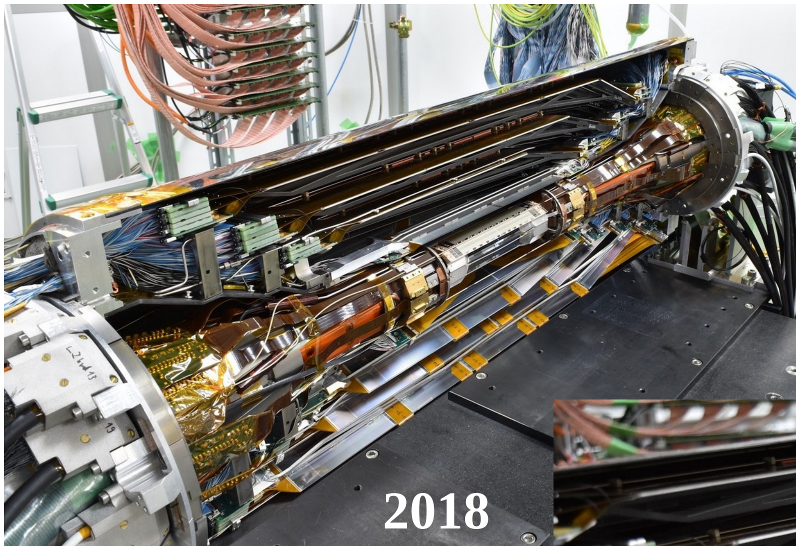
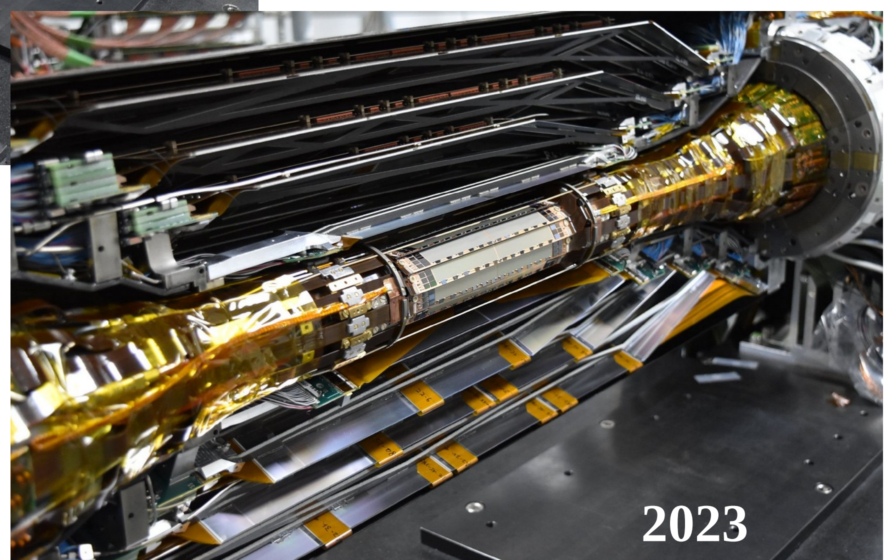
The Belle II Silicon Vertex detectors

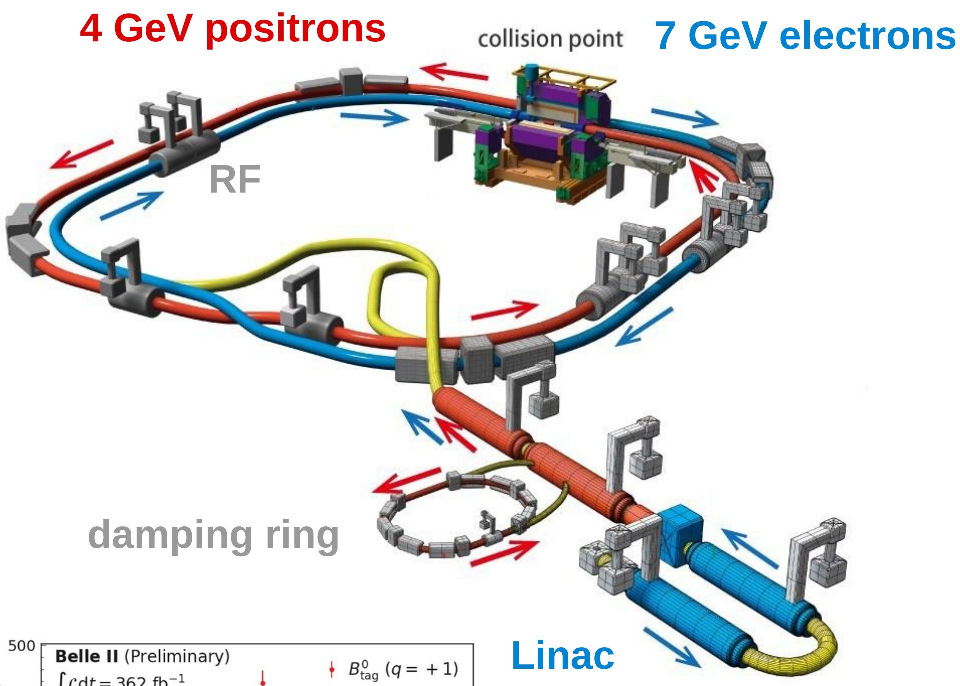
Daniel Pitzl, DESY
London, 7.11.2023

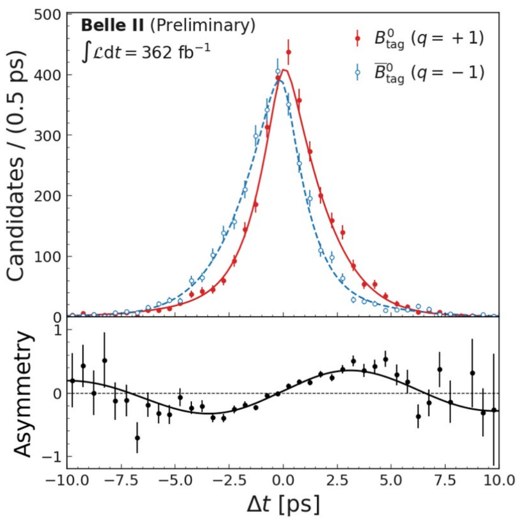


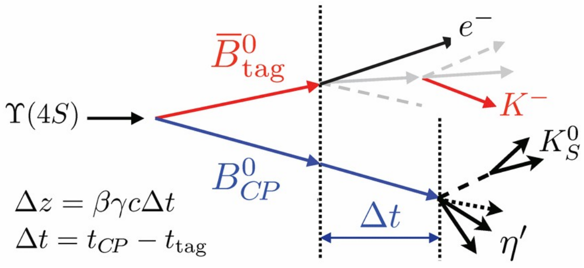


- SuperKEKB
- Belle II
- Vertex detectors:
  - SVD
  - PXD
- performance
- coming years

SuperKEKB

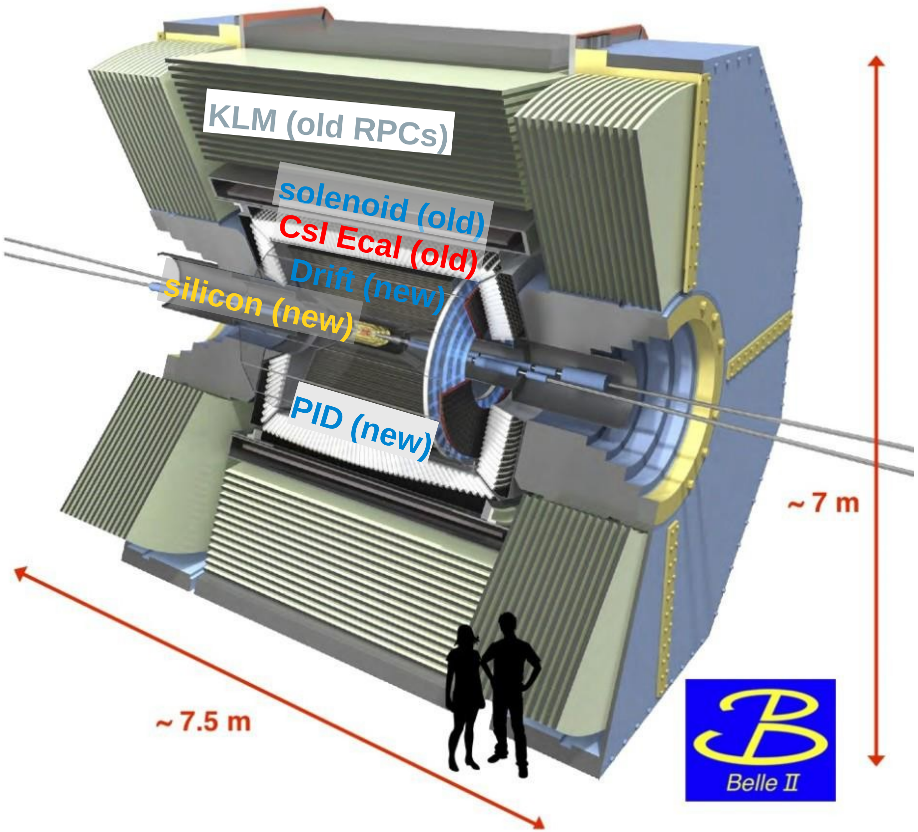






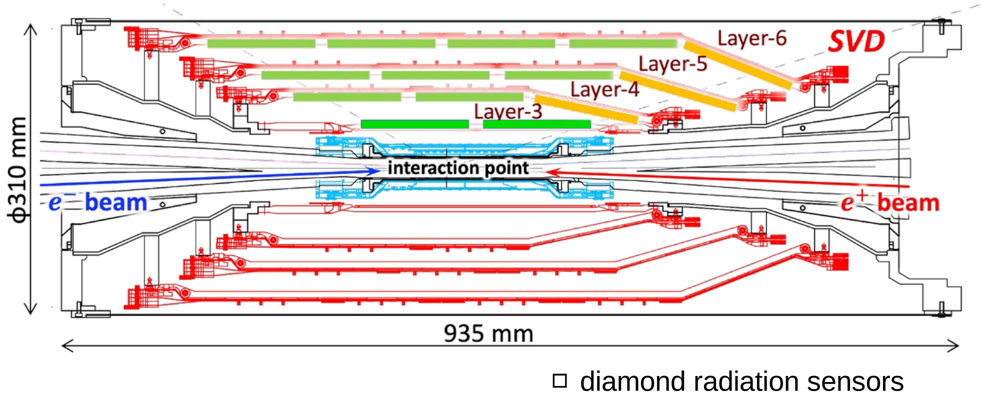
- **7 on 4 GeV: 10.58 GeV**
  - **83 mrad crossing angle**
  - **0.3 mm length of luminous region**
  - **vertical focusing β^* down to 0.6 mm (ultimately 0.3 mm)**
- **beam currents up to 3 A in 2500 bunches**
  - **4 ns bunch spacing**
  - **250 MHz crossing rate (6× LHC)**
  - **continuous top-up injection**
- **“early phase 3”: 2019-2022**
  - **L_{peak} 4.7 10^{34}/cm^{2}s, L = 427 fb^{-1}**

Belle II

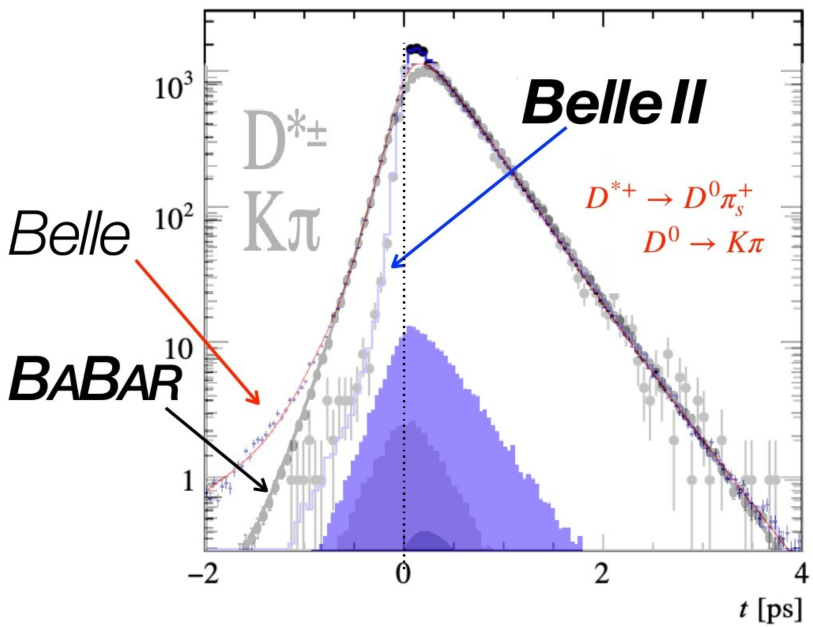


- **partial upgrade from Belle:**
  - **new particle ID (TOP and ARICH)**
  - **new drift chamber (axial and stereo, He-ethane)**
  - **new silicon vertex (strips and pixels)**
  - **new smaller Be beam pipe**
  - **final focus magnets in the detector volume**
- **up to 30 kHz trigger rate**
  - **4 ns bunch spacing not fully resolved**
- 2020-22 operated under strict Covid-19 protocol:
  - no foreign travel
  - PXD had one postdoc at KEK
  - remote operation and monitoring

