Operational Experience with the Belle II Silicon-strip Vertex Detector

Gagan Mohanty
(on behalf of Belle II SVD group)

International meeting on “Tracking detectors for particle colliders - present and future”

Thursday Oct 28, 2021, 8:55 AM → 5:45 PM Europe/London

Virtual

Aashaq Shah (University of London (GB)) , Adrian Bevan (Queen Mary University of London (GB))

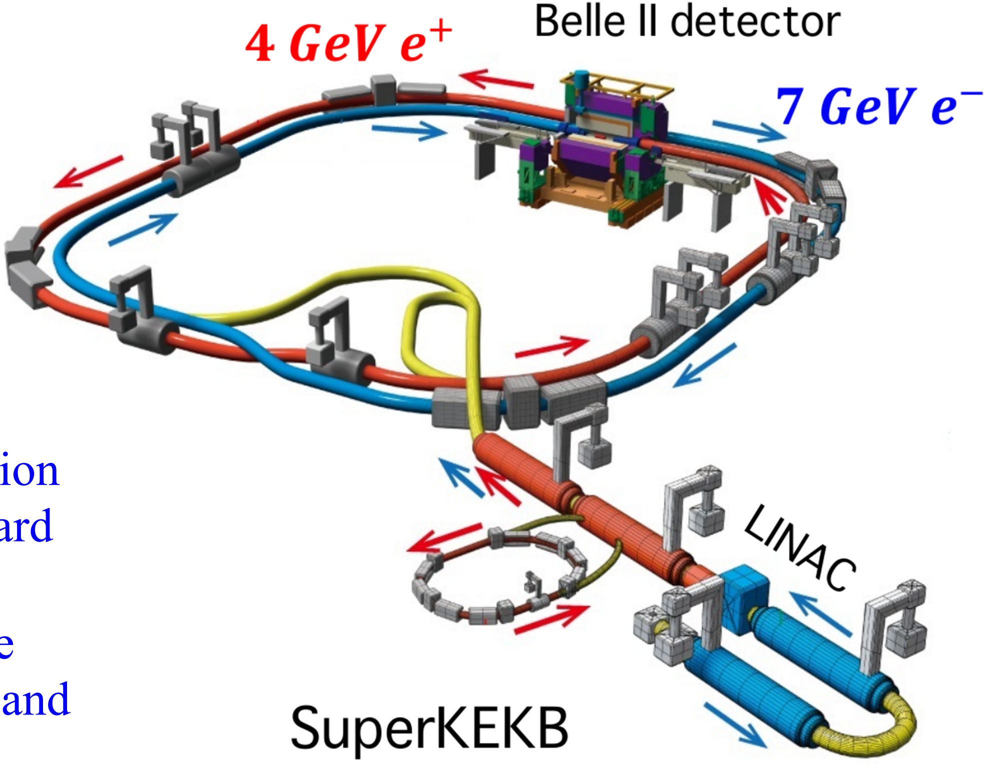
Outline of the talk

- ❑ Enter SuperKEKB and Belle II
- ❑ Silicon-strip vertex detector (SVD) highlights
- ❑ Operational experience
- ❑ Performance
  - ➢ Cluster position resolution
  - ➢ Hit-time resolution
  - ➢ Charged particle identification
- ❑ Beam background and radiation effects
- ❑ Summary and outlook

SuperKEKB and Belle II

- ❑ Second-generation flavor factory
  - ➢ Asymmetric e^+e^- collisions at $\Upsilon(4S)$ resonance ⇒ 10.58 GeV
  - ➢ Target $\mathcal{L}_{\mathrm{int}}$: 50 ab^{-1} and $\mathcal{L}_{\mathrm{peak}}$: $60\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (30× KEKB)
  - ➢ Current record: $3.1\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

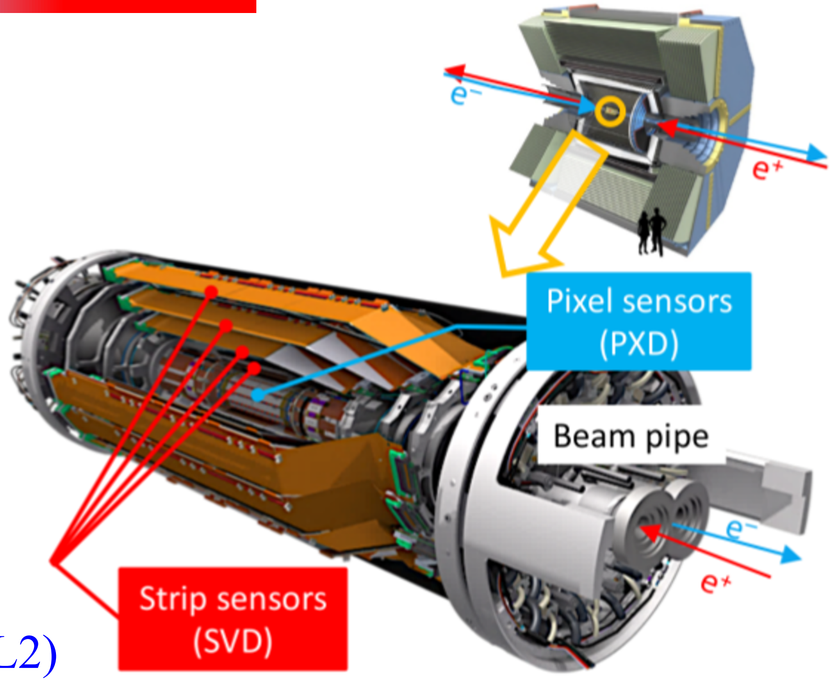
- ❑ Raison d'être of Belle II
  - ➢ Search for new sources of CP violation and probe physics beyond the standard model at the intensity frontier
  - ➢ Physics requirements call for precise vertexing, low-momentum tracking and particle identification (PID)



