Belle II KLM的升级研究与CEPC缪子探测器的研发

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2024超级陶粲装置研讨会

兰州大学

2024/07/09

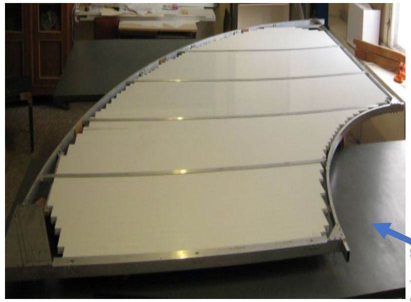
Structure of the current KLM detector

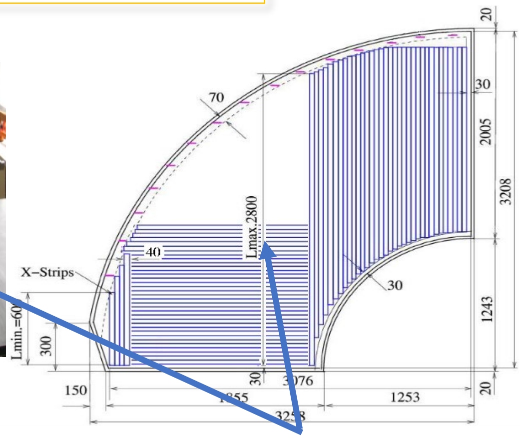
Belle II KLM

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

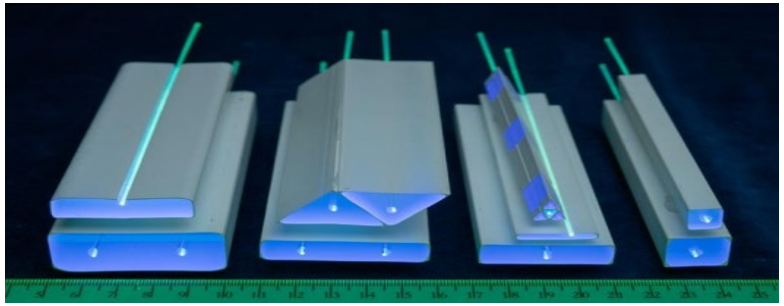
$$\sigma = \text{width} / \sqrt{12}$$

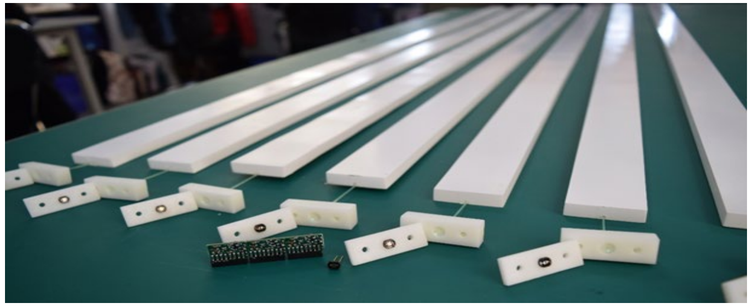
- Wave length shift (WLS) fiber inside scintillator to collect photons and guide them to SiPM.
- Use SiPM at one end, small size, low cost, low operating voltage, high gain and can work at high magnetic field.

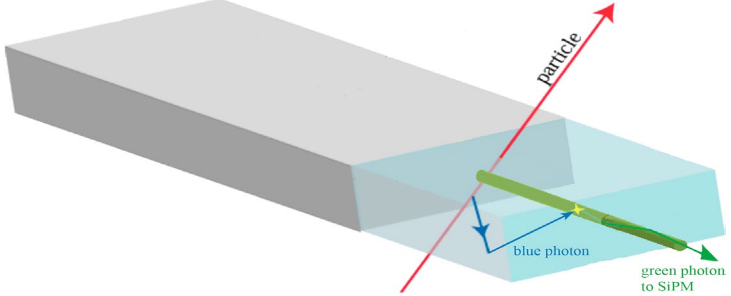




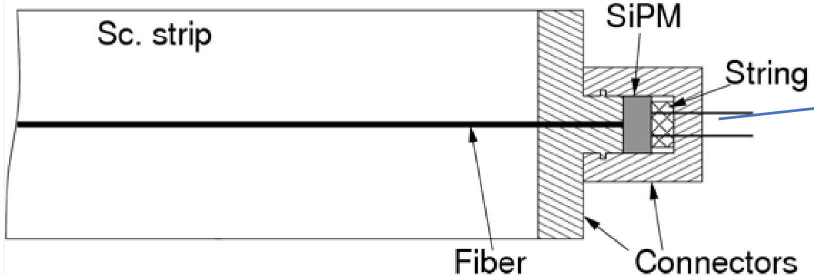
Superlayer for good 2-D resolution

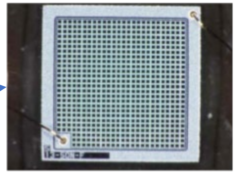






- ➢ **Extruded scintillator**: cheap in massive production, but the attenuation length is only several centimeters.
- ➢ **WLS**: Kuraray Y11(200), a diameter of 1.2 mm.
- ➢ **SiPM**: Hamamatsu MPPC, S10362, 1.3mm × 1.3mm.





CEPC muon system

CEPC : FUTURE LEPTON COLLIDER

- Higgs/W/Z bosons, top, BSM searches, etc.
- Precision jet measurement.

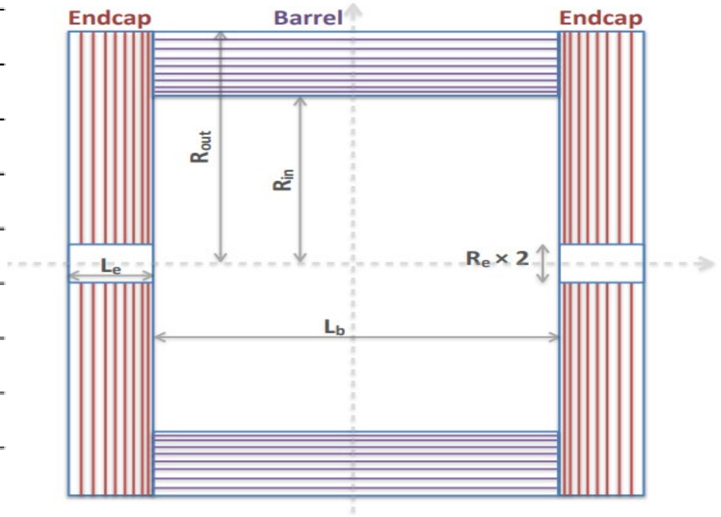
CEPC MUON SYSTEM

- **Muon identification.**
- **Standalone measurements of the muon momenta.**
- **Improve the identification of muons produced inside jets.**
- **Improve the jet energy resolution.**

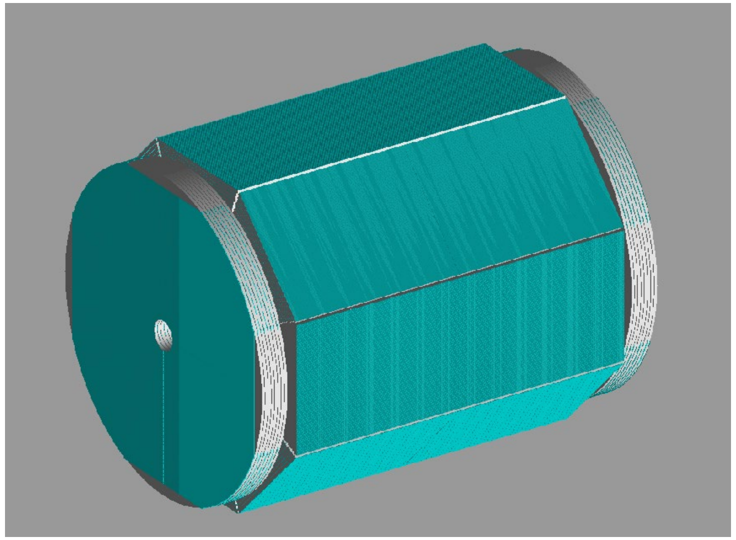
SCINTILLATION DETECTOR:

- Low costs
- High efficiency

Parameter	Baseline
$L_b/2$ [m]	4.14
R_{in} [m]	4.40
R_{out} [m]	6.08
L_e [m]	1.72
R_e [m]	0.50
Segmentation in ϕ	12
Number of layers	8
Total thickness of iron (λ = 16.77 cm)	6.7λ (112 cm) (8/8/12/12/16/16/20/20) cm
Solid angle coverage	0.98 $\times 4\pi$
Position resolution [cm]	$\sigma_{r\phi}$: 2 σ_z : 1.5
Time resolution [ns]	1 – 2
Detection efficiency (P_μ > 5 GeV)	> 95%
Fake($\pi \to \mu$)@30GeV	< 1%
Rate capability [Hz/cm^2]	~60
Technology	RPC (super module, 1 layer readout, 2 layers of RPC)
Total area [m^2]	Barrel: ~4450 Endcap: ~4150 Total: ~8600



The structure of muon system at CEPC.



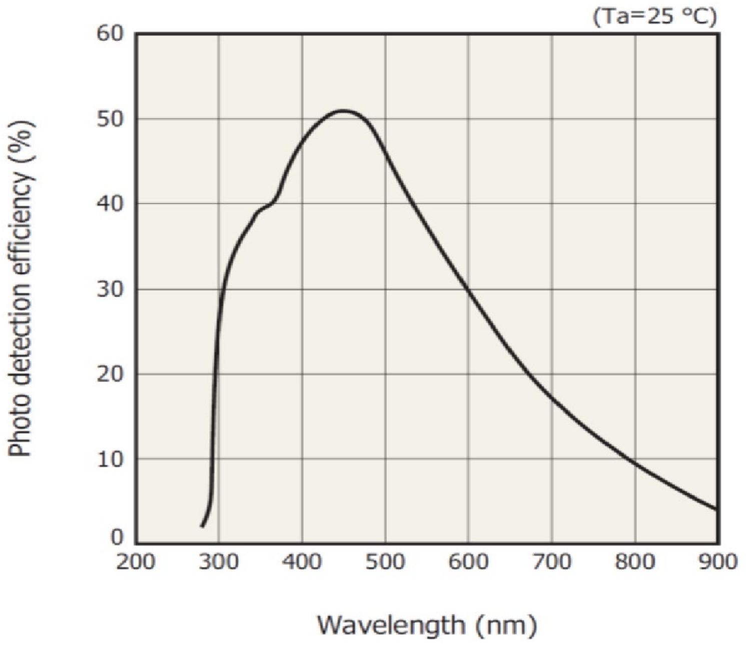
Hamamatsu MPPC and NDL SiPMs

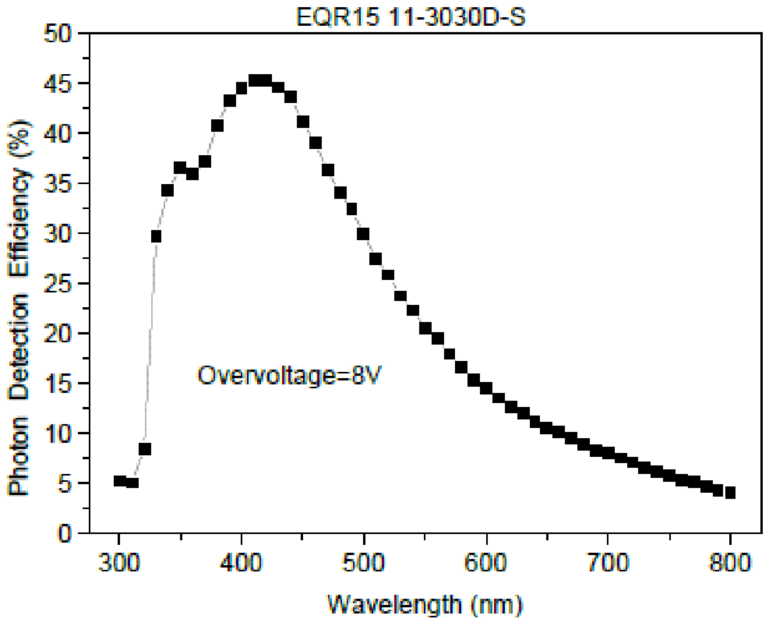
MPPC (Multi-Pixel Photon Counter) | **S14160/S14161 series**

Electrical and optical characteristics (Typ. Ta=25 °C, Vover=2.7 V, unless otherwise noted)

Parameter		Symbol	S14160/S14161 -3050HS-04, -08	S14160/S14161 -4050HS-06	S14160/S14161 -6050HS-04	unit
Spectral response range		λ	270 to 900			nm
Peak sensitivity wavelength		λp	450			nm
Photon detection efficiency at λp[*3]		PDE	50			%
Breakdown voltage		VBR	38			V
Recommended operating voltage[*4]		Vop	VBR + 2.7			V
Vop variation between channels in one product[*5]	Typ.	-	0.1			V
	Max.		0.3			
Dark current	Typ.	ID	0.6	1.1	2.5	μA
	Max.		1.8	3.3	7.5	
Crosstalk probability		-	7			%
Terminal capacitance		Ct	500	900	2000	pF
Gain		M	2.5×10^6			-
Temperature coefficient of recommended reverse voltage		ΔTVop	34			mV/°C

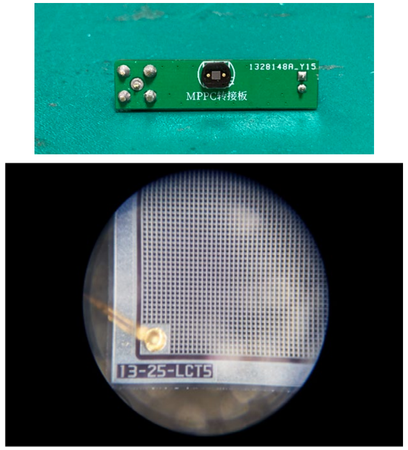
Type	EQR15 11-3030D-S/E	EQR15 22-1313D-S/E
Pitch	15 μm	
Element Number	1×1	2×2
Active Area	3.0×3.0 mm²	1.3×1.3 mm²
Micro-cell Number	40000	7396
Breakdown Voltage (V_B)	28±0.2 V	28±0.2 V
Temperature Coefficient for V_B	28 mV/°C	28 mV/°C
Recommended Operation Voltage	V_B+8 V	V_B+8 V
Peak PDE @420nm	45.4 %	45.7 %
Gain	4×10^5	4×10^5
Dark Count Rate (DCR)	2380 kHz	413 kHz
Terminal Capacitance	50 pF	10 pF



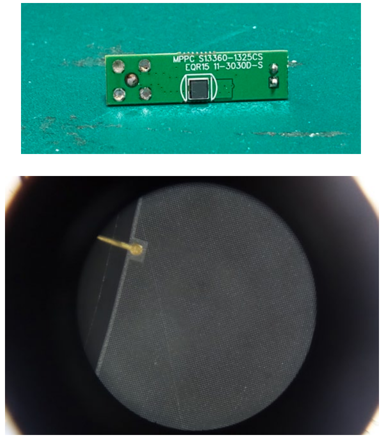


- Lower gain and higher DCR.
- Lower Vop and smaller Capacitance.
- Very small pixel size.
- PDE curve is similar

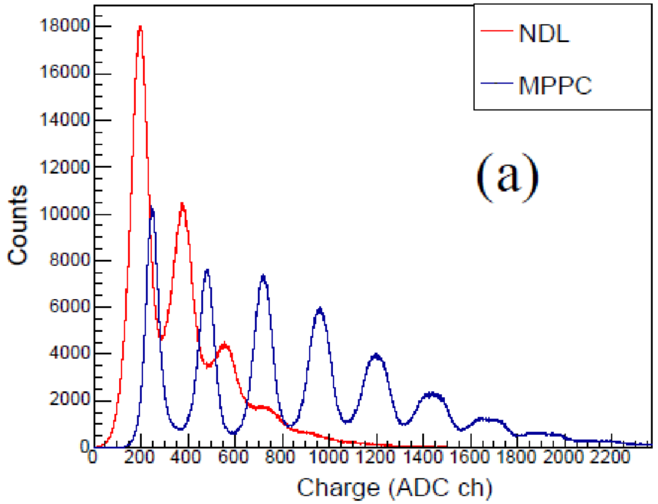
Photoelectron peak test of NDL & MPPC with laser

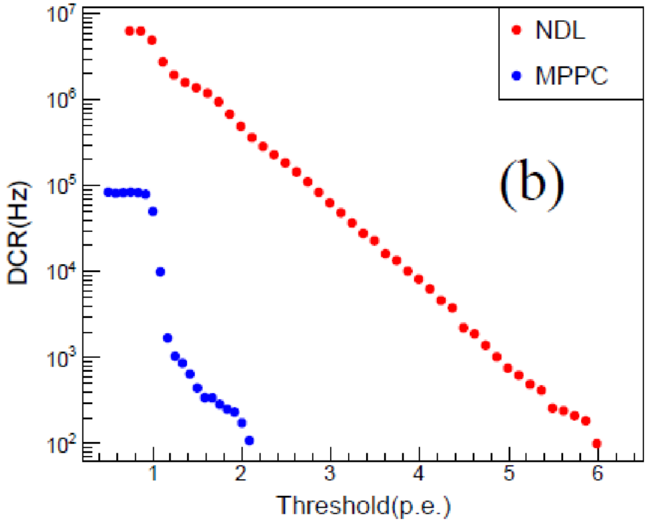


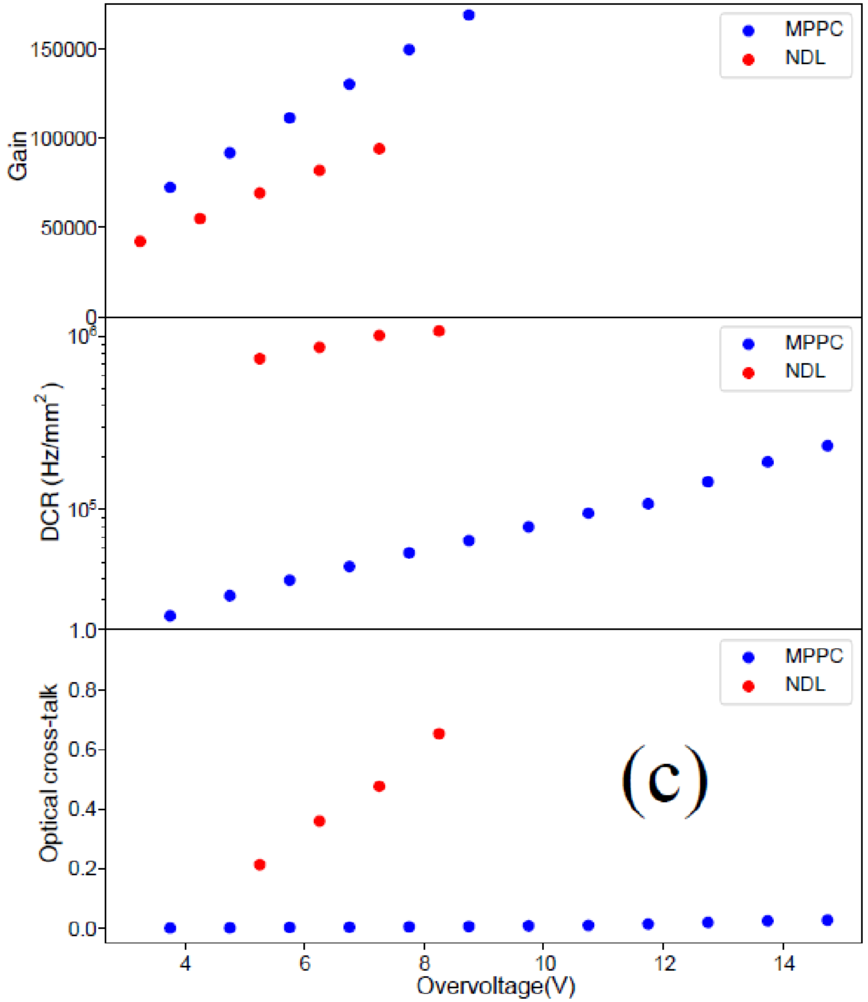
MPPC ($1.3 \times 1.3\ mm^2$)



NDL ($3 \times 3\ mm^2$)

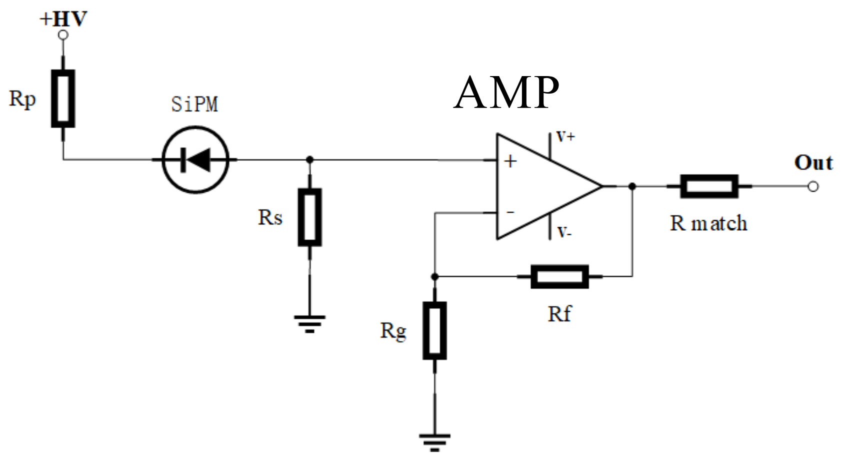






- ➢ High DCR and cross talk of NDL.
- ➢ Development ongoing.

