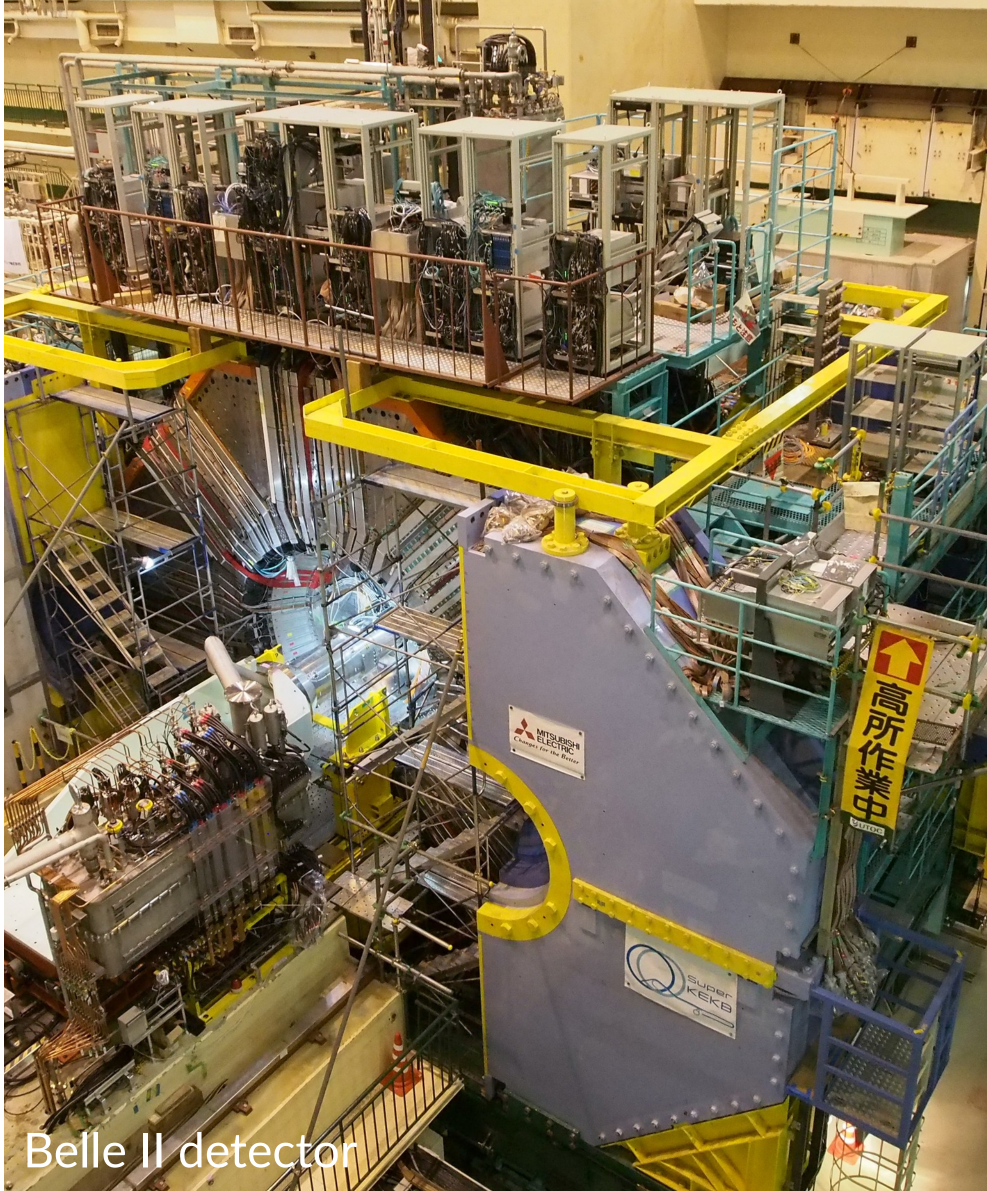
Outline

- Introduction to Belle II at SuperKEKB
- Introduction to SVD
- SVD time
- SVD time applications
- Conclusions



Belle II detector

Introduction to Belle II

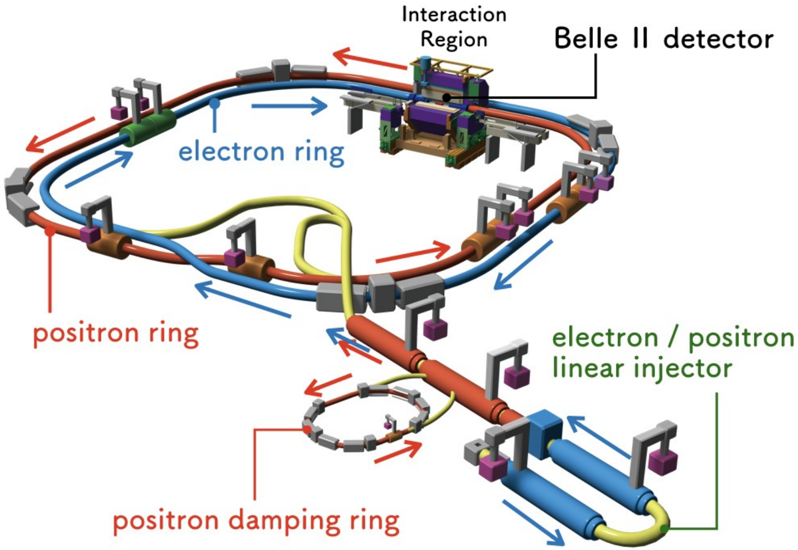


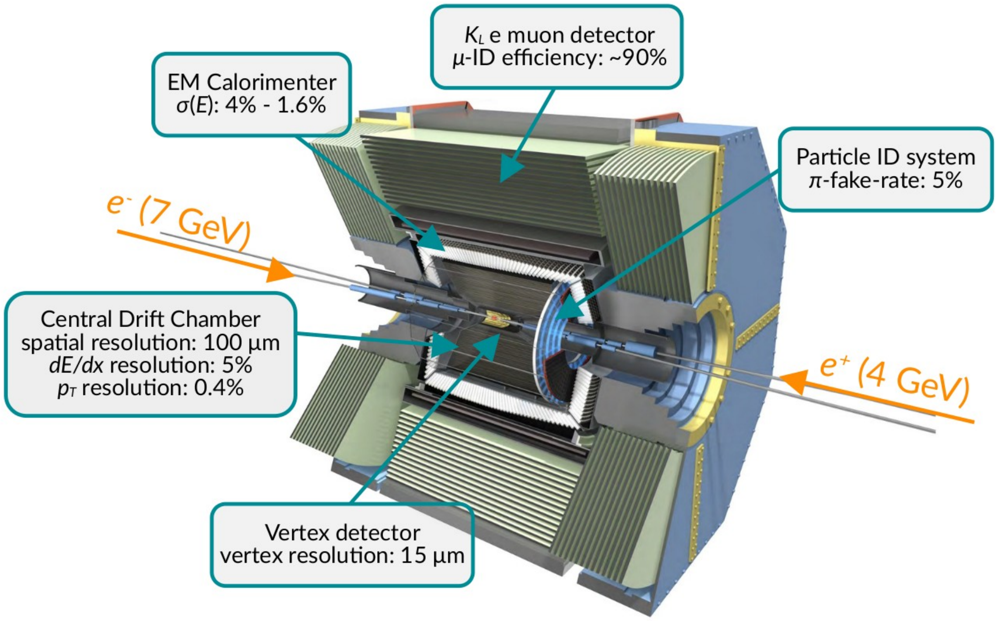
Belle II detector

Belle II at SuperKEKB

SuperKEKB

- **Asymmetric e^+e^- collider** operated at **√s = 10.58 GeV** [Υ(4S)]
- **Well know initial-state condition** and **low multiplicity environment**