👉 Vertex Detector is a key component in this pursuit

The Vertex Detector

- Physics requirements:
  - Better vertexing resolution than Belle to compensate reduced boost ⇒ improved point resolution, reduced inner radius, and lower material budget
  - Able to operate in high beam background ⇒ hit rate: 3 MHz/cm^2@ SVD layer-3
  - Radiation hard ⇒ 0.2 Mrad/yr @ SVD layer-3
- Pixel Detector (PXD)
  - DEPFET pixel sensors: Layers 1-2 (partial L2)
- Silicon-strip Vertex Detector (SVD)
  - Double-sided Si strip sensors: Layer 3-6
  - Standalone tracking and PID for low p_T charged particles
  - Extrapolate tracks to PXD (Region of interest)

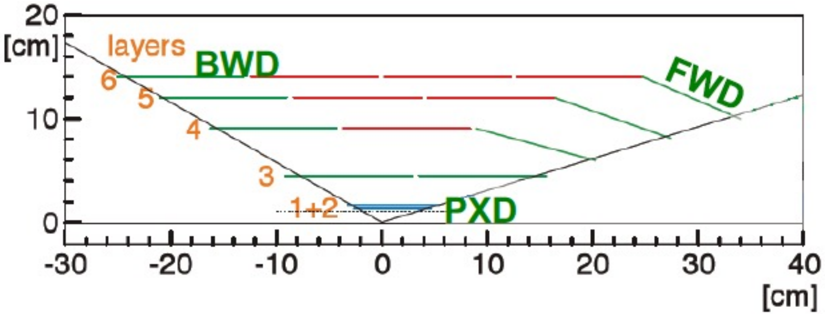


SVD in one slide

- 4 layers of modules ('ladders') mounted on end-rings supported by CF structures
  - Barrel shape in L3
  - Lantern shape in L4-6 (slanted FW sensors) ⇒ minimize material budget
  - Polar angle coverage: $17^{o} < \theta < 150^{o}$
- Signals from all sensors are routed to frontend ASICs via flexible circuits
- Dual-phase CO_2 cooling (-20^{o}c) with thin stainless steel pipes
- Total silicon surface area: $1.2\ m^2$
- Material budget: $0.7\%\ X_0$ per layer

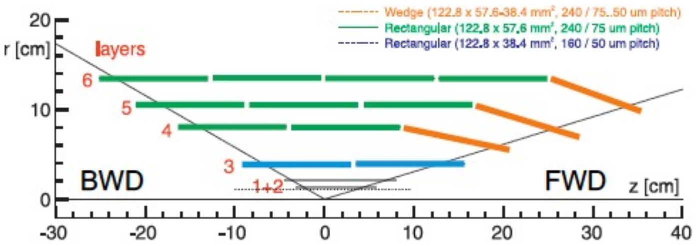
Layer	Ladder	Institute
3	7(+1)	Melbourne
4	10(+2)	TIFR Mumbai
5	12(+3)	HEPHY Vienna
6	16(+4)	Kavli IPMU

INFN Pisa: Layer 4-6 forward (FWD) and backward (BWD) modules

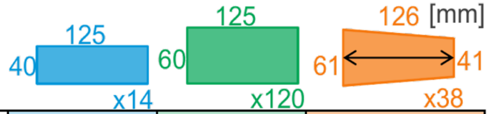


Sensors and ASIC

AC coupled strips
V_{dep}: 2–60 V
V_{op}: 100 V

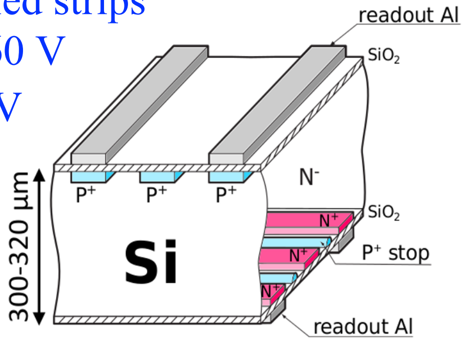


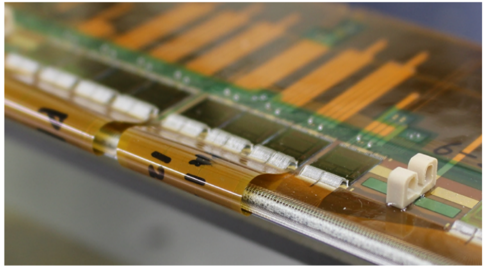
172 sensors



	Small	Large	Trapezoidal
# of p-strips*	768	768	768
p-strip pitch*	50 µm	75 µm	50-75 µm
# of n-strips*	768	512	512
n-strip pitch*	160 µm	240 µm	240 µm
thickness	320 µm	320 µm	300 µm
manufacturer	HPK		Micron

