Muon detector development

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01 **CEPCSW and Geant4 simulation**

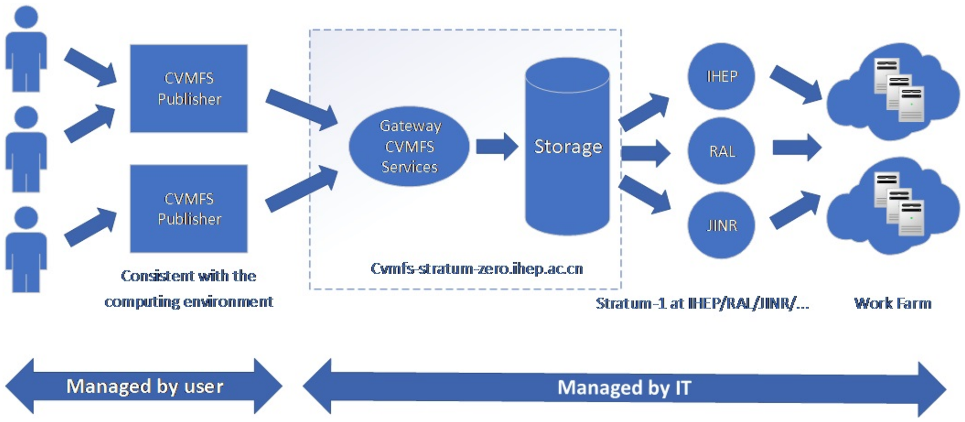
02 **Performance of current KLM design**

03 **Using new NDL SiPM and fast amplifier**

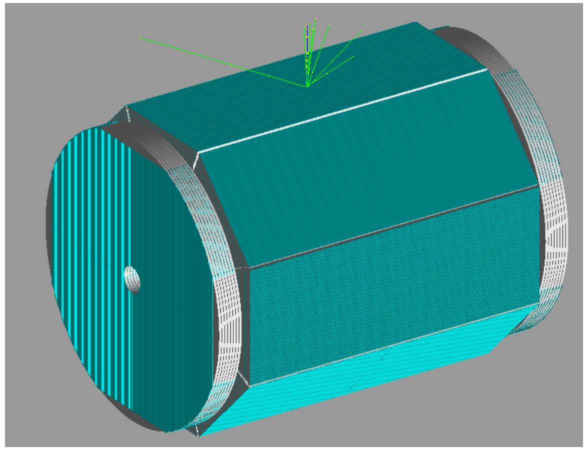
Implement of muon detector in CEPCSW

Scintillator + SiPM readout

- Set up
  - Geometry
  - Scintillator parameters
  - WLS fiber
- Simulation
  - Detector efficiency for muon
  - Behavior of long-lived particle
  - Tail of hadron cluster from HCAL
  - Spatial resolution
  - Time resolution



CEPCSW installed



40 GeV $\mu^{\pm}$ hits

Structure of current KLM design

- Scintillator shape is flexible, easy to get good spatial resolution:
  - $\sigma = \text{Width}/\sqrt{12}$
- Wave length shift (WLS) fiber inside scintillator to collect photons and guide them to SiPM.
- Use SiPM at one or both ends, small size, low cost and can work at high magnetic field.

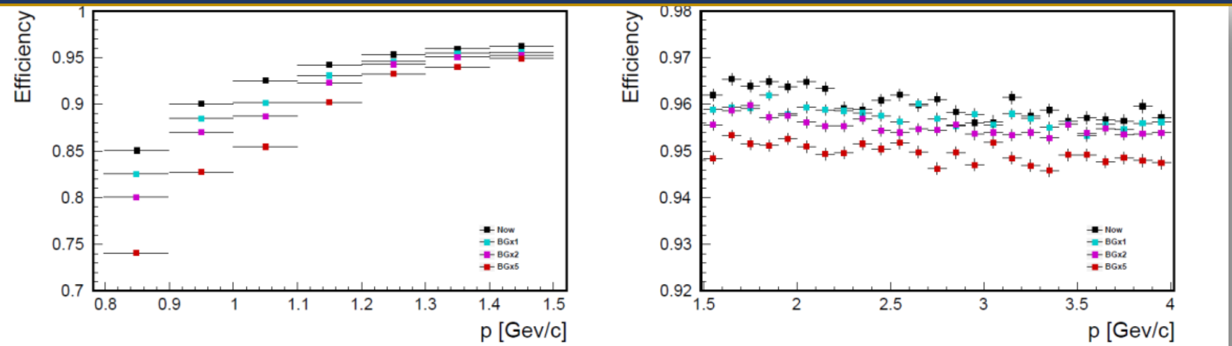
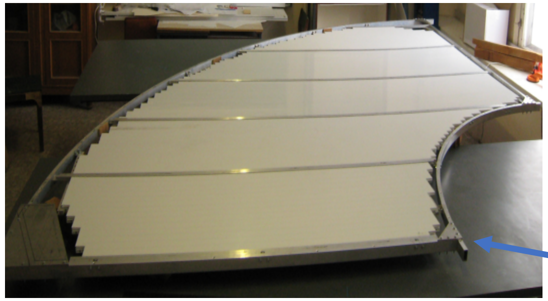
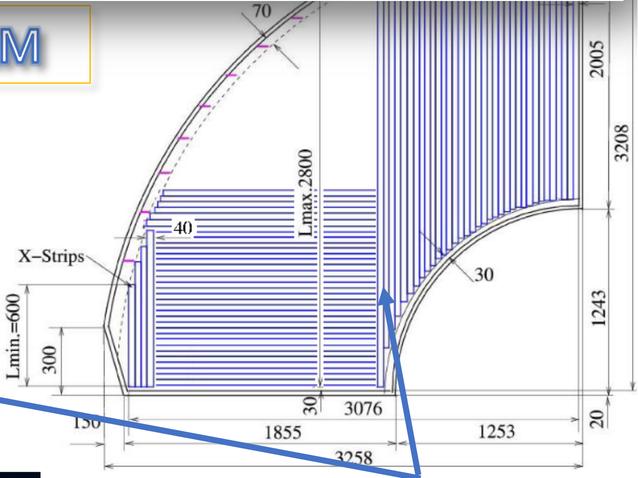
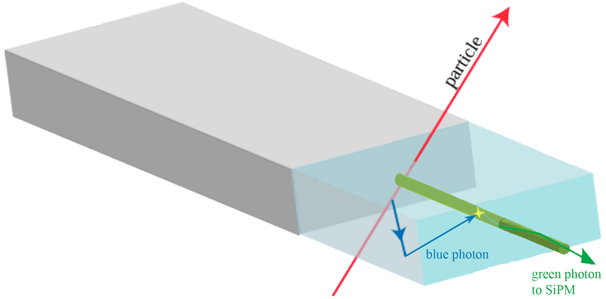


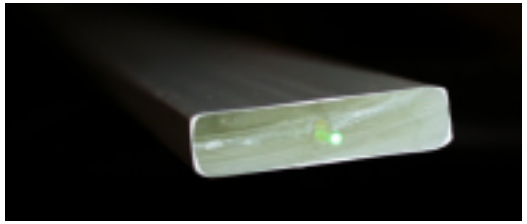
Figure 4: Muon identification efficiency after the requirement muonID > 0.9 in the three considered scenarios for tracks with $0.8 < p < 1.5$ GeV/c (on the left) and for tracks with $1.5 < p < 4.9$ GeV/c (on the right).

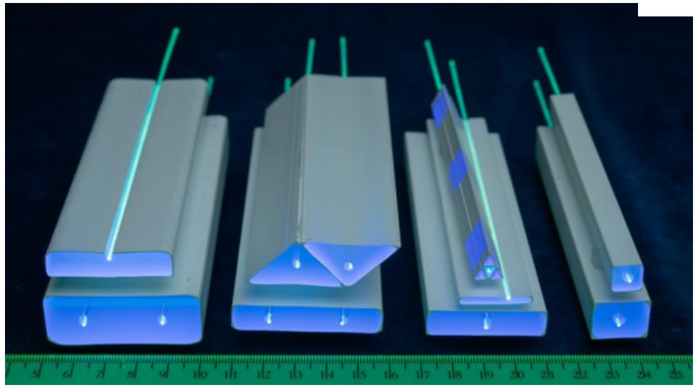
Belle II KLM

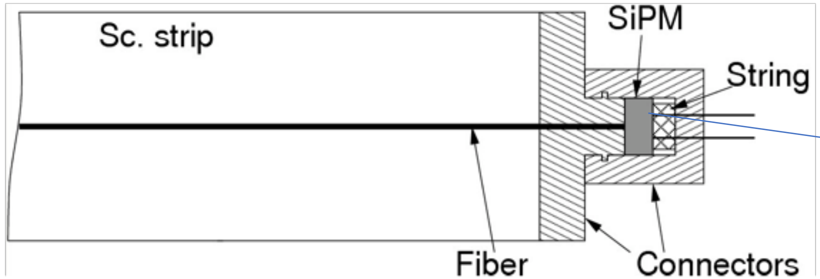


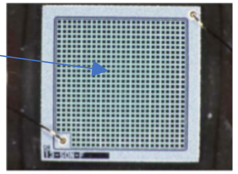






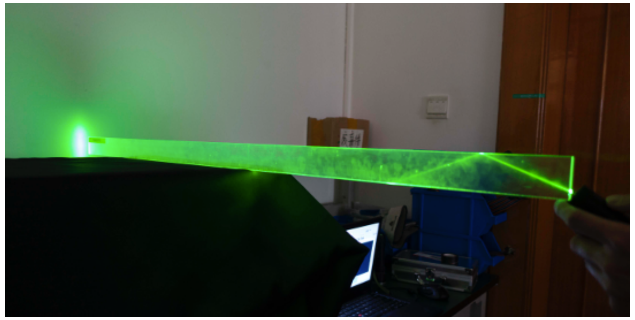


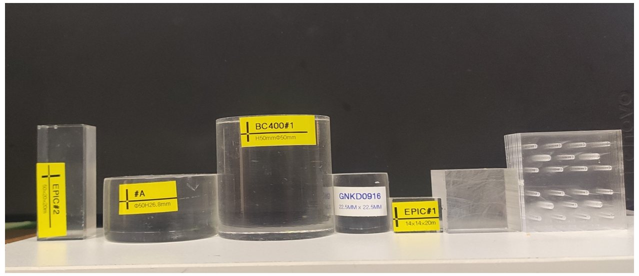




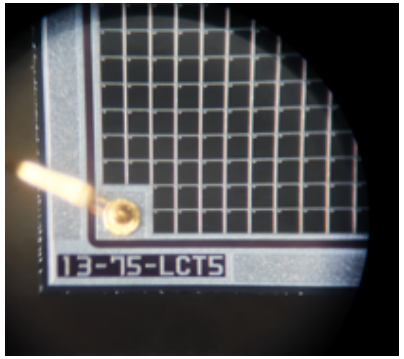
Superlayer for good 2-D resolution

Set up of scintillation detector

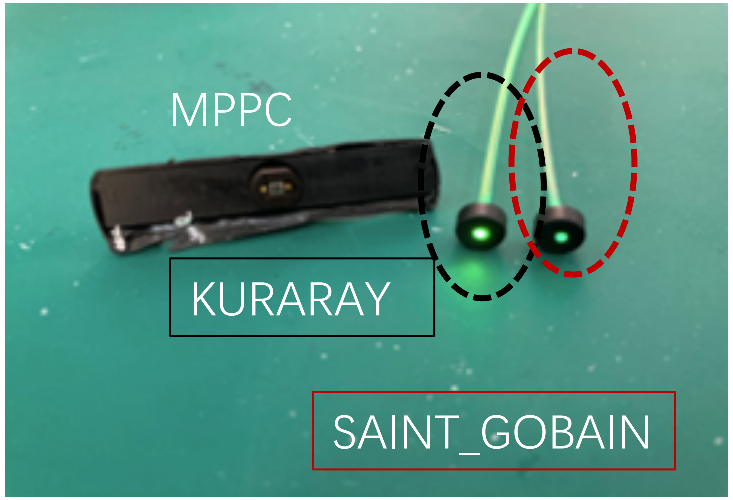




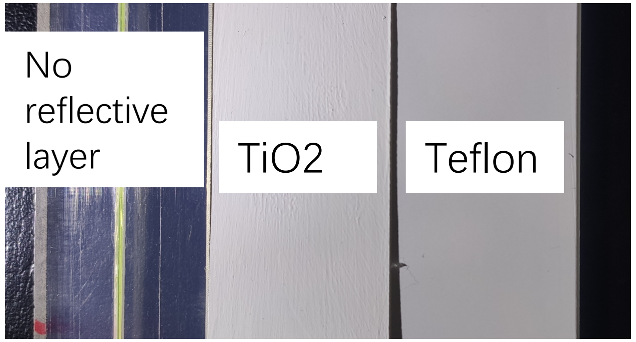
Scintillators with different size



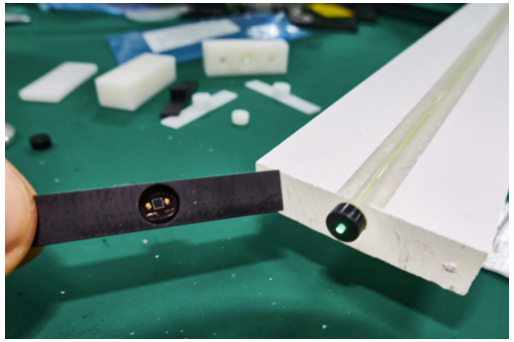
S13 series SiPM from Hamamatsu



WLS fibers

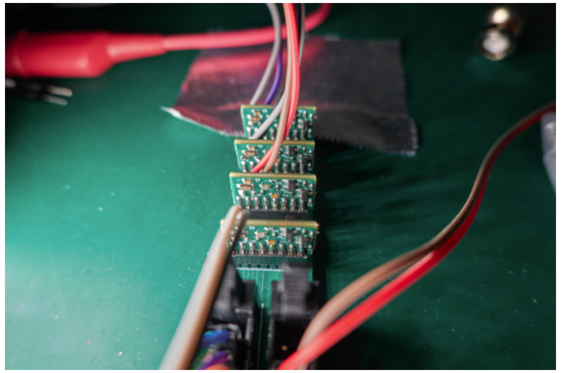


Reflective layer



Coupling between SiPM and fiber

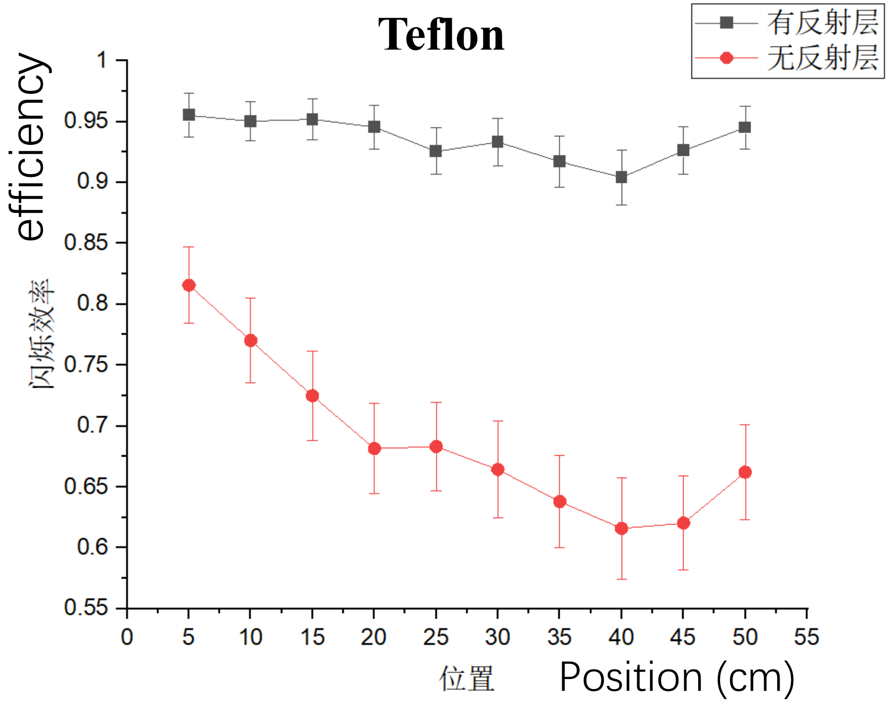
Optical glue, silicone oil

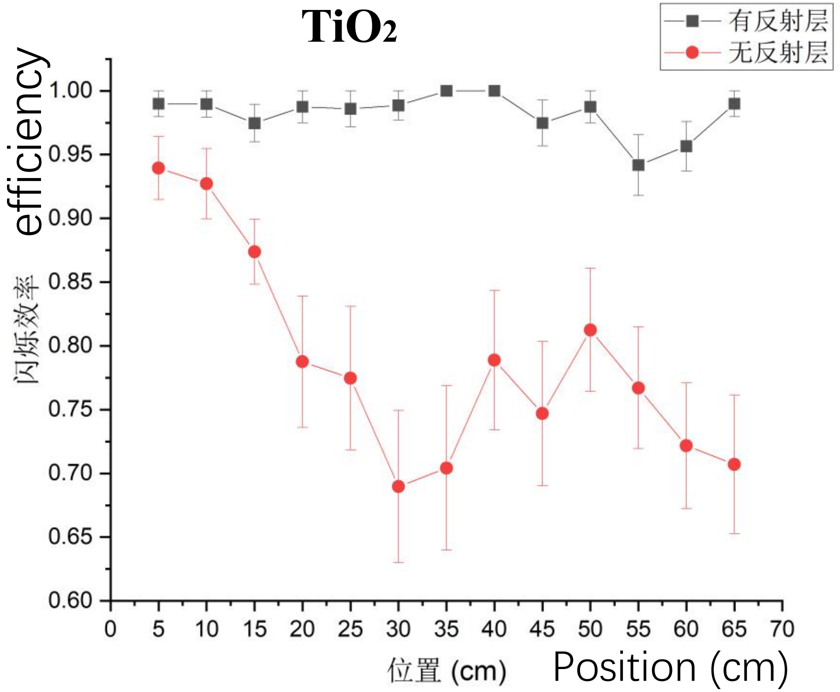


Differential preamplifier

Efficiency of different reflective layer

➢ Reflective layer improves efficiency a lot.

