The Belle II Silicon Vertex Detector (SVD)

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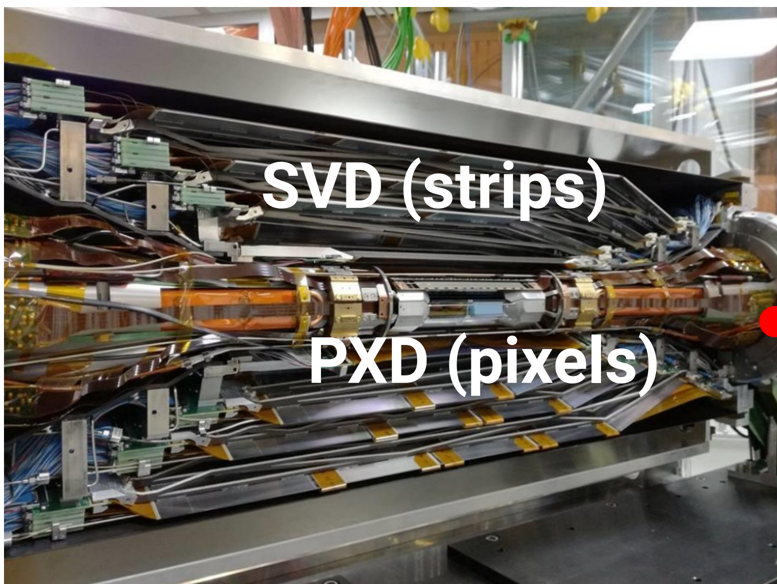
Outline

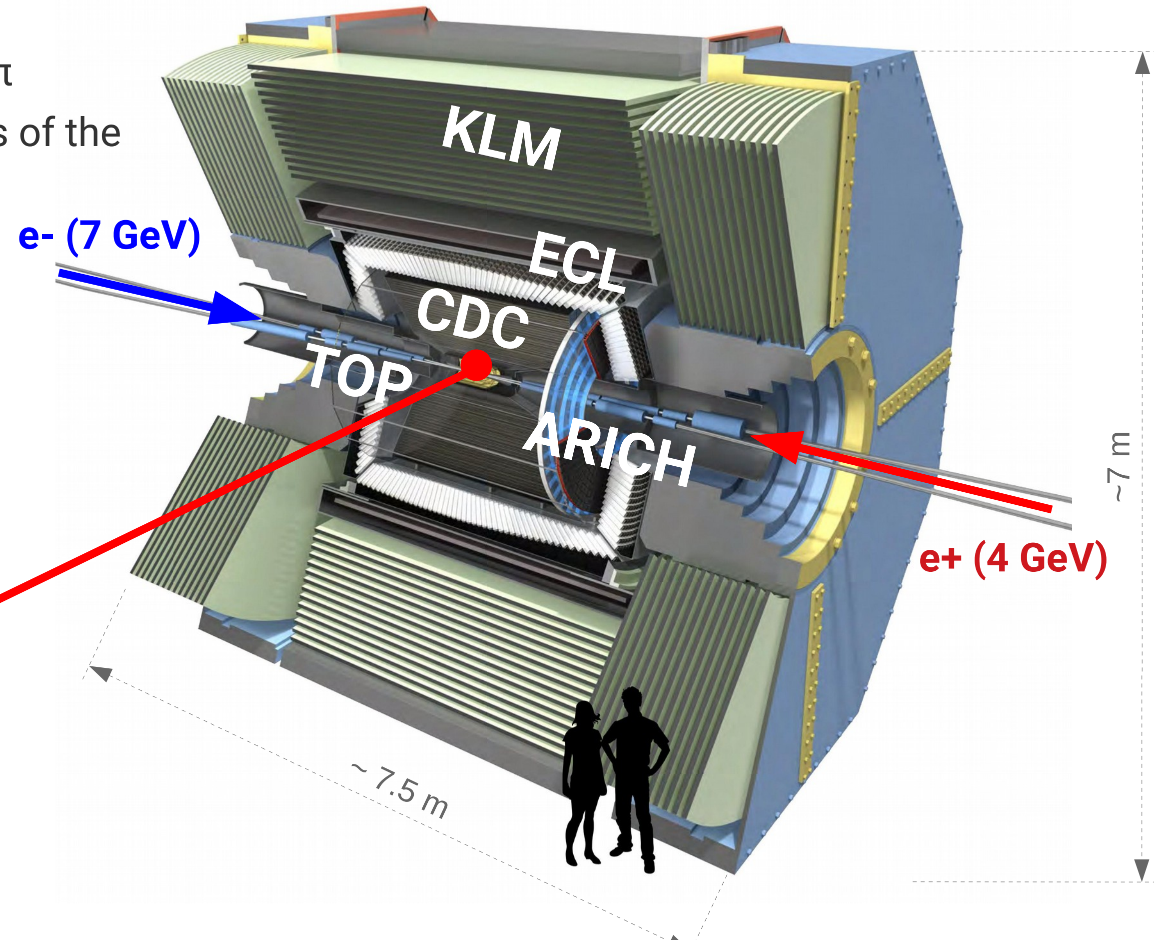
- Introduction to the Belle II vertex detector
- The structure of Belle II SVD
- SVD reconstruction and performance on data
- Summary

The Belle II detector

- The Belle II detector is a magnetic spectometer surrounding the interaction point (IP) of the SuperKEKB collider
- Its angular coverage exceeds the 90% of 4π
- High hermeticity → reconstruct all products of the e^+e^- interaction

VerteX Detector (VXD)



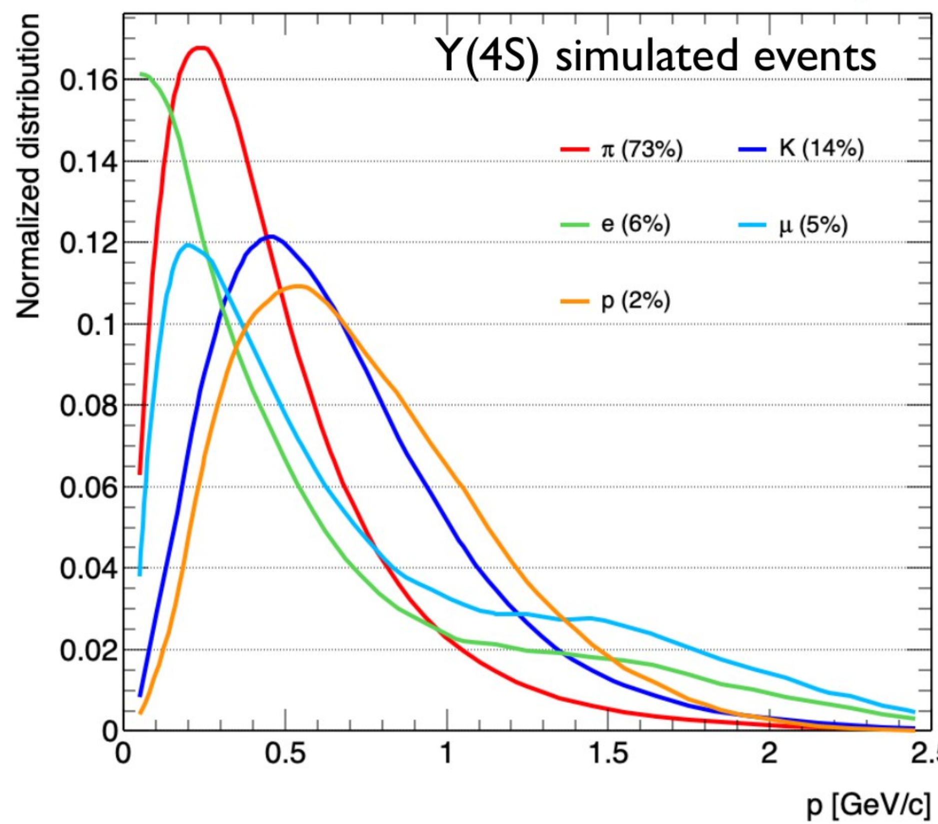


- The VXD provides the precise measurement of the primary and secondary vertices of short-lived particles