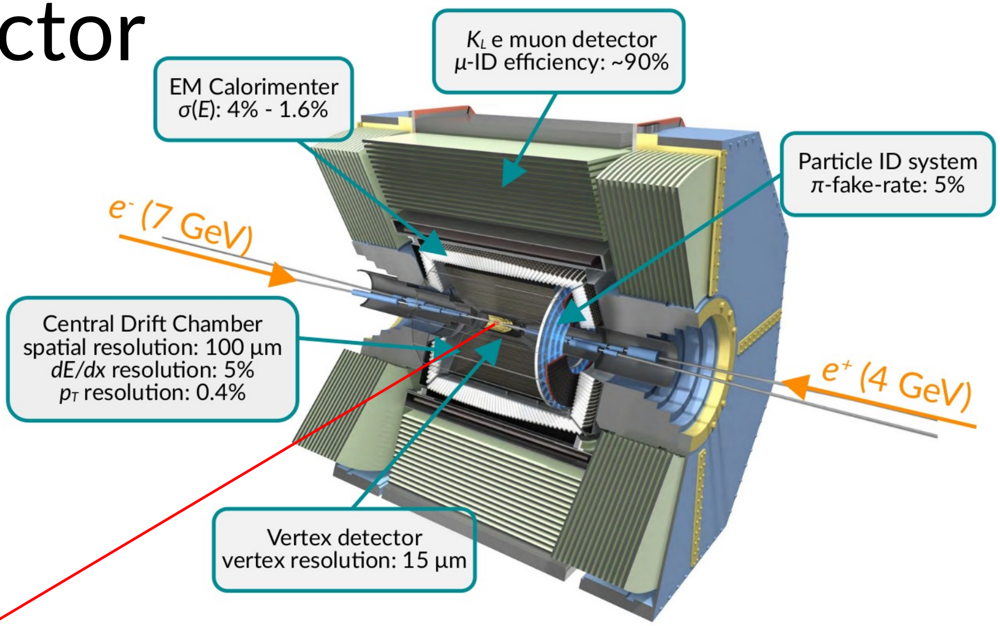
Belle II

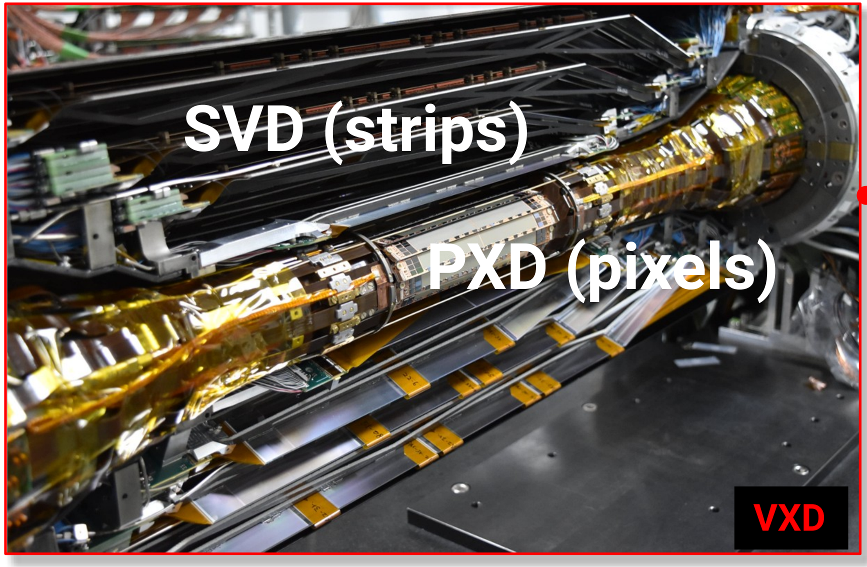
- **Hermetic detector** with **high performances** (upgrade of Belle at KEKB)
- **Run1** (2019-2022) → **424 fb^{-1}**, Run2 just started
- **Dedicated low-multiplicity trigger** → Belle II dataset unique

The Belle II Vertex Detector

Vertex detector (VXD)

- Provide the **precise measurement of the primary and secondary vertices of short-lived particles**





VXD detectors

- Pixel Detector (**PXD**): **2-layer** DEPFET **pixel sensors**
- Silicon Vertex Detector (**SVD**): **4-layer Double-Sided silicon Strip Detector**
- Position of layers: 1.4 cm, 2.0 cm, 3.9 cm, 8.0 cm, 10.4 cm, 13.5 cm

Typical event at Belle II

- **Average multiplicty in a Y(4S) event**

    - 11 charged tracks
    - 5 neutral pions
    - 1 neutral kaon

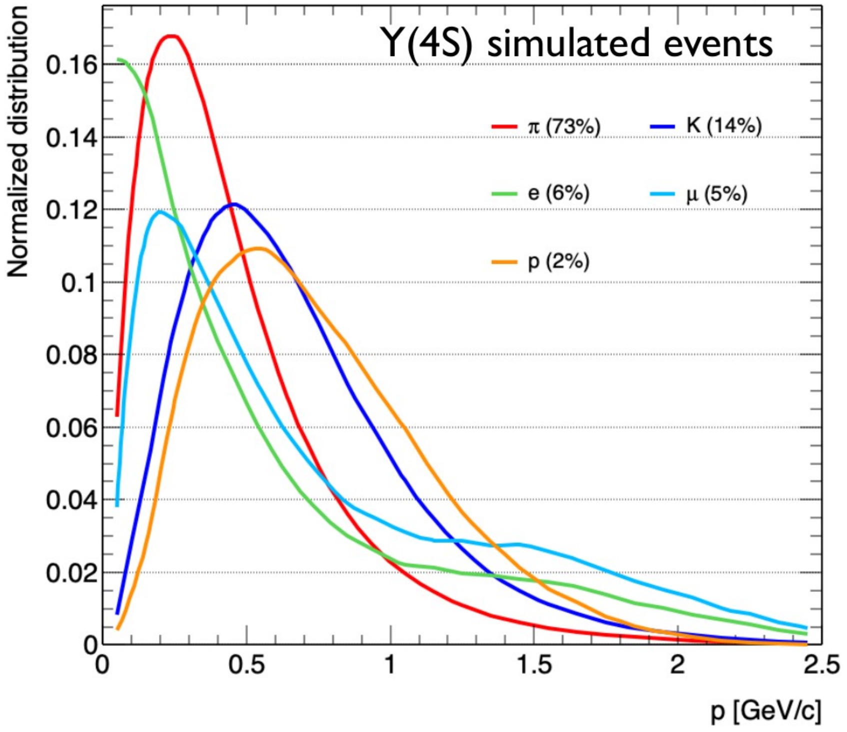
- **Few tracks with small momentum to reconstruct**

    ➔ They are significantly affected by multiple scattering

- Signal hits in VXD are overwhelmed by beam-background hits

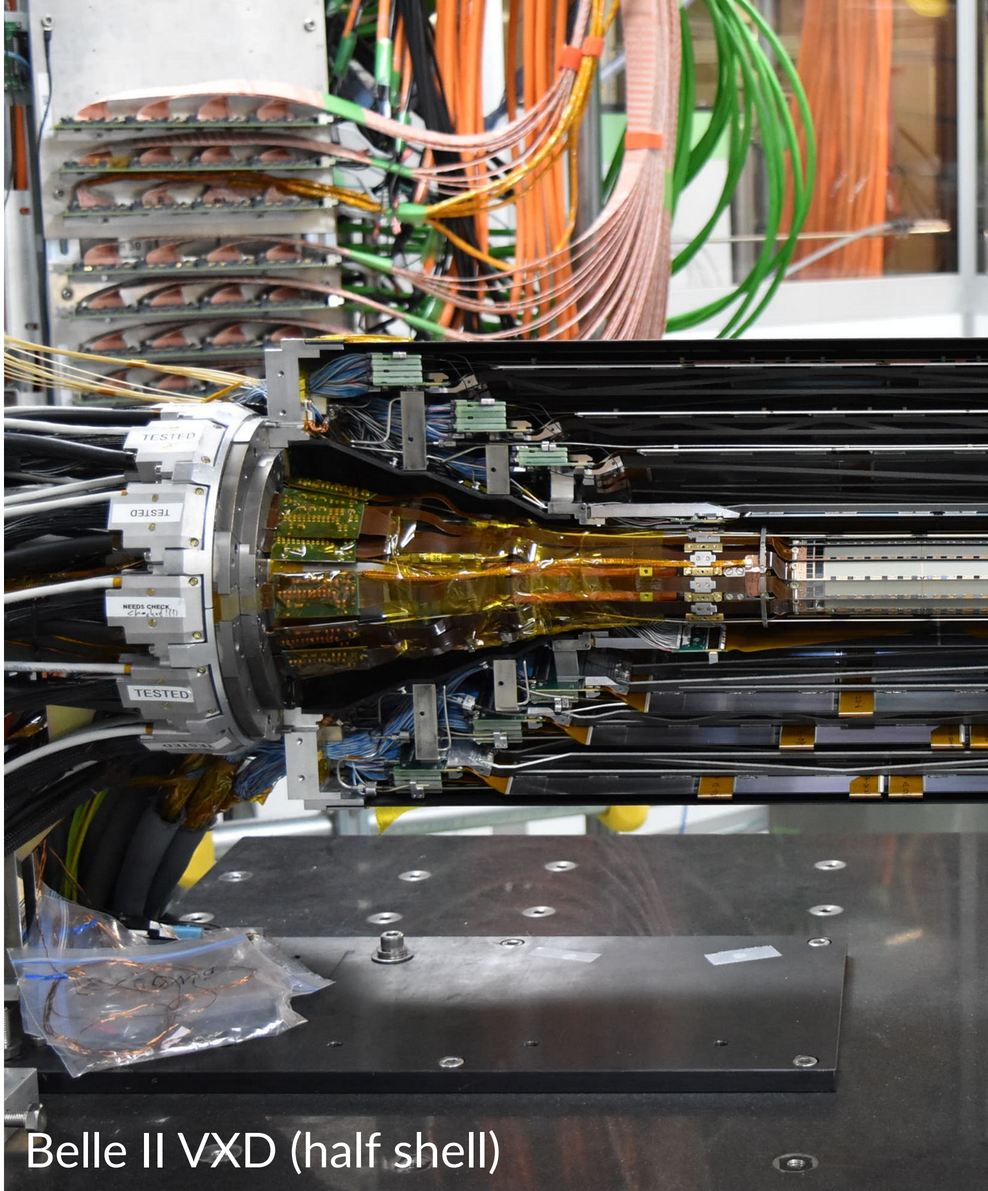
- SuperKEKB nominal luminosity: 6×10^{35} $cm^{-2}s^{-1}$