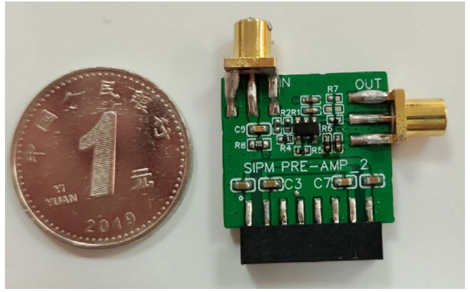
Design of preamplifier

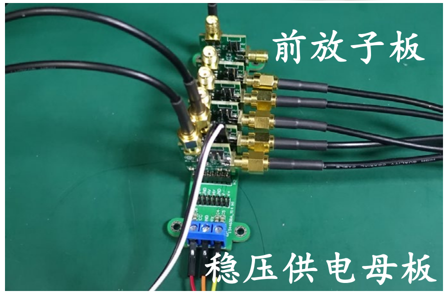


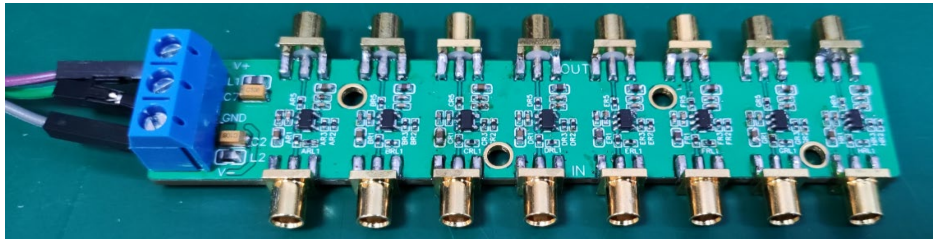
Gain： +20 V/V

Bandwidth(-3dB)： 400 MHz

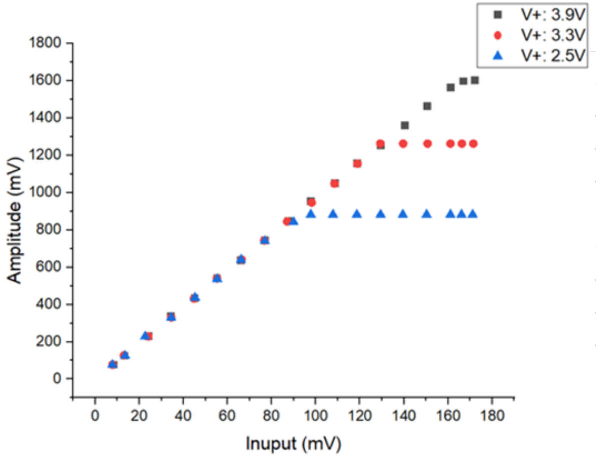
Baseline noise(RMS): 300uV

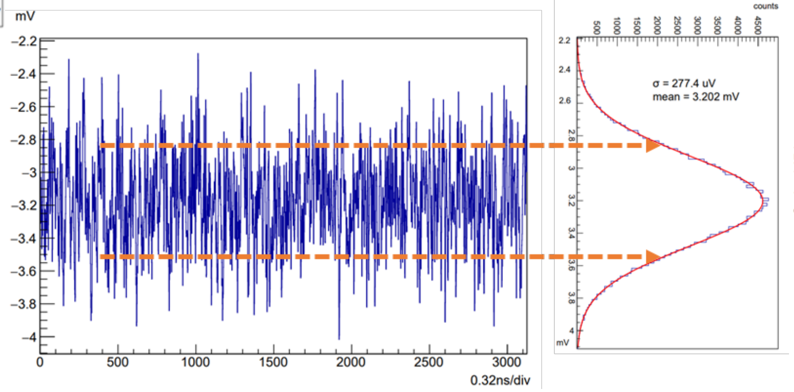


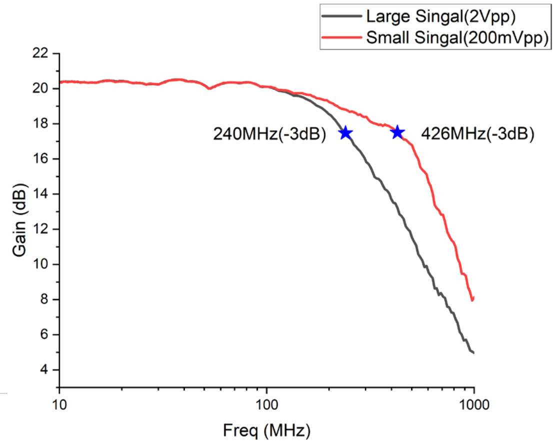


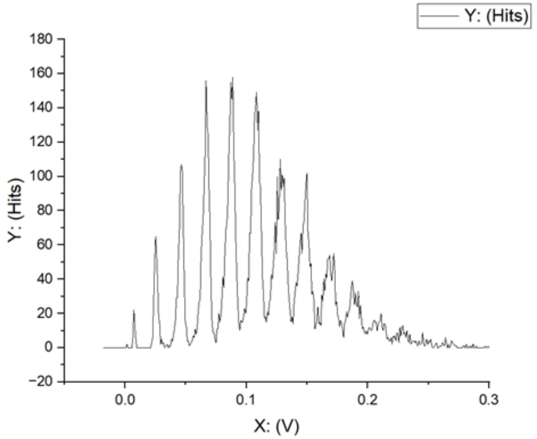


➤ Performance test of preamplifier









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

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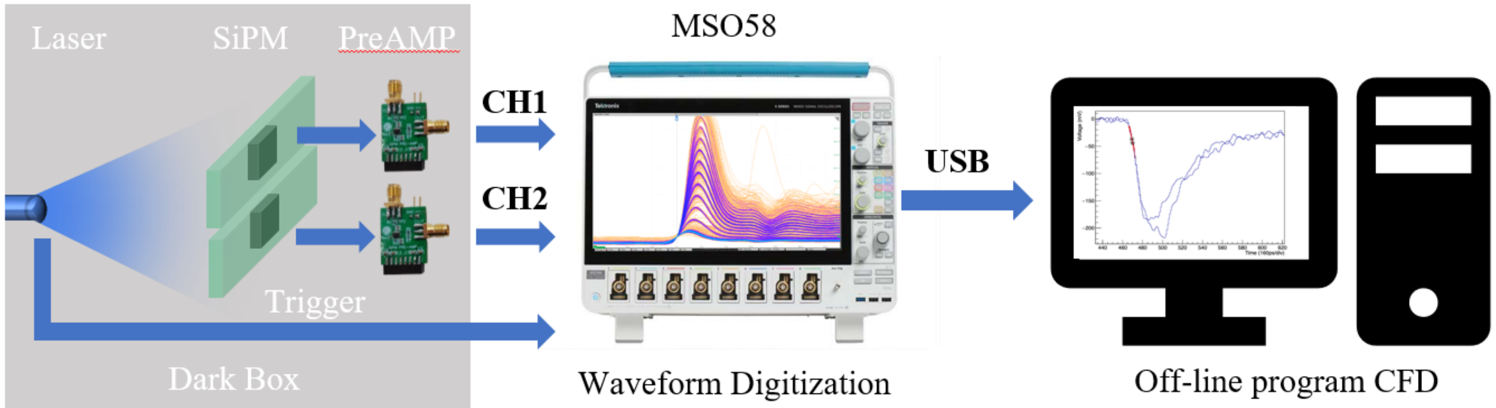
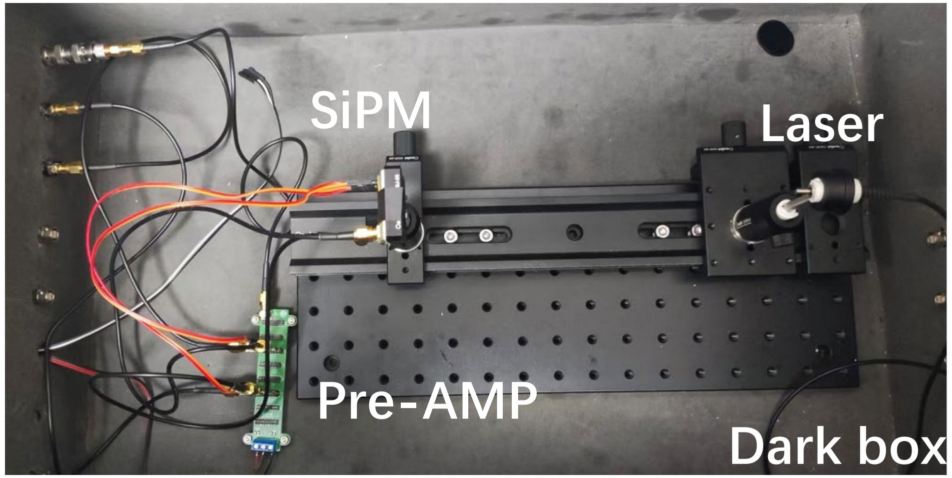
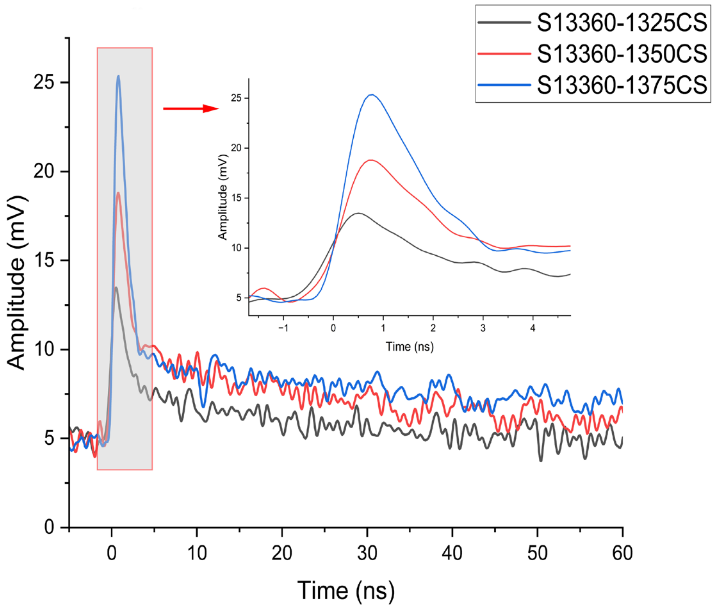
SiPM time resolution test

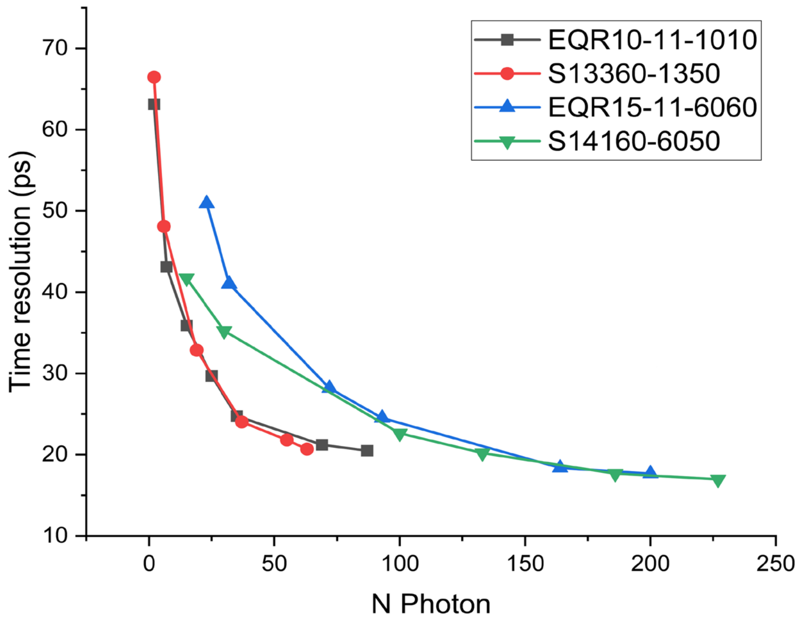




Time resolution test setup



Single photon signal of SiPMs



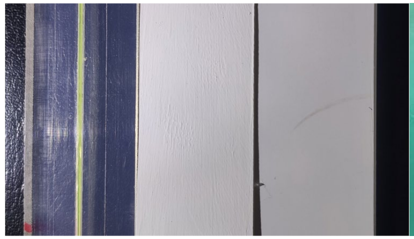
Time resolution varies with the number of photons

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

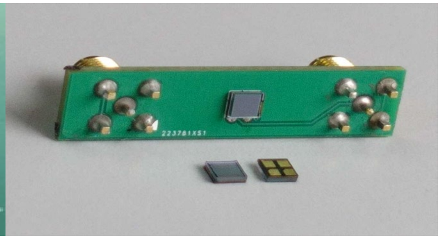
Test bench

Scintillator with
Reflective layer



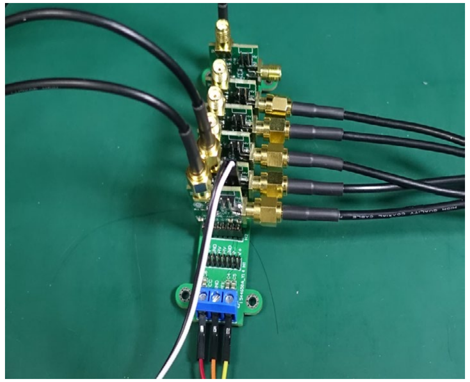
WLS fiber

SiPM

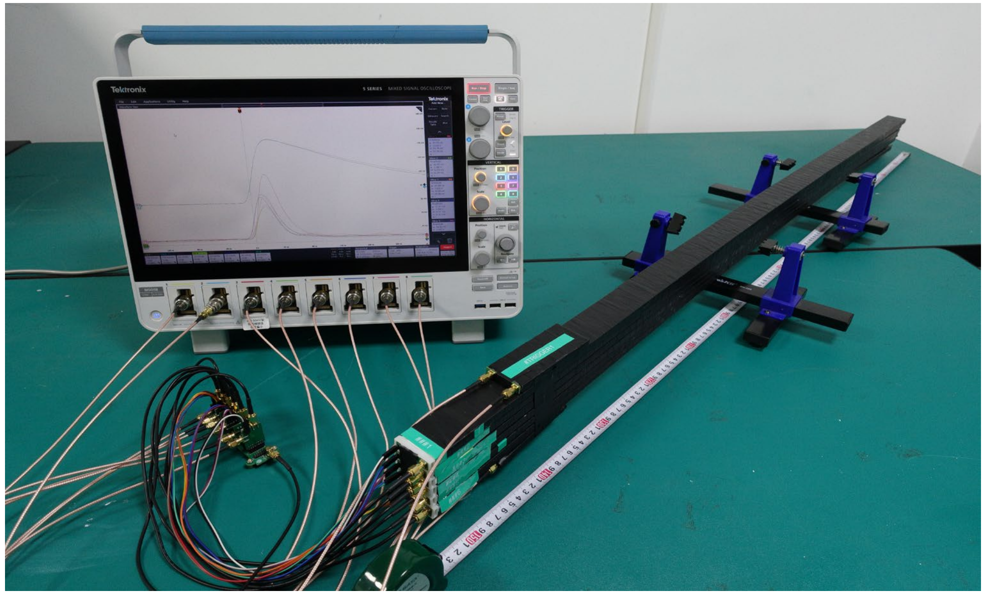


Dark box

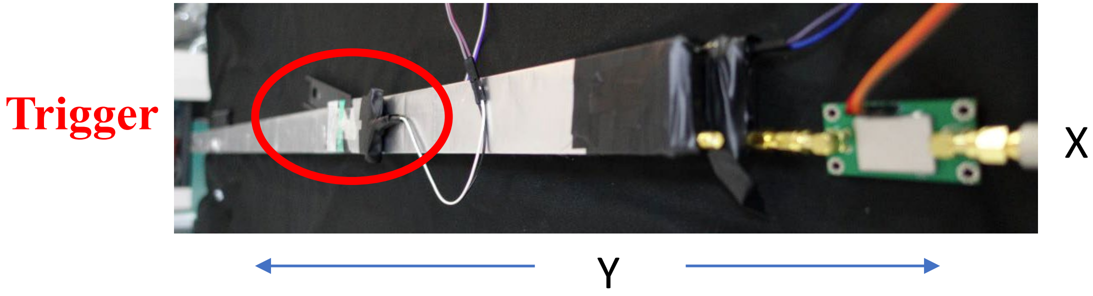
1.5 m scintillation detector



Preamplifier



Light collection of scintillator detector



Wavelength-shifting fiber keeps good photon collection at long distance, and time resolution is 1-2 ns .

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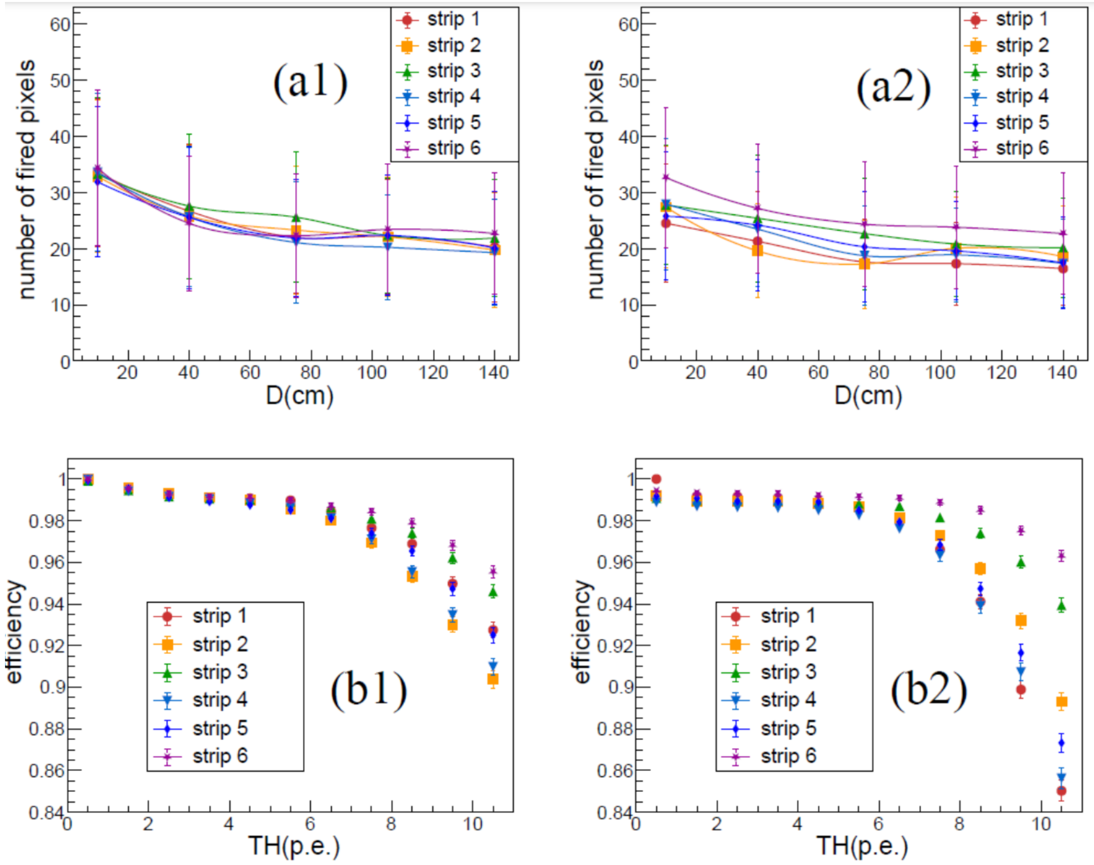
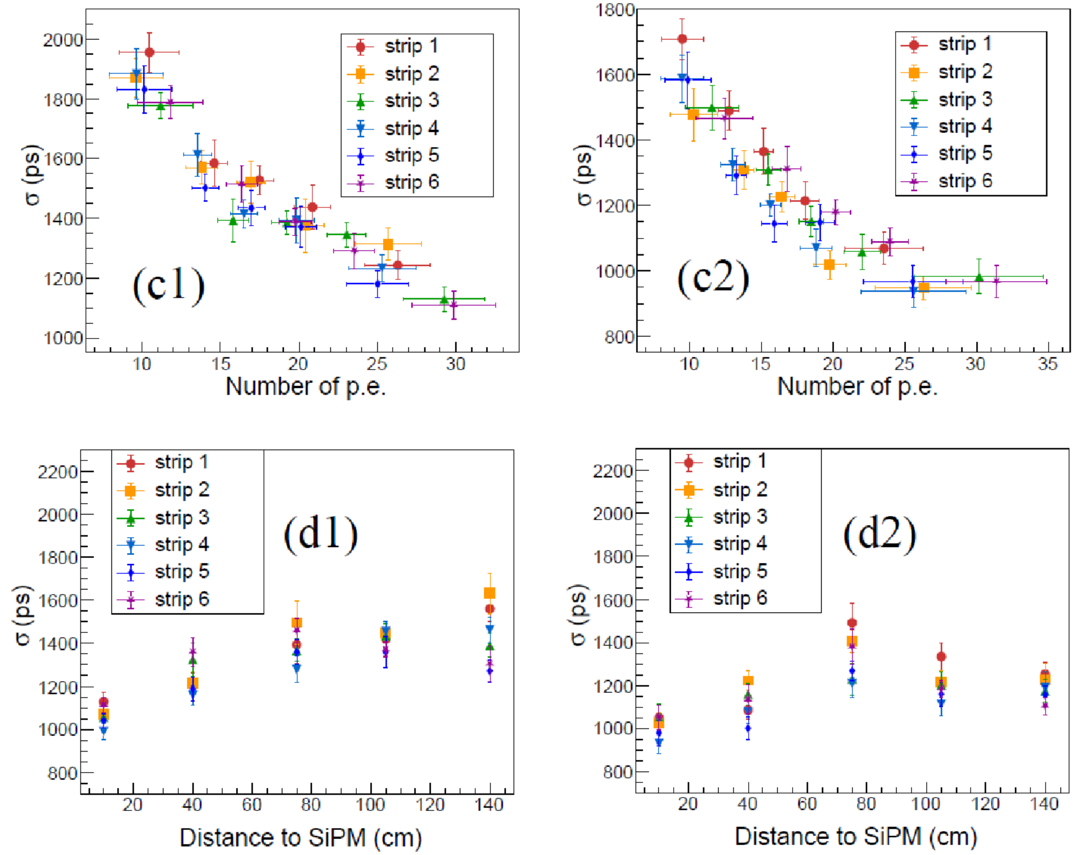
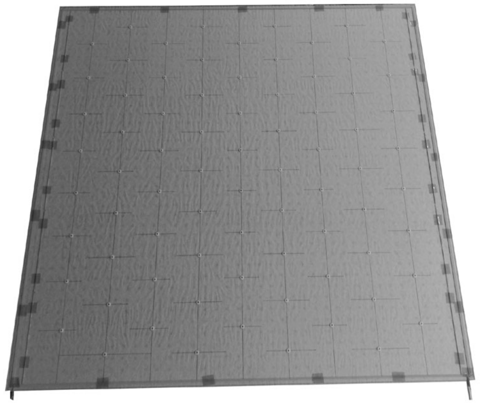
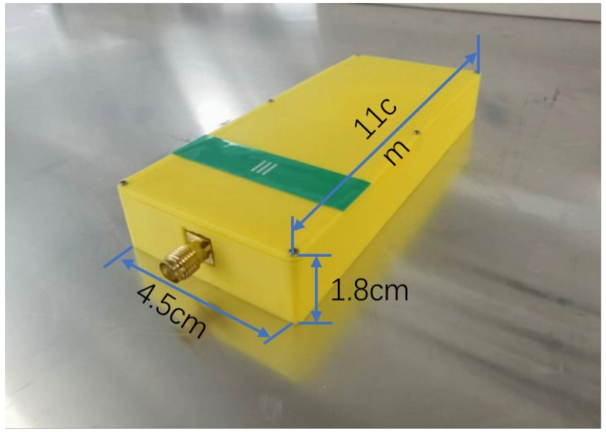




NDL MPPC NDL MPPC

RPC in SJTU and test setup





Efficiency test setup

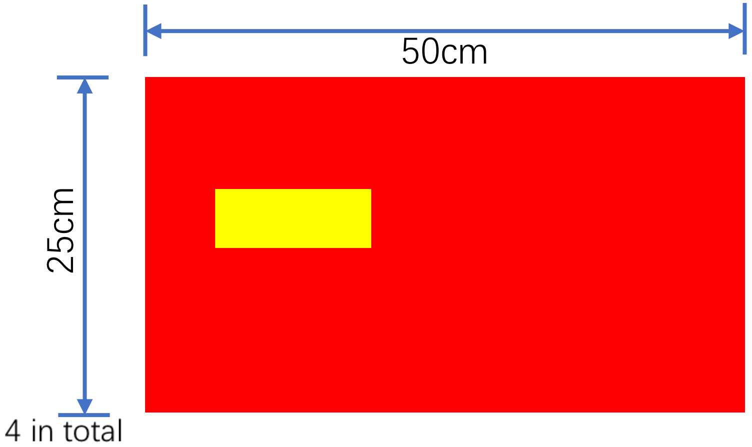
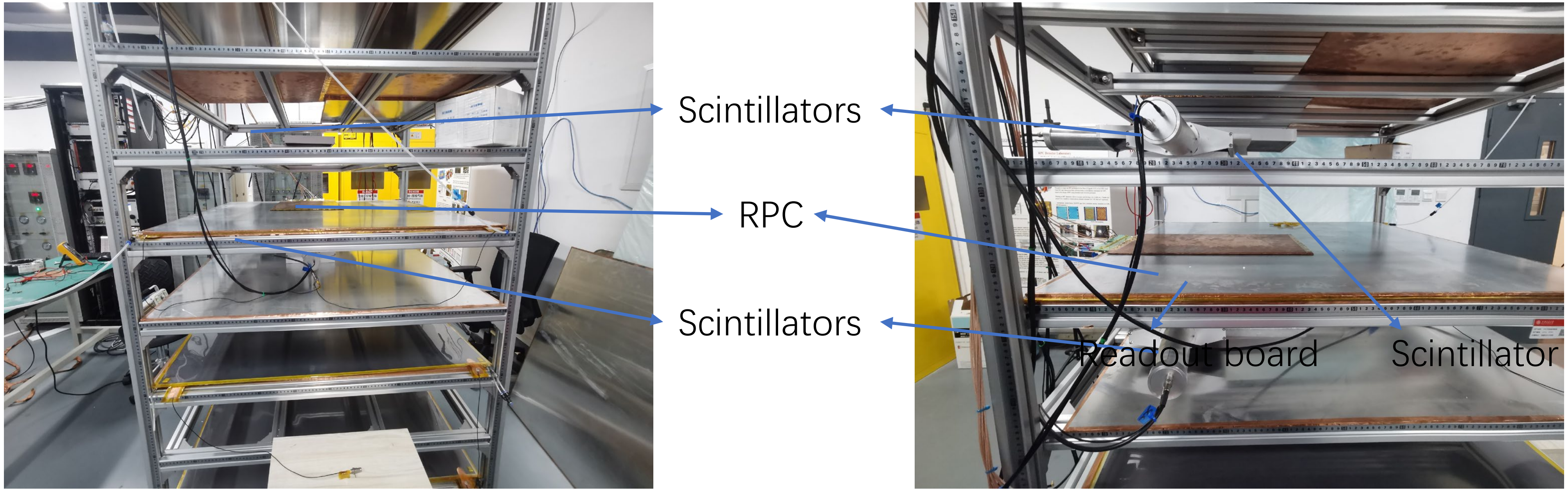
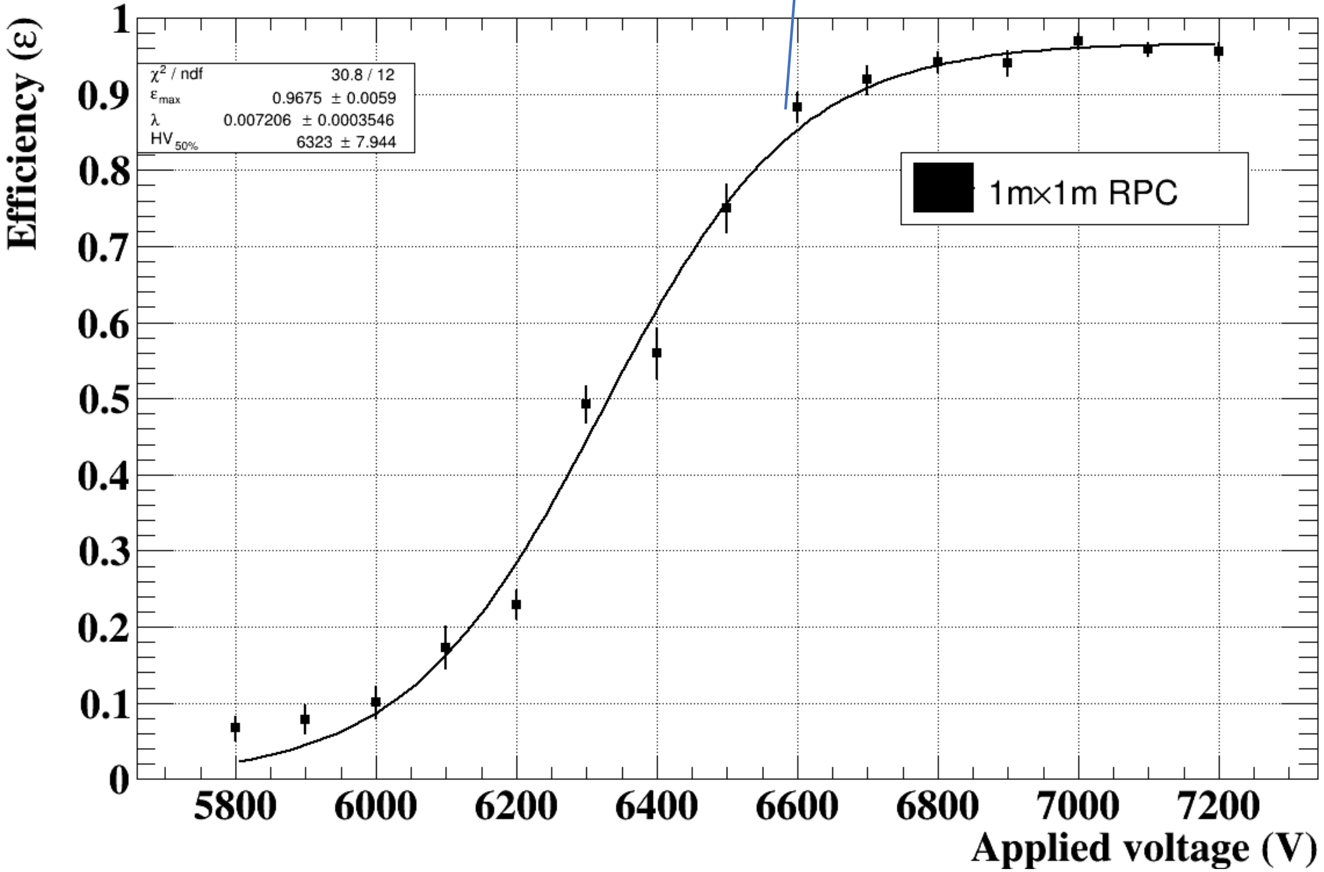