Typical Υ(4S) event

- SuperKEKB → B-factory that works at the center of mass energy corresponding to the Υ(4S) resonance (10.58 GeV)
  - collision of 7 GeV e^- and 4 GeV e^+ → $\beta\gamma = 0.28$
- Average multiplicities in a Υ(4S) event:
  - 11 charged tracks
  - 5 neutral pions
  - 1 neutral kaon
- Few tracks to be reconstructed but with small momentum → they are significantly affected by multiple scattering

- Soft charged tracks momentum spectrum



Background hits vs Signal hits expected in a silicon detector

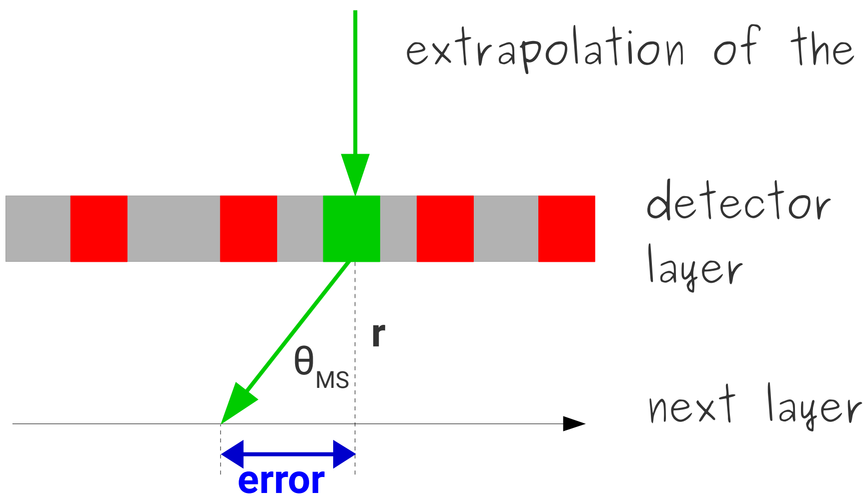
- The nominal luminosity of SuperKEKB is $8 \cdot 10^{35}$ cm^{-2} s^{-1}
- Signal hits on the VXD are overwhelmed by beam-background hits
  - at nominal background:
    - 11 signal hits, because of the average multiplicity of a typical Υ(4S) event
    - many background hits → hits of particles not produced at triggered Υ(4S) events

Belle II full luminosity	Layer 1 of pixels		Layer 3 of strips (closer to IP)	
	Number of hits	Occupancy	Number of hits	Occupancy
Υ(4S)	11	$5 \cdot 10^{-6}$	11	0.2%
beam bkg	50000	3%	3200	3%

→ Occupancy: the averaged fraction of strips (pixels) fired per event

Precision on the vertex position determination

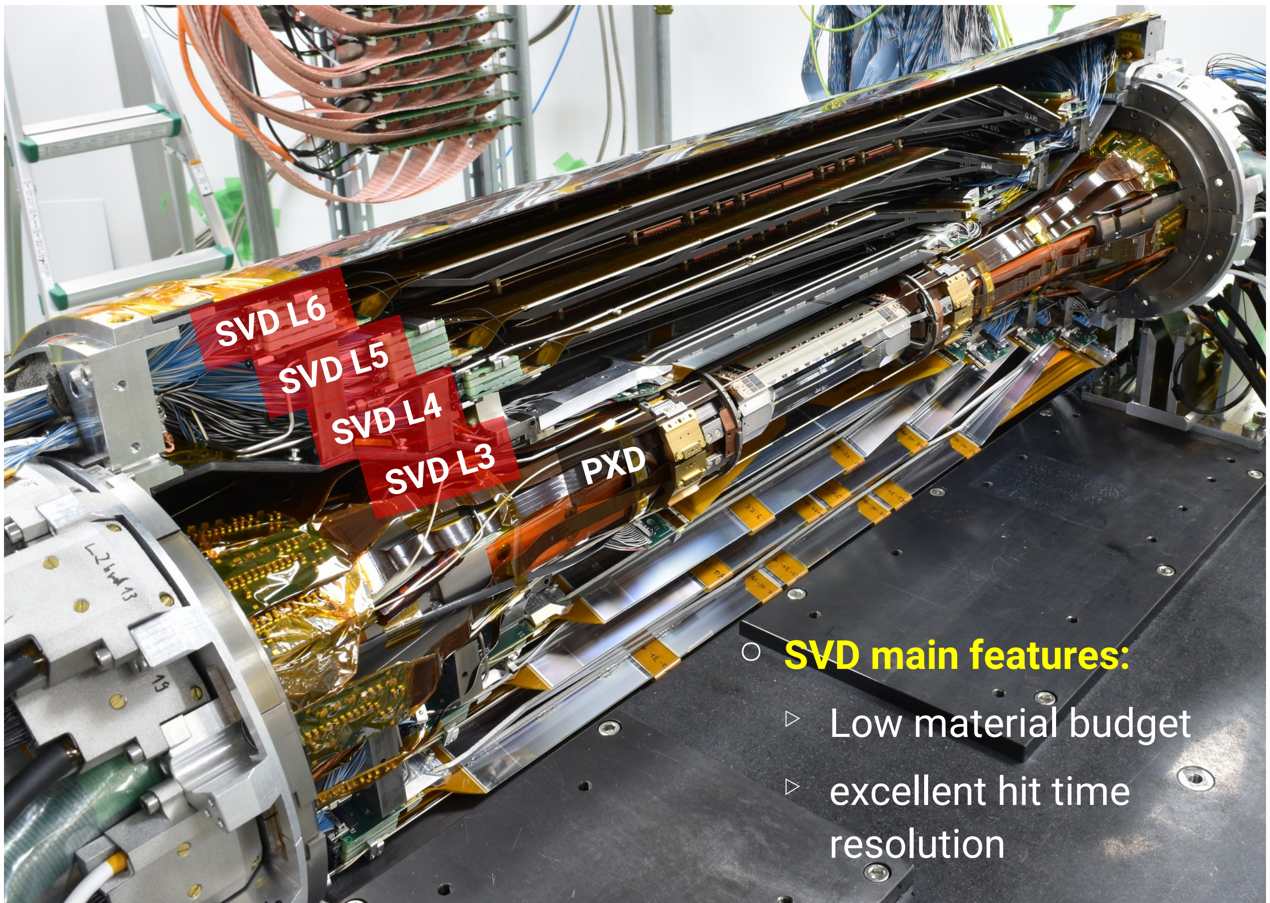
- We need at least two tracks to reconstruct the vertex
- In order to determine correctly the vertex position, the impact parameters of the tracks must be measured very well
- The most important factors affecting the precision of the impact parameters determination are:
  - Multiple scattering ($r \cdot \theta_{MS}$) → a detector with low material budget and closer to where we want to extrapolate needed
  - probability to associate the correct hit to the track → low occupancy preferred



- Higher occupancy → higher possibility to associate the wrong hit
- Higher r and/or θ_{MS}
  - higher error on the extrapolation of the track

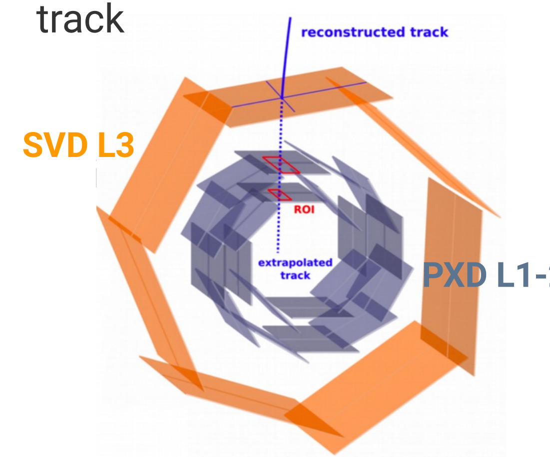
The Belle II Vertex Detector

- The Belle II VXD consists of two different silicon detectors, complementary to each other:
  - PiXel Detector (PXD): 2-layers of DEPFET pixel sensors, innermost layer @ 1.4 cm from IP (see previous talk!)
  - Silicon Vertex Detector (SVD): 4-layers of double-sided silicon strip detectors (see next slides)

