Belle II KLM upgrade

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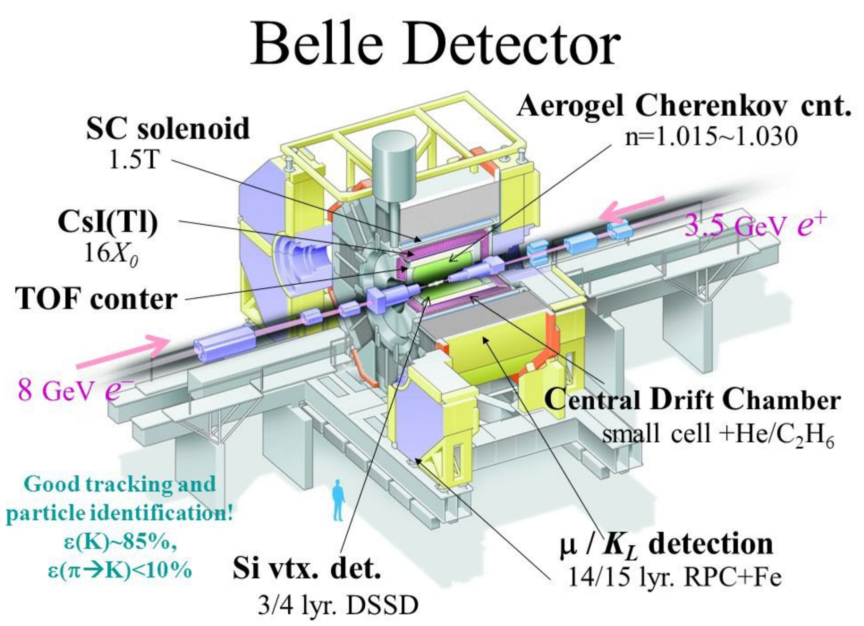
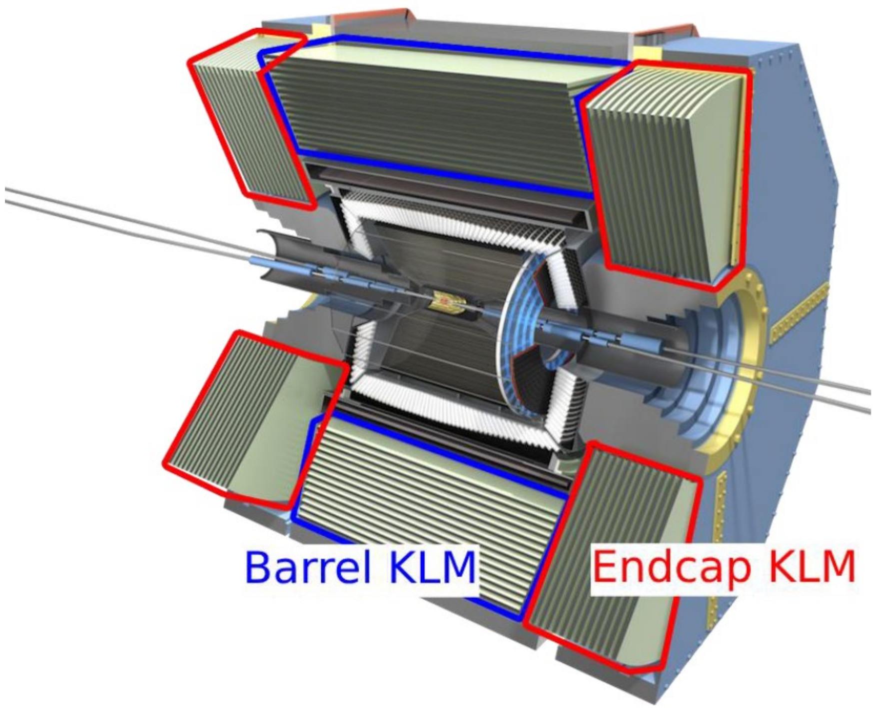
The 7th International Workshop on Future Tau-Charm Facilities

Huangshan, Anhui

Belle KLM -> Belle II KLM





Belle KLM:

- All the layers are implemented with glass-electrode resistive plate chambers (RPC).
- The long dead time of the RPCs reduces the detection efficiency under high background fluxes.

Belle II KLM:

- The two inner layers of the barrel and all the superlayers of the endcap have been replaced with plastic scintillators.
- Keep good muon identification.
- The relative uncertainty for K_L^0 momentum measurement is about 30% at 1.5 GeV/c.

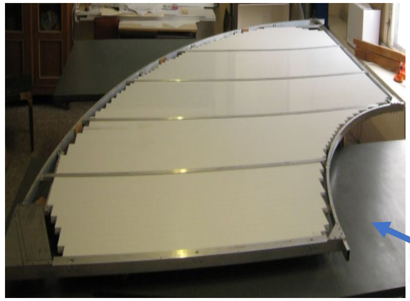
Belle II KLM structure

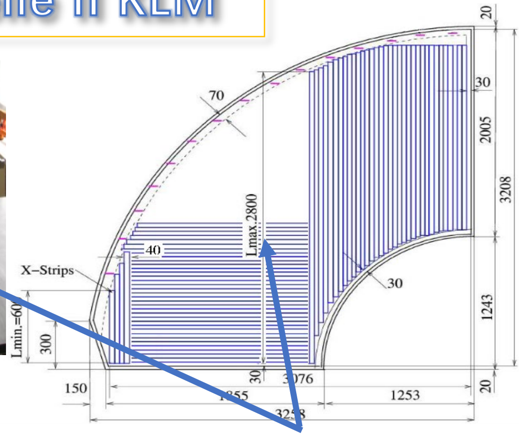
- Scintillator shape is flexible, easy to get good spatial resolution:

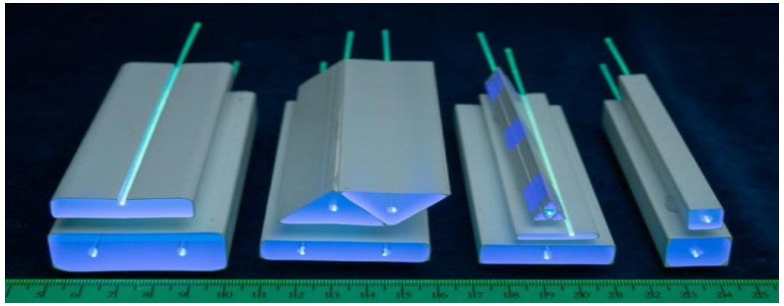
$$\sigma = \text{width} / \sqrt{12}$$

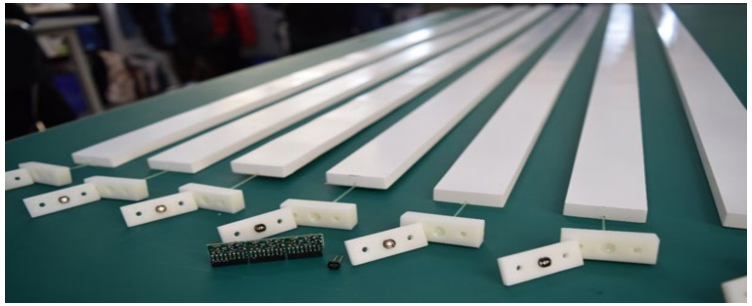
- Wave length shift (WLS) fiber inside scintillator to collect photons and guide them to SiPM.
- Use SiPM at one or both ends, small size, low cost, low operating voltage, high gain and can work at high magnetic field.

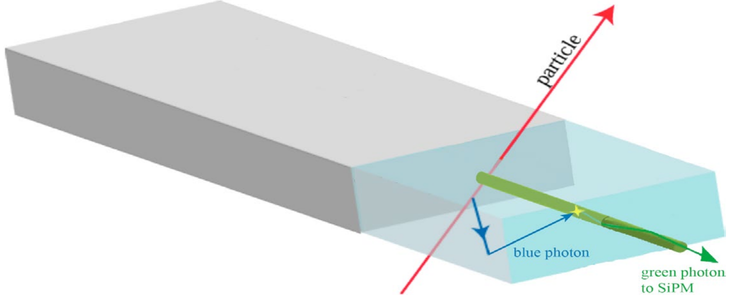
Belle II KLM



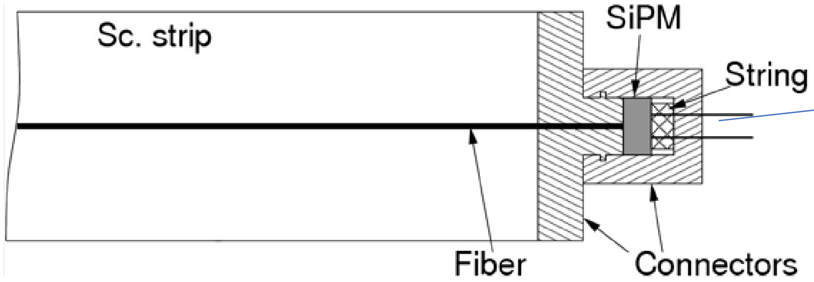


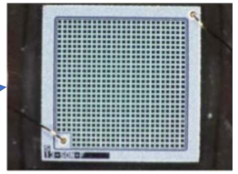






- ➢ **Extruded scintillator**: cheap in massive production, but the attenuation length is only several centimeters.
- ➢ **WLS**: Kuraray Y11(200), a diameter of 1.2 *mm*.
- ➢ **SiPM**: Hamamatsu MPPC, S10362, 1.3*mm* × 1.3*mm*.





KLM upgrade for K_L^0 momentum measurement

Scintillator for detection

Precise measurement of the four-momentum of neutral hadrons

- Uncharged
- Complex hadron shower

Scintillator detector

- High time resolution
- Fast time response components in hadron showers
- Flight velocity： from the collision point to the KLM detector & solid angle and particle identification information

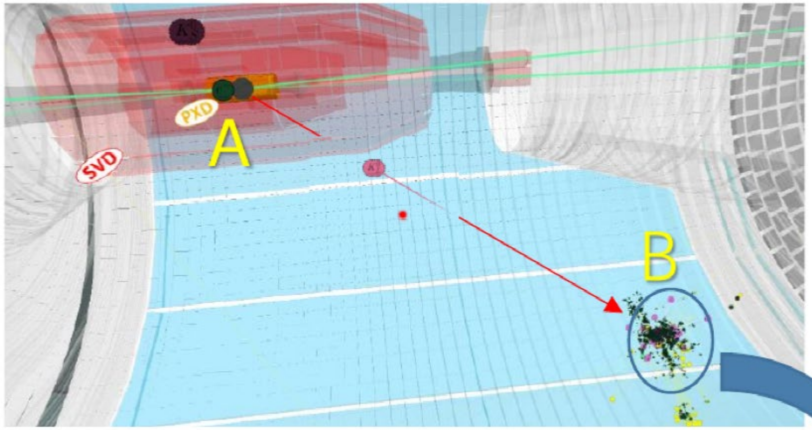
$$p = \gamma m v = \frac{mcL}{\sqrt{t^2c^2 - L^2}}$$

