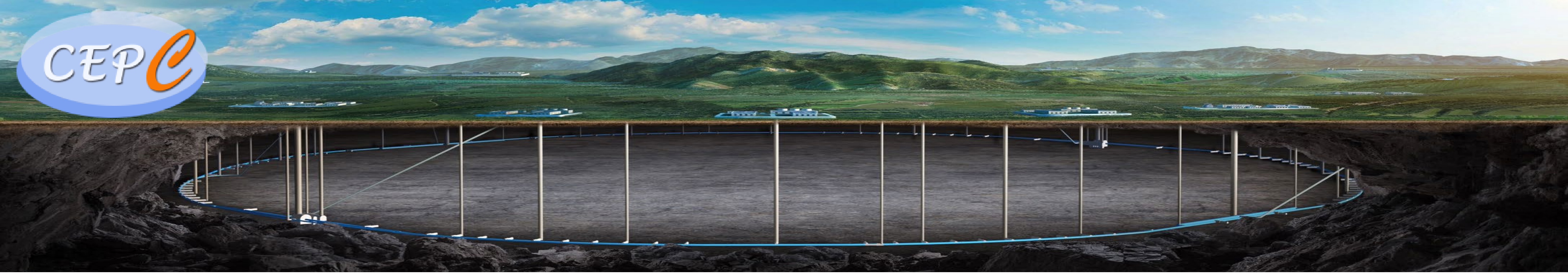


CEPC Muon Detector

Xiaolong Wang
(for the Muon Detector Group)
Fudan University

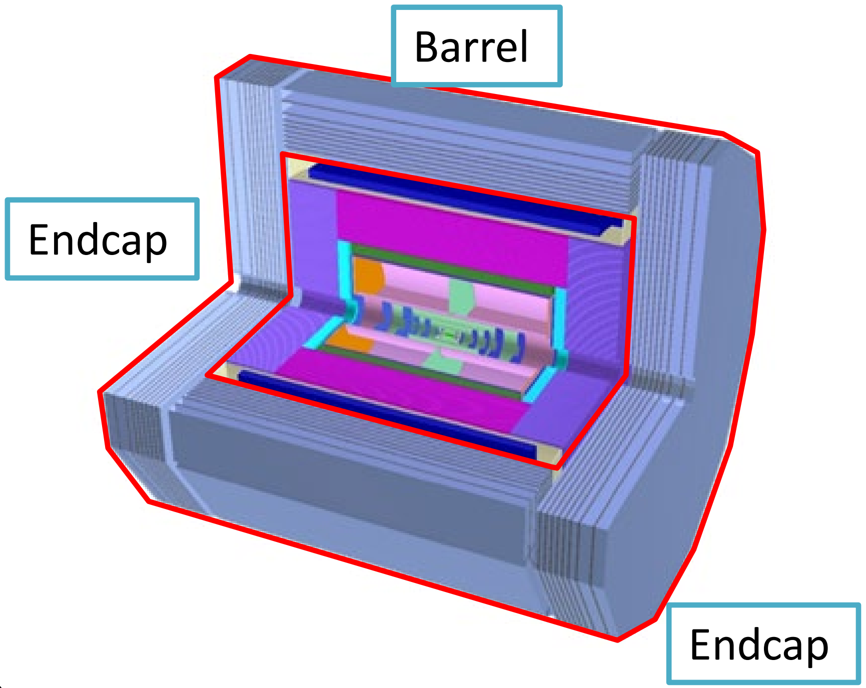
Content

- Introduction
- Requirements
- Technology survey and our choices
- Technical challenges
- R&D efforts and results
- Detailed design
- Performance from simulation
- RPC related and testing
- Research team and working plan
- Summary

Introduction

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

- Production of Higgs: $e^+e^- \rightarrow ZH$, Higgs could be determined in the recoil of $Z \rightarrow \mu^+\mu^-$.
  - Special determination of muon with $p \approx 40\ \mathrm{GeV}/c$.
- 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.
  - Could be useful for T0 determination. $\sigma(T0) = \sigma(T_{hit})/\sqrt{n_{hits}}$
  - Can be used to search for Long-lived particles, with its large volume, and **relatively clean environment** outside HCAL.
- 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

Requirements

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

Solid angle coverage and detection efficiency → High efficiency

Fake rate → Low fake rate

Position resolution → Resolution due to the multiple scattering of muon

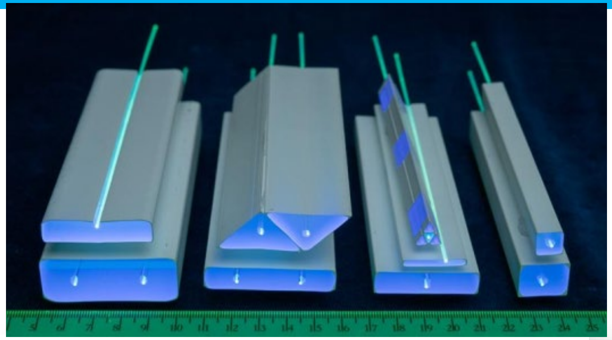
Time resolution → A typical time resolution of modern muon detector, and useful for trigger, T0 and background suppression.

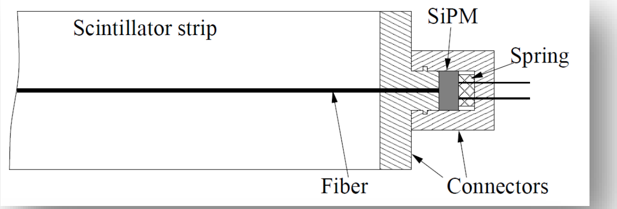
Rate capability → Compatible with the high luminosity operation

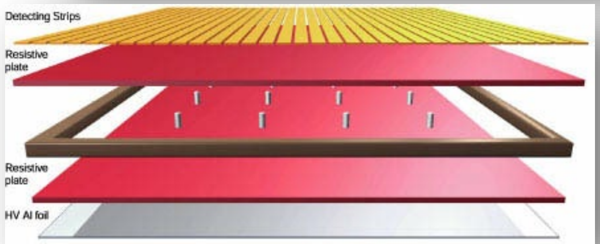
Technology survey and our choices

- Extruded plastic scintillator (PS) technology
  - Belle II, JUNO-TAO, MATHUSLA, LHAASO, sPHENIX, etc.
- RPC technology:
  - Belle, BESIII, Dayabay, ATLAS, CMS
- μ-RWELL (MGPD) technology
  - IDEA
- Experiments @ LHC
  - ATLAS: Thin Gap Chamber, RPC, Monitored Drift Tube, Small-Strip Thin-Gap Chamber, and Micromegas
  - LHCb: MWPC, RPC
  - CMS: Drift tube, Cathode Strip Chamber, RPC

Simple structure:
PS bar, fiber, SiPM





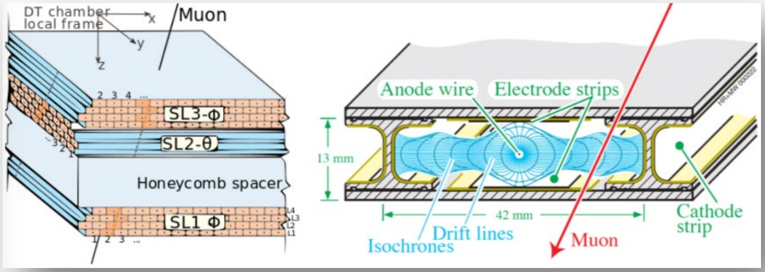


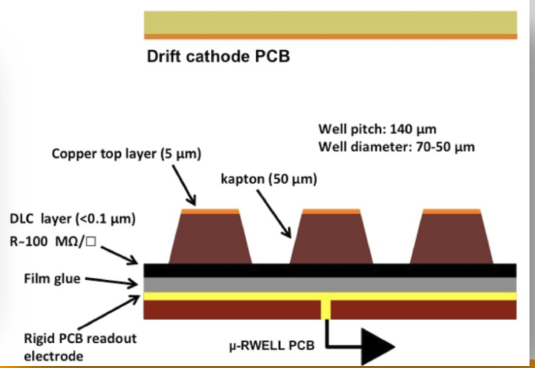
Summary of performance and technical requirements for different gaseous μ detectors

	MDT/DT	CSC	TGC	MRPC	RPC
Spatial resolution [µm]	150	100	5mm	15mm	15mm
Time resolution [ns]	40	7	4.3	0.075	2
Averaged efficiency [%]	98	98	99	95	95
Hit rate [Hz/cm^2]	200	500	1000	500	100
Eletronic dependence	A	A	B	A	C
Software dependence	B	A	B	C	C
Technology requirement	A	A	B	B	C
Cost per channel	H	H	M	M	L

A-C are in descending order of the requirements,H-High,M-Middling,L-low.

+PS





Comparisons

	Advantages	Disadvantage
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.

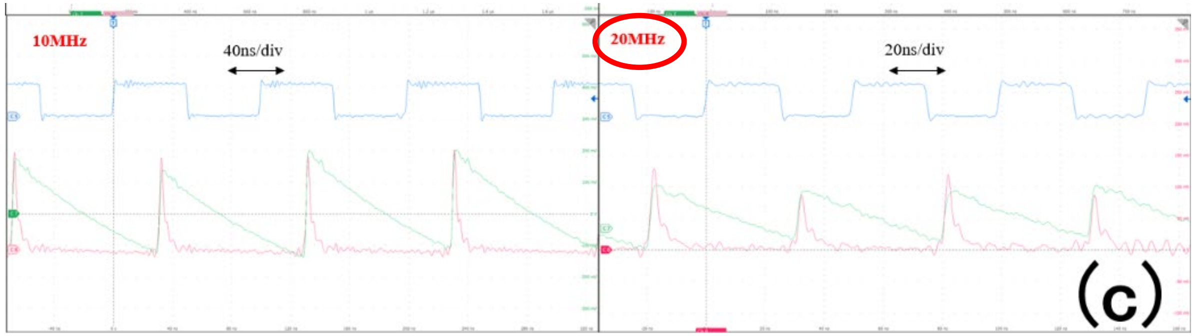
Consideration of rate capability:

- Decay time: ns level
- SiPM+FE: $< 100\ ns \rightarrow 10$ MHz
- Typical area of a bar: 1600 cm^2
- Pulse shape: width ~ 10-20 ns
- Rate capability: $5\sim10\text{kHz}/cm^2$

Scintillator	base	density ϱ [g/cm^3]	τ_D [ns]	L_{ph}, N_{ph} [per MeV]	λ_{em} [nm]	$n(\lambda_{em})$
Anthracene		1.25	30	16 000	440	1.62
BC-408 (BICRON)	PVT	1.032	2.1	10 000	425	1.58
BC-418 (BICRON)	PVT	1.032	1.5	11 000	391	1.58
UPS-89 (AMCRYS-H)	PS	1.06	2.4	10 000	418	1.60
UPS-91F (AMCRYS-H)	PS	1.06	0.6	6 500	390	1.60

PS bar and RPC have similar cost.

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



Test on SiPM+FEE with 20 MHz laser.

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?
  - $2.8m$ bar has been used at Belle II;
  - $1.5m$ bar has been tested in lab;
  - It's possible since Kuraray fiber has an attenuation length of $6.8m$.
  - Effective attenuation length of $2.63m$ from lab testing on WLS fiber.

Content

- Introduction
- Requirements
- Technology survey and our choices
- Technical challenges
- R&D efforts and results
- Detailed design
- Performance from simulation
- RPC related and testing
- Research team and working plan
- Summary

R&D efforts and results

- Simulation and software
- Performance of PS bars
- Front-end electronics
- Prototype and CR testing

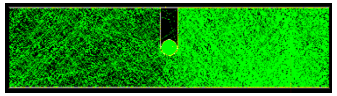
Published papers:

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)

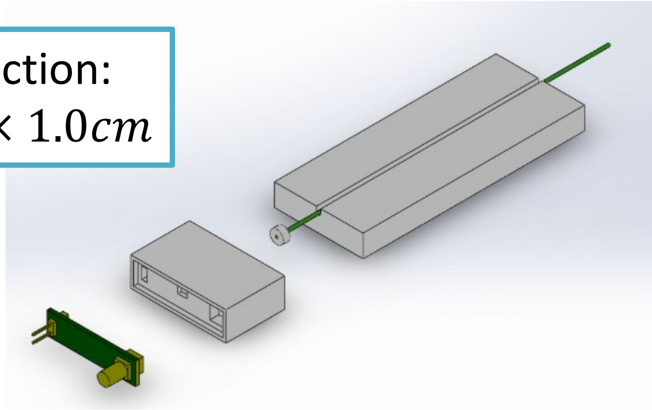
Performance of PS bars

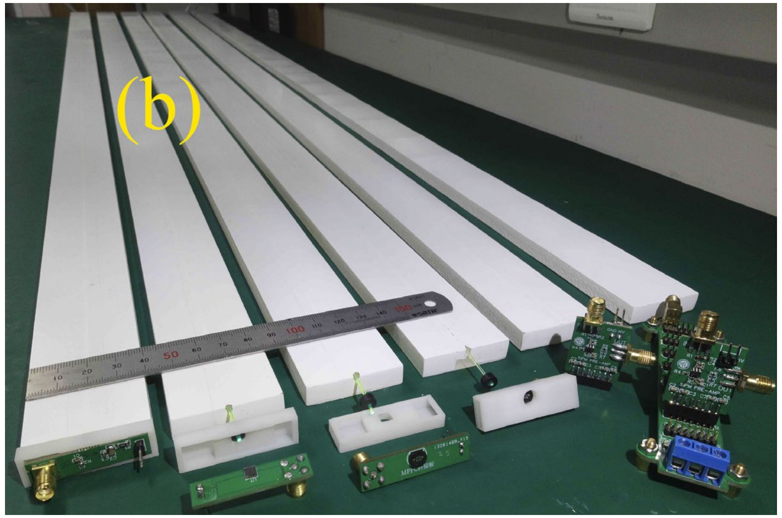
- PS bars made by GNKD company (Beijing)
  - Increase the light yield;
  - Develop/improve the reflection layer with Teflon;
  - Strip production, with a width of $4cm$.
- The quality of $1.5m$ bars has achieved the required performance, which will be described later.
- R&D on longer bar with hole has started

