Performance of the Belle II Silicon Vertex Detector and Standalone Track Finder

CTD/WIT 2019

Connecting the Dots and Workshop on Intelligent Trackers

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INFN Istituto Nazionale di Fisica Nucleare

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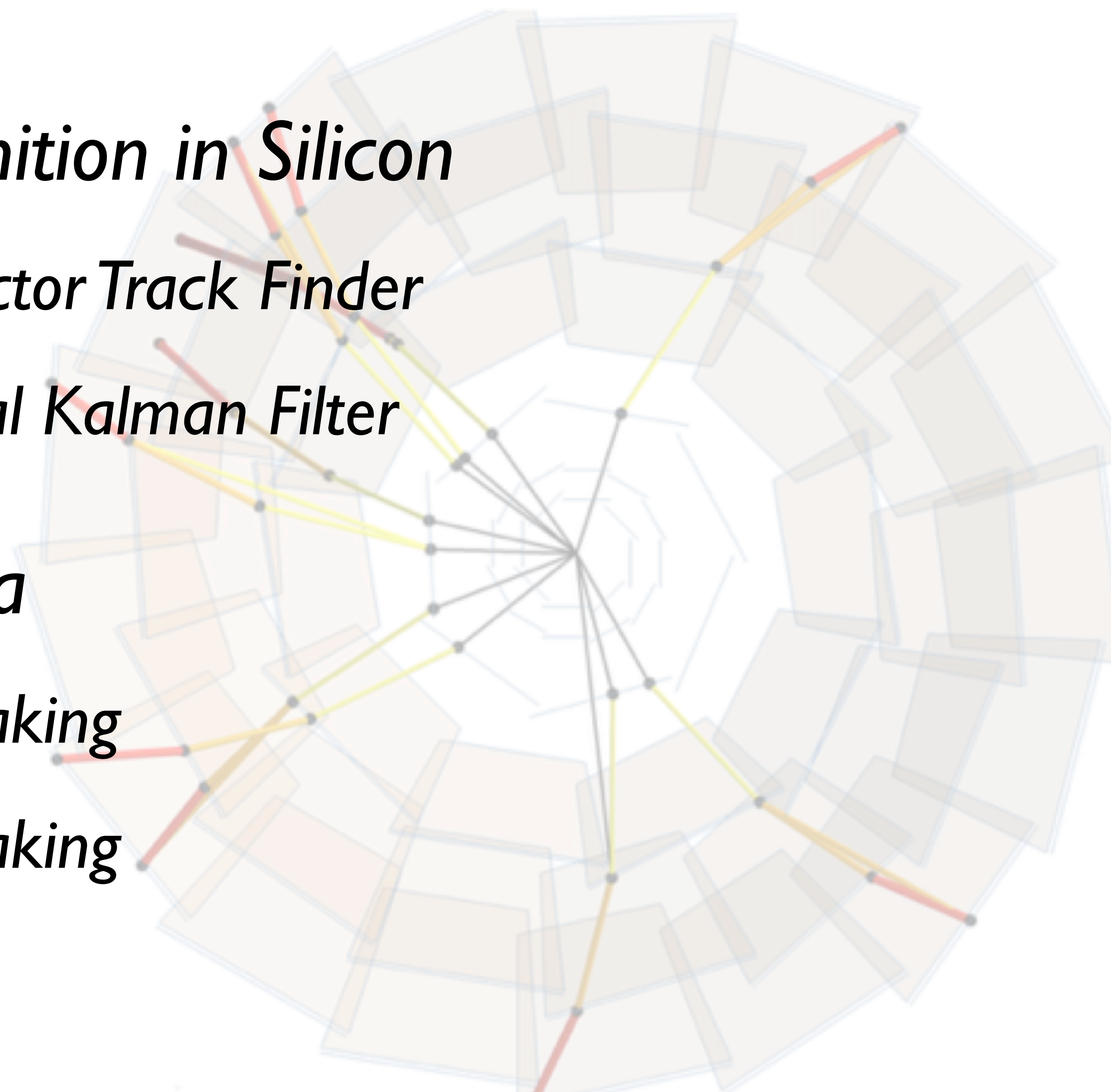
Belle II

on behalf of the *Belle II* Tracking Group

Outline

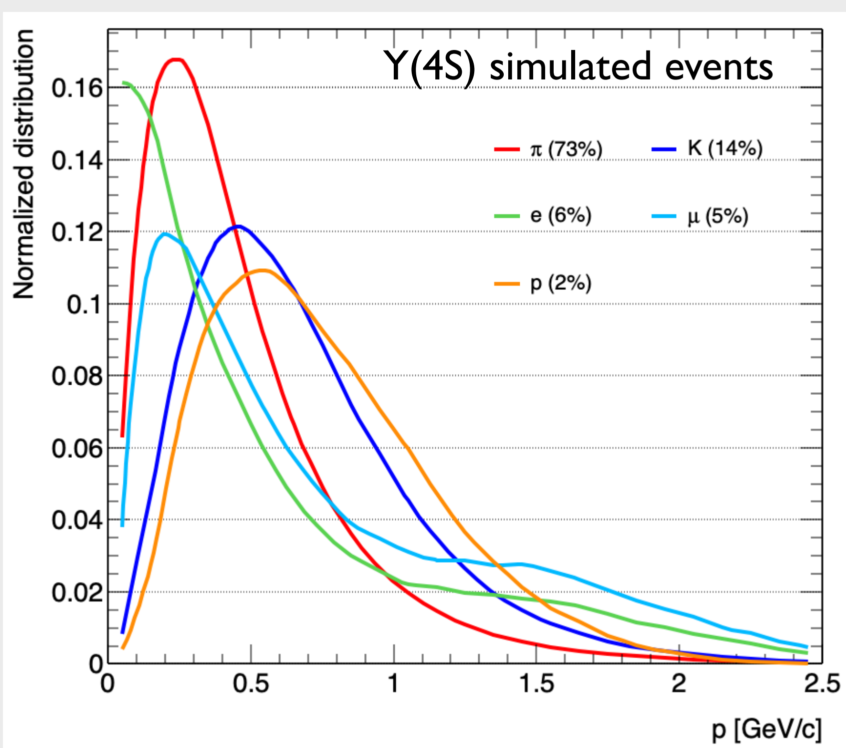
- The Belle II Vertex Detector
- Pattern Recognition in Silicon
  - VerteX Detector Track Finder
  - Combinatorial Kalman Filter
- Results on data
  - 2018 data taking
  - 2019 data taking



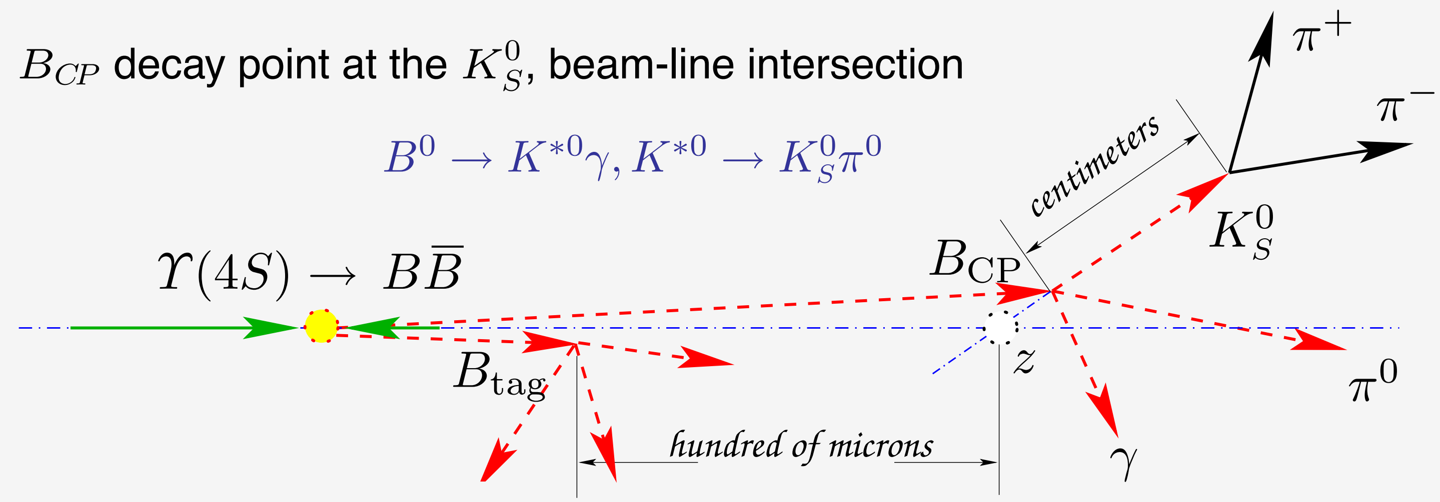
Tracking at a B-Factory Experiment

Typical Υ(4S) Event

- ➡ Υ(4S) center of mass is boosted
  - 7 GeV e^- on 4 GeV $e^+ \rightarrow \beta\gamma = 0.28$
  - reduced boost w.r.t. Belle
- ➡ average multiplicities
  - 11 charged tracks
  - 5 neutral pions
  - 1 neutral kaon
- ➡ soft charged tracks momentum spectrum

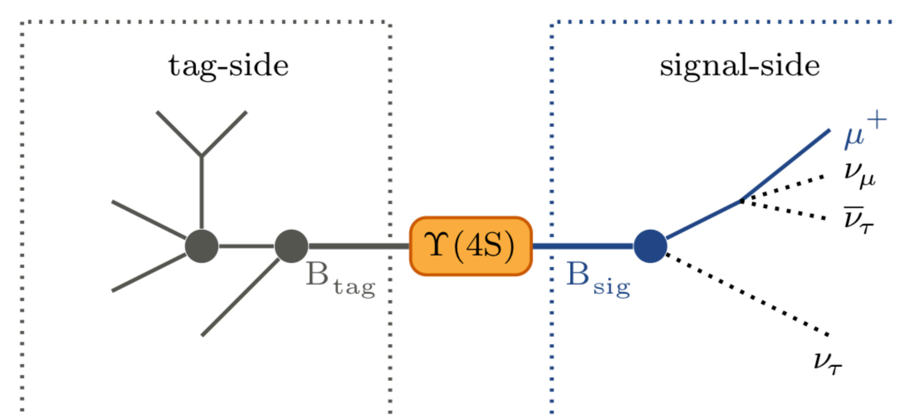


- ➡ The Vertex Detector provides the precise measurement of the primary and secondary vertices of short-lived particles



courtesy by E. Paoloni

- ➡ Many analysis are based on the full reconstruction of the event
  - *all* tracks should be reconstructed (down to p_T = 50 MeV/c)
  - *no* fake or ghost tracks



The Full Event Interpretation, T. Keck et al. arXiv:1807.08680v4

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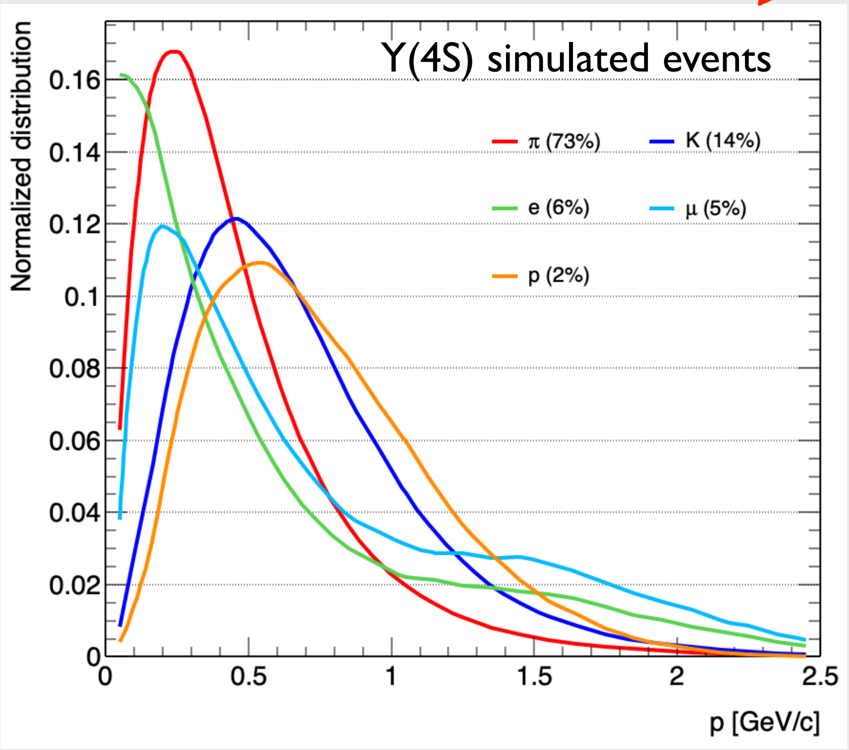
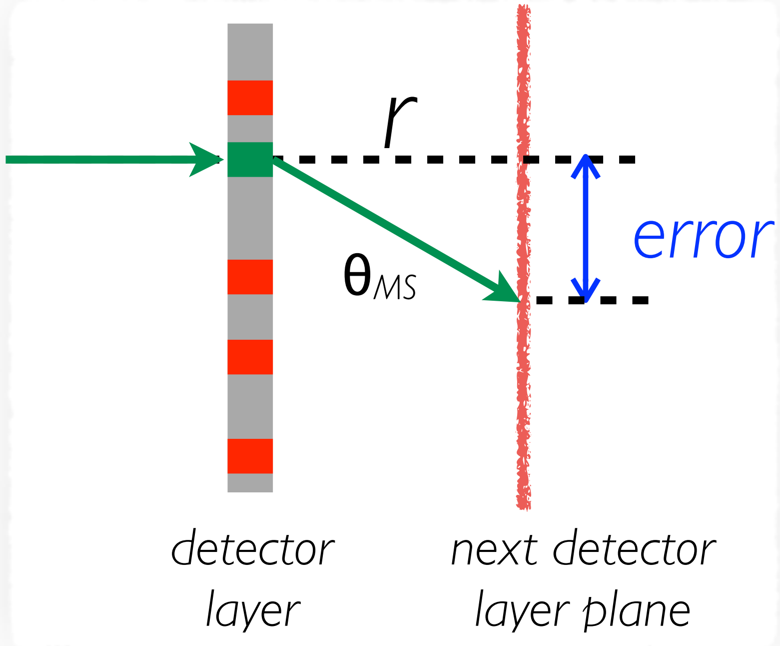


- The most important factors affecting the *precision* of the vertex position determination are:

1. the effect of **multiple scattering** ($\to r \cdot \theta_{MS}$)
2. the distance of the first (*correct*!) measured hit ($\to$ occupancy)



Signal hits on the vertex detector are sinked in an ocean of hits from **beam-background** particles

Belle II full lumi	layer1 (pixels)		layer3 (strips)	
	# hits	occupancy	# hits	occupancy
Υ(4S)	11	5 10^{-6}	11	0.2%
beam bkg	50k	3%	3.2k	3%