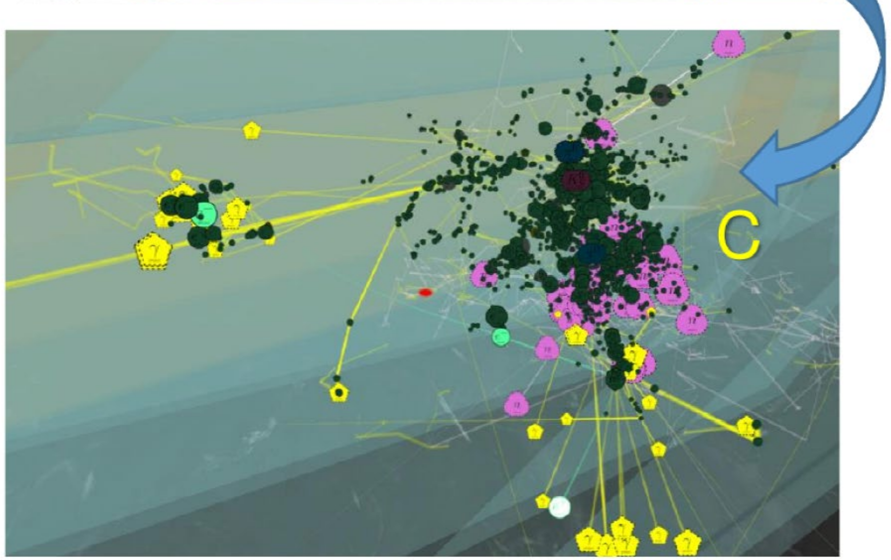
$$\frac{\delta t}{\delta p} = -\frac{m^2L^2}{t \cdot p^3} = -\frac{m^2Lv}{p^3}$$

if $L = 2$ m, $\gamma = 3$, $p \approx 1.5$ GeV/c

$\delta t = 100$ ps so $\delta p = 0.19$ GeV/c

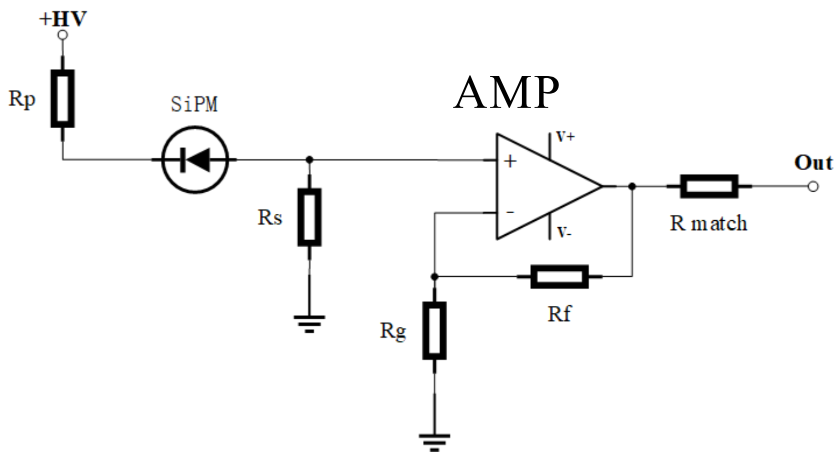
Relative error ～ 13%





Paper of R&D accepted by NIMA, arXiv:2503.06128

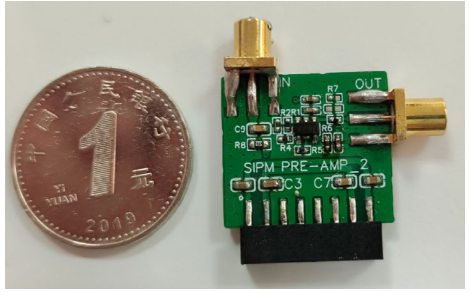
Design of fast pre-amplifier

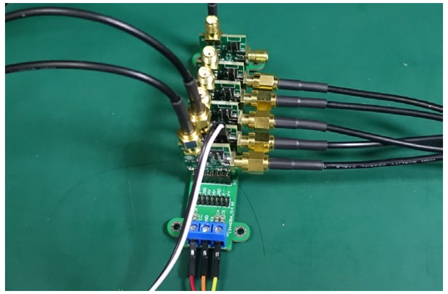


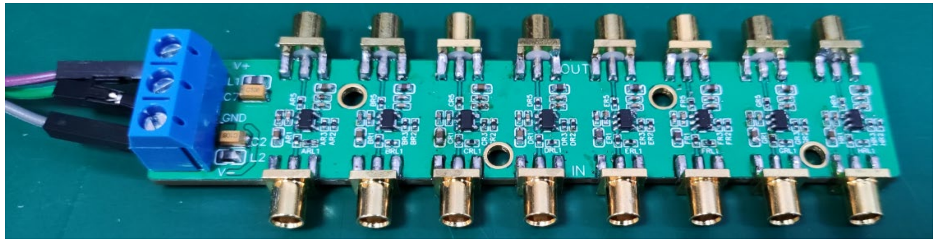
Gain: +20 V/V

Bandwidth(-3dB): 400 MHz

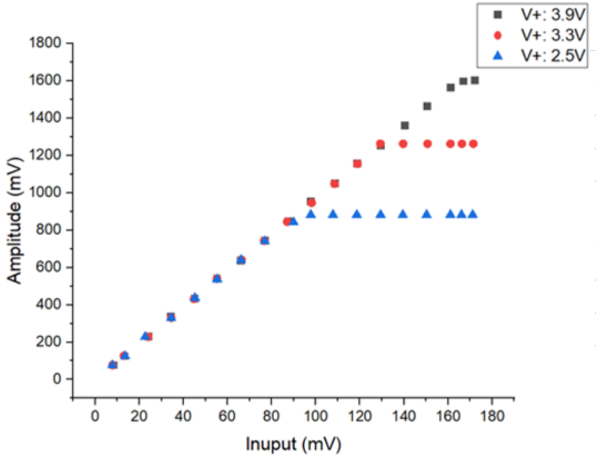
Baseline noise(RMS): 300uV

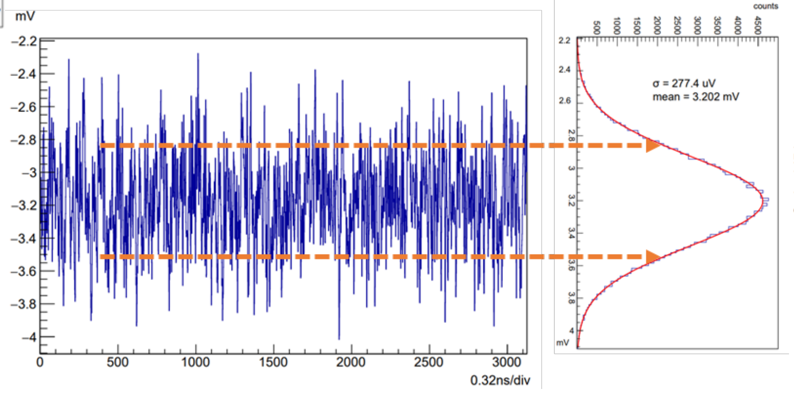


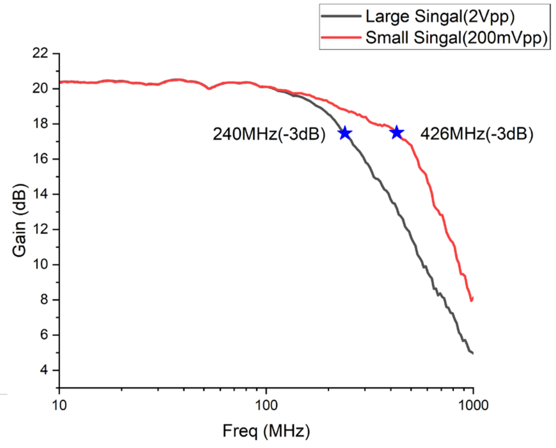


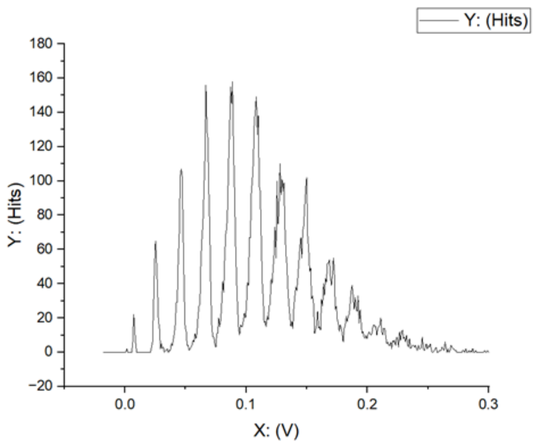


➢ Performance test of preamplifier





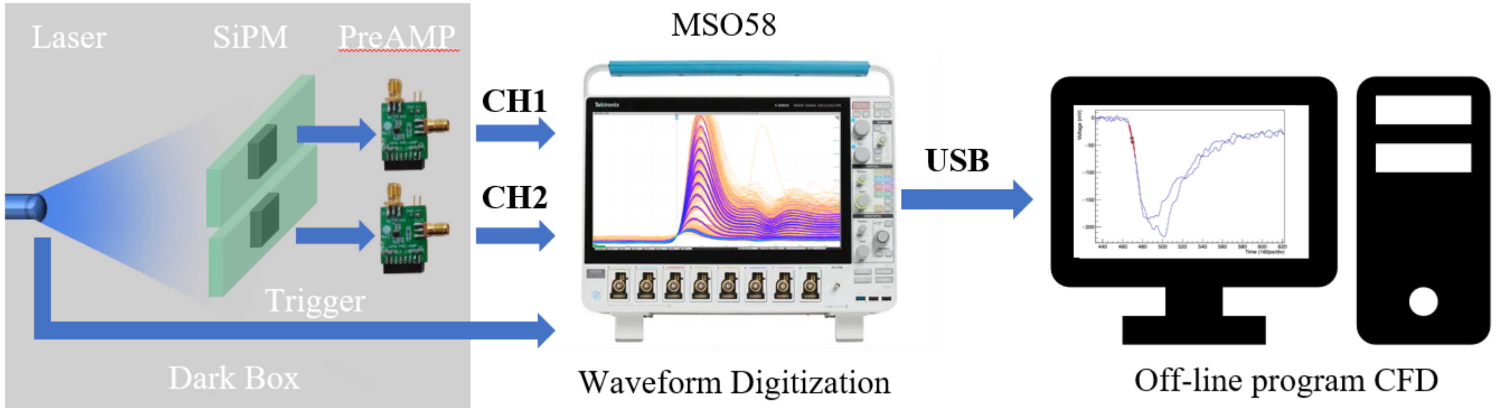


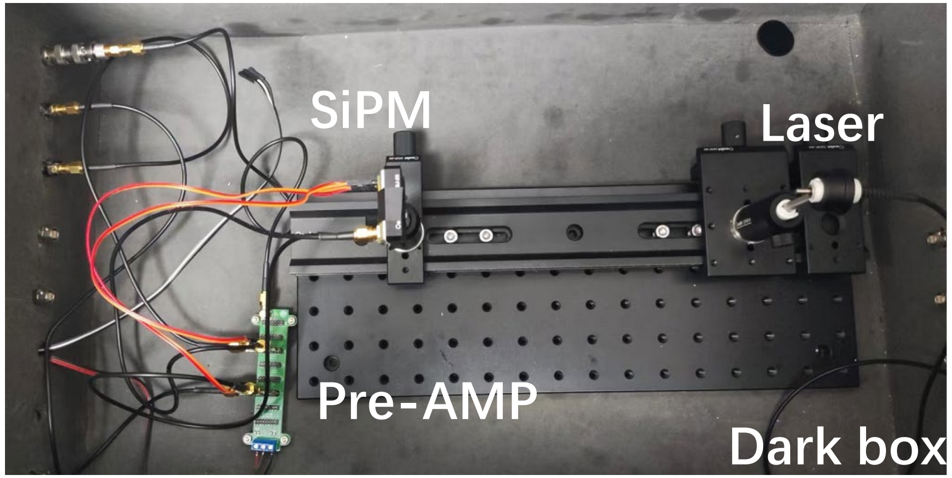


- Dynamic range testing
- Baseline noise test
- Bandwidth testing
- SiPM photoelectron peak

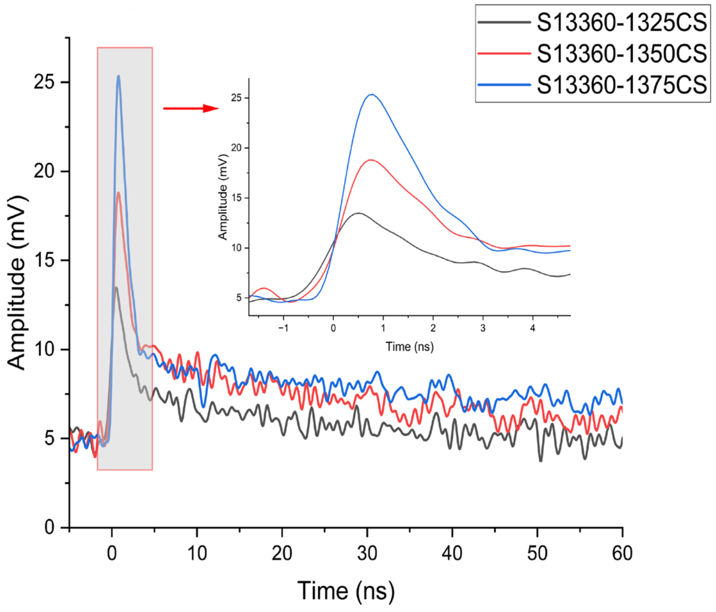
Nucl. Sci. Tech, 34, 169(2023)

