Simulations for an upgraded Belle II vertex detector

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on behalf of the Belle II Collaboration

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XXVII Cracow Epiphany Conference

Outline

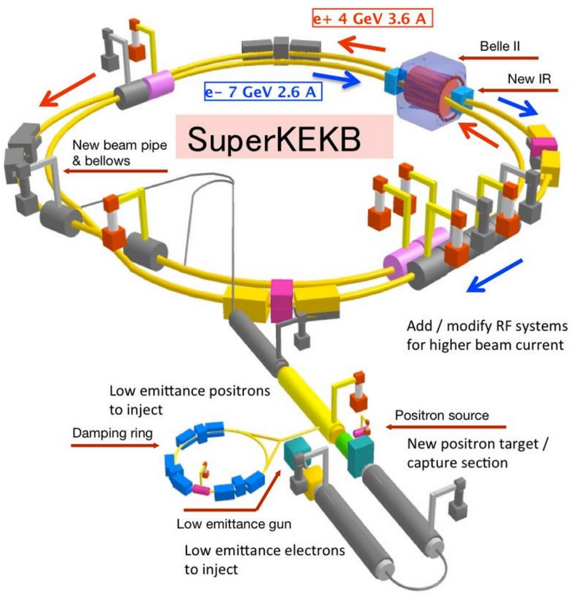
Belle II

I. Presentation of Belle II experiment: why do we consider an upgrade ?

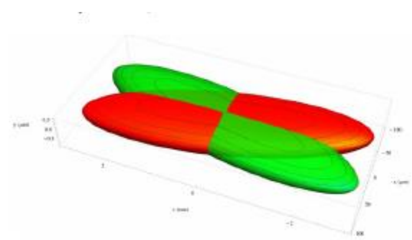
II. Detailed simulation development: Digitizer

III. Performance results for two new geometries

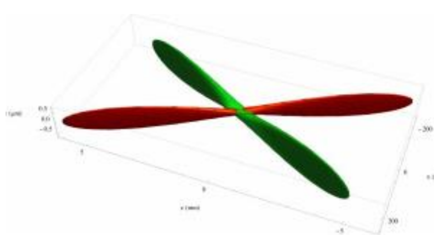
SuperKEKB collider



- Electron (7 GeV) - Positron (4 GeV) collider
- B, charm and τ factory



KEKB Interaction region beam overlap



SuperKEKB Interaction region beam overlap

Current ↗
(continuous injection)
Beam size ↘
↓
30x KEKB peak luminosity

Today

- Peak luminosity: $2.4 \cdot 10^{34}$ cm^{-2} s^{-1} **(WR!)**
- Int. luminosity: ~ 90 fb^{-1} of data collected

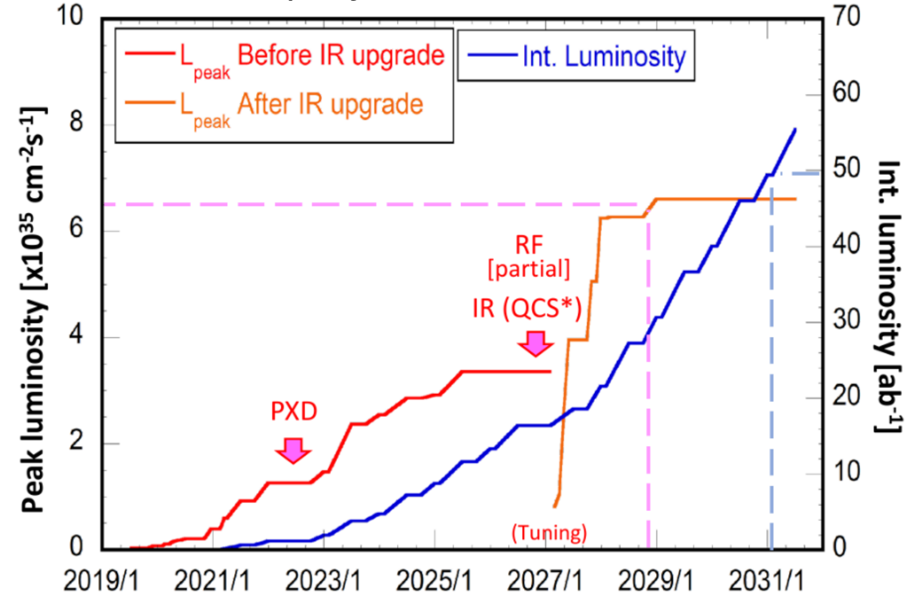
Goal

- Peak luminosity: $6 \cdot 10^{35}$ cm^{-2} s^{-1}
- Int. luminosity: 50 ab^{-1}

Long shutdown in 2026:

> Opportunity for upgrade of detector

Current projection

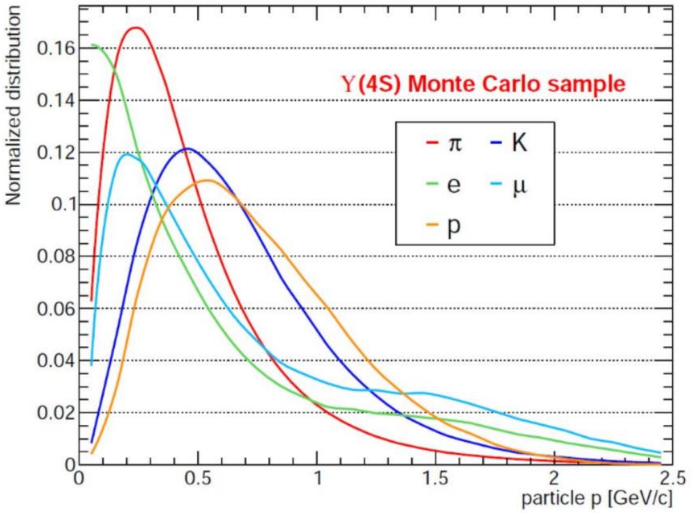


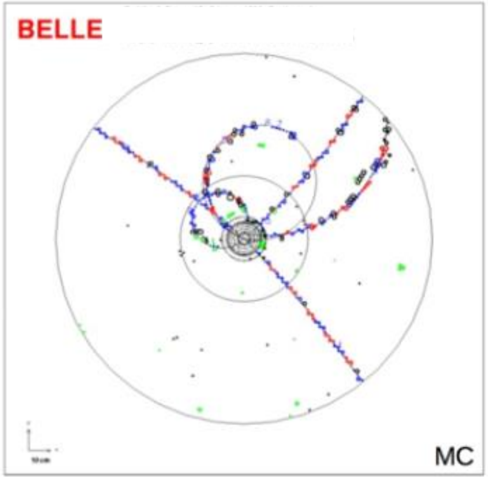
Challenge of tracking at Belle II

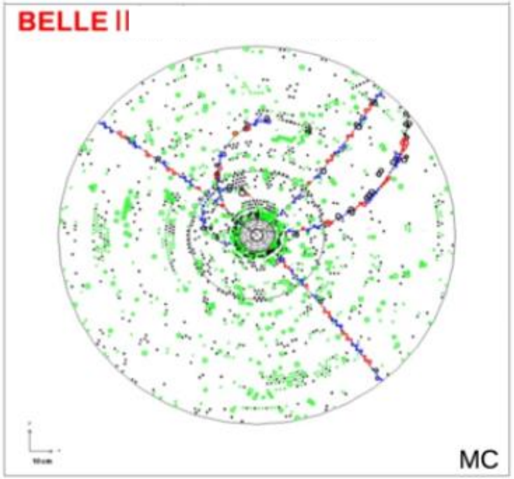
- Average track multiplicity:
  - **11 physics tracks**.
- **Similar momentum ranges and distributions**.
- **Low momentum tracks**
  > multiple scattering, curling tracks.

Particle types visible in Tracking Detectors of typical Υ(4S) event

Particle type	Average fraction
$\pi^{\pm}$	72.8%
$K^{\pm}$	14.9%
$e^{\pm}$	5.8%
$\mu^{\pm}$	4.7%
$p^{\pm}$	1.8%