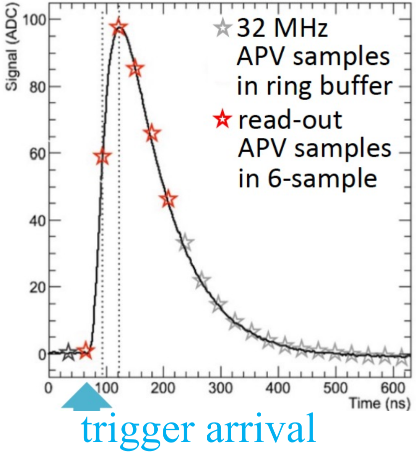
*readout strips – one floating strip on both sides



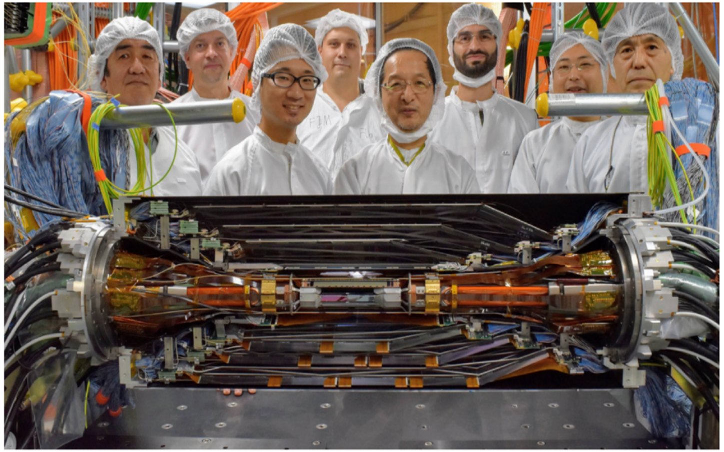


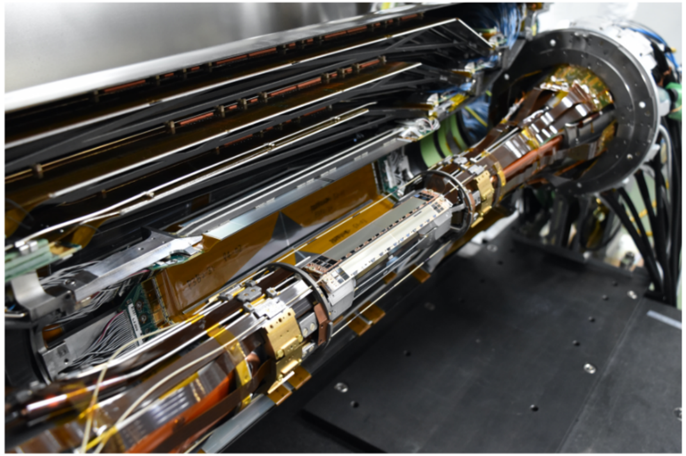
- ❑ Origami 'chip-on-sensor' concept⇒ small capacitive noise

- ❑ APV25 chips designed for CMS tracker
  - ➢ Fast: 50 ns shaping time
  - ➢ Rad hard: > 100 MRad
  - ➢ 128 channels per chip
  - ➢ Operate in the multipeak mode @ 32 MHz
  - ➢ Consume 0.4W per chip