Samples with U groove



Cross section: $4.0cm \times 1.0cm$

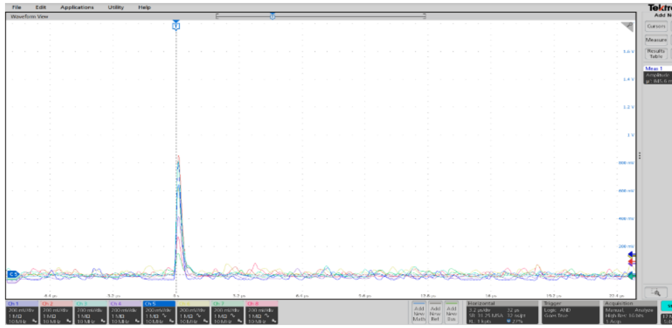


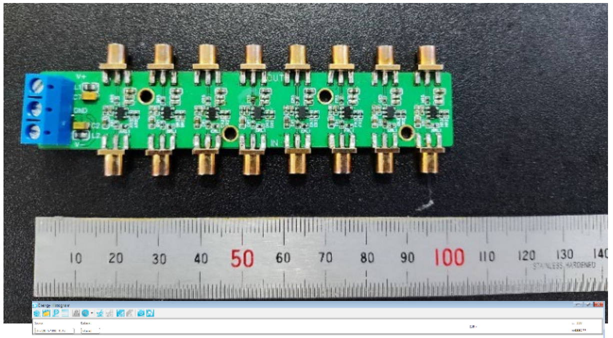


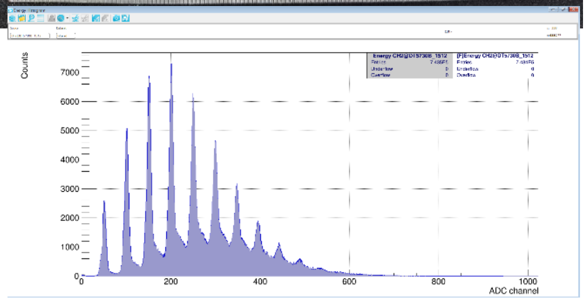
R&D for front-end electronics

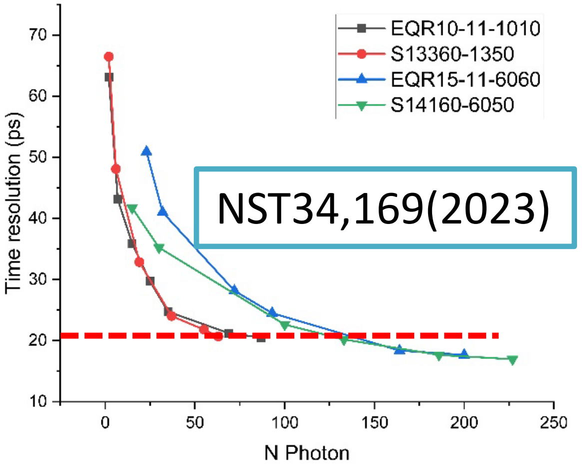
- Many different kinds of preamps for SiPM have been designed and tested, such as:
  - Design high-speed and low-noise preamp for SiPM.
    - Baseline noise of 0.6 mV, bandwidth of 426 MHz, and time resolution of 20 ps.
    - Test with laser input at 20MHz.
    - Clear N_{pe} spectrum.
  - Design FEE to test with 16 ch ADC
    - Develop the FPGA for ADC.
    - Works well, but time resolution is several ns due to the DCR.

ADC output signals of scintillators



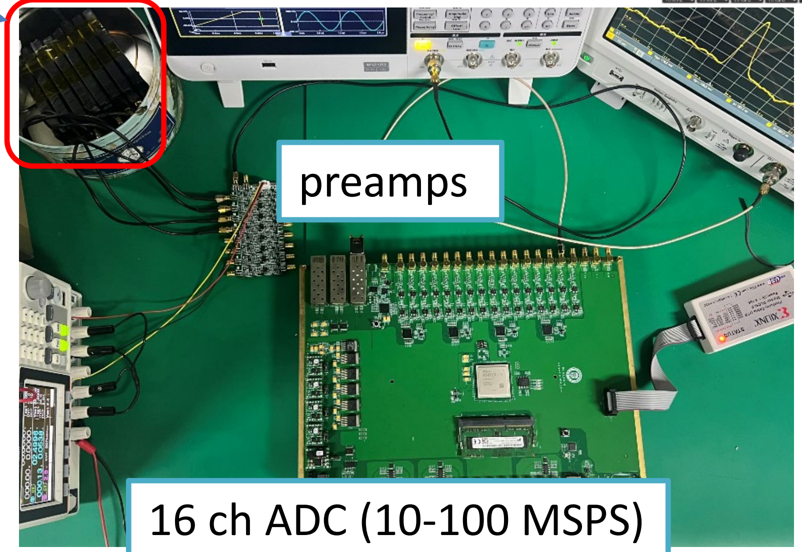


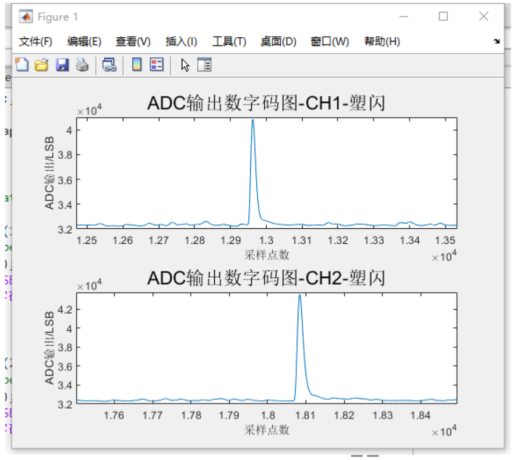




NST34,169(2023)

8ch PS short bars

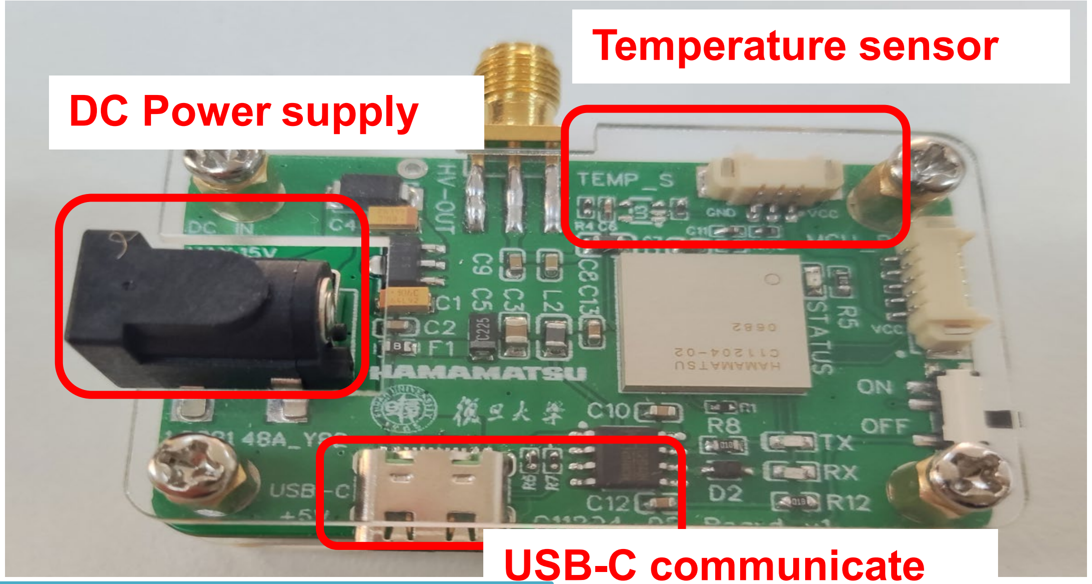




16 ch ADC (10-100 MSPS)

SiPM mini power

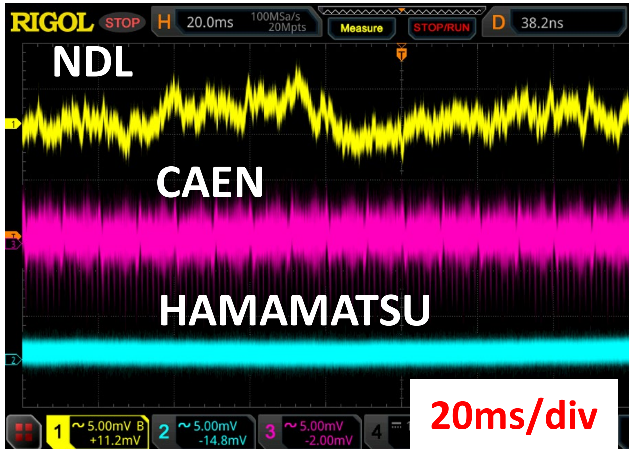
- Study on mini power to be integrated into the FEE.

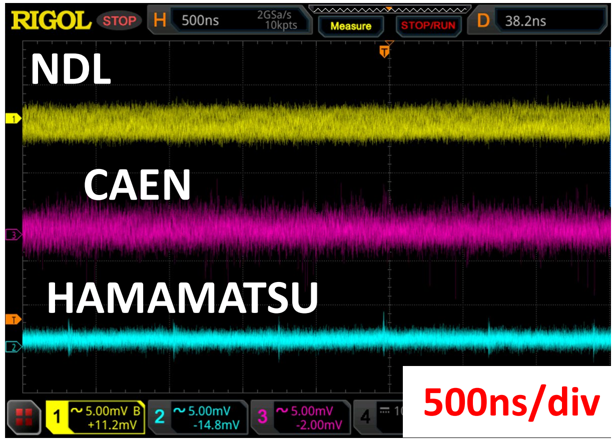


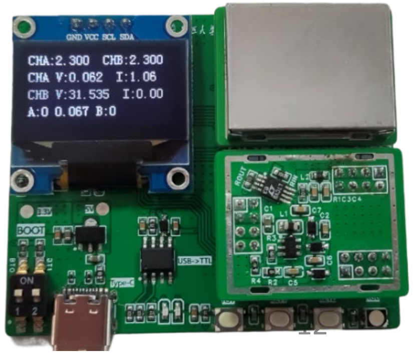
SiPM POWER	BIAS-2-14/70 @NDL	C14156 @Hamamatsu	MAX5026 @Fudan
Voltage (V) Output Range	14~70	0~80	0~71
Current (mA) Output Range	0.5	2	2
Number of SiPMs driven	100	400	400
Power consumption (mW)	250	100	200
Ripple noise (mV/Vpp)	5.2	0.1	2
Price (¥)	~2000	500	30

1$ = 7¥

Ripple noise @ OUTPUT:45V

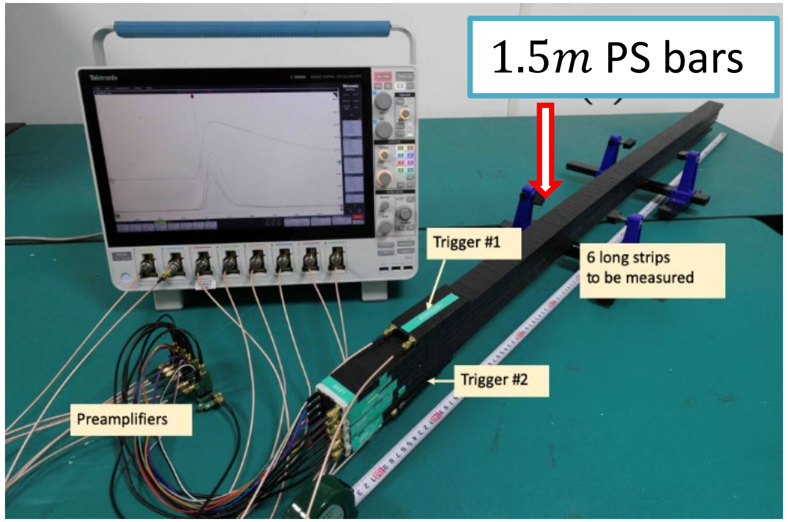






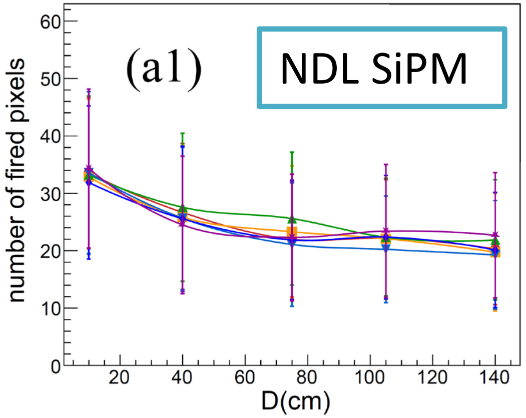
Prototype and CR test

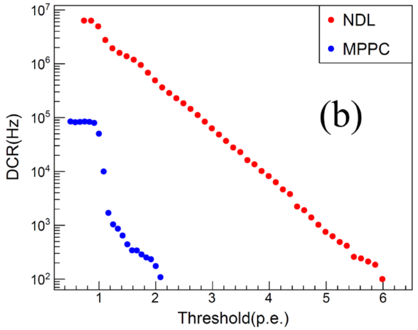
- Study of SiPMs, WLS fibers
- Prototype:
  - $1.5m$ PS bar + WLS fiber ($1.2mm$) + NDL SiPM/MPPC ($3.0mm/1.3mm$)
- Performance:
  - $\epsilon > 98\%$
  - Time resolution better than $1.5ns$