Photo of the 1m*1m*1.2mm RPC



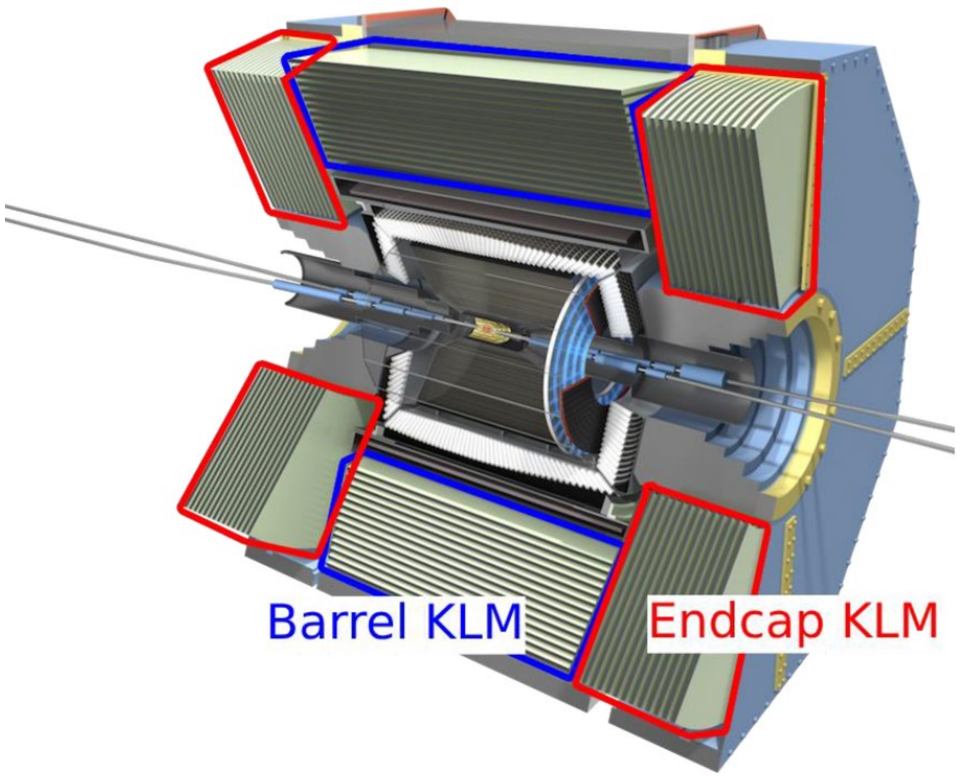
RPC in SJTU and test setup

Fit to $\boldsymbol{\varepsilon} = \frac{\varepsilon_{max}}{1+e^{\lambda\times(HV_{50\%}-U)}}$, error $= \sqrt{\frac{\varepsilon(1-\varepsilon)}{N_{total}}}$



- Plateau efficiency > 95%

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?

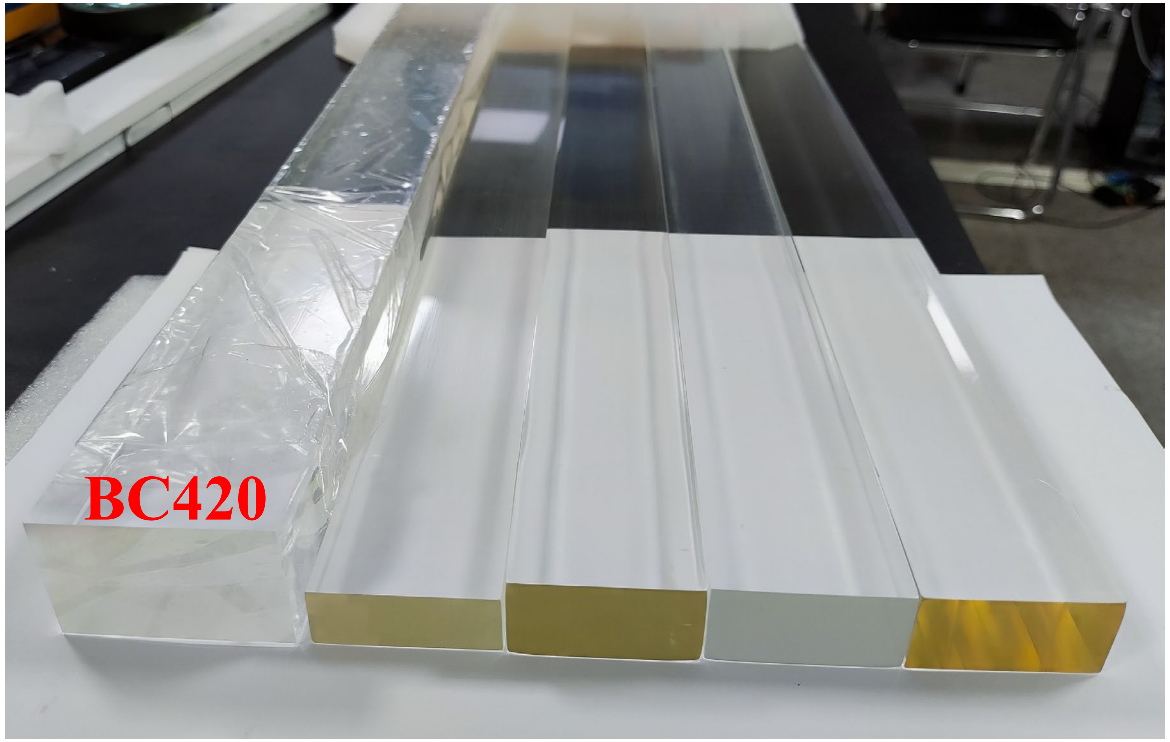
1. Improve the KL ID. Better identification and better neutrino veto.
2. TOF-like to determine the momentum of a neutral hadron directly.
3. Contribute to dark sector search?
4. Keep the good muon ID.

Snowmass whitepaper: arXiv: 2203.11349

FCDR: arXiv:2406.19421.

The scintillators and SiPMs

Solid scintillator (no WLS fiber)



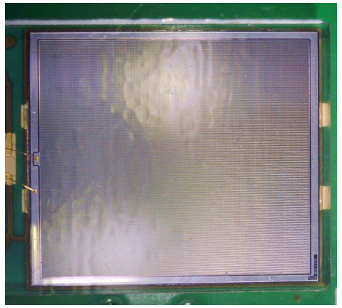
SAINT-GOBAIN

高能科迪 GAONENGKEDI

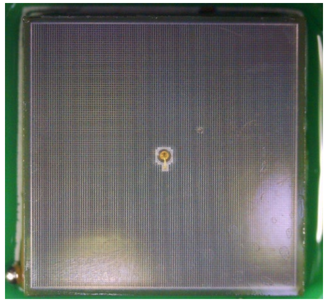
Multiple SiPMs

HAMAMATSU PHOTON IS OUR BUSINESS

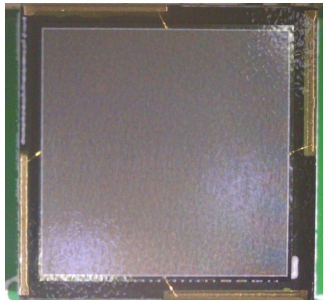
NDL



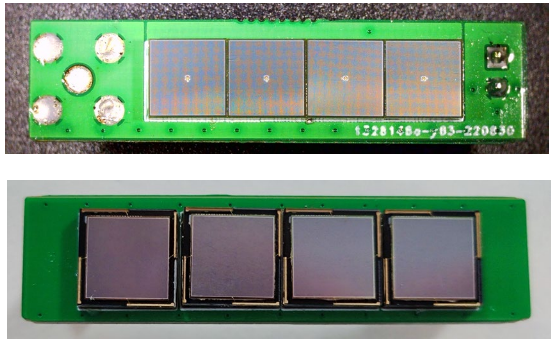
S13360-6025PE



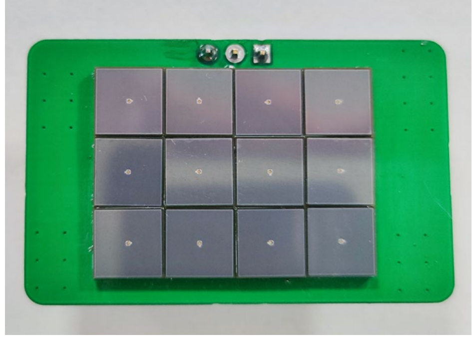
S14160-6050HS



EQR1511-6060D-S



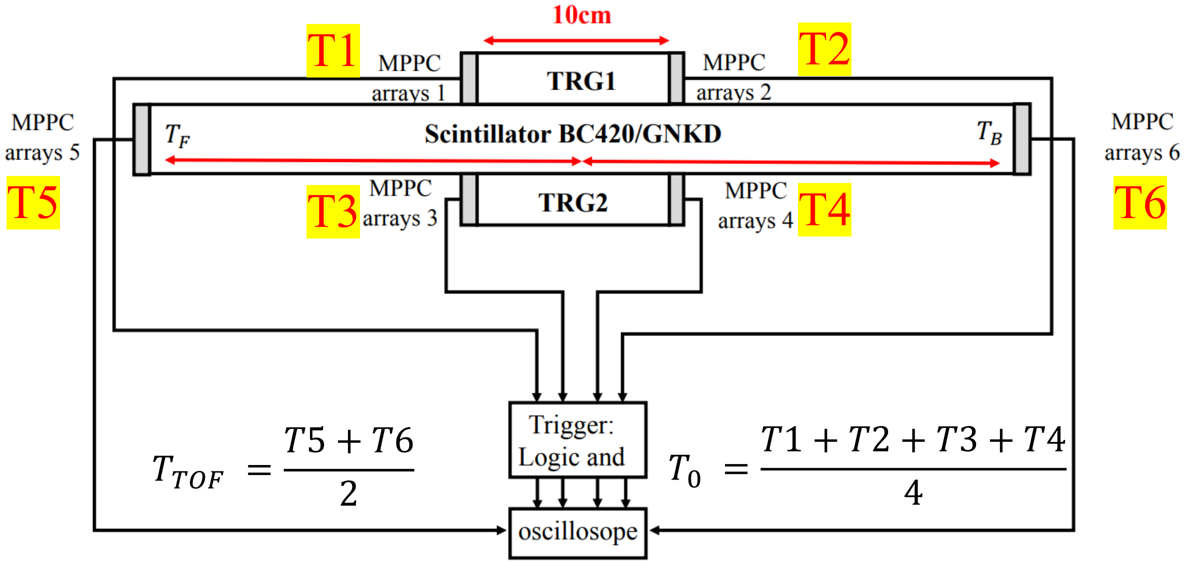
4×SiPM

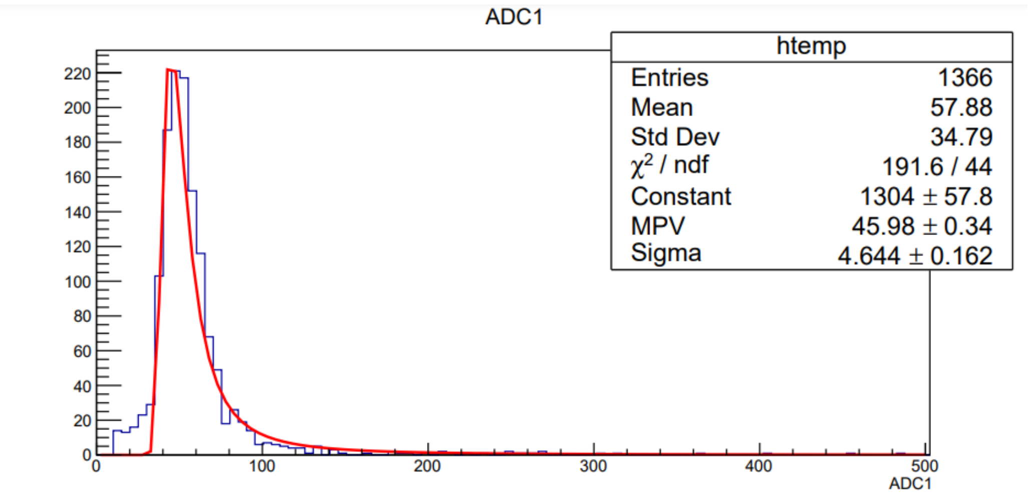


12×SiPM

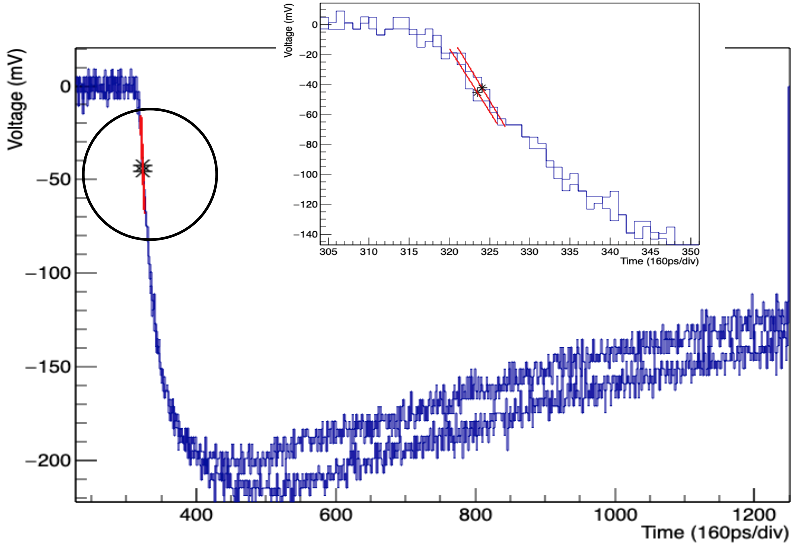
- Thicker scintillators with longer attenuation lengths and large areas of SiPM can improve photon collection.

Plastic scintillator test using cosmic rays



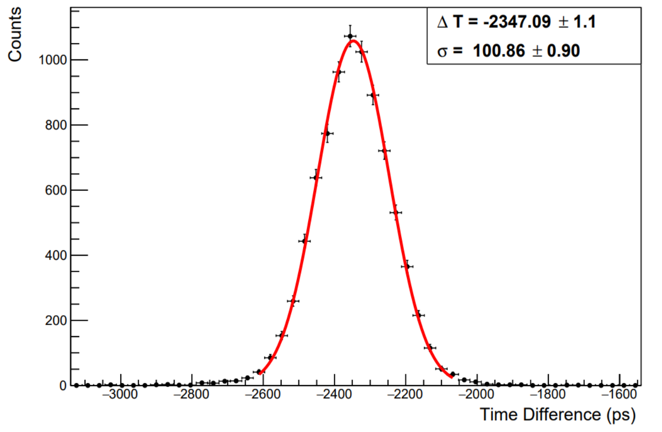


Energy spectrum of cosmic rays



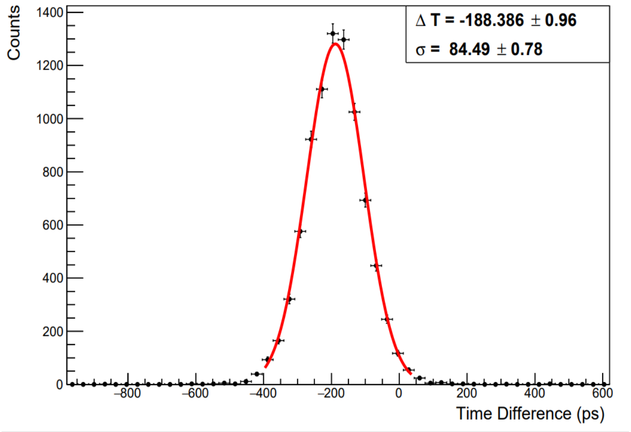
CFD timing of waveform

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



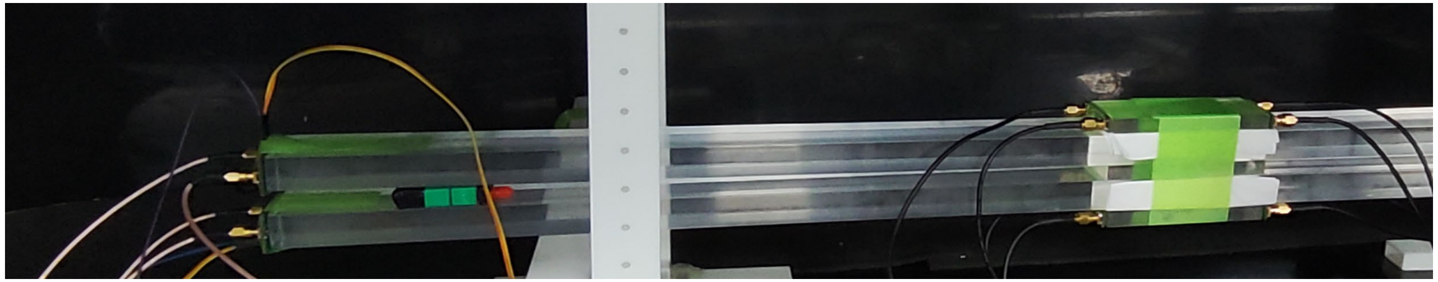
$\sigma_{TRG} = 100.8\text{ps}$ $\quad \sigma_{T_0} = 50.4\text{ps}$

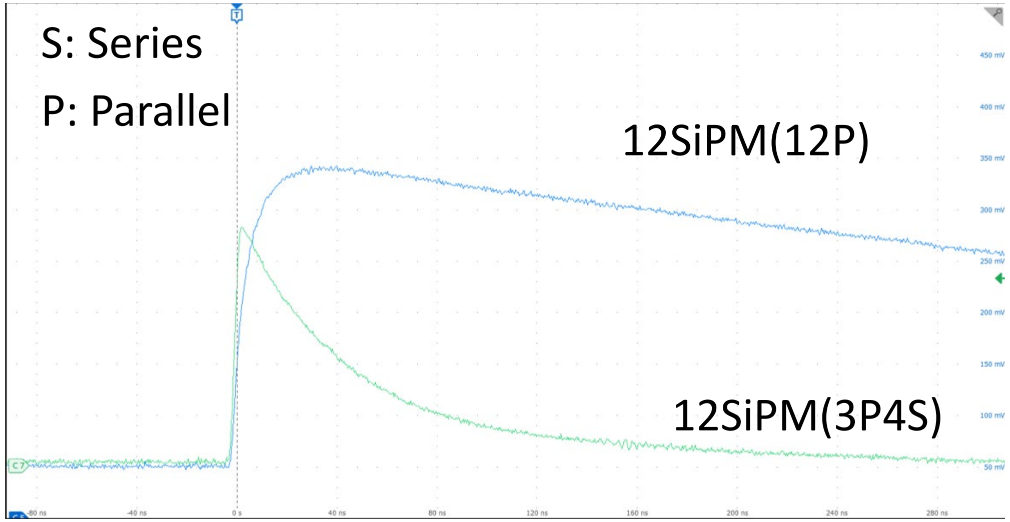
$$T_0 - T_{TOF} \rightarrow \sigma_{T_{TOF}}$$

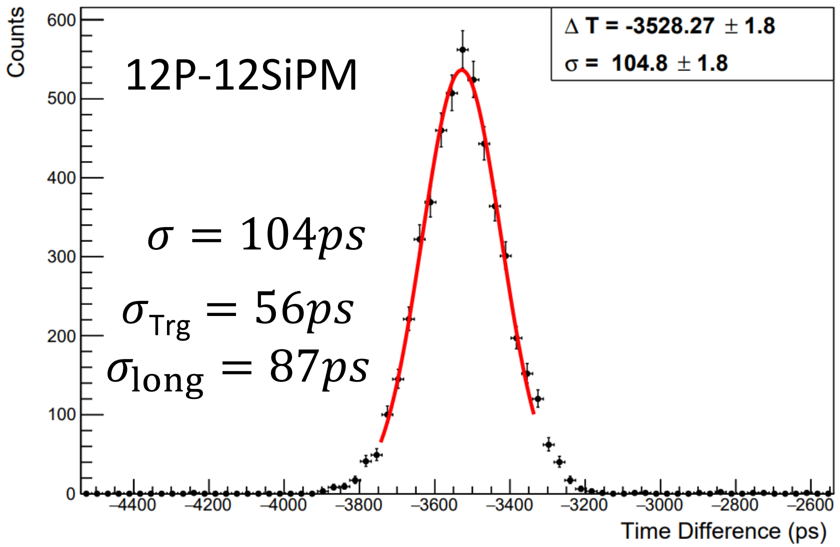


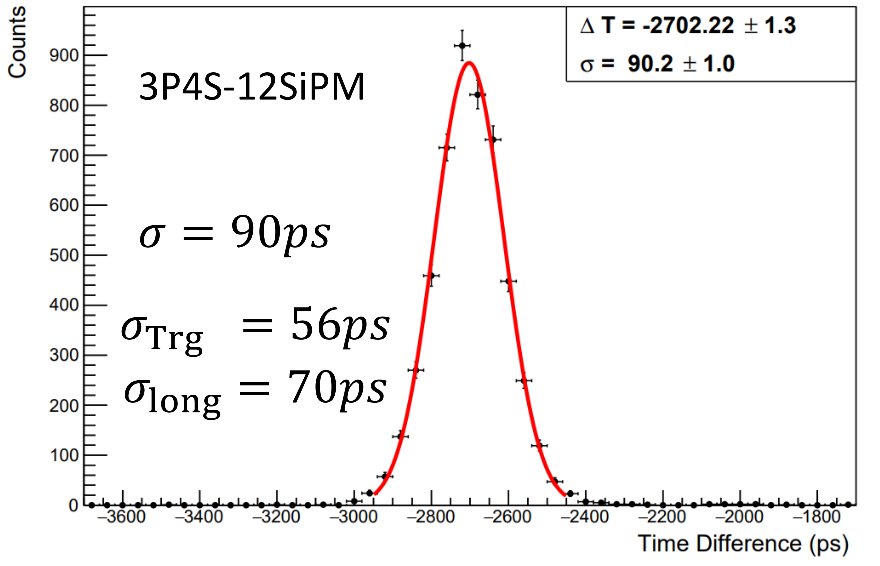
$\sigma_{T_{TOF}} = 67.5\text{ps}$

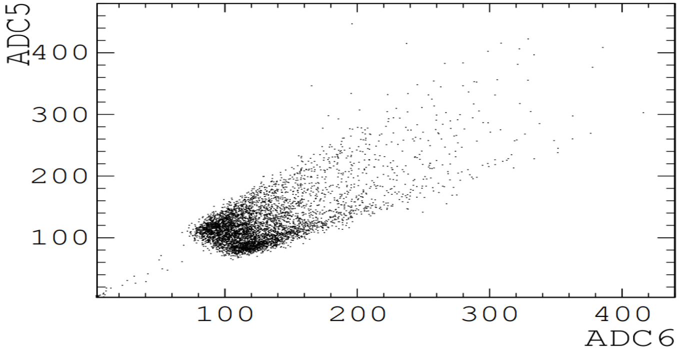
Time resolution of long strip: GNKD_new(2cm)

