R&D status of the muon detector for CEPC

Xiyang Wang

(On behalf of Muon Group)

Institute of modern physics, Fudan University

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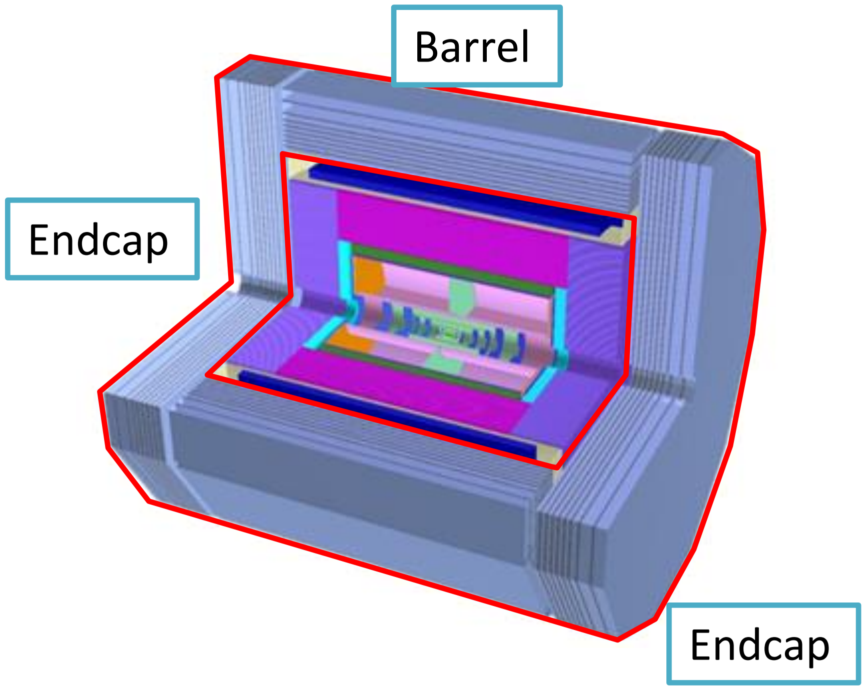
Outline

- Introduction
- R&D efforts and results
- Mechanical Structure and Electronic
- Performance from simulation
- Summary

Introduction

Muon detector, the outermost detector with the largest volume, clean environment.

- Production of Higgs: $e^+e^- \to ZH$, Higgs could be determined in the recoil of $Z \to \mu^+\mu^-$.
- Muons provide in many theoretical models a characteristic signature for new physics.
- Muon detector is designed for muon identification, but not limited to this. Benefits:
  - Could be used to detect the leakage of HCAL.
  - Can be used for trigger, like in ATLAS.
  - Can be used to search for Long-lived particles.
- Functions: muon ID, search for NP, leakage of HCAL, trigger and timing information.
- Furthermore, it must be robust and low cost.



Key requirements:
- **Muon ID**
- Track reconstruction

Requirement

- Solid angle coverage: $0.98 \times 4\pi$
- Detection efficiency ($p_\mu^T > 4.0$ GeV$/c$): $> 95\%$
- Fake ($\pi \rightarrow \mu$) @ 30 GeV$/c$: $< 1\%$
- Position resolution: $\sim 1\ cm$
- Time resolution: $\sim 1\ ns$
- Rate capability: ~ 60 Hz$/cm^2$

Solid angle coverage and detection efficiency → High efficiency

Fake rate → Low fake rate

Position resolution → Resolution due to the multiple scattering of muon

Time resolution → A typical time resolution of modern muon detector, and useful for trigger, T0 and background suppression.

Rate capability → Compatible with the high luminosity operation

Technology survey and our choices

Our choice: PS as the baseline option, RPC for comparison in R&D.

	Advantages	Disadvantage
Plastic Scintillator (PS+SiPM)	Solid detector, structure simple, high rate capability, low operation voltage, use SiPM similar to HCAL, time resolution	DCR of SiPM
RPC	Cost, mature tech., time resolution	Fill gas, HV system
μ-RWELL	Spatial resolution, high rate capability	Structure, number of readout channels, time resolution, cost.

Main Technical Challenges

- Long detector module: $> 5m$, due to the large size of the muon detector.
- How to achieve the required efficiency and the time resolution from a long PS bar?
  - Kuraray fiber has an attenuation length of $6.8m$.
  - We got the effective attenuation length of $2.6m$ from lab testing on WLS fiber.

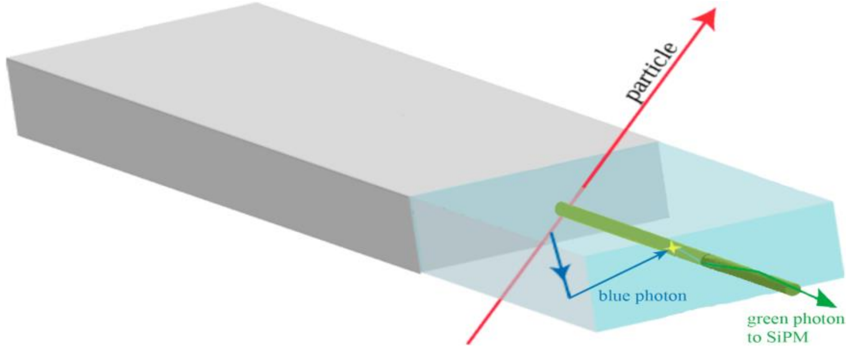
R&D efforts and results

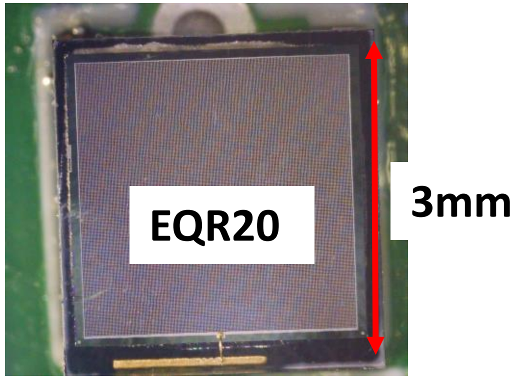
- Structure of PS Strips
- Prototype and CR test
- Simulation for improvements
- New R&D on PS bars

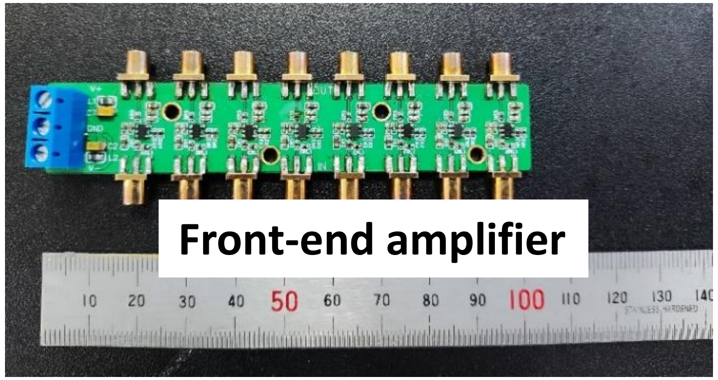
Published papers:

1. Design and performance of a high-speed and low-noise preamplifier for SiPM, Nucl. Sci. Tech. 34, 169(2023)
2. Design and test for the CEPC muon subdetector based on extruded scintillator and SiPM, JINST 19 P06020(2024)

Structure of PS Strips

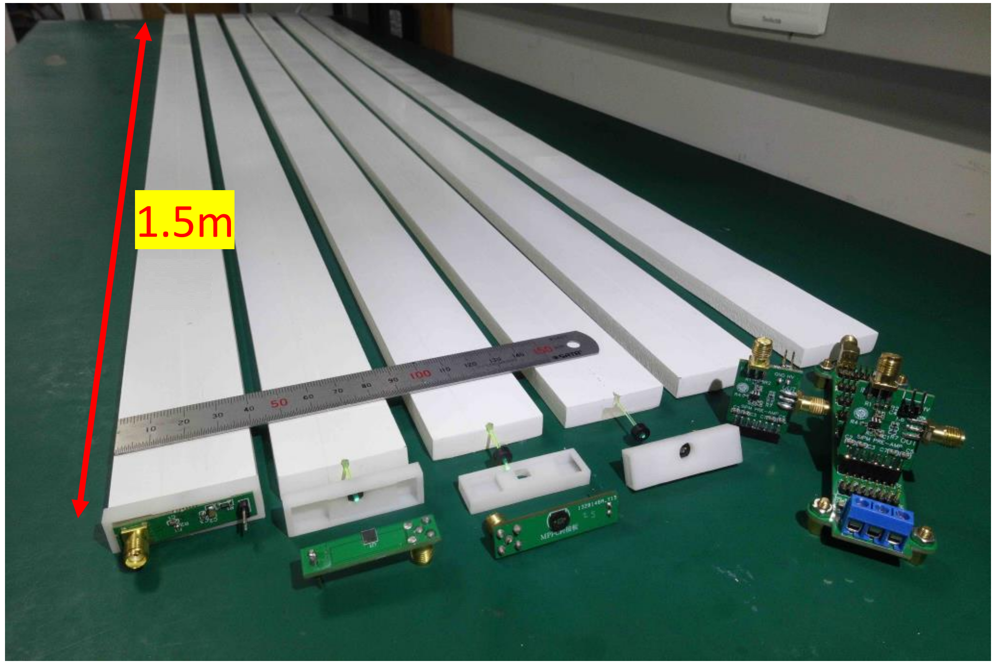






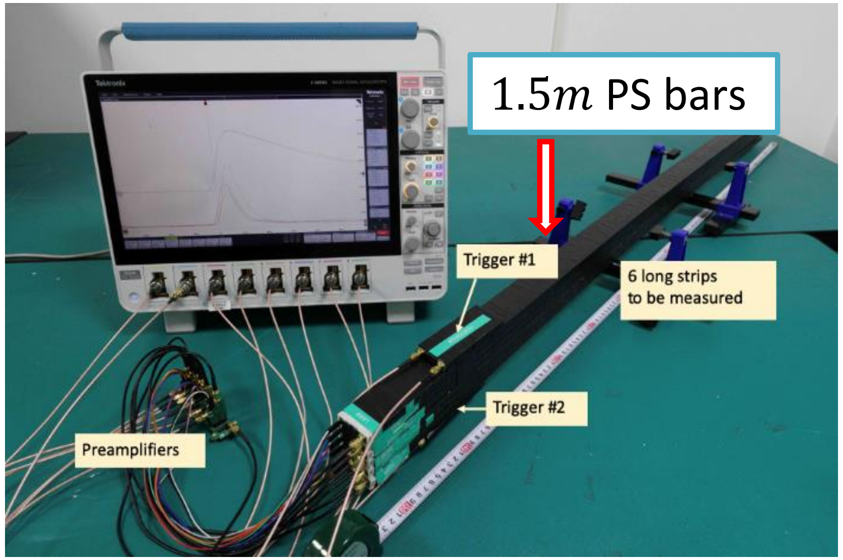
Baseline noise: 0.6 mV Bandwidth: 426 MHz

- **PS bars made by GNKD company**
  - –Increase the light yield;
  - –Develop/improve the reflection layer with Teflon;
  - –Strip production.
- **WLS made by Kuraray company**
  - –Attenuation length of 6.8 m
  - –Improve the diameter **1.2mm → 2.0mm**
- **SiPM made by NDL company (EQR20 11-3030D-S)**
  - –Gain: 8.2×10^5
  - –Dark Count Rate: 150 kHz/mm^2
  - – Active Area: 3mm×3mm



Prototype and CR test

- Studies of SiPMs, WLS fibers
- Prototype:
  - Groove PS($1.5m$)+WLS($1.2mm$)+SiPM ($3.0mm$)
- Performance:
  - $\epsilon > 98\%$ can be obtained
  - Time resolution better than $1.5ns$



