Timing at Belle-II Vertex Detector (VXD)

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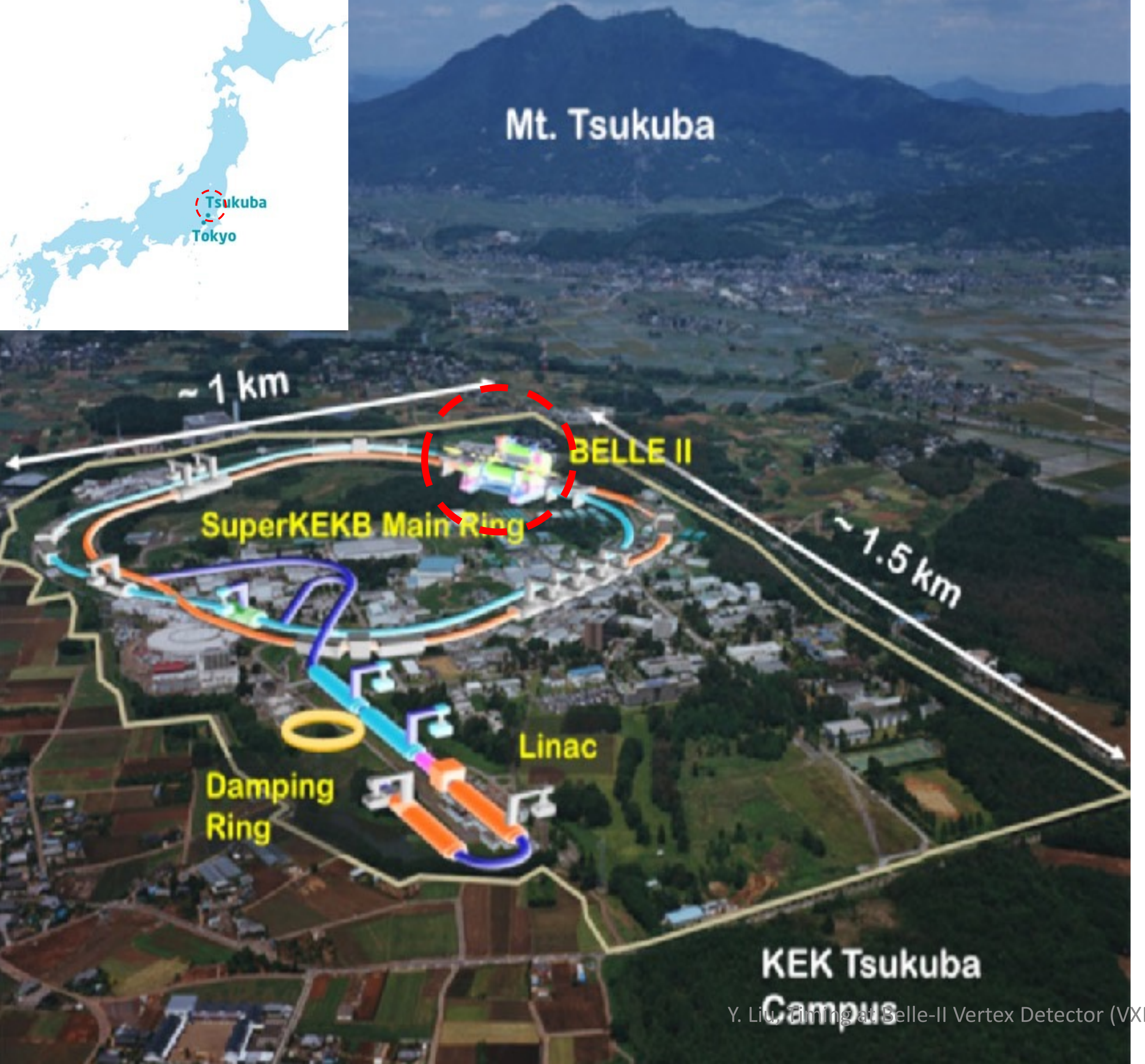
Support from: **Christian Finck** & **Ajit Kumar**

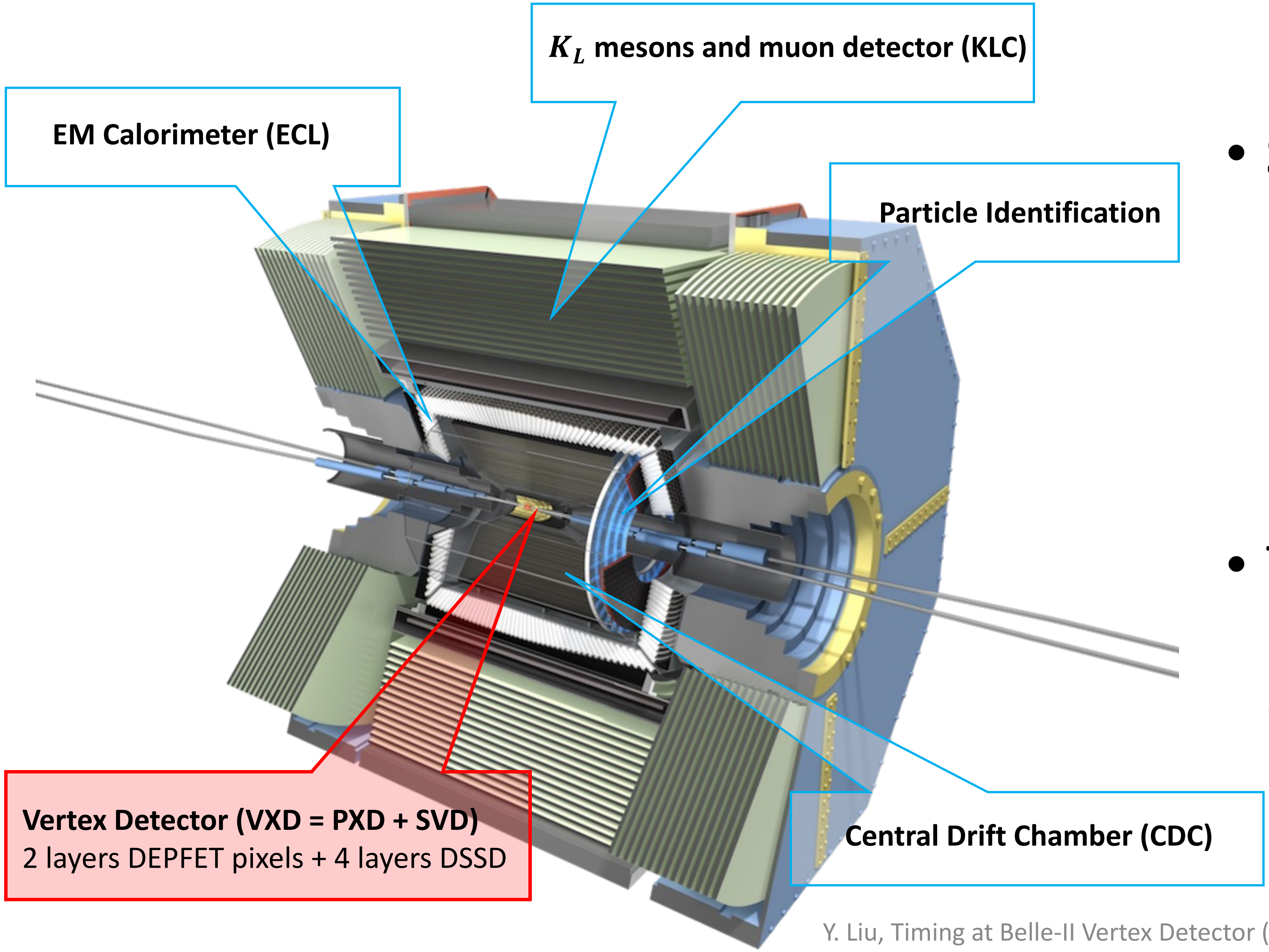
PSA M2 Defense 22/06/2023



SuperKEKB is an e^-e^+ collider:

- Asymmetric energy:
  - 7GeV e^- + 4GeV e^+
- Center of mass energy: $\mathbf{10.5\ GeV}$
- Bunch crossing: **4 *ns***
  - **Continuous background**
- Luminosity goal: $\mathbf{6 \times 10^{35} cm^{-2} s^{-1}}$
- Rare events & high precision

Belle-II detector



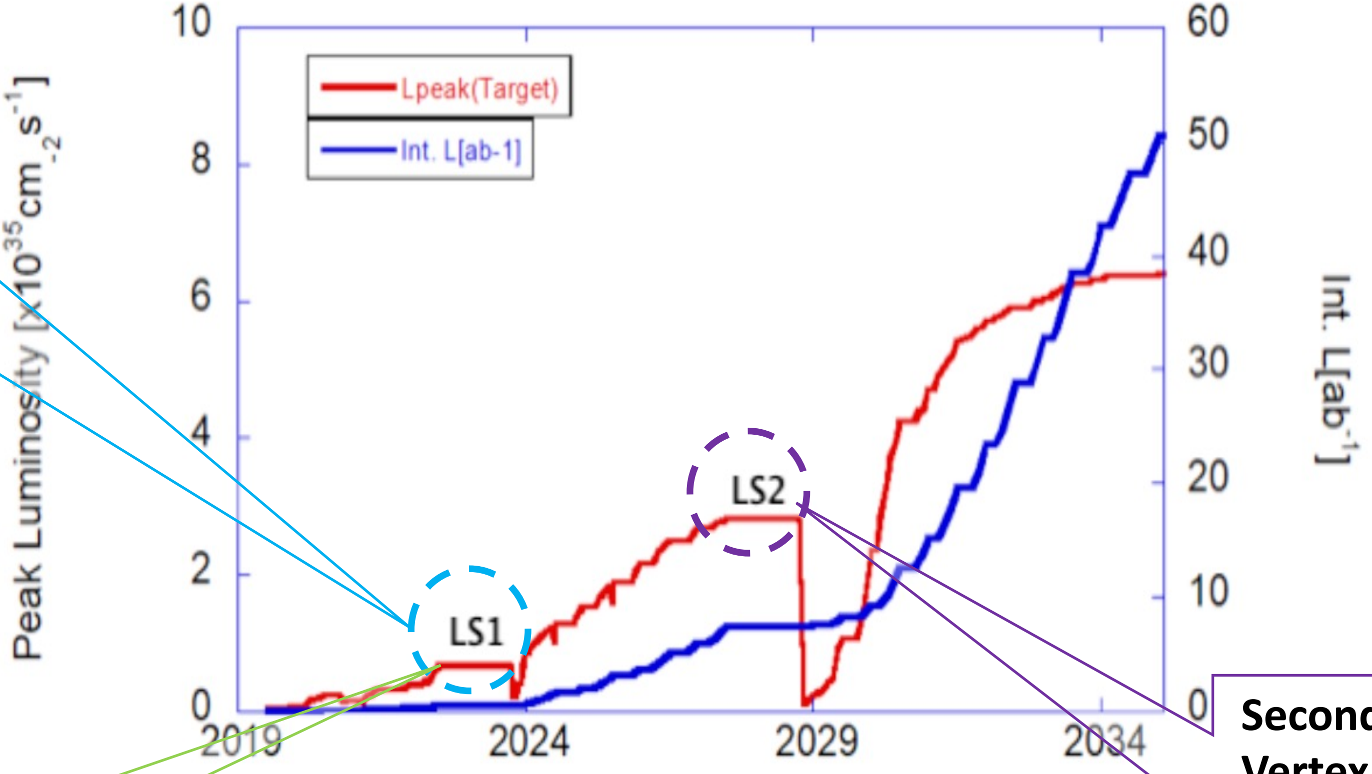
- **Silicon Vertex Detector (SVD):**
  - 4 outer layers of the VXD
  - Strip detectors