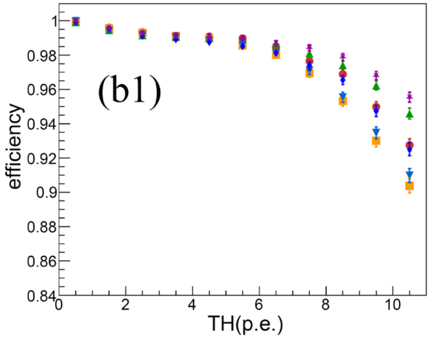


JINST 19 P06020(2024)

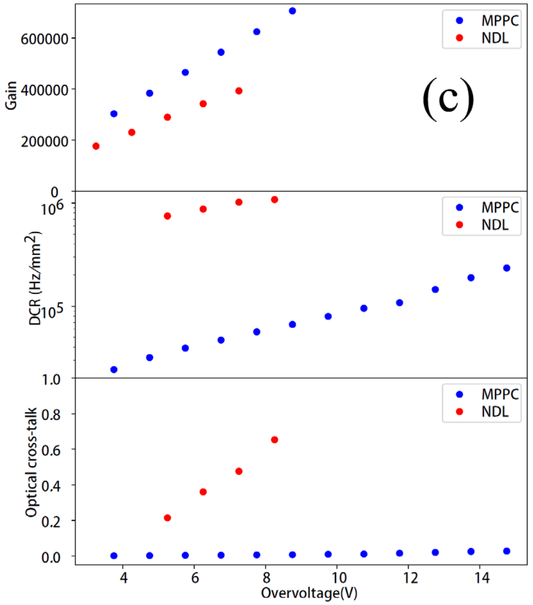
Effective attenuation length of fiber $L_{Att} = 2.63 \pm 0.37\ m$

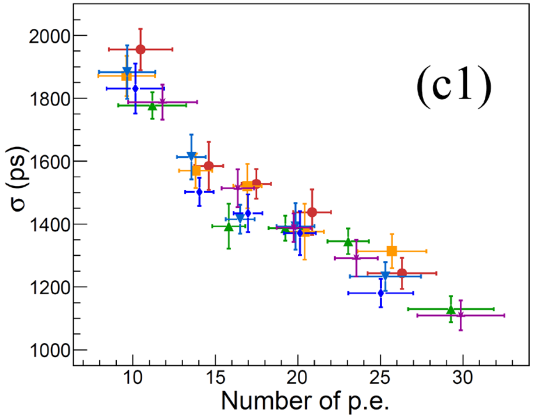


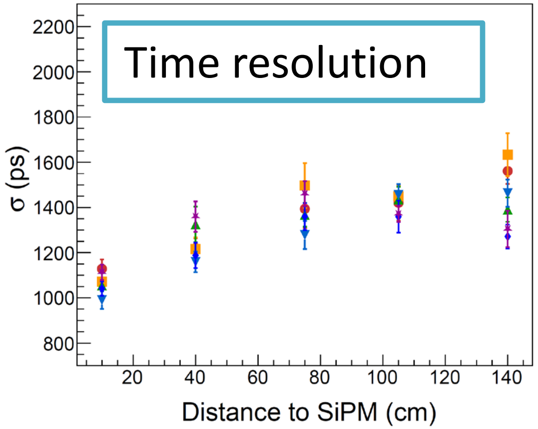




Properties of SiPMs

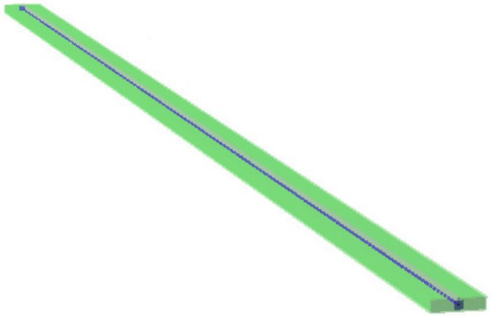


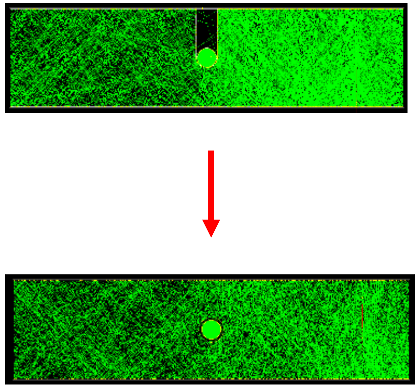




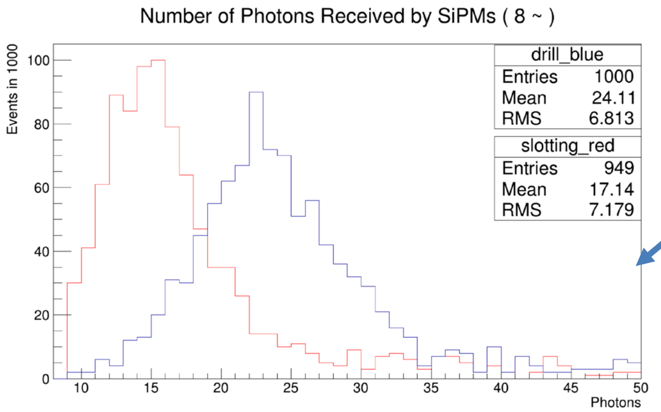
Standalone simulation

- Improving the performance of a single channel is to the key for a long detector module.
  - Light yield and light collection
- Simulation for single channel
  - Light collection and compared to lab test
  - Fiber embedding: Groove → hole, $N_{pe} \times 1.4$
  - Diameter: $1.2mm$ → $2.0mm$, $N_{pe} \times (2-2.8)$

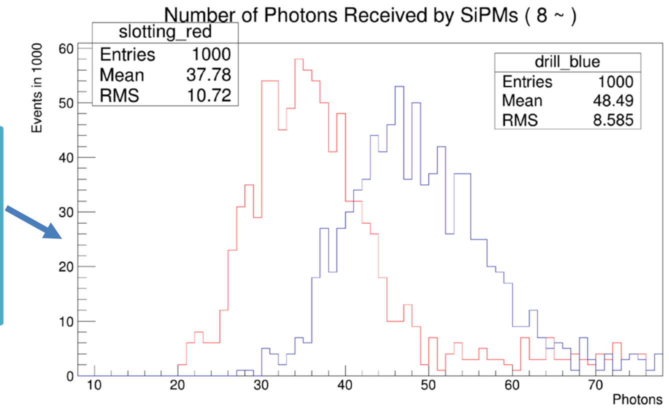


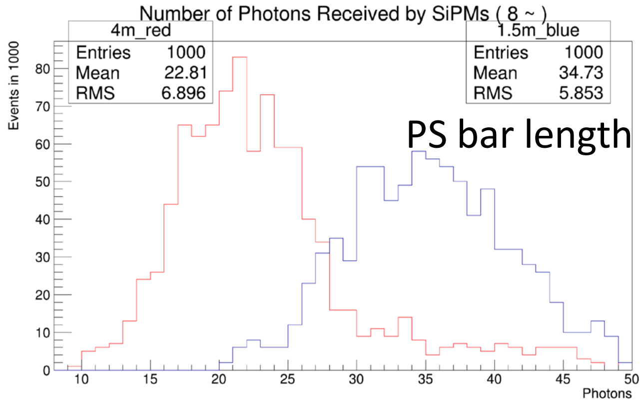


Simulation shows potential to increase the light yield by a factor of $(2.8-3.9)$, which is helpful for building long detector module.



Groove vs hole

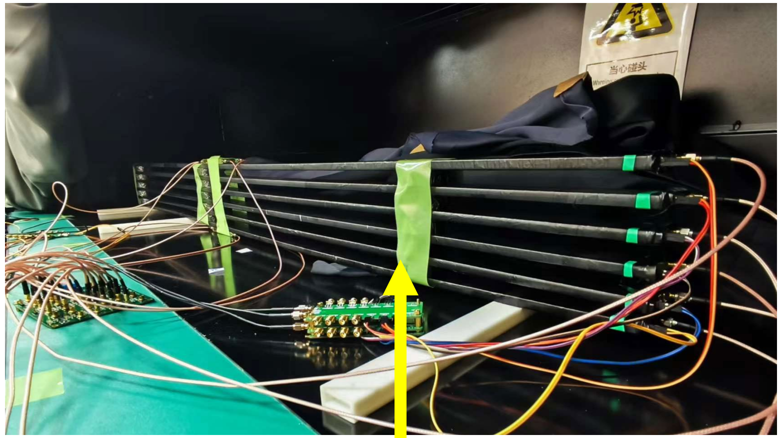




Improvements on the scint. strip

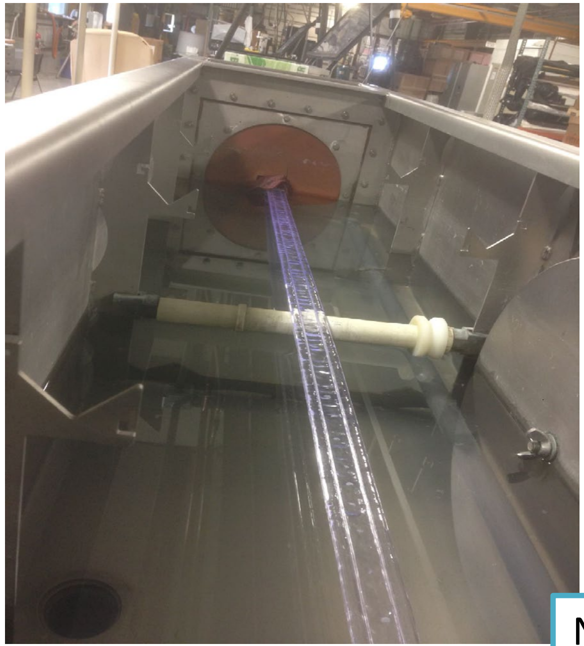
- Very new R&D in the past months, like the production in Fermi Lab.
- Fiber embedding: Groove → hole
- Diameter: no new fiber available yet, we use three 1.2mm fibers instead.

Use NDL EQR15 $3mm \times 3mm$



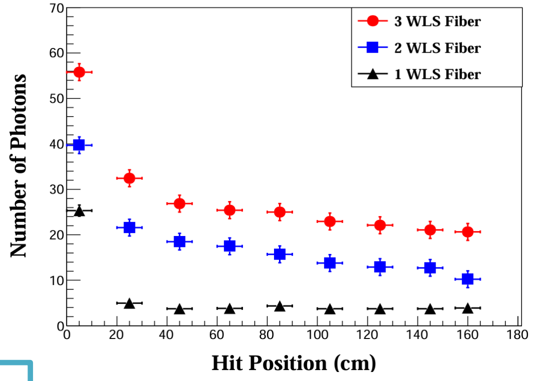
Trigger at middle

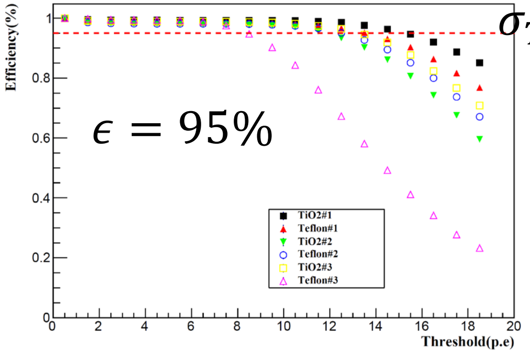
Scintillator production at Fermilab



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

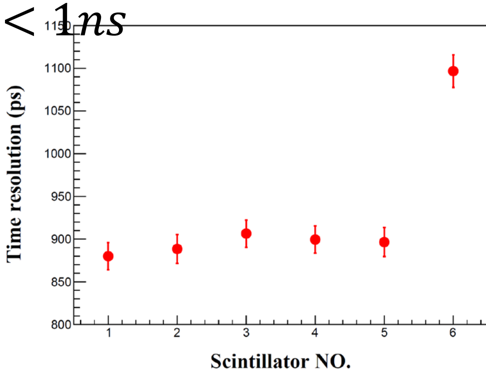
1.65m new scint with 2.5mm diameter hole





$\epsilon = 95\%$

$\sigma_T < 1ns$



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

Content

- Introduction
- Requirements
- Technology survey and our choices
- Technical challenges
- R&D efforts and results
- Detailed design
- Performance from simulation
- RPC related and testing
- Research team and working plan
- Summary