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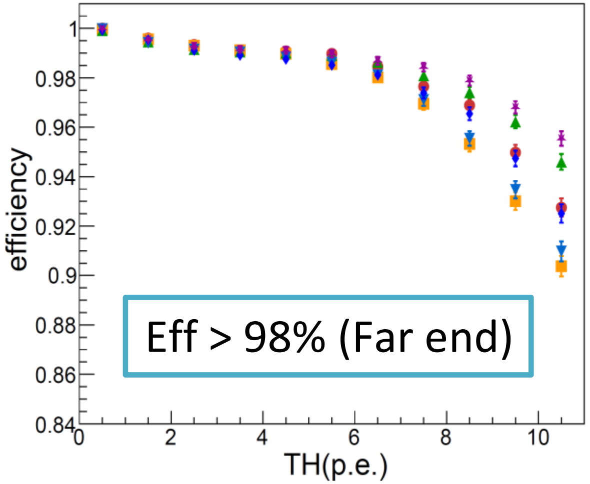
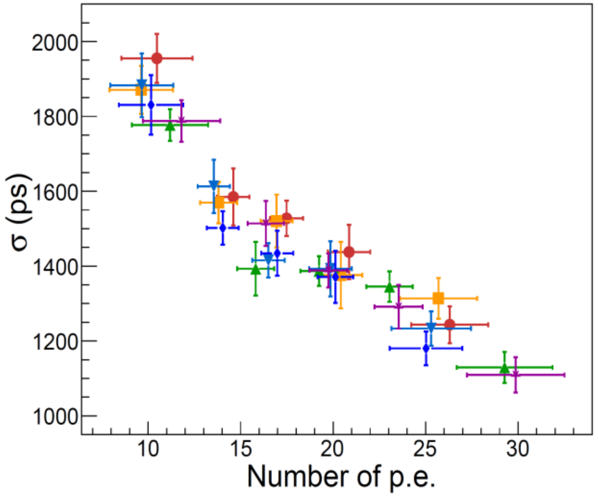
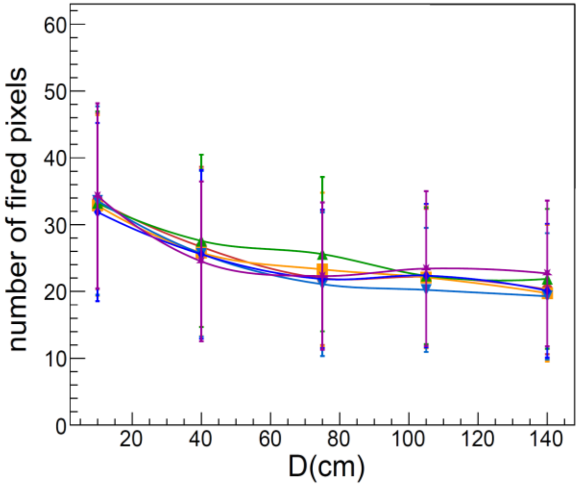
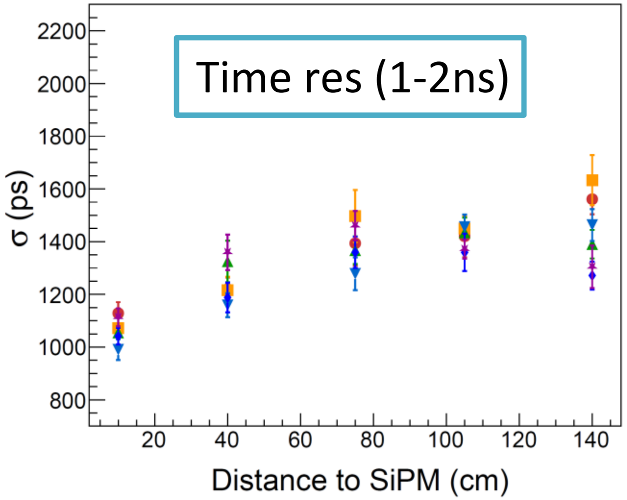






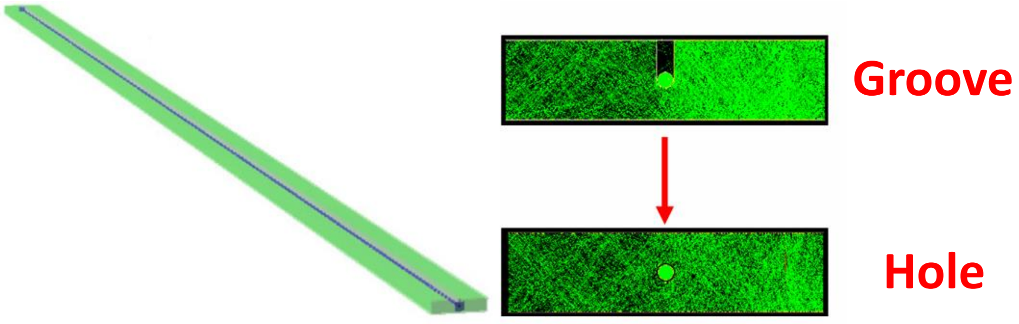


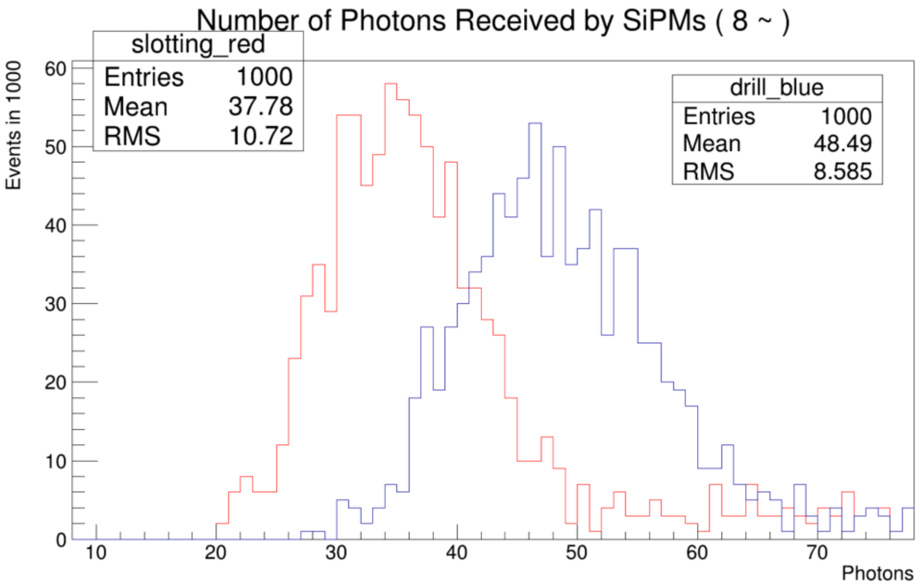
Effective attenuation length of fiber $L_{Att} = 2.63 \pm 0.37\ m$

Geant4 Simulation (Groove VS Hole)

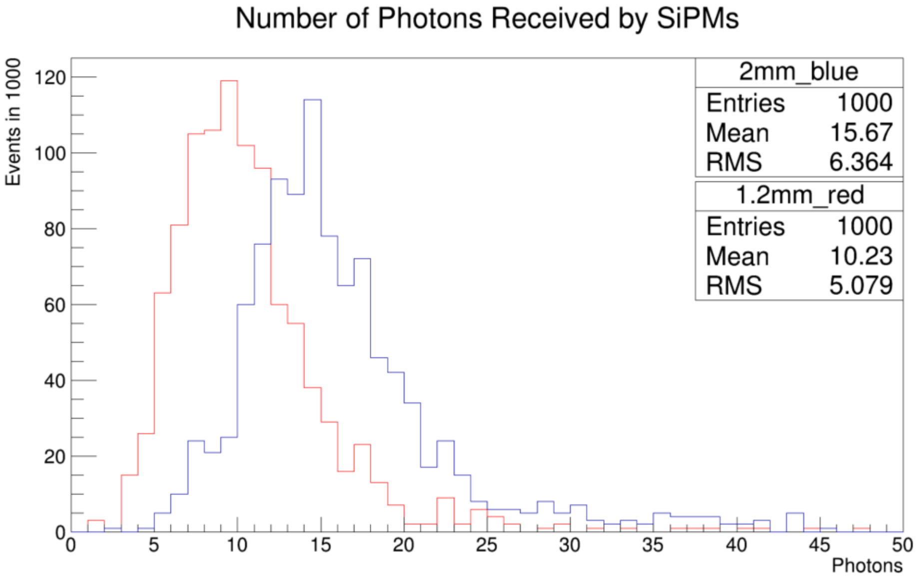
Simulation for single channel

- Fiber embedding: Groove → Hole, $N_{\mathrm{p.e}} \times 1.4$
- Diameter: 1.2mm → 2.0mm, $N_{\mathrm{p.e}} \times (2-2.8)$





Groove VS Hole



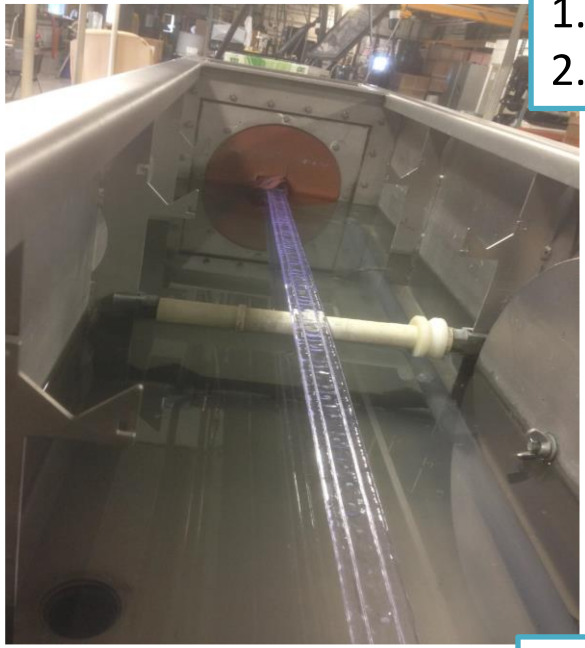
1.2mm VS 2.0mm

Simulation shows potential to increase the light collection by a factor of (2.8 – 3.9), which is helpful for building long detector module.

Improvements on the scint. strip

- Very new R&D in the past months, like the production in Fermi Lab.
- Fiber embedding: Groove → Hole
- Diameter: no new fiber available yet, we use three 1.2mm fibers instead.

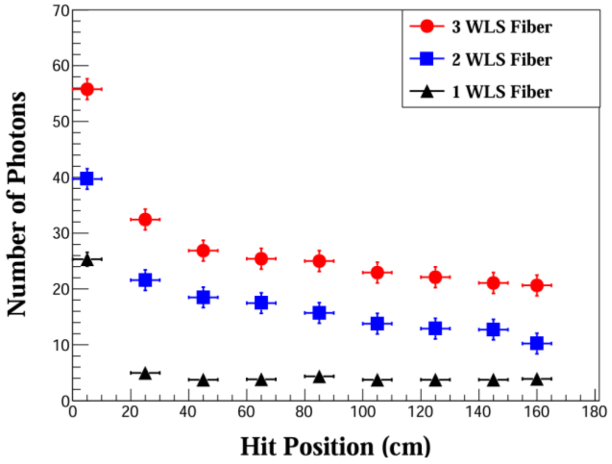
1.65m new scint with 2.5mm diameter hole



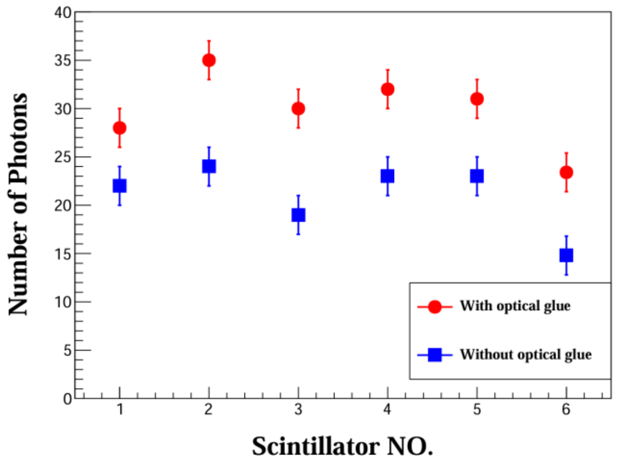
Scintillator production at Fermilab

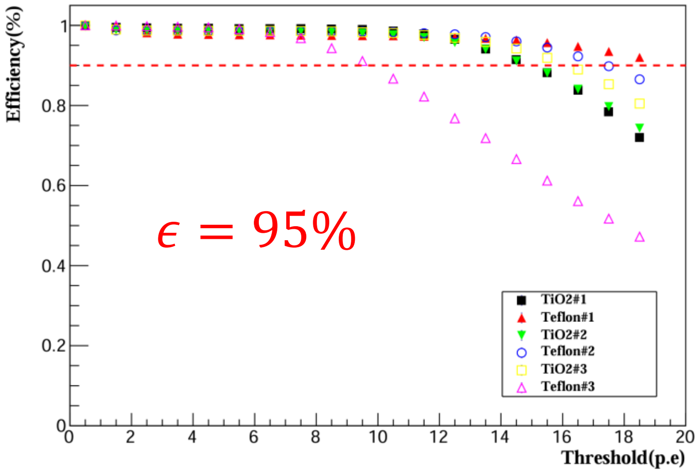
New scintillator provided by GNKD, with our R&D!