The *Belle II* Vertex Detector

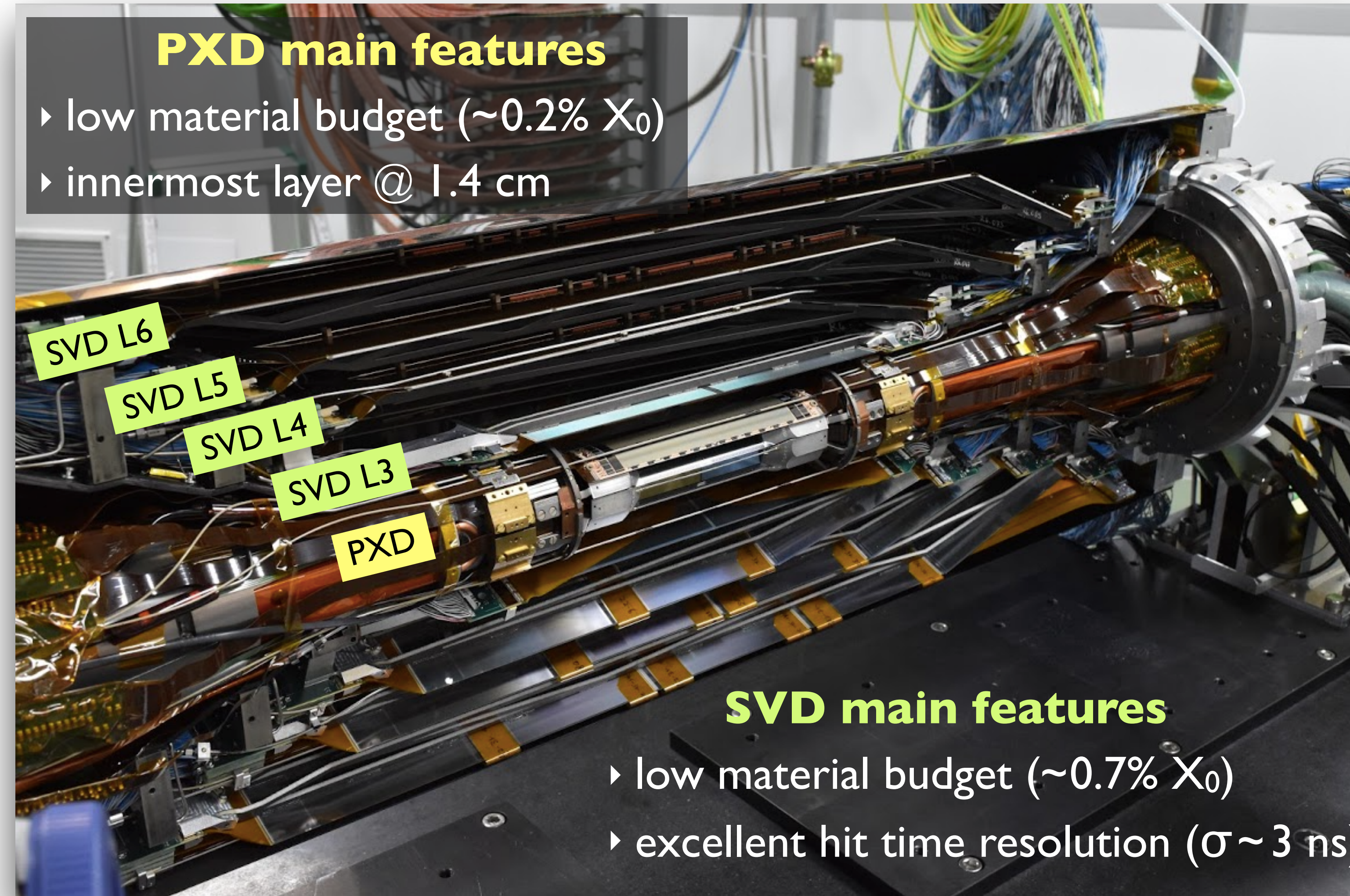
The Vertex Detector (VXD) is composed of two detectors, complementary to each other:

➡ PiXel Detector (PXD)

guarantees the precision on the impact parameters needed for the determination of primary and secondary vertices

➡ Silicon Vertex Detector (SVD)

guarantees the finding of the correct pixels to attach to the track, despite the machine background & provide standalone tracking (and PID) of low p_T tracks



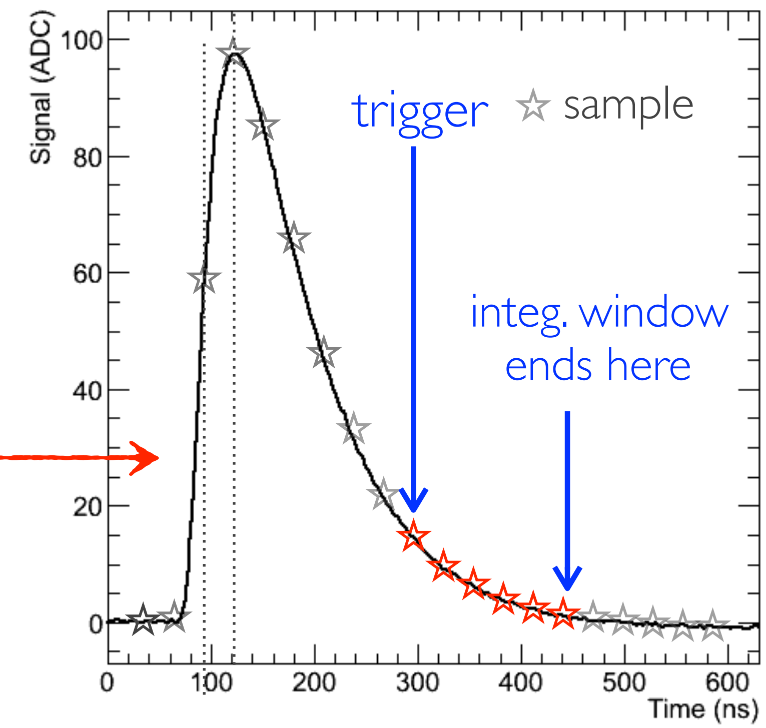
	layer	radius (cm)	thickness (μm)	r/φ pitch (μm)	Z pitch (μm)	# sensors	total # channels
PXD	1	1.4	75	50	55 - 60	2 x 8	**8 M**
	2(*)	2.2	75	50	70 - 85	2 x 12	
SVD	3	3.9	300 - 320	50	169	2 x 7	**225k**
	4	8.0	300 - 320	50	240	3 x 10	
	5	10.4	300 - 320	50	240	4 x 12	
	6	13.5	300 - 320	50	240	5 x 16	

(*) only 2 ladders installed

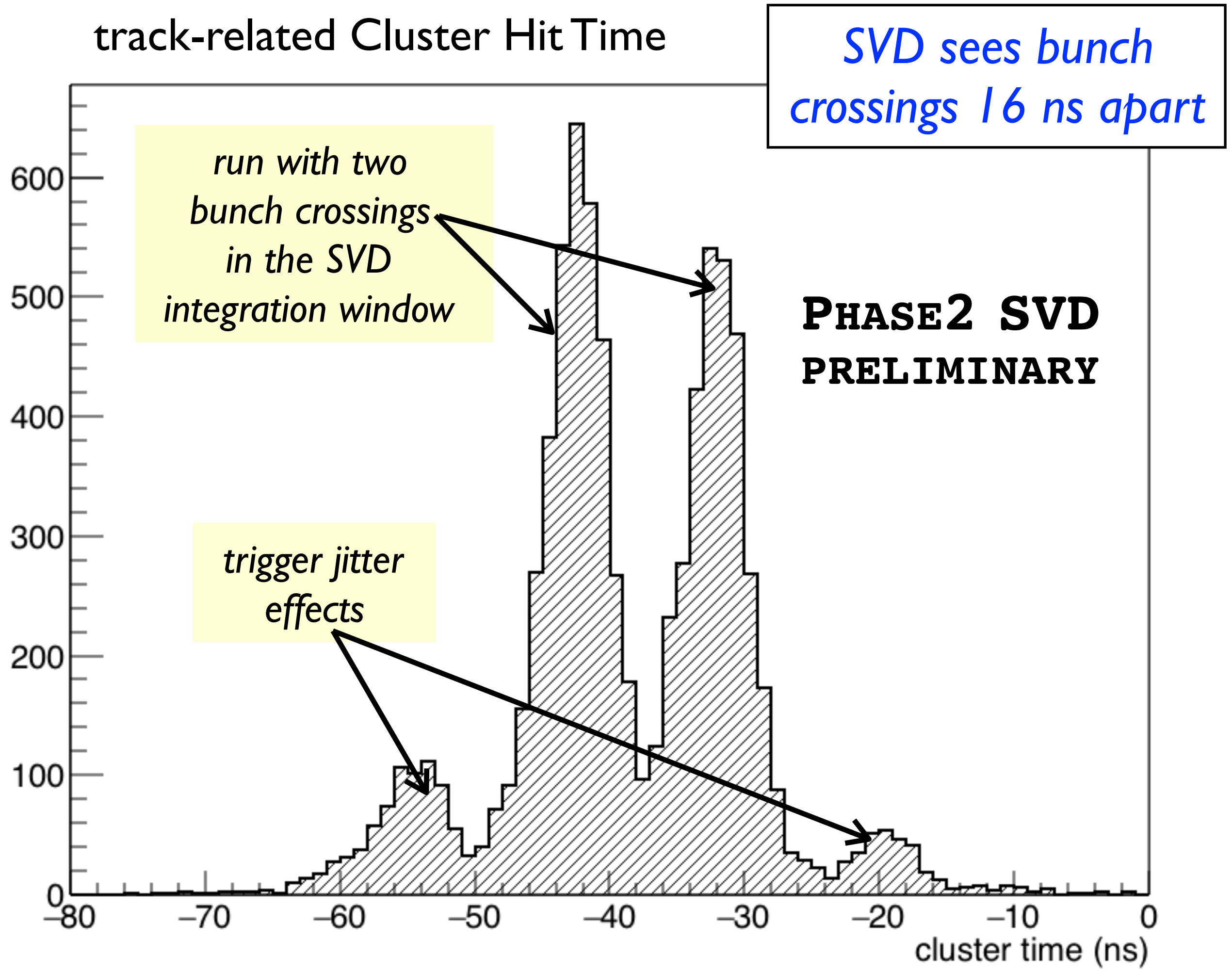
The SVD Hit Time

- ➡ Precise determination of the SVD hit time is crucial to significantly *reduce the occupancy by rejecting off-time particles*
  - beam-background particles are produced at <u>each</u> bunch crossing at 256 MHz (level1 trg ~ 30kHz, HLT ~ 10 kHz)
- ➡ SVD will be sensitive to off-time particles produced up to 100 bunch crossings before the triggered event

OFF-time particle noiseless response



track-related Cluster Hit Time



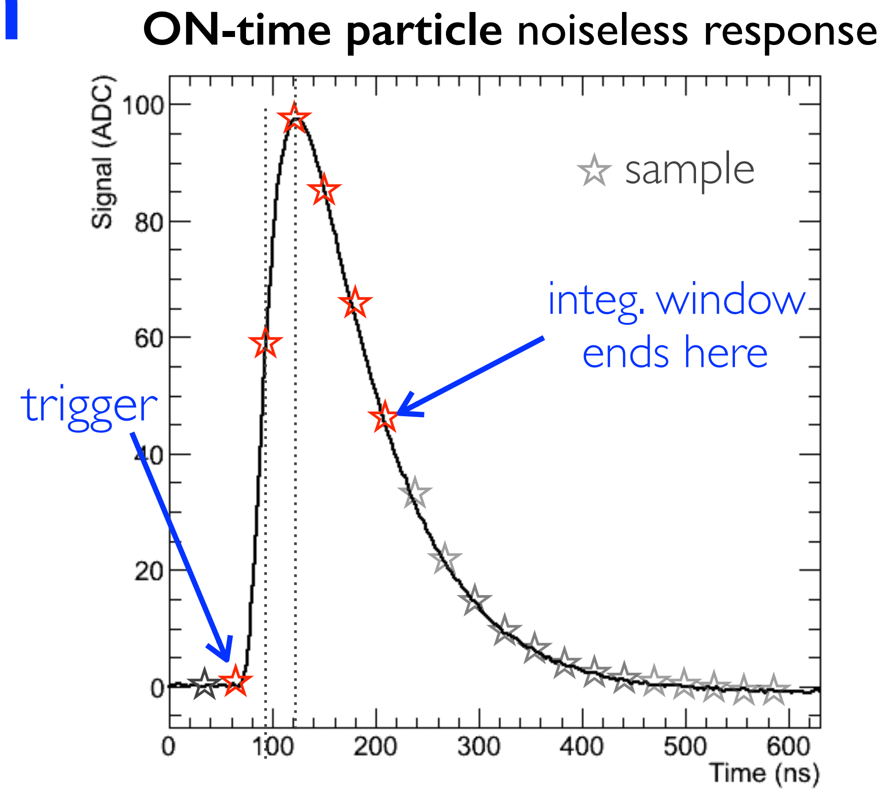
note: SVD hit time is not calibrated in this plot

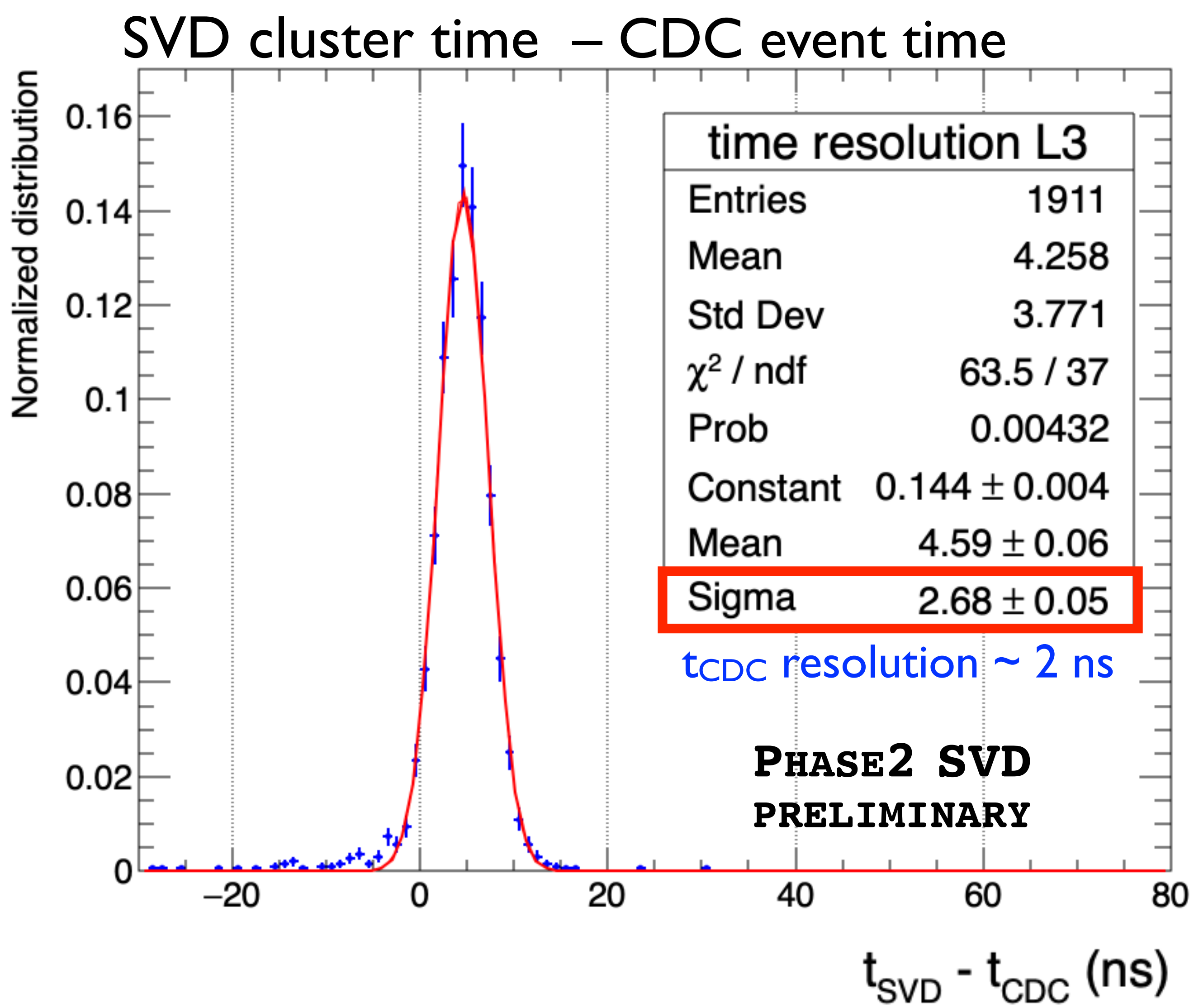
- Determine the SVD hit time will allow to reject particles produced in a different bunch crossing
- expected rejection of ~30% clusters per sensor side→ ~50% of space points (3D hits) per sensor
- also, use the *time difference* of the remaining clusters in the pattern recognition algorithms
  - opposite-side clusters of the same sensor
  - same-side clusters of different sensors

<u>*4D (space+time) pattern recognition allows to significantly reduce the occupancy, especially important in the innermost SVD layer*</u>