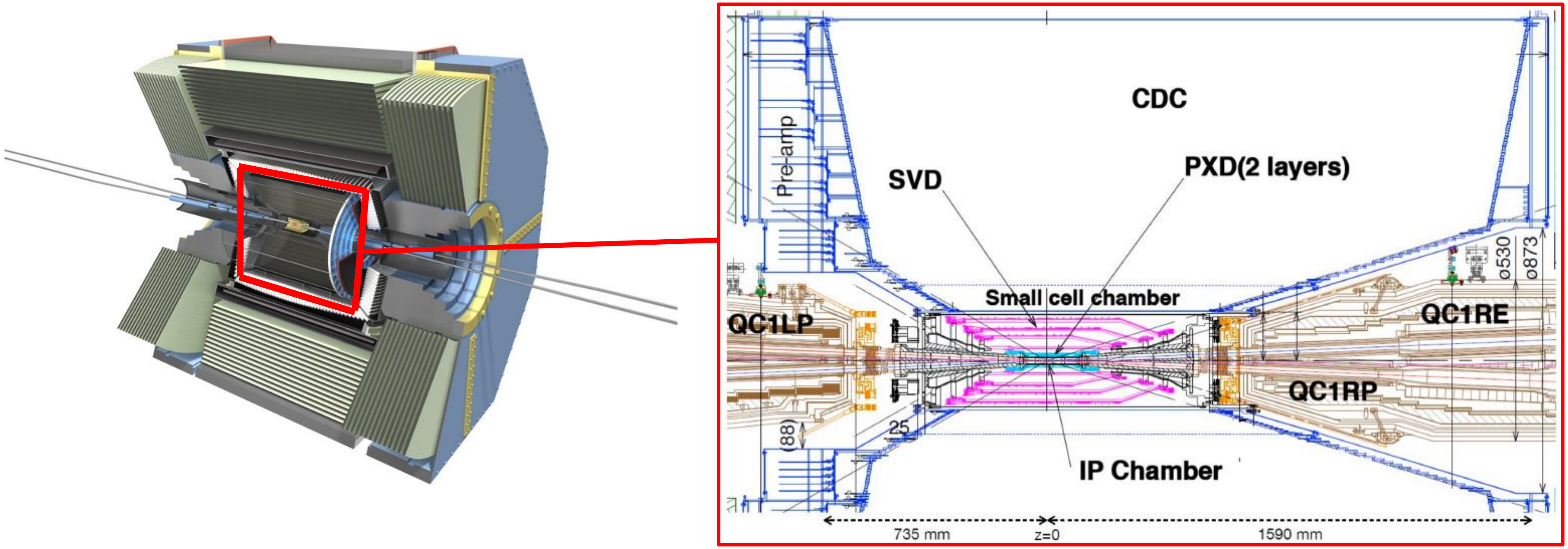






- Sizeable **beam-induced background**.
- Occupancy **dominated** by background

Belle II detector



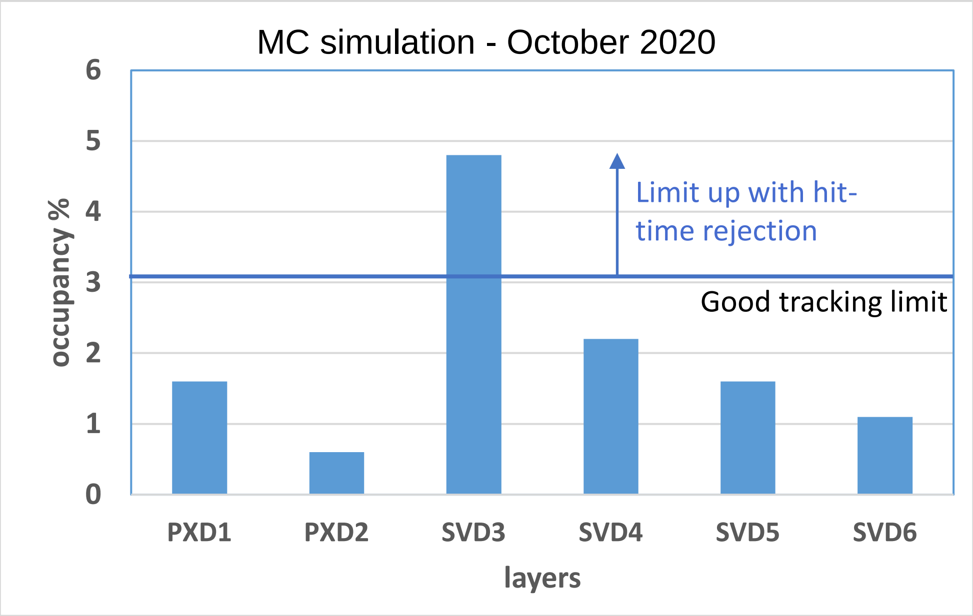
Challenges addressed by dedicated detectors:

- Central drift chamber CDC
- Vertex detector VXD:
  - Four double-sided silicon strip detectors SVD
  - Two pixelated vertex detectors PXD

Track finding (CDC, SVD)

Precise vertices measurement (SVD, PXD)

Vertex detector upgrade?



Current occupancy extrapolation at peak luminosity (background hard to extrapolate) close to a limit (above 3-5% occupancy, serious performance degradation) + large uncertainty on background from continuous injection.

- Opportunity to upgrade the vertex detector in 2026:
  - Better performances
  - Better background handling
  - Fully pixelated and fast detector (CMOS technology)

- $occupancy \propto \frac{t_{integration}}{granularity}$ (fast ↑ $t_{integration}$; pixel ↓ $granularity$)

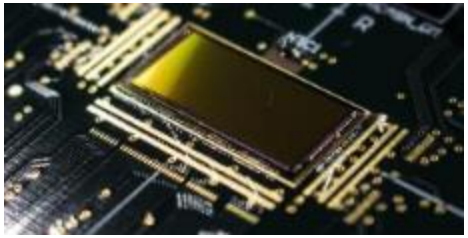
- Goals:
  - Use current Belle II software
  - Implement new technologies and geometries
  - Develop a full simulation
  - Show that Belle II can benefit from a fully pixelated vertex detector

CMOS pixel sensors

Belle II

Requirements for the new detector:

- **Same acceptance:**
  - Radius: first layer at 1.4 cm
    last layer at 14 cm
  - Length: from 12 cm to 72 cm


MonoPix-1 chip

- **Reduce occupancy and increase tracking performances:**
  - Pitches: 30-40 µm
  - Integration times < 100 ns
  - Material budget: 0.1% to 0.5%
    - Thickness < 50 µm
    - Power dissipation < 200 mW/cm^2

- MonoPix-1 / 2:
  Pitches: 33x33 / 40x36 µm
  Integration times: 25 ns
  Thickness: 30 µm

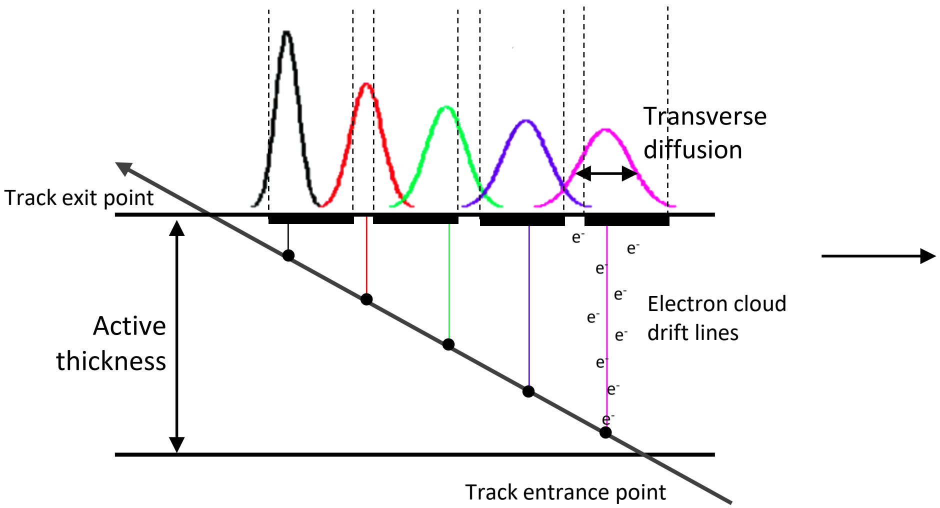
- Match CMOS sensor technology
- MonoPix-1 & 2 good candidates

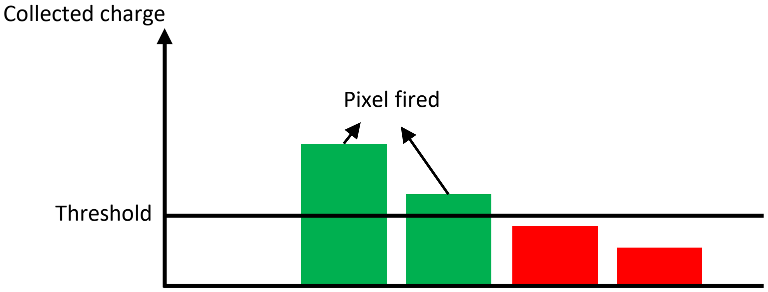
First task

> Implementation of the hit response in the Belle II software.

Tuning of the digitizer

- When a particle goes through the pixelated layer, it creates charge diffusion inside the depleted width. Those charges are then converted to digits to process them.





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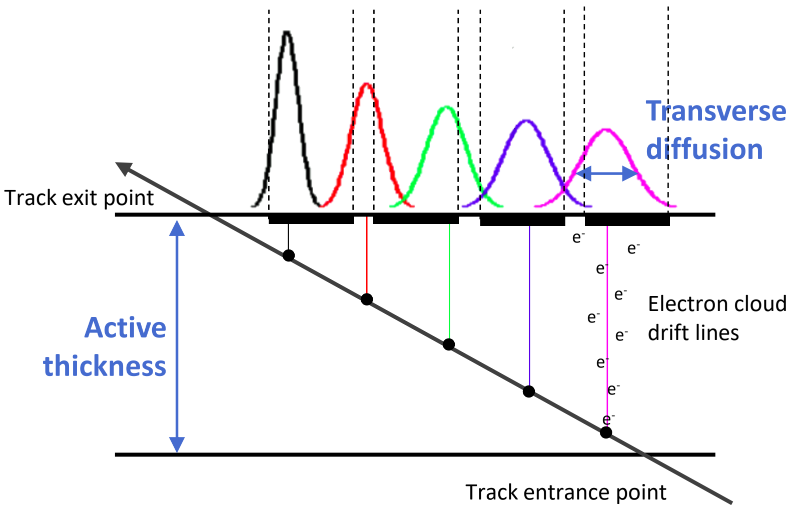
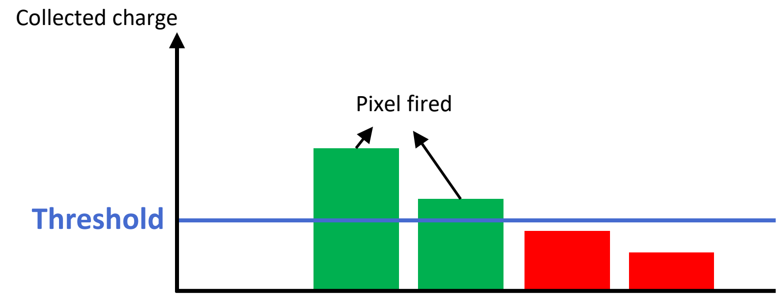