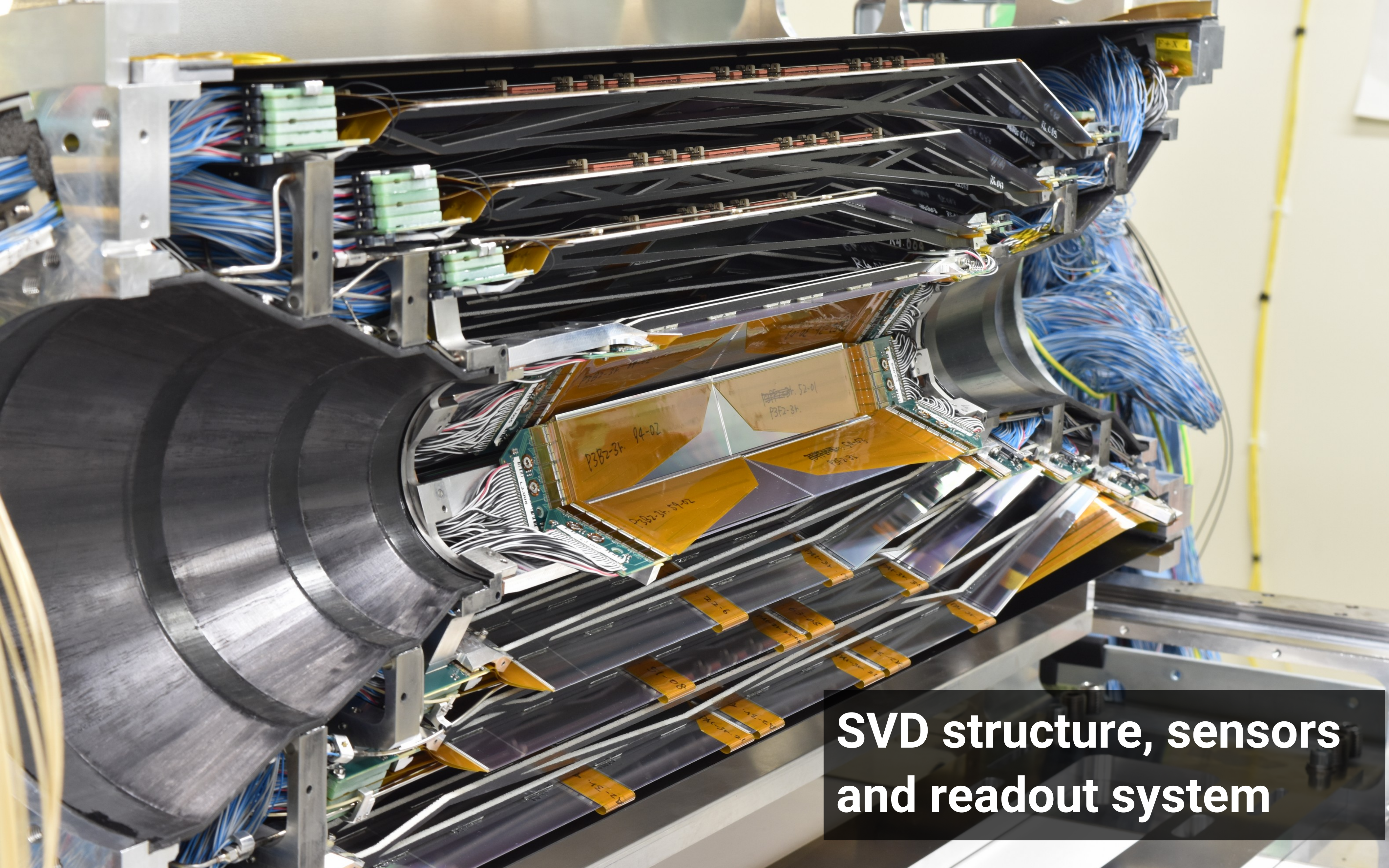


- **SVD main features:**
  - Low material budget
  - excellent hit time resolution

- **SVD:**
  - Standalone reconstruction (and PID) of low-p_T tracks
  - Extrapolates tracks to PXD → find the correct pixel to attach to the track

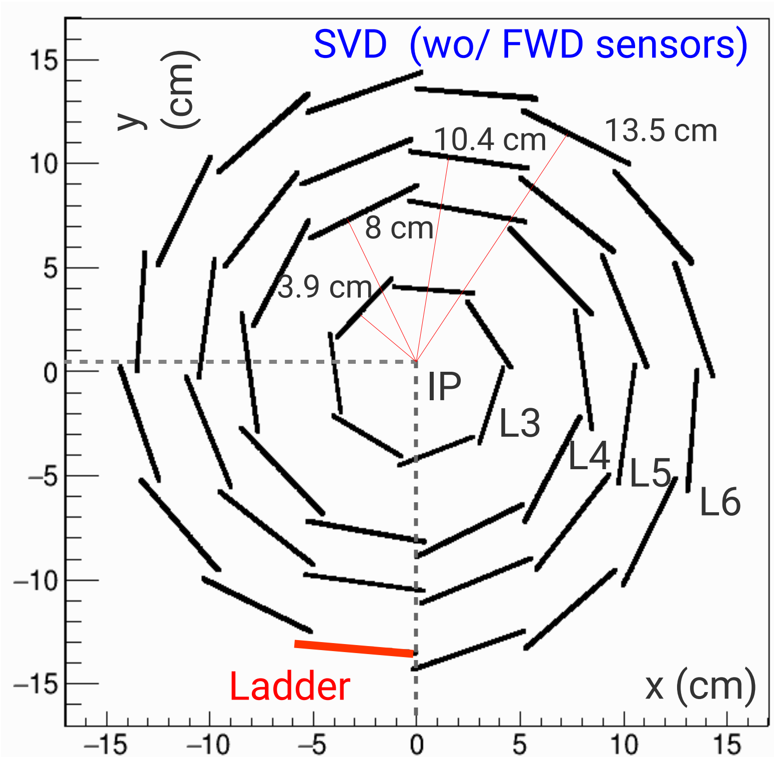


  - PXD data reduction to cope with storage and bandwidth limits

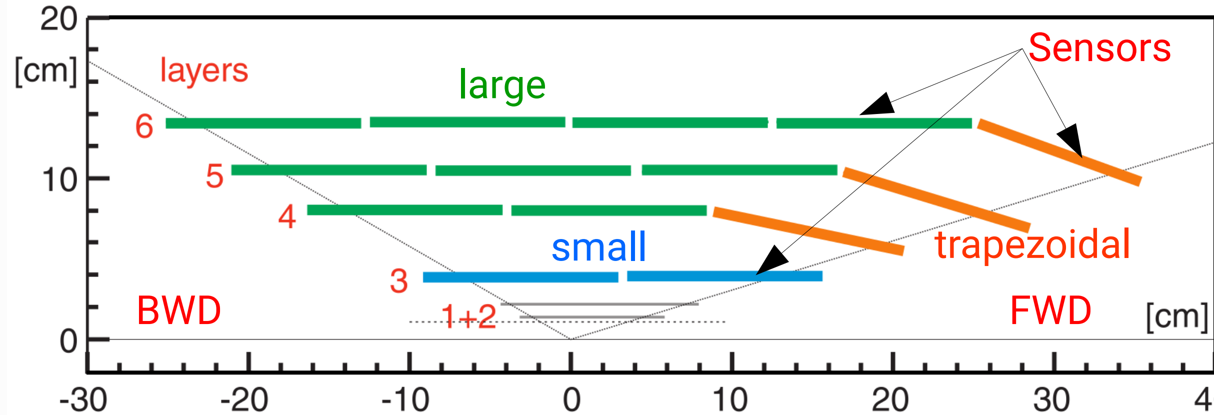

SVD structure, sensors and readout system

Structure of the Belle II SVD

- SVD section in the (xy) plane



- SVD section in the (rz) plane
- Angular acceptance: 17° - 150° → it covers the full tracking volume