Soft charged track momentum spectrum



S.KEKB nominal luminosity	Layer 1 of pixels		Layer 3 of strips	
	Number of hits	Occupancy	Number of hits	Occupancy
Y(4S)	11	$5 \cdot 10^{-6}$	11	0.2%
beam bkg	50000	3%	3200	3%

Introduction to SVD



Belle II VXD (half shell)

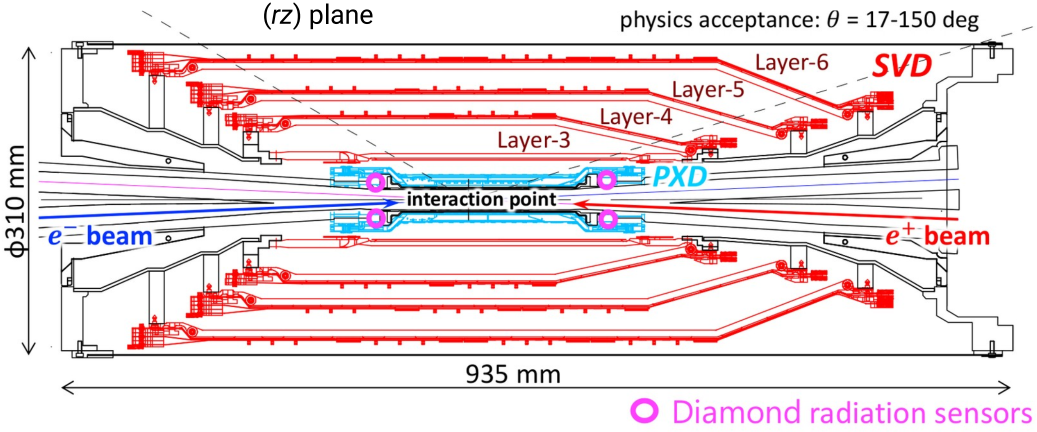
Silicon Vertex Detector (SVD)

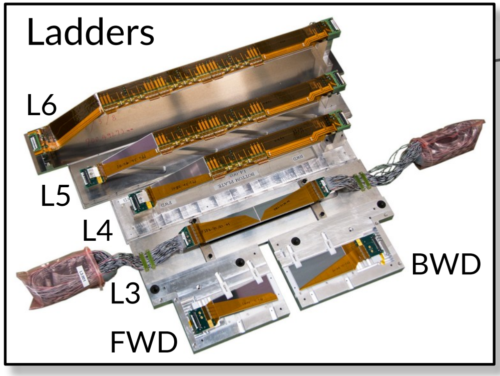
SVD structure:

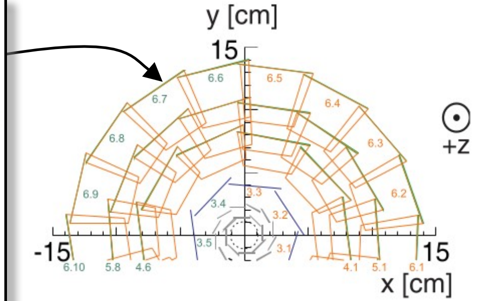
- **172 sensors**, 1.2 m^2 of sensitive area, **224k readout strips** → grouped into **ladders**
- **Slanted forward sensors** → maximize acceptance with smaller incidence angle
- **Low material budget** of 0.7% X_0/layer
- Diamond sensors for radiation monitor and beam abort

Main SVD functions:

- Standalone **tracking for low p_T tracks**
- **Extrapolate tracks to PXD**
- Precise and efficient **vertexing of K_S**
- Provide **particle identification** with dE/dx





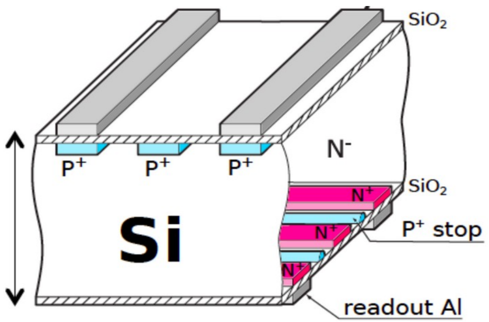


Layer	Ladder/Layer	Sensor/Ladder	Slant angle
3	7	2	0^o
4	10	3	11.9^o
5	12	4	17.2^o
6	16	5	21.1^o

SVD sensors

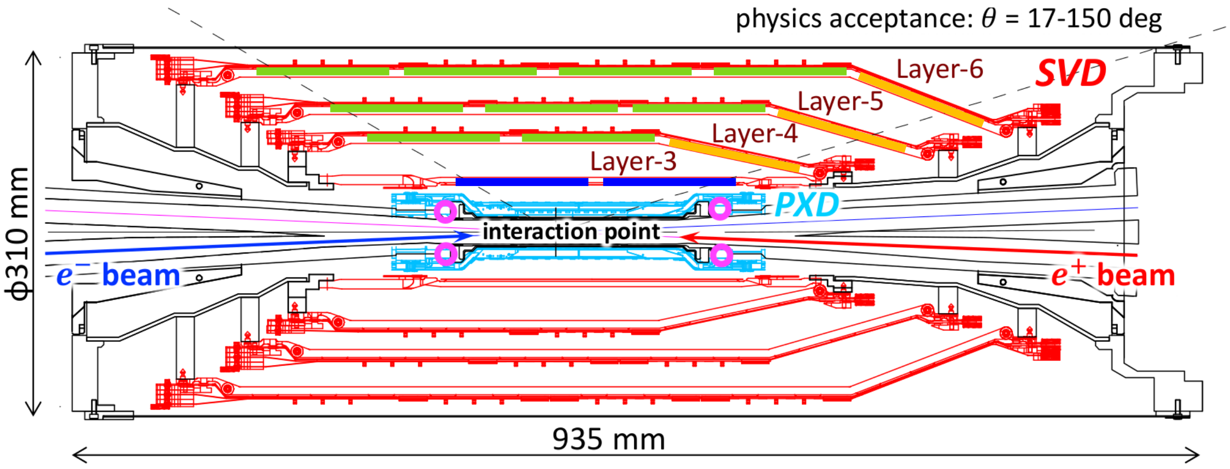
- **Double-Sided Strip Detector (DSSD)**
  - Provide **2D spatial information**

P side: u = $r\Phi$



N side: v = z

  - Sensor thickness: 300–320 μm
  - Depletion voltage: 20-60 V
  - Operation voltage: 100 V