Belle II silicon vertex detectors

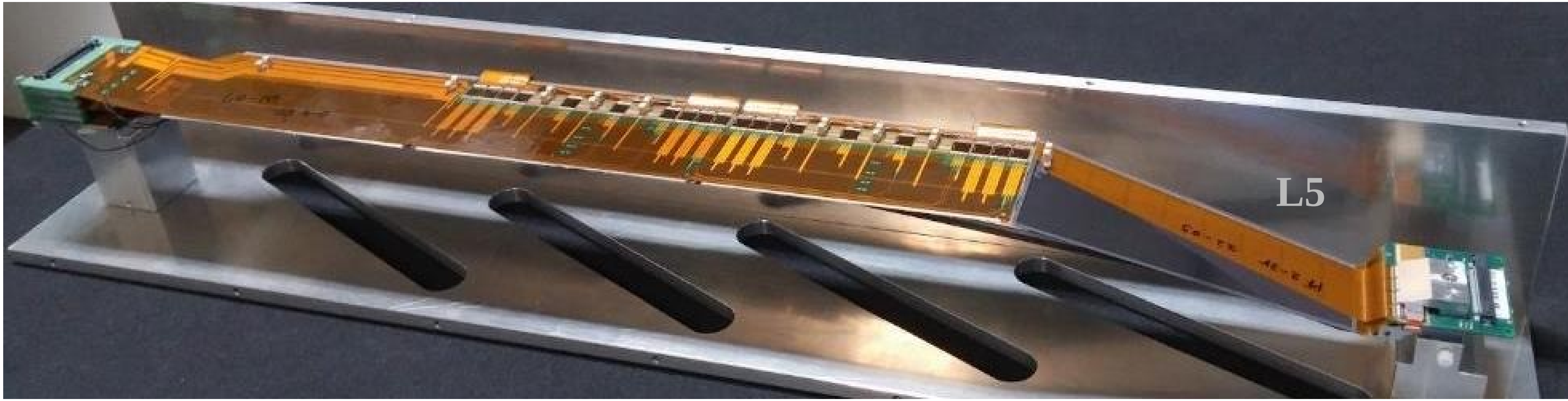


- **six layers of silicon sensors:**
  - **4 strip layers (SVD, slanted forward sensors)**
  - **2 pixel layers (PXD)**
  - **covering polar angles from 17° to 150° (like the drift chamber)**
- **double-walled Be beam pipe (with paraffin cooling)**
  - **inner radius 10 mm**



~25 µm transverse vertex resolution (70 fs)

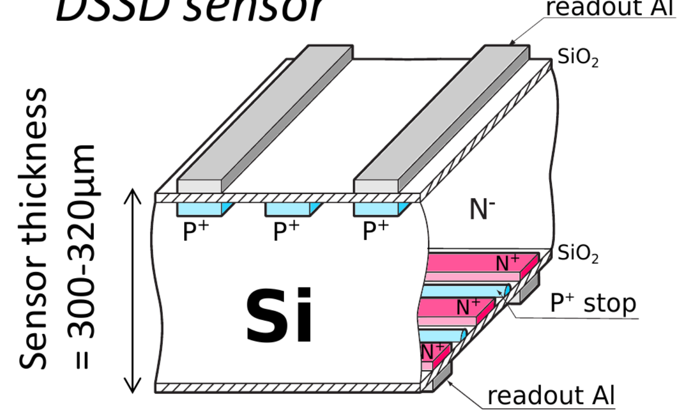
SVD Ladder



- Ladder: 2 to 5 Double-Sided Si strip sensors along *z*
  - AC coupling: block leakage current and bias potential
  - intermediate floating strips improve resolution
  - readout and power distribution on flexible Kapton prints

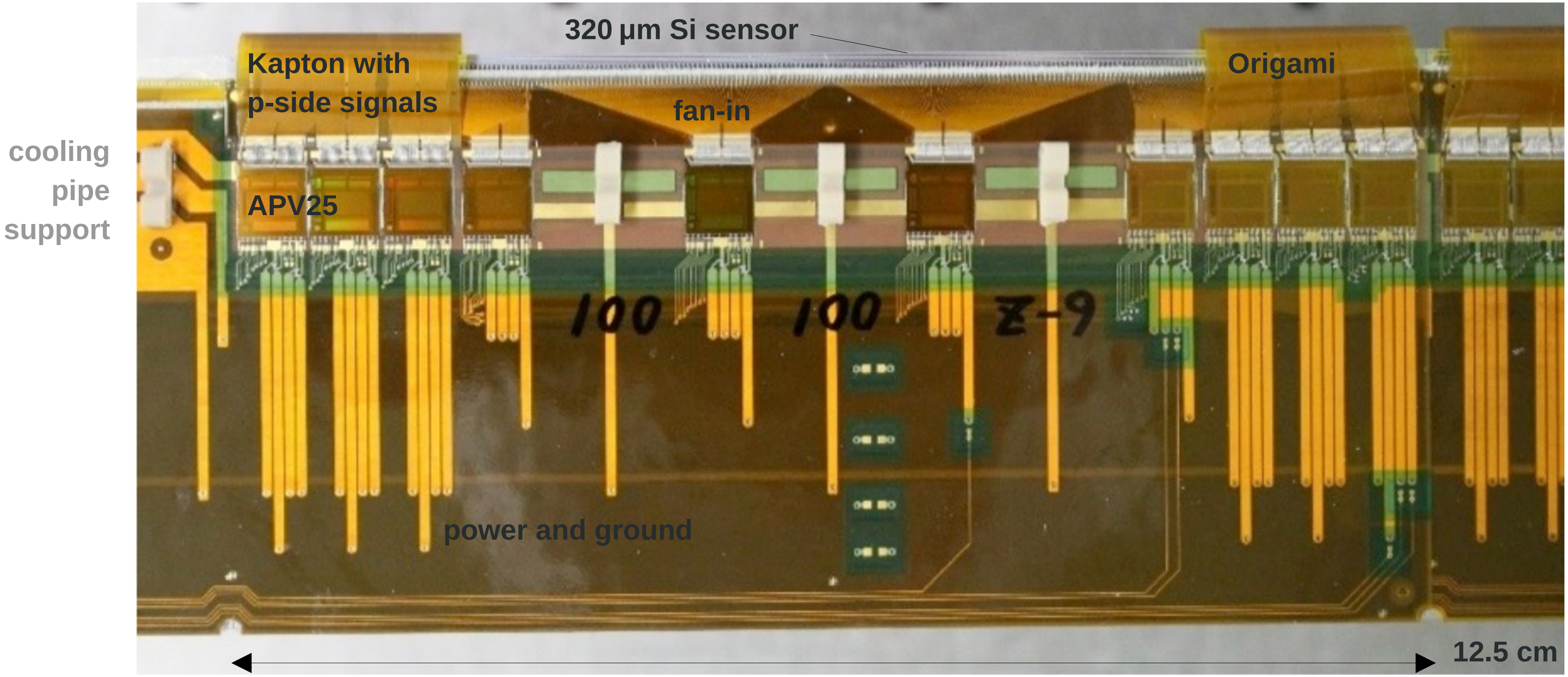
	Small sensors	Large sensors	Trapezoidal sensors
Readout strips *P*-side	768	768	768
Readout strips *N*-side	768	512	512
Readout pitch *P*-side	50 μm	75 μm	50 – 75 μm
Readout pitch *N*-side	160 μm	240 μm	240 μm
	L3	L4-6	L4-6

DSSD sensor



AC-coupled strips on N-type substrate
Full depletion voltage: 20-60V
Operation voltage: 100V

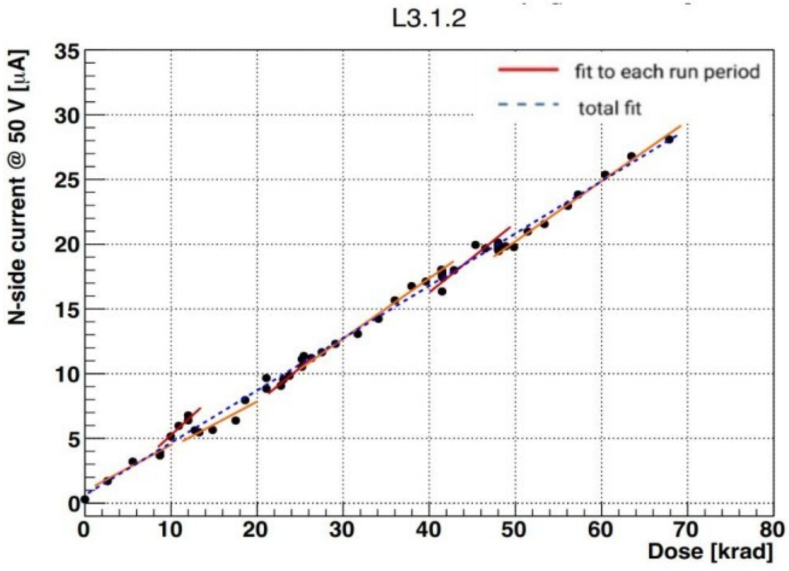
readout on flexible Kapton prints

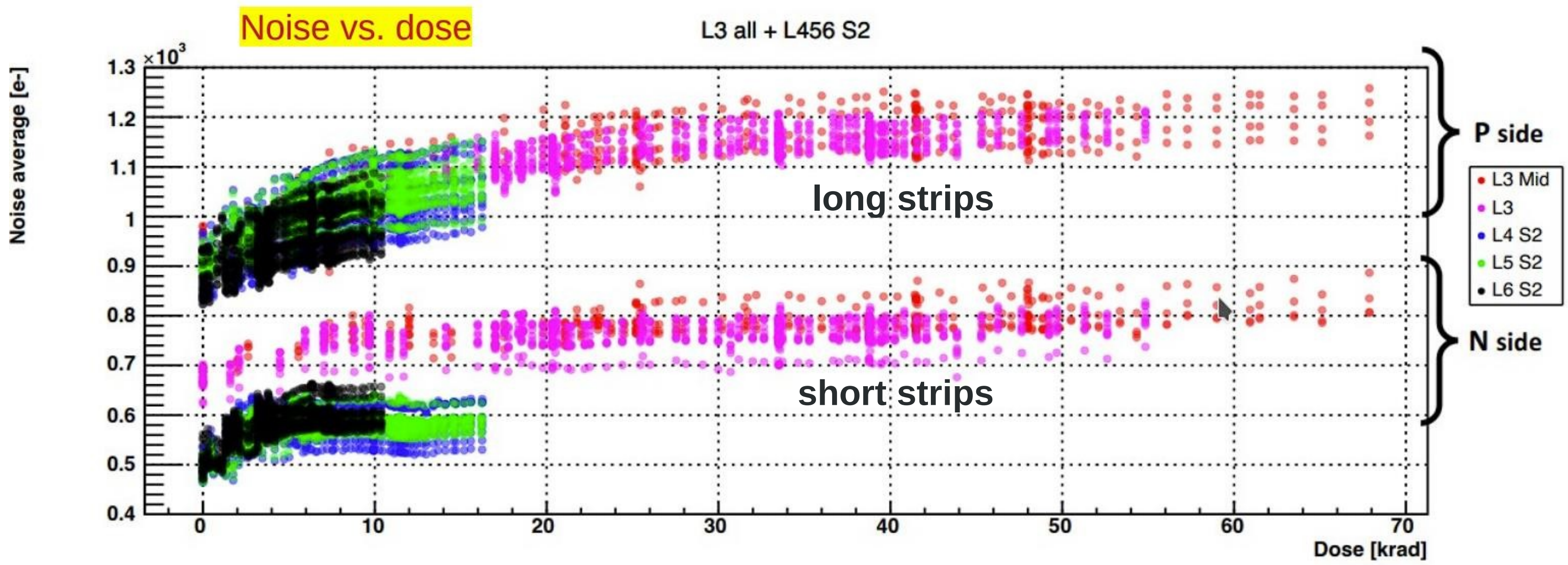


- APV25 (0.25 µm radiation hard IBM CMOS designed at IC and RAL for CMS)
  - thinned to 100 µm, wire bonded to Kapton flex print (fan-in, power, readout)
  - 128 channels: 4 APV for *z*-readout (512 short strips), 6 for rφ (768 long strips)
  - 4 W per module: CO_2 cooling pipe attached on top of APVs (not shown)

