Development of an RPC-based photodetector with picosecond resolution

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Outline

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- The gaseous photomultiplier
  - Architecture
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- The digitizer
  - Architecture
  - Calibration
- Beam test
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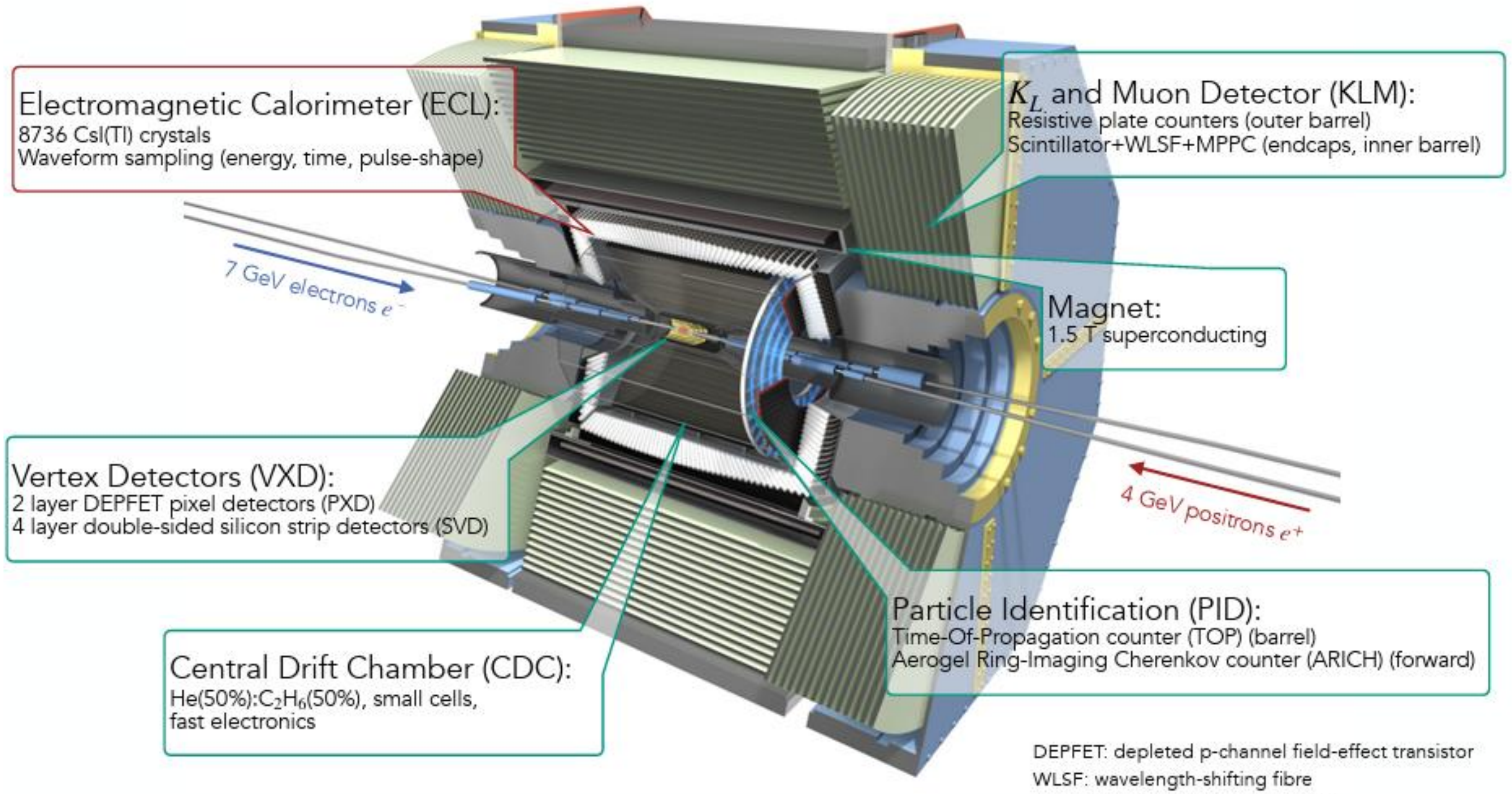
- LaB_6 photocathode characterisation
  - Cosmic-ray test
- Summary and conclusions

The Belle II experiment

- Hermetic magnetic spectrometer surrounded by particle identification, calorimeter, and muon detectors
- SuperKEKB electron-positron collider
  - 10.58 GeV centre-of-mass energy
  - High luminosity 5×10^{34} cm^{-1} Hz
- Indirect searches for non-Standard-Model physics
  - Properties of billions of B, D, τ decays at low background
- Unique reach in final states with photons and neutrinos
- Crucial role of the calorimeter

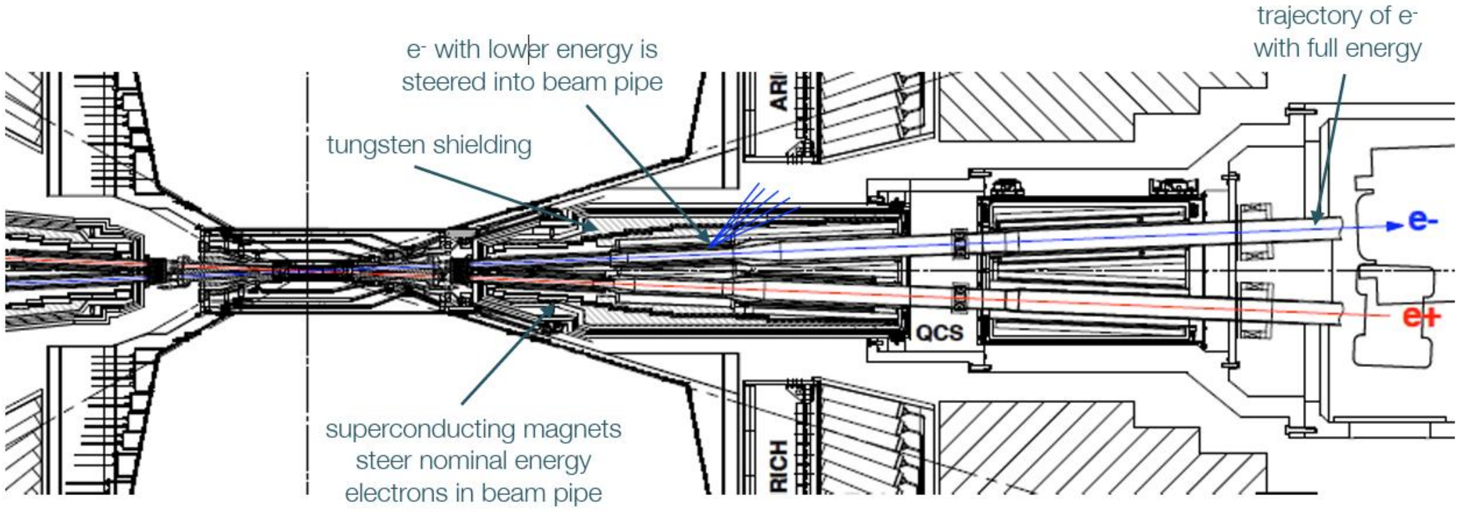
Haide I. – CHEP 2023



DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fibre
MPPC: multi-pixel photon counter

Beam background

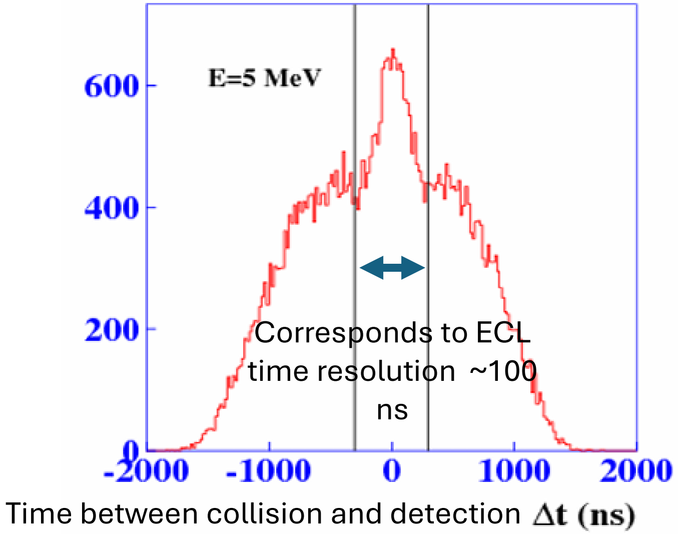
- Precision requires intensity: collimated beams in a ~50 nm region
- Beam backgrounds: calorimeter energy deposits from single beams interactions with residual gas in the vacuum or between electrons in bunch
- Mostly low-energy photons (few MeV), but degrade calorimeter performance