SVD Hit Time Resolution

- ➡ The SVD hit time is determined using the sampling of the signal response and the information of the trigger arrival
- ➡ The sensor-dependent calibration is performed using the event time provided by the CDC
- ➡ An overall shift is applied to bring SVD time centered in 0



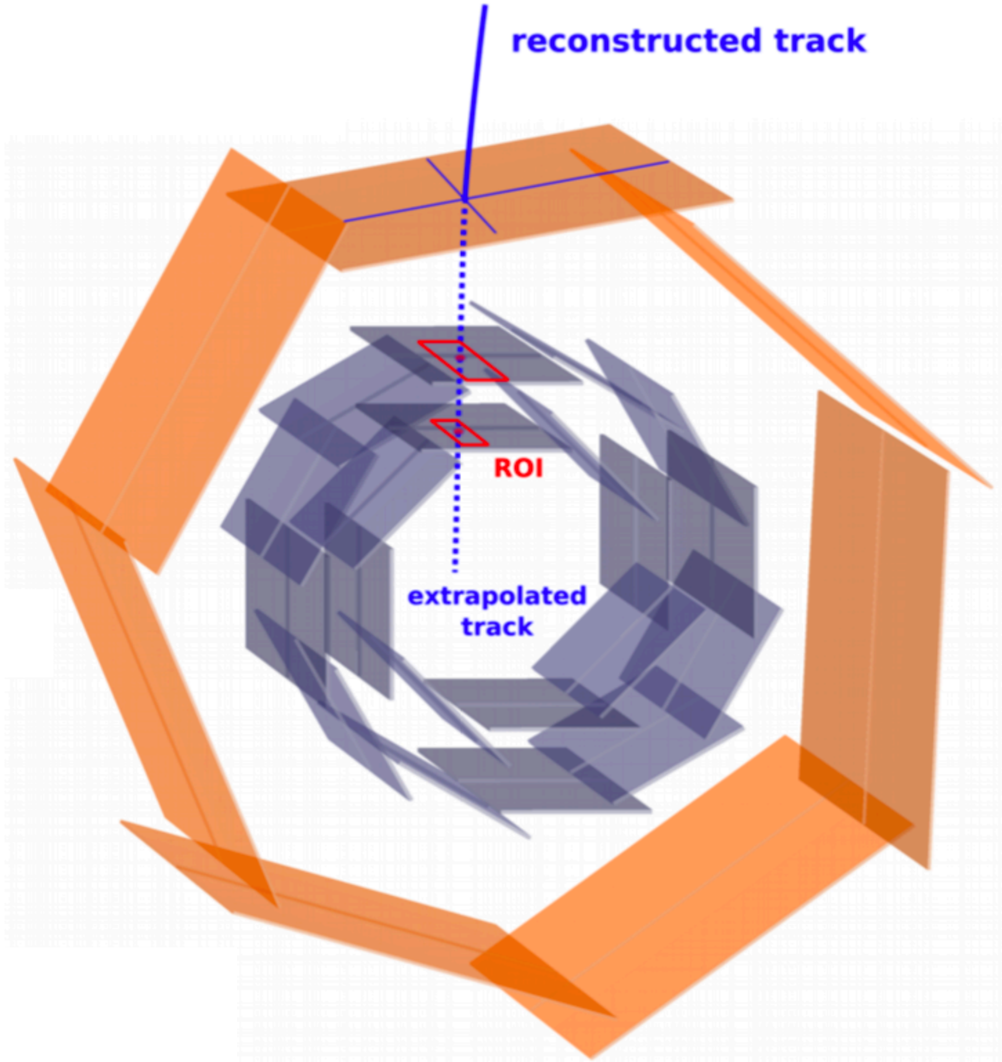


excellent hit time resolution

1. *SVD hit time resolution better than 2 ns for Bhabha events*
2. *shift from zero is due to CDC time shift*
3. *SVD can measure time of flight of "slower" particles (hadron events)*
4. *SVD hit time can contribute in the determination of the event time*

Region Of Interest Finding

- The long PXD integration time coupled to the high beam background yields a data rate of 20 Gb/s from the PXD. One order of magnitude data reduction is necessary to cope with storage and bandwidth limits.
- The data reduction happens online on the High Level Trigger (HLT):
  - SVD tracks are extrapolated toward the PXD sensors and Regions of Interests (ROIs) containing the signal pixels are determined
  - only pixels in the ROIs are used for the offline reconstruction, all the other pixels are rejected at the DAQ level and are not stored to tape



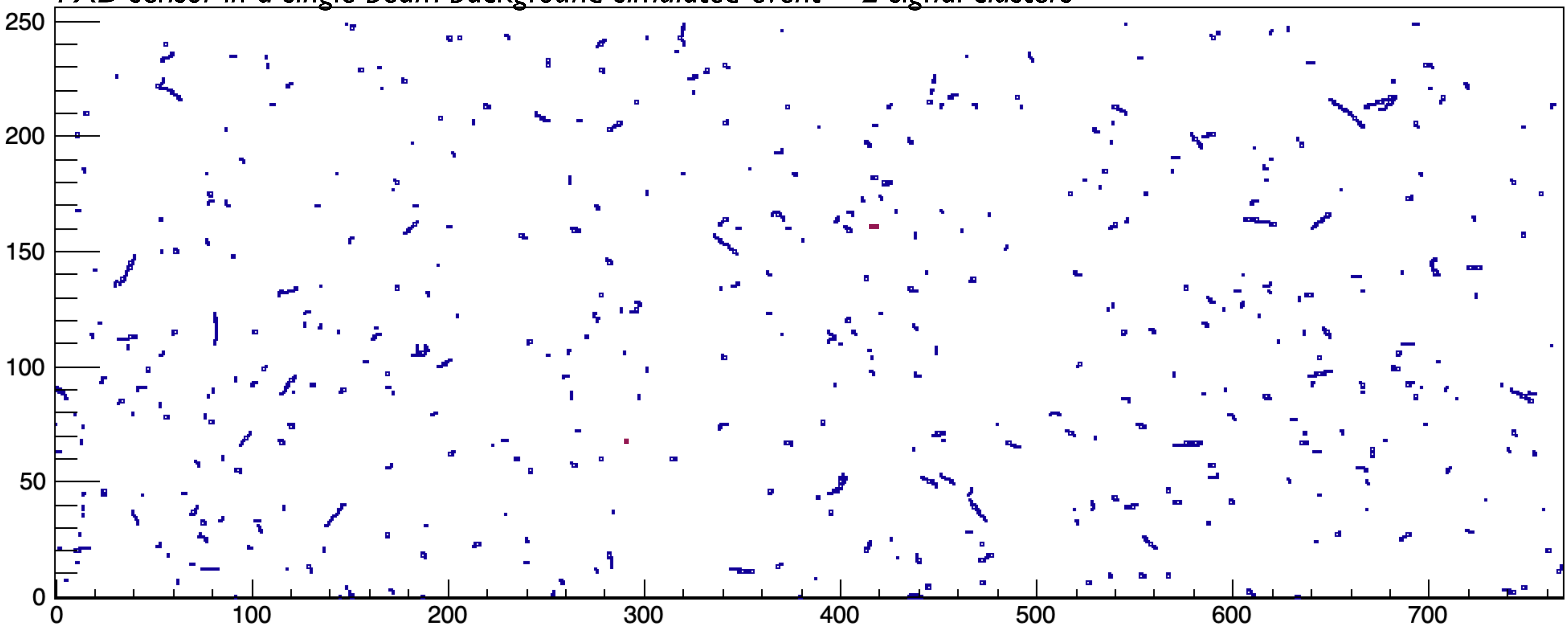
__ROI finding on HLT increases the requirements on tracking:__

1. *100% reliability (program crashing means data taking stops)*
2. *execution time under control*
3. *efficient ROI finding, no pixels otherwise!*
4. *calibration of the tracking algorithm ready for new data*

PXD Screenshot of One Event

1. pixels over threshold integrated in 20 μs at nominal luminosity and nominal background
   - cluster shape can be used to reduce the occupancy
2. two signal clusters (can you find them?)
   - in Y(4S) event, on average: 0.7 signal clusters are expected on one sensor of `layer1` and 0.45 on one sensor of `layer2`

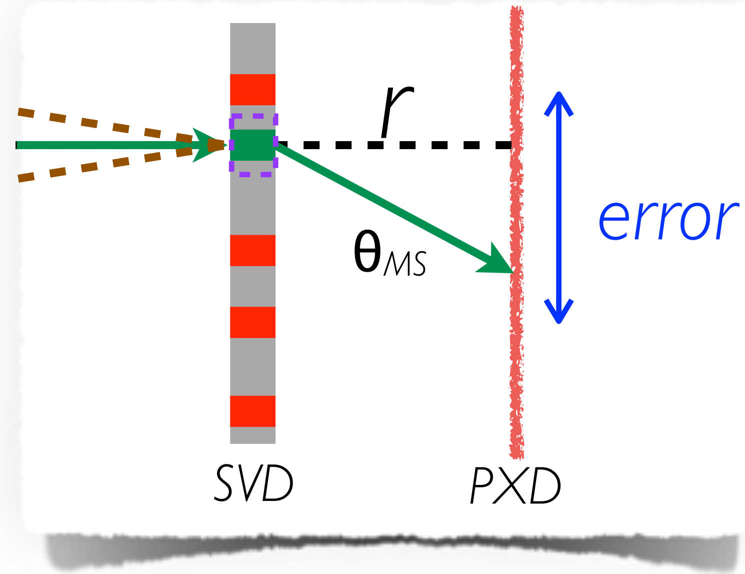
PXD sensor in a single beam-background simulated event + 2 signal clusters



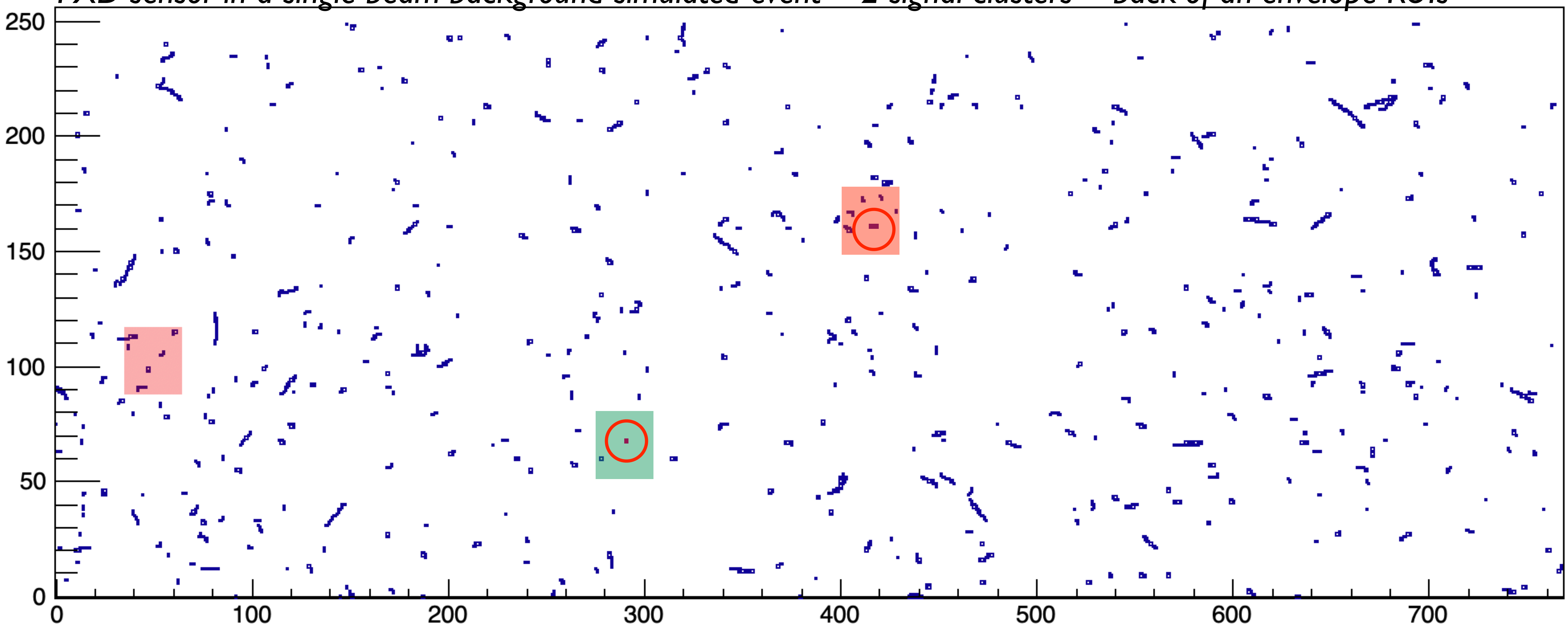
Back-of-an-Envelope ROIs

➡ Estimation of the ROI size for100 MeV/c signal particle extrapolated from the innermost SVD layer

beam (z) direction	hit position	multiple scattering	track direction	total (10 σ)
	45 μm	110 μm	90 μm	1.5 mm



PXD sensor in a single beam-background simulated event + 2 signal clusters + back-of-an-envelope ROIs



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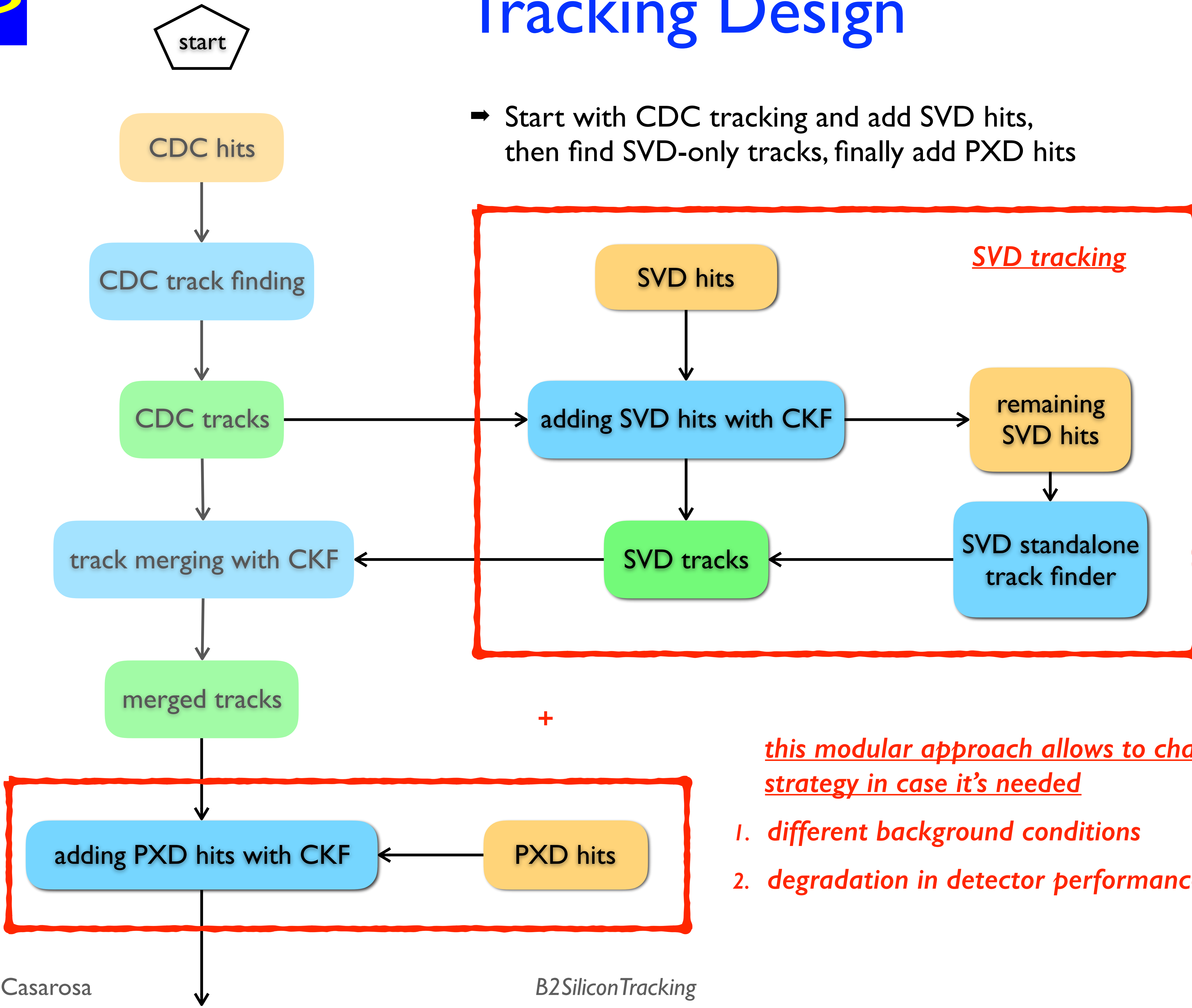
Tracking Design