Design of fast pre-amplifier

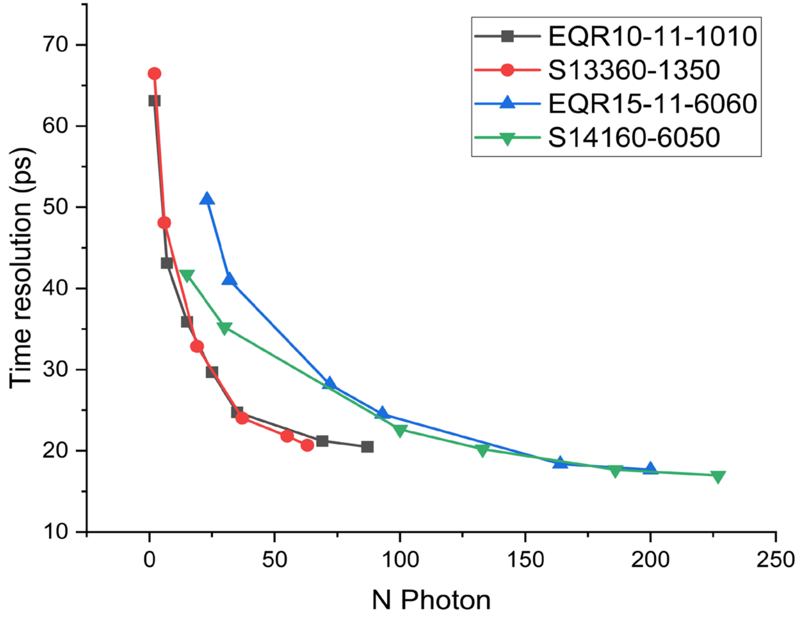




Time resolution test setup



Single photon signal of SiPMs



Time resolution varies with the number of photons

Small area: (1×1 mm^2 / 1.3×1.3 mm^2)
Photons > 5 , Time resolution < 50ps
Photons > 40 , Time resolution < 25ps

Large area: (6×6 mm^2)
Photons > 20 , Time resolution < 50ps
Photons > 70 , Time resolution < 25ps

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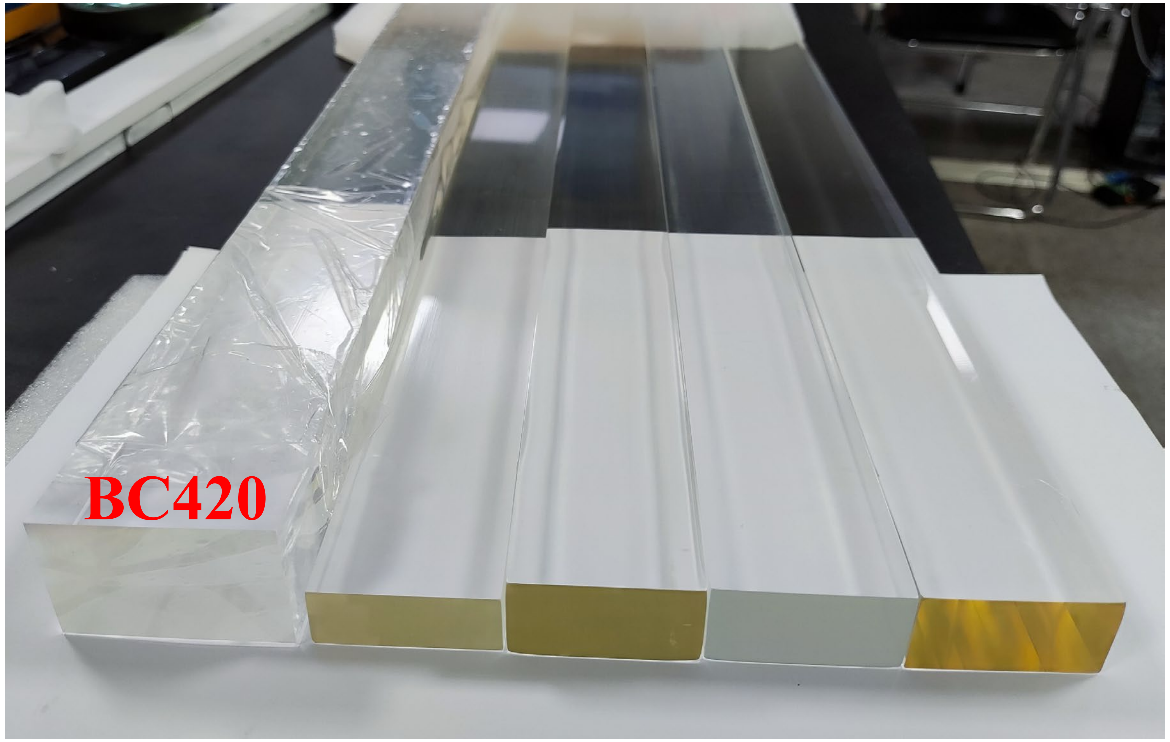
Scintillators and SiPM array

Solid scintillator (no WLS fiber)



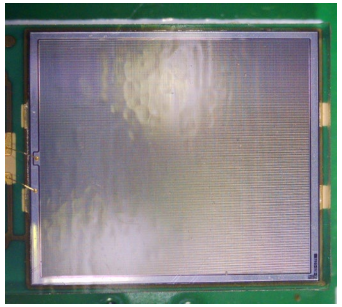
SAINT-GOBAIN

高能科迪 GAONENGKEDI

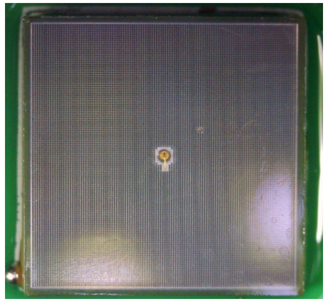
Multiple SiPMs

HAMAMATSU
PHOTON IS OUR BUSINESS

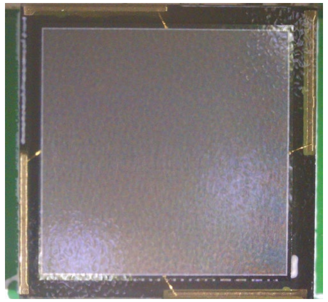
NDL



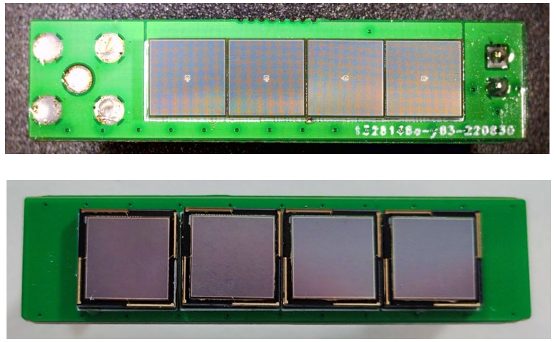
S13360-6025PE



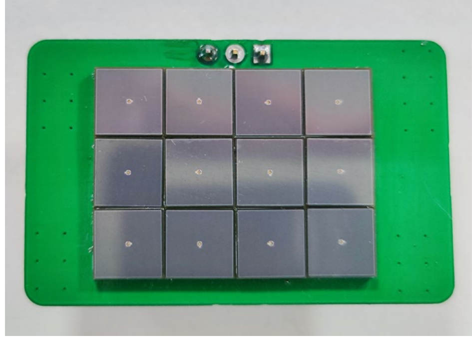
S14160-6050HS



EQR1511-6060D-S



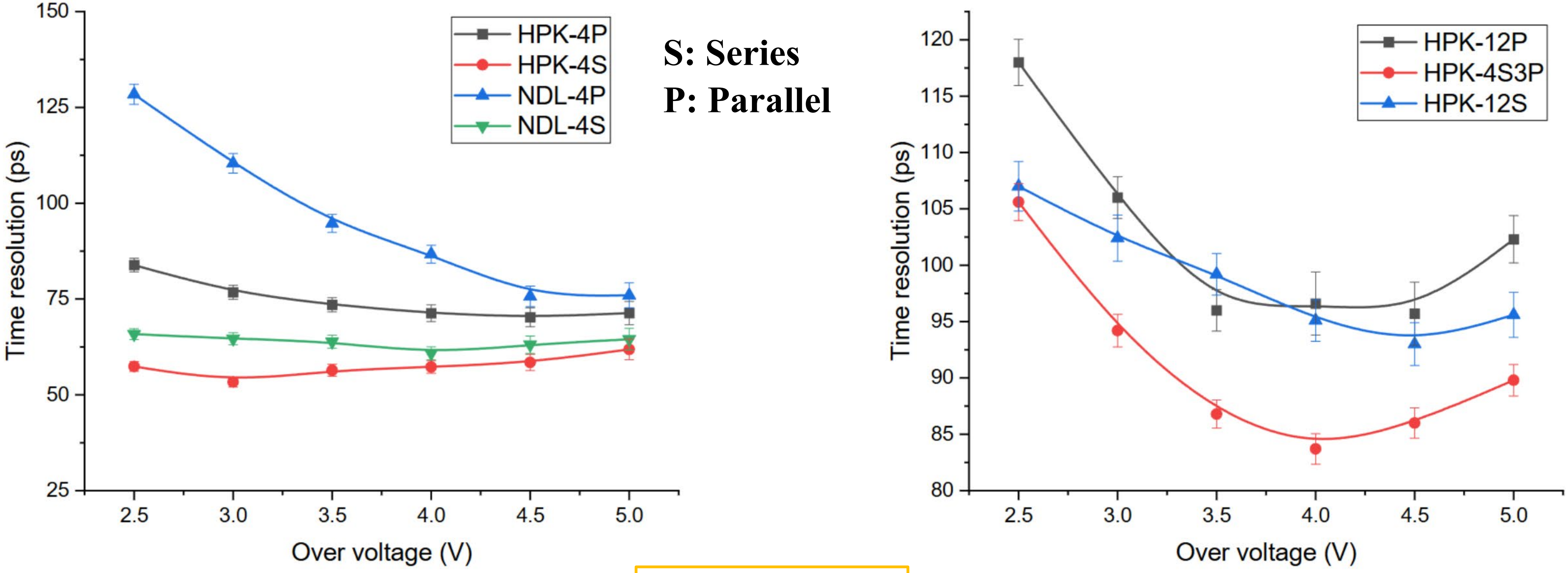
4×SiPM



12×SiPM

- Thicker scintillators with longer attenuation lengths and large areas of SiPM can improve photon collection.

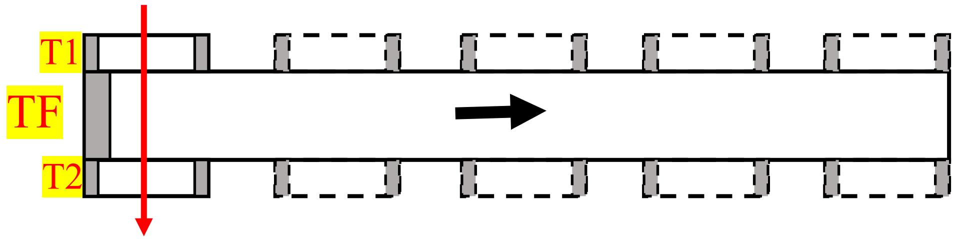
Different connection of SiPMs



arXiv:2503.06128

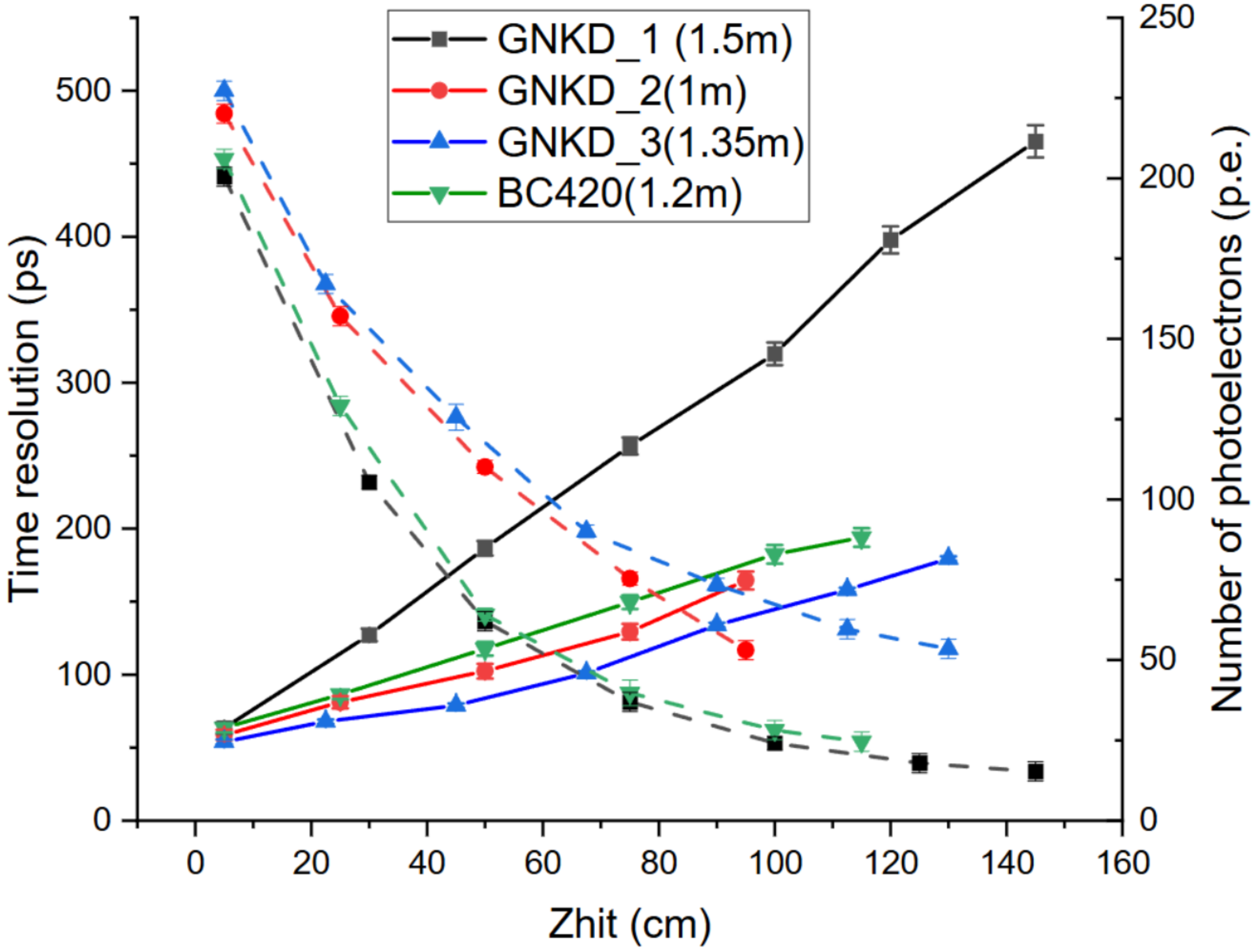
- We test the time resolution for 1 × 4 and 3 × 4 SiPMs array under different connection configurations.
- The 4S and 4S3P configurations show the best time performance.