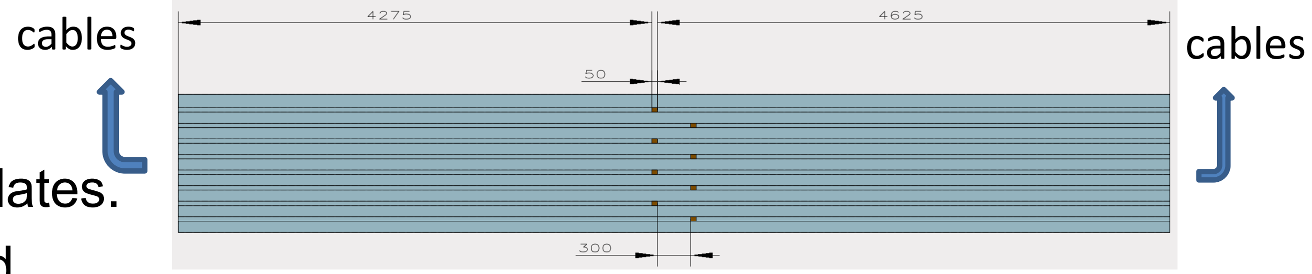
Detailed design

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

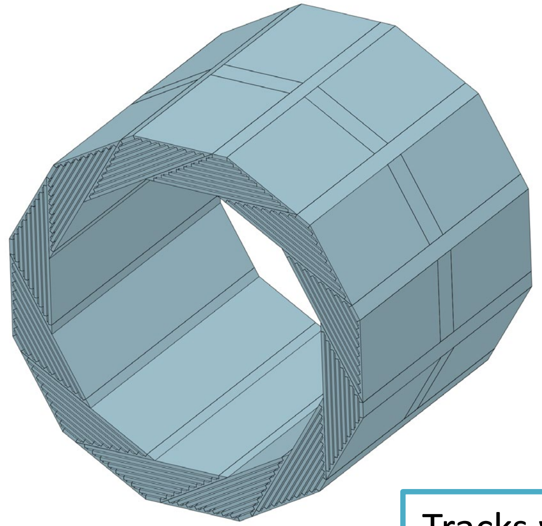
Detailed design - geometry

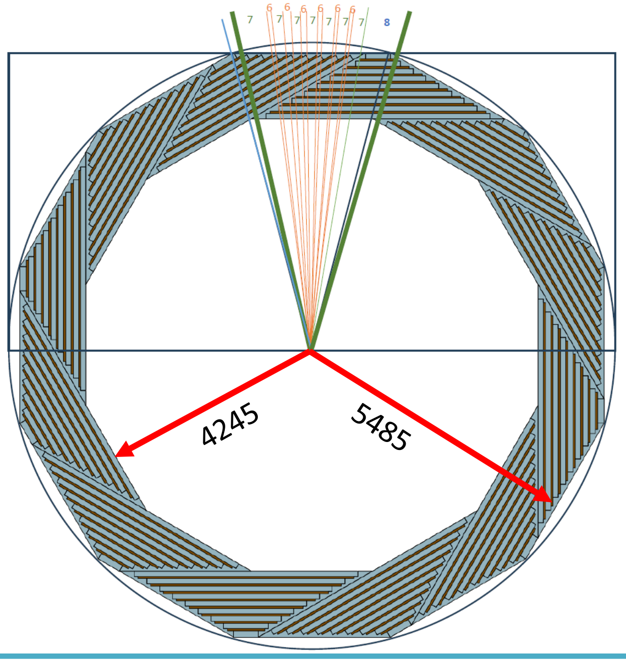
- Geometry: to cover the detection as much as possible
  - Barrel: Helix dodecagon sectors.
  - Rectangle modules inserted between iron plates.
  - Cable: towards the gaps between barrel and endcaps.

$L = 4.275m$ or $4.625m$



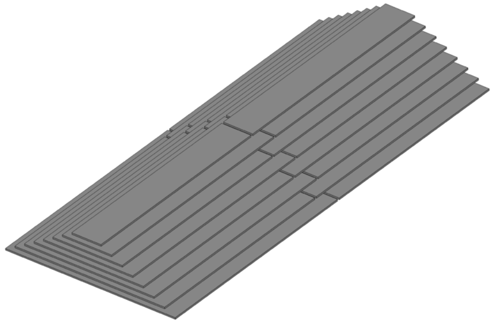
Vary the separation position to avoid dead zone in the middle of barrel.

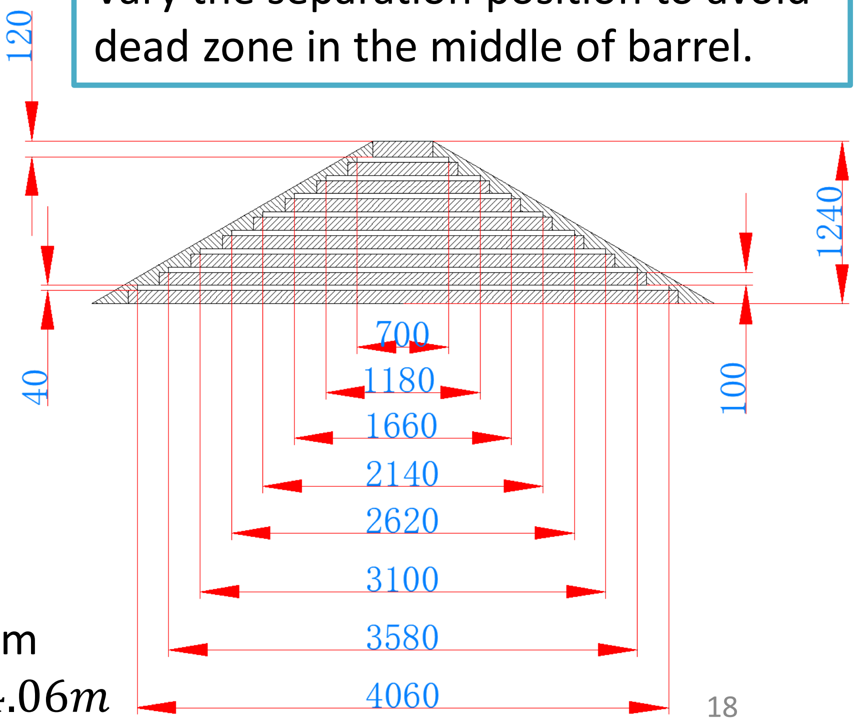




Tracks with high momentum passing 6, 7, or 8 layers.
6-layers: ~25%, 7-layers: ~50%, 8-layers: ~25%