- Track reconstruction for low momentum charged particles & decay vertex reconstructions

Timing stratigies to high-luminosity conditions

First long shut down (currently):

Lighter data format for bandwidth reduction (reaching 3% occupancy limit)



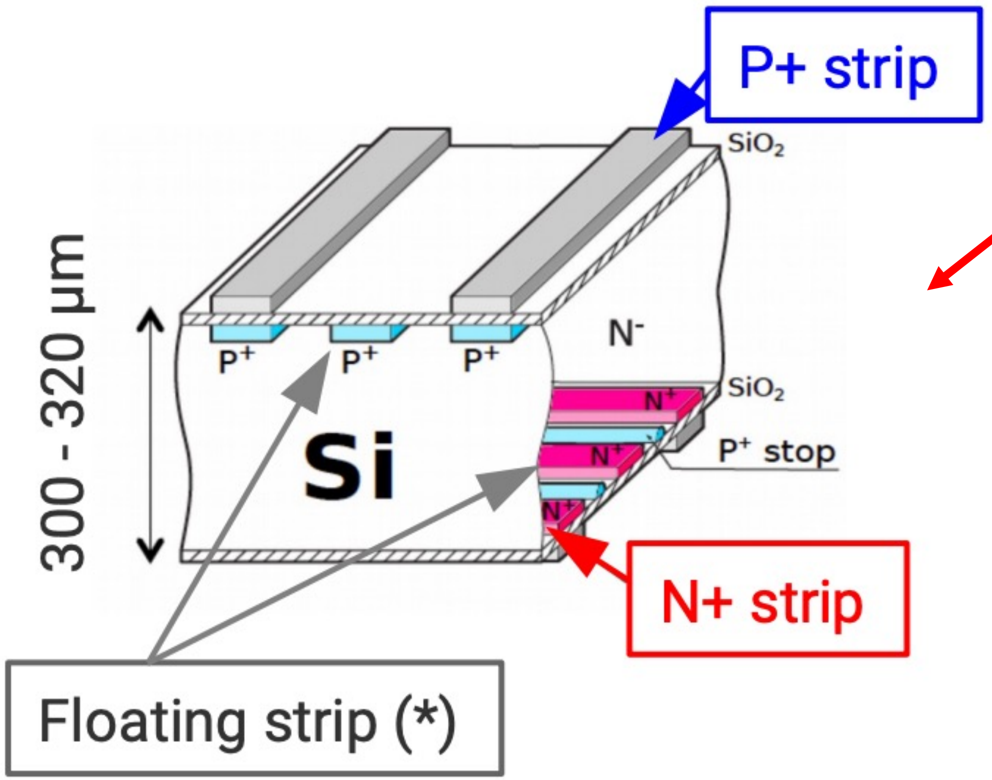
Highest peak luminosity recorded in 2022: $\mathbf{4.7 \times 10^{34} cm^{-2} s^{-1}}$

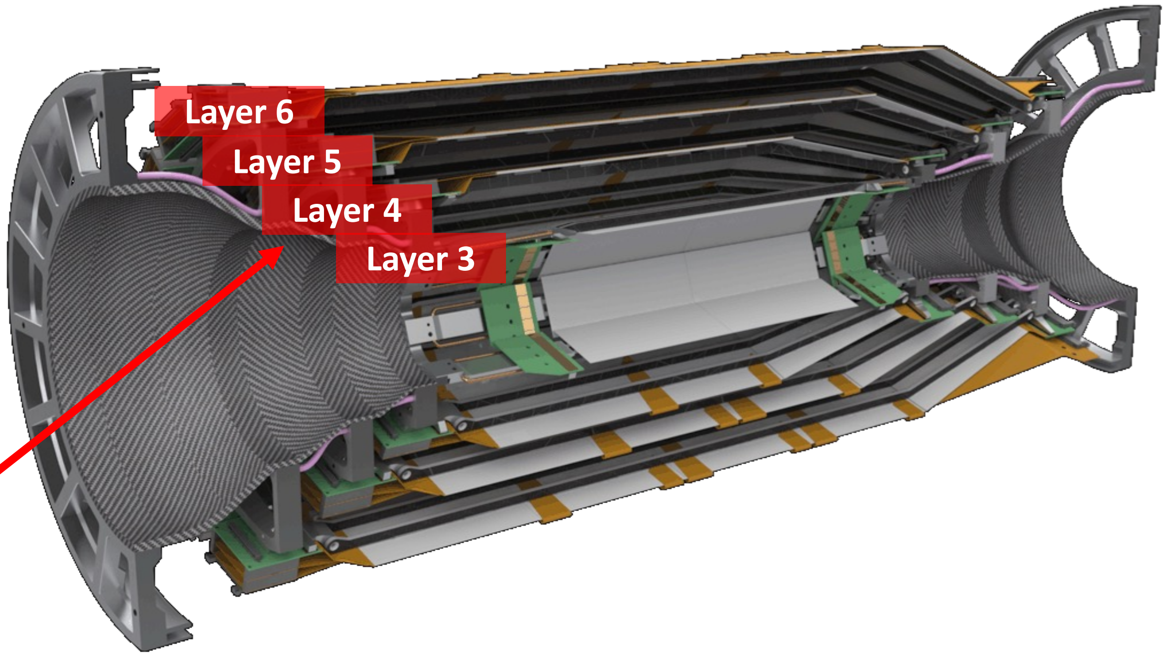
2 long shut downs/upgrades

Second long shut down (~2027): **Vertex Detector (VTX)** upgrades using pixel sensors to lower occupancy
→ Finer space and time granularity

SVD strip silicon sensors

Double-Sided Strip Detector (DSSD)





- **Signal generated by the drifted charge in the sensor:**
  - ~ 24000 e/h pairs

- **Layer 3:**
  - Strip pitch : $50(\mathrm{p}) \times 160(n)\ \mu m$
  - # strips : $768\ (p) \times 768(n)$

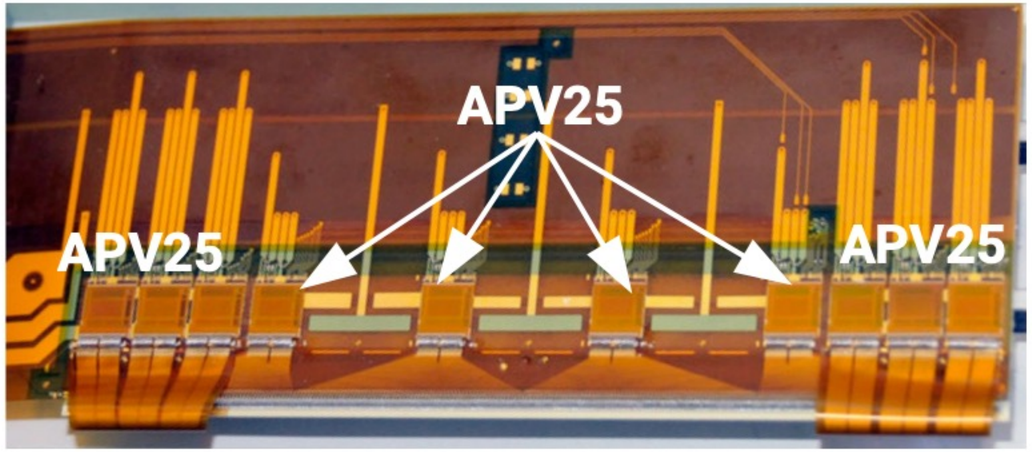
Readout system: APV 25

- **APV 25 is connected to the strip sensor for signal readout:**
  - **Clock frequency: ~ 32 MHz**

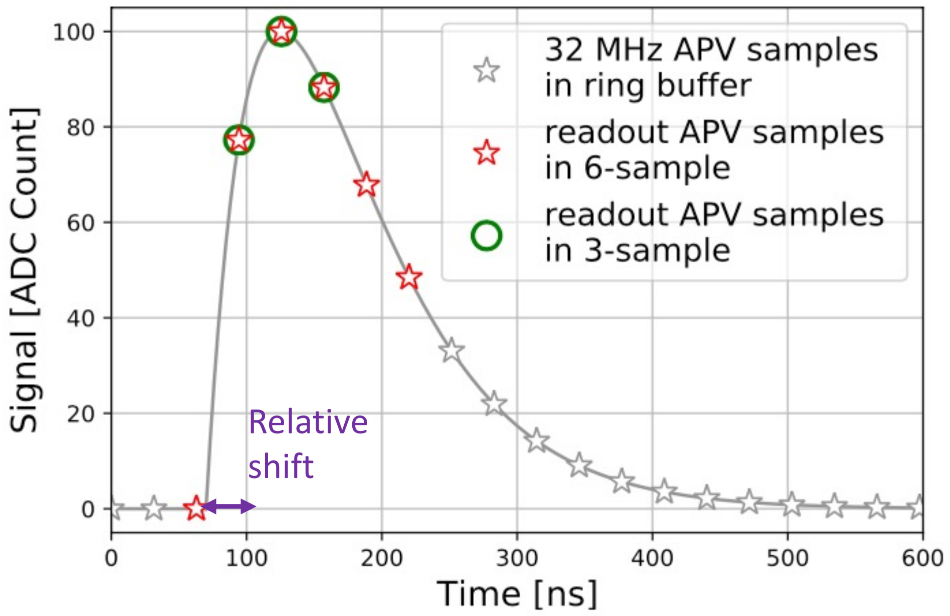
- After a trigger is specified, the chip will go back in time to search for the samples in the buffer that match the trigger