Exploit precise time information to identify and exclude off-time photons

Need

- **High time resolution**
- **Scalable to large area** ~30 m^2 calorimeter surface
- **Cost-effective**



The gaseous photomultiplier

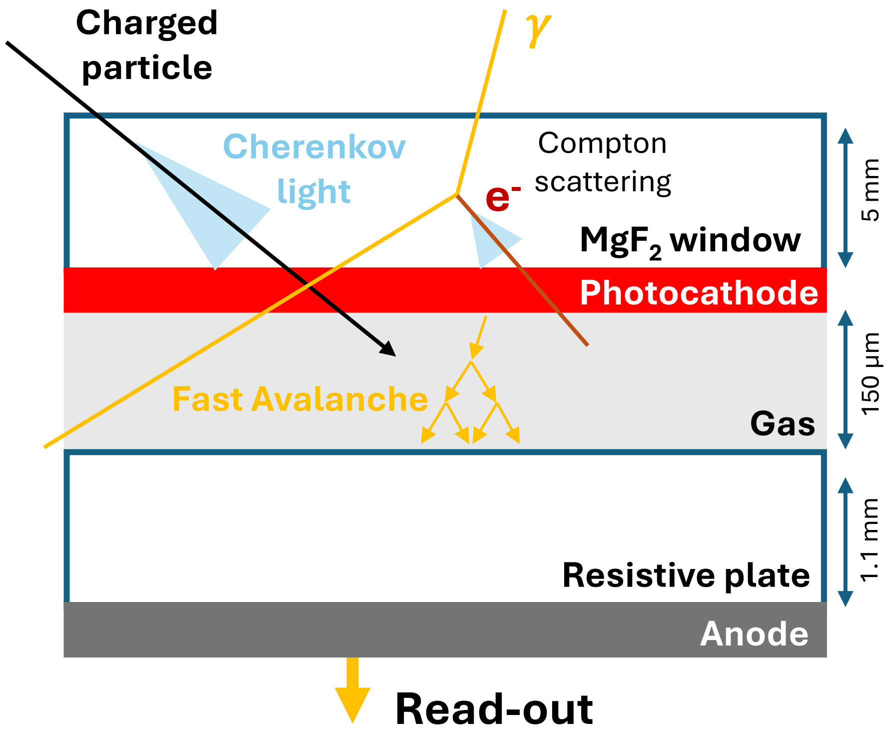
Architecture and target performance

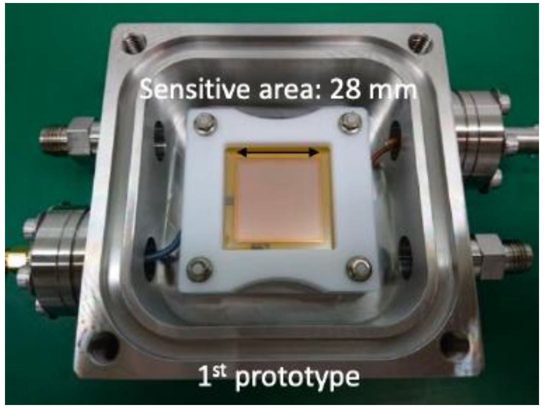
A gaseous photodetector that combines a photocathode with an RPC

- ➢ Photons converted into photoelectrons by photocathode
- ➢ 100 – 200 kV/cm electric field in the gap
- ➢ Resistive plate avoids breakdown discharges
- ➢ Fast avalanche, 10^6 multiplication in 90% R134a + 10% SF_6

- **Photon time with 90% efficiency and 20 ps resolution**
- Offers also use as Cherenkov detector
  → PID by high-resolution time of flight

When used as a Cherenkov detector, signals include both Cherenkov and ionization contributions

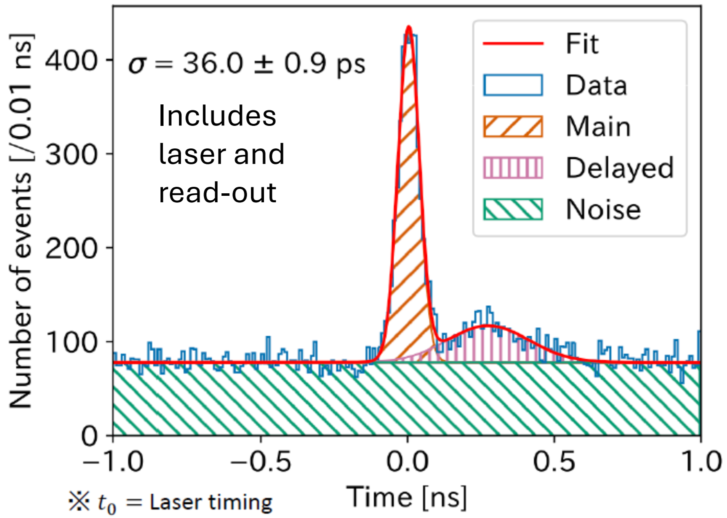




Previous results

K. Matsuoka, R. Okubo, and Y. Adachi: https://doi.org/10.1016/j.nima.2023.168378

- **2022: single-photon time resolution using laser**
  - High electric field 187 kV/cm, LaB_6 photocathode
  - **Time resolution** σ **= 25.0 ± 1.1ps**
- **2023: beam test**
  - Field lowered to 140 kV/cm, CsI photocathode
  - **Time resolution** σ = 62.3 ± 4.8 ps (large pulse height)

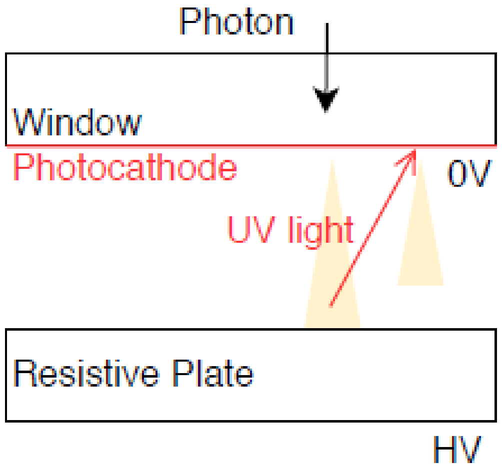


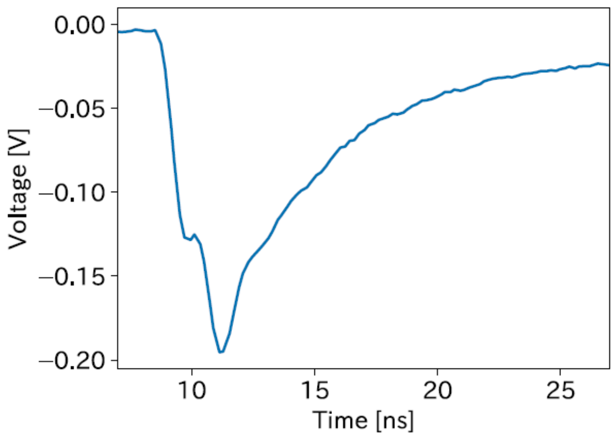
Limitations

- **Photon feedback:** UV photons emitted during gas excitation and de-excitation trigger secondary electron avalanches in the gas gap

In addition, need to mitigate

- **Ion feedback:** avalanche ions drift back, damaging the photocathode over time