Performance of different scintillators



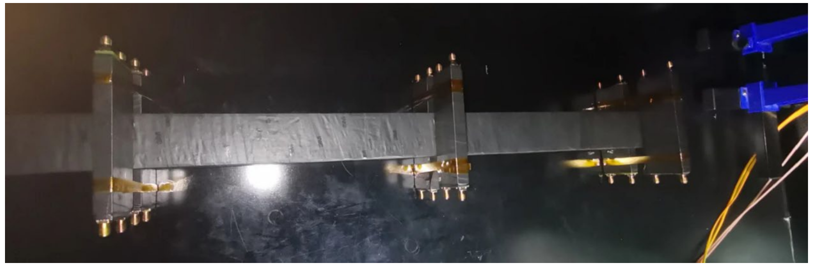
- Change the location of the trigger, we can get the time resolution of different position.
- Less light collection at the far end makes the Signal-to-Noise Ratio smaller, resulting in worse time resolution.

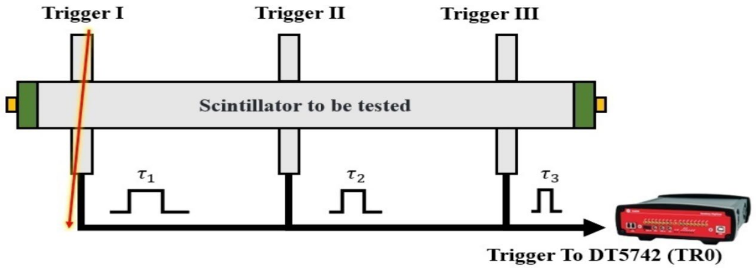
Type	Size	Attenuation length (cm)
BC420	5*3*120 cm^3	80 ± 7
GNKD_1	4*2*150 cm^3	73 ± 7
GNKD_2	4*2*100 cm^3	63 ± 2
GNKD_3	4*2*135 cm^3	115 ± 5



arXiv:2503.06128

Performance with dual-end readout





Schematic diagram of the multi-trigger test system with trigger pulses of different widths.

Unweighted average:

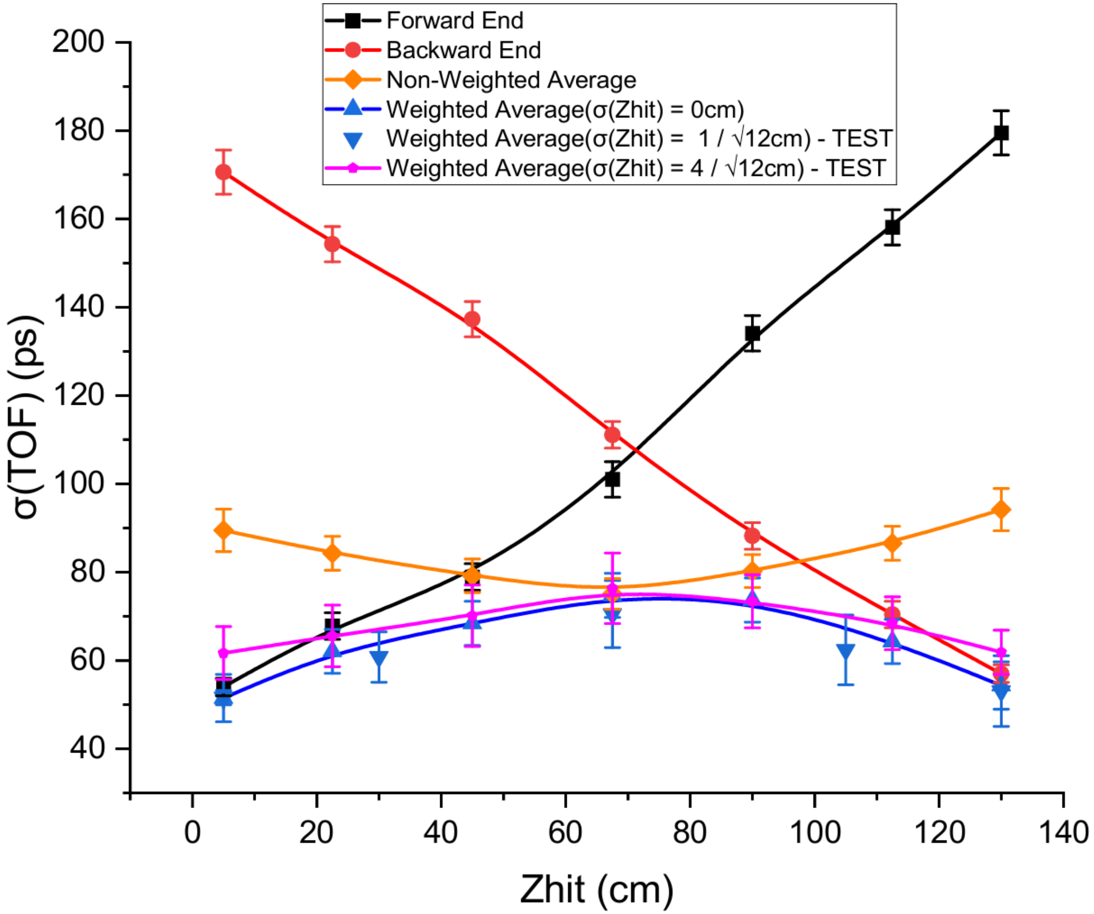
$$T_{s.c.} = \frac{T_F + T_B}{2} = T_0 + \frac{L}{2v} \qquad \sigma_{s.c.}^2 = (\sigma_F^2 + \sigma_B^2)/4$$

Weighted average:

$$T_{s.c.} = \frac{T_F/\sigma_F^2 + T_B/\sigma_B^2}{1/\sigma_F^2 + 1/\sigma_B^2} \qquad \frac{1}{\sigma_{s.c.}^2} = \frac{1}{\sigma_F^2} + \frac{1}{\sigma_B^2}$$

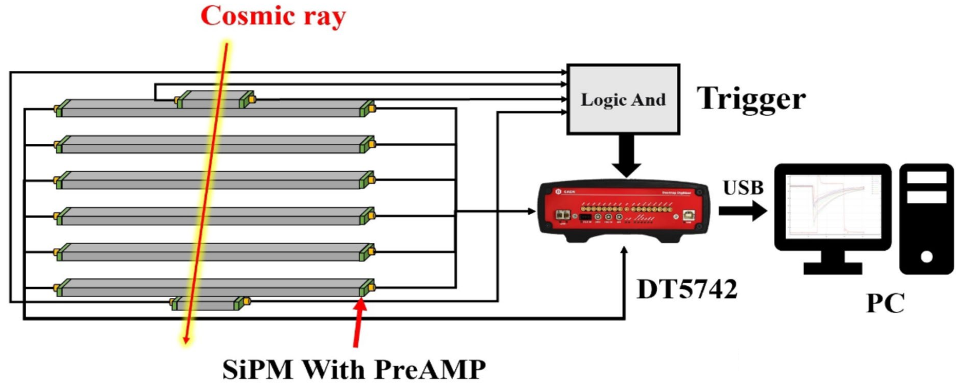
***$T_{s.c.}$* related to hit position 'x'**

The uncertainty of hit position is also taken into account.

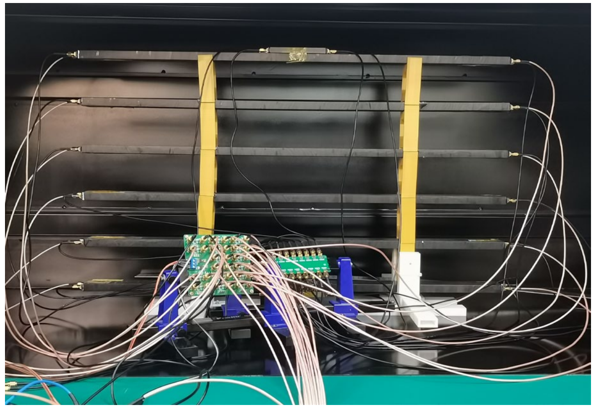


arXiv:2503.06128

Measurement of cosmic ray velocity

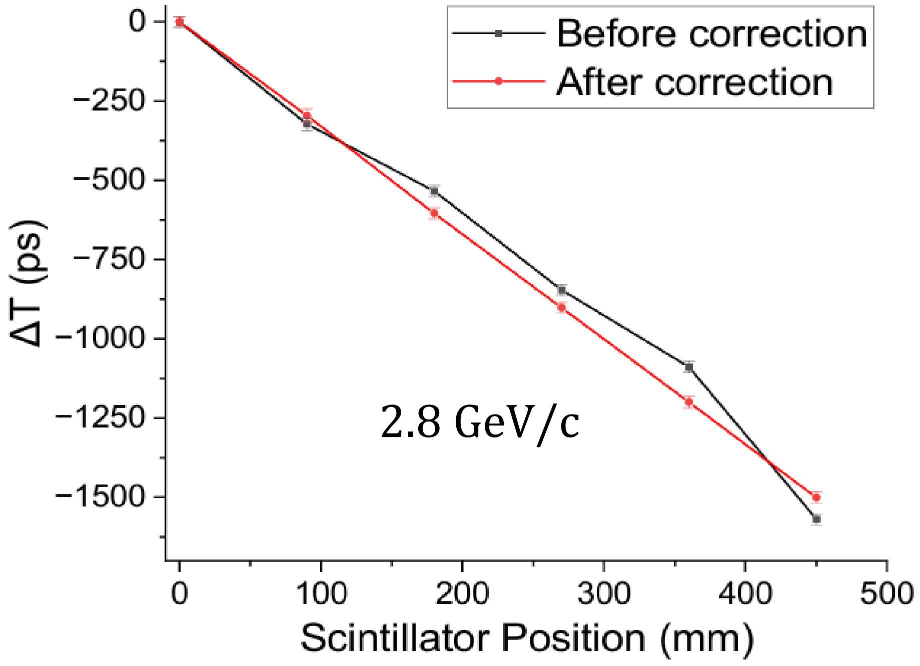


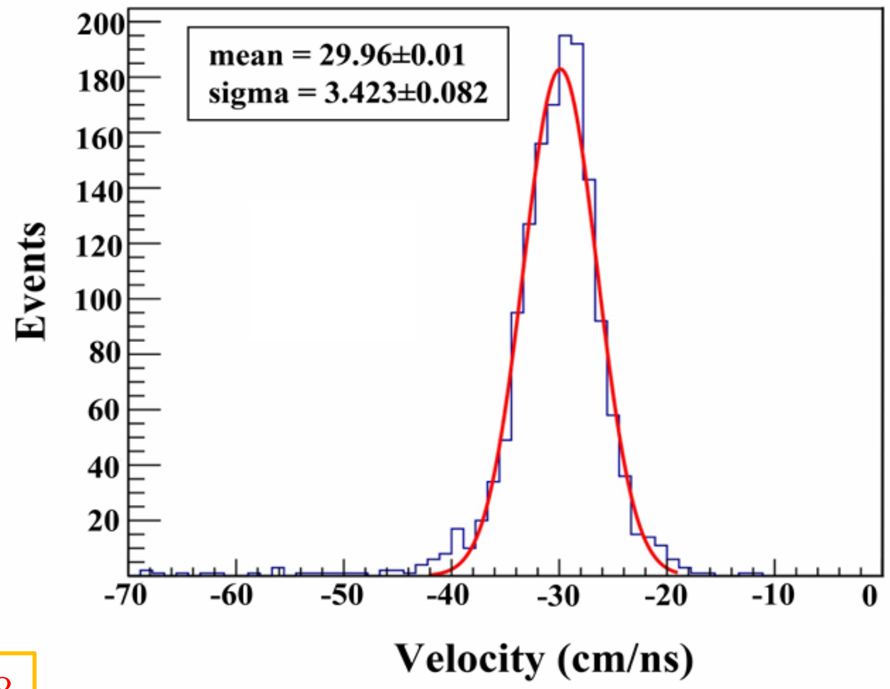
Each strips has time resolution about 120 ps.