- **Currently, 6-sample mode is being used:**
  - 3-sample is emulated from the 6-sample by doing a **relative shift**

Readout front-end on a sensor



APV 25 readout



SVD cluster time reconstruction

- **Sum APV outputs:** 3 best summed consecutive samples
- **Two main algorithms** for $t_{cluster}$ reconstruction:
  - **CoG3**: center of gravity

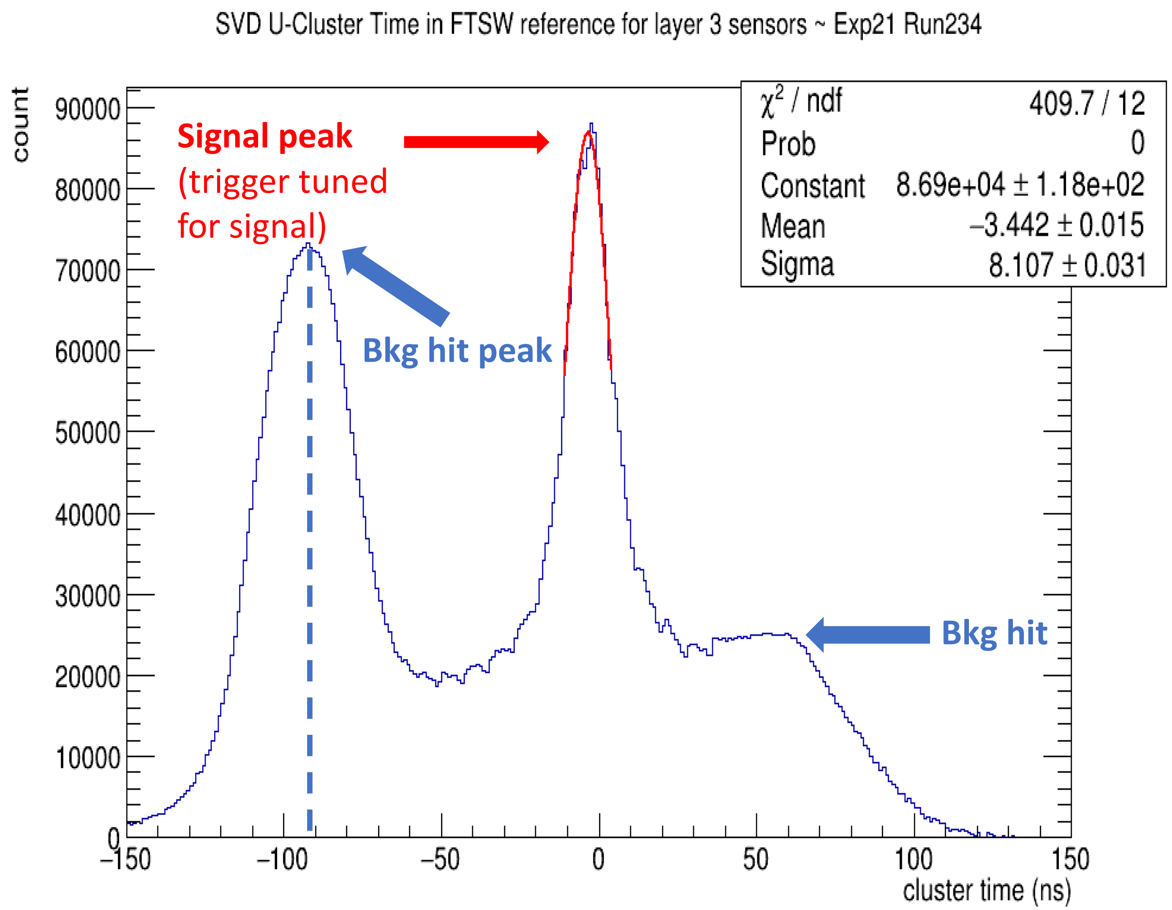
$$T_{\mathrm{SVD;raw}} = \frac{\sum_{i=0}^{2} a_i \cdot i\Delta t}{\sum_{i=0}^{2} a_i}.$$

  - **ELS3**: approximate pulse shape + least square

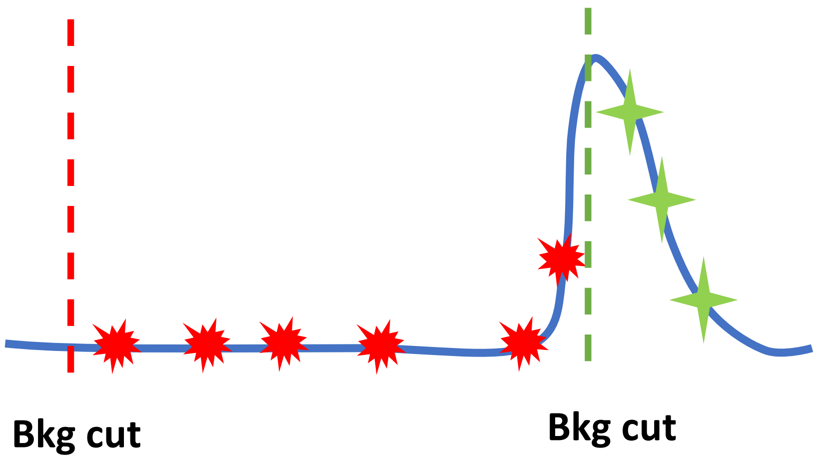
$$a(t) = A\frac{t - T_{\mathrm{SVD;raw}}}{\tau}\exp\left(1 - \frac{t - T_{\mathrm{SVD;raw}}}{\tau}\right)$$

  - Currently, **CoG3 is the default**
  - However, ELS3 might be better for high luminosity