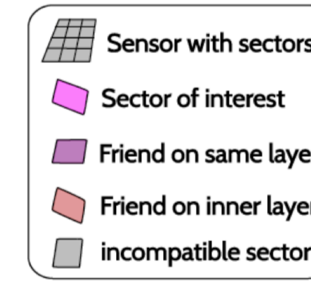
➡ Start with CDC tracking and add SVD hits, then find SVD-only tracks, finally add PXD hits



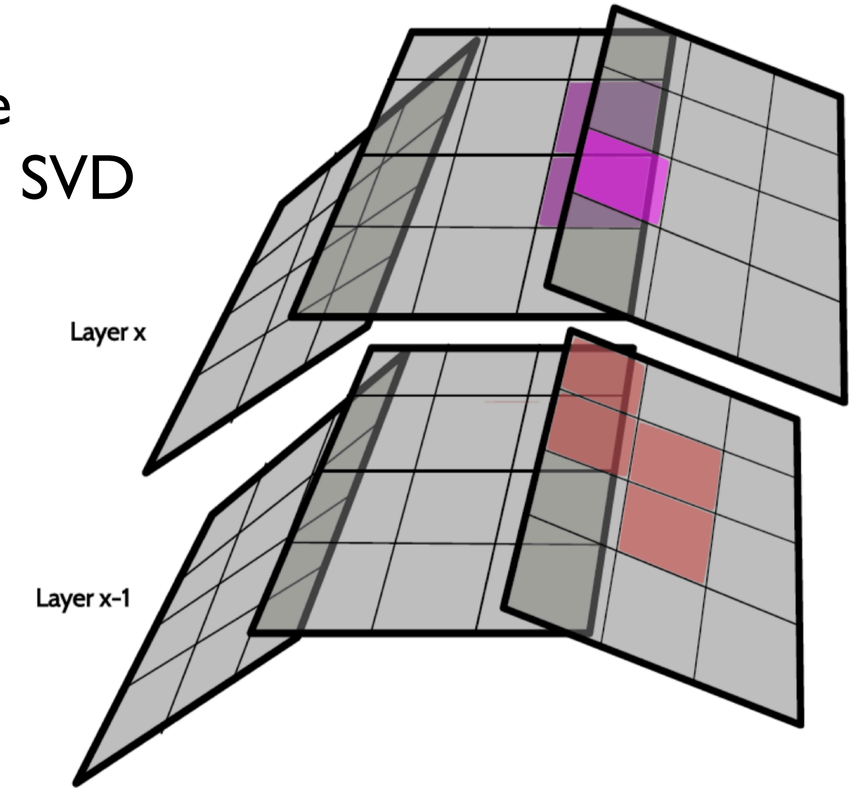
this modular approach allows to change the strategy in case it's needed

1. *different background conditions*
2. *degradation in detector performances*

SVD Standalone Track Finding



- GOAL extract track patterns from a huge number of possible combinations of space points (3D hits) in the 4 layers of the SVD



- IDEA to significantly reduce the number of combinations
  1. divide the sensors into virtual sectors (3x3)
  2. combine space points belonging to ***friend-sectors*** only

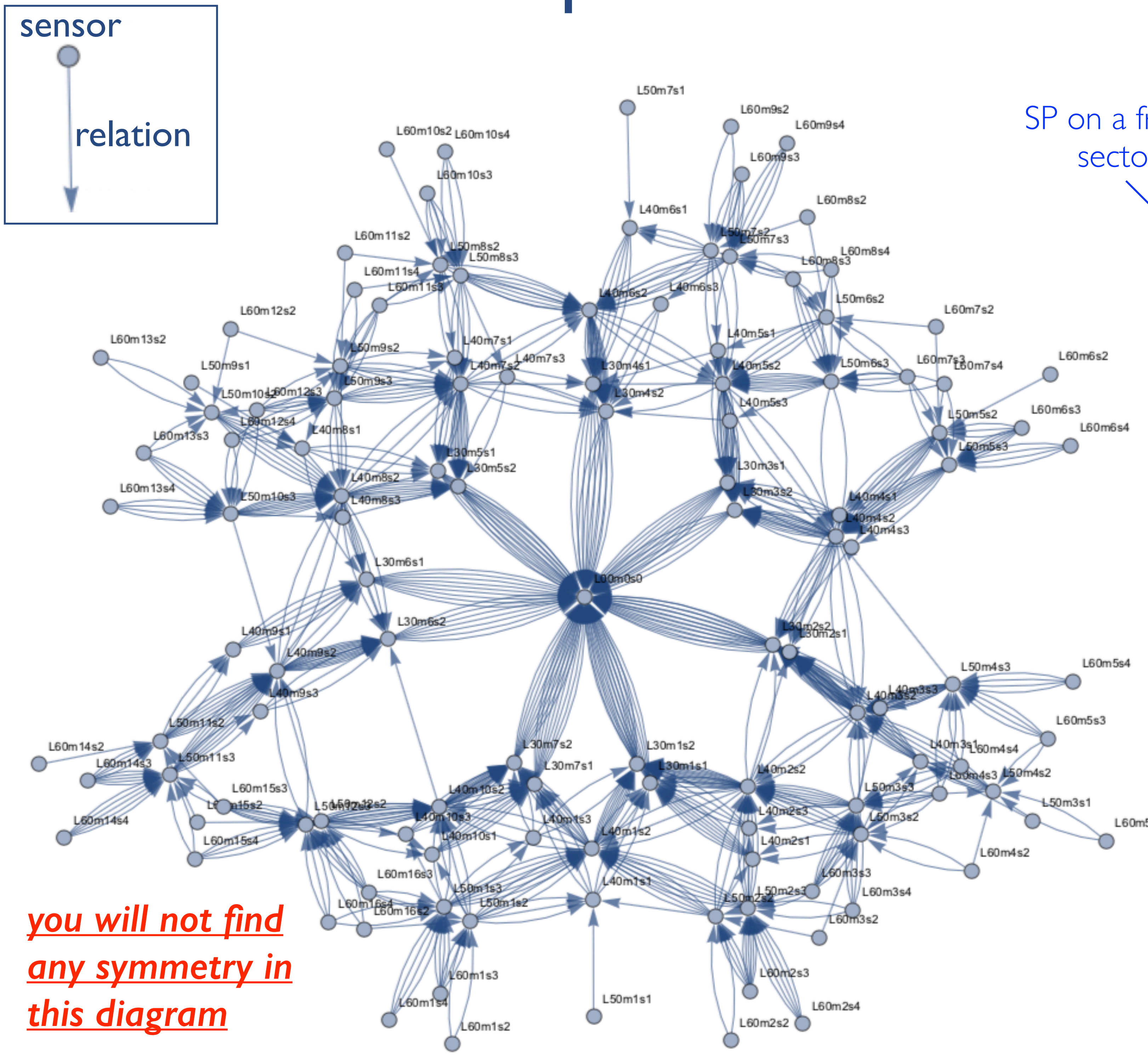
  "two sectors are friends if a track has passed both of them without having passed any other sector"

- TOOLS a SectorMap stores the information about the friendship relations between sectors and a set of selection requirements (filters = {variable, range}) used to reject background hits

- TRAINING of the SectorMap with simulated events to determine
  - the friendship relations, taking into account multiple scattering & energy loss effects
  - two-hit filters: use simple variables like distance in space and time, angles of the direction defined by the two space points
  - three-hit filters: use more complex quantities computed with 3 space points

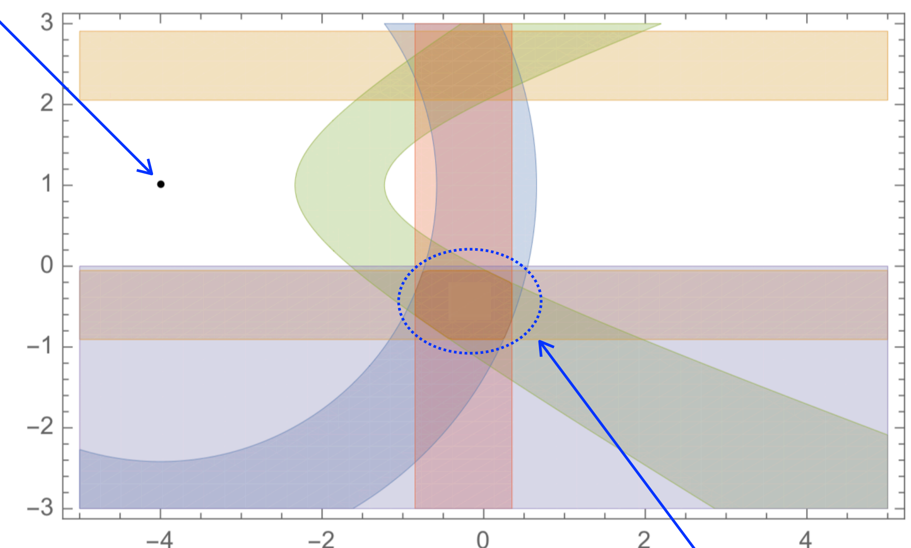
SectorMap Graphical Illustration

friendship relations + filters



SP on a friend sector

visive example of two-hit filter:



consider SP only in this allowed region

- Cut(Distance3D)
- Cut(Distance2D)
- Cut(SlopeRZ)
- Cut(Distance1DZ)
- Cut(CosXY)
- AllCuts = allowed region

\+

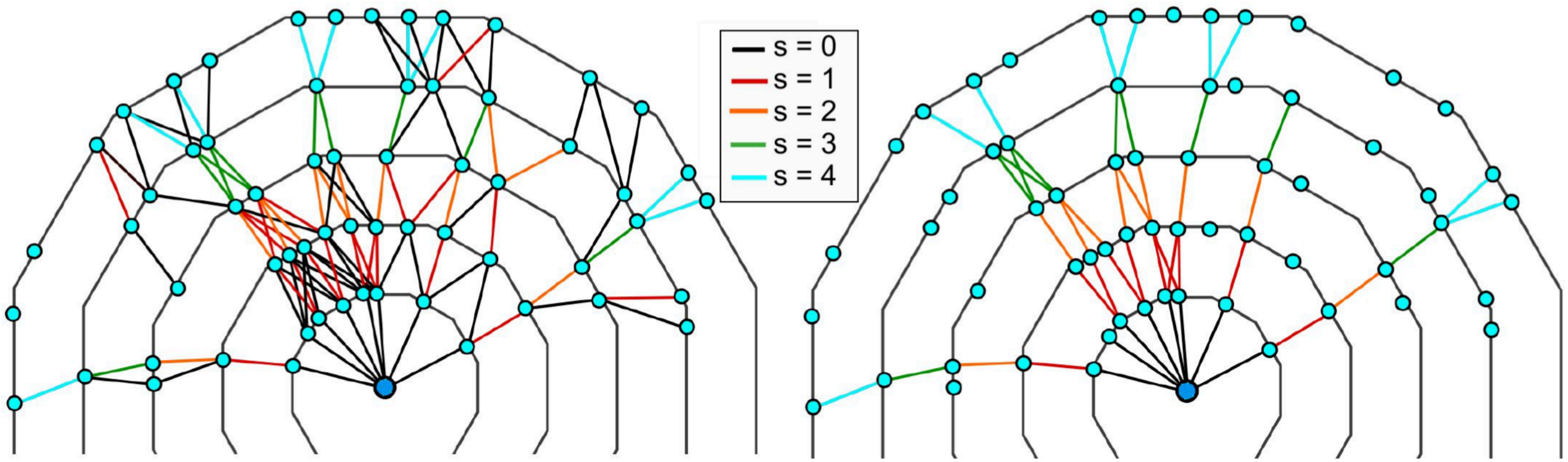
cluster time difference

you will not find any symmetry in this diagram

note: only one sector per sensor shown!

The Final Track Candidates

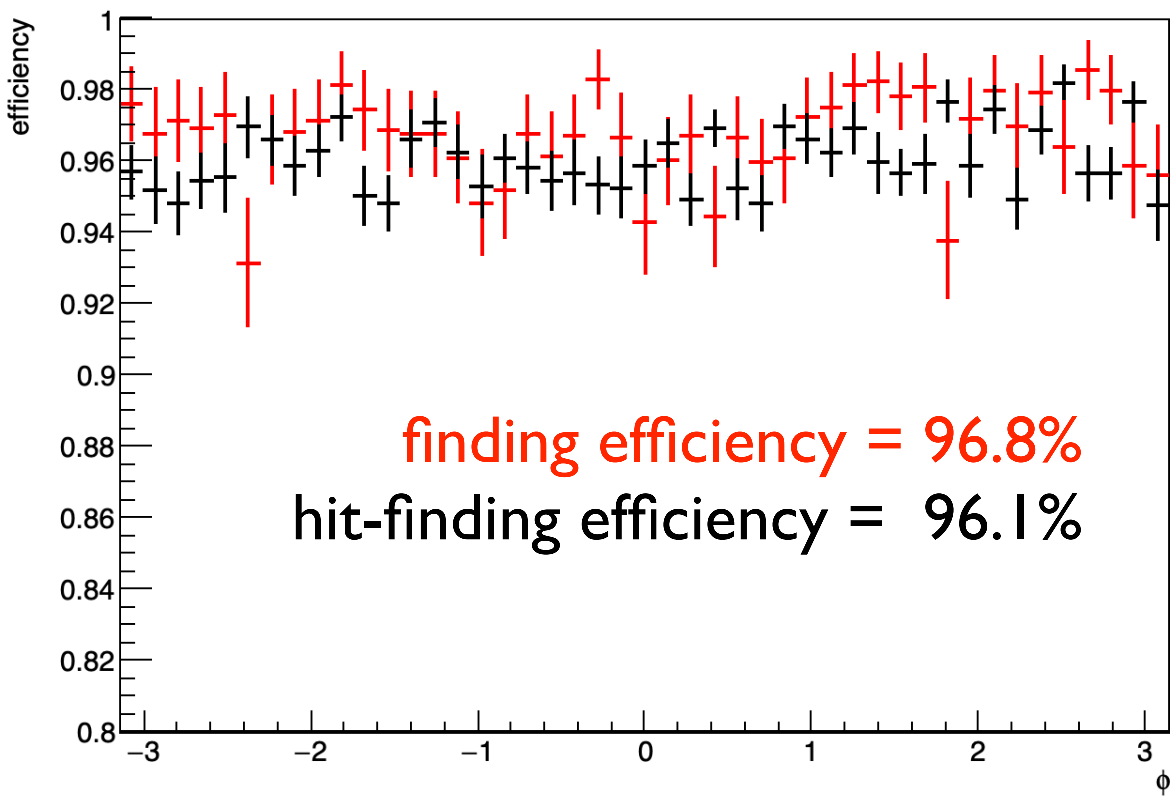
- The SectorMaps is used to produce the Segment Network, a set of pairs of space points, *segments*, that satisfy the friendship relations and the filters
- A Cellular Automaton using segments as cells is run to gather the longest paths

