Development of a large acceptance Cherenkov time-of-flight detector

with picosecond time resolution for the backward region of Belle II

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Physics motivation

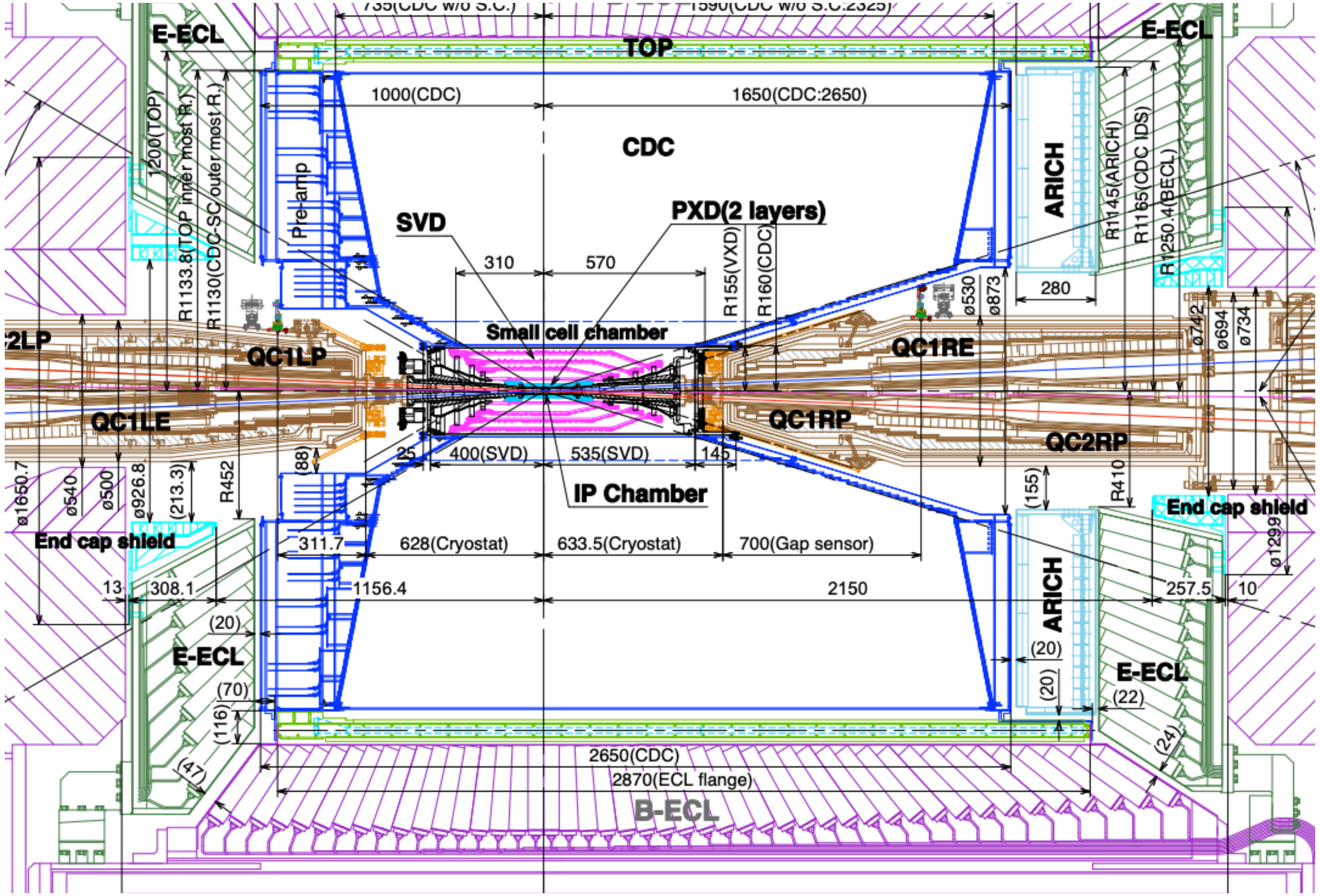
Why a dedicated TOF detector is needed in the Belle II backward region?

Primary motivation → **Background rejection**

- Precise timing → rejection of beam-induced γ-ray background from SuperKEKB

Secondary motivation if the beam asymmetry is reduced→ **PID**

- If β is reduced to we expect more particles coming to backward region
- Fills the PID gap in the backward region for π/K separation in hadronic B decays

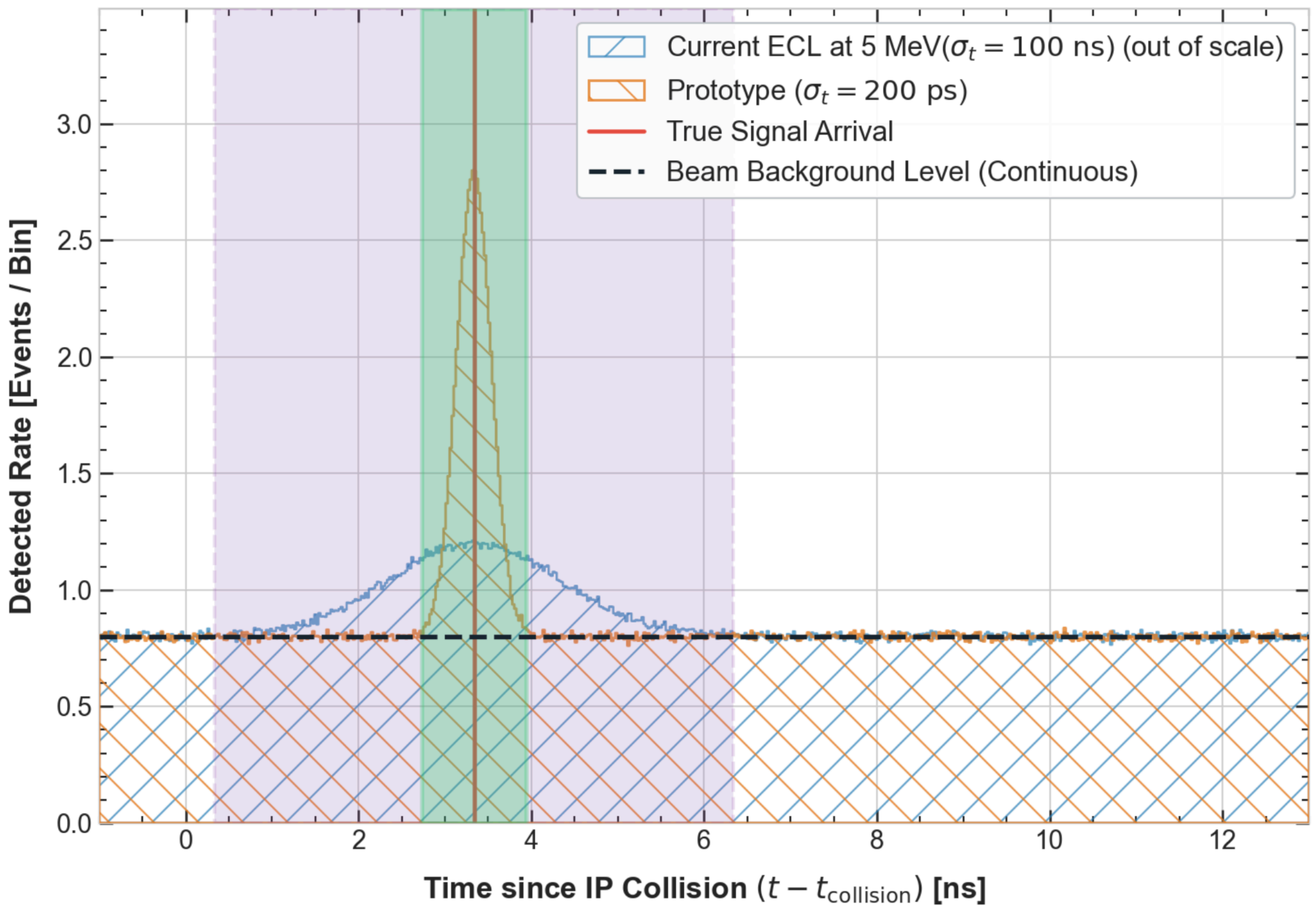


Target resolution for vetoing accelerator background

Determining σ_t required for background veto.

Low energy γ from accelerator O(MeV) have high probability of Compton scattering and e^+e^- pair production → these secondary electrons are detected with assumed 100% efficiency.

- Beam background is uniform in time while physics γ have specific timing due to collision frequency
- A narrow timing gate (3σ) around the signal cuts out-of-time background while keeping 99% of physics γ
- Integrated continuous background scales linearly with gate width (BG $\propto \Delta t_{\text{gate}} \propto \sigma_t$).