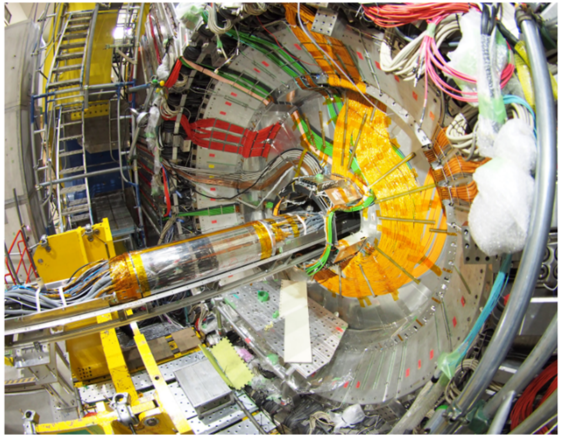


Various milestones

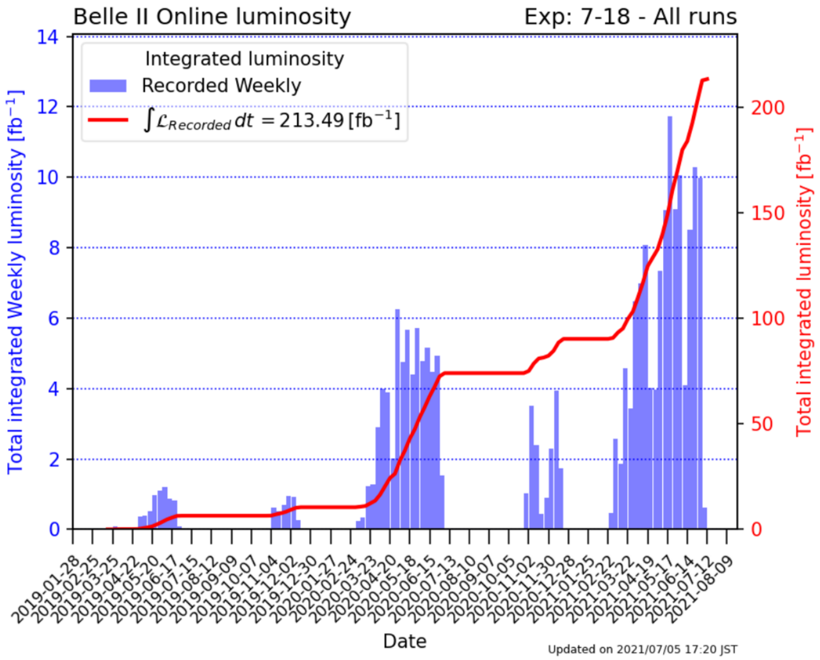




- ☐ 09-2008: Origami concept established
- ☐ 10-2010: Belle II TDR arXiv:1011.0352
- ☐ 05-2015: First completed SVD ladder
- ☐ 02/07-2018: 1st/2nd “half shell” assembled
- ☐ 11-2018: Installed to Belle II
- ☐ 03-2019: 1st collision data with full VXD

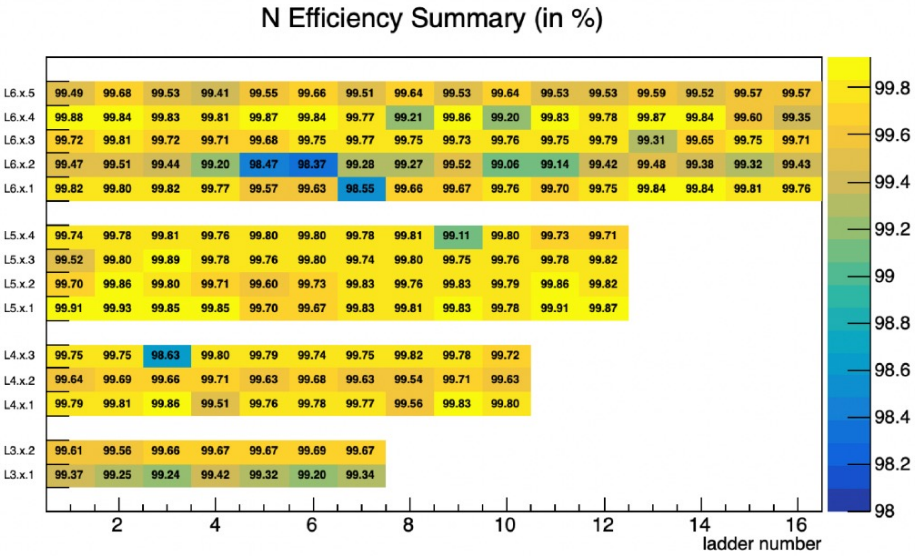


Operational experience in brief



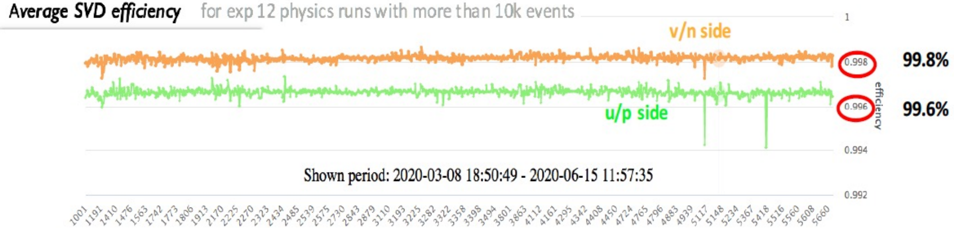
- ❑ Reliable and smooth operation since Mar 2019
- ❑ Excellent detector performance
- ❑ Hit efficiency > 99% in most sensors
- ❑ Reasonable cluster charge distribution
- ❑ Very good SNR in the range 13-30
- ❑ Improved simulation better agrees with the collision data