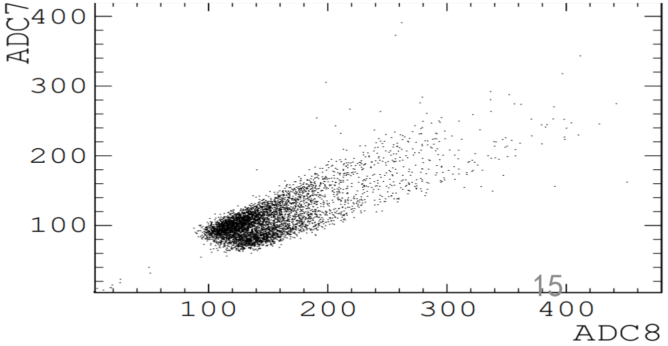




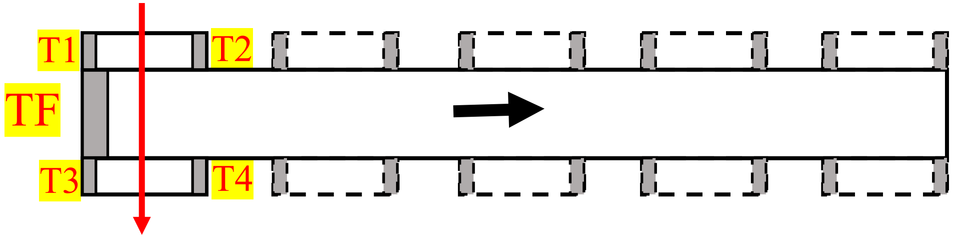




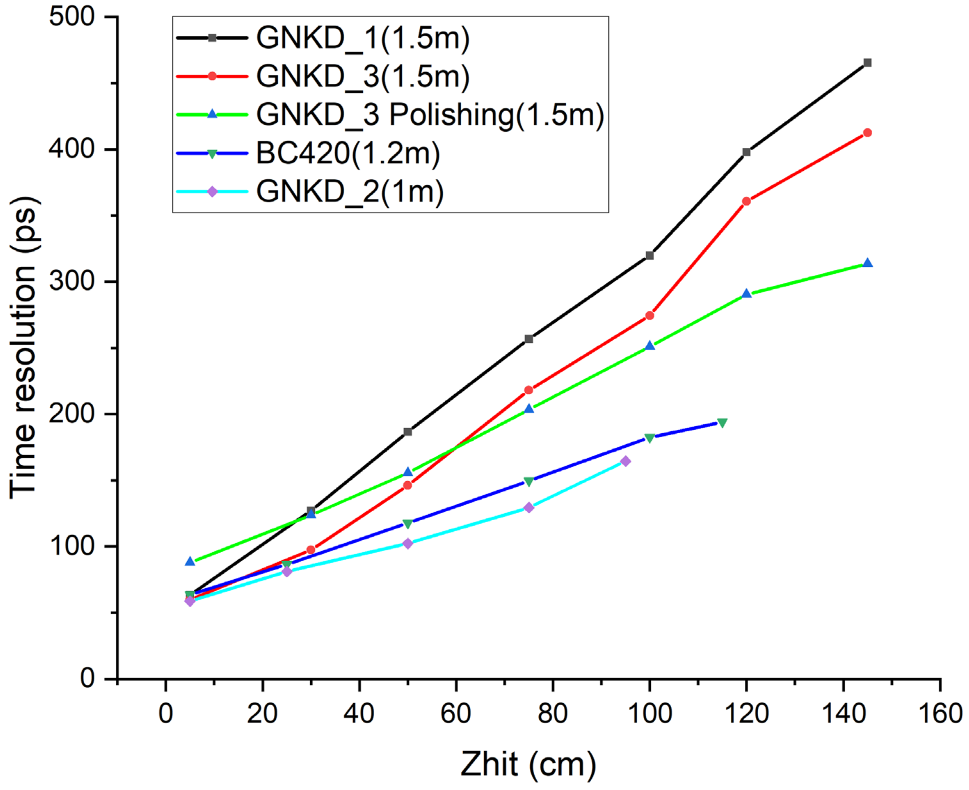




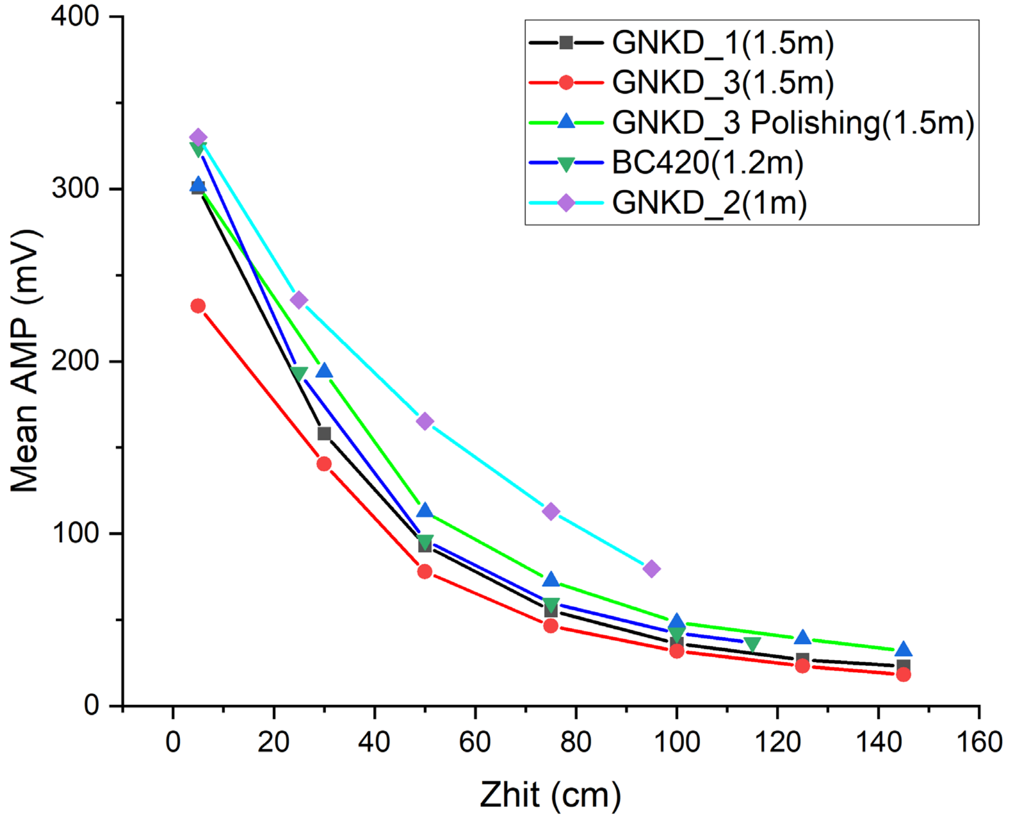
Time resolution test for different position(single-ended)



- Change the location of the trigger, we can get the time resolution of different position.



Time resolution of different positions of scintillator



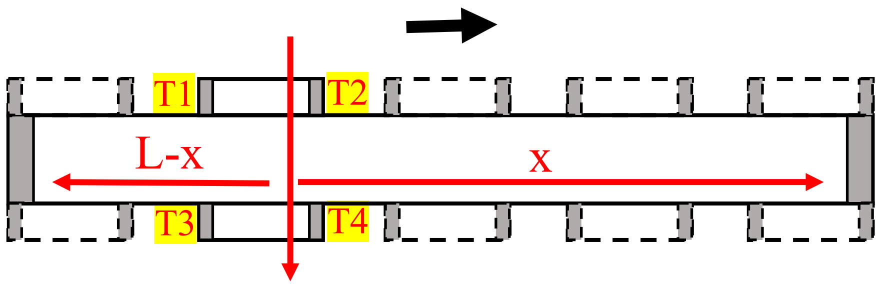
Signal amplitude at different locations of the scintillator

- Less light collection at the far end makes the SNR smaller, resulting in worse time resolution.

Time resolution test for different position(both averaged)

Backward

$T_B = T_0 + \frac{L-x}{v}$



Forward

$T_F = T_0 + \frac{x}{v}$

Unweighted:

$$T_{s.c.} = \frac{T_F + T_B}{2} = T_0 + \frac{L}{2v}$$

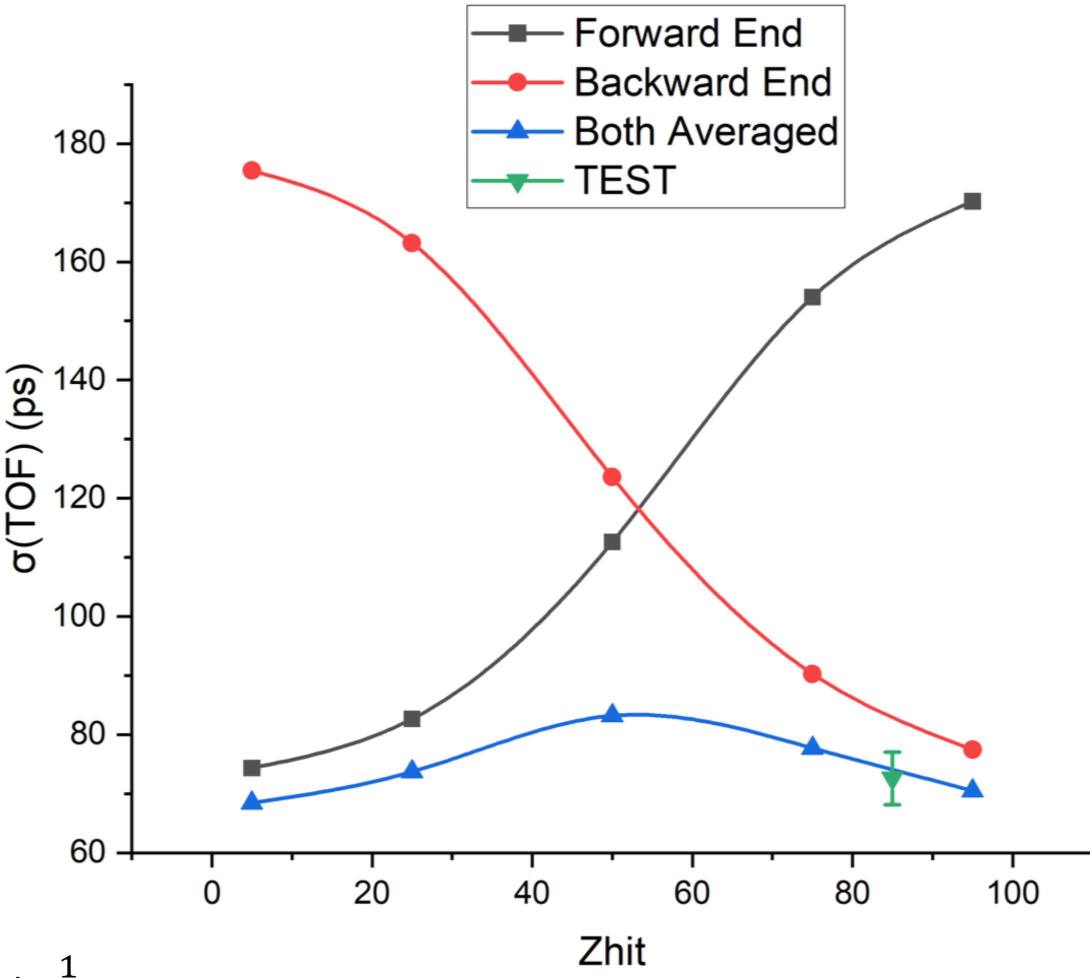
$$\sigma_{s.c.}^2 = (\sigma_F^2 + \sigma_B^2)/4$$

Weighted average:

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

$$\frac{1}{\sigma_{s.c.}^2} = \frac{1}{\sigma_F^2} + \frac{1}{\sigma_B^2}$$

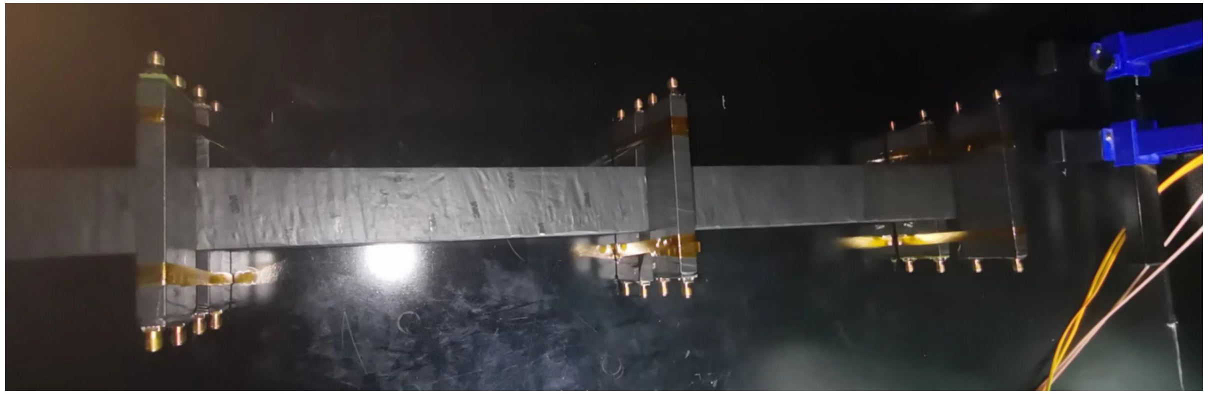
***$T_{s.c.}$* related to hit position 'x'**

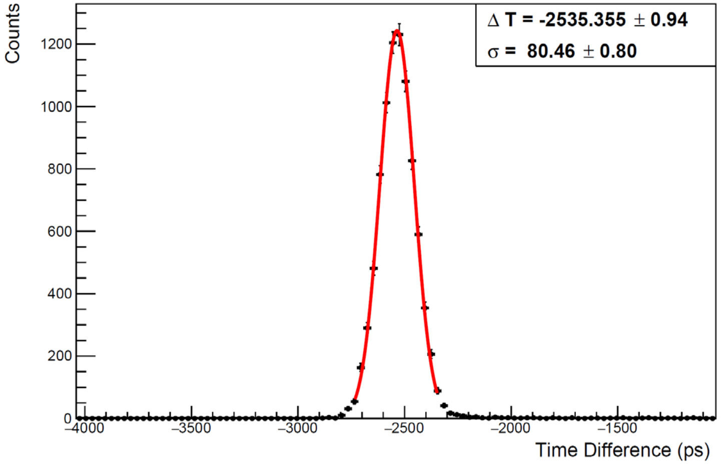


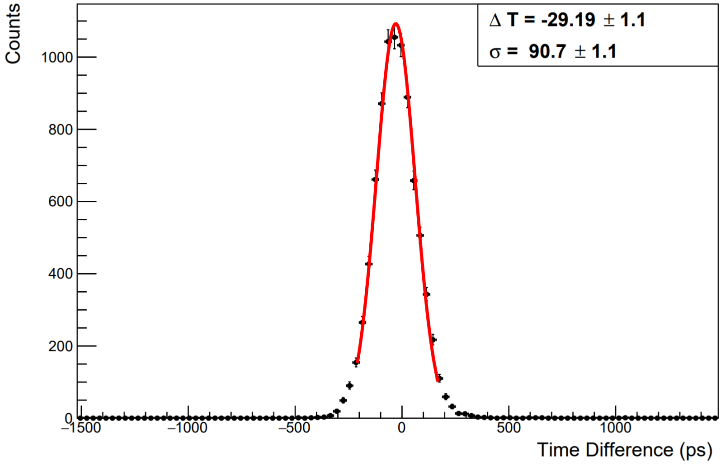
Both Averaged Calculated by the error transfer formula $\frac{1}{\sigma_{s.c.}^2} = \frac{1}{\sigma_F^2} + \frac{1}{\sigma_B^2}$.

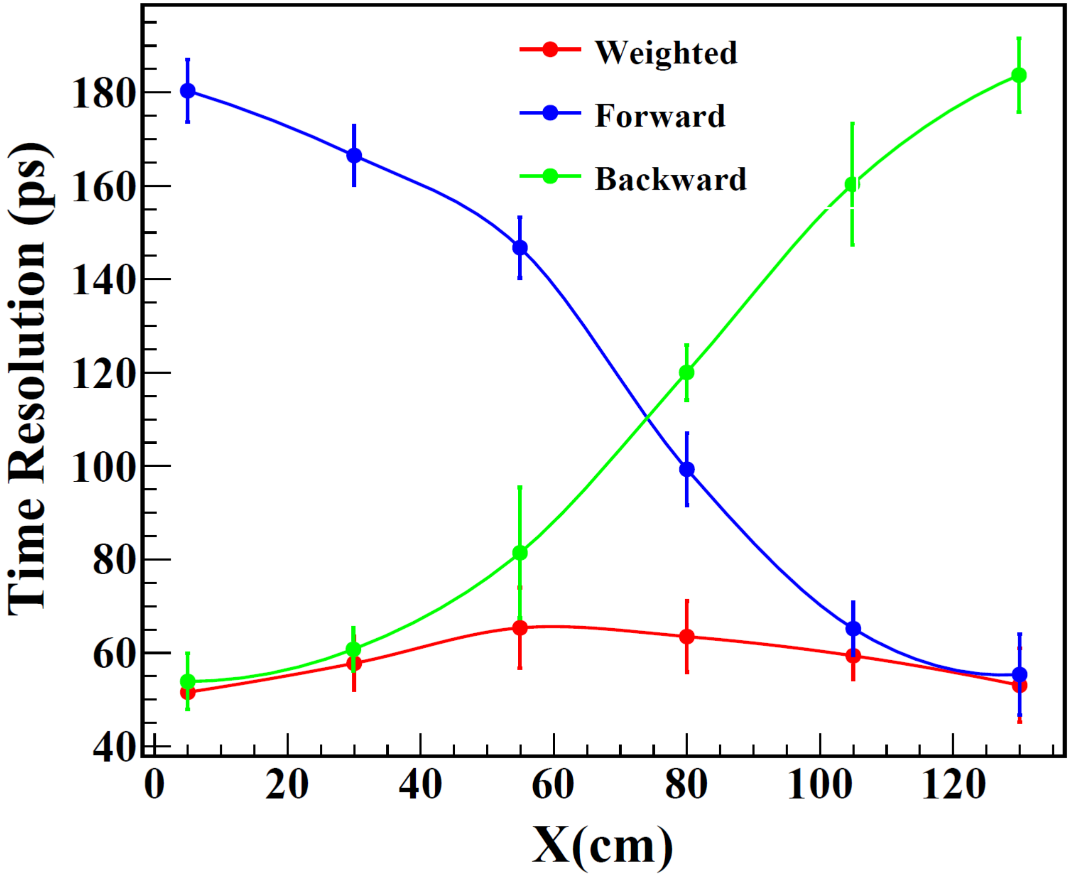
TEST Reduce the length of the Trigger (1cm) to reduce the 'x' uncertainty.

Time resolution test for 1.35 m new GNKD scintillator(both averaged)



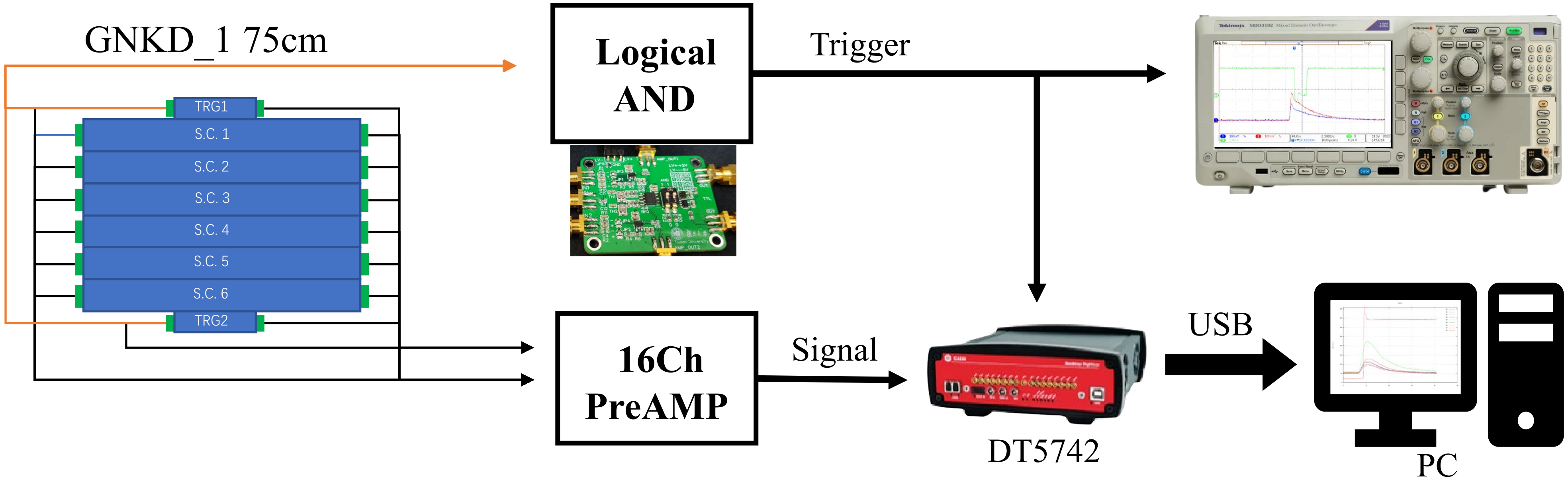






Middle position: $\sigma = \sqrt{(80.5^2 - \left(\frac{90.7}{2}\right)^2} = 66.5\ ps$

Prototype Test



DT5742

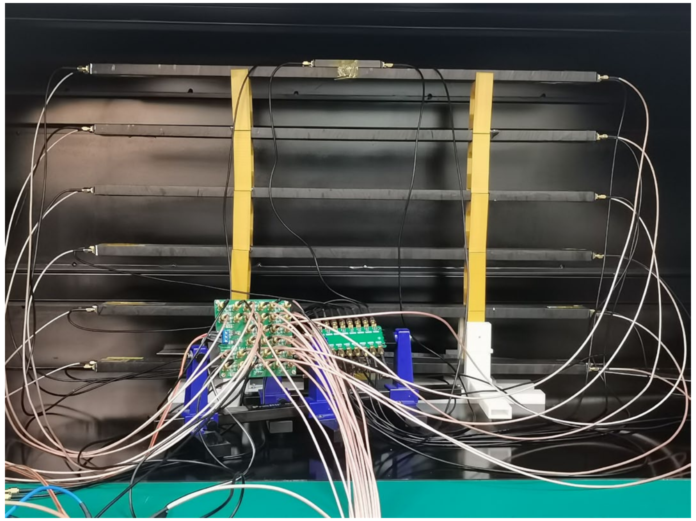
DRS4 chip

16 + 1 channel

12 bit @ 5 GS/s

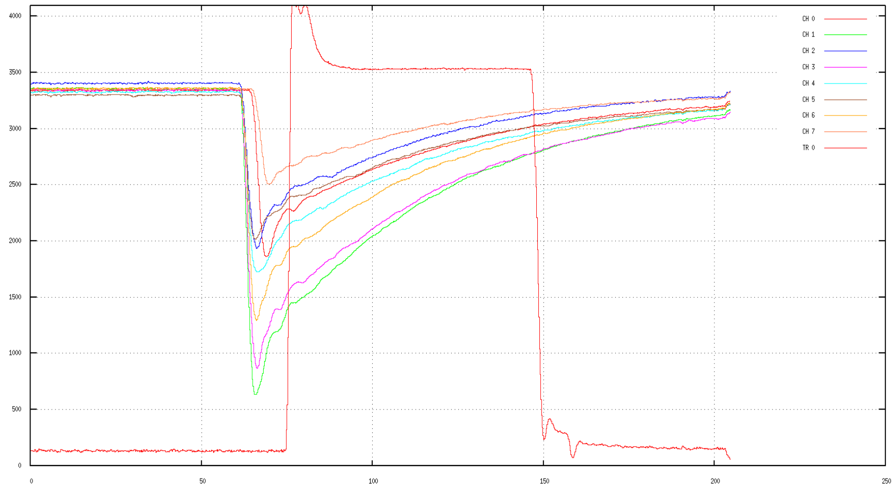
BW: 500 MHz

-1.5V ~ +1.5V



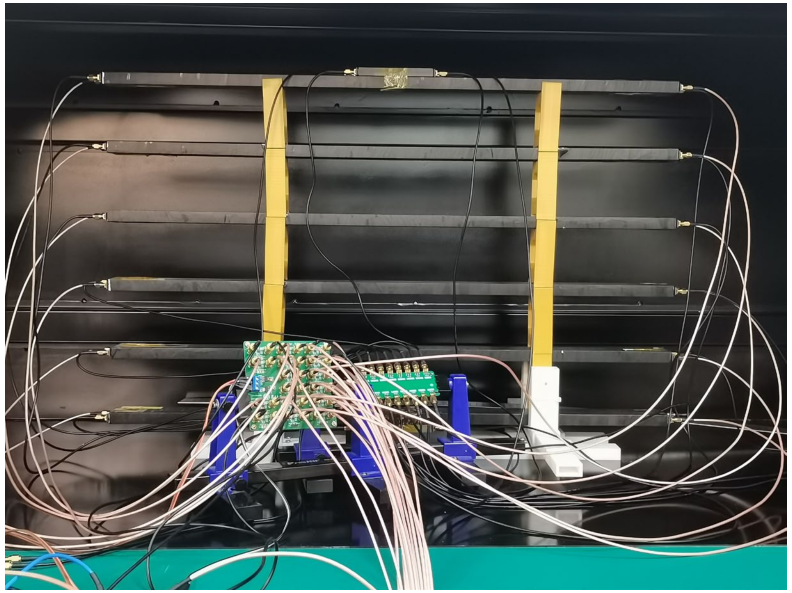
Prototype test setup

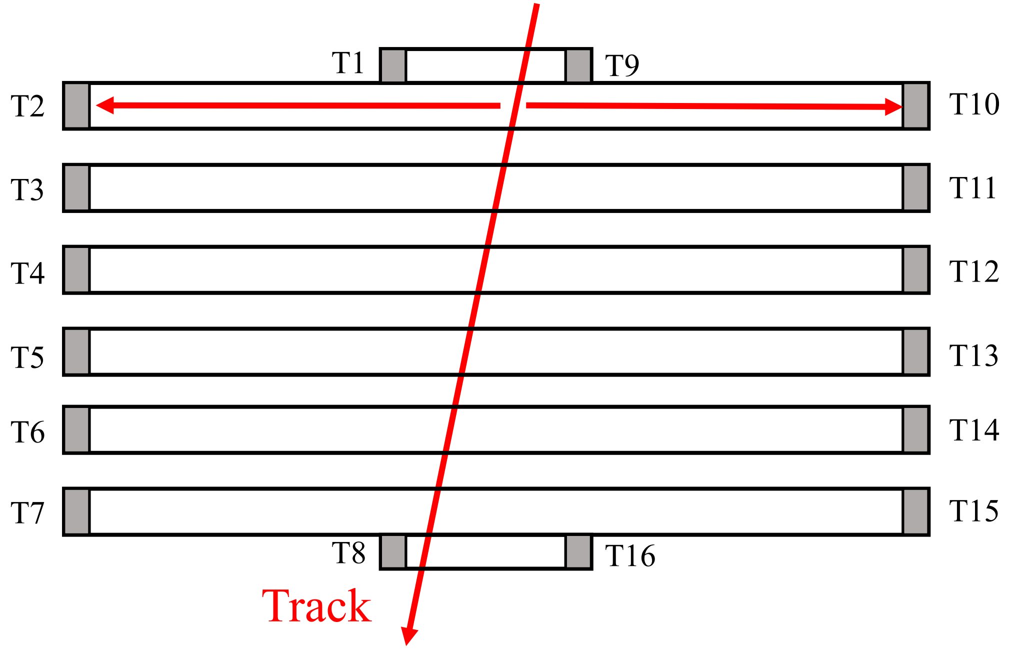
Time Calibration of prototype



DT5742 signal waveform

Prototype Test (Velocity of CR Muon)