$t_{collision}$ = 0 is the time of beam collision obtained from RF signal

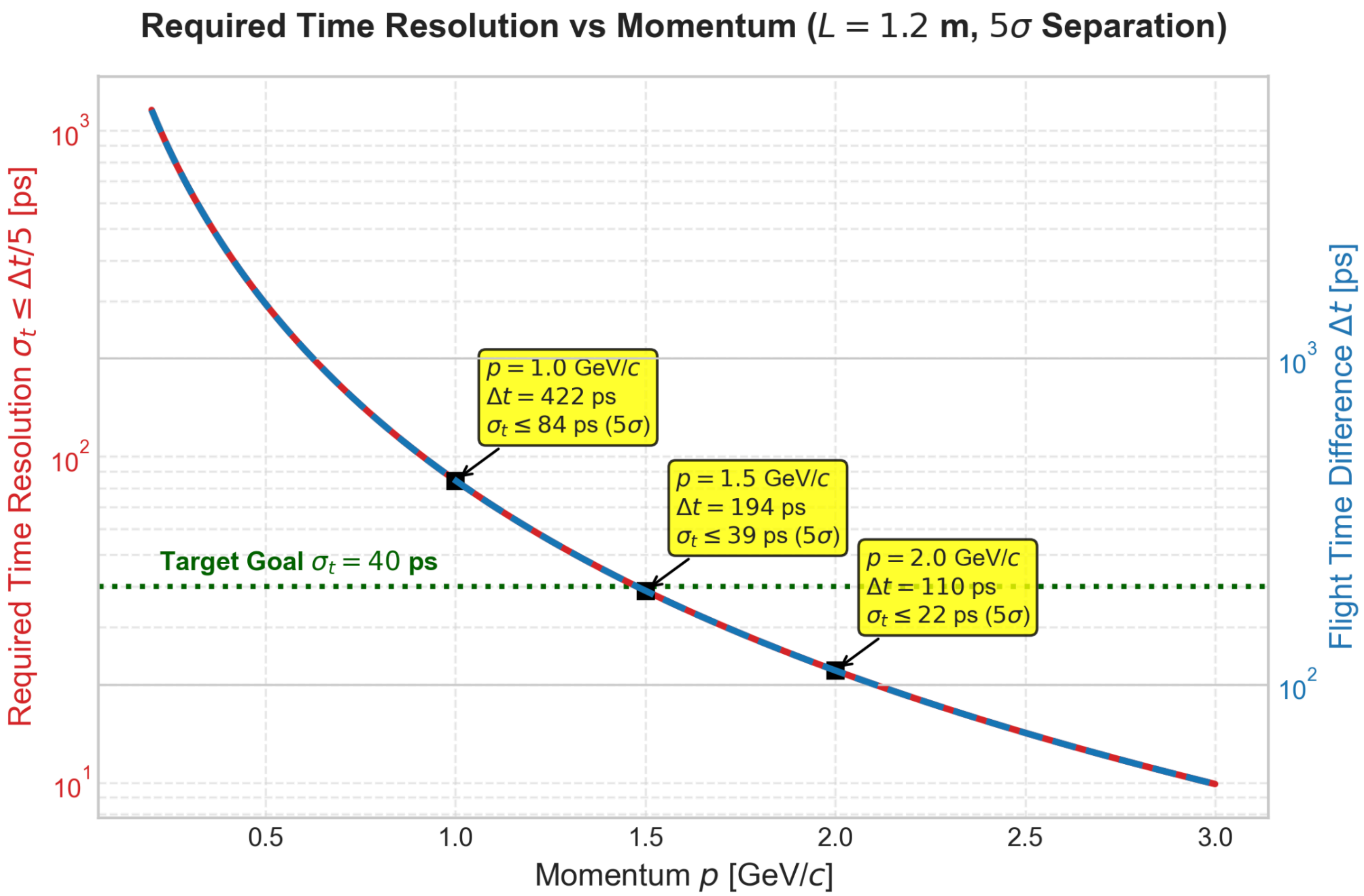
$\sigma_t \leq$ **200 ps** →**500x** background suppression (99.8% cut) at identical signal efficiency

PID target time resolution

Determining σ_t required for π/K identification.

PID via mass-dependent time-of-flight difference:

- $t = \frac{L}{c\beta}$ with $\beta = \frac{p}{\sqrt{p^2 + m^2c^2}}$
- $\Delta t = t_K - t_\pi = \frac{L}{c}\left(\frac{1}{\beta_K} - \frac{1}{\beta_\pi}\right)$
- Detector distance ~1 m from IP → $L \approx 1$ m (backward angle + magnetic field)
- Requiring $N_\sigma = \frac{\Delta t}{\sigma_t} \geq 5$ for PID

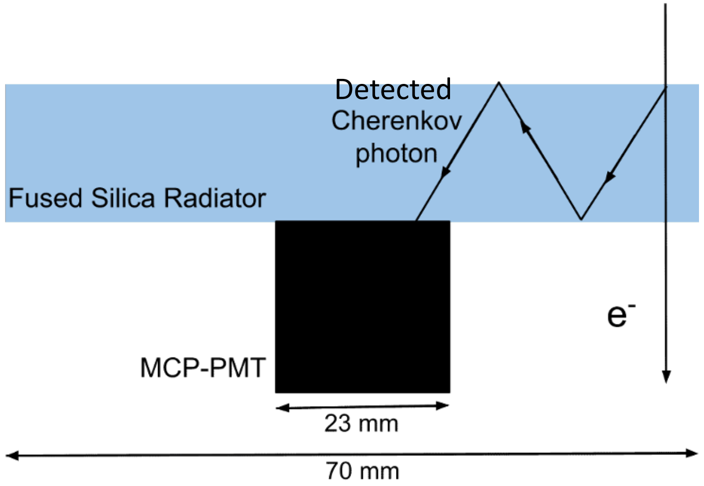


$\sigma_t \leq$ **40 ps → 5σ π/K up to 1.5 GeV/c**, sufficient also for background veto (> 99.9% cut)

Detector concept

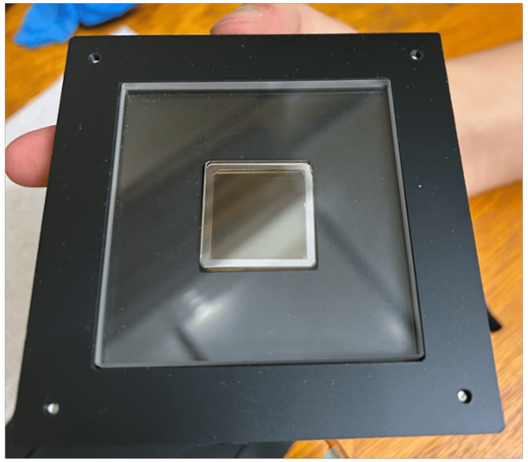
Extending acceptance by coupling an oversized radiator with a compact sensor

- Fused silica slab radiator + photodetector via index-matched optical grease
- Charged particles → Cherenkov photons → total internal reflection → photodetector
- Large radiator = lightguide → extends sensitive area



Photodetector used is MCP-PMT

- Multi-alkali photocathode + two stacked microchannel plates (inclined micro-pores)
- Gain of $10^5 - 10^6$
- Transit time spread of the order 30 – 40 ps



Recycle and economic advantage

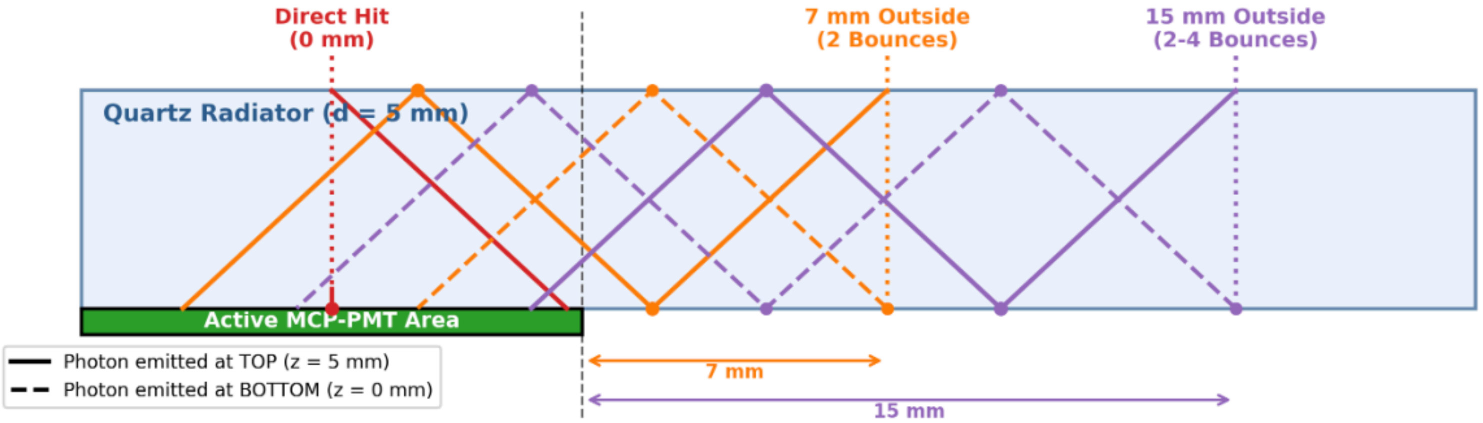
- MCP-PMT recycled from TOP upgrade → limited hardware cost
- 1 sensor + radiator ≈ 9 MCP-PMT area coverage
- With 500 sensors and 85 x 85 mm^2 radiator → full coverage backward endcap