Test bench

Lasers for time calibration





arXiv:2503.06128

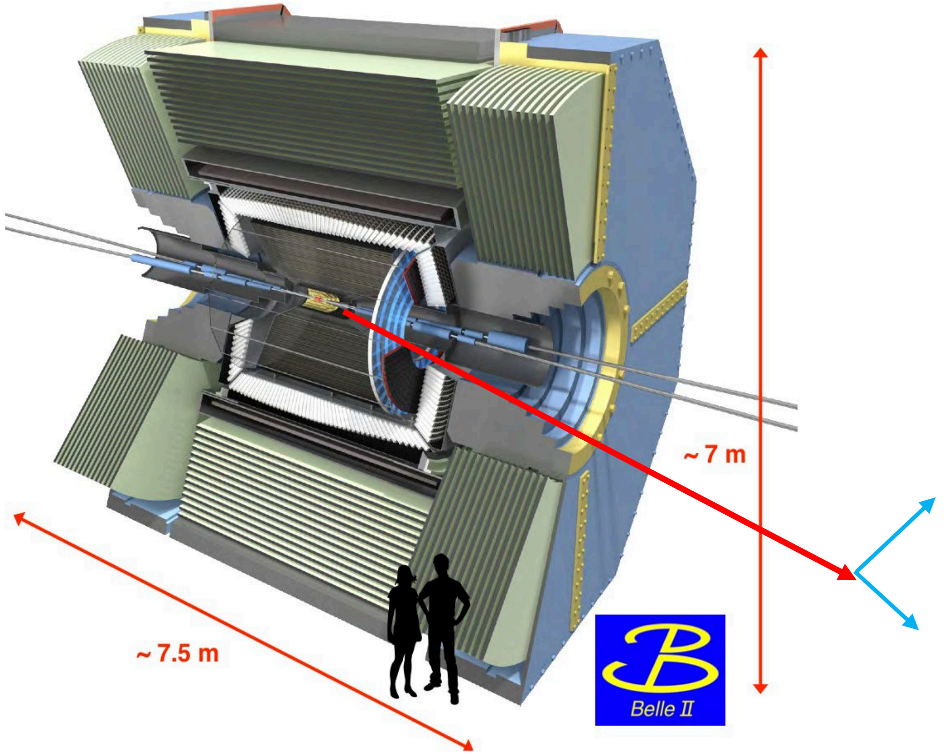
Small detector outside KLM

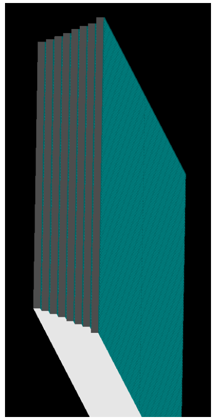
What can a new small detector can do :

- There are still some K_L^0 mesons or other long-lived particles that may escape from the KLM, and an external detector outside Belle II could effectively detect them.

The structure:

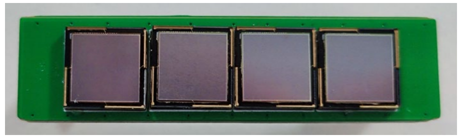
- We can design a new small detector with several scintillator layers.
- We can add iron yoke layers and make the structure like KLM.



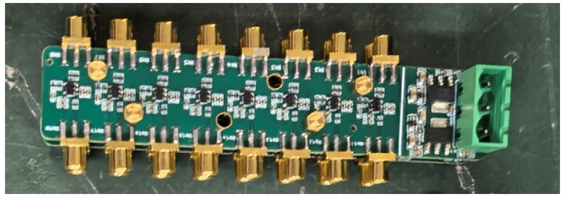


Components of the prototype

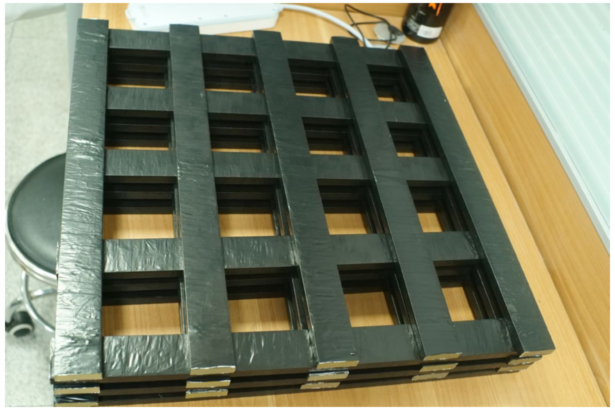
- About 90 scintillator strips, each measuring 1 cm × 4 cm × 50 cm, are ready. Each channel has a time resolution of ~80ps.
- SiPM array composed of four NDL EQR20-11-6060 SiPMs.
- Preamplifier with time resolution of about 20 ps. NST34,169(2023)
- DAQ system with 250MSPS is ready, and new DAQ with 160 channels is ongoing .
- We are building a small detector prototype with about 90 strips. It can be located near the Belle II detector for KL mesons and muons escaping the KLM.
- Photon detector is compact. Only LV power supply and a laptop for data taking are required.