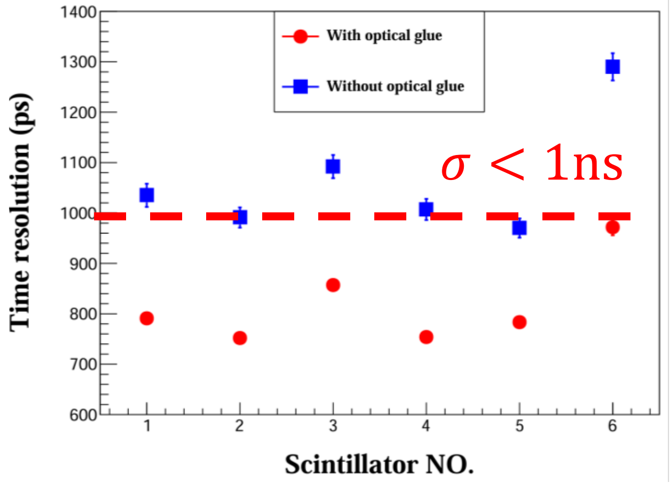
Adding fiber (1→3)



Adding optical glue







Very positive to the design of long module (>4m)

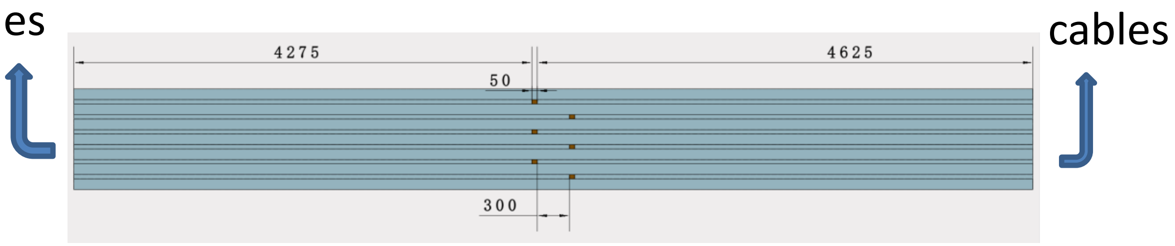
Mechanical Structure and Electronic

- Geometry: barrel and endcaps
- Detector channel elements and module
- Consideration on readout electronics

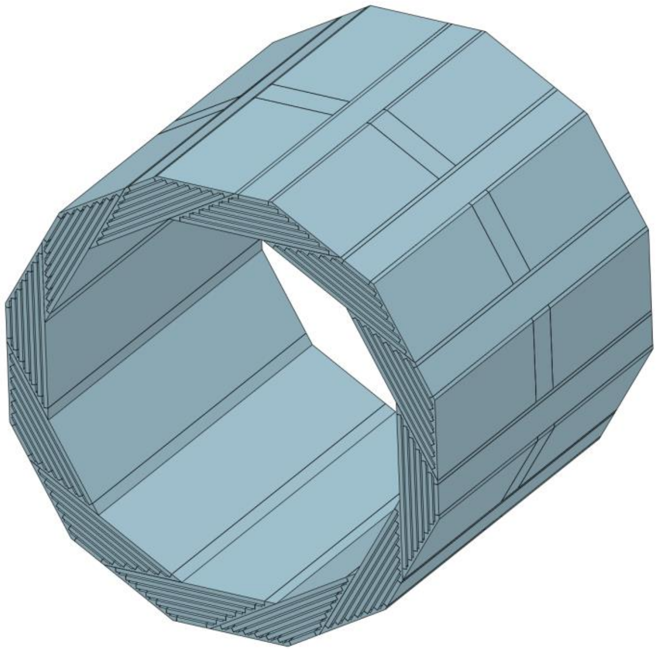
Structure of Muon detector (Barrel)

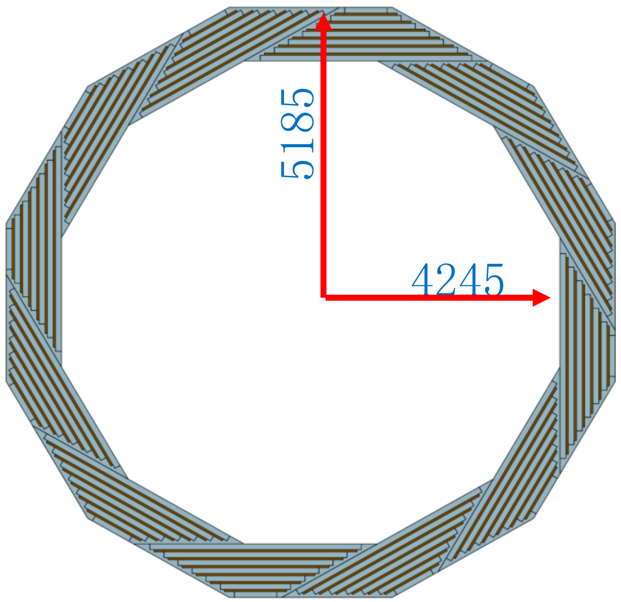
- Geometry: 6 superlayers, to cover the detection as much as possible
  - Barrel: Helix dodecagon sectors.
  - Rectangle modules inserted between iron plates.
  - Cable: towards the gaps between barrel and endcaps.

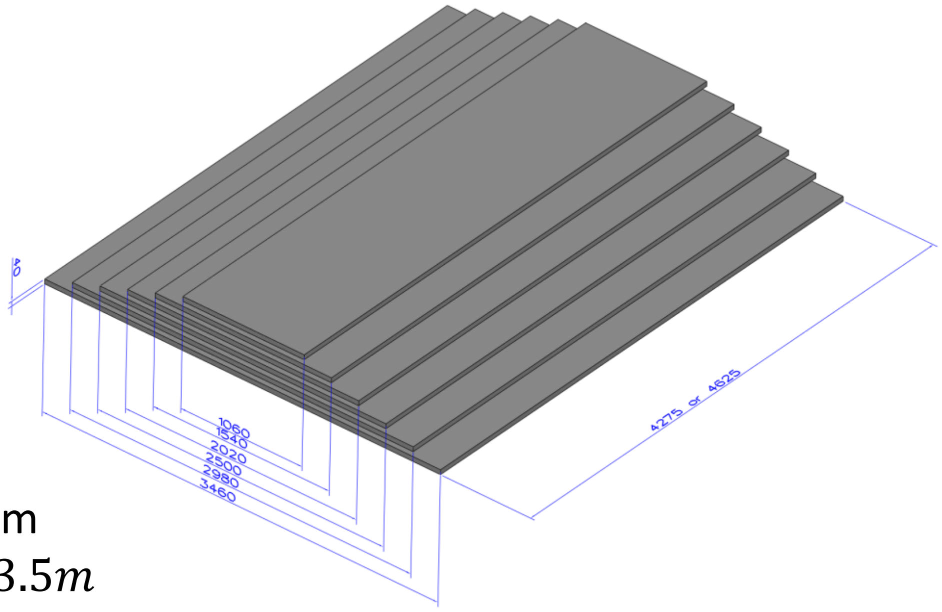
$L = 4.275m$ or $4.625m$



Vary the separation position to avoid dead zone in the middle of barrel.







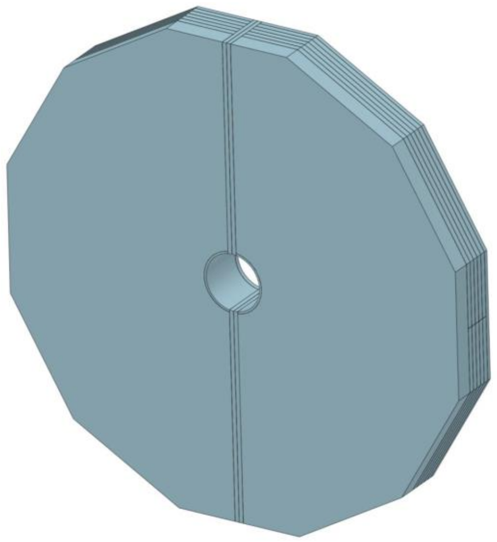
Width from $1.1\ m$ to $3.5m$

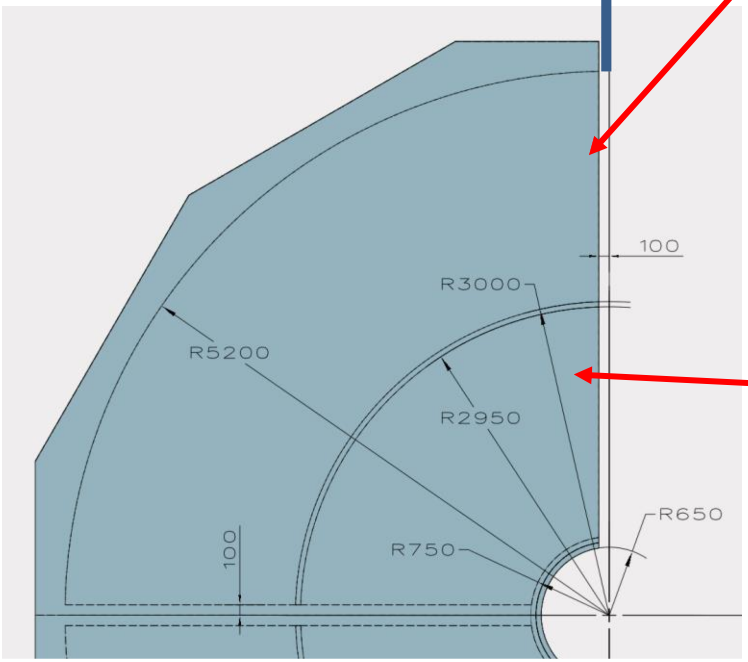
Refer to Xia Shang's poster for more details.

