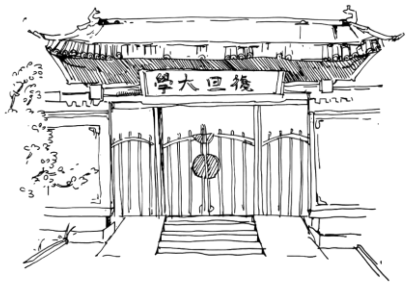
R&D for a TOF-like KLM in Belle II upgrade and a muon detector of CEPC based on SiPM and scintillator



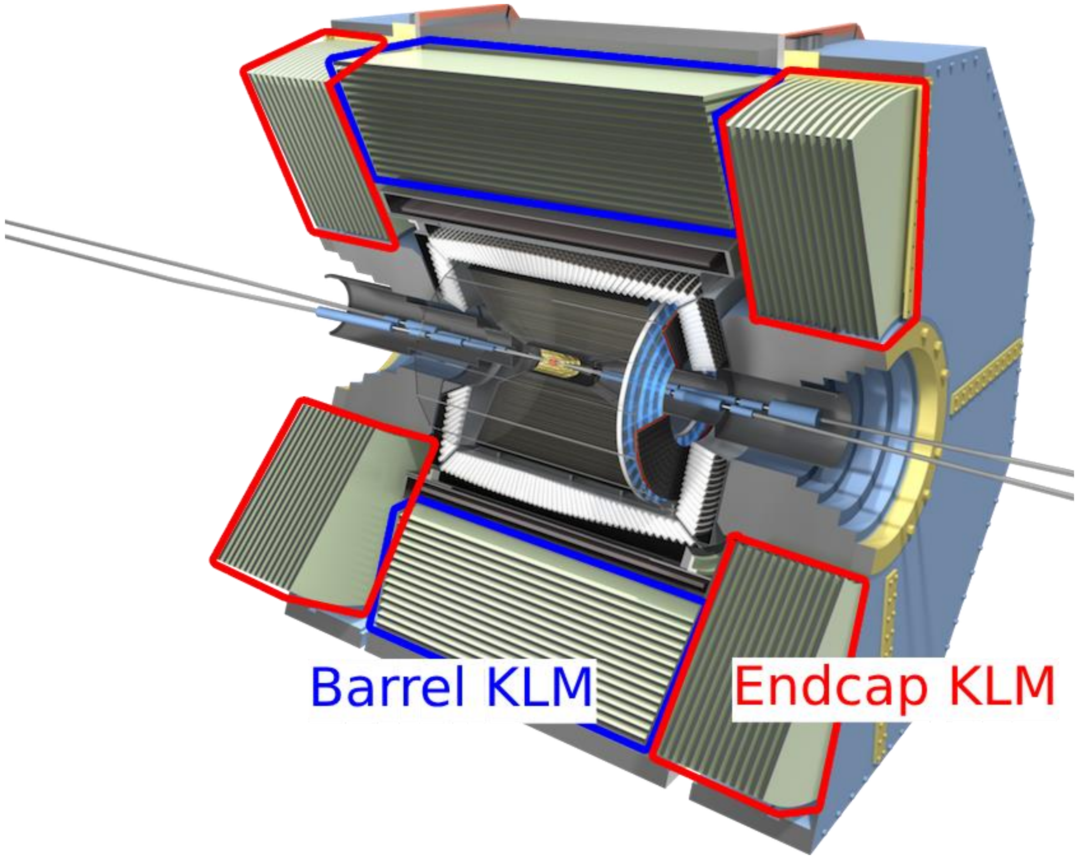
XiaoLong Wang

Fudan University

Workshop on “Photodetectors and sensors for particle identification and new physics searches” (PHOSE 2023)

CERN(remote), 11/22/2023

Belle II KLM and the upgrade proposal

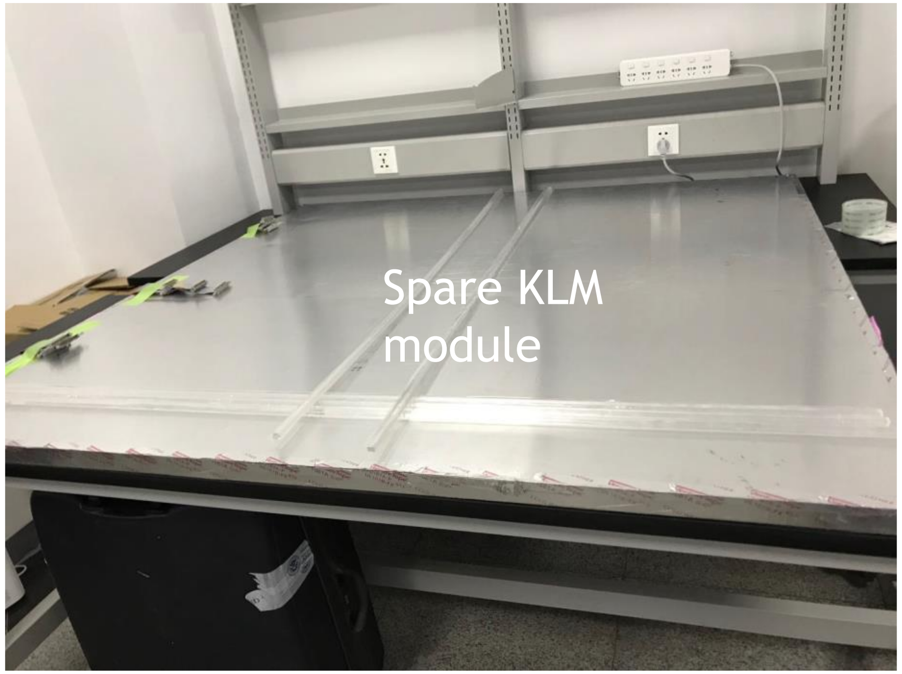


Subdector	Function	upgrade idea	time scale
PXD	Vertex Detector	2 layer installation	short-term
		new DEPFET	medium-term
SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
PXD+SVD	Vertex Detector	all-pixels: SOI sensors	medium-term
		all-pixels: DMAPS CMOS sensors	medium-term
CDC	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

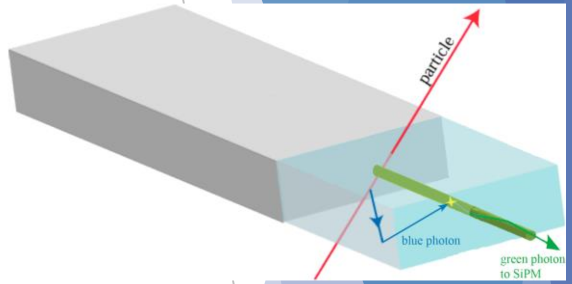
Table 1.1: Known short and medium-term Belle II subdetector upgrade plans, starting from the radially innermost. The current Belle II subdetectors are the Silicon Pixel Detector (PXD), Silicon Strip Detector (SVD), Central Drift Chamber (CDC), Time of Propagation Counter (TOP), Aerogel Rich Counter (ARICH),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

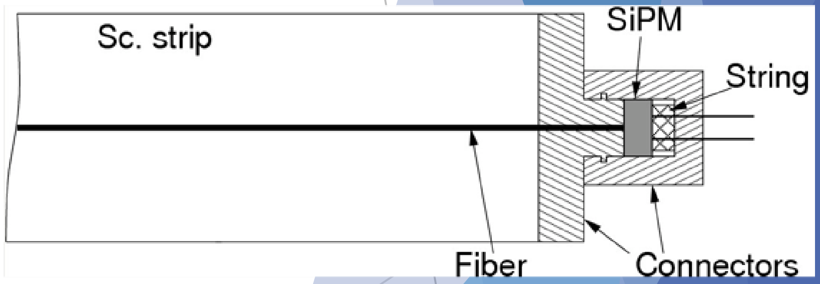
CDR for Belle II Detector upgrade in preparing,
or see the Snowmass whitepaper, arXiv:2203.11349v1

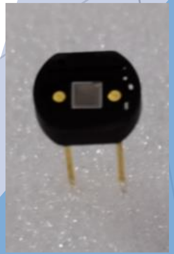
Structure of scintillator-based KLM

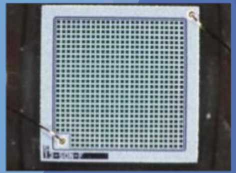


The structure:
- Extruded scintillator
- WLS fiber
- SiPM





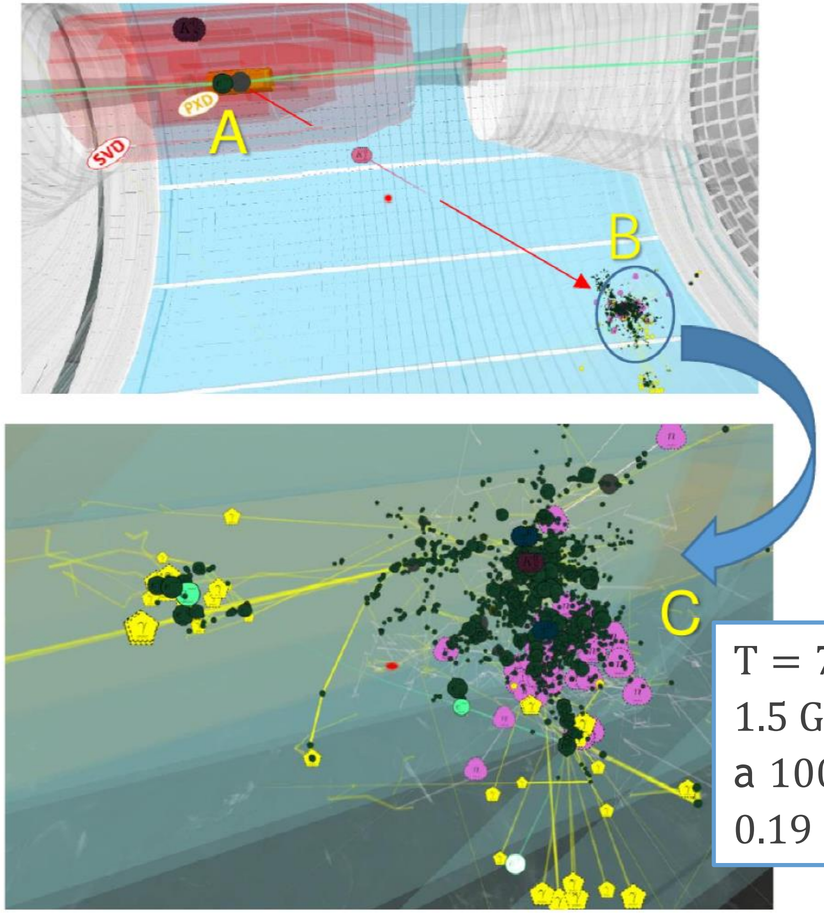




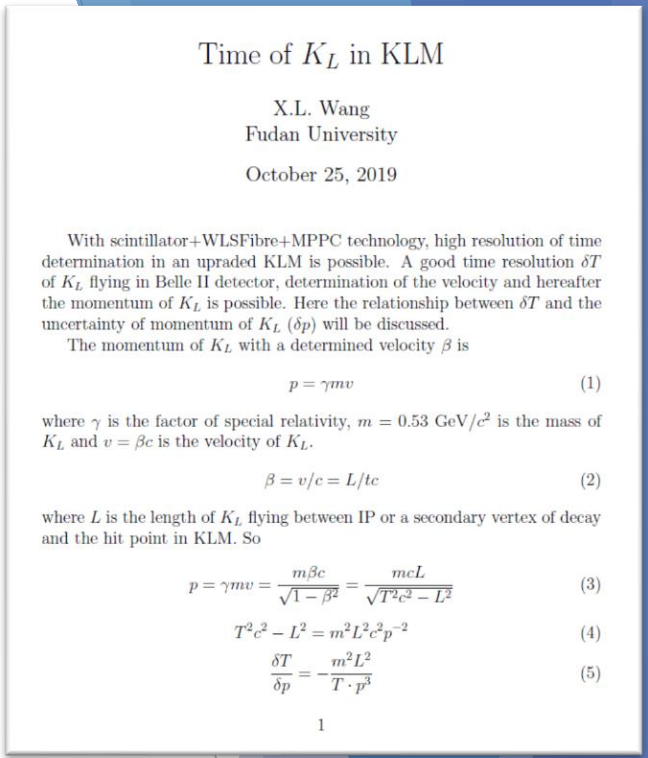
- Extruded scintillator: cheap in massive production, but the attenuation length is only several centimeters.
- WLS: Kuraray Y11(200), a diameter of $1.2mm$.
- SiPM: Hamamatsu MPPC, S10362, $1.3mm \times 1.3mm$.
- The scintillator-based KLM has a good performance in Belle II operation. So that, it’s a good reference for a muon detector for CEPC.

Why to upgrade KLM?

- **KLM is the largest subdetector of Belle II**
- How to take advantage of its large volume?
- 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.



Captured from Belle II VR



Time of K_L in KLM

X.L. Wang
Fudan University

October 25, 2019

With scintillator+WLSFibre+MPPC technology, high resolution of time determination in an upraded KLM is possible. A good time resolution δT of K_L flying in Belle II detector, determination of the velocity and hereafter the momentum of K_L is possible. Here the relationship between δT and the uncertainty of momentum of K_L (δp) will be discussed.

The momentum of K_L with a determined velocity β is

$$p = \gamma m v \quad (1)$$

where γ is the factor of special relativity, $m = 0.53$ GeV/c^2 is the mass of K_L and $v = \beta c$ is the velocity of K_L.

$$\beta = v/c = L/tc \quad (2)$$

where L is the length of K_L flying between IP or a secondary vertex of decay and the hit point in KLM. So

$$p = \gamma m v = \frac{m\beta c}{\sqrt{1-\beta^2}} = \frac{mcL}{\sqrt{T^2c^2 - L^2}} \quad (3)$$

$$T^2c^2 - L^2 = m^2L^2c^2p^{-2} \quad (4)$$

$$\frac{\delta T}{\delta p} = -\frac{m^2L^2}{T \cdot p^3} \quad (5)$$

1

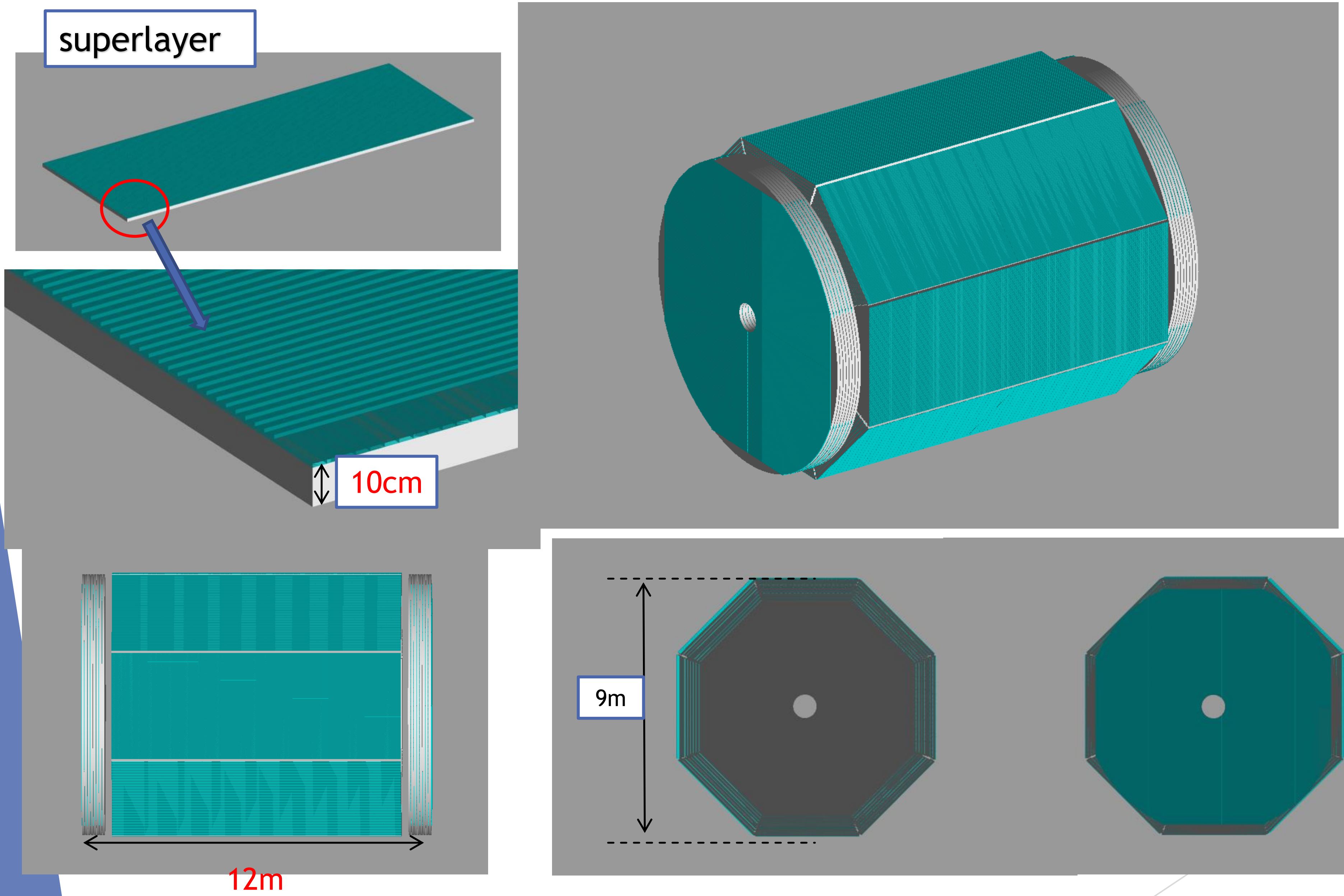
T $= 7.07\,ns$ with assumptions of $p = 1.5$ GeV$/c$ K_L travels $2m$ to arrive KLM, a $100\,ps$ time resolution leads to $\delta p = 0.19$ GeV$/c$, relative precision is 13%.