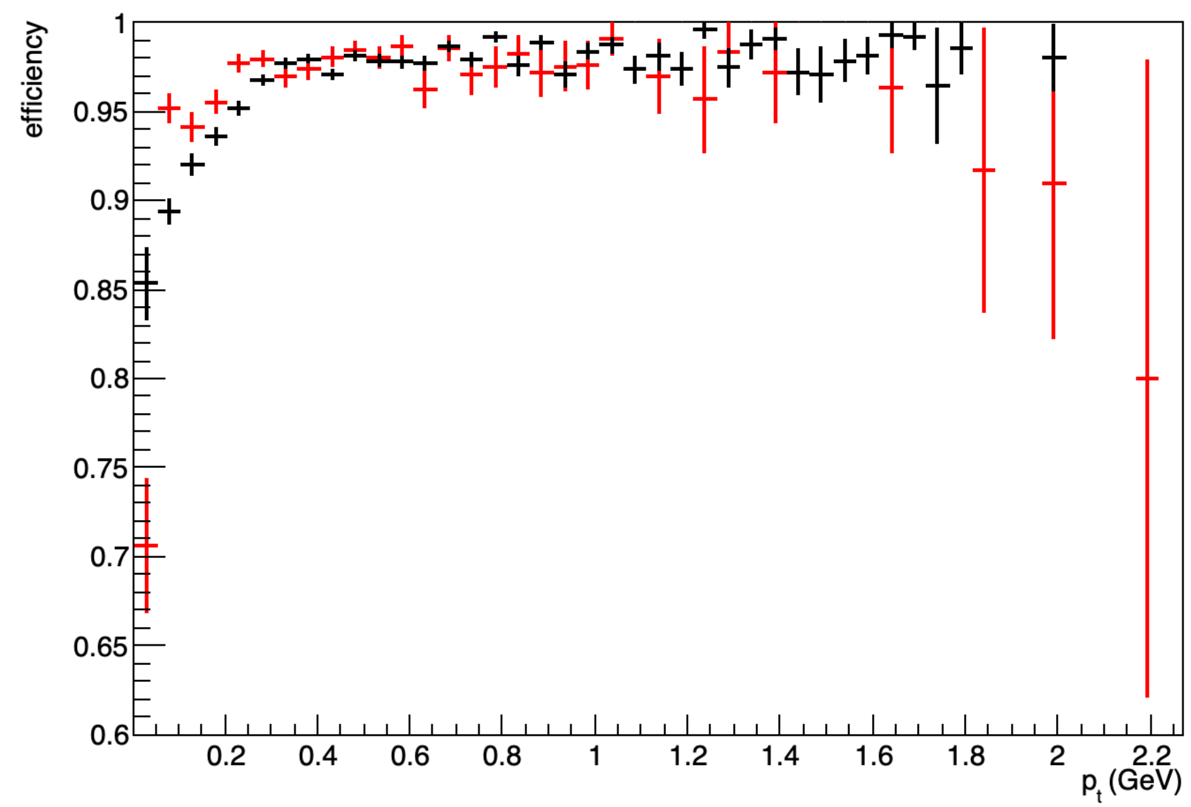


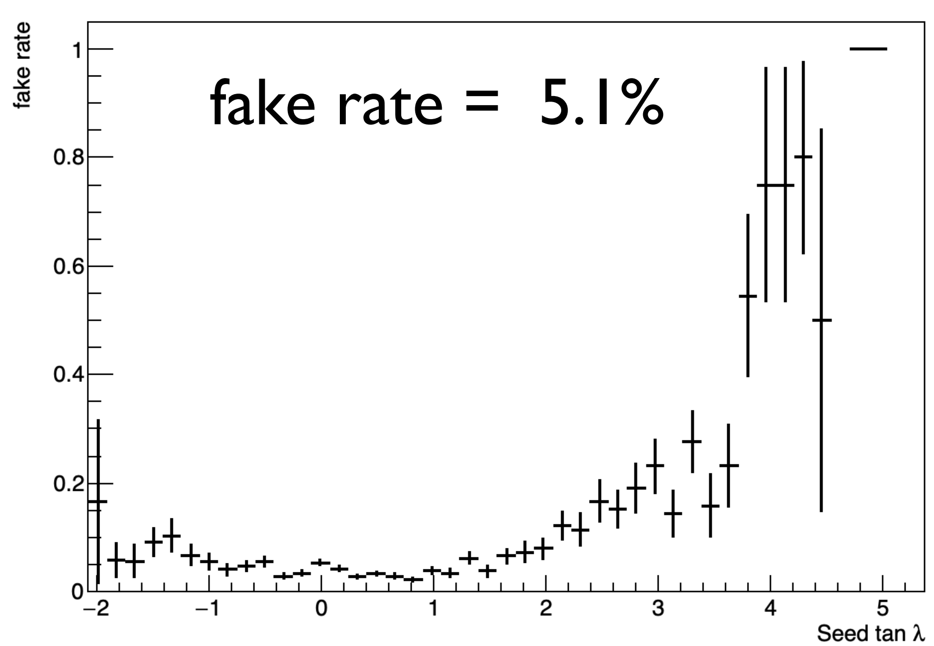
- The fake and clone track candidates, as well as track candidate sharing one or more space points are removed based on a quality indicator
  - a Triplet Fit is applied to each path and sub paths obtained by excluding one or more space points
  - for each track candidate the sum of the chi^2 of each triplet is computed
  - the p-value of each track candidate is used to select the track candidates competing for one or more space points

Performance on Simulated Events

including beam background hits expected for nominal luminosity
and factoring out the geometrical acceptance





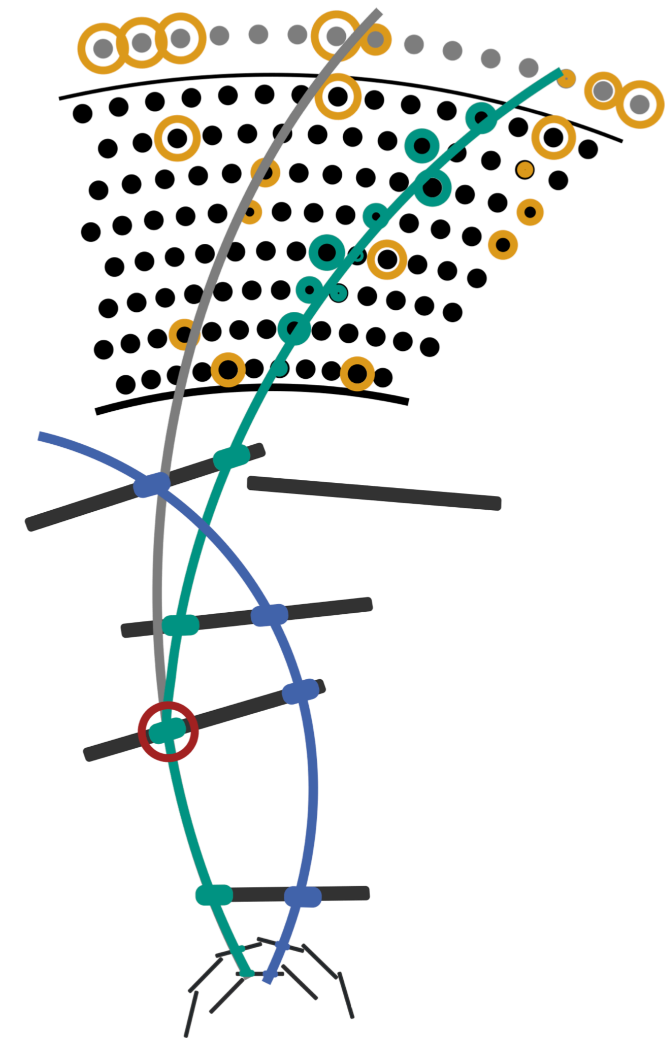


excellent performance on simulated events

1. *flat efficiency in phi, as expected*
2. *efficiency degradation at low p_t, but still above 95% at p_t = 100 MeV/c*
3. *fake rate of 5% mostly due to tracks in the forward direction*

Combinatorial Kalman Filter

- ➡ Start with a track, extrapolate it inward and look for hits to attach
  - applied to CDC tracks to add SVD hits, and to SVD tracks to add PXD hits
- ➡ extrapolation is done with the Runge-Kutta-Nystrom method and allows to consider multiple scattering, energy loss and magnetic field distortions
- ➡ hits nearby the extrapolated point are attached only if they pass certain *filters* (based on BDT algorithm)
- ➡ in case of more than one compatible hit, paths are duplicated and at the end a BDT-based selection allows to determine the final set of track candidates



CKF	SVD	PXD
purity	98%	96%
efficiency	85%	89%

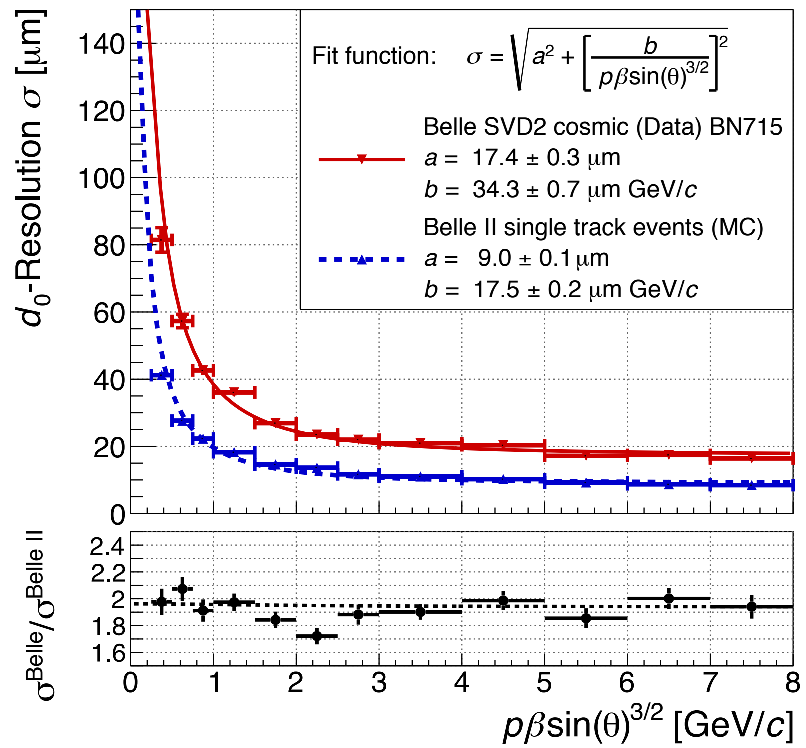
excellent performance on simulated events

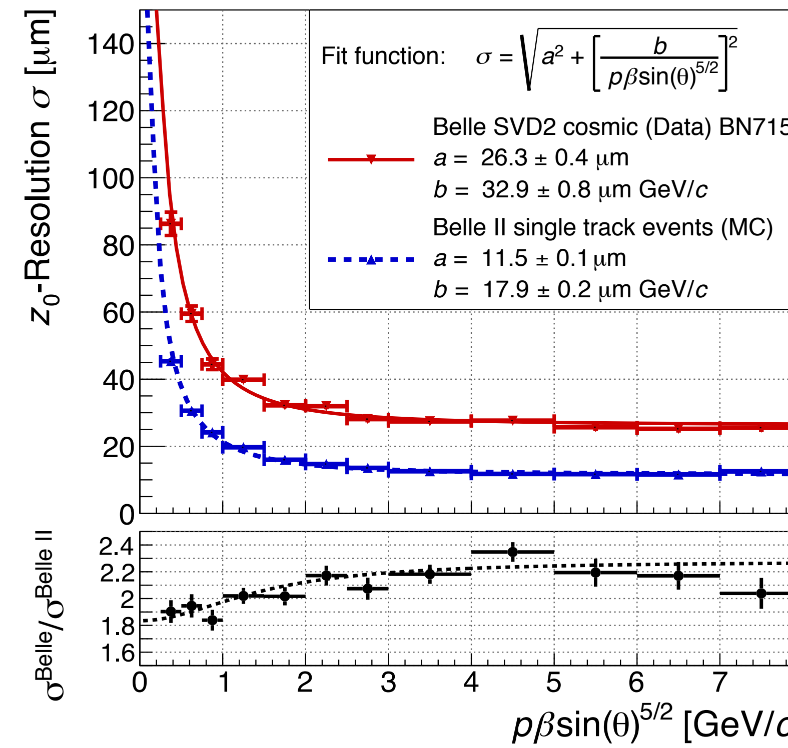
1. *very high purity*
2. *high efficiency, given the occupancy due to beam background hits*
3. *shortens processing time as it provides track parameters with an increased precision*

Overall Tracking Performance

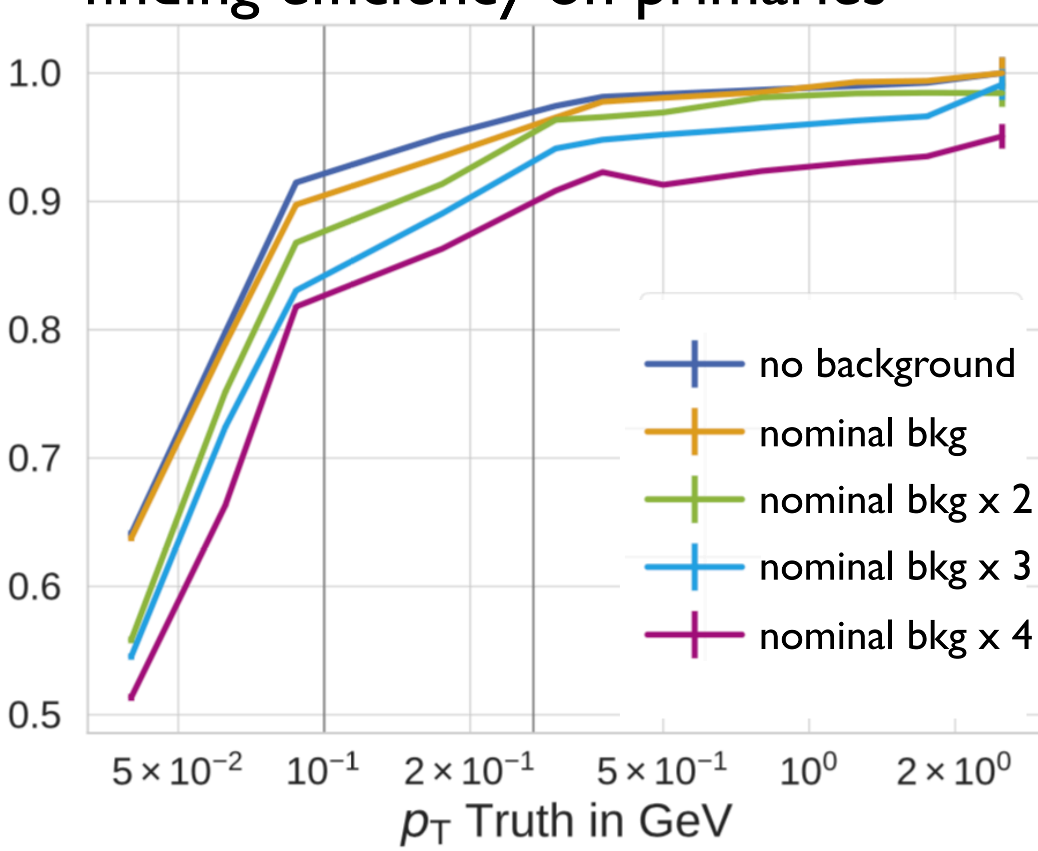
improved impact parameters resolution

factor 2 improvements in both d_0 and z_0 with respect to Belle, thanks to PXD hits





finding efficiency on primaries(*)



- ➡ The finding efficiency for *CDC+SVD+PXD II* tracking robust against beam background
- ➡ The performances are acceptable with twice nominal background
- ➡ Still room for improvement as no optimisation has been studied for background higher than the nominal one