Structure of Muon detector (Endcap)

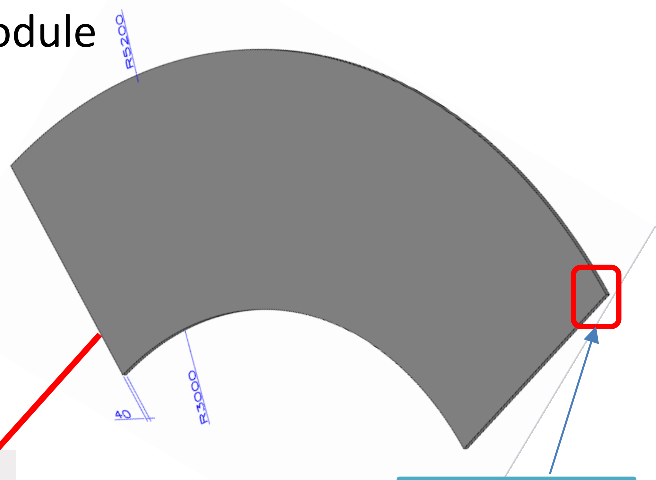
- Geometry: 6 superlayers
  - Endcaps: inner and outer modules
    - Inner: $R = 0.75 - 2.95m$
    - Outer: $R = 3.00 - 5.20m$
  - High hit rates for the inner modules
  - Longest bar in a outer module: $4.2m$

Cables



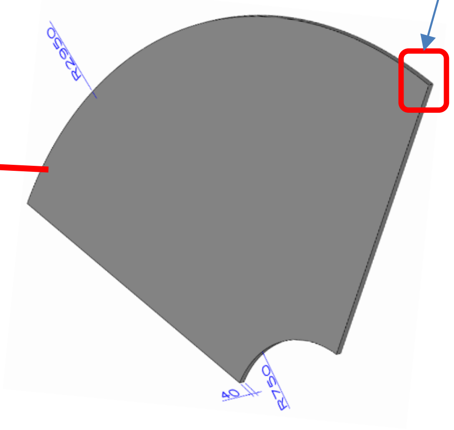


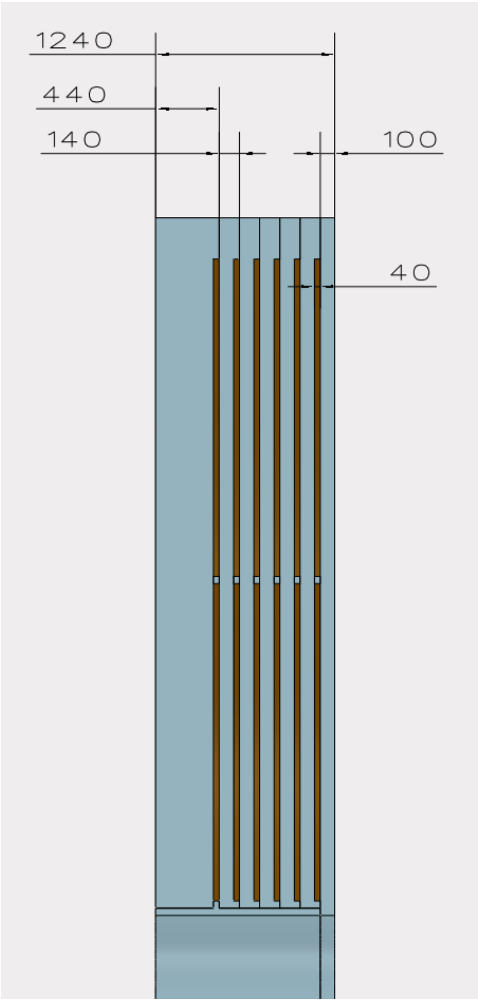
Outer module



Windows for cables

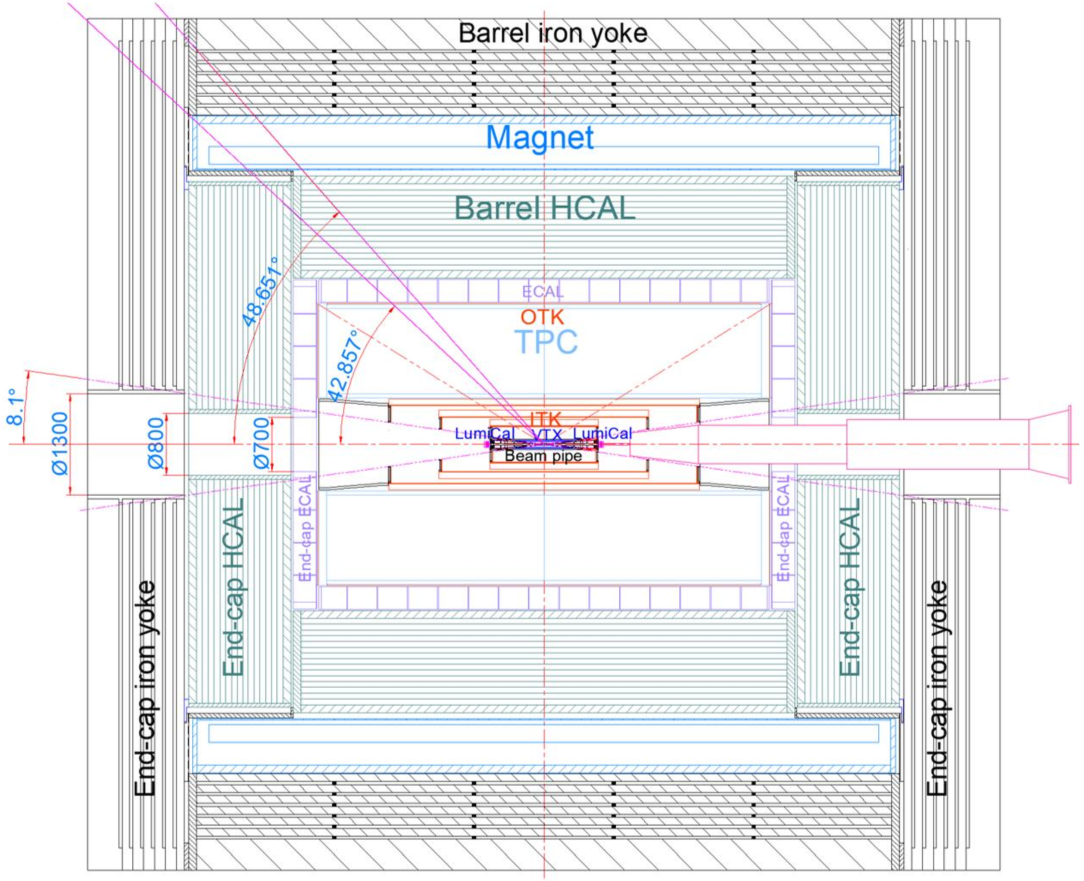
Inner module



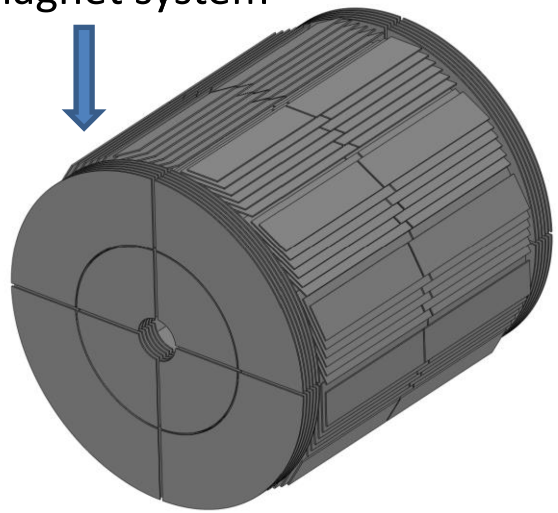


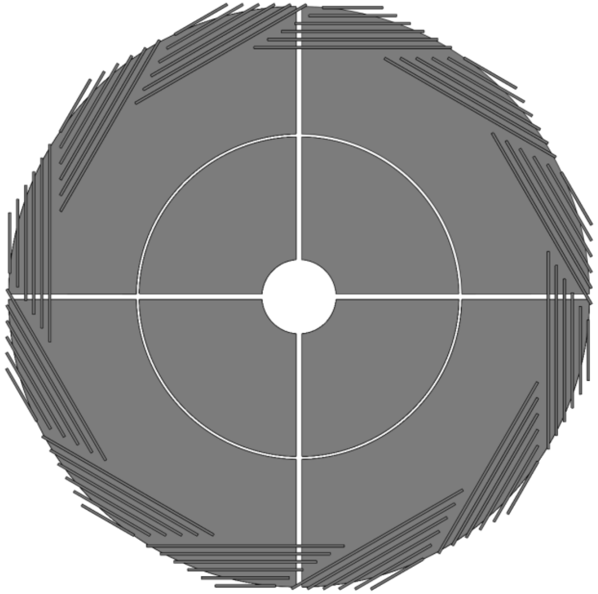
Overall of the design

- Number of channels: (288 modules) 43,176
  - Barrel: 144 modules, 23,976 ch
  - Inner endcaps: 48 modules, 6,912 ch
  - Outer endcaps: 48 modules, 12,288 ch
- Sensitive length: $119{,}563m$
  - Length for PS bar and WLS fiber
- Sensitive area: $4782m^2$



Chimney for magnet system



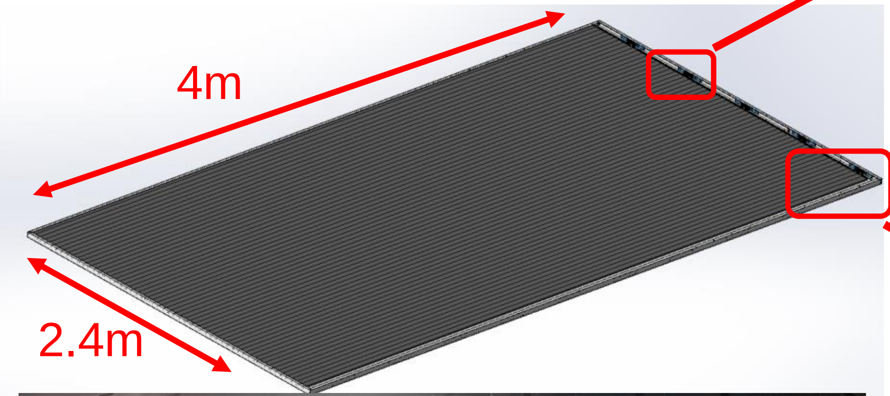


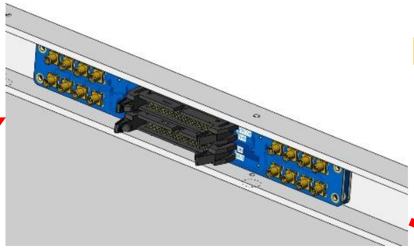
Detection dead area: ~1.5%
0.04% due to chimneys in the barrel for magnet system, 0.07% from the cross in endcaps, and 1.4% due to the beampipe.

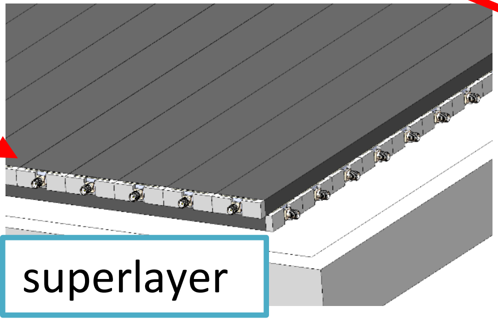
Detailed design of the channel and module

- **Detector channel**
  - PS bar: $4cm \times 1cm$ cross section
  - WLS fiber: $\phi = 2.0mm$
  - SiPM: $3mm \times 3mm$

- **Detector module**
  - Superlayer with perpendicular channels
  - Carriers for preamps held at the frame
  - Space between PS bars and aluminum layer is allowed for long cables.
- **Mechanics**
  - Aluminum frame, PS bars







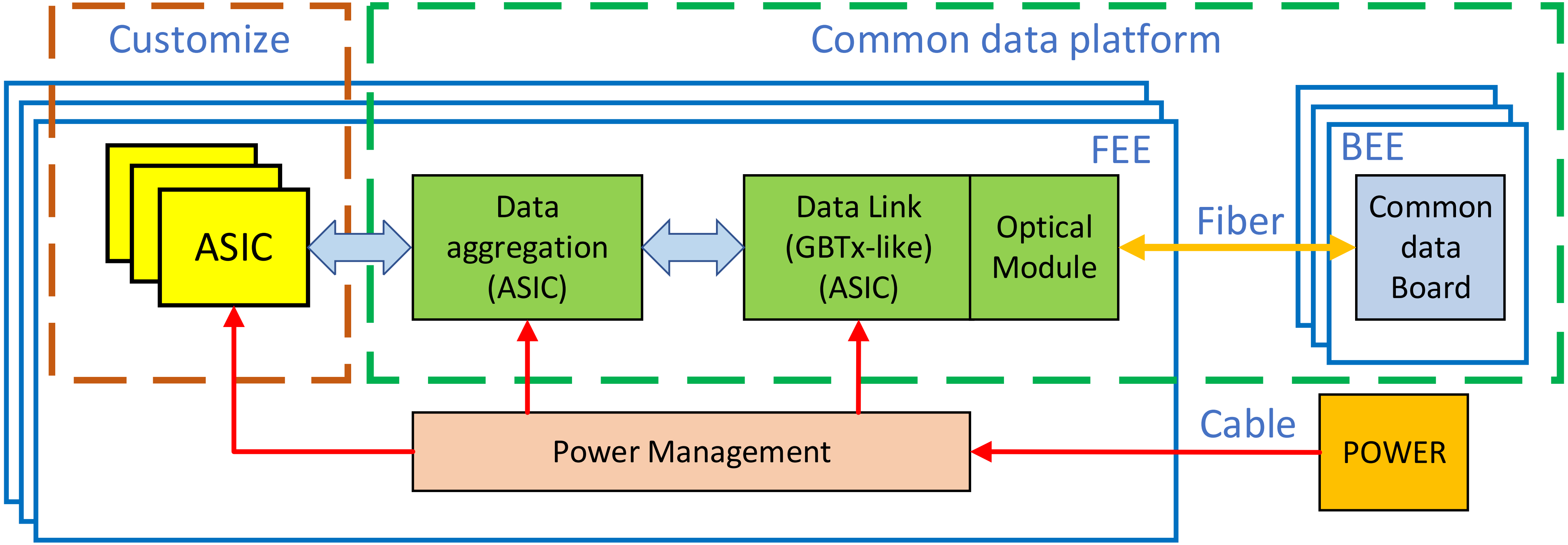
superlayer

To BEE with ribbon cables

Carrier for the FEE, inside the module. Can be modified for the new electronics in the future.