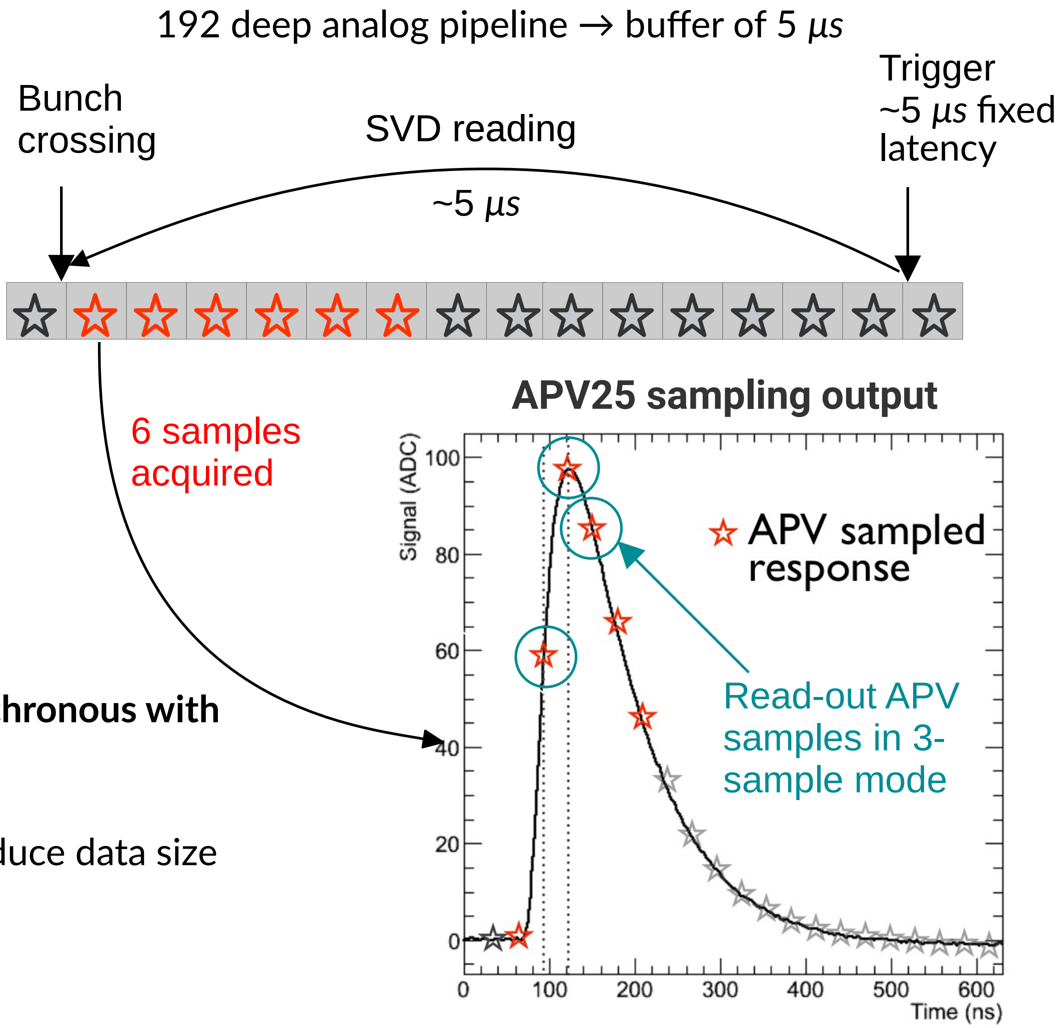


	Small sensors	Large sensors	Trapezoidal sensors
Readout strips P-side	768	768	768
Readout strips N-side	768	512	512
Readout pitch P-side	50 μm	75 μm	50 – 75 μm
Readout pitch N-side	160 μm	240 μm	240 μm
Sensor active area (mm^2)	122.90 × 38.55	122.90 × 57.72	122.76 × (38.42 – 57.59)
Sensor thickness	320 μm	320 μm	300 μm
Manufacturer	Hamamatsu	Hamamatsu	Micron

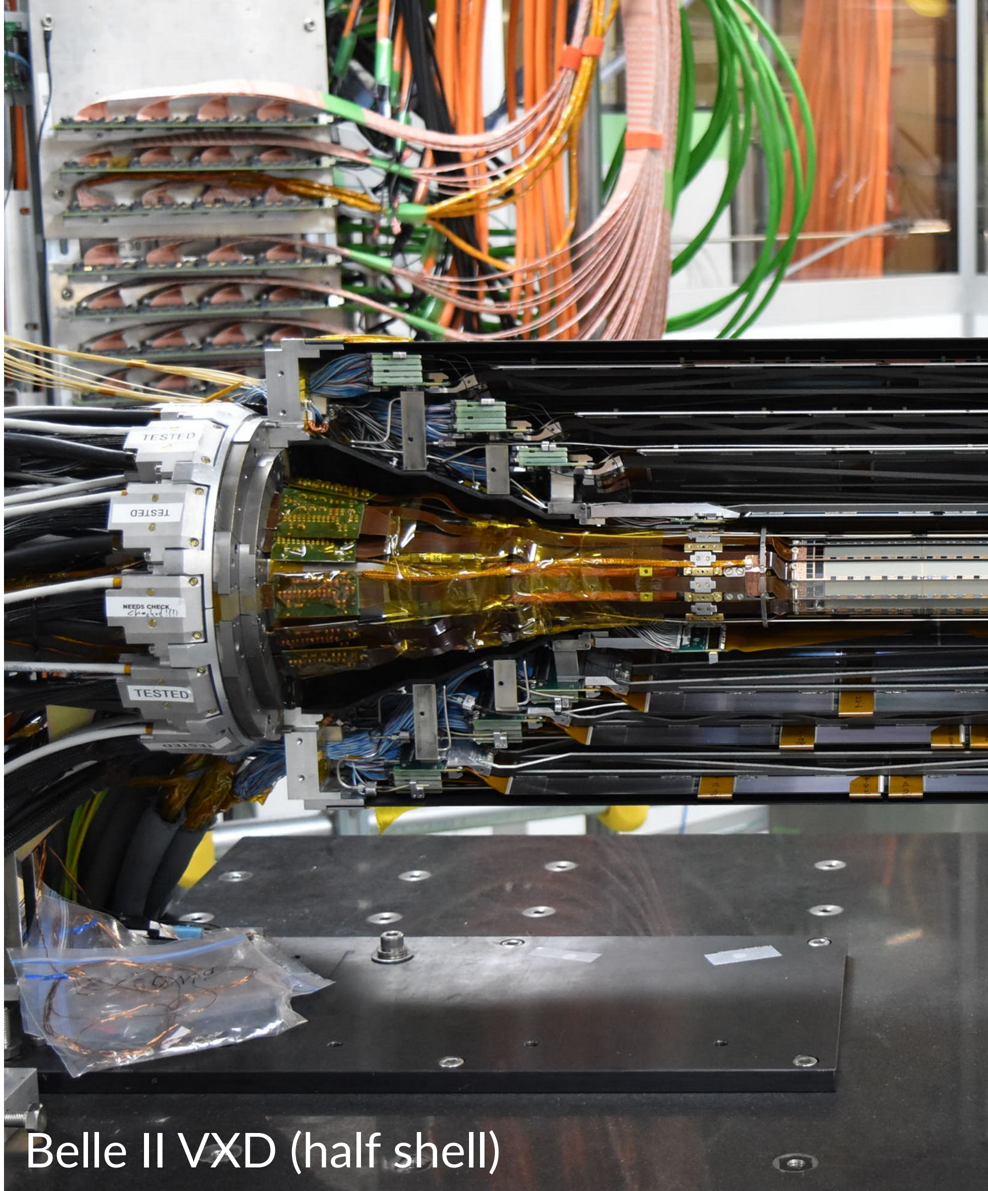
SVD readout system

Front-end ASIC: APV25 chip

- **Radiation hardness** > 100 Mrad
- **Shaping time of 50 ns**
- 128 channel inputs
- Operated in **multi-peak mode at 32 MHz**
  - Collision frequency 256 MHz and **clock not synchronous with collisions**
  - **6 samples** recorded, **3/6 samples in future** to reduce data size
- Physics **events are triggered at maximum 30kHz**



SVD Hit Time

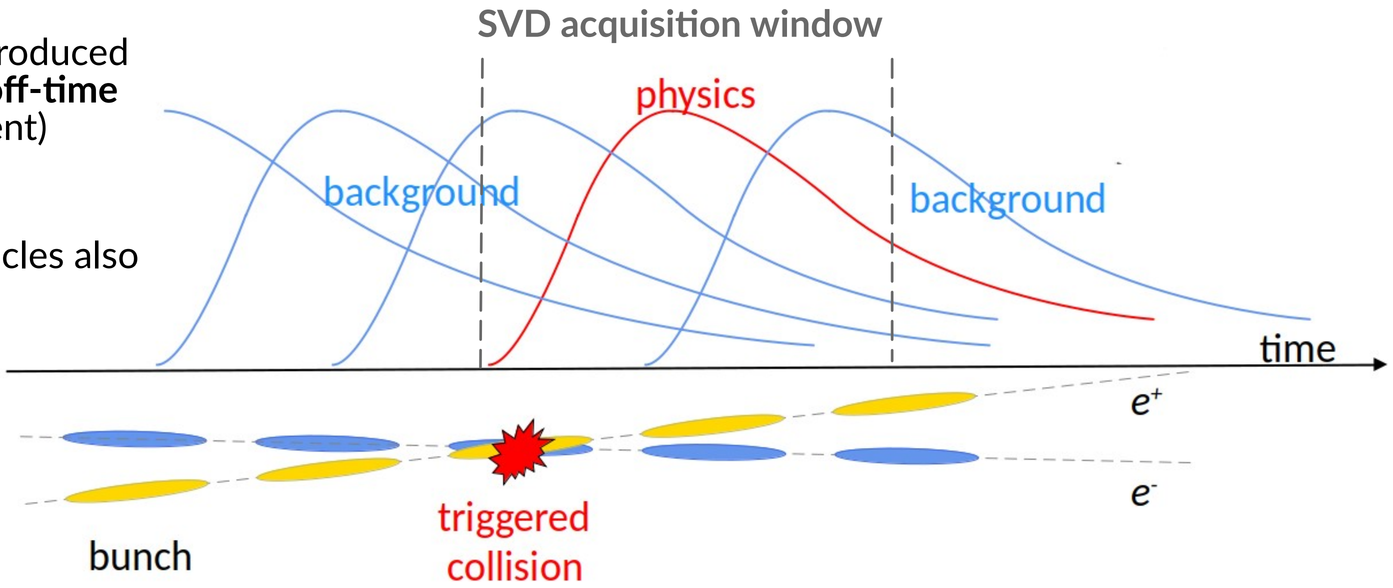


Belle II VXD (half shell)