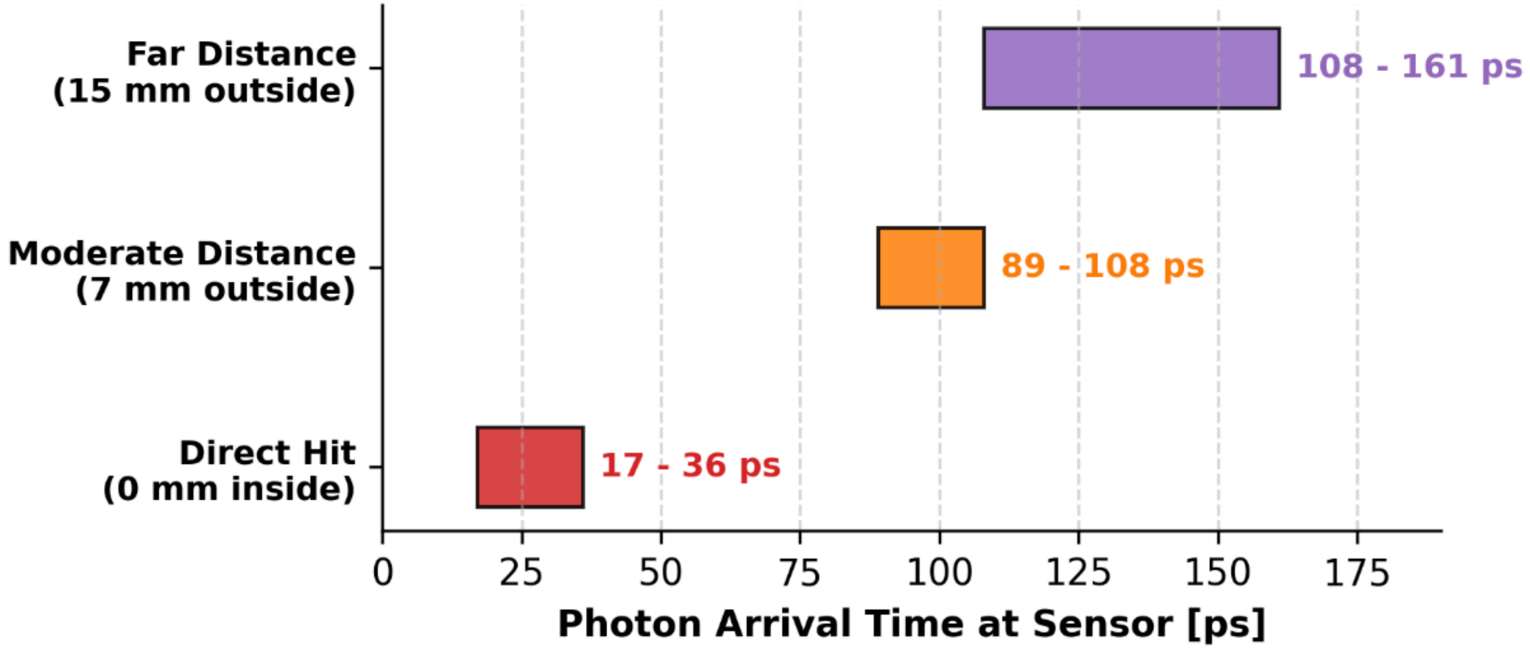
Structure of the photon-arrival timing

Does the impact position significantly affect the temporal resolution or does it just produce a temporal delay?

Assumptions to why arrival time depends on impact position:

- Photons propagate via total internal reflection inside the radiator.
- Sensor glued to the bottom face.
- To hit the sensor: **even number of reflections** (0, 2, 4) → odd number has the photon move away
- Intrinsic time dispersion ≈ arrival time difference between photons emitted at the top/bottom of the radiator.

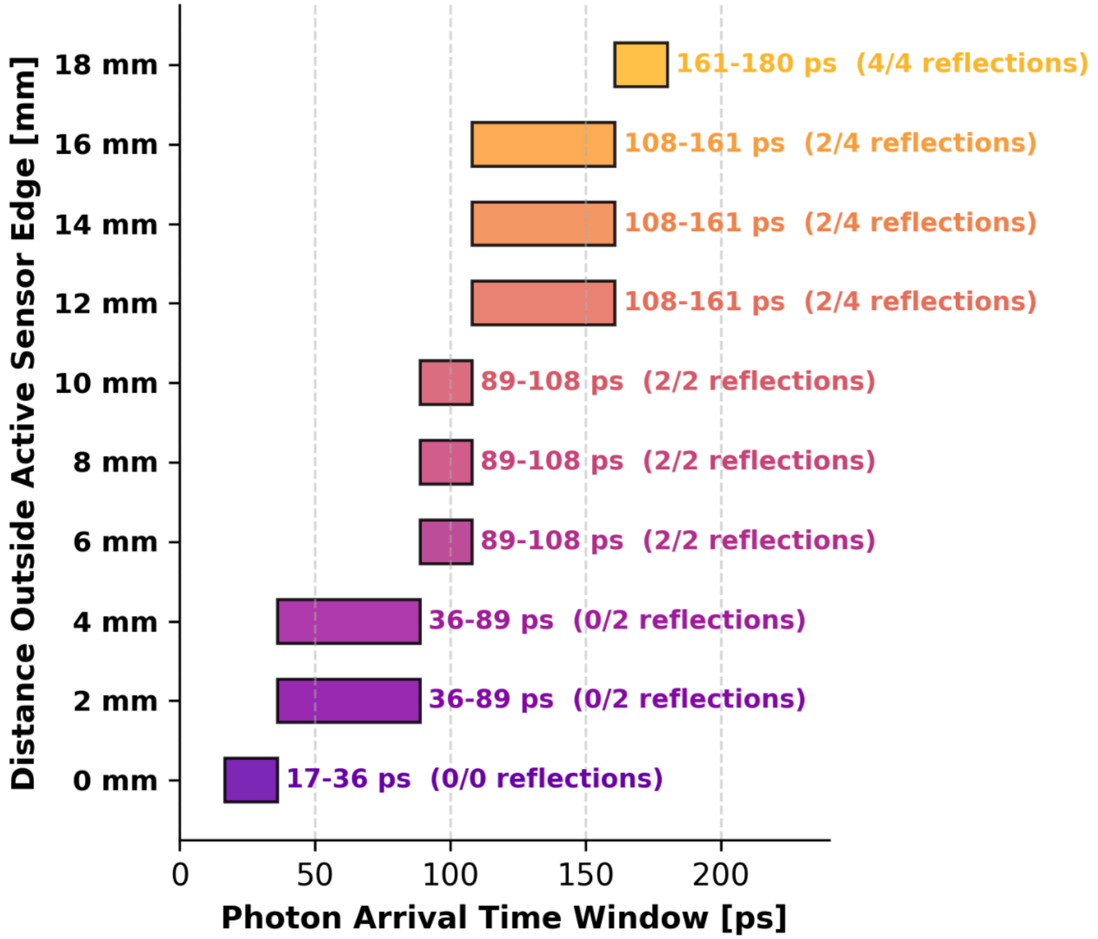




Structure of the photon-arrival timing

Looking at the effect of local spread, acceptance drop, and chromatic contribution

- Near reflection transitions boundaries → local peaks on single-event dispersion
- Increasing distance → less subtended azimuthal angle → fewer detected photons → worse time resolution ($\sigma_t \propto \sqrt{N_{\text{ph}}}^{-1}$)
- Chromatic dispersion ($n(\lambda)$): net contribution is < 0.4 ps for the optical range → negligible



Distance affects timing in three ways, it shifts global propagation delays while reducing detected photon statistics, and also peaks at some positions near reflection boundaries.