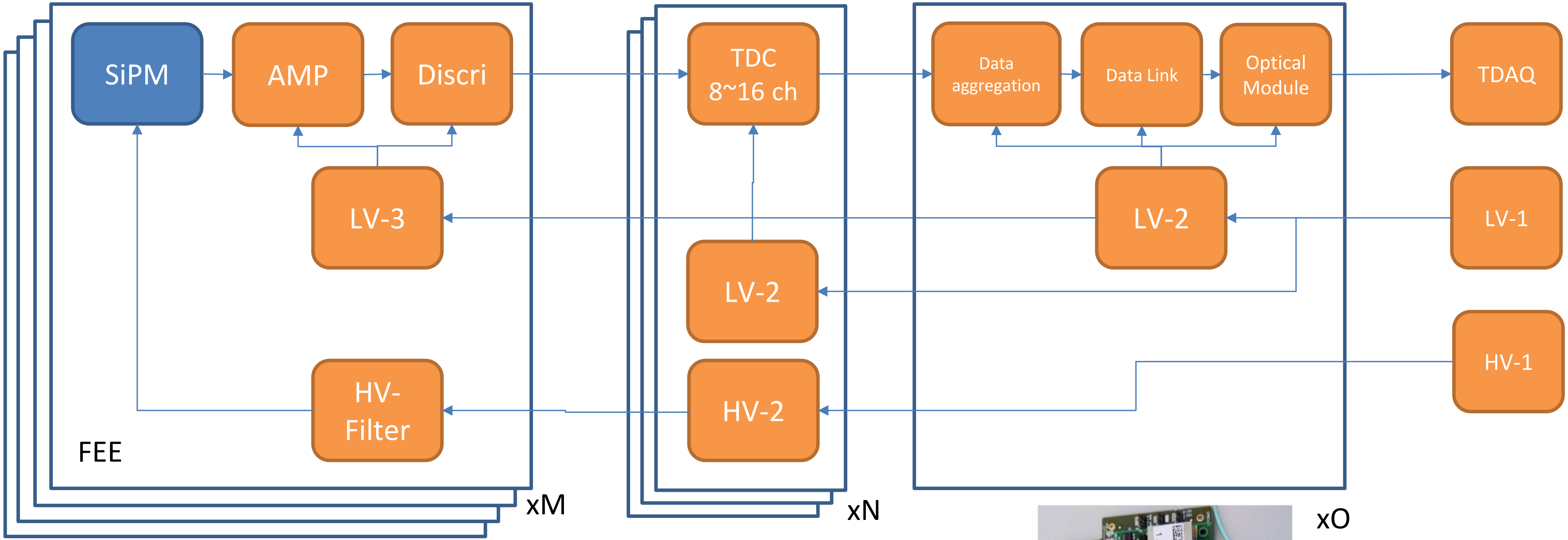
First Al frame ($1.7m \times 1.7m$) is ready for module prototype.

Readout electronics

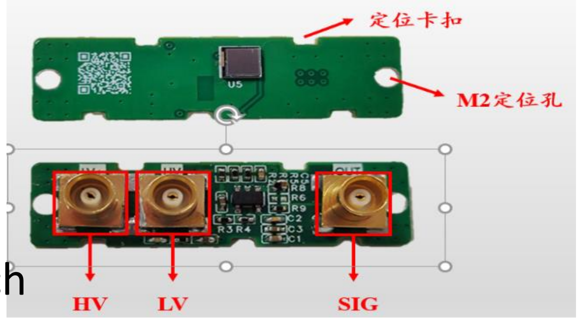


- Readout design for ECAL and HCAL covers the requirements of Muon detector: $N_{pe} < 100, \sigma_T < 0.5ns$
- Use the ASIC scheme from ECAL or HCAL, and customize the FEE based on ASIC.
- Revise according to the constraints from cooling and mechanical structure of the detector

Readout electronics (Stage scheme)



Example:



For each ch

For each module

For each sector

Performance from simulation

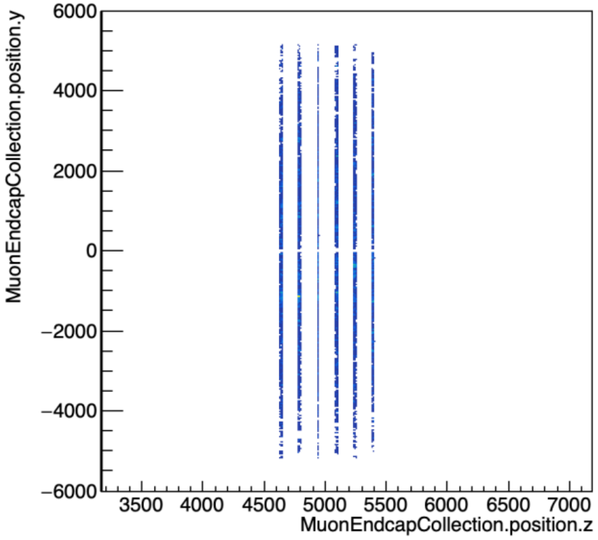
- Geometry and Geant4 simulation is implemented in CEPCSW, reconstruction and performance studies are ongoing:
  - Study of the Molière radius of muons originating at the interaction point and traversing the ECAL and HCAL. → Spatial resolution ✓
  - Muon ID efficiency based on hit layers. ✓
- More work required:
  - Tracking reconstruction.
  - Fake rate of $\pi \rightarrow \mu$.
  - Impact of physics performance.
  - Background and hit rate.

Geant4 simulation of muon position

- Everything based on CEPCSW framework.

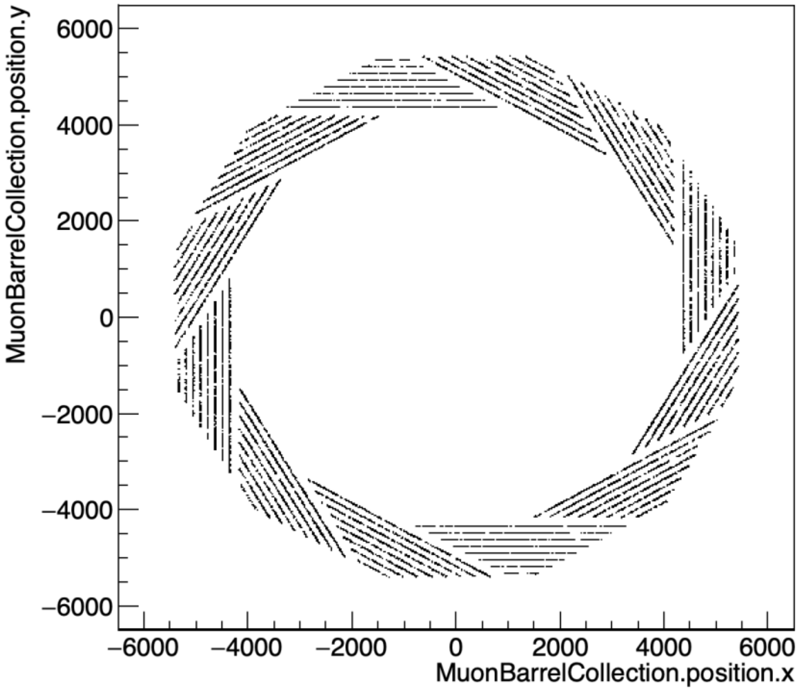
Muon Sim
Hit positions

z-y position
map in Endcap



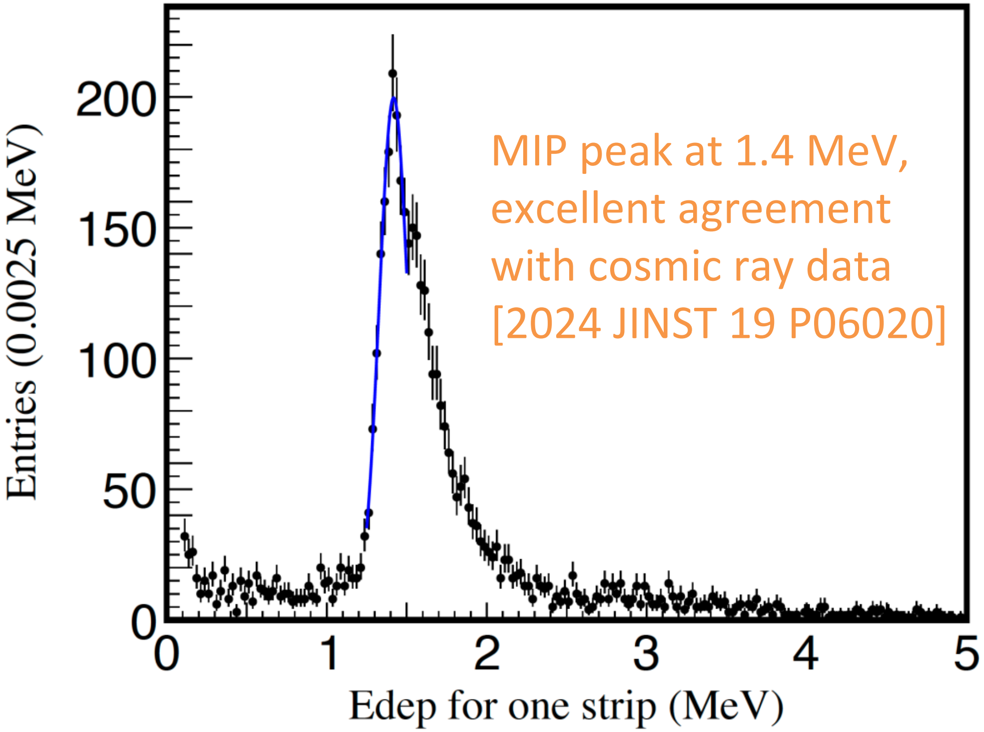
1k muons at 10 GeV muons

x-y position map in Barrel



Muon detector geometry is clearly visible!