Hit efficiency



N Efficiency Summary (in %)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
L6.x.5	99.49	99.68	99.53	99.41	99.55	99.66	99.51	99.64	99.53	99.64	99.53	99.53	99.59	99.52	99.57	99.57
L6.x.4	99.88	99.84	99.83	99.81	99.87	99.84	99.77	99.21	99.86	99.20	99.83	99.78	99.87	99.84	99.60	99.35
L6.x.3	99.72	99.81	99.72	99.71	99.68	99.75	99.77	99.75	99.73	99.76	99.75	99.79	99.31	99.65	99.75	99.71
L6.x.2	99.47	99.51	99.44	99.20	98.47	98.37	99.28	99.27	99.52	99.06	99.14	99.42	99.48	99.38	99.32	99.43
L6.x.1	99.82	99.80	99.82	99.77	99.57	99.63	98.55	99.66	99.67	99.76	99.70	99.75	99.84	99.84	99.81	99.76
L5.x.4	99.74	99.78	99.81	99.76	99.80	99.80	99.78	99.81	99.11	99.80	99.73	99.71				
L5.x.3	99.52	99.80	99.89	99.78	99.76	99.80	99.74	99.80	99.75	99.76	99.78	99.82				
L5.x.2	99.70	99.86	99.80	99.71	99.60	99.73	99.83	99.76	99.83	99.79	99.86	99.82				
L5.x.1	99.91	99.93	99.85	99.85	99.70	99.67	99.83	99.81	99.83	99.78	99.91	99.87				
L4.x.3	99.75	99.75	98.63	99.80	99.79	99.74	99.75	99.82	99.78	99.72						
L4.x.2	99.64	99.69	99.66	99.71	99.63	99.68	99.63	99.54	99.71	99.63						
L4.x.1	99.79	99.81	99.86	99.51	99.76	99.78	99.77	99.56	99.83	99.80						
L3.x.2	99.61	99.56	99.66	99.67	99.67	99.69	99.67									
L3.x.1	99.37	99.25	99.24	99.42	99.32	99.20	99.34									

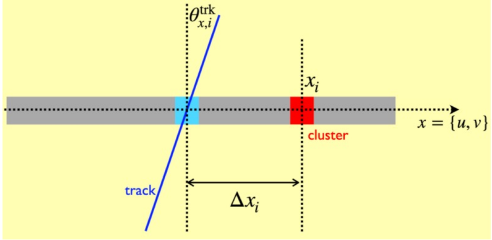


2020 data

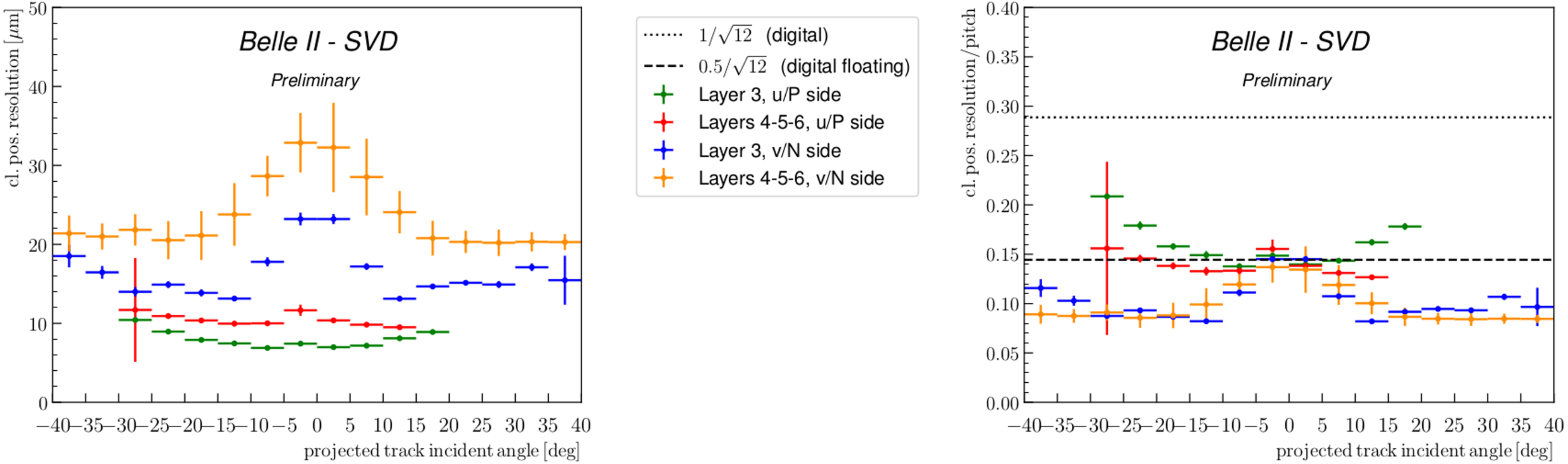
layer	$\varepsilon(u/P)(\%)$	$\varepsilon(v/N)(\%)$
3	99.83 ± 0.01	99.48 ± 0.03
4	99.69 ± 0.03	99.68 ± 0.03
5	99.66 ± 0.03	99.77 ± 0.04
6	99.31 ± 0.08	99.58 ± 0.06