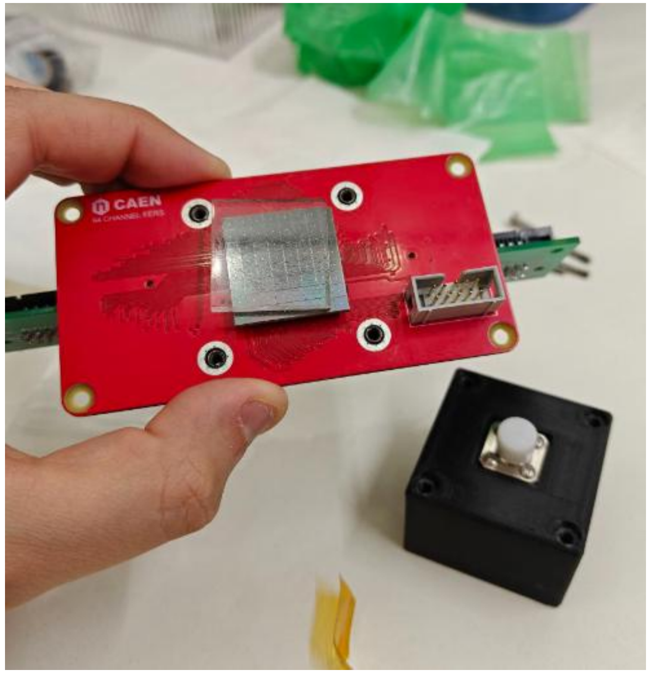
R.Okubo, PD24

This work

Objective is to address these issues through

1. **Improved beam test**
   - Digitizer upgrade to better discriminate secondary peaks due to photon feedback
   - Single-electron discrimination with multi-pixel photon counter for unbiased time-resolution determination

2. **Cosmic-ray test**
   - Explore ion-feedback mitigation using a lanthanum hexaboride photocathode

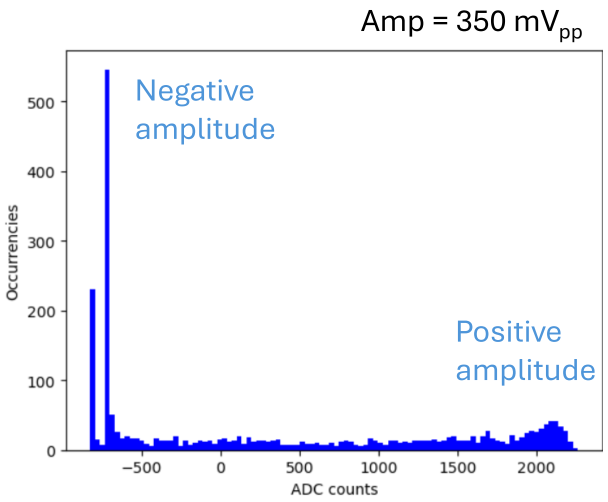


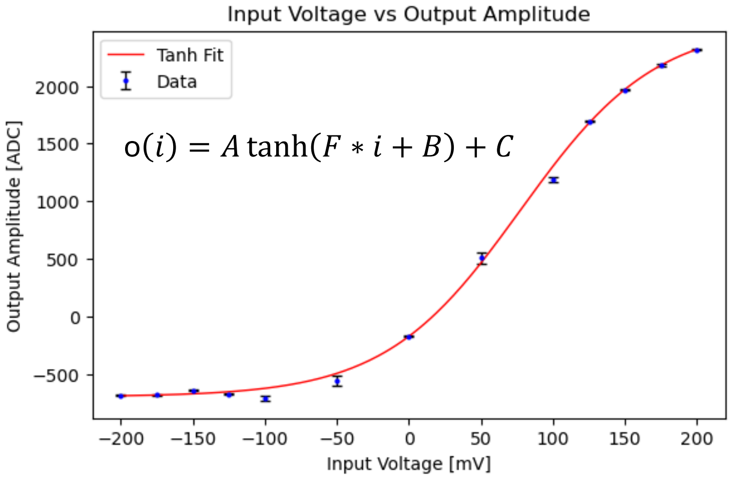
The high frequency digitizer

The NALU DSA-C10-8+

- 8 channels, 10 GSPS
- 128 sampling cells and 32640 storage cells organised in 510 *windows*
- ±100 mV dynamic range

Variance of GasPM signal amplitudes requires to extend calibration outside of dynamic range

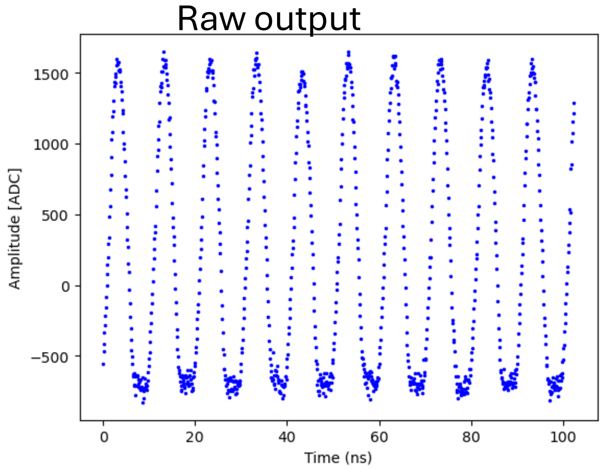


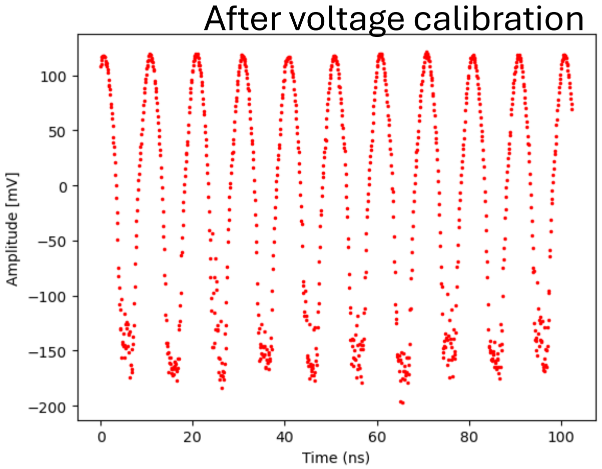


Voltage calibration

Ensure unbiased digitisation

- Use extrema of sinewave inputs since digitizer does not accept DC
- Peaks are reasonable, valleys highly distorted





Calibration is acceptable for our (positive only) signals

Time calibration and resolution

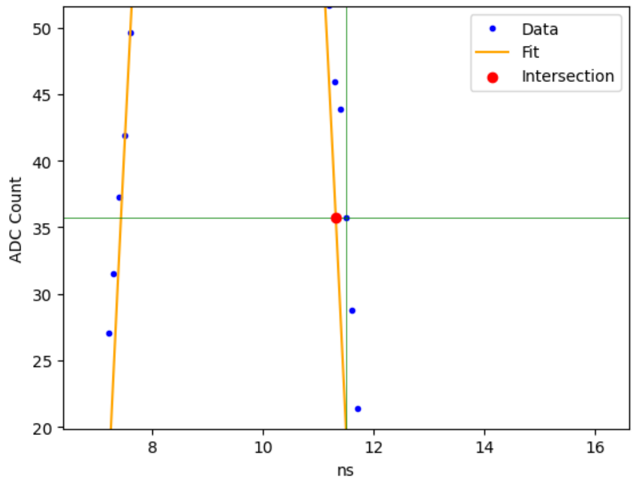
Determine sampling time of each cell from distribution of distances of data from sinewave fit

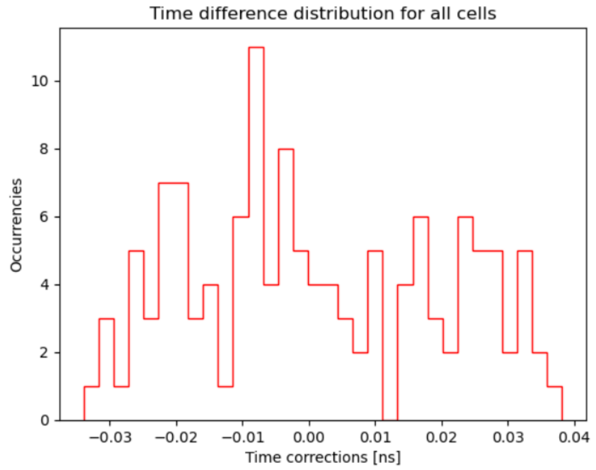
Then test results with assessment of time resolution

- Split a 1 ns time pulse into two channels
- Compare timing
- Uncalibrated: 6.99 ± 0.05 ps
- After voltage calibration: 7.01 ± 0.05 ps
- After voltage and time calibration: 9.49 ± 0.07 ps