$T_{S.C.1} = (T_2+T_{10})/2 - 0$

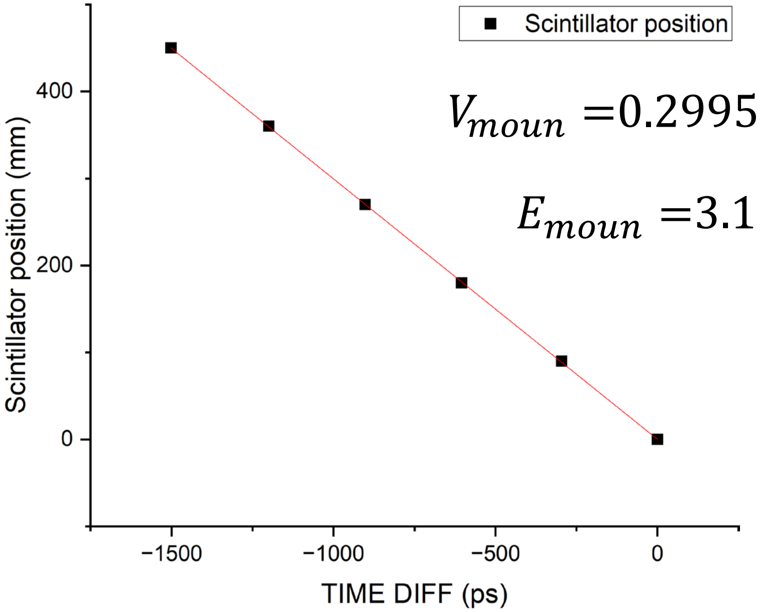
$T_{S.C.2} = (T_3+T_{11})/2 - \Delta T_1$

$T_{S.C.3} = (T_4+T_{12})/2 - \Delta T_2$

$T_{S.C.4} = (T_5+T_{13})/2 - \Delta T_3$

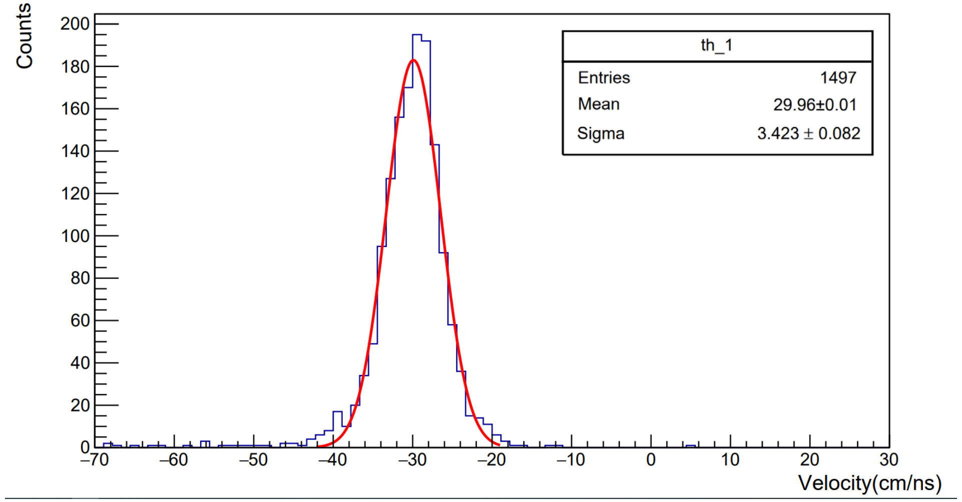
$T_{S.C.5} = (T_6+T_{14})/2 - \Delta T_4$

$T_{S.C.6} = (T_7+T_{15})/2 - \Delta T_5$



$V_{moun} = 0.299582 \pm 0.00011$ mm/ps

$E_{moun} = 3.1 \pm 0.4$ GeV/c^2



Muon velocity distribution of cosmic rays

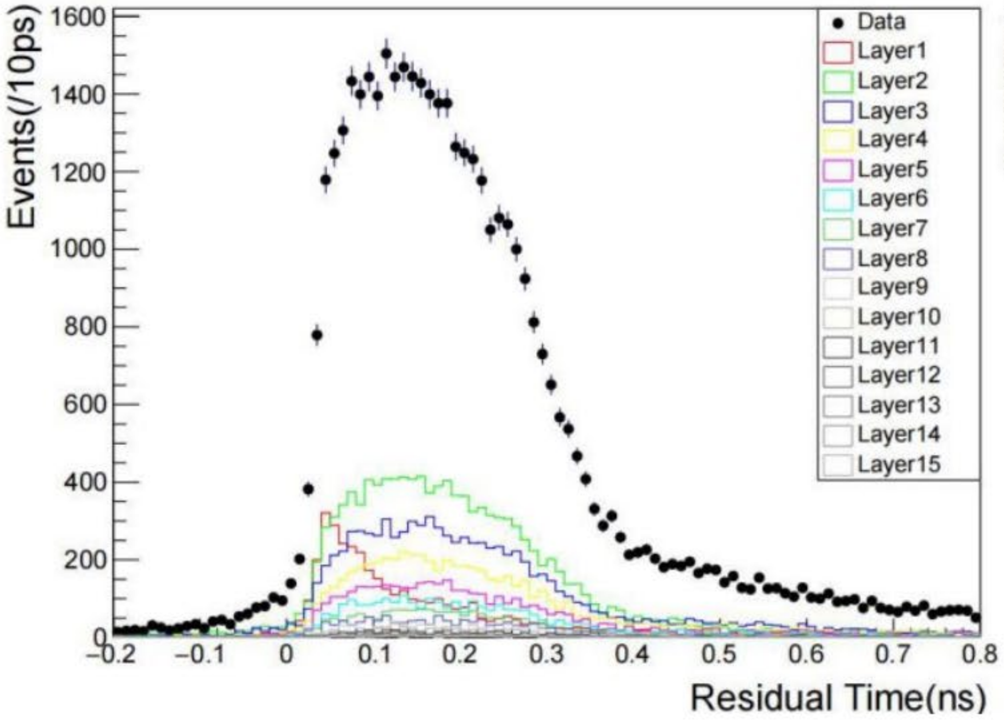
Summary

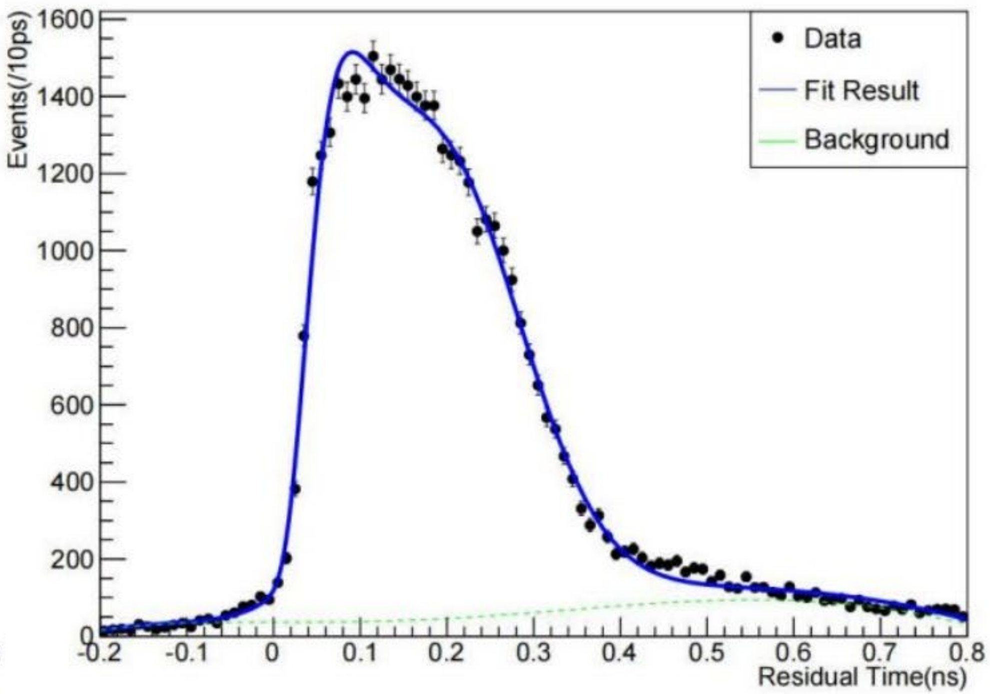
- Good performance of the current design for efficiency.
- The time resolution is less than 1.5 ns for scintillator + WLS + SiPM system.

- A preamplifier with time resolution of 20ps is designed.
- The combination of series and parallel can improve the time resolution of multiple SiPM arrays.
- The GNKD plastic scintillator (1.35 m) achieves a time resolution of 65ps.
- The prototype of scintillator realizes the energy measurement of cosmic ray Muon ($3.1 \pm 0.4\ GeV/c^2$).

THANKS !

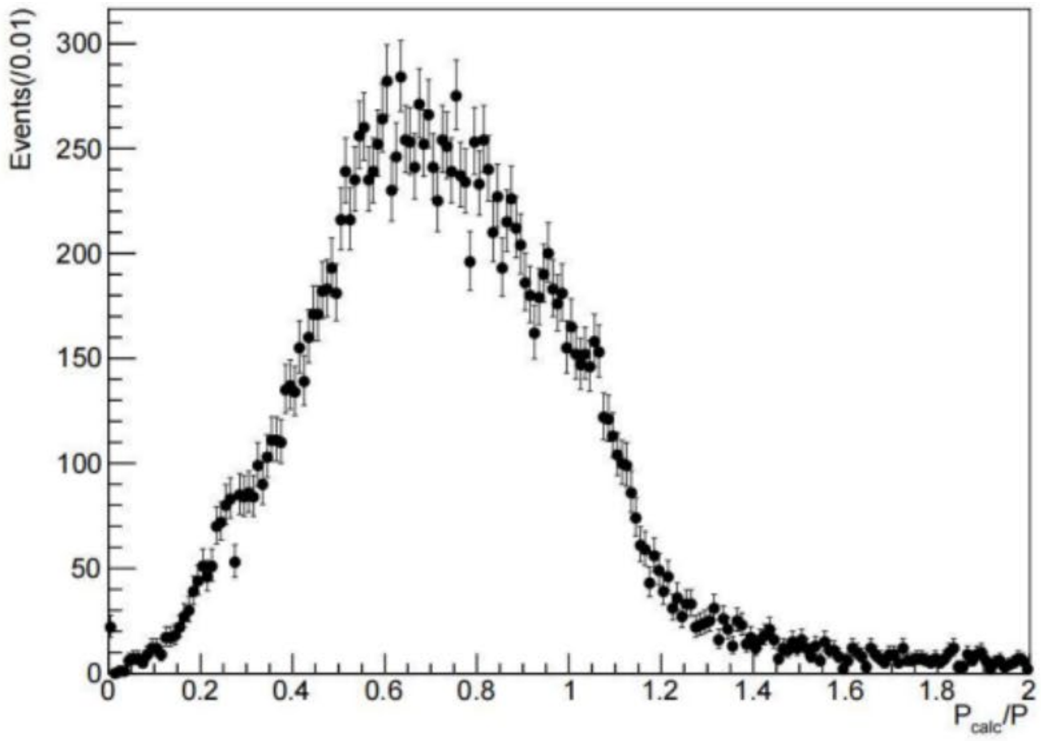
back up



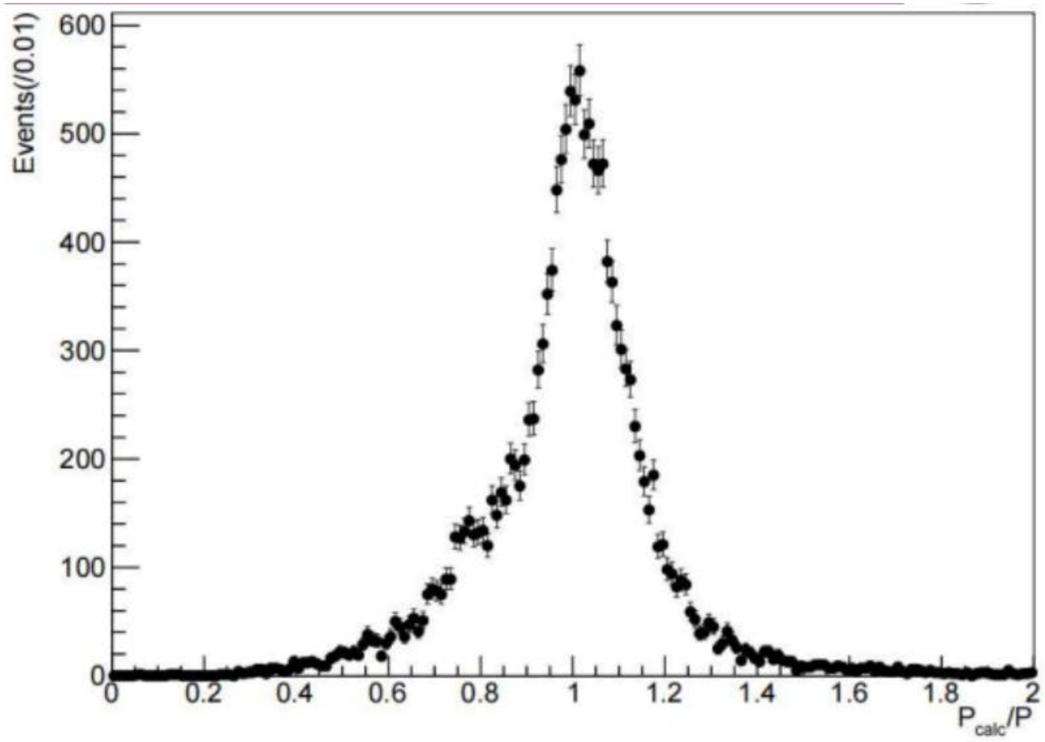


Cuts	Number
N_{events}	5×10^4
K_L Decay in KLM Detector	4.79×10^4 (95.8%)
Scintillator Signals > 0	4.76×10^4 (95.2%)

The rough estimation of K_L ID may be great than 90%.



The distribution of P_{calc}/P for events that K_L undergoes hadronic showers in the ECL detector.



The distribution of P_{calc}/P for events that K_L undergoes hadronic showers in the KLM detector.

P_{calc}: The reconstructed momentum of K_L.

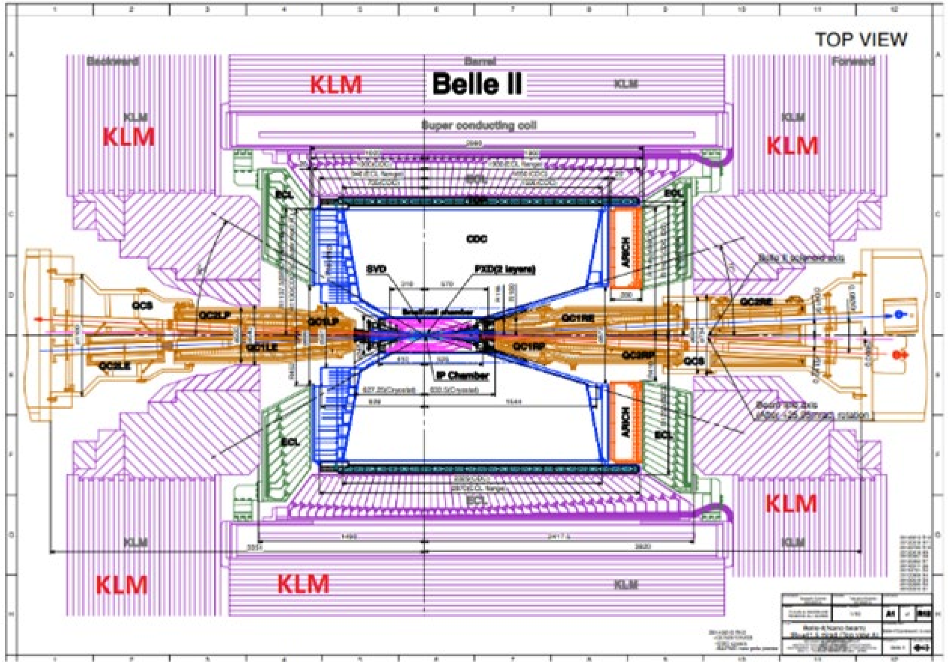
P: The momentum of K_L emitted (1.5 GeV/c).

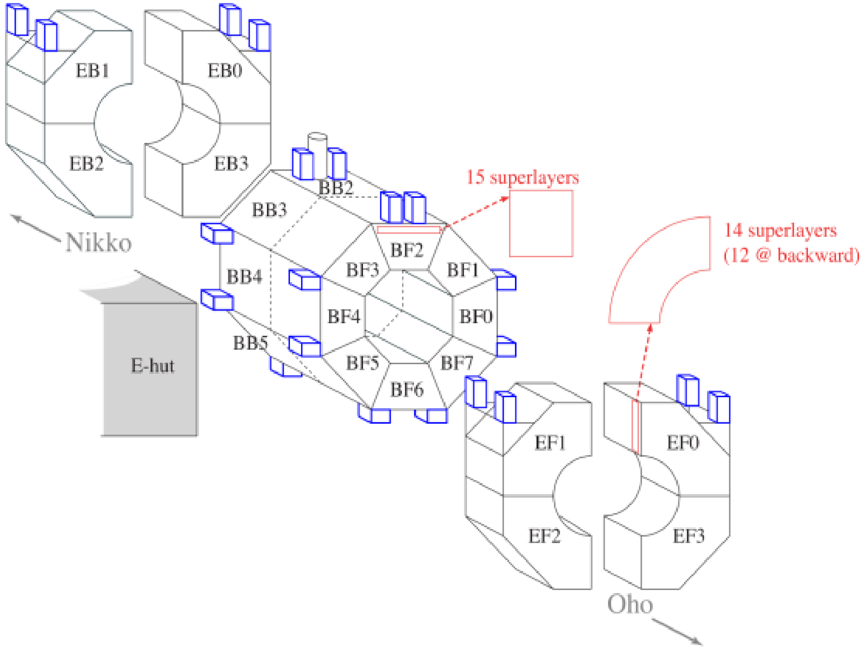
P_{calc}/P is supposed to be equal to 1.

1

K-long & Muon Detector upgrades

- Replace remaining RPCs in barrel with scintillator strips.
- Re-design electronics layout， high-resolution timing for K_L momentum via time of flight.



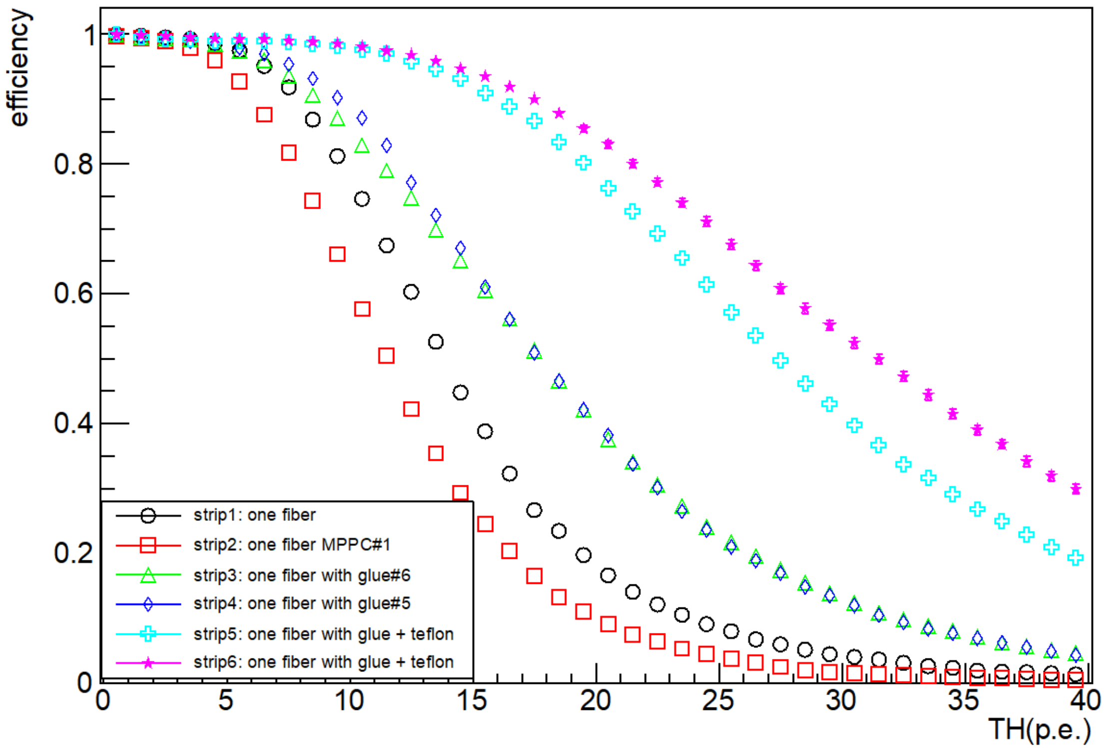


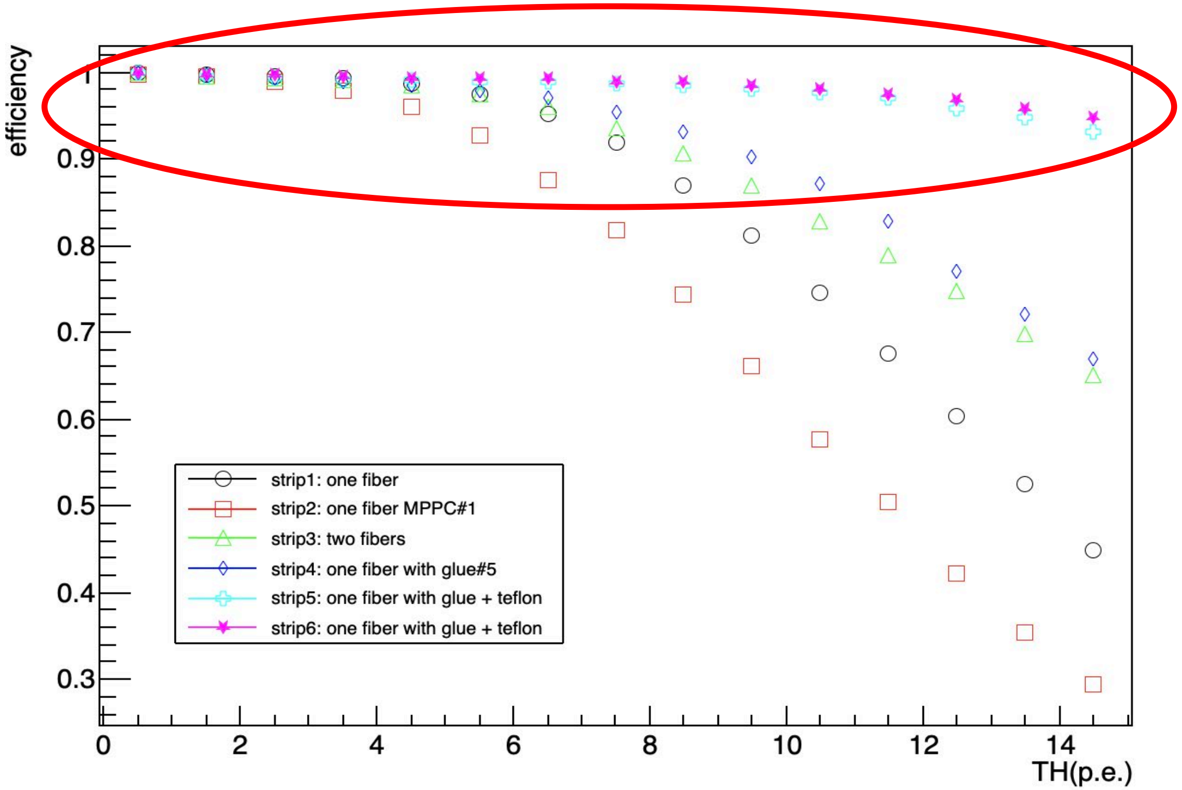
The structure of Belle II KLM

Snowmass whitepaper, arXiv: 2203.11349

Efficiency measurement

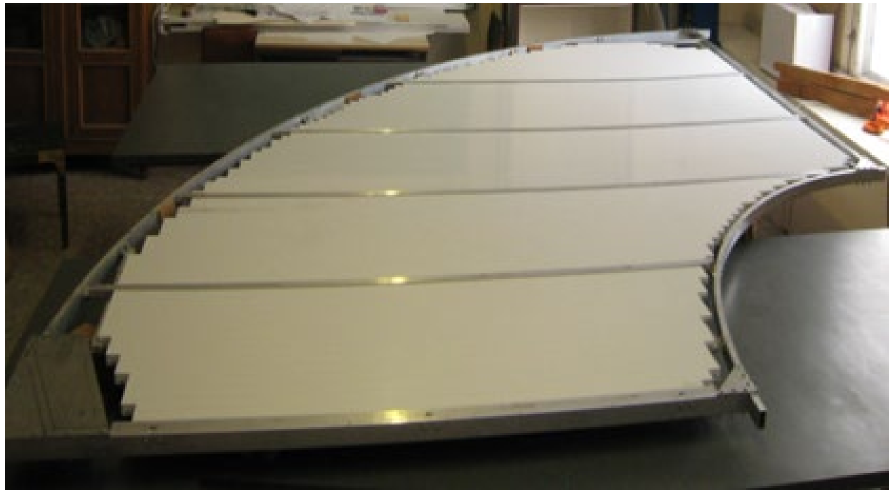
The efficiency of GNKD_150cm at far end.



