# R&D for Belle II  KLM upgrade with timing measurement

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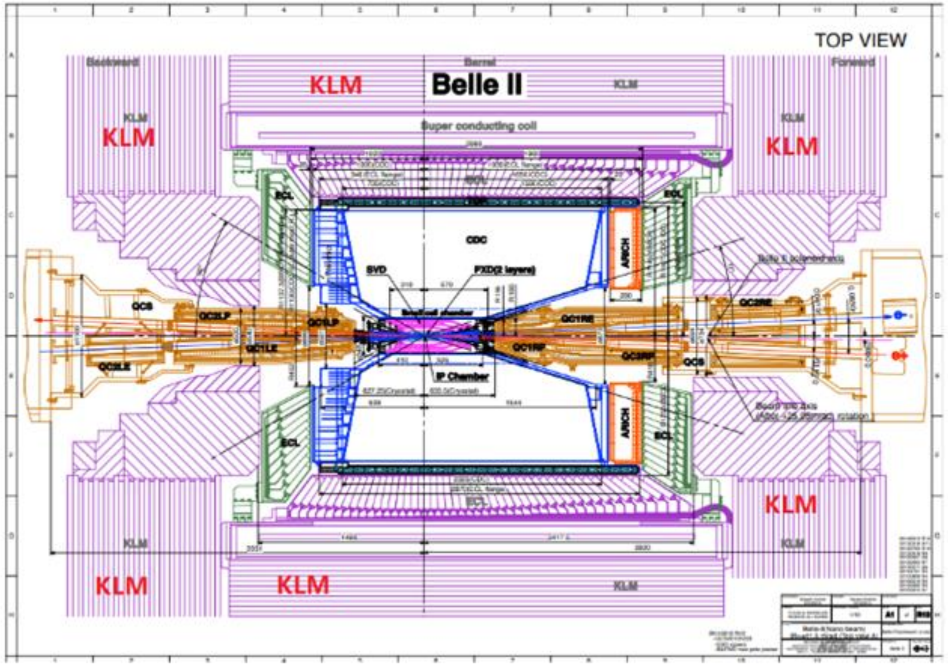
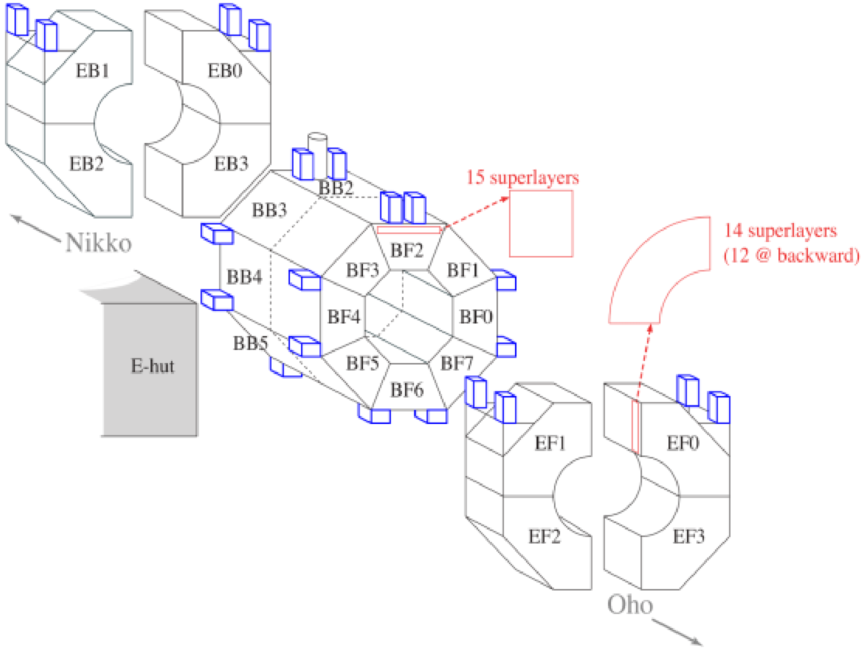
# Contents

## 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.

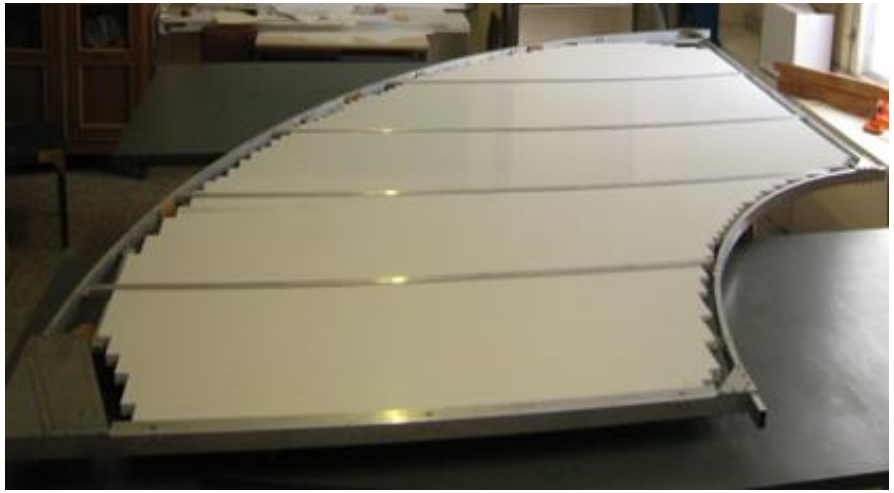


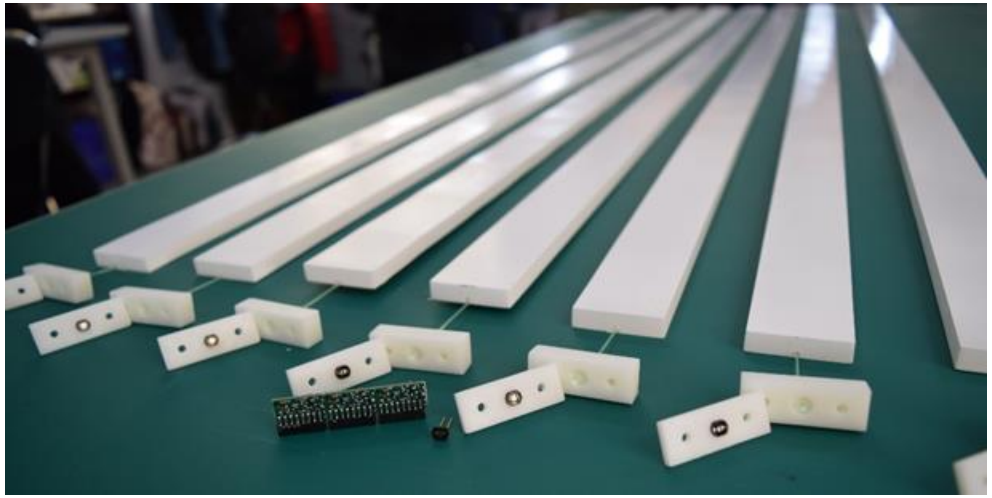

The structure of Belle II KLM

Snowmass whitepaper, arXiv: 2203.11349

# Structure of current KLM design



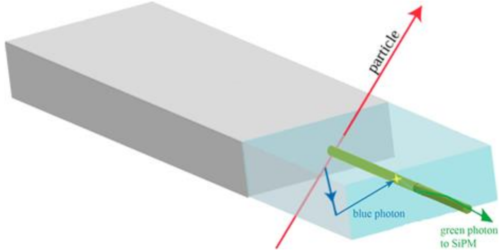
Scintillators of KLM end cap scintillators

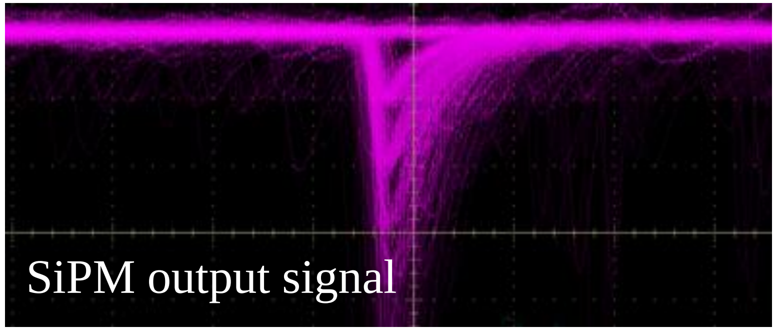


Scintillator + WLS fiber + SiPM

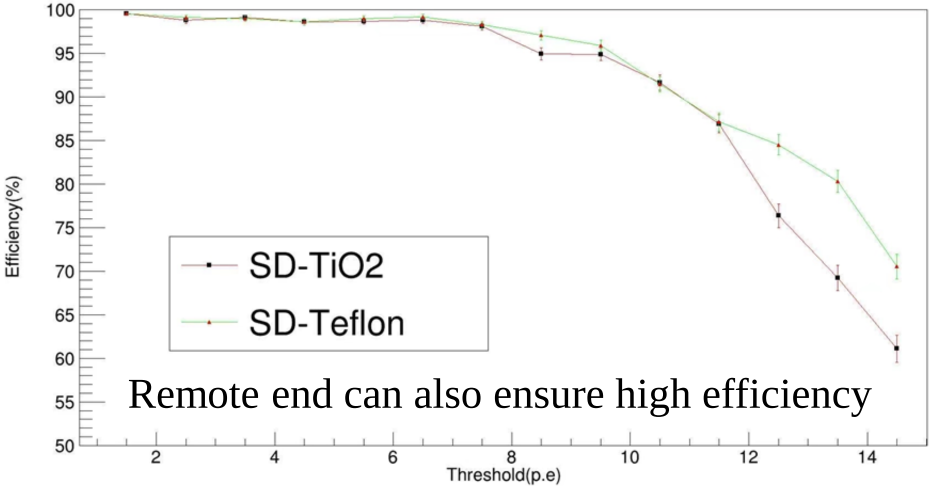
- CR testing with two strips
- High efficiency
- Time resolution: $< 1.5ns$