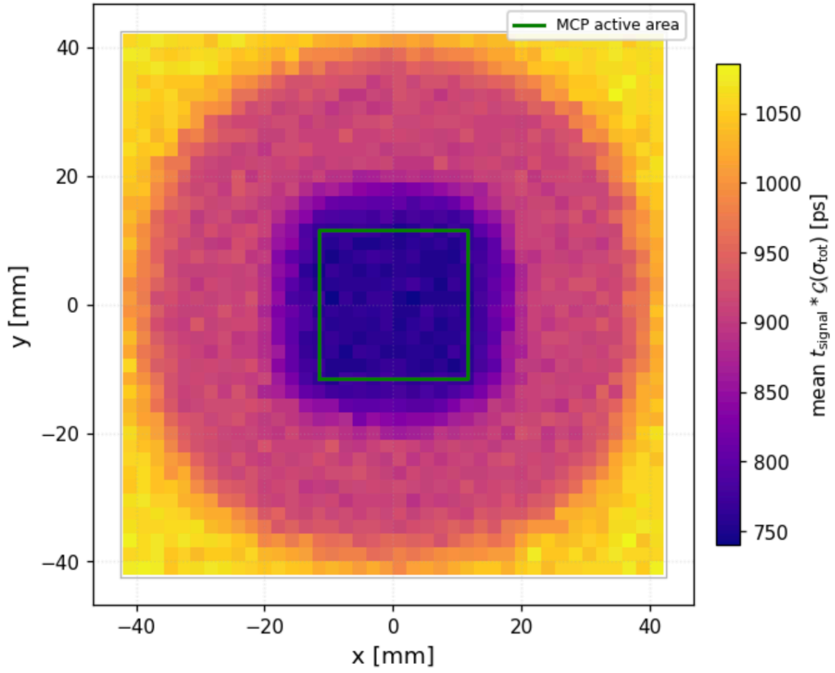
Possible effective usage

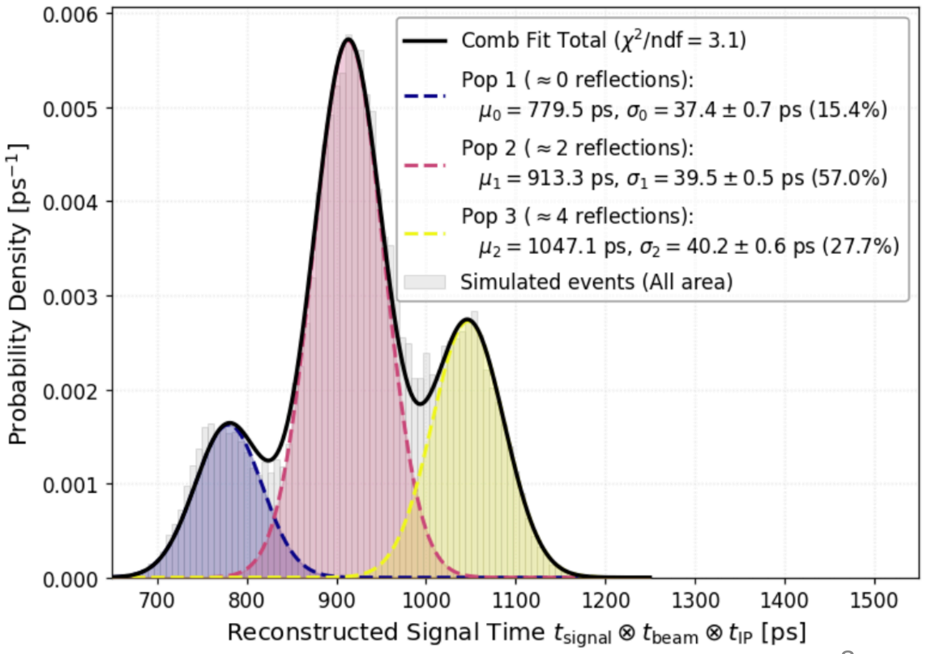
A possible effective usage of the detector as PID coupled with the track detector of Belle II

Plot examples using a 10 mm thick fused silica radiator of 85 x 85 mm^2 area

Idea of usage

- Detector surface divided into regions corresponding to a certain number of reflections of the detected photons
- Information on the position given by tracking detector ($\sim$1 mm error) $\rightarrow$ knowledge what band the particle crossed $\rightarrow$ knowledge on the population of signal time
- Time resolution is only that of the specific band





The time resolution of each band meets our goal for PID, which makes perspectives of usage of this detector promising

Prototype validation requirements

Experimental validation and performance characterization of the detector prototype

1. Time resolution mapping across impact positions
   Measure the intrinsic time resolution (σ_t) aa function of impact positions on the quartz radiator.
   Assess the impact of optical propagation delays and photon statistics on time precision as distance from the sensor increases.

2. Position-dependent detection efficiency
   Quantify signal loss and N_{pe} detected due to geometric acceptance and light attenuation during internal reflections.

To address these key objectives and evaluate the prototype under realistic conditions, we carried out a test beam.

Single photon laser test

To measure the number of photoelectrons detected during test beam it's required a gain measurement

Experimental setup

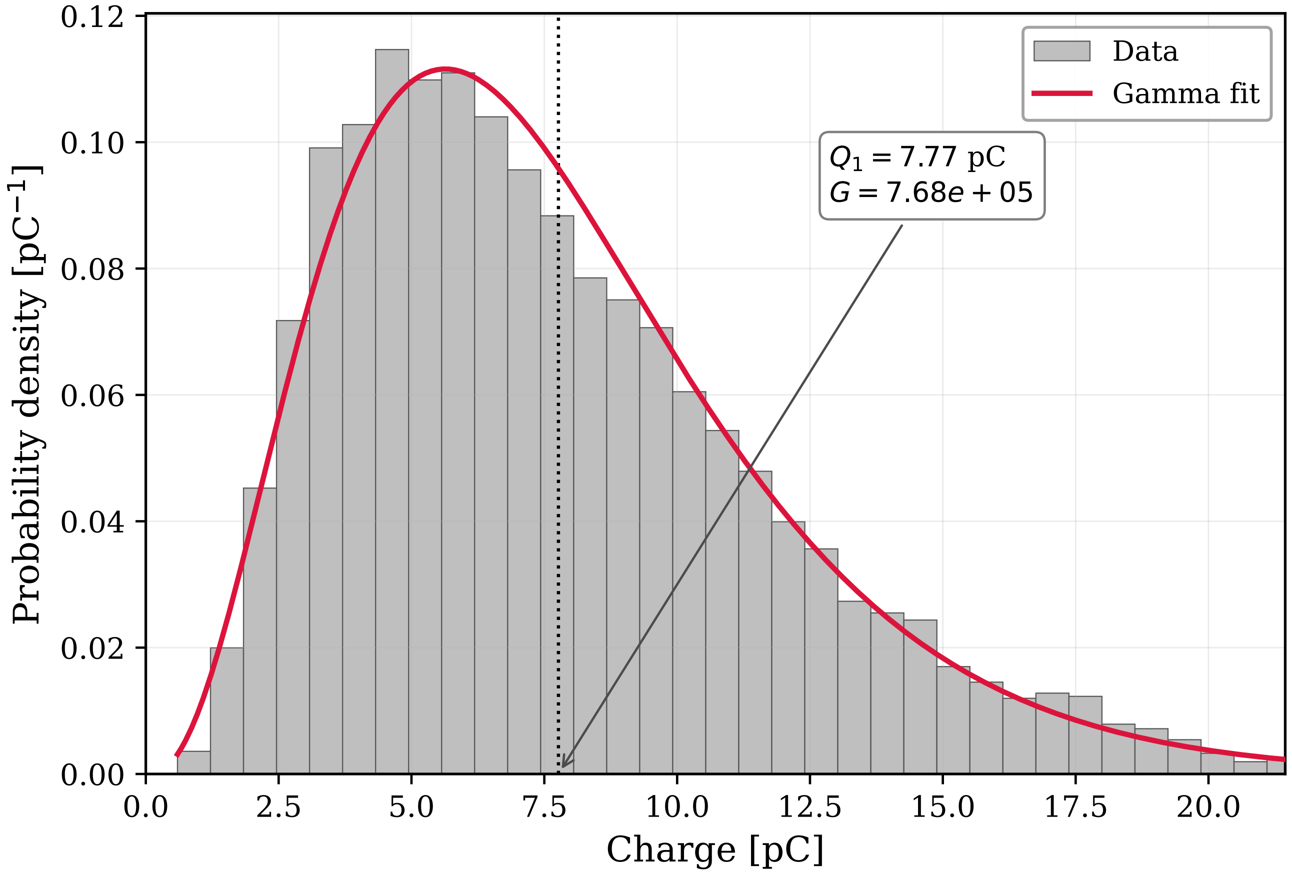
- Low intensity laser, further attenuated, at $\sim$1 m from sensors yielding <1 incident photon.
- External temporal reference by the laser synchronism $\rightarrow$ cleanly isolate single photoelectron events.

Gain measurement

- Single photoelectron charge spectrum fitted with a Gamma distribution (SER Polya model).
- From fitted average charge Q_1 the extracted gain

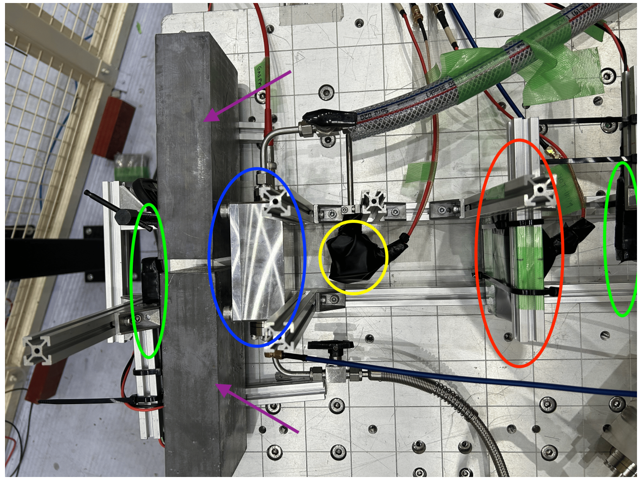
$$G = \frac{Q_1}{A \cdot e} = (7.68 \pm 0.03) \times 10^5$$

(A is the electronic amplification)