- ❑ Efficiency very high and stable in time
- ❑ > 99% for majority of sensors

Cluster position resolution

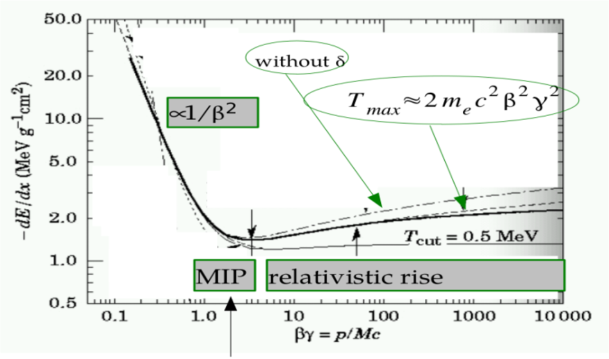


- Measured in $e^+e^- \rightarrow \mu^+\mu^-$ data
- Estimated from the residual of cluster position with respect to the track
- Position resolution in agreement with expectations from strip pitch
- Work continues to further improvement, especially in the u/P side

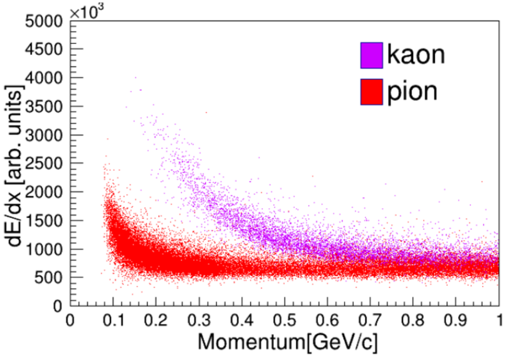


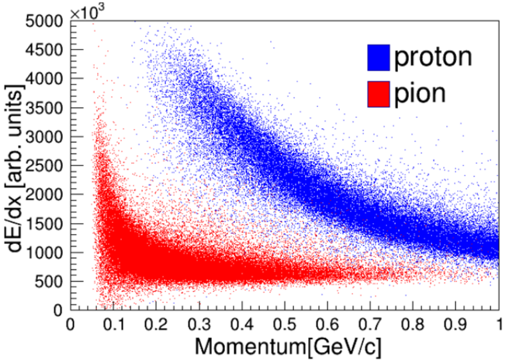
PID using SVD

- ☐ Low p_T charged particles are mostly unable to reach CDC
- ☐ Exploit the specific ionization (dE/dx) information of SVD to identify various charged particles, especially pions vs. kaons
- ☐ Use control samples of kinematically identified $D^{*+} \to D^0(K^+\pi^-)\pi_s^+$ and $\Lambda \to p\pi^+$ decays