WLS fiber limits the improvement of time resolution

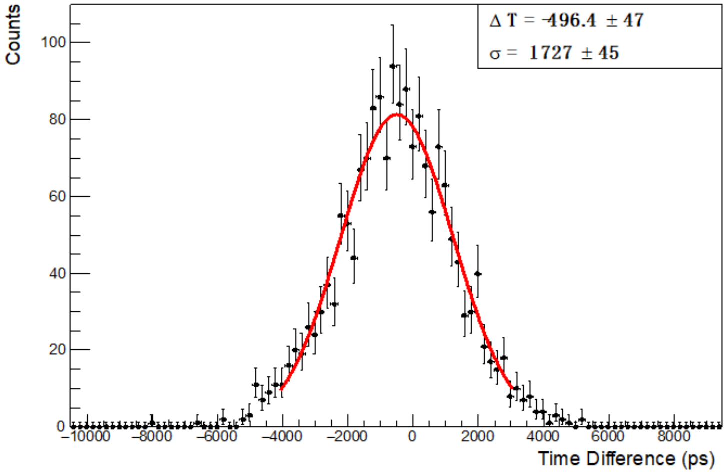


SiPM output signal



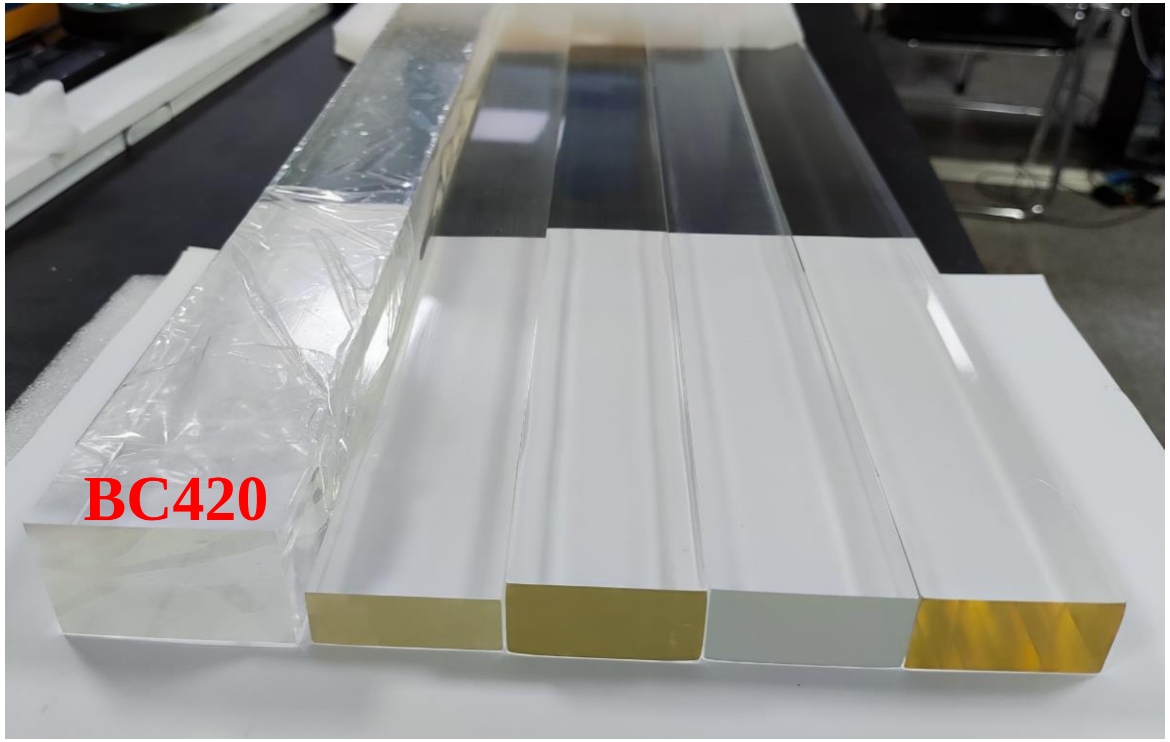

Keeping high efficiency at 10 p.e. threshold




Time difference of two channel

# K-long & Muon Detector upgrades

## Solid scintillator (no WLS fiber)



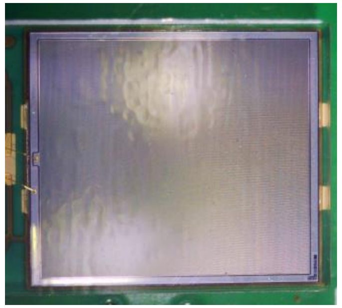

SAINT-GOBAIN

高能科迪 GAONENGKEDI

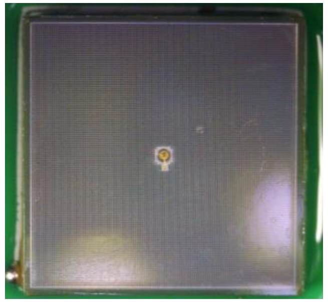
## Multiple SiPMs

HAMAMATSU
PHOTON IS OUR BUSINESS

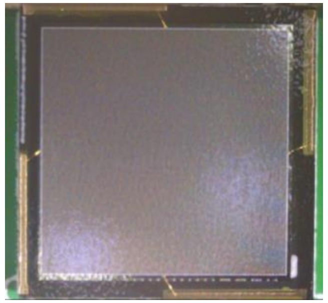
NDL



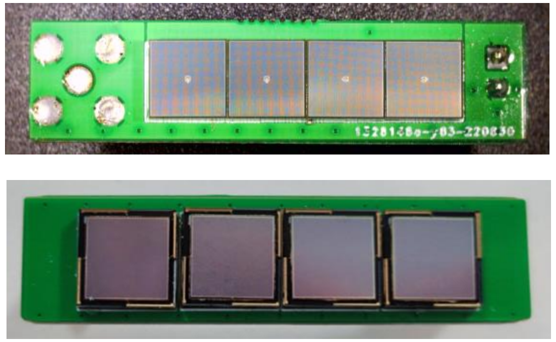
S13360-6025PE



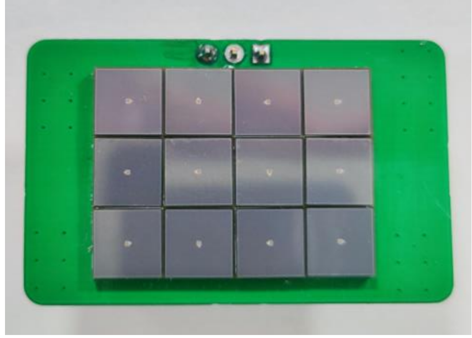
S14160-6050HS



EQR1511-6060D-S



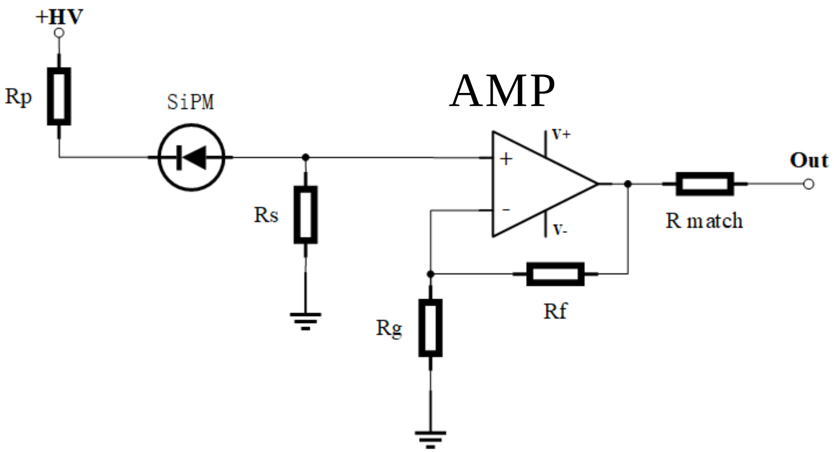
4×SiPM



12×SiPM

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

# Design of preamplifier



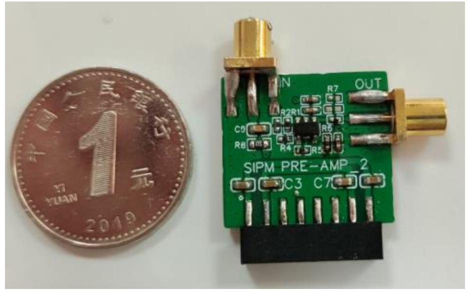
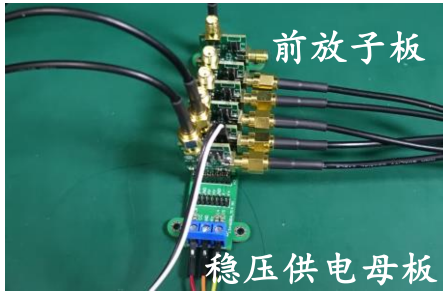

Gain: +20 V/V

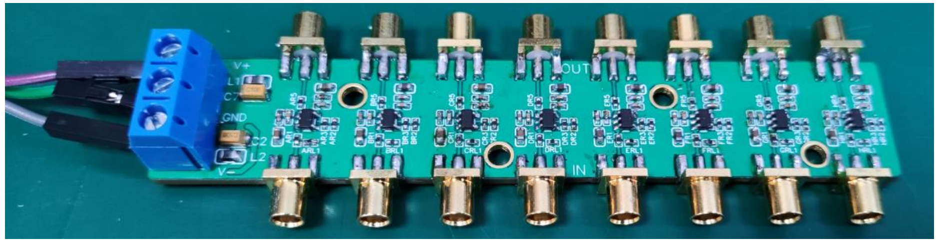
Bandwidth(-3dB): 400 MHz

Baseline noise(RMS): 300uV

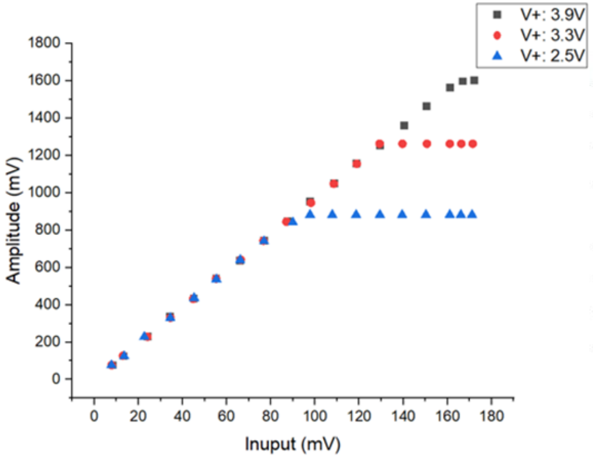
Input impedance: 50Ω

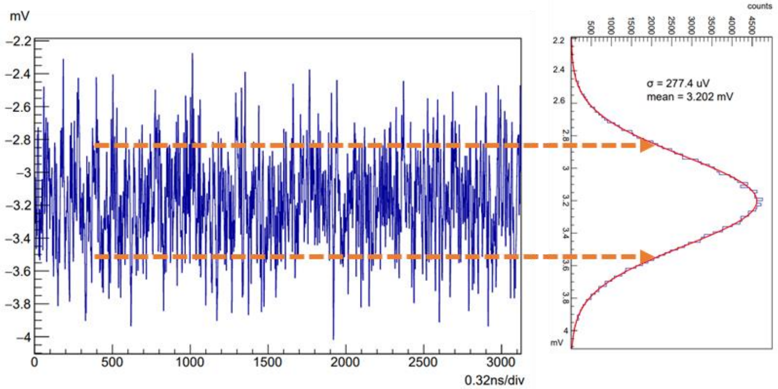
Cost :30 ¥/Ch

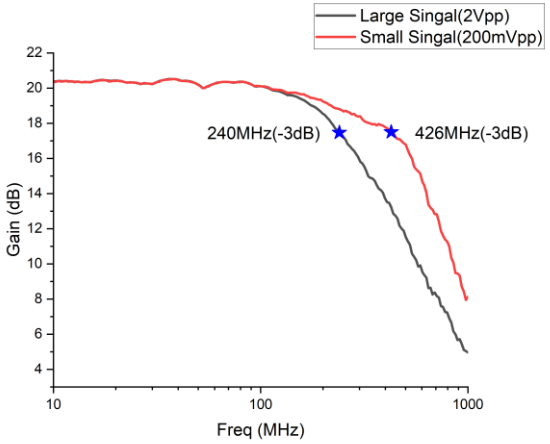



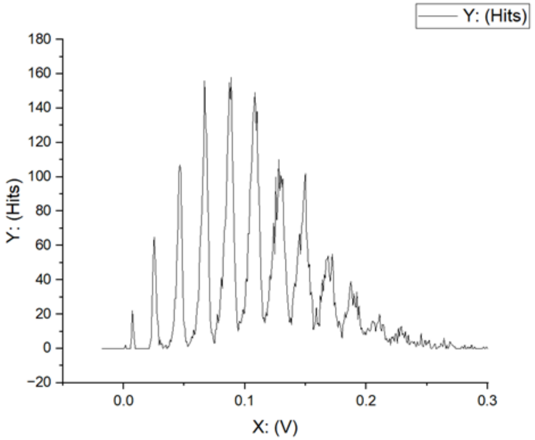


## ➢ Performance test of preamplifier



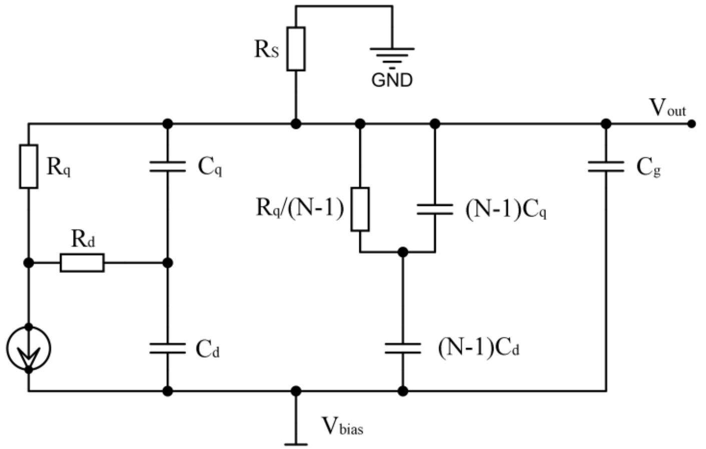




- Dynamic range testing
- Baseline noise test
- Bandwidth testing
- SiPM photoelectron peak

# Pole-zero Cancellation ( PZC )




SiPM equivalent circuit model

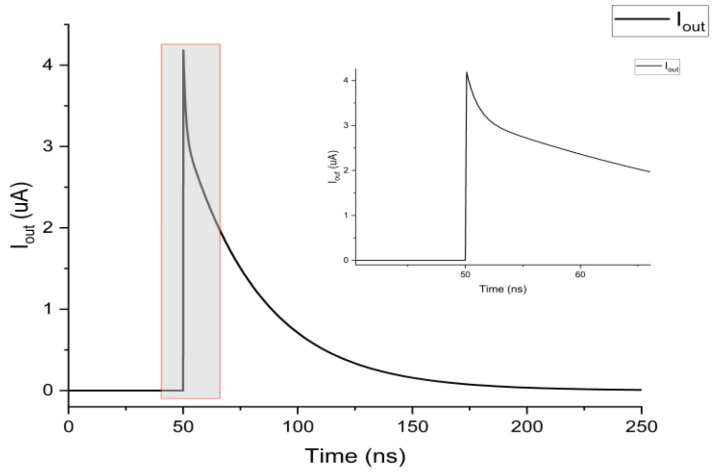
$$\tau_{rise} = R_d(C_d + C_q)$$
$$\tau_{fast(fall)} = R_{load} \times C_{tot}$$
$$\tau_{slow(fall)} = R_q(C_d + C_q)$$

Cd: diode capacitance  Rd: diode resistor

Rq: quenching resistor

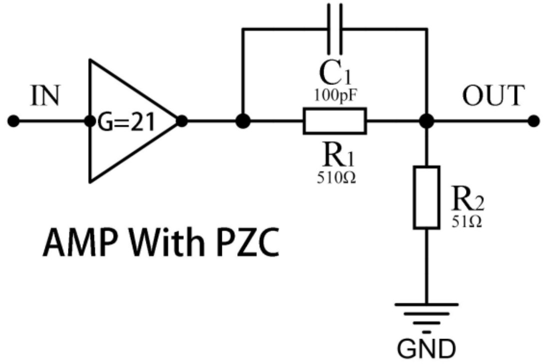
Cq: parasitic capacitance of Rq

Cg: lumped contributions of the parasitics




SiPM single photon signal

➢ **This long tail will cause pile up in the case of high luminosity**

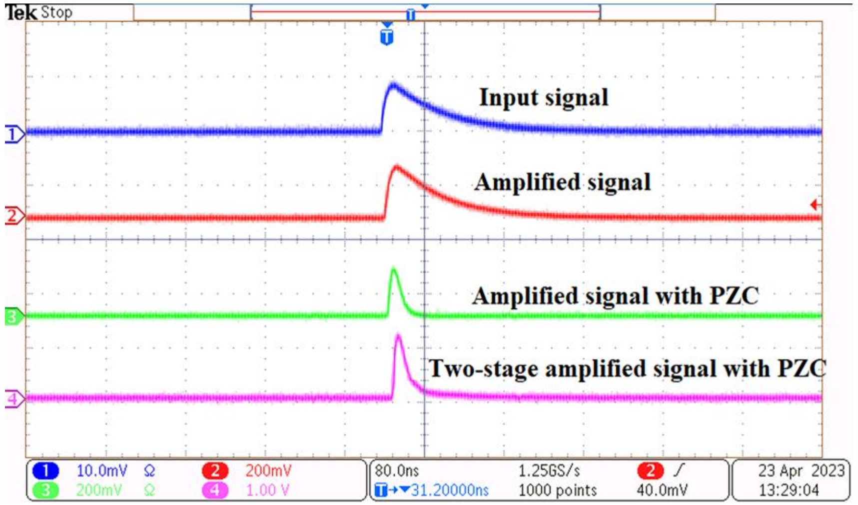


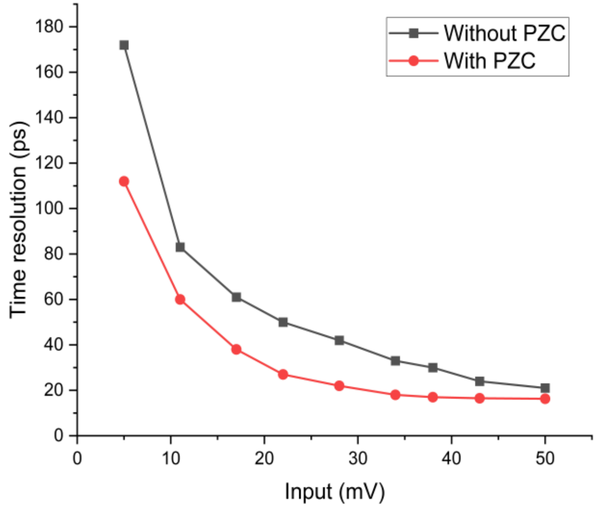

AMP With PZC

$$\tau_1 = R_1 C_1$$
$$\tau_f = R_q(C_q + C_d)$$
$$\tau_2 = \frac{R_1 R_2 C_1}{R_1 + R_2}$$