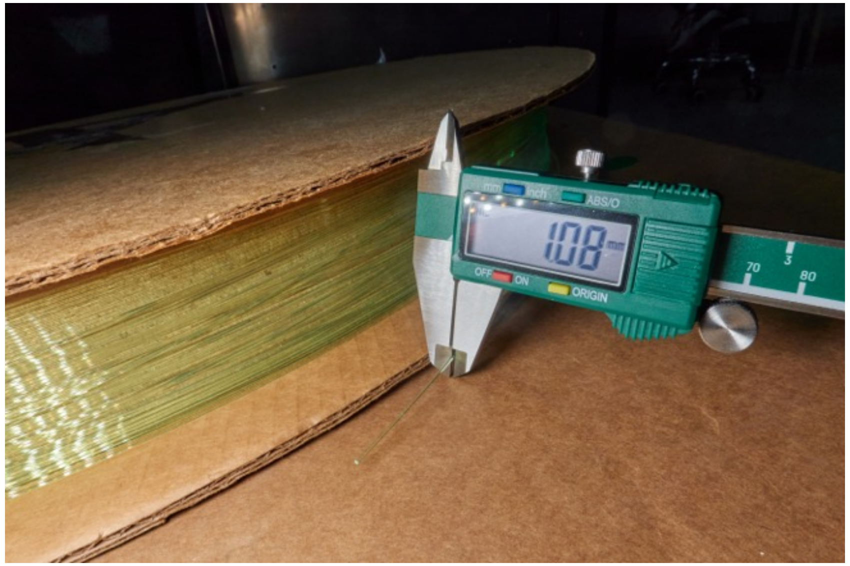




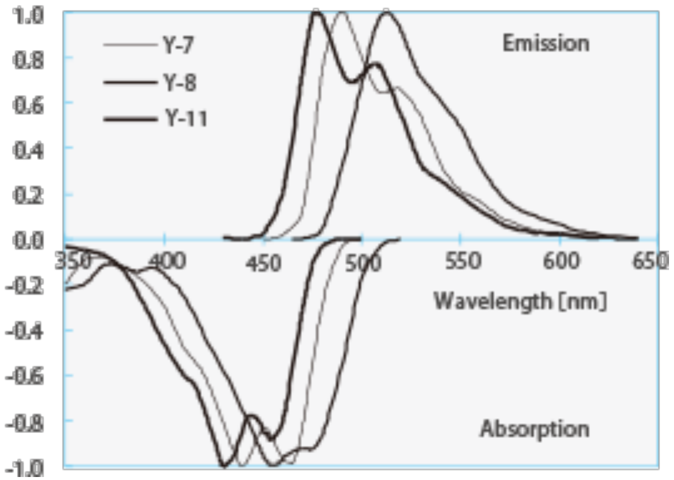
- ■ With reflective layer
- ● Without reflective layer

Two kinds of WLS fiber

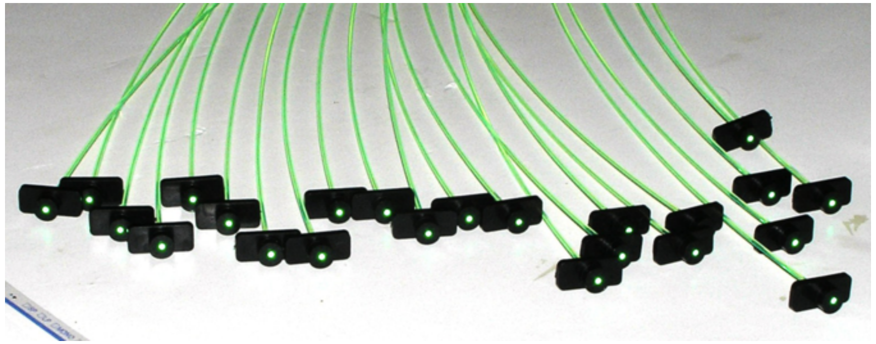
- Wavelength-shifting fibers



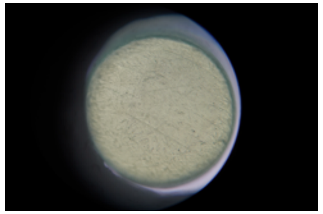
Saint-Gobain WLS Fiber
1.0mm Dia.



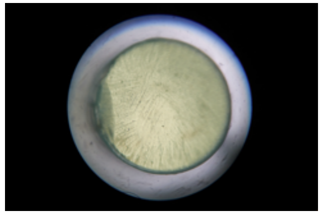
Blue to Green Shifter (Kuraray)



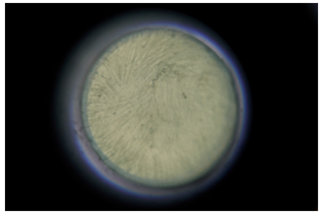
KURARAY WLS Fiber
Y-11(200)MSJ
1.2mm Dia.



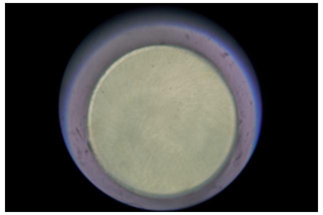
- File



- 1000 grit sandpaper



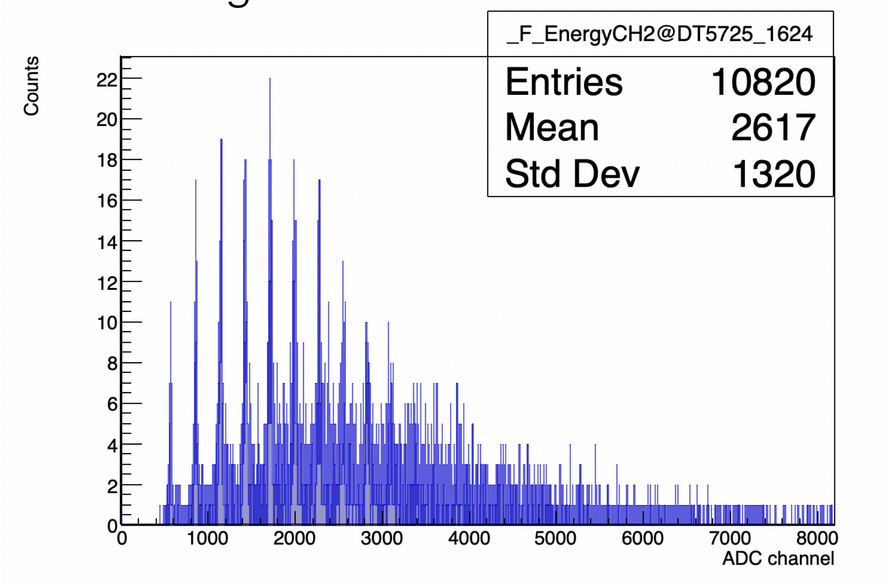
- 1500 grit sandpaper



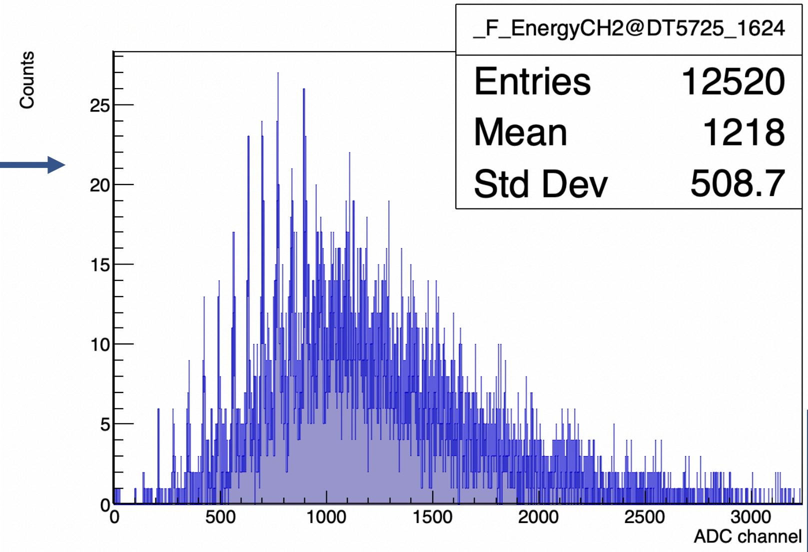
- 2000 grit sandpaper

Comparison of two WLS fibers

Choosing better fiber



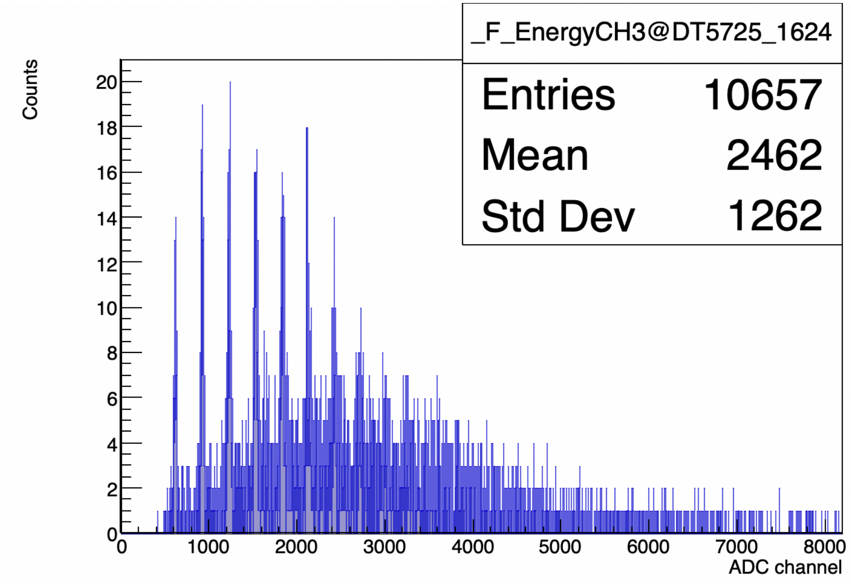
SD#1



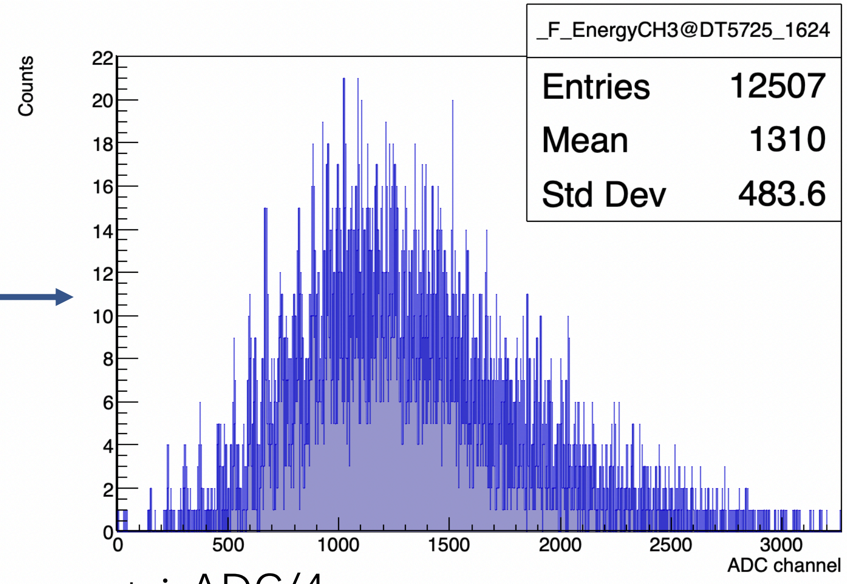
Better light yield

Left：saint_gobain
Right：kuraray

scintillator：150cm



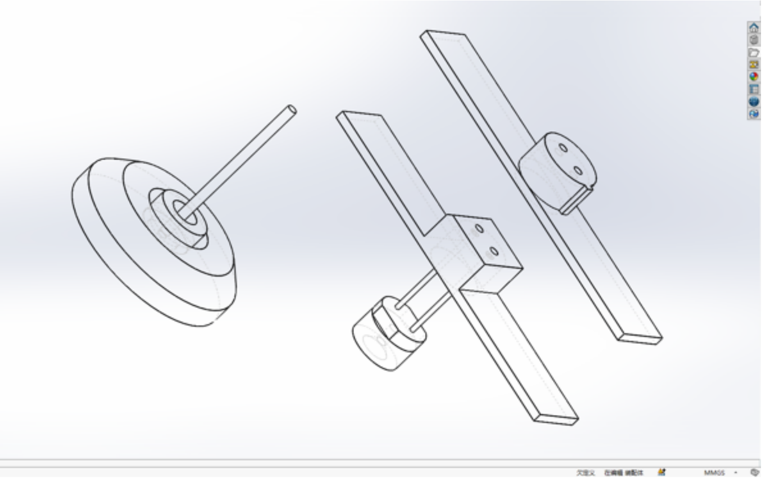
SD#2



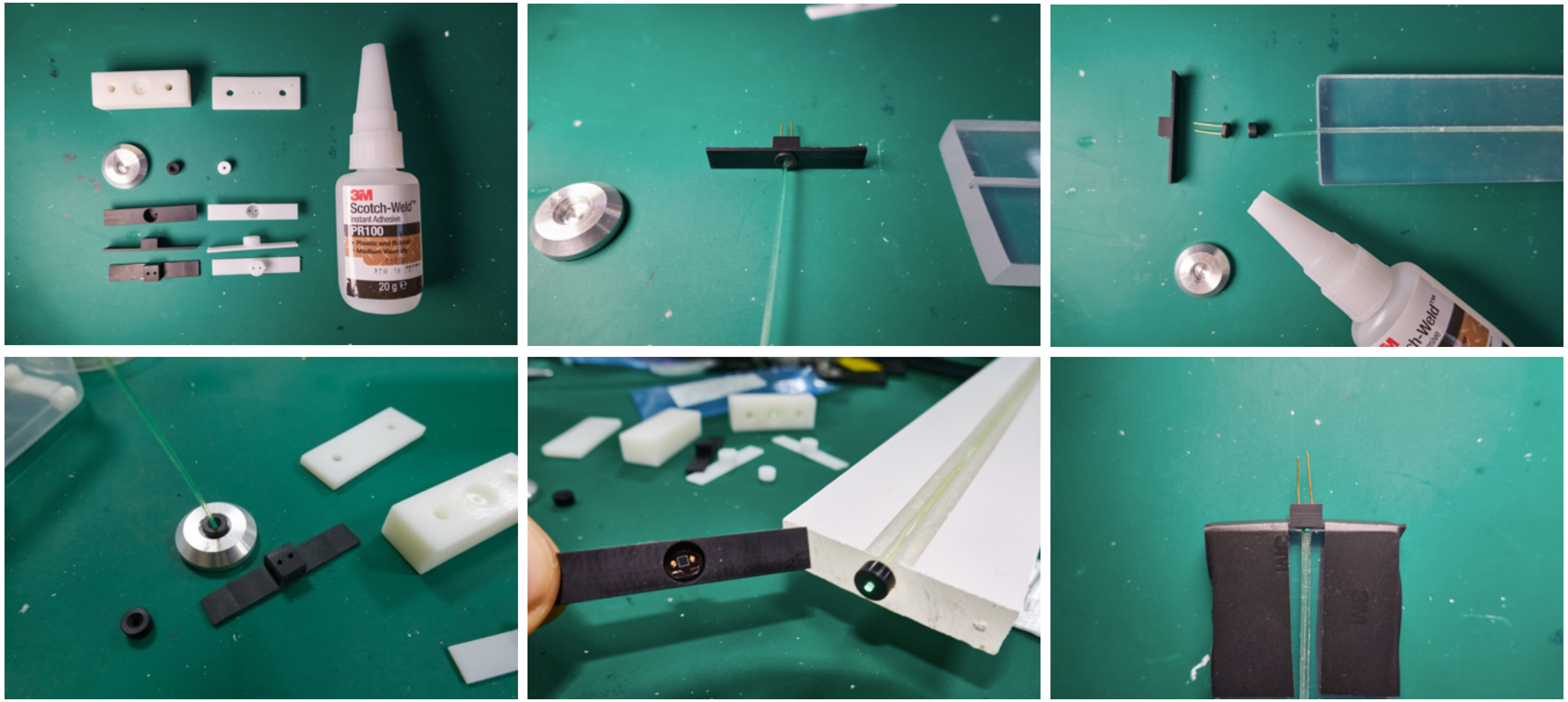
*：ADC/4

Coupling between SiPM and fiber

➢ Coupling of WLS fiber and MPPC



Design on SolidWorks



Easily and strongly connected

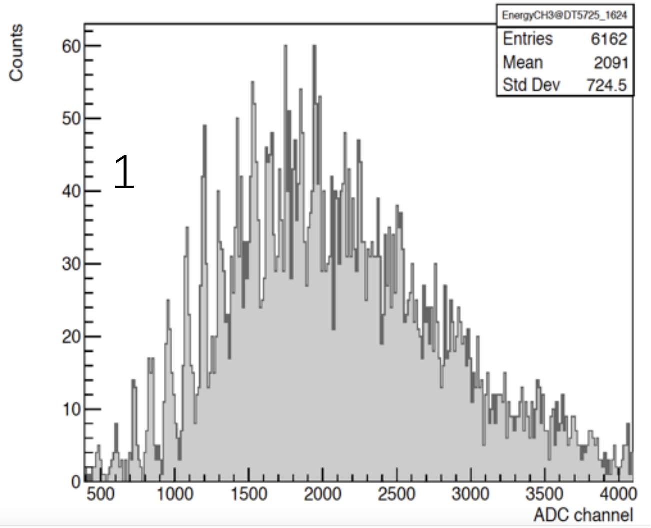
Scintillation detector

- Coupling between MPPC & fiber

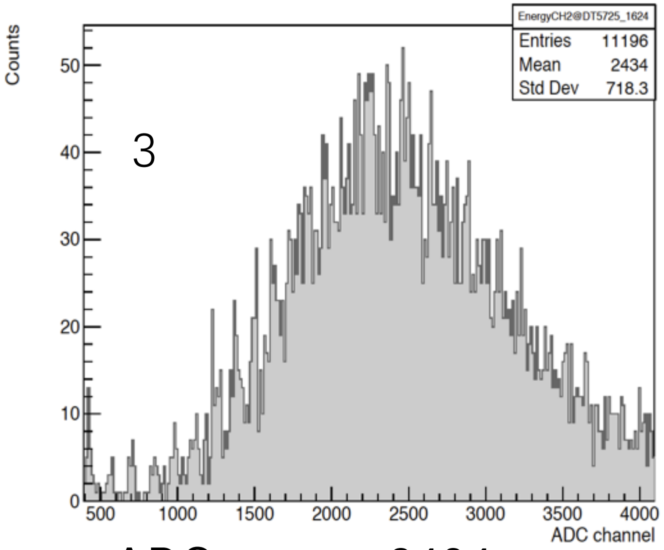
No.	Coupling	N3	N2	efficiency	error	ADC Mean * Entries
1	directly taped	237	243	97.53%	1.00%	12.8M
2	phenolic resin	225	236	95.34%	1.37%	21.5M
3	white new design (3D printing)	209	210	99.52%	0.48%	27.3M
4	black new design (CNC)	212	217	97.70%	1.02%	31.7M