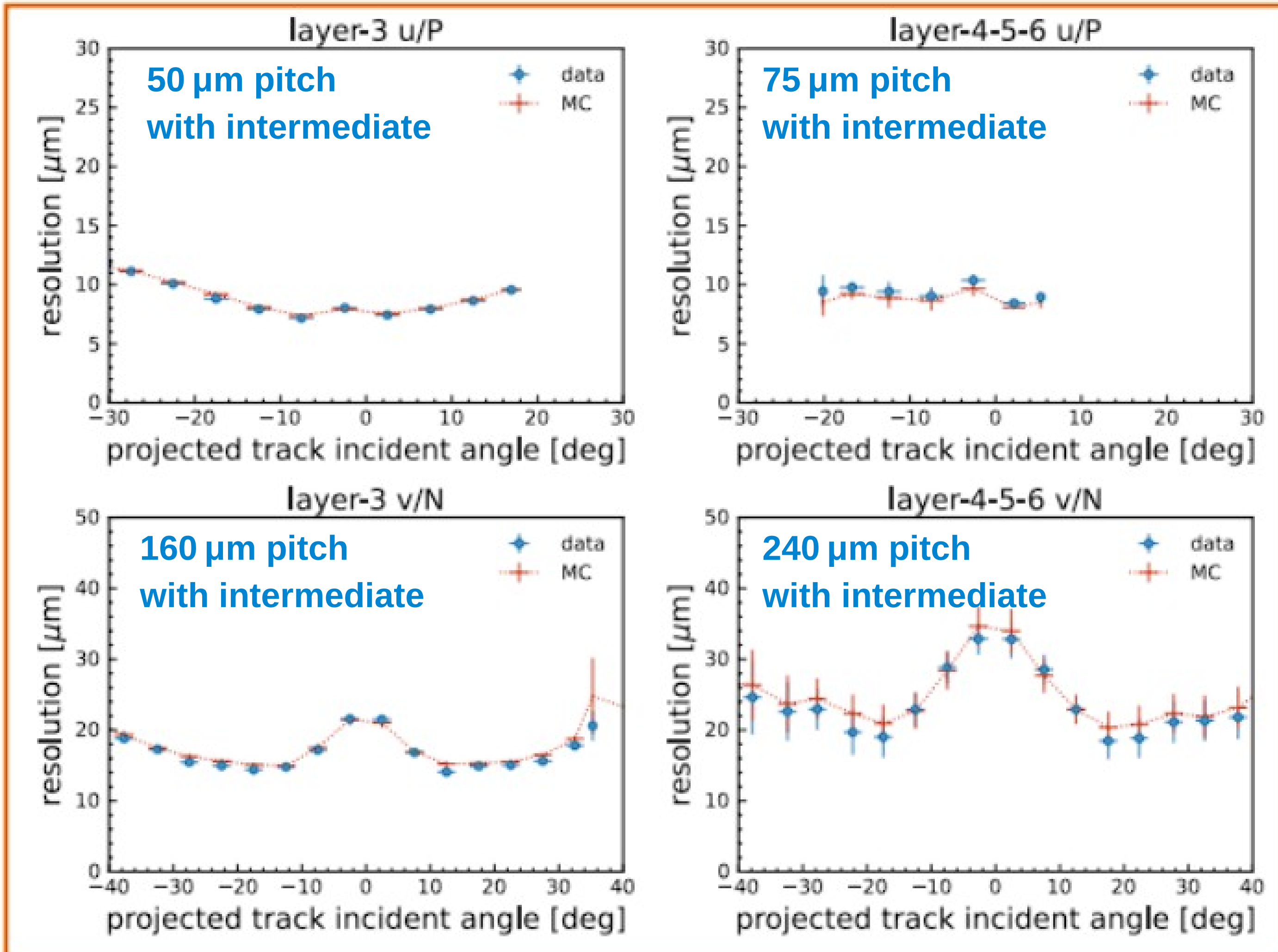
SVD status 2023

- after 4 years of operation:
  - no dead chip (in 1748)
  - very few dead channels (in 224k)
  - efficiency always and everywhere above 98.5%
  - leakage currents as expected from ionizing dose
  - (capacitive) noise increase already saturated:





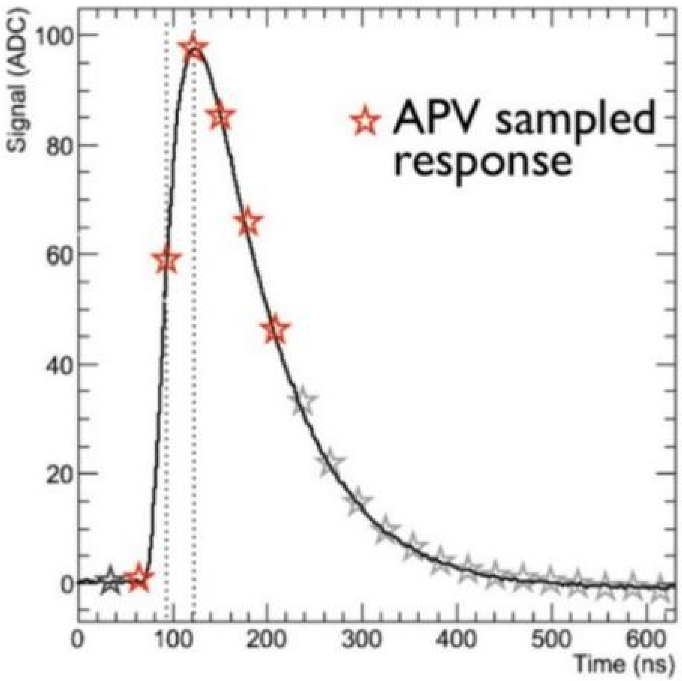
SVD cluster position resolution

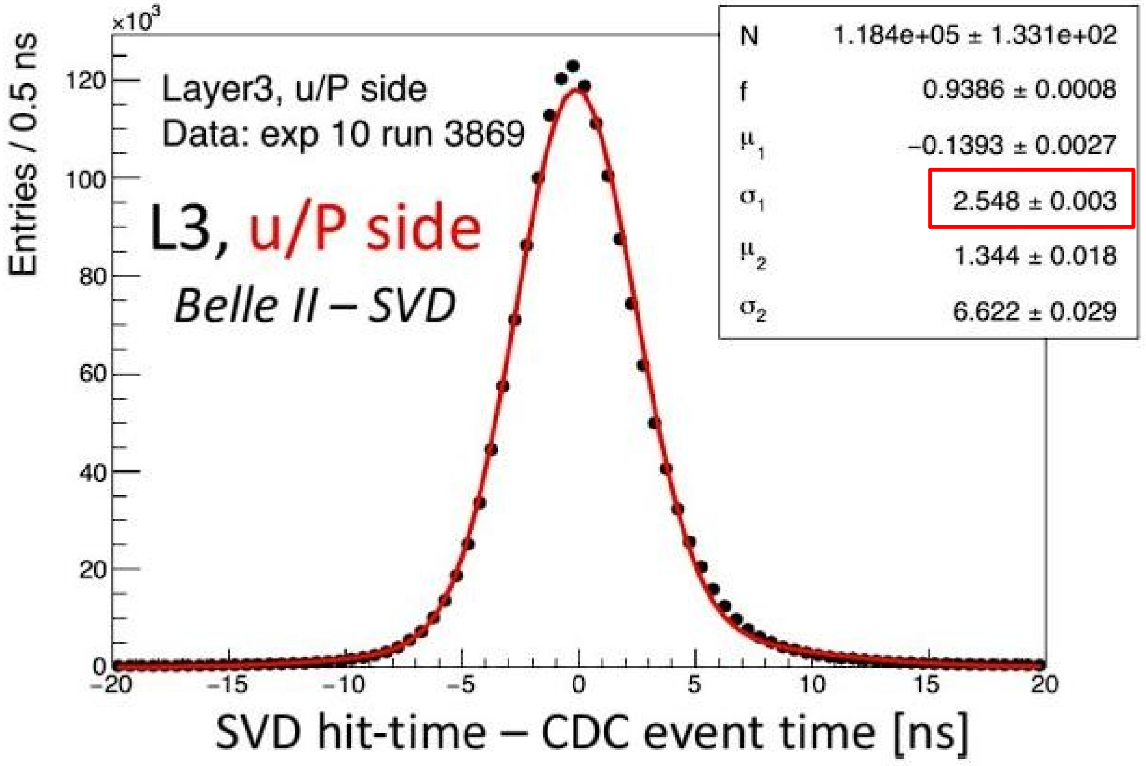


r-φ

z

SVD timing

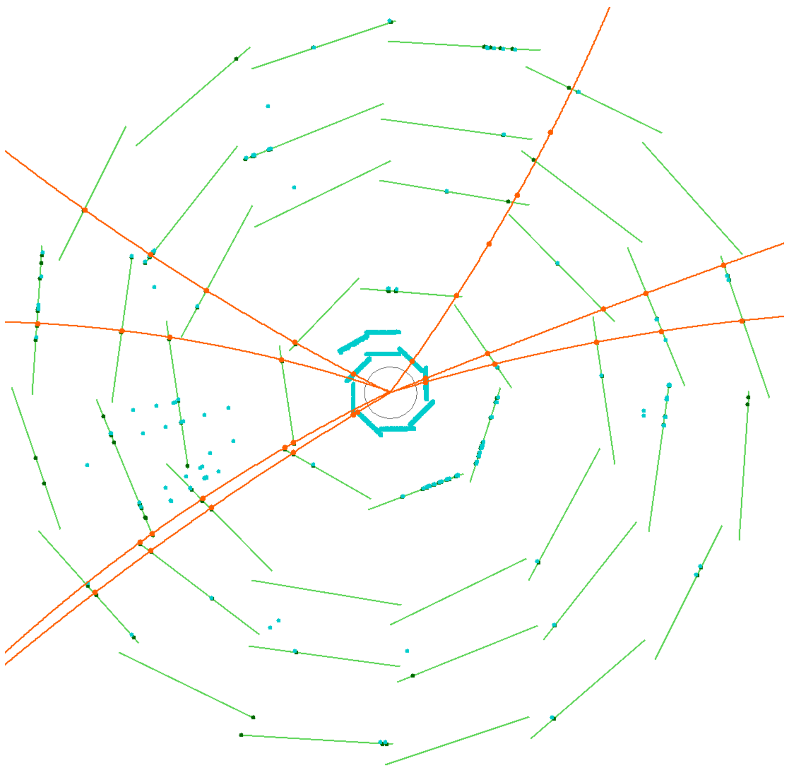




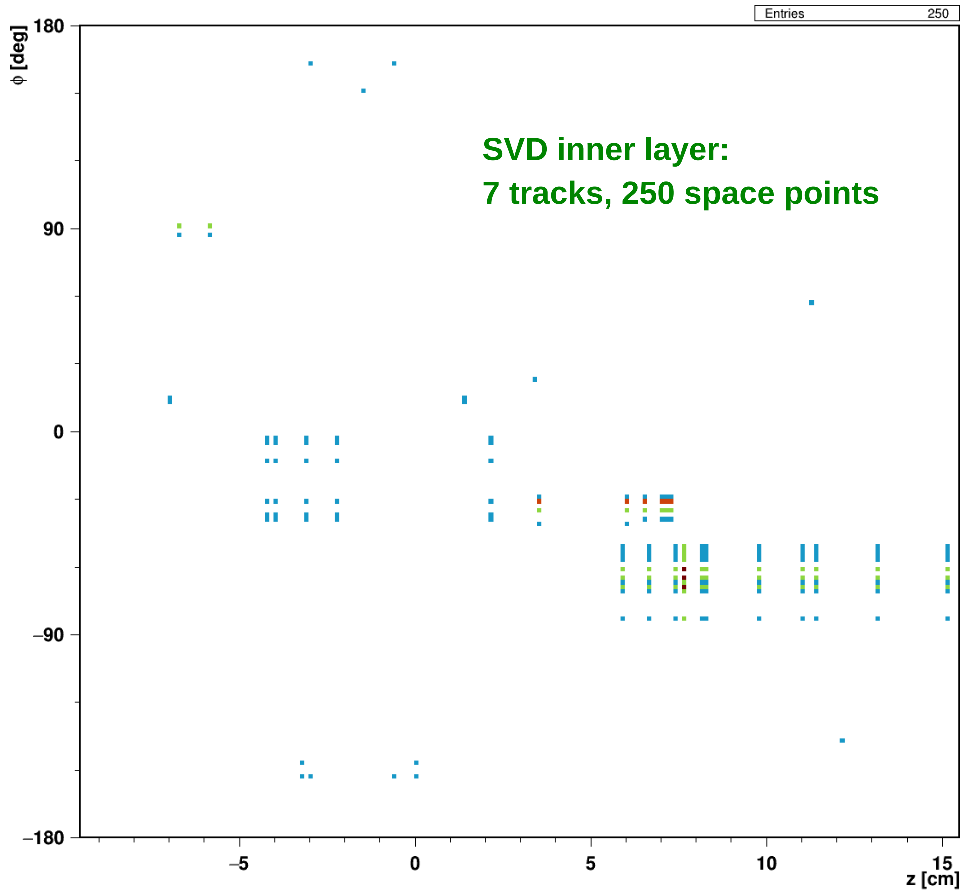
- **APV: 50 ns rise time**
  - **32 MHz sampling**
  - **reading 6 or 3 samples**

- **SVD hit timing:**
  - **2.5 ns resolution (p-side: 20 ns drift)**
  - **cluster time 'grouping' for background rejection**