(*) factoring out the geometrical acceptance

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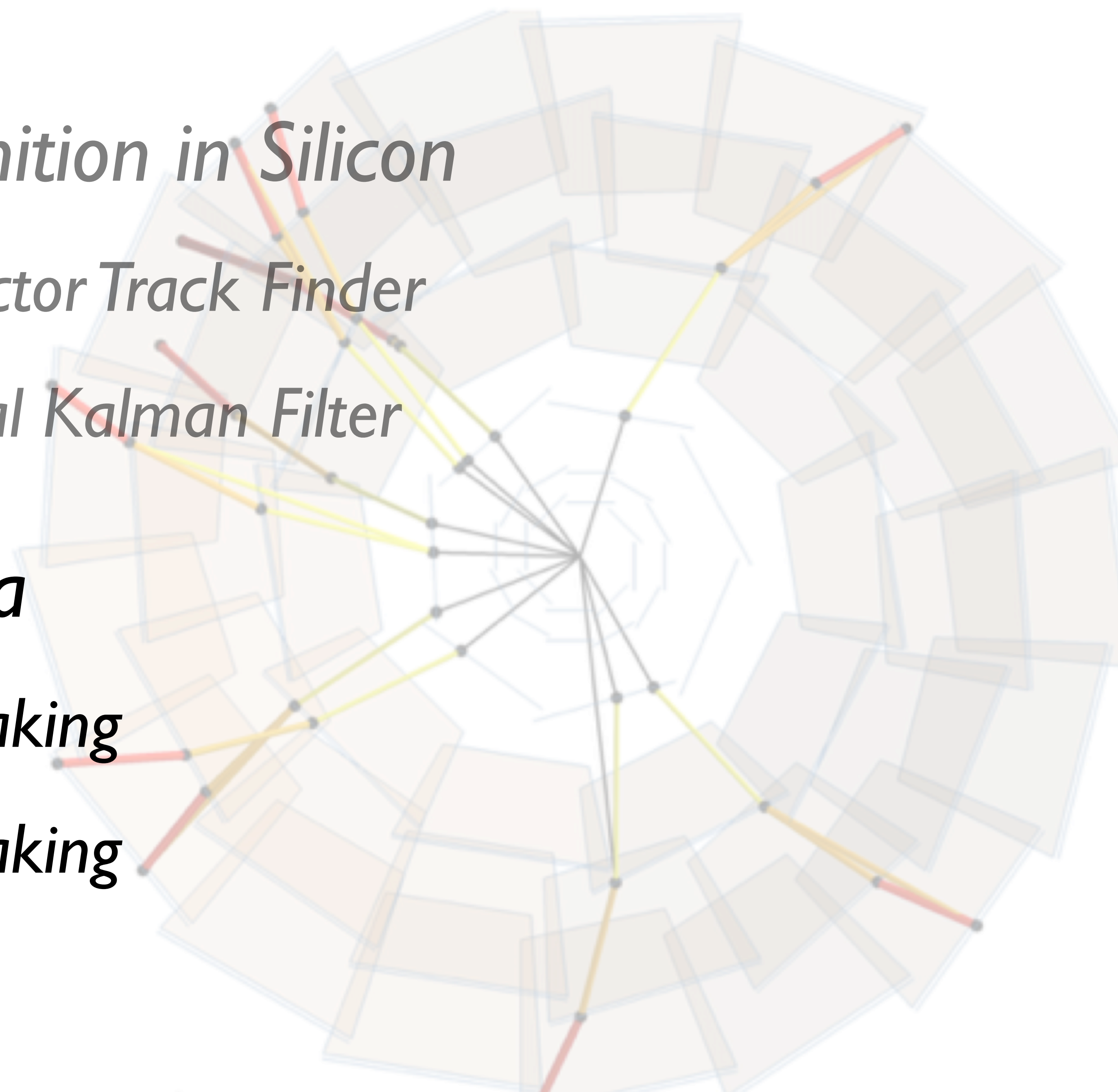
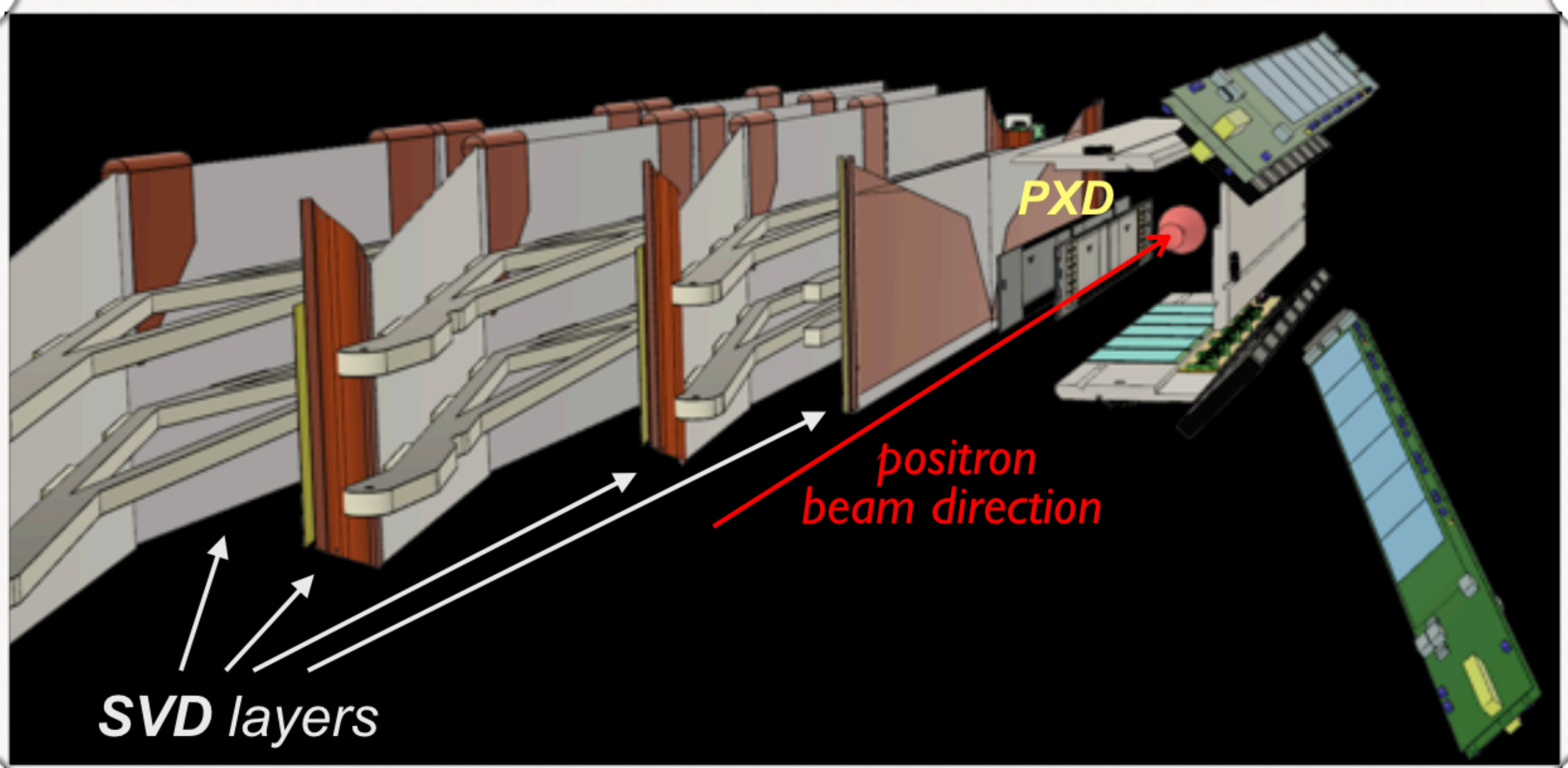


2018 Data Taking

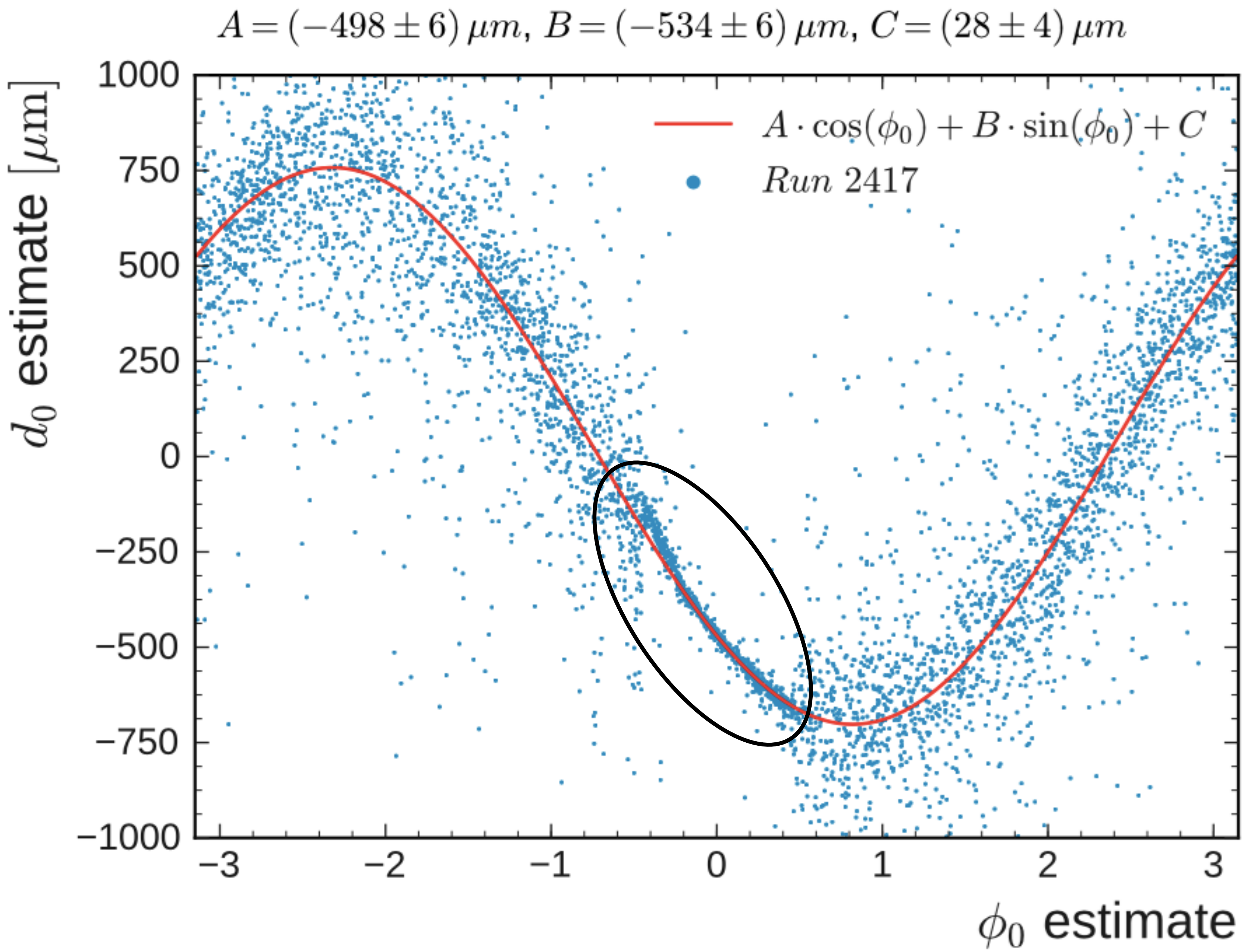
- *During the SuperKEKB commissioning from April to July 2018, Belle II recorded a sample of 500 pb^{-1} to study beam-background and reconstruction*
- *Only one ladder per layer of the vertex detector was installed, covering an azimuthal angle of ~100 mrad, small but enough to test the tracking reconstruction of particles coming from the interaction point (IP)*



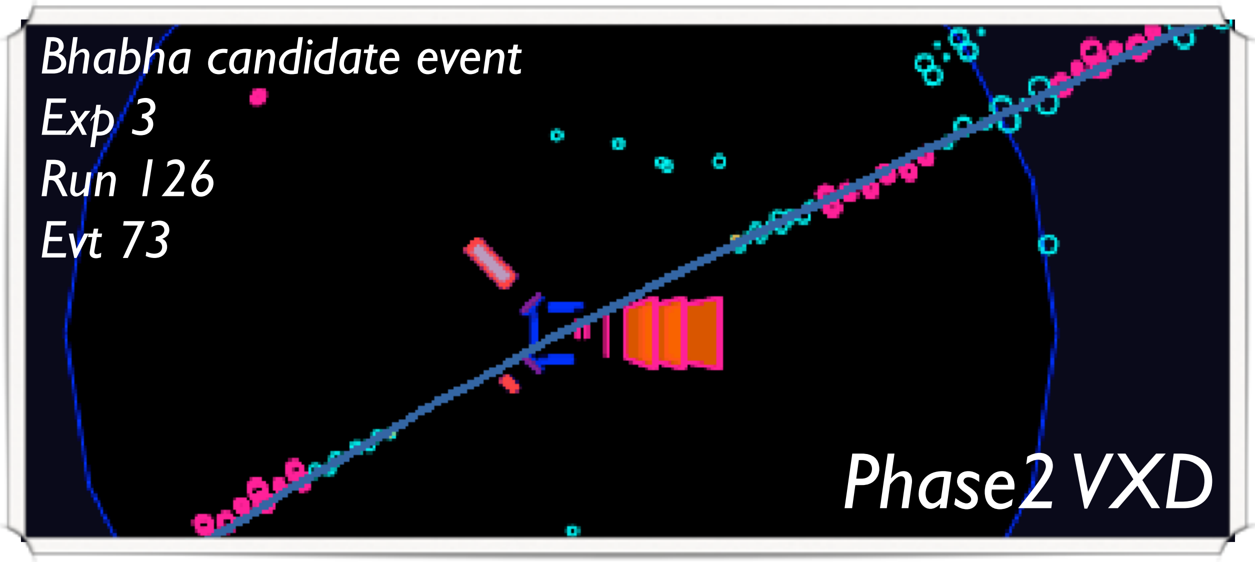
Visual effect of the (partial) VXD

➡ IP not in the nominal position, sinusoidal correlation between the track parameters d_0 and φ_0