Best choice

Trigger: ch2&ch4

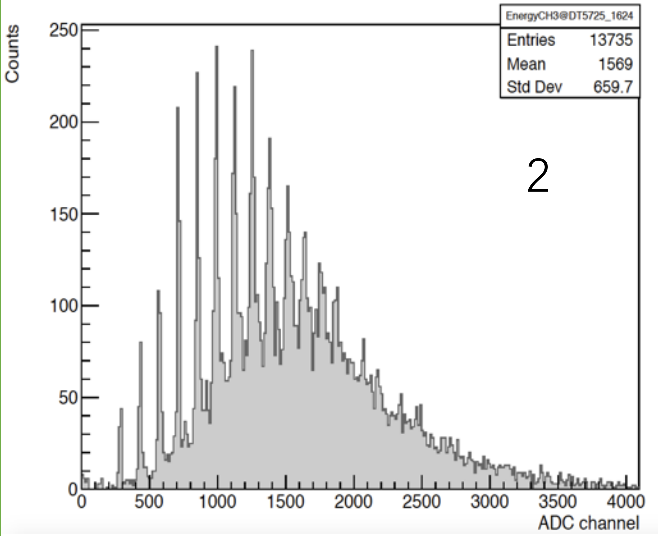


ADC mean : 2091

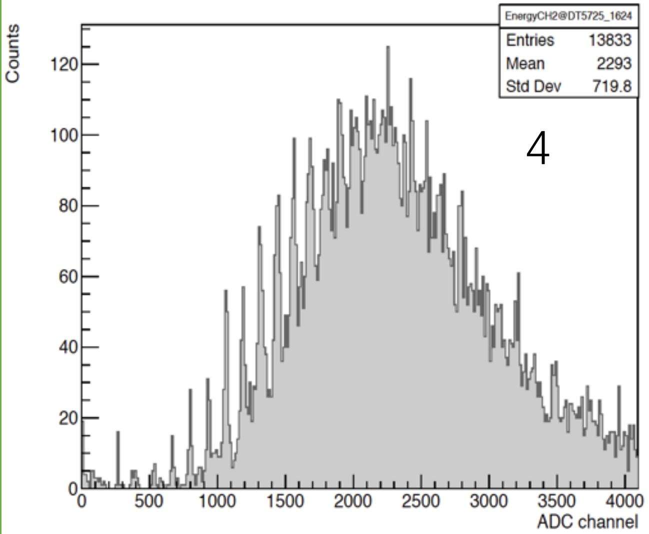


ADC mean : 2434

Trigger: ch1&ch3

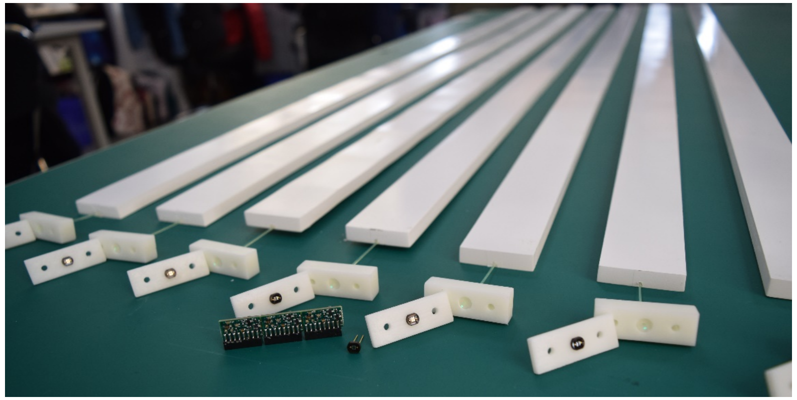


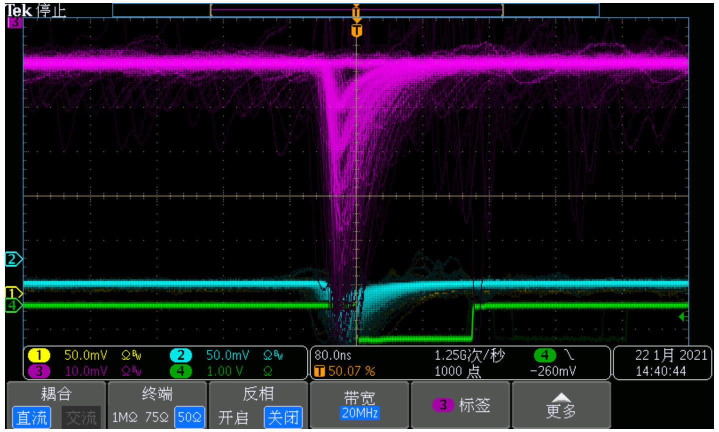
ADC mean : 1569



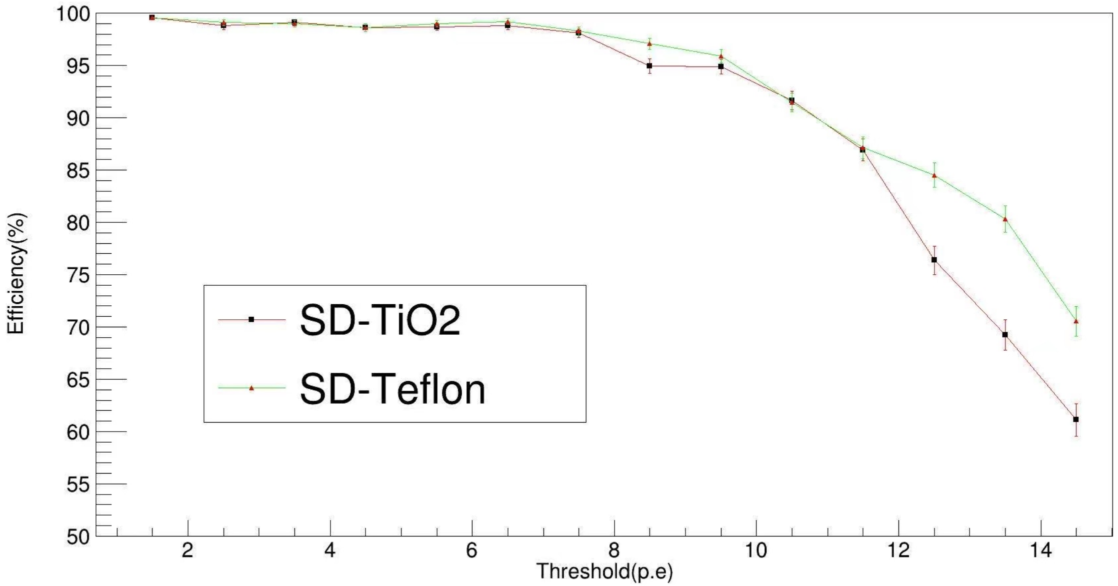
ADC mean : 2293

Performance of current Belle II KLM design

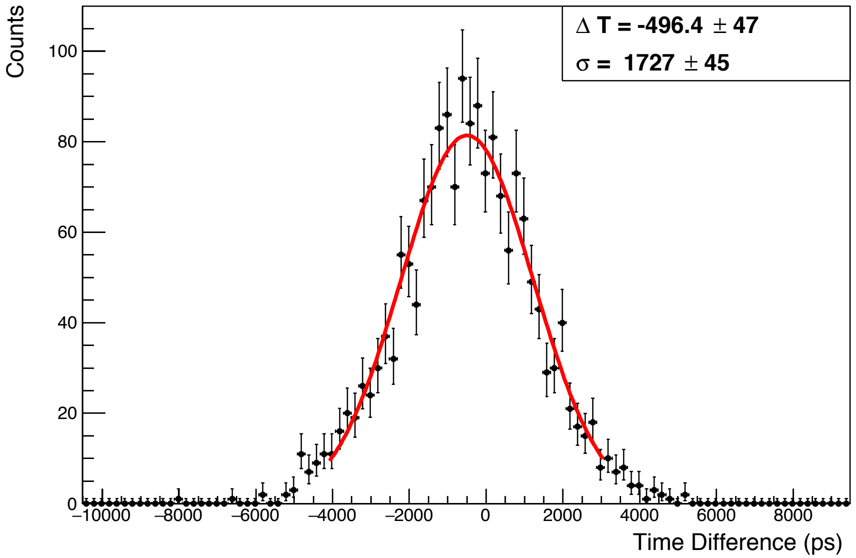




- CR testing with two strips
- High efficiency
- Time resolution: $< 1.5ns$

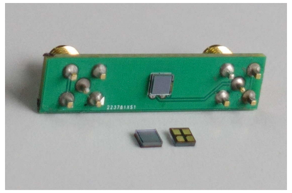


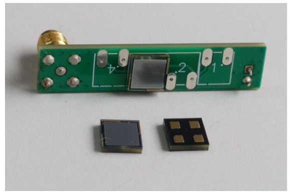
Keeping high efficiency at 10 p.e. threshold



Time difference of two channel

Using new NDL SiPM





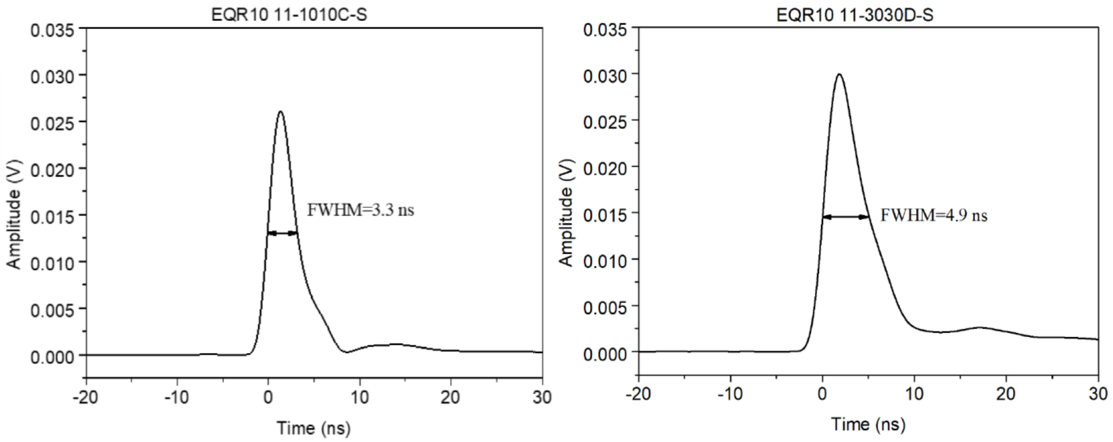
Specifications

Type	EQR10 11-1010C-S	EQR10 11-3030D-S
Effective Pitch	10 μm	
Element Number	1×1	1×1
Active Area	1.0×1.0 mm^2	3.0×3.0 mm^2
Micro-cell Number	10000	90000
Breakdown Voltage (V_B)	26.4 ± 0.4 V	28.5 ± 0.5 V
Temperature Coefficient for V_B	21 mV / °C	19 mV / °C
Recommended Operation Voltage	V_B + 6 V	V_B + 12 V
Peak PDE @420nm	32 %	36 %
Gain	2.0×10^5	1.7×10^5
Dark Count Rate (DCR)	500 kHz / mm^2	400 kHz / mm^2
Terminal Capacitance	7 pF	31 pF

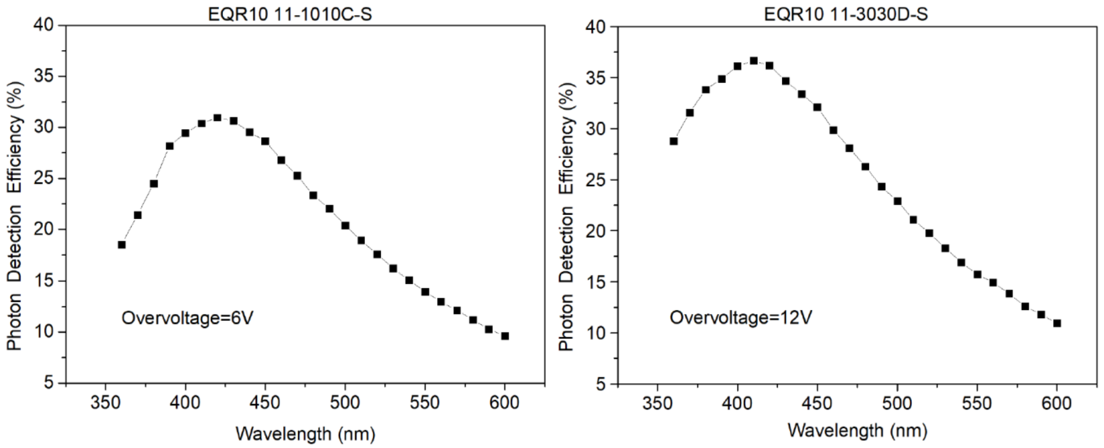
Above parameters are measured at their recommended operation voltage and 20 °C.

The EQR10 11-1010C-S can operate at 77 K.

Characteristics

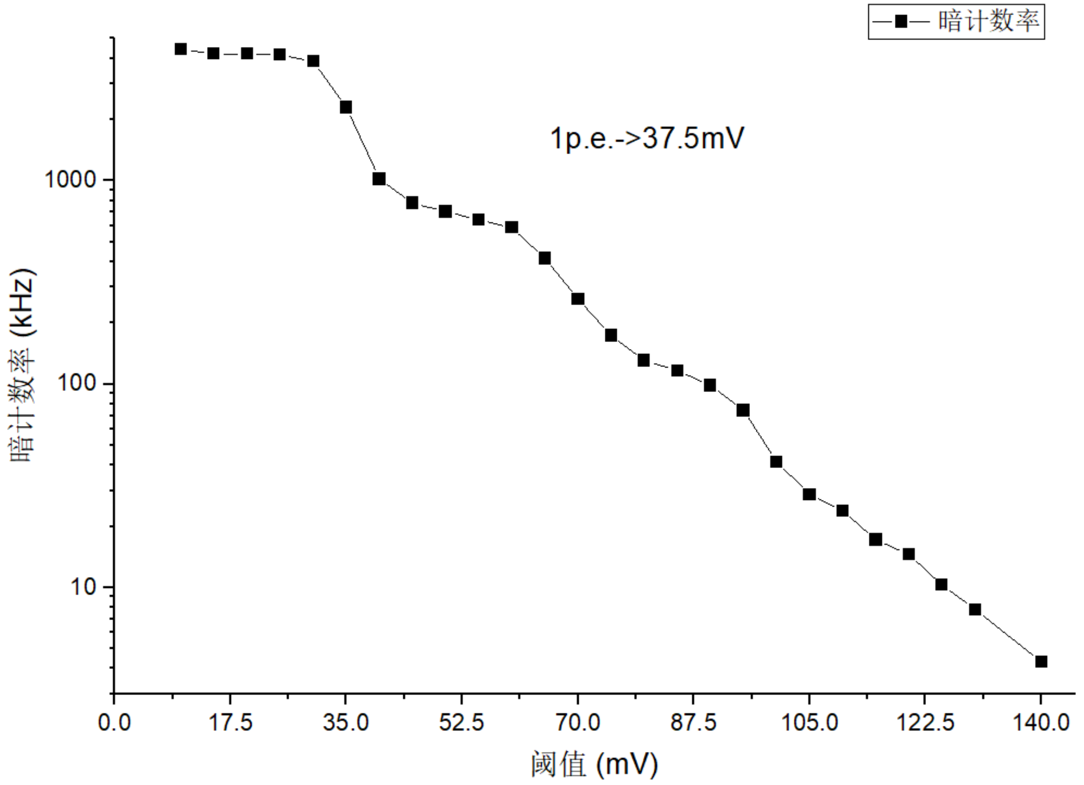


The single photoelectron pulse (amplified by a 40dB fast amplifier).



The PDE versus overvoltage and wavelength, deducted crosstalk and afterpulse and measured at 20 °C .