SVD space points and ghosts

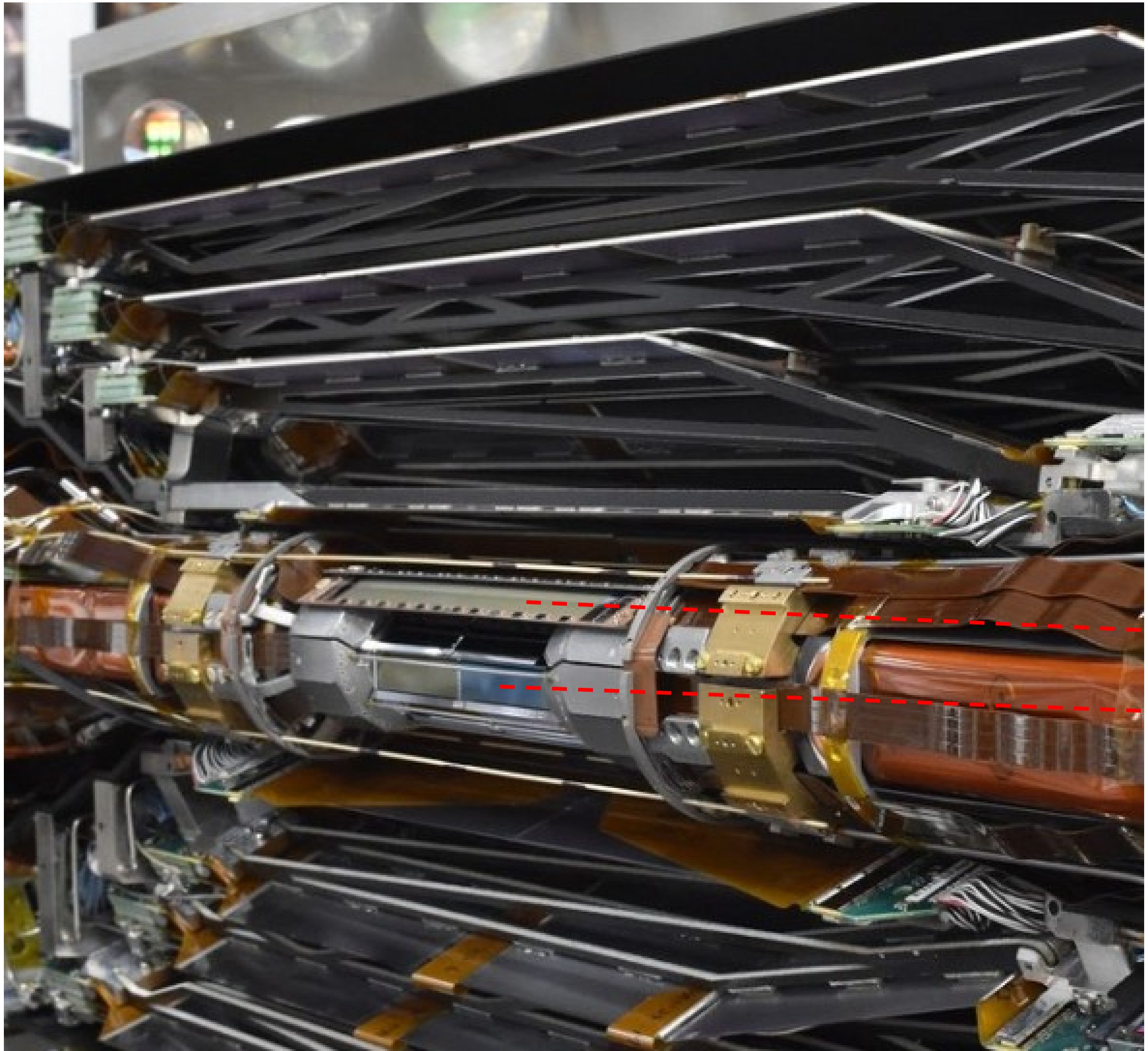


ex26.r1140.HLT1.f01.ev486



- **double sided silicon strips: measure *z* and ϕ projections**
  - **space points: all *z*-ϕ combinations per module: ghosts**
- **options: exploit charge and time correlations**

Pixel detector



SVD L6

SVD L5

SVD L4

SVD L3

PXD L2 (2 of 12 ladders)

PXD L1 (8 ladders)

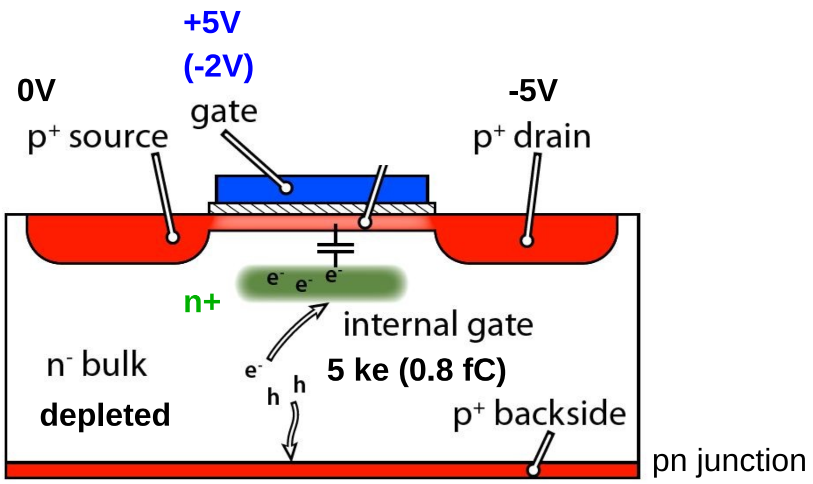
SVD L3

SVD L4

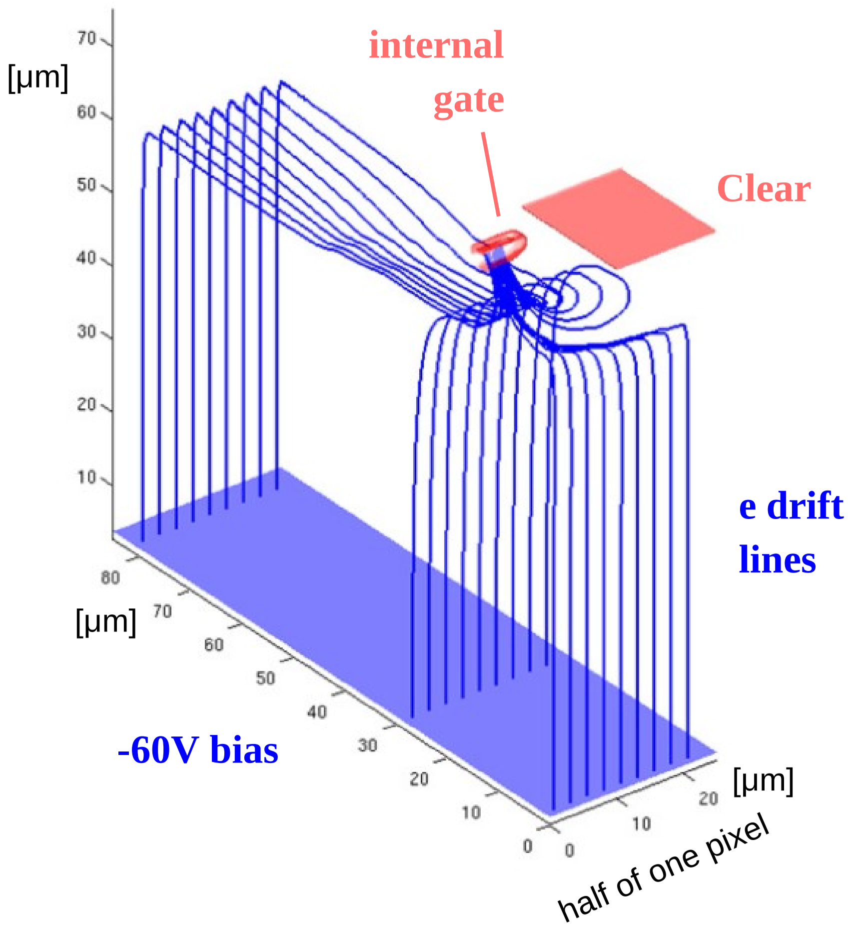
2018

DEPFET pixel

- **monolithic pixel detector: depleted FET**
- **ionized charge collected by drift at an internal gate (small deep implant)**
- DEPFET is off for 19.9/20 μs: **gate** at +5V
- "**readout**": modulated drain current: **gate** at -2V
- **reset** after readout: **Clear** at +15V (punch through)



-60V bias (top surface punch through)

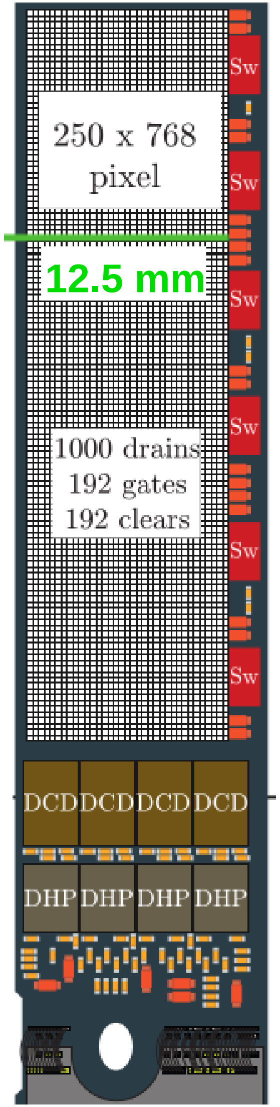


Pixel module

pixel size:
50 µm (trans)
55-85 µm (long)
192k pixels

all-silicon module
thickness:
75 µm (active)
450 µm (rim)
0.21% X_0

8 W in readout region
2-phase CO_2



operated in continuous rolling shutter readout mode
sensitive for 19.9/20.0 µs

0.5 W in active region: N2 flow cooling

Switcher: 5V gate, 15V clear, 10 MHz
(180 nm AMS/IBM HVCMOS)
sensor provides power and readout lines

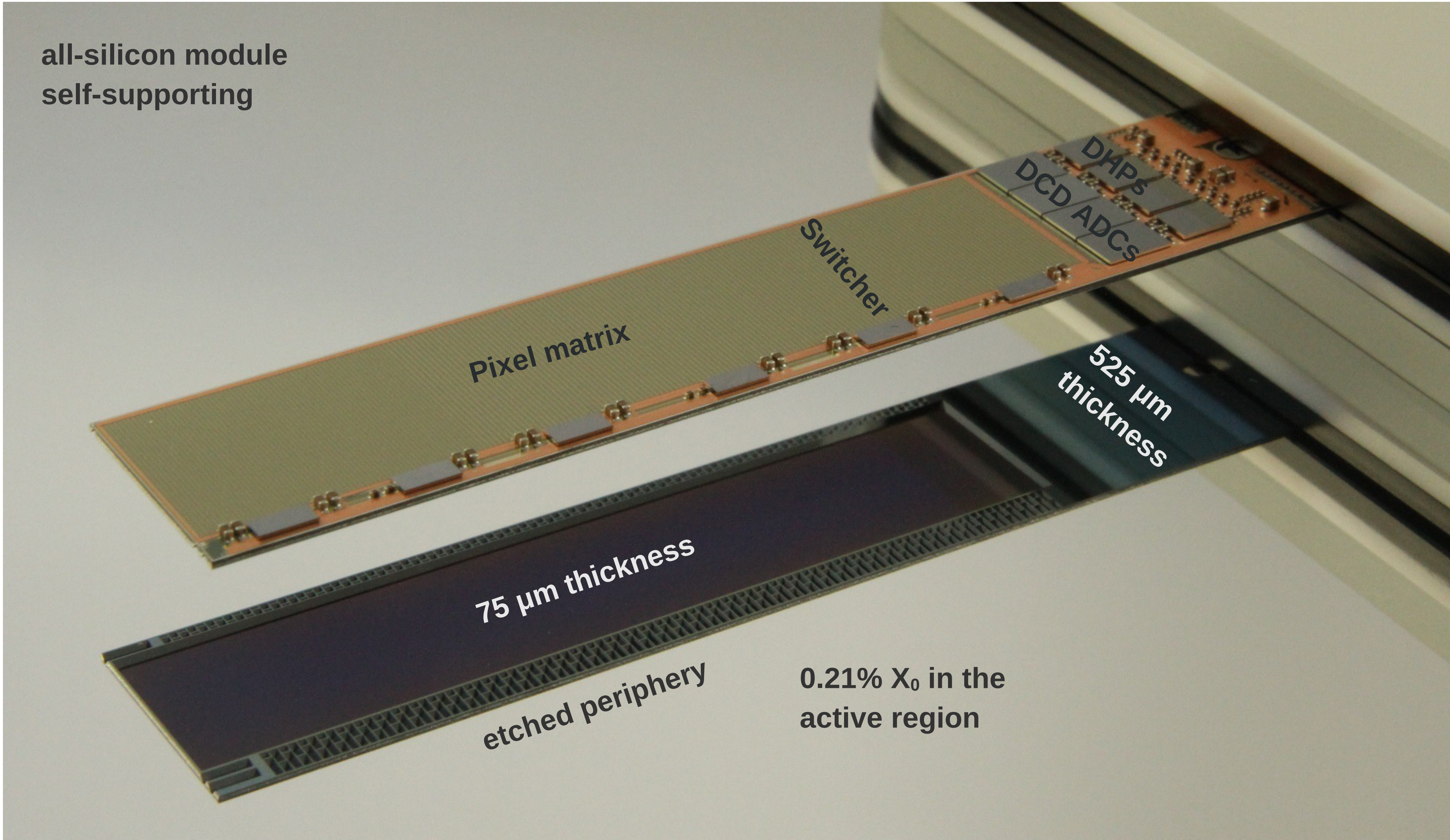
flip chip bump bonding to sensor

Drain Current Digitizer: analog common mode, 256 ADCs (8 bit)
(160 nm UMC)

Data Handling Processor: pedestal, zero suppression
(65 nm TSMC) trigger, LVDS output

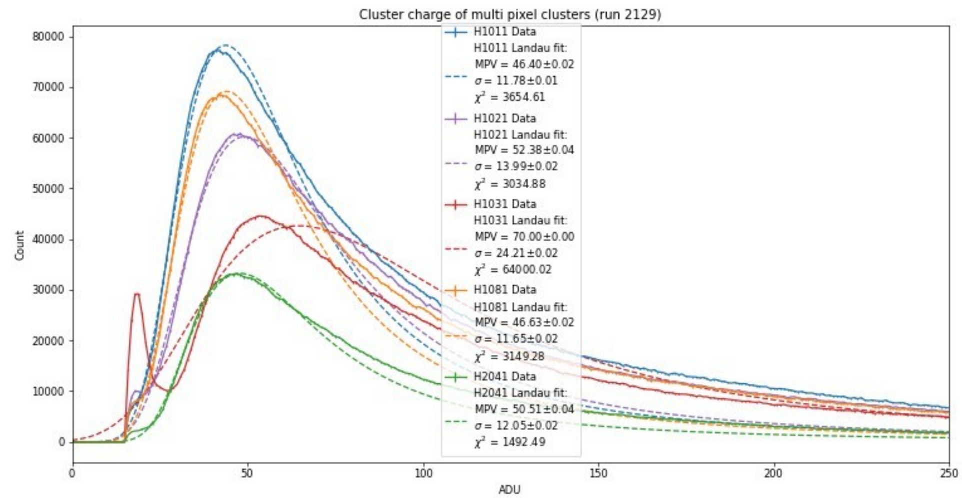
mounting on cooling block: long hole for thermal contraction