Snowmass whitepaper, arXiv: 2203.11349

CEPC muon detector

Preliminary simulation by Fudan group

CEPC CDR 2018



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 ($\lambda = 16.77$ 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 ($P_\mu > 5$ 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

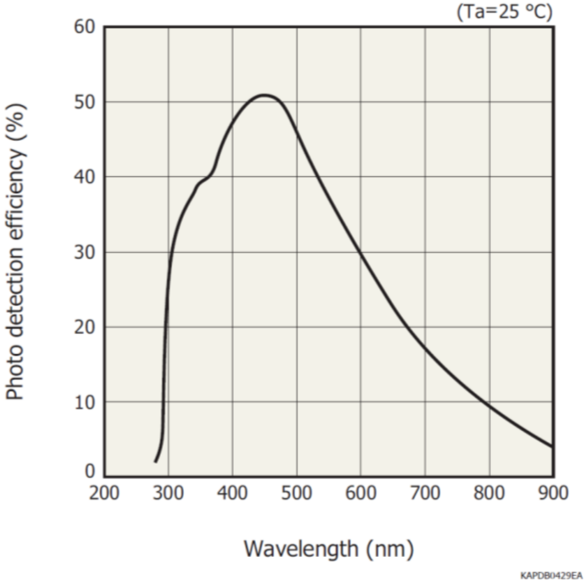
Hamamatsu MPPC and NDL SiPM

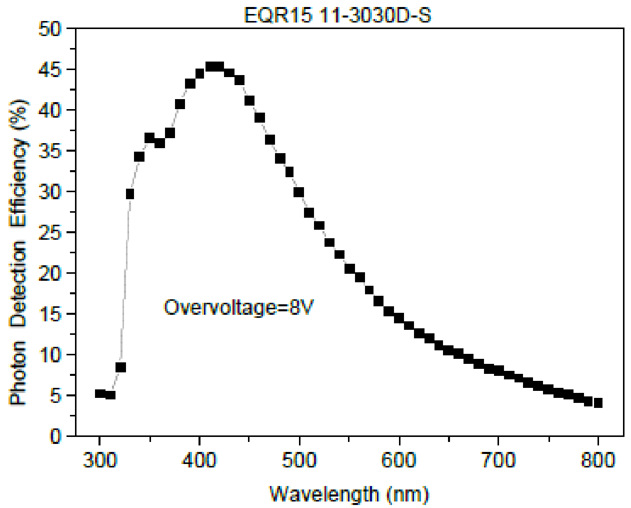
MPPC (Multi-Pixel Photon Counter) | **S14160/S14161 series**

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		V_{BR}	38			V
Recommended operating voltage*4		Vop	V_{BR} + 2.7			V
Vop variation between channels in one product*5	Typ.	-	0.1			V
	Max.		0.3			
Dark current	Typ.	I_D	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

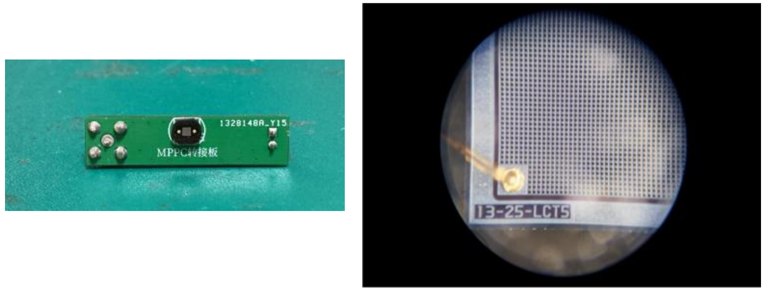
Type	EQR15 11-3030D-S/E	EQR15 22-1313D-S/E
Pitch	15 μm	
Element Number	1×1	2×2
Active Area	3.0×3.0 mm^2	1.3×1.3 mm^2
Micro-cell Number	40000	7396
Breakdown Voltage (V_B)	28±0.2 V	28±0.2 V
Temperature Coefficient for V_B	28 mV/°C	28 mV/°C
Recommended Operation Voltage	V_B+8 V	V_B+8 V
Peak PDE @420nm	45.4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



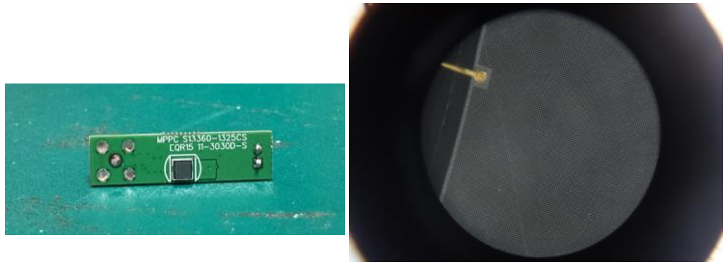


- Lower gain and higher DCR.
- Lower Vop and smaller capacitance.
- Very small pixel size.
- QE is similar.
- We got new NDL SiPM for testing recently.

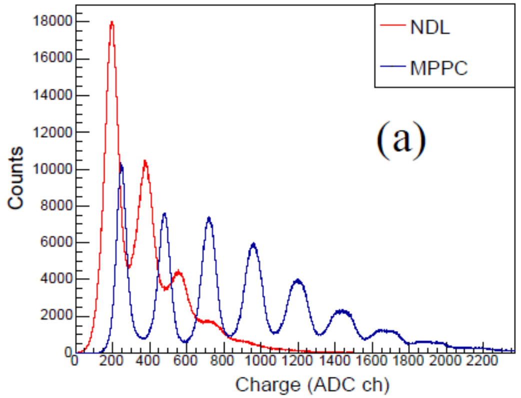
Hamamatsu MPPC and NDL SiPM in our testing

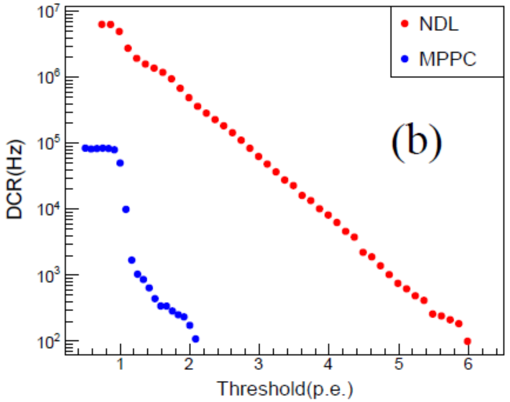


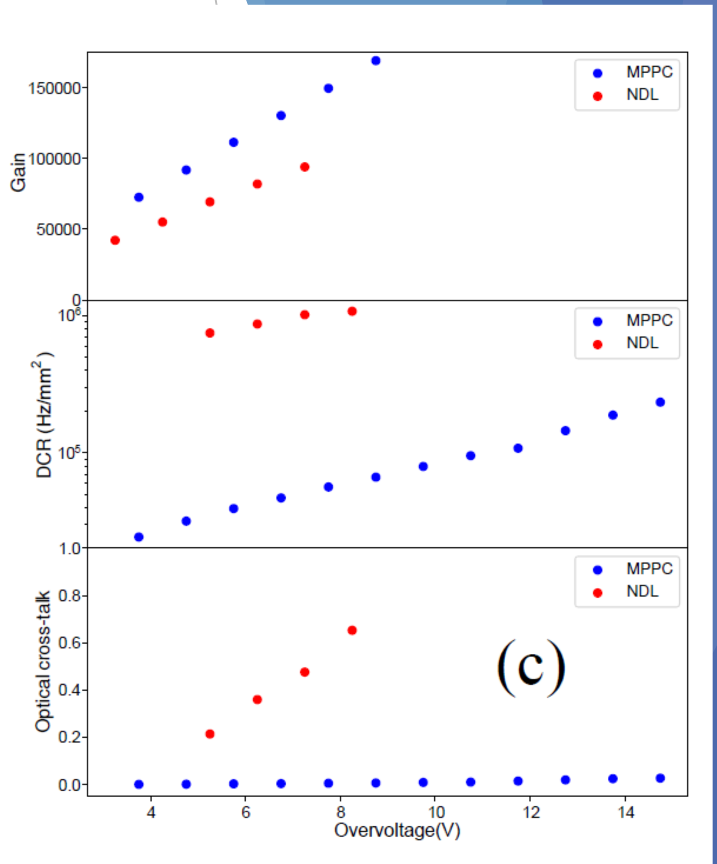
MPPC ($1.3 \times 1.3\ mm^2$)



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







- Too high DCR of NDL SiPM, partially due to the pixel size.
- Too high cross talk.
- Development ongoing.

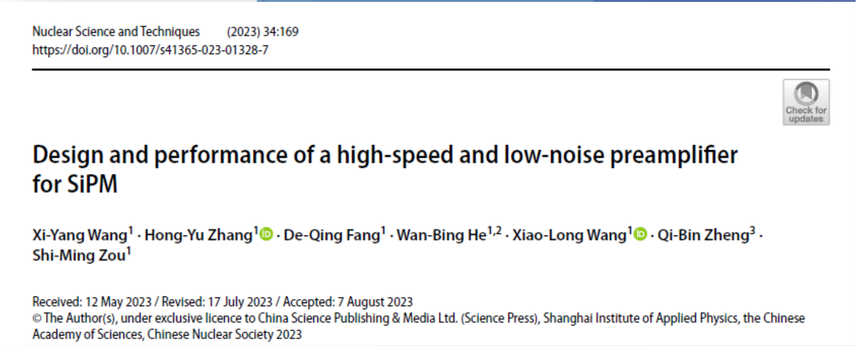
Our R&D works

I. Front-end readout for high time resolution

II. Regular design like current KLM scintillator modules.
   - Extruded scintillator, WLS fiber, and small size SiPM

III. New design for high-time resolution.
   - Scintillator with long attenuation length, large size SiPM
   - Design like traditional TOF

Design of FE with preamplifier


Nuclear Science and Techniques (2023) 34:169
https://doi.org/10.1007/s41365-023-01328-7

Design and performance of a high-speed and low-noise preamplifier for SiPM

Xi-Yang Wang[1] · Hong-Yu Zhang[1] · De-Qing Fang[1] · Wan-Bing He[1,2] · Xiao-Long Wang[1] · Qi-Bin Zheng[3] · Shi-Ming Zou[1]

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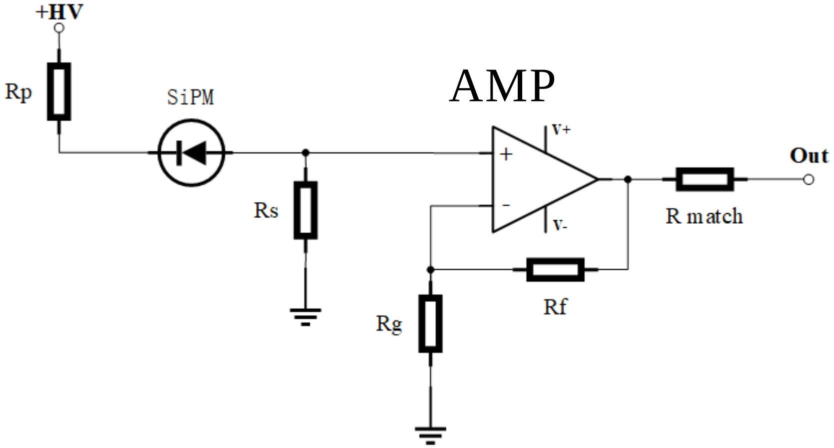
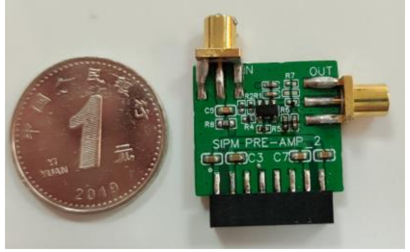
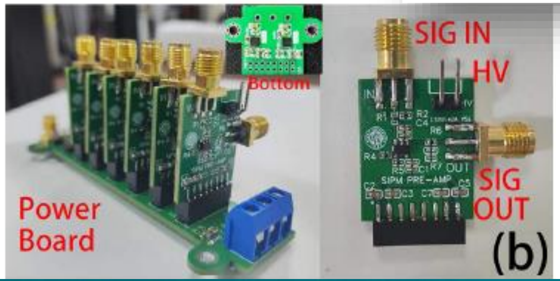
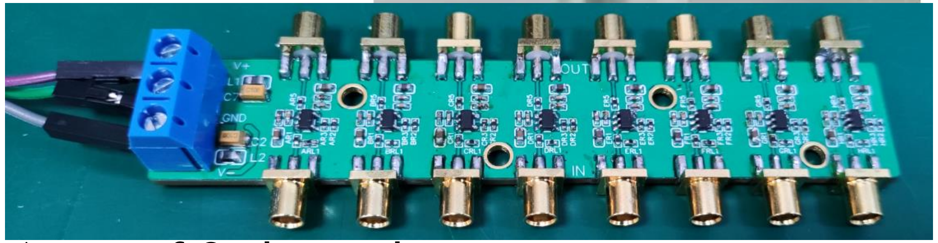








Array of 8 channels

Gain： +20 V/V

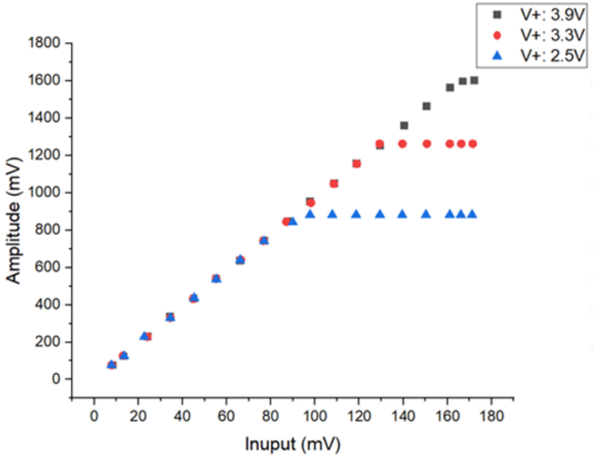
Bandwidth(-3dB)： 426 MHz

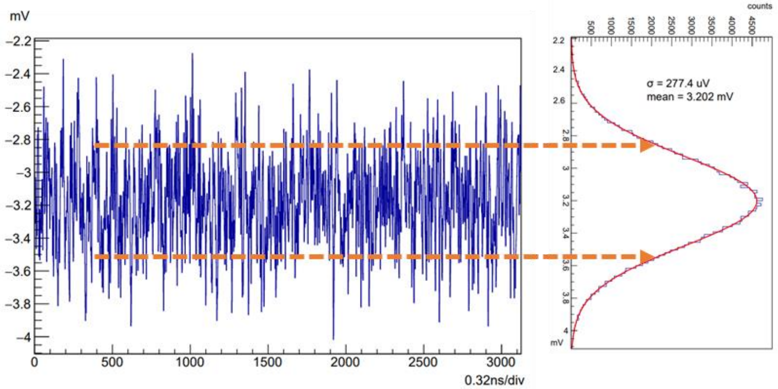
Baseline noise(RMS): 600uV

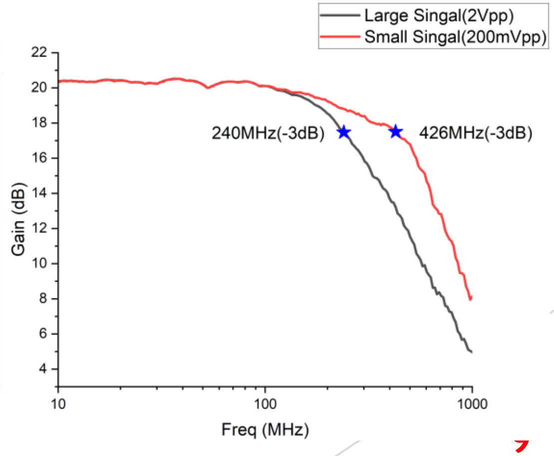
Input impedance: 50Ω

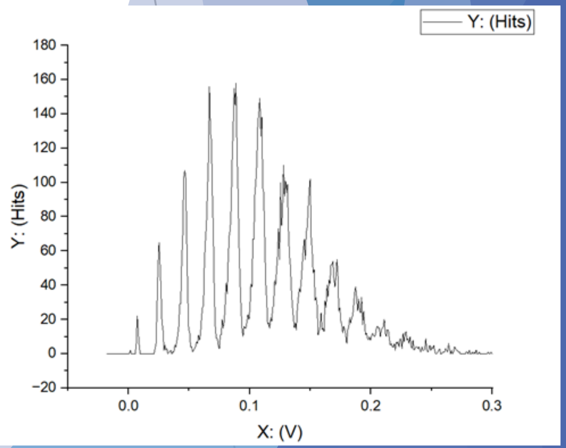
Simple and low cost.