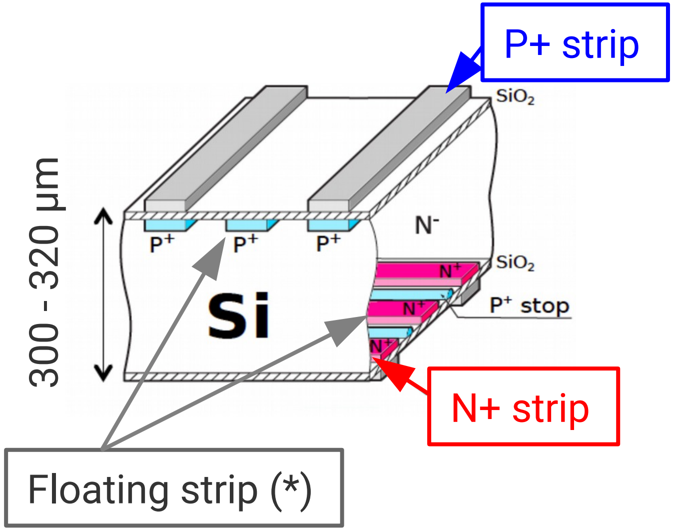


layer	number of ladders / layer	number of sensors / ladder	θ_{FWD}
3	7	2	0°
4	10	3	11.9°
5	12	4	17.2°
6	16	5	21.1°

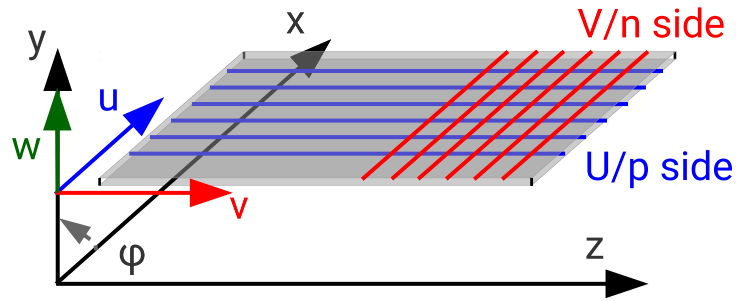
- FWD sensors slanted (L4, 5, 6):
  - optimize track incident angle
  - reduce material budget in the FWD region

SVD strip silicon sensors

- Double-Sided Strip Detector (DSSD)



- 2D information about position



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

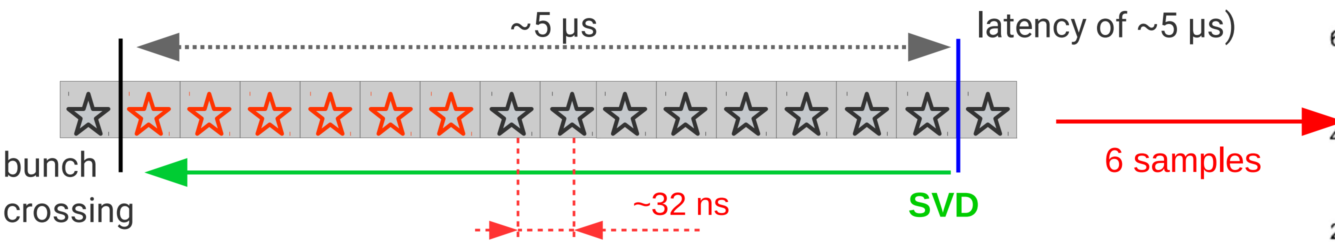
- SVD operates applying an operation voltage of 100 V on each sensor
- Signal is generated by the drift of the charges in the sensor

(*) Floating strips are not readout

layer	type	readout strip (p/r-φ)	readout strip (n/z)	strip pitch (p/r-φ)	strip pitch (n/z)	number of sensors	sizes (mm)	thickness	total number of strips
4,5,6	large	768	512	75 μm	240 μm	120	125, 60	320 μm	224000
4,5,6 FWD	trapeizoidal	768	512	50-75 μm	240 μm	38	126, 61, 41	300 μm	
3	small	768	768	50 μm	160 μm	14	125, 40	320 μm	

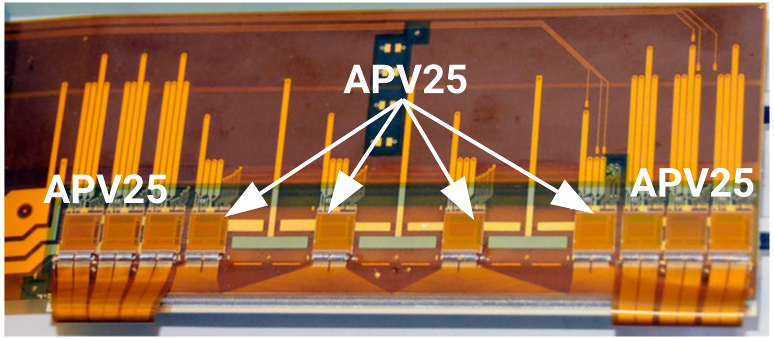
SVD front-end ASIC readout system: APV25

- Electric signals from sensors are processed by readout chips (APV25) on the sensors (inside the tracking volume):
  - high radiation hardness (designed for CMS)
  - shaping time of 50 ns → low occupancy
  - thinned to 100 μm → low material budget
  - clock frequency: ~32 MHz, equipped with a 192 deep analog pipeline (buffer of ~5 μs)