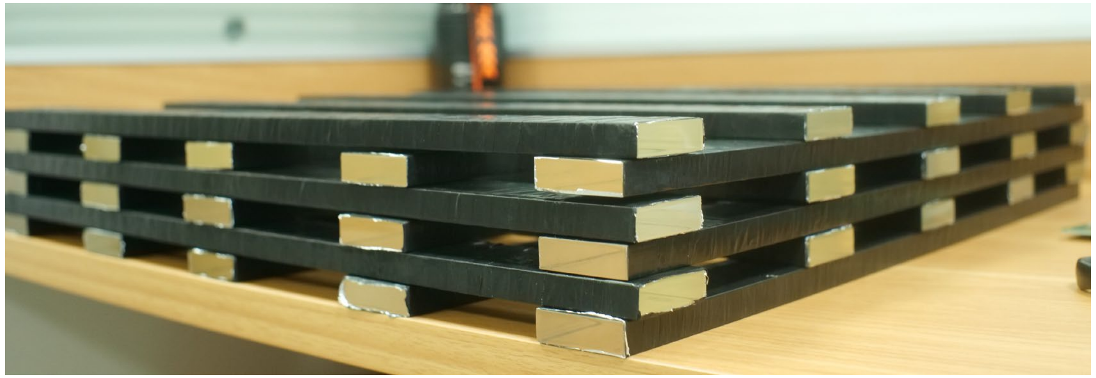


SiPM array

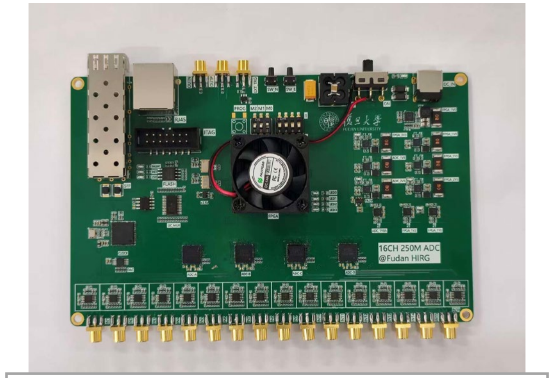


16chs preams, 10 cm × 3 cm



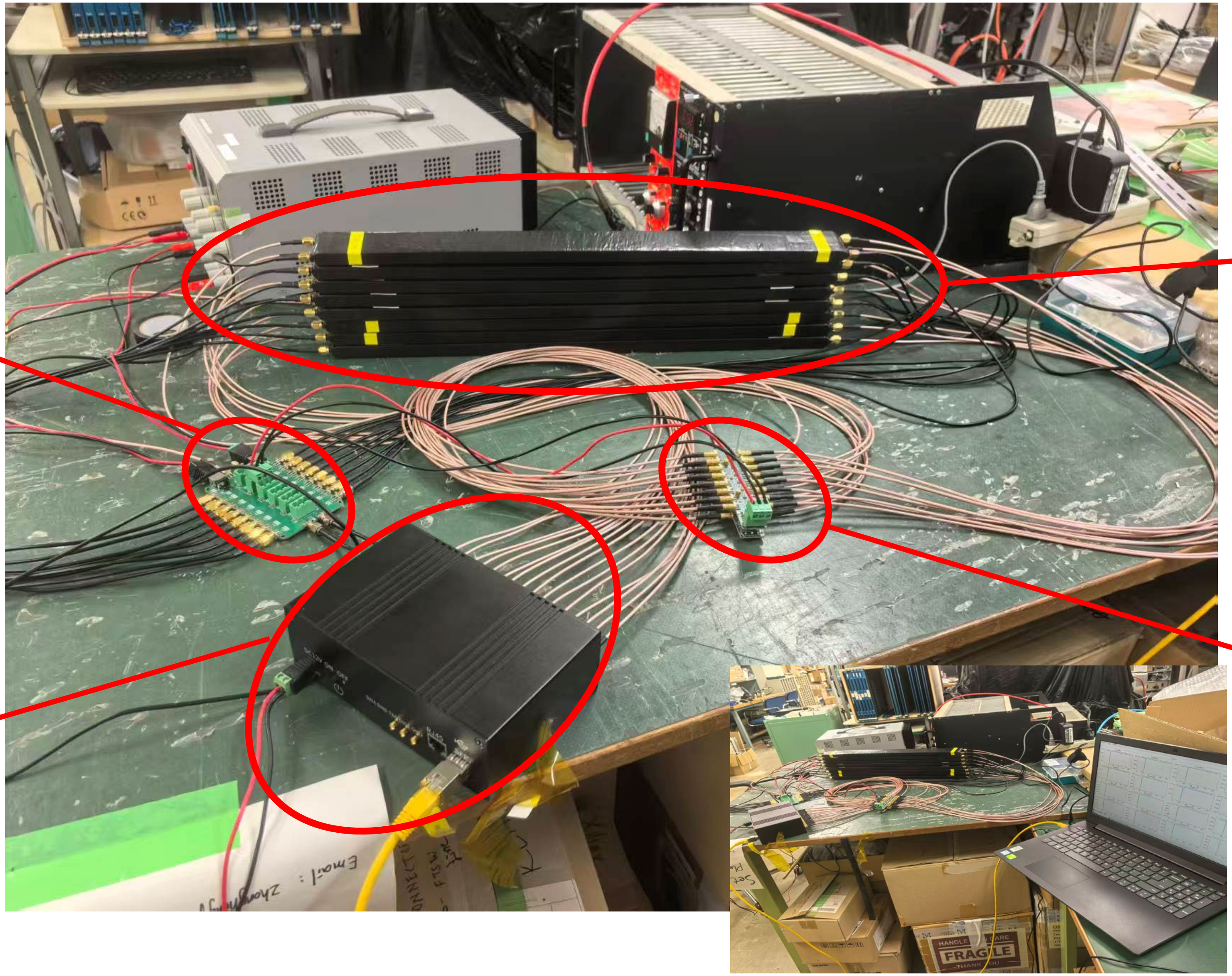


30 scintillator strips. Array size: 50 cm × 50 cm × 6 cm



250MSPS DAQ board, 10 cm × 15 cm

Setup in KEK



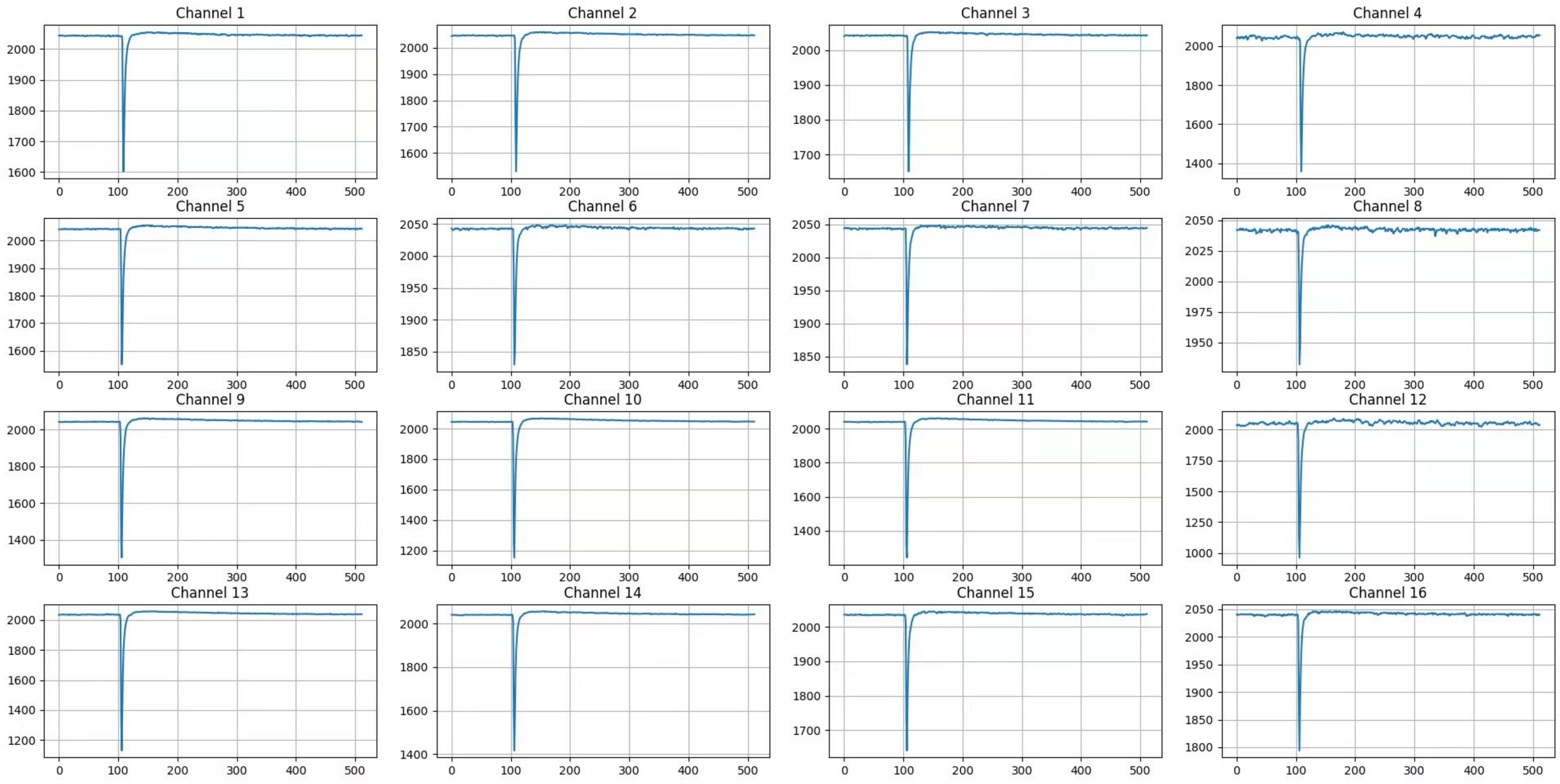
Scintillators with length of 50cm, and a time resolution of ~80 ps using an array of four 6 mm × 6 mm NDL EQR20 SiPMs for readout.

Power supply board.

Fast pre amplifier with 16 channels.

16ch DAQ with 250MSPS ADC.

Typical signals



Typical signals demonstrated by the DAQ when a CR muon passed through the eight PS strips. This picture was captured online, like shown in screen of the laptop.

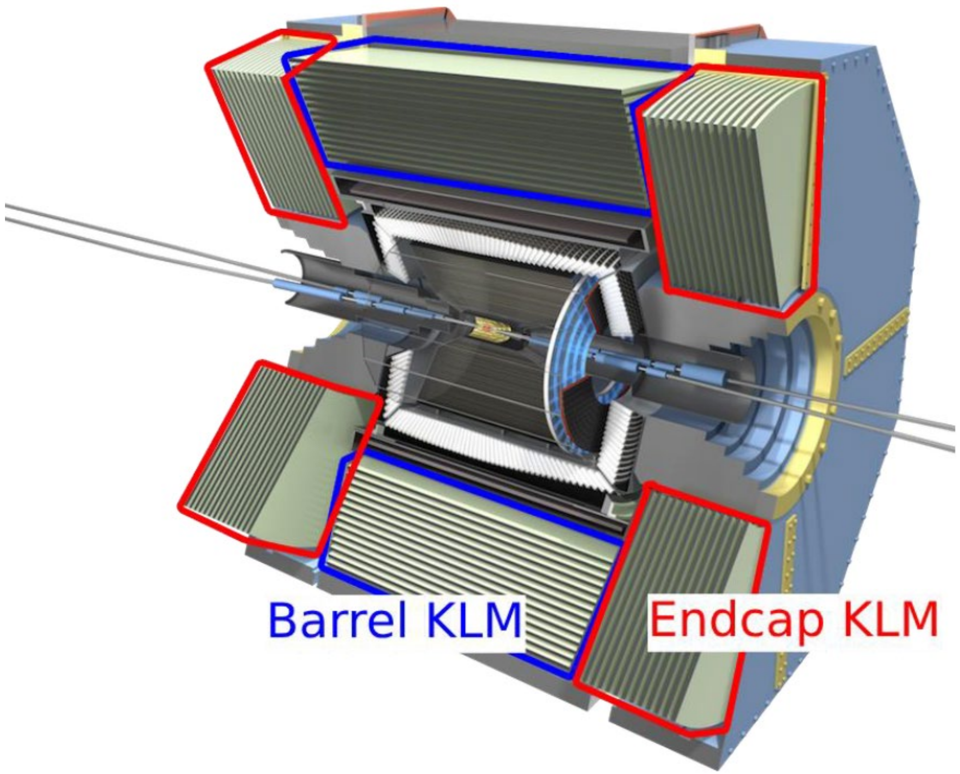
Summary

- Time resolution for 135 cm long scintillators can reach about 70 ps.
- The prototype can measure the velocity of cosmic ray muon well.
- A small detector will be held outside KLM to detect long-lived particle.
- The Belle II Detector Upgrades Framework Conceptual Design Report have been published.

Thanks!

Back up

Belle II upgrade



Subdector	Function	upgrade idea	time scale
PXD	Vertex Detector	2 layer installation	short-term
		new DEPFET	medium-term
SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
PXD+SVD	Vertex Detector	all-pixels: SOI sensors	medium-term
		all-pixels: DMAPS CMOS sensors	medium-term
CDC	Tracking	upgrade front end electronics	short/medium-term
		replace inner part with silicon	medium/long term
		replace with TPC w/ MPGD readout	long-term
TOP	PID, barrel	Replace conventional MCP-PMTs	short-term
		Replace not-life-extended ALD MCP-PMTs	medium-term
		STOPGAP TOF and timing detector	long-term
ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers	long-term
		replace HAPD with Large Area Picosecond Photodetectors	long-term
ECL	γ, e ID	add pre-shower detector in front of ECL	long-term
		Replace ECL PiN diodes with APDs	long-term
		Replace CsI(Tl) with pure CsI crystals	long-term
KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators	medium/long-term
		on-detector upgraded scintillator readout	medium/long-term
		timing upgrade for K-long momentum measurement	medium/long-term
Trigger		firmware improvements	continuos
DAQ		PCIe40 readout upgrade	ongoing
		add 1300-1900 cores to HLT	short/medium-term

Table 1.1: Known short and medium-term Belle II subdetector upgrade plans, starting from the radially innermost. The current Belle II subdetectors are the Silicon Pixel Detector (PXD), Silicon Strip Detector (SVD), Central Drift Chamber (CDC), Time of Propagation Counter (TOP), Aerogel Rich Counter (ARICH), EM Calorimeter (ECL), Barrel and Endcap K-Long Muon Systems (BKLM, EKLM), Trigger and Data aquistion (DAQ). DAQ includes the high level trigger (HLT).

What can a new KLM do?

1. Improve the KL ID. Better identification and better neutrino veto.
2. TOF-like to determine the momentum of a neutral hadron directly.
3. Contribute to dark sector search?
4. Keep the good muon ID.

Snowmass whitepaper: arXiv: 2203.11349

FCDR: arXiv:2406.19421.

Influencing factor of time resolution

- Coincidence time resolution（CTR）

$$CTR \propto \sqrt{\tau_{d}/n_{p}}$$

τ_d: scintillation decay time

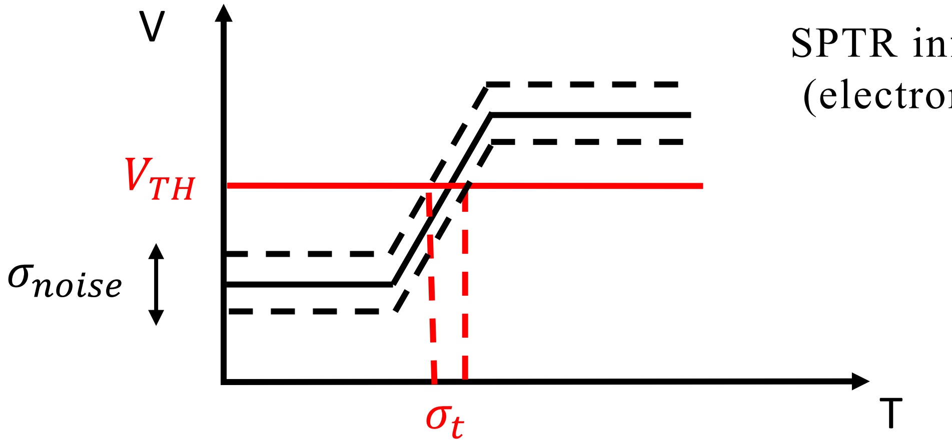
n_p: the number of photons detected

- the contribution of electronic noise on SPTR[2]:

$$\sigma_t = \frac{\sigma_{noise}}{dV/dt}$$

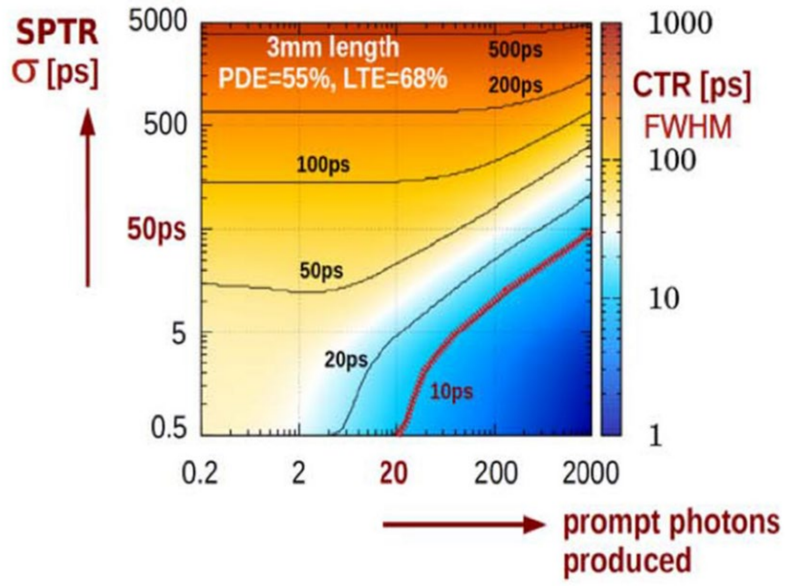
σ_{noise} : the RMS of baseline noise

dV/dt : The slope of single photon waveforms



SPTR influenced by: (electronics、SiPM)

- Improve the rise time → High bandwidth, high swing rate (>350MHz)
- Readout electronics noise reduction → Low-noise transistors, filter circuits* (<1mV)