➢ **Performance test of preamplifier**





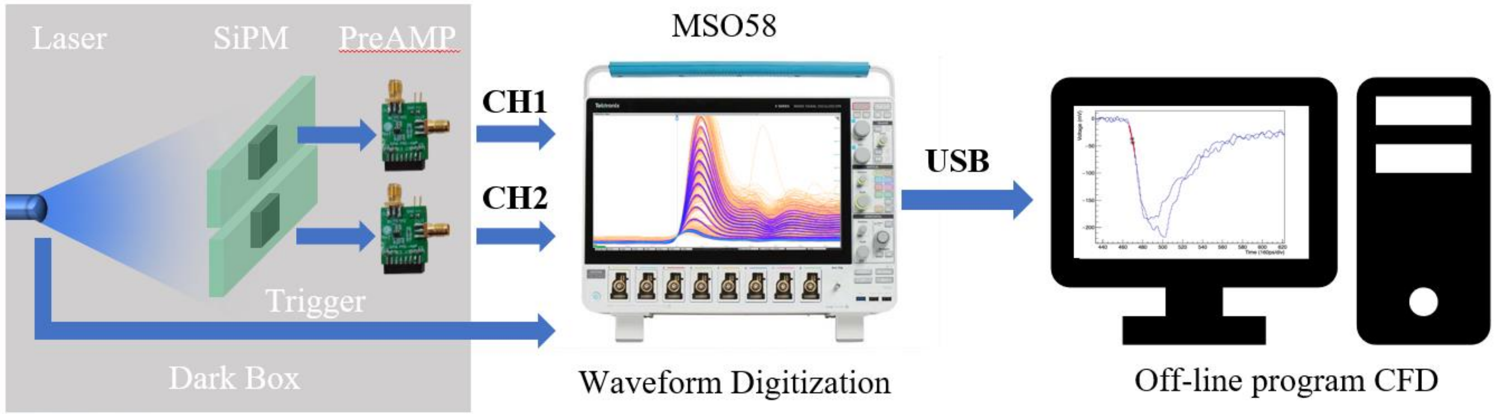


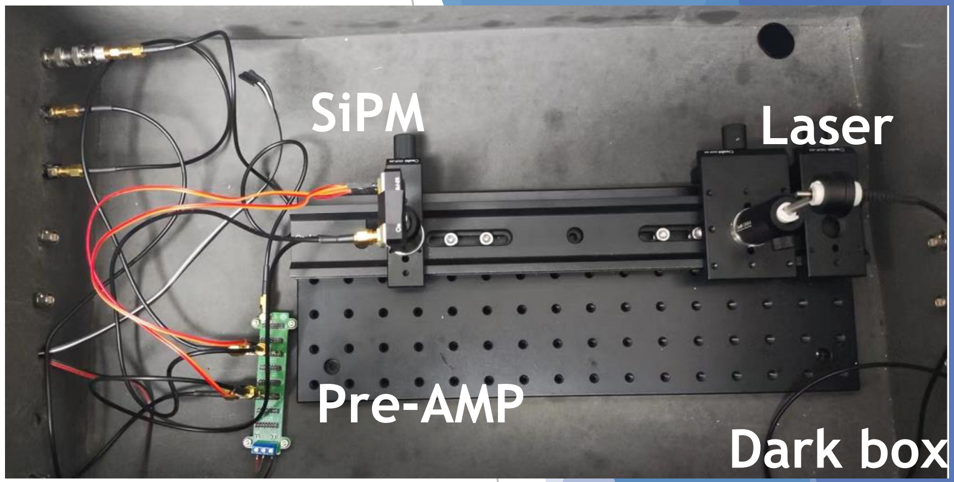


- Dynamic range testing
- Baseline noise test
- Bandwidth testing
- SiPM photoelectron peak

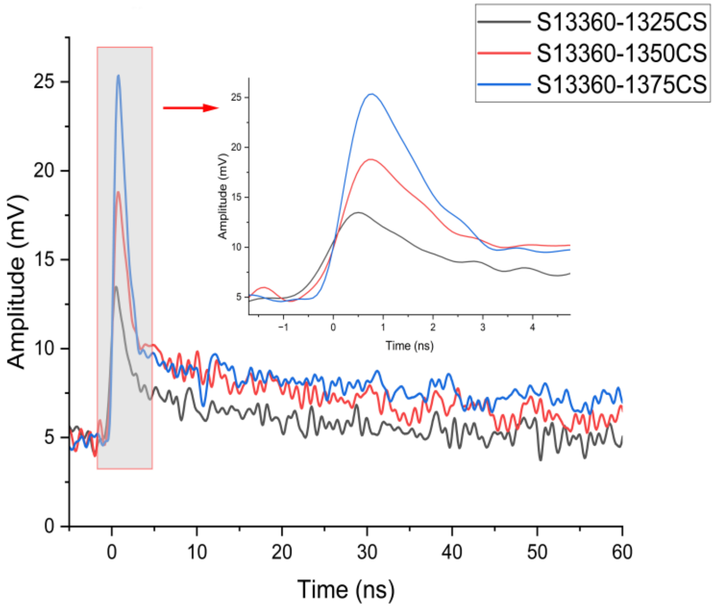
SiPM time resolution test

X.Y. Wang et al., NST 34, 169(2023)

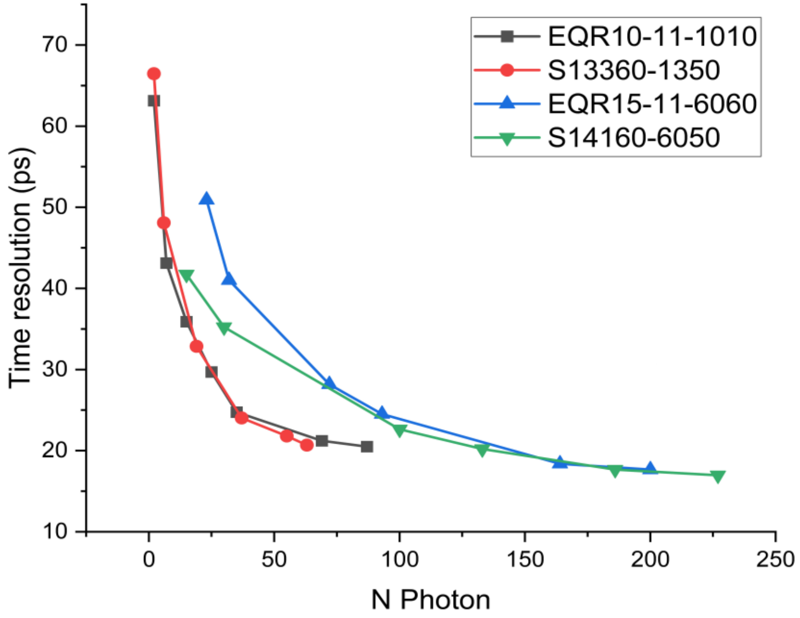




Time resolution test setup



Single photon signal of SiPMs



Time resolution varies with the number of photons

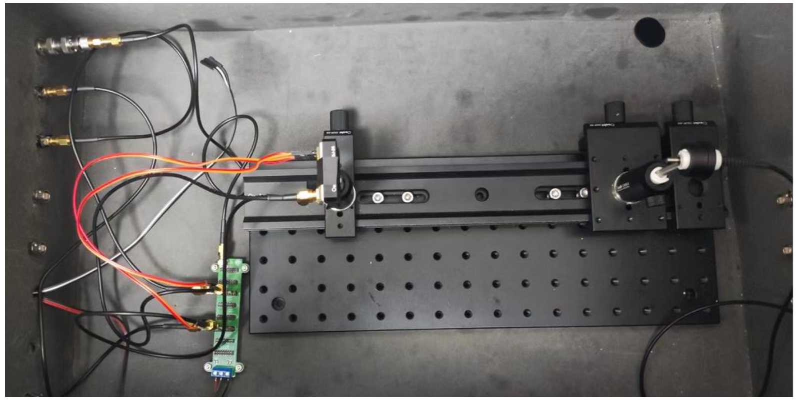
Small area: (1×1 mm^2 / 1.3×1.3 mm^2)
Photons > 5 , Time resolution < 50ps
Photons > 40 , Time resolution < 25ps

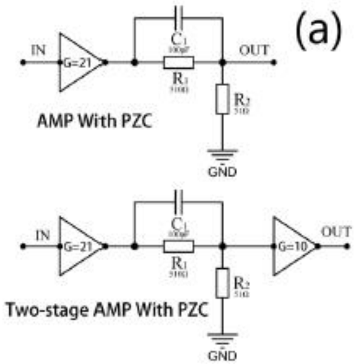
Large area: (6×6 mm^2)
Photons > 20 , Time resolution < 50ps
Photons > 70 , Time resolution < 25ps

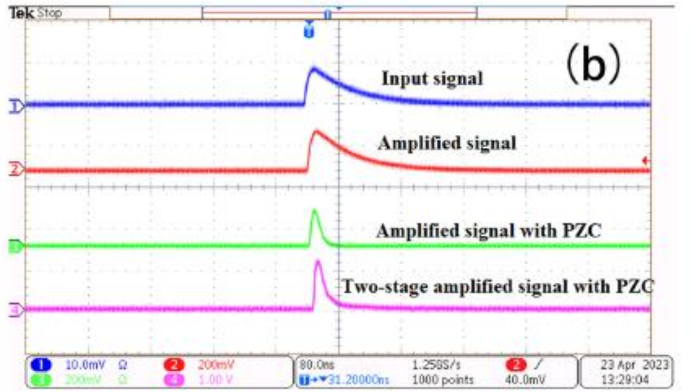
PZC to reduce pile-up

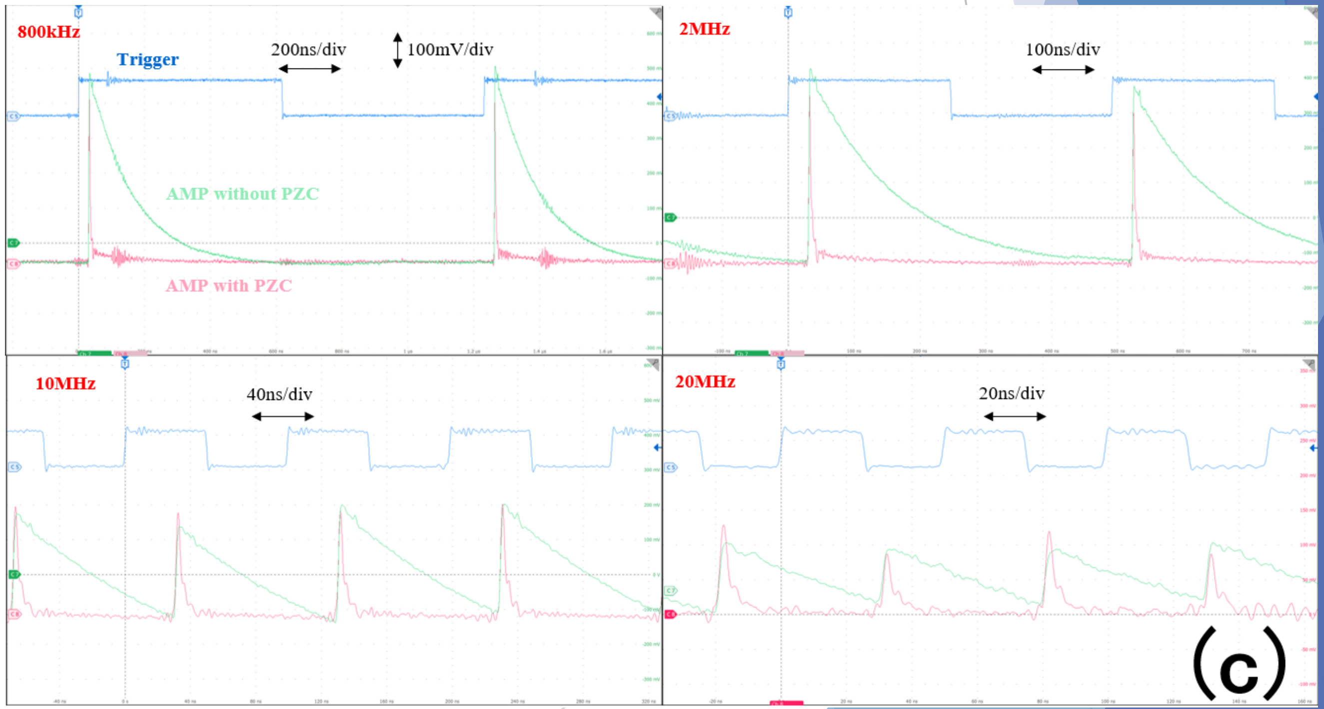
X.Y. Wang et al., NST 34, 169(2023)

- Some SiPMs (Hamamatsu MPPCs) have long fall time edge.
- We add pole zero cancelation (PZC) in the preamplier.
- The rise time is also improved by PZC.







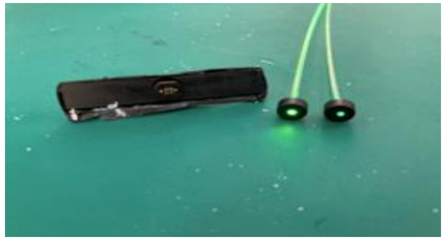


- Increase the frequency of laser to test the pile-up.
- The limit of the laser is 20 MHz.
- No pile-up is found in the implementation of PZC.

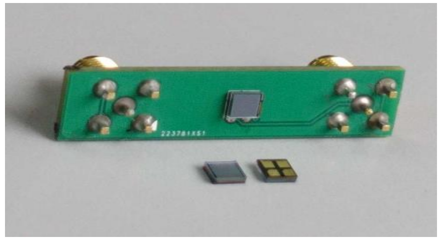
Regular stintillator strips, original design