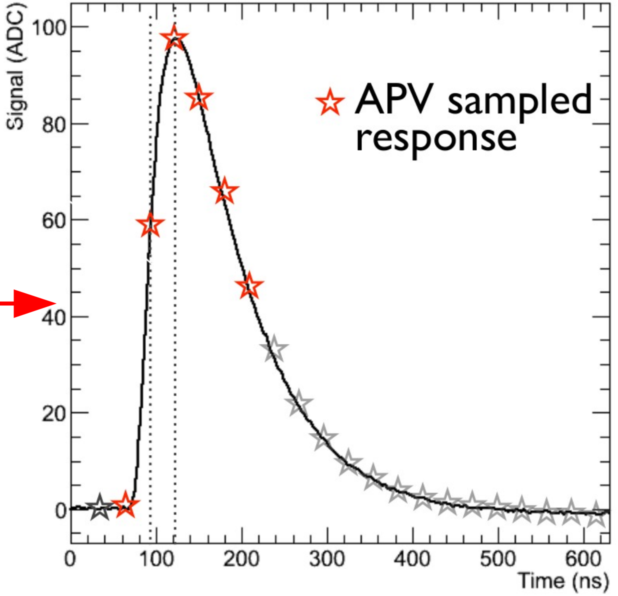


  - each APV25 reads 128 strips

Readout front-end on a sensor

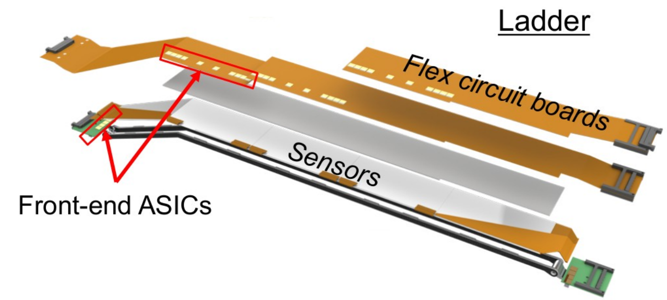


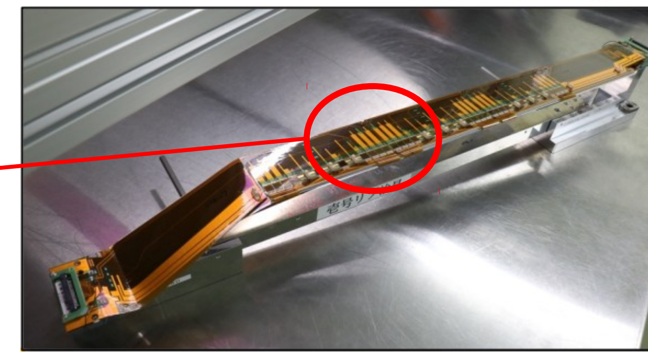
APV25 sampling output

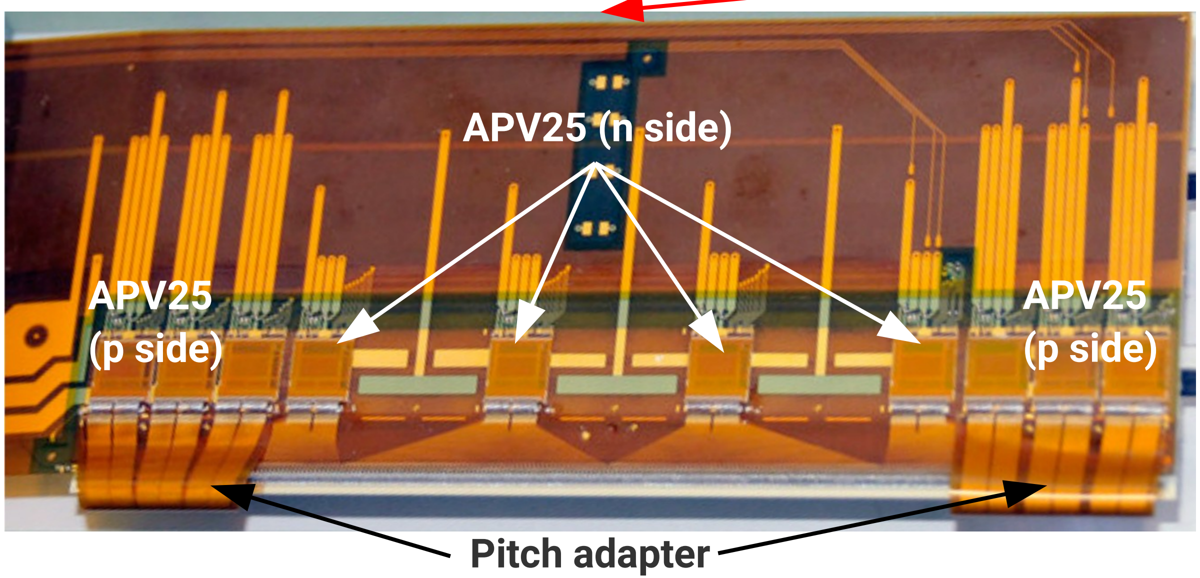


SVD front-end ASIC readout system: Origami

- SVD will operate at a high-luminosity machine ($8 \cdot 10^{35}$ cm^{-2} s^{-1})
- Need short strips and short pitch adapters:
  - reduce the occupancy
  - reduce the noise
- The Origami *chip-on-sensor* → flex circuits that allows to minimise the analog path lenght
- Signals are readout on the sensors







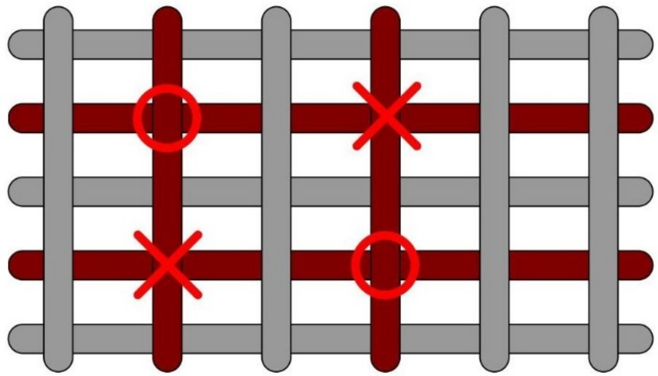
- Pitch adapter folded and connected to the strips on the other side of the sensor
- APV25 are only on one side and they can be cooled down with only one CO2 cooling pipe
  - reduce the material budget

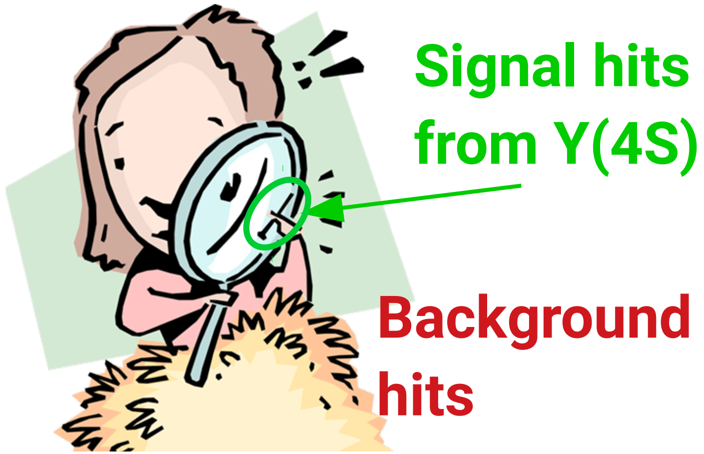
SVD background hits

- Considering a particle that crosses one sensor and fires only one strip for each side → one signal hit (combination of the strips on the two sides) on that sensor
- Considering two particles that cross the same sensor and each of them fires only one strip per side → two signal hits and two *ghost hits*
- Beam background at very high luminosity → many hits on each sensor

Belle II full luminosity	SVD layer 3 only	
	Number of hits	Occupancy
Y(4S)	11	0.2%
beam bkg	3200	3%

- Considering all possible combinations, these numbers explode!
- Additional background from electronic noise (1% of the strips)





SVD data reconstruction and performance on data

SVD performances overview

SVD people after a good work!

- Successful operations without major problems up to now:
  - all sensors are working fine
  - very few strips are defective and disabled (< 1%)
  - all of 1748 readout chips are working since October (one of them was disabled during Spring Run)
- Performances of the detector are excellent:
  - cluster energy and signal-to-noise-ratio (SNR) distributions look as expected
  - the hit efficiency of all sensors is very high
  - the SVD hit time measurement shows very promising results → the hit time resolution after calibration is excellent
- Beam background studies:
  - the measured occupancy from beam-background is ~0.3% during data taking
  - limit for good tracking performance is ~3%

SVD reconstruction software

- Raw data from APV25 → Low-level and position information provided by the APV25 (SNR ≥ 3)
- Unpack and write information in a simpler format → For each strip readout:
  - number of layer, ladder, sensor and side
  - amplitude of each of the six samples provided by the APV25
- Reconstruction of strips →
  - charge collected by the strip
  - hit time
  - preserves information about position
- Clusterizer → Merges adjacent strips applying some criteria:
  - cluster position
  - cluster time

  Cluster:
  one strip SNR: ≥ 5 (seed)
  adjacent strips: SNR ≥ 3
- Hit reconstruction → 2D information used by the tracking combining clusters on the two sides
- Tracking

The cluster postion can be corrected using the information of the estimated incident angle of the track on the sensor → improve quality of tracks

Future improvement

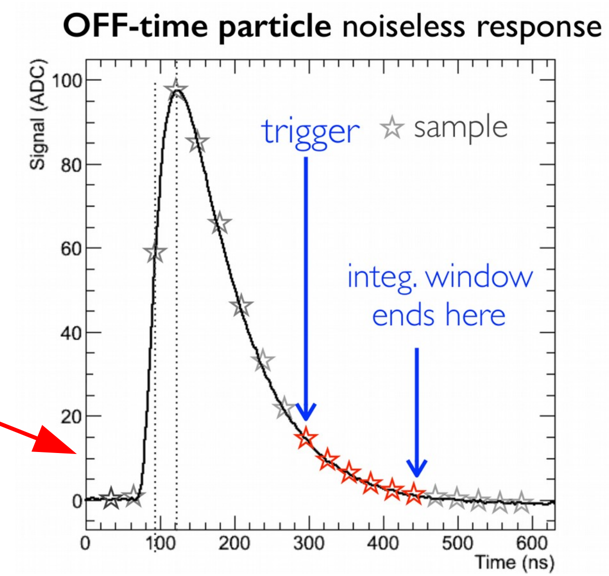
link to confluence page:
SVD Offline Software