$$V_O(S) = \frac{s + \tau_1^{-1}}{(s + \tau_f^{-1})(s + \tau_2^{-1})} V_{max}$$

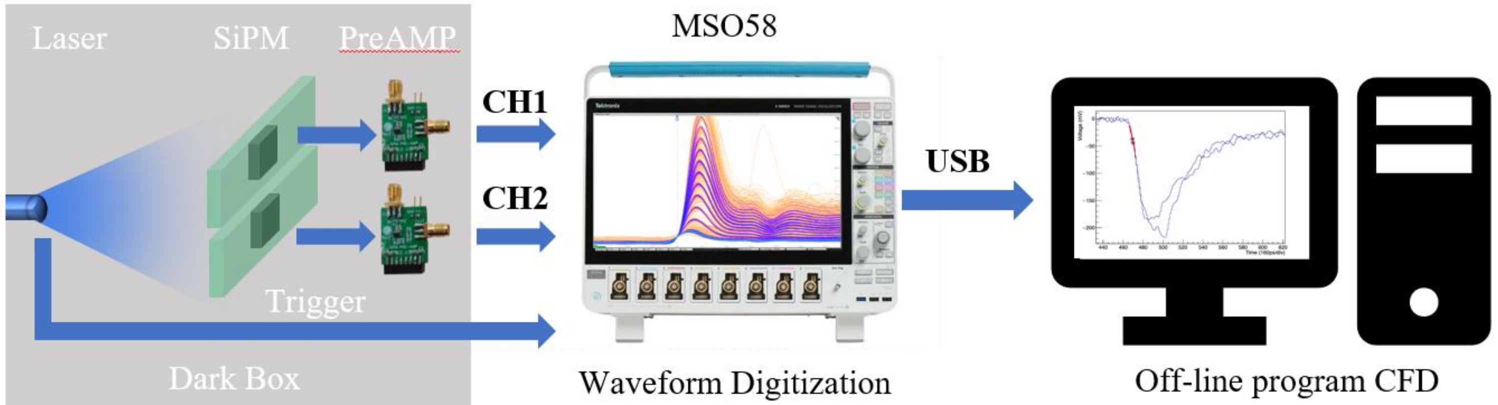
When $\tau_1 = \tau_f$, the fall time of output signal changes to $\tau_2$

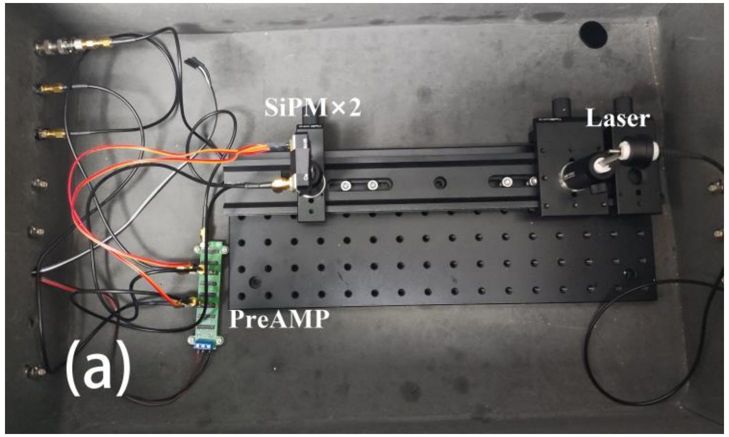


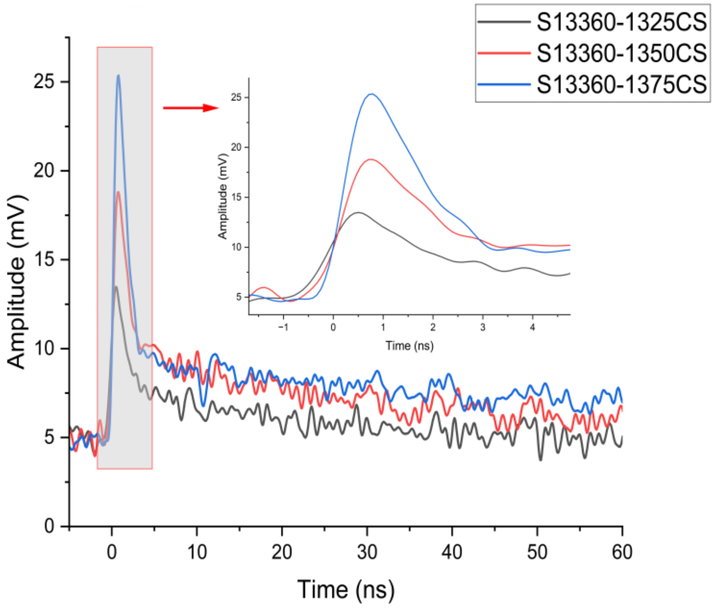

Effect of PZC on time resolution

# SiPM time resolution test

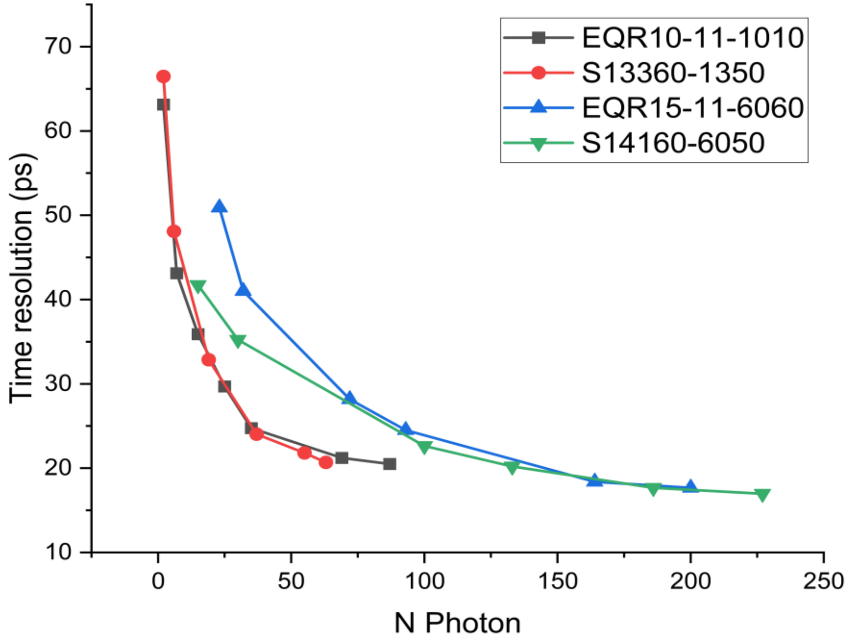



Time resolution test setup




Single photon signal of SiPM

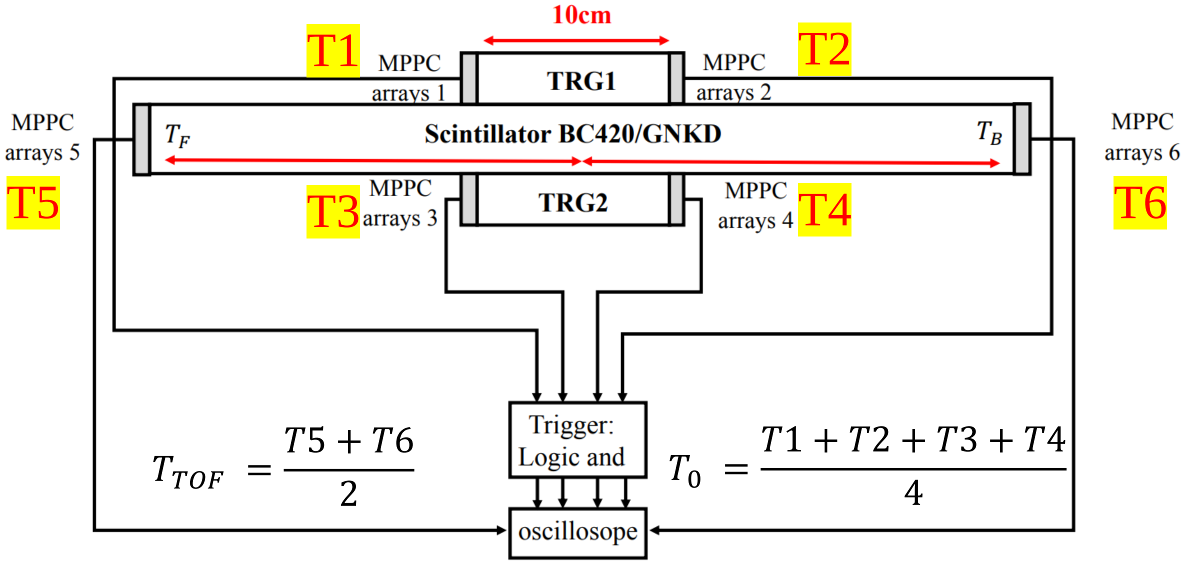



Time resolution varies with the number of photons

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

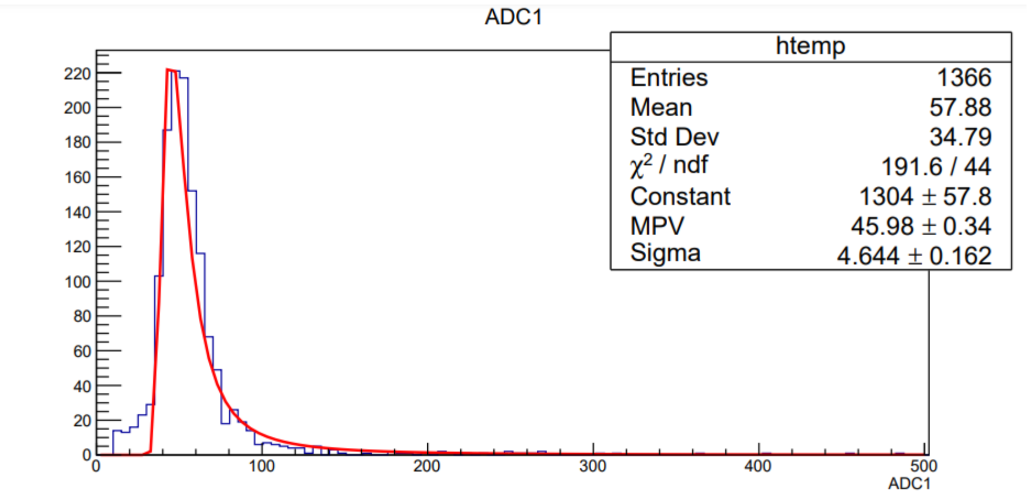
Large area: (6×6 $mm^2$)
Photons > 20 , Time resolution < 50ps
Photons > 70 , Time resolution < 25ps

# Plastic scintillator test using cosmic rays

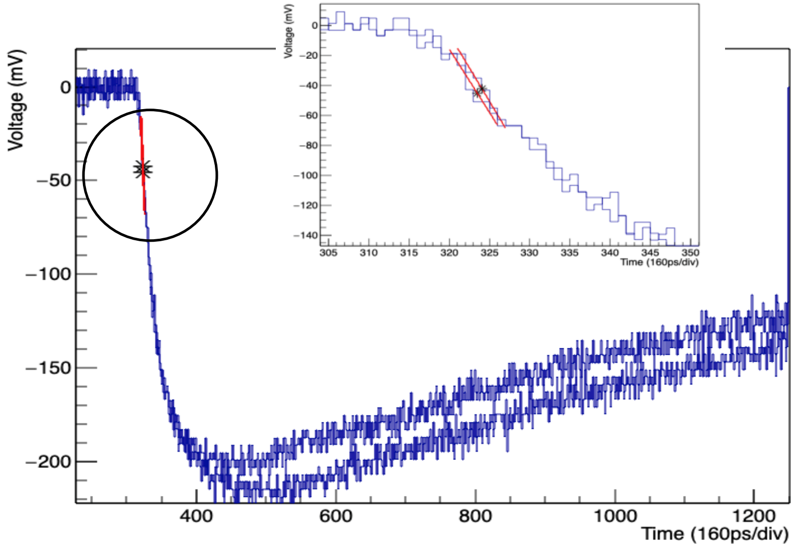



$$T_{TOF} = \frac{T5 + T6}{2}$$

$$T_0 = \frac{T1 + T2 + T3 + T4}{4}$$



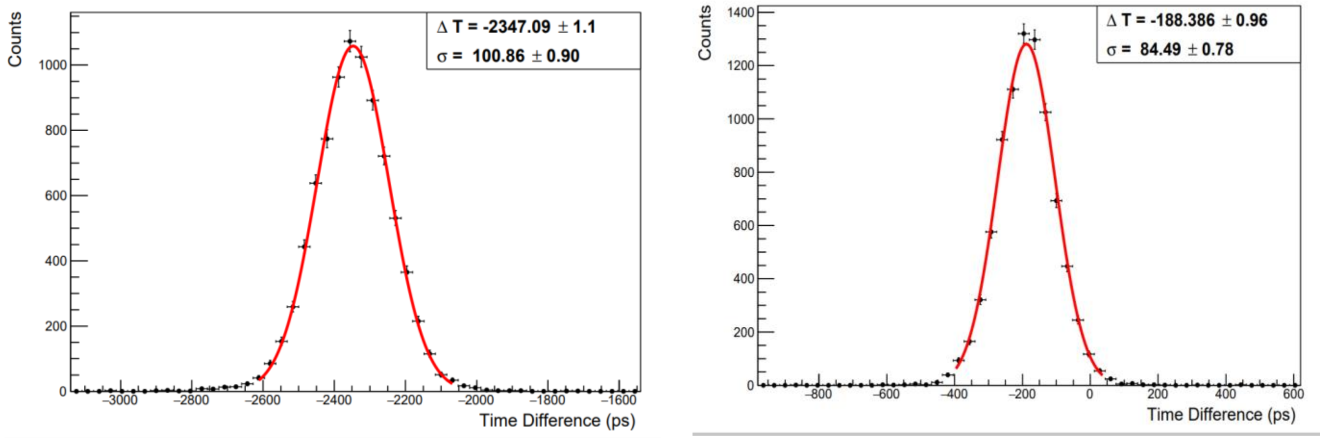

Energy spectrum of cosmic rays




CFD timing of waveform

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

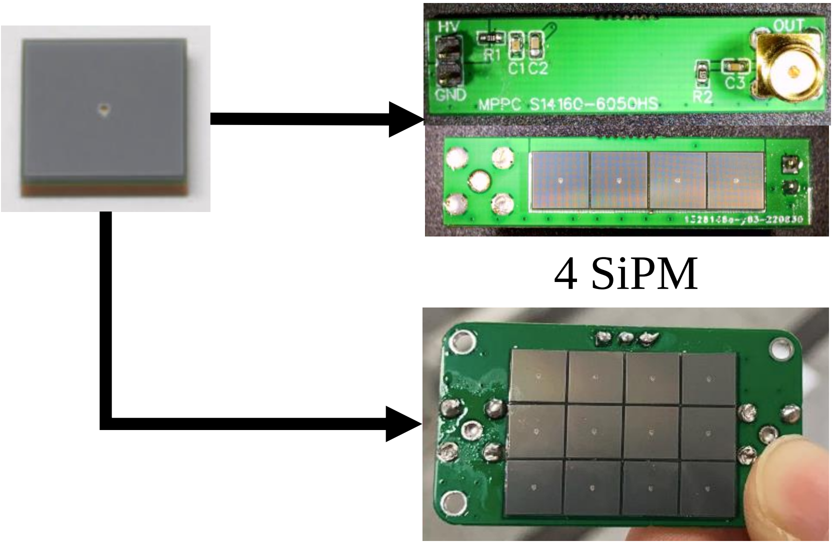
$$T_0 - T_{TOF} \rightarrow \sigma_{T_{TOF}}$$