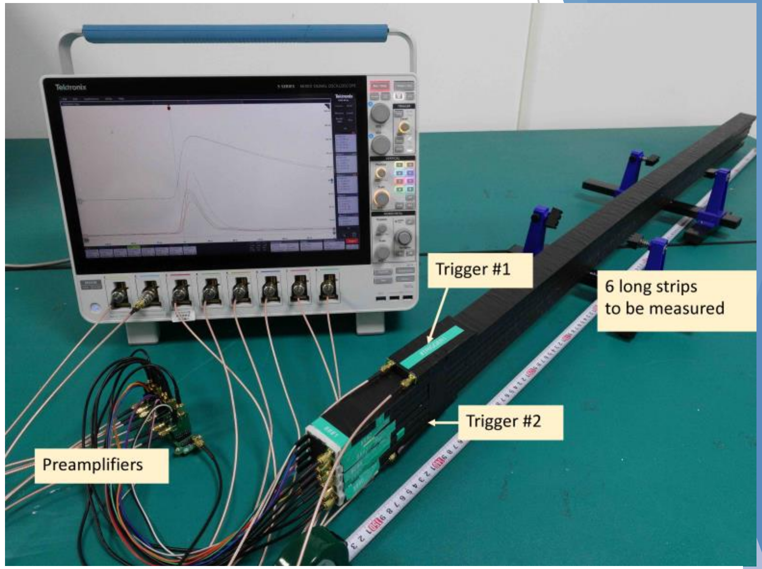
Scintillator with
Reflective layer

WLS fiber

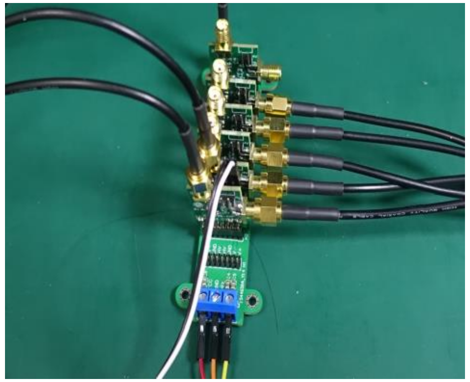


SiPM

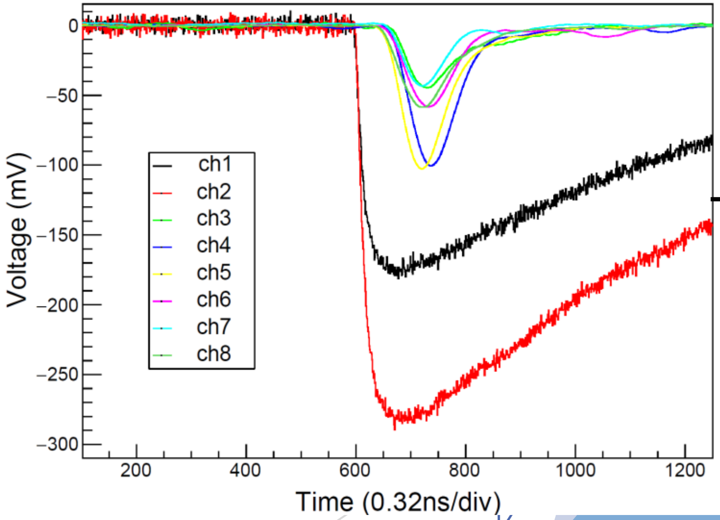




1.5 m scintillation detector



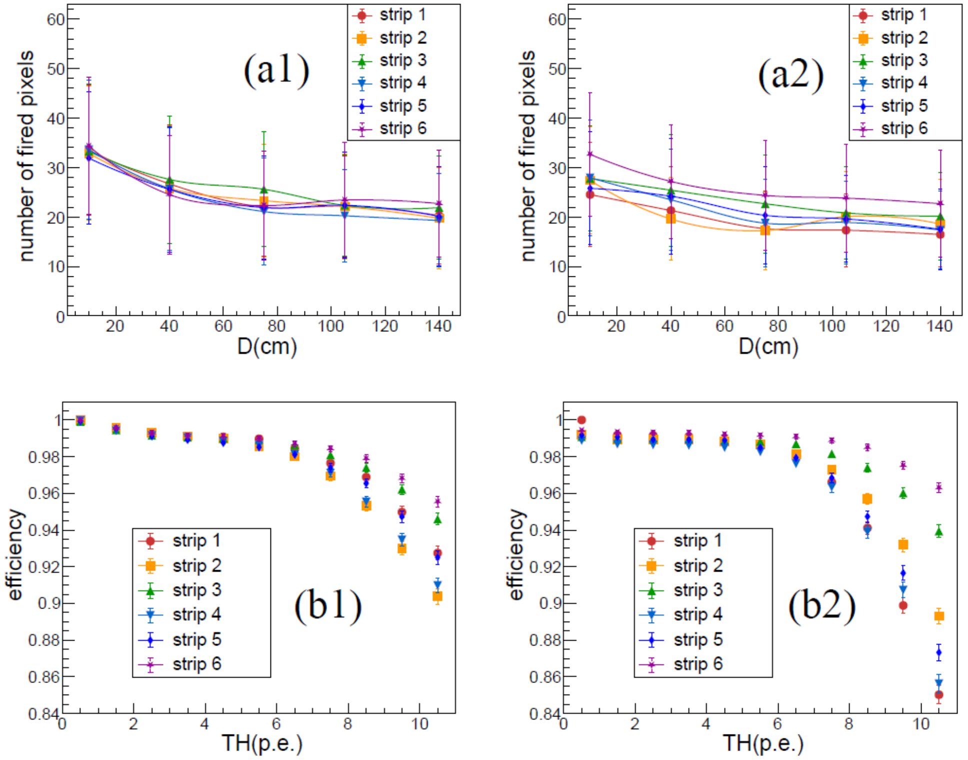
Preamplifier



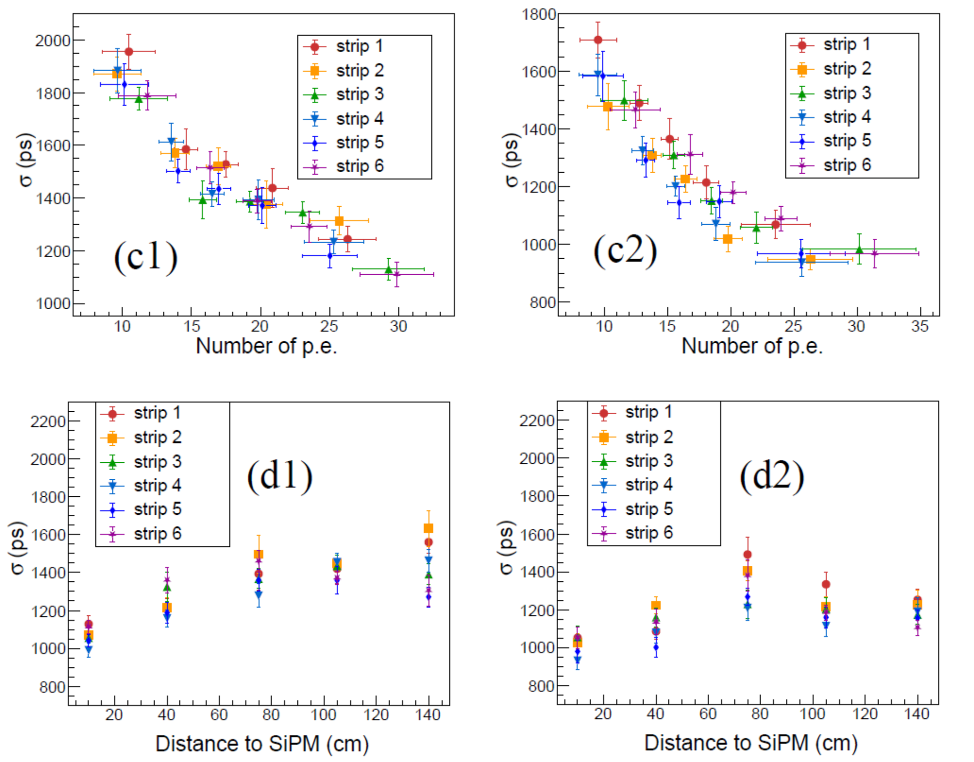
Long bars

Triggers

Performance in CR



NDL MPPC



NDL MPPC

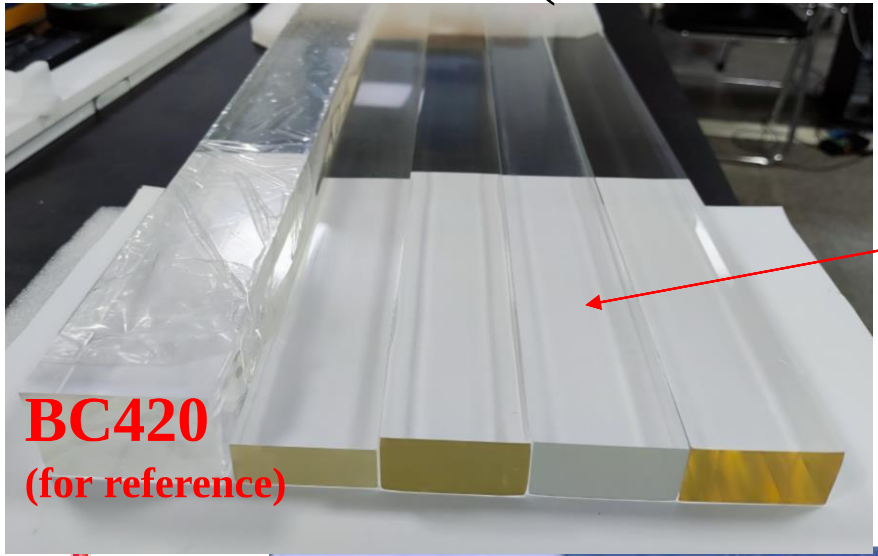
Time resolution triggered at the far end

Time resolution triggered at different positions

Wavelength-shifting fiber keeps good photon collection at long-distance.
There are good efficiencies, but the time resolution is 1-2 ns.

Design for time measurement

Solid scintillator (no WLS fiber)



This one!

SAINT-GOBAIN

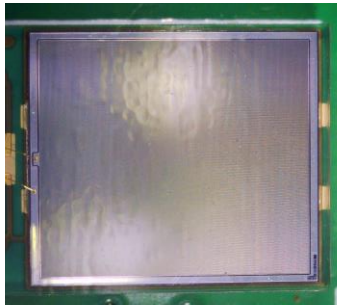
高能科迪
GAONENGKEDI

GNKD Company

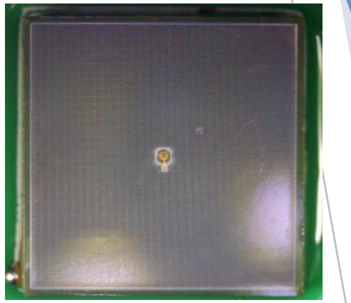
Multiple SiPMs

HAMAMATSU
PHOTON IS OUR BUSINESS

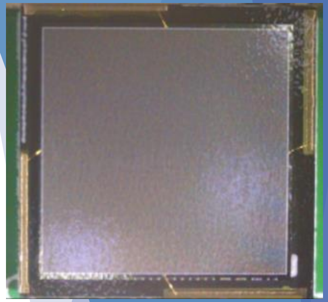
NDL



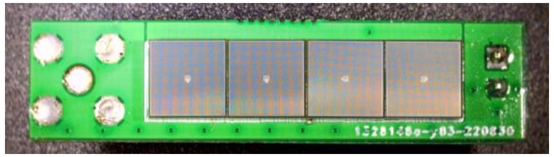
S13360-6025PE

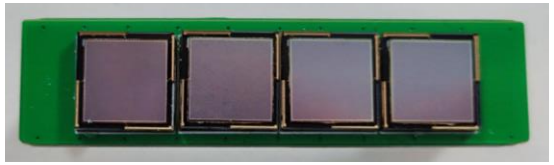


S14160-6050HS

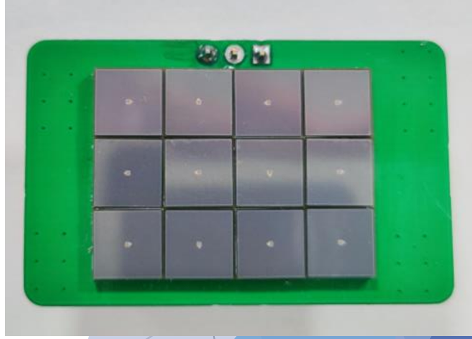


EQR1511-6060D-S





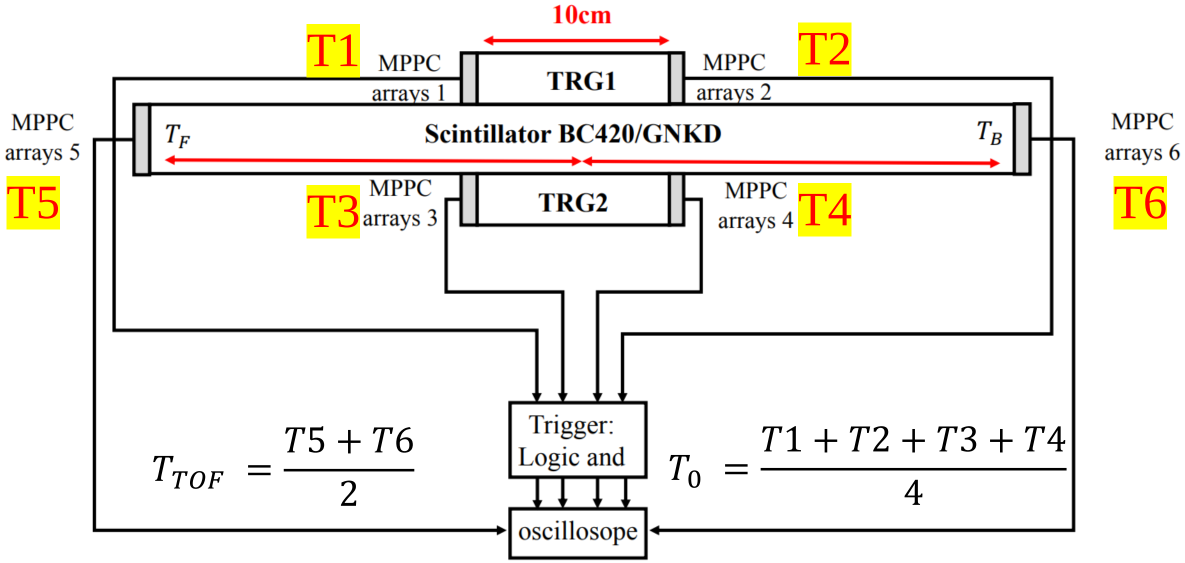
4×SiPM



12×SiPM

- After many tries, we find the key is the photon collection.
- We use scintillators with longer attenuation lengths and large areas of SiPM, which is like the design of traditional TOF.
- We have to consider the cost in building a large size KLM.
- Fortunately, two companies in Beijing offer the choice.

Plastic scintillator test using cosmic rays

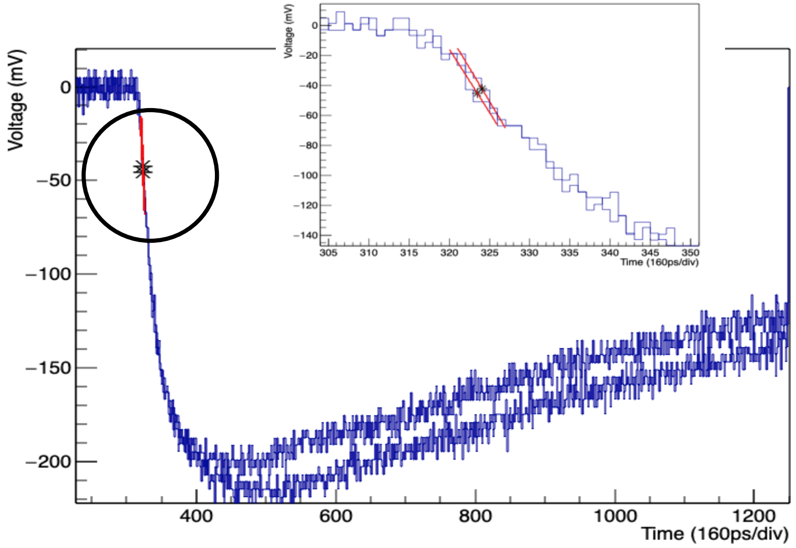


BC420

Trigger strip

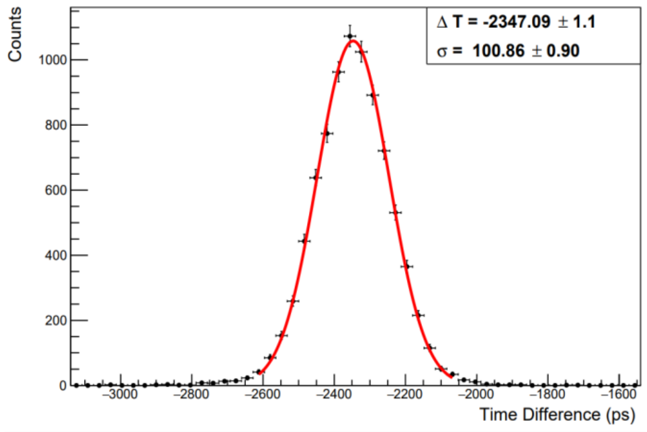
4 MPPCs

4 MPPCs



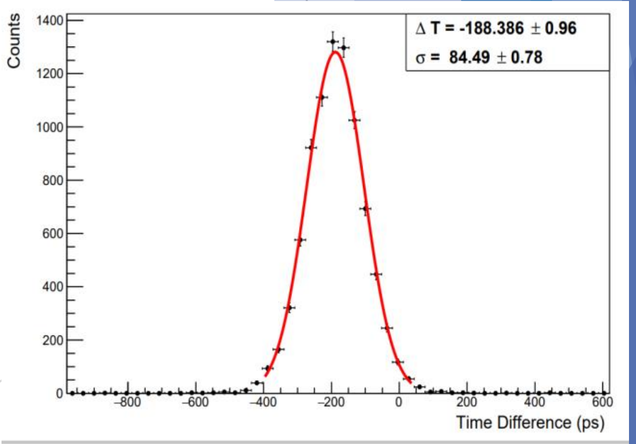
CFD timing of waveform

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



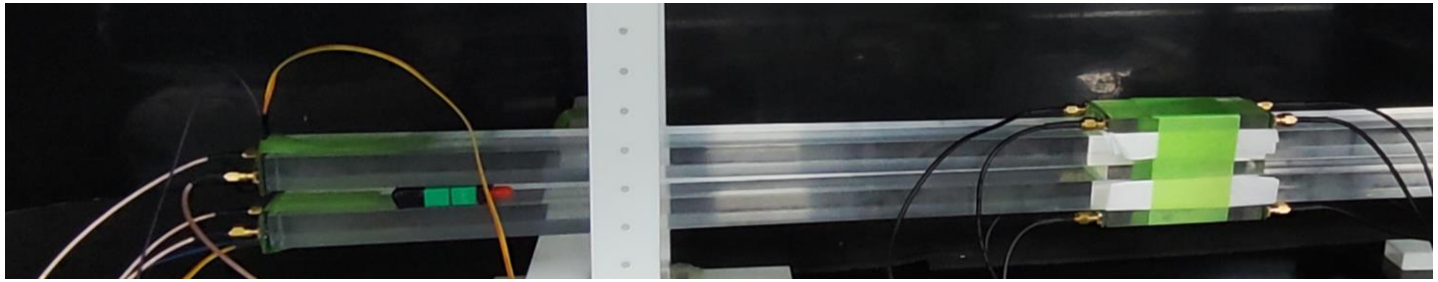
$\sigma_{TRG} = 100.8\text{ps}$ $\sigma_{T_0} = 50.4\text{ps}$

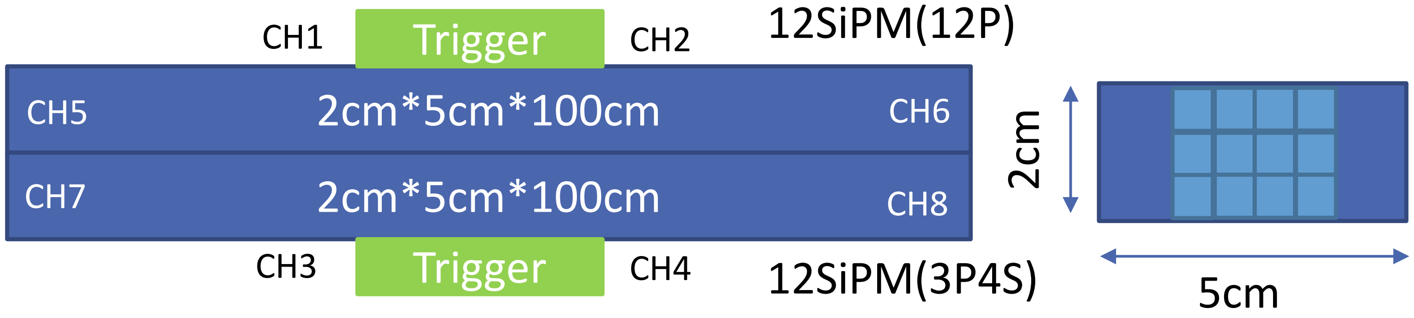
$$T_0 - T_{TOF} \rightarrow \sigma_{T_{TOF}}$$