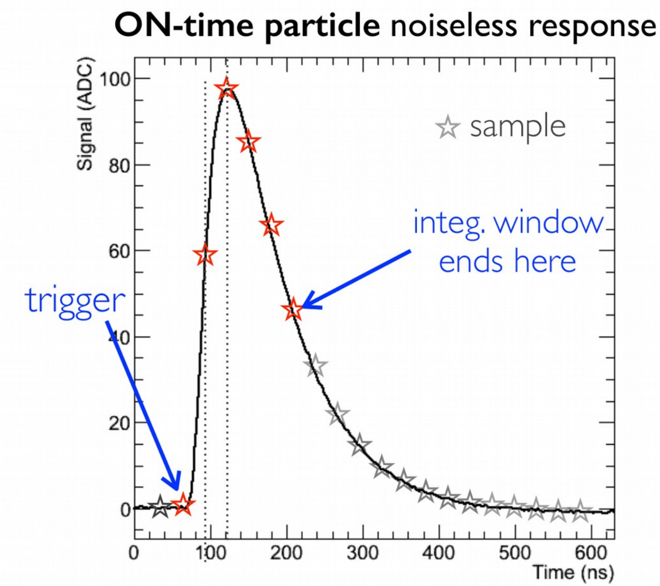
SVD hit time

- Precise determination of the SVD hit time is crucial to significantly reduce the occupancy by rejecting off-time particles
- SVD will be sensitive to off-time particles produced up to 100 bunch crossing before the triggered event
- Physics events are triggered at 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). The signals of those particles stays over threshold for several bunch crossings
- The SVD hit time is determined using the sampling of the signal response and the information of the trigger arrival

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

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

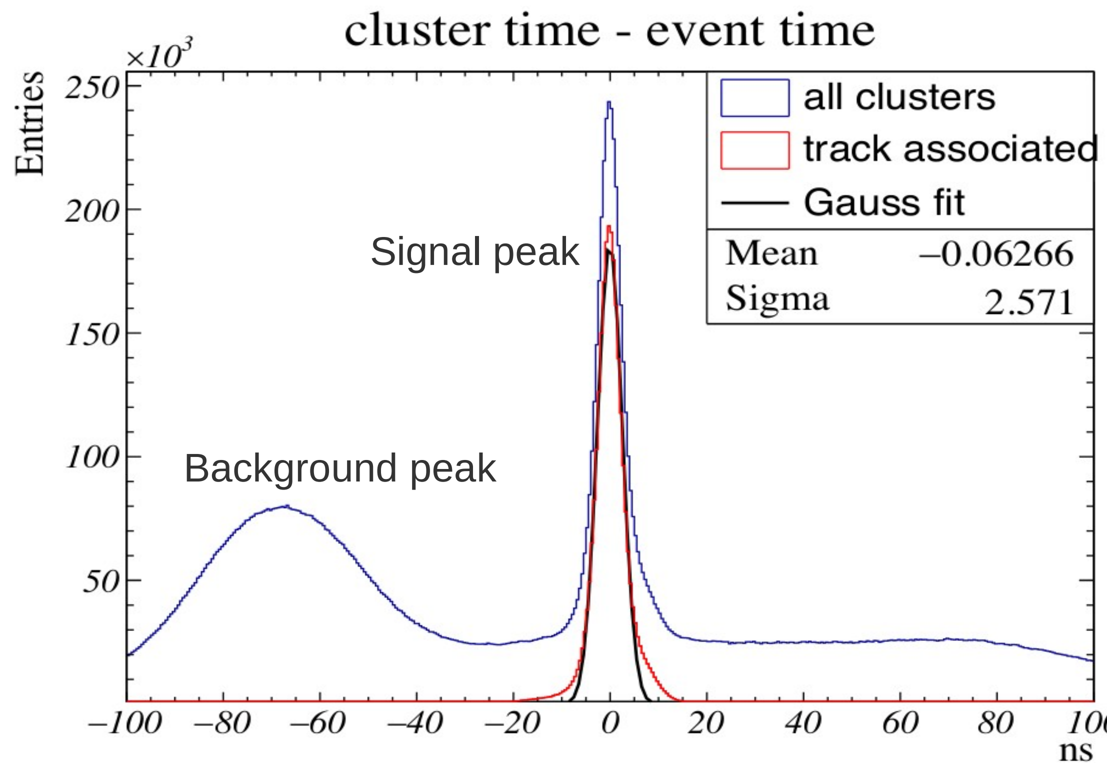




SVD hit time resolution

- Calibrated using the estimation of the event time (t_0) provided by the Central Drift Chamber (CDC)
- The SVD hit time resolution is ~ 3 – 4 ns
- Expected rejection of ~30% of clusters per sensor side. This corresponds to reject ~50% of hits per sensor
  - time information allows to reduce the occupancy → very important in the innermost layer of SVD
  - improvement in tracking, but currently time is not used in tracking on data and run dependent MC!

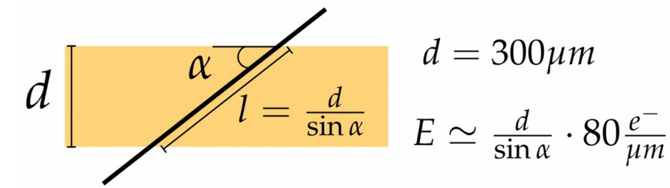
- (cluster time – event time) for Bhabha events from a subset of the 2019 Spring Run data sample



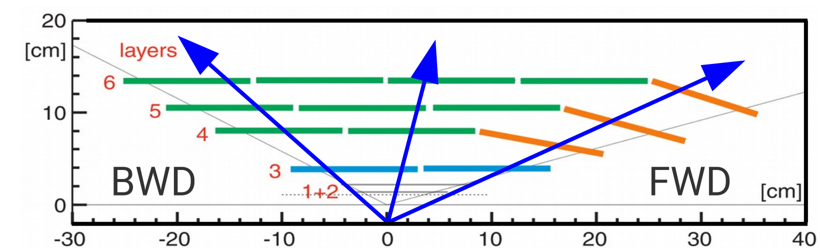
- cluster time is obtained as weighted mean of the time of the strips where the weight is the charge of the strips

SVD cluster energy

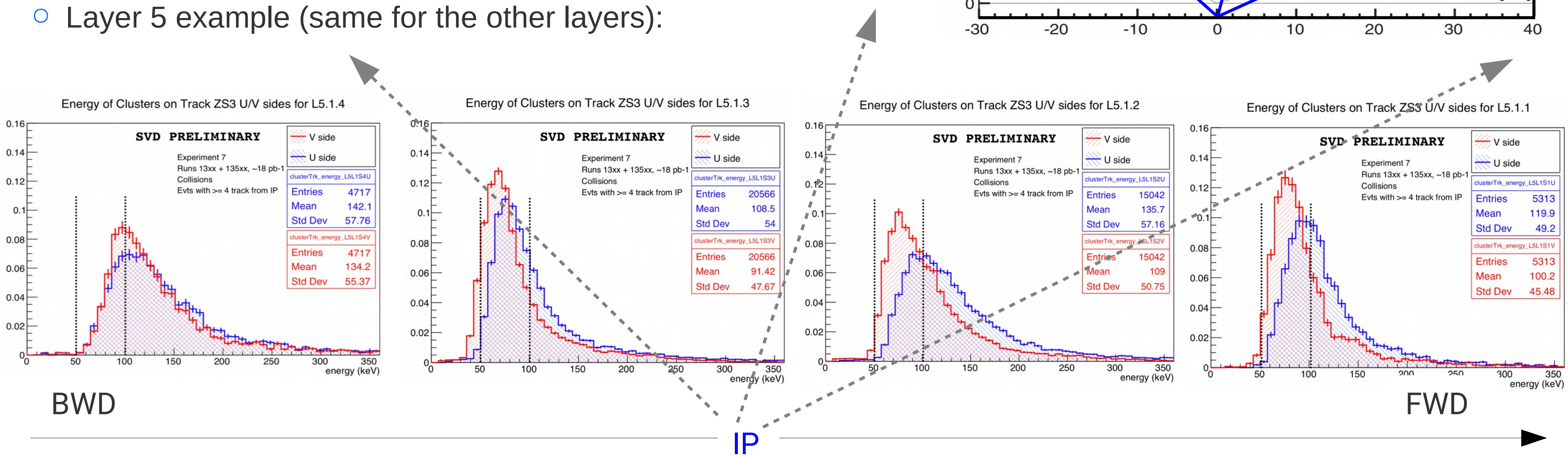
- The cluster energy depends on the track incident angle 90° - α on the sensor



- With tracks from the IP, cluster energies are higher in the forward and backward sensors because of larger incident angle, as expected