Dark Count Rate



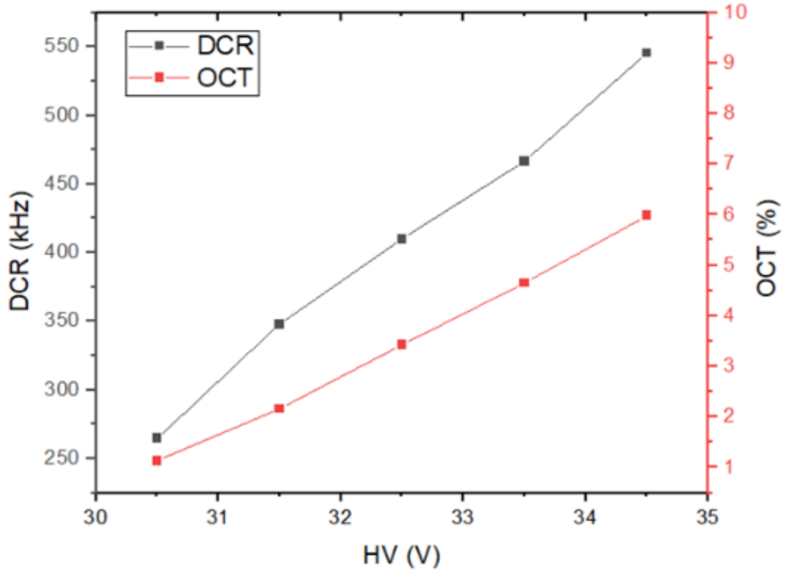
NDL-EQR15 At optical voltage

Single p.e. : 37.5mV

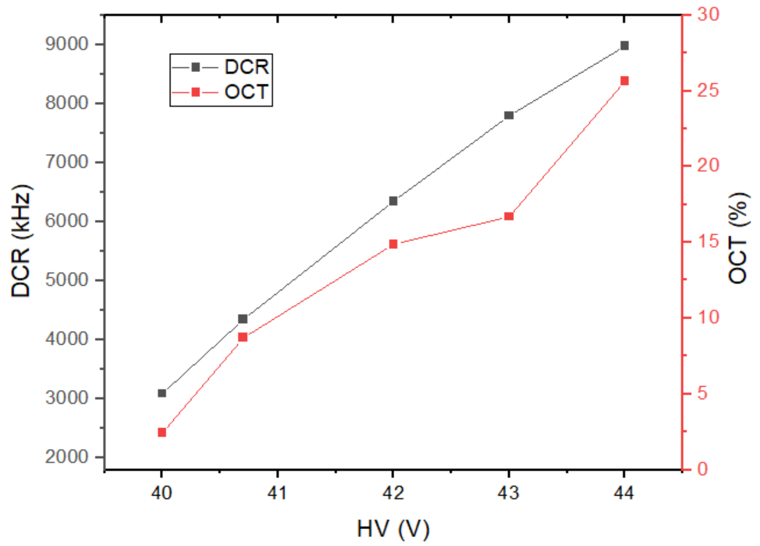
Threshold>6p.e. DCR<10 Hz
Threshold>7p.e. DCR<1 Hz

Test of new NDL SiPM

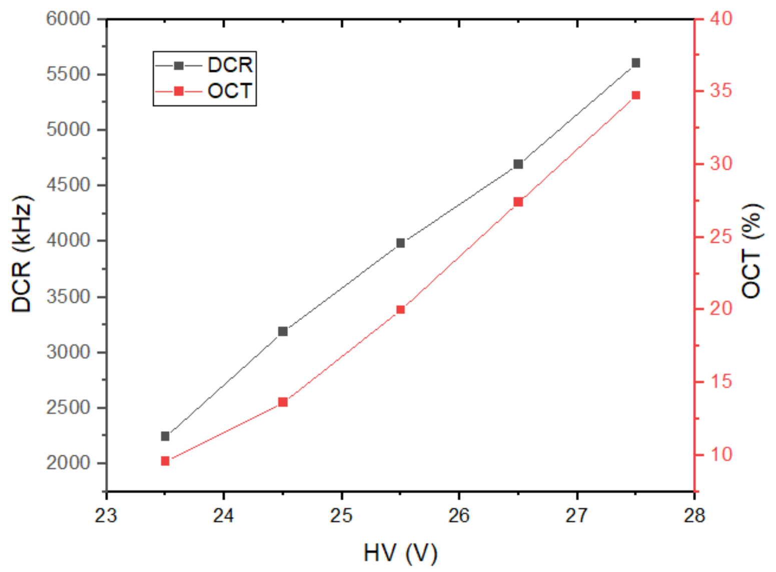
Dark Count Rate and optical crosstalk



EQR10 11-1010C-S



EQR10 11-3030



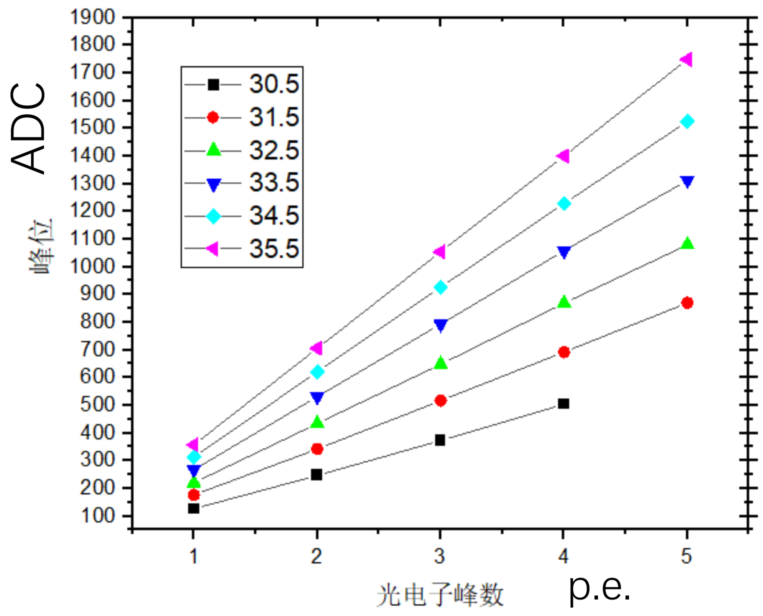
EQR15 11-3030D-S

At optical voltage,

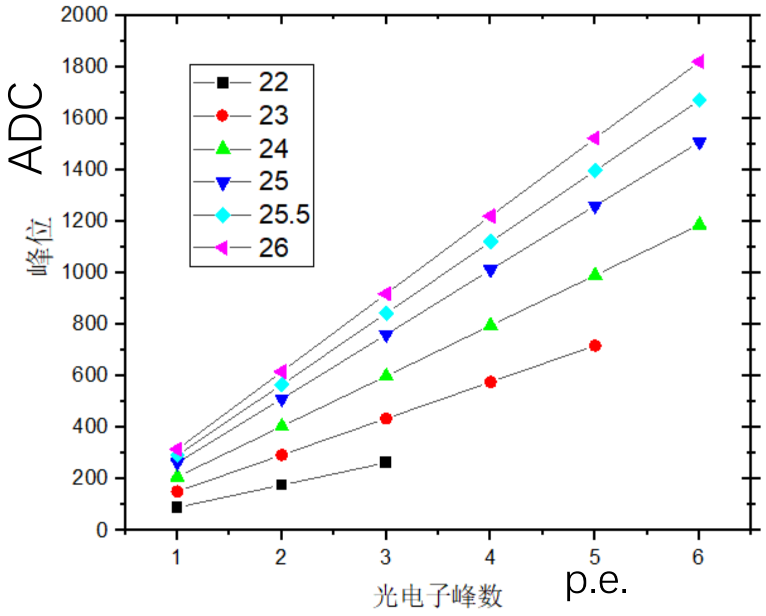
- the larger the pixel spacing (the fewer the number of pixels), the lower the DCR;
- the larger the sensitive area, the higher the DCR and OCT.

Test of new NDL SiPM

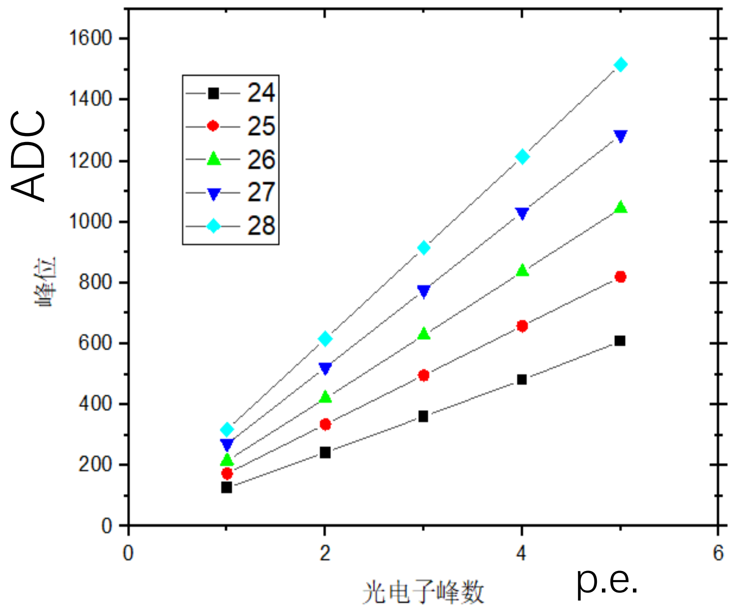
Gain



EQR10 11-1010C-S



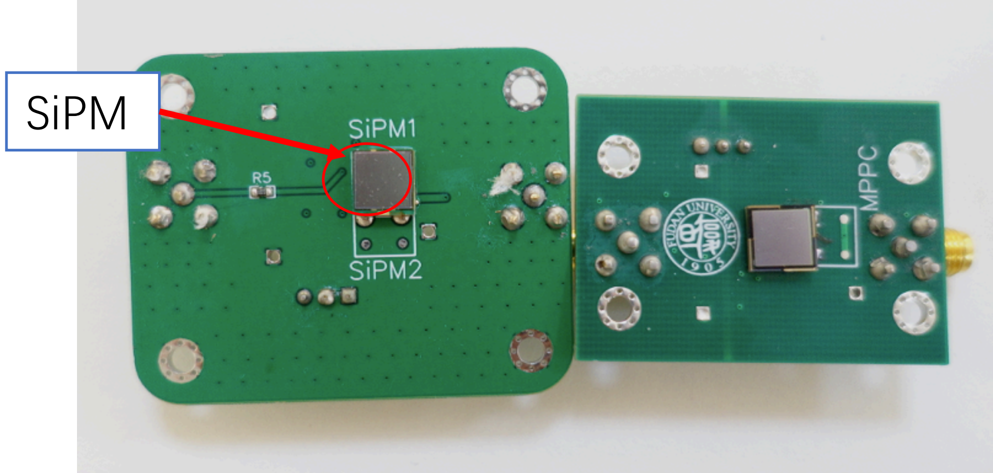
EQR10 11-3030D-S

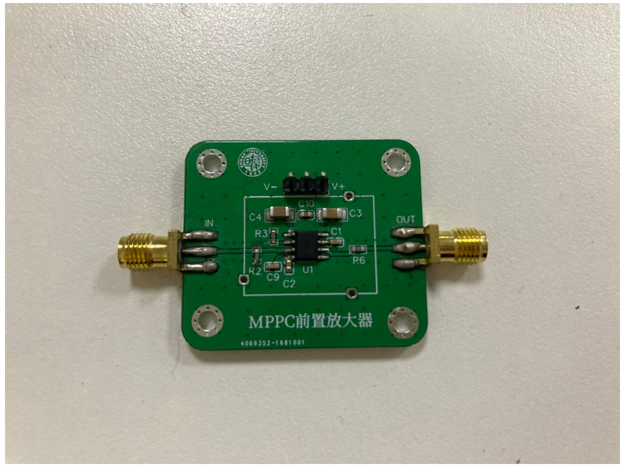


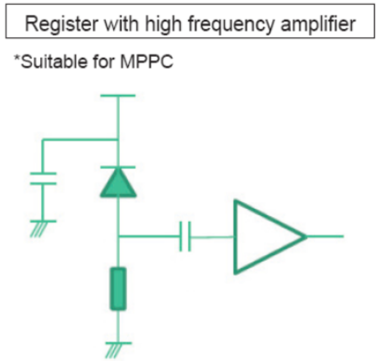
EQR15 11-3030D-S

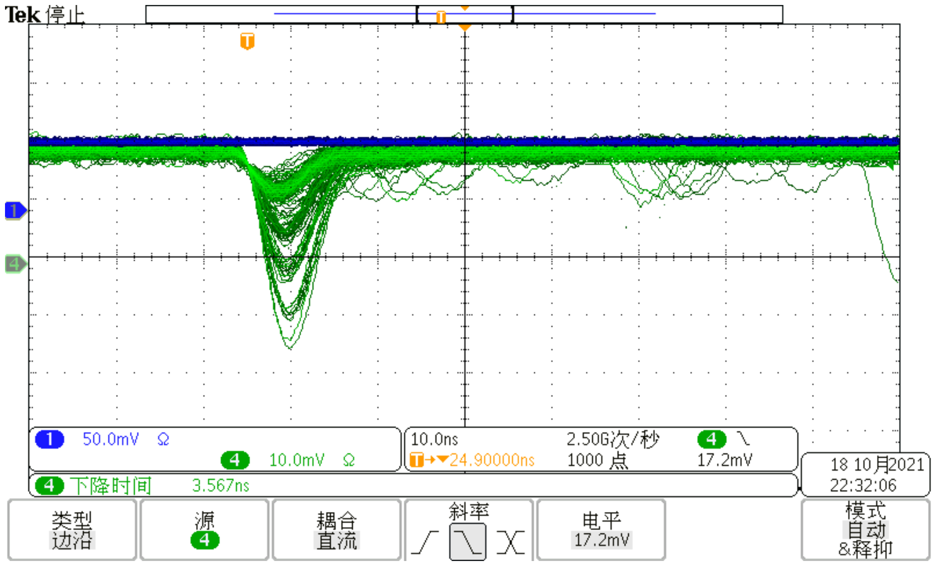
- Independent, equally spaced peaks.
- The higher the HV, the larger the gain.

New design on the FE and NDL SiPM

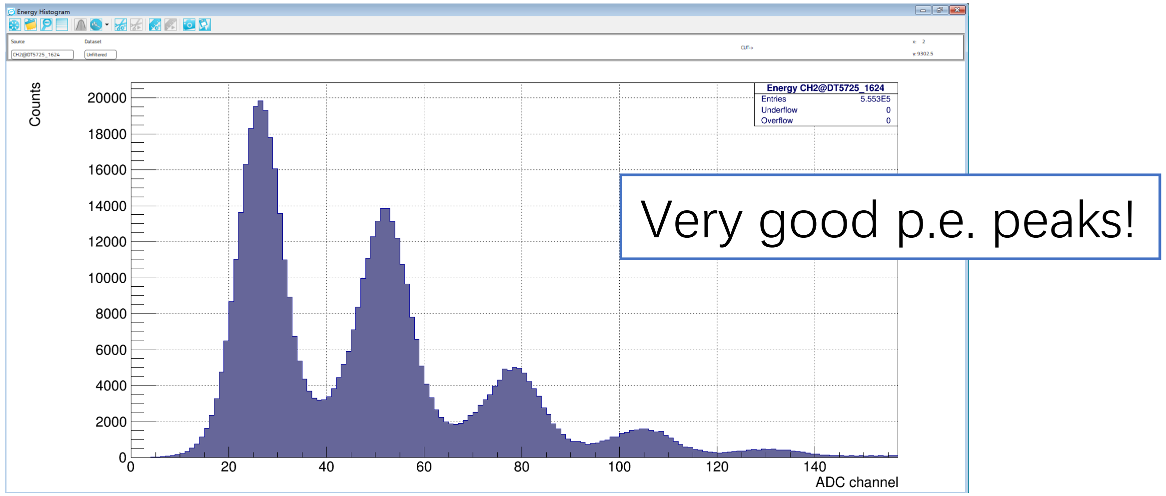








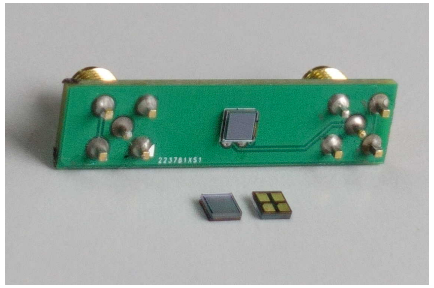
Rising time: ~3.5 ns!

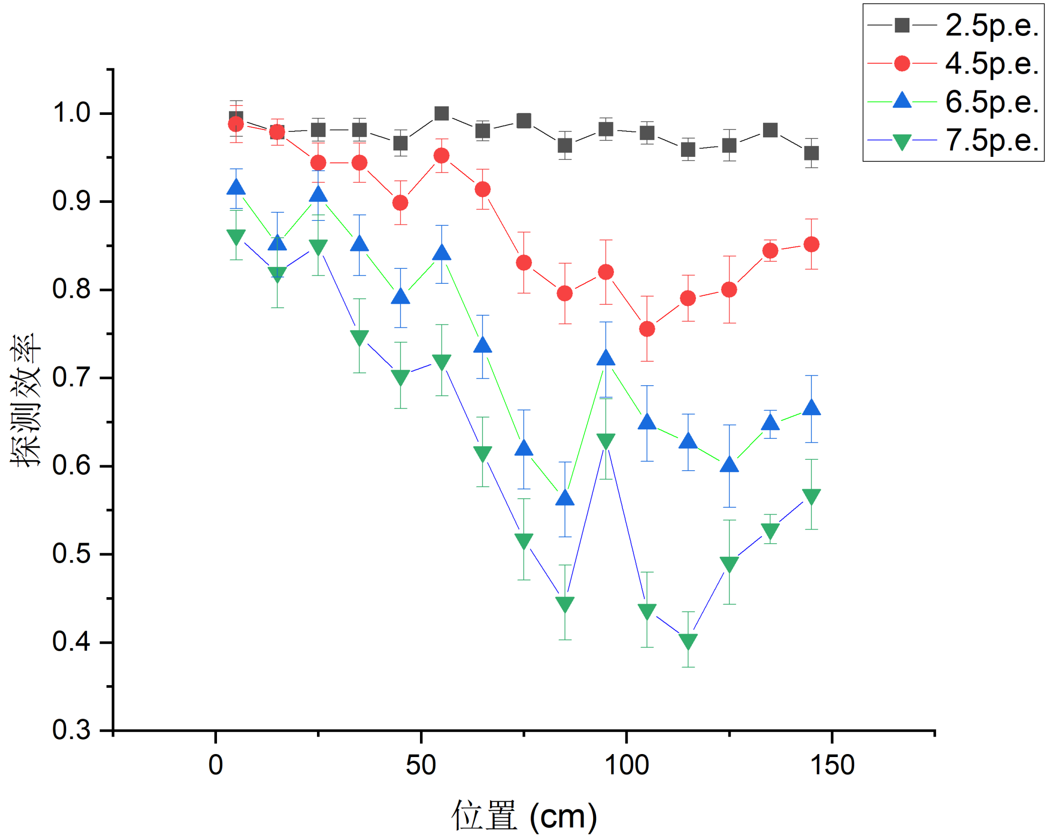


The preams are tuned at FDU for different kinds of SiPMs.