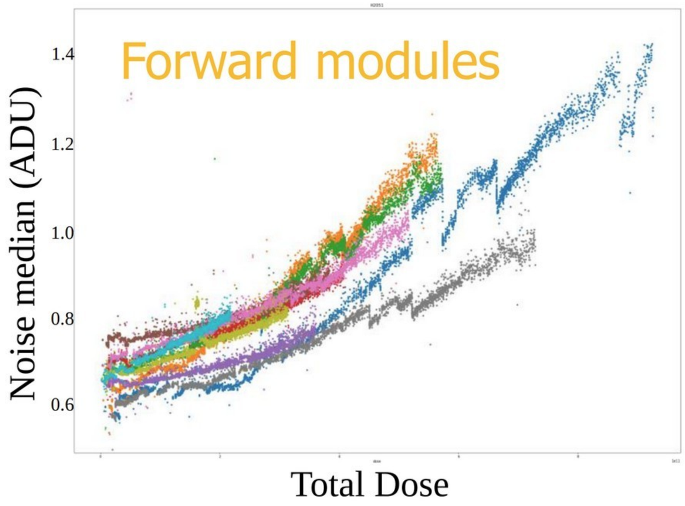
Pixel module



DEPFET signal, ADC noise

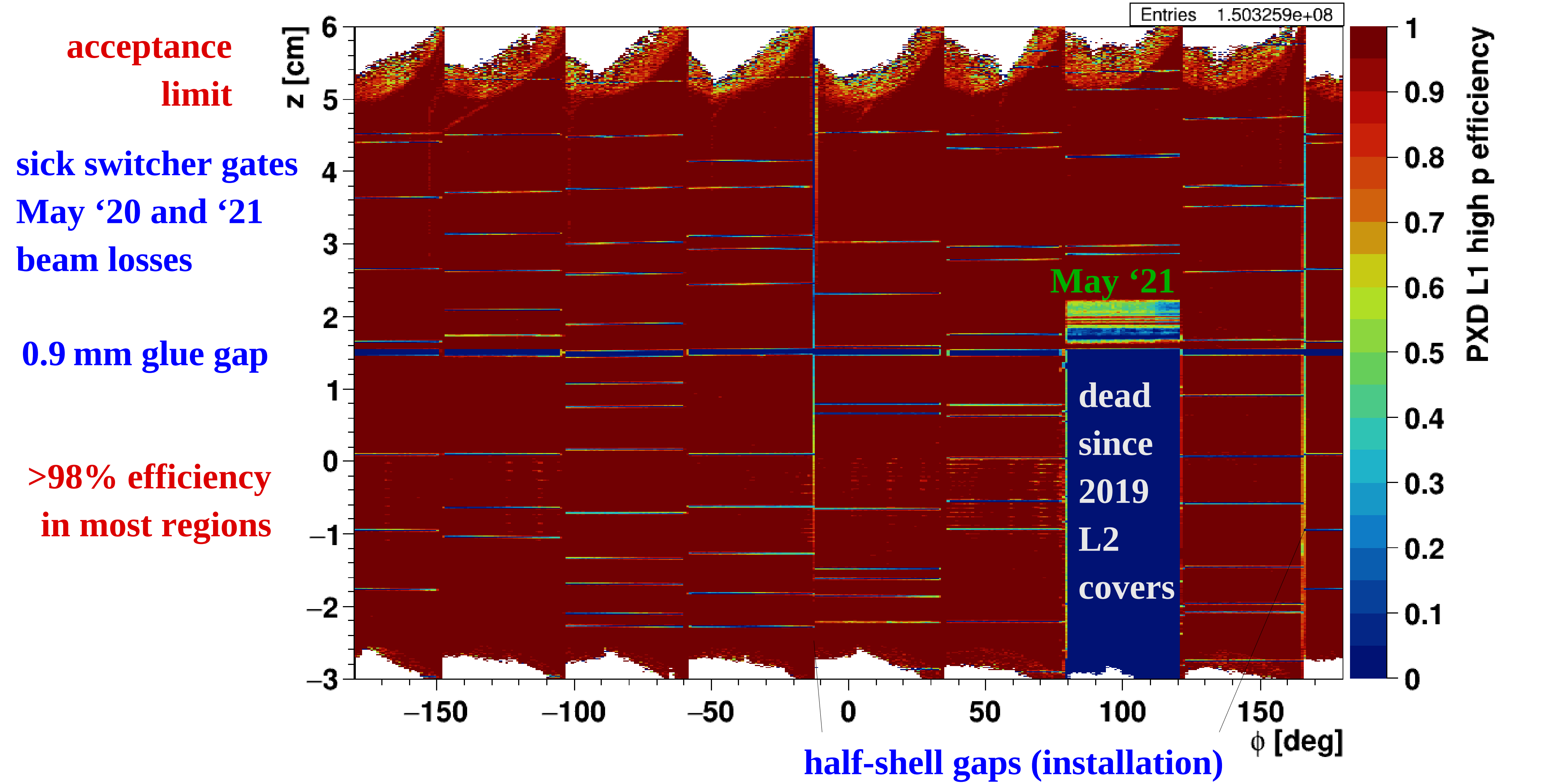
- **most probable cluster signal:**
  - **45-70 ADC units**
- **ADC noise:**
  - **0.7 ADU rising to 1.4 with dose**
- **online threshold:**
  - **pixel signal > 7 ADU**
- **(most probable > 3× threshold is enough for > 98% efficiency)**





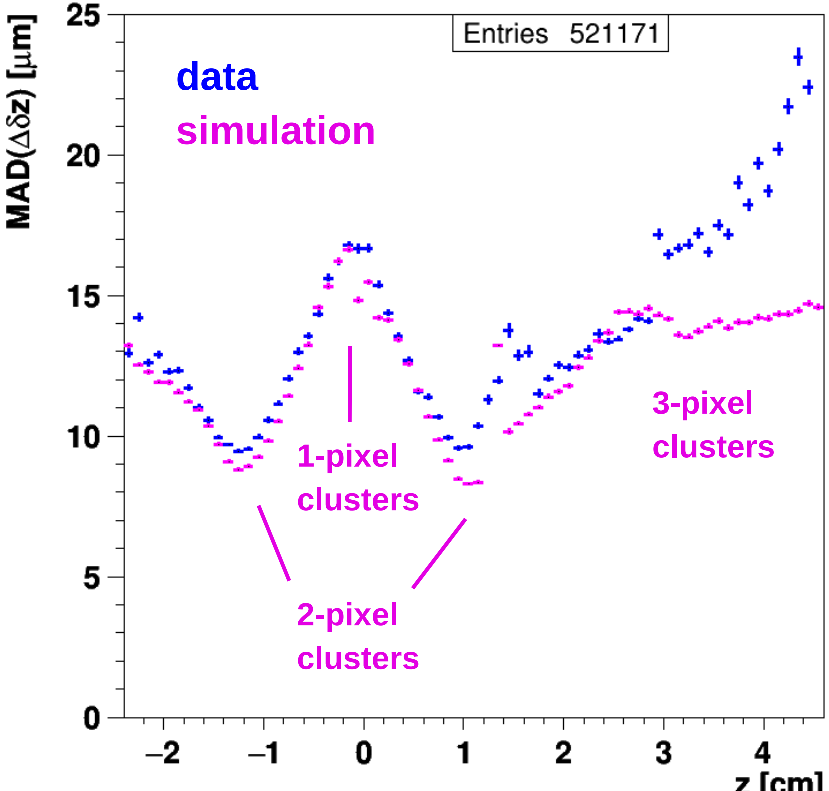
PXD L1 efficiency map

in the 4th year of operation (May 2022)

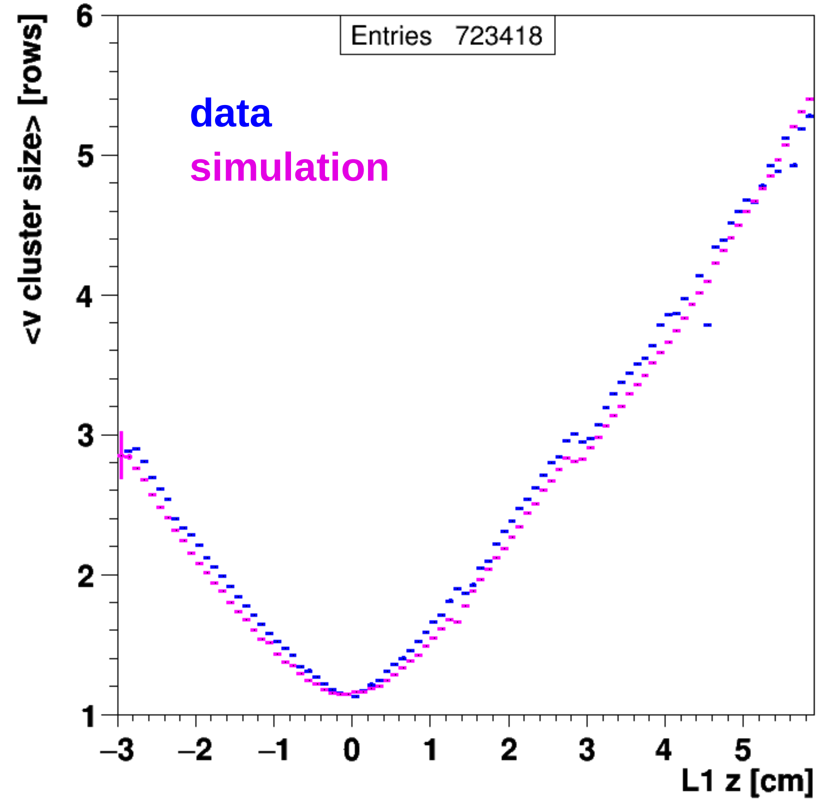


pixel position resolution

- overlap residuals: 2 hits in the same layers
- MAD = Mean Absolute Deviation (for Gaussian: MAD = 0.8 RMS)
- long clusters: limited head tail algorithm



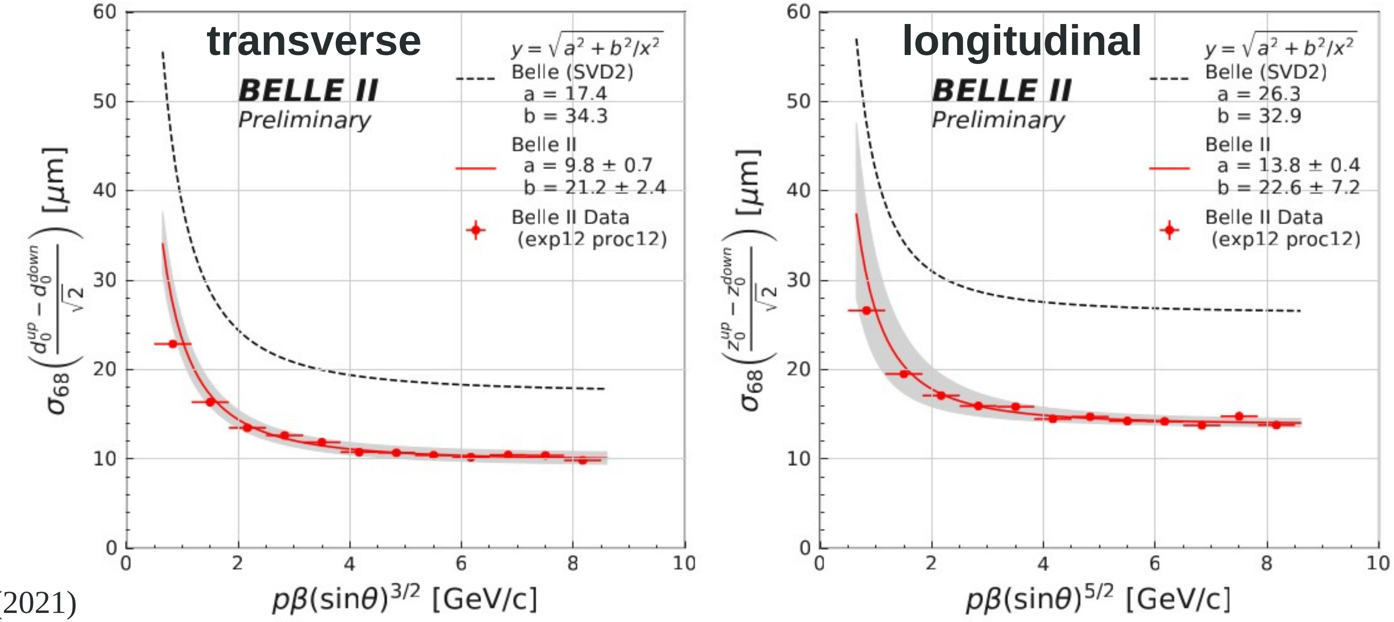
cluster length



alignment

- tracker alignment uses MillePede II algorithm
  - 6 rigid body parameters per Si sensor
  - 12 deformation parameters (4th order 2D Legendre polynomials) per sensor
  - total 3726 parameters (plus 57'680 for drift chamber wires)
- using collision data and cosmics: reaching micron precision
- hierarchical alignment:
  - half-shells
  - ladders
- updated every few days
  - thermal effects

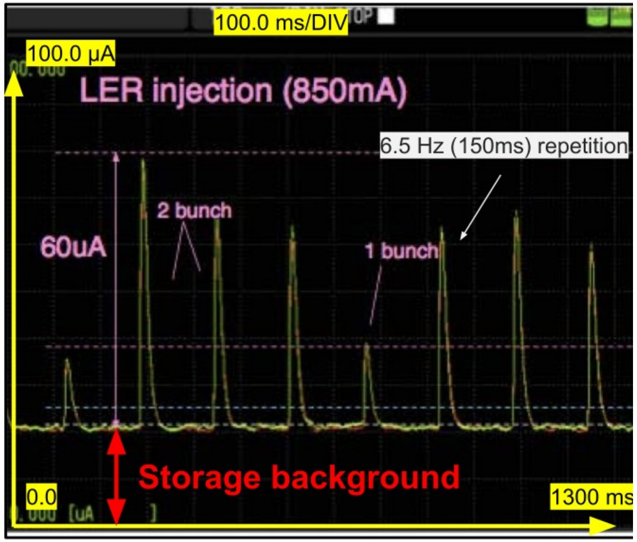
- di-muons: compare upper and lower track