- Layer 5 example (same for the other layers):



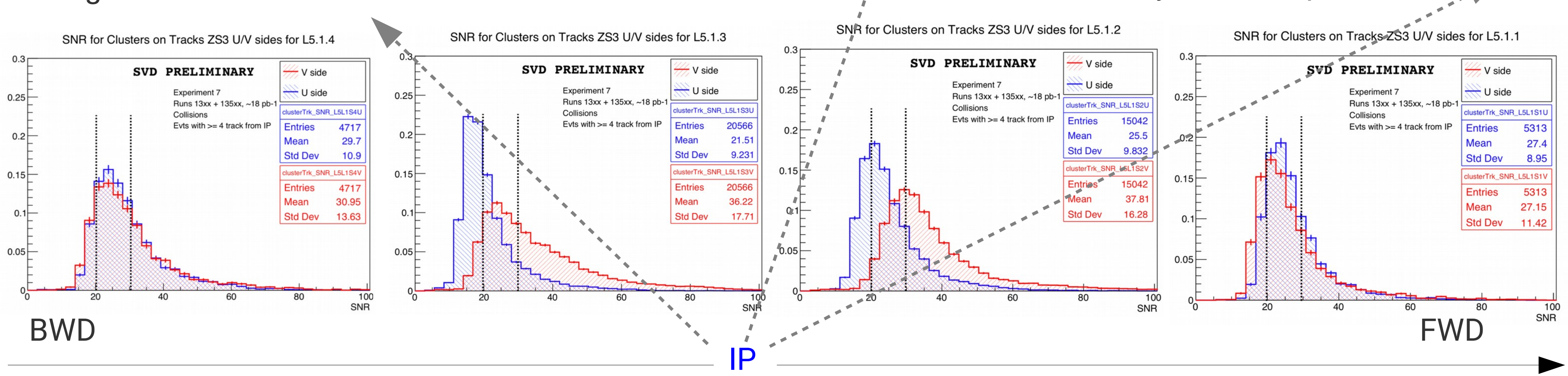
- Cluster energy is similar for **U/p** and **V/n** sides; 20% charge loss in the **V/n** side due to capacitance effects between strips

SVD cluster SNR

- The signal-to-noise-ratio is used for example in the Clusterizer (SNR ≥ 5 for the seed strip and ≥ 3 for the adjacent strips)
- SNR depends on the collected charge and on the strip noise
  - noise of the **U/p** side > noise of the **V/n** side → dominant difference
  - signal of the **U/p** side > signal of the **V/n** side, and it also depends on the track incident angle, i.e. on the position of the sensor
- Expectations:
  - higher SNR on **V/n** side with respect to **U/p** side of the same sensor
  - higher SNR on FWD and BWD sensors

$$SNR_{cls} = \frac{\sum_{strips} S_i}{\sqrt{\sum_{strips} N_i^2}}$$

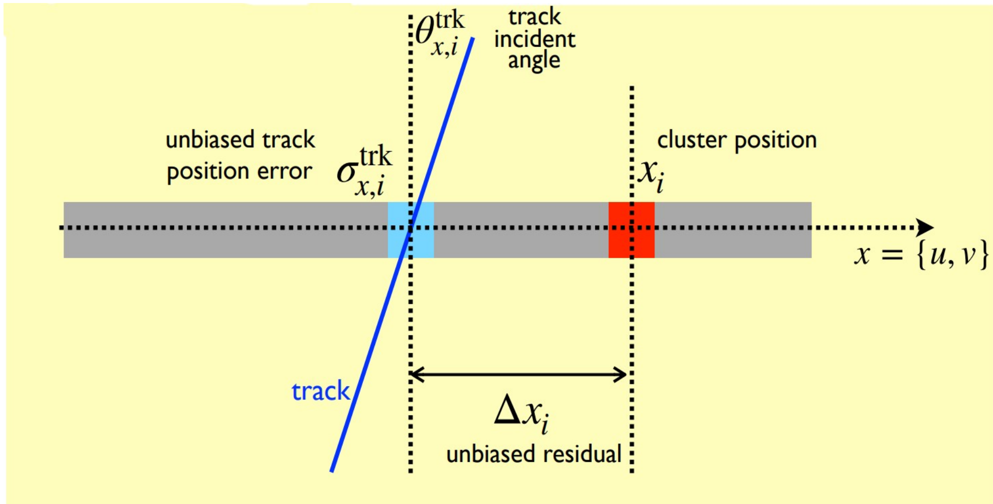
Layer 5 example

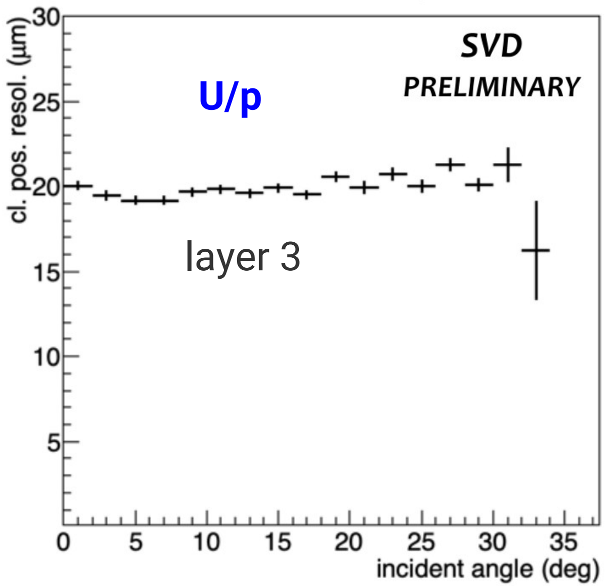


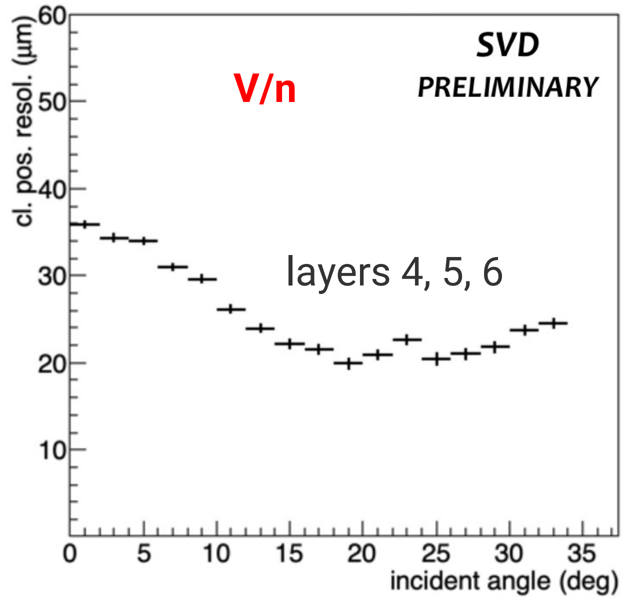
SVD cluster position resolution

- Cluster position resolution is estimated using $\mu^+\mu^-$ events from Spring run data
- Resolution is estimated from the residual of N selected cluster position with respect to the unbiased track (reconstructed removing the selected cluster) position
- The track position error is subtracted under squared root from the residual

$$\sigma_x = \sqrt{\frac{1}{N}\Sigma_i^N (\Delta x_i)^2 - \left(\sigma_{x,i}^{trk}\right)^2}$$







- Preliminary cluster position resolution is ~20 – 30 μm vs the track incident angle
- Worse than optimistic MC prediction, ~10 μm. SVD simulation needs to be tuned!