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

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

# SiPM time resolution test

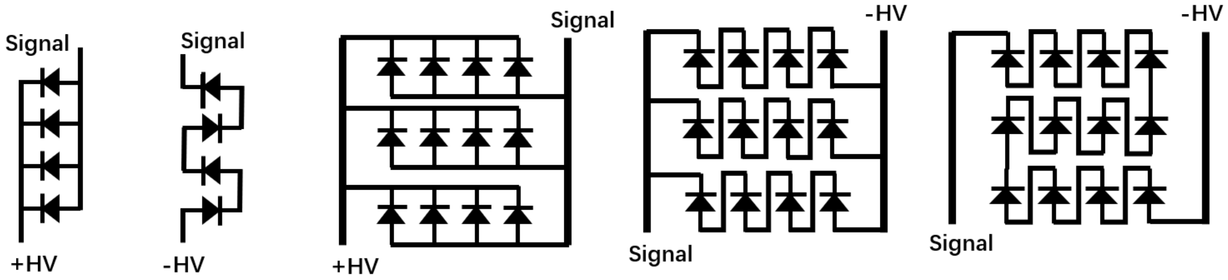



4 SiPM

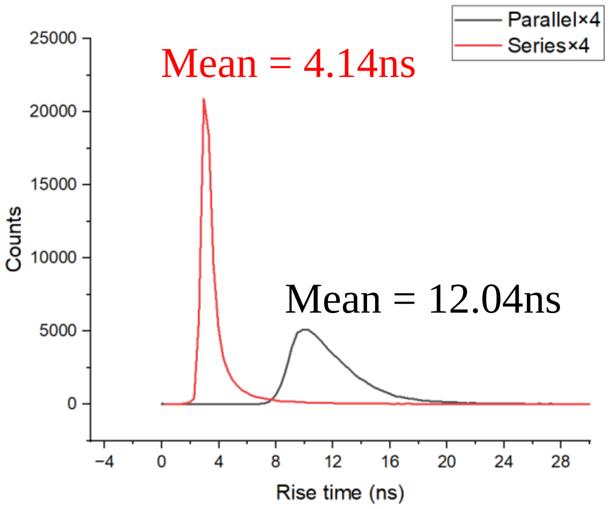
12 SiPM

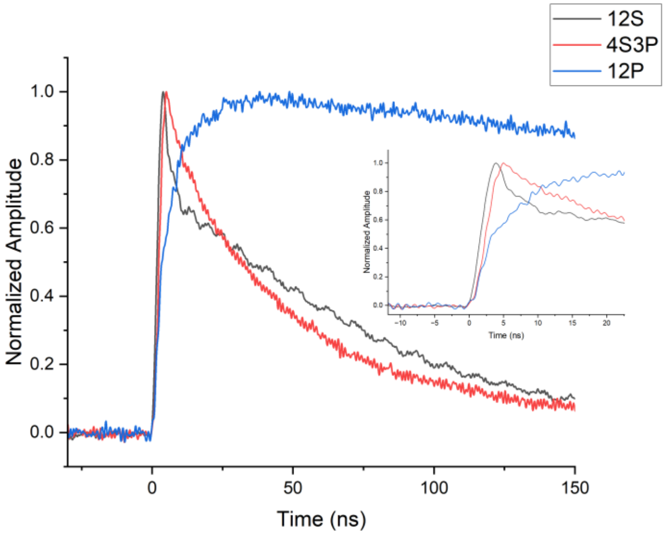
In parallel (P)
N SiPM ↑ Cd ↑ → $\tau_{rise}\uparrow$ $\sigma_{noise}\uparrow$ $Gain\uparrow$

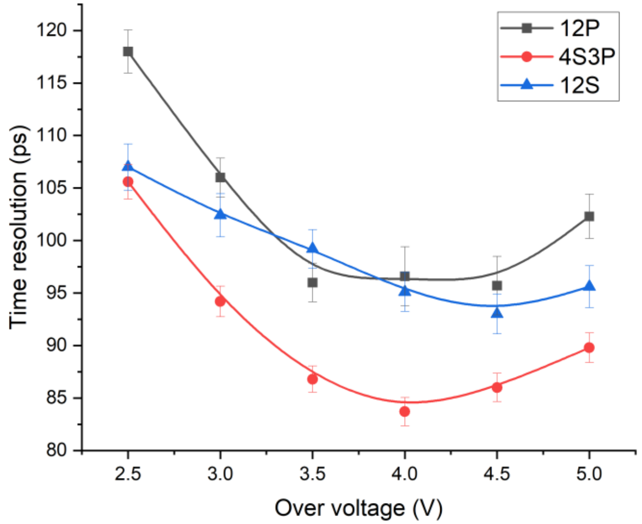
In series (S)
N SiPM ↑ Cd ↓ → $\tau_{rise}\downarrow$ $\sigma_{noise}\uparrow$ $Gain\downarrow$




**4P** **4S** **12P** **4S3P** **12S**



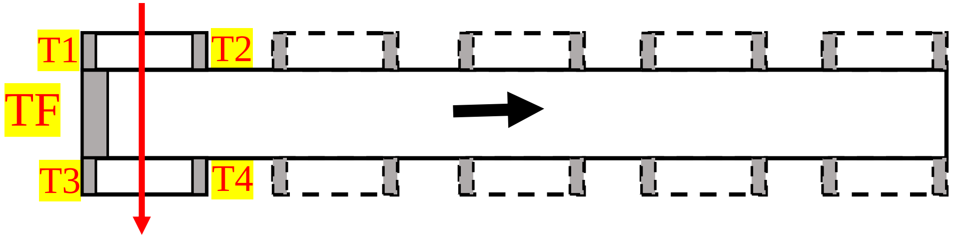




**12P** $\sigma_{TOF}$=95 ps

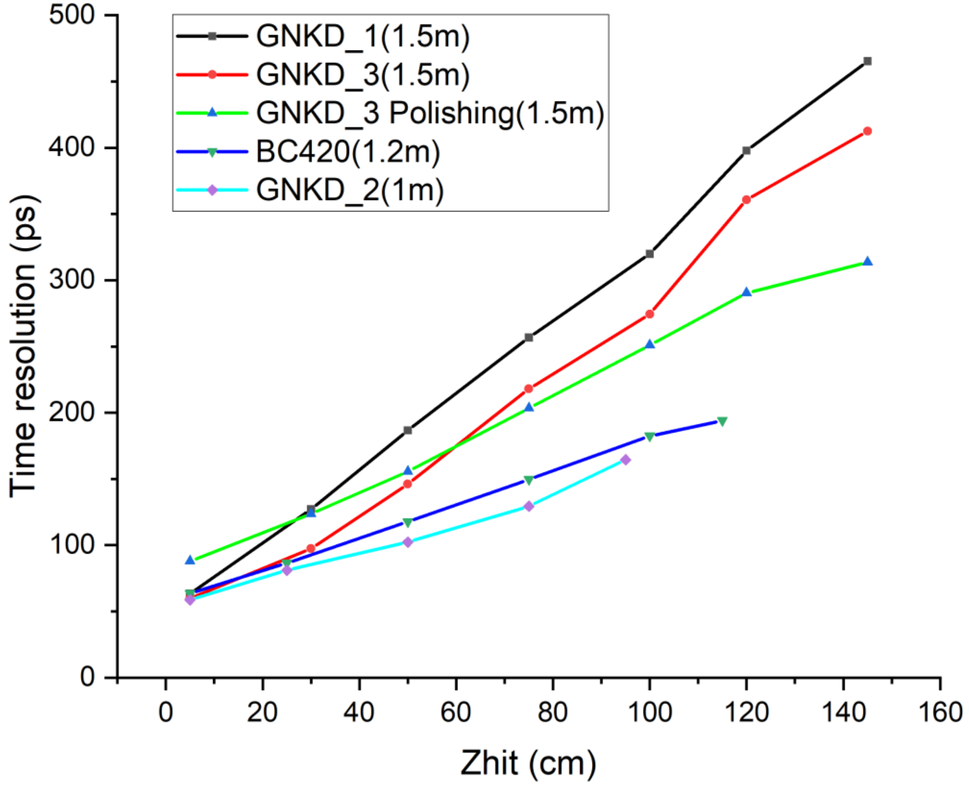
**4S3P** $\sigma_{TOF}$=83 ps

**12S** $\sigma_{TOF}$=94 ps

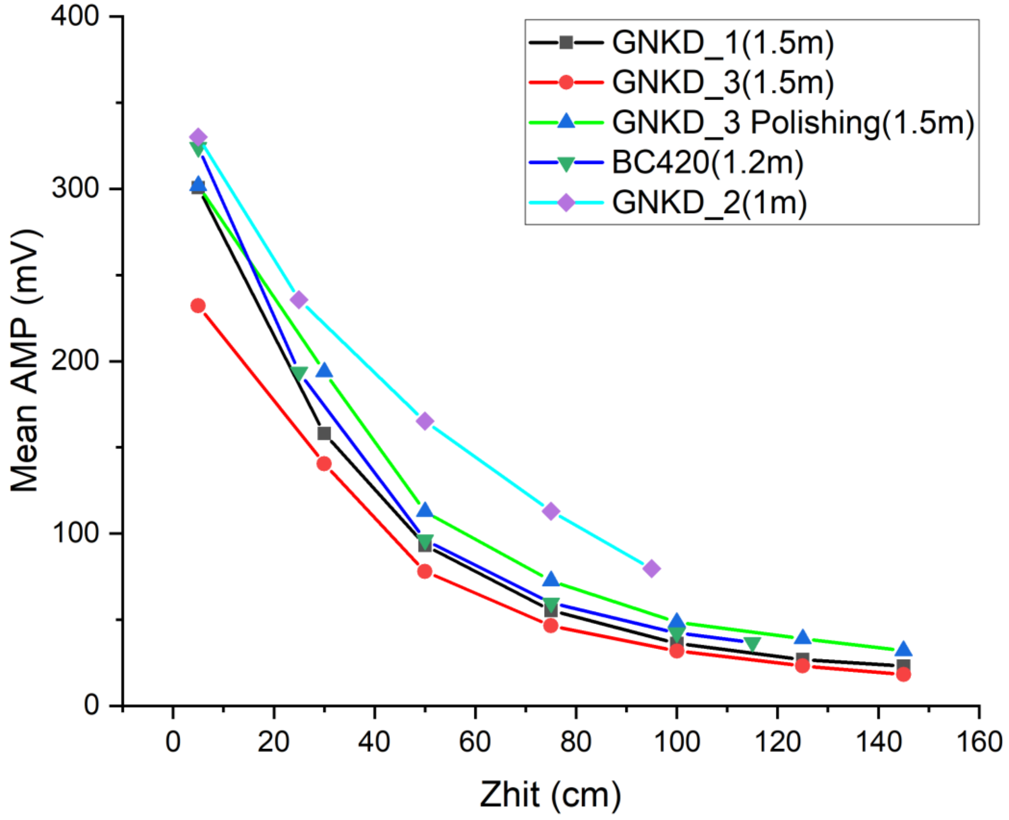
# Scintillator time resolution test (single-ended)