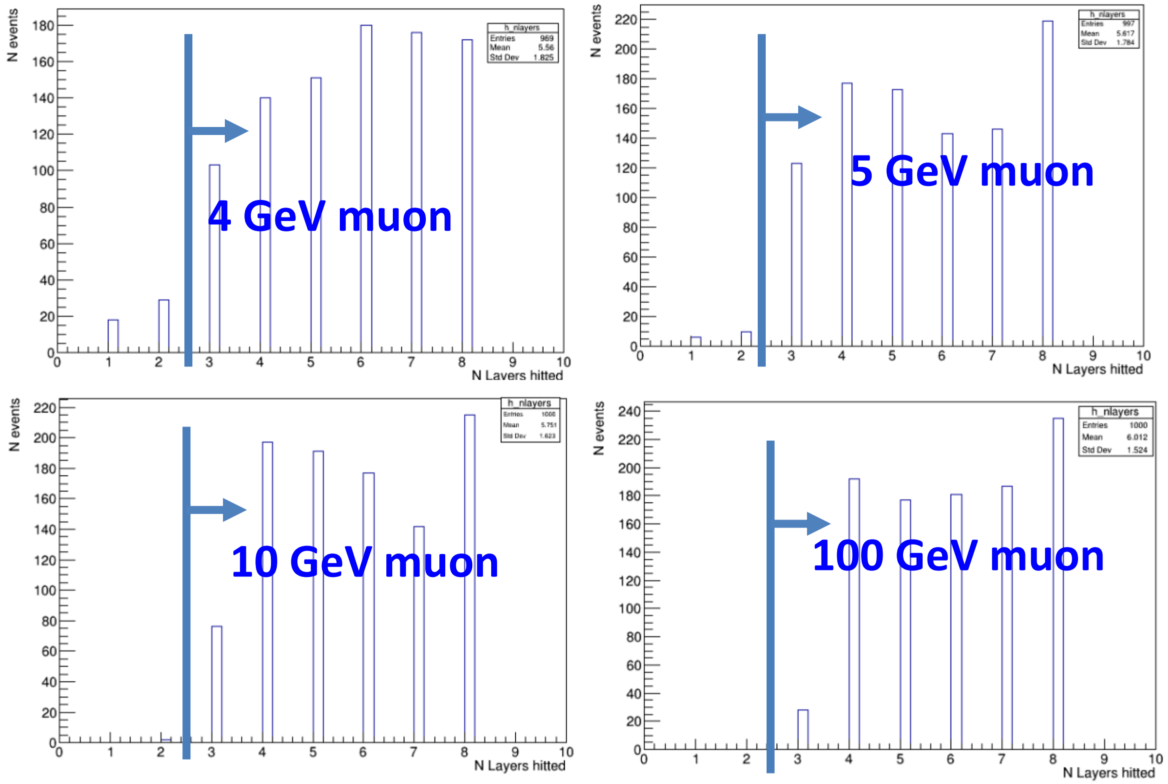
Muon Sim
Hit Energy deposition

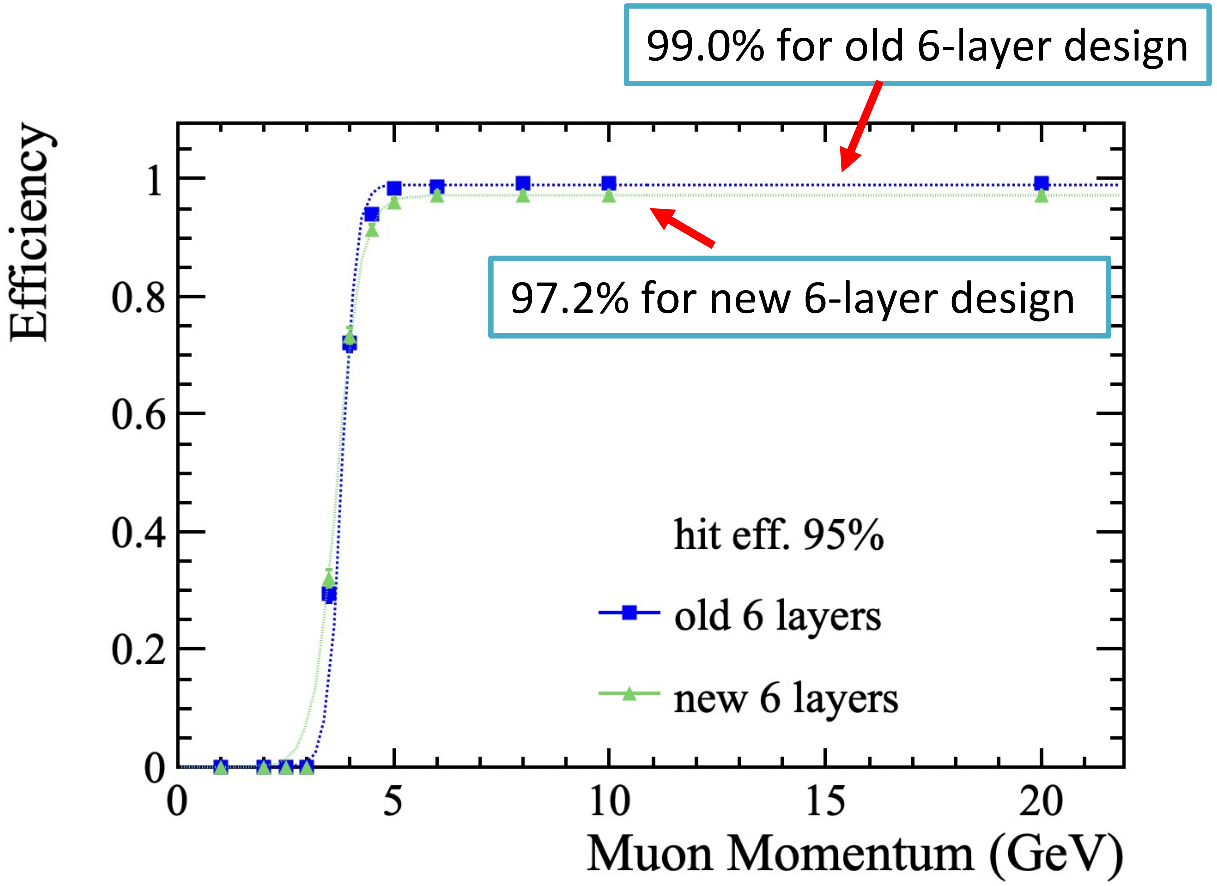


Muon ID from simulation

- Muon ID efficiency vs. momentum
- Define Muon ID:

  If a muon candidate has 3 or more hits reconstructed in the muon detector, it is identified as a muon.



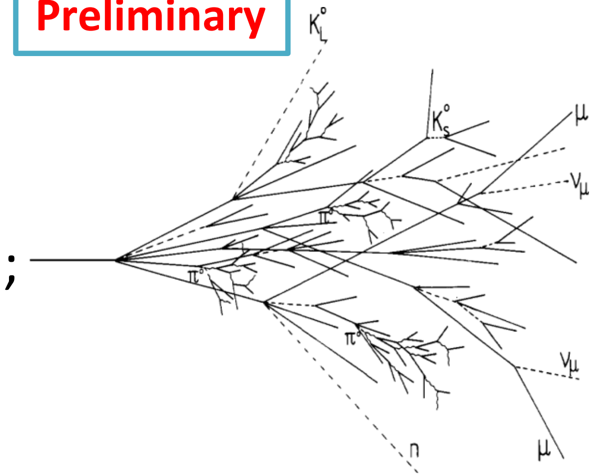


Muon ID efficiency of the barrel

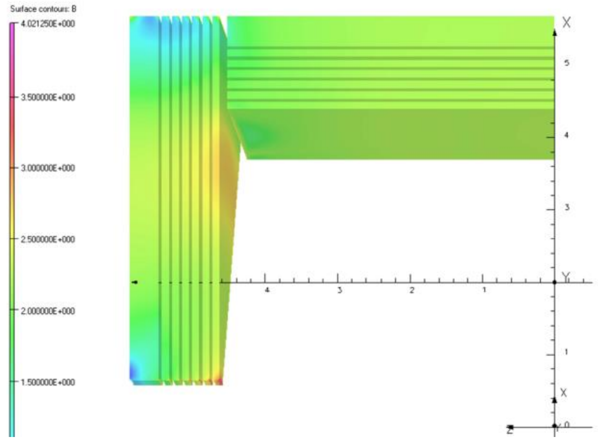
About track reconstruction

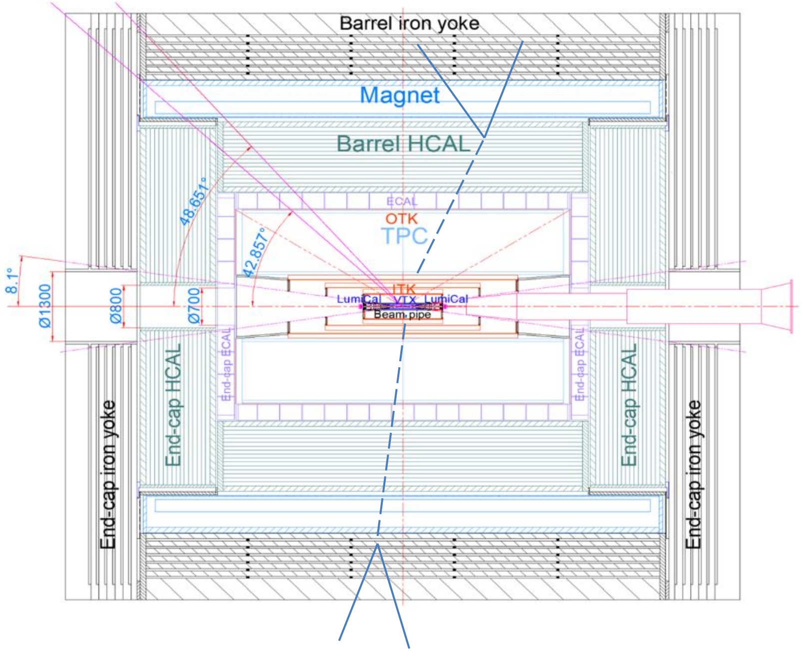
- Tracking in the muon detector may be used to rescue some energy leakage of HCAL:
  – Magnet field in the iron layers can be simulated;
  – Most charged particles in the tail of a hadronic shower are $\pi^{\pm}$ and $\mu^{\pm}$.
  – If we can reconstruct the momentum of these charged particles, or add their masses, at least.
  – K_L may be reconstructed from its decay to $\pi^{+}\pi^{-}\pi^{0}$.
- Tracking in the Muon detector can extend the search of LLP from $L < 3.5\ m$ to $L < 4.9m$.

Preliminary



Magnet field





Summary

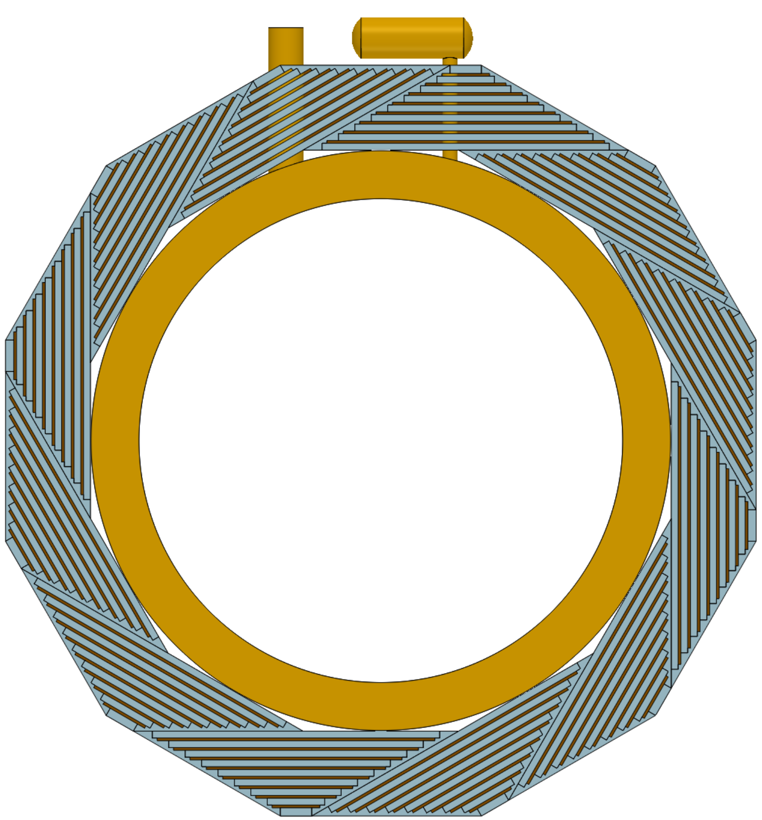
- Muon detector will be designed for muon ID, but not limited to this.
- Many R&D efforts have been performed: FEE, prototype, simulation, etc.
  - Performance of a $1.5m$ prototype: $\epsilon > 98\%$, $\sigma_T < 1.5\ ns$
  - R&D on new scintillator with hole shows very good performance.
- Detailed design:
  - Barrel: 6 layers, 2 long modules per layer, helix dodecagon
  - Endcaps: 6 layers, 4 sectors per layer, two modules (inner and outer) per sector
  - Large area modules with long PS bars.
  - $43{,}176$ channels, $4782\ m^2$ area, and $119{,}563\ m$ long fiber, in total.
- Work plan will focus on electronics, software and simulation for performance, prototype modules with long bars.