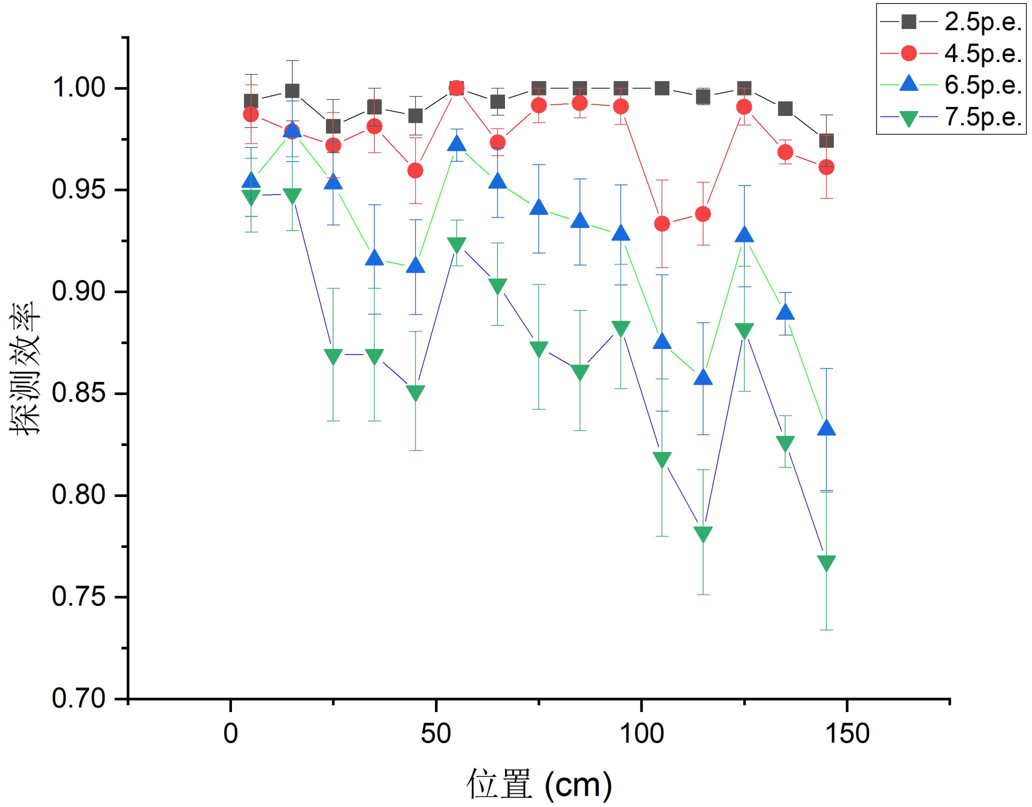
Efficiency of new design

- The efficiency is high enough.
- Still needs improvement on coupling, light collection, etc.



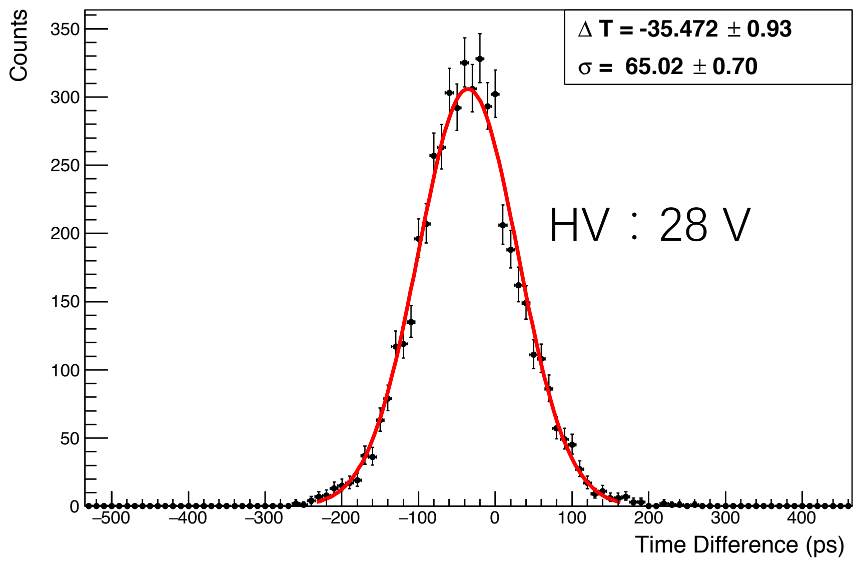


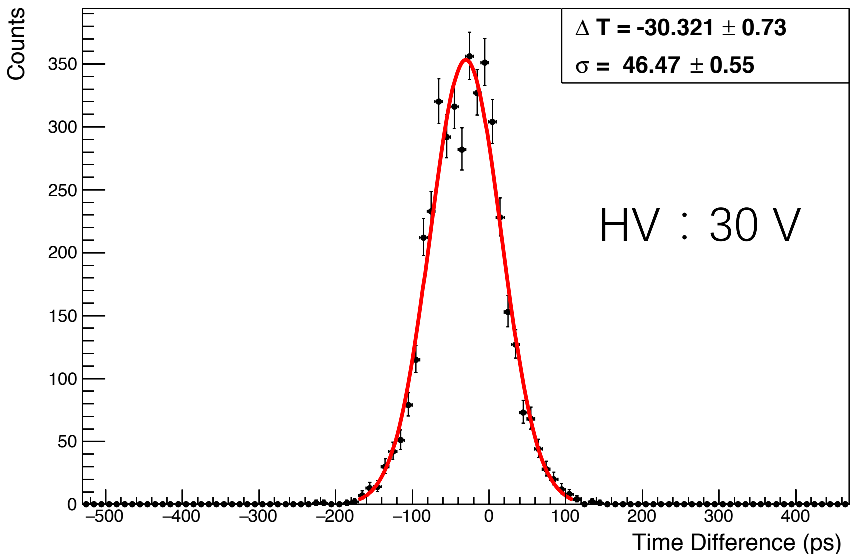
W/o optical glue

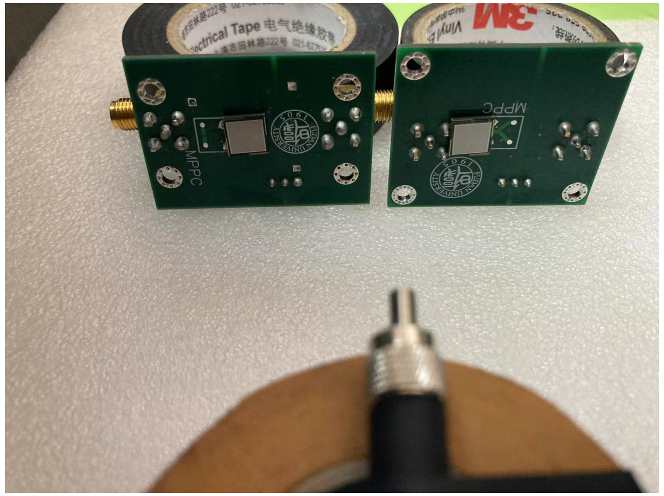


With optical glue

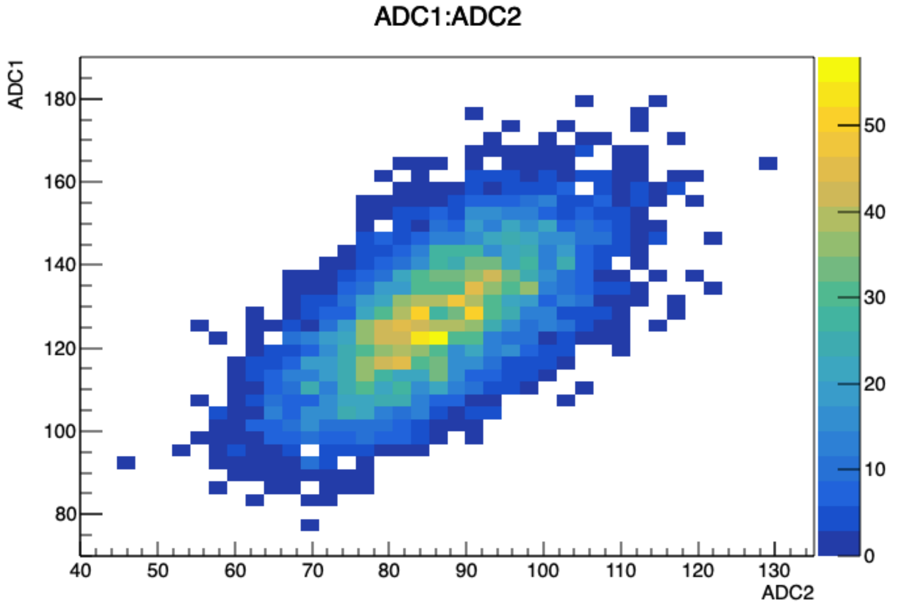
Time resolution: SiPM with $6mm \times 6mm$

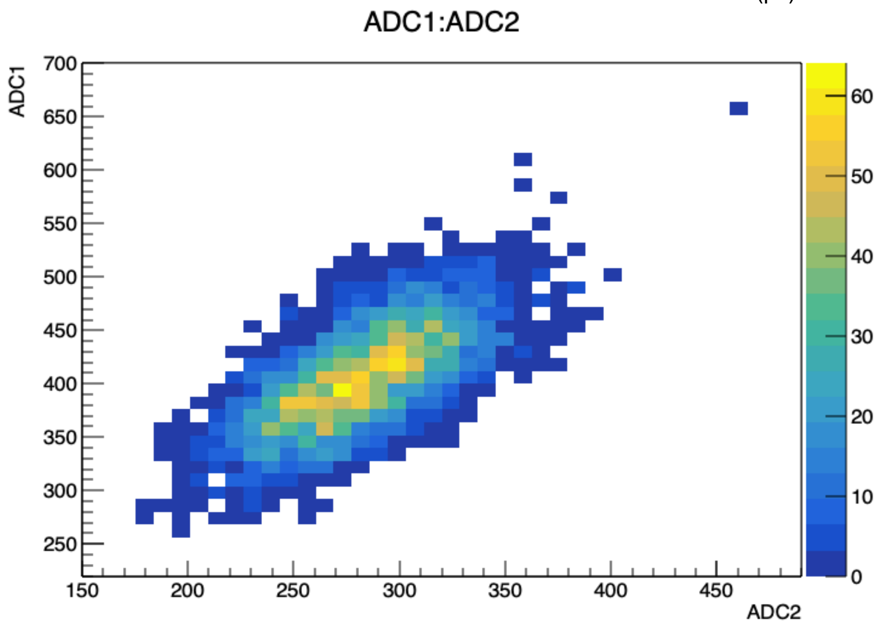






Keep laser constant



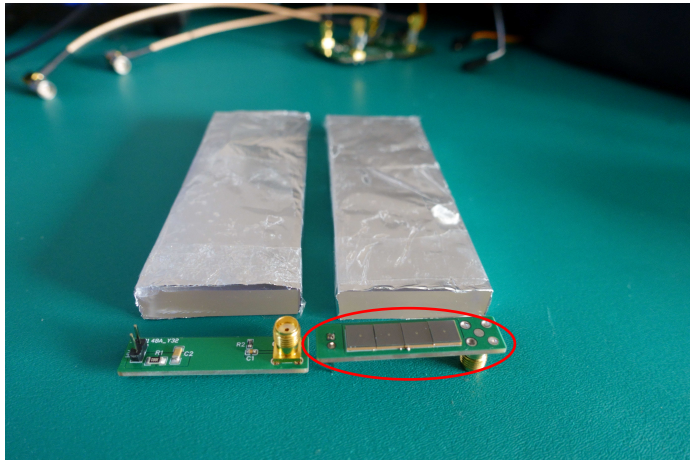


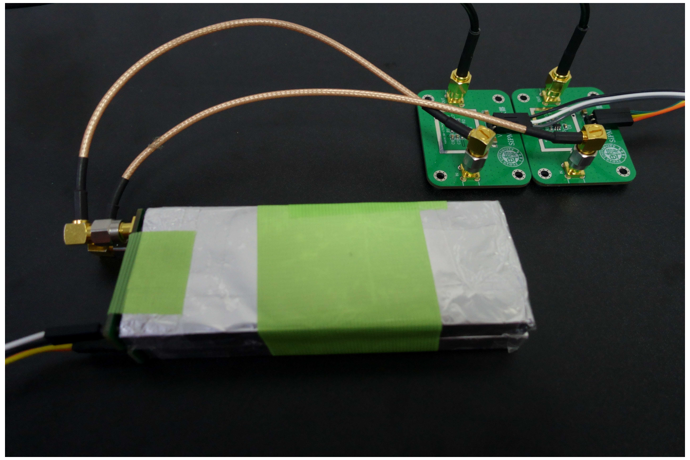
HV/ V	Pedestal	ADC	σ of time difference
28	1.2	140，90	65
30	2.9	400,270	46

Time resolution = $\sigma/\sqrt{2}$

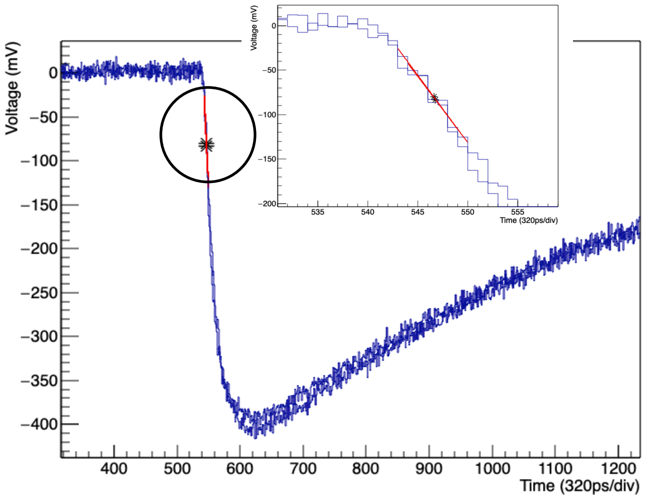
New design for good timing

Scintillator+4SiPMs+new pream

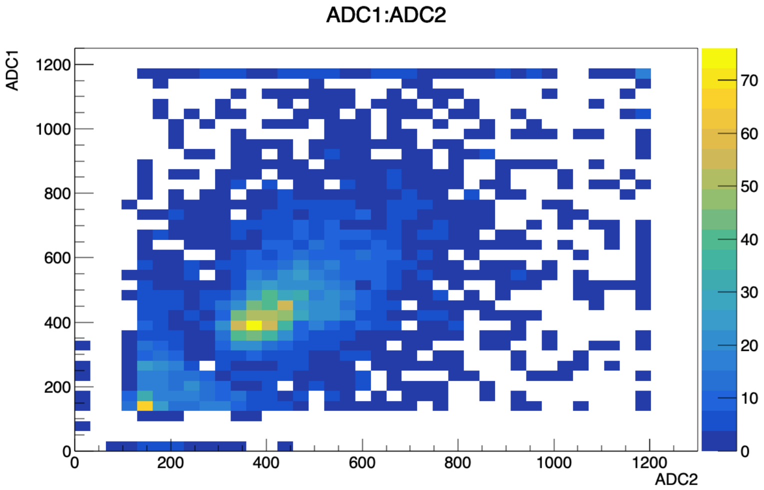


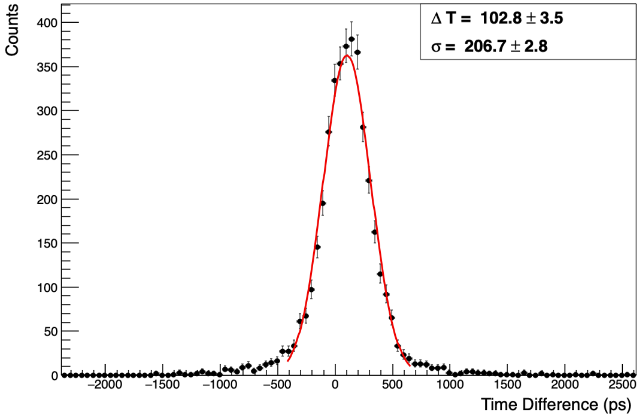


Two strips: $4cm \times 1cm \times 10cm$

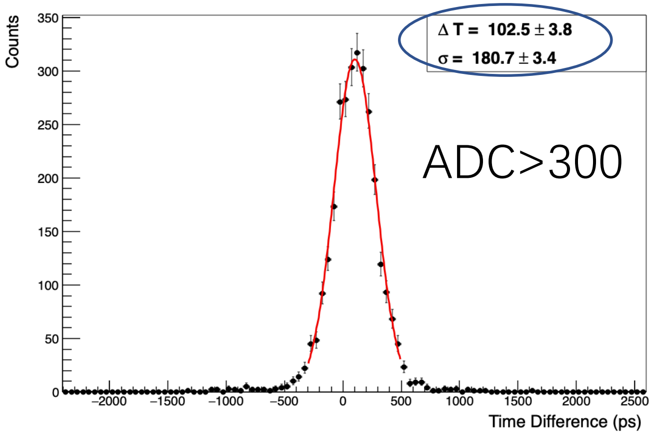


Pulse shapes





Time resolution: (146.2±2.0) ps



(127.8±3.0) ps

Summary

- Detector simulation is ongoing, and will be implemented into CEPCSW.
- Good performance of the current KLM design for efficiency.
- Good performance of new NDL SiPM for gain, DCR, and efficiency.
- Fast preamplifier is designed for much better time resolution.
- Time resolution of about $130ps$ has been obtained with short strips.