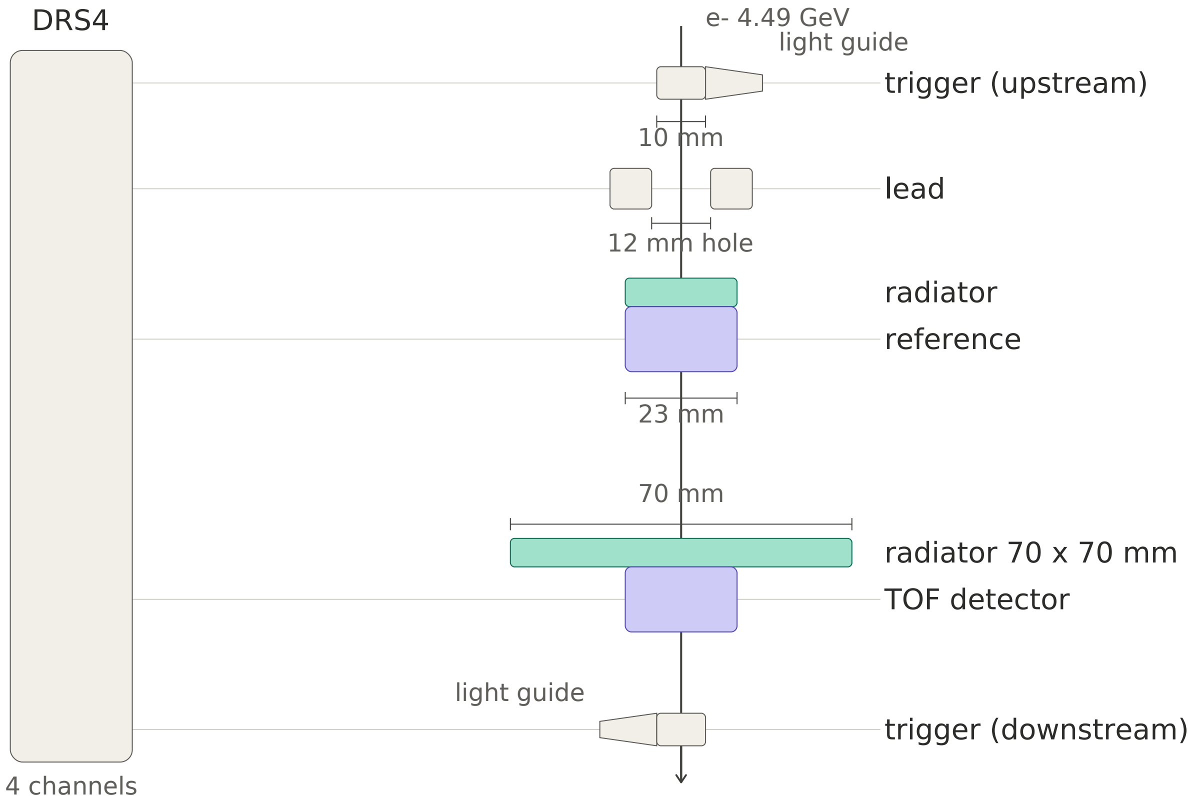
Beam test setup and instrumentation

KEK PF-AR test beamline



Beam properties

- 4.49 GeV monochromatic electrons
- Trigger rate of ≈ 10 Hz; transverse beam area defined by a 1 cm^2 trigger area

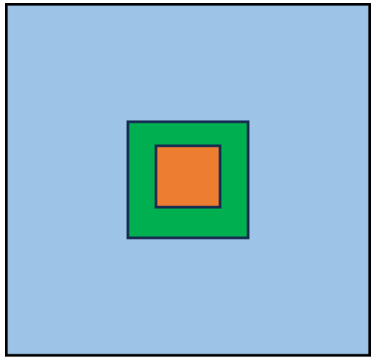


Experimental layout and readout chain

- **Trigger**: two plastic scintillators upstream/downstream, HV = 1.1 kV, att. 20 dB.
- **Reference MCP-PMT**: standard-sized radiator, t_{ref}, HV = 2.1 kV, att. 20 dB + ampli. 46 dB.
- **Detector prototype**: HV = 2.3 kV, att. 46 dB + ampli. 46 dB. Net zero, used as protection.
- **Digitizer**: DRS4 sampling up to 4 analog channels at 5 GS/s

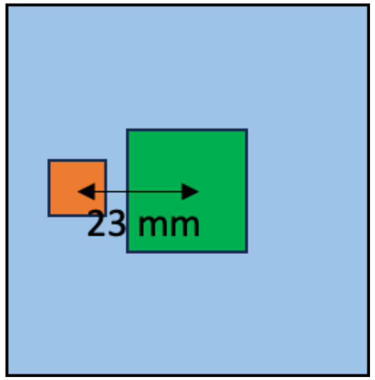
Tested configurations

Evaluate how time resolution and number of detected photons depend on the impact position due to optical path dispersion.



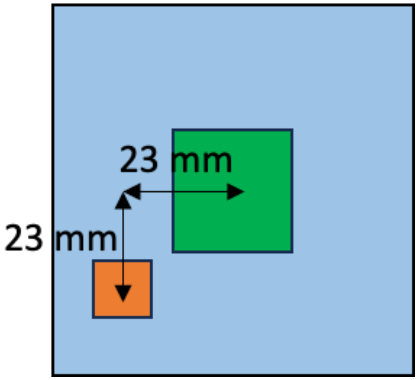
Center

Reference validation run
Performed before detector insertion using two identical MCP-PMTs to measure $\sigma_{\text{ref}} = (22.5 \pm 0.7)$ ps



Edge

- Position-dependent scan across the radiator surface.
- Three impact configurations tested ($\approx$ 10000 events acquired for each):



Corner

Since the MCP-PMT photocathode area is +-11.5 mm and the beam size is 1 cm^2, Edge and Corner particles hit strictly outside the active area, enabling the verification of the detector operating principle

Waveform analysis

From the raw data of the digitiser one must derive the important physical quantities

Sampling and baseline estimation

- Digitizer at 5 GS/s (0.2 ns step) over a 200 ns window
- V_{ped} and noise (σ_V) estimated on the first 50 ns

Signal time extraction

- Error Function (erf) on leading edge (50 samples preceding the pulse minimum):

$$V(t) = V_{\text{ped}} + \frac{A}{2}\left[1 + \text{erf}\left(\frac{t - t_0}{\sigma\sqrt{2}}\right)\right]$$

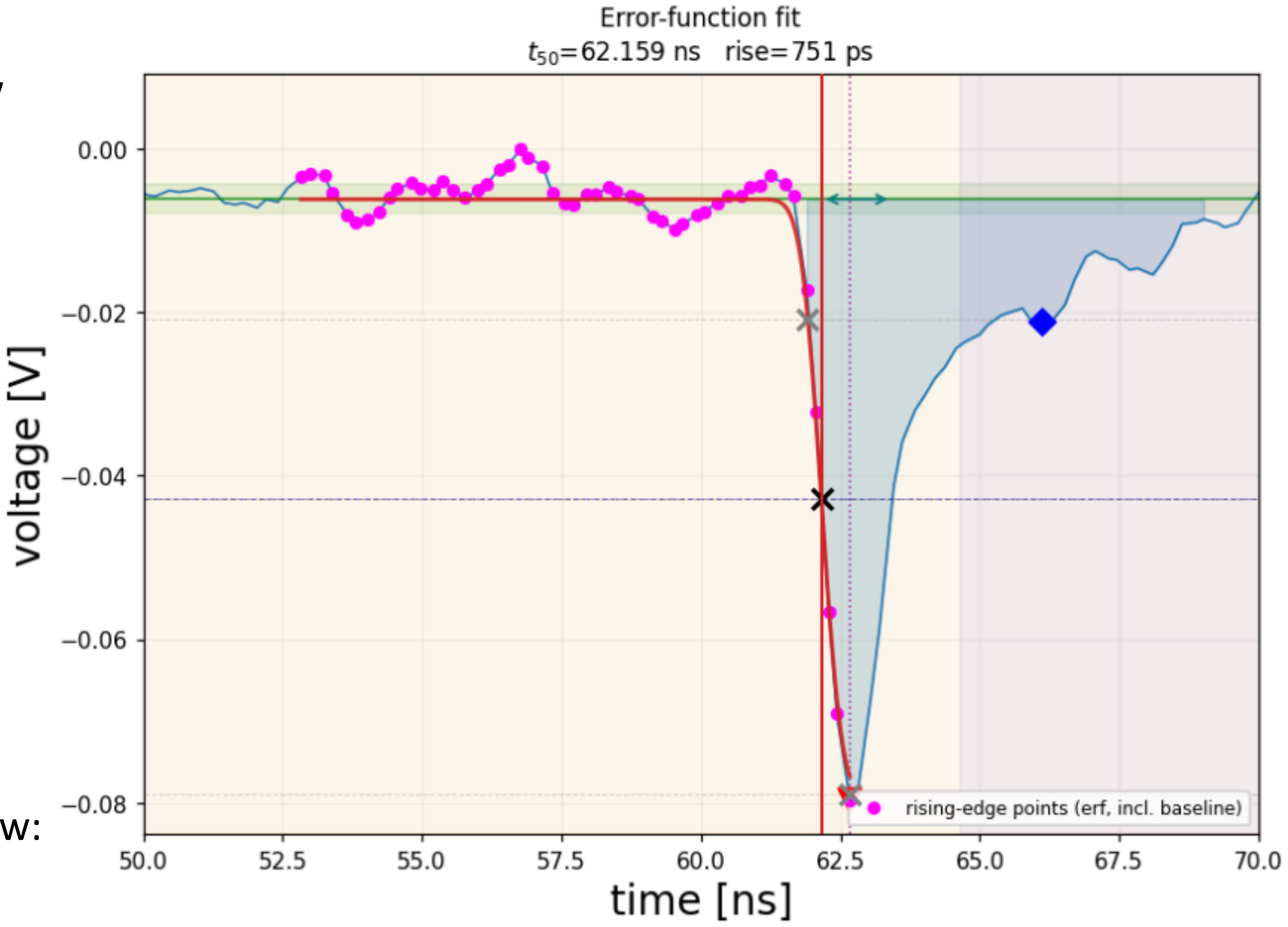
- Signal time t_{50} = t_0 fit.

