The Silicon Vertex Detector of the Belle II Experiment

Alice Gabrielli
On behalf of the Belle II SVD collaboration

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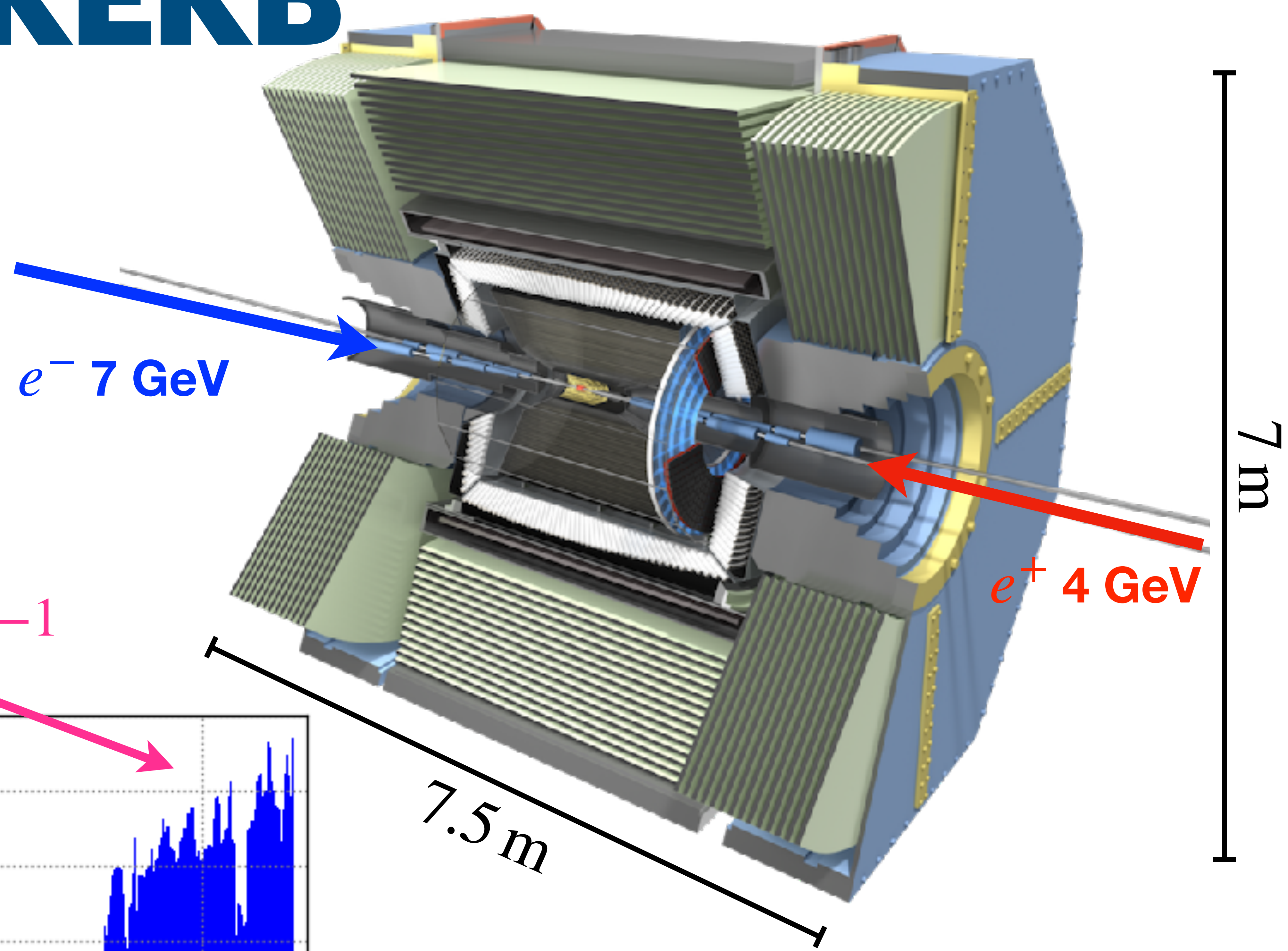
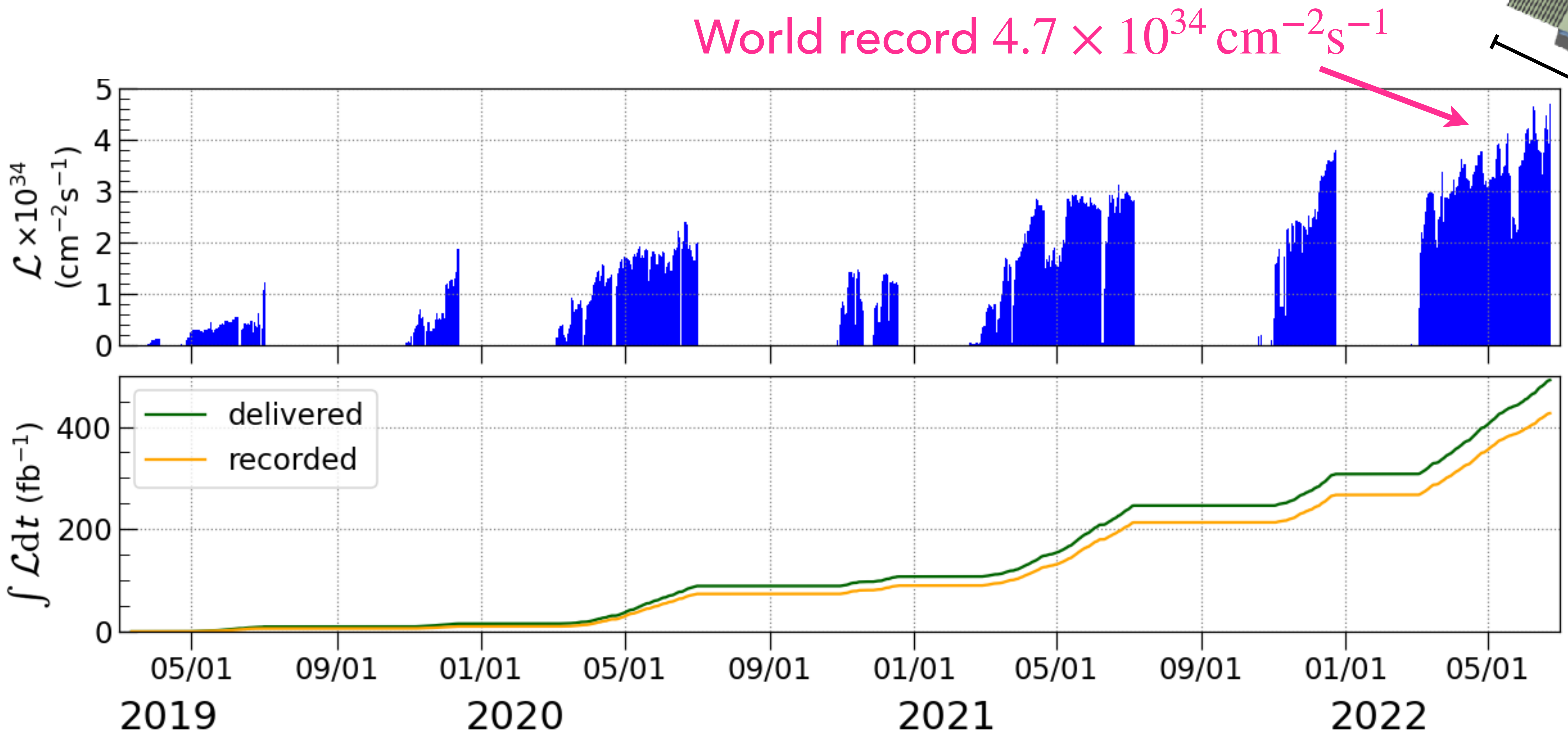
Outline

- Belle II experiment and Silicon Vertex Detector (SVD)
- SVD operation status by 2022 and Long Shutdown 1 (LS1)
  - ⇒ Detector performance
  - ⇒ VXD re-installation
- Towards high luminosity
  - ⇒ Offline software developments towards high luminosity
  - ⇒ Radiation damage effects
- Summary

Belle II experiment at SuperKEKB

- Belle II searches for new physics beyond standard model at luminosity frontier
- SuperKEKB collider: asymmetric e^+e^- collisions at $\Upsilon(4S)$ resonance at 10.58 GeV





Target

$\int \mathcal{L}\mathrm{d}t = 50\ \mathrm{ab}^{-1}$

$\mathcal{L} = 6 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$

Achieved

$\int \mathcal{L}\mathrm{d}t = 424\ \mathrm{fb}^{-1}$

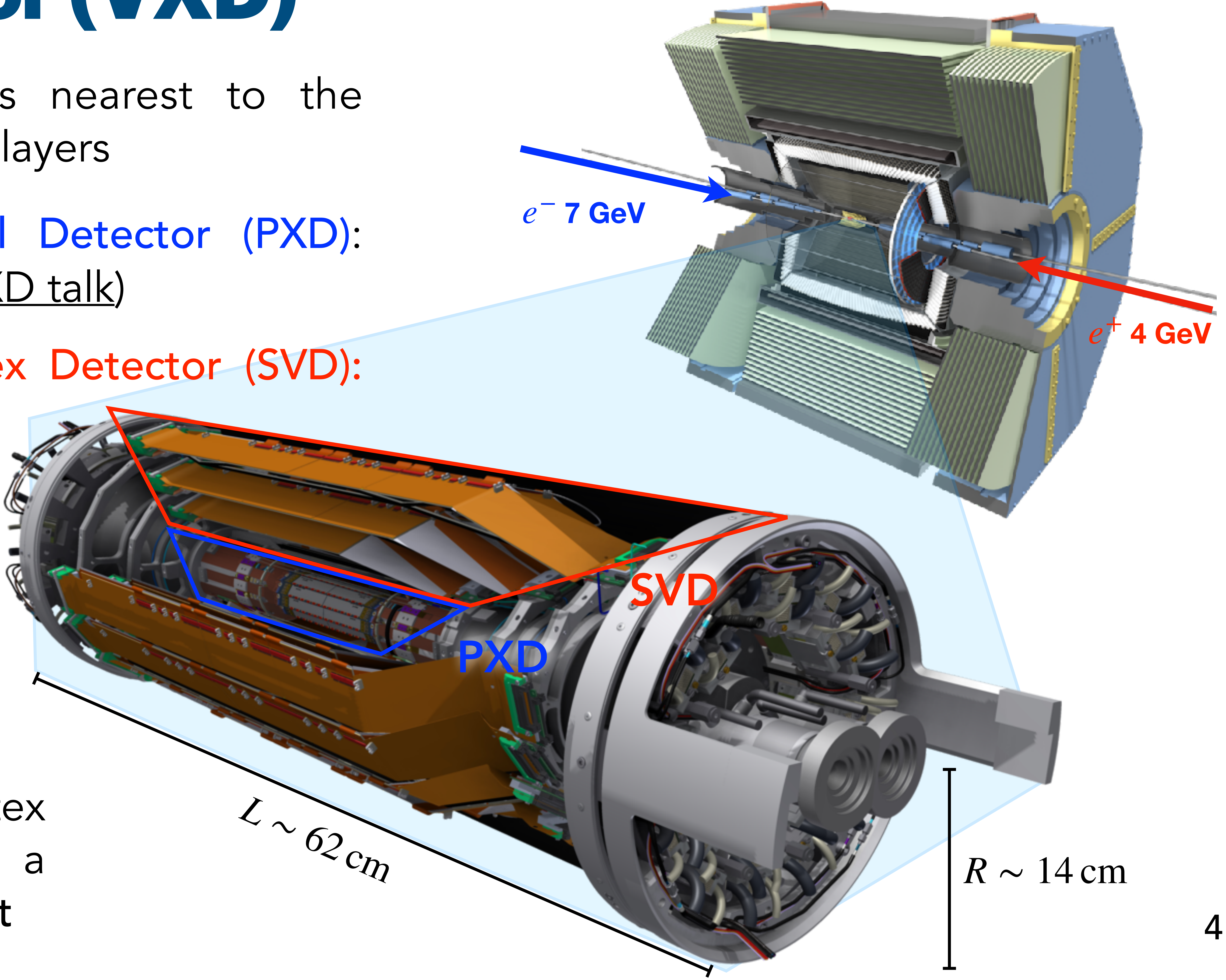
$\mathcal{L} = 4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

Vertex Detector (VXD)

- Vertex Detector (VXD) sits nearest to the interaction point with total 6 layers

  ⇒ Inner 2 layers of Pixel Detector (PXD): DEPFET pixel sensor (see PXD talk)

  ⇒ 4 layers of Silicon Vertex Detector (SVD): Double-sided strip



- PXD was partially installed in 2018: the second layer covered only 1/6 of the azimuthal angle

- **Requirements:** excellent vertex resolution and operation in a high-background environment

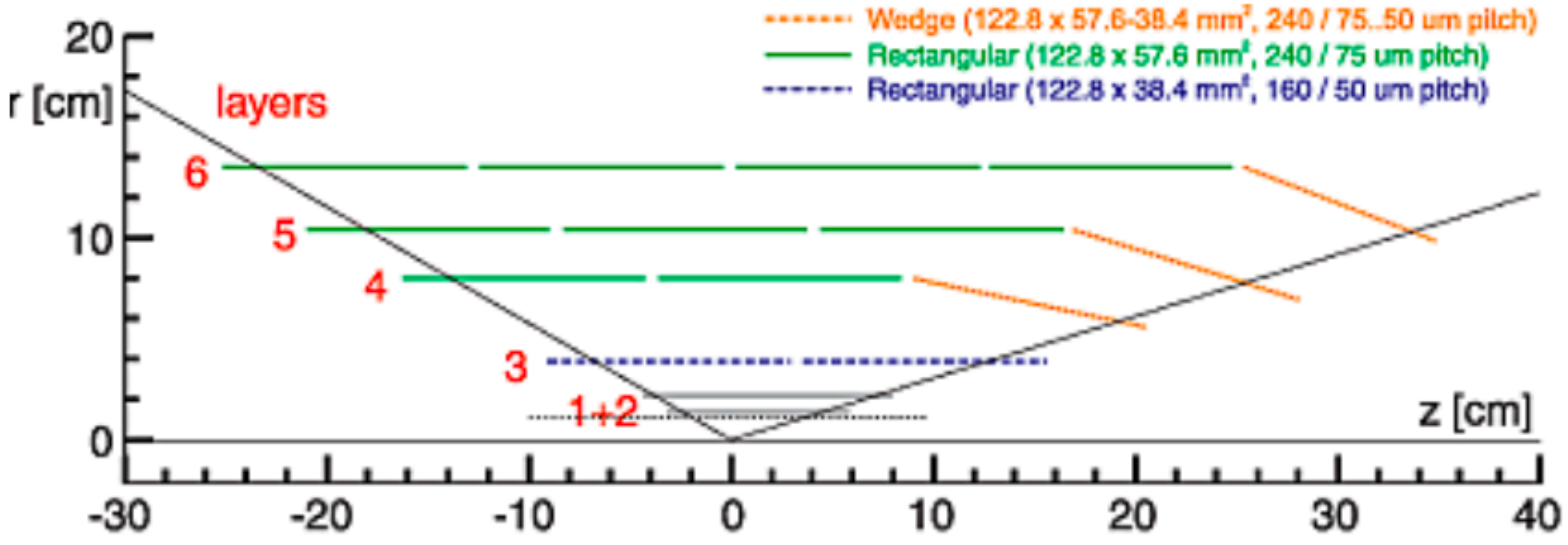
Silicon Vertex Detector (SVD)

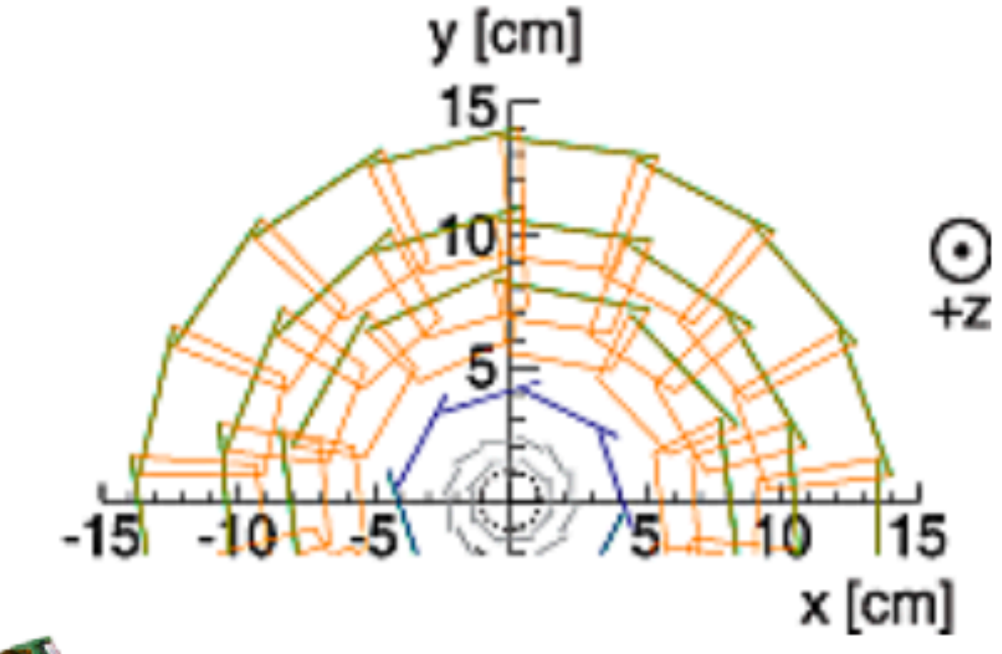
SVD structure :

- Sensors grouped into ladders: 172 sensors, $1.2\,\mathrm{m}^2$ sensor area, 224k readout strips
- Forward sensors are slanted to maximise acceptance with smaller incidence angle
- Low material budget of $0.7\,\%\,X_0$ /layer

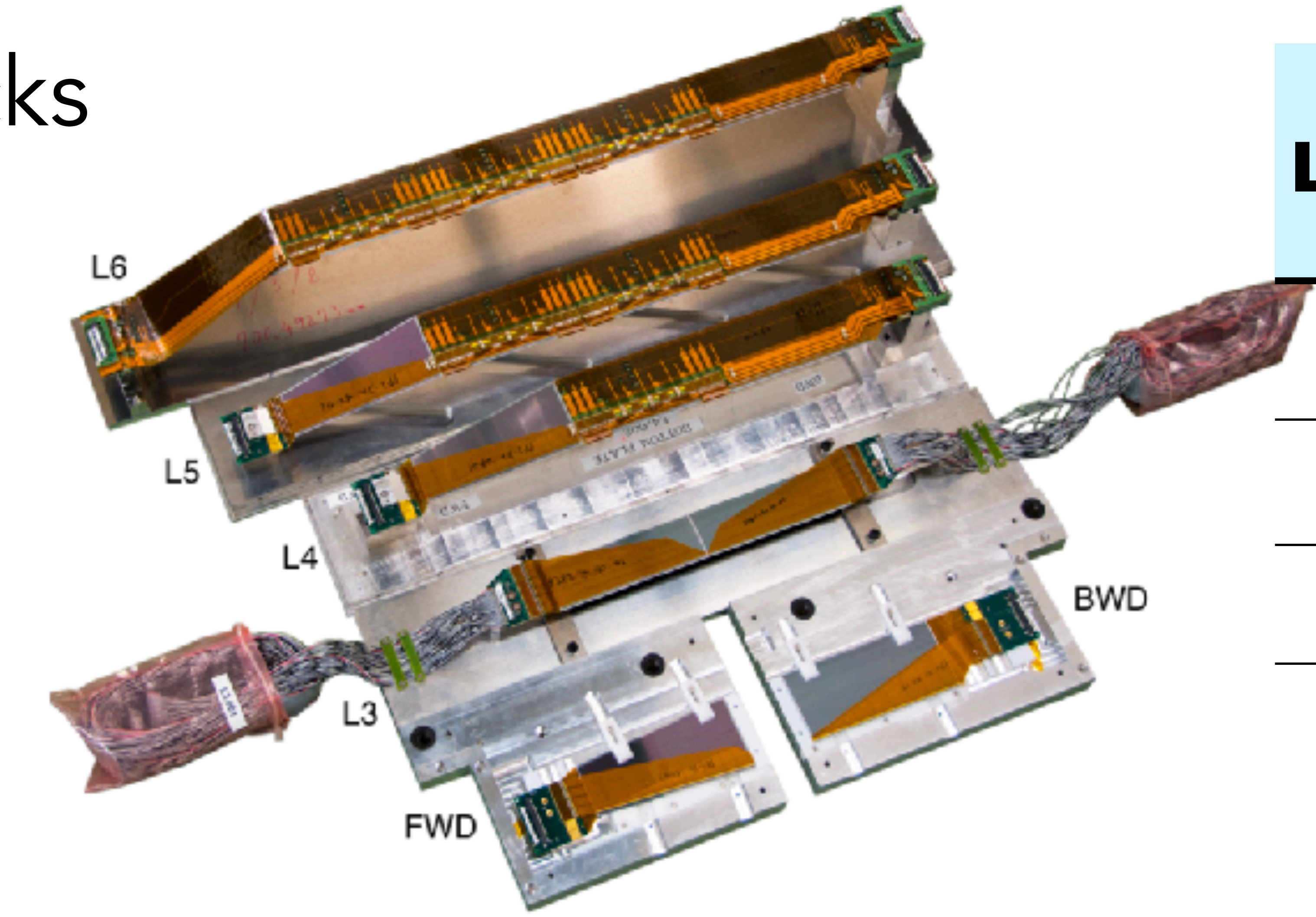
Main SVD functions:

- Standalone tracking for low p_T tracks
- Extrapolate tracks to PXD
- Precise & efficient vertexing of K_S
- Particle identification with dE/dx