SVD 6-sample CoG3 cluster time



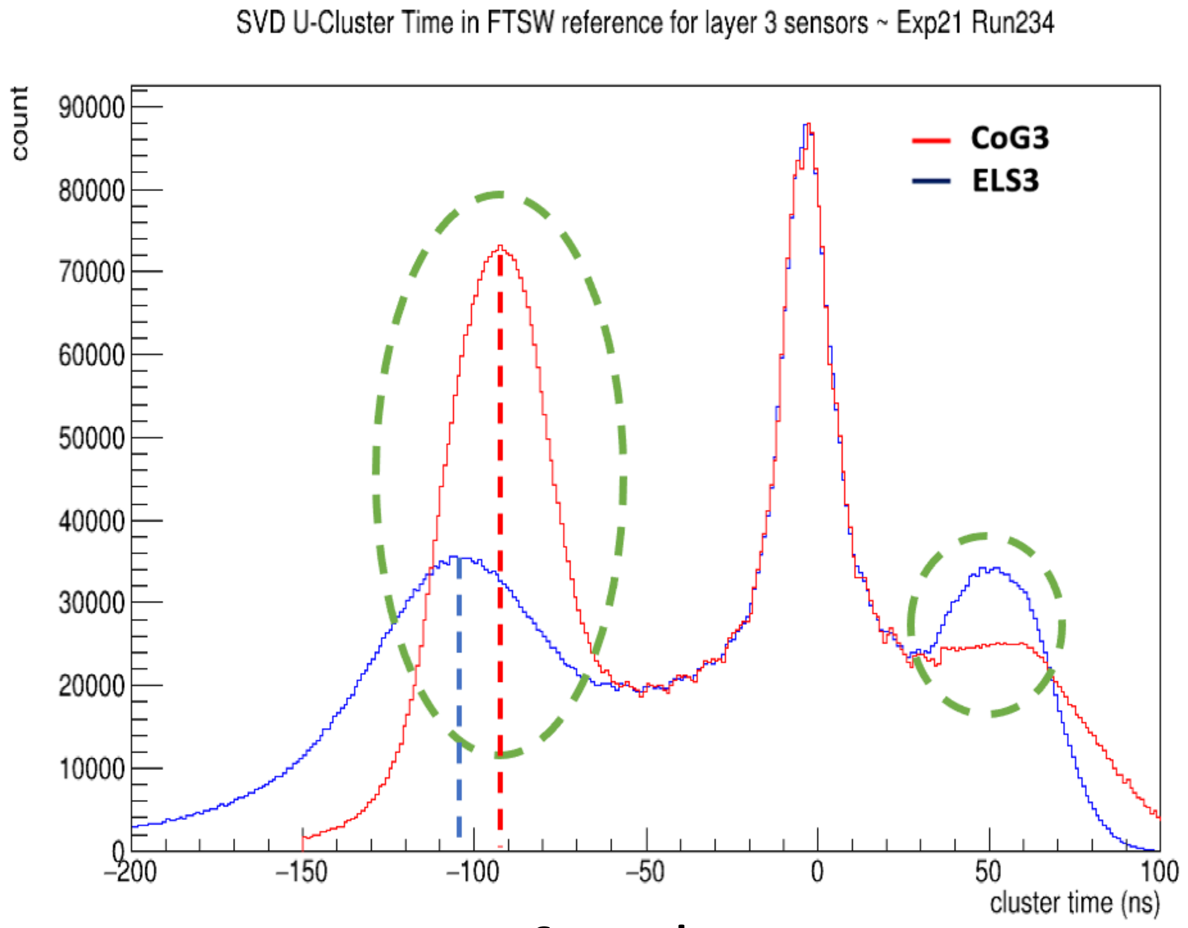
Cluster-level



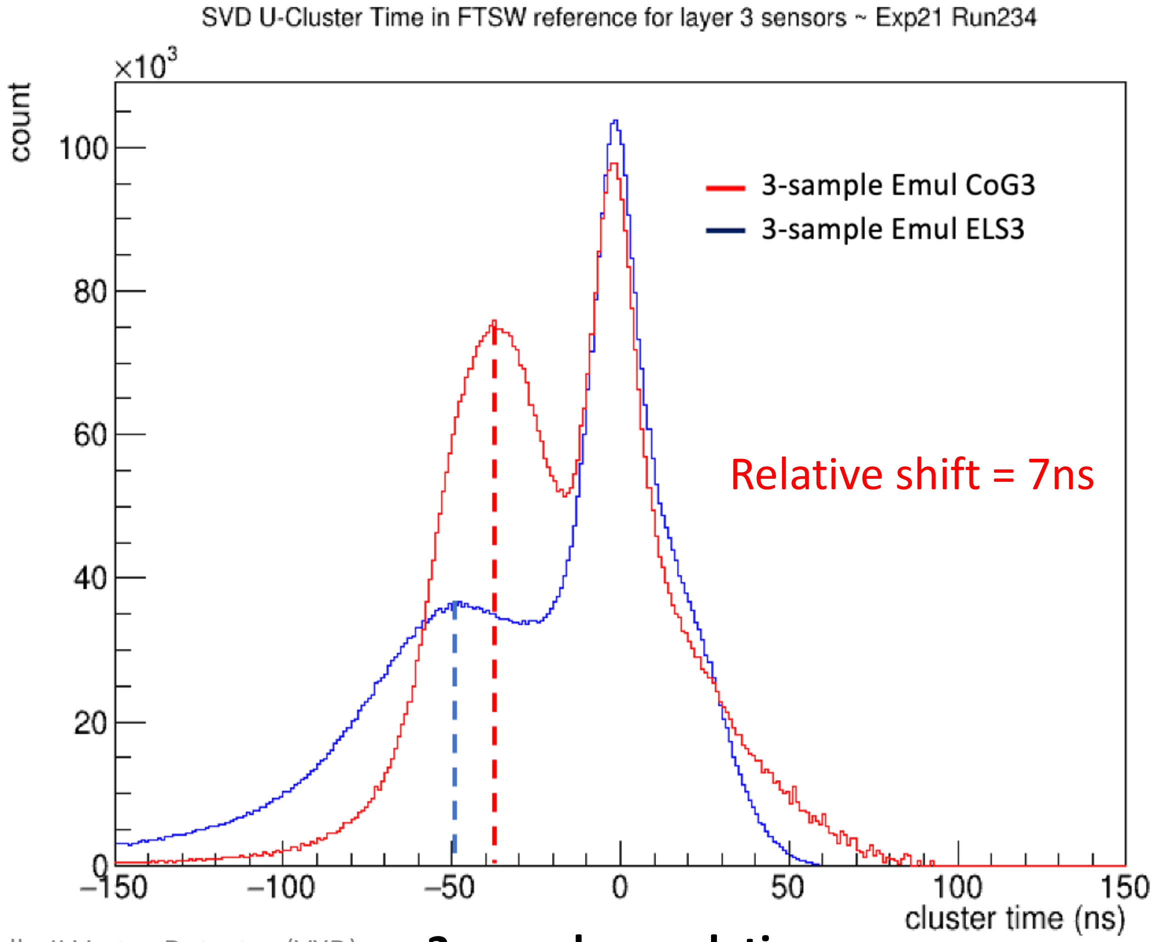
- ➢ The background arrival time is not synchronous to the trigger time.
- ➢ **The distorted bkg time estimation leads to the bkg hit peak**

SVD algorithm comparison

Hard to tell which algorithm performs better in background rejection



6-sample



3-sample emulation

ROC
(Receiver Operating Characteristic)

Parameter settings

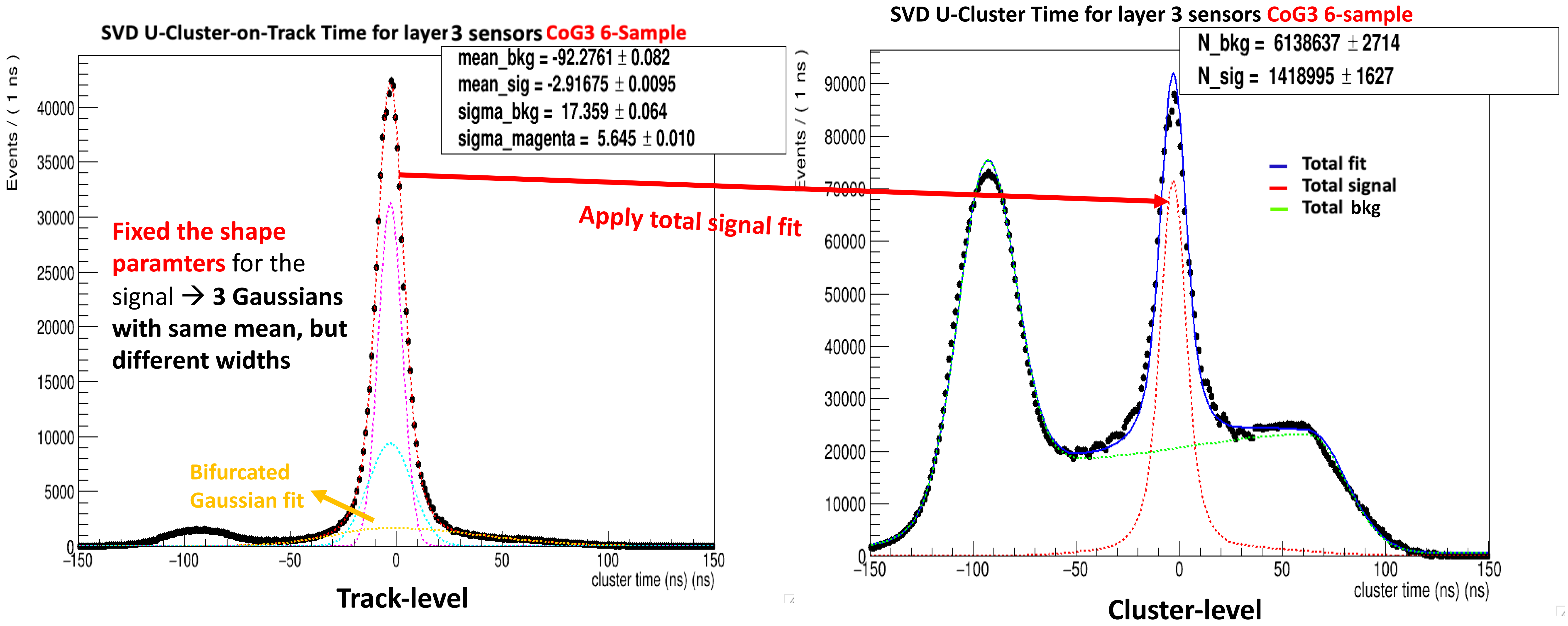
- Using **ROC curve** to compare the performance of **4 different cases** (CoG3 & ELS3 6-sample, CoG3 & ELS3 3-sample) with different cluster time threshold cuts:
  - **Define variables**
    - S_{total} = total # of signal hits (no constraints)
    - B_{total} = total # of background hits (no constraints)
    - S_{sel} = # of signal hits selected within certain time cut
    - B_{sel} = # of bkg hits selected within certain time cut

  Need to fit the cluster time plot to get these parameter values

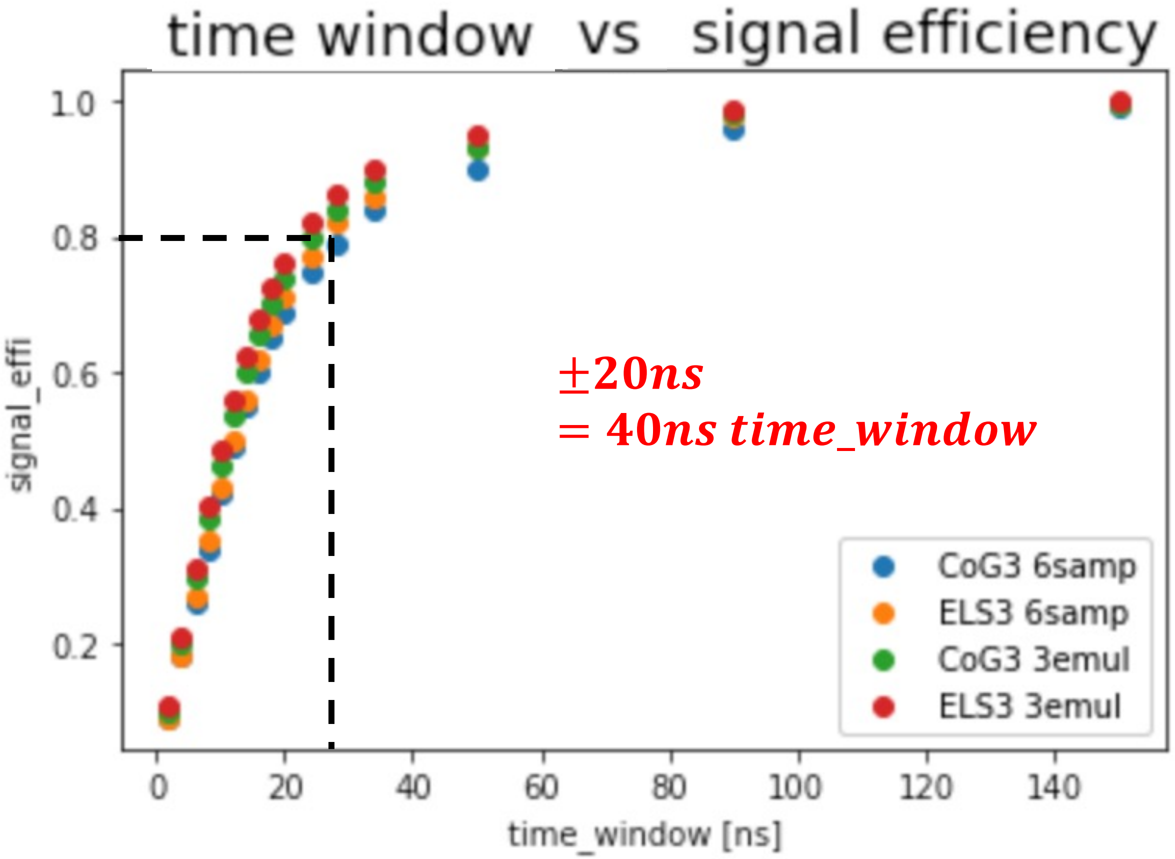
  - **For different time cuts:**
    - $S_{eff} = \frac{S_{sel}}{S_{total}}$
    - $B_{rej} = 1 - \frac{B_{sel}}{B_{total}}$
    - ***Purity*** $= \frac{S_{sel}}{S_{sel} + B_{sel}}$
    - Build S_{eff} **vs** B_{rej} & **Purity vs** S_{eff} curves

CoG3 6-sample cluster time fit

*Same method to fit other three cases. Tune on the parameter.