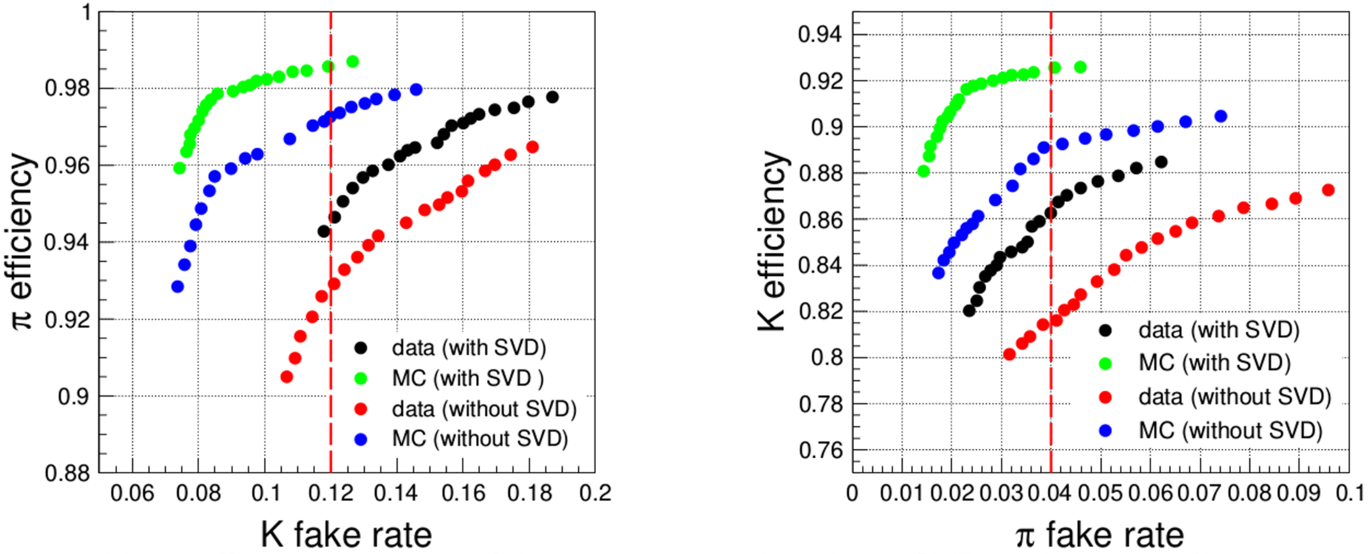


$\beta\gamma \simeq$ 3-4





PID performance

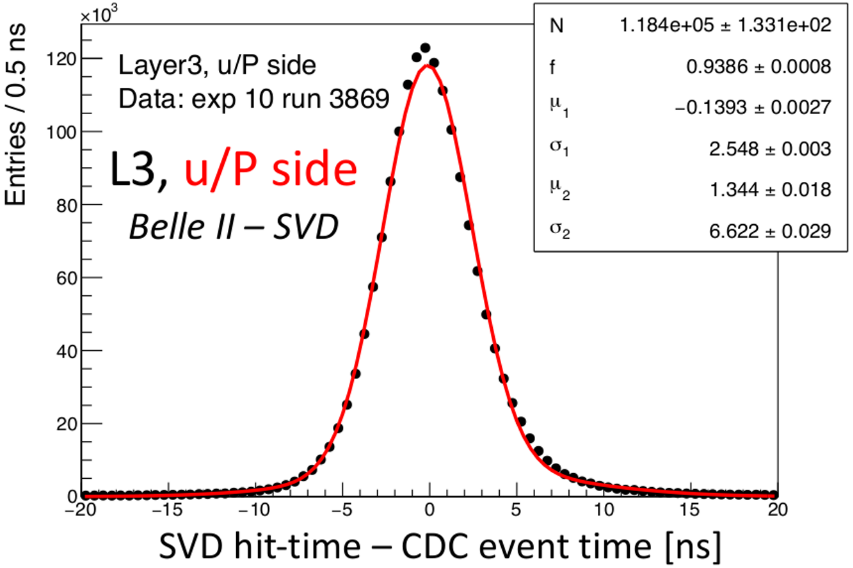


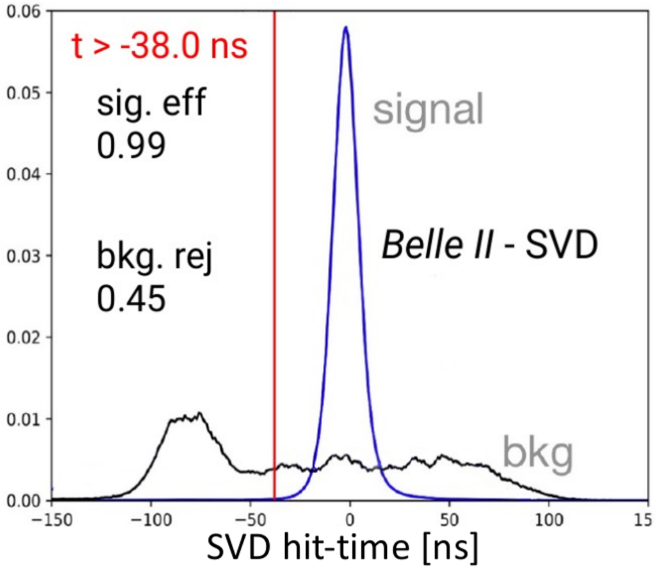
Kaon efficiency vs. pion fake rate with and without SVD with $p < 1\,\mathrm{GeV}$

- Addition of SVD dE/dx information leads to significant improvement in the PID performance
- Data-MC difference arises mostly due to a suboptimal simulation of the cluster energy ⇒ work in progress

Hit-time resolution

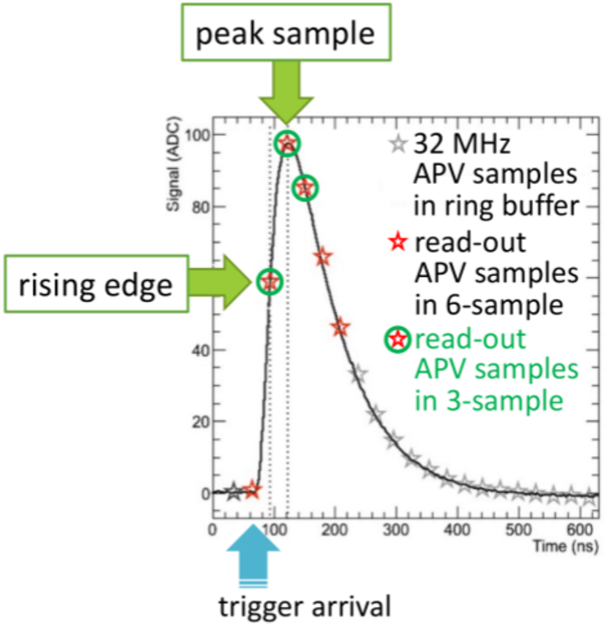
- ☐ 6 samples per strip are available for reconstruction
- ☐ Study of waveform of the APV25 output signal yields an excellent hit-time resolution of ~2.35 ns
- ☐ Cluster time information will be exploited in future to suppress off-time beam background (“pileup”) hits