Manufacturer calibration probably sufficient
Voltage calibration does not affect resolution - as expected
30% degradation after time-calibration, needs investigation

For our photon-feedback study, time calibration not critical

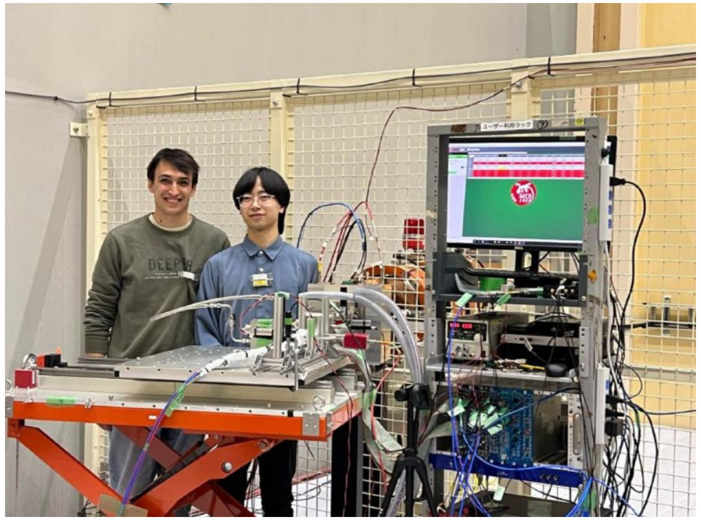




Beam test

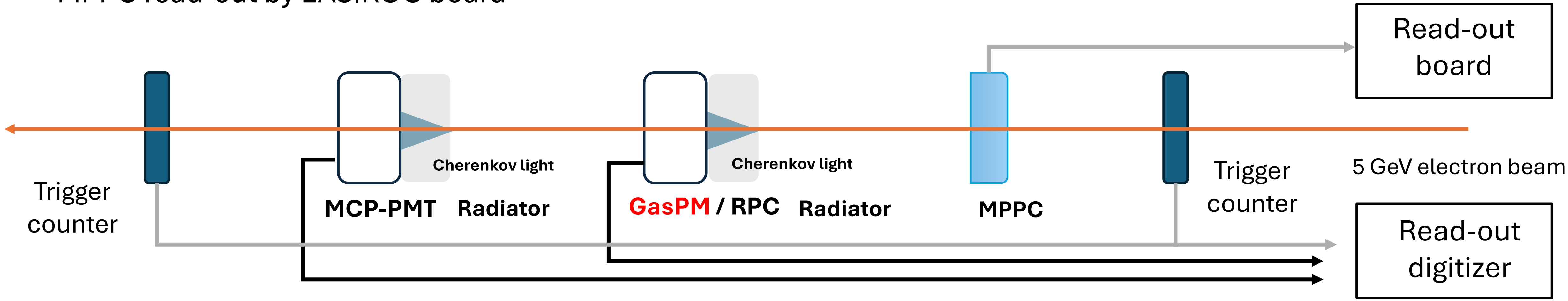
Beam test

Study photon feedback in view of improved time-resolution measurement



Setup

- PF-AR test beam line at KEK (Japan); 5 GeV electron beam at 23 Hz
- GasPM with Cherenkov radiator (gap voltage = 2.8 kV/150 μm = 187 kV/cm)
- MCP-PMT for beam timing measurement (35 ps time resolution)
- MPPC – multi-pixel photon-counter for single-electron discrimination
- RPC – resistive plate chamber, for comparison with GasPM
- Coincidence of plastic scintillators read by PMTs as trigger
- Read-out by DRS4 (5 GSPS) / NALU digitizer (10 GSPS)
- MPPC read-out by EASIROC board



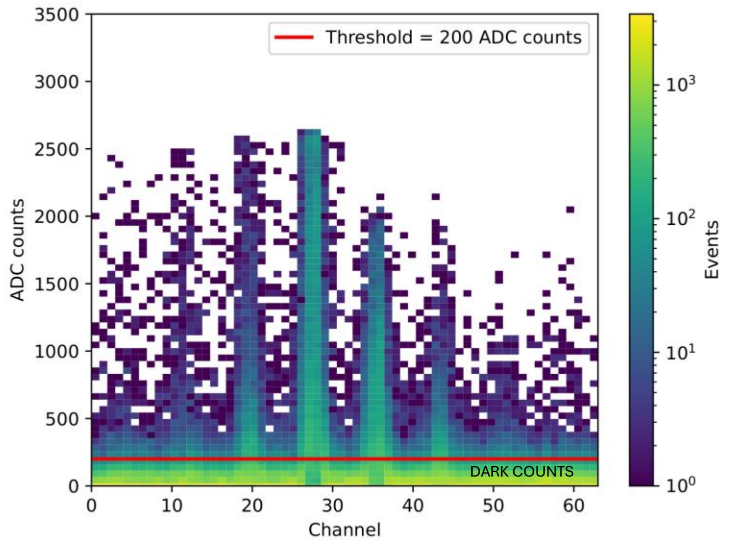
Single-electron event selection

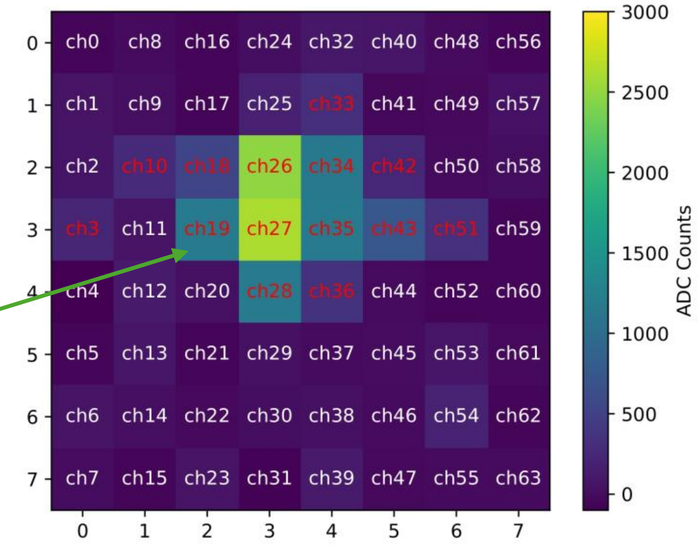
Reject events with multiple electrons from upstream δ-rays

Use multi-pixel photon-counter (silicon photomultiplier)

- 64-channel MPPC arranged in an 8×8 matrix (3×3 mm per channel)
- 3-mm-thick acrylic plate radiator
- 200 ADC threshold to distinguish photon hits from dark counts
- Cherenkov ring diameter around 3.75 mm

Need single-electron discrimination criterion

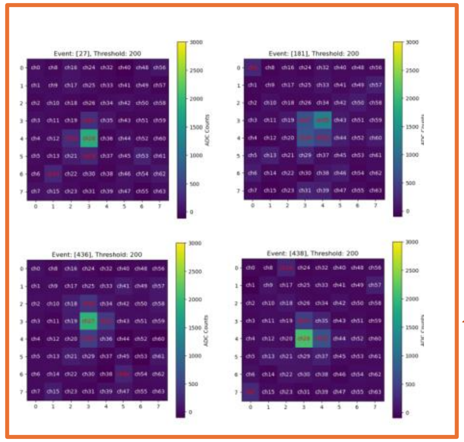


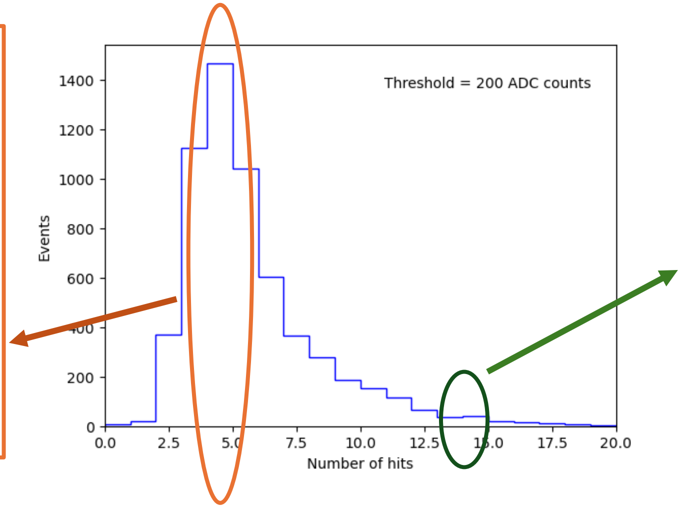


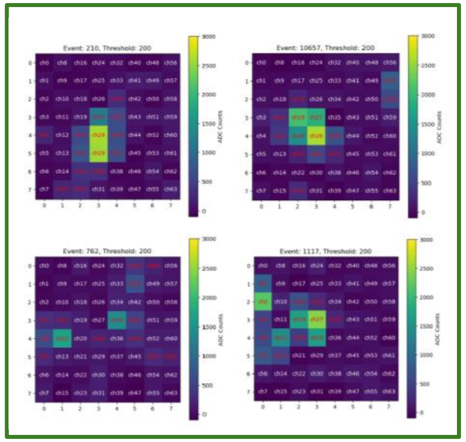
Red labels indicate a photon hit (ADC over threshold)