⇒ Windmill geometry

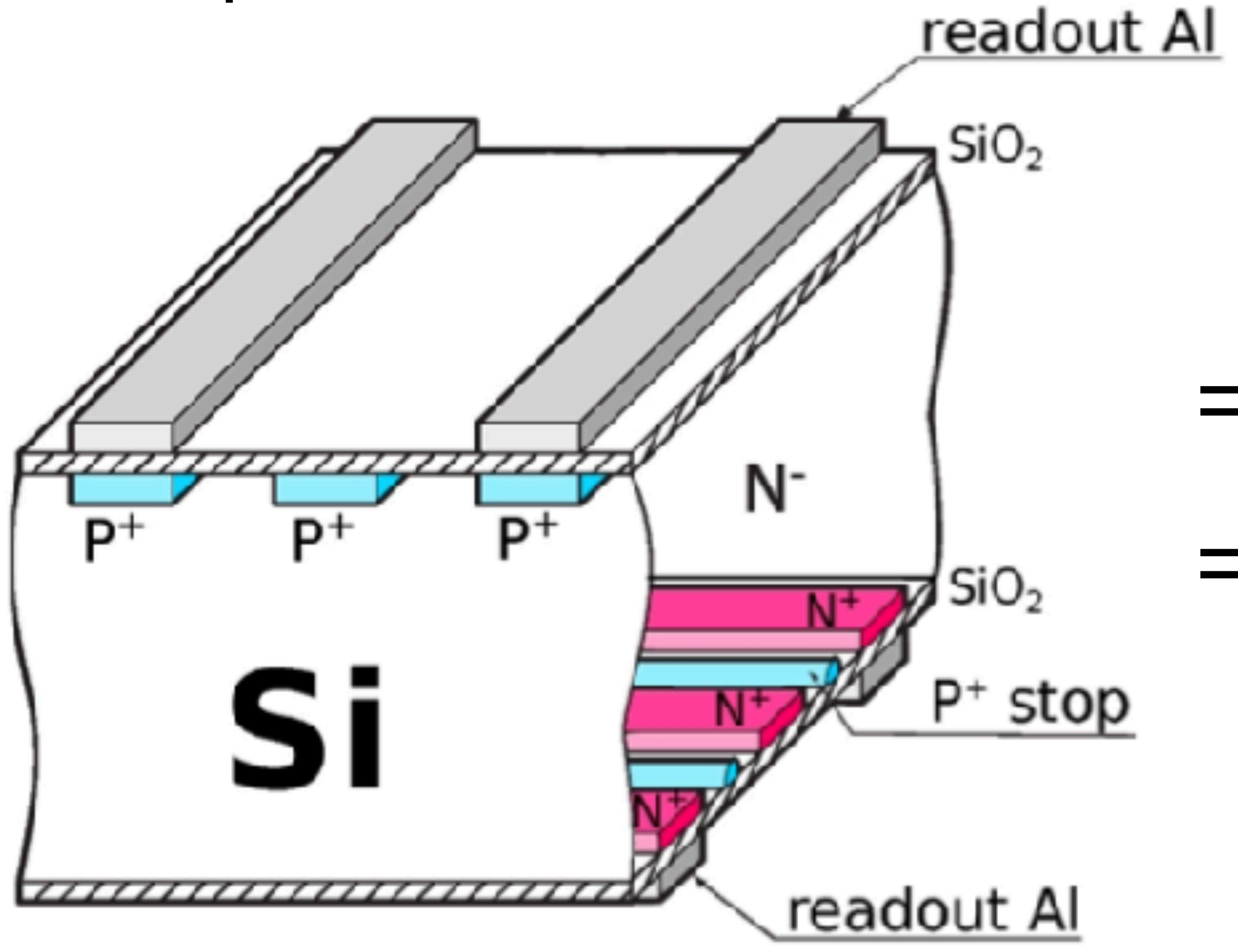


Layer	Ladder	Sensor/ ladder	Radius [mm]
3	7	2	39
4	10	3	80
5	12	4	104
6	16	5	135

SVD sensors and front-end ASIC

- Double-Sided Strip Detector (DSSD):

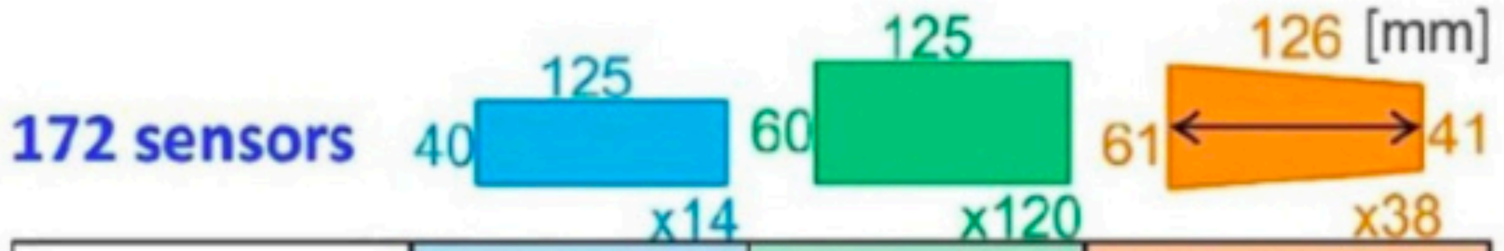
  2D spatial information P-side: $u \equiv r\phi$, N-side: $v = z$



⇒ Depletion voltage: 20-60V

⇒ Operation voltage: 100V

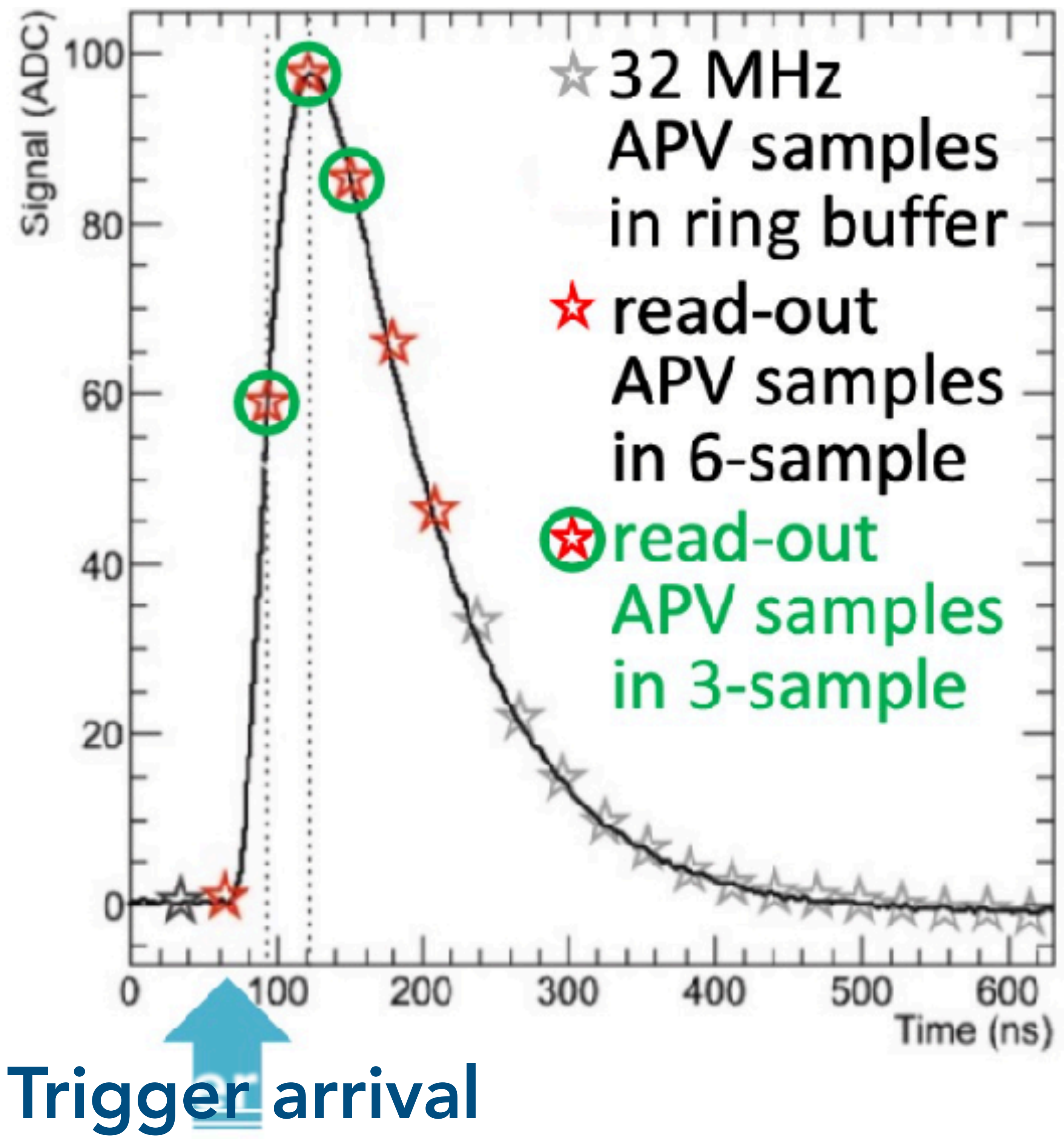
- 3 different types of DSSD shapes



	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

- Front-end ASIC: APV25 chip
  - Radiation hard: >100 Mrad
  - Shaping time of 50 ns
  - 128 channel inputs
  - Multi-peak mode at 32 MHz



⇒ 6 subsequent samples readout

⇒ 3/6-mixed acquisition mode ready for high luminosity runs: reduce background occupancy, dead-time and data-size

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SVD operation status

March 2019

First Physics Data with VXD "Run1"

July 2022

LS1 activities:
1. Accelerator and detector maintenance & improvements
2. VXD reinstallation

January 2024

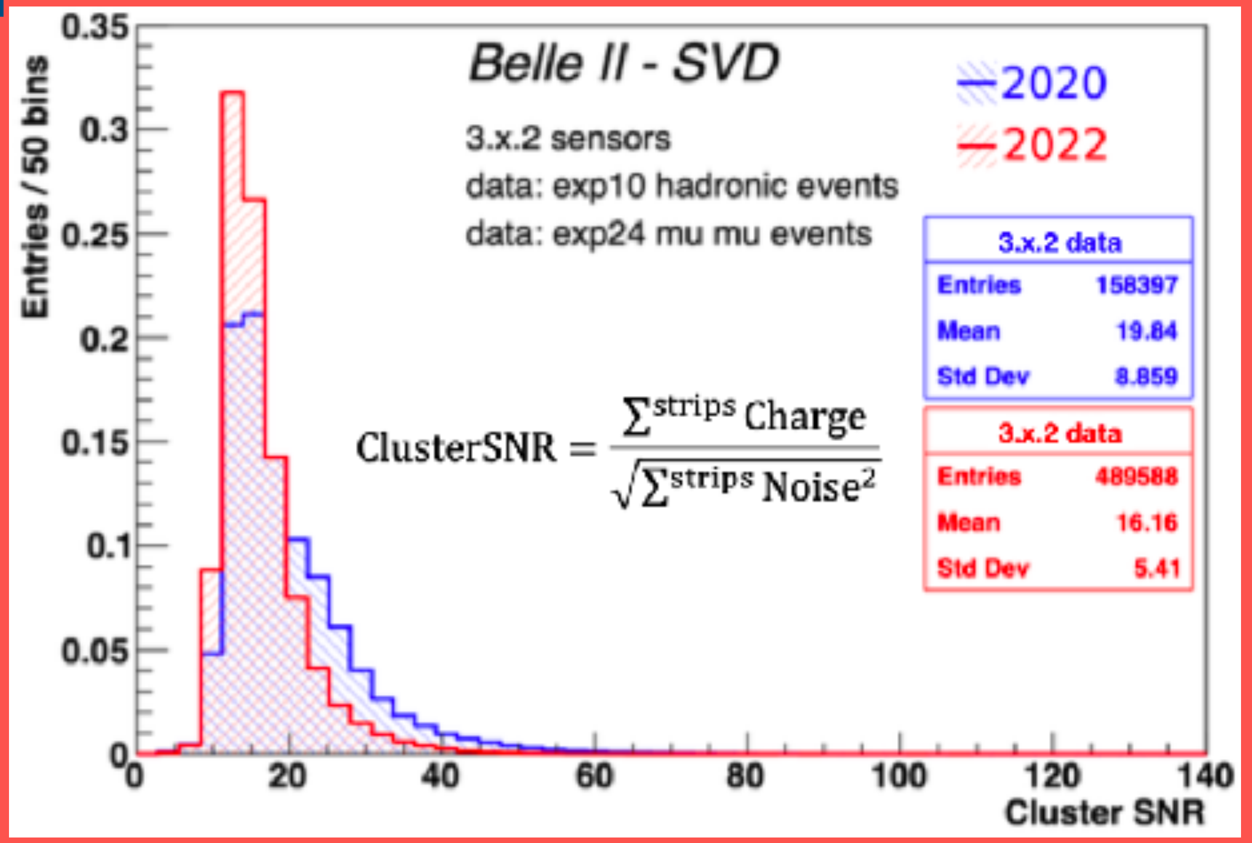
Resume beam operation "Run2"

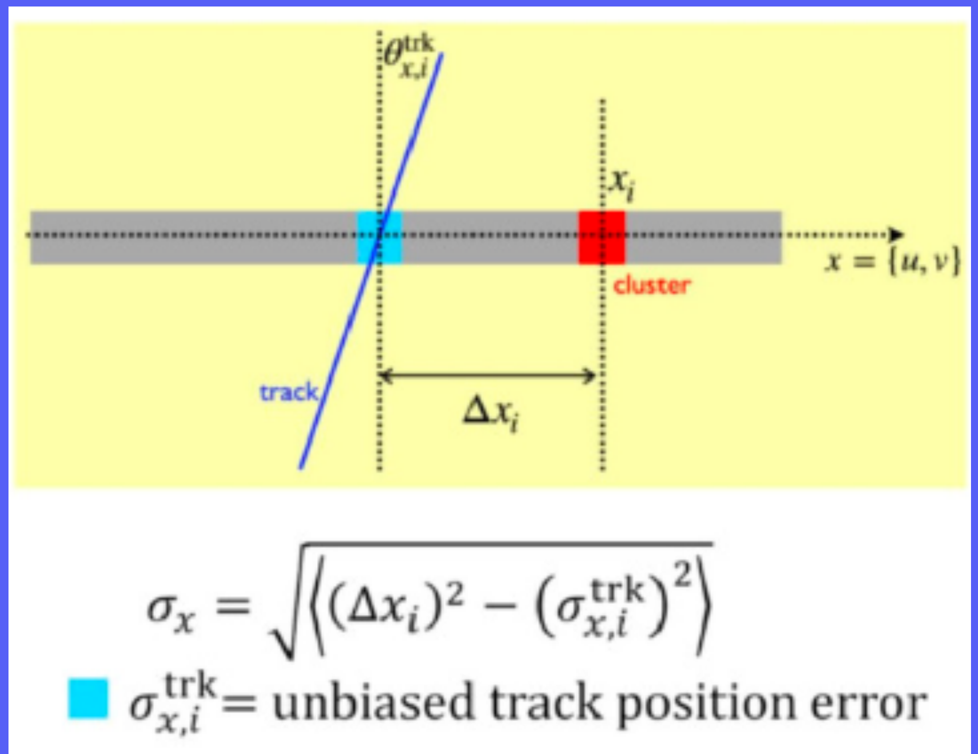
- Smooth and stable operation without major issues
- Masked strips are less than 1%
- Stable environment and calibration constants evolution consistent with expectation
- Excellent detector performance:
  Good signal-to-noise ratio (SNR), precise position and time resolution and large hit efficiency (>99% and stable over the data taking period)
- Background effects are well under control

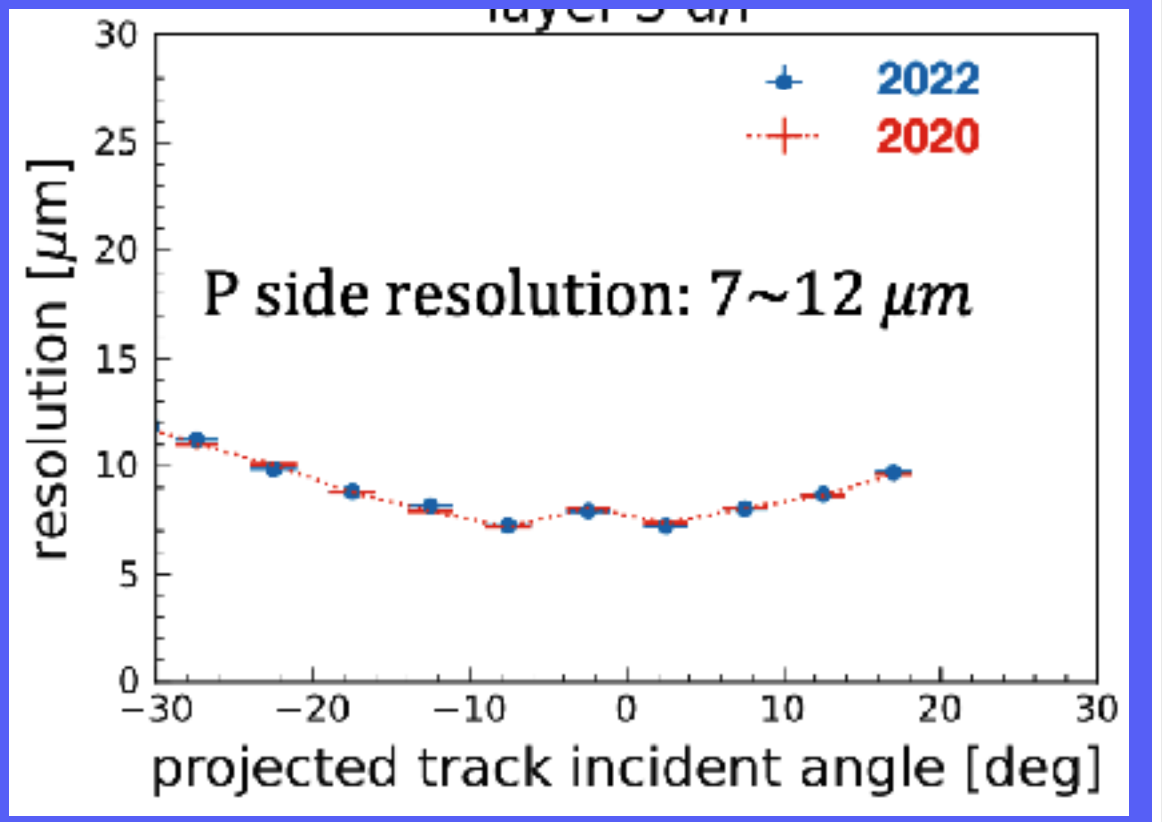
SVD performance 2020 - 2022

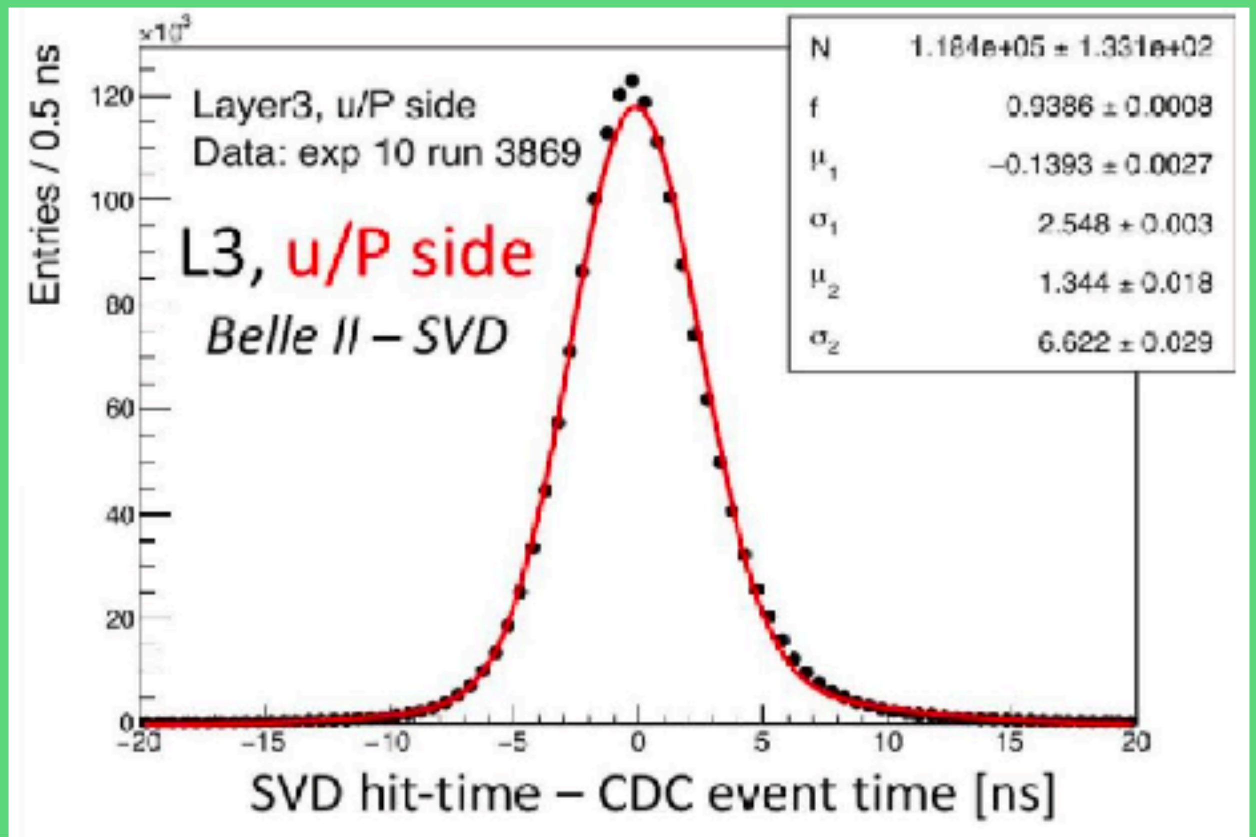
- **Good stability** of cluster charge and SNR from 2020 to 2022
- **Small changes** observed in **SNR** due to noise increase by radiation damage, as expected
- **SNR 13-30**, depending on sensor position and side
- Position resolution is calculated from the cluster position with respect to the track extrapolation using $e^+e^- \rightarrow \mu^+\mu^-$sample
- **Good and stable position resolution** is observed during the operation, as expected from pitches
- **Hit time** resolution: measured w.r.t. **event time** of the collision, provided by Central Drift Chamber (CDC) ⇒ **excellent result of < 3 ns**

Layer 3 - u/P side









VXD reinstallation

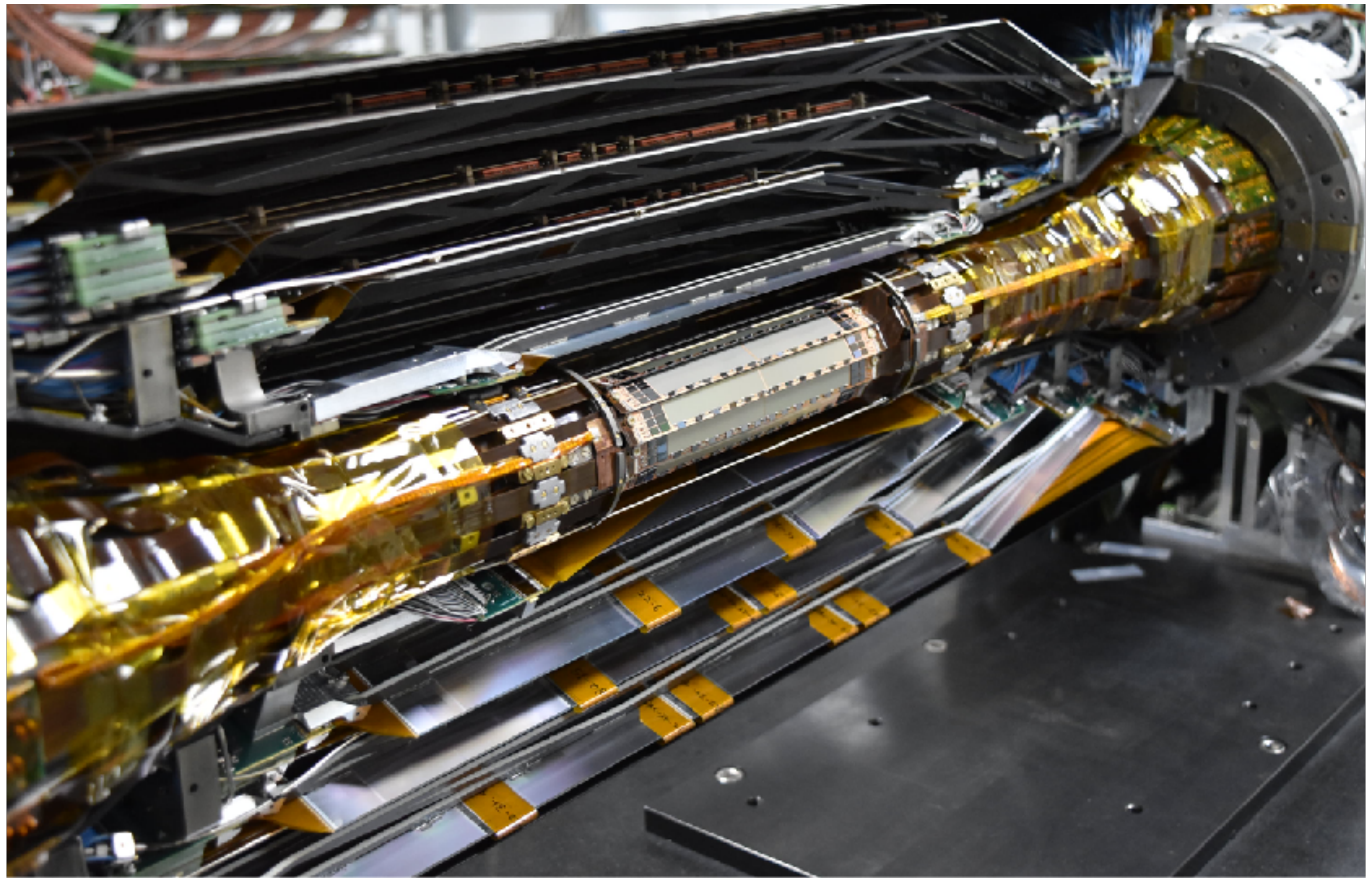
- Upgrade VXD with a complete PXD and the same SVD
- Intense hardware activities on SVD for the VXD deinstallation/reinstallation