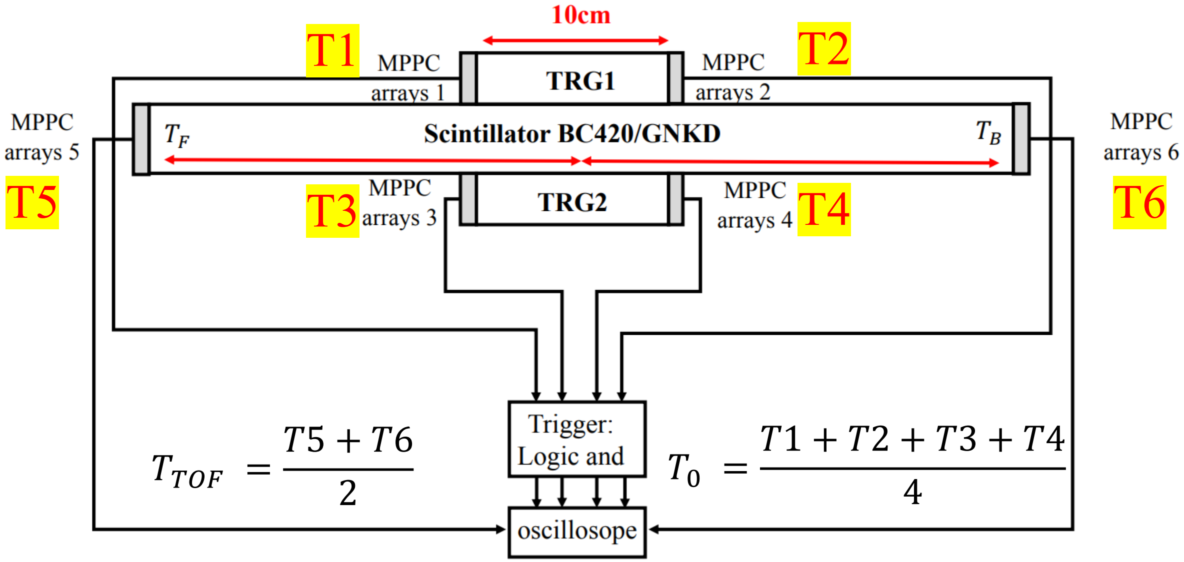
single photon time resolution (SPTR)[1]

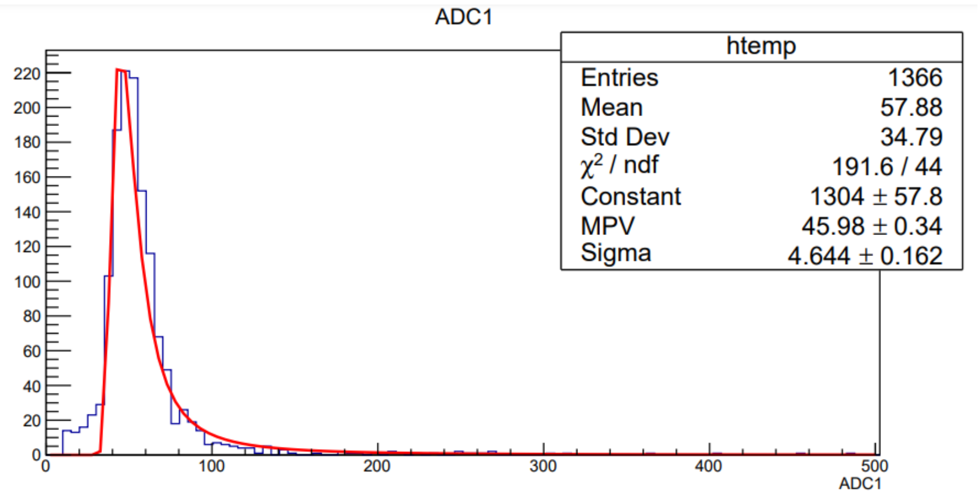
scintillator: 3mm length LSO:Ce,Ca(0.4%) crystal

To improve CTR:
- Selection of scintillators --short decay time
- Increase photon number collection (high light yield)

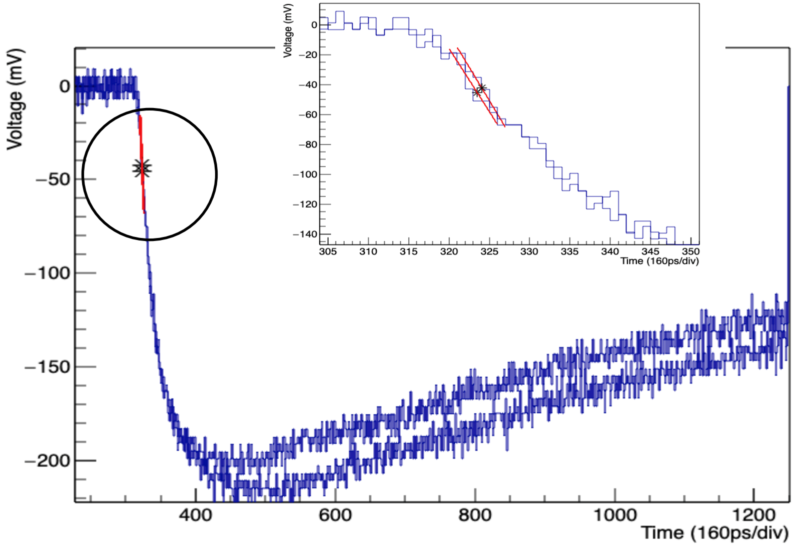
[1]Stefan Gundacker, ect Measurement of intrinsic rise times for various L(Y)SO and LuAG scintillators with a general study of prompt photons to achieve 10 ps in TOF-PET[J],2016,61(7).
[2]Joshua W Cates,ect Improved single photon time resolution for analog SiPMs with front end readout that reduces influence of electronic noise[J],2018,63(18).

CFD method





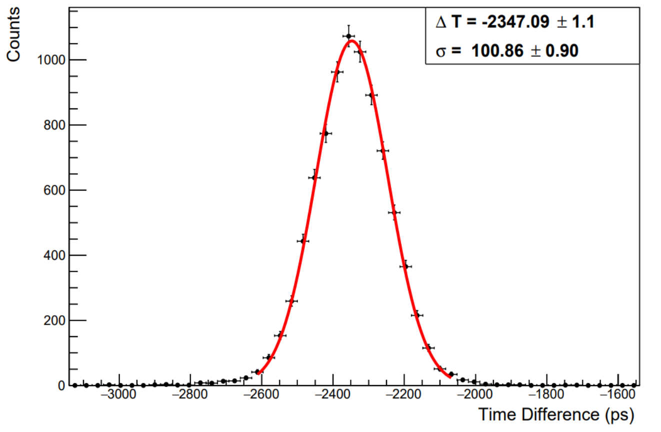
Energy spectrum of cosmic rays

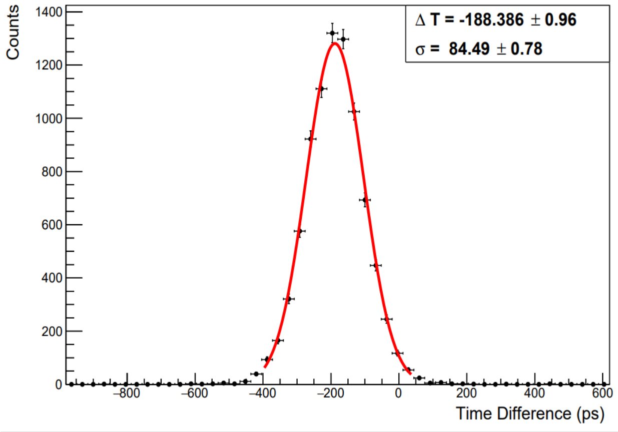


CFD timing of waveform

$$\frac{T1+T2}{2} - \frac{T3+T4}{2} \rightarrow \sigma_{TRG} \rightarrow \sigma_{T_0}$$

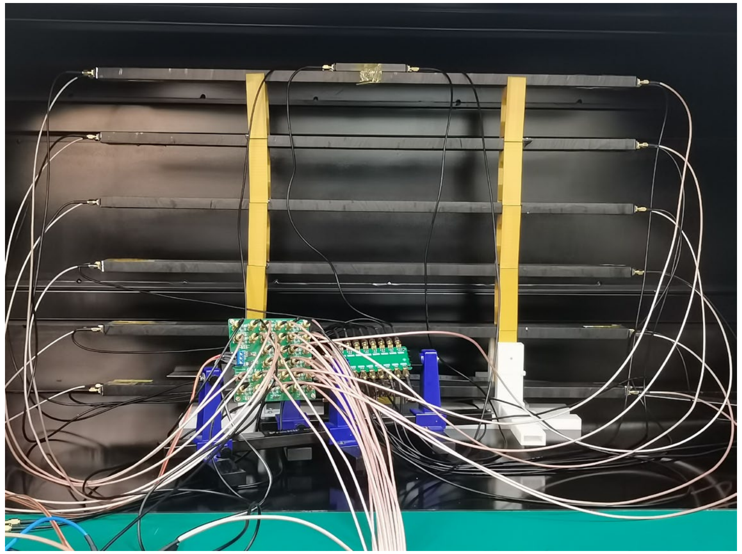
$$T_0 - T_{TOF} \rightarrow \sigma_{T_{TOF}}$$

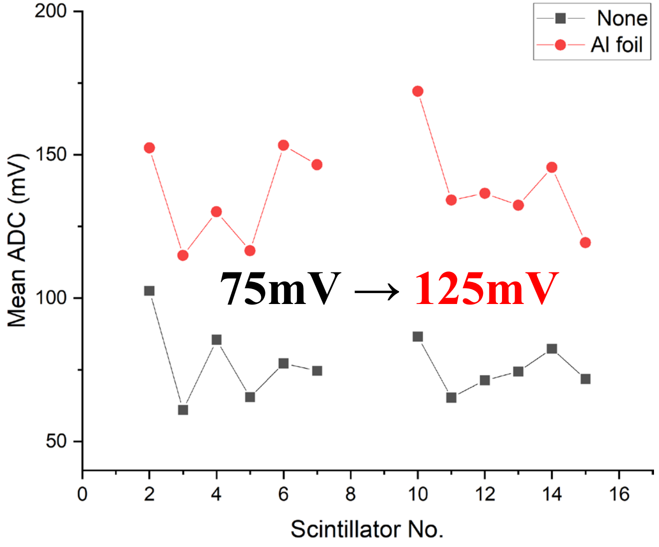


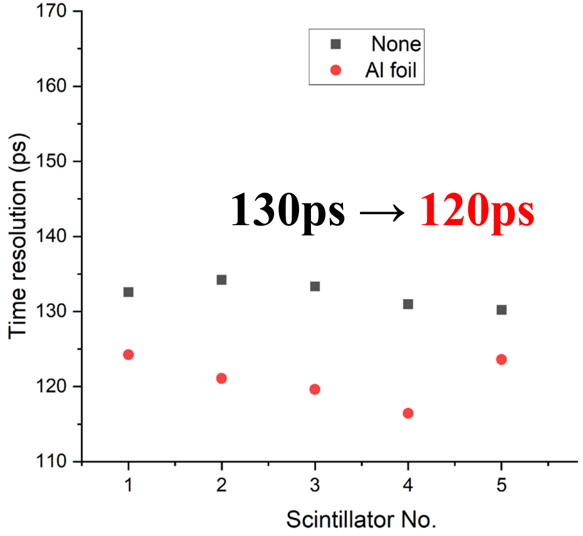


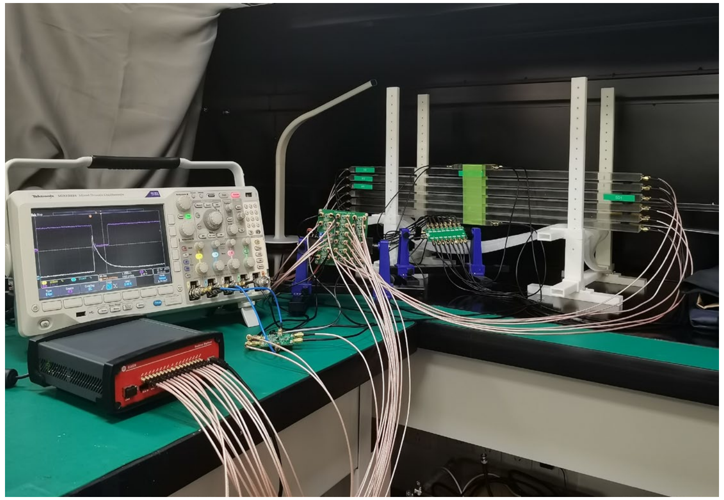
Prototype test

- Using aluminum foil as the reflector can improve the signal amplitude, thus improve the time resolution.