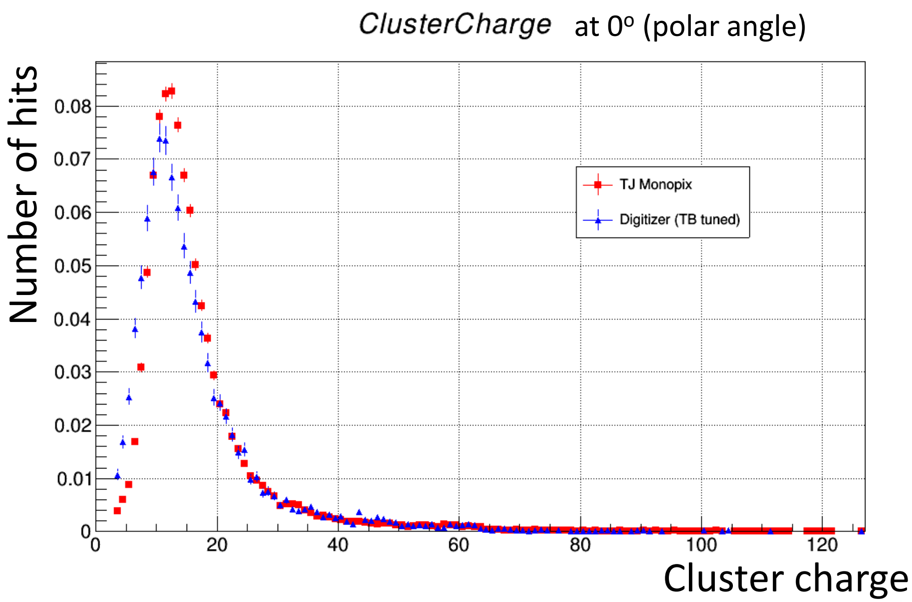


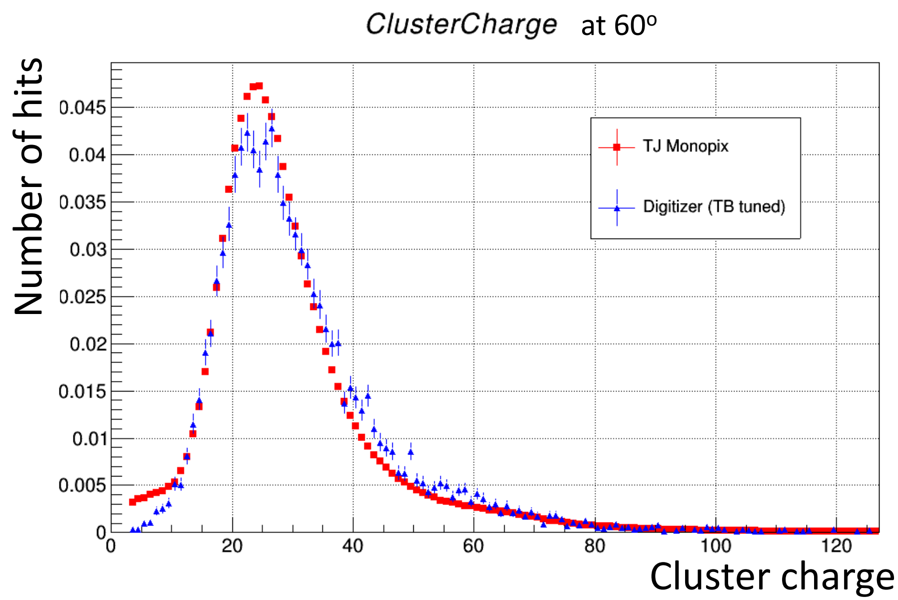
- A few parameters can be adjusted, like the integration time window, the active thickness, the transverse diffusion or the hit threshold.

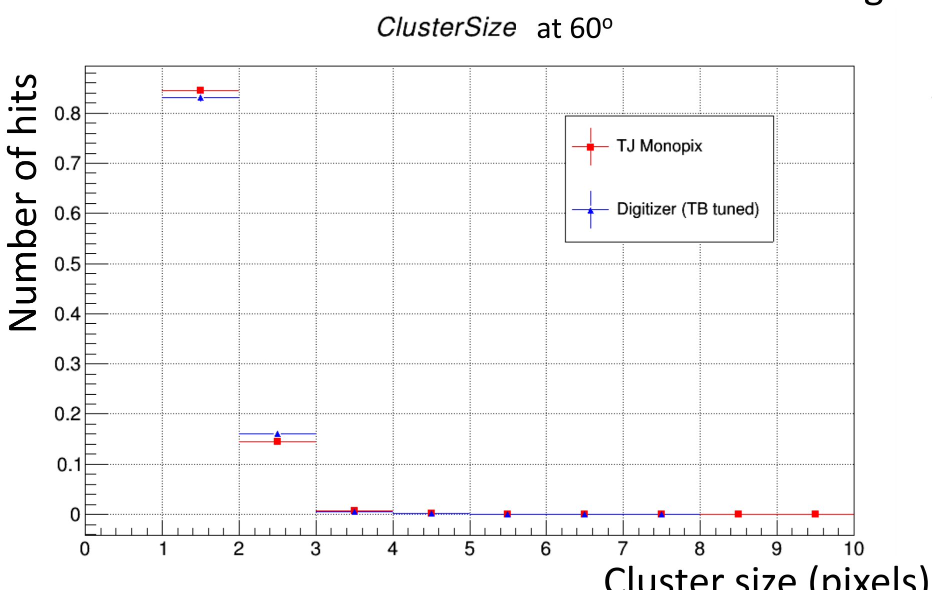
- Those parameters have been tuned to match a test-beam experiment made at DESY with TJ MonoPix-1 **[1]** chips, predecessor of TJ MonoPix-2 which is a good candidate for the upgrade.

[1] https://indico.cern.ch/event/884089/

MonoPix-1 simulation results: clusters







The tuned digitizer reproduces fairly well the MonoPix-1 test-beam data:

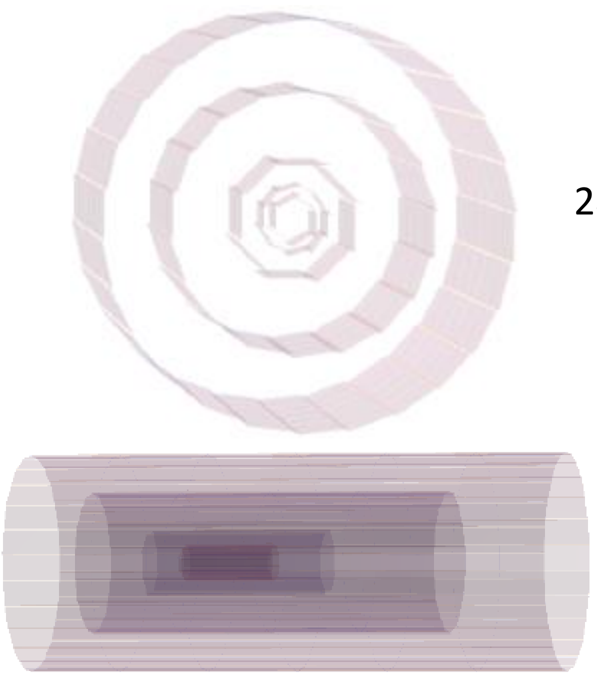
- Good agreement with cluster charge and cluster size
- resolution reproduced within 20%

> Digitizer validated for the full simulation

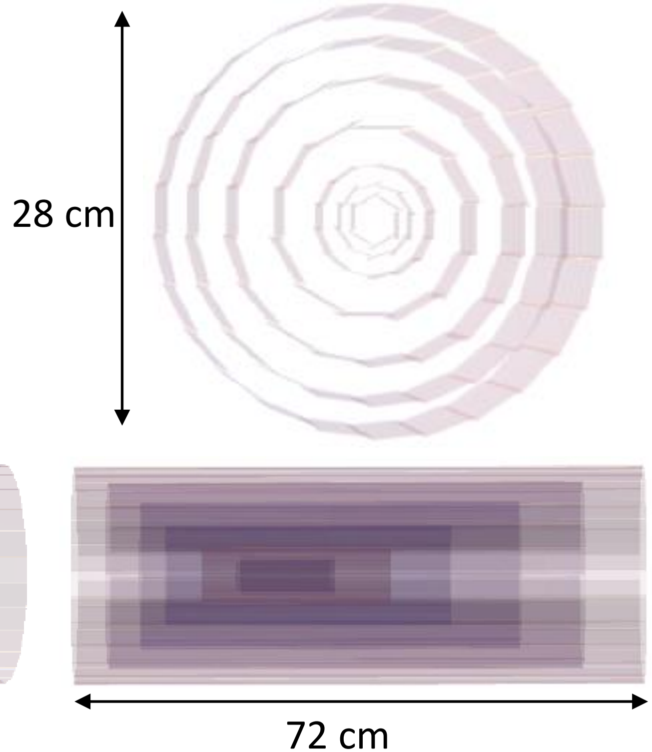
New Geometries

- Three new “**VTX**” (*Vertex*) geometries implemented and connected to existing tracking:

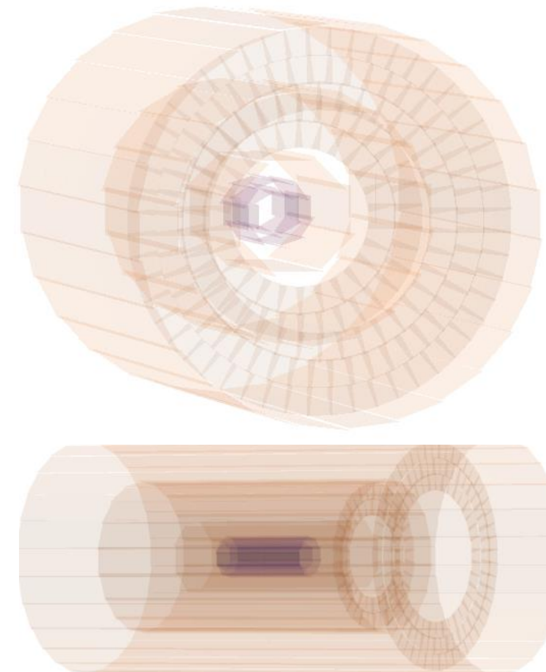
CMOS 5 layer



CMOS 7 layer



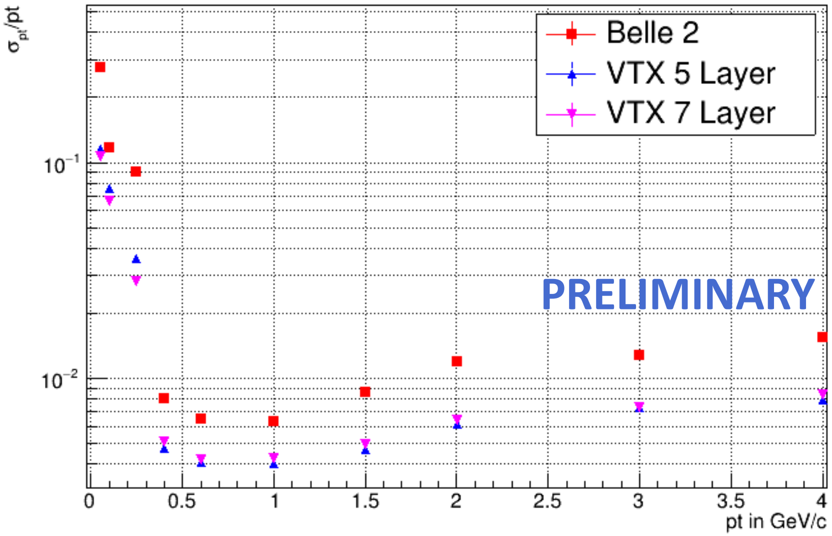
CMOS 5 layer + forward discs



Performance

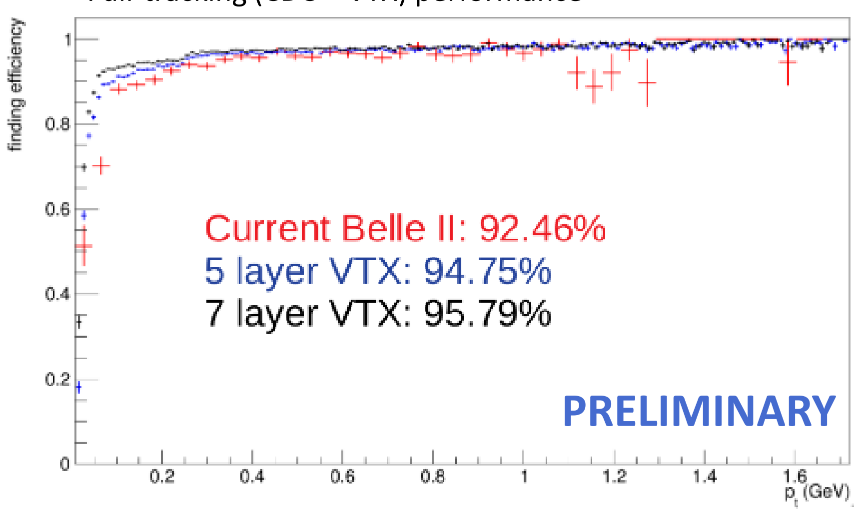
- **Transverse momentum resolution vs p_t**

  Full-tracking performance, muon particle gun, with background



- **Finding efficiency vs p_t**

  Full-tracking (CDC + VTX) performance



> Stand-alone figure of merits with background from 2019 predictions

- **Occupancy**
  - Average VTX layer 1 occupancy: 0.0016%

    > 3 order of magnitude lower than VXD

- **Tracking efficiency**

	Background x 1	Background x 5
Current SVD	0.961	0.907
5 layer	0.984	0.979
7 layer	0.987	0.978

- Better tracking performances at low momentum range
- Very low occupancy in innermost VTX layers
- Robust to the increase of the background

Conclusion

Belle II

- Opportunity for a VXD upgrade in 2026.
- Digitizer is well tuned to reproduce MonoPix-1 and predicts the MonoPix-2 performances.
- According to MC:
  - Better tracking performances
  - More robust to background
  - Lower occupancy
- Next step: Study the impact of the upgrade on physics channels.

Thank you for your attention

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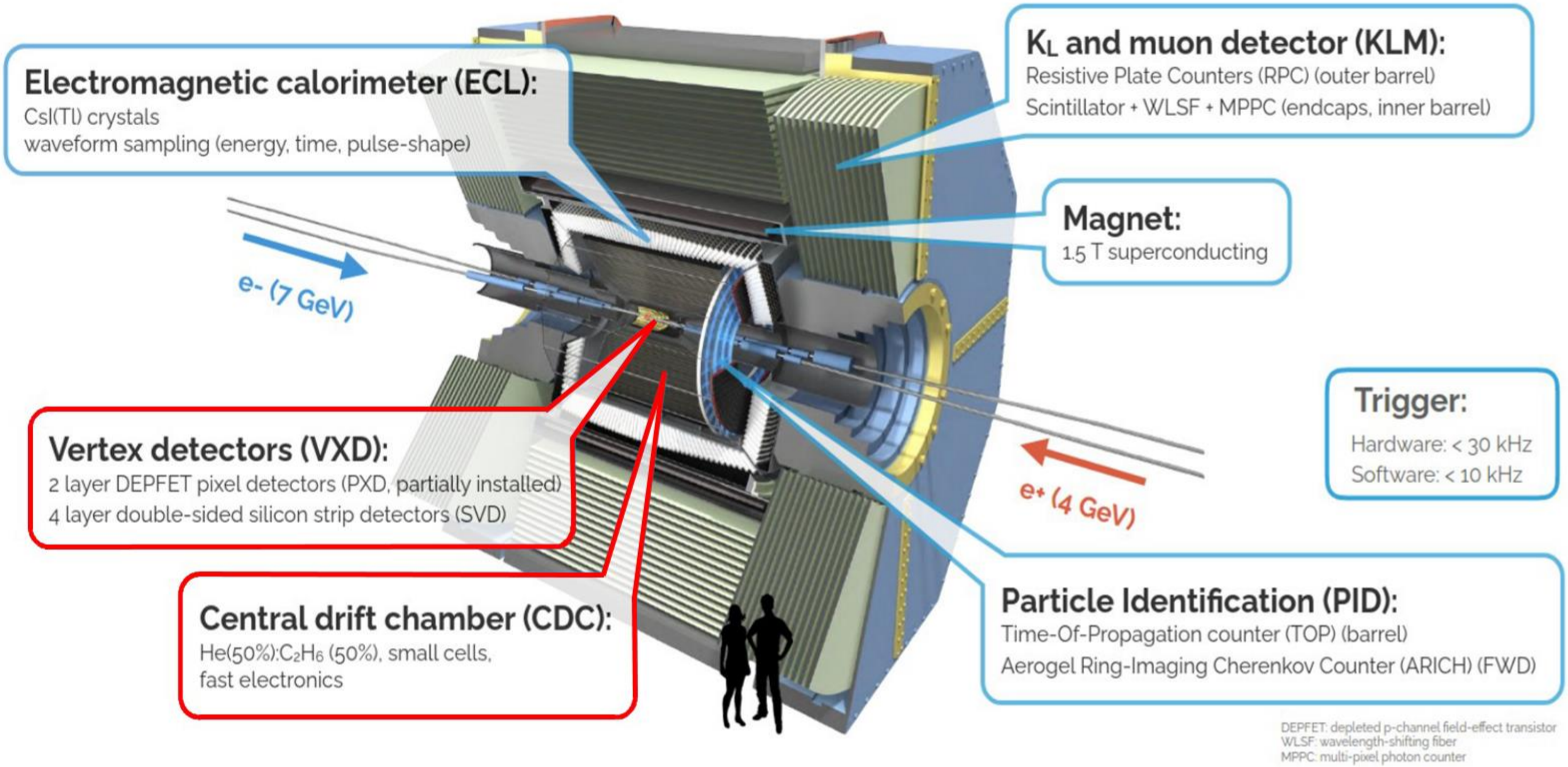
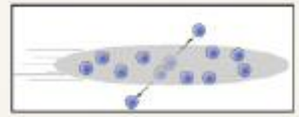
Belle II detector



Background types

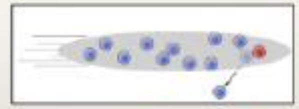
Machine background

Touschek scattering: single Coulomb scattering event between two particles of the same bunch, that are lost.