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




Time resolution of different positions of scintillator



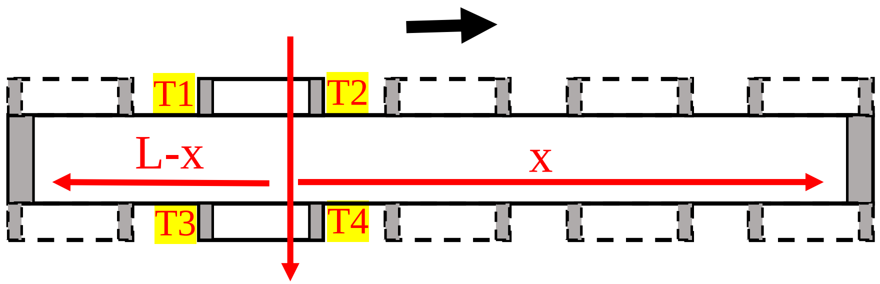

Signal amplitude at different locations of the scintillator

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

# Scintillator + WLS fiber + SiPM

Backward

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




Forward

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

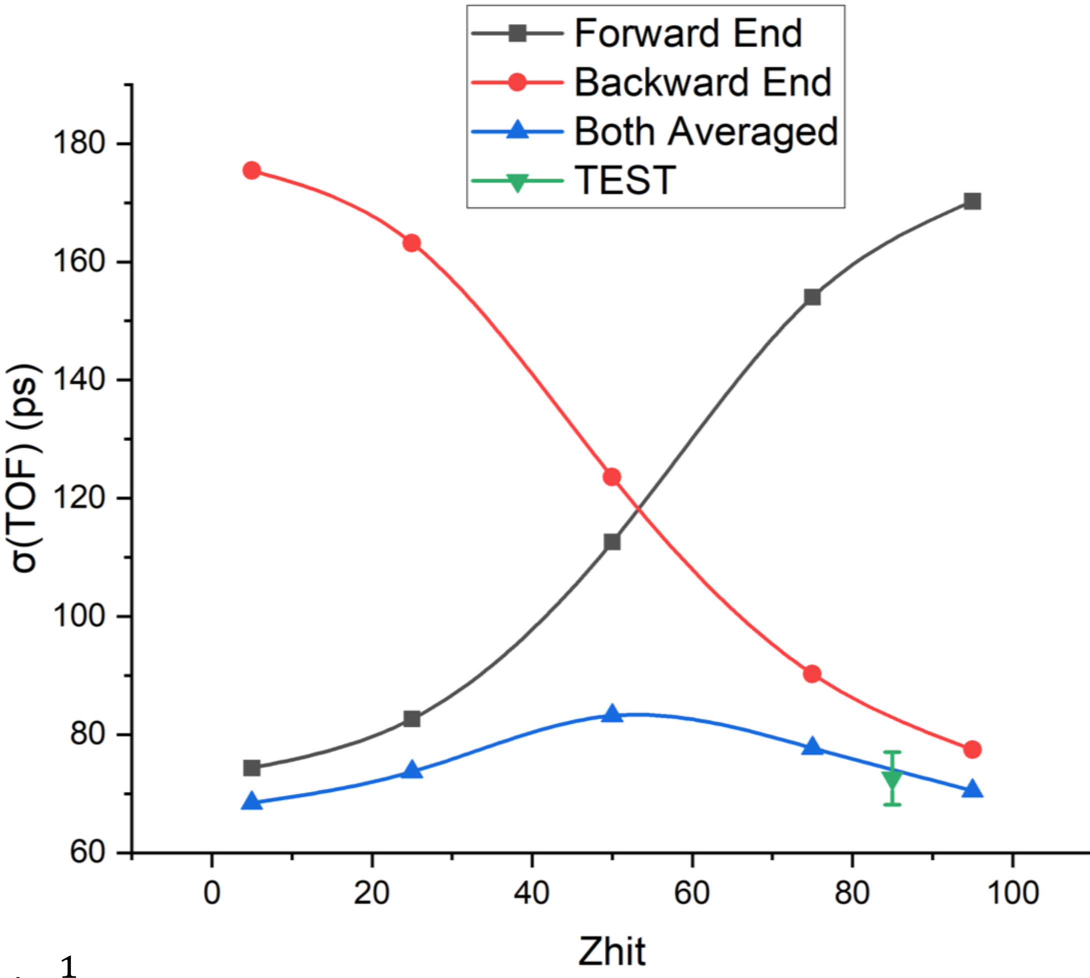
**Unweighted:**

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

**Weighted average:**

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

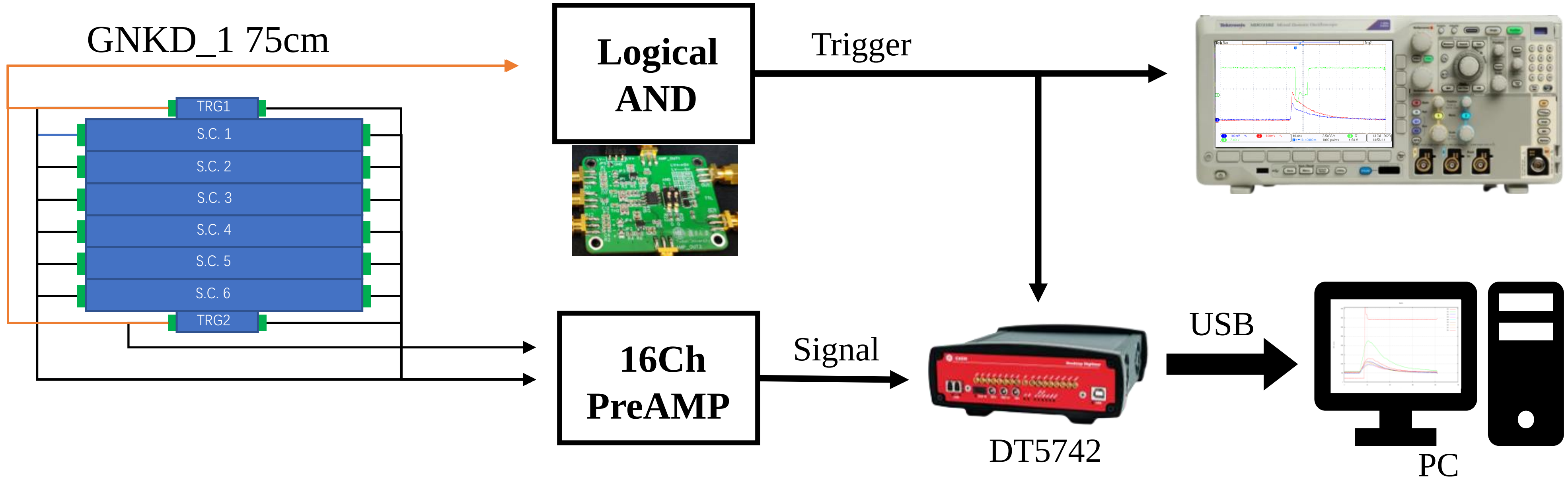
***$T_{s.c.}$* related to hit position 'x'**




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.

# Prototype Test




**DT5742**

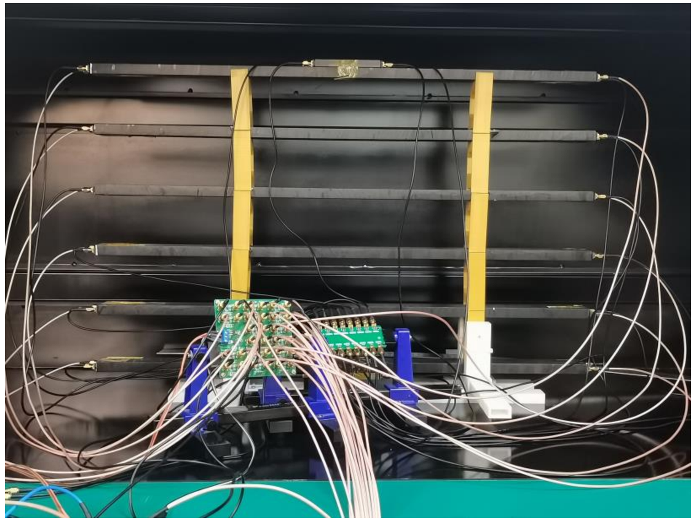
DRS4 chip

16 + 1 channel

12 bit @ 5 GS/s

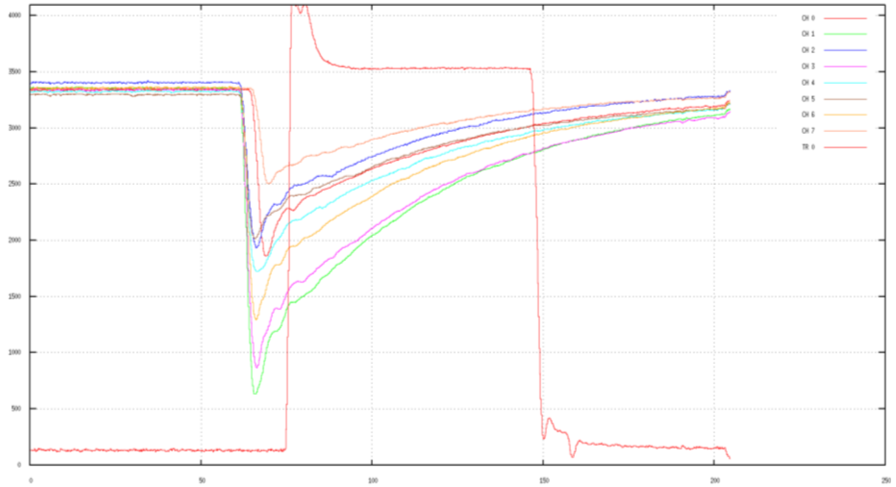
BW: 500 MHz

-1.5V ~ +1.5V



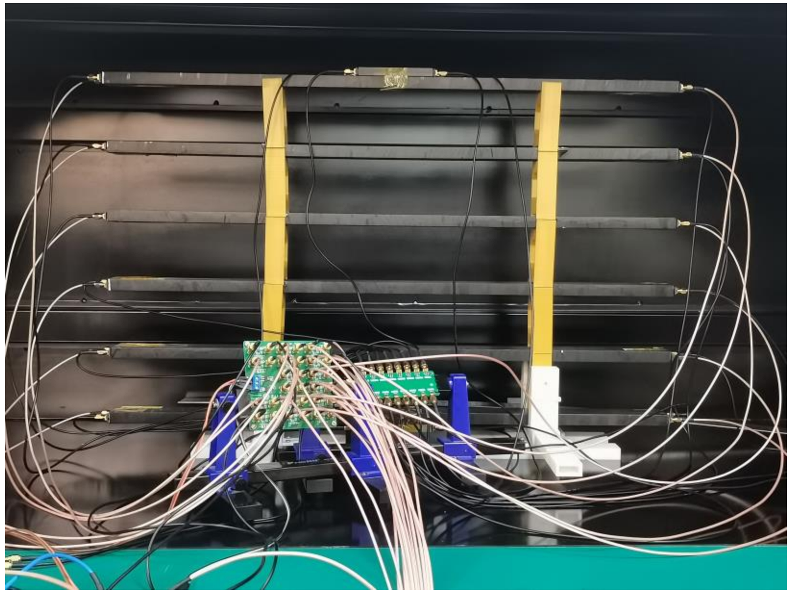
Prototype test setup

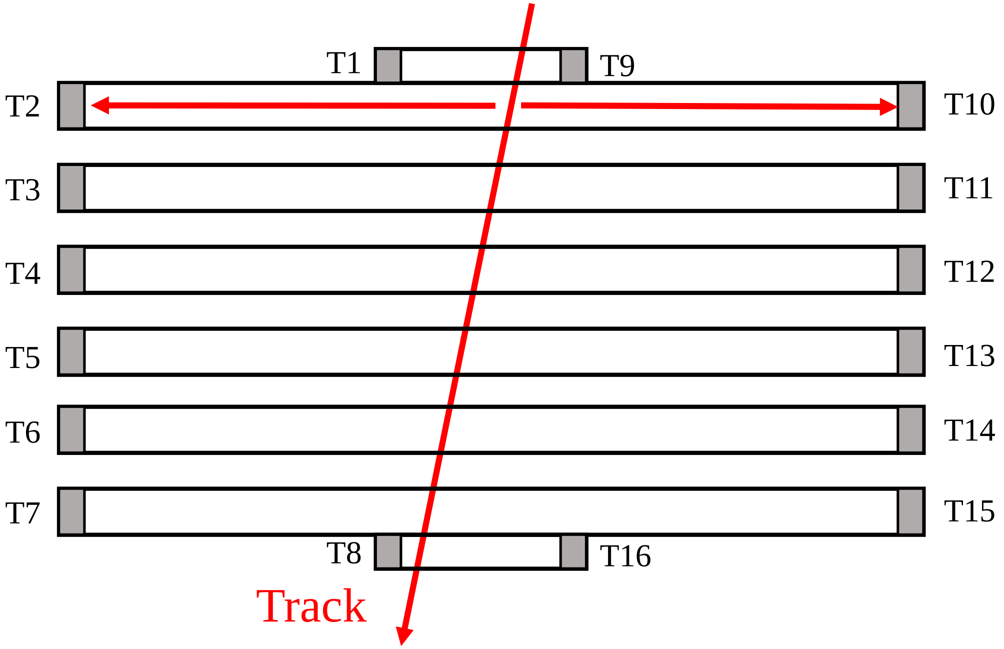
Time Calibration of prototype



DT5742 signal waveform

# Prototype Test (Velocity of CR Muon)






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

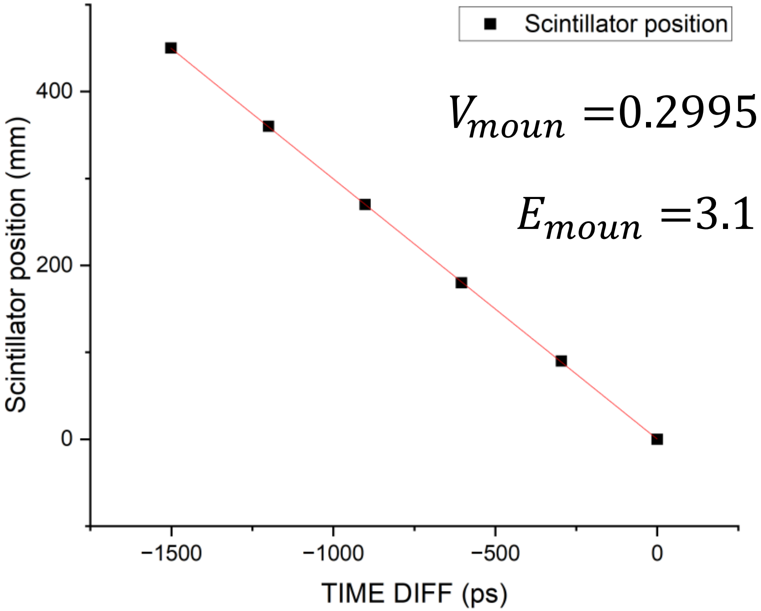
$T_{S.C.2} = (T_3+T_{11})/2 - \Delta T_1$

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

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

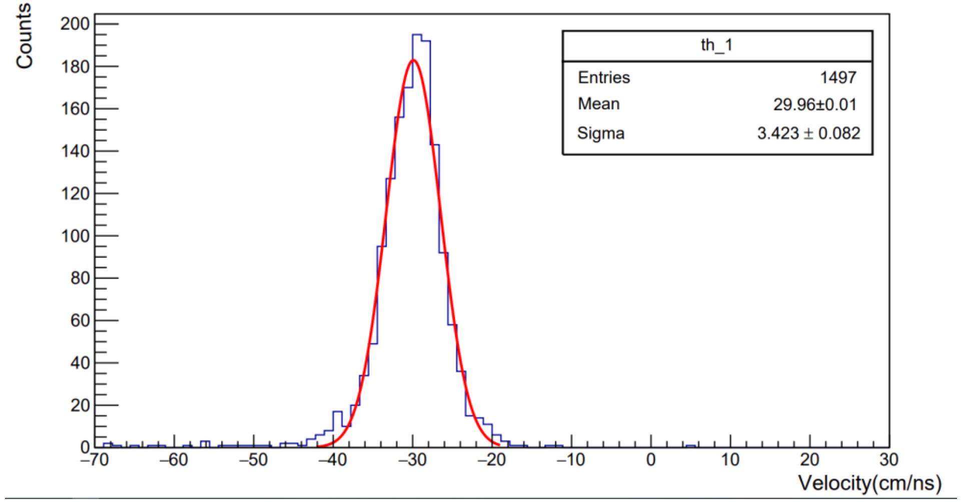
$T_{S.C.5} = (T_6+T_{14})/2 - \Delta T_4$

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




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

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




Muon velocity distribution of cosmic rays

# Summary

- Good performance of the current KLM design for efficiency.
- 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 (1m) achieves a time resolution of 80ps.
- The prototype of scintillator realizes the energy measurement of cosmic ray Muon ($3.1 \pm 0.4\ \mathrm{GeV}/c^2$).