  ⇒ >5 months with many delicate steps

- Several SVD test campaigns organised and performed after each step during LS1 (in the clean room and Belle II)

  ⇒ Important to promptly spot problems and sanity check the detector performance at each step

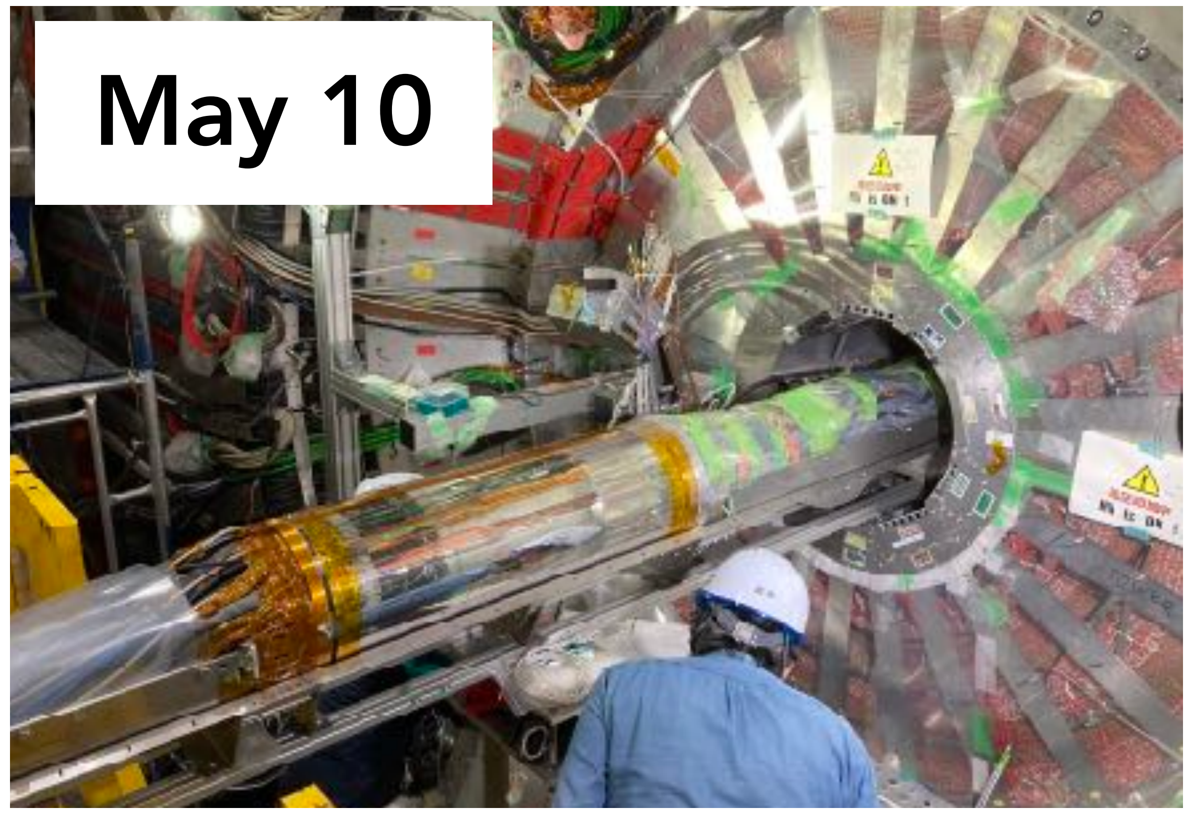
  ⇒ Optimised the cooling conditions with the PXD higher power consumption before starting the operation

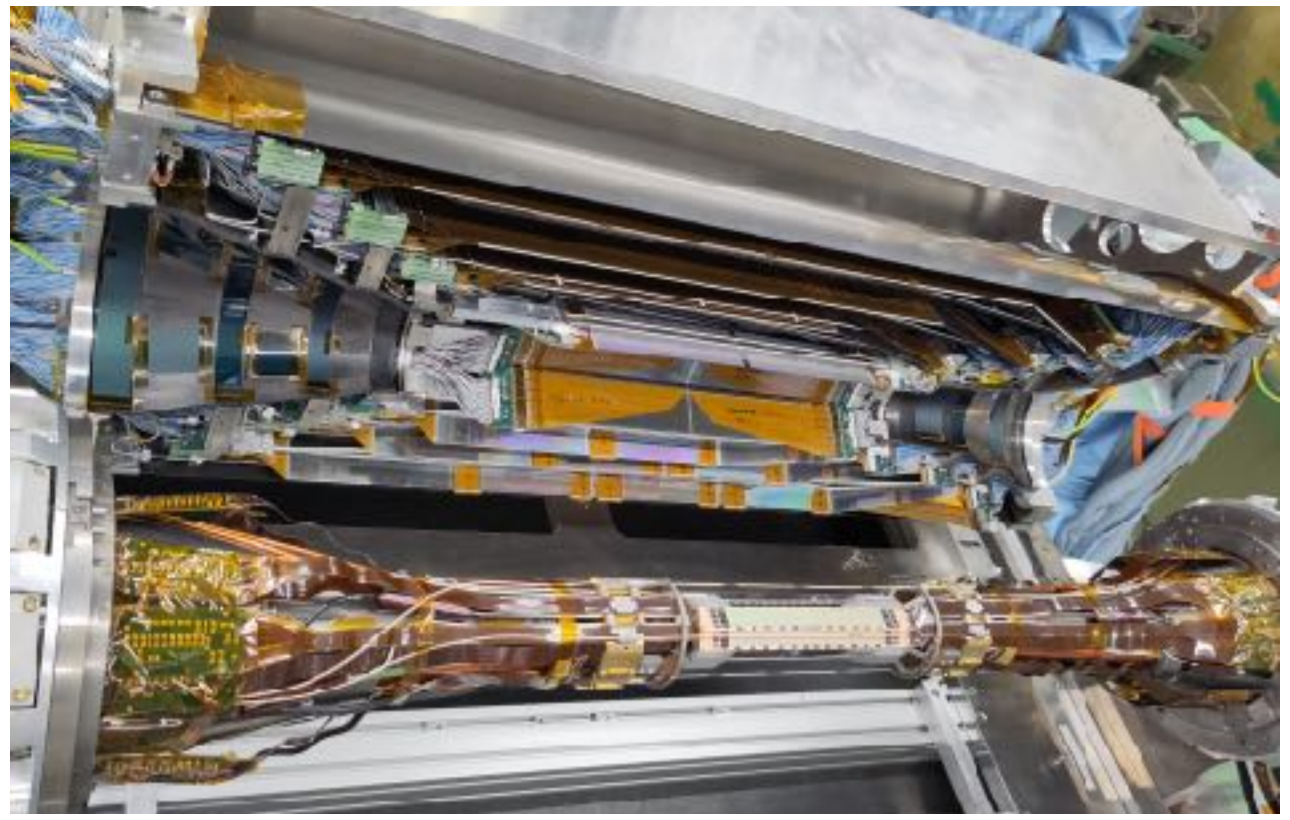


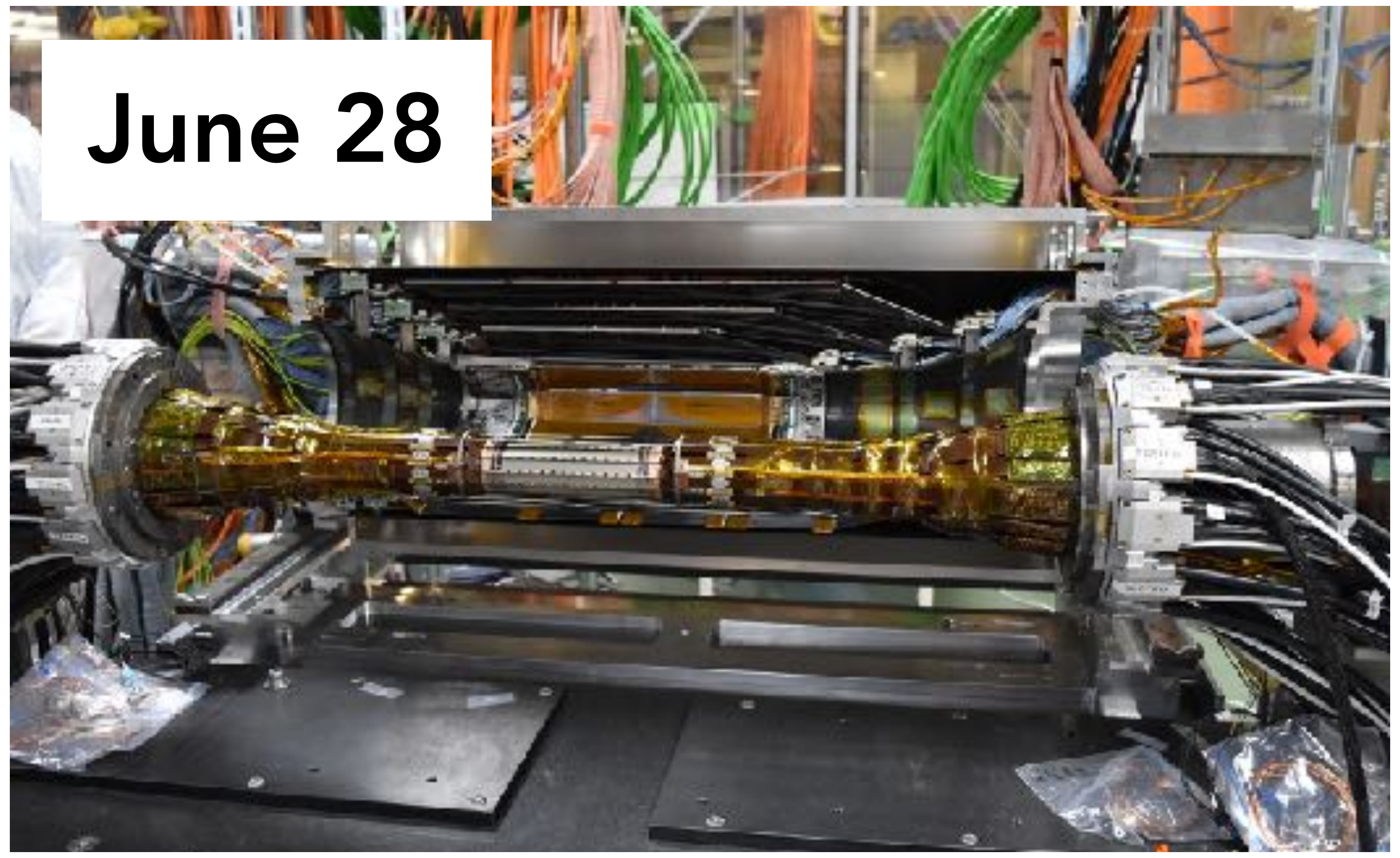
May, 10th 2023	VXD extraction	Belle II
May, 17th 2023	SVD detachment	clean room
June, 1st 2023	SVD commissioning	clean room
June, 28th 2023	New VXD assembly	clean room
July, 14th 2023	New VXD commissioning	clean room
July, 28th 2023	New VXD installation	Belle II
Sept, 22nd 2023	Functional tests and commissioning with cosmic-ray	Belle II

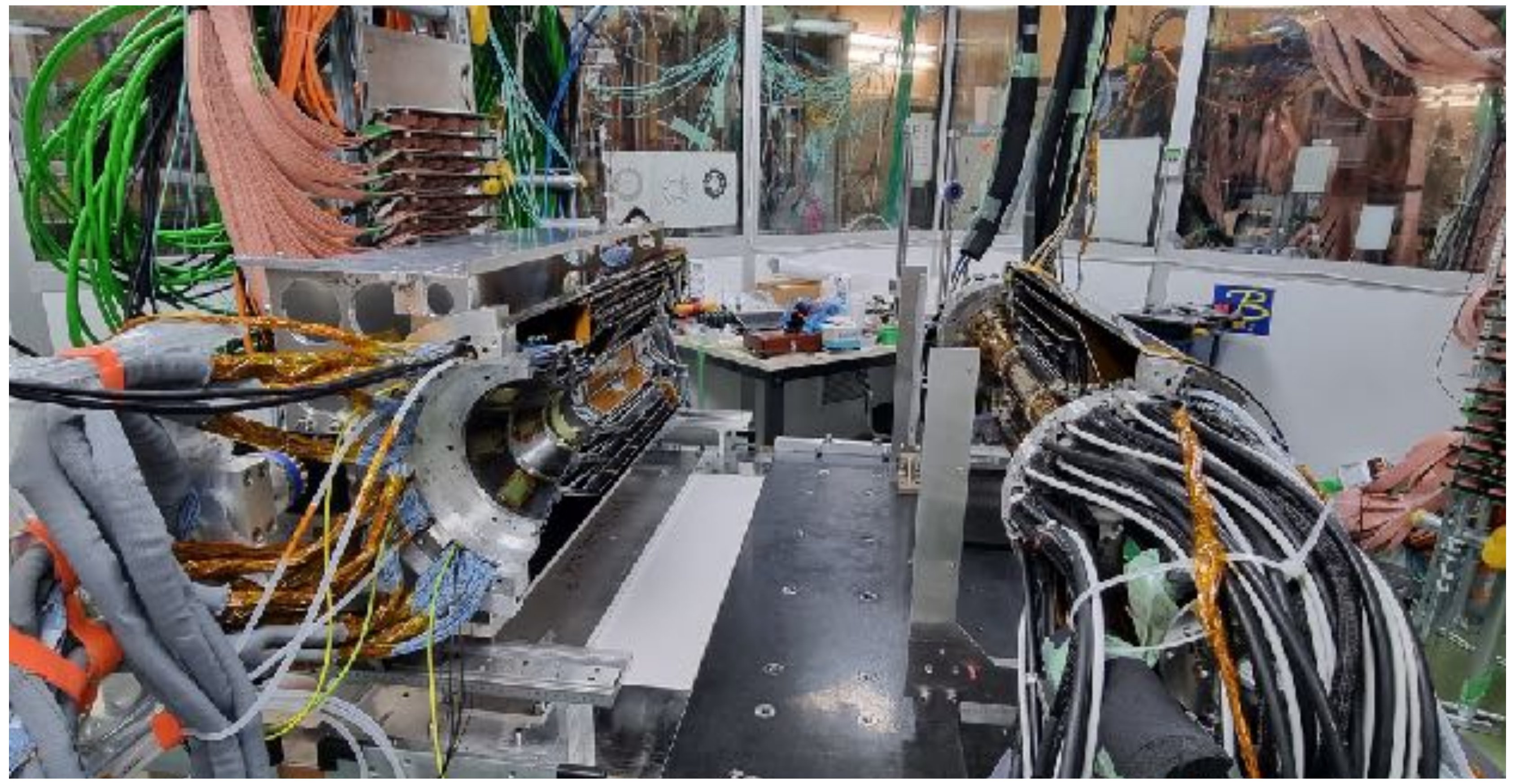
Operation January 2024

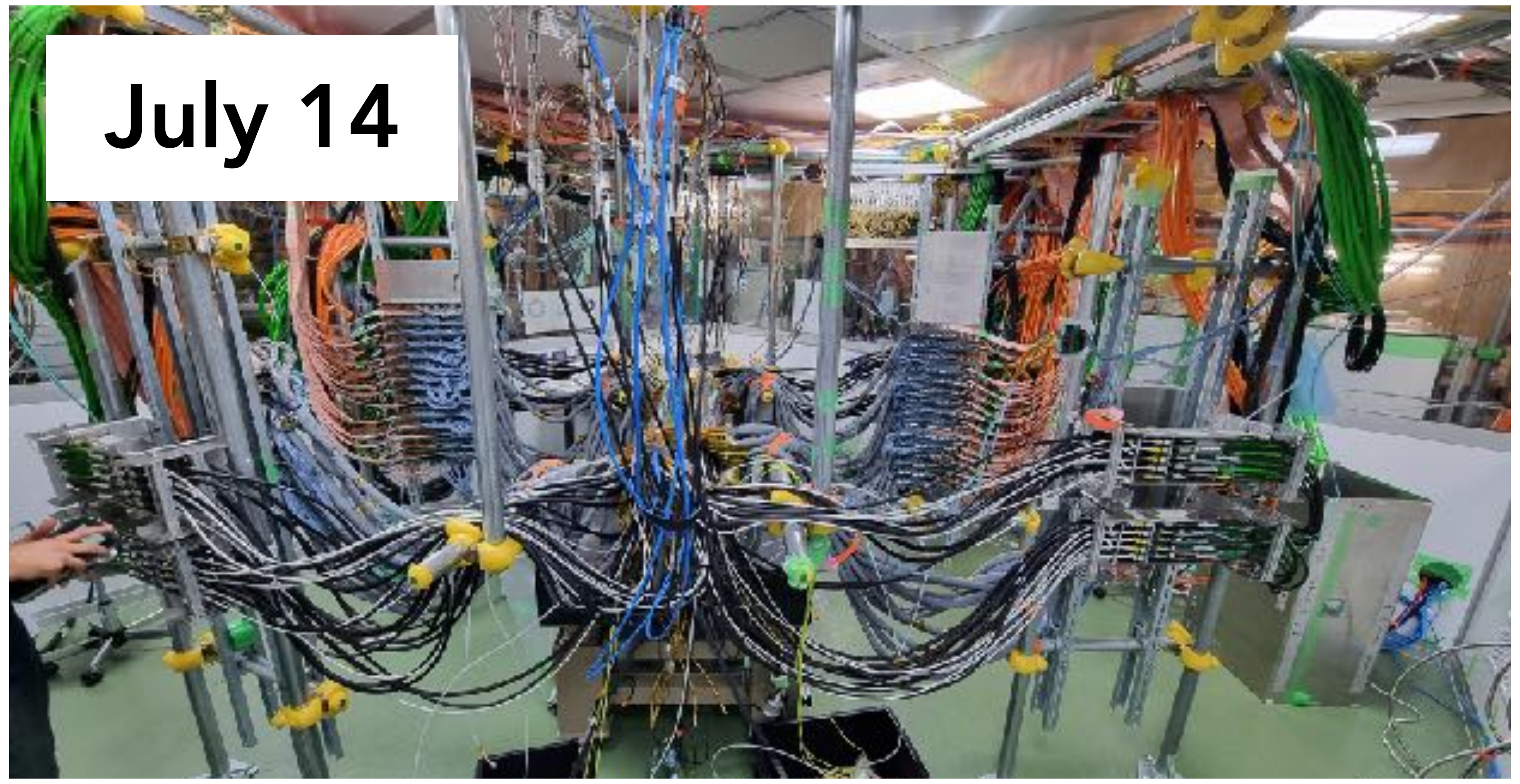
VXD reinstallation

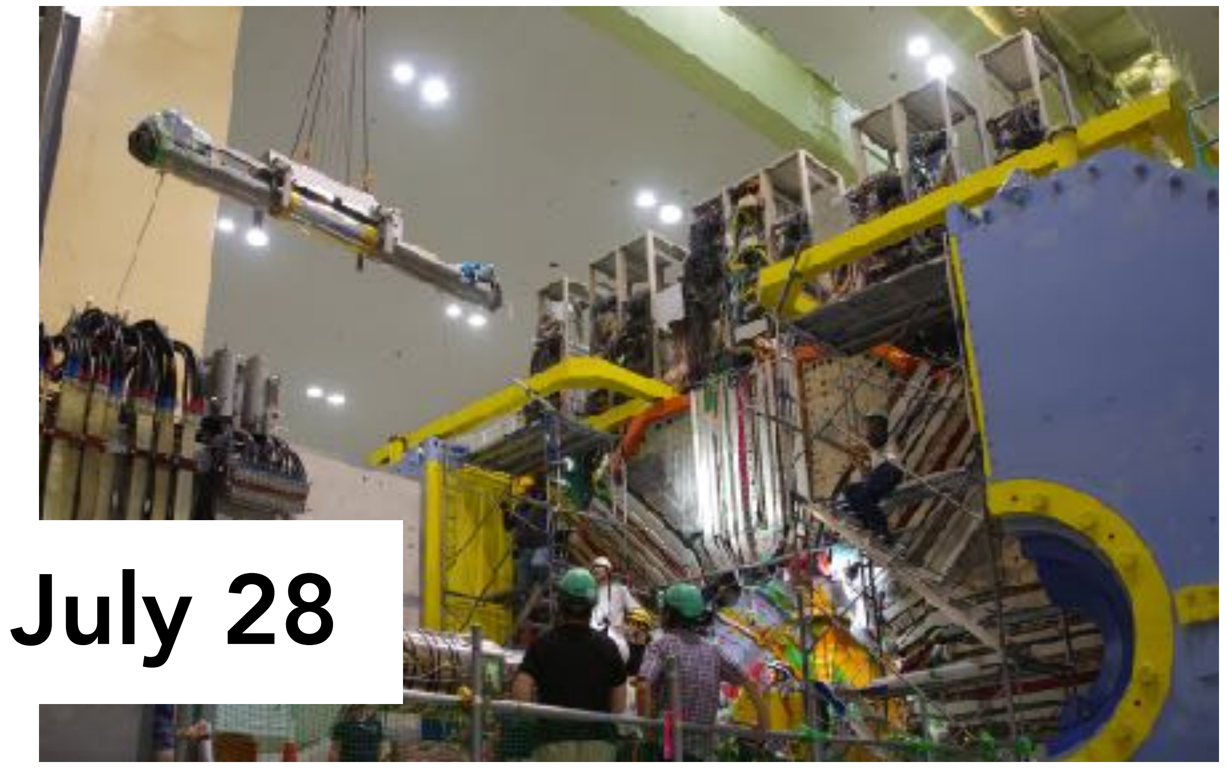


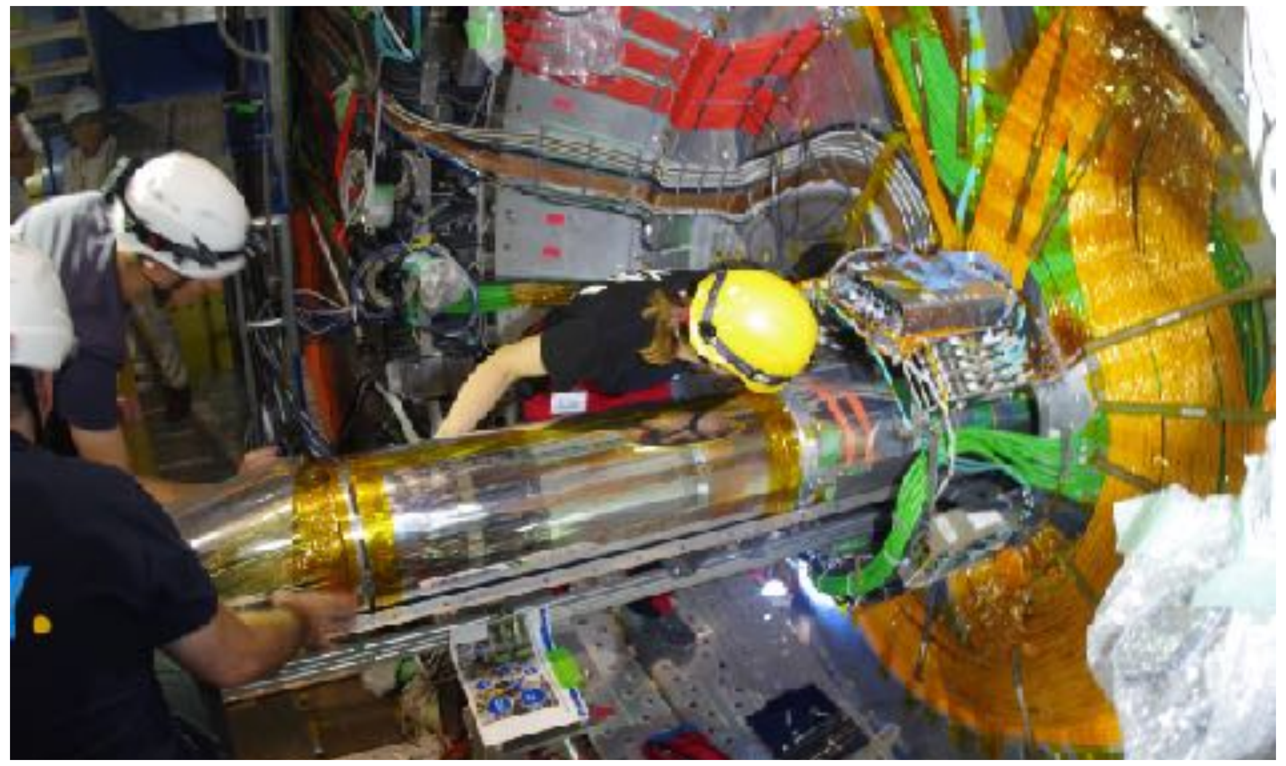












SVD functional tests and commissioning

- SVD main goals:

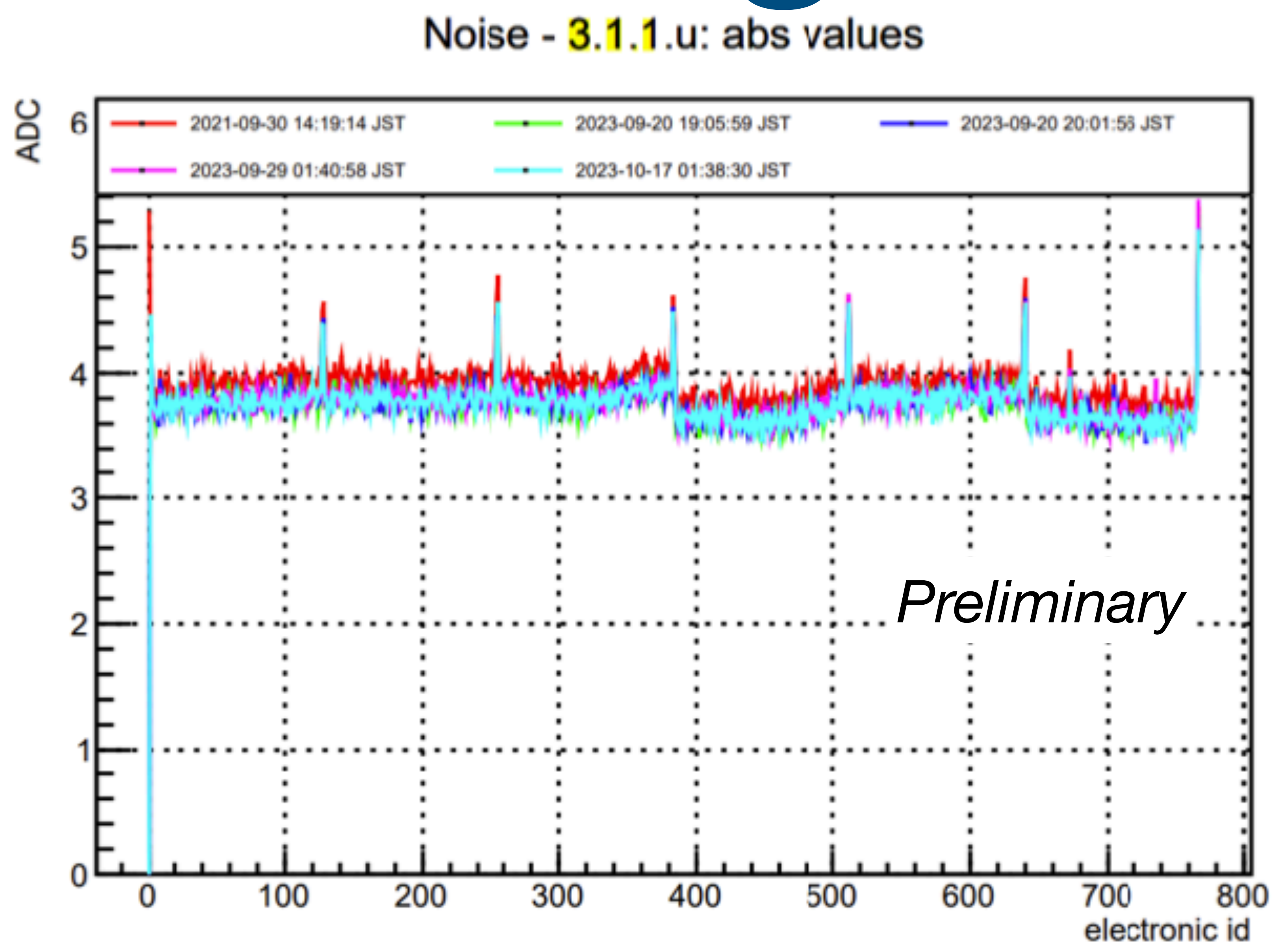
  ⇒ Confirm all **sensors working** as before LS1 and the detector performance

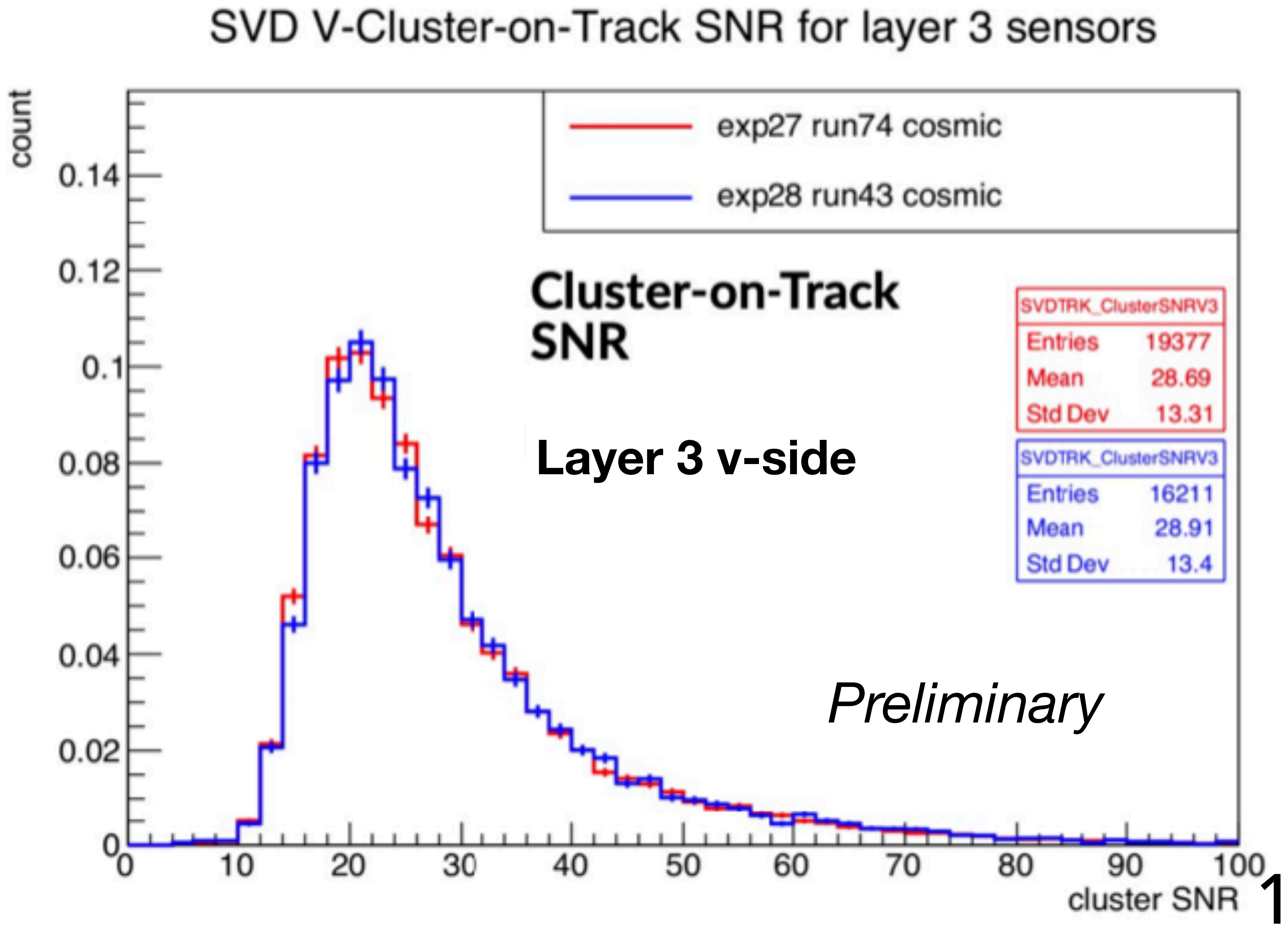
  ⇒ Check the impact of possible temperature increase on the sensor current (increased PXD power consumption) and determine the best cooling condition to operate the detector with similar/better performance as during Run1

- Functional tests and commissioning main results:

  ⇒ **Very small variation in the calibration constants** (noise/gain) depending on the temperature, but similar to Run1

  ⇒ Comparison of cosmic runs in June 2022 and September 2023, both without B field, confirmed **good performance as before re-installation**





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  - ⇒ Offline software developments towards high luminosity
  - ⇒ Radiation damage effect
- Summary

Beam background effects

Towards high luminosity…

⇒ Nominal occupancy extrapolation to target luminosity is 4.7% for Layer 3, but large uncertainties because the machine will change

⇒ Estimated radiation levels of 0.35 Mrad/yr ($8 \times 10^{11} n_{eq}/cm^2/yr$)

- **High instantaneous SVD hit occupancy** ⇒ can degrade tracking performance

  → Present average hit occupancy in Layer 3 is <0.5%

  → Developments in SVD reconstruction software

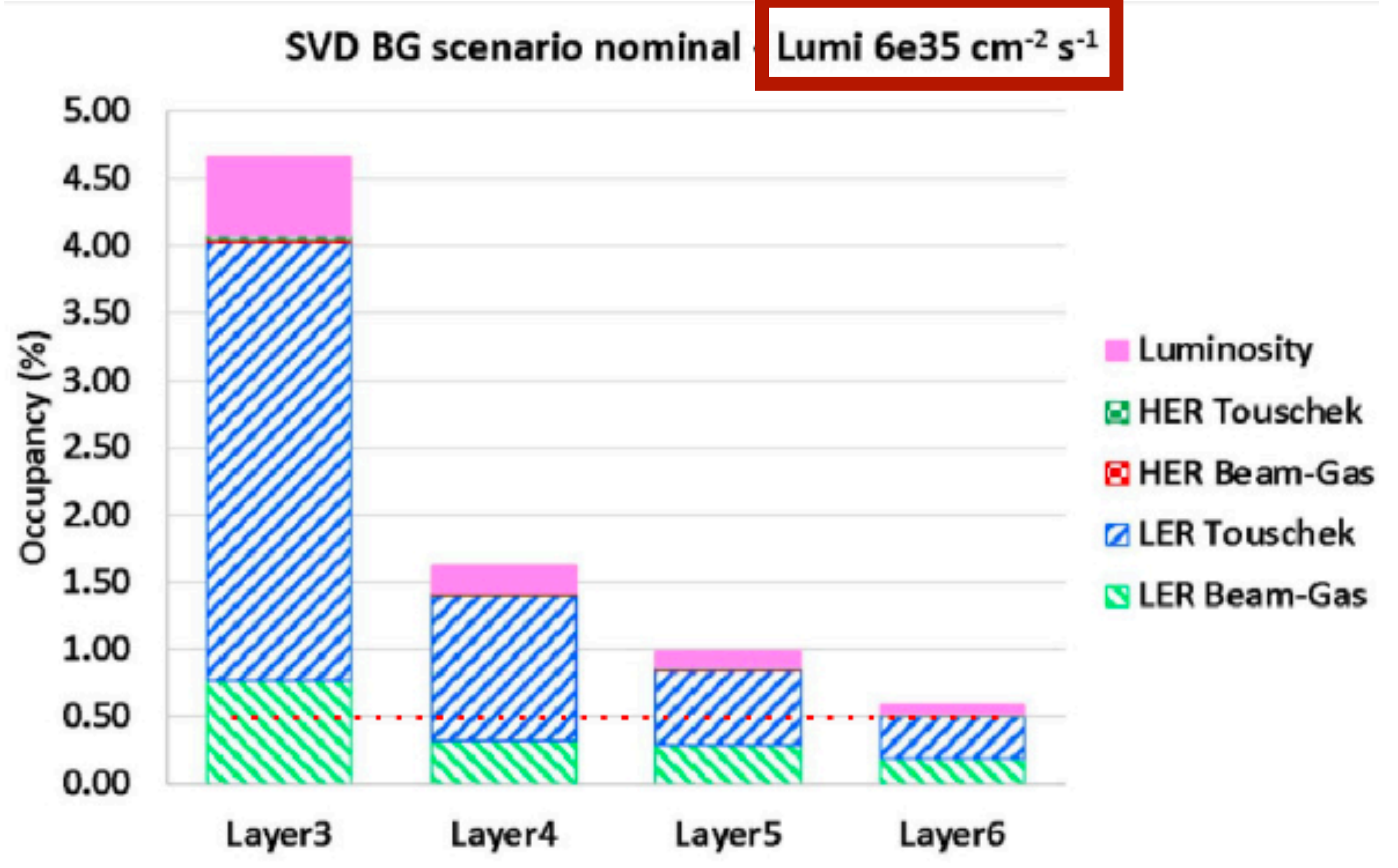
- **Integrated radiation damage** ⇒ can deteriorate sensor performance increasing leakage current, strip noise and changing depletion voltage

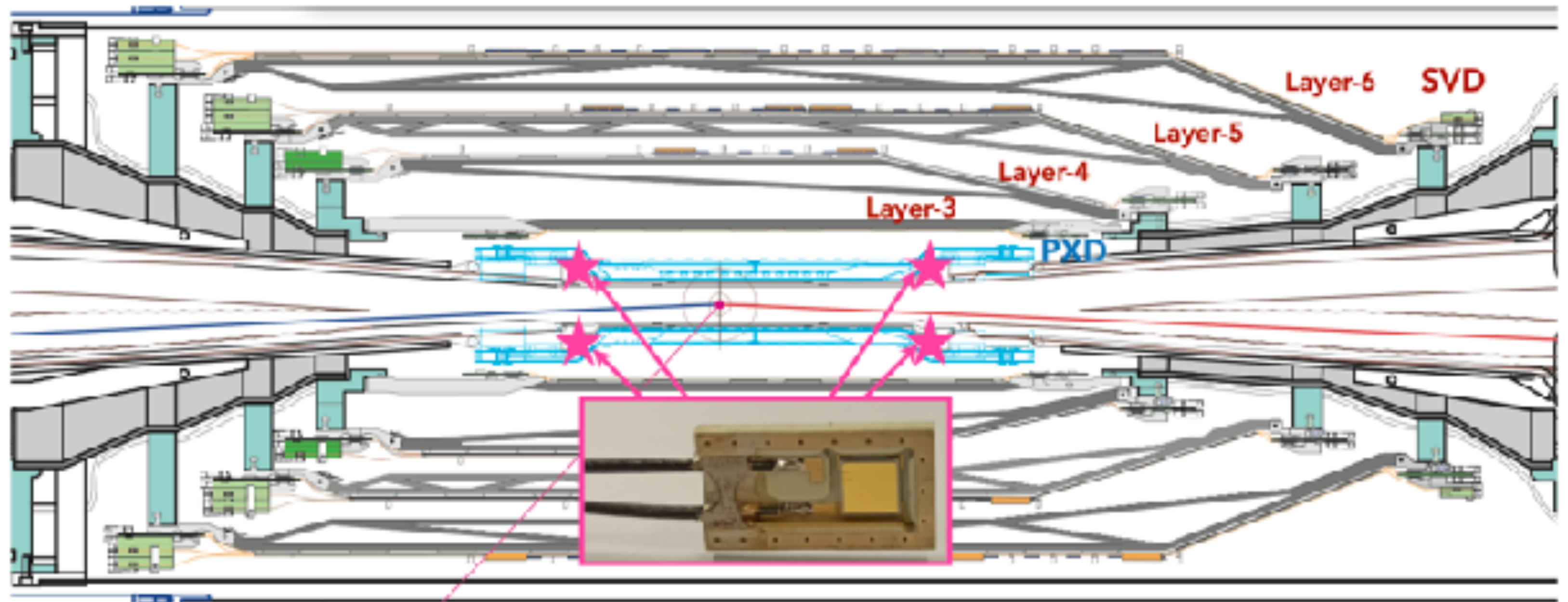
  → Dose on SVD is constantly monitored using diamond detectors and hit occupancy

  → Total SVD integrated dose on Layer 3 <70 krad ($1.6 \times 10^{11} n_{eq}/cm^2/yr$)

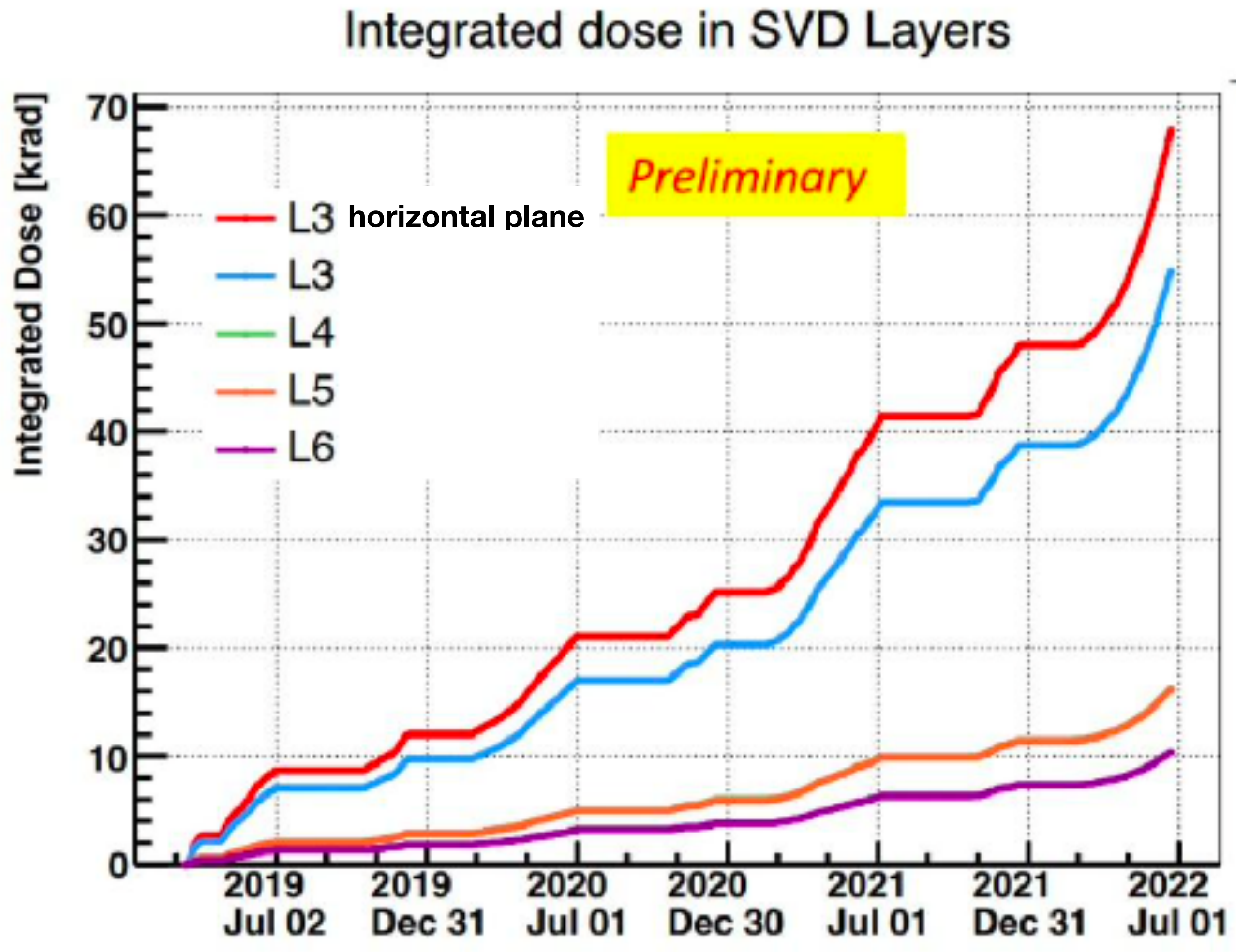
  → New irradiation campaign in July 2022 to extend the studies performed in the past

Target luminosity





★Beam pipe diamond radiation detectors



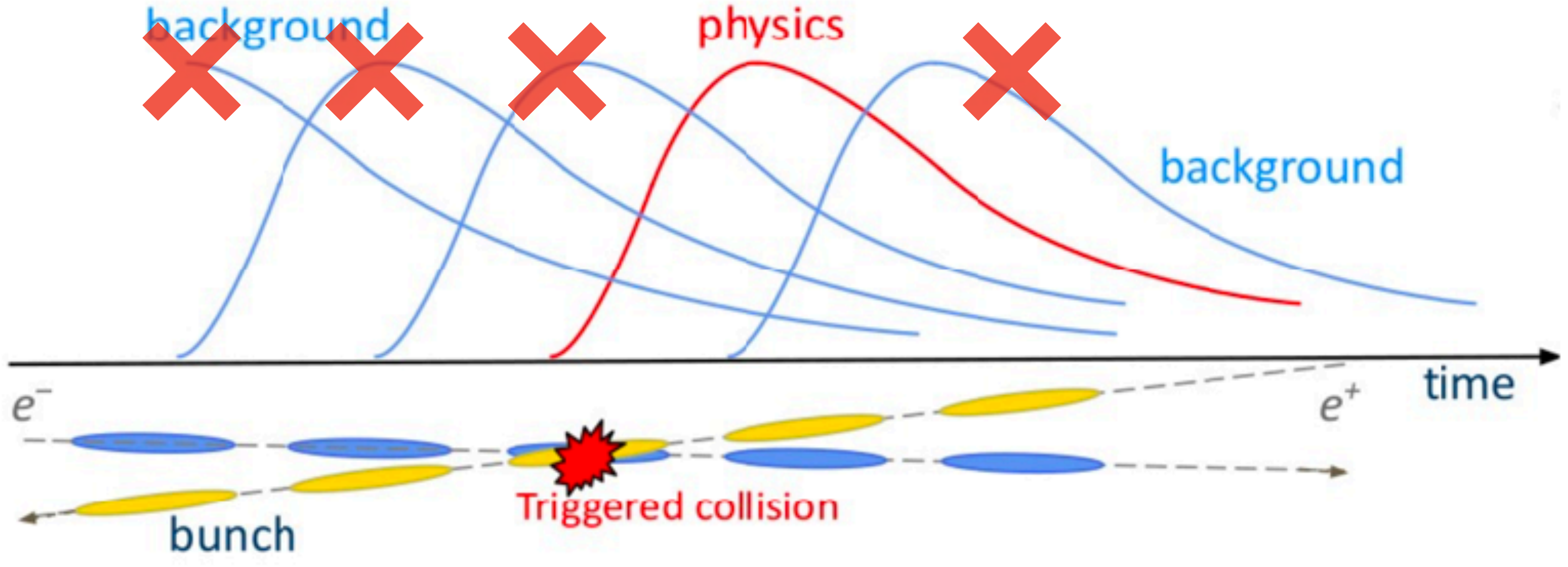
Background rejection

Improving SVD software robustness against high background data expected with increasing luminosity