Modules

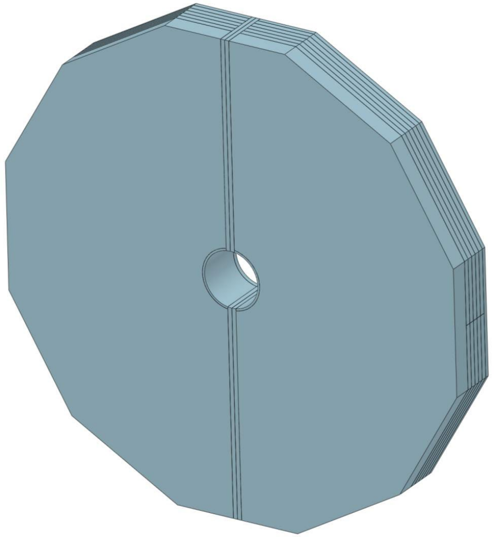


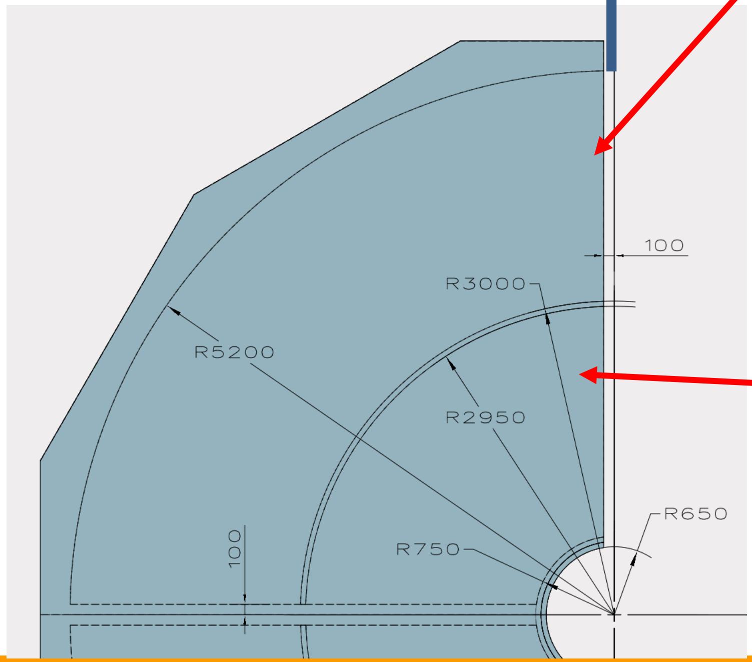


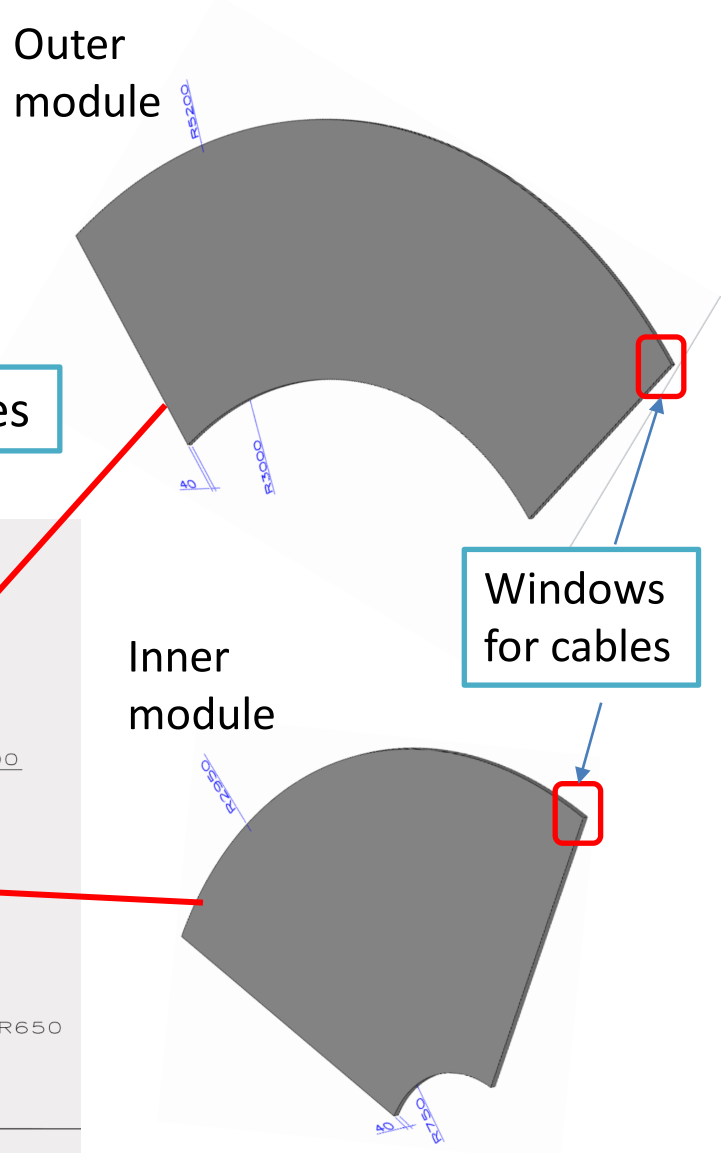
Width from $0.7m$ to $4.06m$

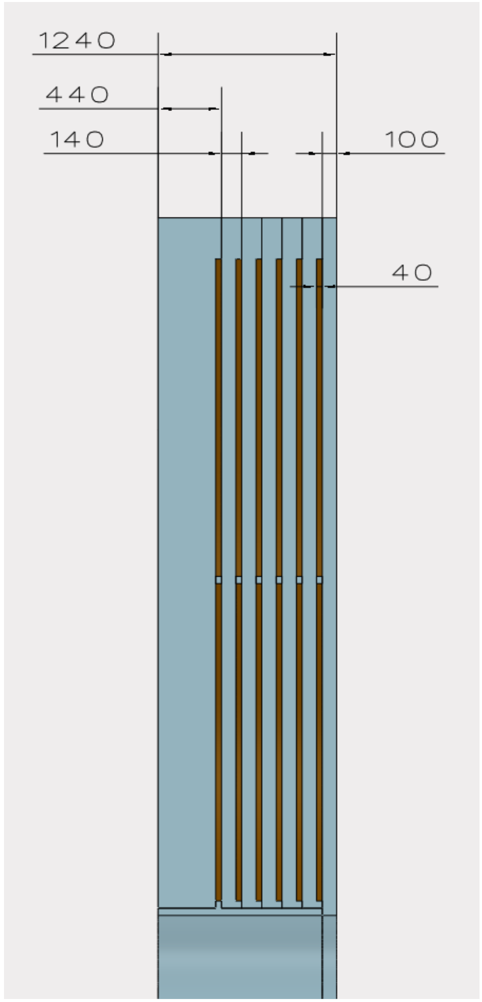
Detailed design - geometry

- Geometry:
  - 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: $4.2m$





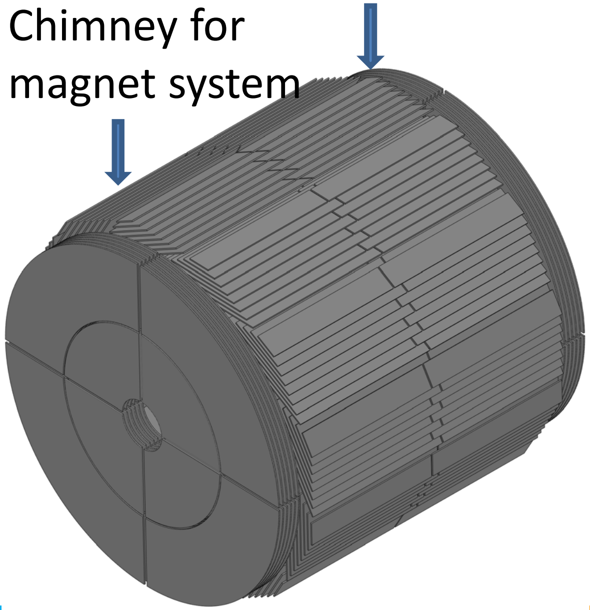


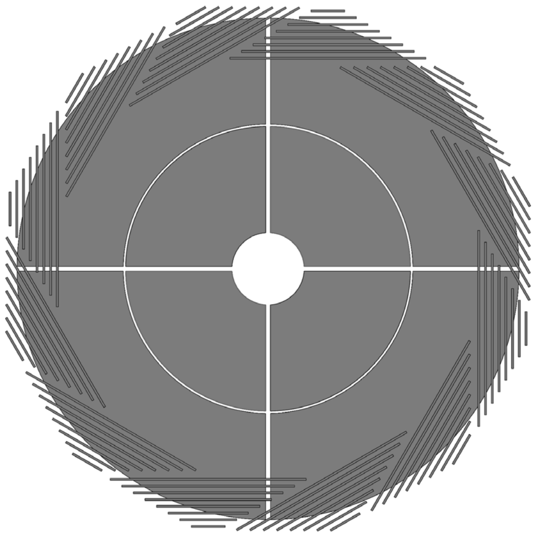


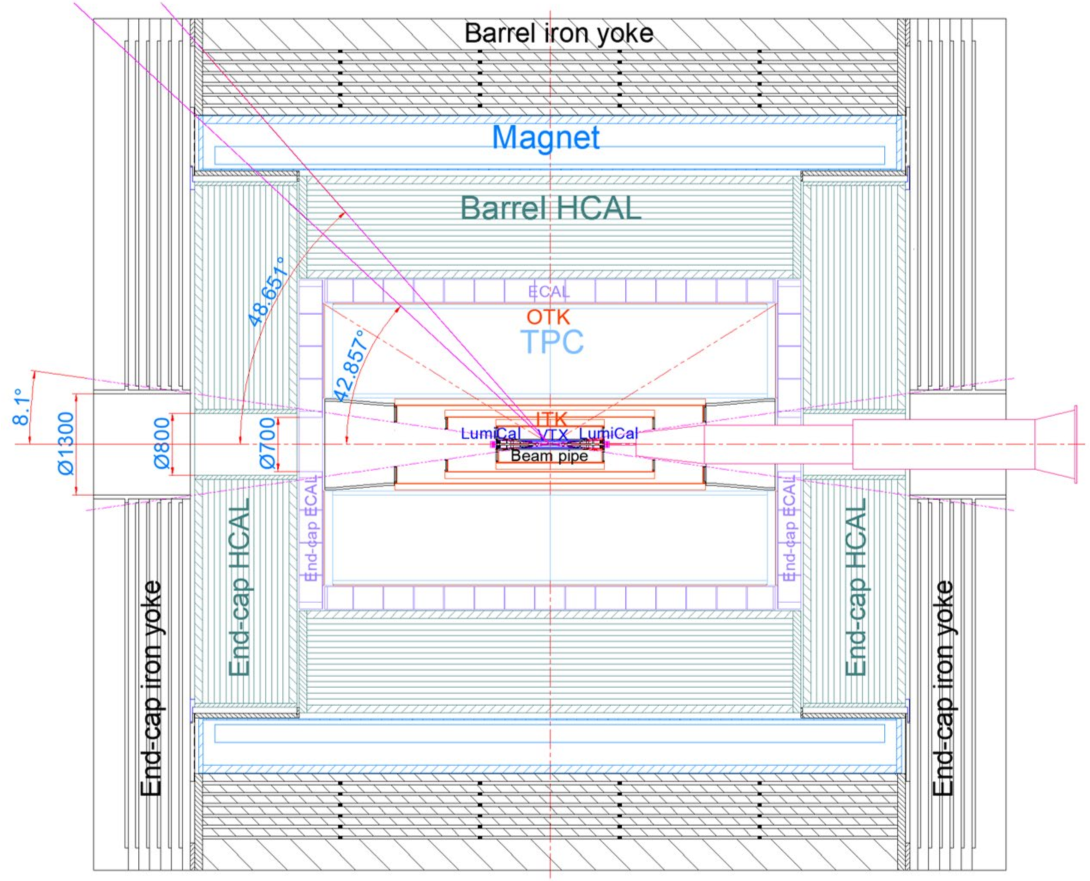
Overall of the design

- Number of channels: (288 modules) 51,744
  - Barrel: 192 modules, 32,544 ch
  - Inner endcaps: 48 modules, 6,912 ch
  - Outer endcaps: 48 modules, 12,288 ch
- Sensitive length: $148{,}416m$
  - Length for PS bar and WLS fiber
- Sensitive area: $5936m^2$

Chimney for magnet system







Detection dead area: $\sim 1.5\%$
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.

Scenarios of geometry

1$ = 7¥ RMB

- Different number of the layers are considered.
- Scenario #1 (current selection): 8 layers of barrel, 6 layers of endcaps
  - Cost ¥27M
- Scenario #2: all 8 layers
  - Cost ¥30M; better performance in endcaps
- Scenario #3: all 6 layers
  - Cost ¥25M; OK for muon ID, tracking will be difficult in some area
- Scenario #4: all 4 layers
  - Save the cost, but it only works for muon ID, and 50% in barrel has only 3 superlayers.
  - Width of iron plate is ~20cm, too thick.

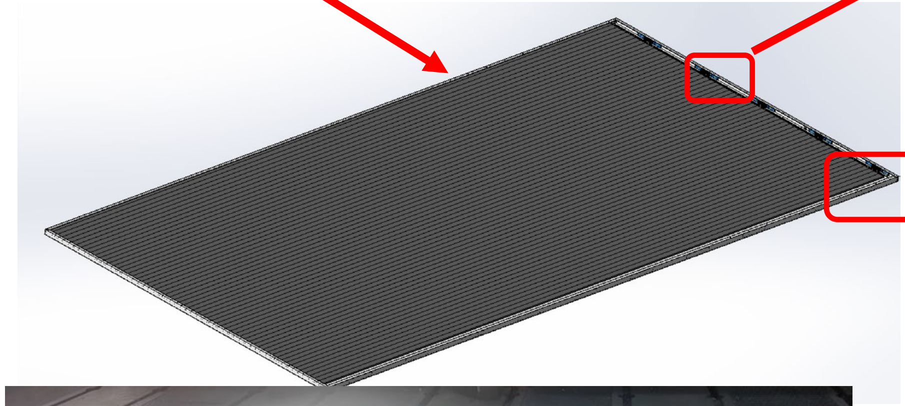
Will show the comparisons on the performance later.

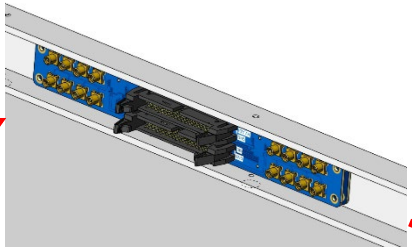
Detailed design of the channel and module

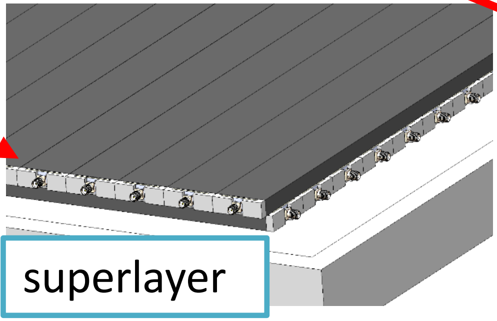
- Detector channel
  - PS bar: $4cm \times 1cm$ cross section
  - WLS fiber: $\phi = 2.0mm$
  - SiPM: $3mm \times 3mm$

- 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

Space covered by aluminum layer.







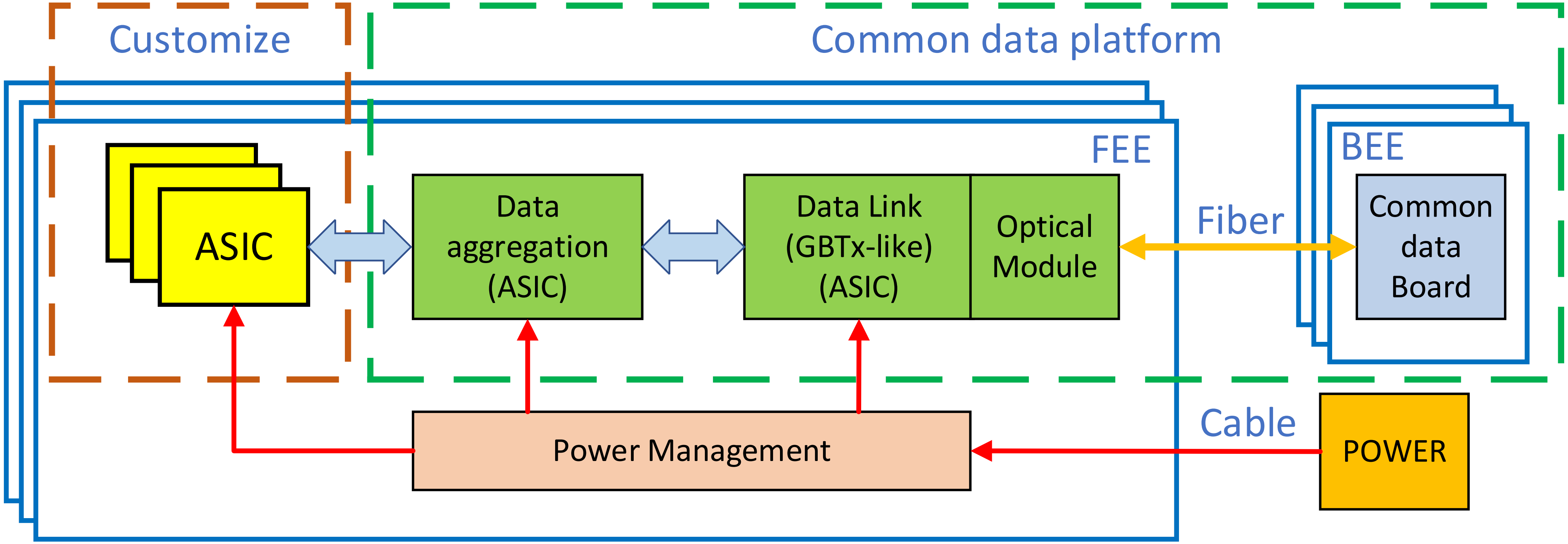
superlayer

To BEE with ribbon cables

Al frame is ready, considerations for prototype: Time resolution, FEE, power consumption, space, temperature, mechanic support, COST, etc.

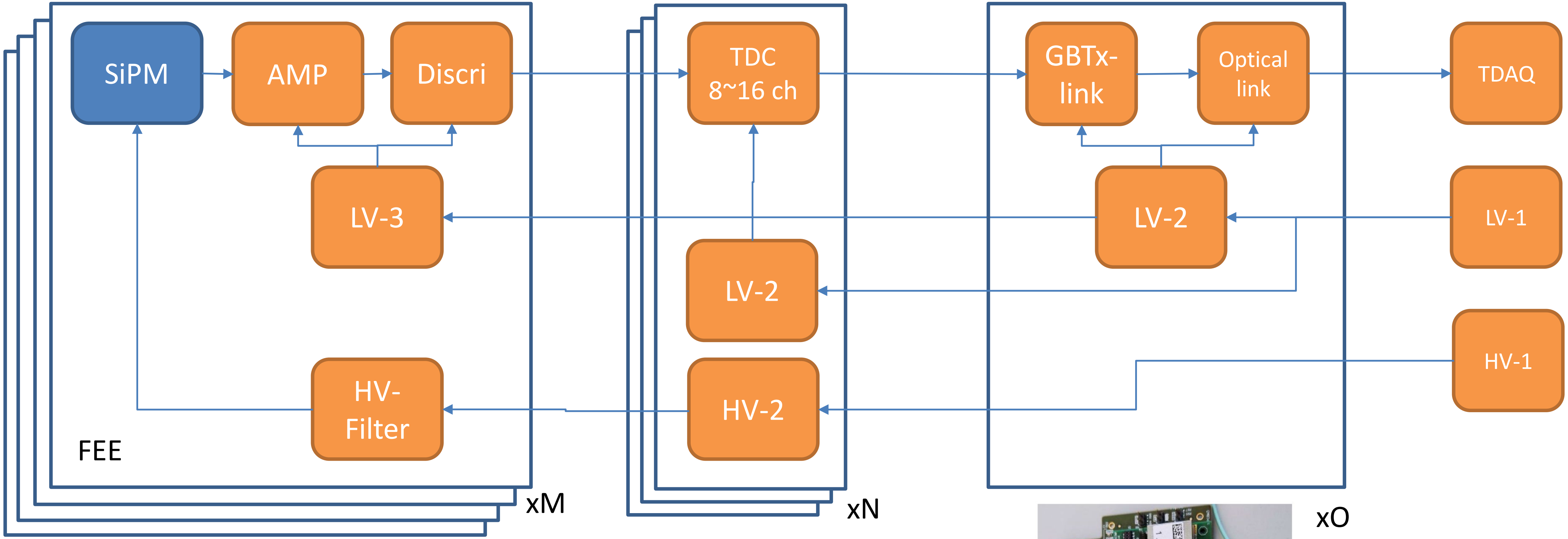
Carrier for the FEE, inside the module. Can be modified for the new electronics in the future.