# THANKS !

# back up

# Time resolution upgrade

## 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

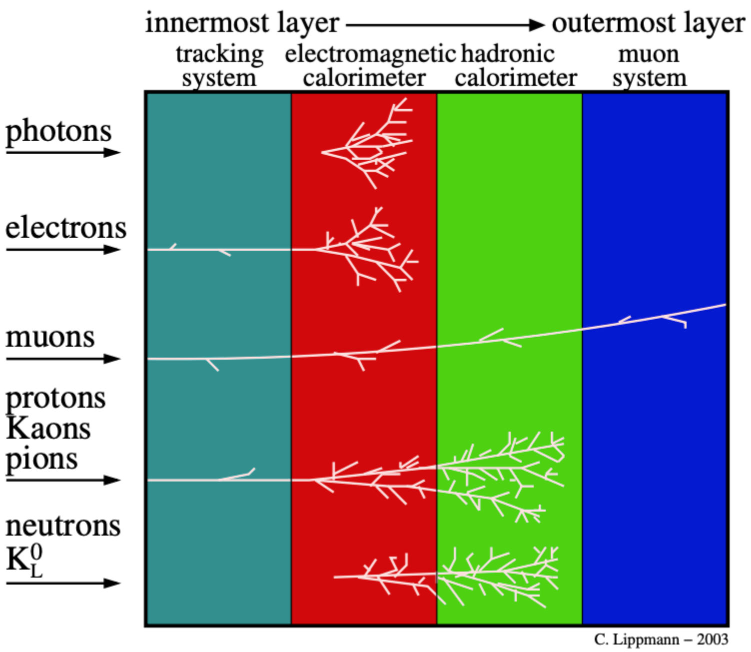
$$p = \gamma m v = \frac{mcL}{\sqrt{t^2c^2 - L^2}}$$

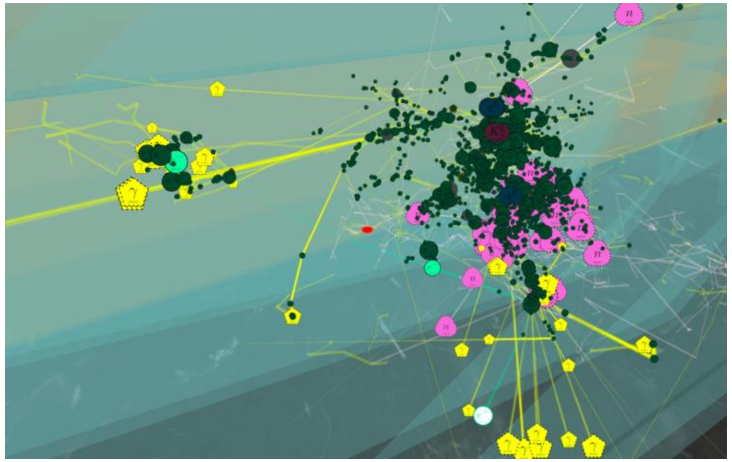
$$\frac{\delta t}{\delta p} = -\frac{m^2L^2}{t \cdot p^3} = -\frac{m^2Lv}{p^3}$$

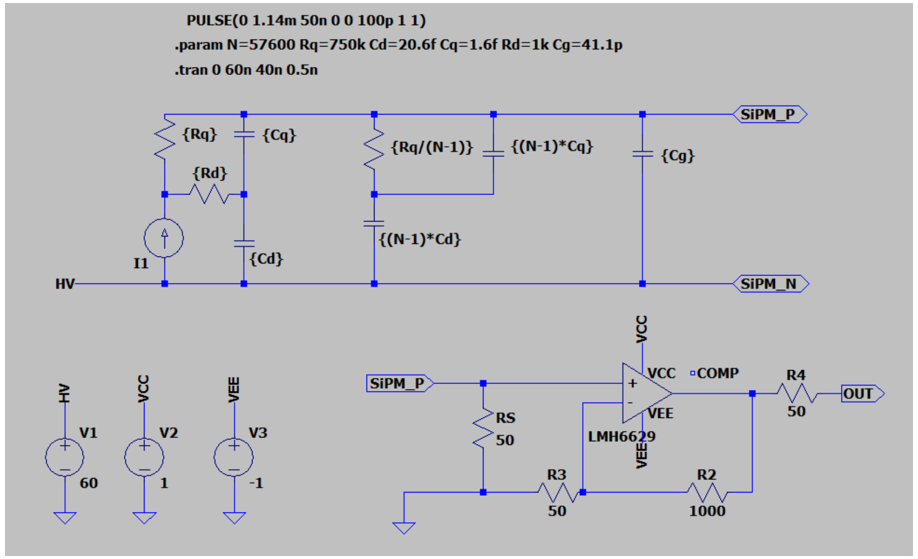
if $L$= 2 m,  γ= 3,  $p \approx 1.5$ GeV/$c$

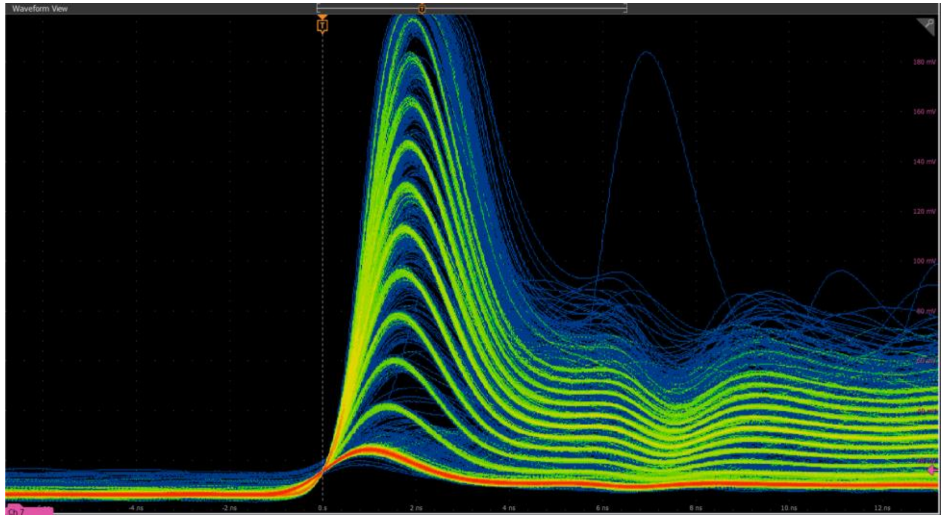
$\delta\, t$ = 100 ps   so $\delta p$ = 0.19 GeV/c