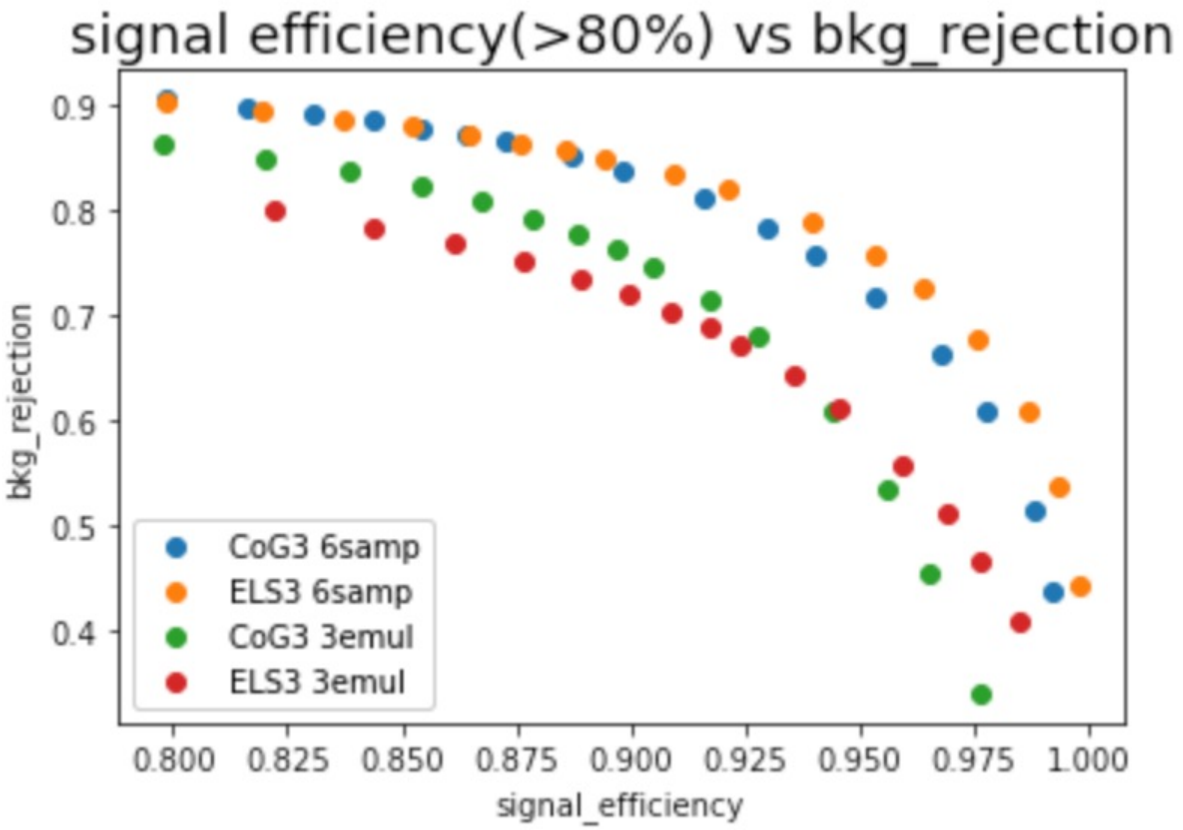


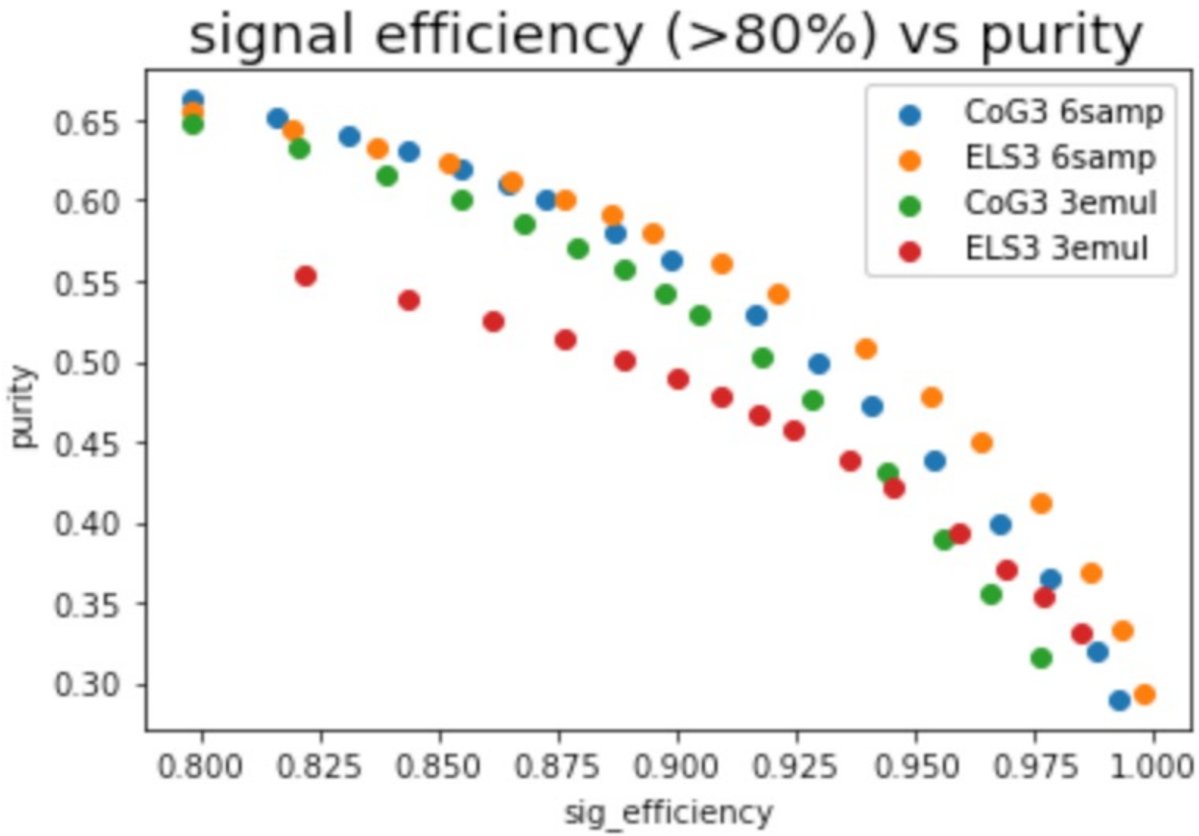
General time window scan



- General time window scan:
  - **From 0 ns to 150 ns**
- ROC curve is rougly the same for four different cases
  - **Similar signal distribution**
- Physics analysis usually focus on **high signal efficiency ($> 80\%$)**
  - Time window ~ **28 ns** ($\pm 14\ ns$)