Baseline for SiPM readout

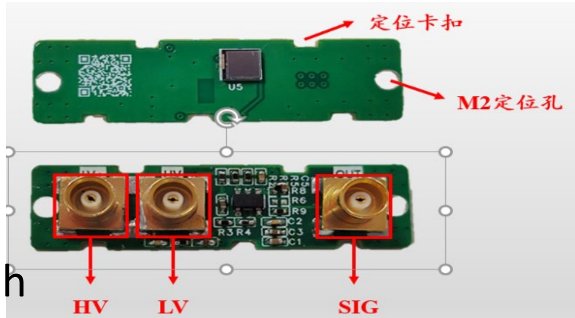


- Readout design for ECAL and HCAL covers the requirements of Muon detector: $N_{pe} < 100, \sigma_T < 0.5ns$
- Use the ASIC scheme from ECAL or HCAL, and customize the FEE based on ASIC.
- Revise according to the constraints from cooling and mechanical structure of the detector

Stage scheme



Example:



For each ch

For each module

For each sector

Content

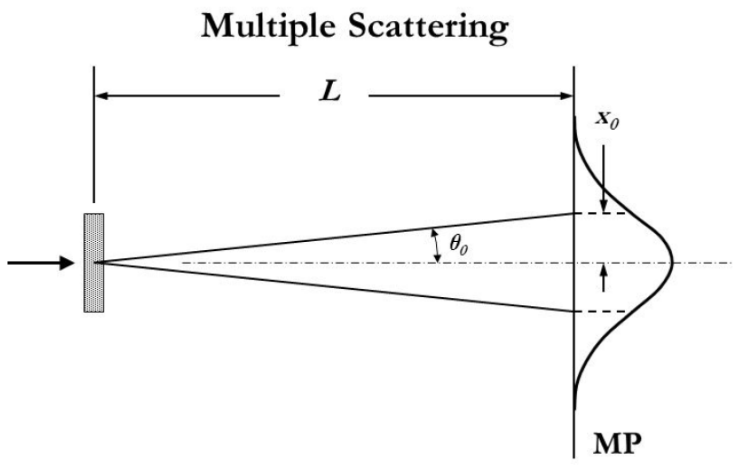
Geant4 simulation for performance

- 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

Spatial resolution

- Spatial resolution due to the multiple scattering:

$$\Theta_{rms}^{proj.} = \sqrt{<\Theta^2>} = \frac{13.6\ \mathrm{MeV}}{\beta c p} z \frac{x}{X_0}[1 + 0.038 \ln(x/X_0)]$$



- From the calculation: $\sim 1.3cm$
- Reference to Belle II (1cm):

  $L \times 2$, $p_{th} \times 4 \rightarrow \sigma_{scat} \sim 1cm$
- The higher momentum, the smaller σ_{scat}

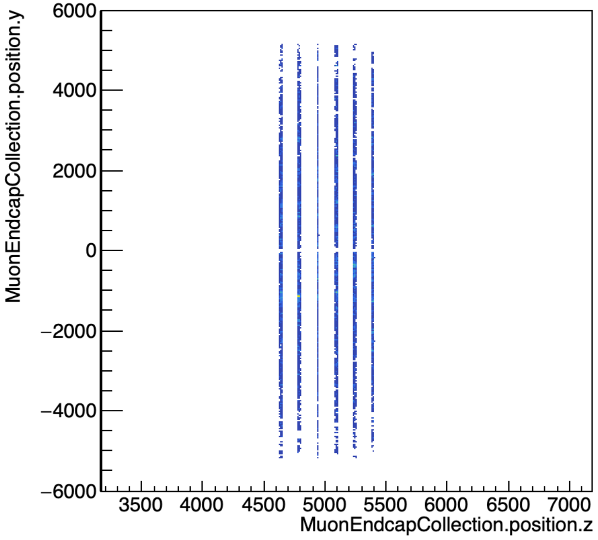
- $\frac{4cm}{\sqrt{12}} = 1.15cm$ for the spatial resolution, but this requires multiple layers.
- Number of superlayers is up to 8.
- The distance between muon detector and HCAL is >0.7m, due to the magnet system.
- The magnet field turns over the direction before and after the magnet system.

Detector Simulation

- Everything based on CEPCSW framework.

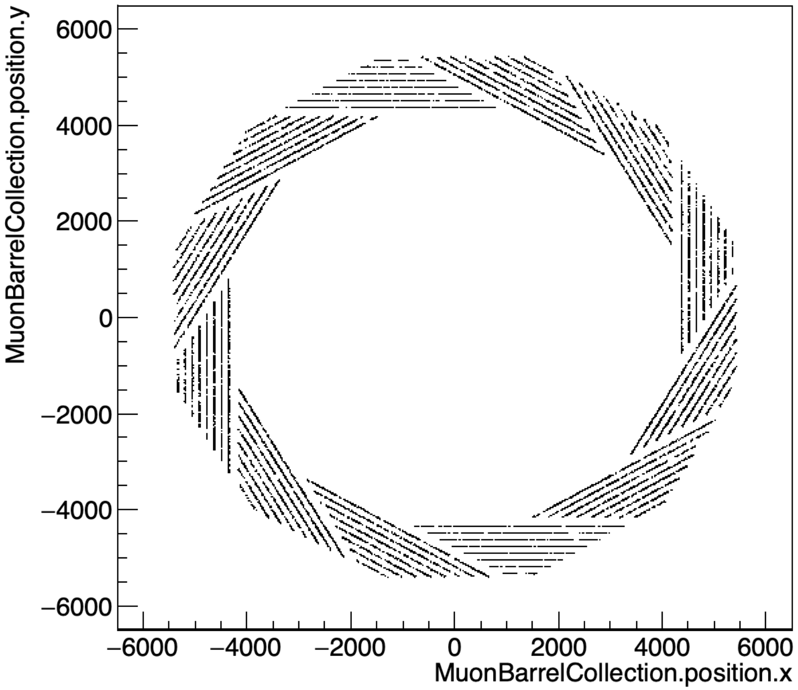
Muon Sim
Hit positions

z-y position
map in Endcap



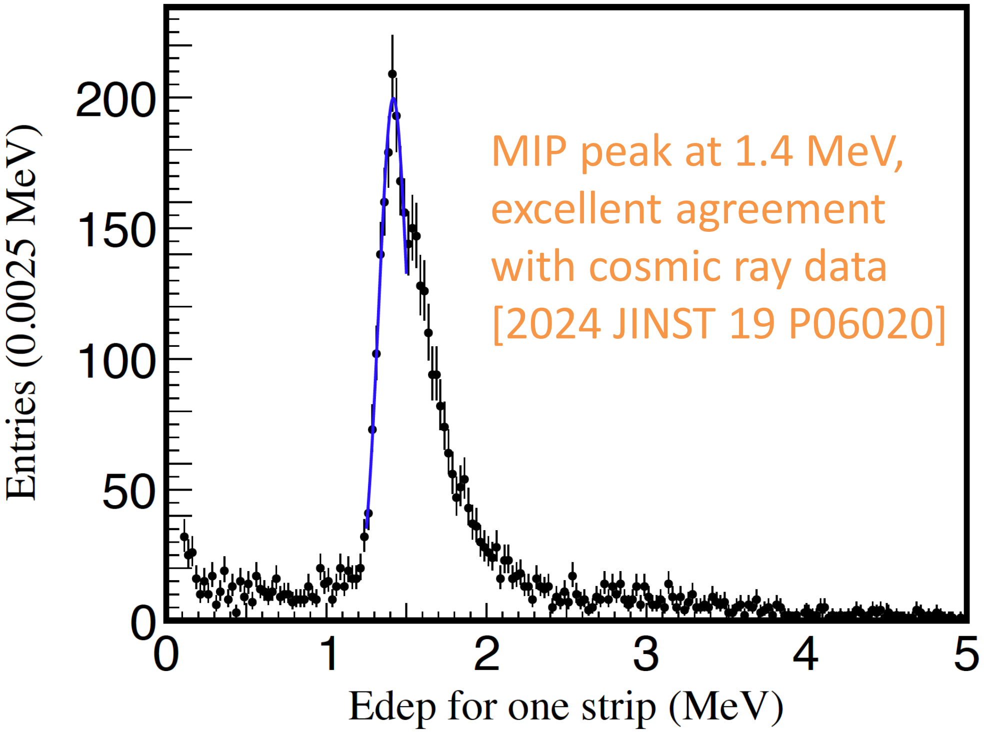
1k muons at 10 GeV muons

x-y position map in Barrel



Muon detector geometry is clearly visible!

Muon Sim Hit Energy deposition



MIP peak at 1.4 MeV, excellent agreement with cosmic ray data [2024 JINST 19 P06020]

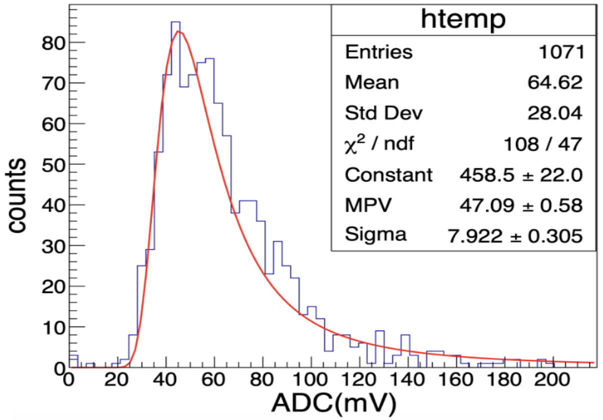
Detector Simulation

- Digitization from “Sim Hit” (deposited energy) to “Raw Hit” (ADC counts)
- A first experimental version implemented:
  - A simplified model from deposited energy to ADC counts.
  - Only for barrel at the moment.

a MIP

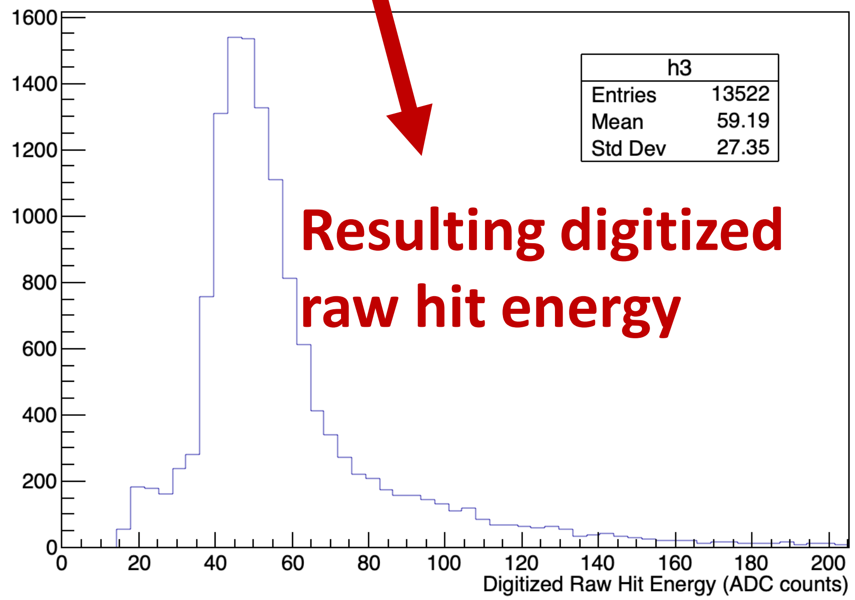
$$E_{dig}\ \text{(ADC counts)} = E_{sim}\ \text{(MeV)} \div 1.4\ \text{MeV} \otimes$$

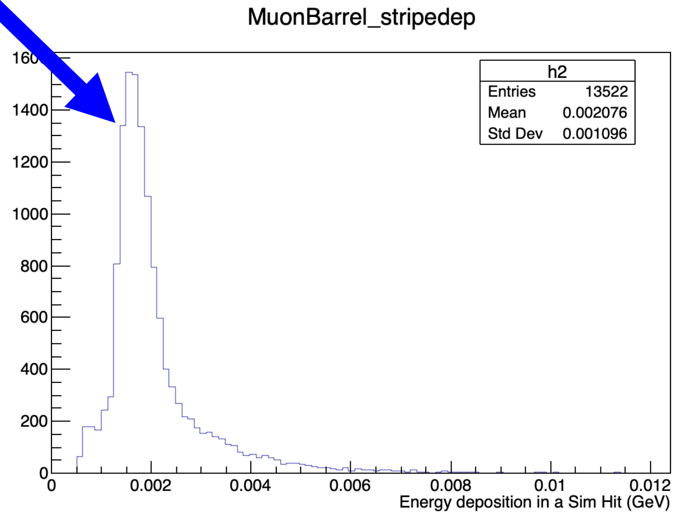
ADC distribution of MIPs from CR testing.