- evident improvement of the resolution of tracks pointing in the VXD direction



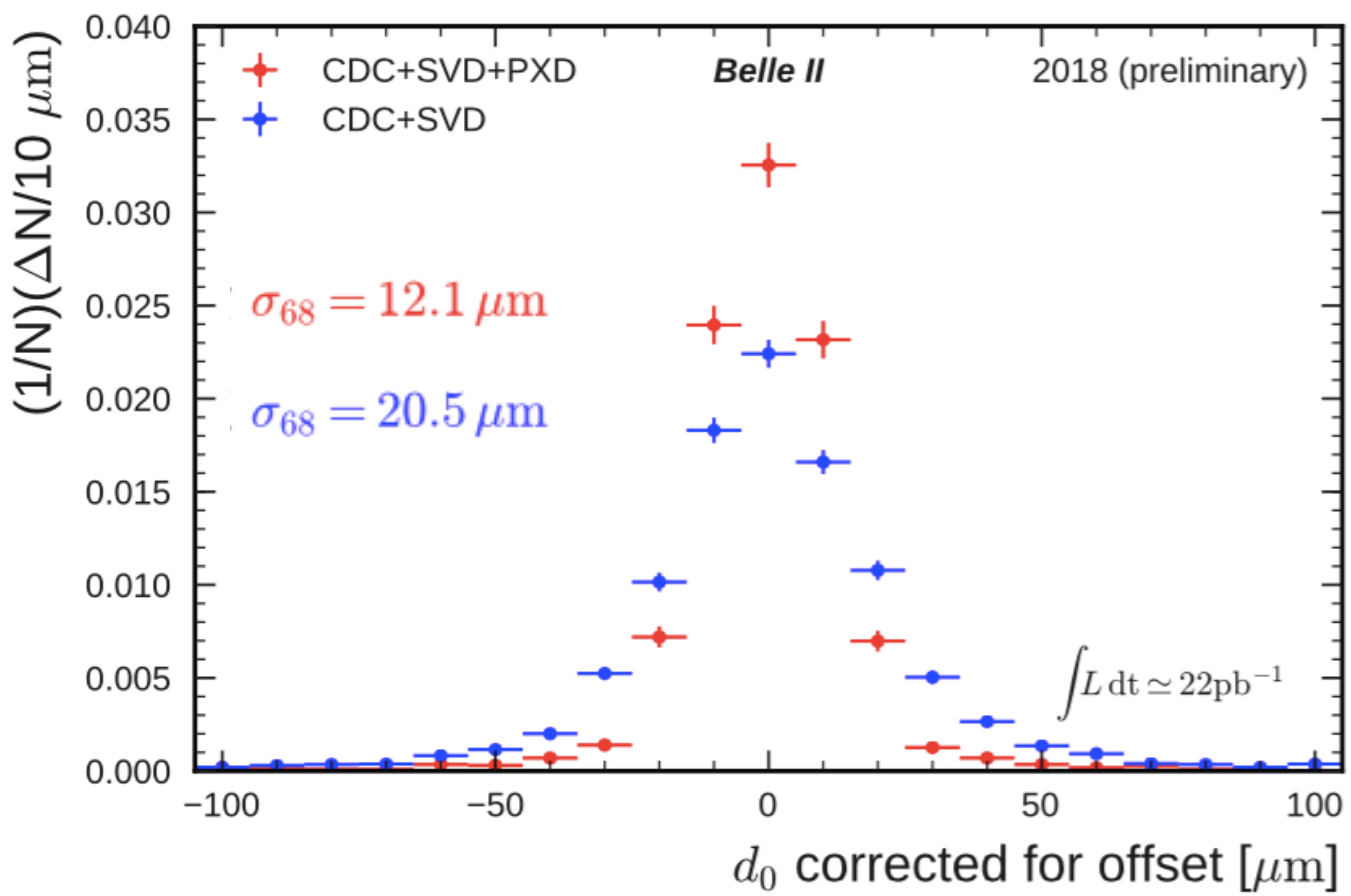
Goals Achieved in Phase2



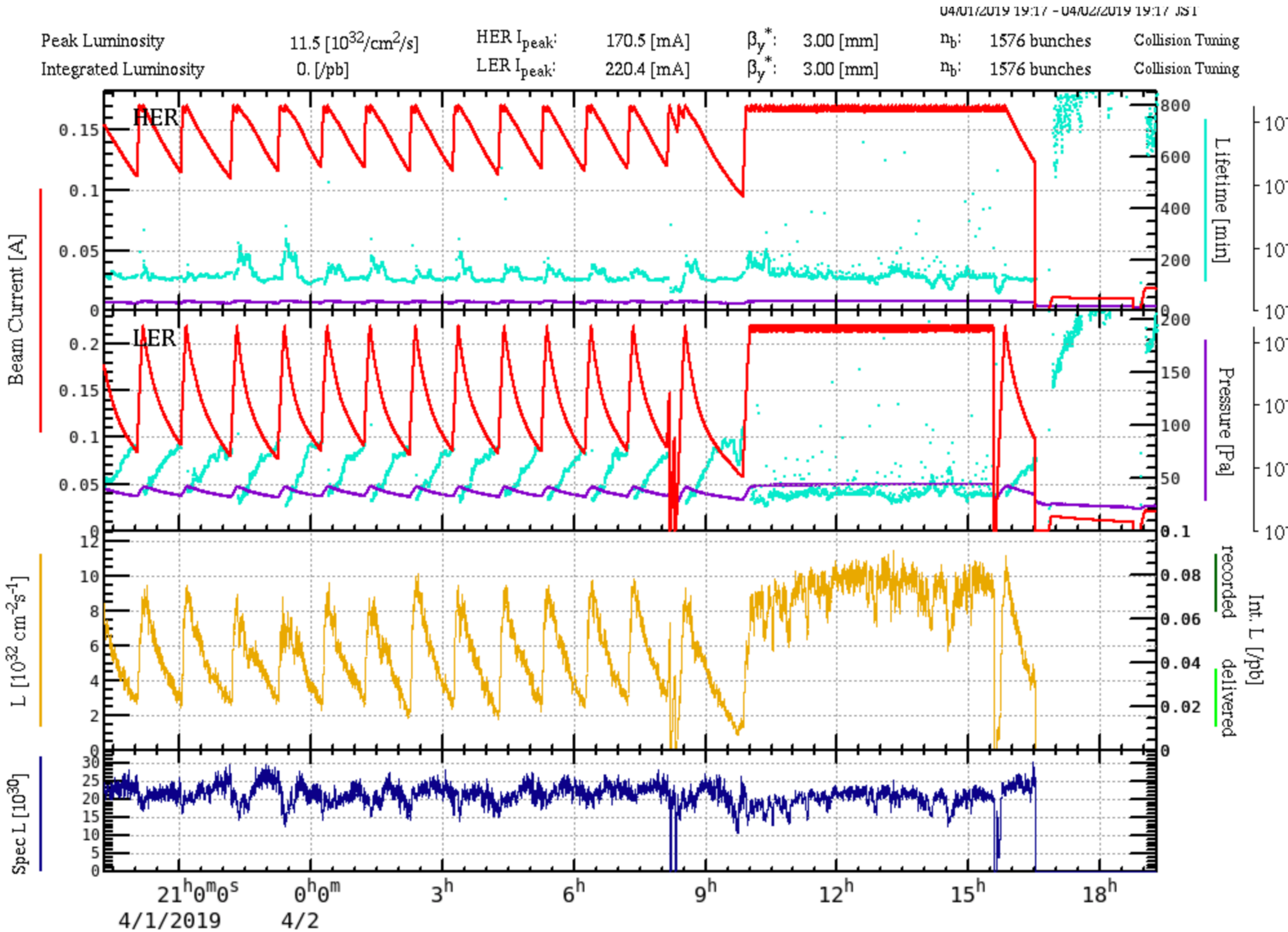
despite the small VXD geometrical acceptance, we confirmed that:

1. *SVD standalone track finder is working*
2. *CKF is working (SVD → PXD and CDC → SVD)*

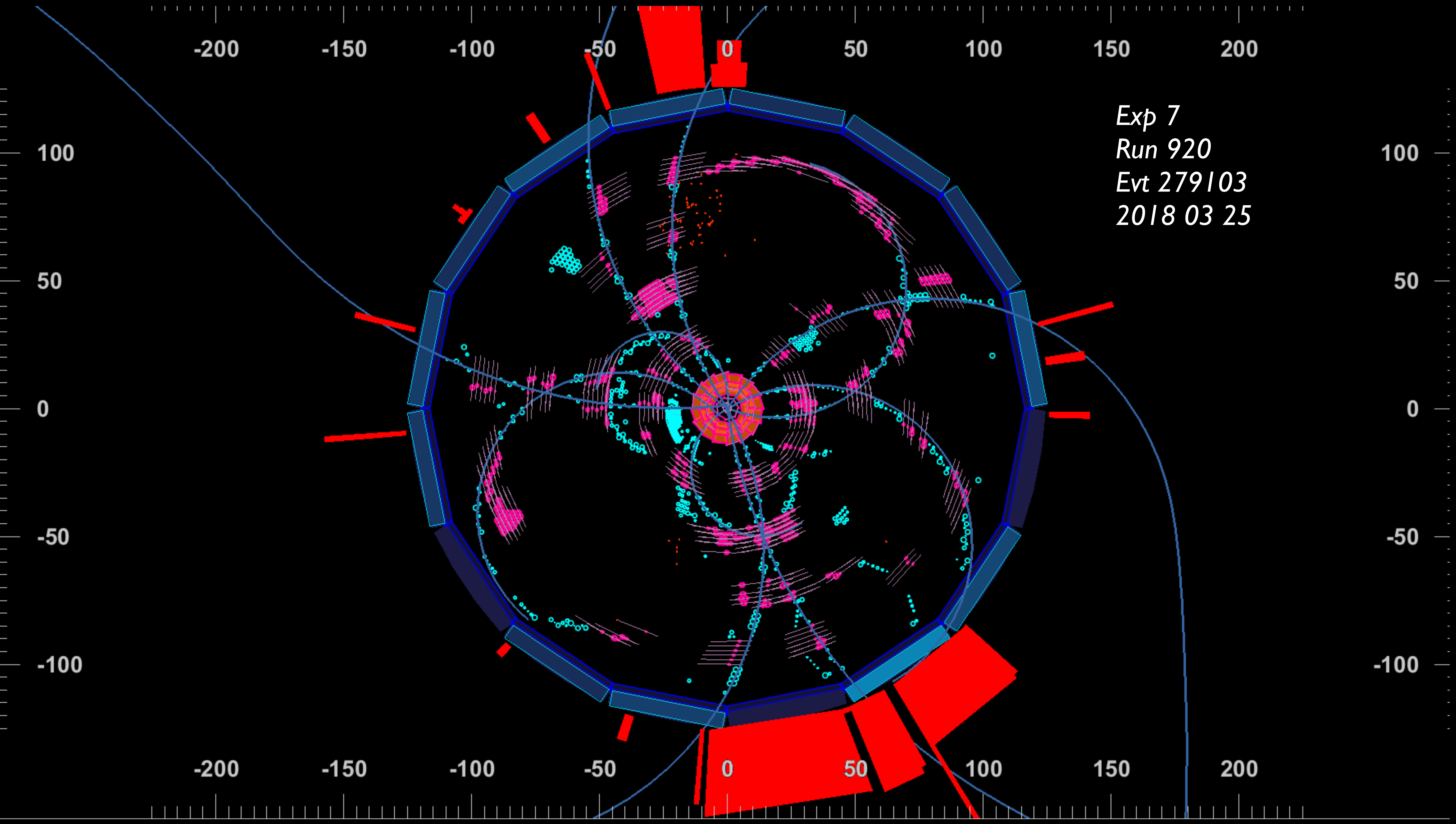
4. *Impact parameter resolution for tracks with hits in the VXD matches expectations*
   - d_0 resolution ~ 12 µm w PXD hits
     - innermost PXD layer at 1.4 cm from IP
   - d_0 resolution ~ 20.5 µm w/o PXD hits
     - innermost SVD layer at 3.9 cm from IP



2019 Data Taking



2019 First Candidate Hadronic Event

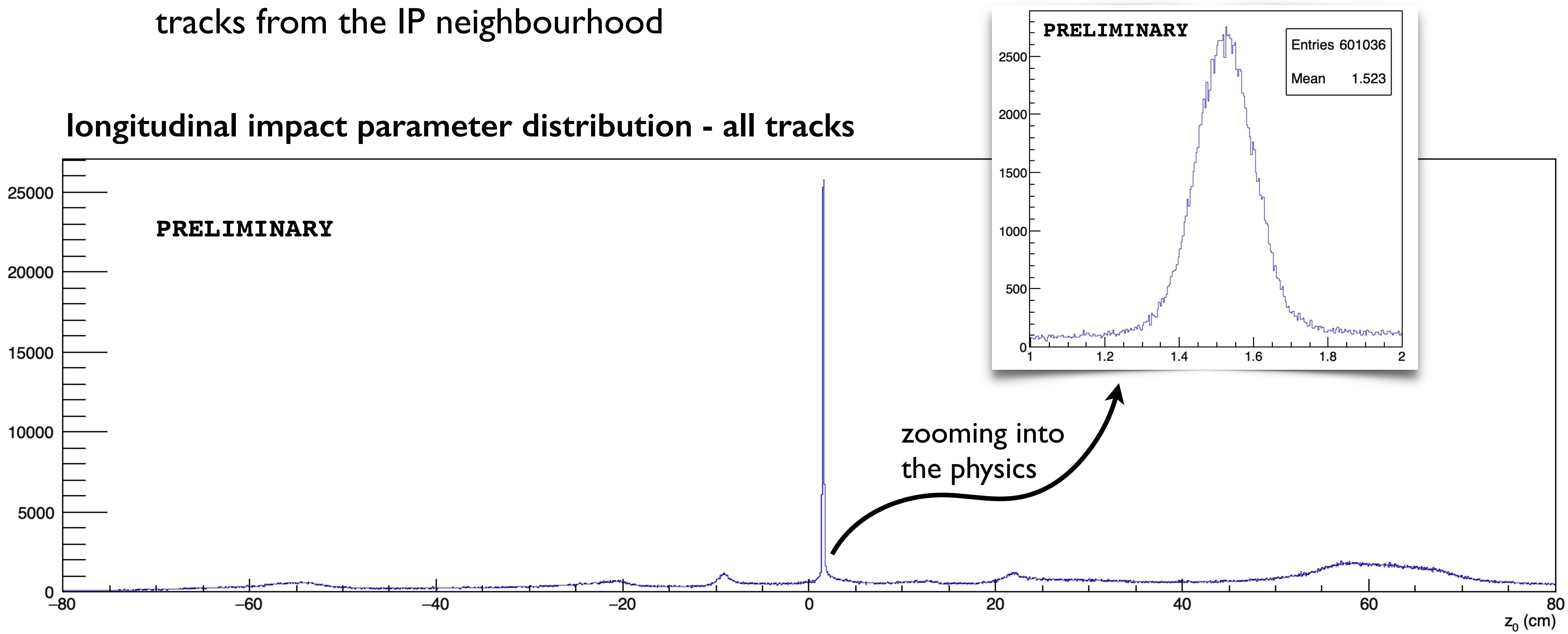


Very First Look at Tracks

- ➡ Successful operation of the VXD detector after installation and first runs of data taking
- ➡ Tracking worked out of the box since day one
- ➡ SVD hit-efficiency better than 99% on CDC tracks from the IP neighbourhood

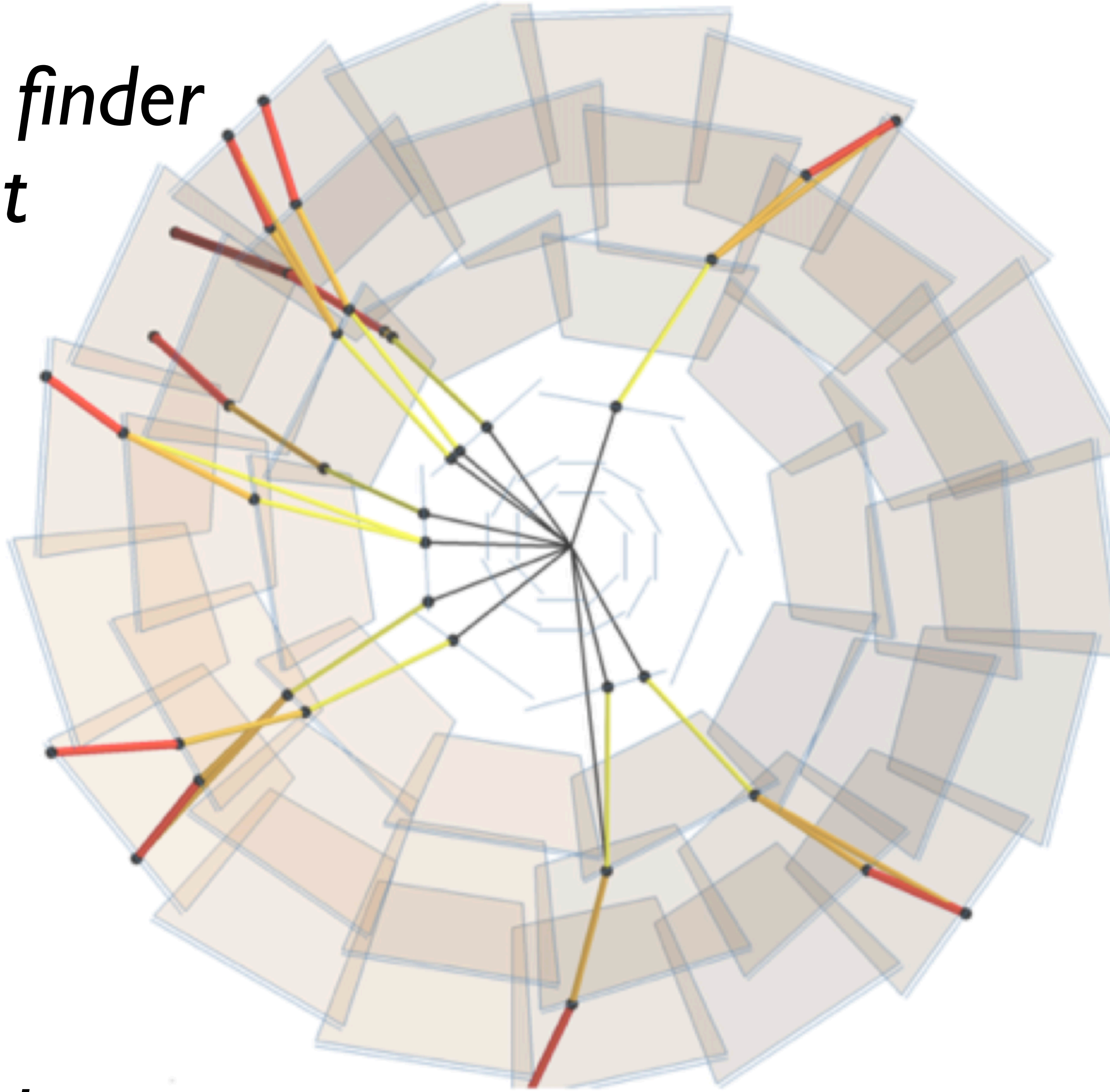
very positive indications after one week of data taking!