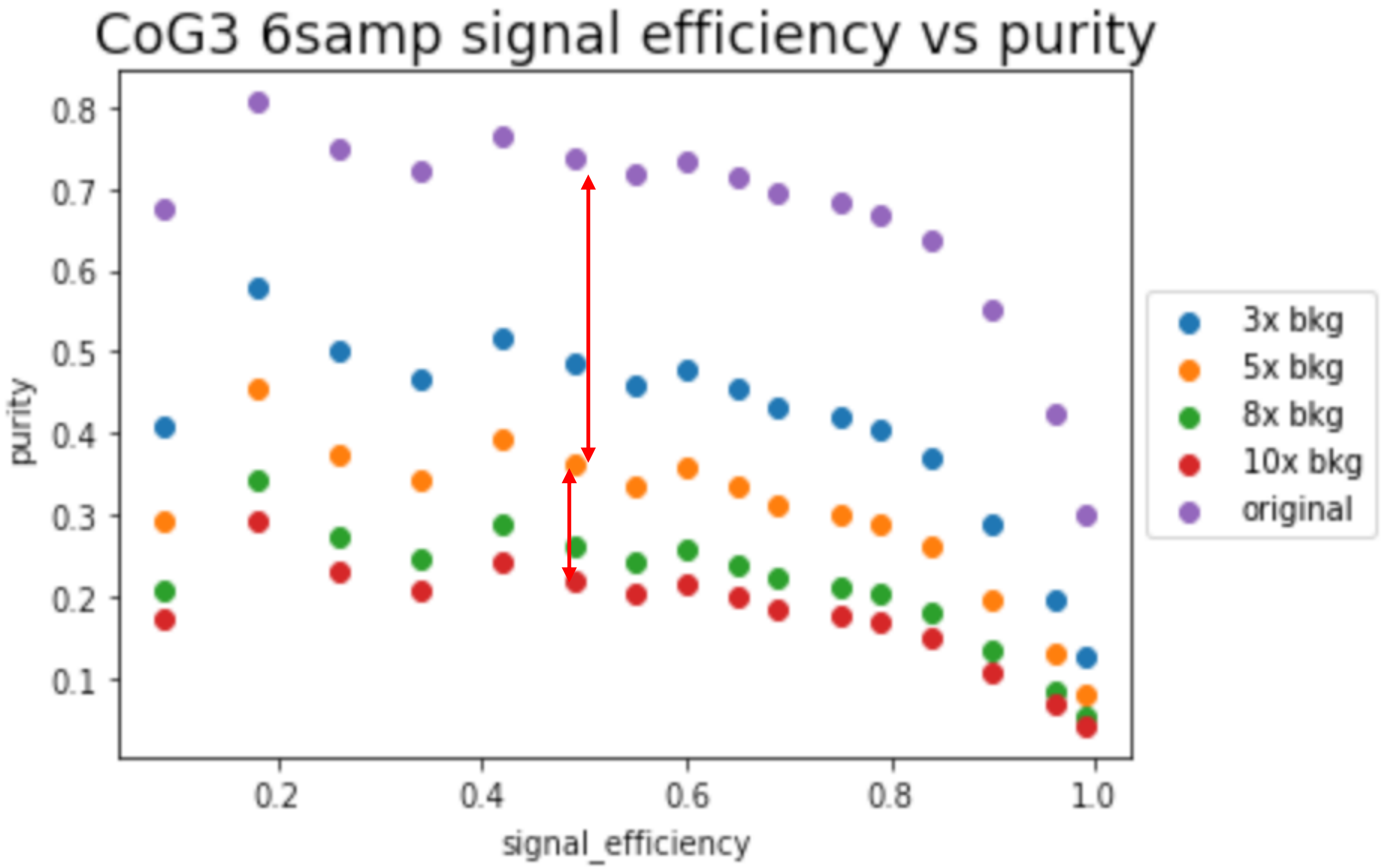
ROC curve: high signal efficiency



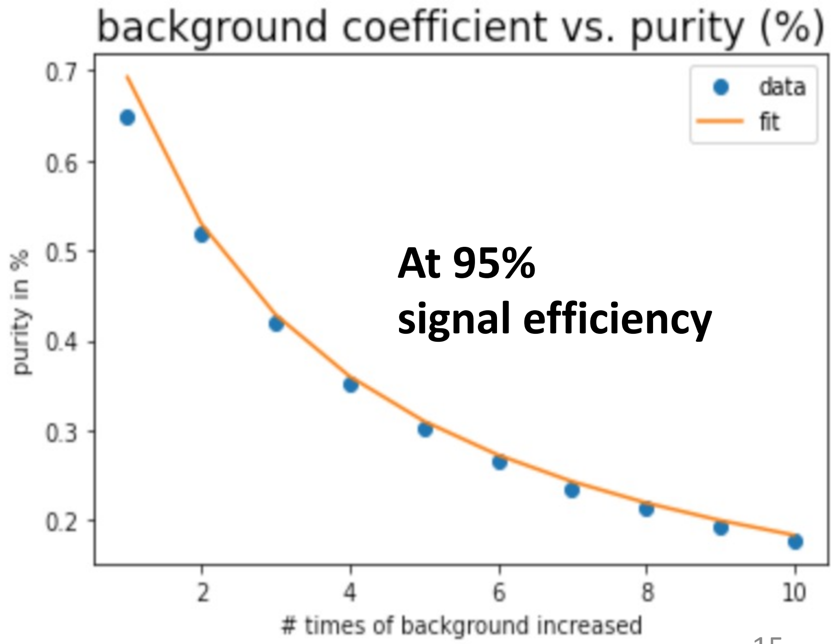


- **For B_{rej} : 6-sample is better than 3–sample**
- **For *purity*: 6, 3-sample perform about the same at high S_{eff}**

S_efficiency vs Purity with increasing bkg

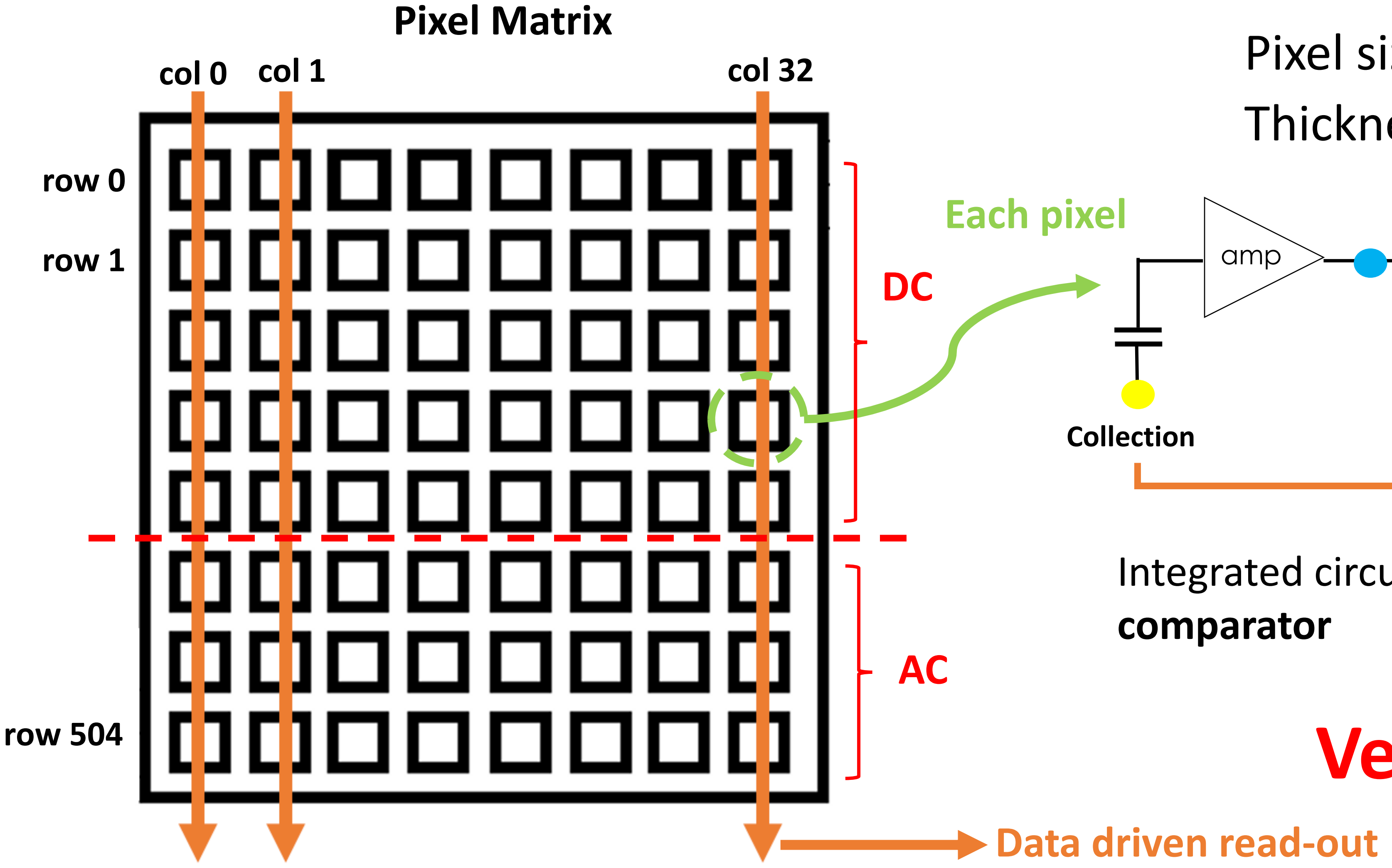


- **Purity is very low at high signal efficiency → need better cut selection**



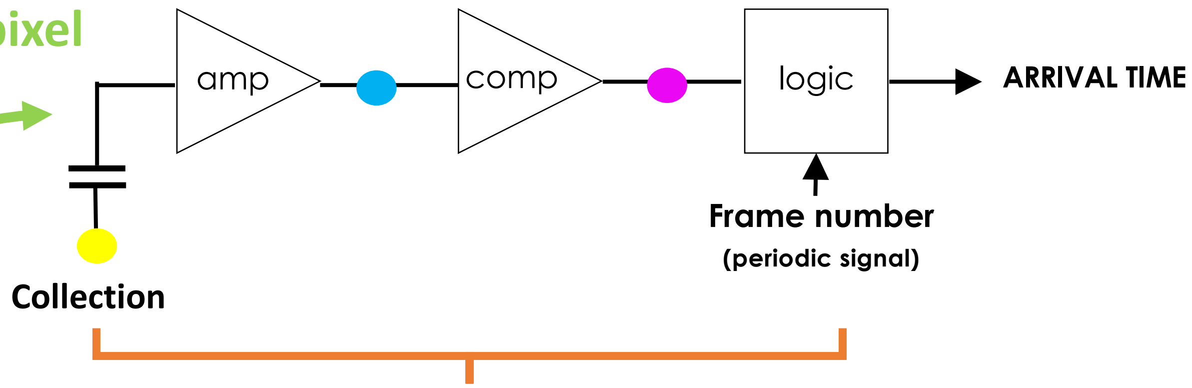
CMOS Sensor
(Complementary Metal Oxide Semiconductor)