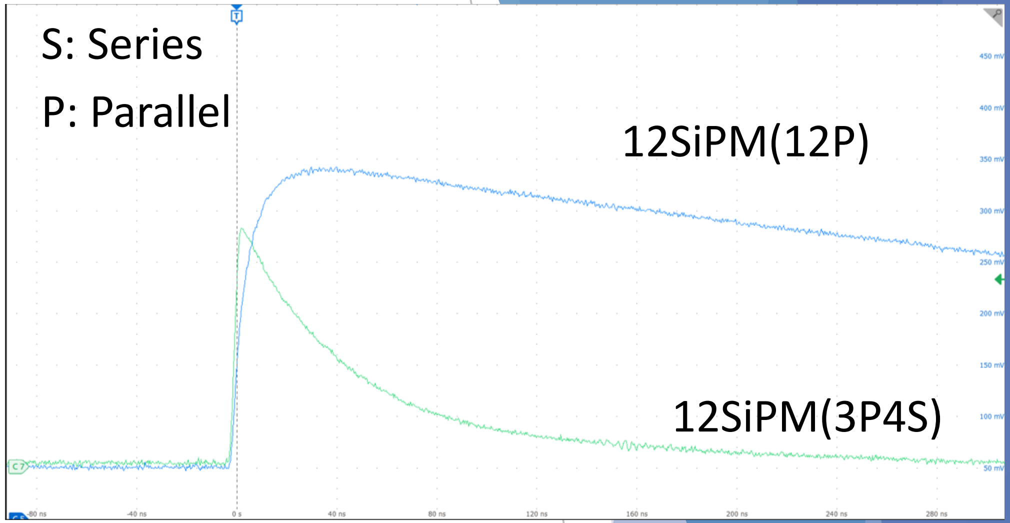


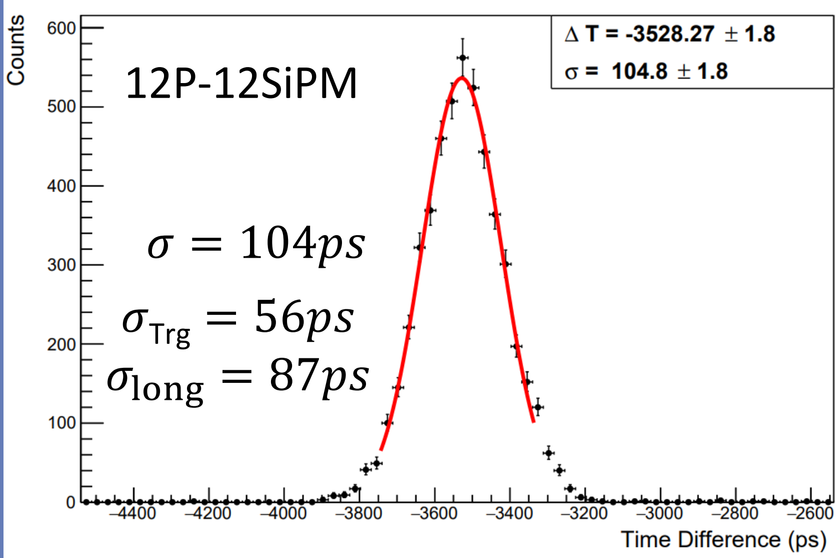
$\sigma_{T_{TOF}} = 67.5\text{ps}$

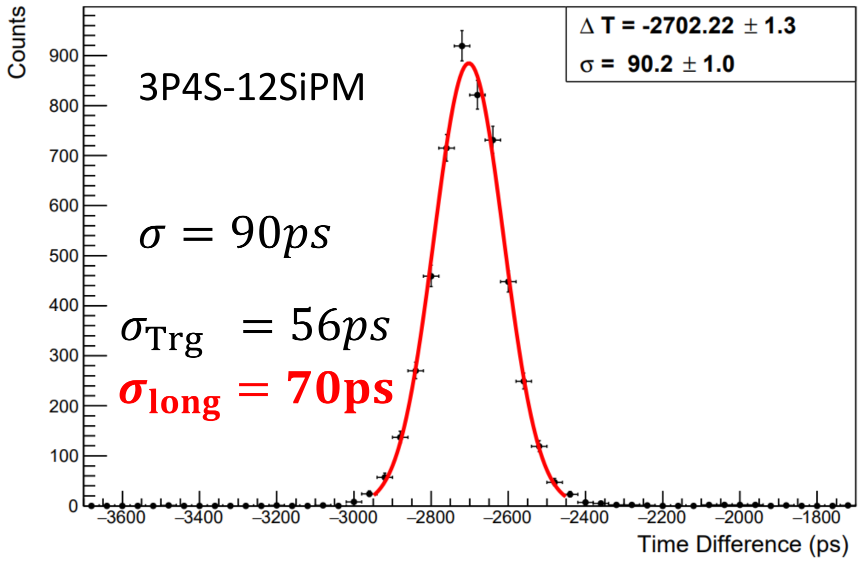
Time resolution of long strip: GNKD_new(2cm)

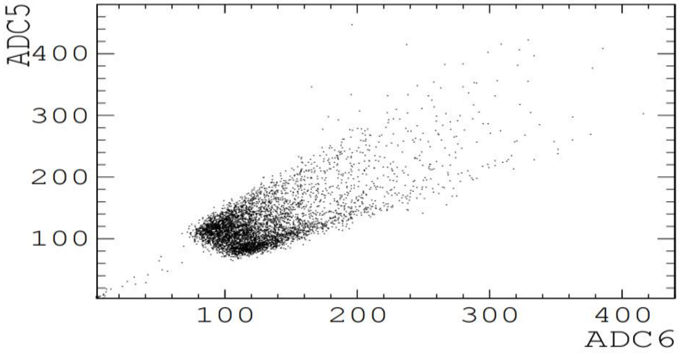


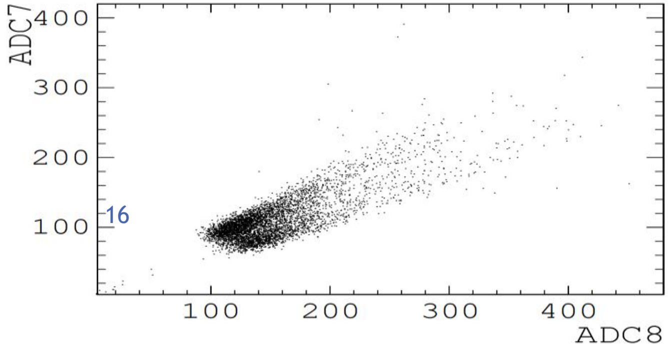




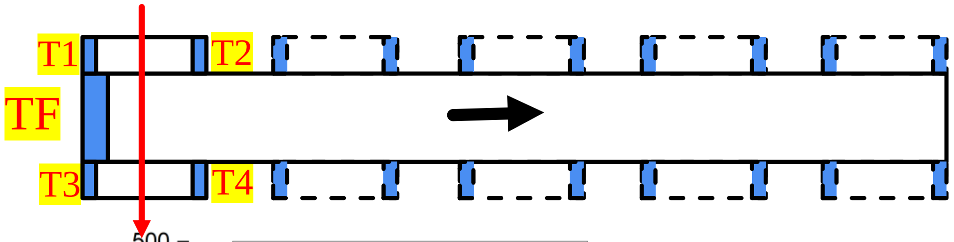




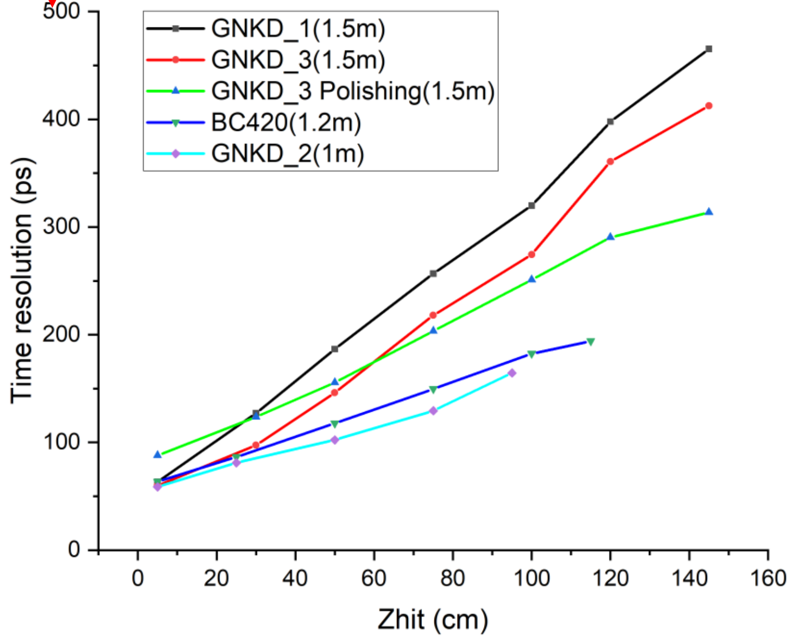




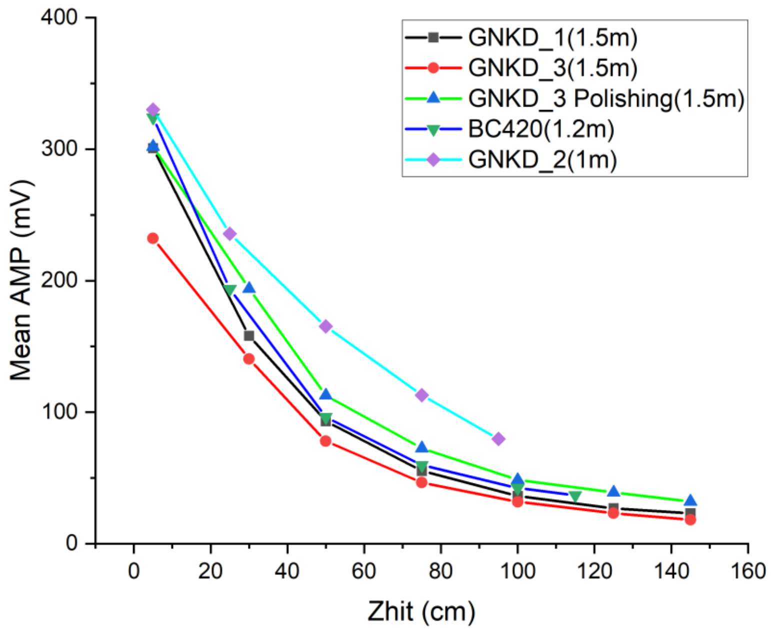
Time resolution at different position (one end)



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



Time resolution of different positions of scintillator



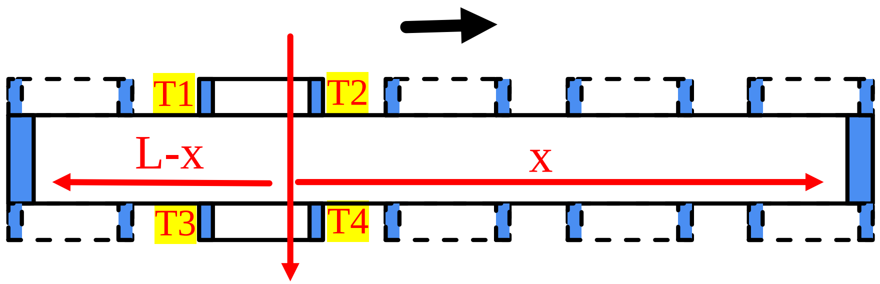
Signal amplitude at different locations of the scintillator

- Less light collection at the far end makes the SNR smaller, resulting in worse time resolution.
- Different time resolutions due to the different qualities of the scintillator samples.
- We are working with GNKD to improve the scintillator quality.

Time resolution at different position (two ends)

Backward

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



Forward

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

Unweighted:

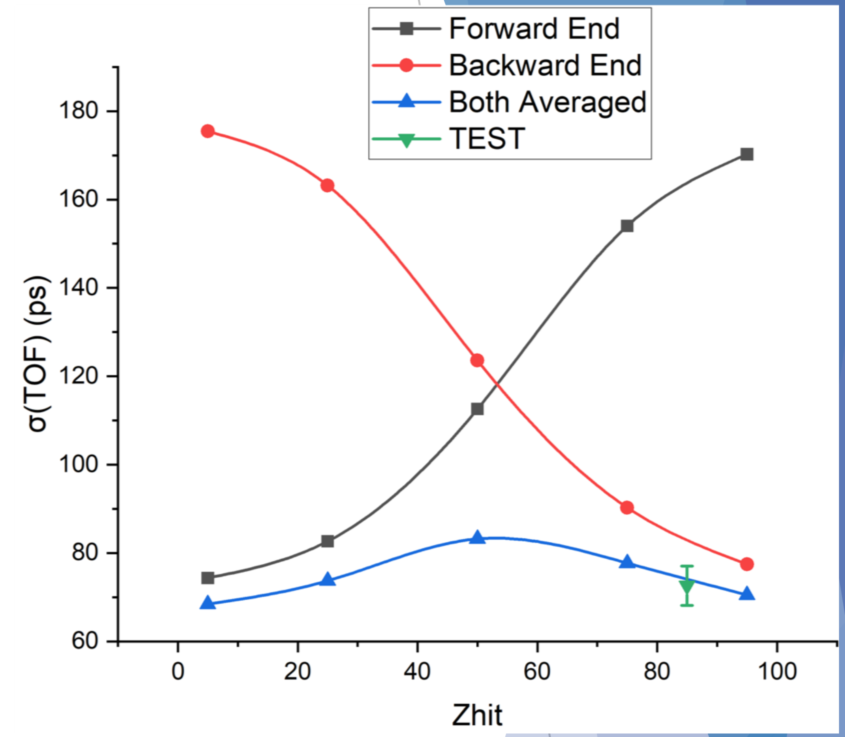
$$T_{s.c.} = \frac{T_F + T_B}{2} = T_0 + \frac{L}{2v} \qquad \sigma_{s.c.}^2 = (\sigma_F^2 + \sigma_B^2)/4$$

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'

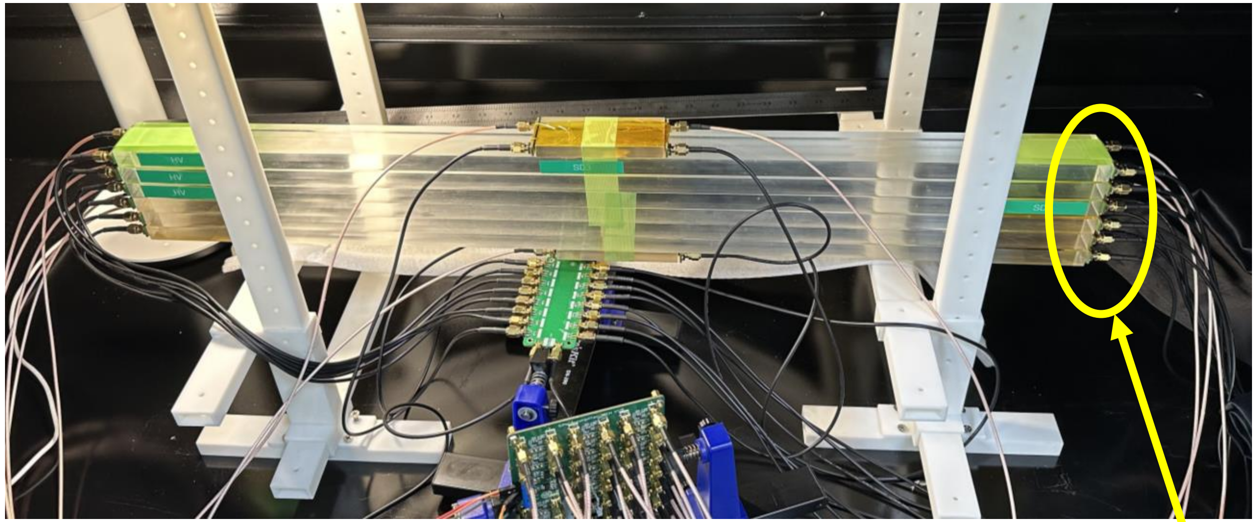
We get a time resolution better than 80 ps from the 1m long bar. This proves the quality of scintillator from GNKD.



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

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

Time resolution of an array of long strips



4SiPMs

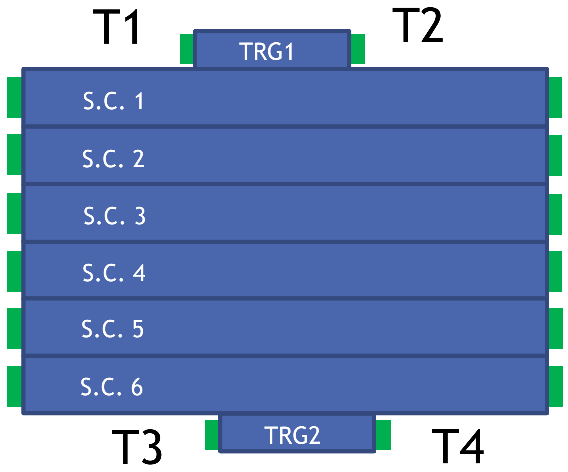
Trigger logic board

- Cut the old $1.5m$ scintillator strips to be $75cm$.
- Six strips for testing, and $10cm$ triggers at the middle.
- CAEN DT5742 for DAQ.
- Logic trigger as input from the two trigger strips.
- 12 SiPMs at both ends of one strip.