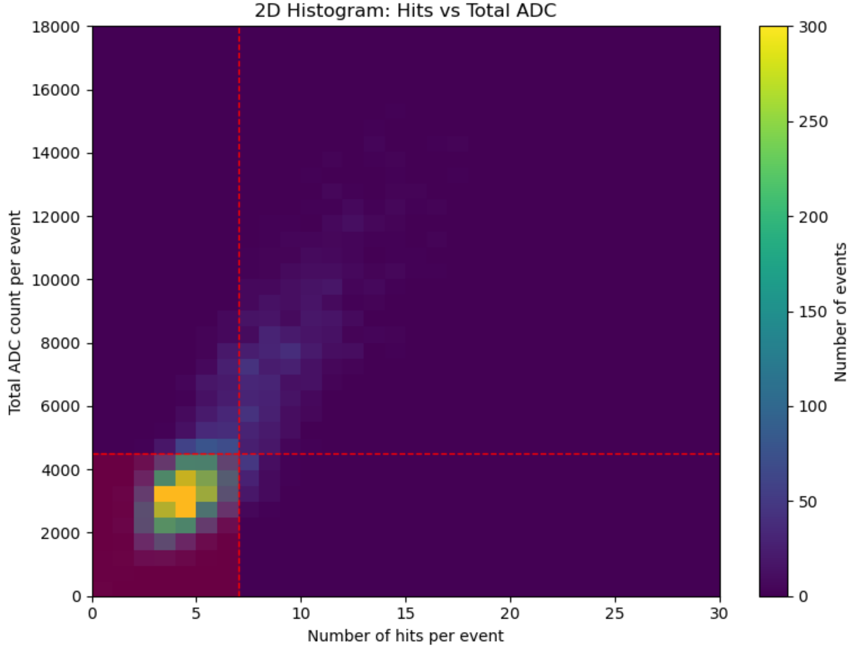
Single-electron event selection

- Visual discrimination of Cherenkov rings not straightforward
- Need higher-dimensions
- Total collected ADC counts vs number of hits









73% of events selected as single-electron

Photon feedback study

Identify **photon feedback events**

- Large variety of signals with many shapes, amplitudes, and charges
- Many processes ongoing:
  - Events with/without photon feedback
  - Events single/multiple electron (no MPPC)
  - Events different photon yield
- Hard to find direct indicator of photon feedback

Focus on rising edge

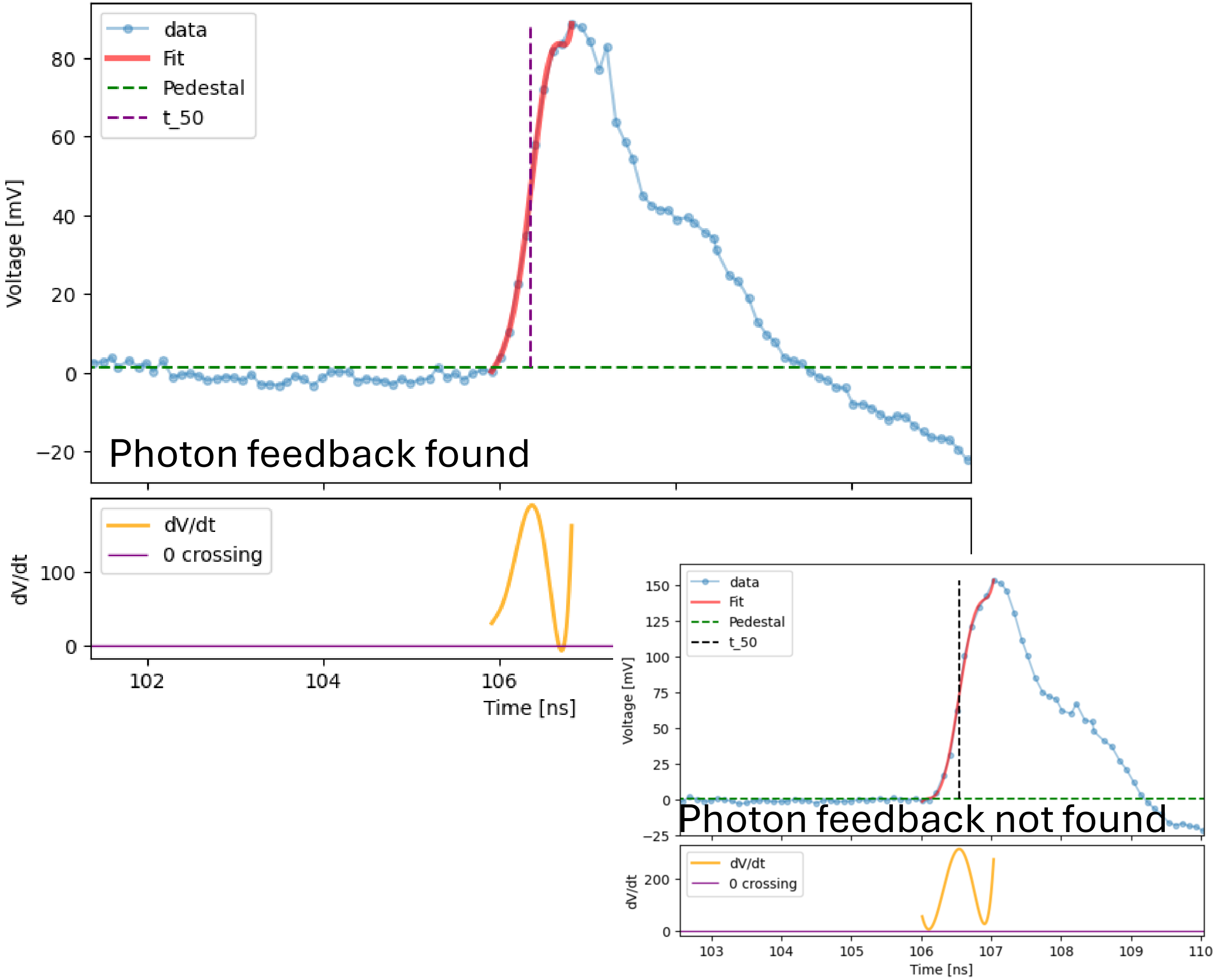
Photon feedback selection

- Fit rising edge with 8th-order polynomial
- Tag as **photon feedback** events with a **stationary-point (dV/dt = 0)** before peak