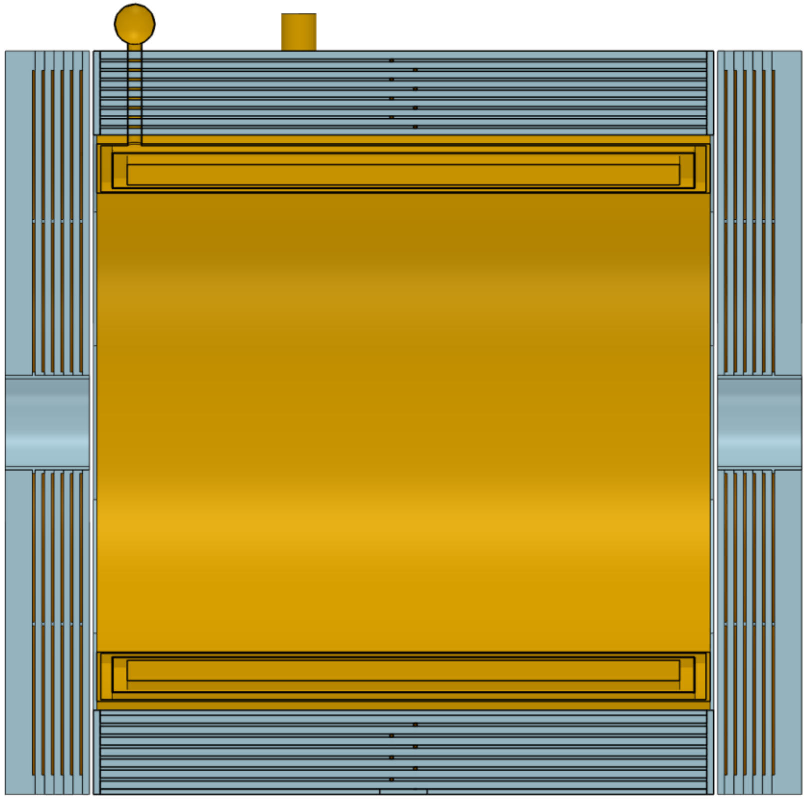
THANKS !

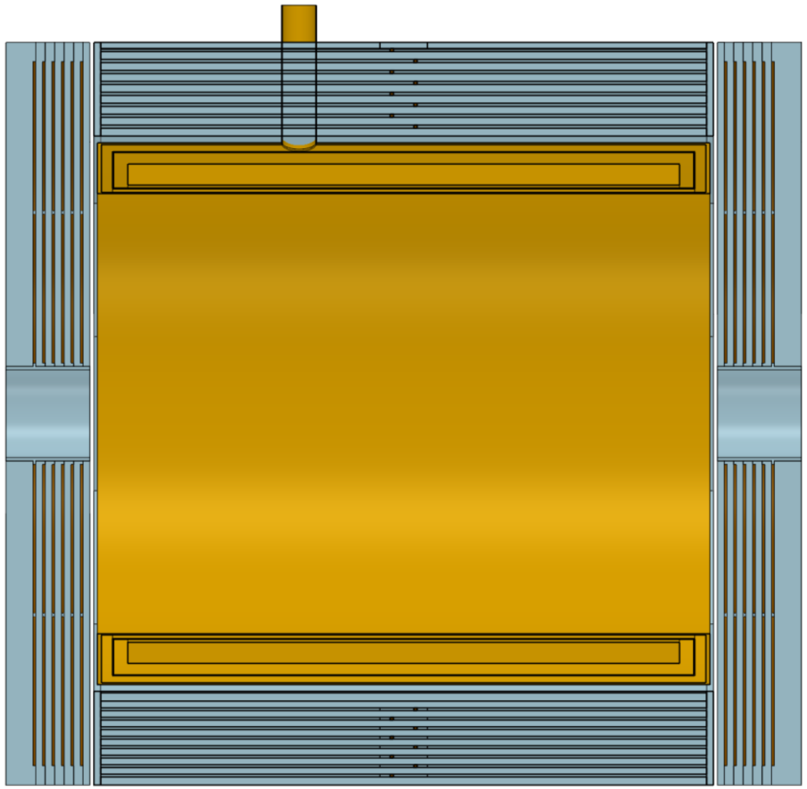
back up

Add chimneys

- Input the chimneys of the magnet system.
- It contributes a dead zone of <0.4%.







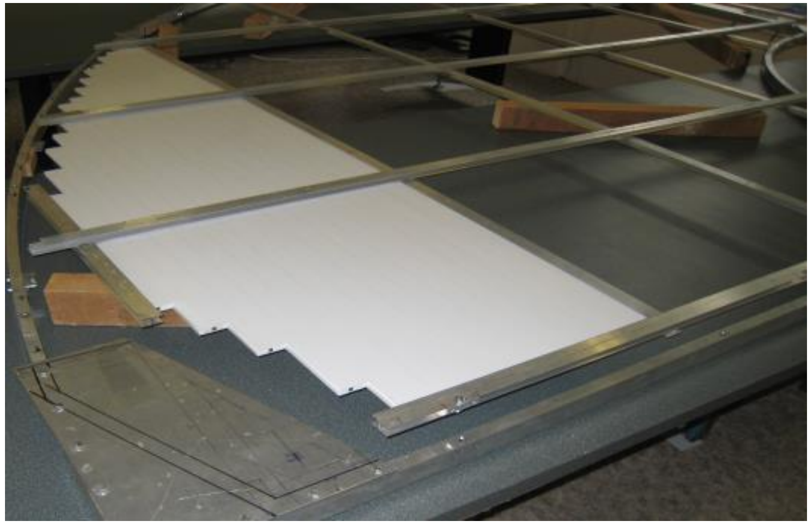
Bandwidth requirement

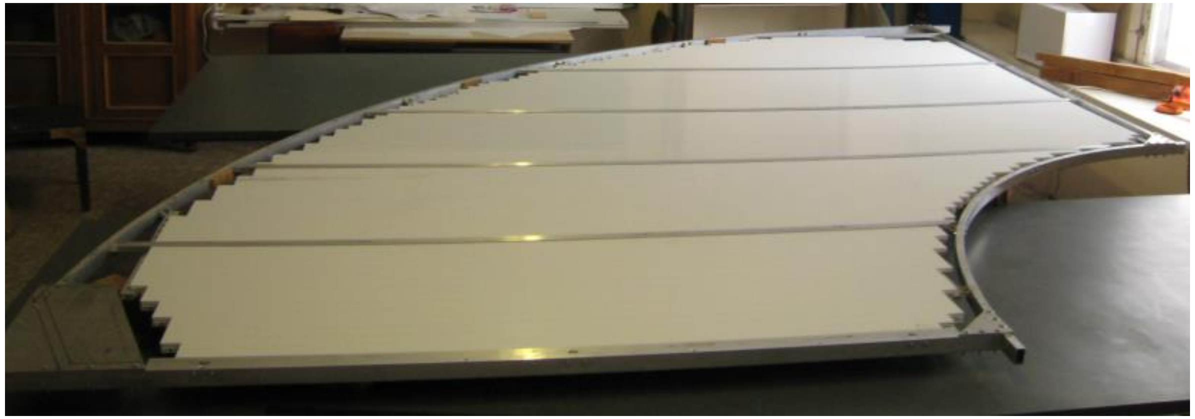
Muon	Module	Channel/Module	Readout Channel	Hit rate/Hz (worst case)	Data format	Raw data rate / Gbps
Barrel	192	169.5	32544	10 k	48bit (8b BX+ 10b ADC + 2b range + 9b TOT + 7b TOA+ 4b chn ID + 8b chip ID)	15.63
Inner endcaps	64	144	9216	10k~100 k, Average 20 k		8.85
Outer endcaps	64	256	16384	10 k		7.87
Total			~58.2 k			~32.4

- Very preliminary, conservative estimation according to data from Belle II experiment.
- We assigning a faculty to take care of this issue.