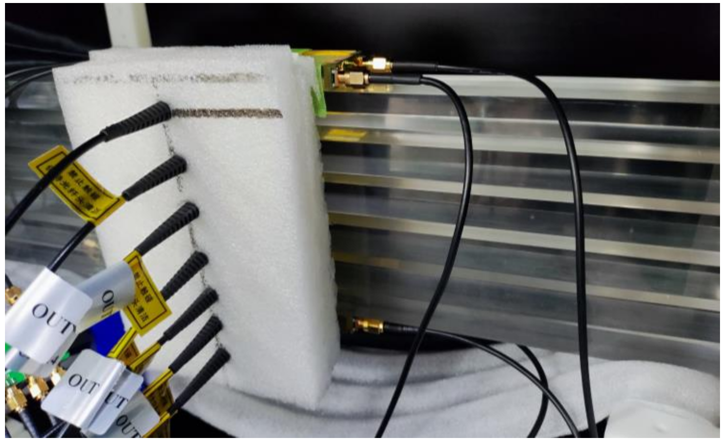
Time resolution of each channel is about 120 ps.

DT5742 with a good time resolution

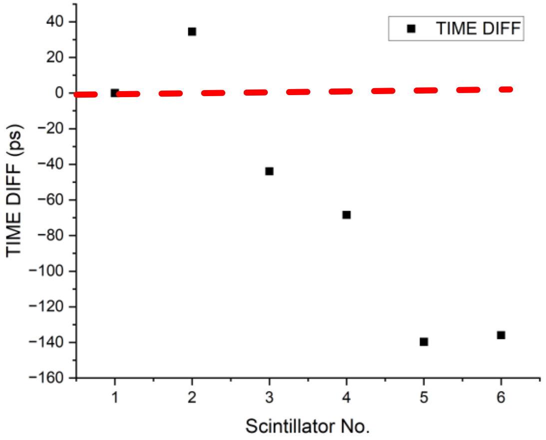
Time calibration with the laser

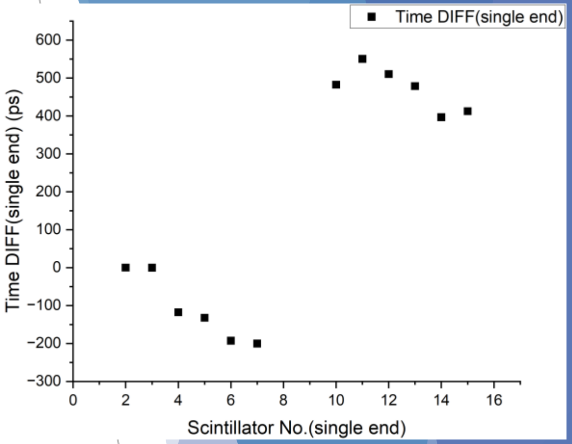


Time calibration with laser



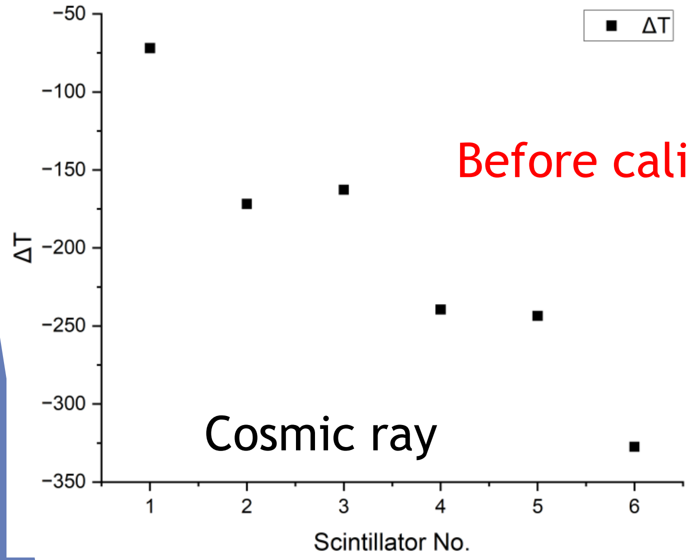
$Time\ DIFF = T_{S.C.X} - T_{S.C.1}$

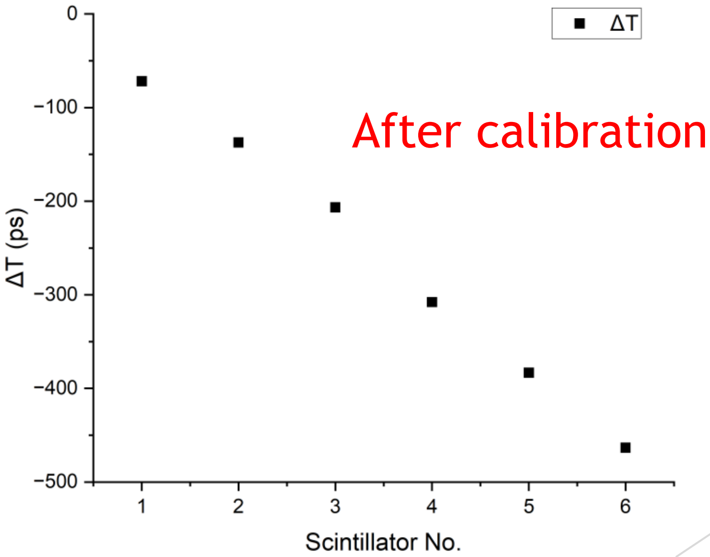


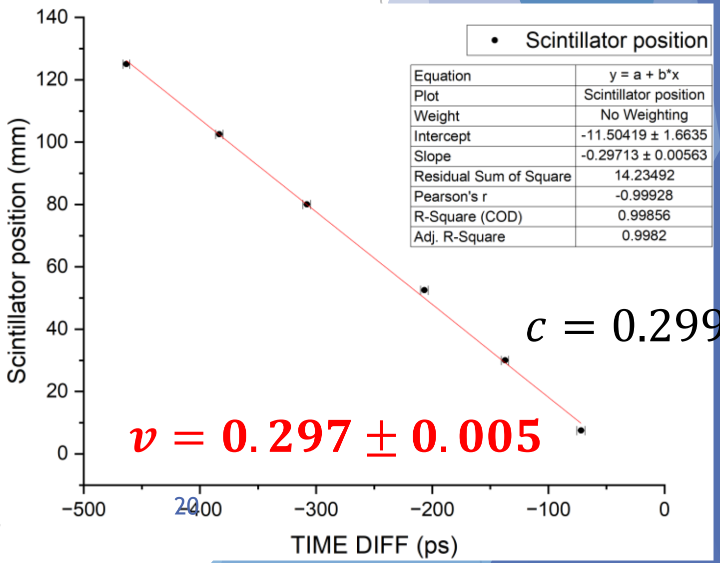


Laser testing for time calibration constants

$\Delta T = T_{S.C.X} - T_0$ (T0 = (T1+T2+T3+T4)/4)





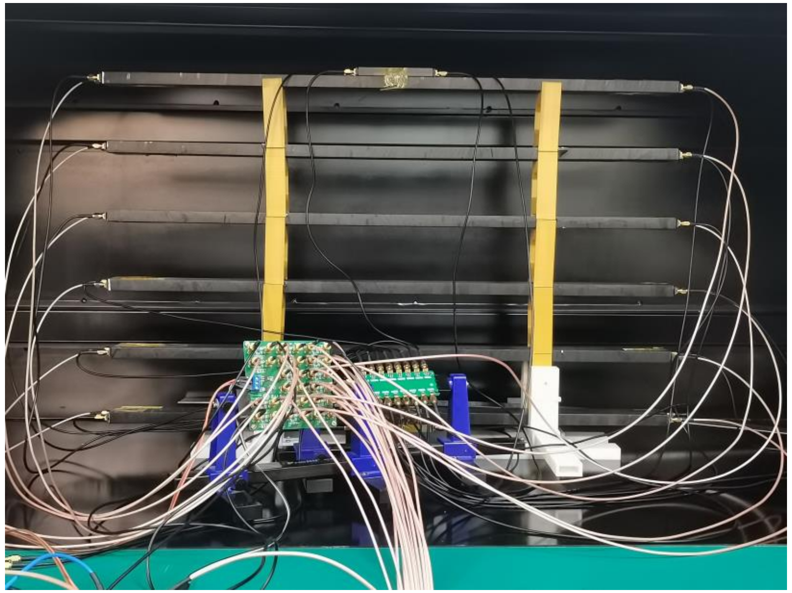


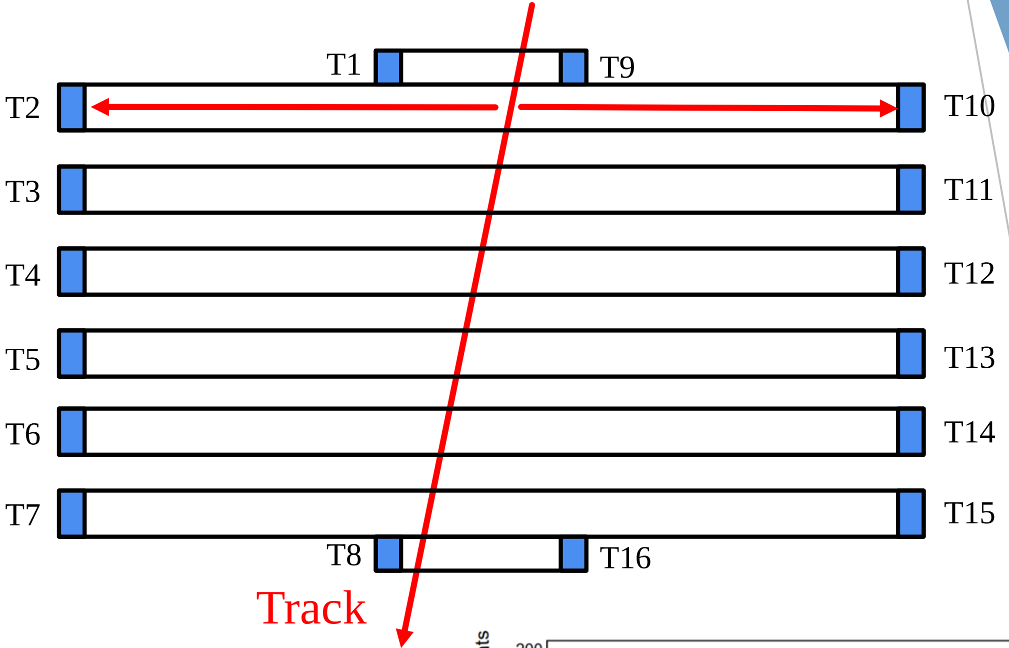
$c = 0.2997$

$v = 0.297 \pm 0.005$

L=12cm is too short.

Prototype Test (Velocity of CR Muon)





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

$T_{S.C.2} = (T_3+T_{11})/2$ - ΔT_1

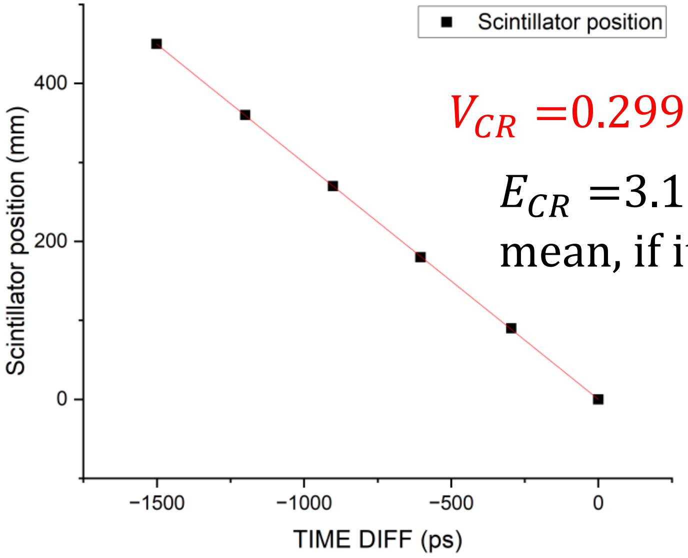
$T_{S.C.3} = (T_4+T_{12})/2$ - ΔT_2

$T_{S.C.4} = (T_5+T_{13})/2$ - ΔT_3

$T_{S.C.5} = (T_6+T_{14})/2$ - ΔT_4

$T_{S.C.6} = (T_7+T_{15})/2$ - ΔT_5

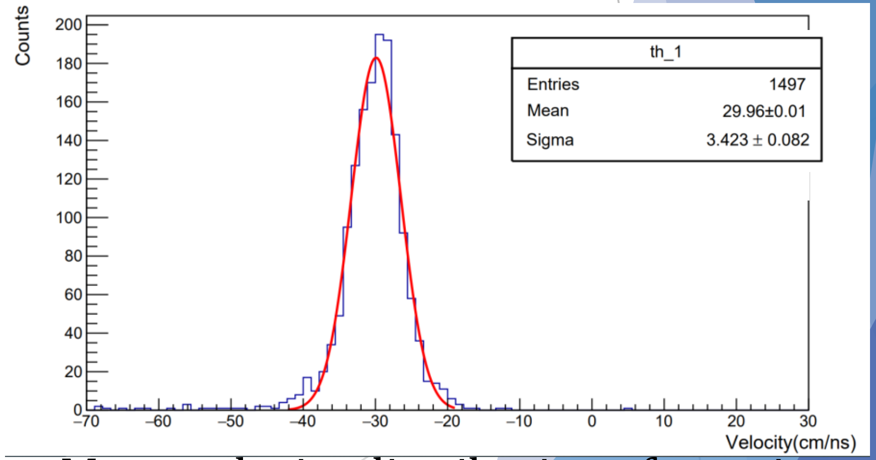
Time calibration



V_{CR} =0.299582 ± 0.00011 mm/ps

E_{CR} =3.1 ± 0.4 GeV/c^2 for the mean, if it's muon.

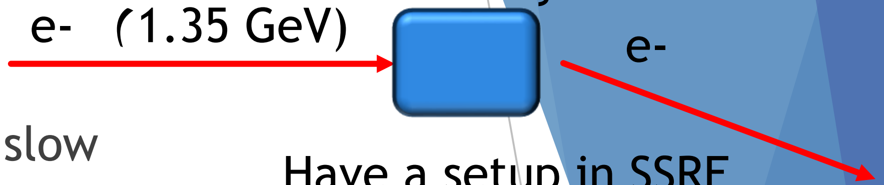
This preliminary test shows good results.



Muon velocity distribution of cosmic rays

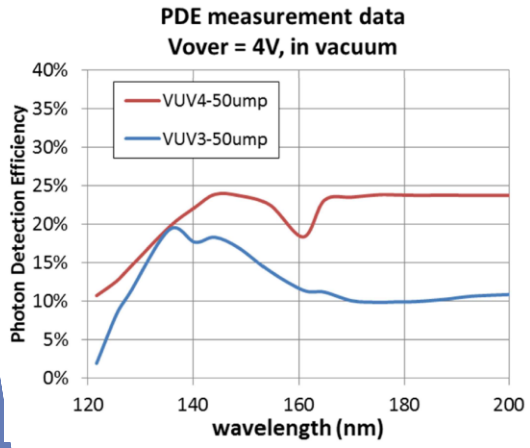
BaF2 + VUV MPPC (preliminary)

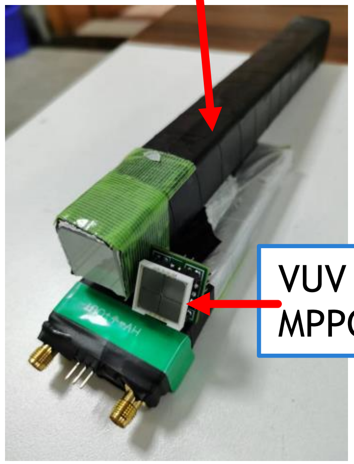
YAG crystal for scattering



- BaF2 from Shanghai Institute of Ceramics (CAS), which has the slow component well suppressed.
- It's a good choice for precise timing measurement.