Finds photon feedback in **35.6%** of events

However, events with nearly overlapping peaks not properly identified

Need better classification



Photon feedback preliminary results

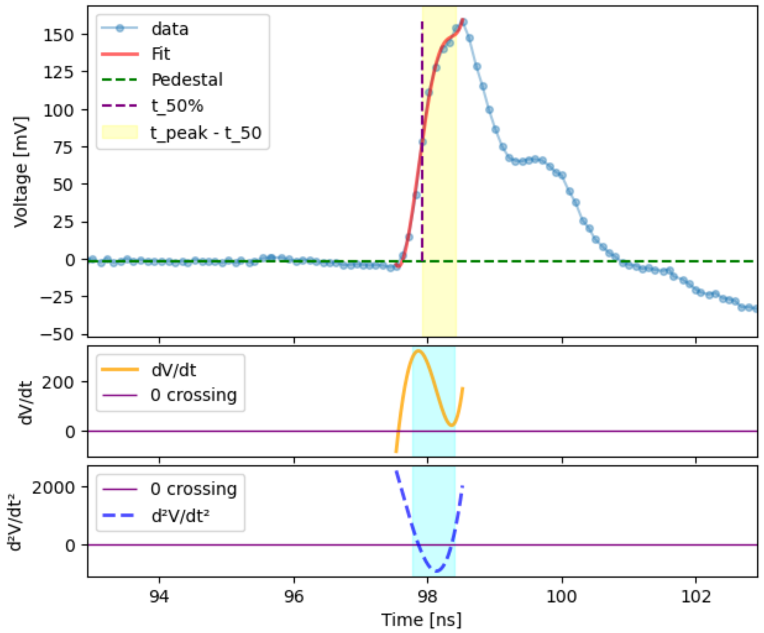
- Select events with two inflection points **($d^2V/dt^2 = 0$)**

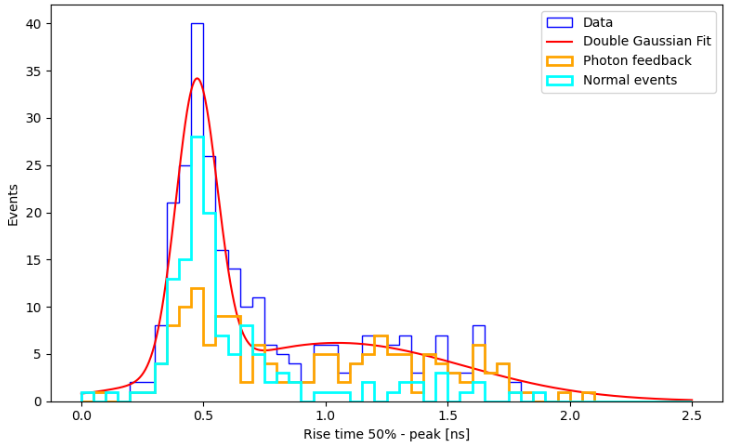
Photon feedback identified in **(53.2 ± 2.3)%** of events

- Check classification using quasi-independent **50%-to-100%** rise time
- Validation is only qualitative

Double-inflection point criterion seems effective

Will be used in future studies.

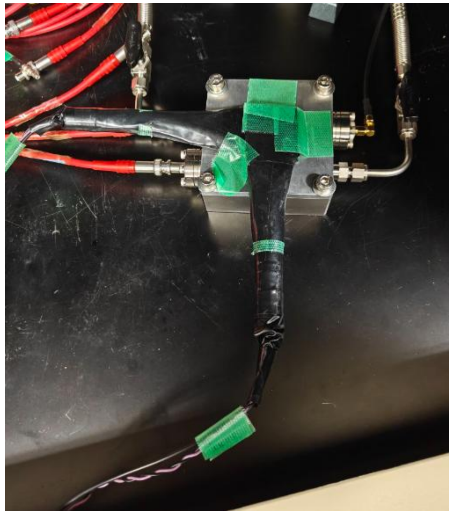




LaB_6 photocathode characterisation

LaB_6 quantum efficiency

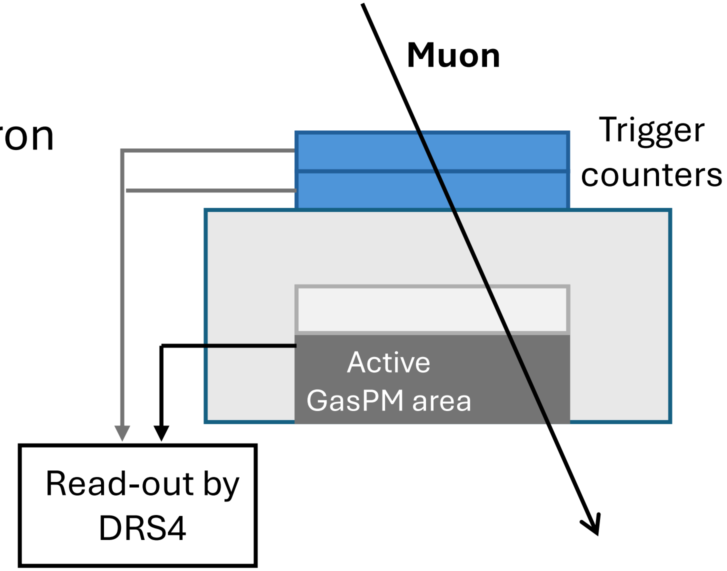
- CsI sensitive to avalanche ions drifting back and degrading photocathode over time **(ion feedback)**
- Revert to LaB_6 - more resistant to ion feedback and exposure to air
- Check if quantum efficiency is sufficient to detect Cherenkov photons for a future beam test aimed at assessing ion feedback resistance



Cosmic-ray test

- As a Cherenkov detector, GasPM produces both Cherenkov and ionization signals
- Comparison of GasPM and RPC hit rates separates the two sources

Quantum efficiency: probability that an incoming photon generates a photoelectron



Cosmic ray test

- Quartz radiator
- Gap E field = 2.64 kV / 150 μm = 176 kV/cm

Frequent streamer discharges observed
Photocathode damaged
Sudden drop in efficiency after 1 week

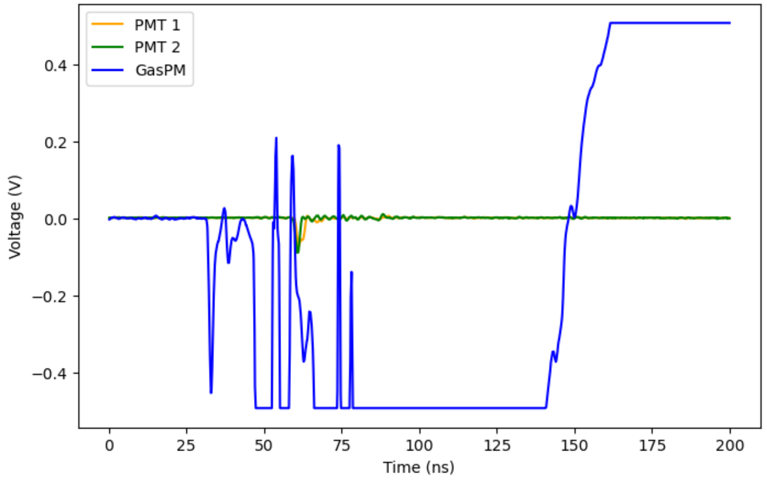
Streamer: self-sustained discharge across the gap, triggered when an avalanche grows too large and distorts the local electric field

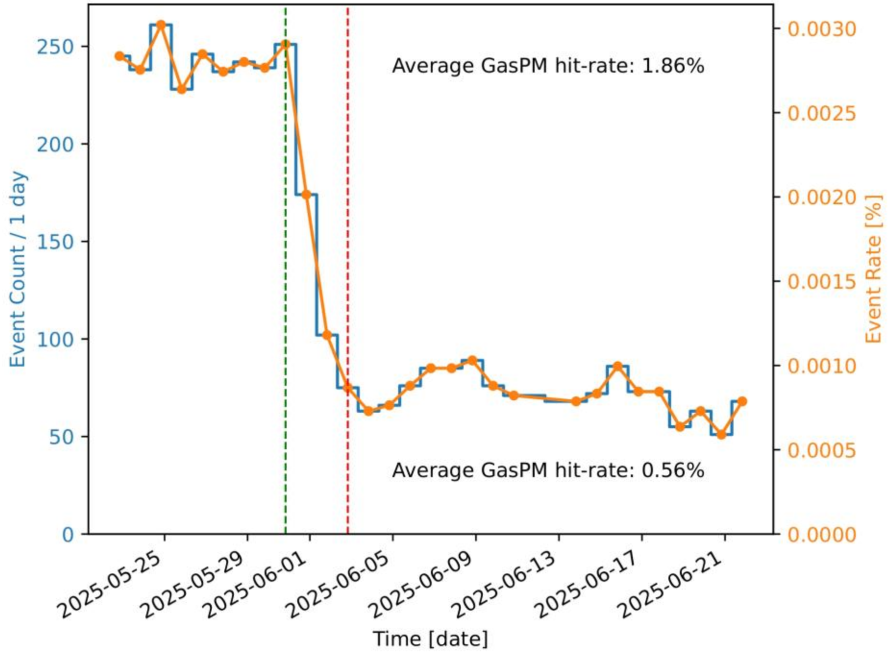
Mitigation

- Replaced photocathode with standard RPC
- Adjusted to 2.5 kV / 200 μm = 125 kV/cm and 80% R134a, 20% SF_6
- Test with a new LaB_6 photocathode

	RPC	GasPM
Hit-rate	7.66 ± 0.18%	7.19 ± 0.49%

Similar hit-rates indicate **ionization-only signals**
LED test now ongoing to assess pure hit-rate without ionization signals





Summary

This thesis contributes to the development of the GasPM, a novel gaseous photodetector aimed at addressing beam backgrounds in the Belle II calorimeter.