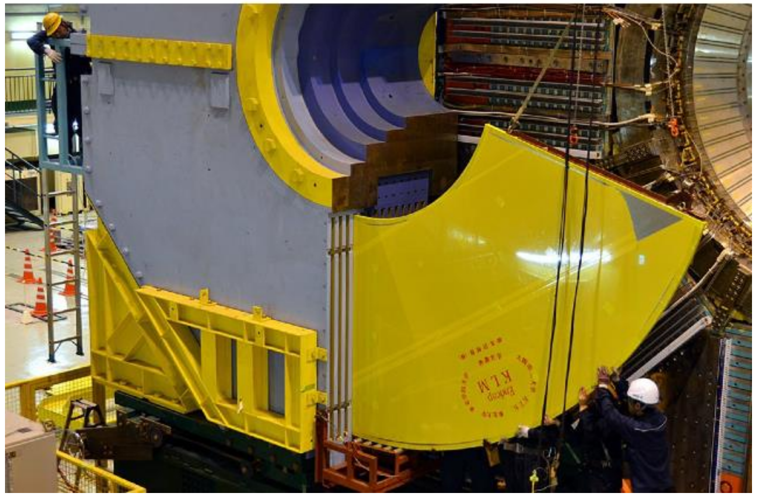
Reference for endcaps

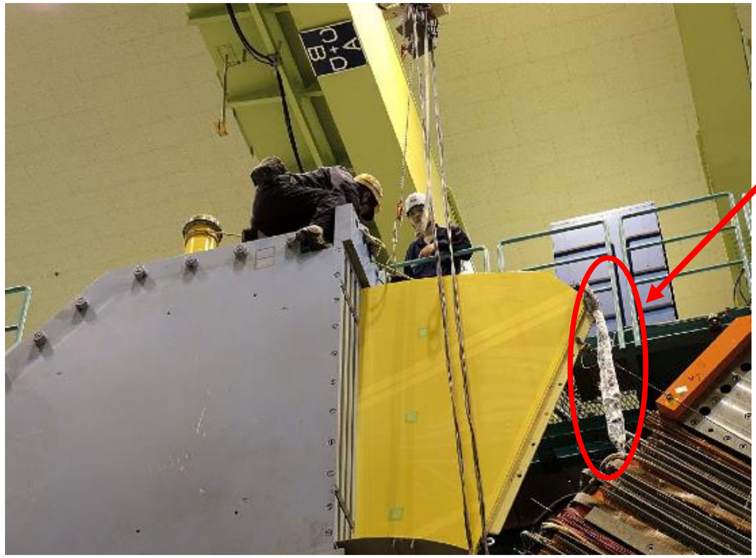
- Structure of a module





- Installation

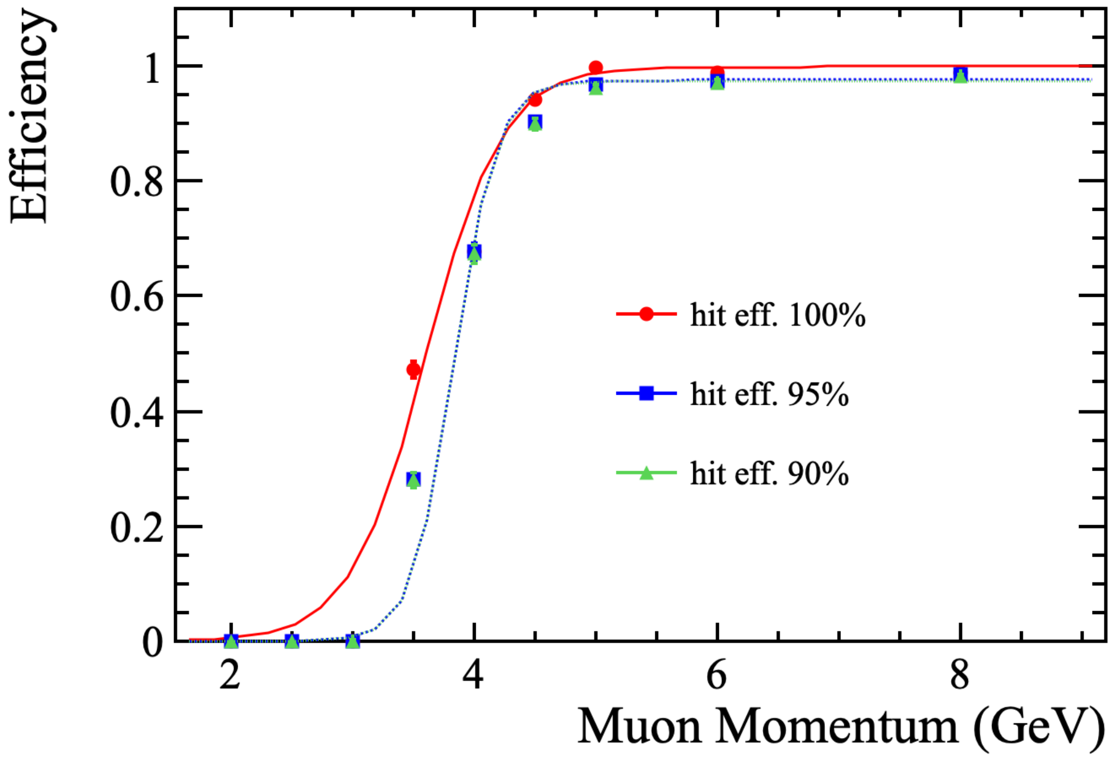




Cables

Detector Optimization

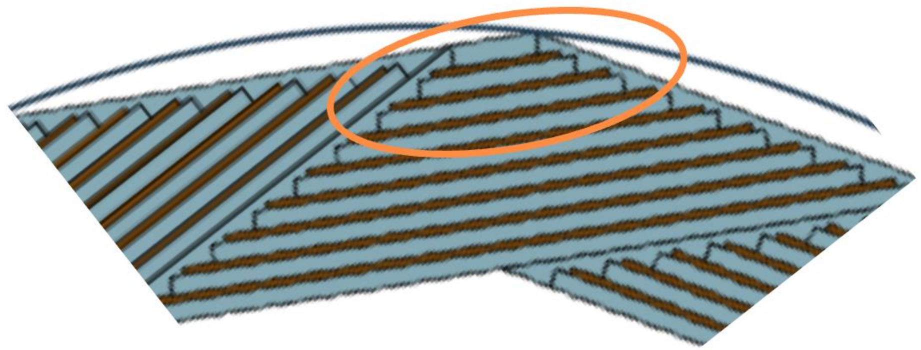
Muon ID efficiency vs efficiency of single channel



6-layer design of the barrel

What we learn from the simulations:

1. Efficiency of a single channel should $\geq 95\%$,
2. Number of superlayers should ≥ 6,
   while, layers #7,8 are not very helpful for the muon ID, due to the short ϕ-length
3. Threshold of momentum $> 4\ \mathrm{GeV}/c$, need help from HCAL for the lower momentum muon track.

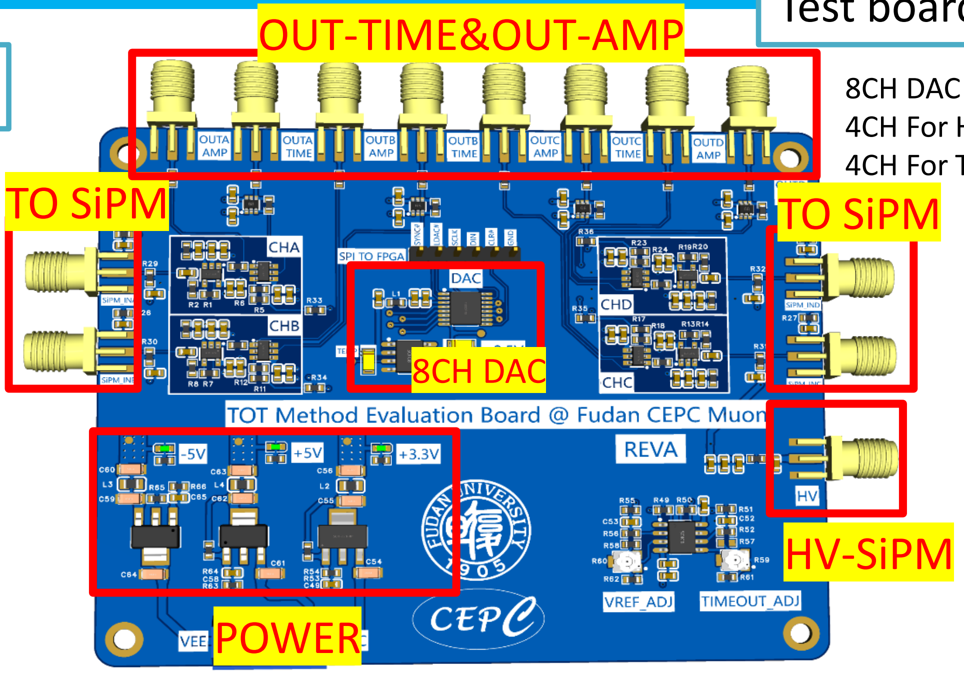


Readout electronics: Time-over-threshold (TOT) scheme

- Front-end electronics ready:
  - High time resolution preamp: $\sigma_T \approx 20\,ps$
  - High-speed discriminator shows $\sigma_T \approx 0.2\,ns$
- Implementation of TOT: operational amplifier + high-speed discriminator + TDC.
- FEE integrated DAC to adjust threshold and SiPM bias voltage.
- It's possible to get N_{pe} according to TOT.
- Investigating the possibility of integrating the BEE into the detector module: only power cable and signal fiber.

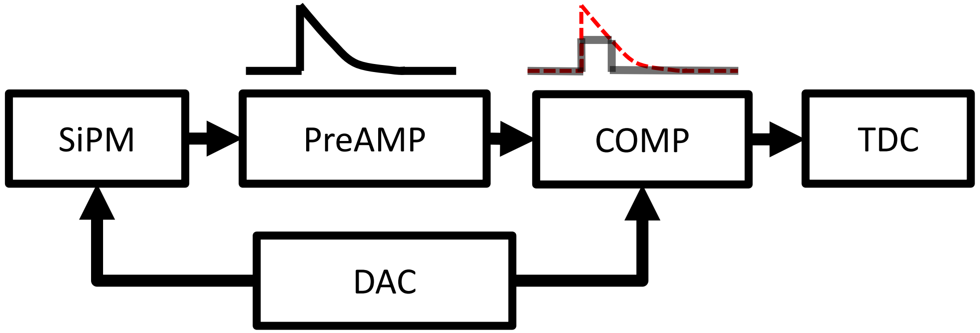
Long cables!

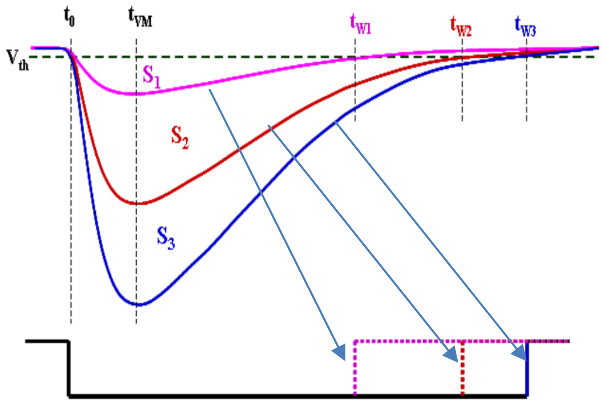
Test board

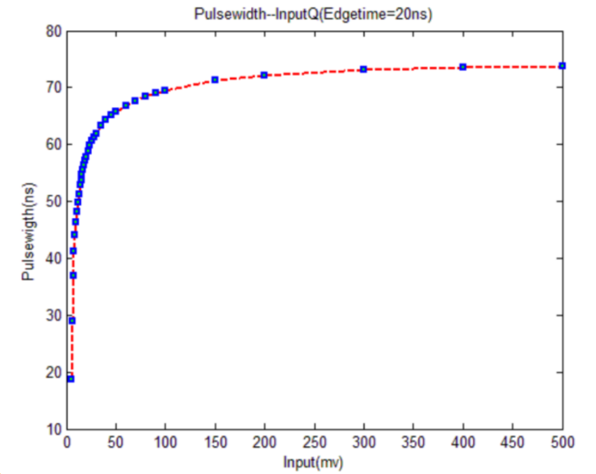


8CH DAC AD562
4CH For HV_ADJ
4CH For TH_ADJ

Temperature sensor will be included.

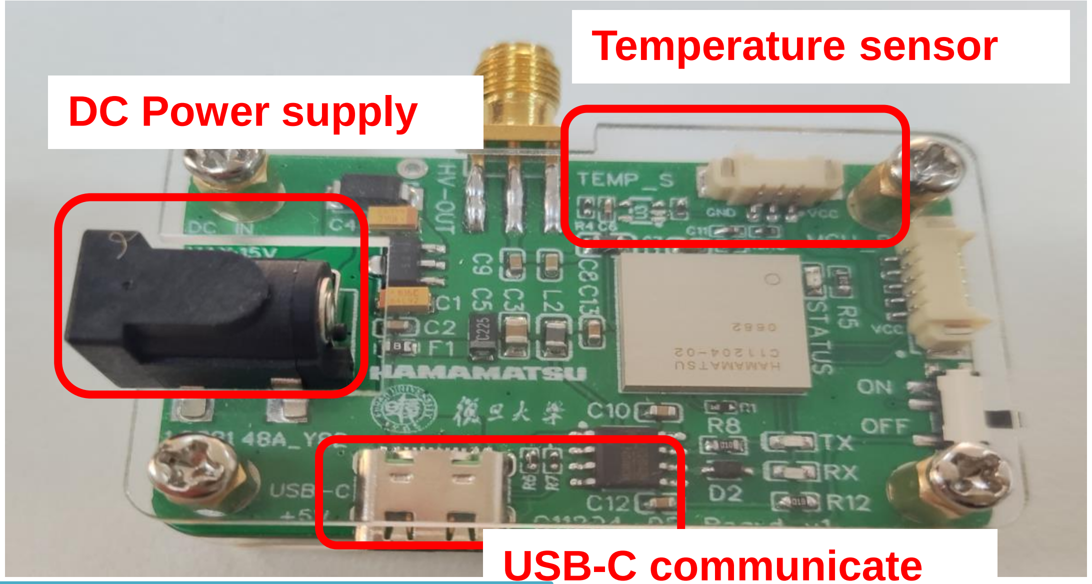




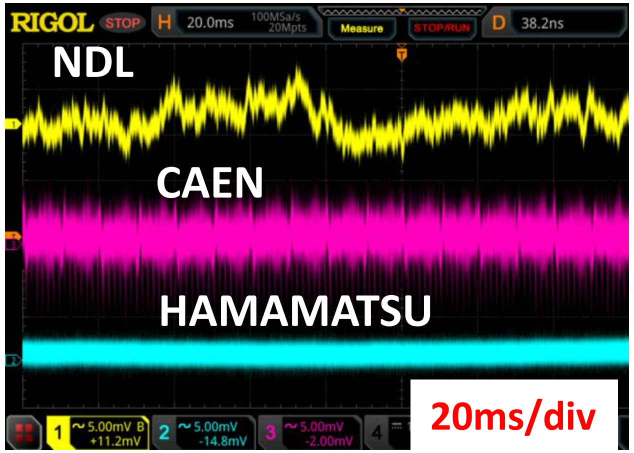


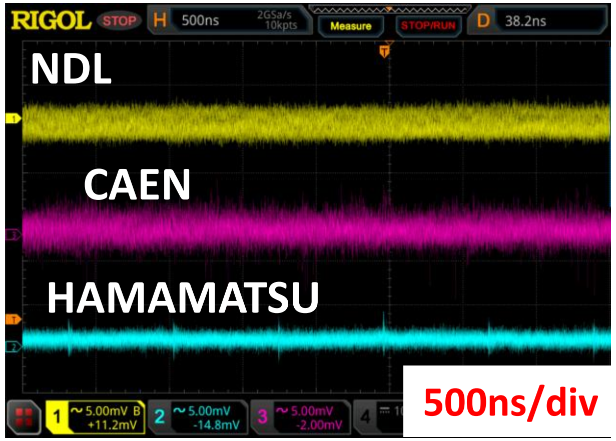
SiPM mini power

- Study on mini power to be integrated into the FEE.



Ripple noise @ OUTPUT:45V





SiPM POWER	BIAS-2-14/70 @NDL	C14156 @Hamamatsu	MAX5026 @Fudan
Voltage (V) Output Range	14~70	0~80	0~71
Current (mA) Output Range	0.5	2	2
Number of SiPMs driven	100	400	400
Power consumption (mW)	250	100	200
Ripple noise (mV/Vpp)	5.2	0.1	2
Price (¥)	~2000	500	30

1$ = 7¥