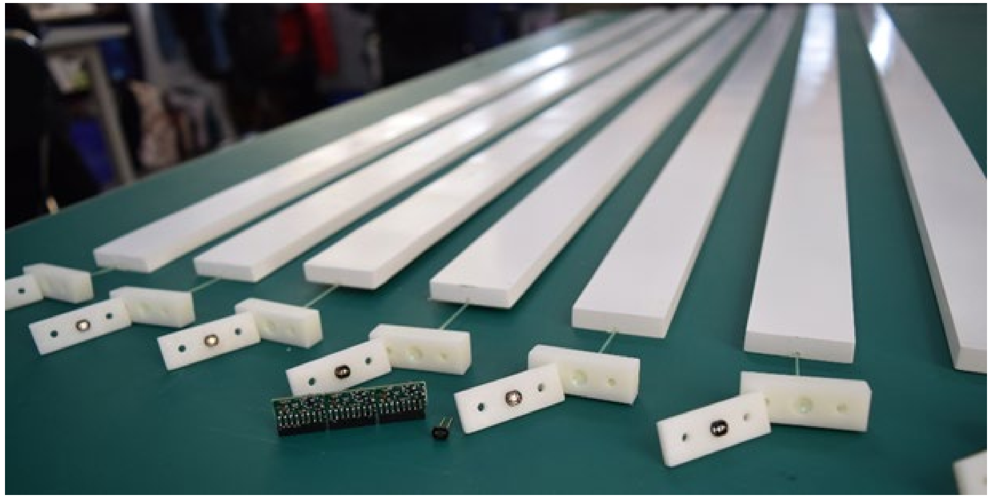


The strips with optical glue and Teflon have highest efficiency, keeping upon 98% at threshold of 10 p.e.

K_L & muon detector in Belle



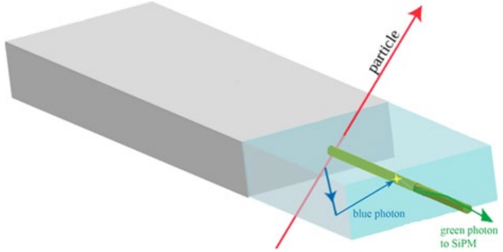
Scintillators of KLM end cap scintillators

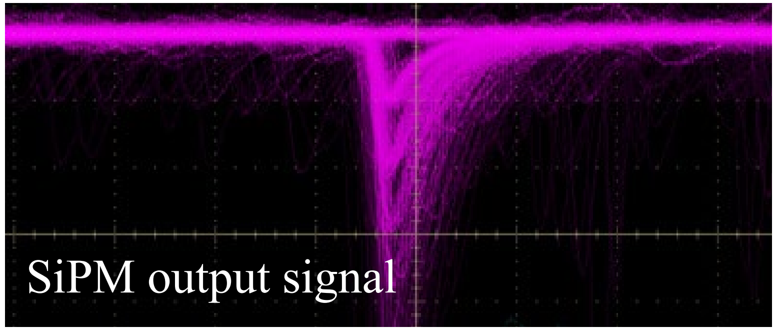


Scintillator + WLS fiber + SiPM

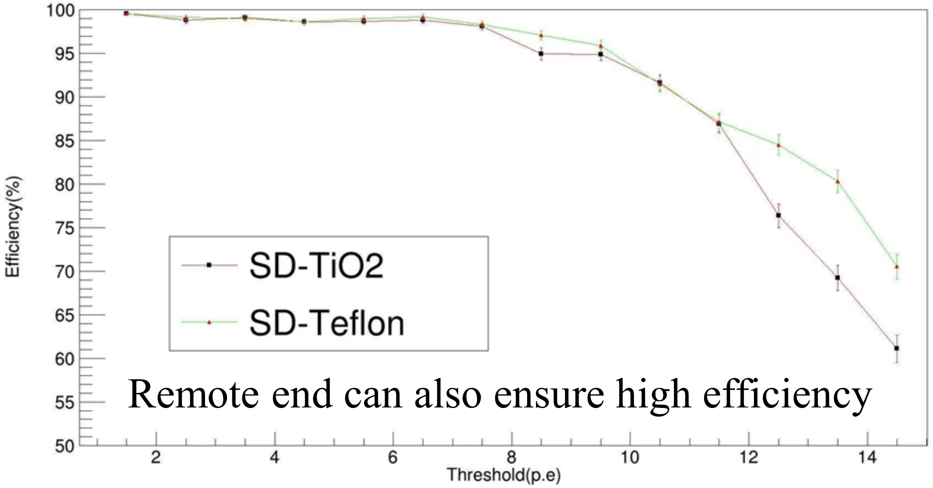
- ➢ CR testing with two strips
- ➢ High efficiency
- ➢ Time resolution: $< 1.5ns$

WLS fiber limits the improvement of time resolution

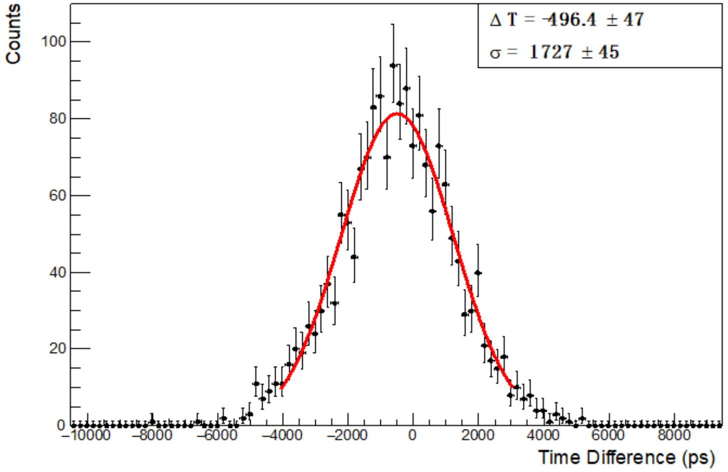




SiPM output signal



Keeping high efficiency at 10 p.e. threshold



Time difference of two channel

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

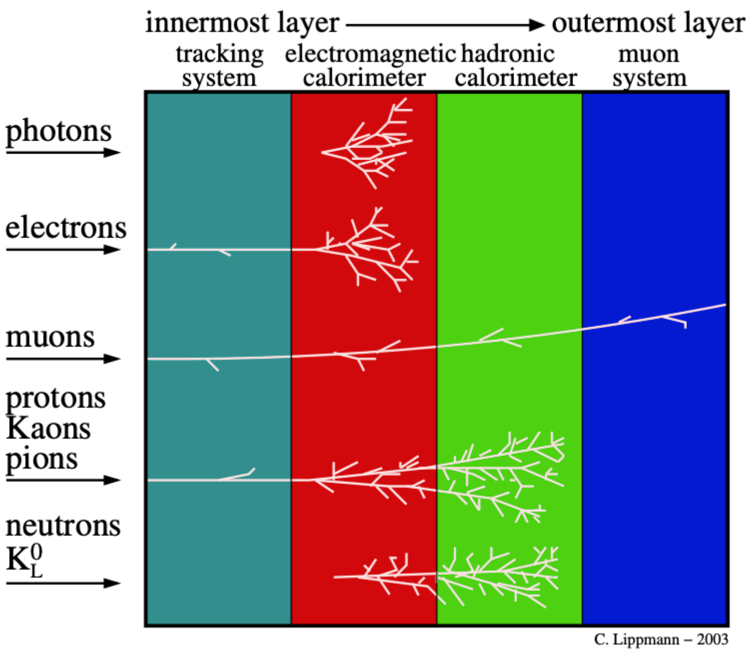
$$p = \gamma m v = \frac{mcL}{\sqrt{t^2c^2 - L^2}}$$

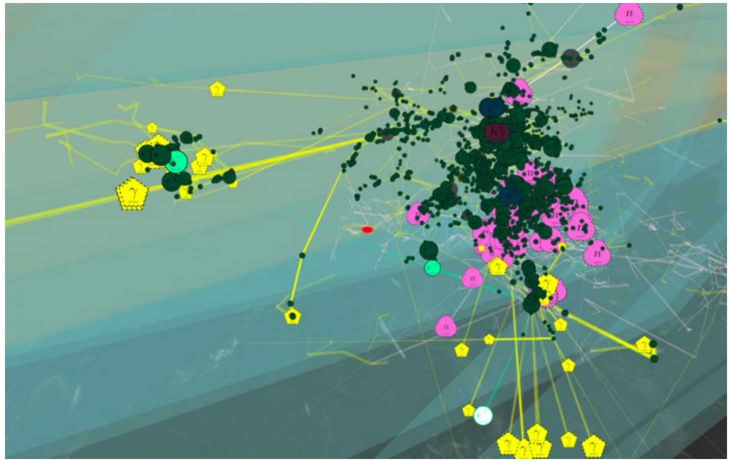
$$\frac{\delta t}{\delta p} = -\frac{m^2L^2}{t \cdot p^3} = -\frac{m^2Lv}{p^3}$$

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%

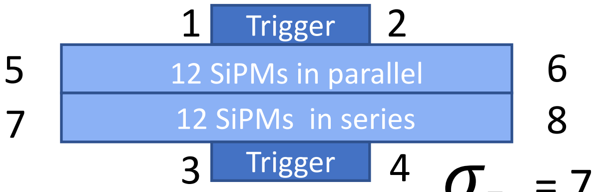




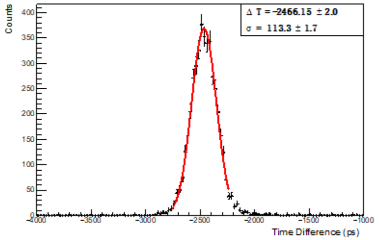
Time resolution of long strip: GNKD(3cm)

GNKD: $4 \times 3 \times 150\ cm^3$

Without polish and light guide



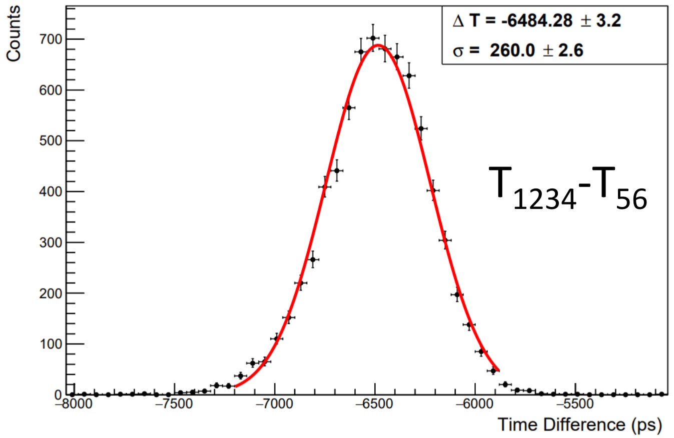
σ_{Trg} = 73ps



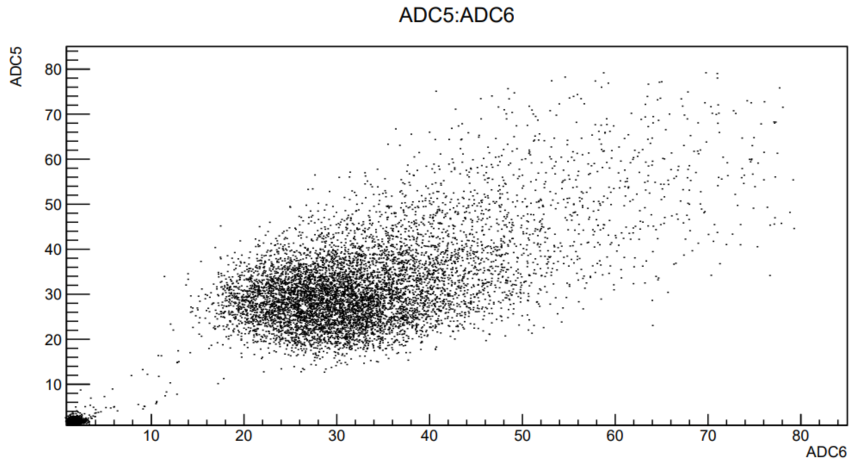
S-G σ_{long}=87 ps

GNKD

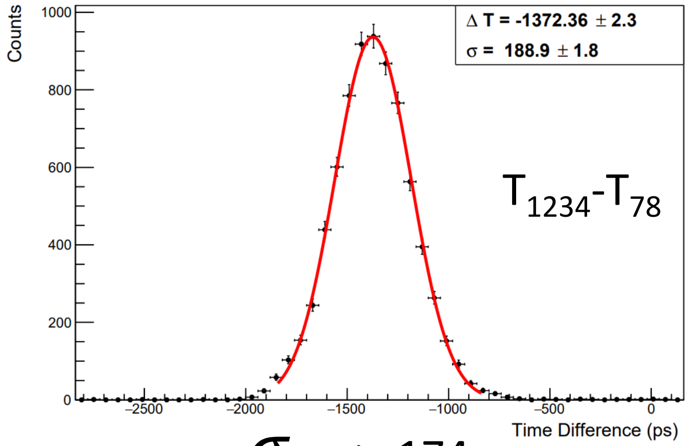
- Longer strip
- Shorter attenuation length



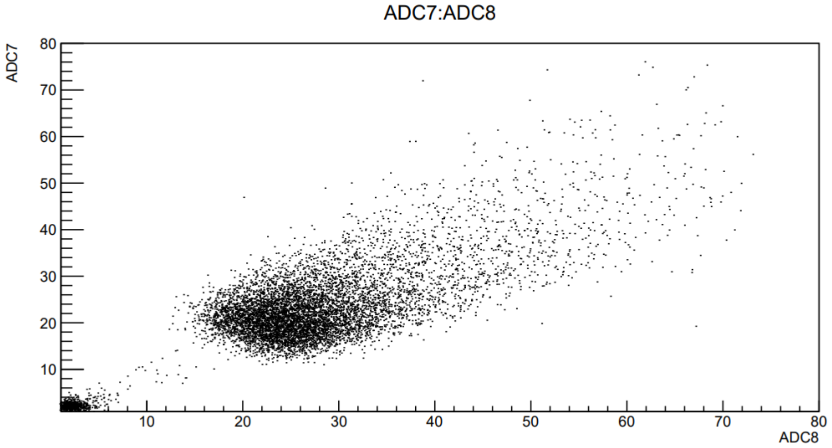
σ_{long}: 249ps



SiPM*12 in parallel



σ_{long}: 174ps



SiPM*12 in series

Influencing factors of time resolution

- Coincidence time resolution（CTR）

$$CTR \propto \sqrt{\tau_{d/n_p}}$$

τ_d: scintillation decay time

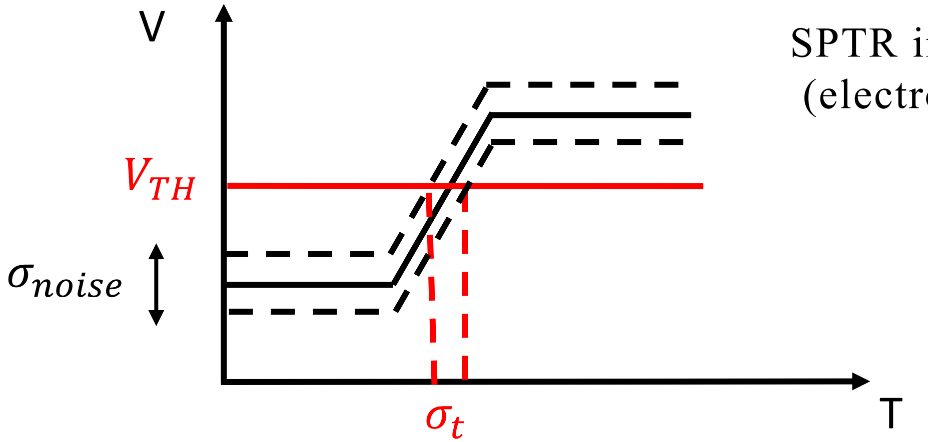
n_p: the number of photons detected

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

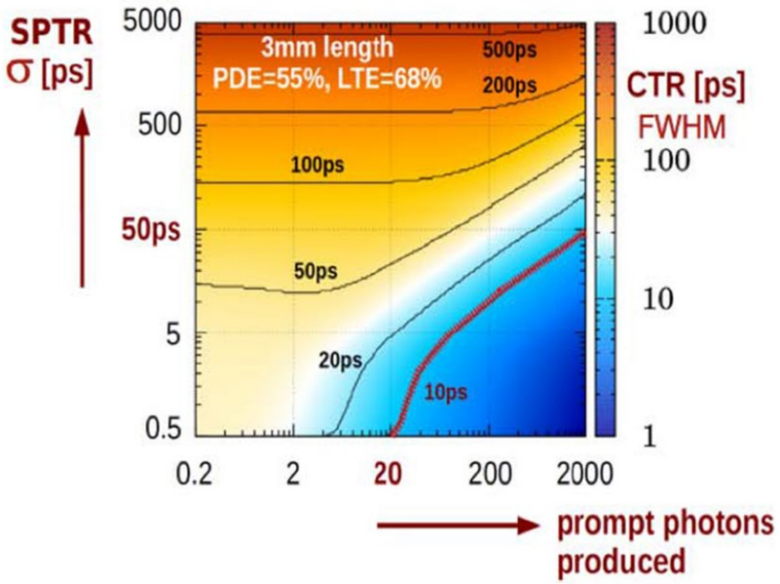
$$\sigma_t = \frac{\sigma_{noise}}{dV/dt}$$

σ_{noise} : the RMS of baseline noise

dV/dt : The slope of single photon waveforms



SPTR influenced by:
(electronics、SiPM)



single photon time resolution (SPTR)[1]

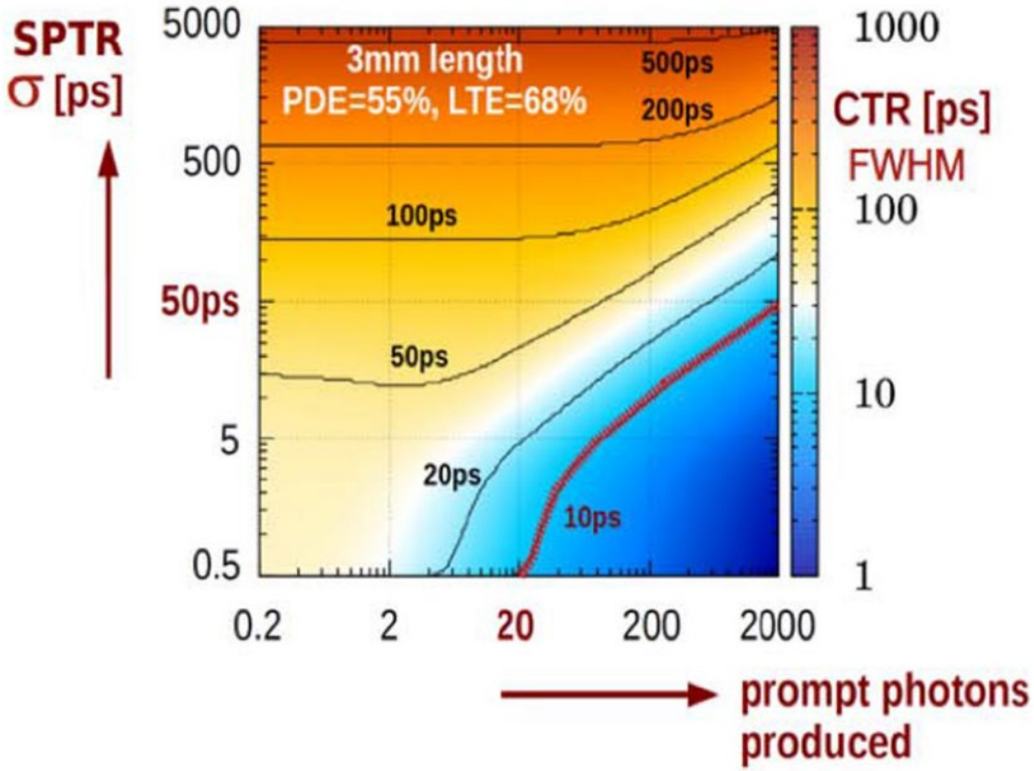
scintillator: 3mm length LSO:Ce,Ca(0.4%) crystal

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

To improve CTR of scintillator:

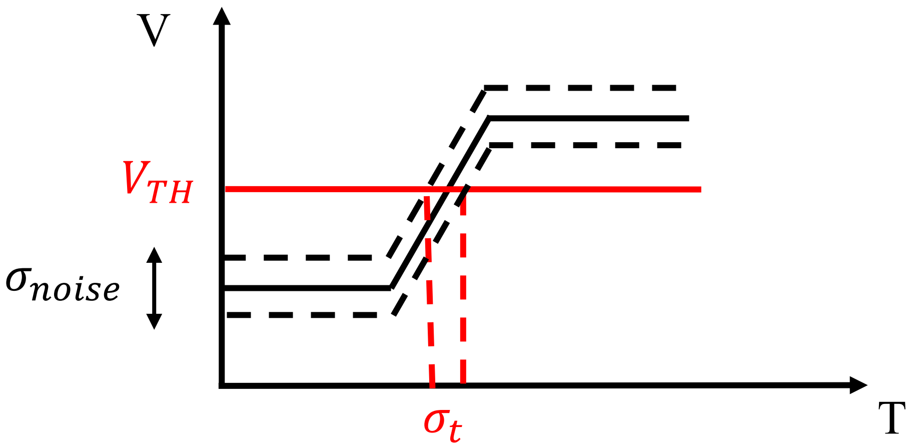
- Reduction of electronic noise
- Selection of scintillators --short decay time
- Increase photon number collection (high light yield)

[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).