- **Hit-time selection**: excellent hit-time performance (resolution <3ns) allows efficient removal of off-time tracks

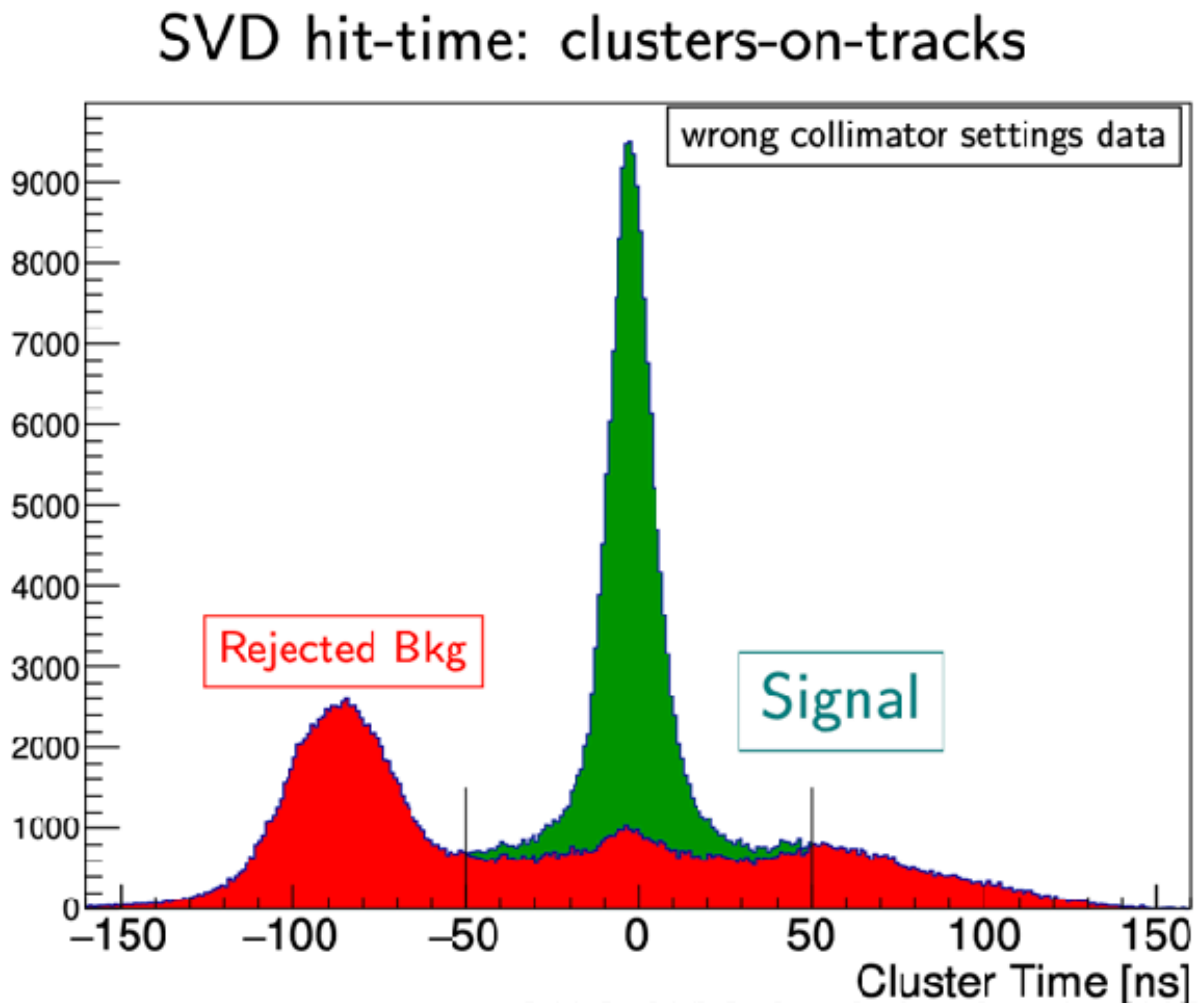
  ⇒ Efficient to remove 50% off-time hit background , keeping signal efficiency >99%

  ⇒ Tested but not yet deployed on real data reconstruction since the actual occupancy level is still low



Hit-time selection

$$|t_{u,v}| < 50\,\mathrm{ns}$$
$$|t_u - t_v| < 20\,\mathrm{ns}$$



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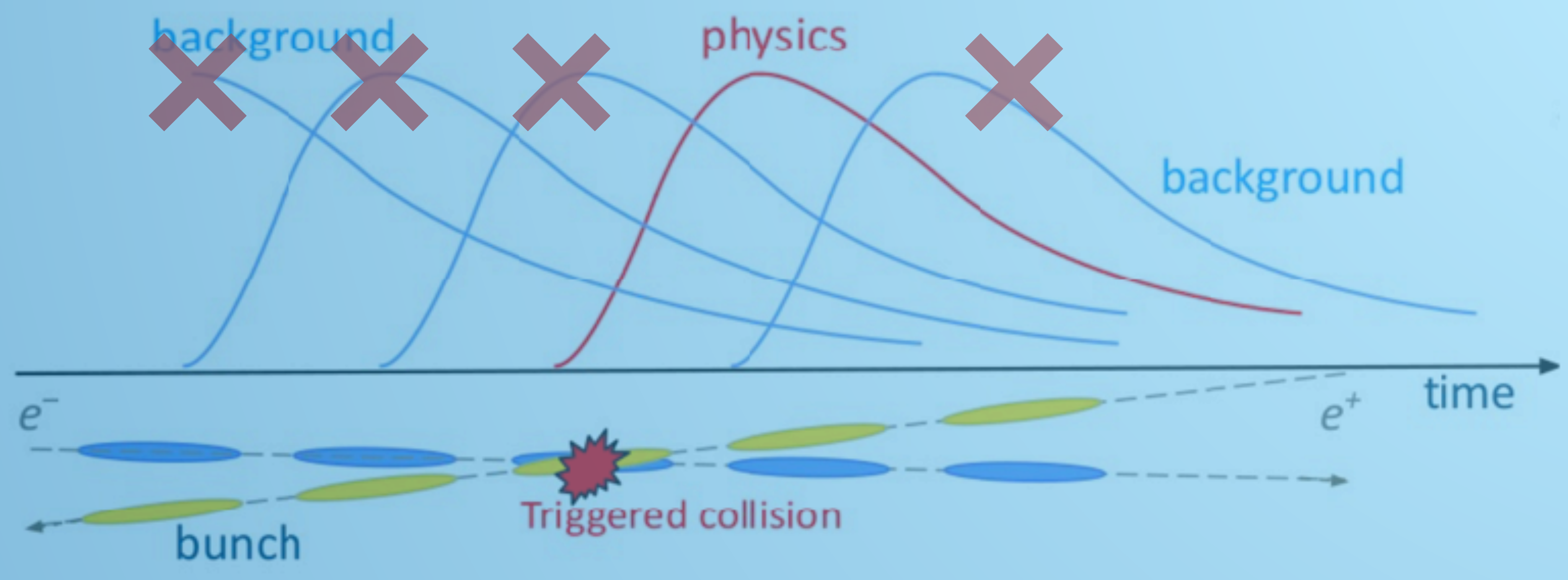
SVD occupancy limit for Layer 3 can be set at 4.7%



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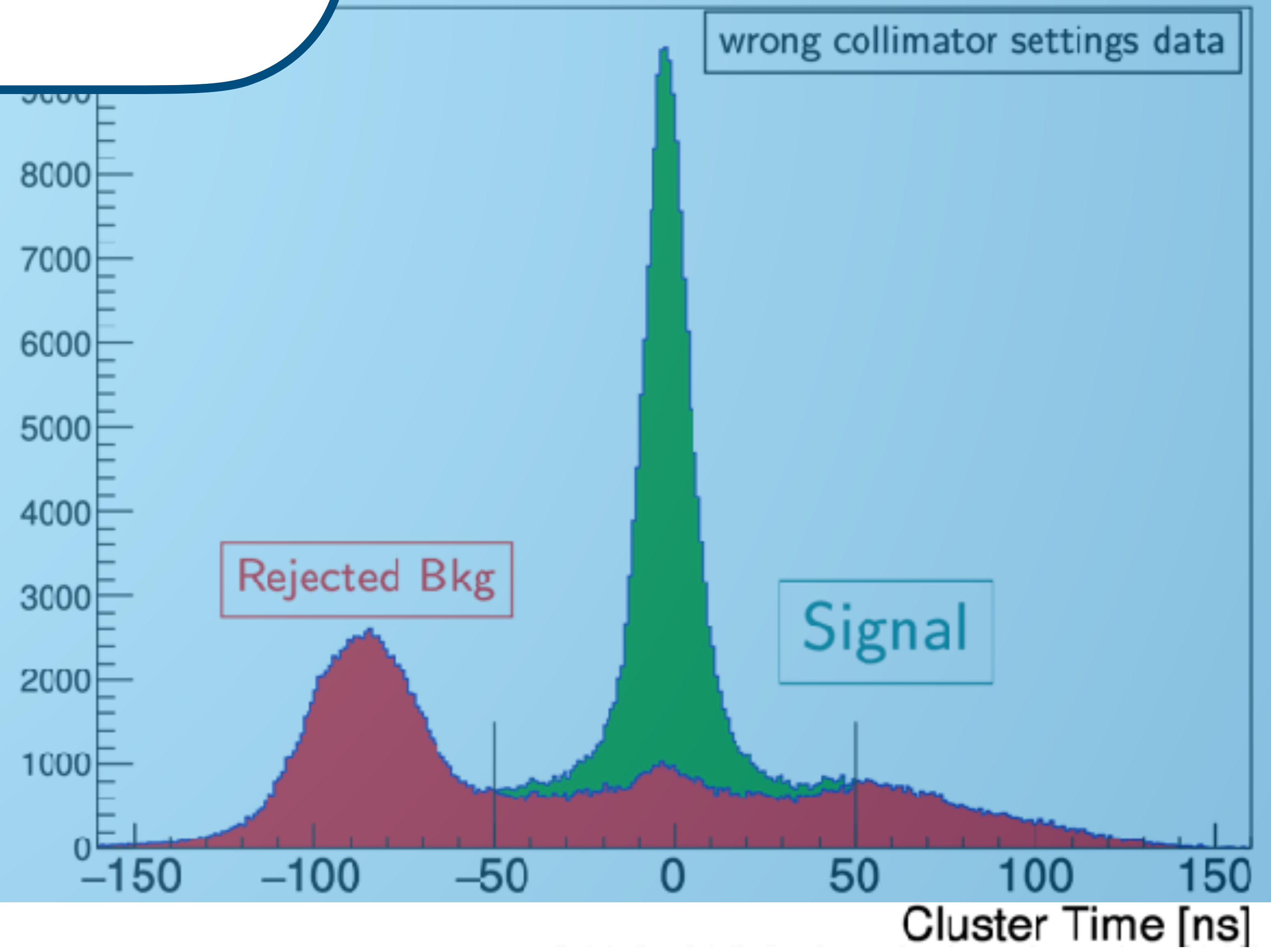
...it-time: clusters-on-tracks



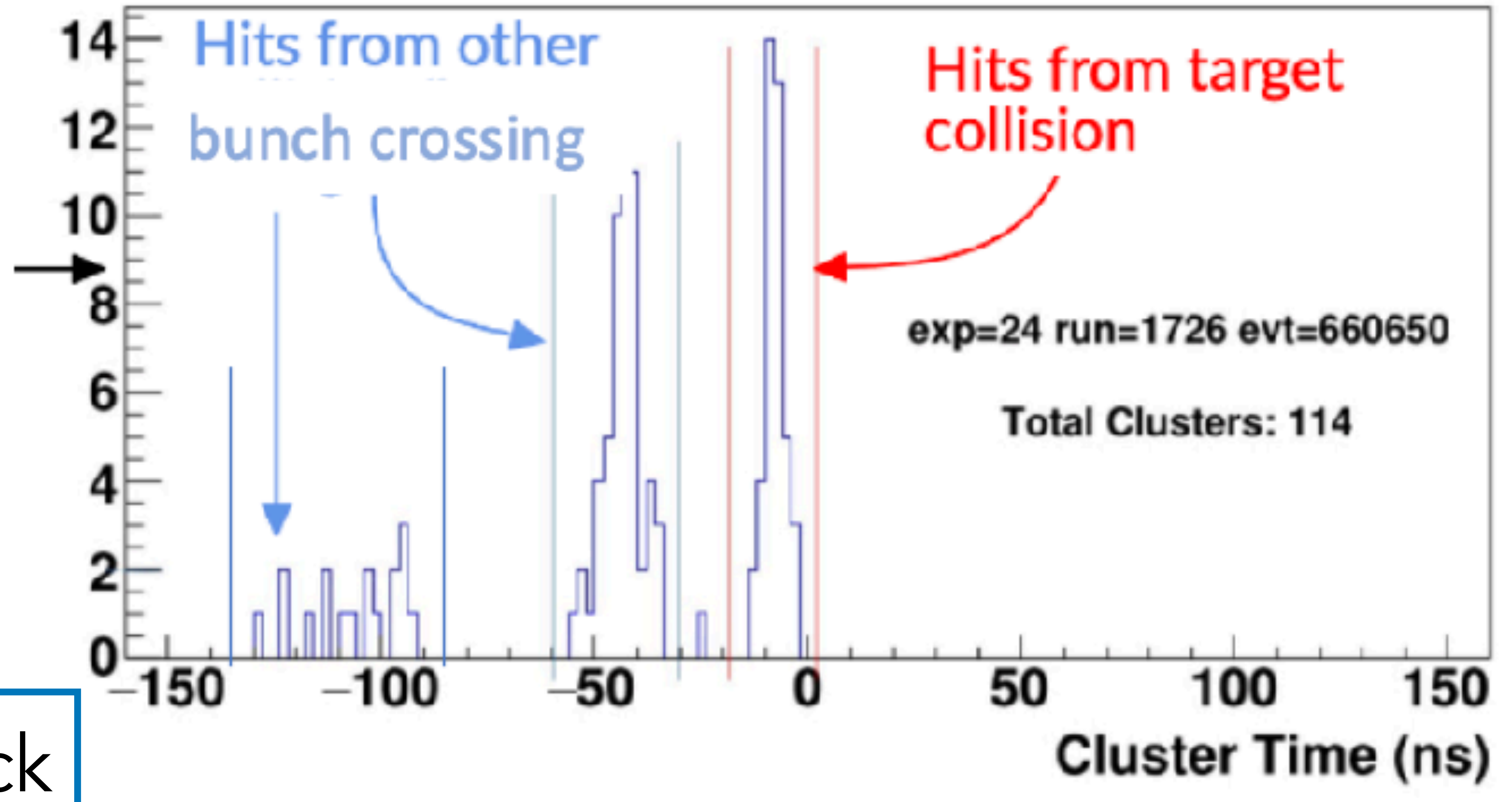
Background rejection

Improving SVD software robustness against high background data expected with increasing luminosity

- **Cluster grouping:** event-by-event classification of clusters into groups based on their time

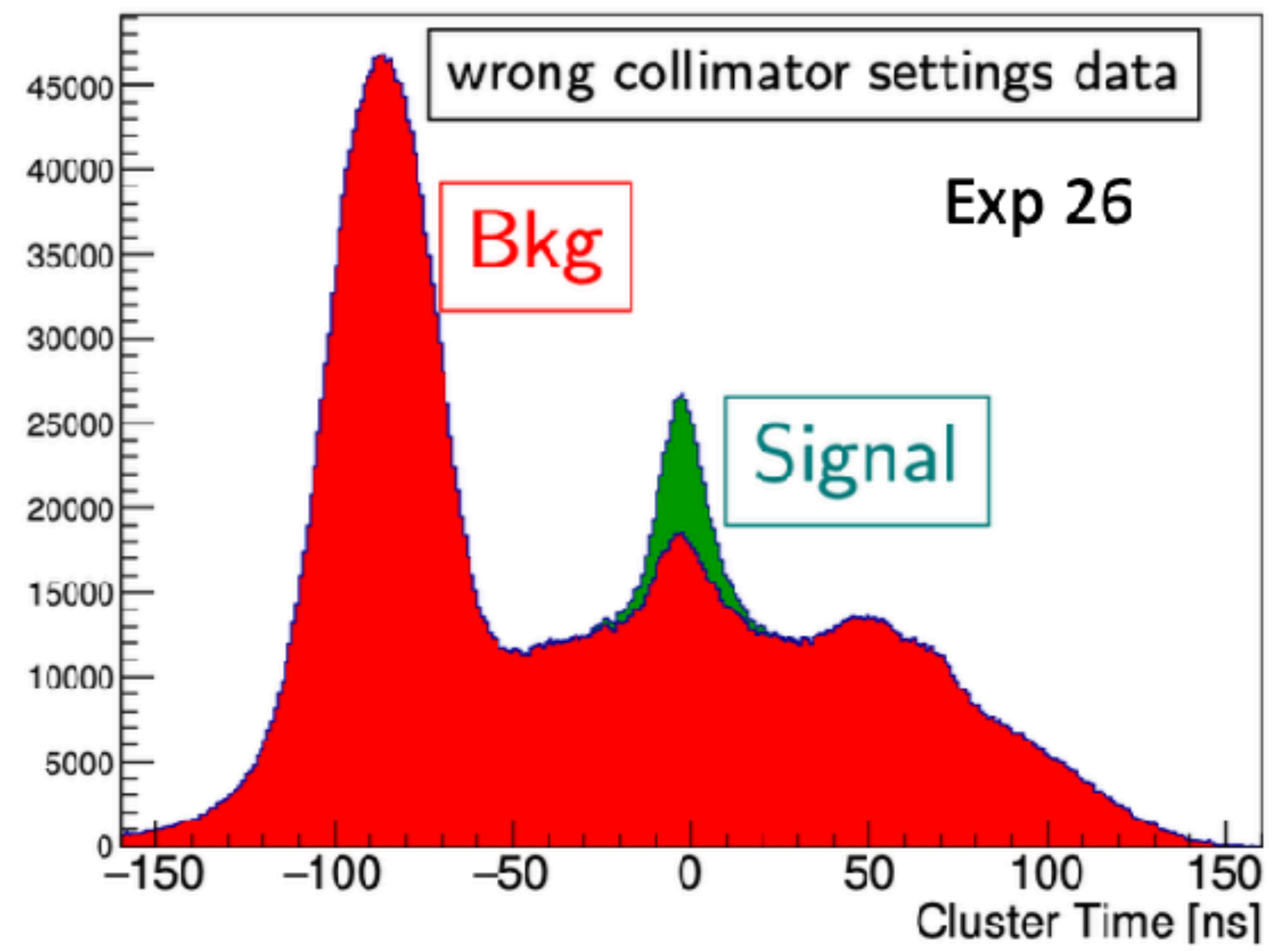
  ⇒ Reduces tracking fake rate by 15% on high background data

- **Track-time selection:** remove off-time track, further reducing fake rate by a factor 1.5 for the high background scenario



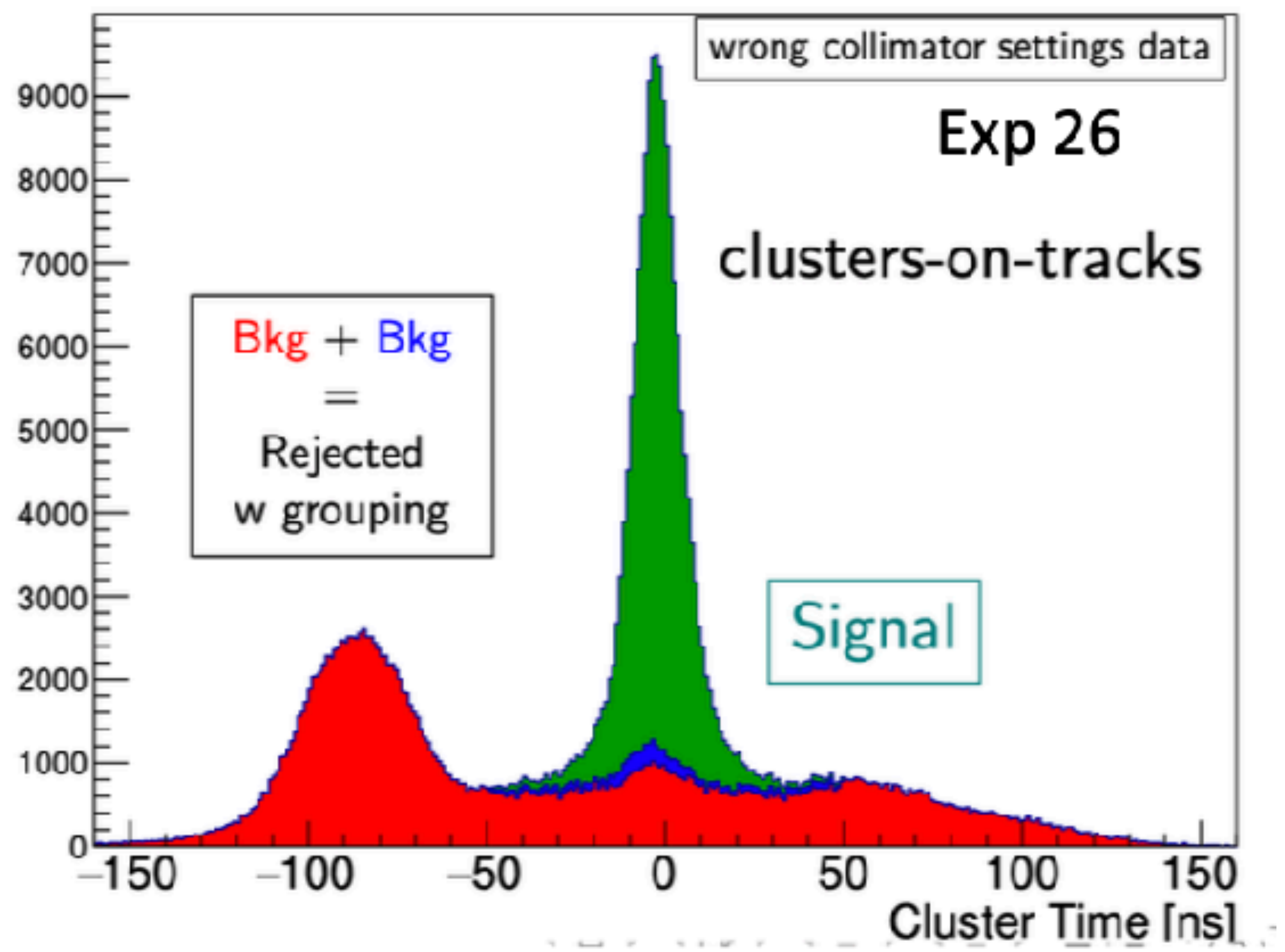
Track time → computed combining hit time of clusters associated to the track