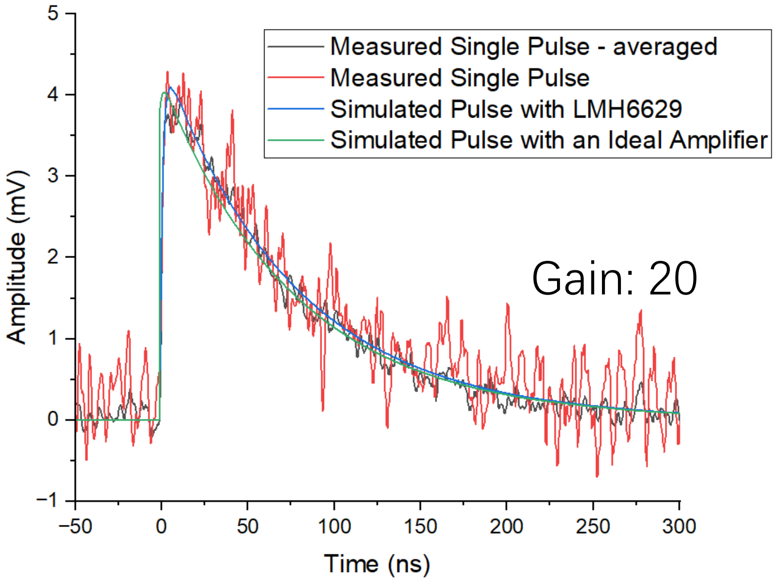
Relative error ～ 13%

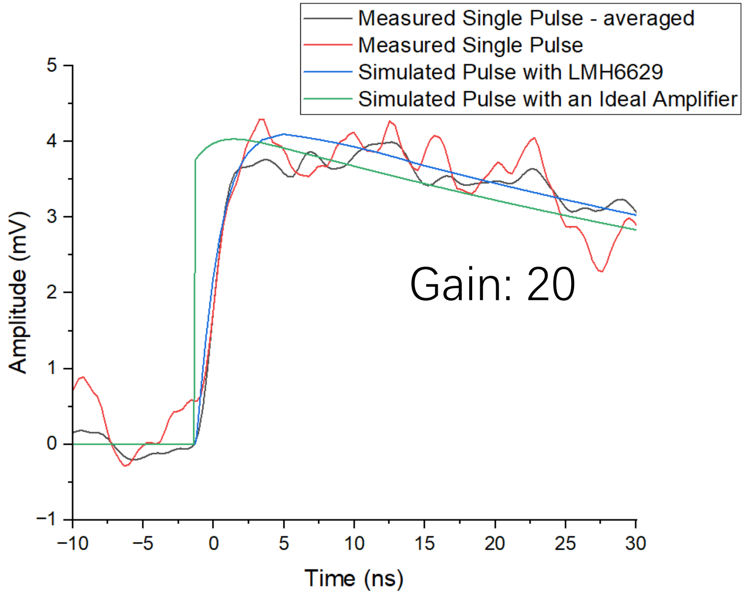


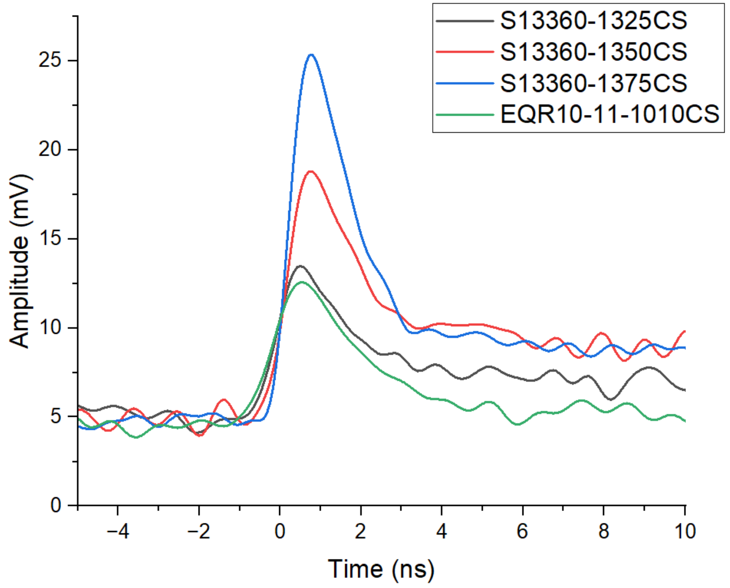



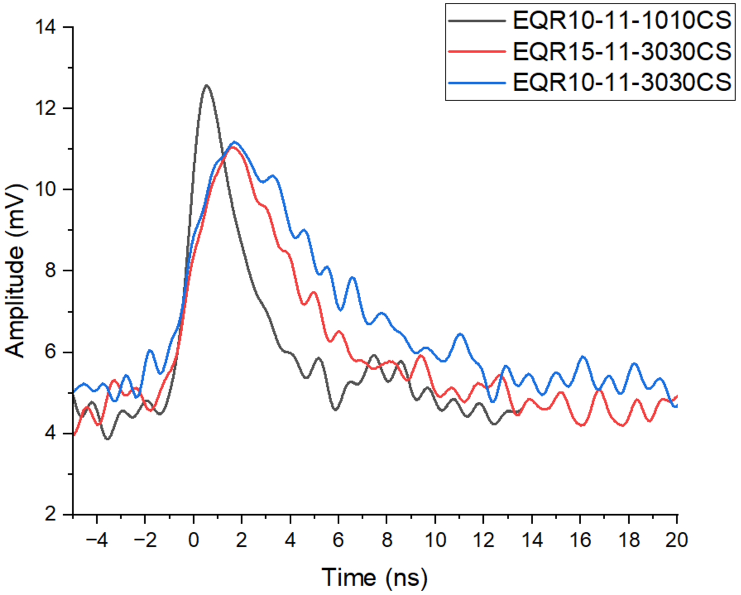


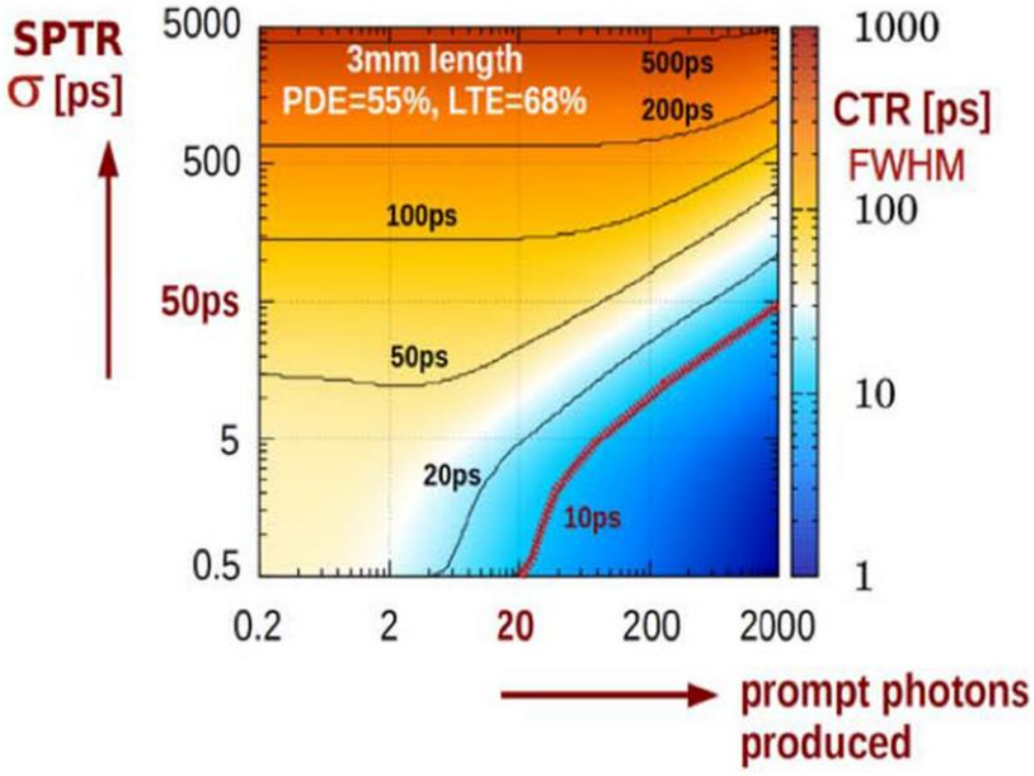



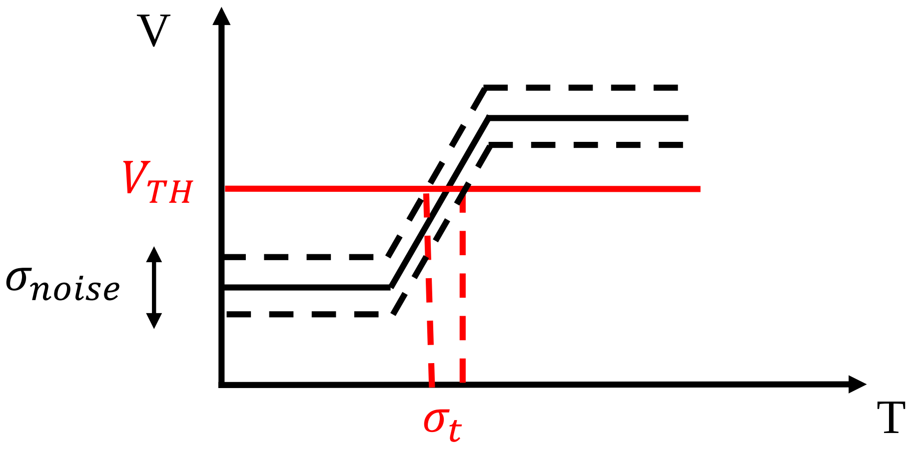




[1] Bretz, T., Hebbeker, T., & Kemp, J. (2020). Extending the dynamic range of SiPMs by understanding their non-linear behavior. arXiv preprint arXiv:2010.14886

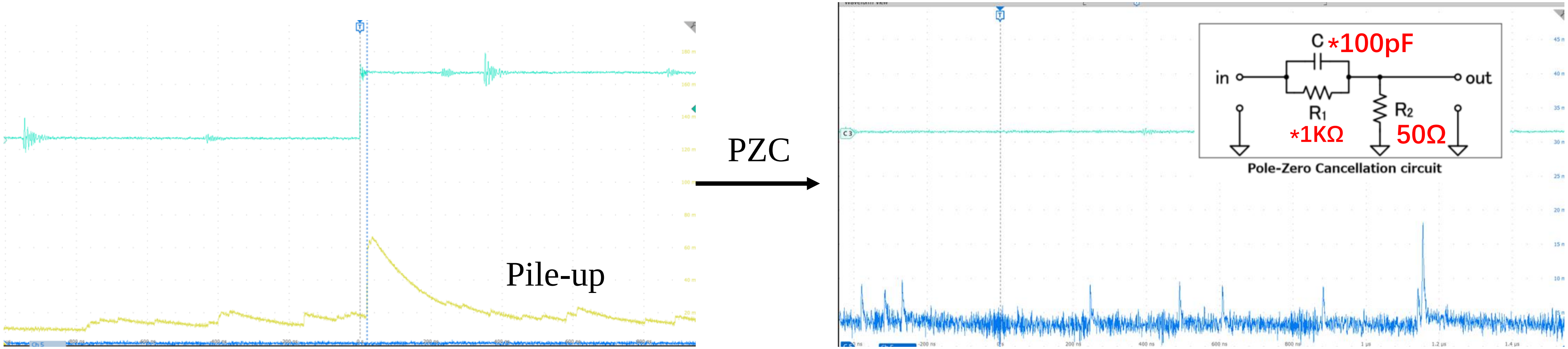



$$CTR \propto \sqrt{\tau_{d/n_p}}$$

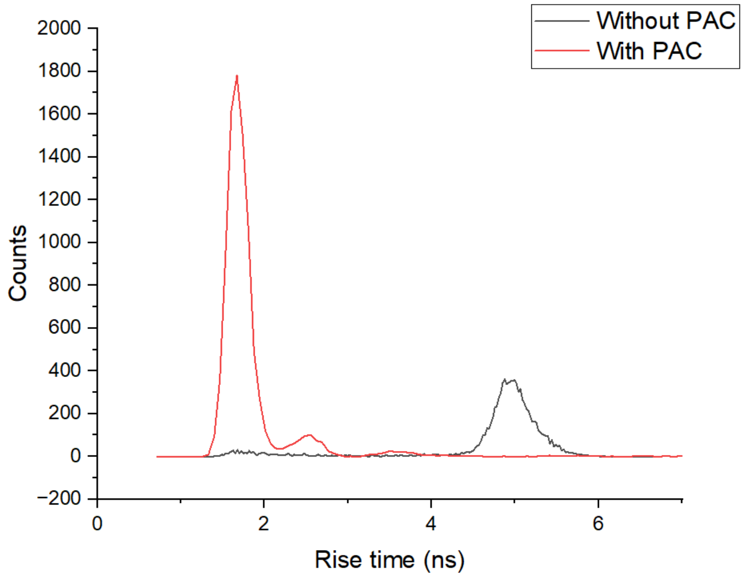
$$\sigma_t = \frac{\sigma_v}{dv/dt}$$



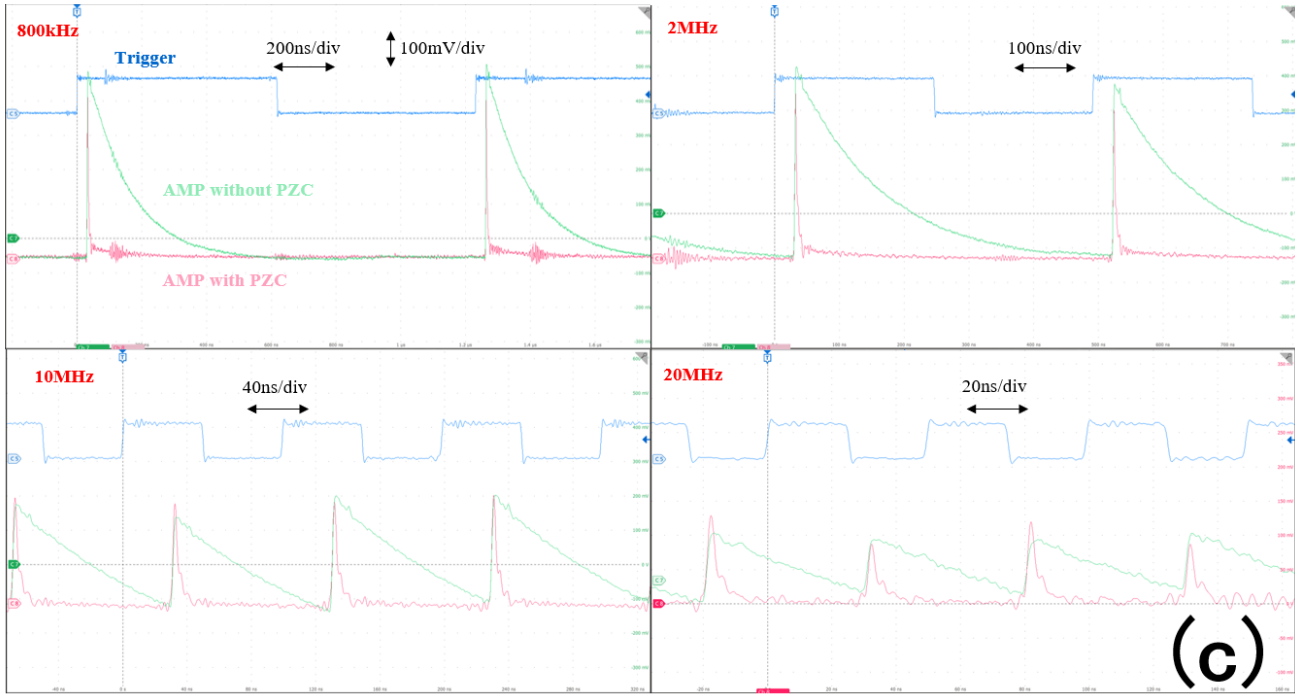
# PZC



Pile-up
PZC
C *100pF
in
out
R1
*1KΩ
R2
50Ω
Pole-Zero Cancellation circuit

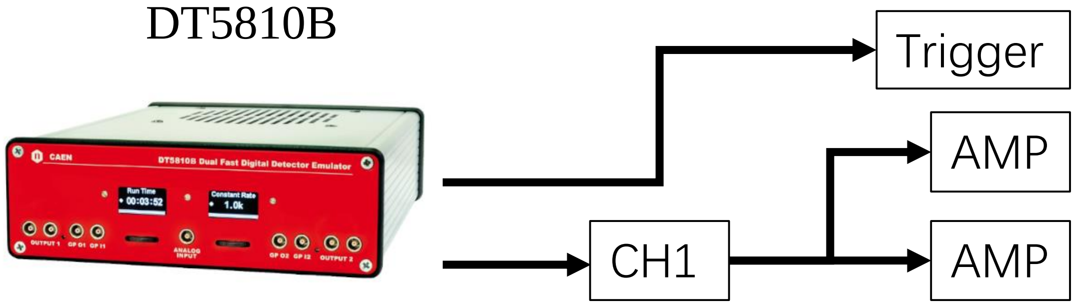



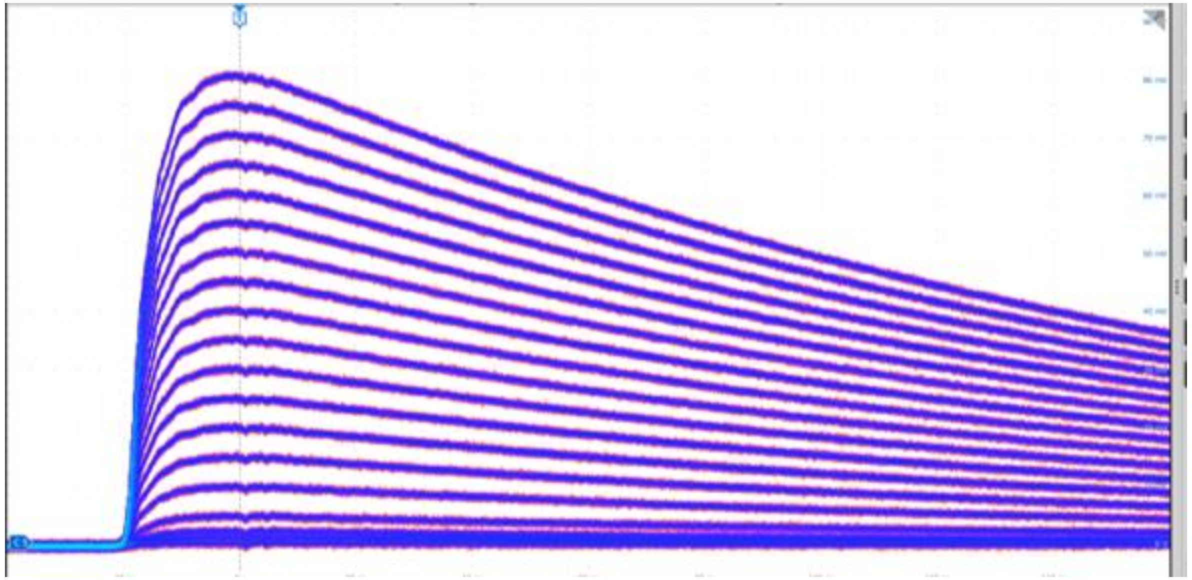
Without PAC
With PAC
Counts
Rise time (ns)