Going from 6- to 3-sample

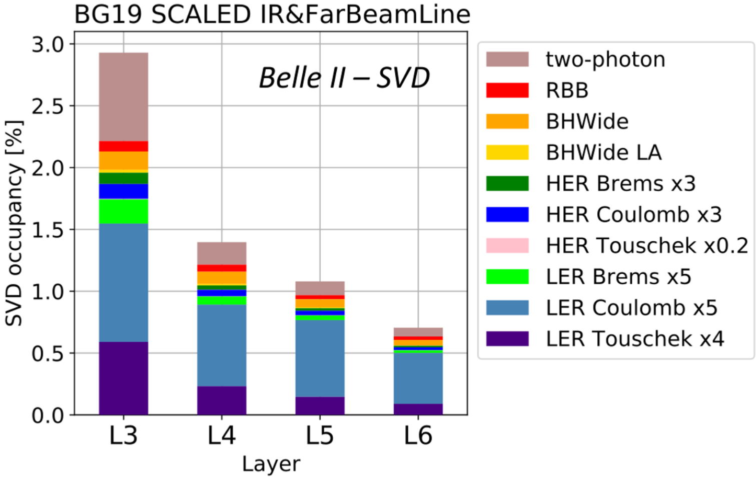
- Ideal 3 samples provide enough information as 6 samples
  - Amplitude: peak ADC sample
  - Hit-time: rising edge of the waveform
- Degrades if the trigger timing is largely shifted
  ⇒ CDC event time is a good estimator
- Determine the relative hit efficiency (3-sample eff./6-sample eff.) using information from CDC, SVD and PXD
- Relative efficiency > 99% for a trigger timing shift within ±30 ns



👉 3-sample reconstruction will be key for the high-luminosity operation

Beam background and hit efficiency

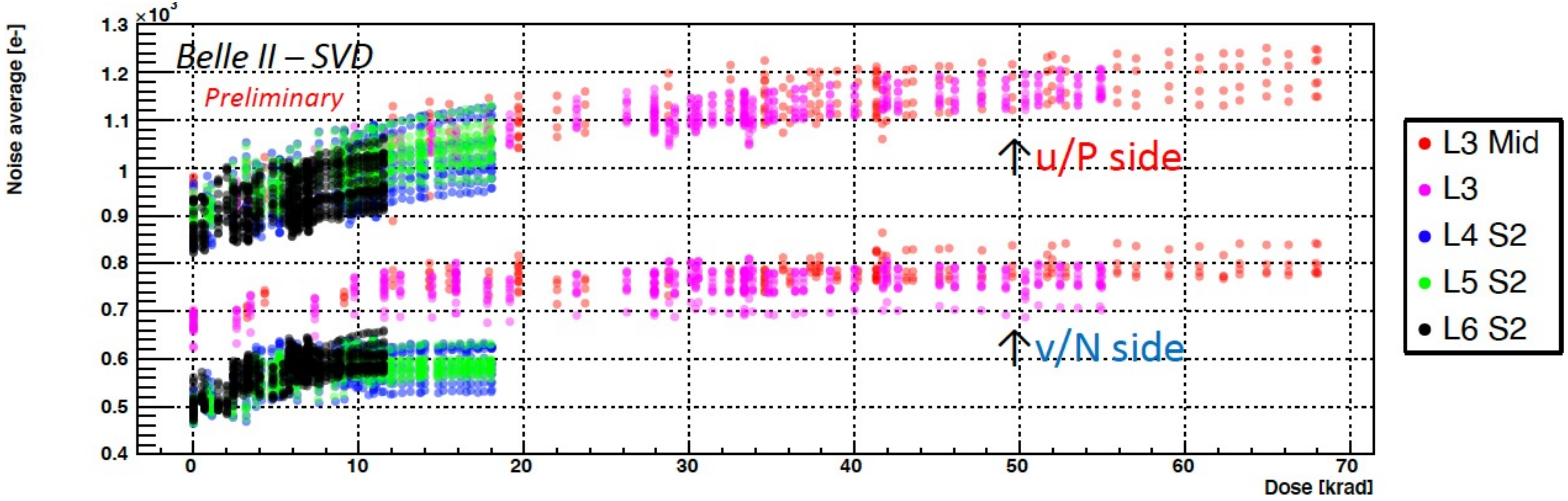
- ☐ Beam background increases SVD hit efficiency, especially for L3, leading to a degraded performance
- ☐ Present limit in L3: ~3% (can be relaxed by twice once we exploit hit-time)
- ☐ With current luminosity, average L3 hit efficiency is under control: < 0.5%
- ☐ Projection of hit occupancy at the design peak luminosity for L3: 3%
- ☐ However, there is a potentially large error associated with background extrapolation



👉 Efforts are underway for VXD upgrade: MAPS, SOI, TFP-SVD

Radiation effects on strip noise

- ❑ Noise increase of 20-25% in layer 3, though does not affect performance
- ❑ Likely due to radiation effects on the sensor surface
  - ➢ Nonlinear increase due to fixed oxide charges that increase the interstrip capacitance, expected to saturate
- ❑ Saturation see on the v/N side and starting to be seen on the u/P side



Summary and outlook

- SVD has been successfully recording data since Mar 2019 ⇒ smooth and reliable operation
- Very good and stable performance ⇒ there is still room for improvement, especially in tuning of simulation
- Radiation damage is visible but has not yet affected performance
- Need to carefully follow operation, data quality and radiation damage effects
- Prepare system to cope with higher beam background condition