Parameter constraints

- σ fixed to the median intrinsic value $\bar{\sigma} \approx$ 258 ps
- A, V_{ped} soft-constrained (penalty terms).

Charge integrated numerically in an asymmetric window:

$$Q = -\frac{1}{R}\int_{t_{50}-1\text{ ns}}^{t_{50}+7\text{ ns}} [V(t) - V_{\text{ped}}]dt \quad (R = 50\,\Omega)$$



Applied selection

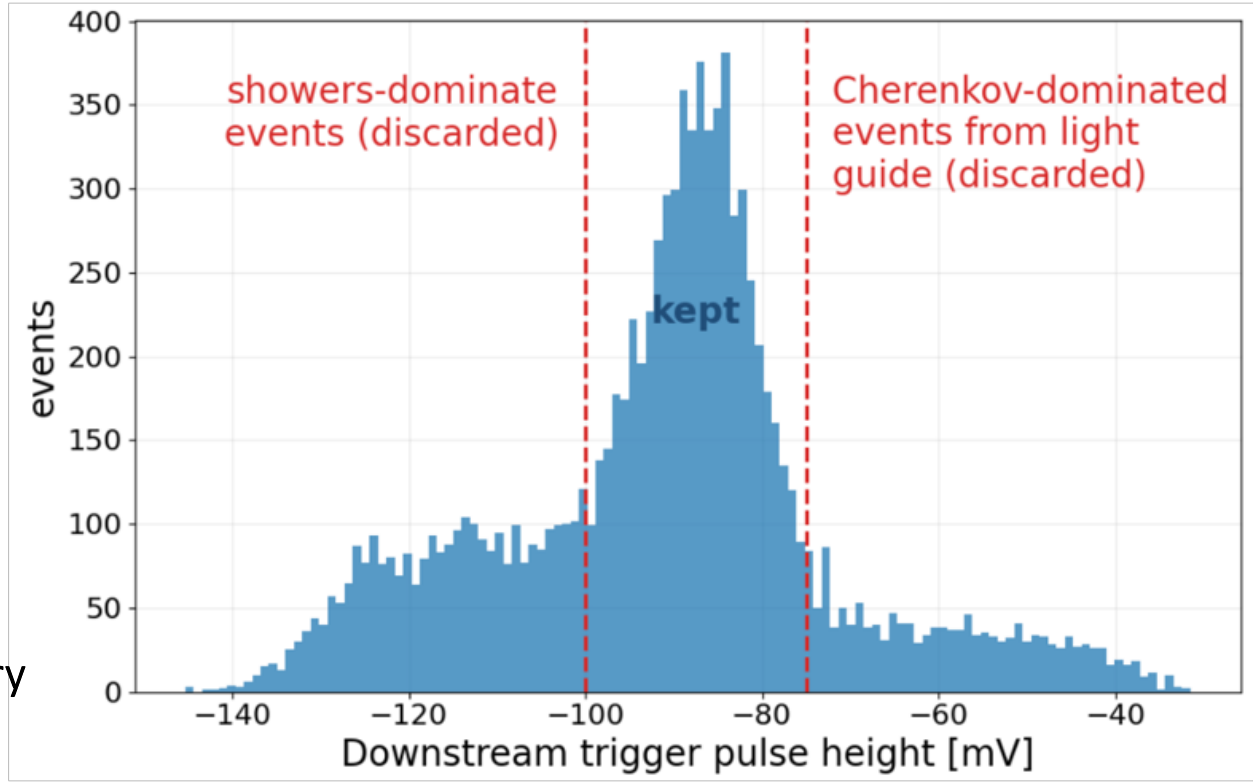
Purifying beam events it's needed to identify better the signal properties

Selection objectives:

- Isolate clean single-particle electron events
- Reject electromagnetic showers and Cherenkov background outside the target region

Trigger pulse-height selection

- **Shower rejection**: high-amplitude tail in trigger spectrum (multiple secondary electrons showers produced upstream)
- **Light guide background rejection**: low-amplitude events (electrons hitting the scintillator light guide)
- **Clean single-electron window**: main single-particle peak → well-defined single-track sample



Outliers selection

Removes unphysical noise fluctuations or early/late secondary interactions to retain high-quality timing signals.

Results: efficiency and event example

Verify uniform, full-surface coverage without dead zones for far-off-center impacts

- **Efficiency Criterion**: Fraction of the events seen by the trigger and reference detector with valid prototype detector pulse height ($PH < PH_{noise}$) and converging fit

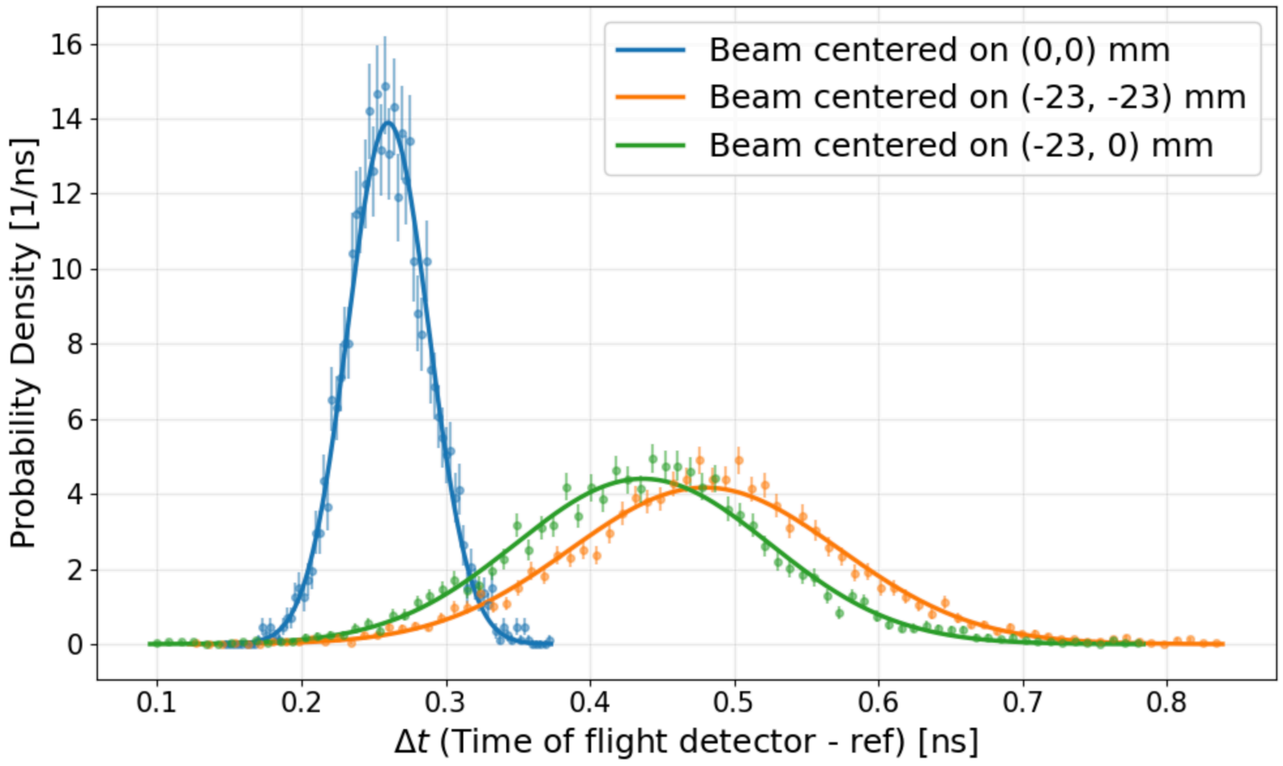
Impact Position	Valid Events	Detected Events	Undetected	Efficiency (68.3% CL)
Center (0, 0) mm	3,683	3,683	0	100.00% (-0.05% / +0.00%)
Edge (-23, 0) mm	3,761	3,759	2	99.95% (-0.07% / +0.03%)
Corner (-23, -23) mm	4,274	4,268	6	99.86% (-0.08% / +0.06%)

The detector prototype achieves near-100% detection efficiency across different position of the radiator surface → the oversized radiator concept reliably guides Cherenkov photons to the sensor

Results: time resolution

Assess how time resolution depends on impact position

- $\Delta t = t_{50}^{detector} - t_{50}^{reference}$
- Fitting the timing distribution with a normal model to extract $\sigma_{\Delta t}$
- Calculate the time resolution σ_t by subtracting in quadrature σ_{ref}