SVD hit time

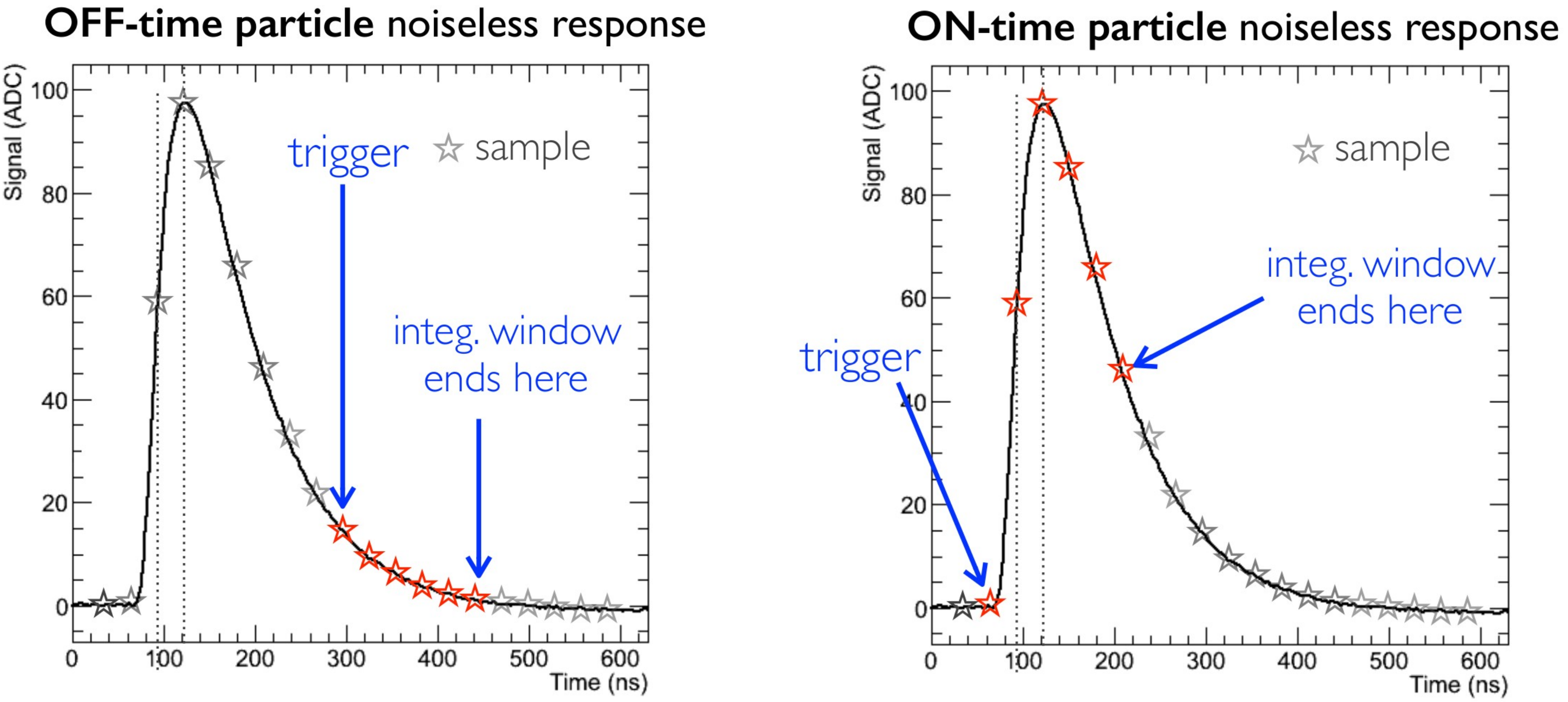
- Precise determination of the **SVD hit time is crucial to significantly reduce the occupancy by rejecting off-time particles**

- Physics **events are triggered at maximum 30kHz**, while the frequency of **bunch crossing is 256 MHz**
  - In each bunch-crossings are produced **beam-background particles (off-time** with respect the triggered event)
  - Single-beam background particles also hitting SVD sensors
  - **The signals of those particles stays over threshold for several bunch crossings**



Off-time and on-time particle signals

- **SVD hit time** determined using the **sampling of the signal response and the information of the trigger arrival**

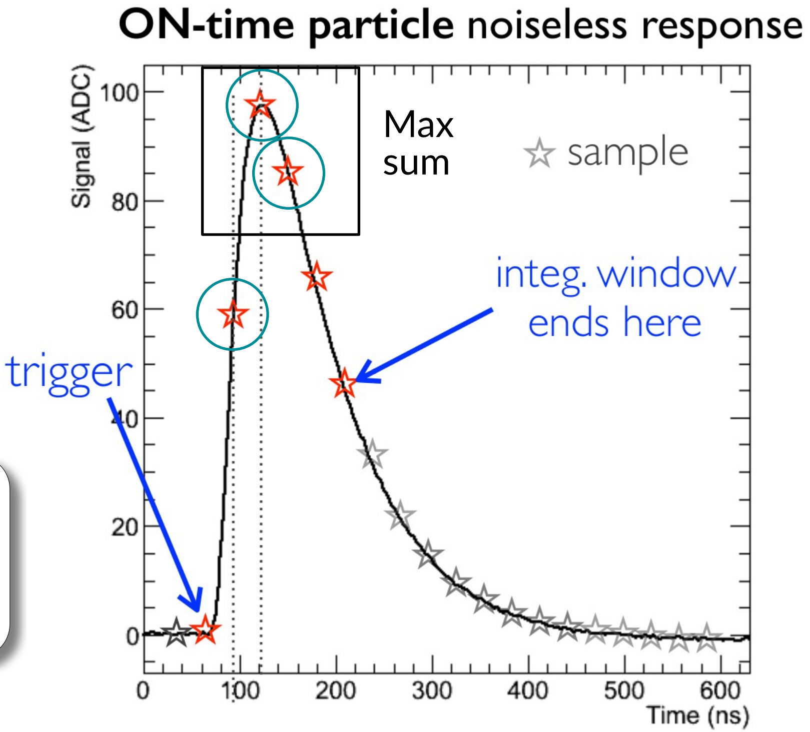


SVD hit time computation

- Default algorithm in reconstruction:
  - **Sum the SVD cluster strips** → a **single strip** where the amplitude of the 6 samples is the sum of the amplitudes of the samples of the strips
  - **Find the best three samples** and take the **weighted average**
    - **Max sum** of samples taken 2-by-2 **+ the sample before**

$$t_{hit} = \frac{\Sigma_n t_n \cdot A_n}{\Sigma_n A_n}$$

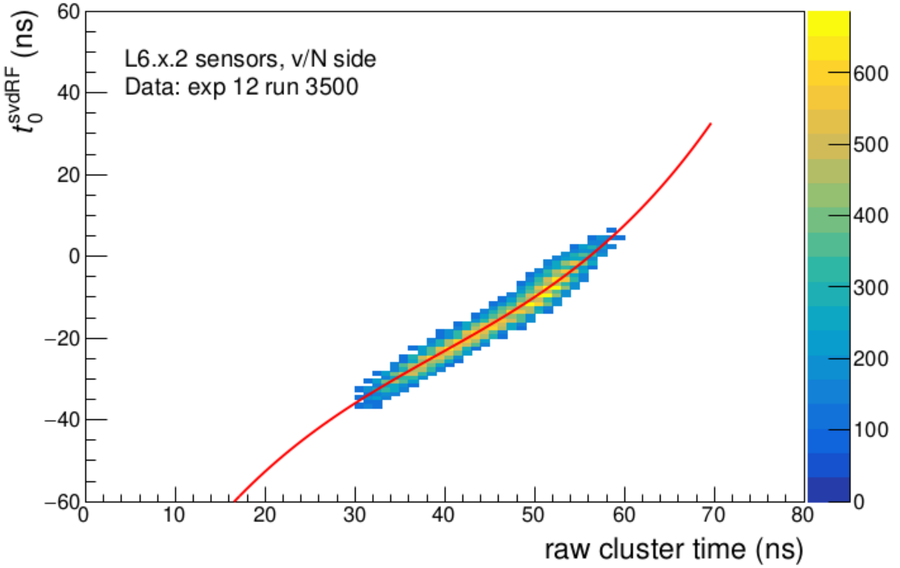
n: sample
A_n: ampltude of the sample
t_n: time of the sample