SVD hit efficiency

- Hit efficiency → number of clusters within ±0.5 mm from the intercept divided by the number of intercepts of the extrapolated tracks on the sensor under study

- Hit efficiency > 99% for most of the sensors and it is stable over time

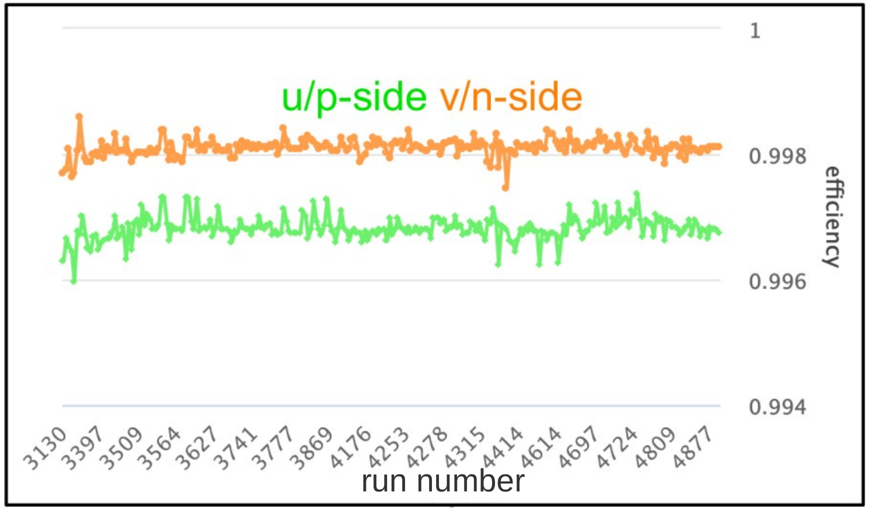
- Averaged hit efficiency of one layer is obtained summing the number of clusters found nearby the intercepts divided by the sum of intercepts overall the sensors

$$\epsilon_{layer} = \frac{\Sigma_{sensors} \ nCls_i}{\Sigma_{sensors} \ nInter_i}$$

- Averaged hit efficiency measured during a data taking run of 3 hours in December 2019, for all layers and sides

Layer	U/p side	V/n side
3	99.72%	99.79%
4	99.71%	99.76%
5	99.73%	99.88%
6	99.50%	99.81%

- Averaged hit efficiency measured in November 2019, it is stable for all the month



Summary

- SVD is a 4-layer silicon strip detector and, together with PXD, makes up the Belle II vertex detector
  - low material budget (~0.7% X_0) and hit time resolution (~3 ns)
- SVD is the detector that “connects” PXD with the central drift chamber (CDC) → it is crucial for Belle II tracking and its rich physics program
  - it provides standalone tracking (and PID) of low p_T tracks
  - it guarantees the finding of the correct pixels to attach to the track → PXD data reduction
- SVD response to particles is excellent and it is ready for the tracking and physics challenges:
  - the detector is stable and the hit efficiency > 99% for most of the sensors
  - cluster SNR and energy distributions as expected
- Improvements of the analysis tools used to study the performances is ongoing and the tuning of the SVD simulation is needed → **Much interesting work to do and help is always welcome!**

Thank you

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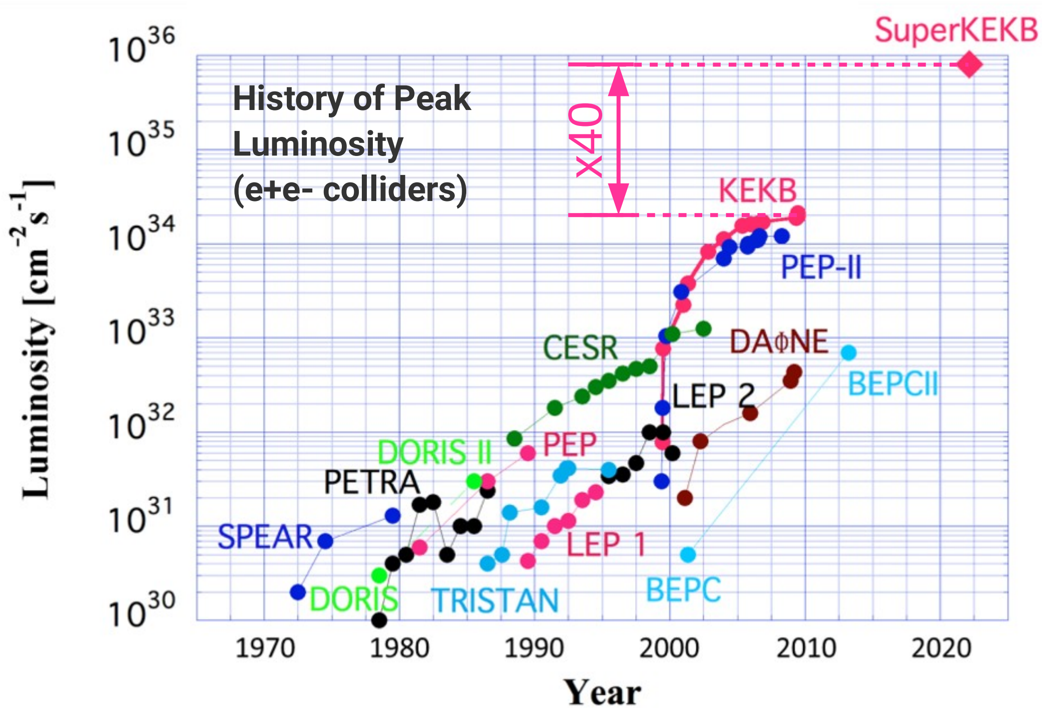
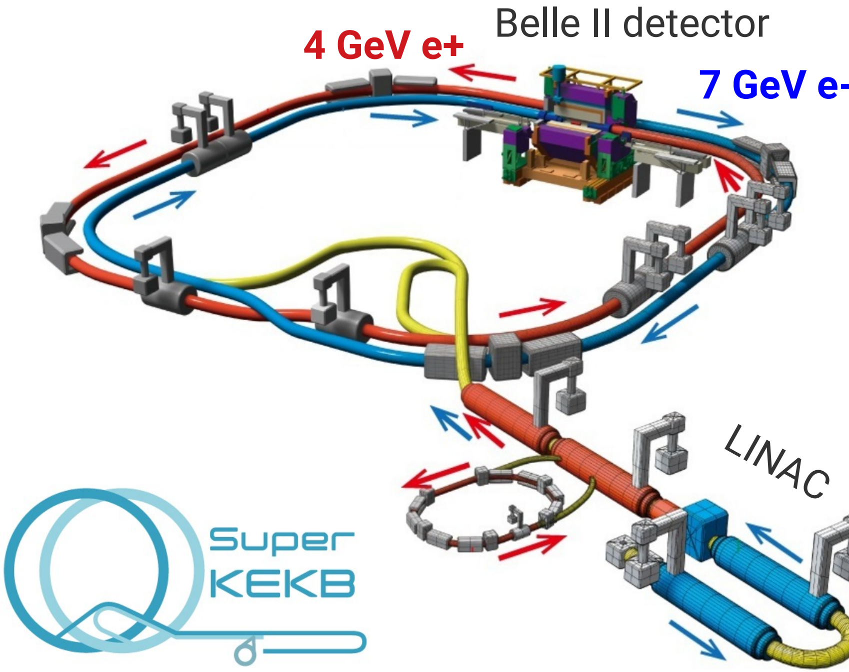
The Belle II experiment at SuperKEKB

The B-factory SuperKEKB (KEK, Japan)

- Asymmetric e+ (4 GeV) e- (7 GeV) collider
- CM energy is set at the Y(4S) resonance (10.58 GeV)
- Target luminosity is $8.0 \cdot 10^{35}$ cm^{-2} s^{-1}
- Target integrated luminosity is 50 ab^{-1} (in 10 years)





The Belle II experiment

- Explores flavor physics at intensity frontier
- Search for new physics
- Physics data taking with the full Belle II detector has started on March 2019

SVD reconstruction software: DataObjects and Modules

- RawSVD (MC: Geant4 output → SVDTrueHits)
  - Unpacker (MC: SVDDigitizer)
- SVDShaperDigits
  - SVDCoGTimeEstimator
- SVDRecoDigits
  - SVDSimpleClusterizer
- SVDClusters
  - SVDSpacePointerCreator
- SVDSpacePoints
- Tracking

Low-level and position information provided by the APV25 (SNR ≥ 3)

For each strip readout:
- number of layer, ladder, sensor and side
- amplitude of each of the six samples provided by the APV25

- charge collected by the strip
- hit time
- preserves information about position

Merges adjacent strips applying some criteria:
- cluster position
- cluster time

2D information used by the tracking combining clusters on the two sides

- Left column: DataObjects
- Right column: Modules