Results:

- **Center**: $\sigma_t = (16.8 \pm 1.1)$ ps
- **Edge**: $\sigma_t = (85.3 \pm 1.2)$ ps
- **Corner**: $\sigma_t = (90.4 \pm 1.2)$ ps

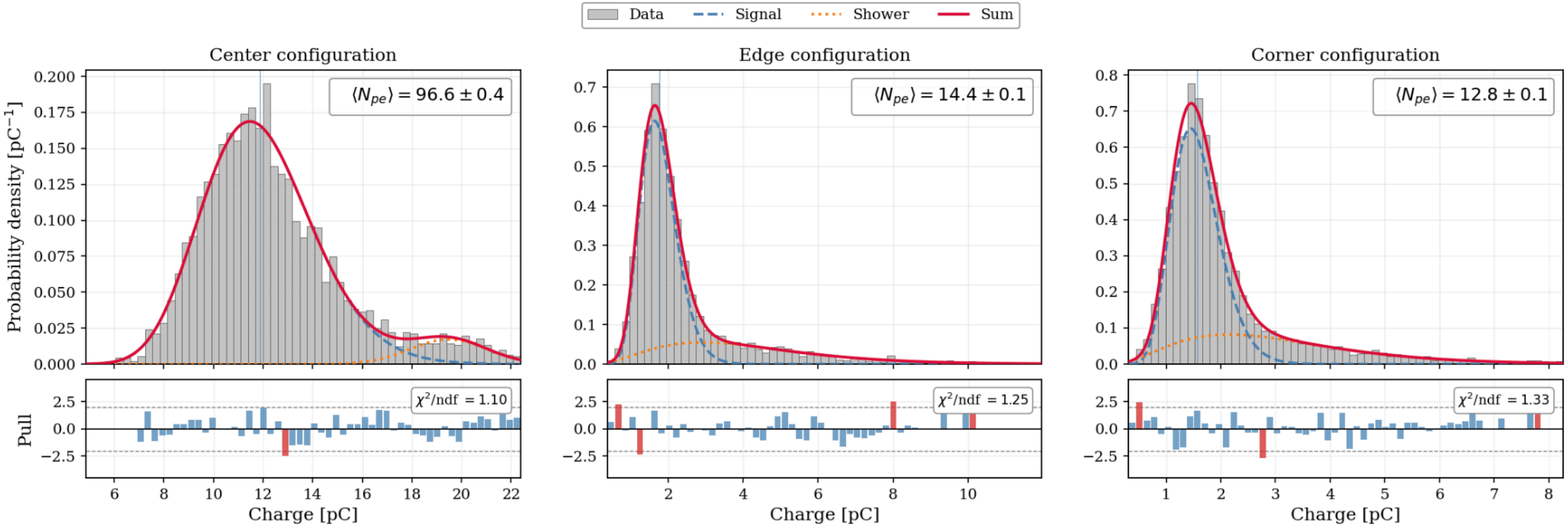
Resolution depends strongly by position. Results compatible with the target for background veto but not for PID detector. Further investigations into the causes of this resolution degradation are needed.

Results: number of detected photons

Check whether the drop in angular acceptance explains the resolution loss

Charge distribution fit

- Two gamma function mixture fit (signal + residual shower population) on the charge spectrum
- From fitted mean signal charge Q the $N_{pe} = \dfrac{Q}{A \cdot e \cdot G}$



The number of detected photoelectron is different between the configurations confirming the drop in angular acceptance. This drop isn't enough to explain the time resolution degradation based on statistical drop ($\sqrt{N_{pe}}$).

Time jitter correction

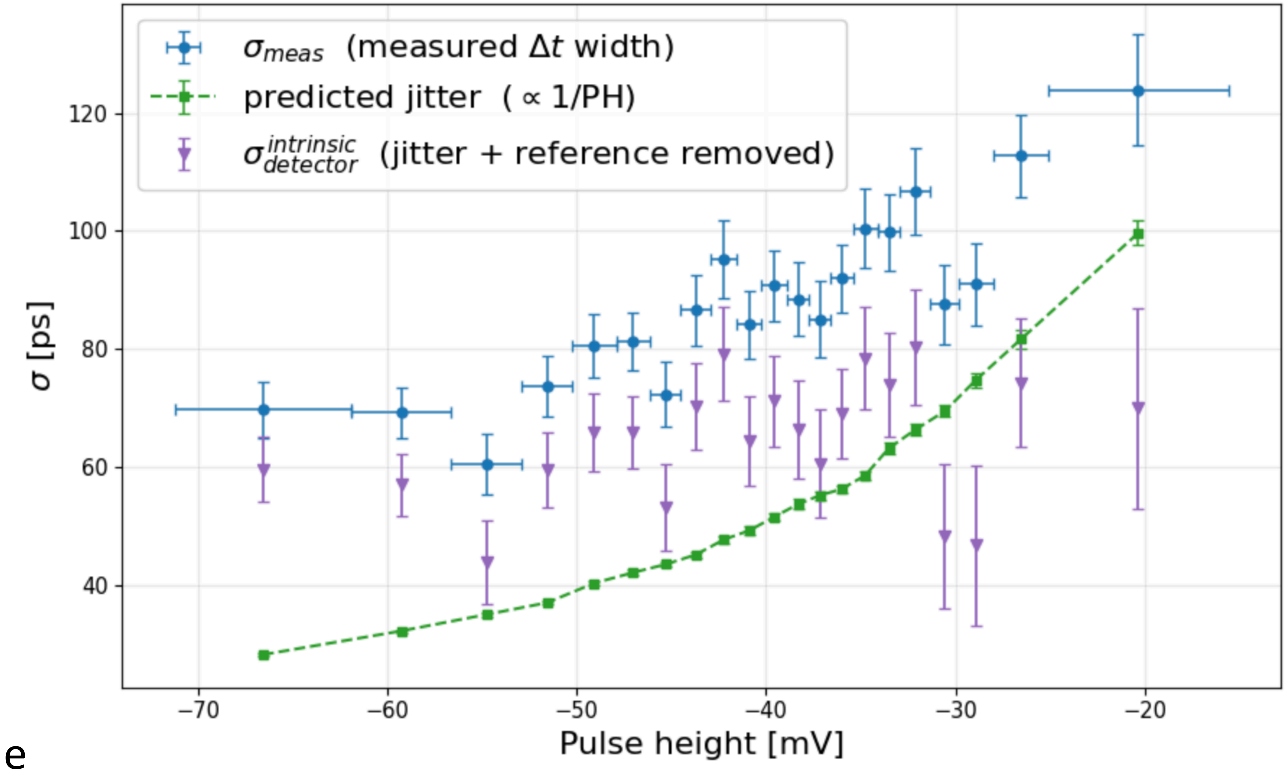
Check if the poor resolution arise from a bad S/N ratio

Noise-induced timing jitter effect

- Baseline noise $\sigma_V \rightarrow$ timing uncertainty: $\sigma_t = \dfrac{\sigma_V}{|dV/dt|}$
- σ_V and the rise time are constant $\rightarrow$ effect is greater at low PH

Checking the time resolution without this effect

- Estimated for every amplitude bin (average slope + noise)
- Subtracting in quadrature the reference resolution and time jitter effect to obtain the intrinsic time resolution per bin
- Weighted average discarding high PH events (residual showers)



Intrinsic time resolution:

- **Center**: $\sigma_t = 14.03 \pm 0.94$ ps
- **Edge**: $\sigma_t = 62.8 \pm 1.5$ ps
- **Corner**: $\sigma_t = 62.7 \pm 1.6$ ps

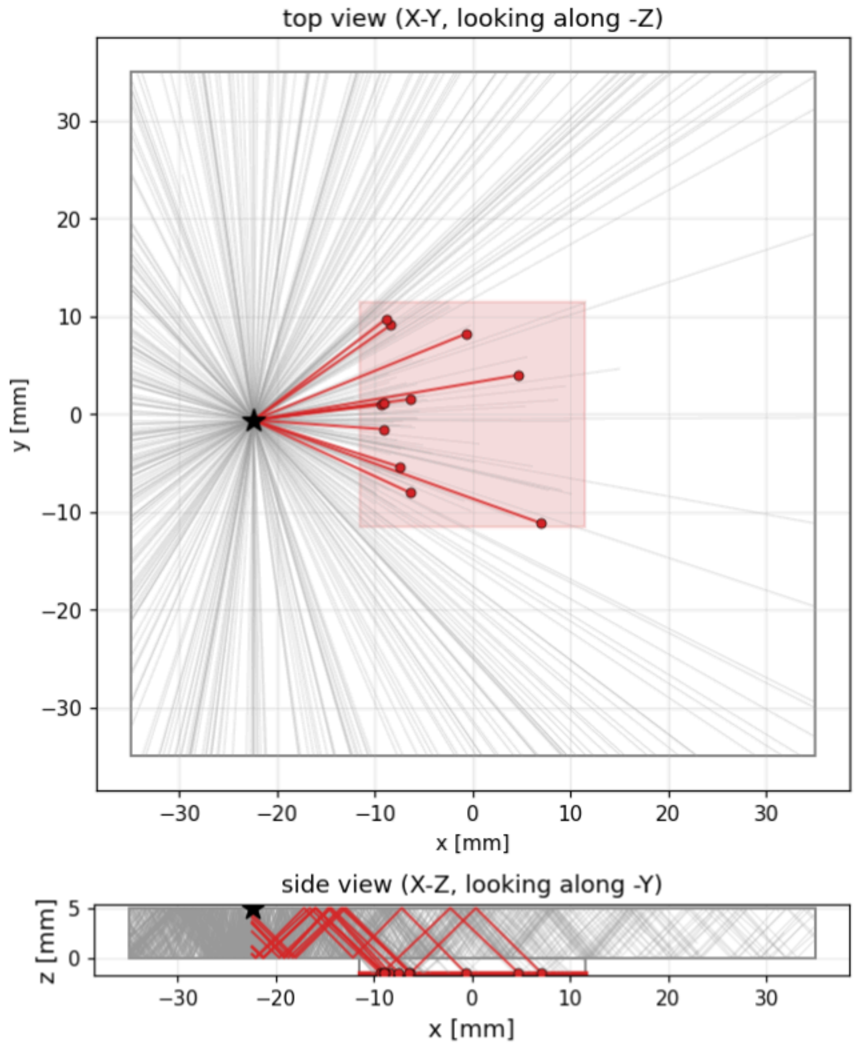
The intrinsic time resolution is better than the measured one $\rightarrow$ some of the degradation is due to this effect, but not all the effect is explained