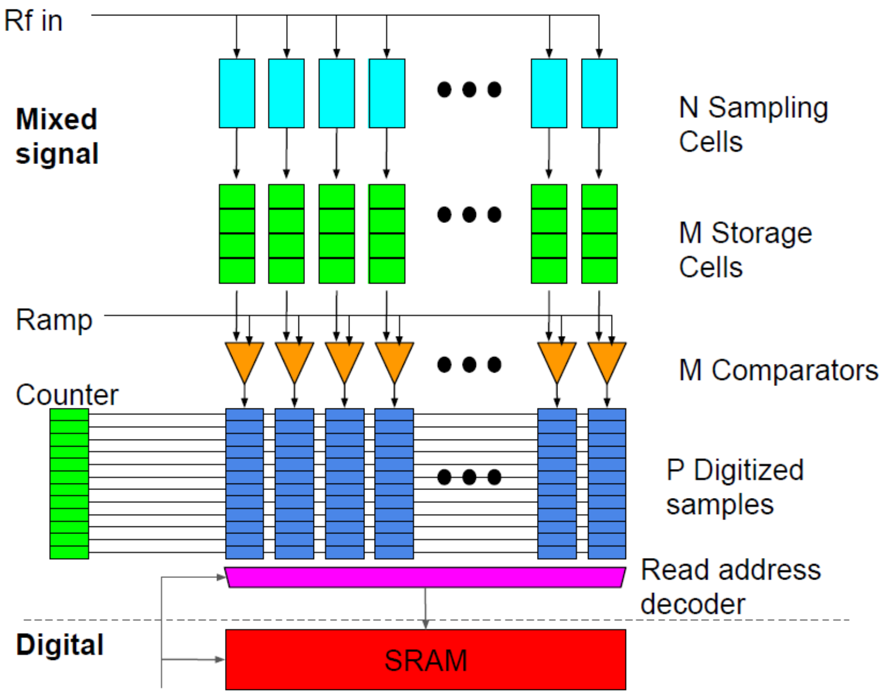
- I designed, prepared, and performed an improved beam test
- I achieved discrimination between single- and multiple-electron events
- I developed an algorithm for the efficient identification of photon feedback
- I performed a preliminary exploration of the LaB_6 photocathode quantum efficiency for usage in a future beam test

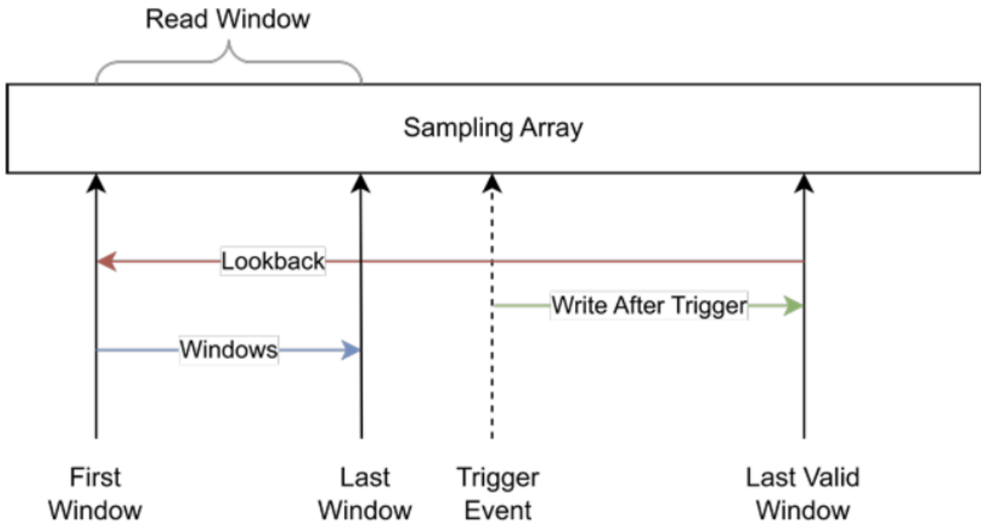
My work advances the development of the GasPM and informs future progress.

These results are being prepared for showing at the upcoming International Workshop on New Photon-Detectors (PD2025) in Bologna this coming December.