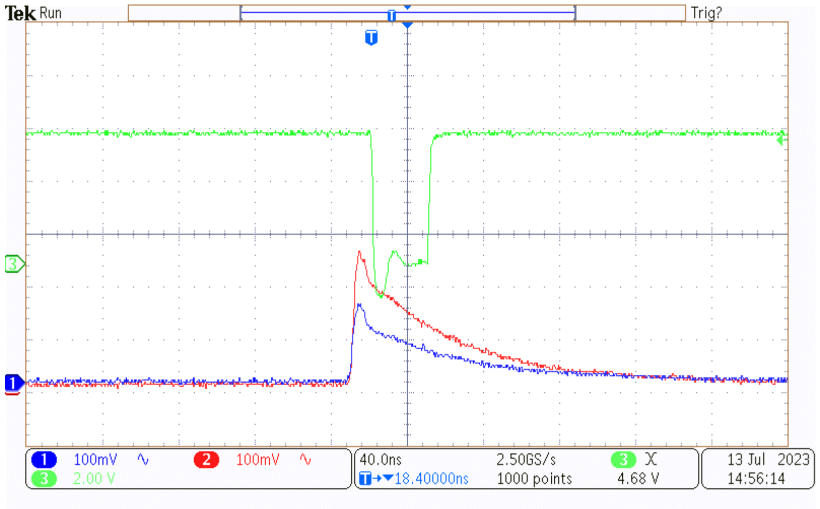




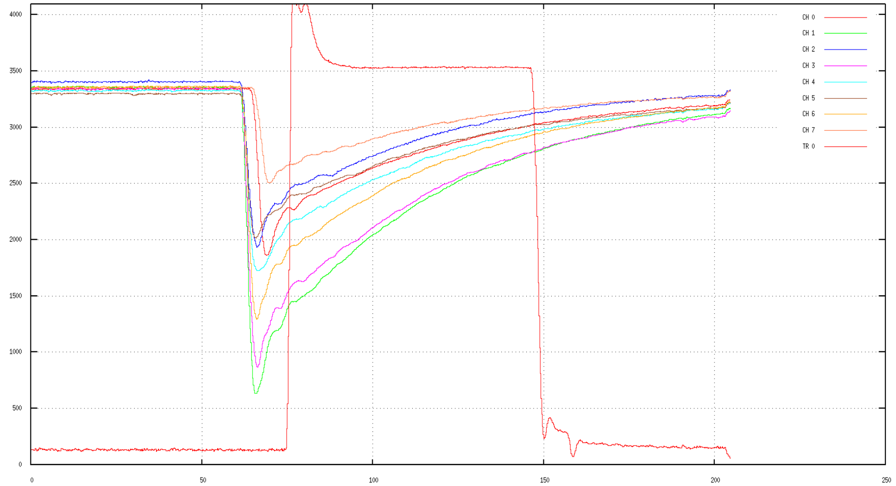




Prototype test setup



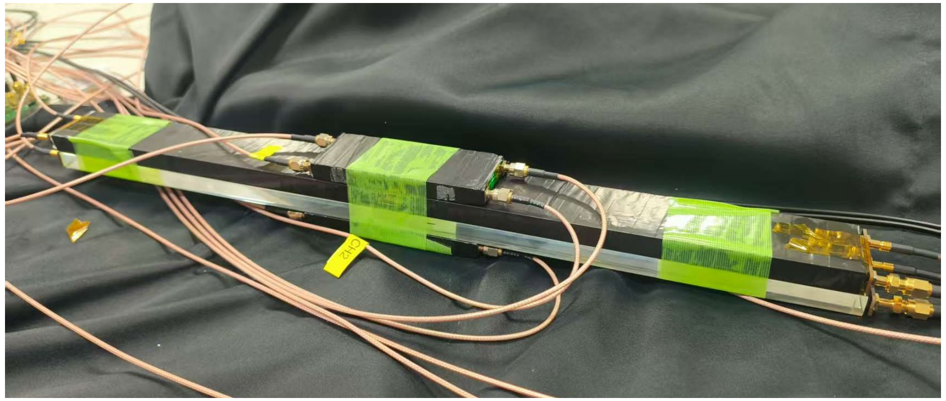
Trigger signal waveform

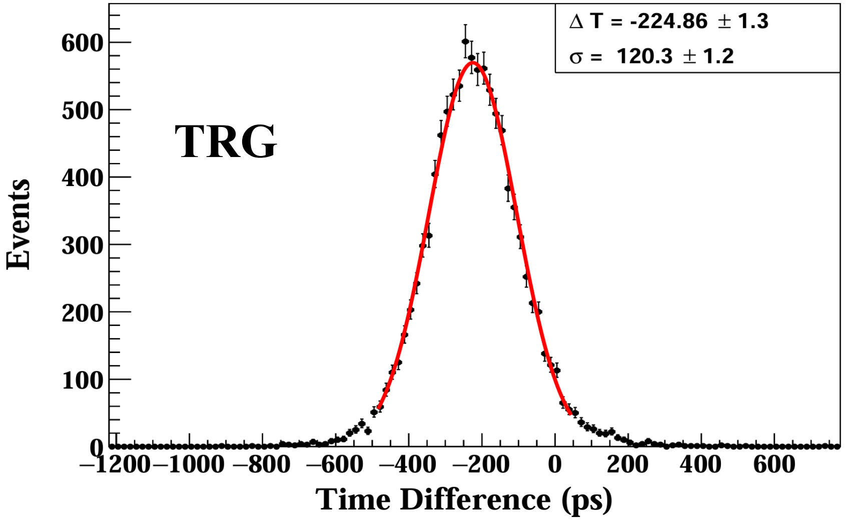


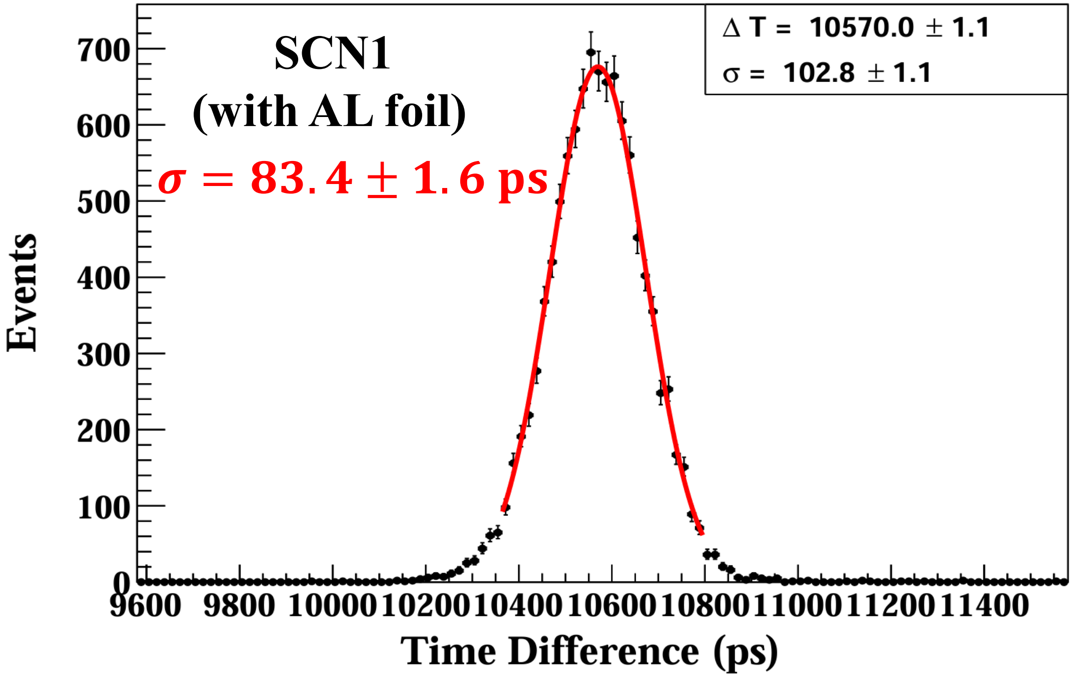
DT5742 signal waveform

Cosmic ray test for NDL_4S

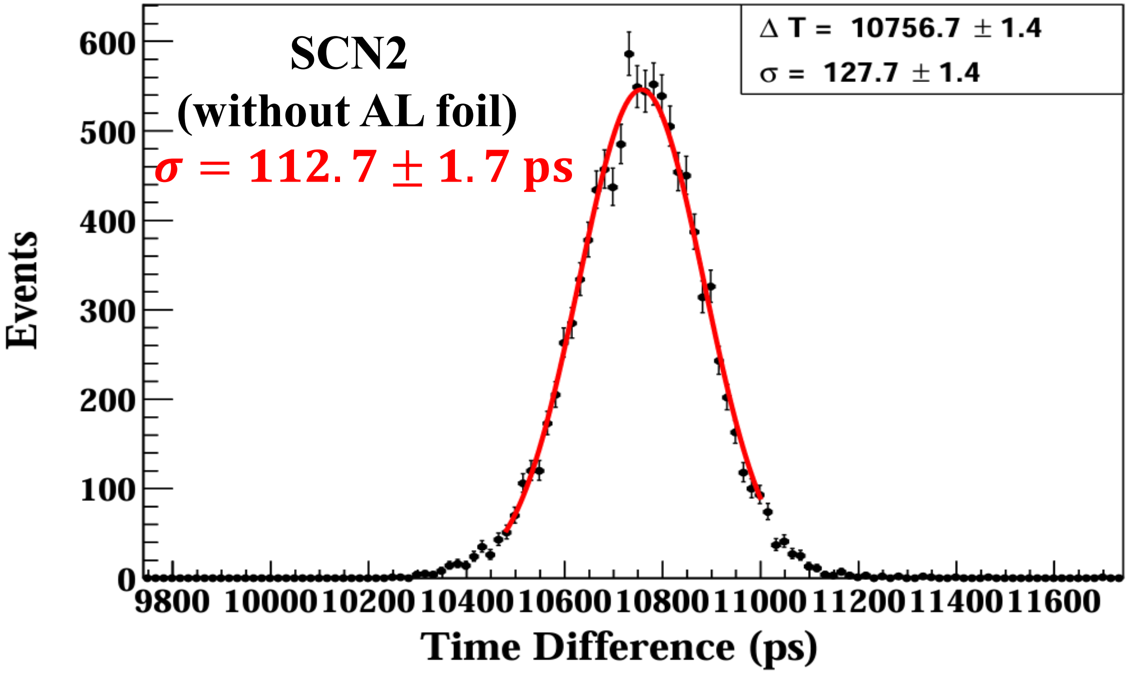
Setup







$\sigma = 83.4 \pm 1.6$ ps



$\sigma = 112.7 \pm 1.7$ ps

High voltage supply module

+7 V

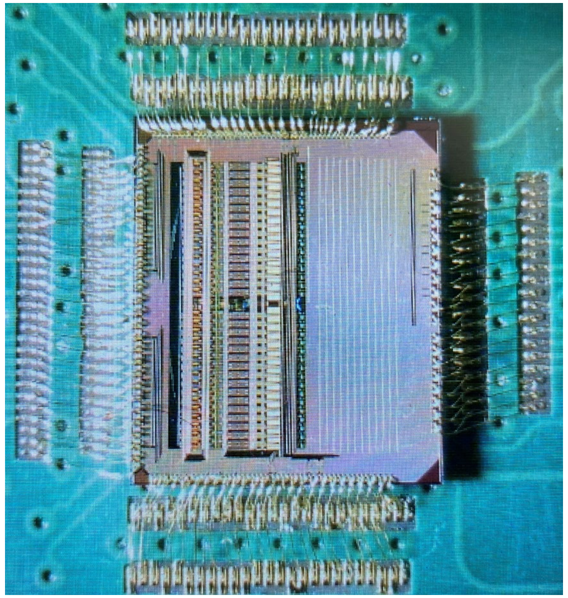
MPT2321

The MPT2321 chip is a SiPM signal processing SoC chip designed for high-precision time-of-flight signal processing.

Joint R&D by Fudan University, Zhejiang University, USTC, and IHEP.

Features

- 32 input channels
- Automatically select the range of measurement signals
- 50ps precision 20-bit TDC
- 12bit ADC
- Complete on-chip signal processing
- Standard IIC Bus Control
- 8b10b encoding transmission
- Multichannel LVDS data transmission
- 12 Mcps transmission event rate
- High integration, low power consumption
- 200M data transmission rate
- The maximum charge measurement dynamic range is 2.4 nC
- Minimum detectable signal range 4fC



MPT2321 chip

宇称电子
MICROPARITY
Sensor and Science

DAQ R&D based on MPT2321 is ongoing, will be used to replace the 250MSPS ADC.

Similar works from EIC

Design and expected performance for the hKLM at the EIC

Ilieva, Jacobs, Kelleher, Kim, Nadel-Turonski, Visser, Vossen

Abstract

This paper describes the design concept and estimated performance for a iron-scintillator sampling calorimeter for the future Electron Ion Collider. The novel aspect of this detector is the excellent time resolution enabling time-of-flight capabilities as well as a more compact design. Machine Learning is used to optimize the detector design and the highly segmented readout is designed with Machine Learning algorithms in mind to reach performances usually reserved to more complex detector systems. The primary physics objective of this detector is to serve as a muon system at a detector at the EIC as well as for the identification and momentum measurement of neutral hadrons. At the EIC, these are mainly K_L's and neutrons. For lower energy, excellent relative momentum measurements of a few 10% are achieved using time-of-flight for higher particle momenta, energy can be measured calorimetrically with a resolution significantly better than has been demonstrated for similar calorimeters that are summarily read out.

Duke and Indiana have been working on a similar proposal for EIC for several years.

Or see arXiv: 2511.08432