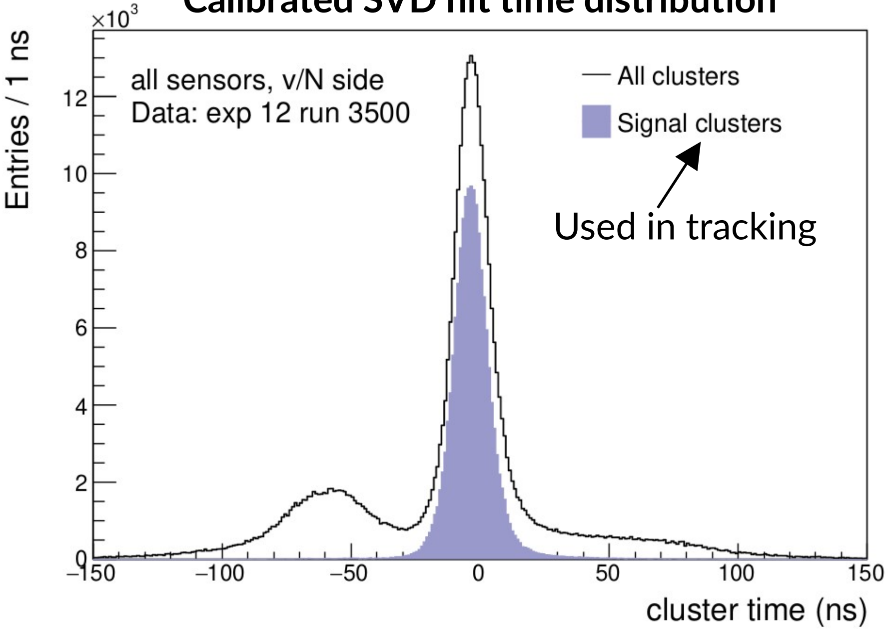
- Estimate the position of the peak in the SVD reference frame (t=0 at first sample)

Hit time calibration

- **Use CDC Event Time to calibrate SVD Time** → from SVD reference frame to trigger reference frame
  - **CDC and SVD** times are **not synchronized** → we exploit the info about **trigger arrival to synchronize them**
  - Exploit the **correlation between CDC and SVD** times to calibrate SVD time → fit with a polynomial function
  - **Performed sensor/side-by-sensor/side**



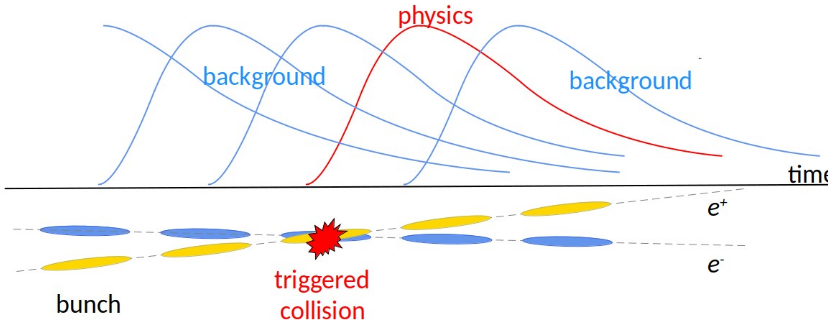
Calibrated SVD hit time distribution

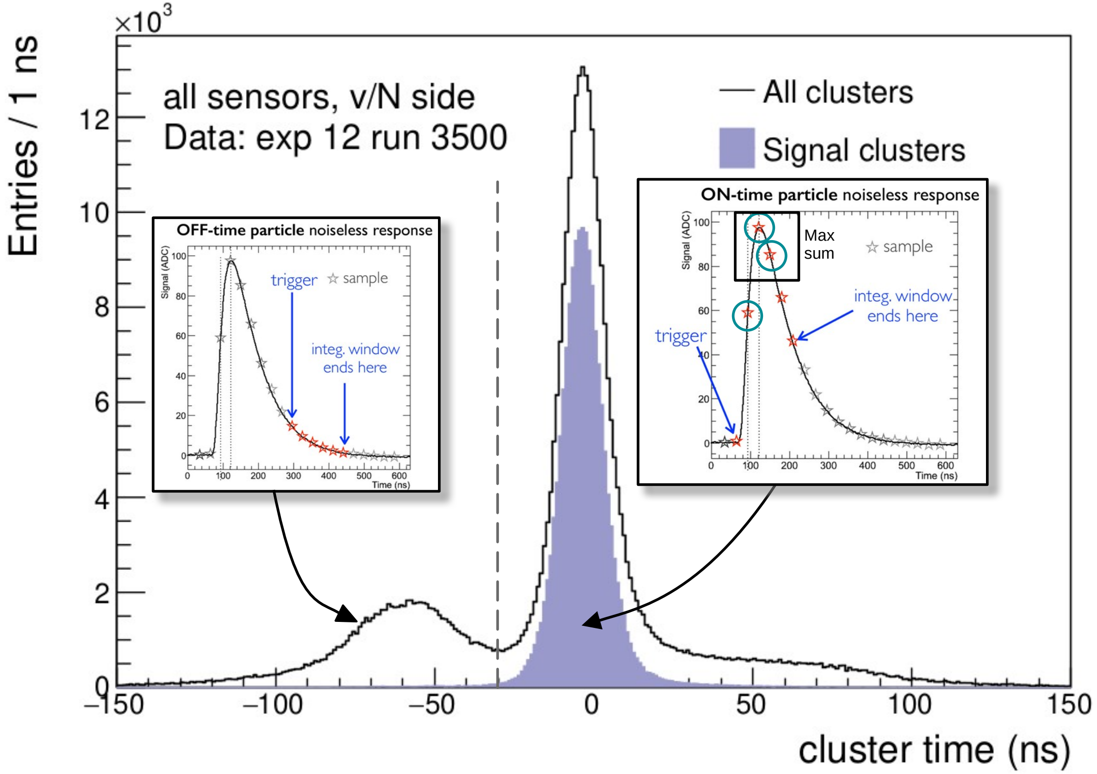


Calibrated SVD time

- **Peak below < 50 ns**: **accumulation of off-time partcles** hitting the sensor **before the beginning of the acquisition window**

- The **rest of the background hits** are more **uniformly** distributed in time
  - Bunch crossing at 256MHz → quasi-continuous machine
  - Single-beam background particles out of collisions

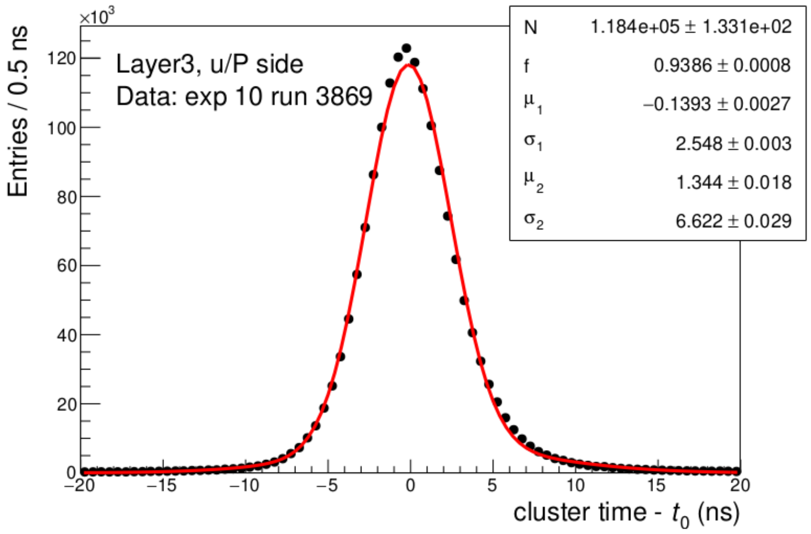




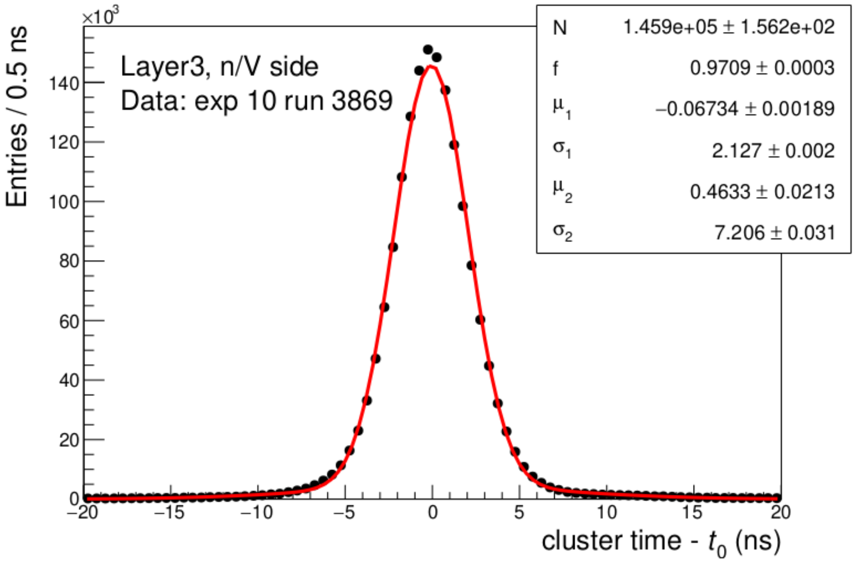
Calibrated SVD time: resolution

- **Resolution is smaller than 3 ns in L3 in both SVD sides** → Can be used to **reject off-time hits**, estimate **Event Time** and **Track Time**
- **Excellent hit time resolution** allows efficient removal of off-time tracks
  - Efficient to **remove 50% off-time hits**, keeping **99% signal efficiency**