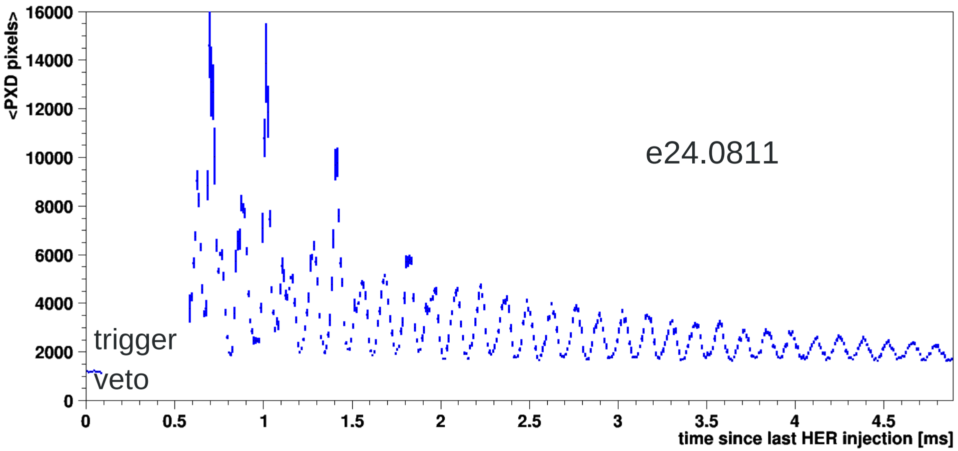


T. Bilka et al. EPJ Web of Conferences 251, 03028 (2021)
https://doi.org/10.1051/epjconf/202125103028

continuous injection

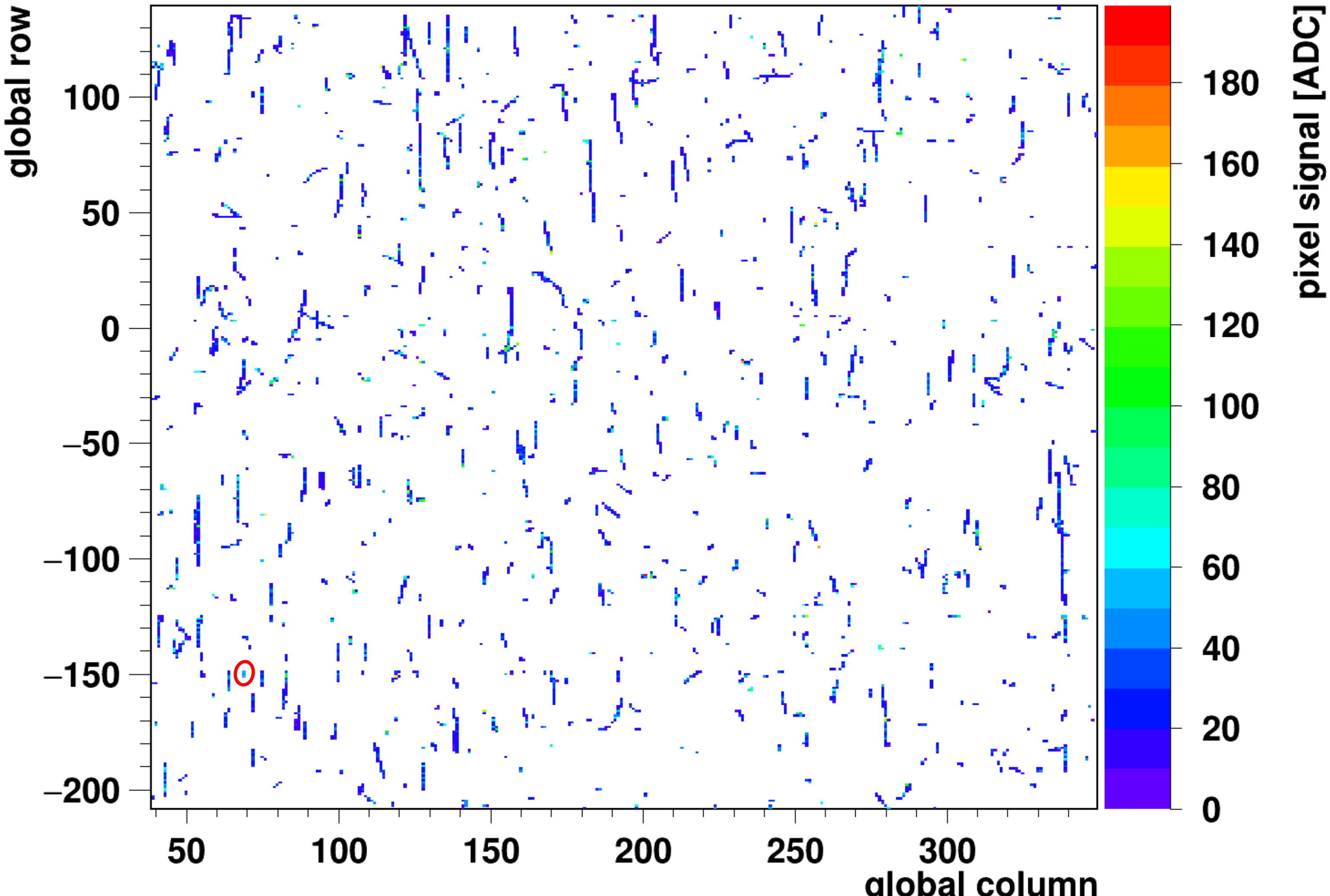
CDC





- beam currents reached 1400 mA (half the design)
  - short lifetime (Touchek scattering, synchrotron radiation, residual pressure, scattering losses)
- permanent injection: up to 25 Hz per ring:
  - single or double bunch top-up
  - injected bunch creates background spikes
  - every 10 μs for a few ms
  - detectors stay active during injection
  - first 0.5 ms masked out in trigger (deadtime)
  - pixel detector always integrates over 2 turns: observe damping oscillations

PXD event display

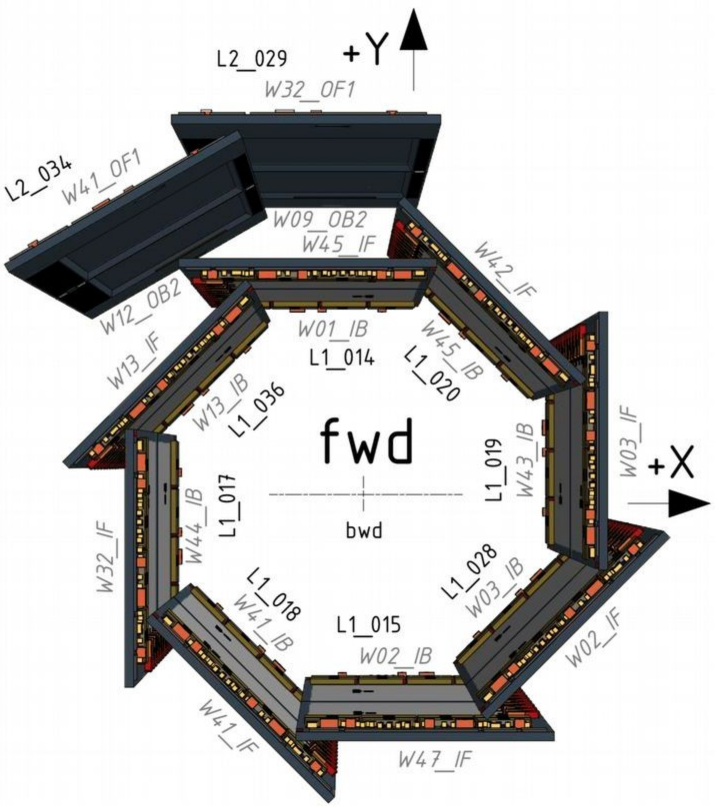


±8σ SVD window

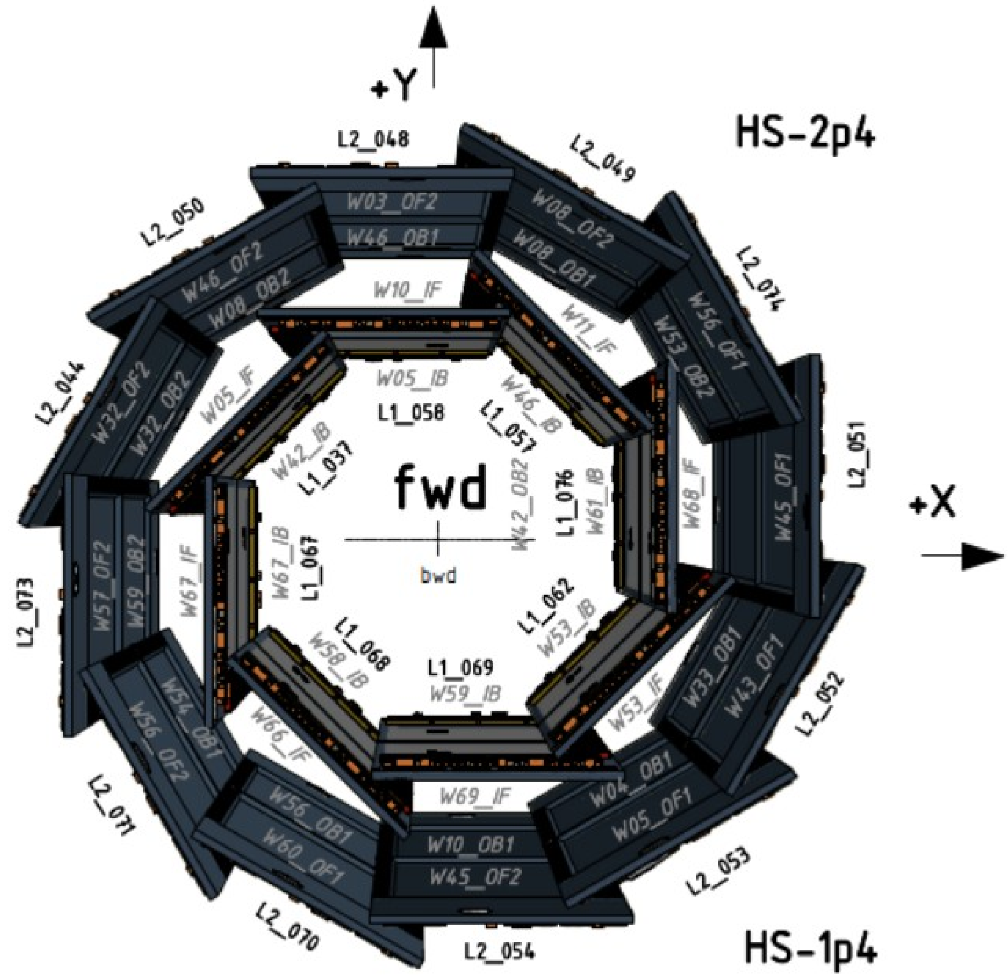
2.6% occupancy

- data event
  - zoomed-in
- 2.6% pixel occupancy
- 50×55 μm pixels
- SVD-PXD matching at the purity limit

2023: PXD completion

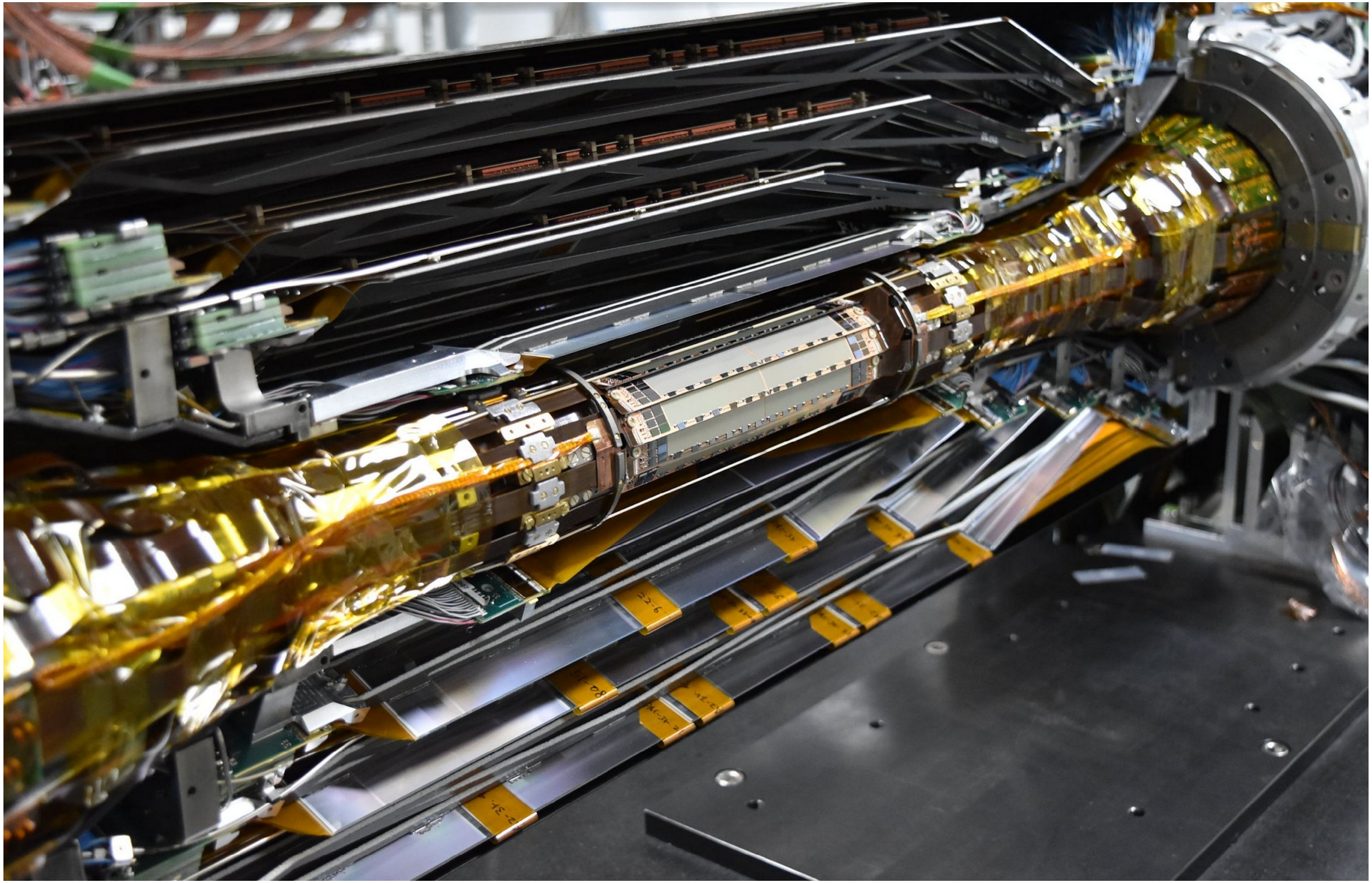


2018: lack of quality ladders
(in-house production)