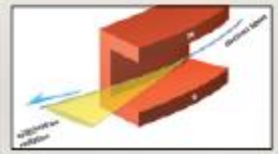
$$R_{Tou} \propto \frac{1}{\sigma E^3 n_b} I^2_{beam}$$

Beam-gas scattering: Coulomb elastic scattering or bremsstrahlung with residual gas atoms.



$$R_{bg} \propto IP$$

Synchrotron Radiation (SR): photon emission from beam particles when subject to acceleration.



$$W_{SR} \propto \frac{E^4}{\rho^2}$$

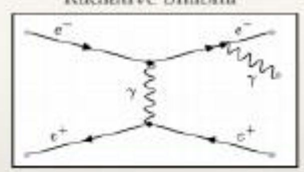
Injection background: injected bunch performing betatron oscillation around the stored bunch, resulting in particle losses especially in the interaction region.

$$R_I \propto R_{inj}$$

Luminosity background

Radiative Bhabha: neutron production from emitted photons (shields used for mitigation); off-energy primary particles lost in final focus magnets.

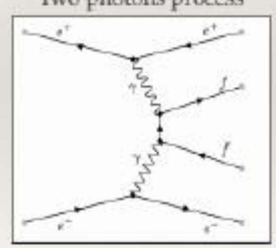
Radiative Bhabha



$$R_{RB} \propto L$$

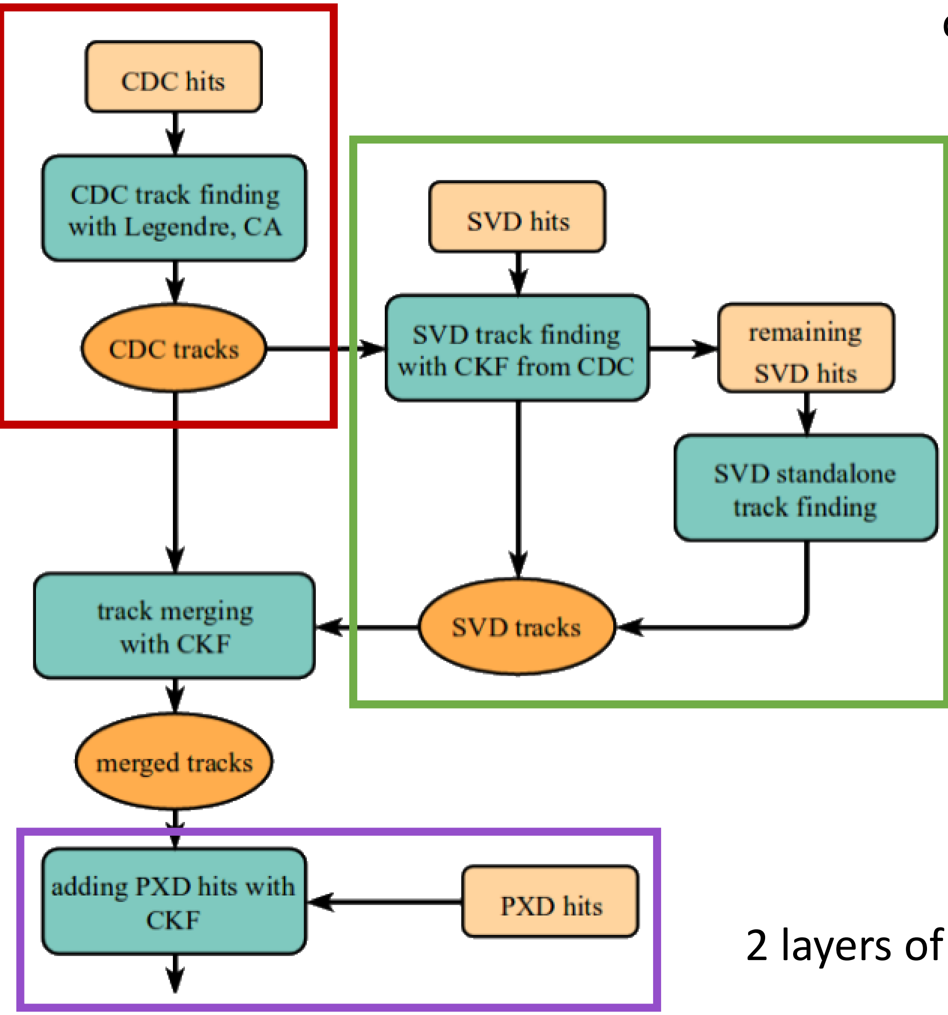
Two photons process: low momentum electron-positron pairs that can generate multiple hit in the VerteX Detector.

Two photons process



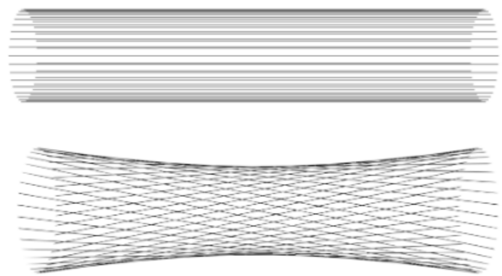
$$R_{RB} \propto L$$

Tracking system of Belle II



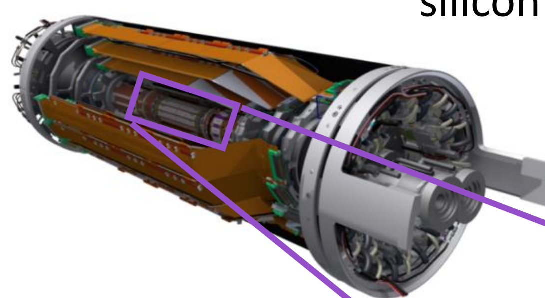
CDC (Central Drift Chamber)

~ 14k sense wires arranged in 56 axial or stereo layers.



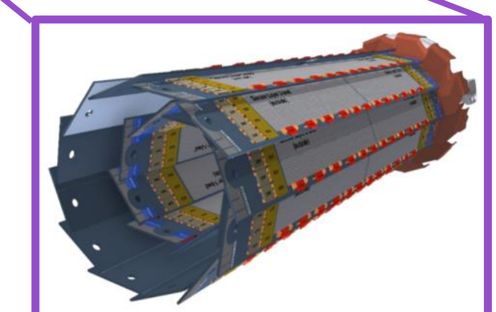
SVD (Silicon Vertex Detector)

4 layers of double-sided silicon strip sensors.

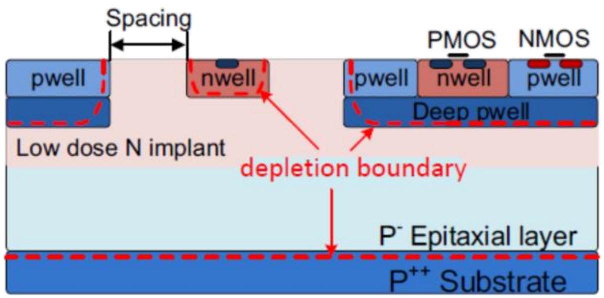


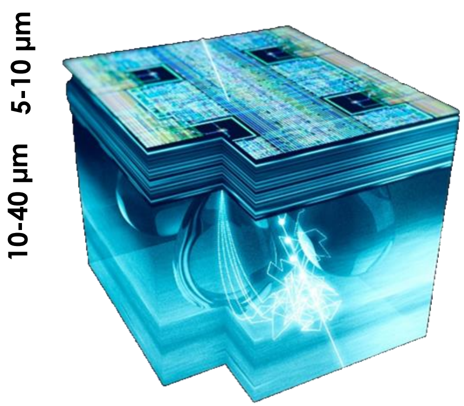
PXD (Pixel Detector)

2 layers of DEPFET pixel sensors.



- **Main features**
  - Small pixel size possible down to few μm^2
  - Signal processing on chip → digital output
    - In-pixel amplification → high SNR: “active”
    - No additional FEE readout: “monolithic”
  - Sensitive (epi) layer
    - Thin (or thick if bulk)
    - Depleted for fast signal & radiation tolerance
  - Operation at room temperature





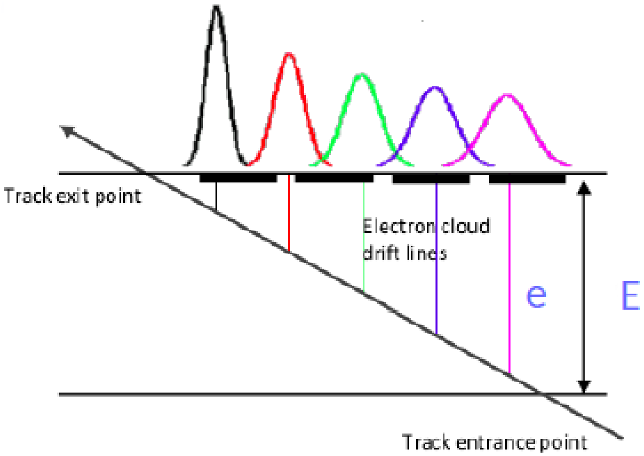
- **Industrial technology**
  - Integrated circuits (chips)
  - Lithography feature size < 200 nm
  - Reticule limits ≃ 25x30 mm2

	Pitch (µm²)	Time resolution (ns)	Sensor thickness (µm)	Comments
DEPFET	50x50	3000	30	Inner layers and disks
Thin strips	50x75	8	140	Outer layers
TSI-180 nm	150x50	25	30	Full volume
TowerJazz 180 nm	30x30	25 - 100	30	Full volume
SOI	35x35	63	75	Full volume

Tuning of the digitizer

When a particle go through the pixelated layer, it creates charge diffusion inside the depleted layer. Those charge are then converted to digits. Based on digitizer of the current Belle II DEPFET layer in the software, Blue parameters are adjustable.