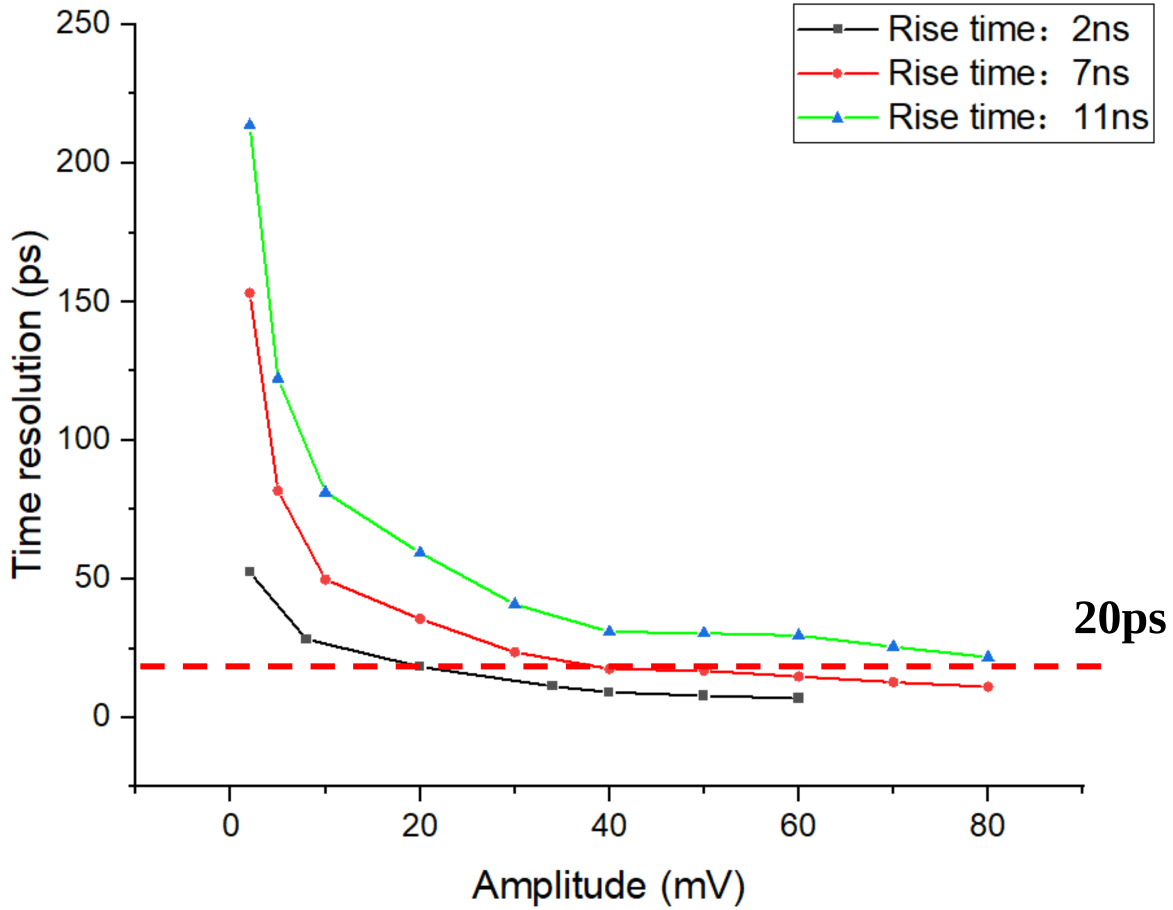



800kHz
Trigger
200ns/div
100mV/div
AMP without PZC
AMP with PZC
2MHz
100ns/div
10MHz
40ns/div
20MHz
20ns/div
(c)

# SiPM readout electronics performance test



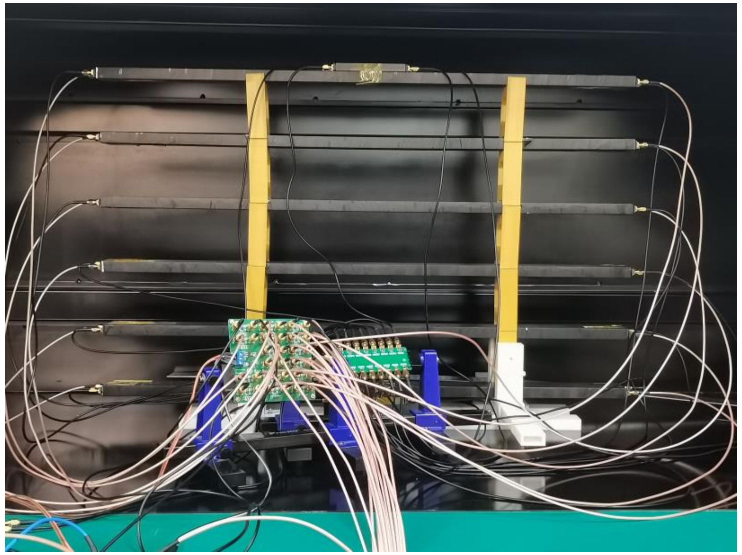


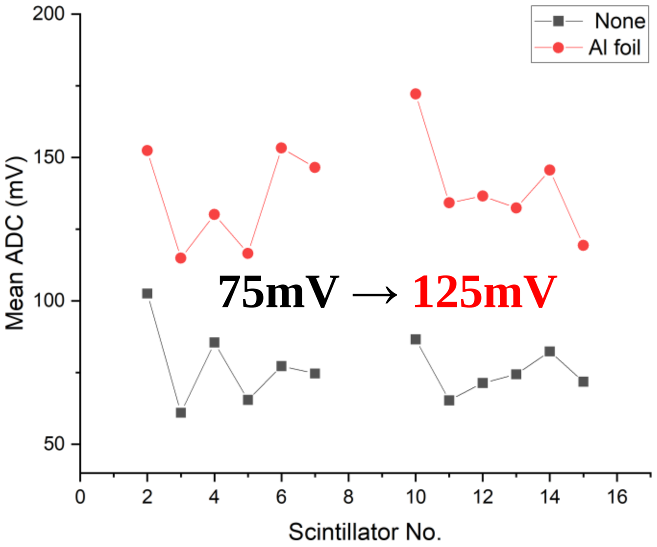

**risetime：** 1ns **fall time：** 100ns
**signal amplitude：** 2 – 80 mV

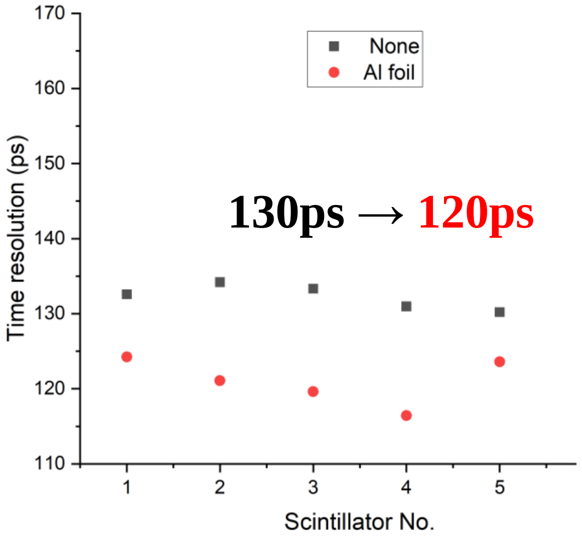
$$\sigma_t = \frac{\sigma_{noise}}{(dV/dt)_{MAX}}$$

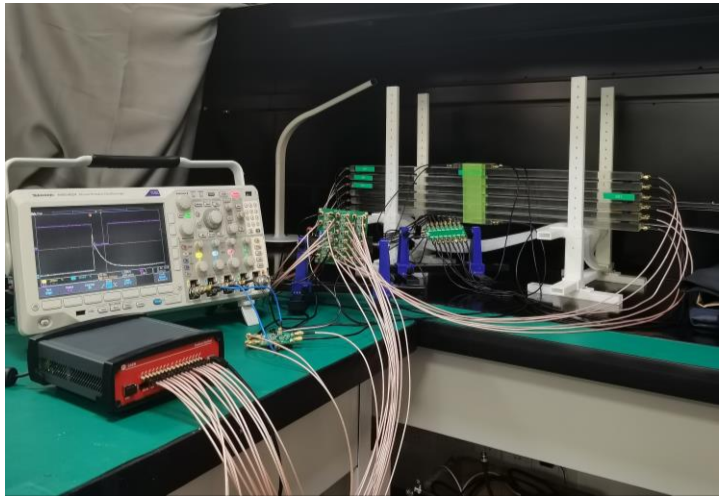
# Prototype Test

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

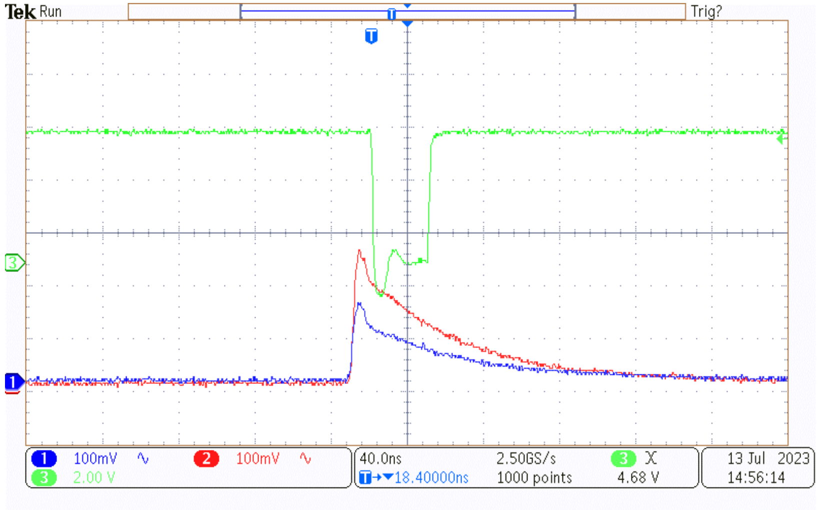




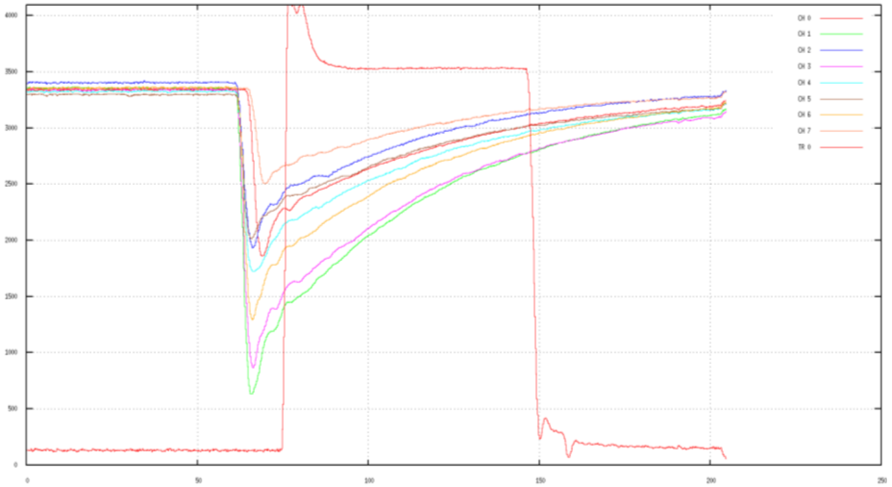



Prototype test setup



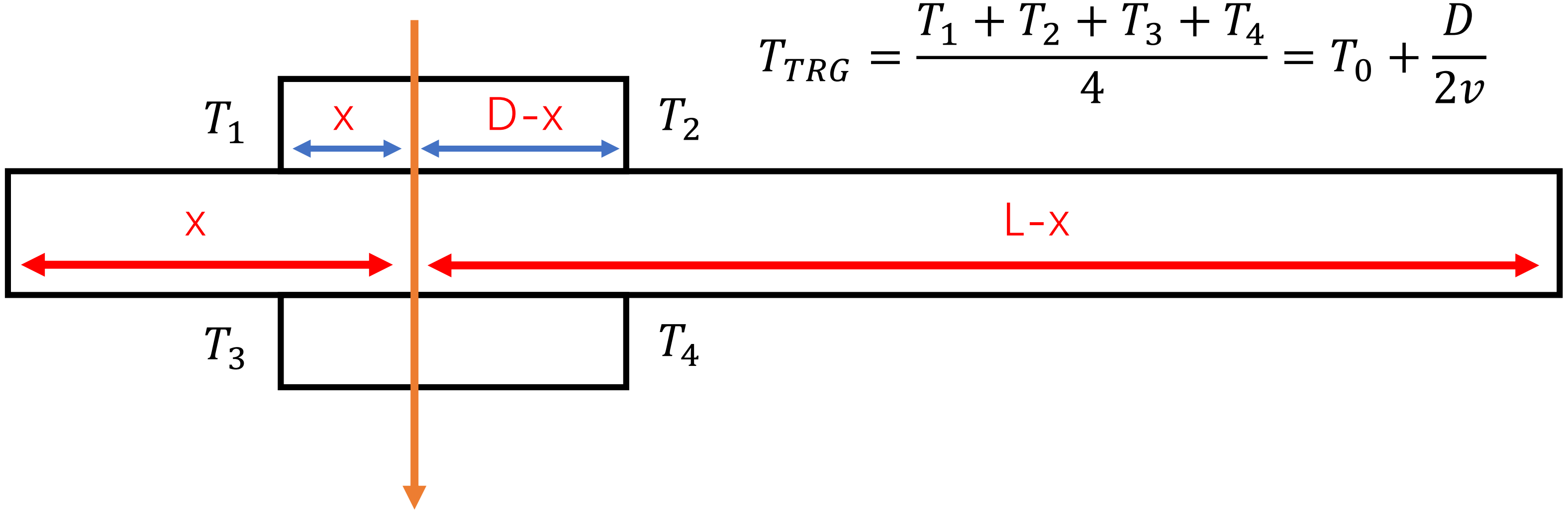

Trigger signal waveform



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:**

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

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

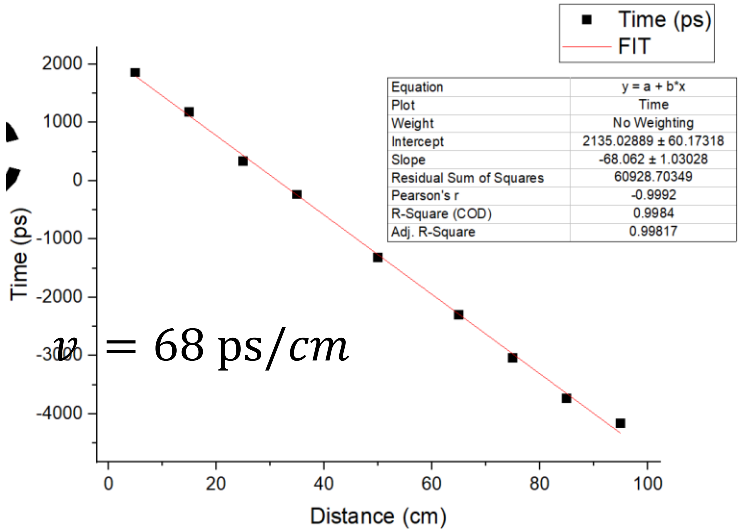
$$\Delta T = T_{TRG} - T_{AVG} = \frac{D - L}{2v}$$

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

**Weighted average:**

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

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




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