2023: 40 (all new) modules, same design
(same in-house production)

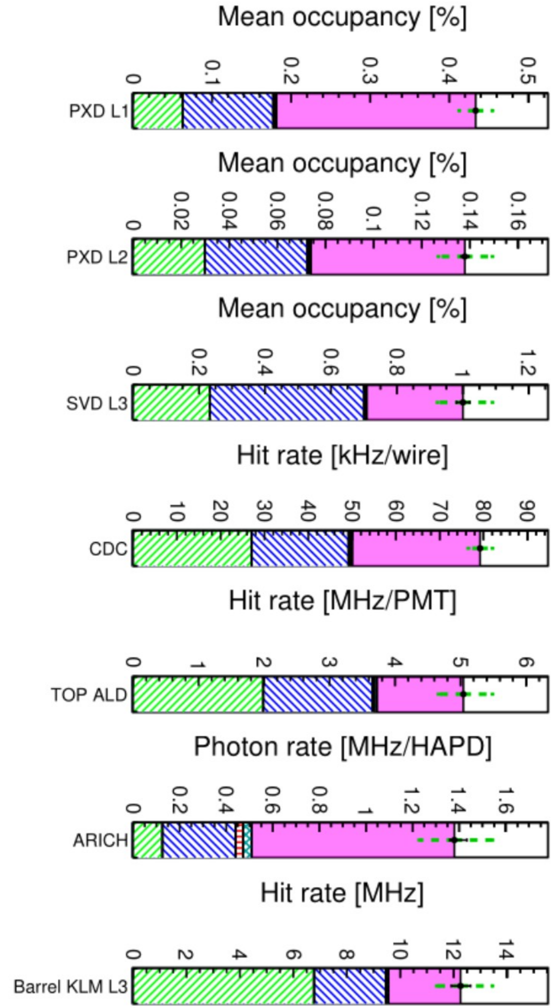
VXD 2023



- SVD and fully-equipped PXD mounted around modified beam pipe (Au coating, cooling)

background prediction for the next years

- **prediction for 2.8 $10^{35}/cm^2s$**
  - (steady state, without injection backgound)
  - simulation
- LER = 4 GeV positrons
- **LER beam gas**
- **LER Touschek**
  - in-bunch Coulomb
- **Luminosity collisions**



factor to performance limit

PXD L1: 7

PXD L2: 22

SVD L3: 5

CDC: 2

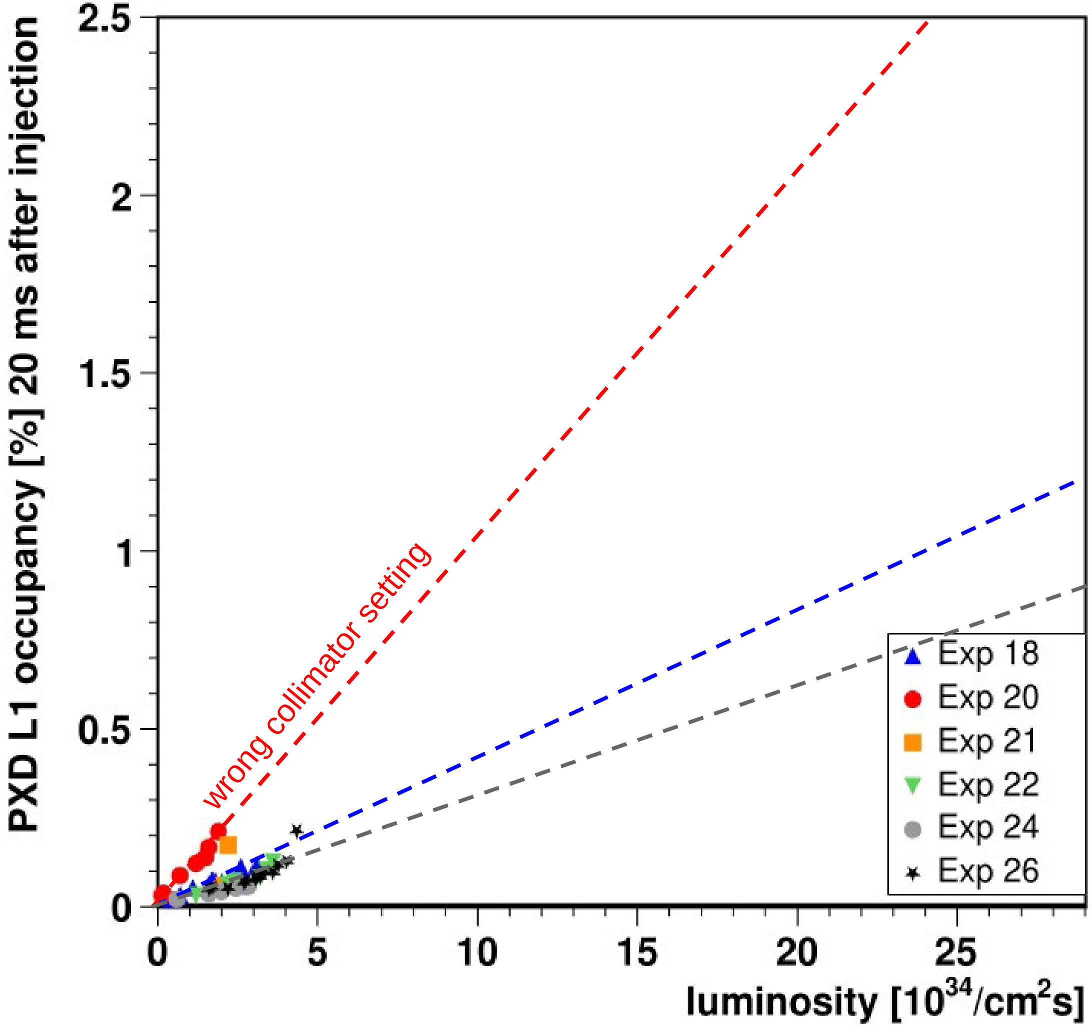
TOP: 1.5 atomic layer deposition multi-channel photomultiplier tubes

ARICH: 7

KLM: 4

A. Natochii et al. https://arxiv.org/abs/2302.01566

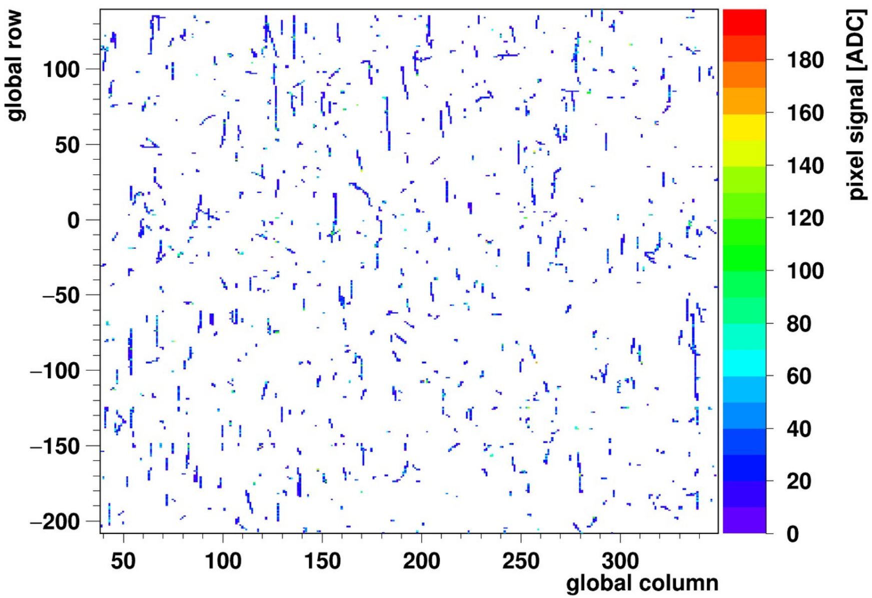
PXD L1 occupancy



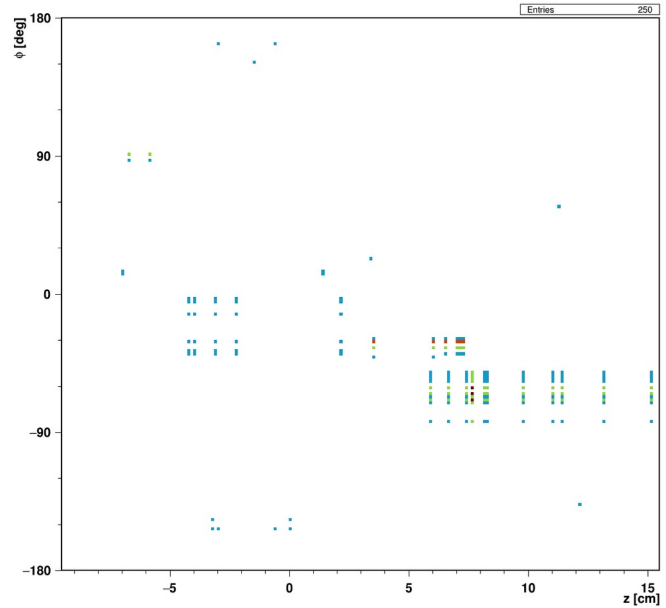
- **PXD L1 occupancy**
  - in the “steady state” (20 ms after the last injection)
  - **various running conditions 2021-2022**
- **extrapolated**
- **performance limits:**
  - **readout buffer size at 3%**
  - **SVD-PXD track matching at 3% (will improve with intermediate 2nd PXD layer)**
- **large uncharted territory**
  - **with some safety margin**

and beyond?

- **pixels: high granularity**
  - **long integration without time stamps**
  - **cluster merging, matching purity**



- **strips: fast readout**
  - **measures projections per sensor**
  - **ghosts**