[2024 JINST 19 P06020]

Resulting digitized raw hit energy



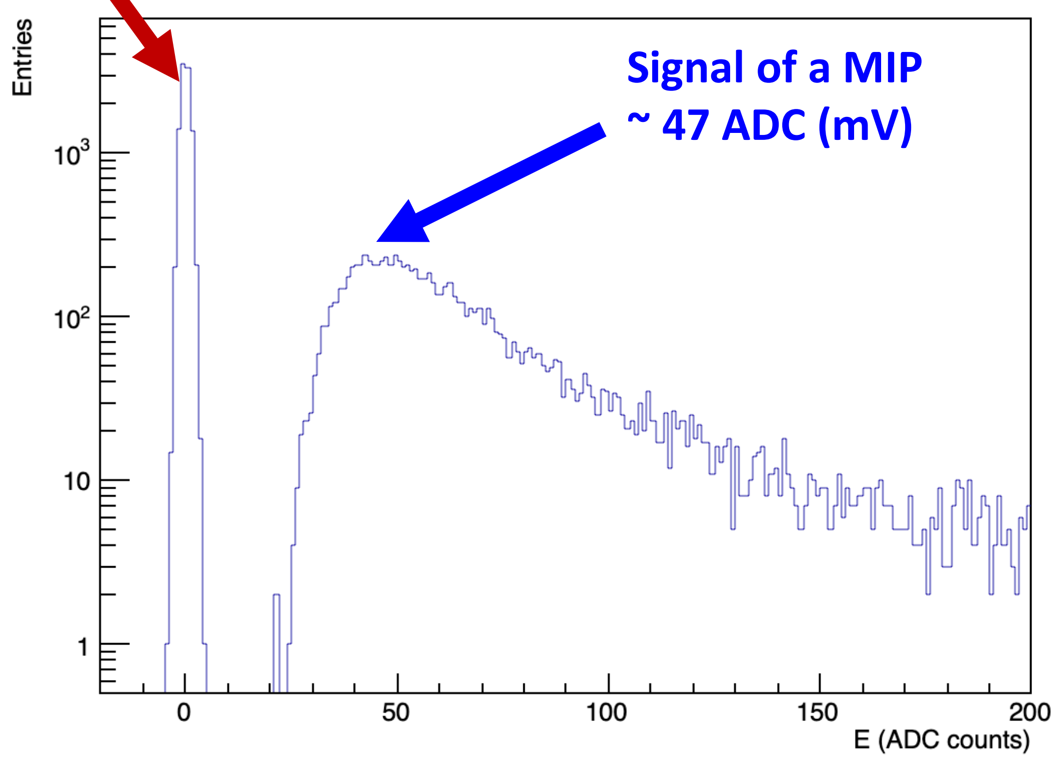


Detector Optimization

- The muon tracker hit vs. energy threshold:

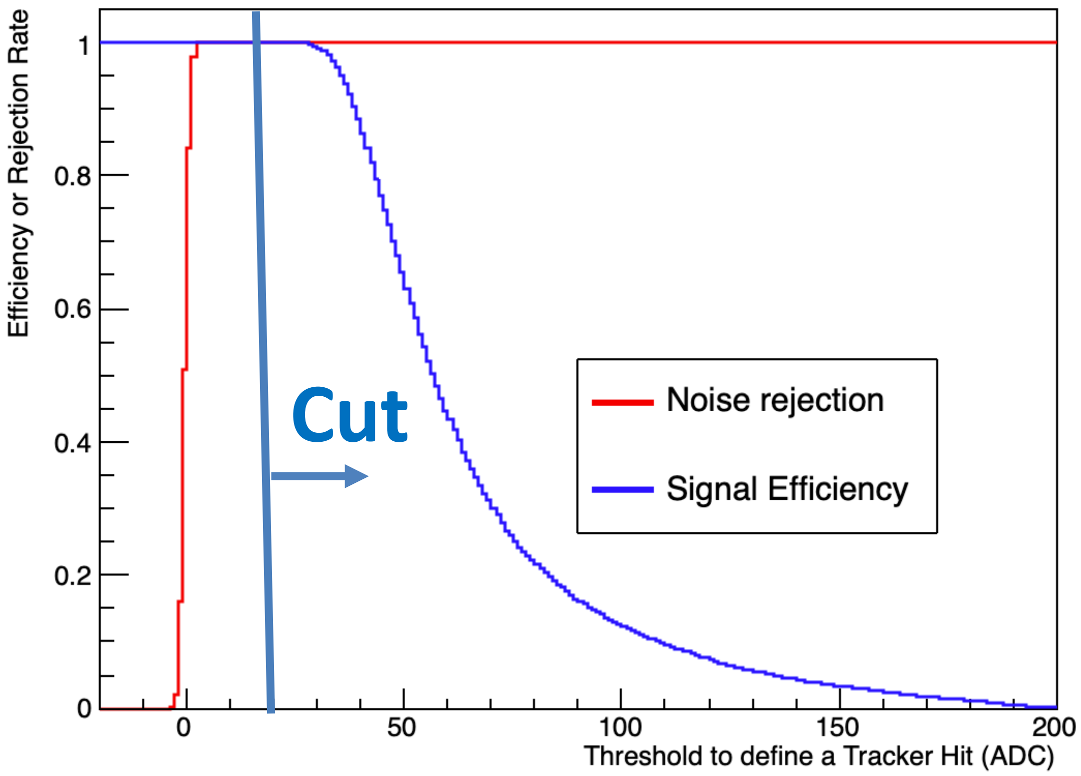
Pedestal peak, width ~ 1 ADC (mV)

Signal and electronic noise are well separated.



[2024 JINST 19 P06020]

The noise rejection (red) as a function of the energy threshold

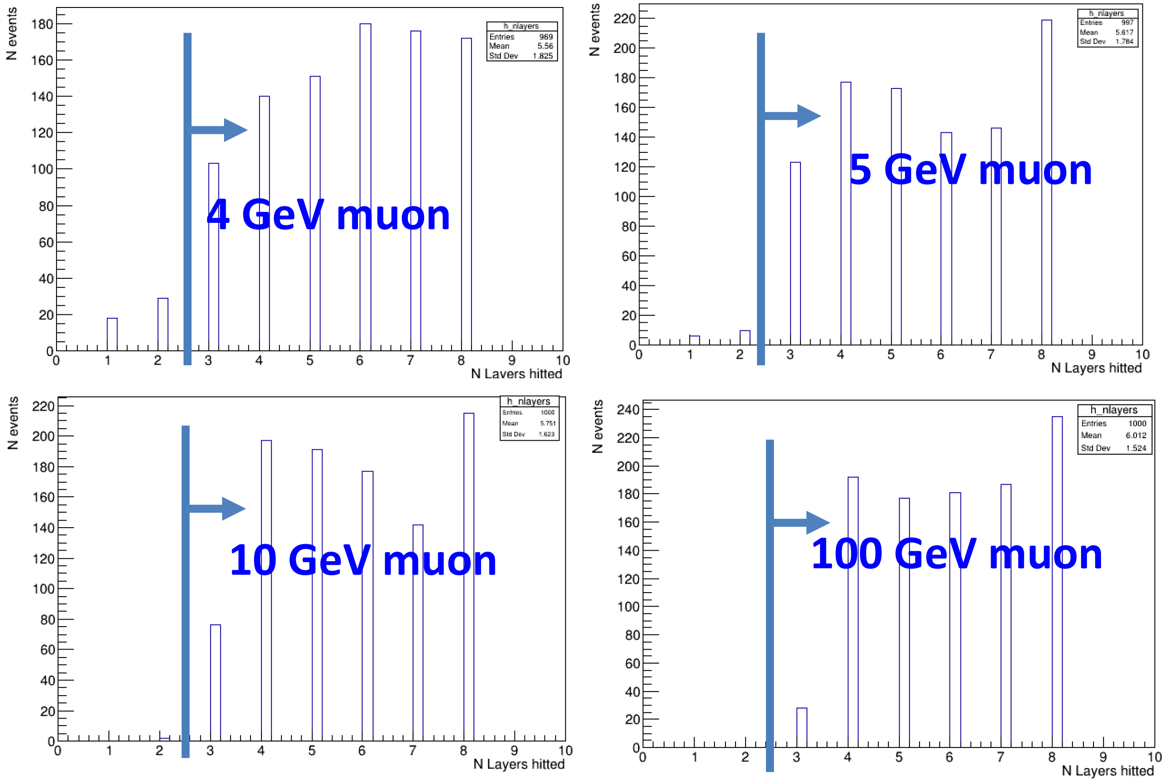


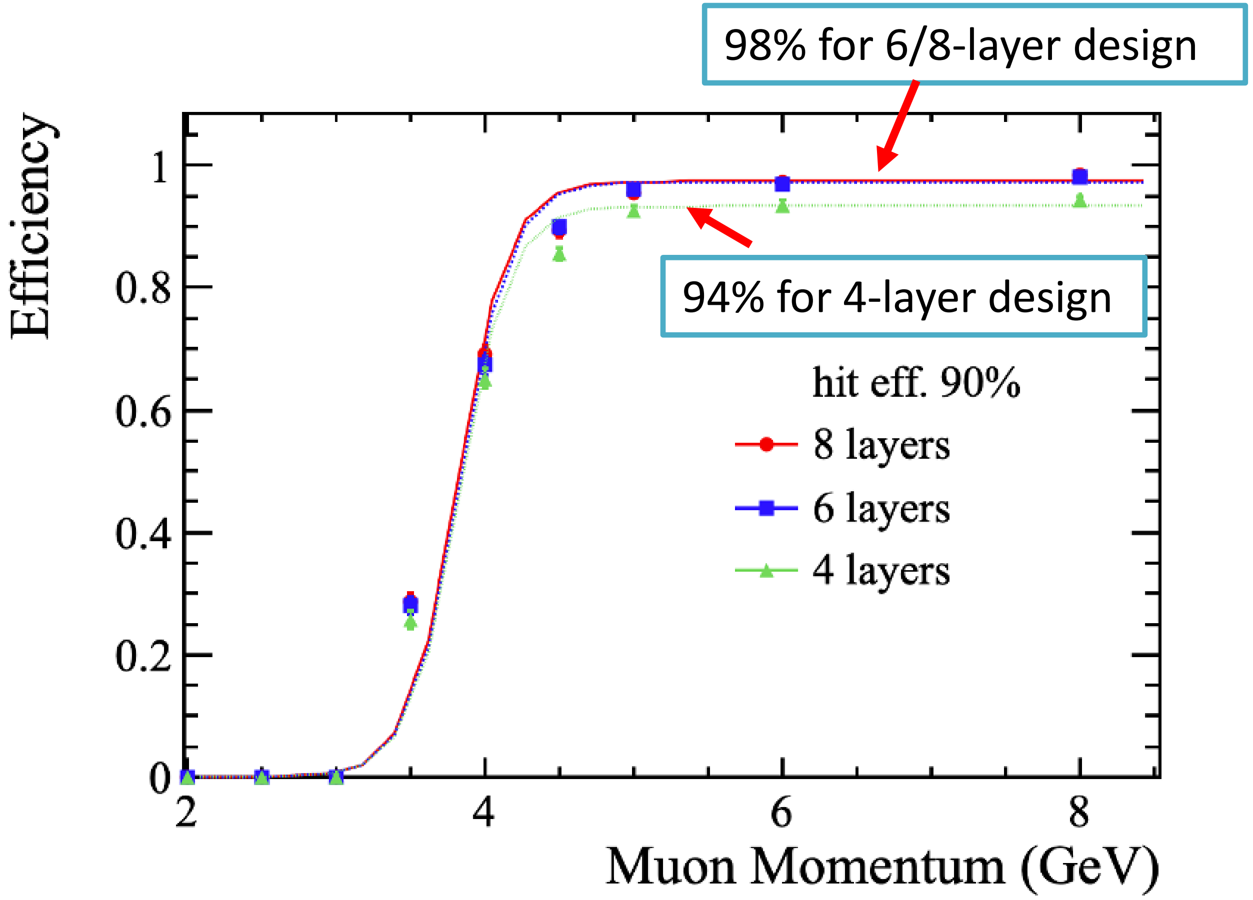
Assuming pedestal : signal = 1:1

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.

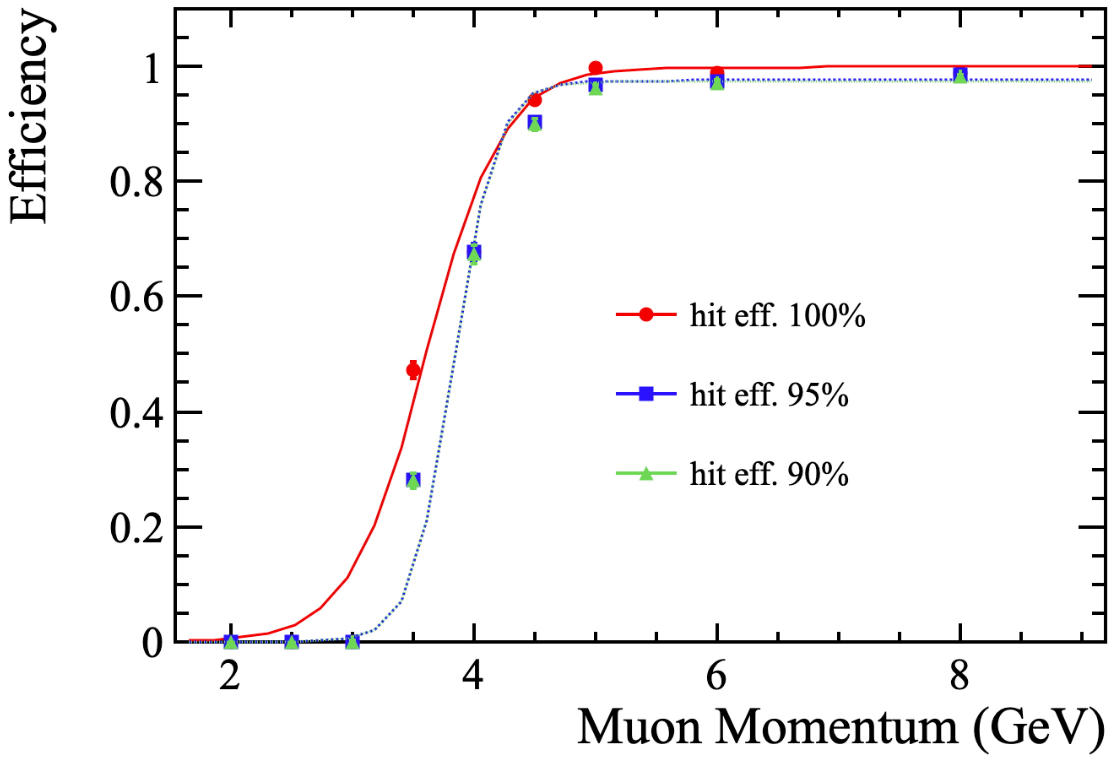




Muon ID efficiency of the barrel

Detector Optimization

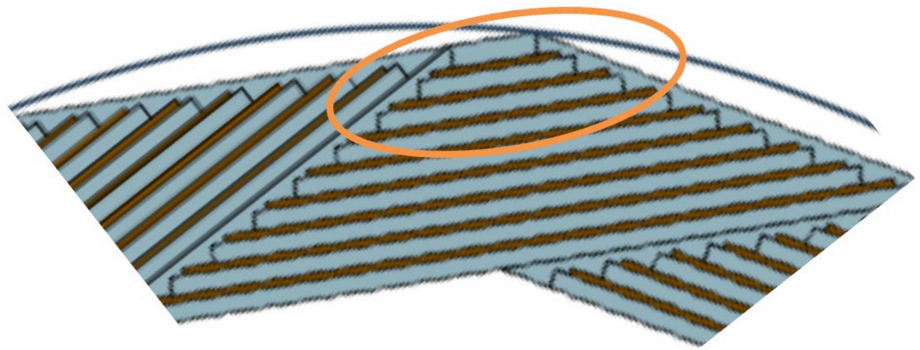
Muon ID efficiency vs efficiency of single channel



6-layer design of the barrel

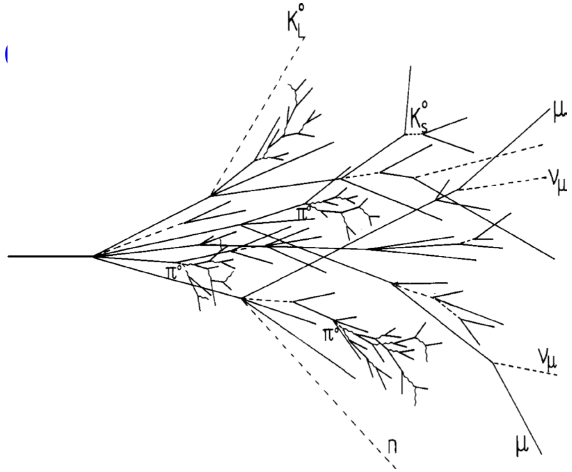
What we learn from the simulations:

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.