Backup

Digitiser architecture

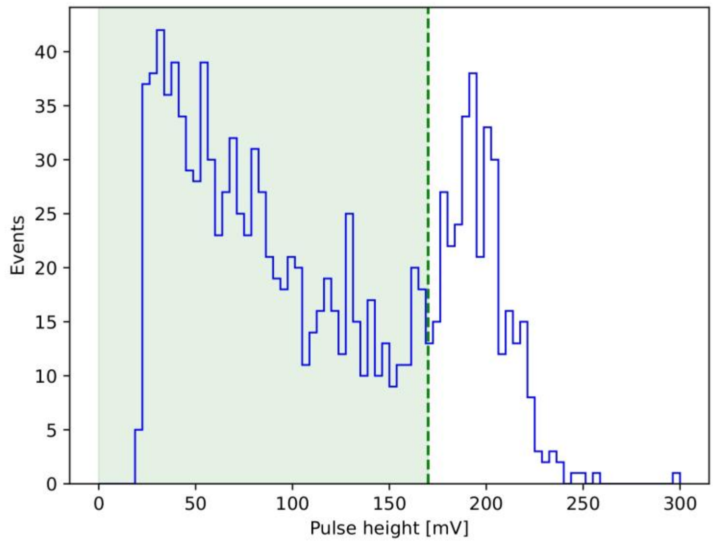


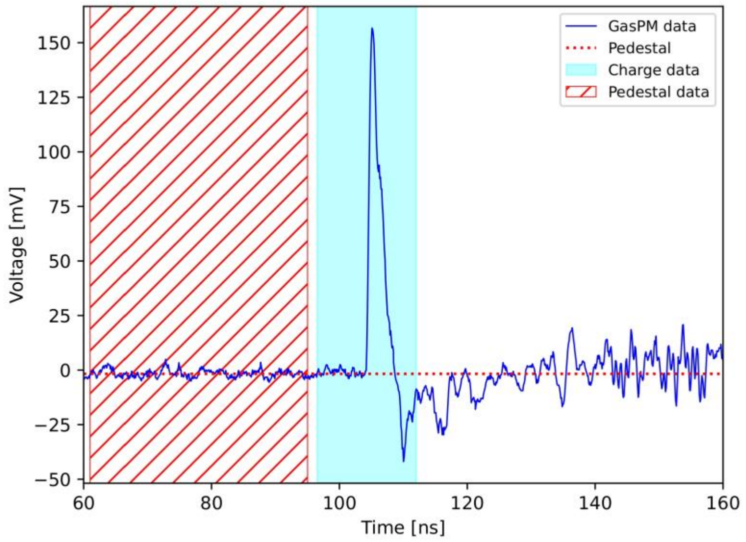


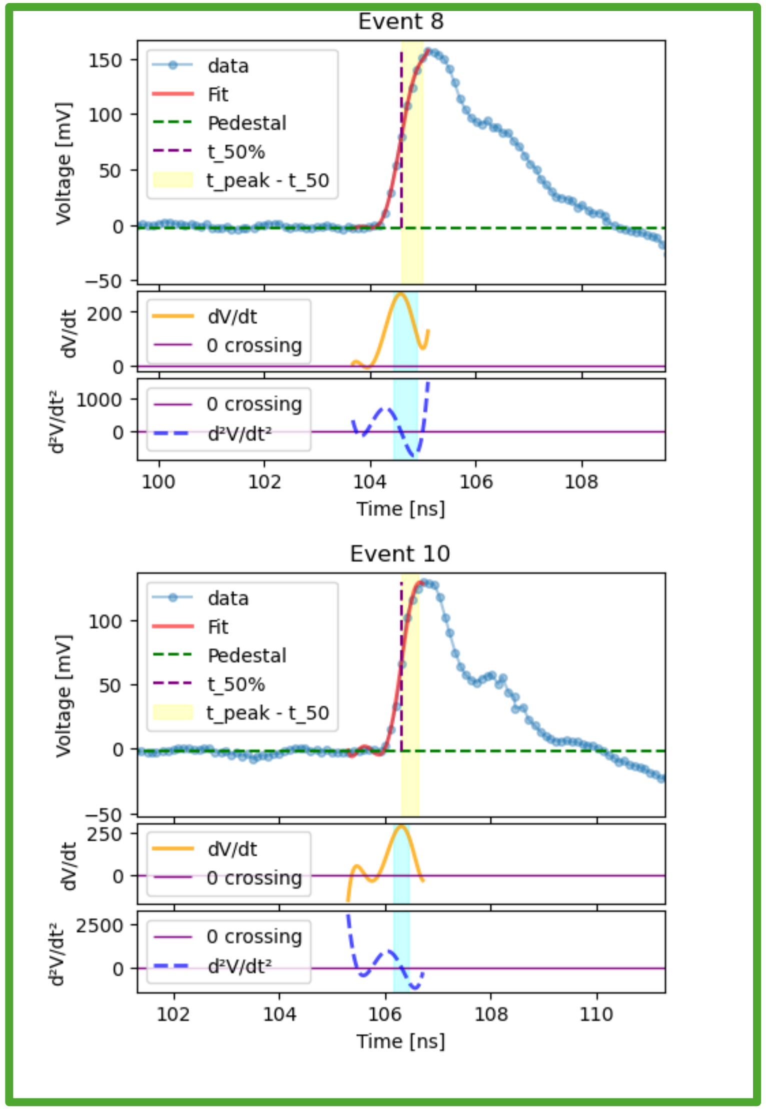
Signal shape survey

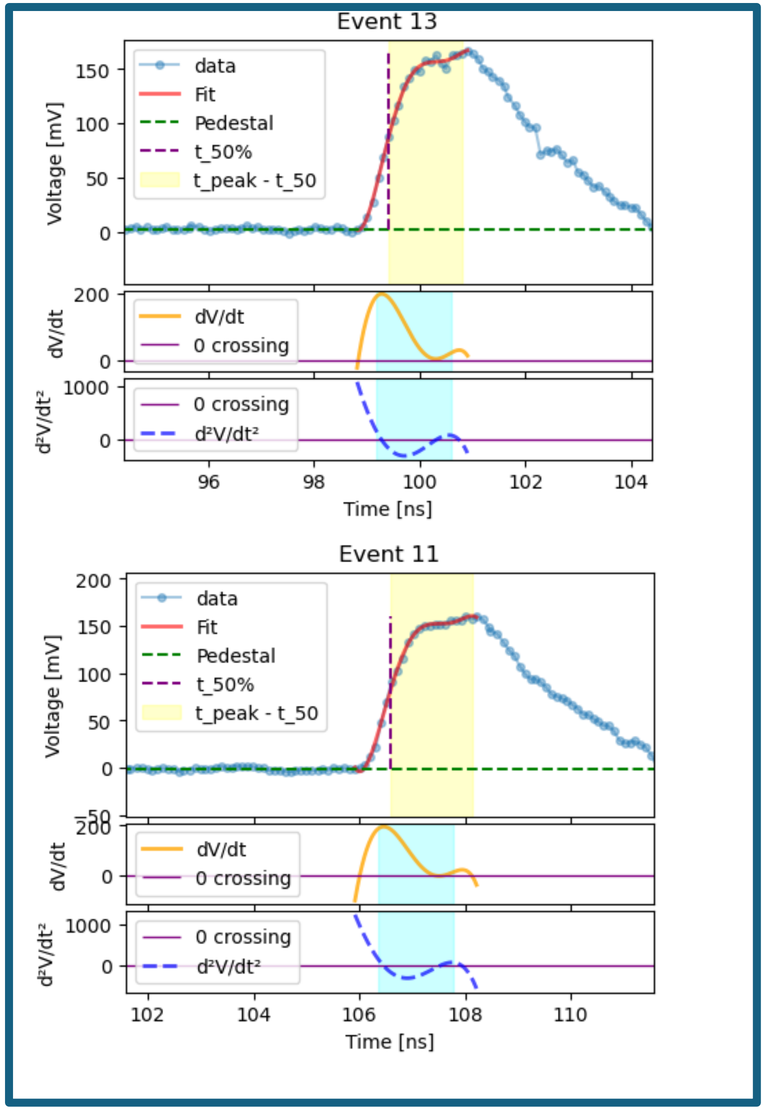
- Pulse heights span broad range
  - Secondary peak likely due to digitiser saturation (working out of range)
  - Only use < 170 mV pulse height signals
- Typical GasPM signal
  - Compute pedestal, height and charge

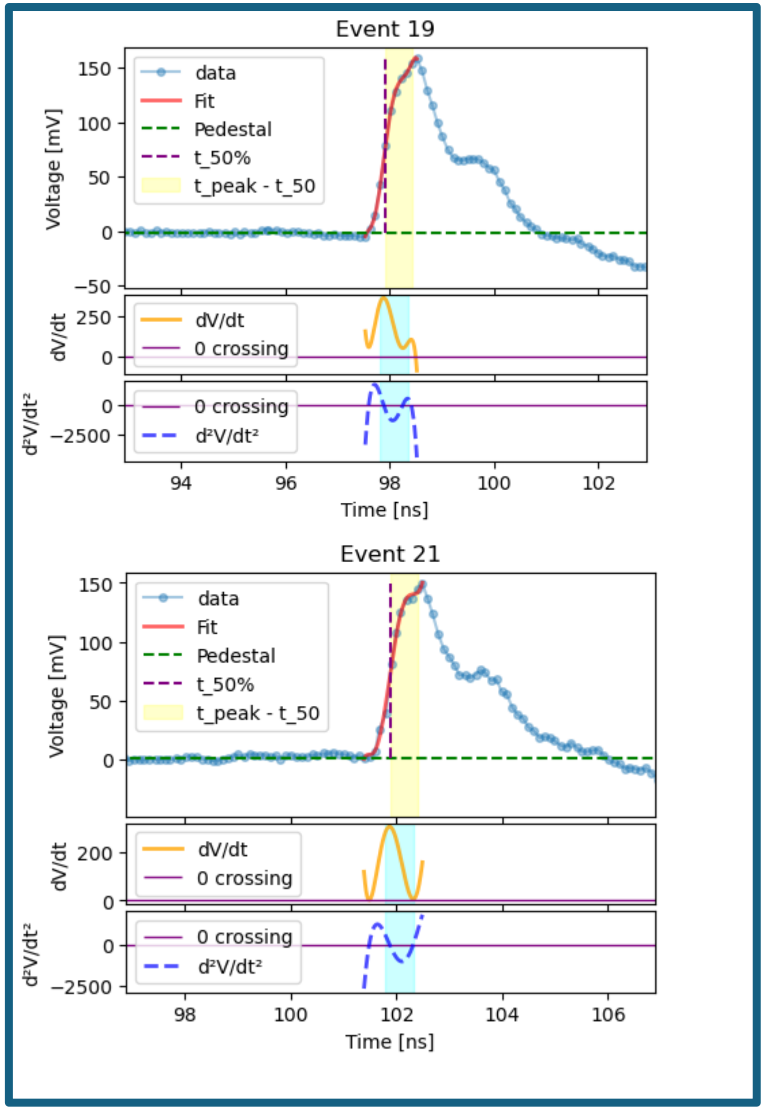
Because of large variety in these features, no correlation with photon feedback found











Normal events

Photon feedback

Photocathode damage