Basic MIMOSIS-Fast architecture



Pixel size: $27 \times 30\ \mu m^2$

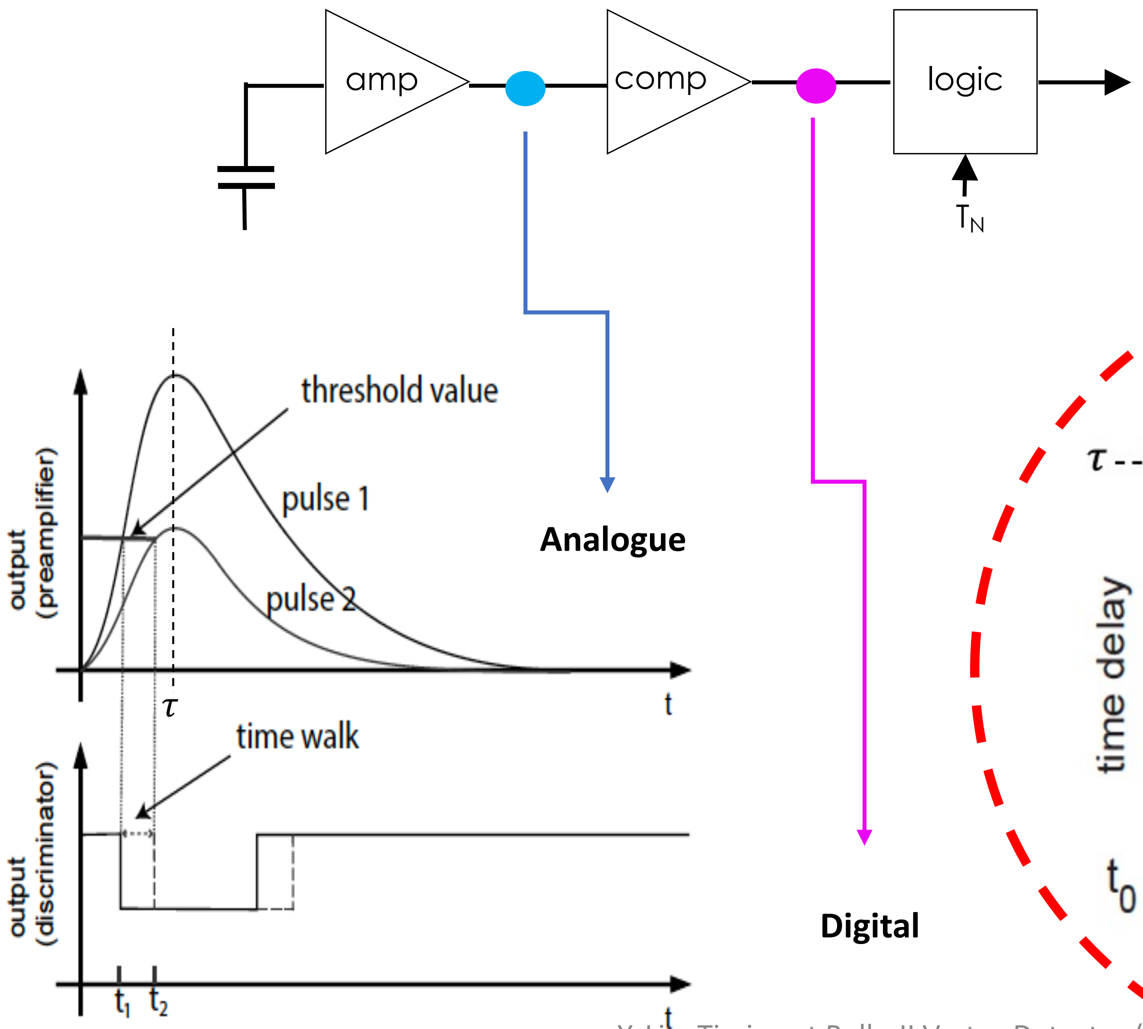
Thickness: $50\ \mu m$



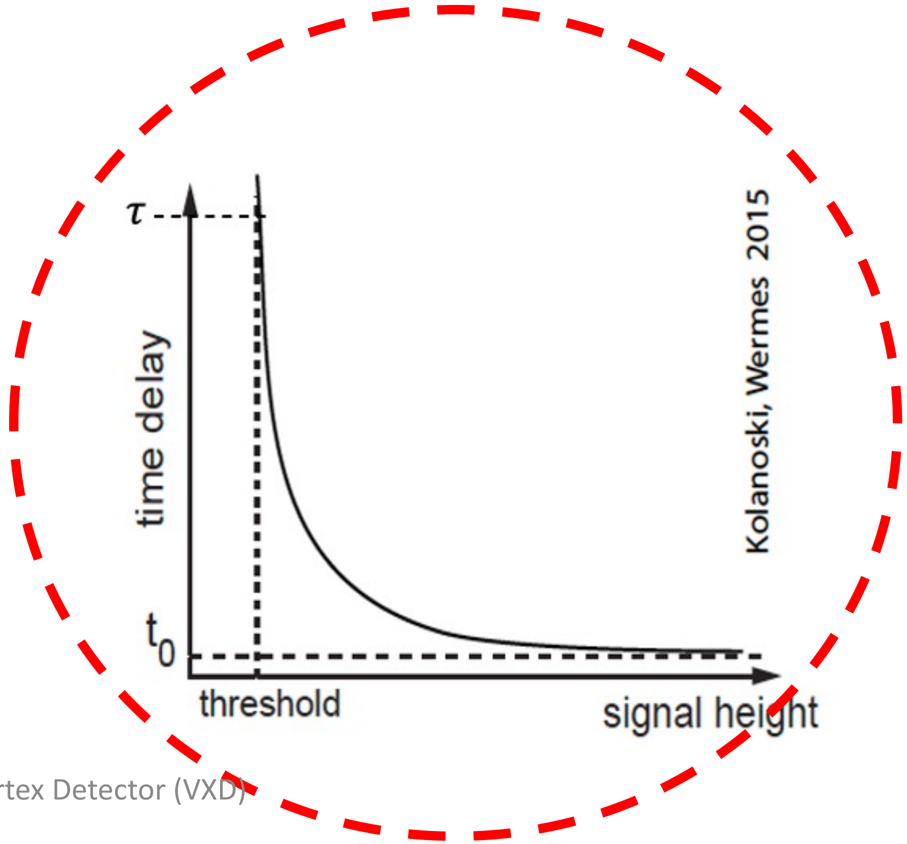
Integrated circuit: **Collection + amplifer + comparator**

Very Fast !!!

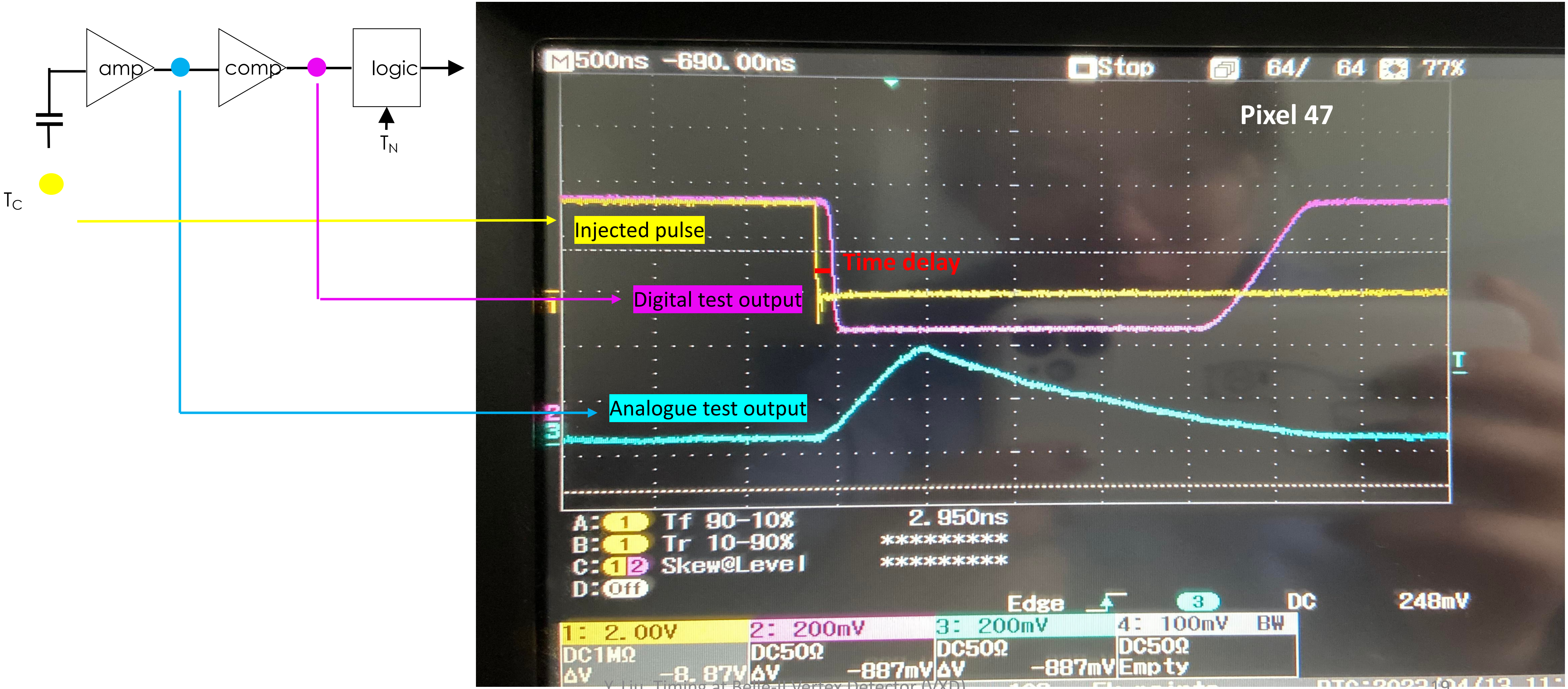
Time walk



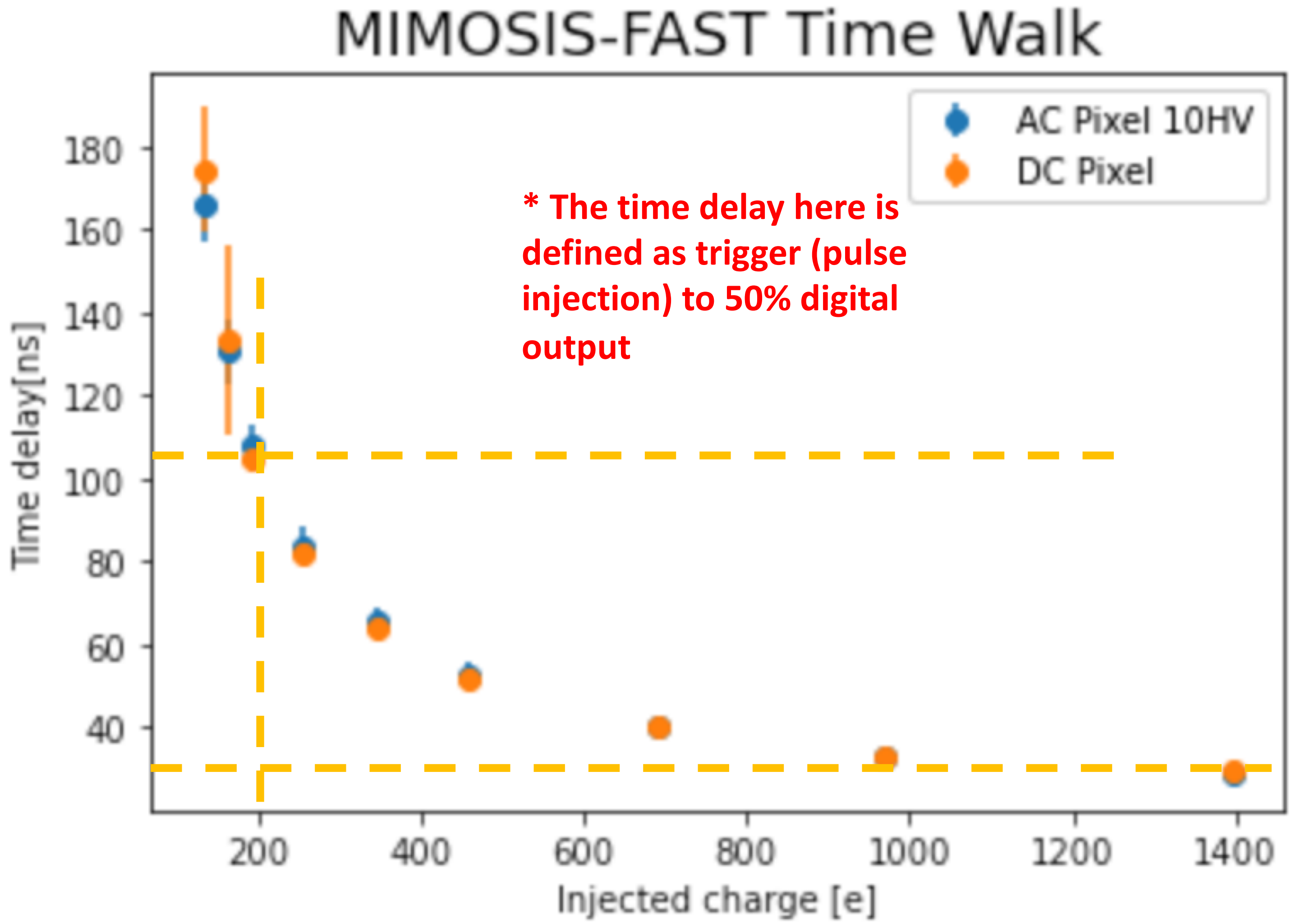
Time delay depends on the different amount of charges



Oscilloscope output



MIMOSIS-Fast time walk



- Average values of the DC, AC pixels
- **No difference in the DC & AC pixles:**
  - **~30ns** at 1400 e charges
  - **Time walk:** 75 *ns* from 200 e to 1400 e charges
- Test only electronic behaviors with injected charges. Further test on ionization charges needed.