- Check if the particle hit is inside the integration time window T_{int}
- Split the path of the particle in the pixel active thickness E into segments and drift the charges from the center of each segments.
  - The transvers diffusion (coeff. D) follows a gaussian with a width defined as:
    sigmaDiffus = sqrt (D * e/2)
- Integrate charges per pixel and add the noise to the charge
- Substract hit threshold
  Charge -= chargeThreshold
- Check if Charge still positive
- Amplify and digitize charge
  Charge = Charge / ElectronToToT
- Clipping of the ToT codes
  Charge = Charge % MaxToT
- Store the digit



Conversion & diffusion factor estimation

Conversion factor :

Equation from H. Bichsel, Rev. Mod. Phys. 60 (1988) 663–699, doi:10.1103/RevModPhys.60.663

- For a normal incidence, we can estimate the conversion factor (c) from the MPV of the cluster charge, which follows :

$$S = \frac{Q(l) - t}{c} = \frac{e\ (100.6 + 35.35\ \ln(e))}{3.6\ \times c} - \frac{t}{c}$$

with e = 30um
t = 500 e^-

- After a Laudau fit of the cluster charge from the testbeam file, we get c = 120 e^-/ADU

Diffusion factor :

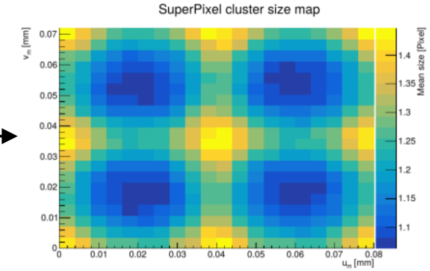
- For normal incidence, the std deviation of the gaussian diffusion of Q follows :

$$\sigma = \sqrt{\frac{De}{2}}$$

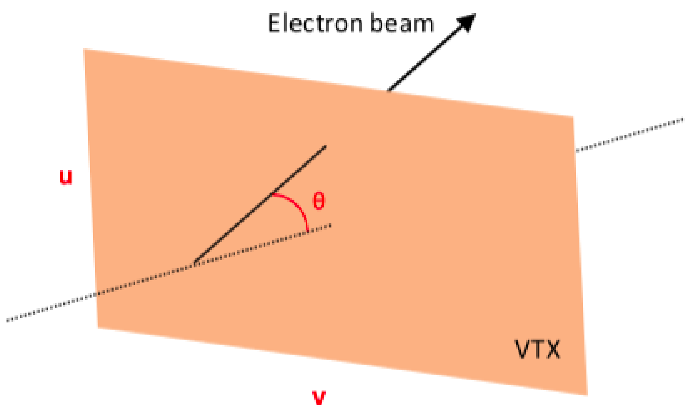
with D the diffusion factor
(CloudSize in the next slide)
σ ~ 3um

- We get D = 0.6 um

-> Those parameters are then tweaked a bit to try to get the same distributions as Monopix1 testbeam data



Test-beam simulation



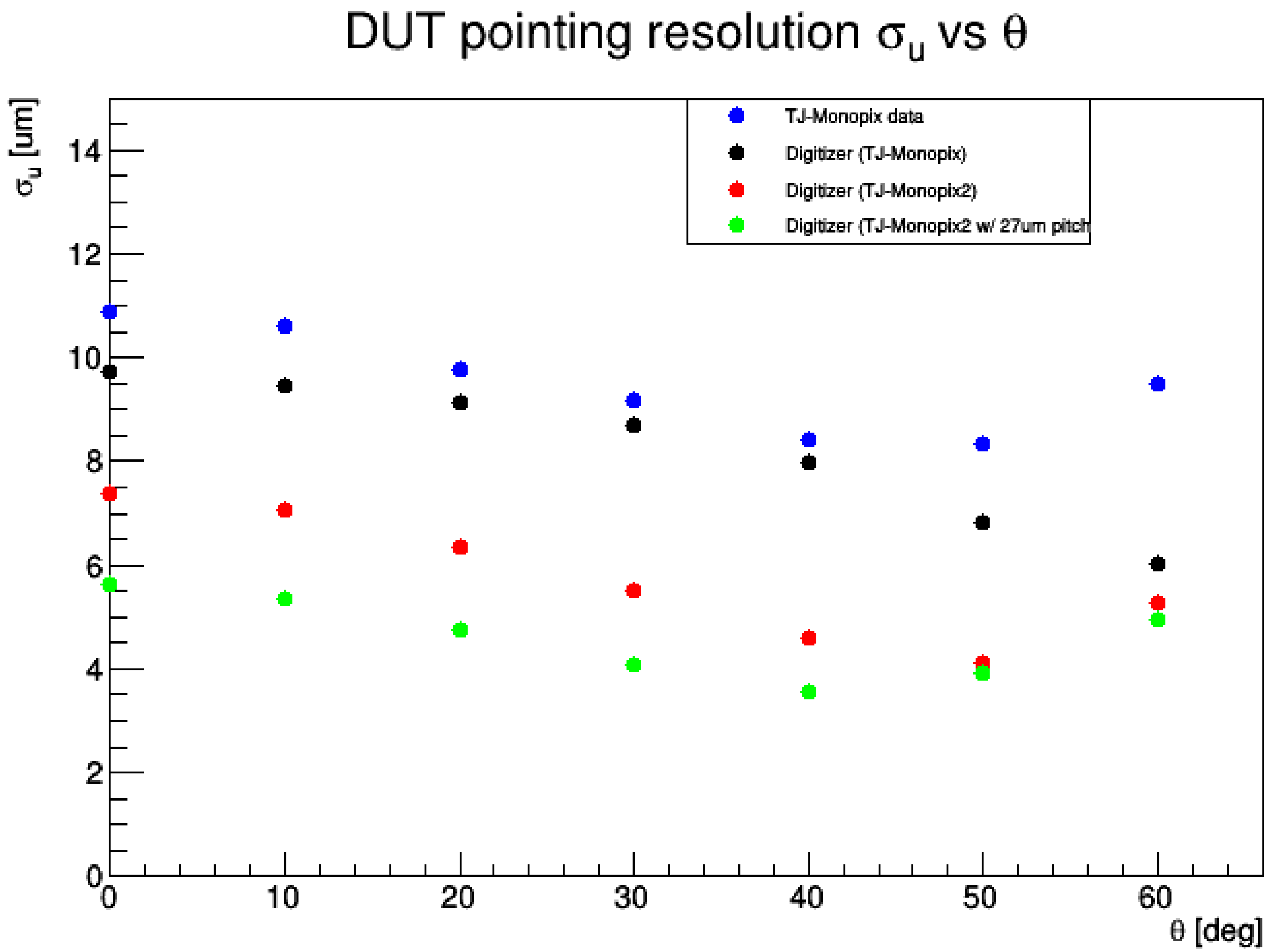
VTX Monopix 1 tune

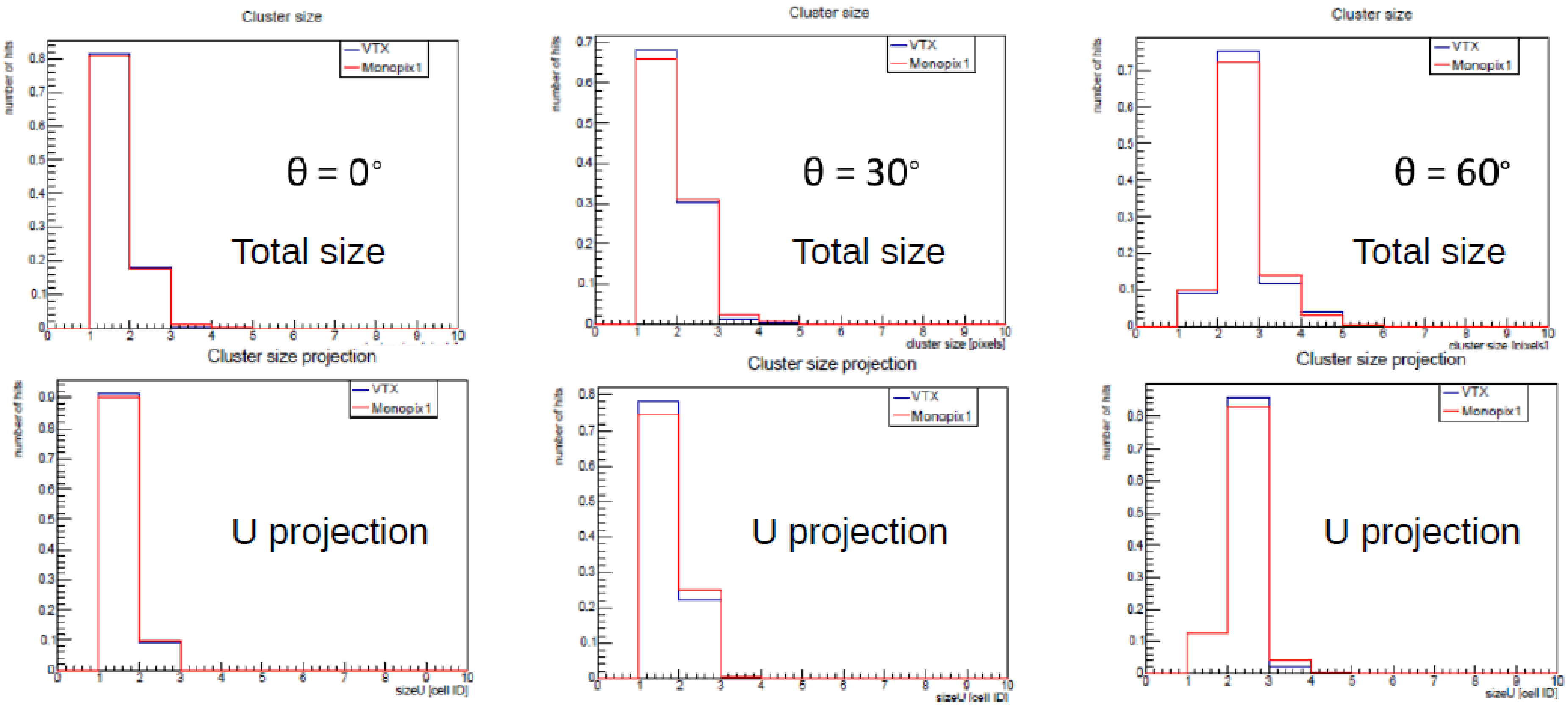
uPitch:	0.004 cm
vPitch :	0.0036 cm
Active Thickness:	0.003 cm
Charge Threshold:	540 e^-
Electronic Noise:	20 e^-
Electron To ADU:	120
ADC bits:	6 bits
Cloud Size:	8.5e-05 cm