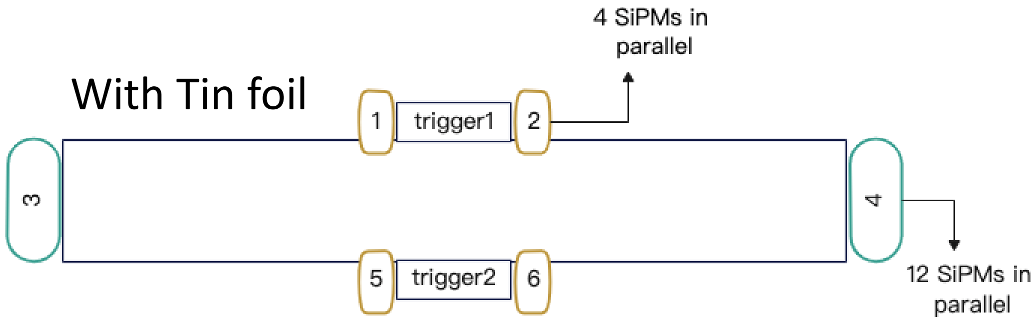
$$CTR \propto \sqrt{\tau_{d/n_p}}$$

$$\sigma_t = \frac{\sigma_v}{dv/dt}$$



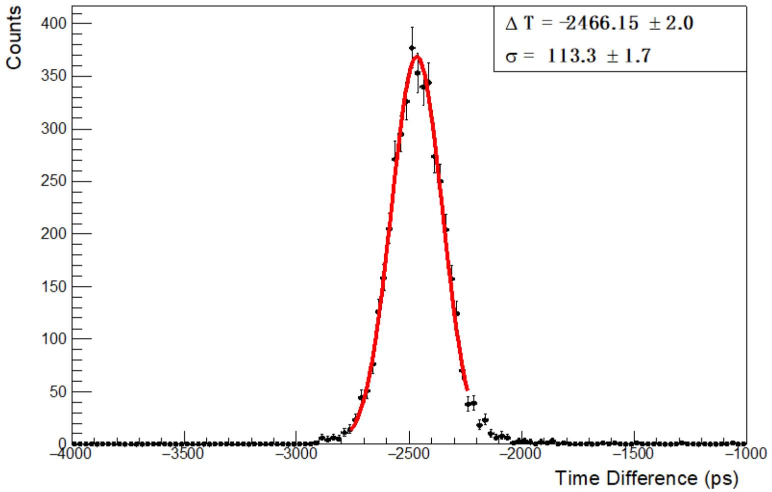
Time resolution of long strip： S-G + 12SiPMs

With Tin foil

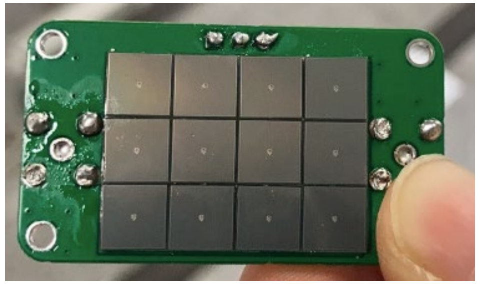


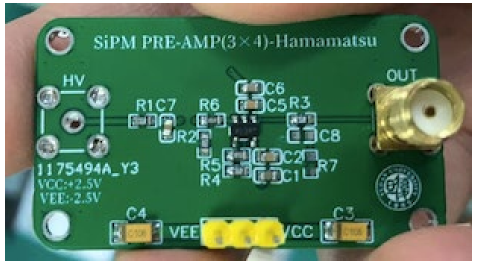
Saint-Gobain (5 × 3 × 120 cm^3)

ΔT=(T1+T2+T5+T6)/4-(T3+T4)/2

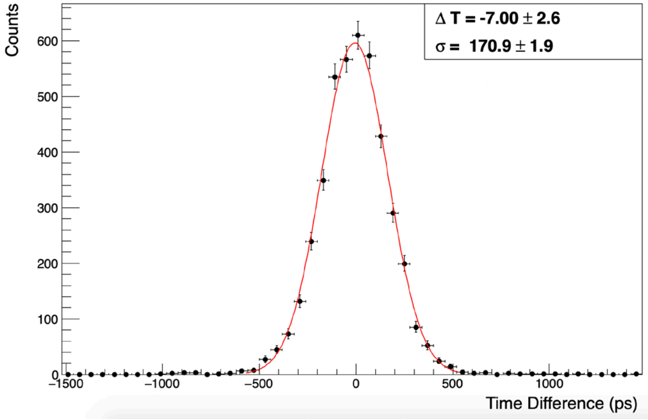


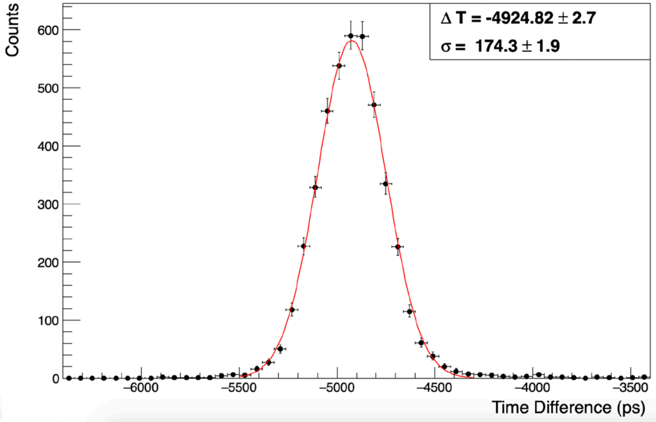
σ_{long}=87 ps





12 SiPMs in parallel

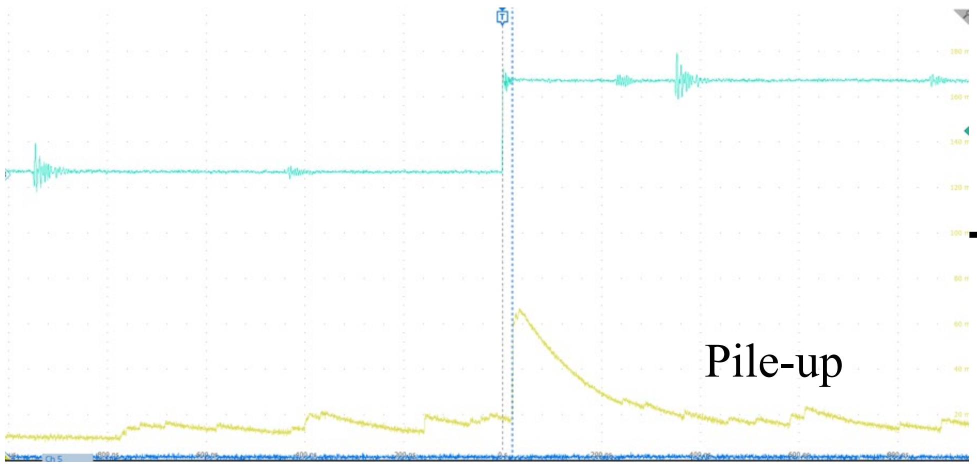




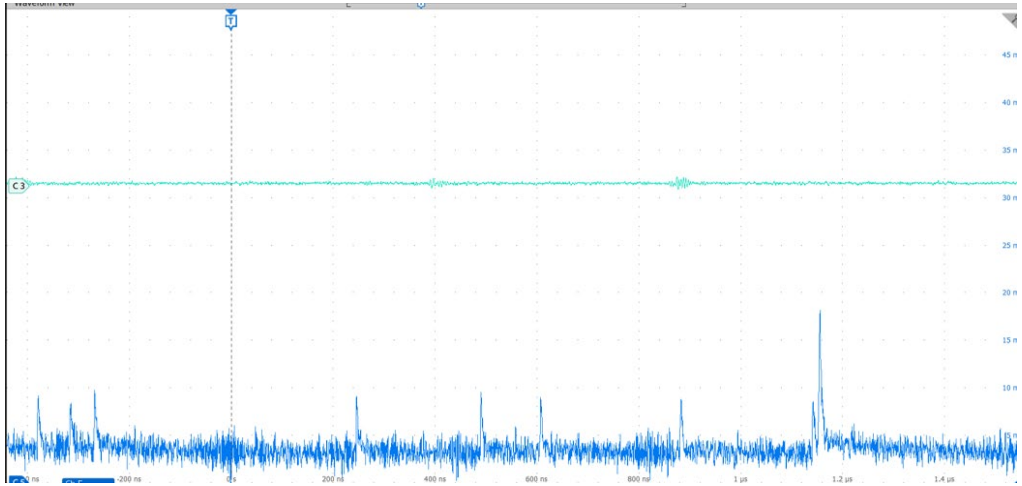
ΔT between 2+6 and 4 (left), or 1+5 and 3 (right)

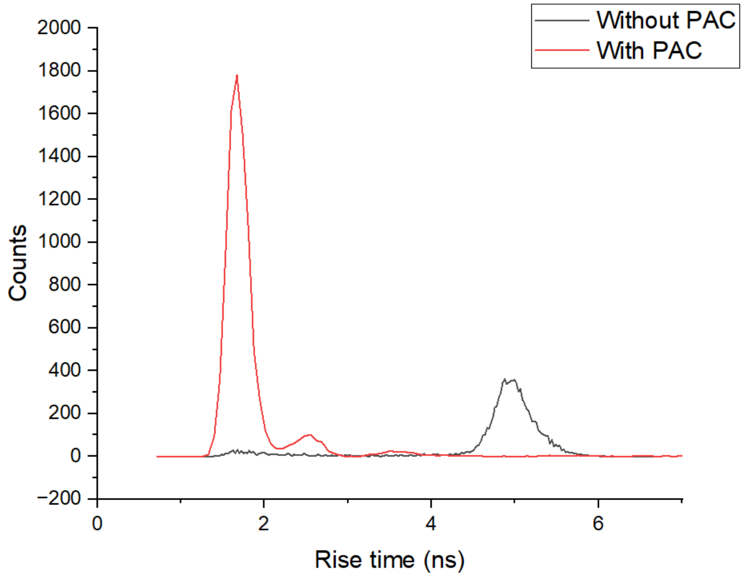
Spatial resolution according to ΔT between 3 and 4 should be $\sim 0.17 \times \frac{30}{n}\ cm$, which is 3.4cm

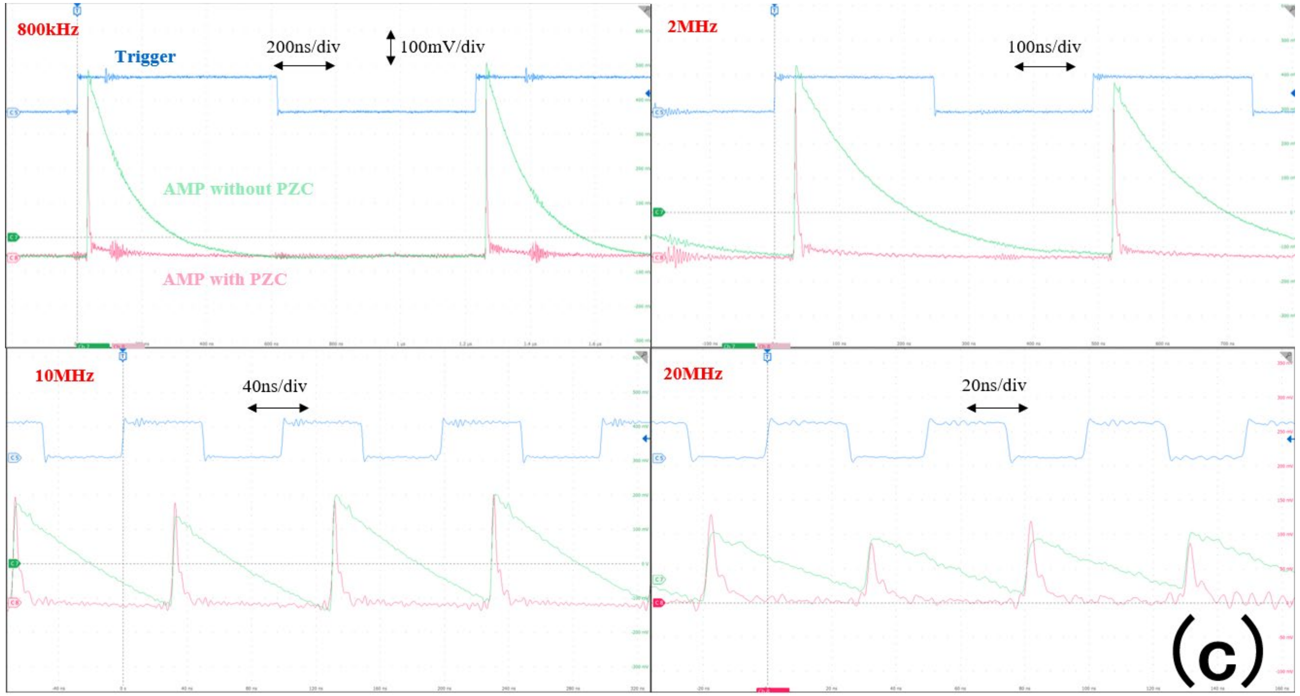
PZC


Pile-up

PZC →

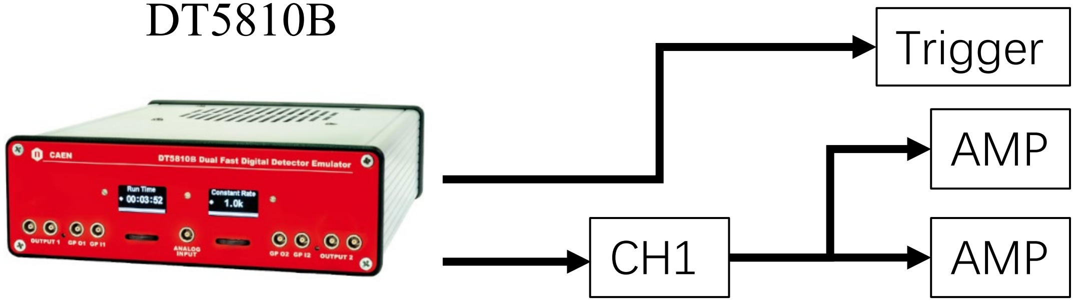


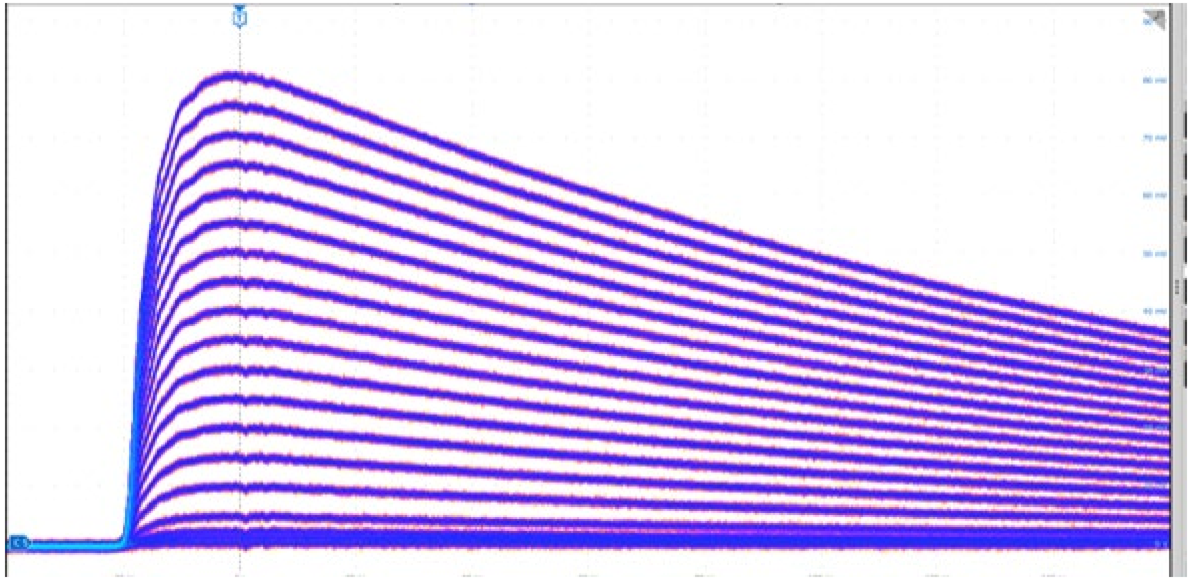

Without PAC
With PAC
Counts
Rise time (ns)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
−200
0
2
4
6

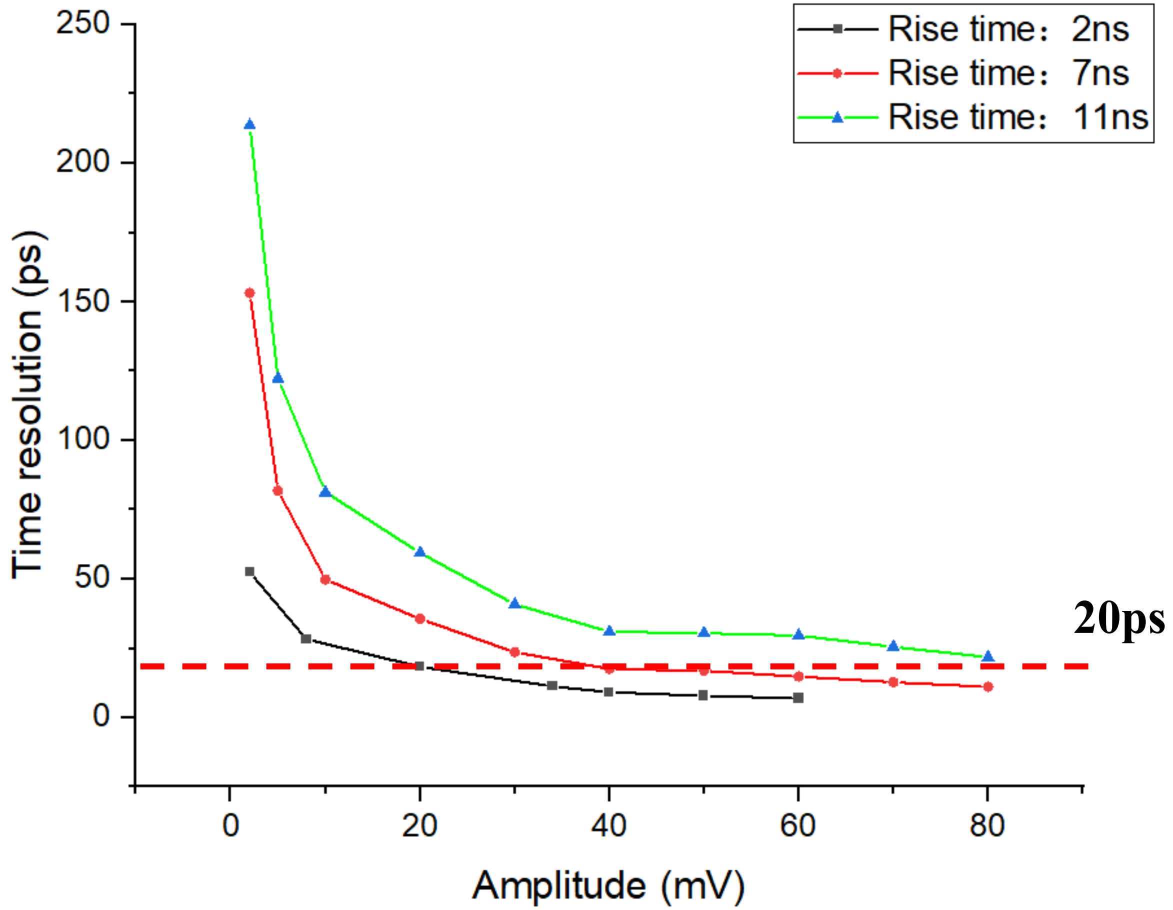

800kHz
Trigger
200ns/div
100mV/div
AMP without PZC
AMP with PZC
2MHz
100ns/div
10MHz
40ns/div
20MHz
20ns/div
(c)

SiPM readout electronics performance test

DT5810B





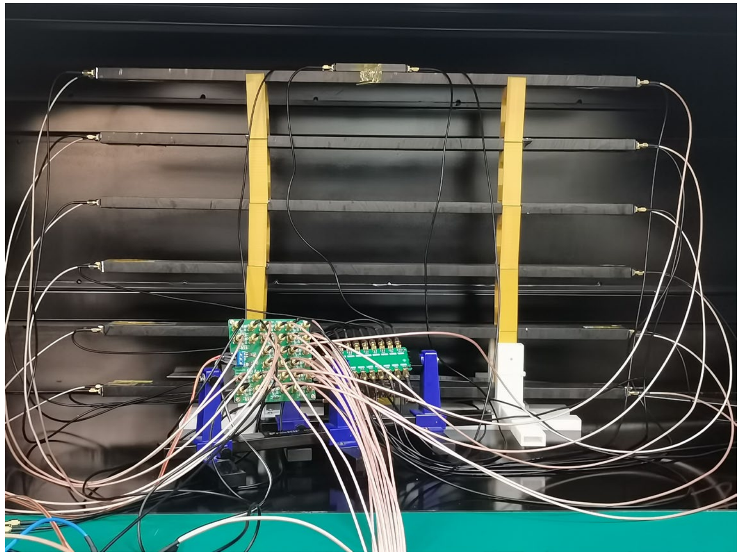


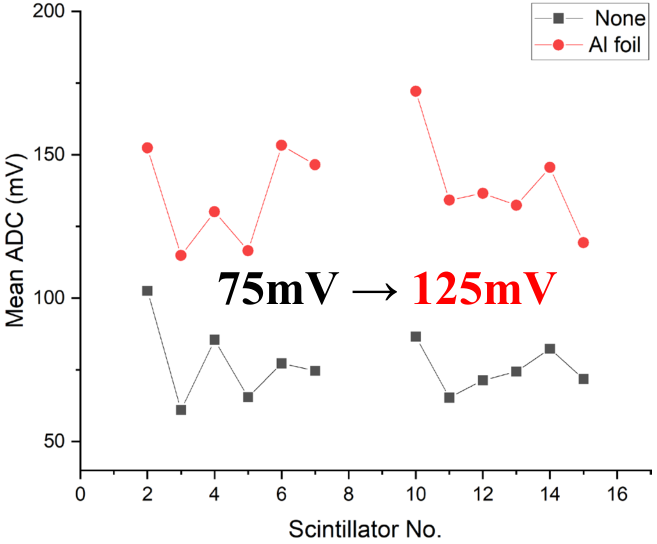
risetime：1ns **fall time**：100ns
signal amplitude：2 – 80 mV

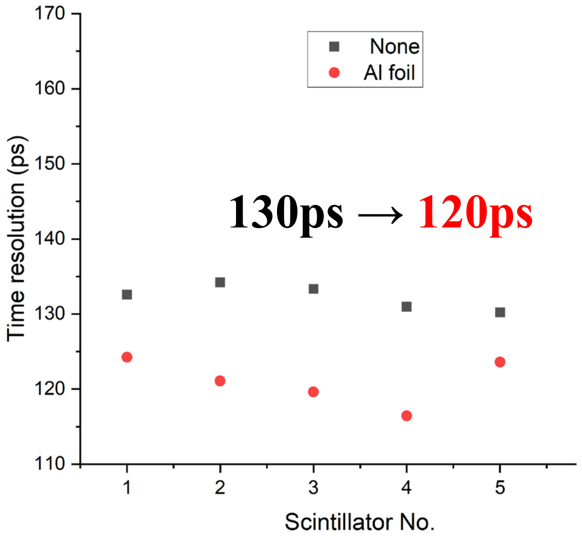
$$\sigma_t = \frac{\sigma_{noise}}{({dV}/{dt})_{MAX}}$$

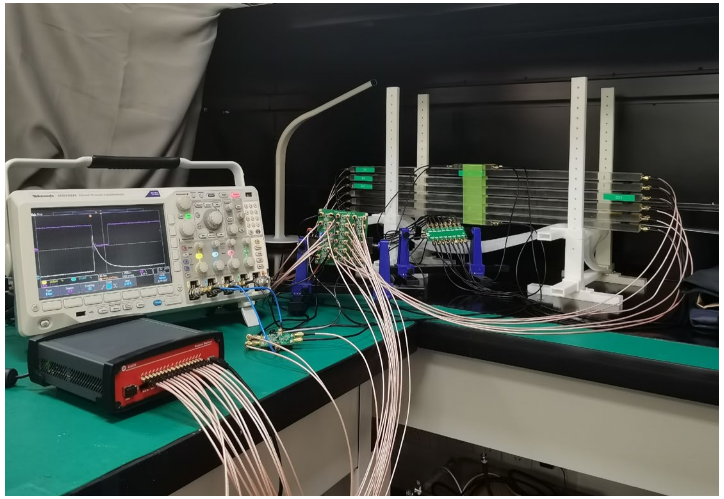
Prototype Test

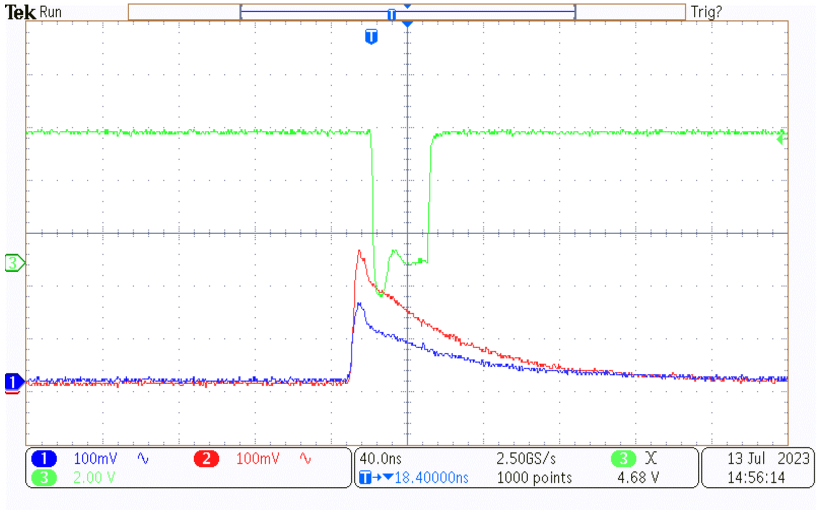
- Using aluminum foil as the reflector can improve the signal amplitude, thus improve the time resolution.