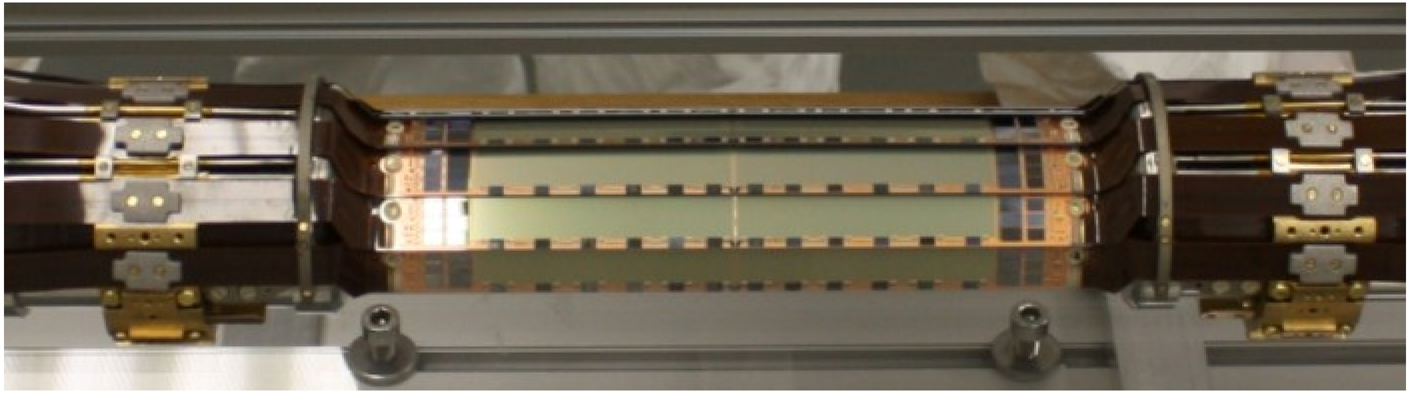


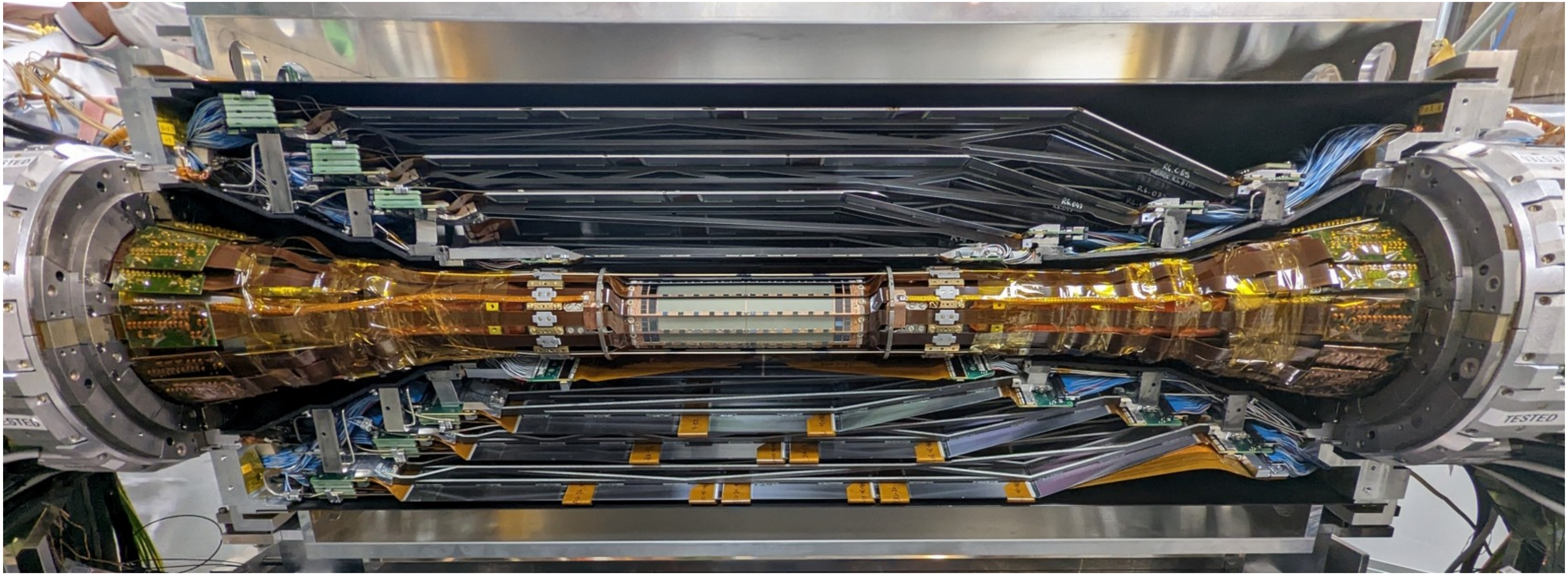
- **want the best of both technologies:**
  - **a fast pixel detector**
  - **see upgrade talk by C. Finck tomorrow**

summary

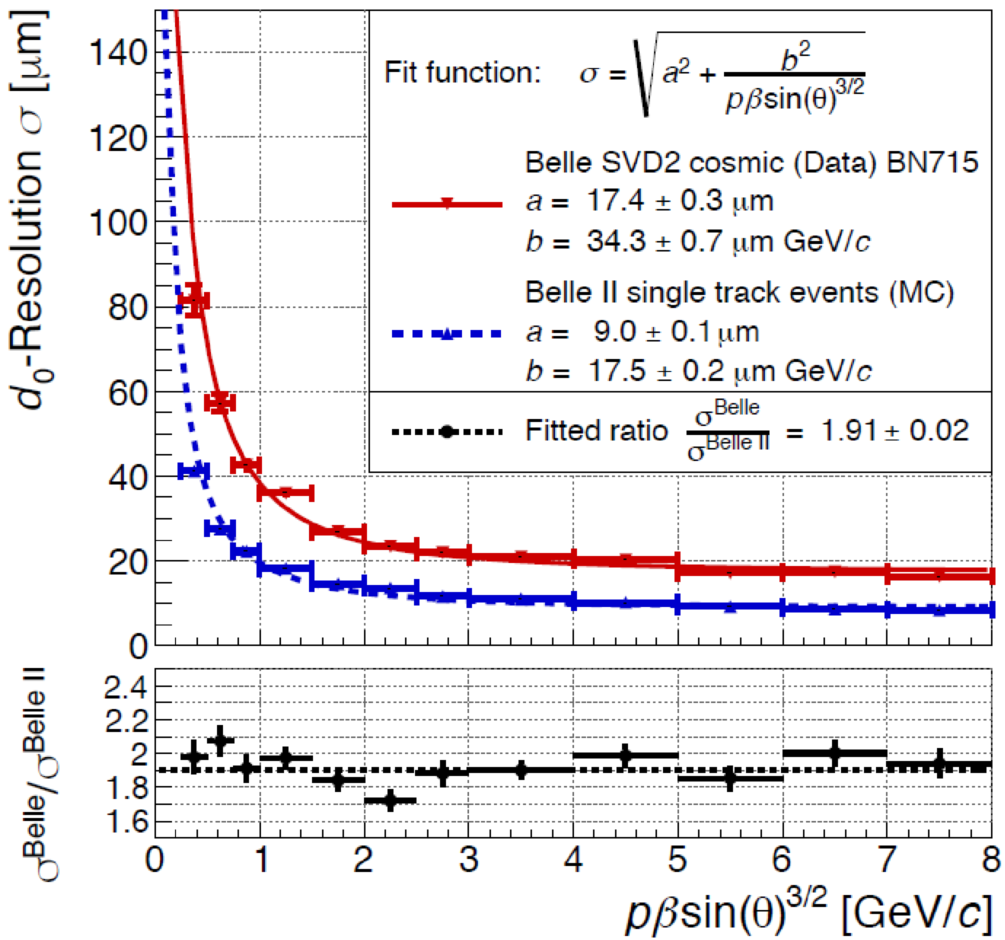
- TheBelle II silicon vertex detectors (strips and pixels) have operated successfully at SuperKEKB since 2019
  - in terms of efficiency, purity, and resolution
  - satisfying the design parameters for the Belle II physics program
- The completed 2-layer pixel detector with all-new modules is expected to provide efficient vertexing for the coming years, with safety margin for occupancy variations

VXD 2023

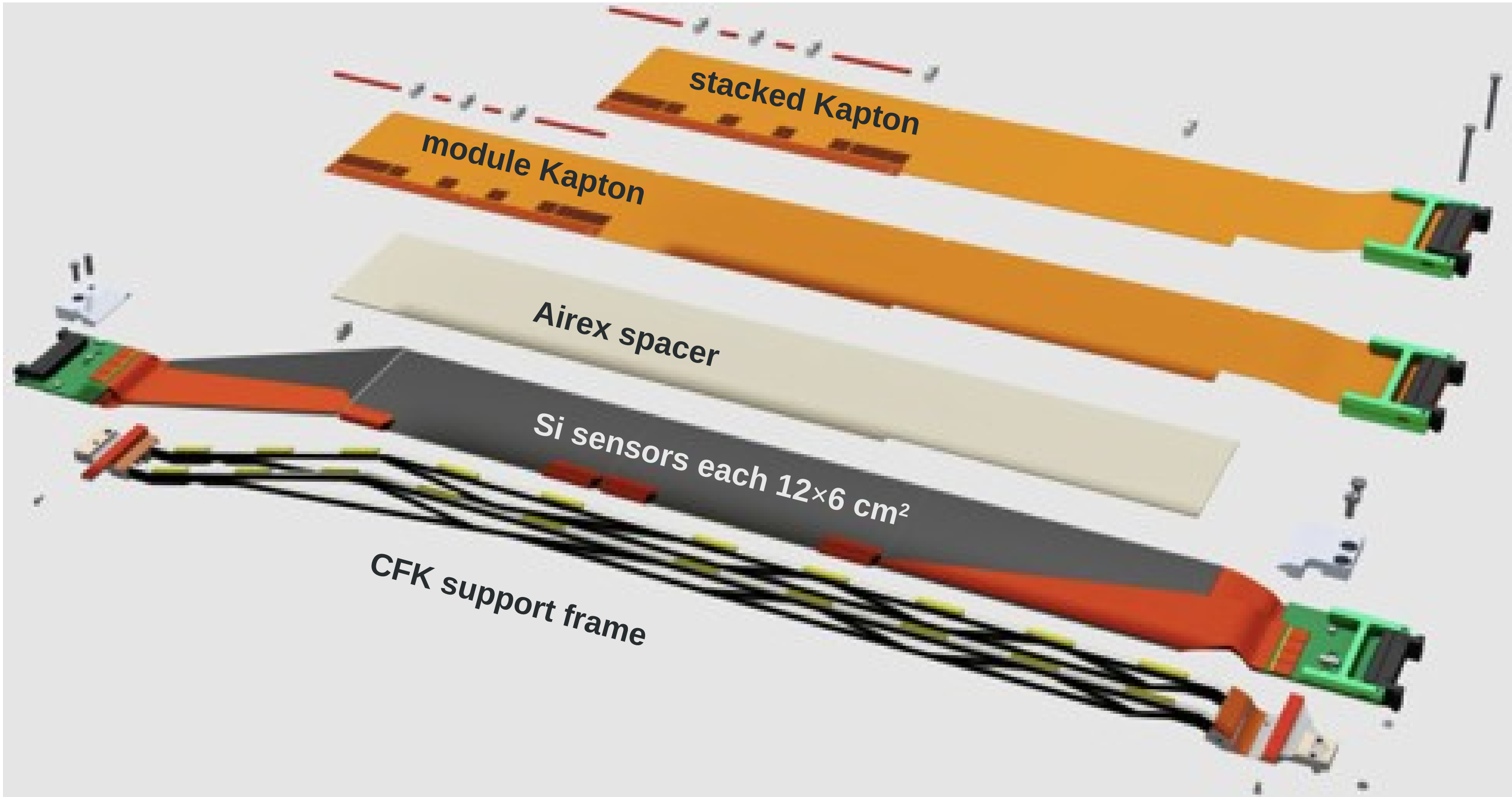




impact parameter resolution: Belle II MC vs Belle

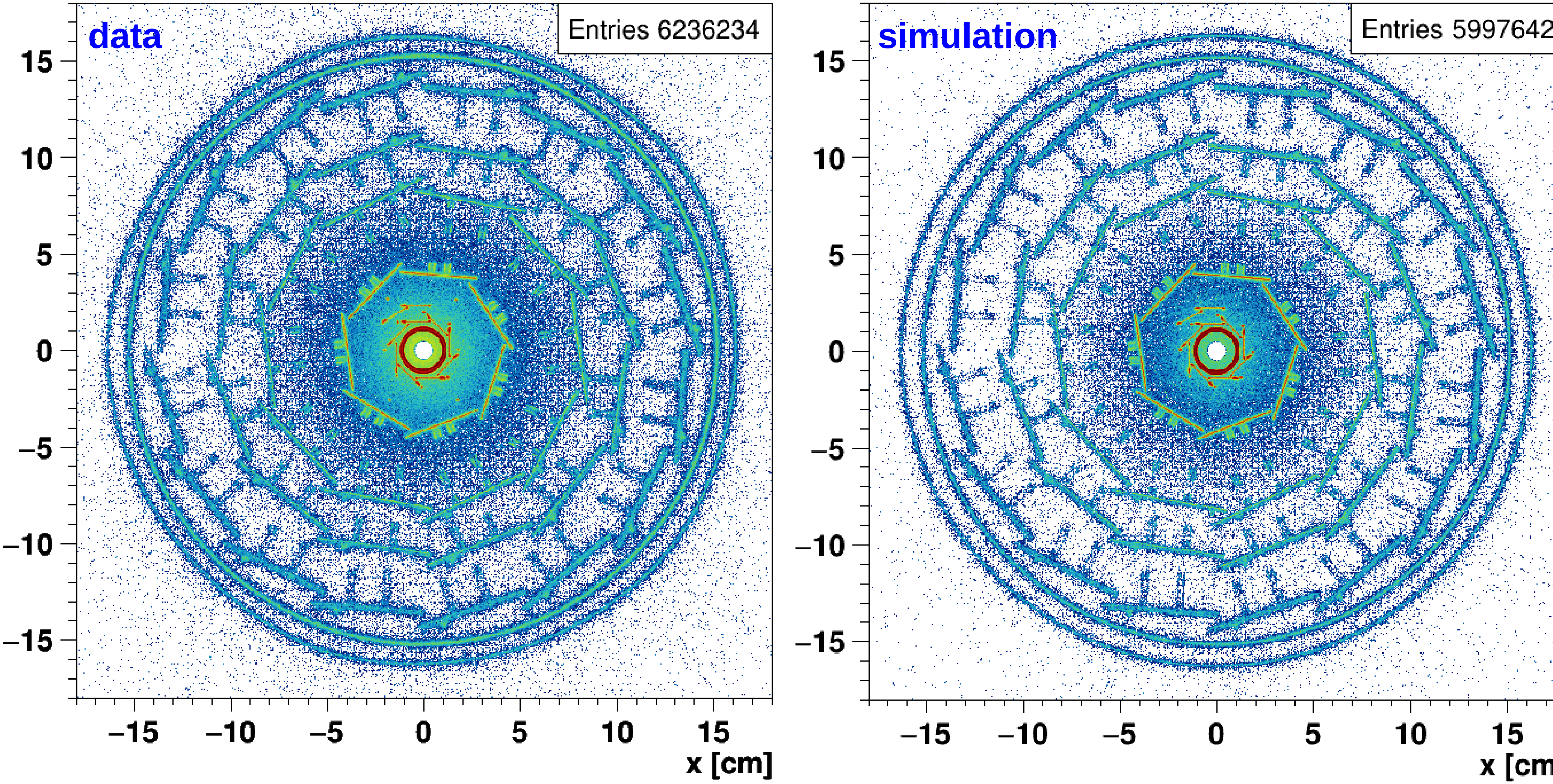


SVD ladder components



0.7% X_0 per layer (in the active volume)

material imaging



3-track vertices from nuclear interactions