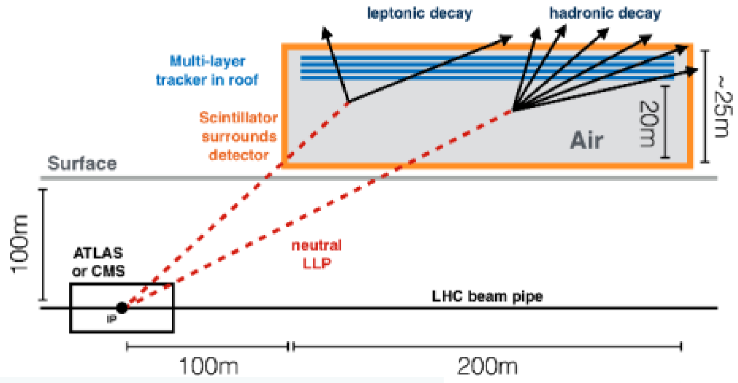
Thank you!

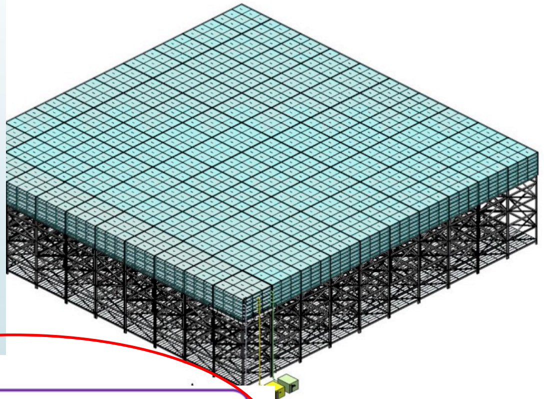
Back up

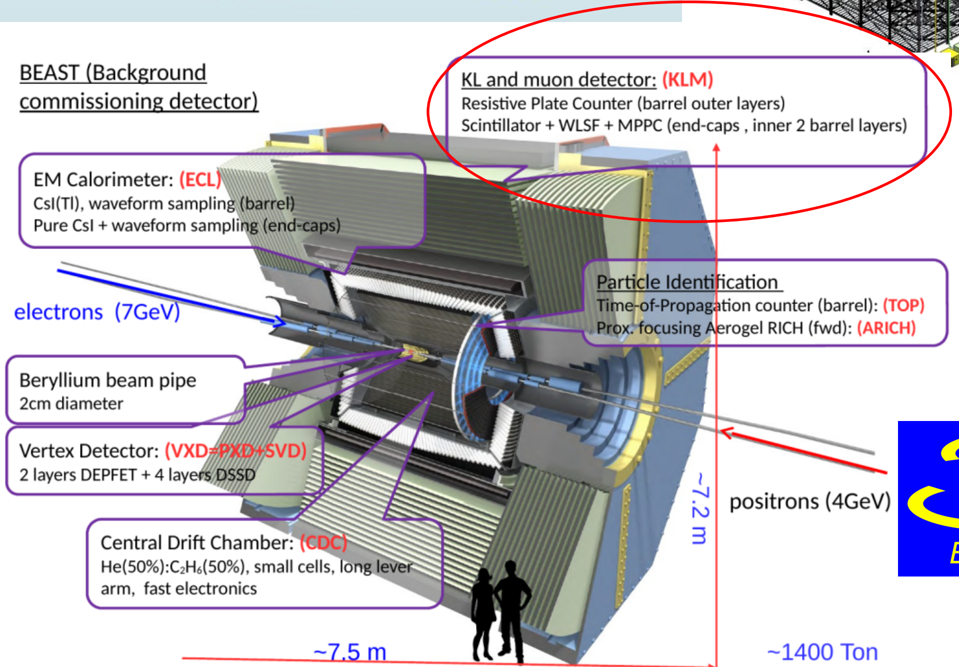
For reference

Scinti + SiPM

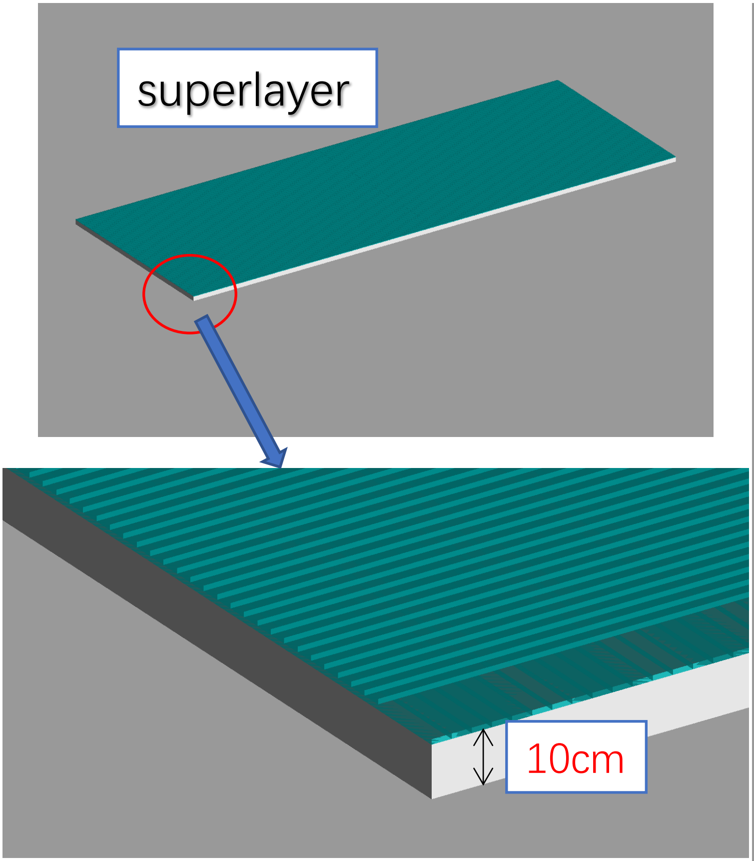
- MUTHUSLA experiment
  - Large size detector based on scintillator to search for long-live particle
  - Institutions: SLAC, Fermilab…
- Belle II experiment: L = 10^{36} $cm^{-2}s^{-1}$
  - Belle II started physics running on 11/3/2019
  - Endcap and inner 2 barrel layers: RPC → Scintillator
  - Good performance achieved
  - Belle II is considering the upgrade: all the barrel RPC → scintillator; new readout system
  - Institutions: Fudan U., U of Hawaii, Virginia Tech, …
- Helpful for R&D, testing, production, price…
- SiPM is becoming popular

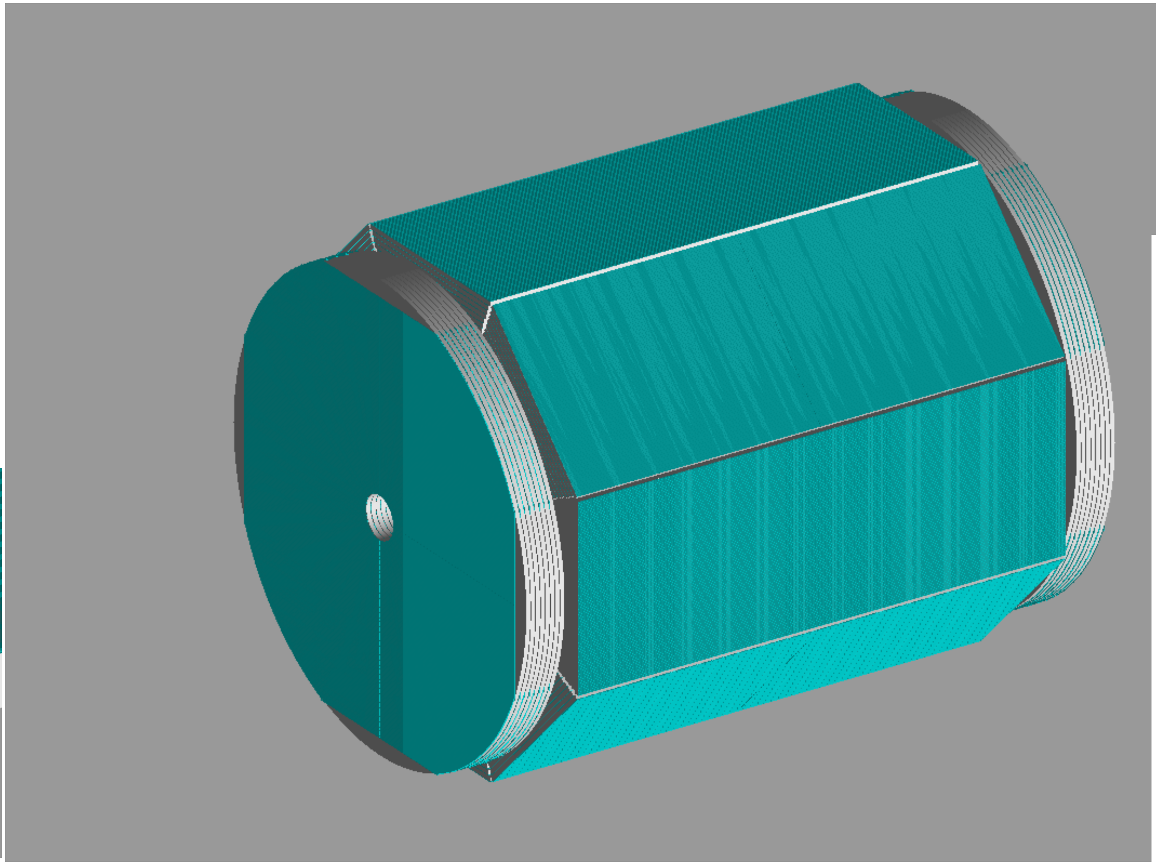






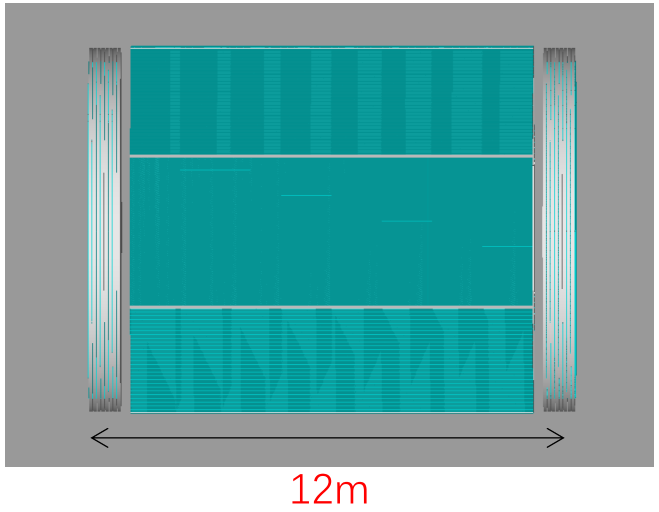
Belle II

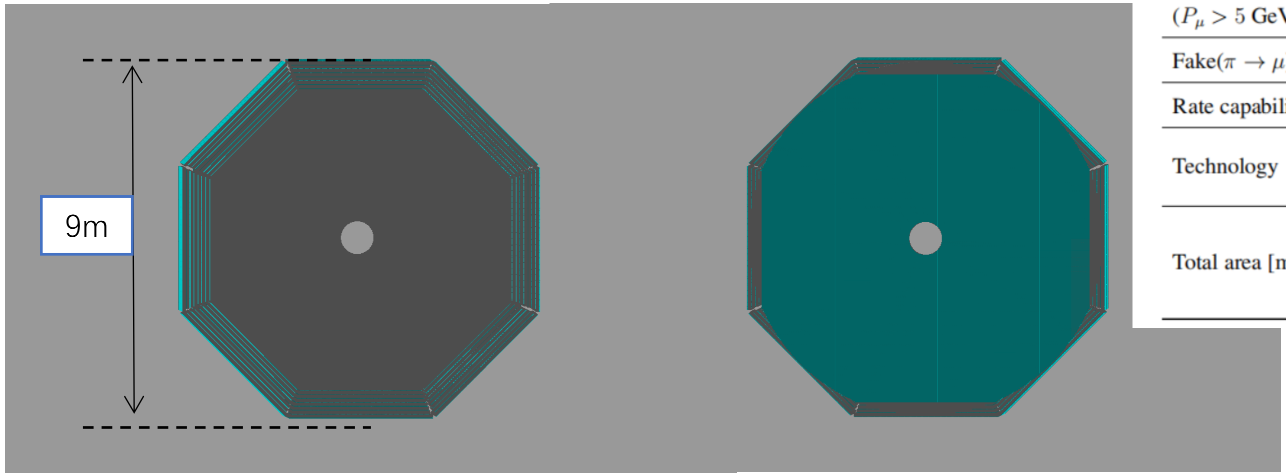




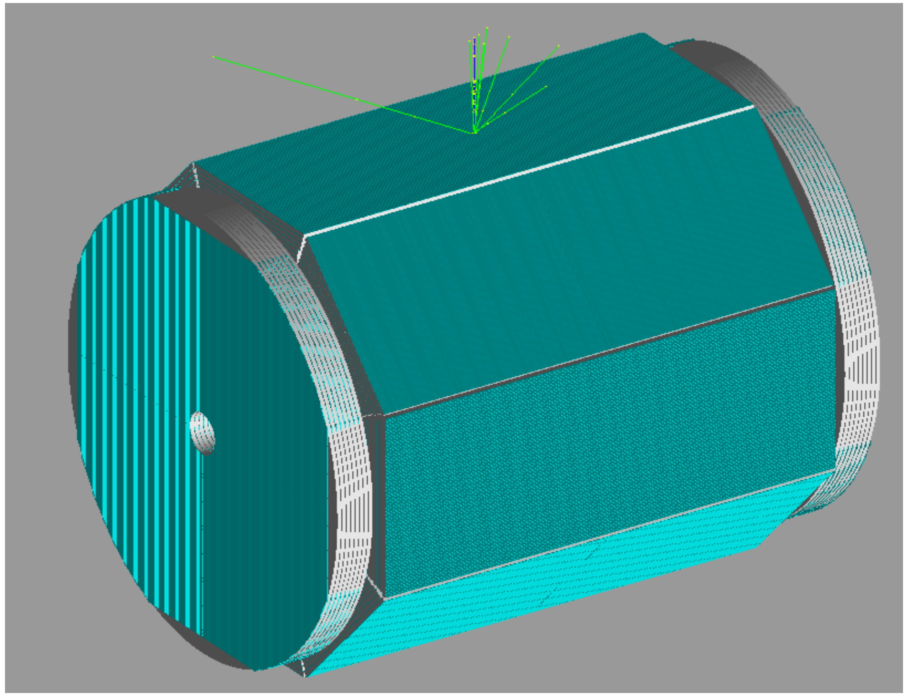
CEPC CDR 2018

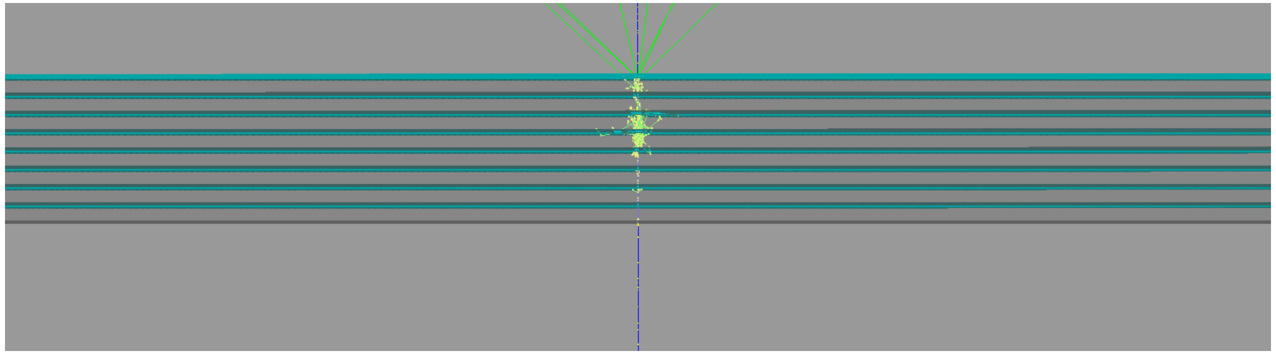
Parameter	Baseline
$L_b/2$ [m]	4.14
R_{in} [m]	4.40
R_{out} [m]	6.08
L_e [m]	1.72
R_e [m]	0.50
Segmentation in ϕ	12
Number of layers	8
Total thickness of iron (λ = 16.77 cm)	6.7λ (112 cm) (8/8/12/12/16/16/20/20) cm
Solid angle coverage	0.98 $\times 4\pi$
Position resolution [cm]	$\sigma_{r\phi}$: 2 σ_z : 1.5
Time resolution [ns]	1 – 2
Detection efficiency ($P_\mu > 5$ 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





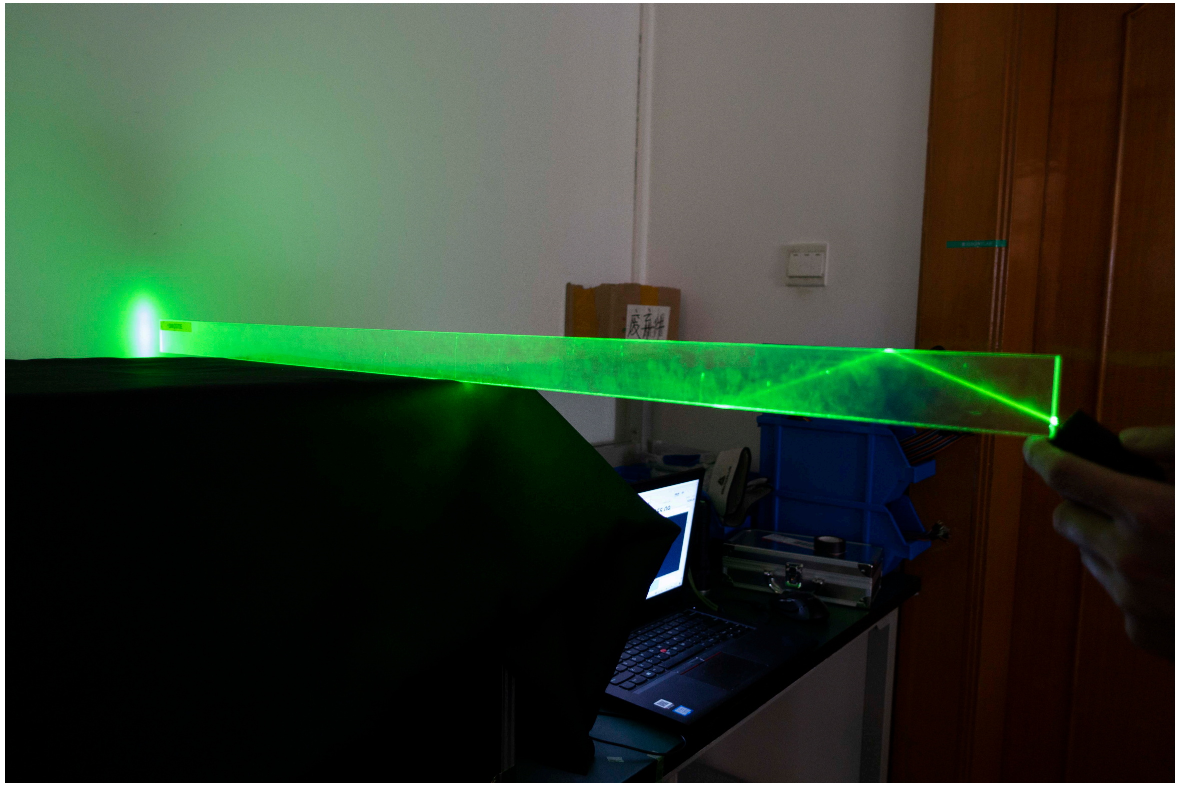
$40\ \mathrm{GeV}\ \mu^{\pm}$ hits





- Fast testing with $40\ \mathrm{GeV}\ \mu^{\pm}$ is performed.
- WLS fibre and SiPMs are not included yet.
- Plan:
  - A complete description of the scintillator-based muon detector.
  - Implementation into the CEPCSW.
  - Optimization according to CEPC physics goals.