Summary

- **The high-luminosity anticipated at Belle-II will create high occupancy in the future**

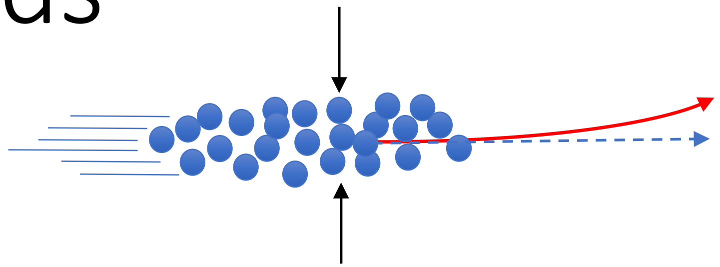
- Simple cut down on the readout sample gives worse purity & bkg rejection.
  - **Machine learning algorithms are currently under development**

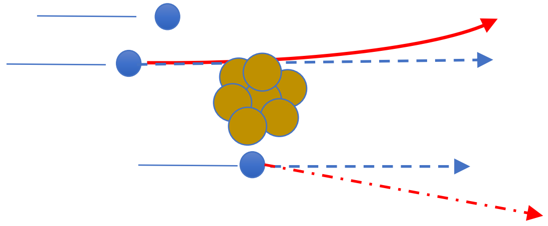
- The charge injection only tests the electronics behavior of the CMOS sensor **(~75ns time from 200 e ~ 1400 e charges)**
  - **Laser with precise time of arrival to test the ionisation charge collection time**

Back-up

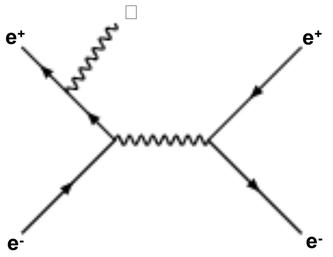
Beam induced backgrounds

- Single beam effects
  - Touschek □ intra-beam scattering
    - rate $\propto \frac{I_{bunch}^2 \ N_{bunch}}{(\sigma_x \ \sigma_y) \ E_{beam}^3} = \frac{I_{beam}^2}{(\sigma_x \ \sigma_y) \ E_{beam}^3 \ N_{bunch}}$
  - Beam gas □ vacuum residues
    - rate $\propto I_{\text{bunch}} \times N_{\text{bunch}} \times P(I)$
    - Dynamic pressure $P(I) = (p_0 + p_1 I_{beam})$
  - Synchrotron radiation □ magnet bending
    - rate $\propto I_{\text{beam}}$
- Beam-beam effects (QED)
  - rate $\propto$ Luminosity

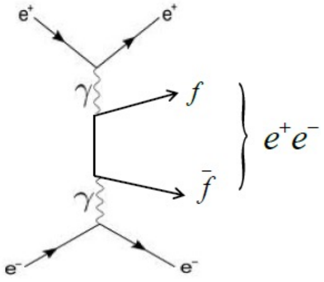




Slide taken from J. Baudot



Radiative Bhabha scattering

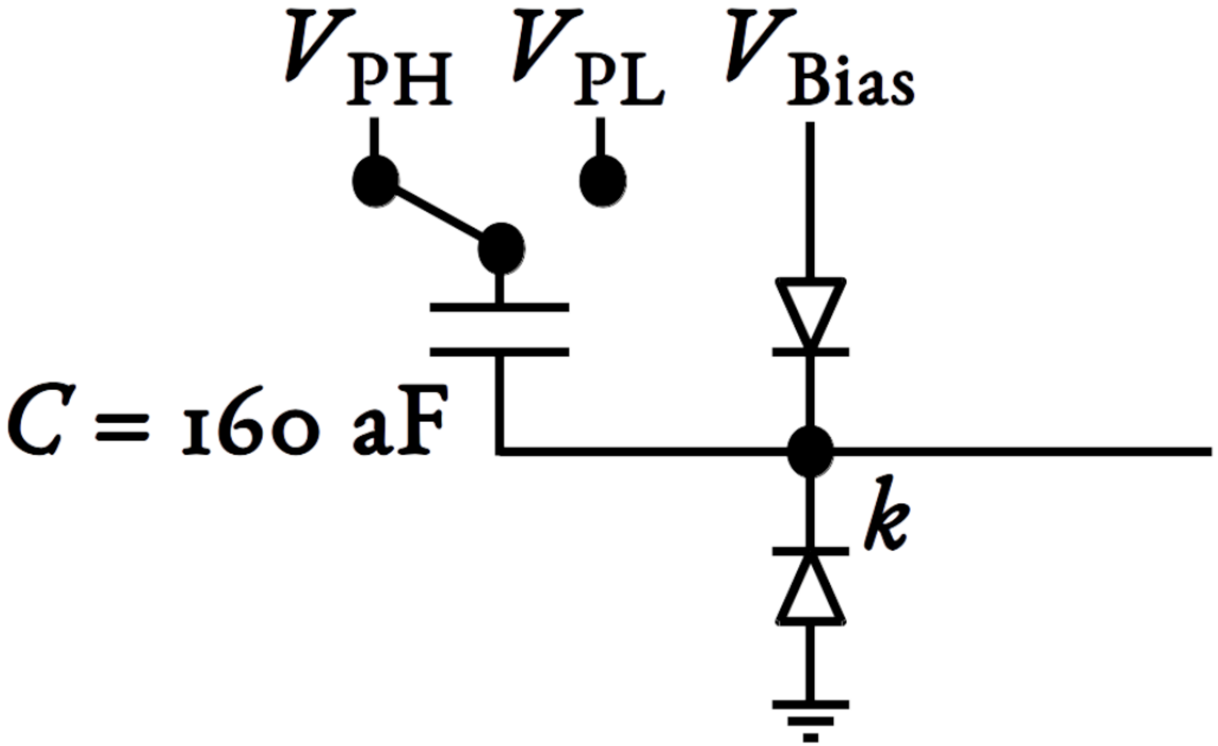


2-photon interaction

VTX upgrade

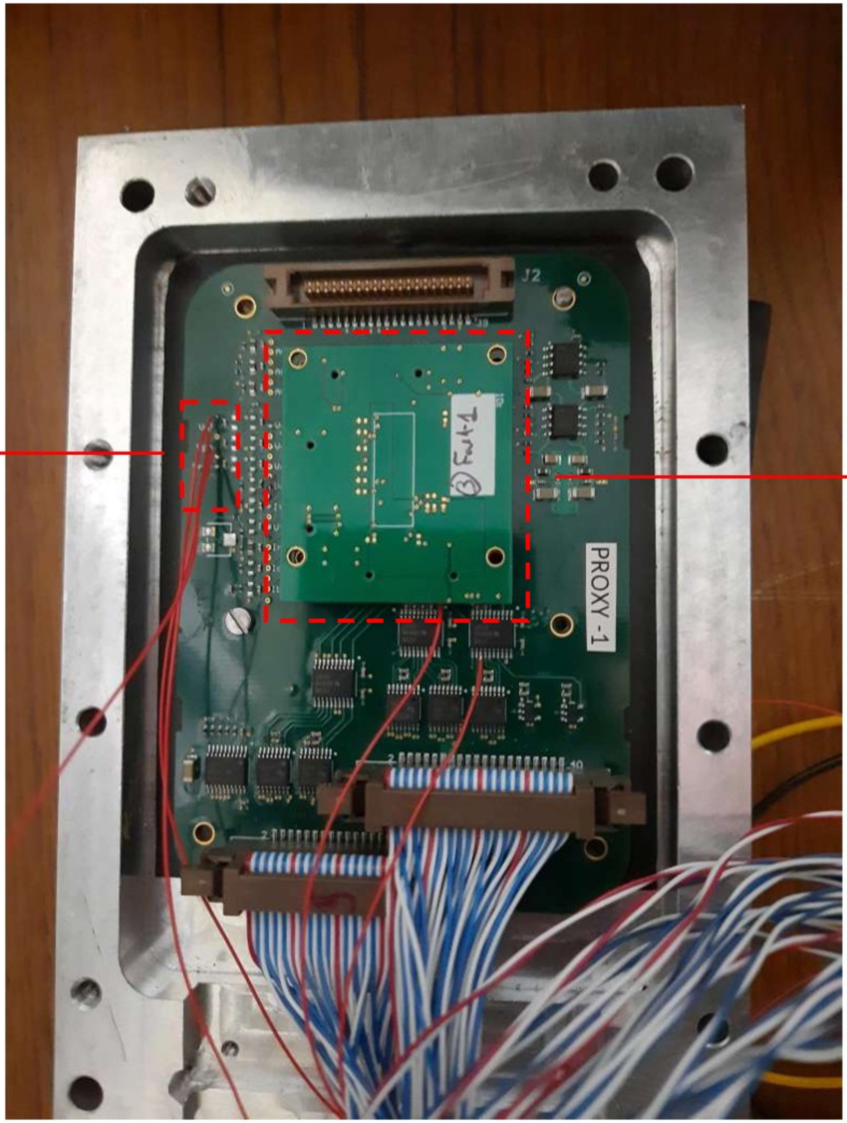
- Replacing the whole VXD with a new vertex detector (VTX), composed with 5-layers of **Monolithic Active Pixel Sensors (MAPS)** based on the **CMOS technology**
- The occupancy level with VTX is expected to be below $1e^{-4}$ in any background level conditions.
- The proposed MAPS has a **25 to 100ns integration time**

Charge injection



- The injected voltage is first set to V_{PL} with V_{Bias} set to the working voltage of a diode.
- Once the charge is injected, the injection voltage will be set to V_{Ph} .
- The quick change of voltages induces the charge to the node k with $Q = C \cdot (V_{PH} - V_{PL})$.
- The capacitance is set to be 160aF so that 1mV voltage difference corresponds to 1e charge generated on the electrodes

Proxy board



VPulseHigh & VPulseLow test connection output

MIMOSIS-Fast chip