SVD hit time: all clusters



Hit-time selection
+
Cluster grouping

SVD hit time: cluster on track



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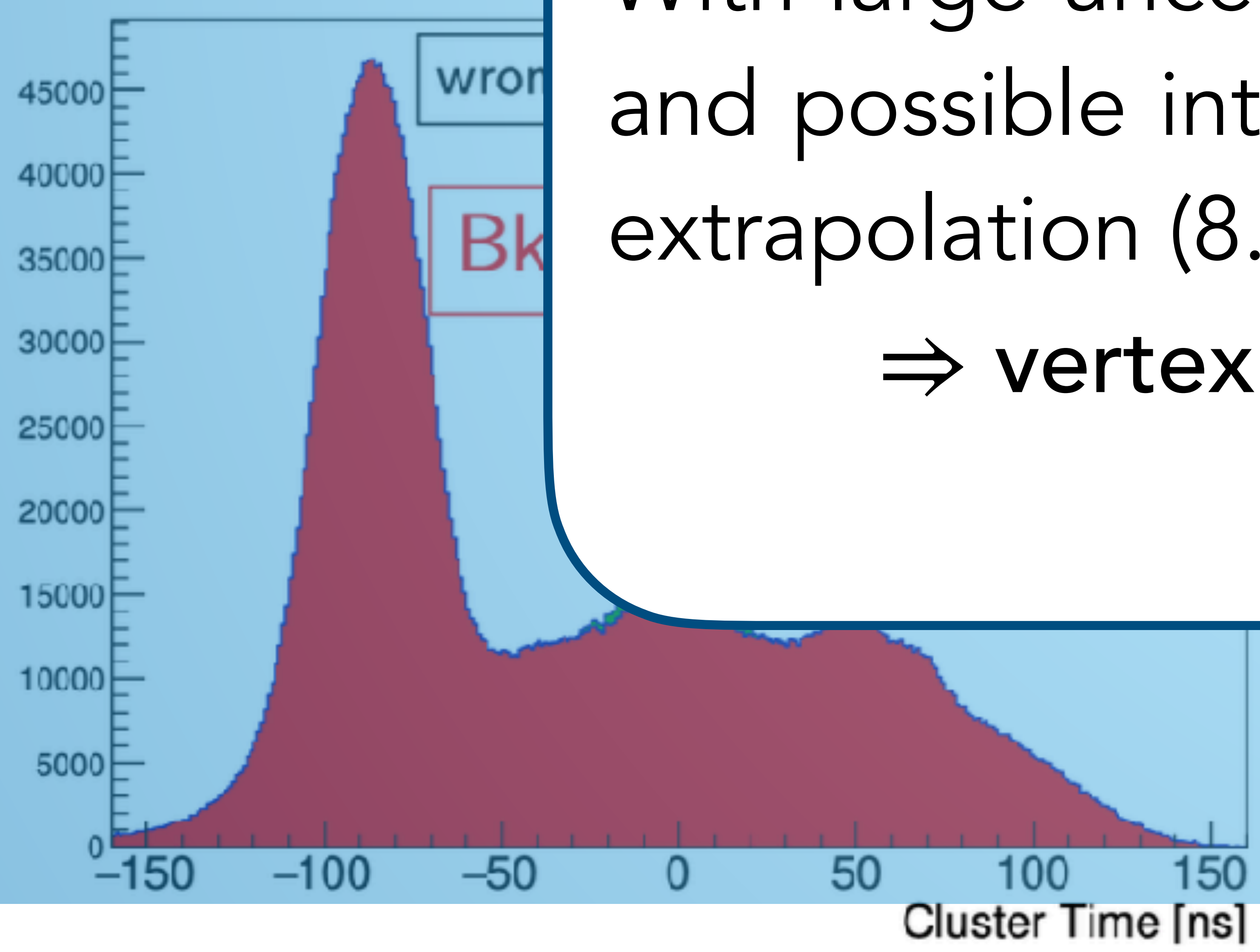
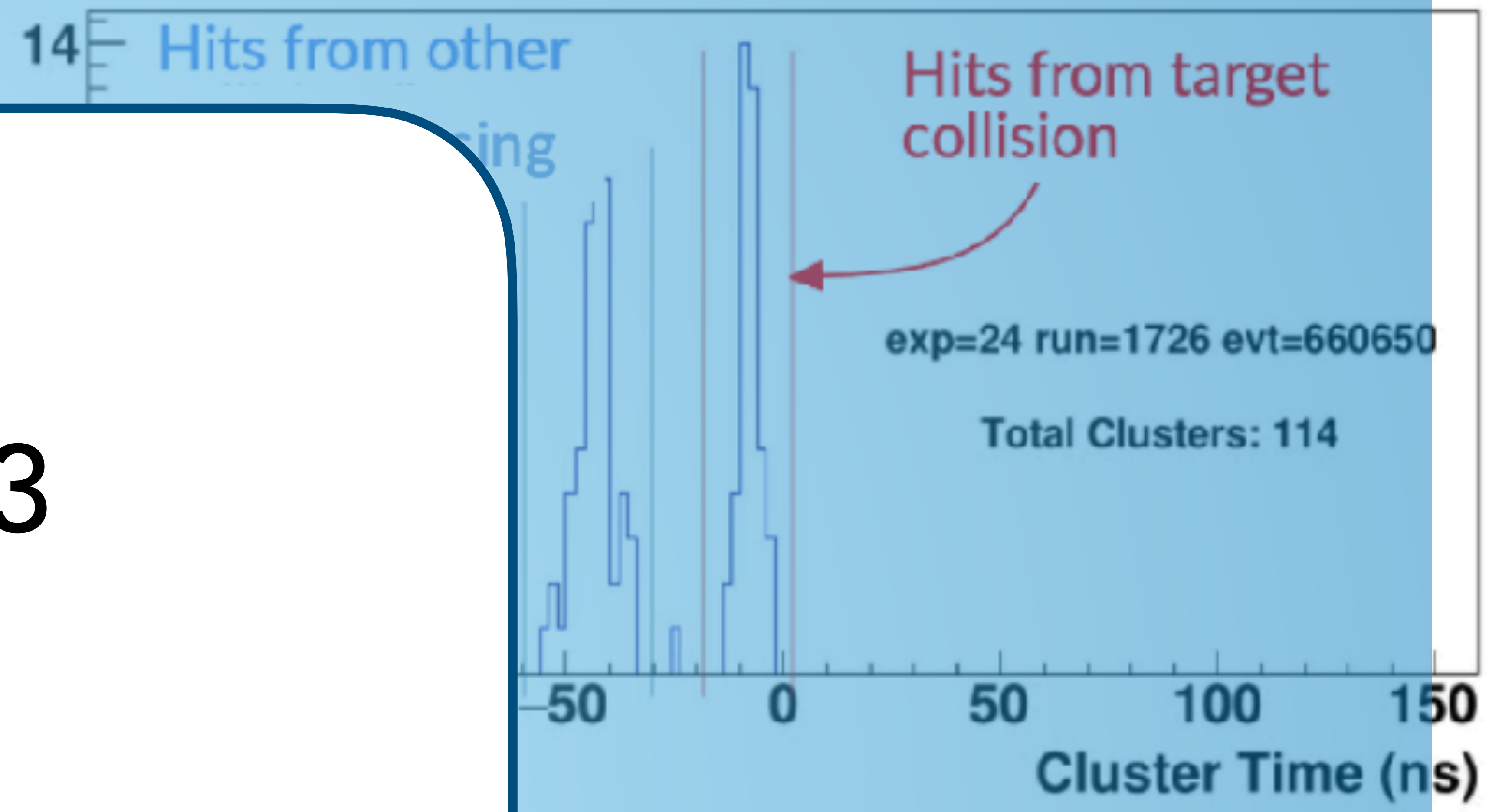
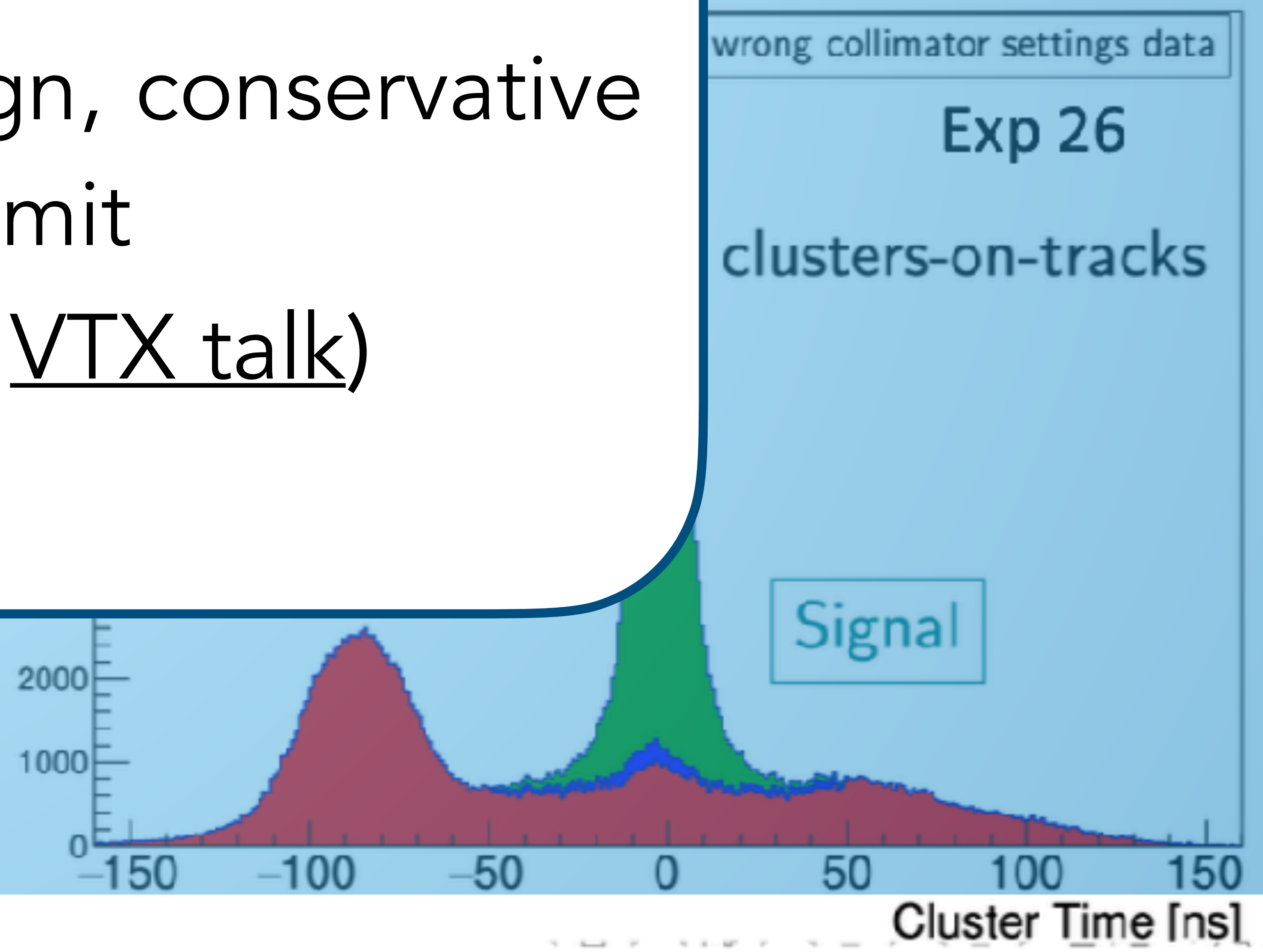
Track time → computed

SVD hit tim





ster on track



Further increase SVD occupancy limit for Layer 3 from 4.7% to ~ 6%

With large uncertainty due to future machine evolution and possible interaction region re-design, conservative extrapolation (8.7%) even exceeds 6% limit

⇒ vertex detector upgrade (see VTX talk)

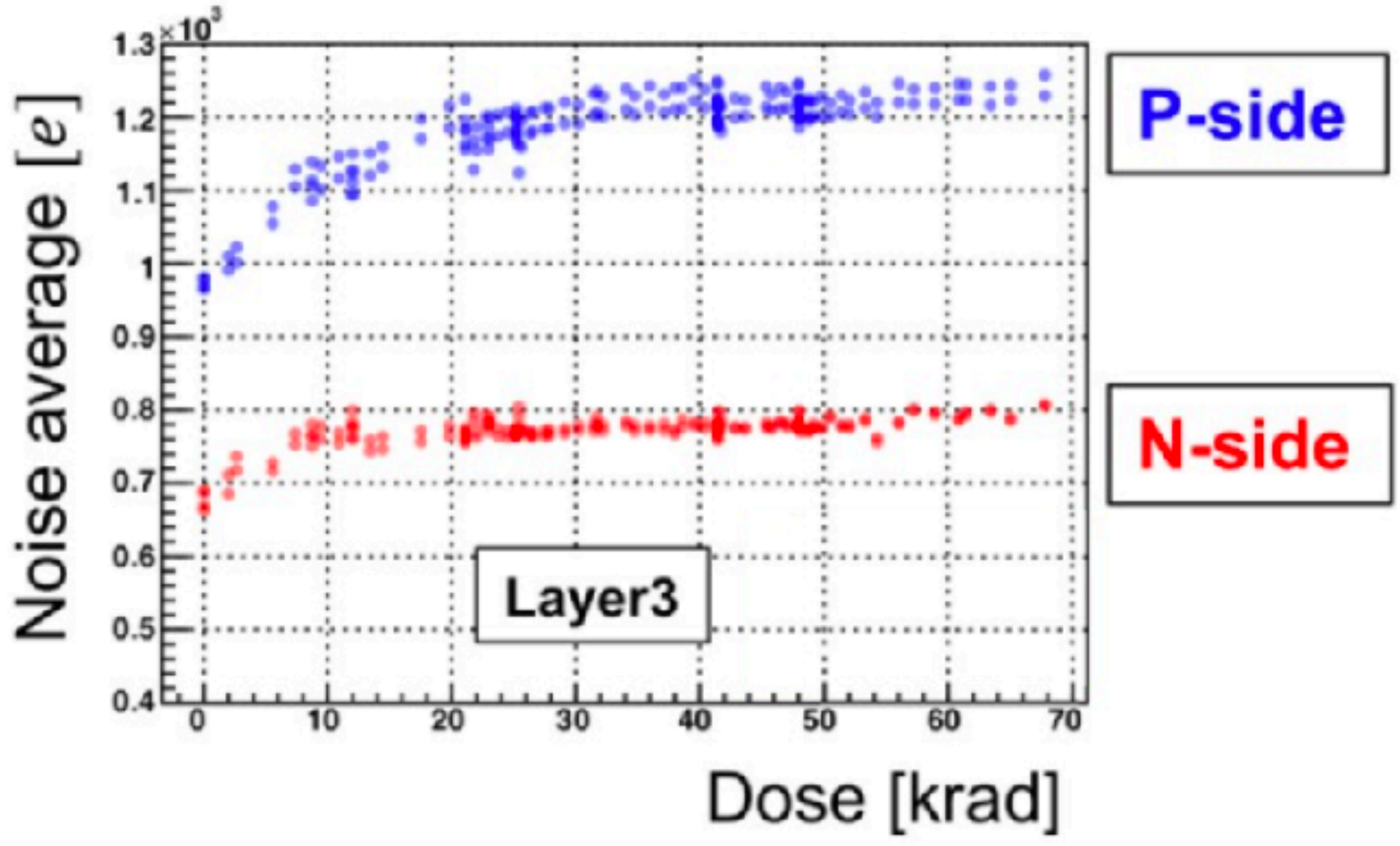
Radiation damage

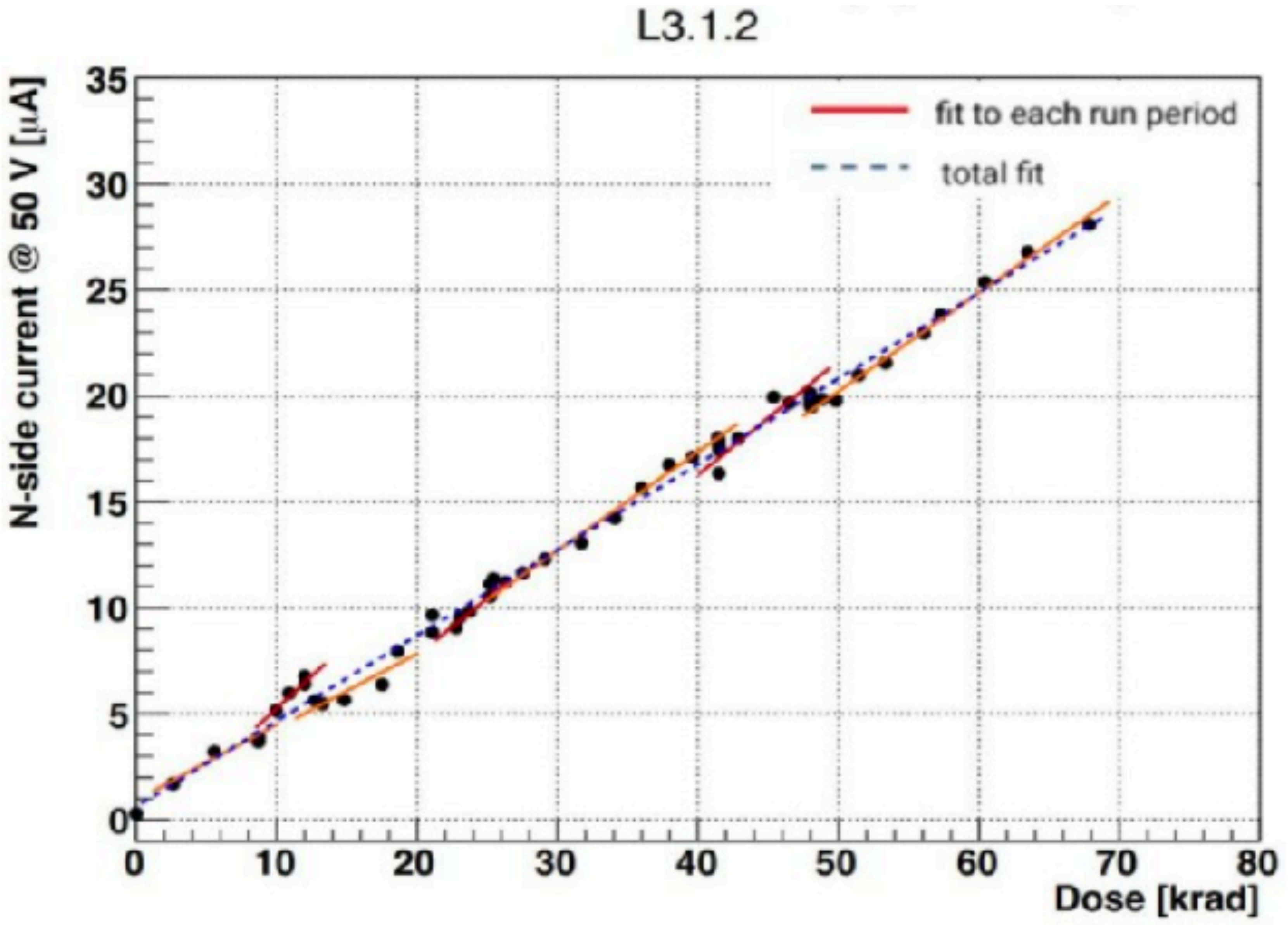
Estimated radiation levels of 0.35 Mrad/yr ($8 \times 10^{11}\,\mathrm{n_{eq}/cm^2/yr}$)

- **Strip noise**: Noise increases of <20% (30%) for n (p) side, not affecting performance ⇒ saturate due to surface charges
- **Leakage current**: Good linear correlation between leakage current and dose as expected from NIEL model

  ⇒ Deterioration in SNR after 6 Mrad (expected SNR<10 in Layer 3 horizontal plane)
- **Depletion voltage**: No change in full depletion voltage due to bulk damage observed so far
- Irradiation campaign with 90 MeV electron beam up to 10 Mrad ($3 \times 10^{13}\,\mathrm{n_{eq}/cm^2/yr}$) to check effects on high radiation on sensors: type inversion confirmed at ~2 Mrad ($6 \times 10^{12}\,\mathrm{n_{eq}/cm^2/yr}$)