longitudinal impact parameter distribution - all tracks



Conclusions

- *The SVD standalone track finder and the CKF have excellent performances on MC*



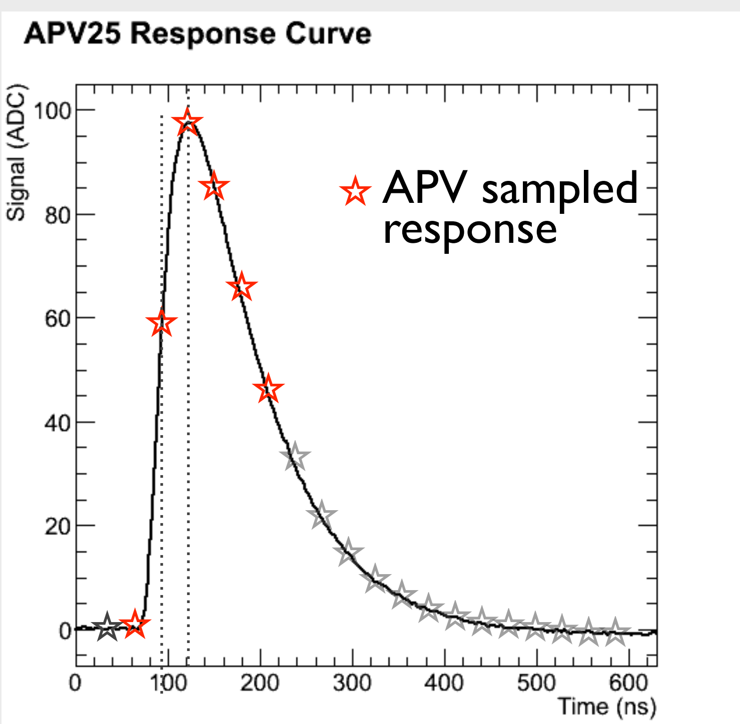
- *Very positive indications from the 2018 data taking and from the first week of Physics run in 2019*

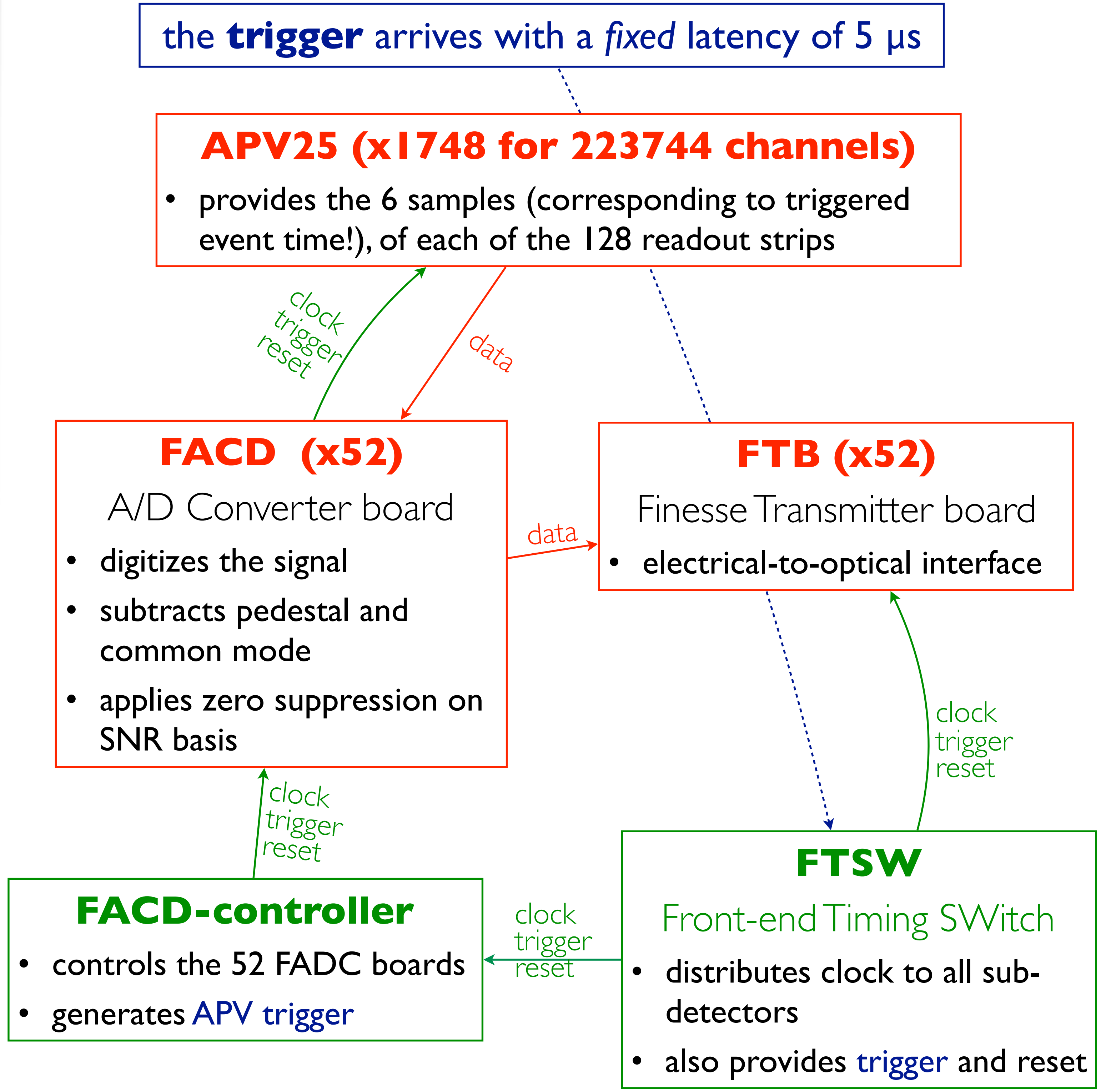
- *The Belle II Vertex Detector Pattern Recognition is ready for the Physics Challenges*

SVD Readout System

The readout chip: APV25

- ➡ originally developed for CMS
- ➡ shaping time of 50 ns
  - → low occupancy
- ➡ thinned to 100 μm
  - → low material budget
- ➡ operated in multi-peak mode @ ~32 MHz, equipped with a 192 deep analog pipeline
- ➡ APV clock synchronised with bunch crossing frequency of ~ 8x32 MHz

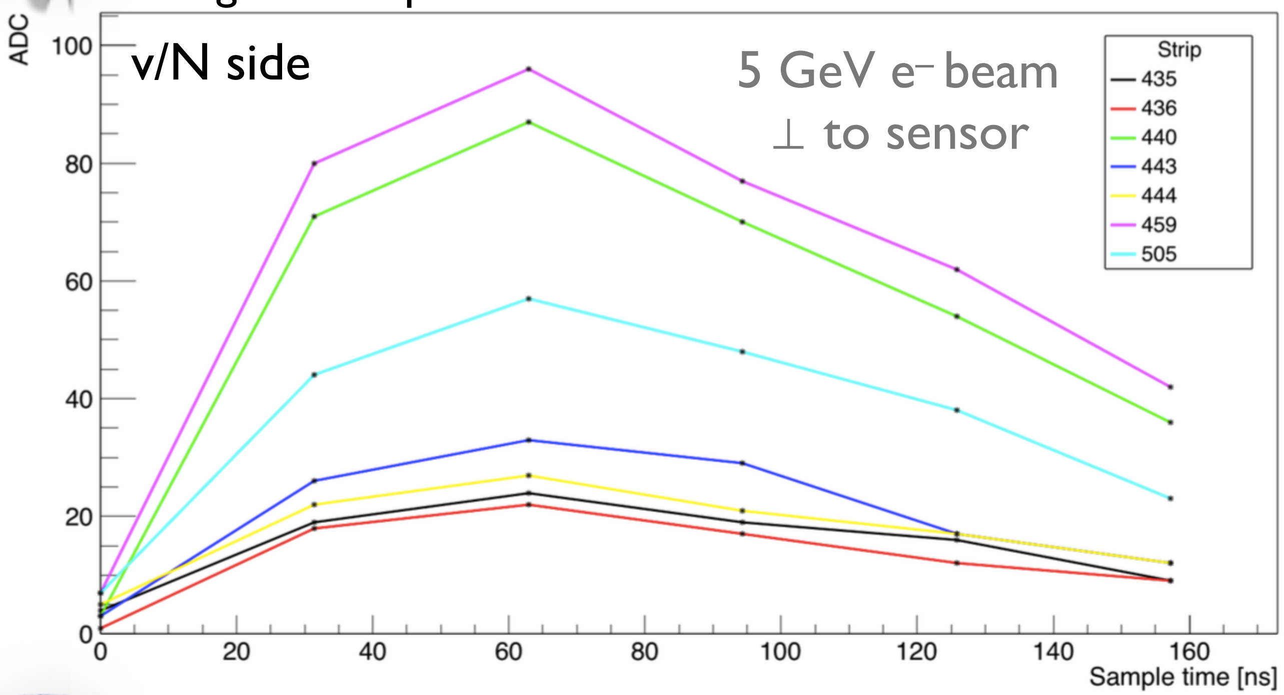




The SVD Hit Time Determination

ingredients

1. 6 ditigized samples available to the offline reconstruction



2. peaking time of each strip, from local calibration of the detector
3. in which the quarter of the integration window, SVD has received the trigger – so-called *trigger bin*

steps

1. raw SVD hit time determined as average of sampling time (t_i) with the samples amplitudes (A_i), corrected for the peaking time of each channel

$$t_{raw} = \sum_{i=0}^{6} \frac{A_i\, t_i}{A_{tot}} - t_{peak}$$

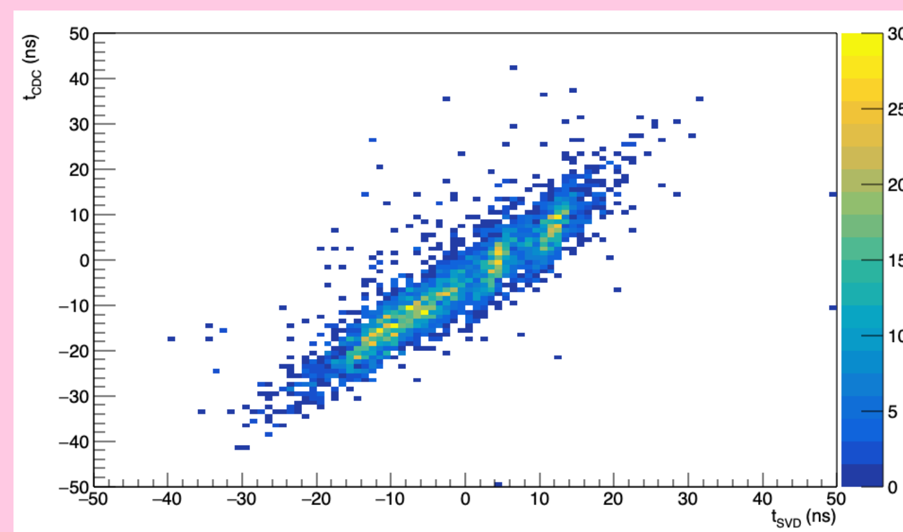
2. calibrate the time using the event time (estimated with other detectors) to correct for:
   - estimator stretching of time scale
   - unknown differences of detectors latencies

calibration

sensor trigger-bin

$$t_{SVD} = \alpha(s, tb) \cdot t_{raw} + \beta(s, tb) + B$$

- α and β determined using t_0 estimation, depend on sensor side and trigger bin
- B single shift to center t_{SVD} distribution in 0



Beam Background from Phase2

➡ Use beam background estimation from Phase2 to get expected background on early Phase3:

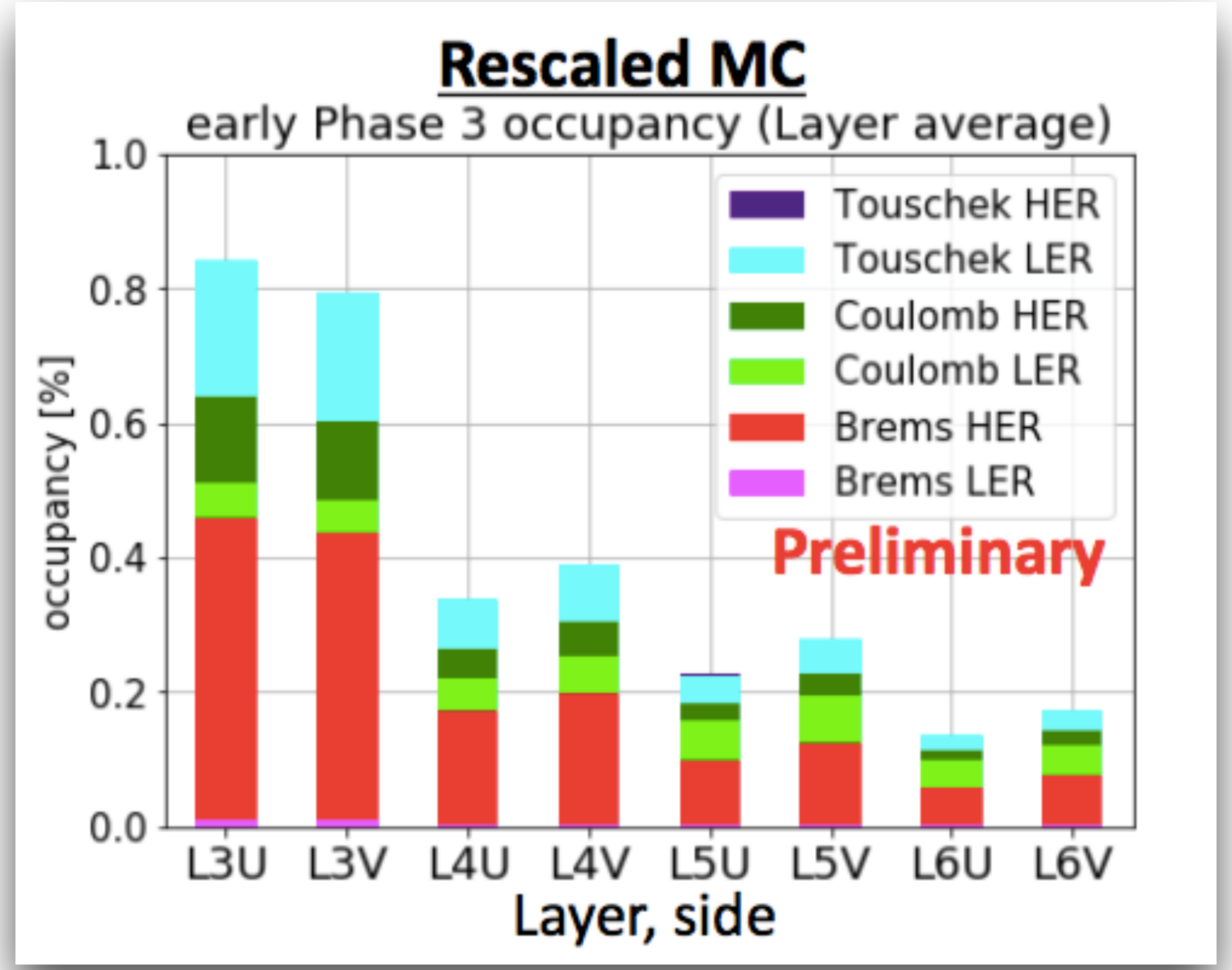
- decomposition of beam-induced backgrounds

occupancy — beam-gas rate — Touschek rate

$$O(I,P,\sigma_Y,n_b) = B \cdot PI + T \cdot \frac{I^2}{\sigma_y n_b}$$

- occupancy measured for different configurations of the beam parameters allows to extract B and T
- data MC comparison to extract scaling factors for beam-gas and Touschek rates:

$$Expected_{Phase3} = MC_{Phase3} \cdot \frac{Data_{Phase2}}{MC_{Phase2}}$$



➡ Background levels in earlyPhase3 will be acceptable for the final SVD detector

- occupancy limit from tracking ~3%
- luminosity background will be negligible in early Phase3

luminosity bkg = 1% at design luminosity & it scales with luminosity