$2cm \times 2cm \times 20cm$ BaF2

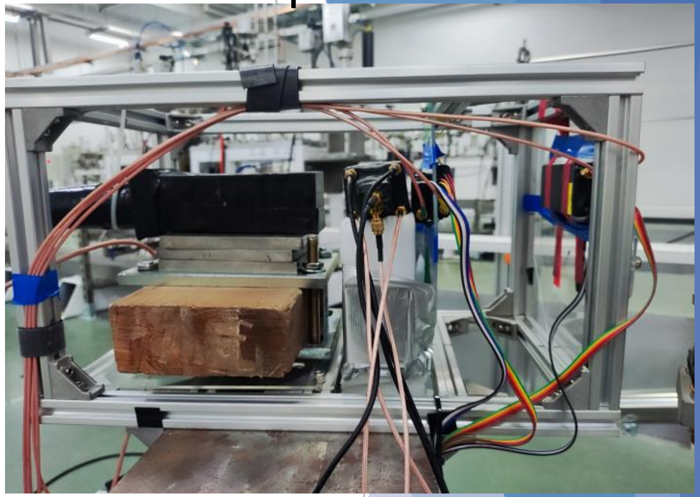


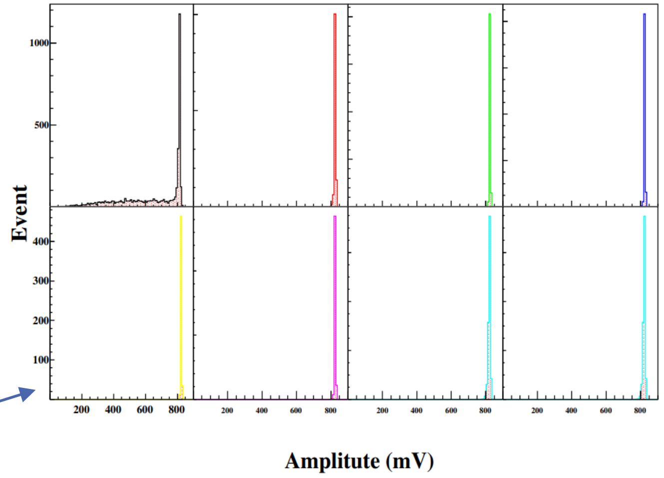


VUV MPPC

Similar trigger, but use one-side readout.

Have a setup in SSRF





Too large signals, reaching the dynamic boundary of the FE. So that the timing is not well measured, even through, …

$$\sigma_{trigger} = 234.62 \pm 1.38\, ps$$
$$\sigma_{T0} = 117.31 \pm 0.69\, ps$$
$$\sigma_{BaF2} = 154.6 \pm 0.91\, ps$$

Summary

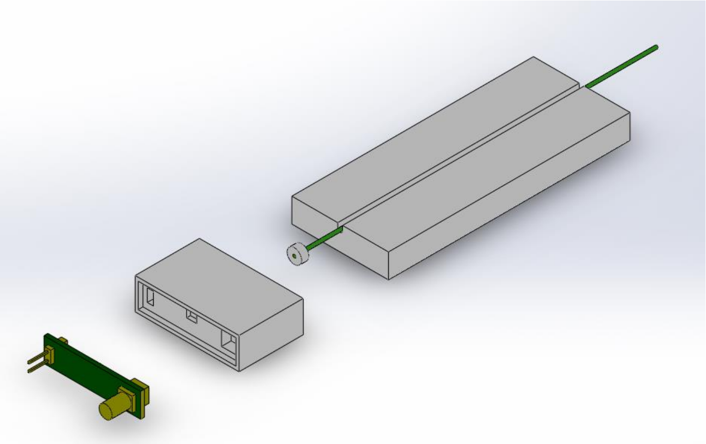
- We have been performing the R&D for detector based on scintillator, SiPM and WLS fiber.
- We can use the technologies for Belle II KLM upgrade and a muon detector for CEPC.
  - KLM upgrade: good timing can be used for momentum measurement of neutral hadrons like K_L and neutrons.
  - Muon detector for CEPC: large size and high efficiency.
- Extruded scintillator+WLS fiber+SiPM shows a good efficiency, but the time resolution is at the ns level.
- Scintillator with long attenuation length and large size SiPMs (array) shows very good time resolution. We get a time resolution of $\sim 70\ ps$ from 1 meter long scintillator from GNKD company.
- Fast BaF2 with VUV MPPC looks like a good choice for timing measurement.

Thank you!

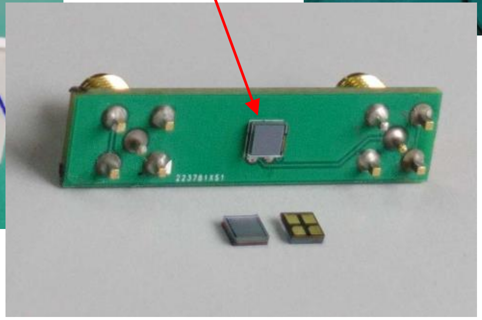
- Backup

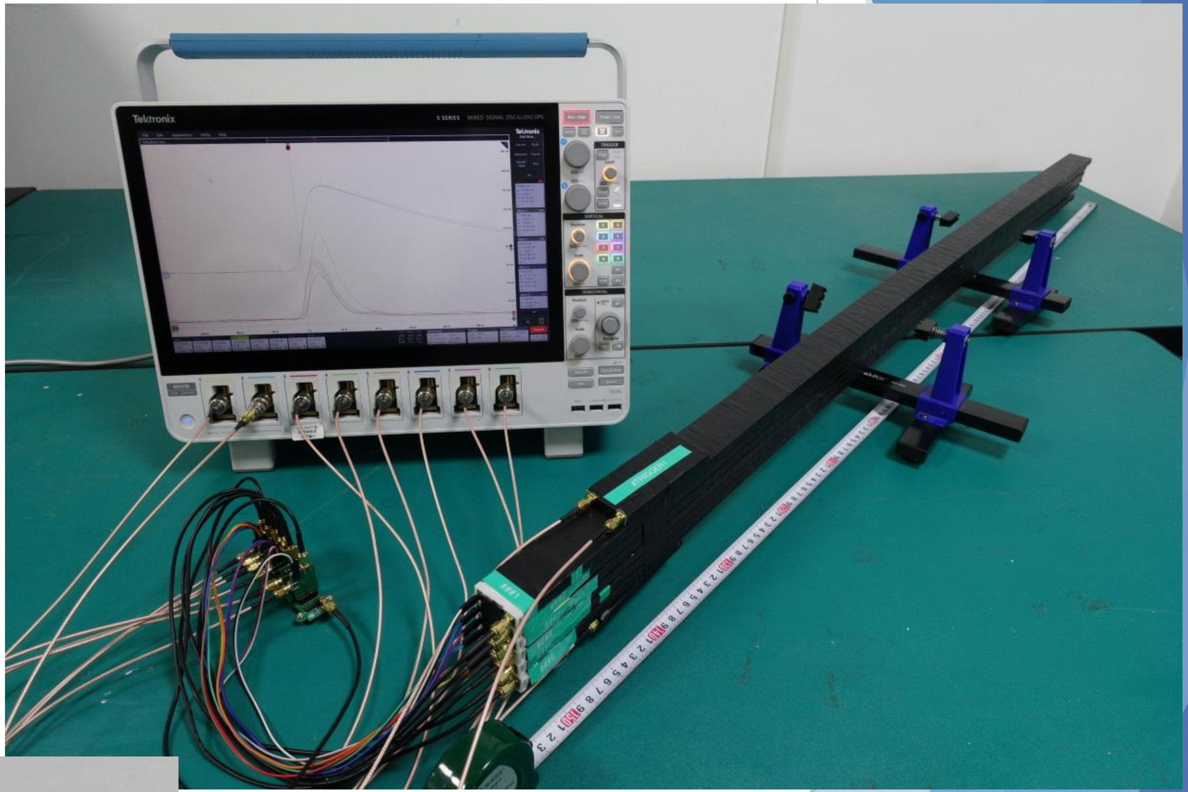
Status of R&D: Regular design

- GNKD scintillator + Kuraray WLS fibre + NDL SiPM($3mm \times 3mm$)



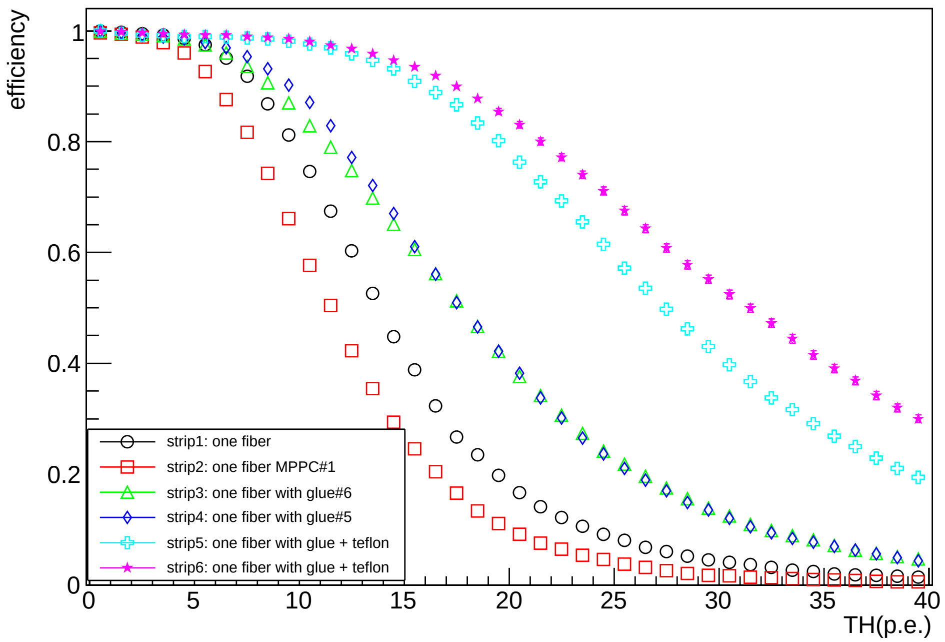
$3mm \times 3mm$
NDL SiPM

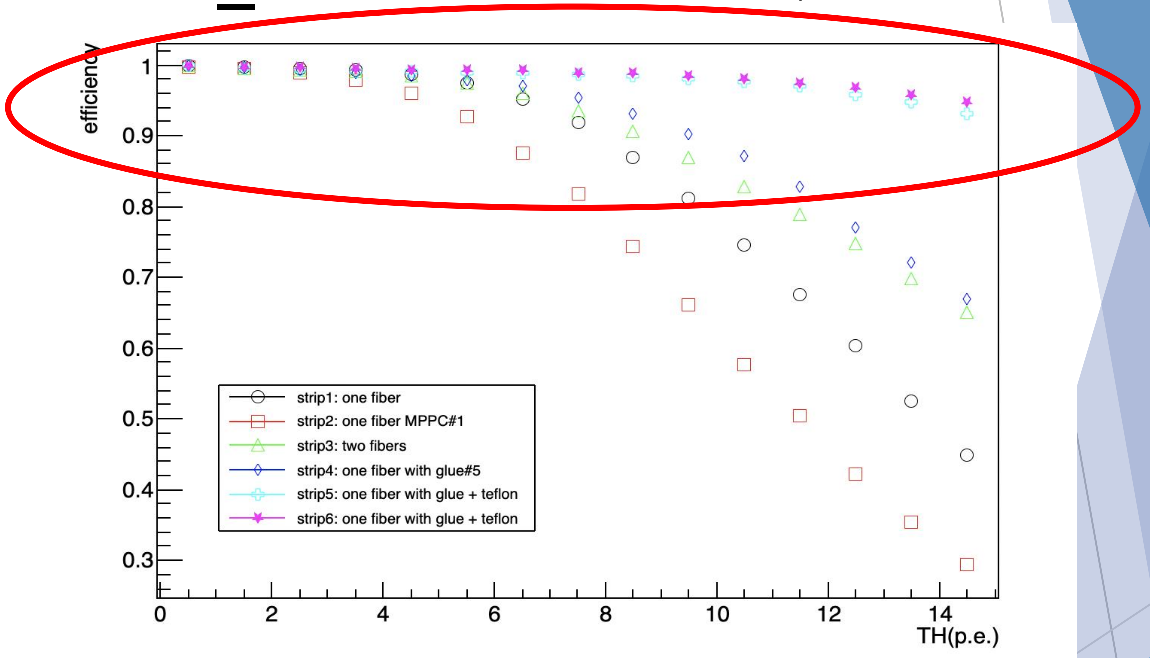




Performance in cosmic ray testing

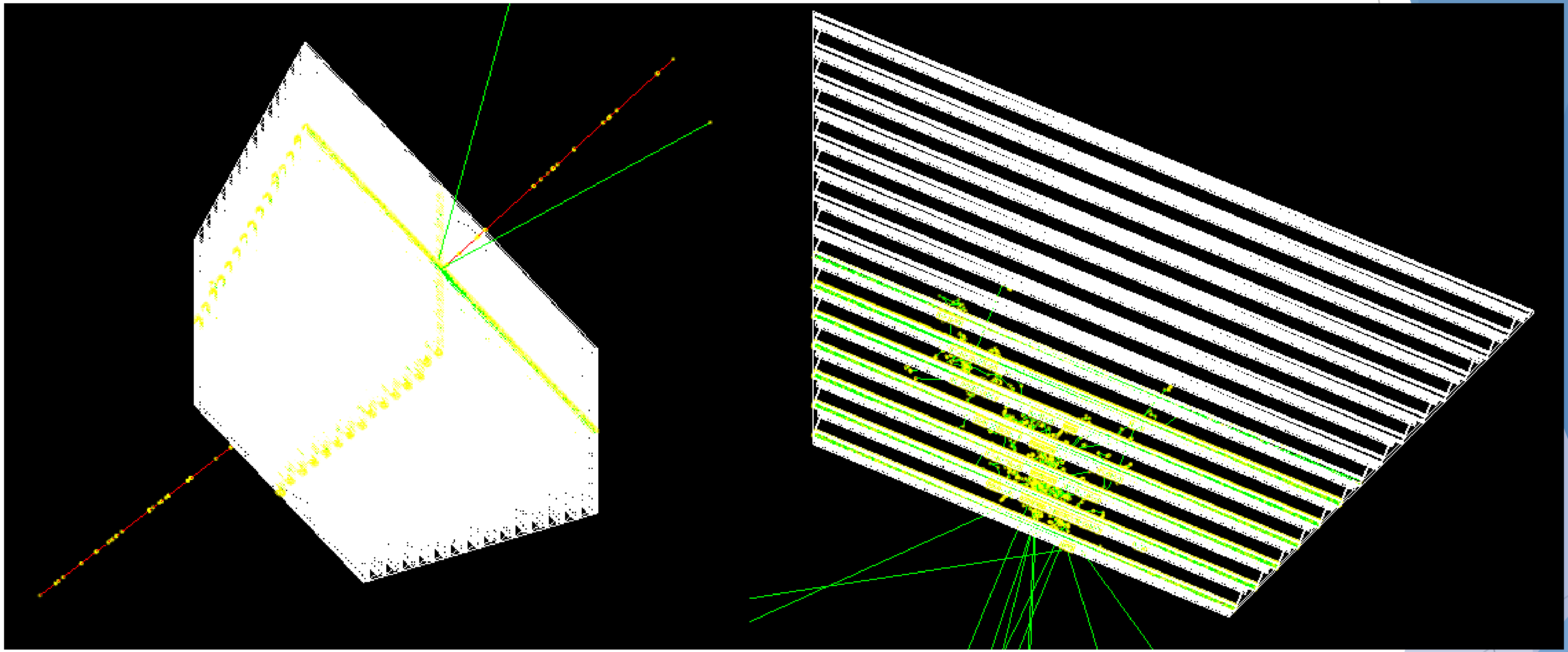
The efficiency of GNKD_150cm at far end.