  ⇒ irradiated sensors confirmed to work well after type inversion





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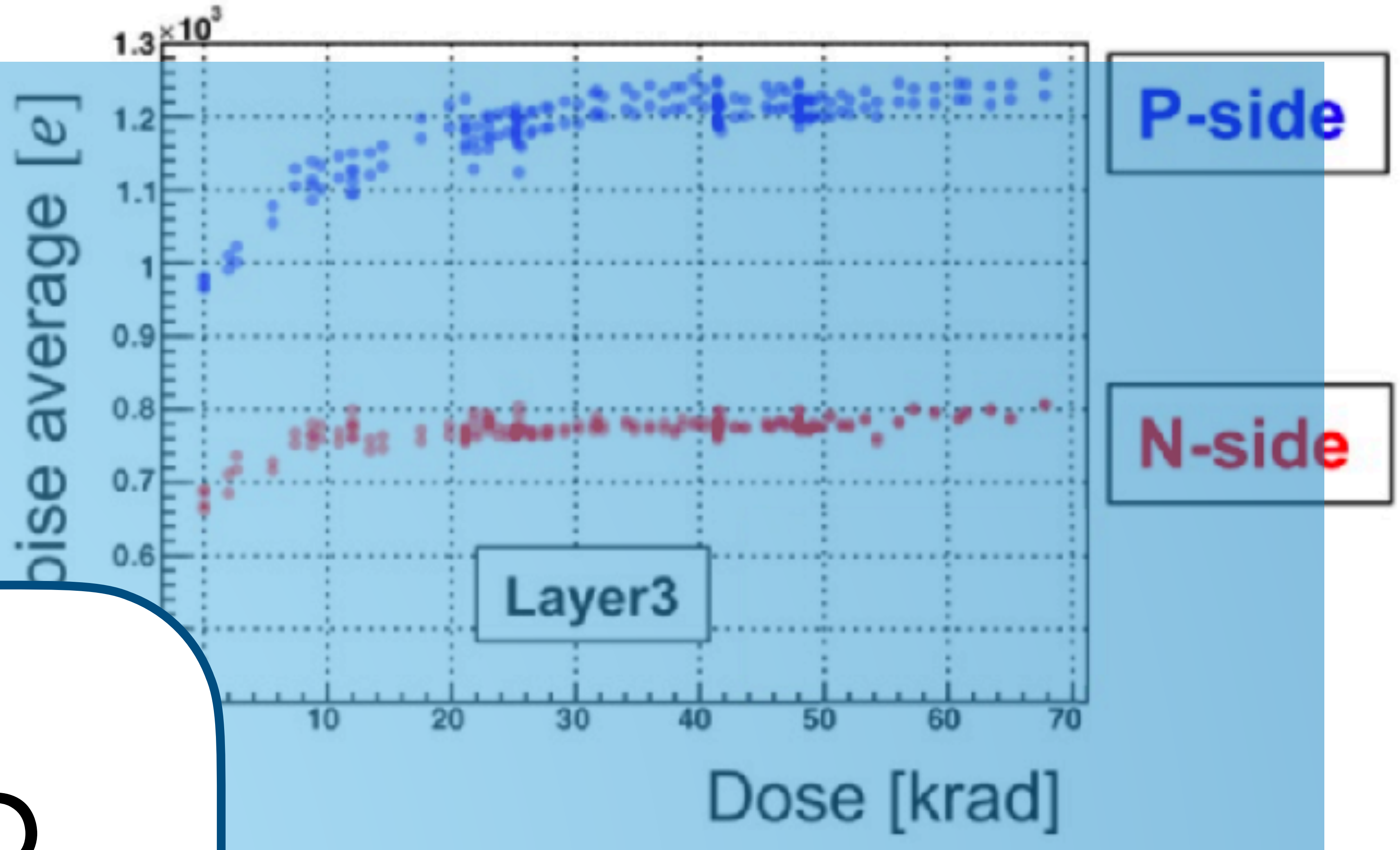
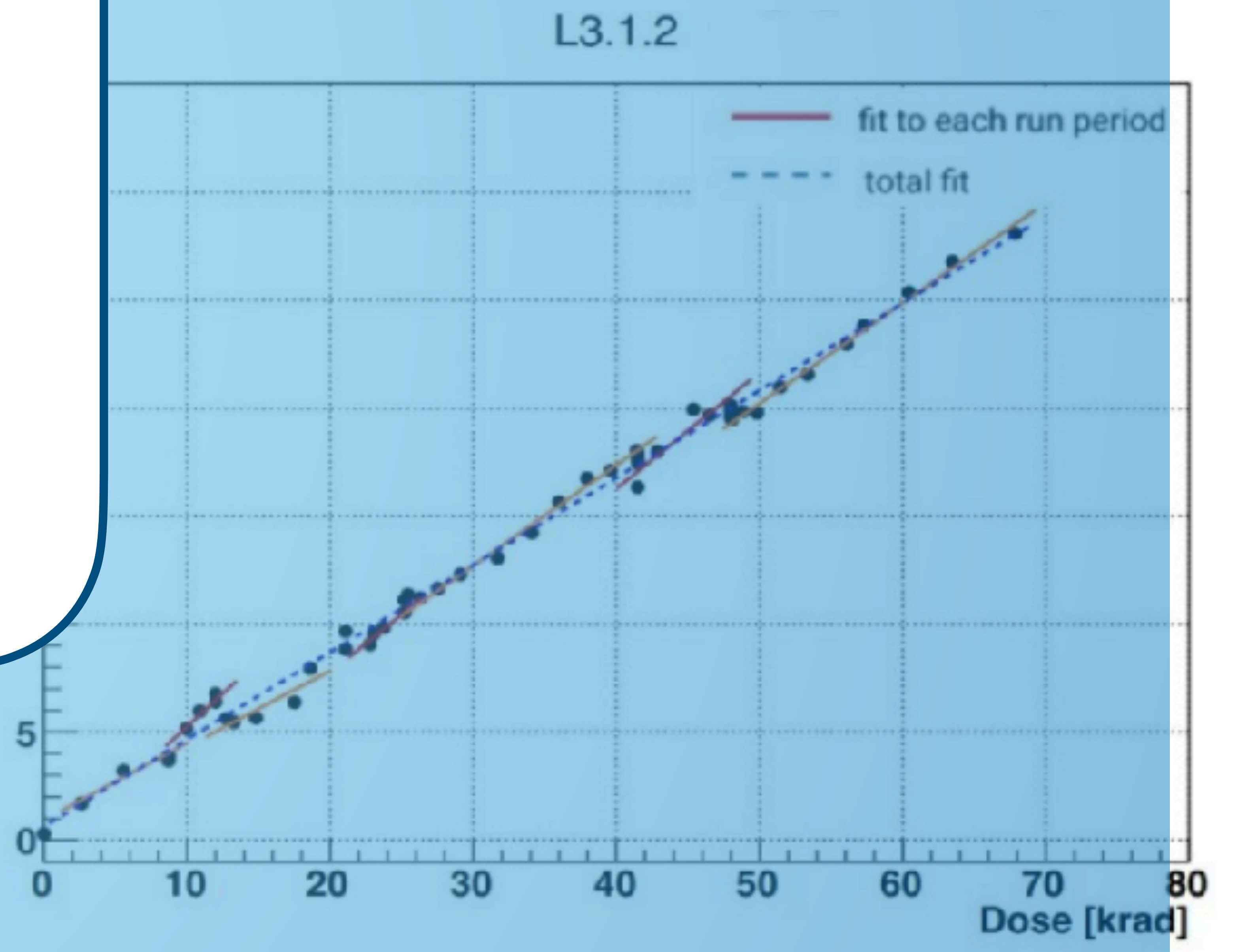
Large safety margin for SVD integrated radiation damage even after 10 years of operation at target luminosity





Summary

- SVD has been taking data since March 2019 smoothly and reliably

  ⇒ excellent detector performance and good stability

  ⇒ first effects of radiation damage are observed

- During the Long Shutdown 1 we installed the new VXD, with complete PXD2 and the current SVD

  ⇒ After intense hardware activities, the commissioning in Sept. 2023 confirmed the good performance of SVD as before LS1

  ⇒ On track to resume data taking in Jan. 2024

- Higher luminosity requires a more robust SVD software

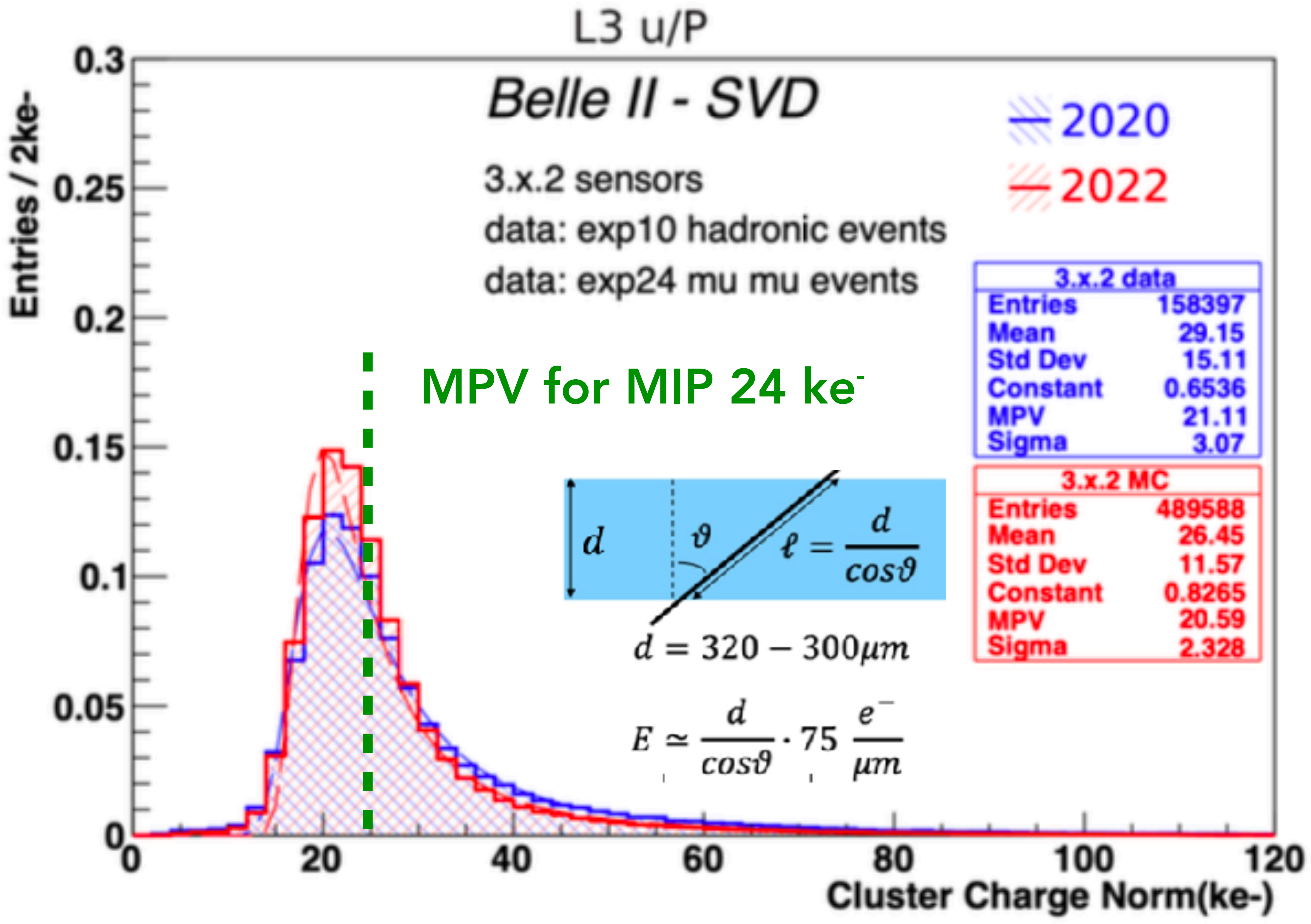
  ⇒ The accurate SVD time will be crucial in rejecting background and maintaining the excellent tracking performance

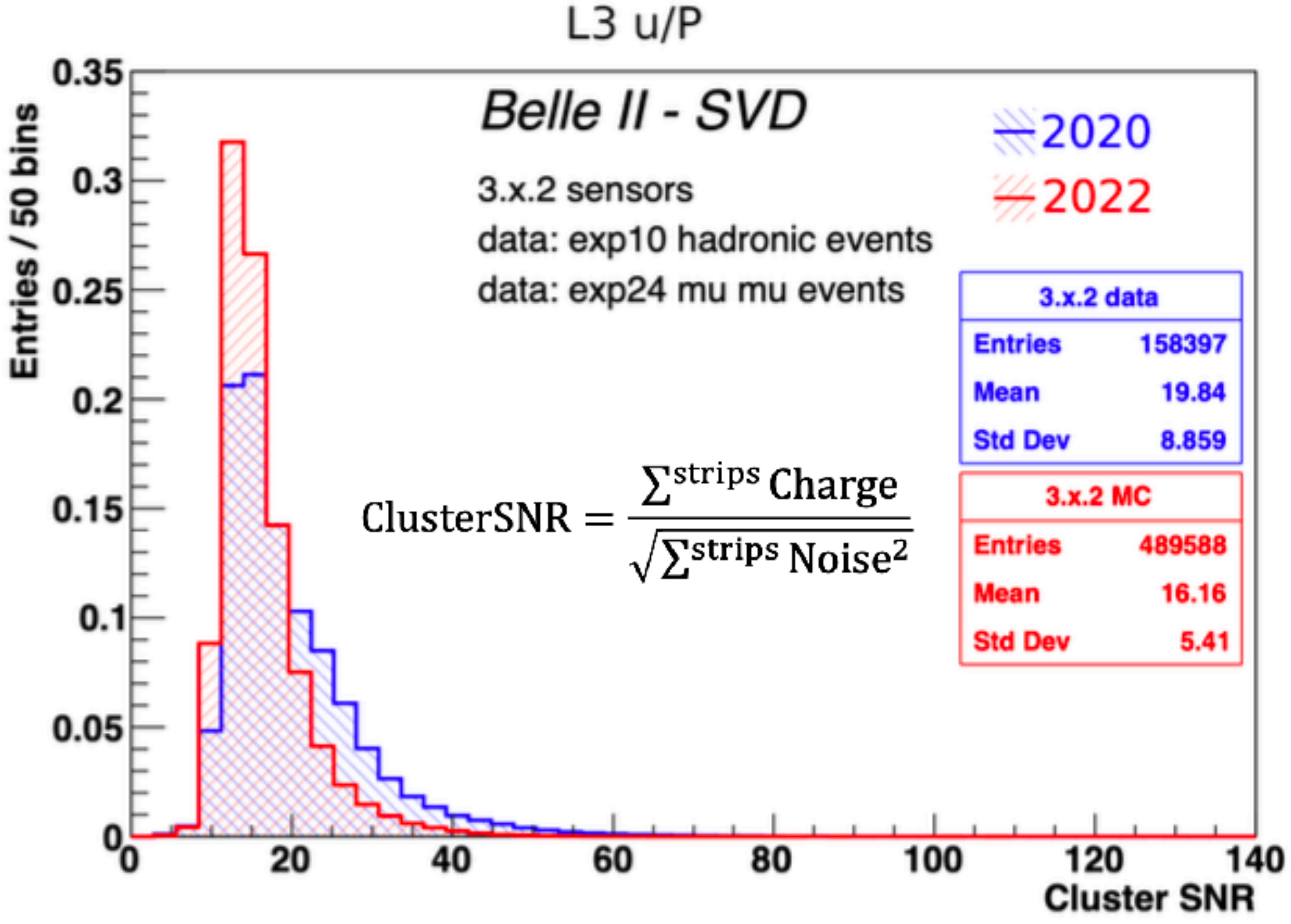
- SVD technical paper published in JINST (JINST 17 P11041 2022)

Back-up

SVD cluster charge and SNR

- **Good stability** of cluster charge and SNR from 2020 to 2022



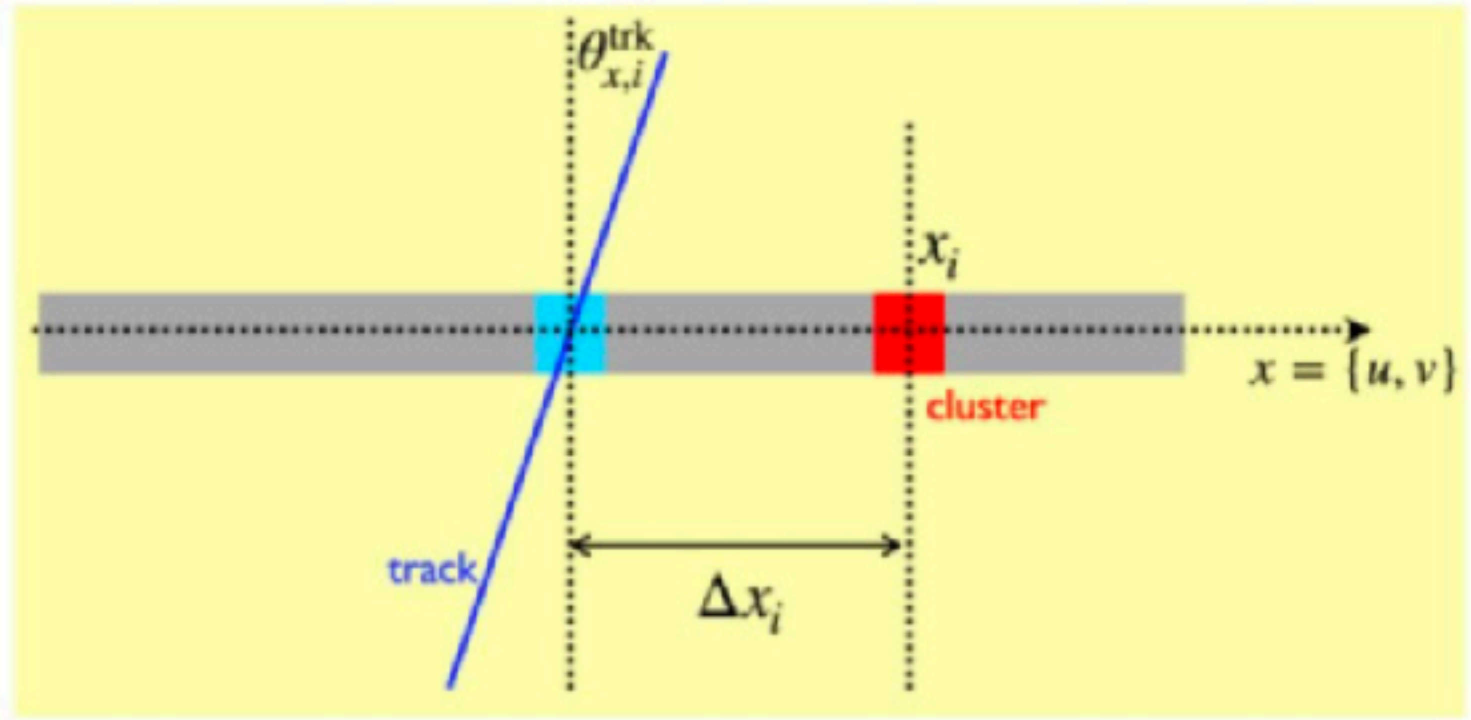


- Signal charge depends on the incident angle
- Cluster charge normalised to track length similar in all sensors

- **Small changes** observed in **SNR** due to noise increase by radiation damage, as expected
- **MPV 13-30** depending on sensor position and side

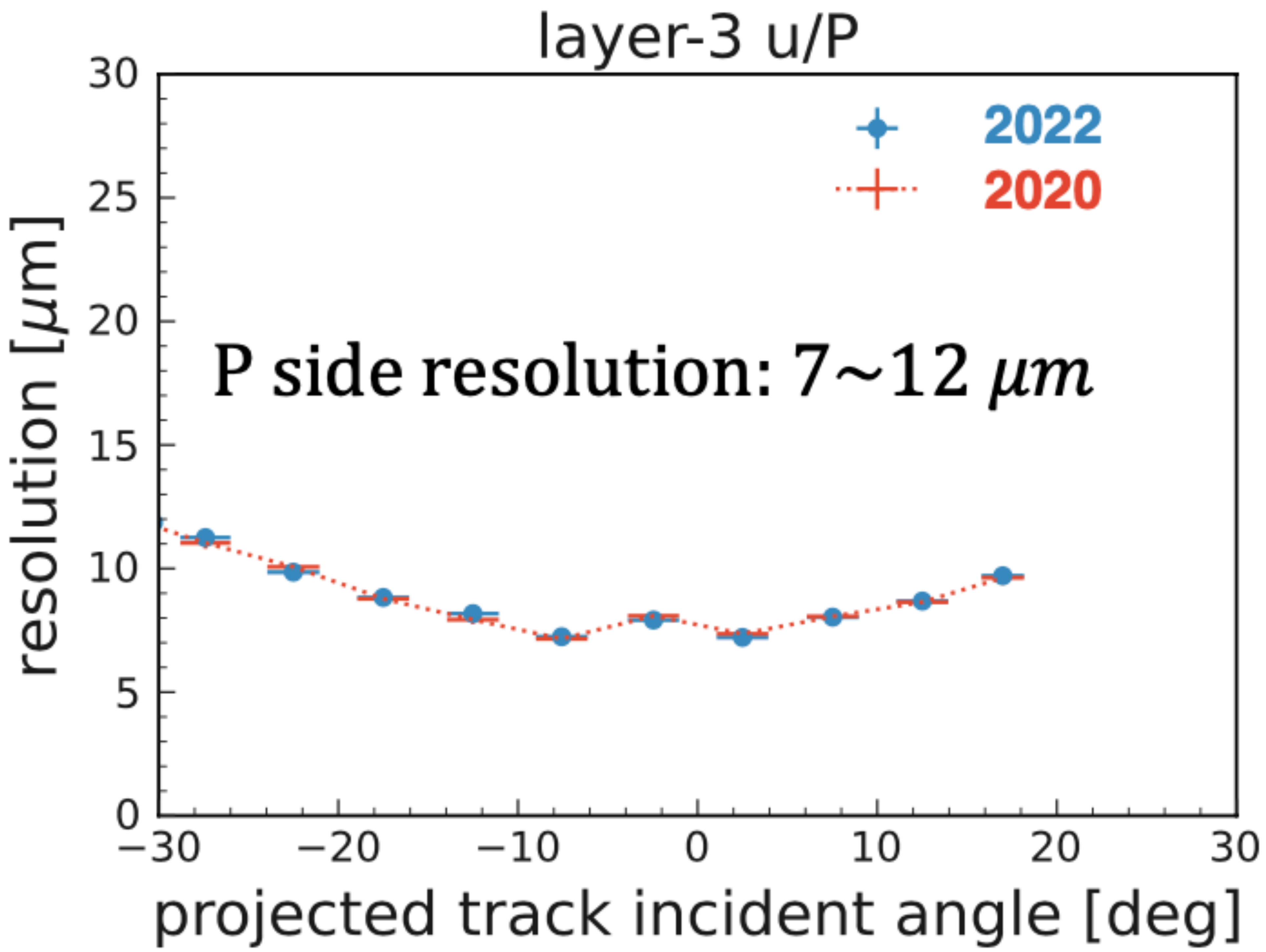
Position resolution

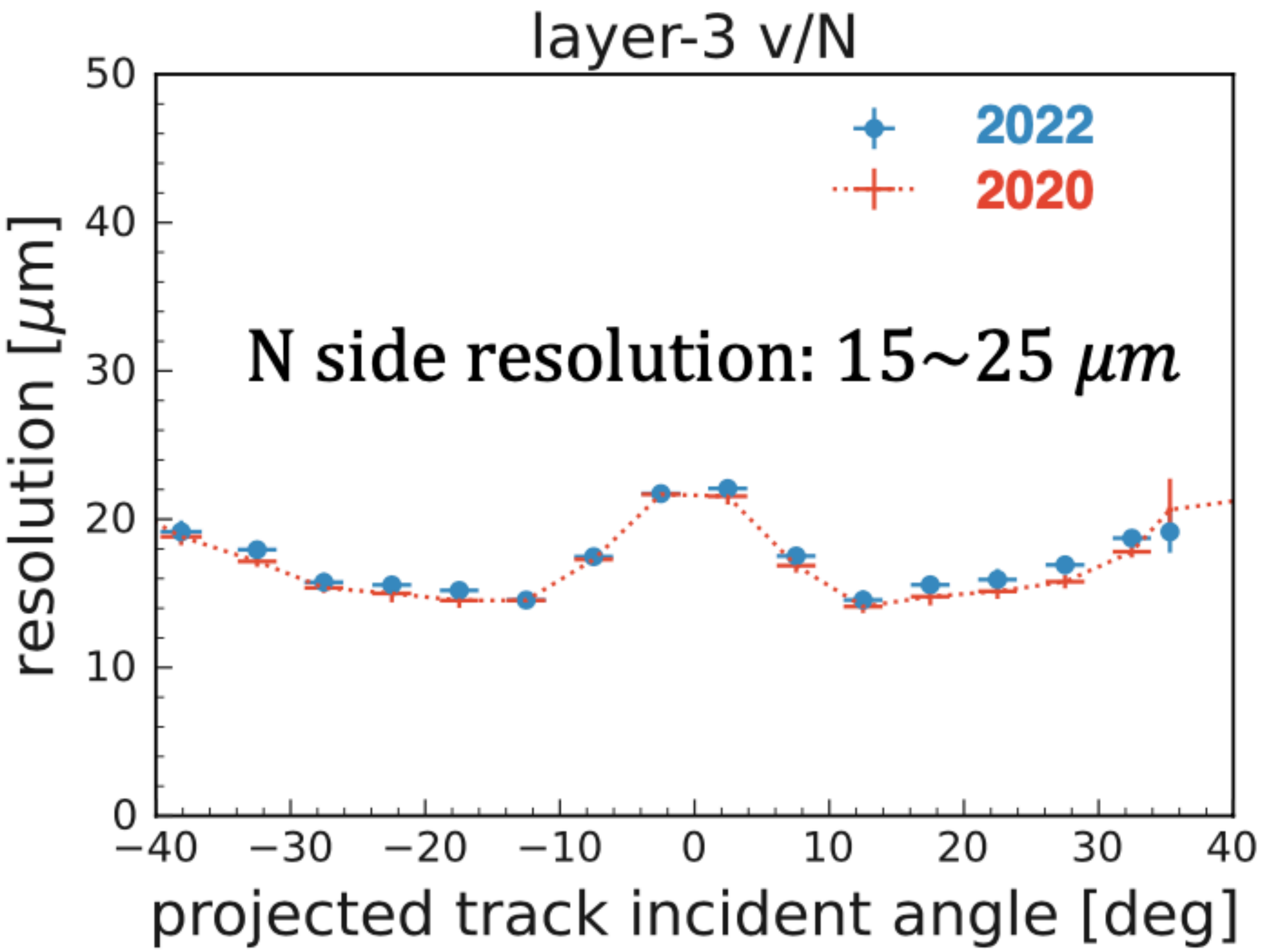
- Position resolution is calculated from the cluster position with respect to the track extrapolation using $e^+e^- \to \mu^+\mu^-$ sample.
- **Good and stable position resolution** is observed during the operation, as expected from pitches



$$\sigma_x = \sqrt{\left\langle (\Delta x_i)^2 - \left(\sigma^{trk}_{x,i}\right)^2 \right\rangle}$$