VTX TJ Monopix2:

uPitch:	0.0033 cm
vPitch :	0.0033 cm
Active Thickness:	0.003 cm
Charge Threshold:	150 e^-
Electronic Noise:	20 e^-
Electron To ADU:	120
ADC bits:	7 bits
Cloud Size:	8.5e-05 cm

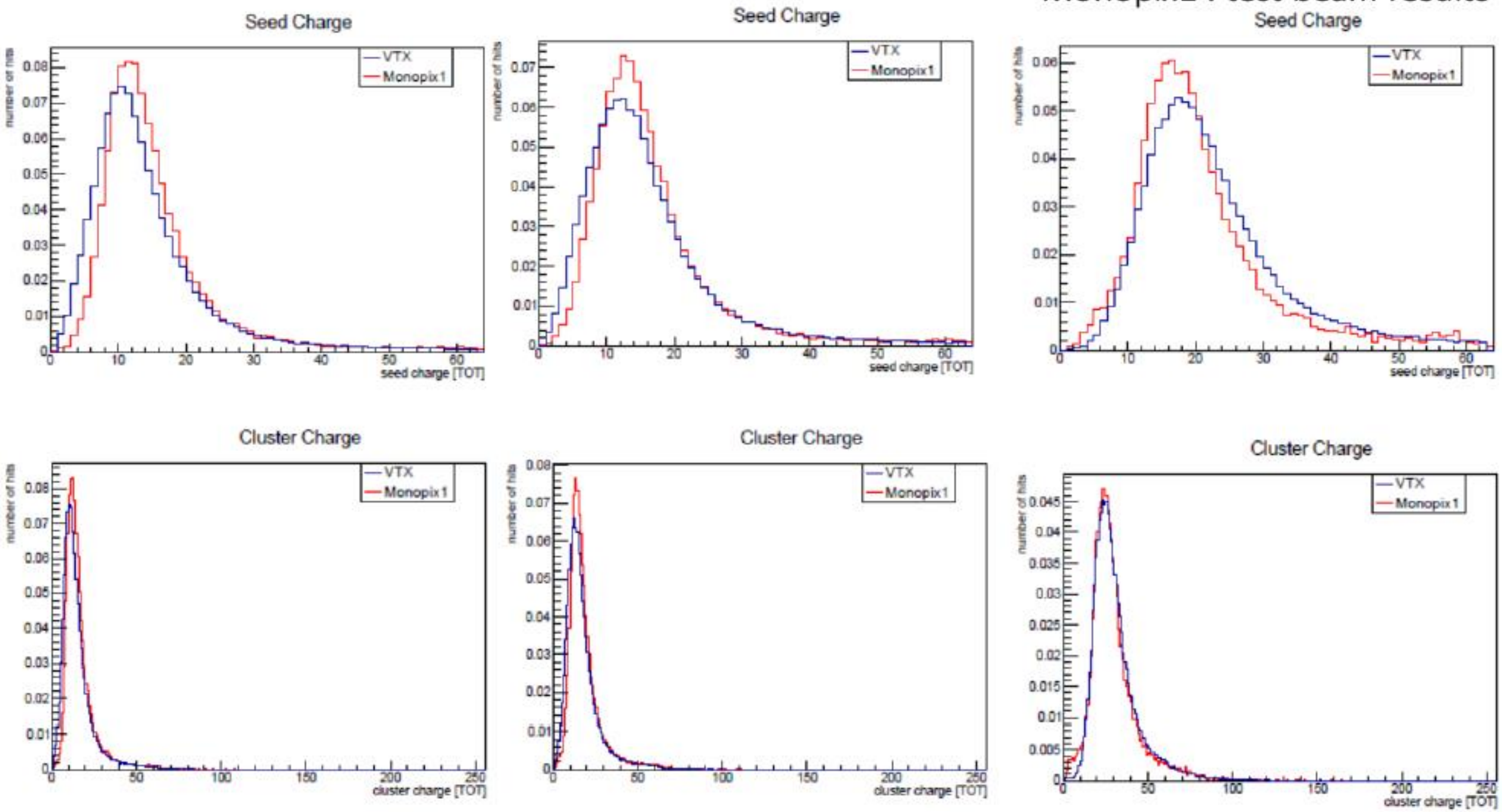
Monopix1 simulation results: Resolution




Cluster size
θ = 0°
Total size
VTX
Monopix1
number of hits
Cluster size
θ = 30°
Total size
cluster size [pixels]
Cluster size
θ = 60°
Total size
Cluster size projection
U projection
sizeU [cell ID]
Cluster size projection
U projection
Cluster size projection
U projection