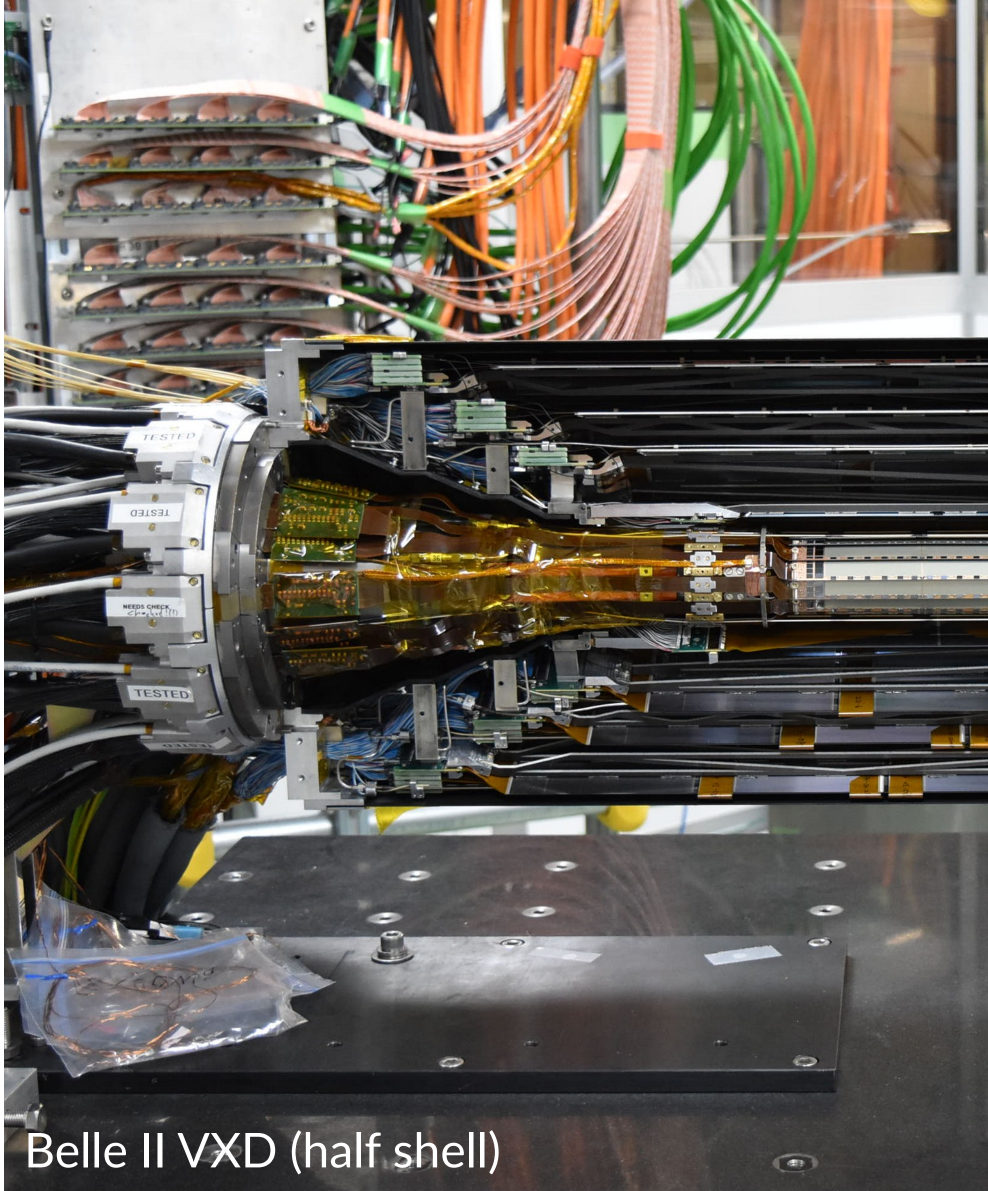
Cluster time – CDC Event Time L3 *u*/P side



Cluster time – CDC Event Time L3 *v*/N side



SVD Hit Time Applications

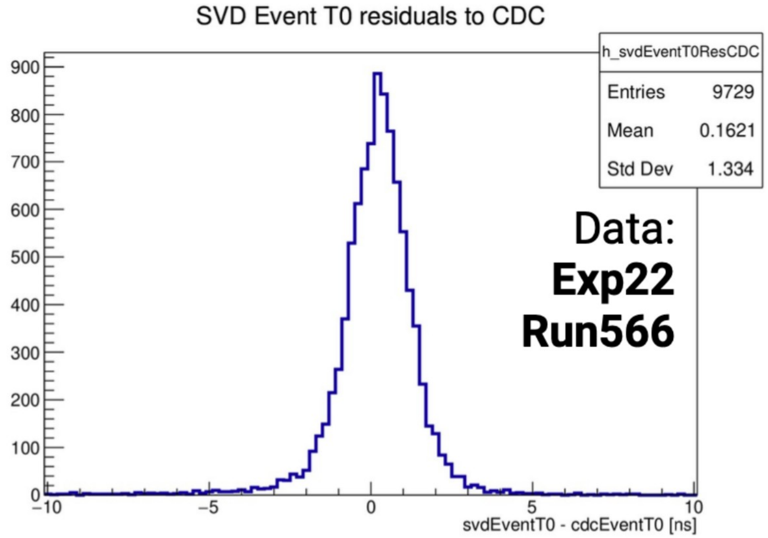


Belle II VXD (half shell)

Event Time with SVD

$$t_0^{\mathrm{SVD}} = \frac{1}{N_{\mathrm{cls}}} \sum_{i=1}^{N_{\mathrm{cls}}} t_i^{\mathrm{cls}}$$

- **Event time (EventT0):** time of the collision w.r.t. to the arrival of the trigger signal
- **EventT0 is used to reduce the impact of beam background in the reconstruction**
  - In a quasi-continuous machine, background hit time distribution is flat, while the signal hit time distribution of peaks around EventT0
  - **Average of cluster times associated to tracks** with p_T > 250 MeV/*c*
- **SVD EventT0 performance is excellent**
  - Similar **resolution o(1ns)** to CDC on **hadronic data**
  - **Higher efficiency than CDC (>98.5%)**, especially in **low-multiplicity events**
  - TOP has a better resolution, but a much lower efficiency



SVD EventT0 **o(1000) times faster** computation time w.r.t. the CDC EventT0

→ **Speed up online reconstruction**

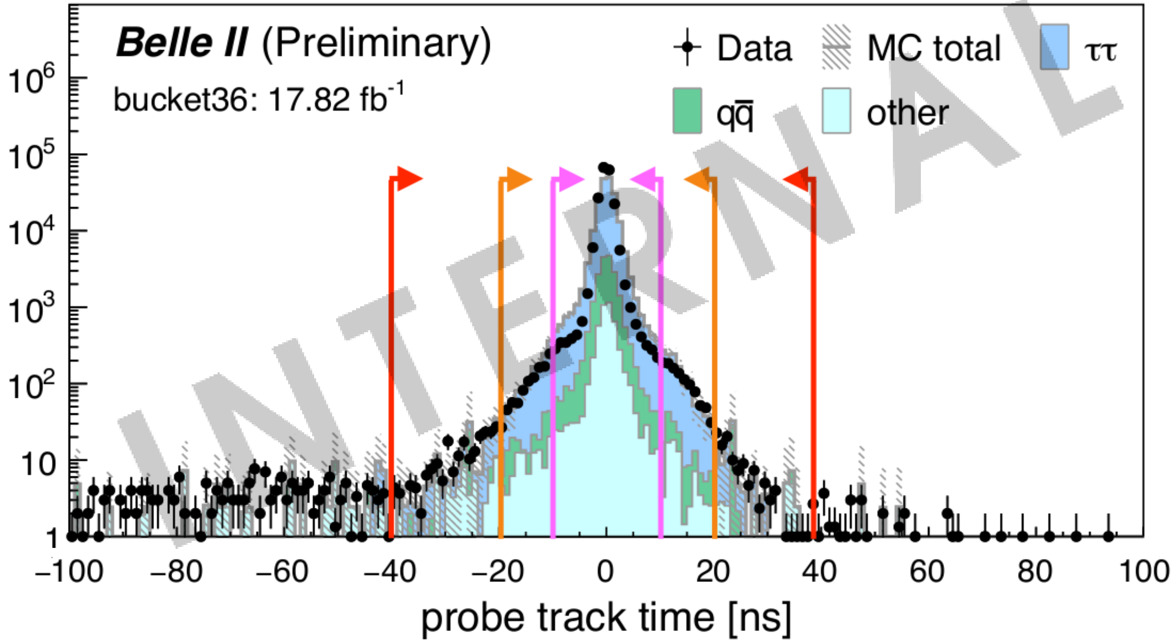
Track time with SVD

Fake rate: tracks reconstructed with hits from beam-induced background or originating from wrong combinations of hits