$\sigma^{trk}_{x,i}$ = unbiased track position error





Time resolution

- **Hit time** resolution: measured w.r.t. **event time** of the collision, provided by Central Drift Chamber (CDC) ⇒ **excellent result of < 3 ns**

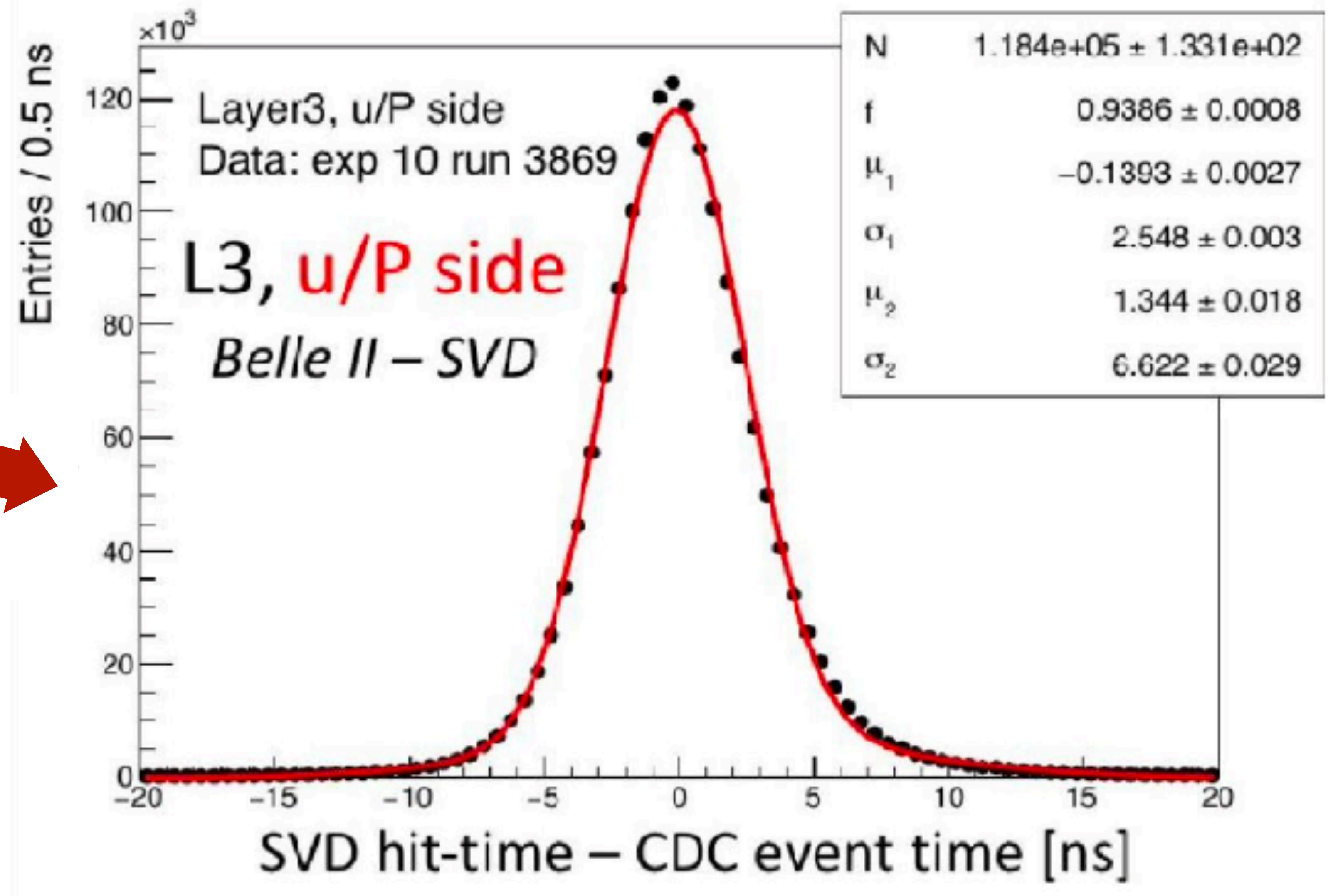
- **Track time**: computed combining hit time of clusters associated to the track

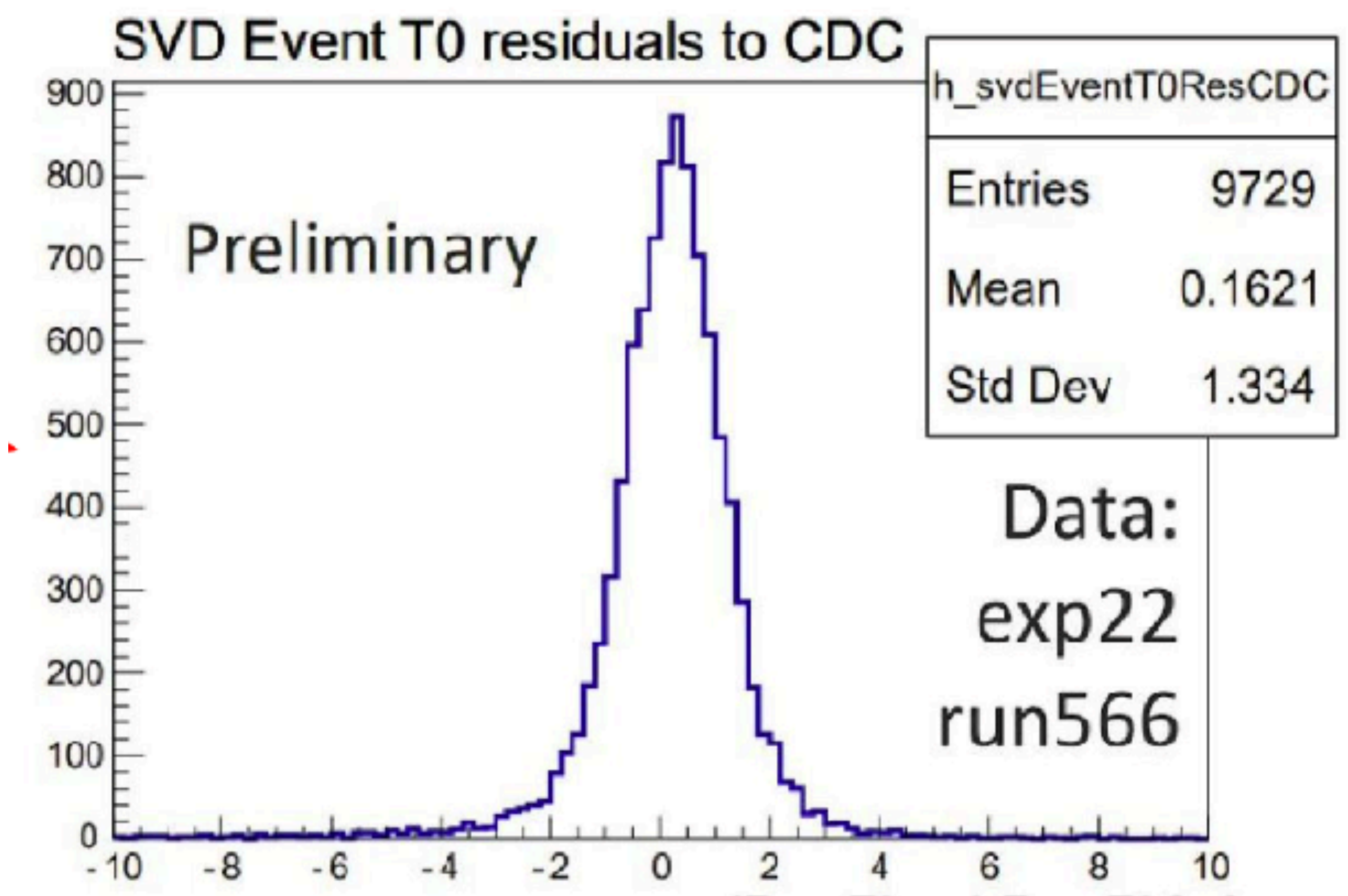
- **Event time**: computed combining hit time of the clusters associated to all tracks of the event

  ⇒ same resolution (~1ns) and 2000 times faster computation time w.r.t. the one computed with CDC

  ⇒ Speed-up the High Level Trigger (HLT) reconstruction: important feature for higher luminosity

SVD hit time resolution (clusters on track)

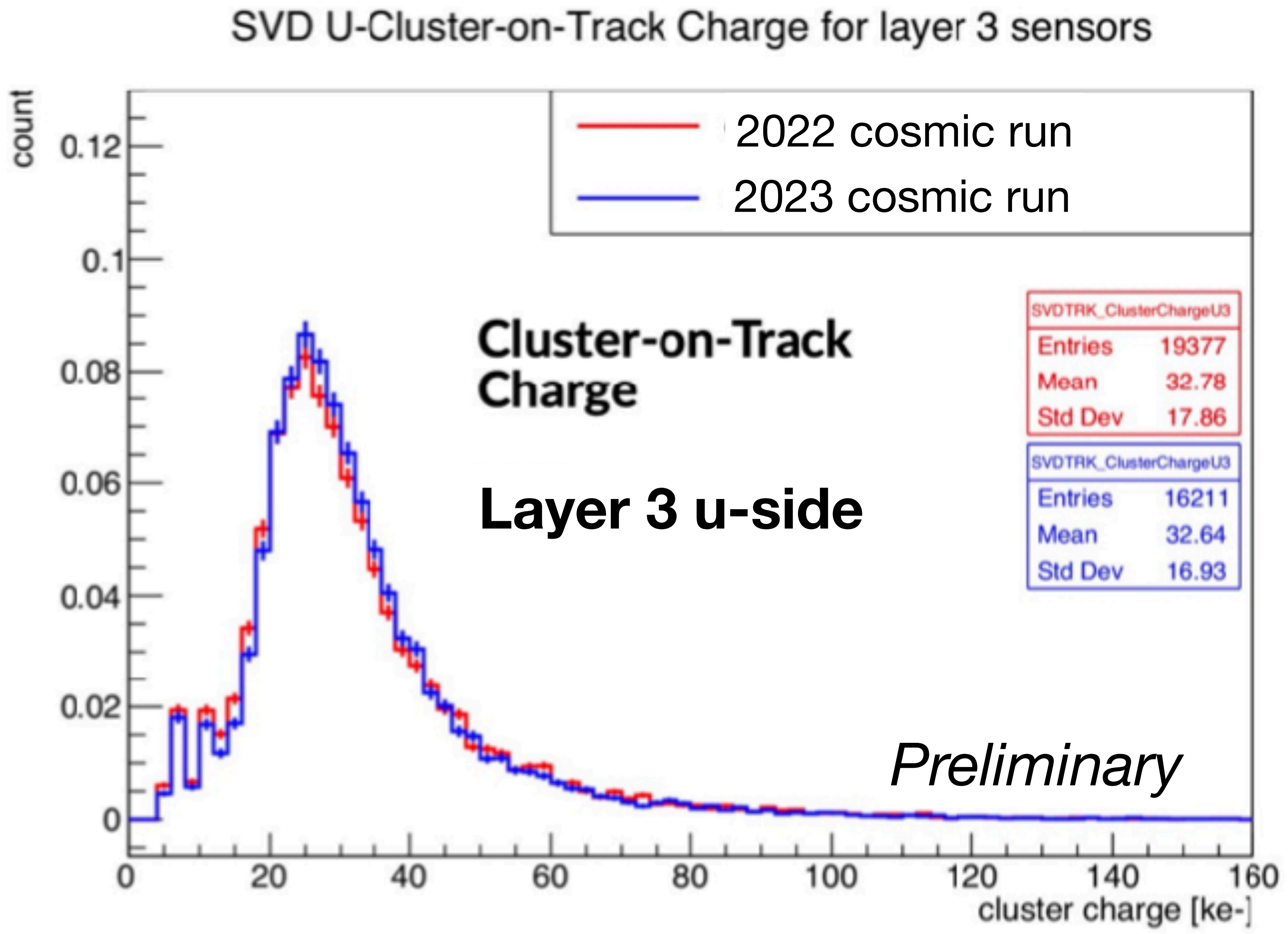


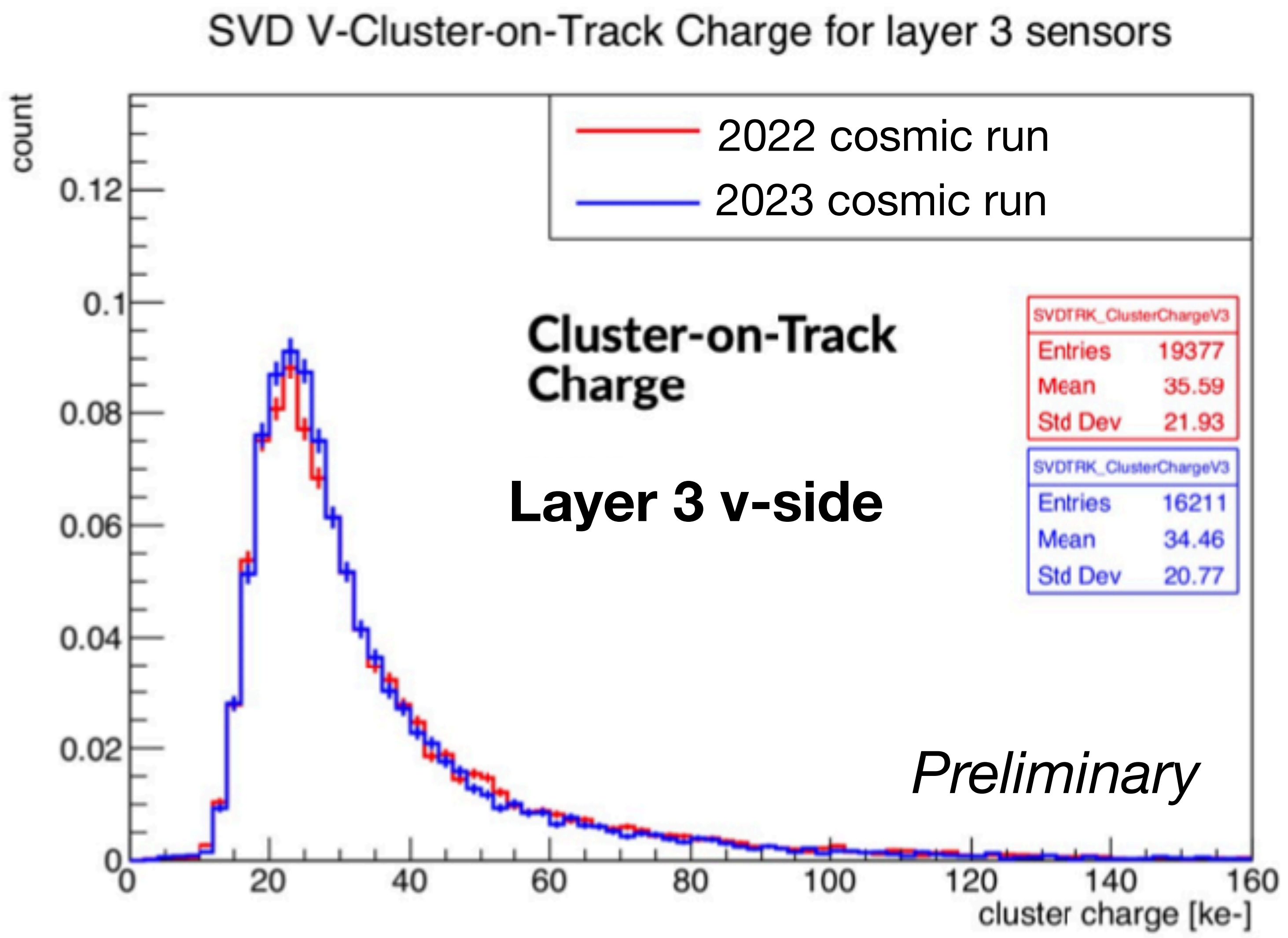


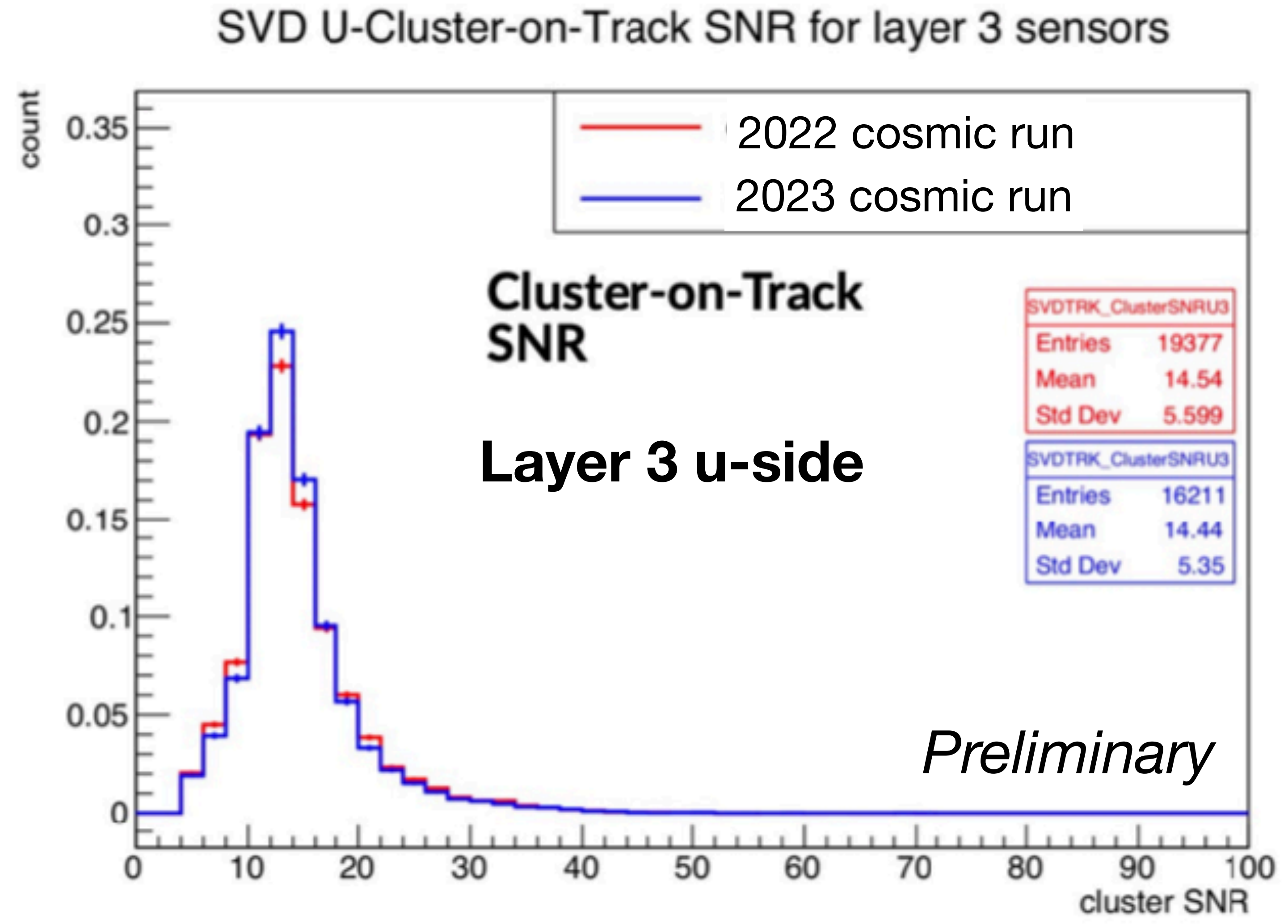
SVD event time – CDC event time [ns]

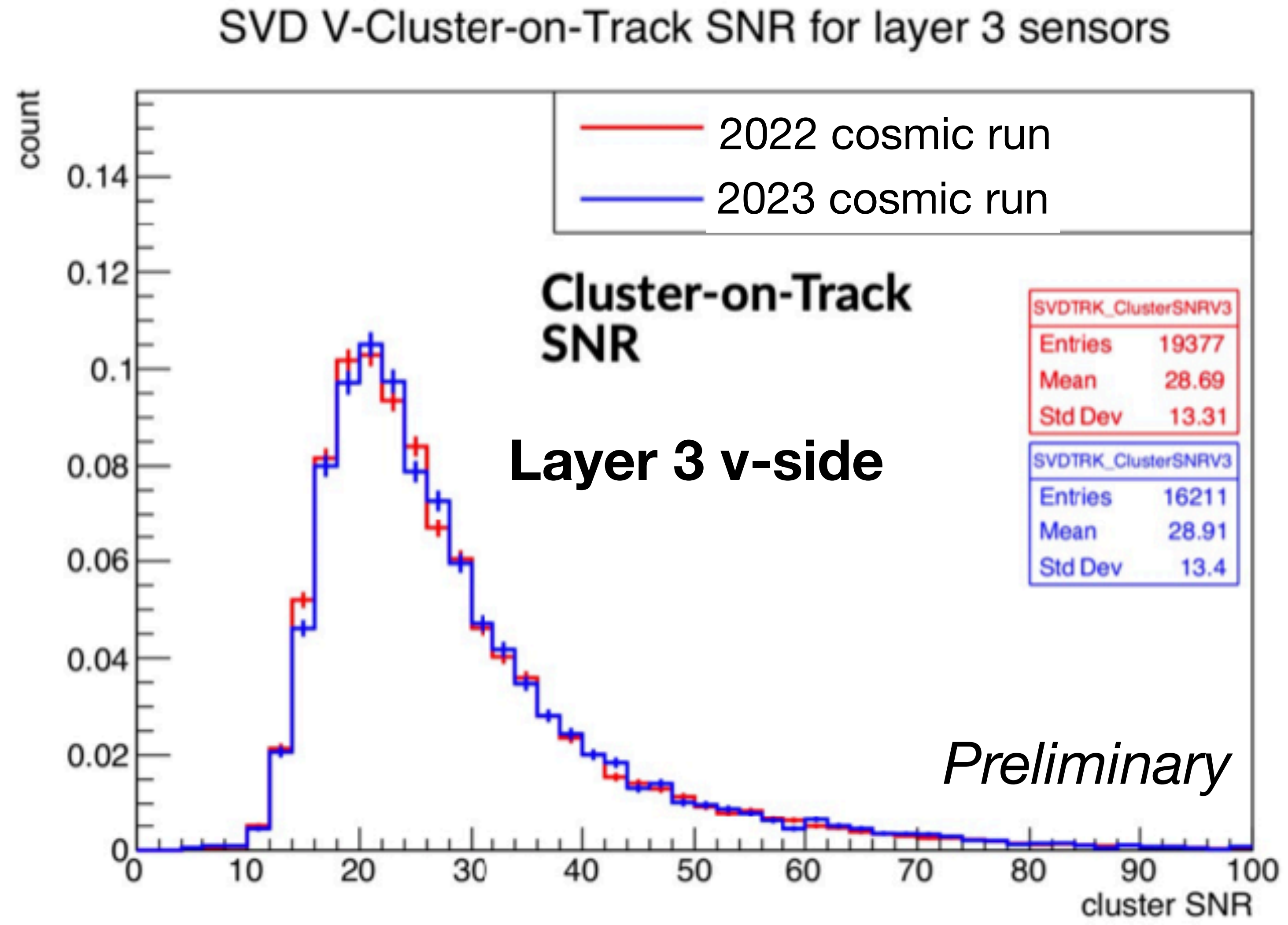
SVD performance after re-installation

- Comparison of cosmic runs in June 2022 and September 2023, both without B field









⇒ Confirmed good performance as before re-installation

⇒ Offline analysis ongoing to check more detailed performance