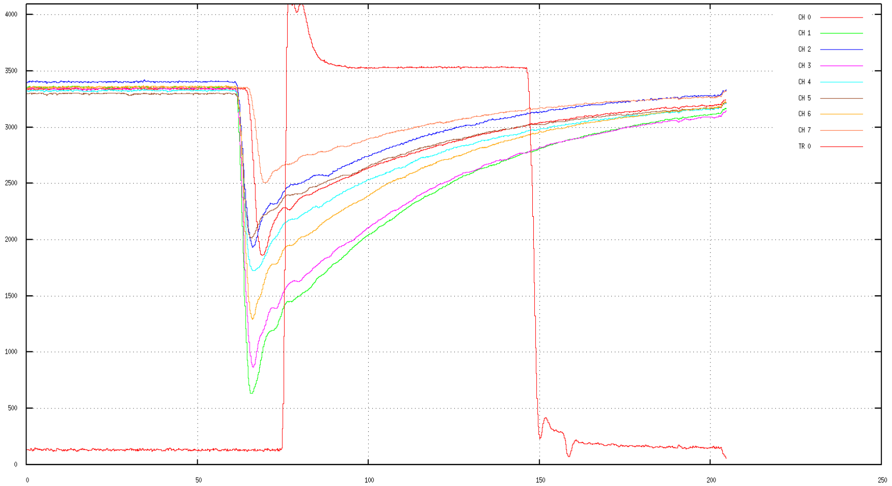












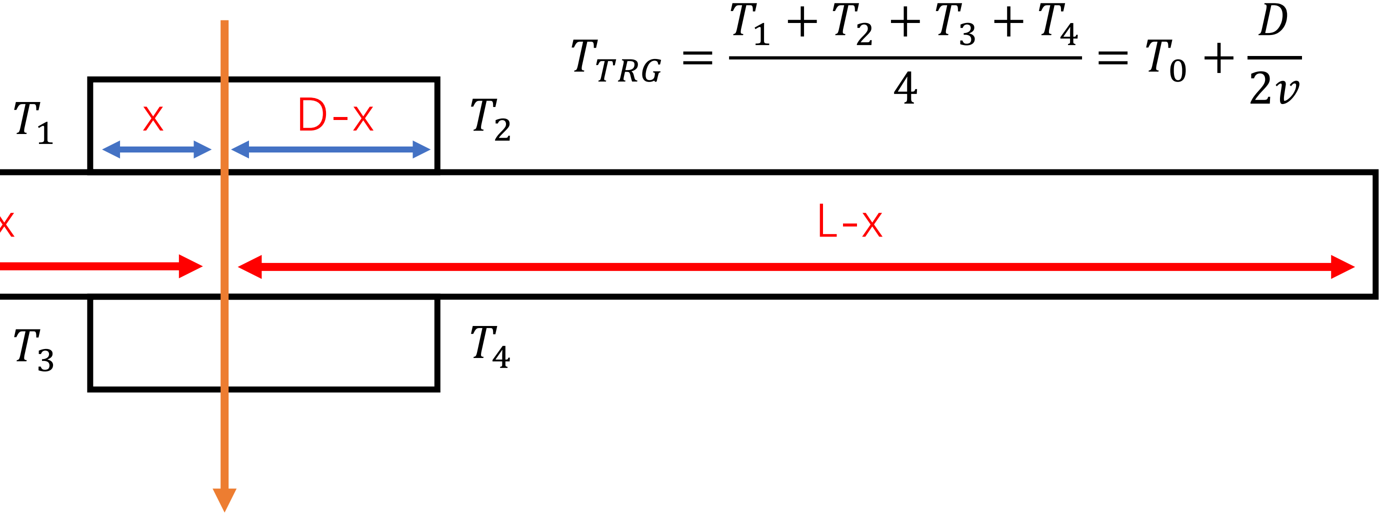
Prototype test setup

Trigger signal waveform

DT5742 signal waveform

$$T_{TRG} = \frac{T_1 + T_2 + T_3 + T_4}{4} = T_0 + \frac{D}{2v}$$

$$T_F = T_0 + \frac{x}{v}$$



$$T_B = T_0 + \frac{L - x}{v}$$

Unweighted:

$$T_{AVG} = \frac{T_F + T_B}{2} = T_0 + \frac{L}{2v}$$

$$\sigma_{AVG}^2 = (\sigma_F^2 + \sigma_B^2)/4$$

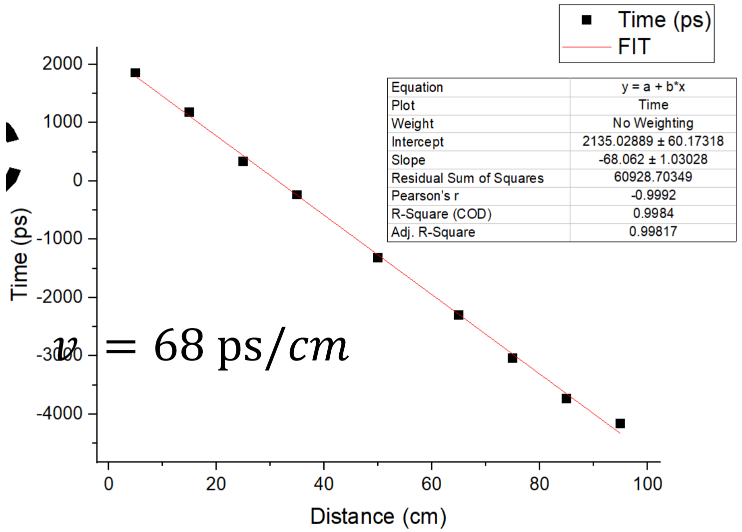
$$\Delta T = T_{TRG} - T_{AVG} = \frac{D - L}{2v}$$

$$\sigma_{\Delta T}^2 = \sigma_{TRG}^2 + \sigma_{AVG}^2$$

Weighted average:

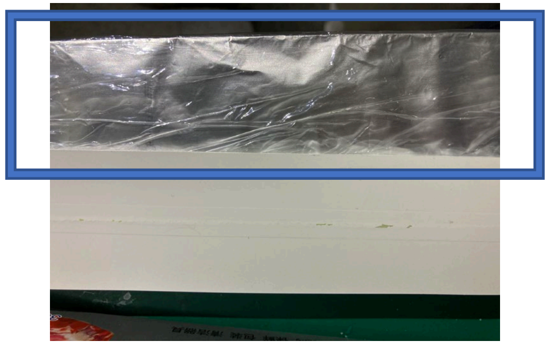
$$T_{AVG} = \frac{(T_F - x/v)\Big/\sigma_F^2 + (T_B - (l - x)/v)\Big/\sigma_B^2}{1\big/\sigma_F^2 + 1\big/\sigma_B^2}$$

$$\sigma_{AVG}^2 = \frac{1}{\sigma_F^2} + \frac{1}{\sigma_B^2}$$

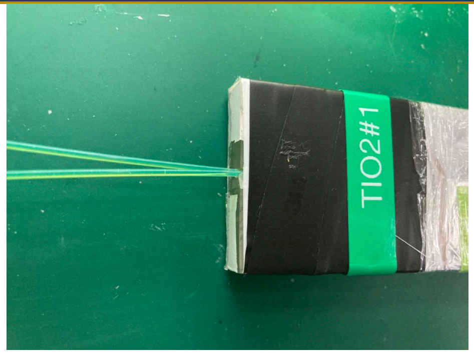


$$v = 68\ \mathrm{ps/cm}$$

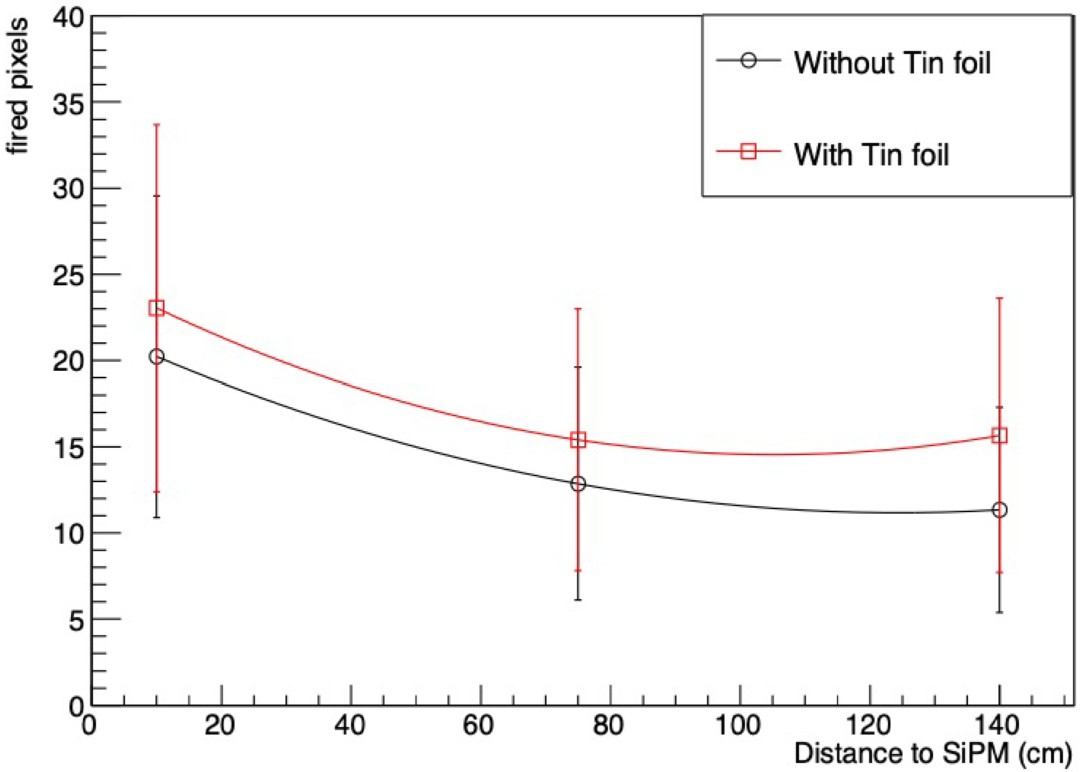
Light collection of scintillator detector

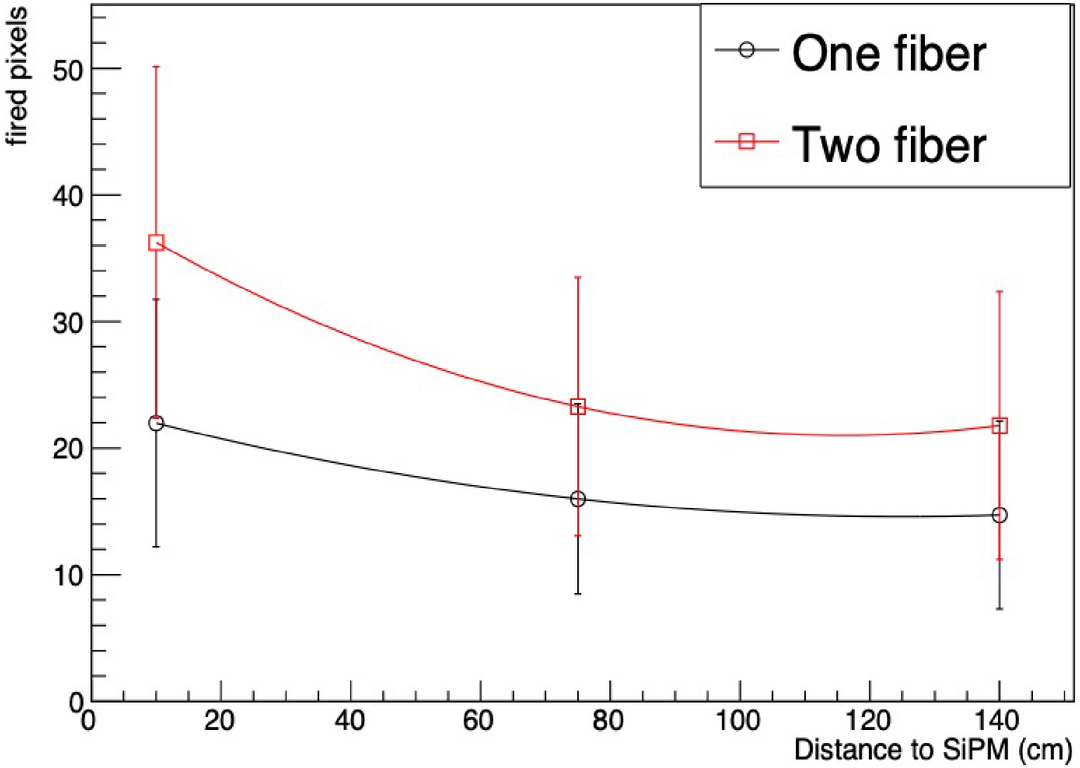


Light collection improved by Tin foil

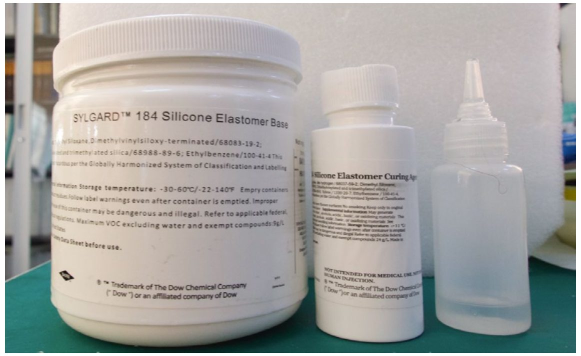


Adding fiber to improve light collection

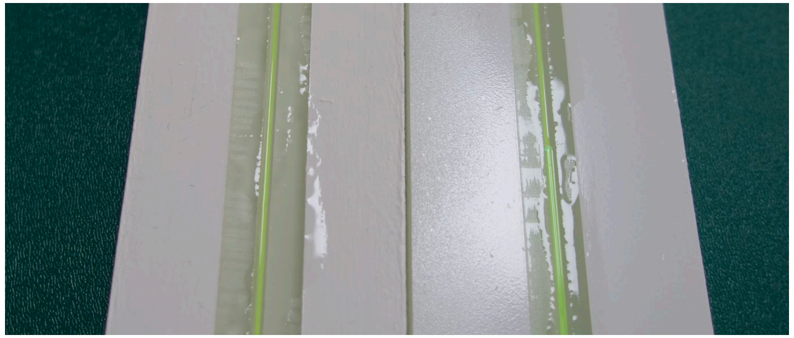




Light collection of scintillator detector

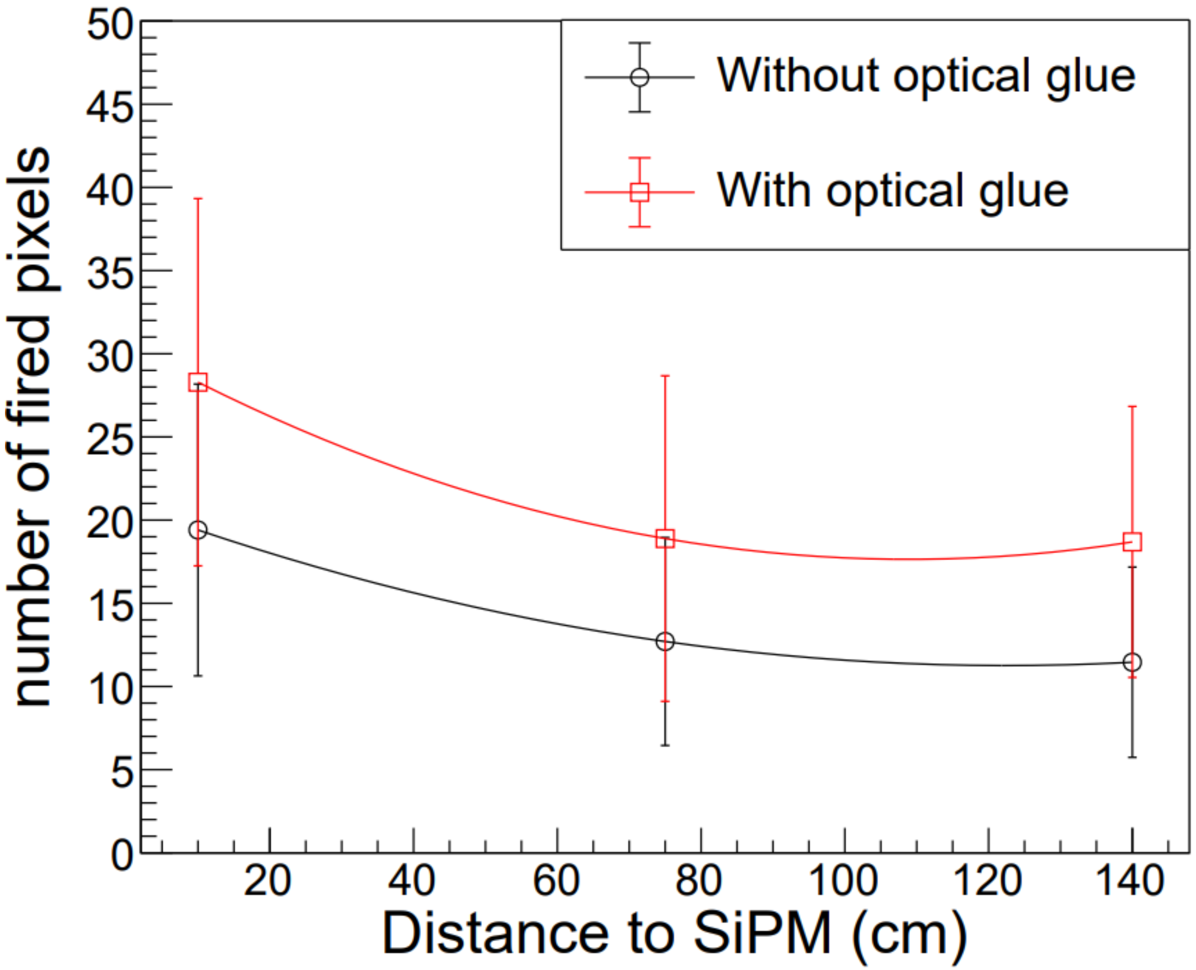


Optical glue： dowcorning 184
(Corrosion-free and light-transparent)



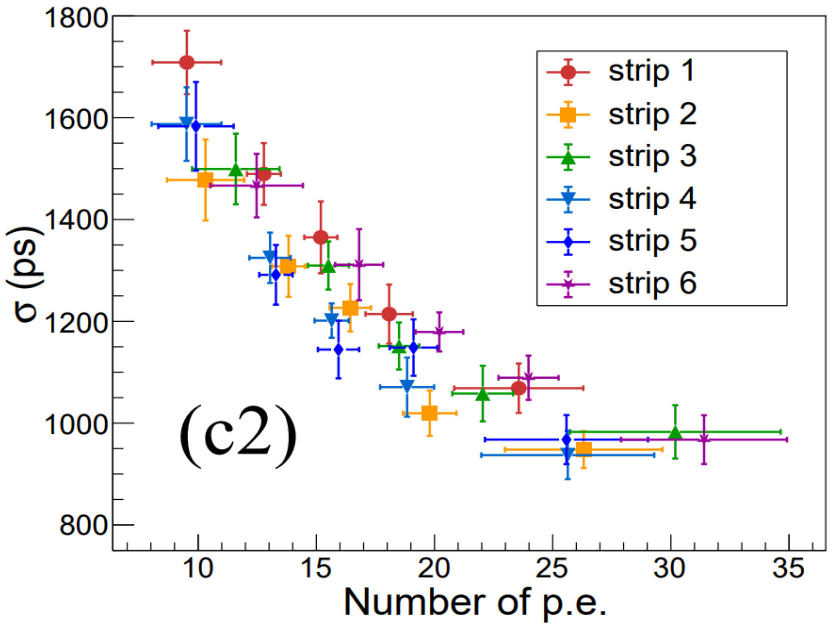
48h room temperature curing

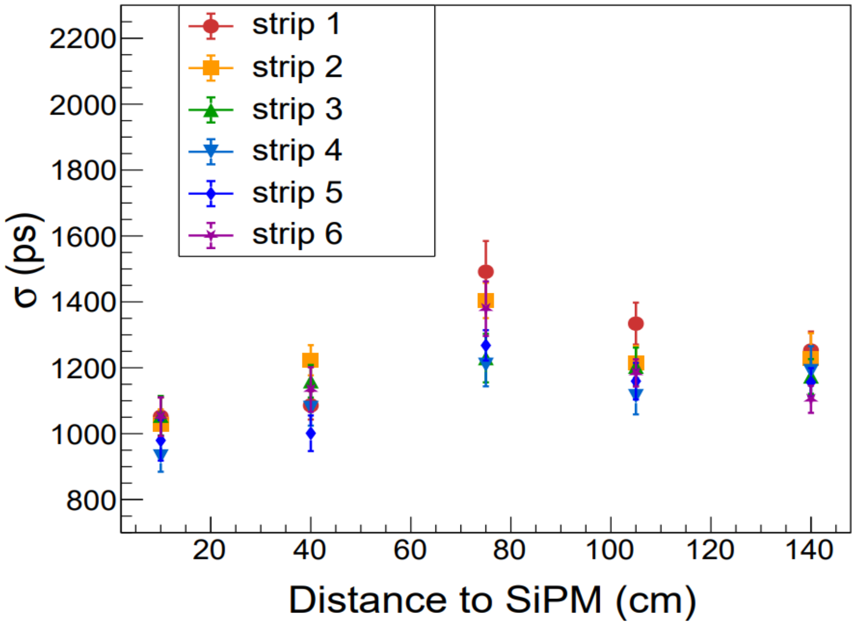
Completely wraps the scintillator to reduce light leakage



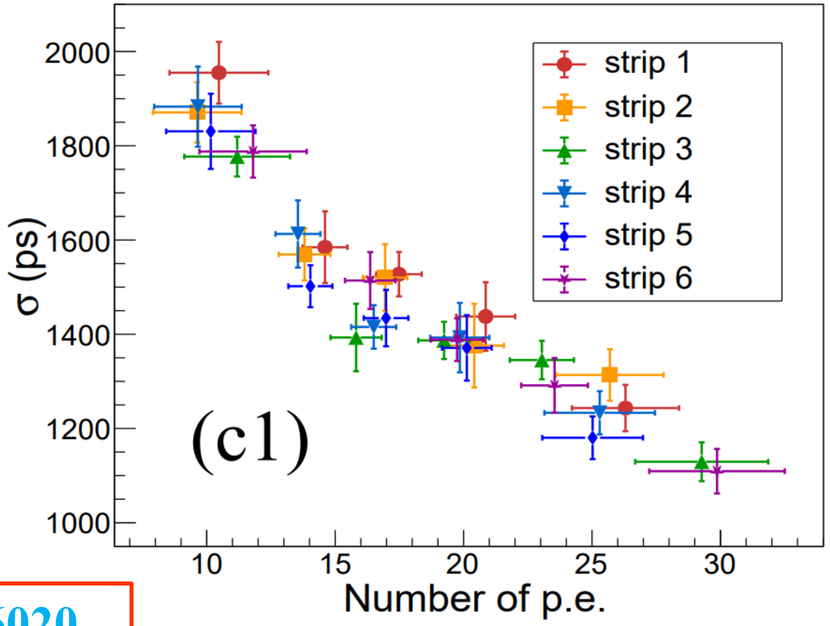
Time resolution test

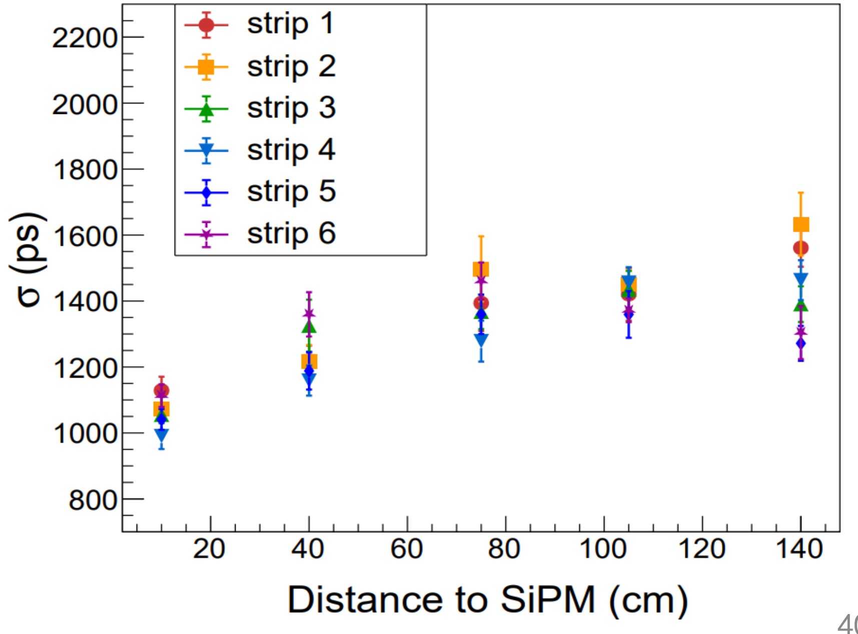
MPPC





NDL





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