3D Cherenkov ray-tracer simulation

Simulate Cherenkov light propagation and evaluate the timing performance of the detector under the same configurations as the beam test to understand if the measured resolution is expected

Methodology

- Uniformly distributed particle beam (as beam test)
- Photon emission along particle tracks using Frank-Tamm distribution.
- Internal reflections on the large slab faces of fused-silica radiator.
- Wavelength-dependent refractive index $n(\lambda)$ + dispersion
- Quantum Efficiency (QE) and Collection Efficiency (CE).
- Includes per-photon TTS = 40 ps + reflection/absorption at the sensor interface.
- Signal time = average of detection time of the photons



Simulation results

Compare simulated vs measured resolution and photon yield

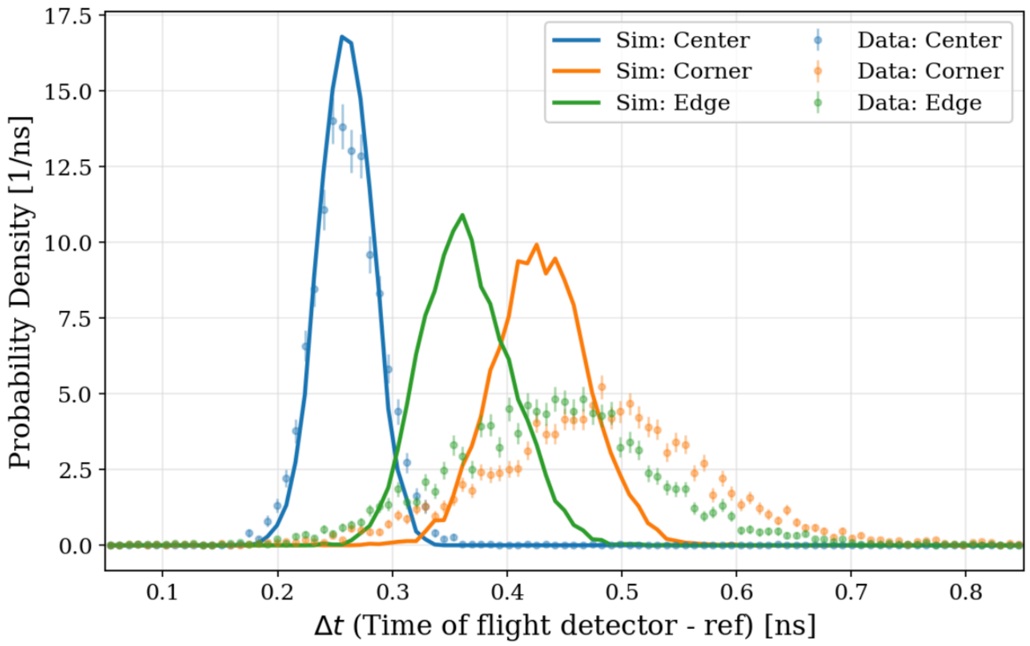
Detection time and resolution

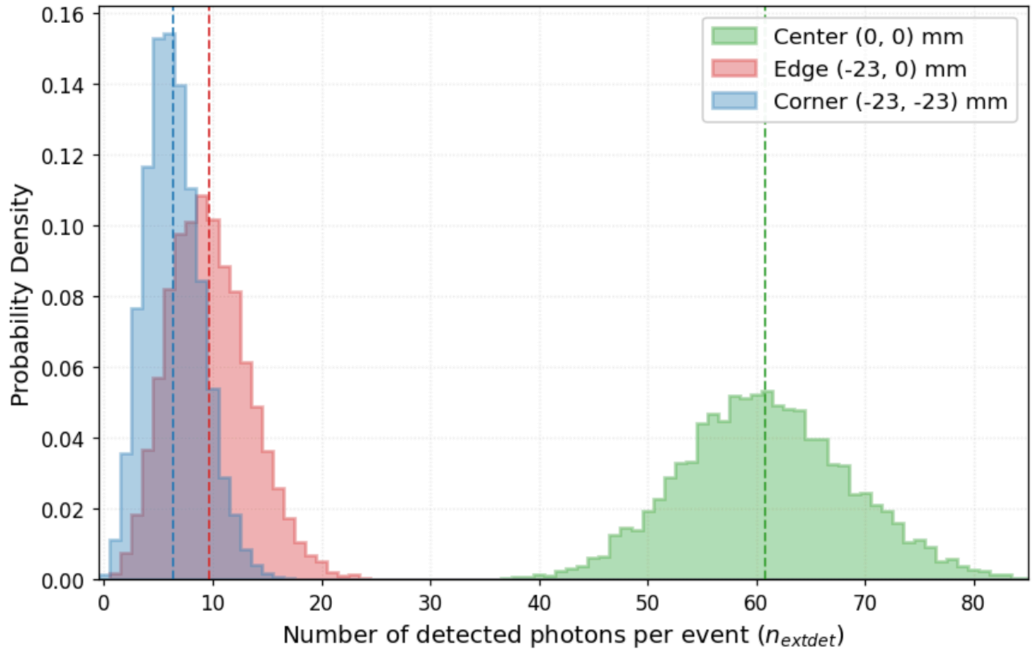
- **Center**: $\sigma_{sim} = 5.8 \pm 0.4$ ps / $\sigma_{data} = 16.8 \pm 1.1$ ps
- **Edge**: $\sigma_{sim} = 31.6 \pm 1.1$ ps / $\sigma_{data} = 82.2 \pm 1.2$ ps
- **Corner**: $\sigma_{sim} = 34.4 \pm 1.1$ ps / $\sigma_{data} = 90.5 \pm 1.2$ ps

Number of detected photons

- **Center**: $N_{ph,sim} = 60.81 \pm 7.78$ / $N_{ph,data} = 92.8 \pm 0.5$
- **Edge**: $N_{ph,sim} = 9.70 \pm 3.72$ / $N_{ph,data} = 14.4 \pm 0.1$
- **Corner**: $N_{ph,sim} = 6.38 \pm 2.57$ / $N_{ph,data} = 12.8 \pm 0.1$

Qualitative trend reproduced for both σ and N_{ph}.
A clear quantitative mismatch remains that cannot be resolved by subtracting electronic jitter alone → unmodeled experimental factors, need to refine the current baseline simulation model.





Conclusions

- The need for a dedicated TOF detector in the backward region of Belle II was assessed and the time resolution targets for the beam background veto ($\sigma_t \leq 200$ ps) and for the PID π/K ($\sigma_t \leq 40$ ps) were defined.
- Studied a cost-effective prototype using an MCP-PMT coupled with an large quartz radiator, and developed a 3D Monte Carlo ray-tracer to simulate Cherenkov light propagation.
- Measured the sensor gain via single-photoelectron laser tests, and conducted a test beam at KEK PF-AR using 4.49 GeV electrons.
- Built a waveform analysis pipeline to measure detection efficiency, photoelectron yield, and the position dependence of time resolution across different impact points, including electronic time jitter corrections.

1. Time resolution is not what's expected from the simulation. It’s enough to use it as accelerator background veto of MeV γ rays to reject $\sim$ 99.9% background events compared to now. It’s not enough though to use it for PID.

2. The efficiency is still almost 100% even for off-centred particles

3. The number of detected photon differs from the simulation but the acceptance drop is almost as expected

Next steps

Things to improve in the next beam test:

- Changing the attenuation level for the off-centered configuration to reduce error given by noise
- Pay more attention to the experimental setup to minimize shower events
- Be careful to position the detector exactly perpendicular to the beam
- Checking position useful to determine time resolution (i.e. only one specific number of reflections)

Possible next step:

- Developing a more advanced simulation to use it as a fit model for the data
- Increasing the radiator thickness to improve time resolution and band resolution

Thank you for your attention and for giving me this opportunity