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

KLM Detector Simulation

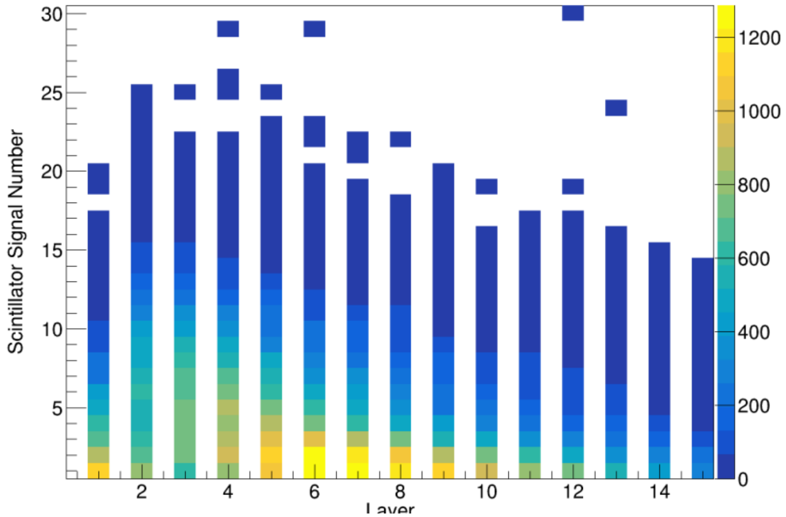


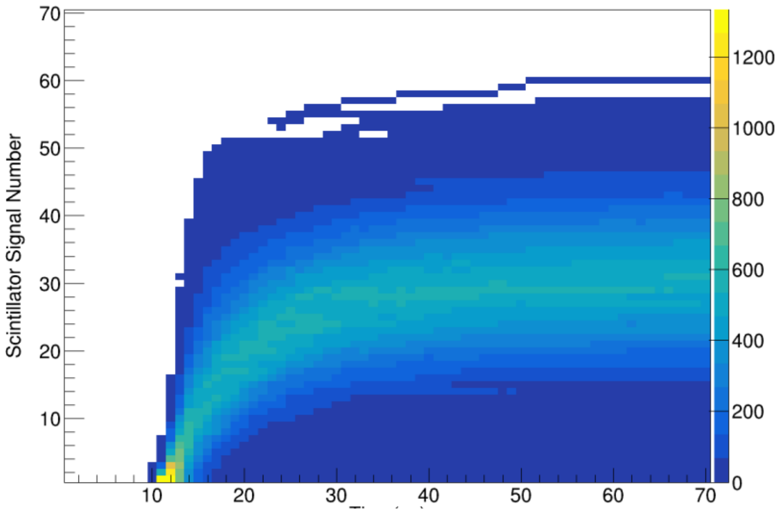
1 GeV/c μ^- Event

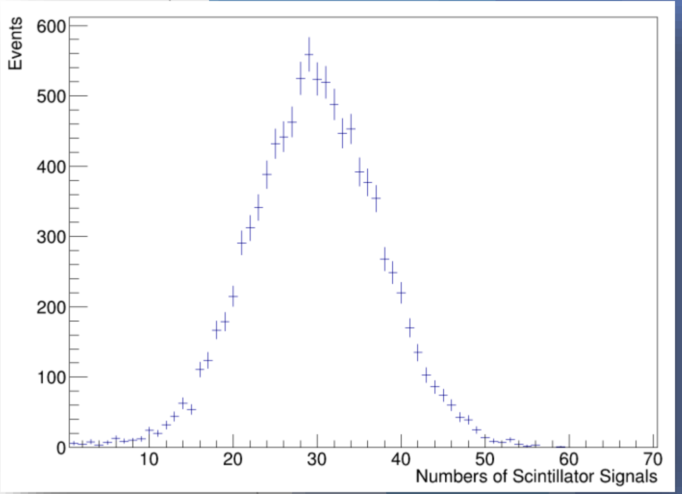
1 GeV/c K_L Event

Particle Identification of K_L

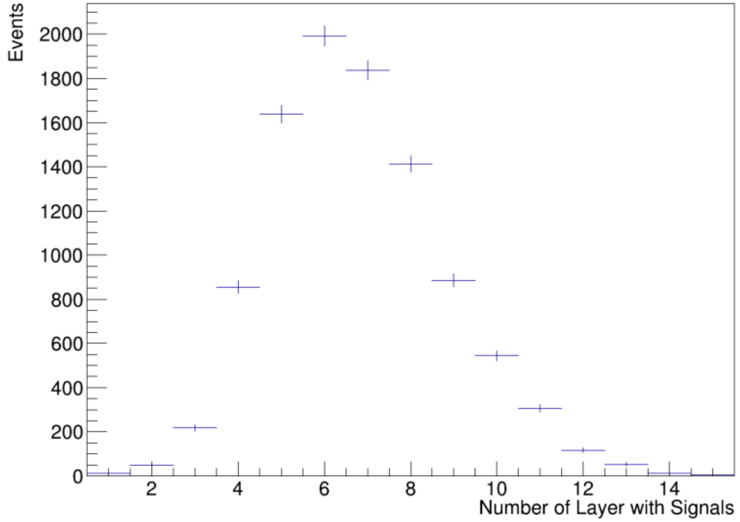
Average ~30 hits.

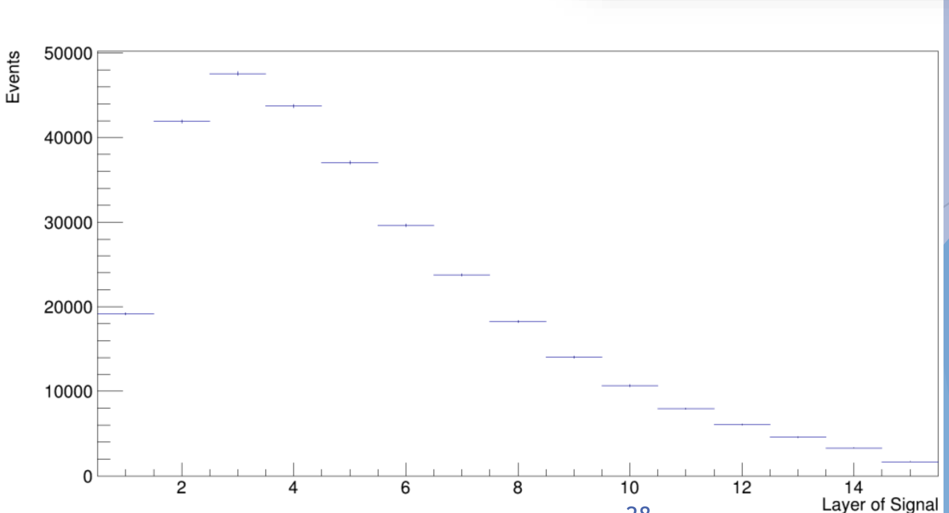






10000 K_L Events

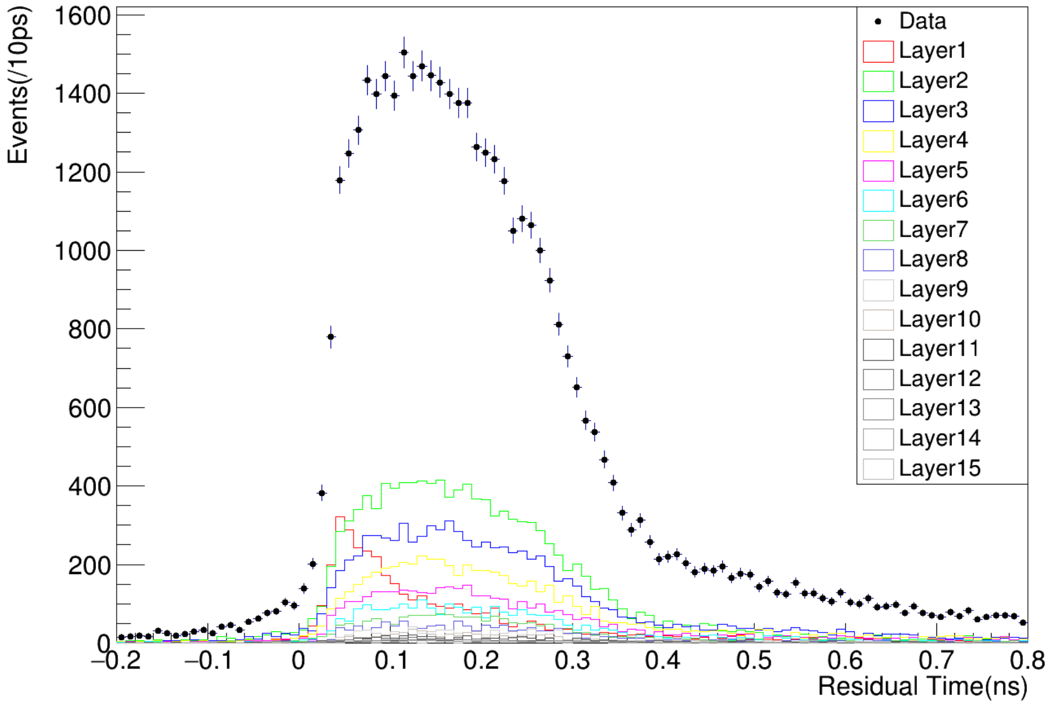




SiPMs will only record the time when there are more than 5 photons passing through them within 50ns.

Flight Time Reconstruction of K_L

Cuts	Number
N_{events}	50000
K_L Undergoes Hadronic Shower	49719 (99.43%)
Scintillator Signal > 0	49654 (99.31%)
K_L Decay in KLM Detector	47598 (95.20%)



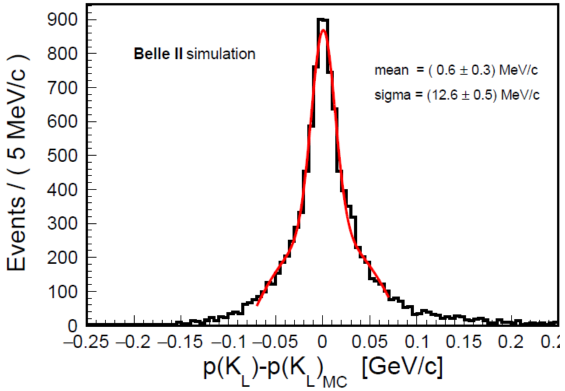
Rough estimation on the
KL ID would be > 90%

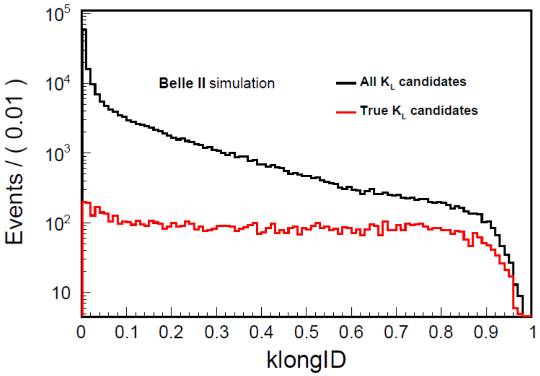
$\sin(2\beta/\phi_1)$ from $B \to J/\psi K_L$

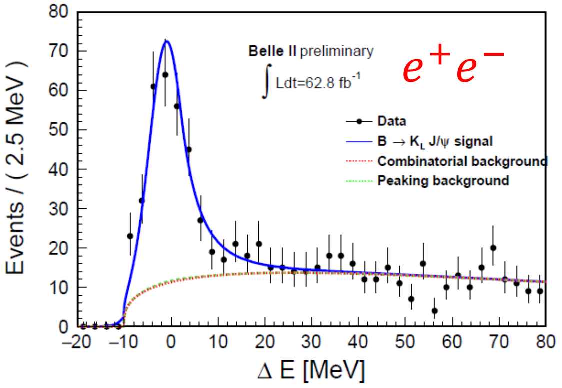
arXiv: 2106.13547 [hep-ex]

K_L reconstruction:

- Get direction of K_L according to cluster in KLM.
- $J/\psi \to e^+e^-$ or $\mu^+\mu^-$
- Mass constraint of $J/\psi K_L$ to get the P_4 of K_L.







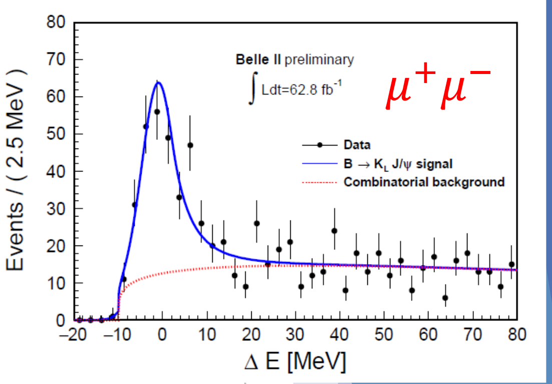


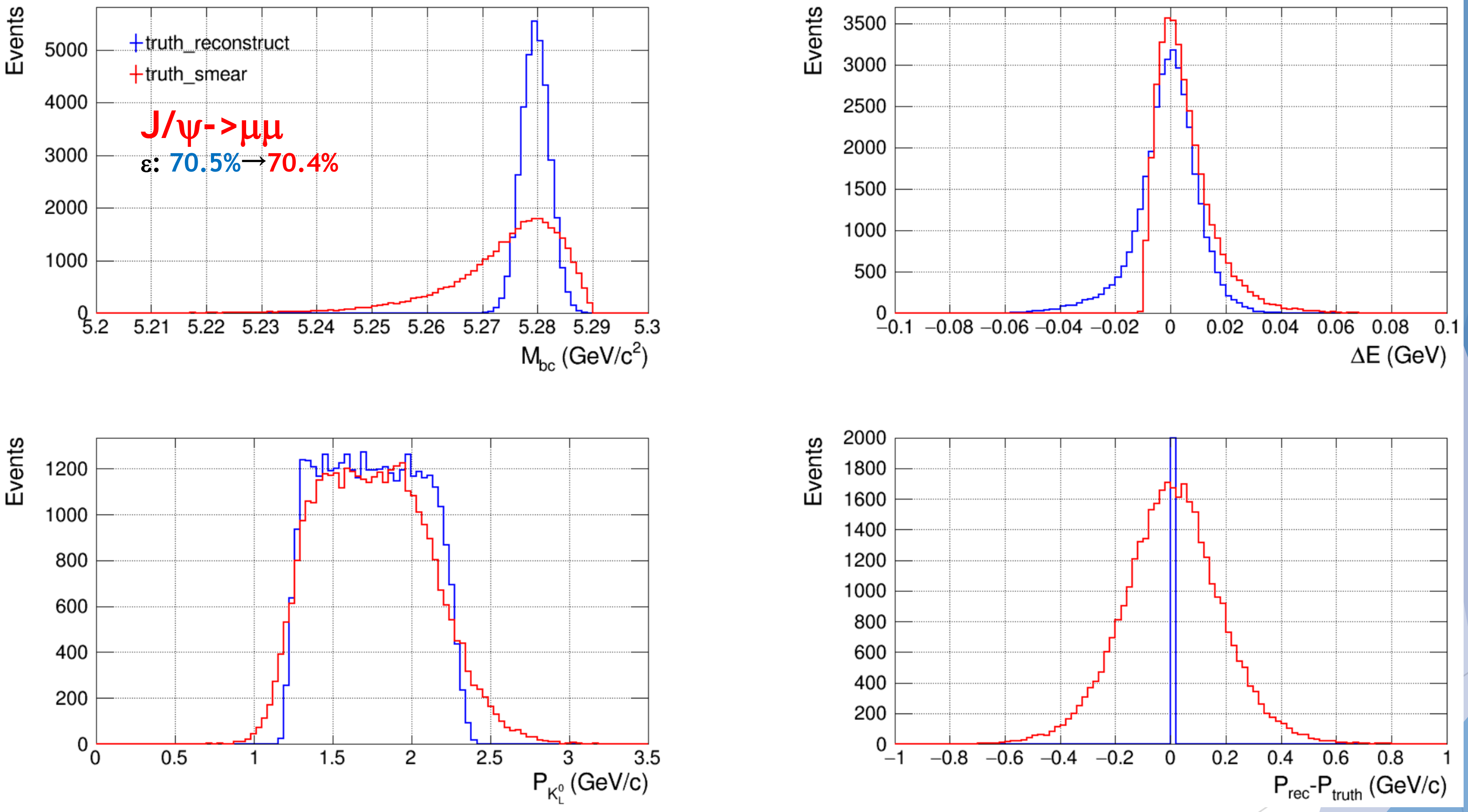
TABLE I. MC samples used for this study.

Sample	Equiv. $\int \mathcal{L}dt$[fb^{-1}]	release/proc	exp
MCsampleA: $J/\psi\,[\ell\ell]\,K_L^0$	300	04-00-01/proc11	8
MCsampleB: generic MC13b	40	04-02-04/proc11	7,8,10

TABLE II. Signal reconstruction and selection efficiency.

Sample	$\varepsilon_{\mu^+\mu^-}$ [%]	$\varepsilon_{e^+e^-}$ [%]
MCsampleA	16.2 ± 0.4	15.2 ± 0.4
MCsampleB	13.3 ± 1.0	11.7 ± 1.0

- $N^{sig}(e^+e^-) = 226 \pm 20$, $N^{sig}(\mu^+\mu^-) = 267 \pm 21$
- In good agreement with Belle.
- But the systematic uncertainties related to peaking background is relatively large.
- $\Delta N_{peaking}(e^+e^-) = 31$, $\Delta N_{peaking}(\mu^+\mu^-) = 28$



truth_reconstruct
truth_smear
J/ψ->μμ
ε: 70.5%→70.4%
Events
Mbc (GeV/c²)
ΔE (GeV)
P_KL0 (GeV/c)
Prec-Ptruth (GeV/c)

Estimation of the improvements with new KL ID

existing result	Lum [fb^{-1}]	NBB [10^6]	eff	Nobs	Branching fraction
B0->(Jpsi->mm)KL	62.8±0.6	68.21	(16.2±0.4)%	267±21±28 @peaking	-
B0->(Jpsi->ee)KL	62.8±0.6	68.21	(15.2±0.4)%	226±20±31 @peaking	-
B0->JpsiKL (Barbar)	20.7	22.72±0.36	22.3%	408	(6.8±0.8±0.8)e-4
B0->(D+->K-pi+pi+)pi-	771	772±11	(24.09±0.04)%	34651±268	(2.48±0.01±0.09±0.04)e-3 @B(D+)
B0->(phi->K+K-)gam	771	772±11	(29.6±0.1)%	3.4+4.6-3.8	<1.0e-7
B+->(K0->Ks)pi	771	772±11	25.23%	3229±71	(23.97±0.53±0.71)e-6
B+->(K0->Ks)rho+ (Barbar)	429	470.9±29.8	~15%	507±30	(9.4±1.6±1.1+0-2.6)e-6 @sigModel
B+->K+KsKs	771	772±11	24%	650.16	(10.42±0.43±0.22)e-6

improvement estimation	Lum [fb^{-1}]	NBB [10^6]	eff_others	eff_KL	eff_global	Nobs_estimate	using branching fraction
B0->(Jpsi->ll)KL	362	387	60.2%	80%	48%	14687	6.8e-4
B0->(D+->KLpi+)pi-	362	387	76.6%	80%	61%	8346	2.48e-3
B0->(phi->KsKL)gam	362	387	53.9%	80%	43%	4	1.0e-7
B+->KLpi	362	387	83.0%	80%	66%	3167	11.99e-6
B+->KLrho+	362	387	46.8%	80%	37%	700	4.7e-6
B+->K+KLKL	362	387	82.2%	80%	66%	2181	10.42e-6

Some channels that Belle can not measure should be included in the future.