Digitizer results

Monopix1 : test beam results



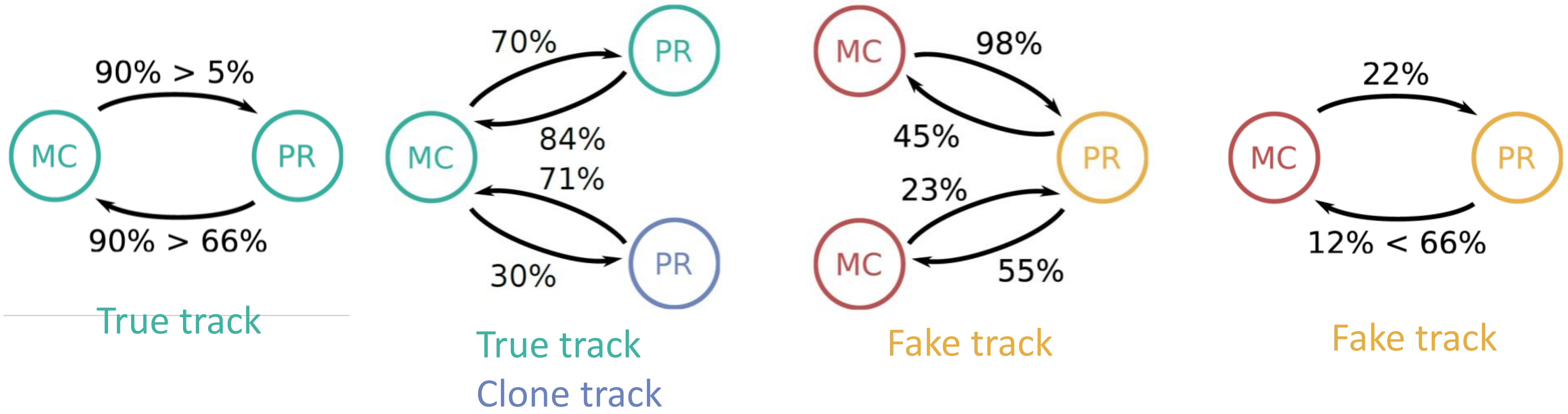
θ = 0°

θ = 30°

θ = 60°

Track definitions

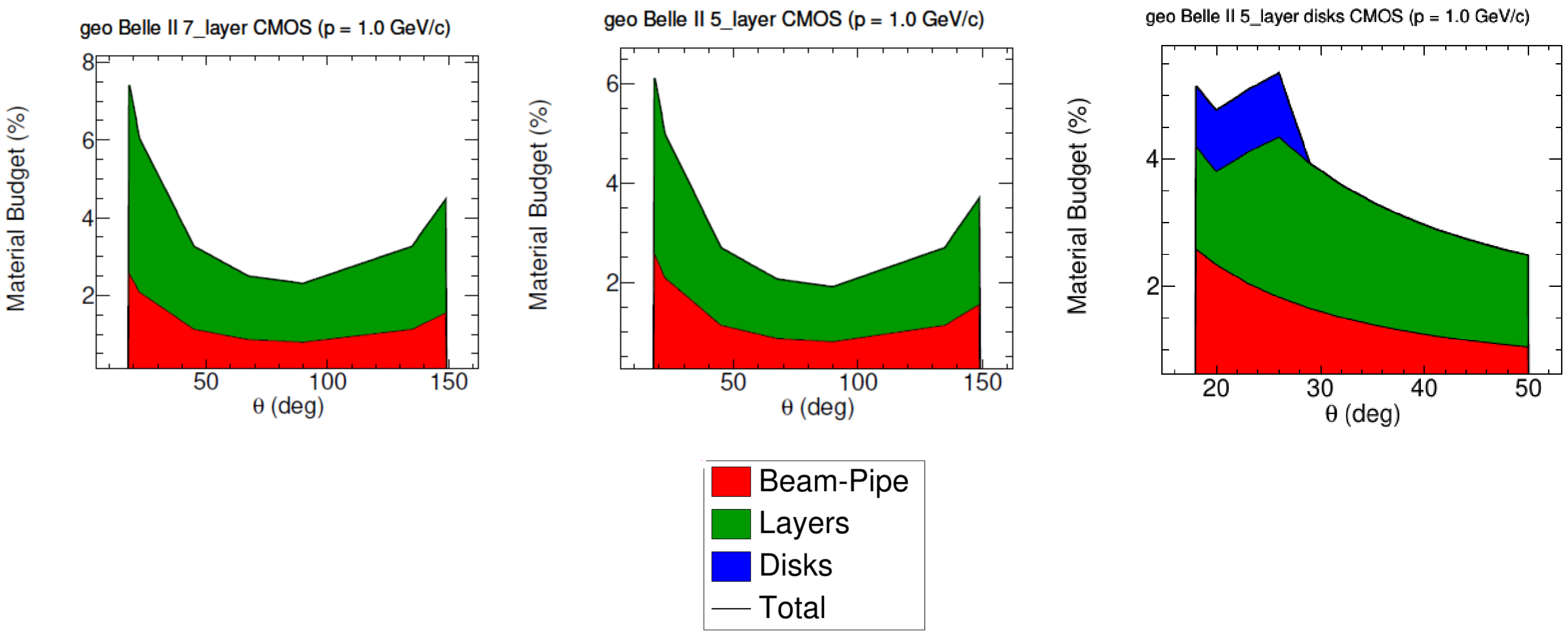
- The reconstructed tracks from pattern recognition (PR) are tagged following the number of hits they share with Monte Carlo tracks (MC)



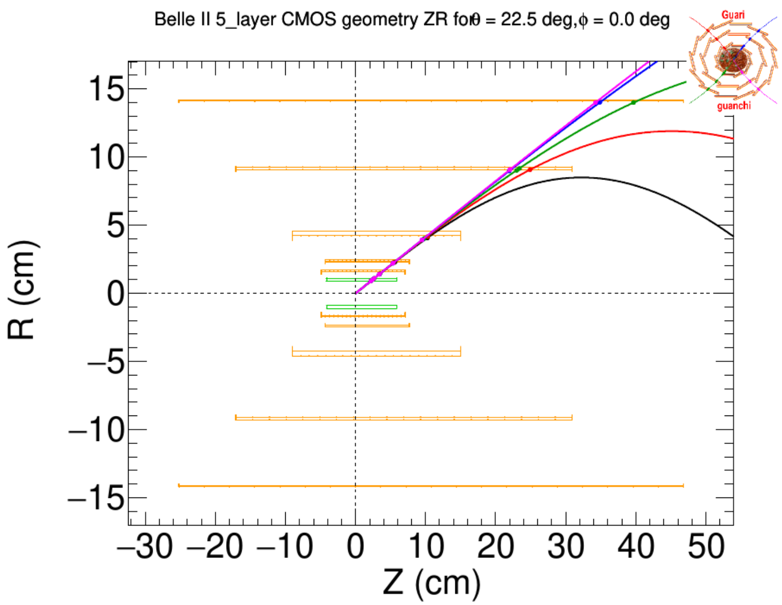
Definitions:

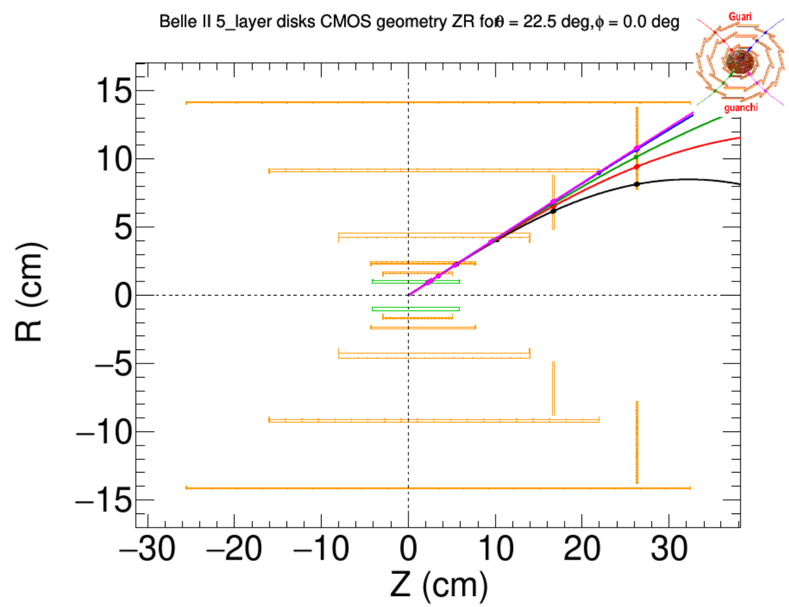
- Finding efficiency: $\frac{\text{number of true tracks}}{\text{number of generated particles}}$
- Clone rate: $\frac{\text{number of clone tracks}}{\text{number of true tracks}}$
- Fake rate: $\frac{\text{number of fake tracks}}{\text{number of reconstructed tracks}}$

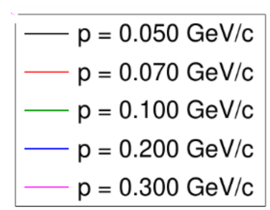
Material budget of the VTX



5 layer with discs: angular acceptance



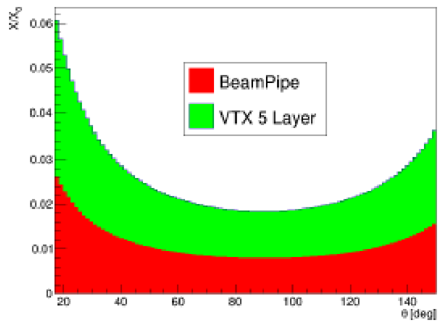




- Geometry with disk increases acceptance for low momentum tracks at small angles but according to simulations, performances doesn't improve compared to CMOS 5 layers.

VTX with 5 pixelated layers

5 layers	1	2	3	4	5
Radius (cm)	1.4	2.2	3.9	8.9	14.0
# ladders	**6**	**10**	**8**	**18**	**26**
Sensor type	**A**	**A**	**A'**	**A'**	**A'**
# Sensor rows along z direction	1	1	2	4	6

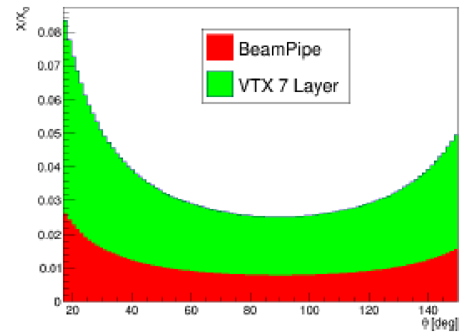


	Sensor A	**Sensor A'**
Width (cm)	2.0	2.0 **(*2)**
Height (mm)	0.4	1.0
Length (cm)	12	
	Sensitive area	
Width (cm)	1.8	1.75 **(*2)**
Height (µm)	40	100
Length (cm)	12	
# Pixels U	512	
# Pixels V	3584 (256*14)	
Charge Threshold (ENC)	150	
Integration time (ns)	100	

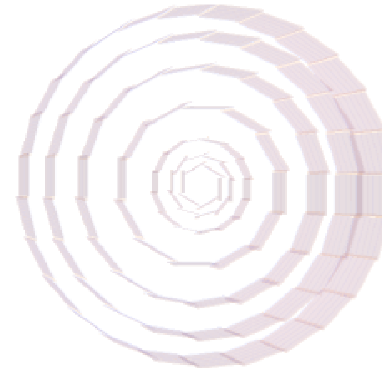
7 layer geometry

VTX with 7 pixelated layers

7 layers	1	2	3	4	5	6	7
Radius (cm)	1.4	2.2	3.5	6.0	9.0	11.5	13.5
# ladders	**6**	**10**	**14**	**12**	**18**	**22**	**26**
Sensor type	**A**	**A**	**A**	**A'**	**A'**	**A'**	**A'**
# Sensor rows along z direction	1	1	2	3	4	5	6



	Sensor A	Sensor A'
Width (cm)	2.0	2.0 **(*2)**
Height (mm)	0.4	1.0
Length (cm)	12	
	Sensitive area	
Width (cm)	1.8	1.75 **(*2)**
Height (µm)	40	100
Length (cm)	12	
# Pixels U	512	
# Pixels V	3584 (256*14)	
Charge Threshold (ENC)	150	
Integration time (ns)	100	



Standalone performance

- **Validation figures for**
  - CMOS 5 layer

Bkg scale	finding efficiency	fake rate	clone rate
x 1	0.984	0.20	0.022
x 2	0.983	0.42	0.023
x 3	0.982	0.60	0.023
x 5	0.979	0.79	0.023
x 10	0.953	0.90	0.018

  - CMOS 7 layer

Bkg scale	finding efficiency	fake rate	clone rate
x 1	0.987	0.22	0.034
x 2	0.986	0.44	0.033
x 3	0.985	0.60	0.033
x 5	0.978	0.79	0.034
x 10	0.943	0.90	0.026