Need new scintillator



New scintillator from Gaonengkedi Company.

- Longer attenuation length.
- Reasonable cost.
- Considering efficiency without fiber and reflective layer.
- New design for fast pream!

How about new NDL SiPM (Made in China)

Specifications

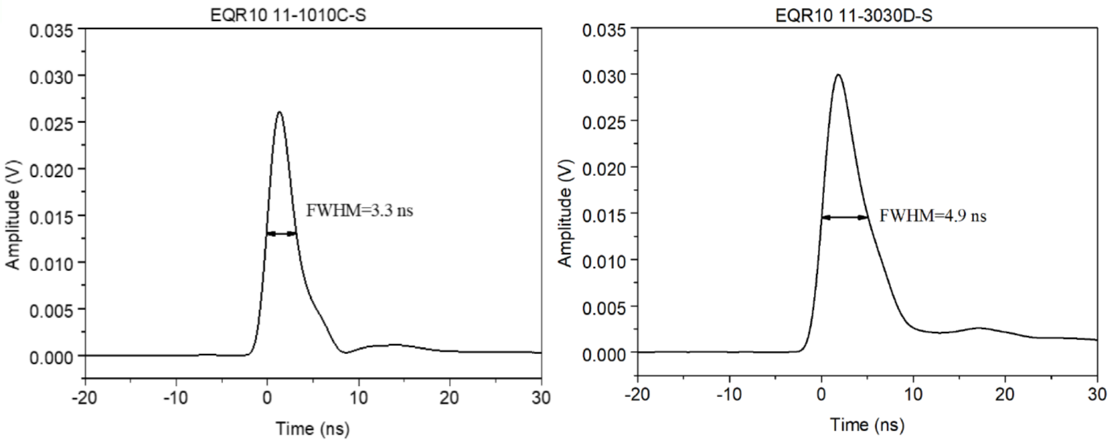
Type	EQR10 11-1010C-S	EQR10 11-3030D-S
Effective Pitch	10 μm	
Element Number	1×1	1×1
Active Area	1.0×1.0 mm^2	3.0×3.0 mm^2
Micro-cell Number	10000	90000
Breakdown Voltage (V_B)	26.4 ± 0.4 V	28.5 ± 0.5 V
Temperature Coefficient for V_B	21 mV / °C	19 mV / °C
Recommended Operation Voltage	V_B + 6 V	V_B + 12 V
Peak PDE @420nm	32 %	36 %
Gain	2.0×10^5	1.7×10^5
Dark Count Rate (DCR)	500 kHz / mm^2	400 kHz / mm^2
Terminal Capacitance	7 pF	31 pF

Above parameters are measured at their recommended operation voltage and 20 °C.

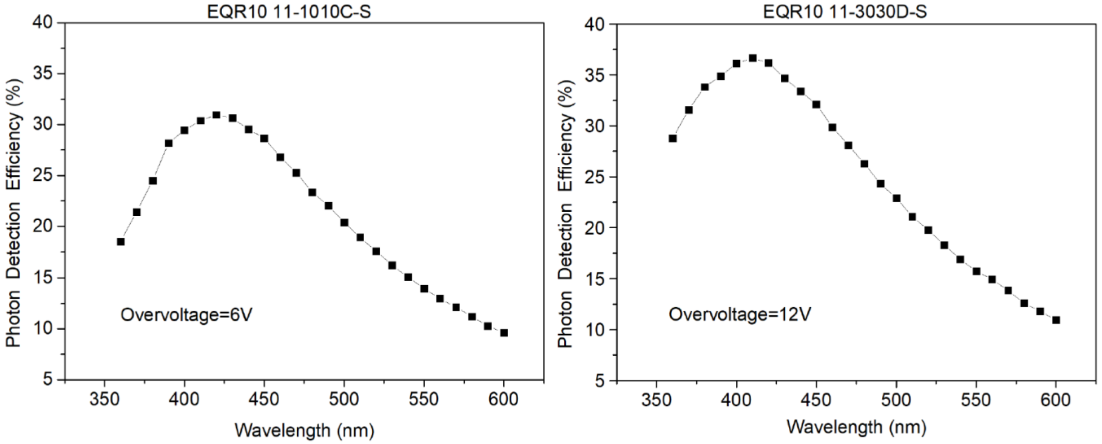
The EQR10 11-1010C-S can operate at 77 K.

Looks good.

Characteristics



The single photoelectron pulse (amplified by a 40dB fast amplifier).



The PDE versus overvoltage and wavelength, deducted crosstalk and afterpulse and measured at 20 °C .

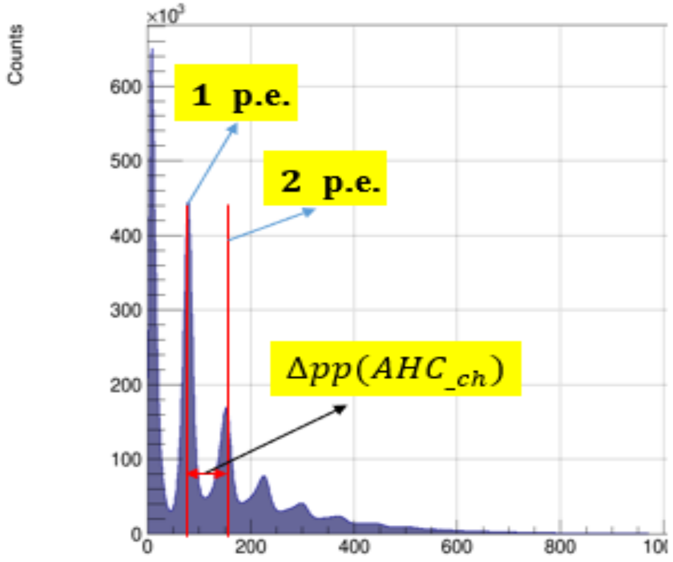
NDL性能测试——增益测量

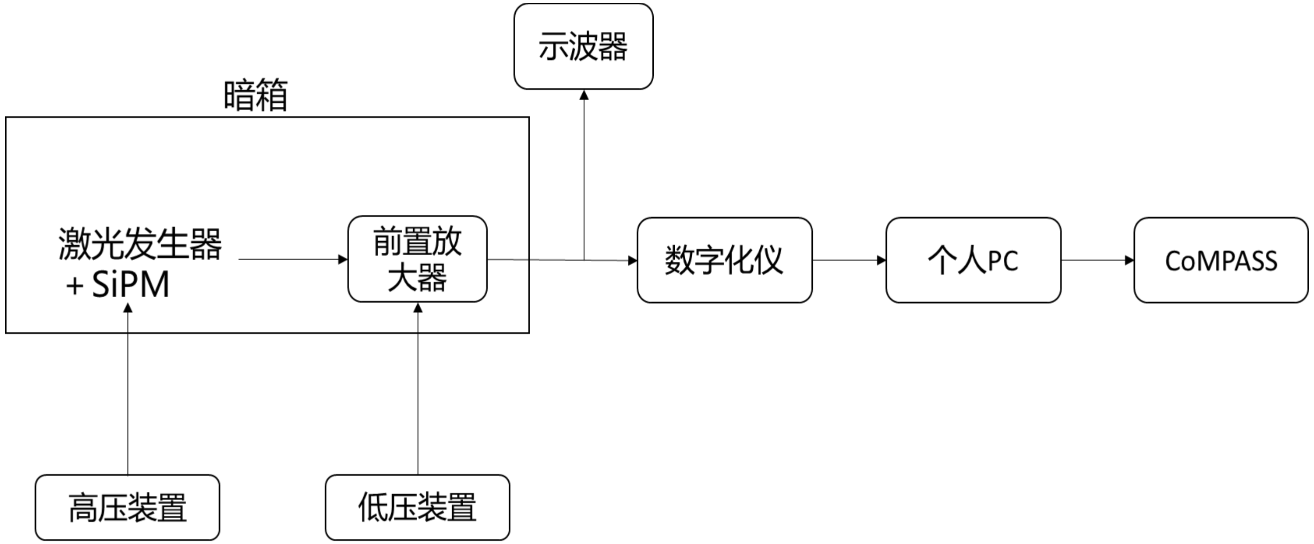
$$Gain = \frac{Q}{e} = \frac{(V_{op} - V_{br})C_{pixel}}{e}$$

$$Gain = \frac{\Delta pp(AHC_{\mathrm{ch}}) \times ADC_{c.r.}}{e}$$

$$\Delta pp(AHC_{ch}) = V_{op}\frac{C_{pixel}}{ADC_{c.r.}} - V_{br}\frac{C_{pixel}}{ADC_{c.r.}}$$

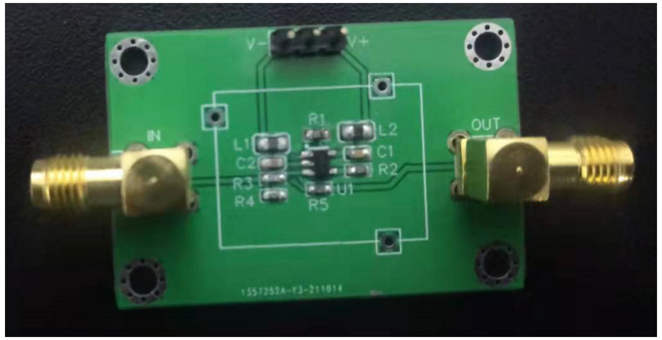
$\Delta pp(\mathrm{AHC_{ch}})$为输出电荷积分频谱中峰与峰之间的道数差；e为电子电量；$ADC_{\mathrm{c.r.}}$为ADC转换系数；n p.e. (photon equivalent)为由n个光子所引发的脉冲





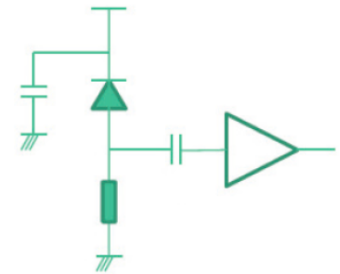
Design of fast preamplifier

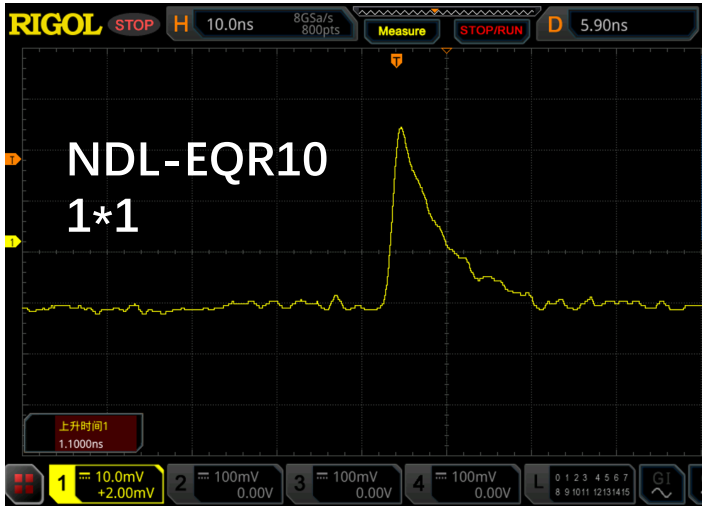
Resistor sampling and negative feedback amplifier circuit