- **Average of the time of SVD hits associated to tracks referred to EventT0**

$$t_{\text{track}} = \frac{1}{N_{\text{cls}}} \sum_{i=1}^{N_{\text{cls}}} t_i^{\text{cls}} - t_0^{\text{SVD}}$$

- Can be used for **background rejection**.
  From preliminary studies, **cuttng at 20 ns wi**
  - **Almost no impact on tracking efficiency in data**
  - **Fake rate by a factor 1.5 on high-background data**



- **Provide track time to analysts** to reject background

Hit time selections

- In **high-background conditions**, **tracking will suffer due to high fake rate**

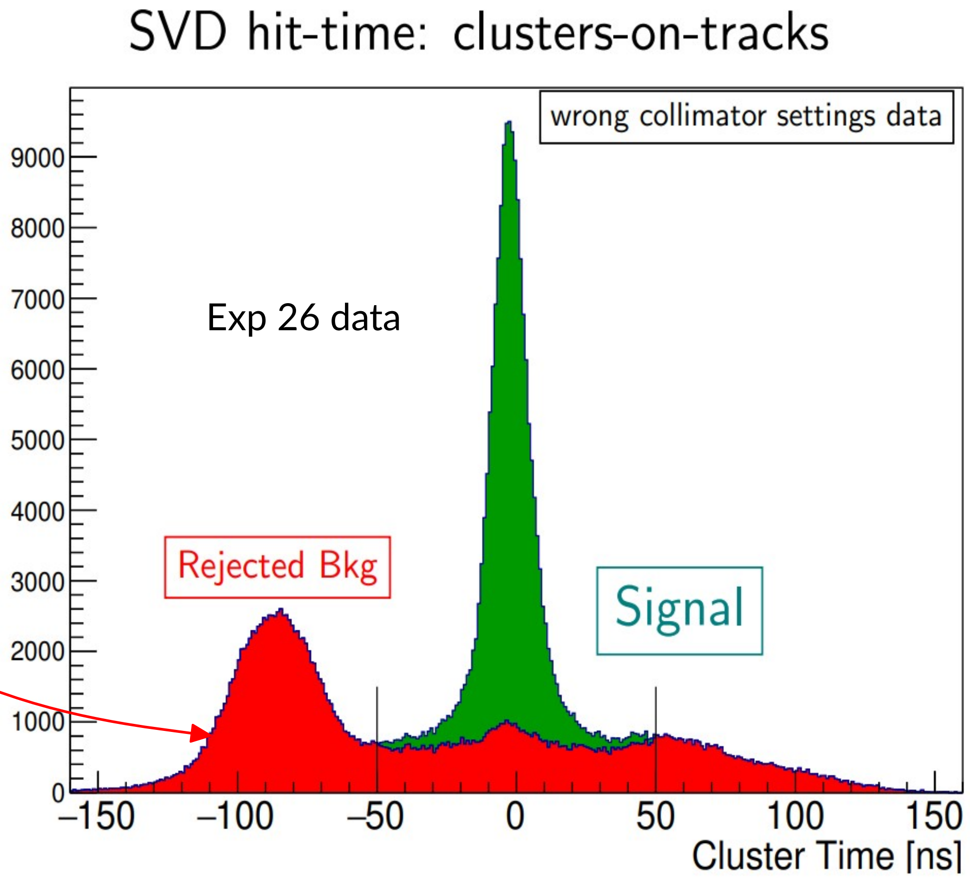
  → **Reject off-time tracks is crucial**

SVD Time Cuts

$|t| < 50$ ns
$|t_U - t_V| < 20$ ns

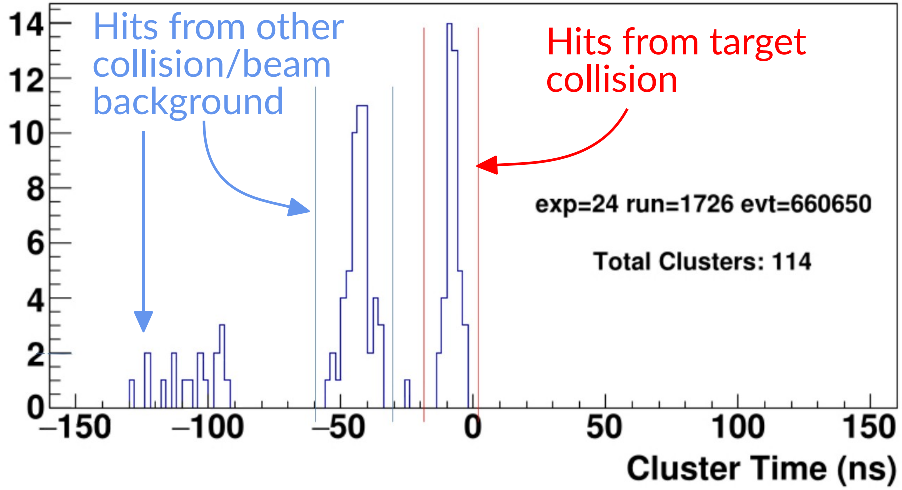
- At nominal luminosity background, **without any SVD-time based selections** the **SVD occupancy limit for tracking is 3%**

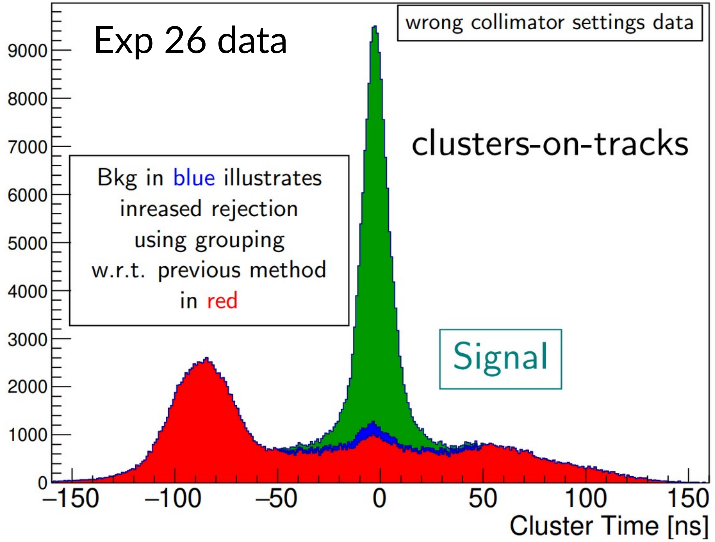
- Applying the **SVD-time based selection** the **SVD occupacy limit for tracking is 4.7%**



SVD hit-time grouping

- Further decrease of fake rate will come from SVD cluster-time grouping and selection based on “track time”
- Grouping
  - Exploit SVD hit-time to implement a event-by-event classification of groups of hits (clusters)
  - Clusters belonging to tracks coming from the same collision belong to the same group
  - The other ones are probably from tracks from different collisions/beam background
- **Selection on track-time to remove off-time tracks**
  - Further reduce the fake rate by a factor 1.5 on high-background data (from preliminary studies)
- **The limit of 5% occupancy can be further increased to ~6%**





Summary and conclusions

SVD is the Silicon Strip Detector of the VXD

- One of the **tracking system** detectors (PXD, SVD, CDC)
- Several functions: standalone **tracking** and **particle identification of low p_T tracks**, **extrapolate tracks to PXD**
- It can do more than what was designed for
  → **excellent performance of SVD Hit Time**
  - **SVD Event Time estimation** → similar resolution (1 ns), higher efficiency, much faster execution time w.r.t. CDC
  - **Track Time** → interesting tool to reduce fake rate
  - **Hit time selections** → reduce fake rate significantly

Belle II SVD paper: JINST, 17, 2022

Belle II VXD (half shell)