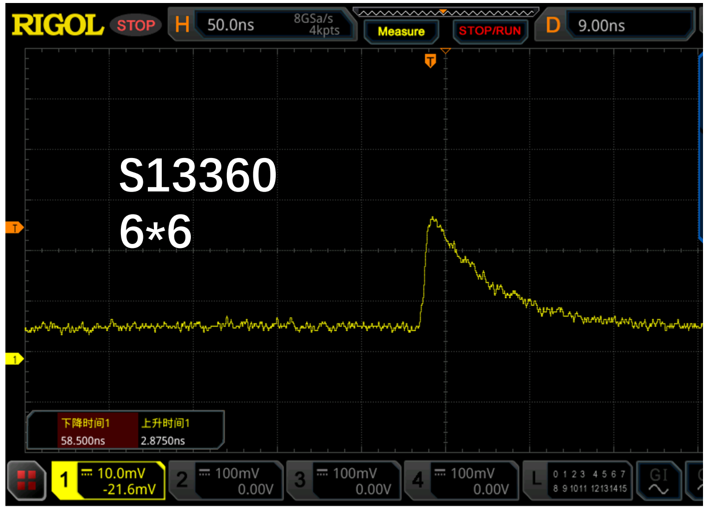


Register with high frequency amplifier

*Suitable for MPPC





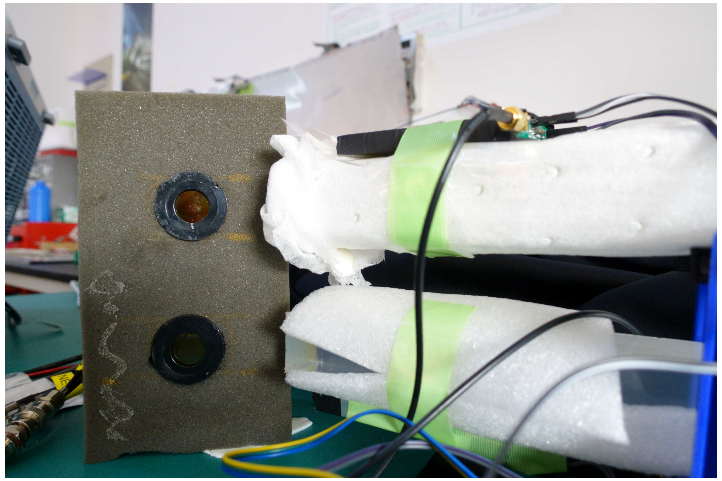


Rise time ：1-2ns
HWHM ：3-4ns

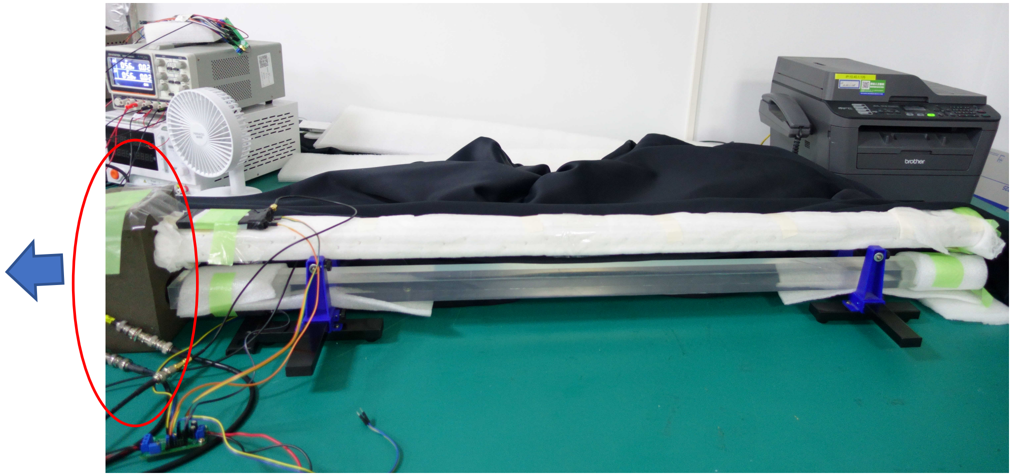
Rise time ：2-4ns
HWHM ：6-8ns

Rise time ：5-10ns
HWHM ：40-60ns

Testing with two long Santi-Gobain scintillators



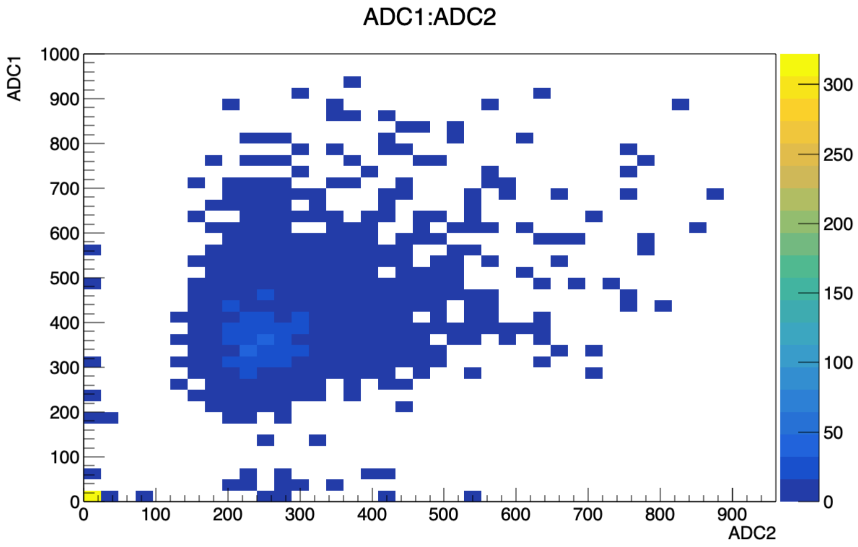
Two MCP-PMT

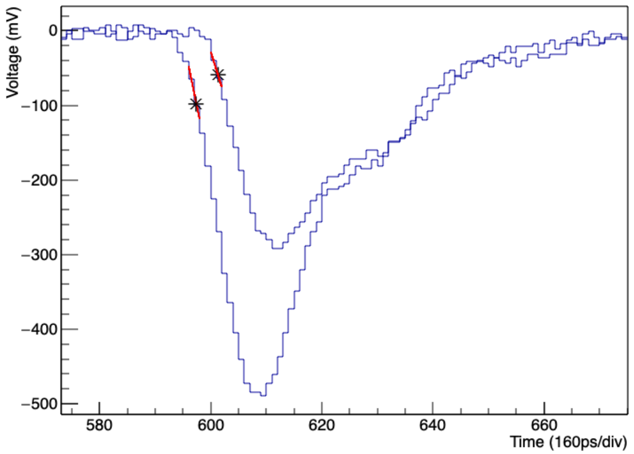


Trigger strips at near end: $4cm\times1cm\times10cm$

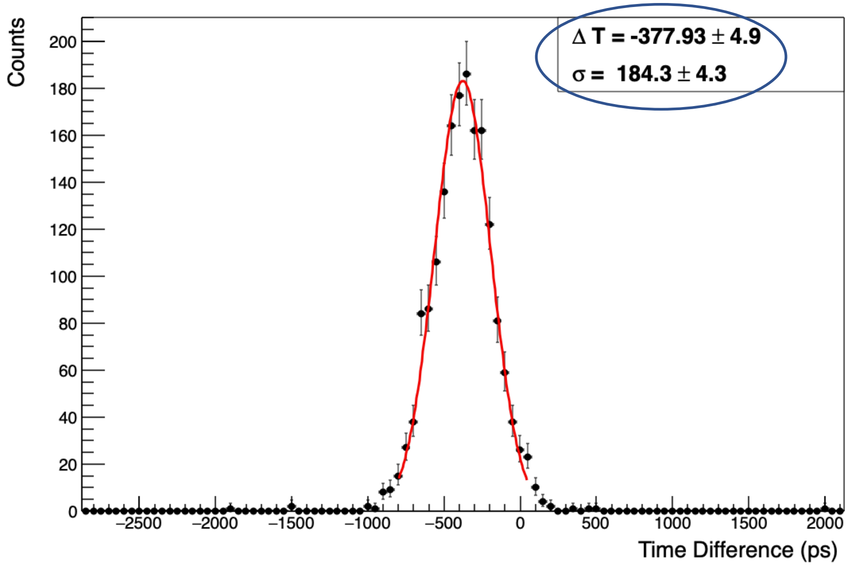
Two long strips from IHEP with excellent time resolution:

$3cm\times5cm\times1m$

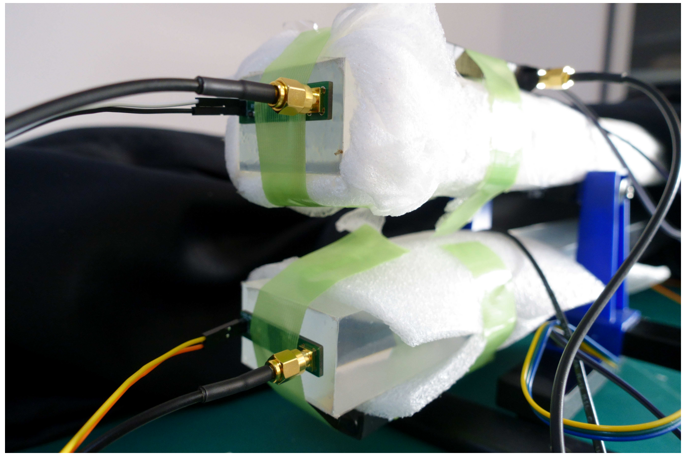


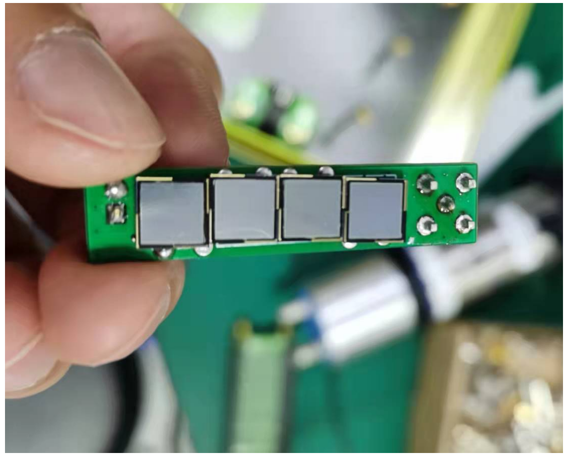


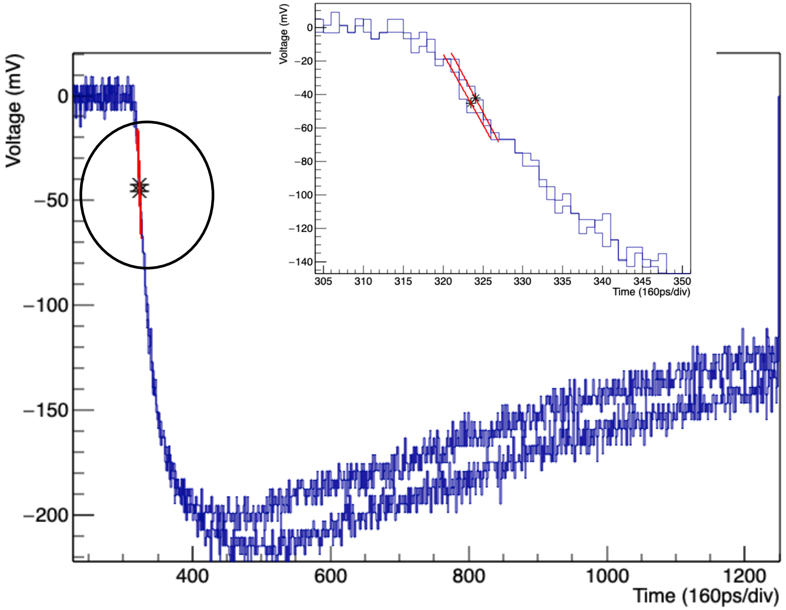
Time resolution: $< 130ps$



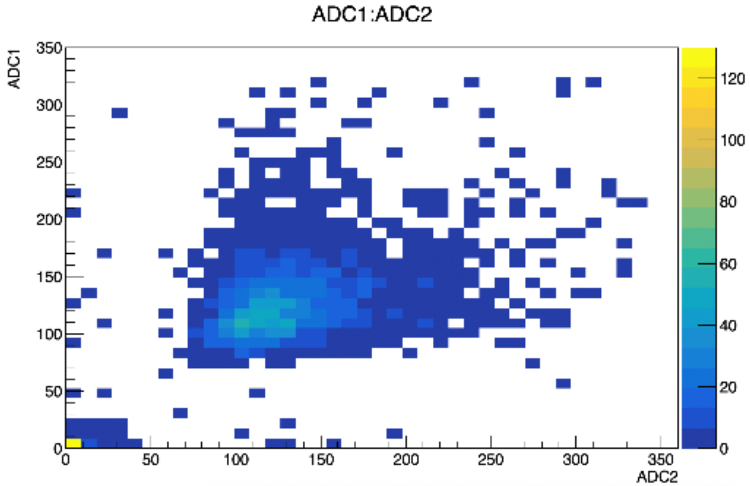
Santi-Gobain scintillators and SiPMs

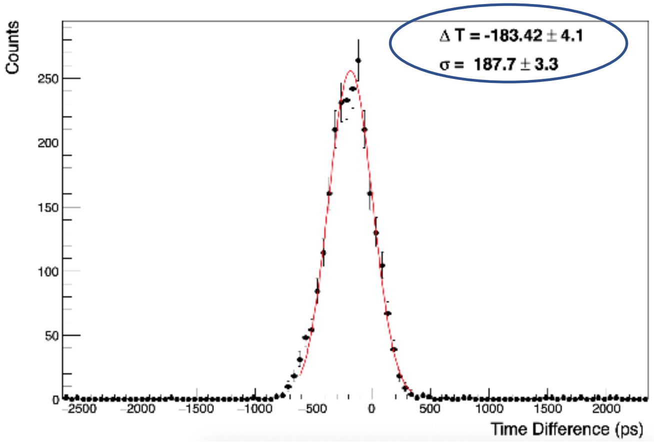






A combination of 4 pieces of $6mm \times 6mm$ SiPMs as the photon sensor.





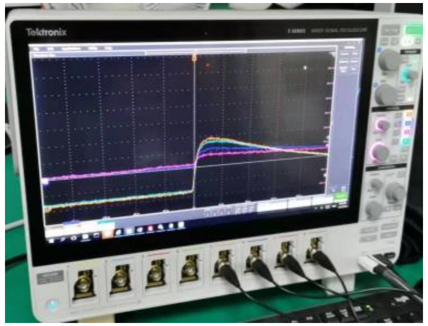
ADC>30

Almost a same performance as MCP-PMT for timing!!!

Time resolution

ch1、ch4

Ch2、ch3



Time resolution:

T2,T3: $132.0 \pm 3.3ps$

T1,T2: $127.2 \pm 2.7ps$

T3,T4: $119.5 \pm 2.0ps$

T1,T3: $199.2 \pm 4.5ps$

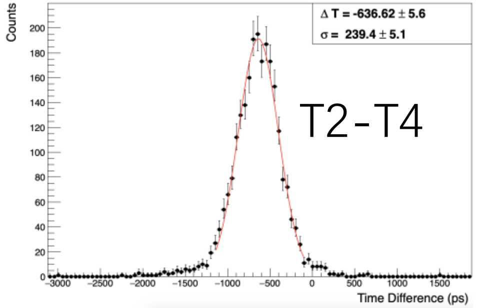
T2,T4: $169.3 \pm 3.6ps$

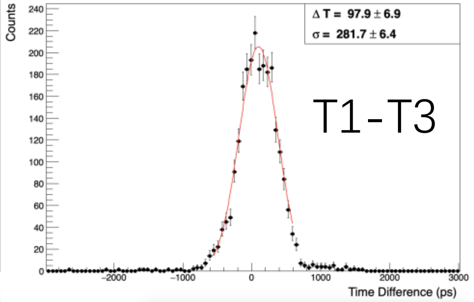
T1,T4: $222.1 \pm 4.4ps$

top to bottom ：1, 2, 3, 4

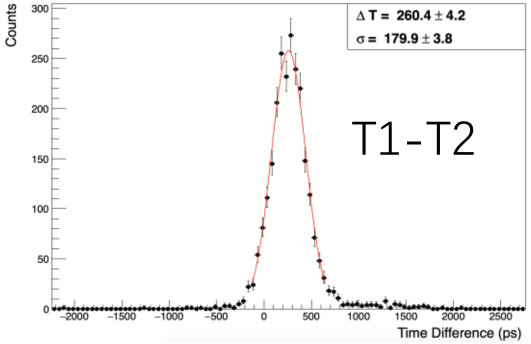
T2 and T3 with distance of $\sim 4cm$

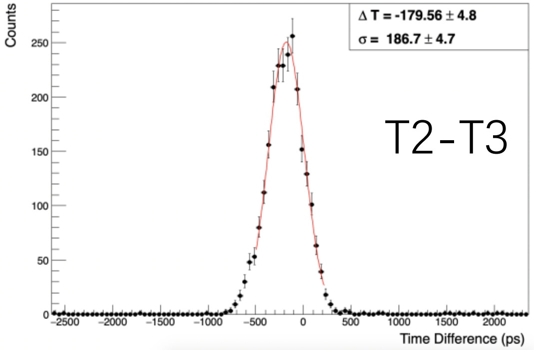
T1 and T4 with distance of $\sim 10cm$

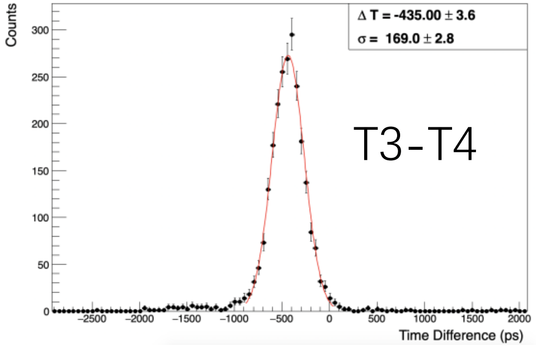


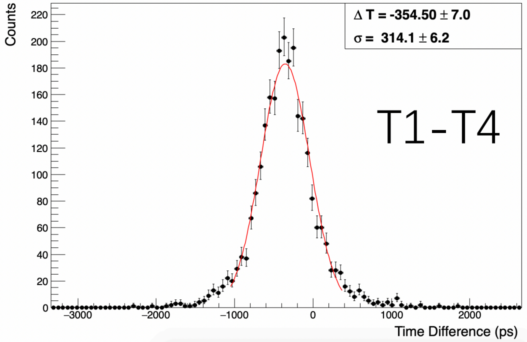


- Increase of time resolution is due to the velocity of CR.
- Velocity of CR should be taken into account.



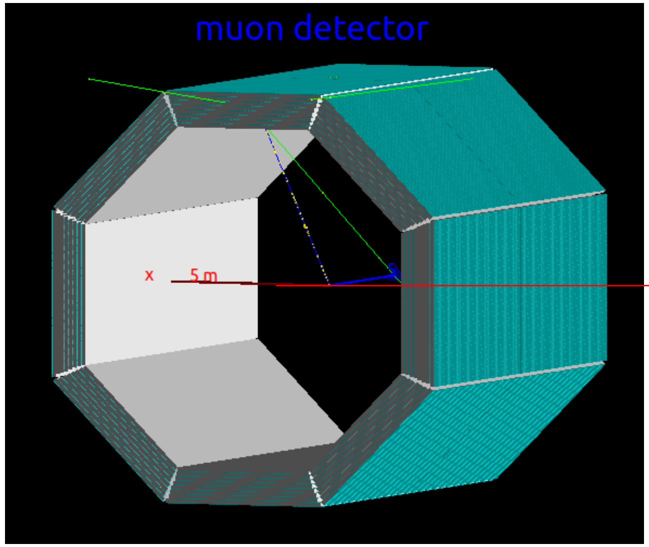


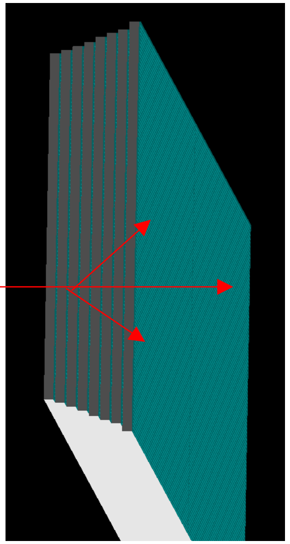


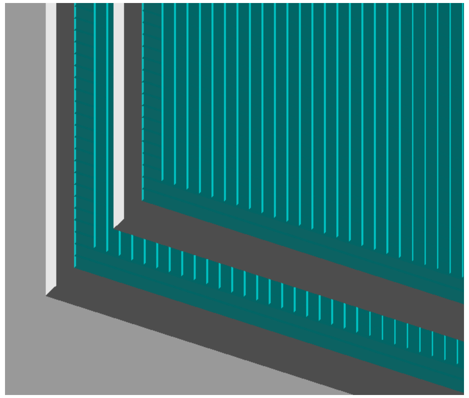


How about implementing timing?

- Two options of scintillator detector:
  - A. Cheap scintillator+WLS fibre+small SiPM, low cost for large size
  - B. Excellent scintillator+large SiPMs, reasonable cost with good timing
- We can combine them for LLP search, to extend the study area of CEPC
  - One sector far away from IP,
  - Measure the tracks with good spatial resolution,
  - Measure the TOF of tracks (and charge?) for velocity (and dEdx?).
  - The distance between layers can be tuned.







LLP decay

MATHUSLA

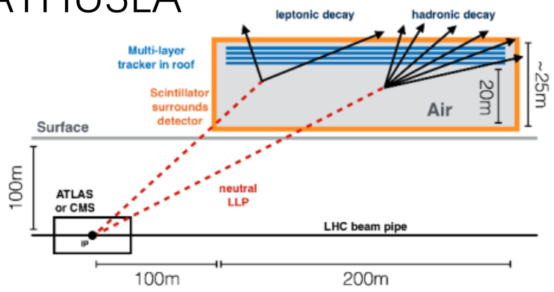


Fig. 1: Simplified detector layout showing the position of the 200 m × 200 m × 20 m LLP decay volume used for physics studies. The tracking planes in the roof detect charged particles, allowing for the reconstruction of displaced vertices in the air-filled decay volume. The scintillator surrounding the volume provides vetoing capability against charged particles entering the detector.