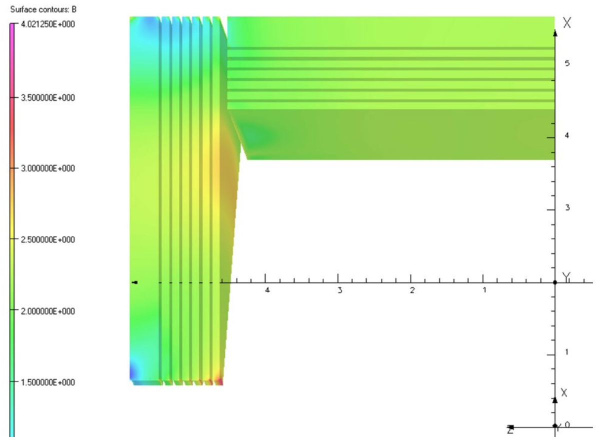


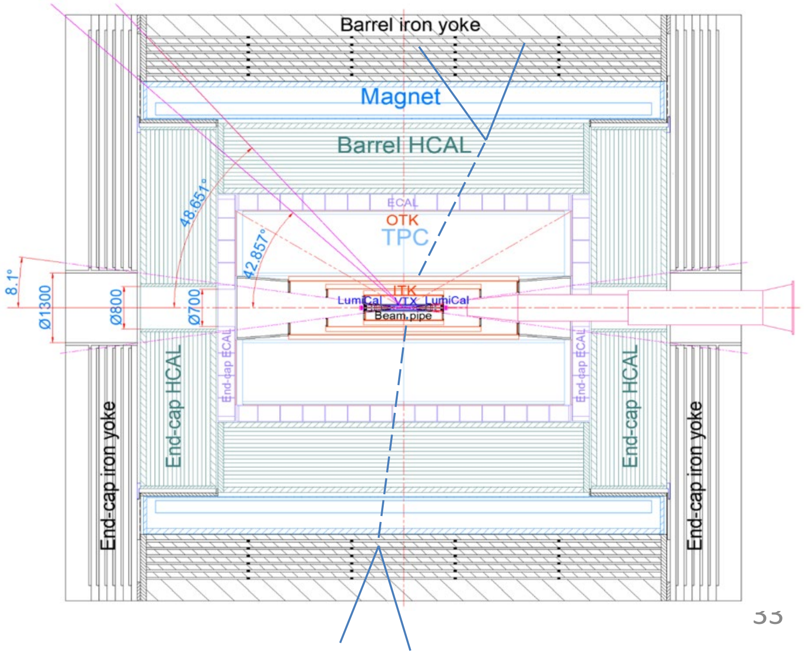
About track reconstruction

- Tracking in the muon detector may be used to rescu some energy leakage of HCAL:
  - Distance between Muon detector and HCAL is 0.7m;
  - Magnet field in the iron layers can be simulated;
  - Most charged particles in the tail of a hadronic shower are $\pi^{\pm}$ and $\mu^{\pm}$. Their deposited energy in HCAL may be low.
  - If we can reconstruct the momentum of these charged particles, or
  - Add their masses, add 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.
- The more layers and the smaller spatial resolution, the better track reconstruction.



Magnet field





Content

- Introduction
- Requirements
- Technology survey and our choices
- Technical challenges
- R&D efforts and results
- Detailed design
- Performance from simulation
- RPC related and testing
- Research team and working plan
- Summary

For the backup option

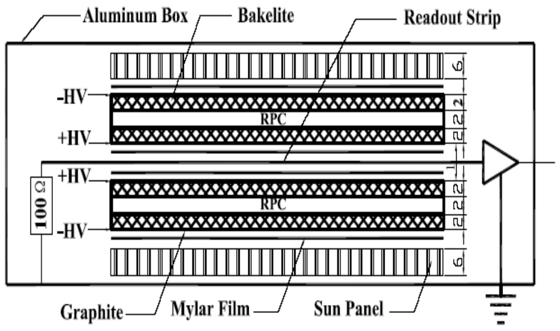
RPC technology – BESIII

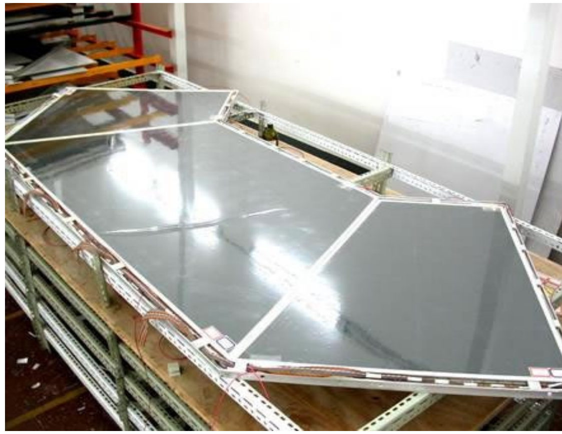
- Homemade Oil-free Bakelite RPC;
- Gas mixture: Ar:R134a:ISO-B=50:42:8
- First time successful mass production in China, bare chamber pass rate $> 90\%$;
- Good performance and keep running even now (>15years)!

Bare RPCs	$1{,}272\ m^2$
Box	136
Readout strip & insulation materials	$636\ m^2$
Electronics	9,152ch

Table 2-4 BESIII Detector Performance

Parameters		Design Target	Real Performance			
			Cosmic Ray	Double μ	$\pi\pi J/\psi(\mu\mu)$	Total
Average Efficiency		95	94.7	95.11	95.17	93.6
Counting Rate		$< 0.1Hz/cm^2$	0.04 (Random Trigger)			
Spatial Resolution	$\sigma_{R\Phi}$	$< 20mm$	19	18	19	17.6
	σ_Z	$< 30mm$	23	21	22	22.5
$P(\pi \rightarrow \mu)@1GeV/c$		$< 5\%$	5.5% (MC)			

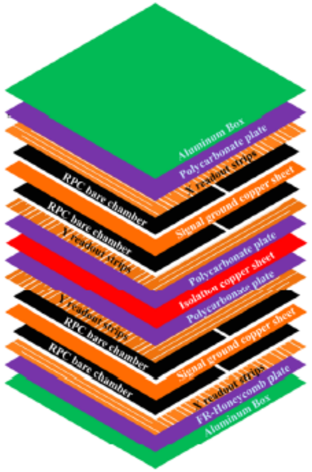


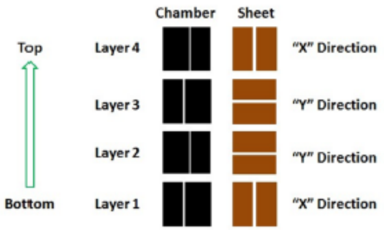


RPC technology – Dayabay

- Super module:
  - Two layers of 2-D readout
  - 4-layer RPCs
- Module size: $2.17m \times 2.20m \times 0.08m$
- Number of modules: 194
- Bare RPC sizes: $1.0m \times 2.10m$, $1.1m \times 2.1m$
- Bakelite plate size limitation: $2.4m \times 1.2m$!

Bare RPCs	$3,200\ m^2$
Box	195
Readout strip & insulation materials	$3,200\ m^2$
Electronics	6,000 ch



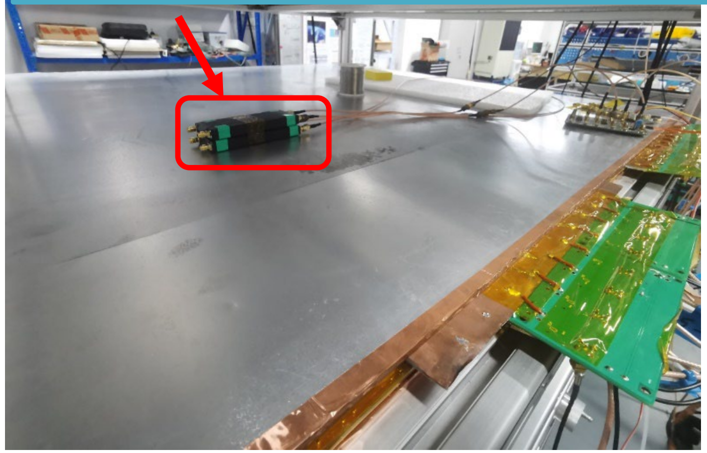


We have the tech. based on Bakelite ready.

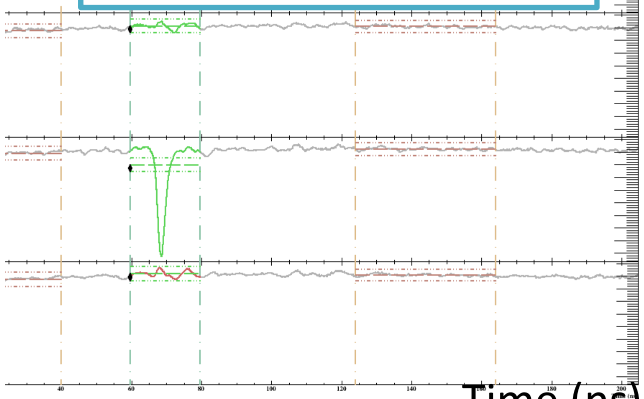
Ongoing test at SJTU

- A prototype from ATLAS (upgrade).
- Use R134a gas, 1.2 mm gas gap.
- Gain of preamp: 16
- Efficiency curve and time resolution determined from CR testing.

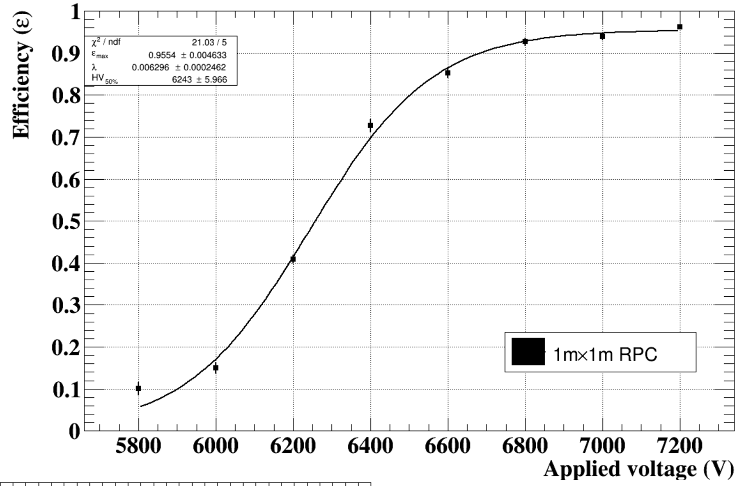
Trigger with time resolution < 0.1ns

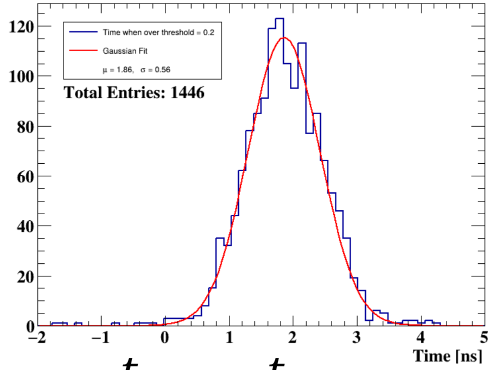


Signal window: $< 20ns$

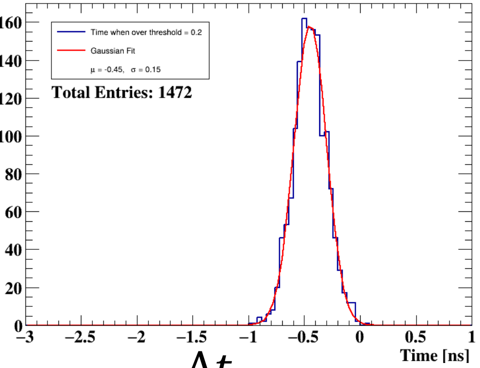


Fit to $\boldsymbol{\varepsilon} = \frac{\varepsilon_{max}}{1+e^{\lambda\times(HV_{50\%}-\boldsymbol{U})}}$





$t_{RPC} - t_{trig}$



Δt_{trig}

For the backup option, we will perform the R&D focusing on glass with low resistance ($10^{10}\Omega m$), which is available in China.

$$\sigma_{RPC} = \sqrt{\sigma^2_{\Delta t_{RPC}} - \frac{\sigma^2_{\Delta t_{12}}}{2}} \approx 550ps$$

Content

Research Team

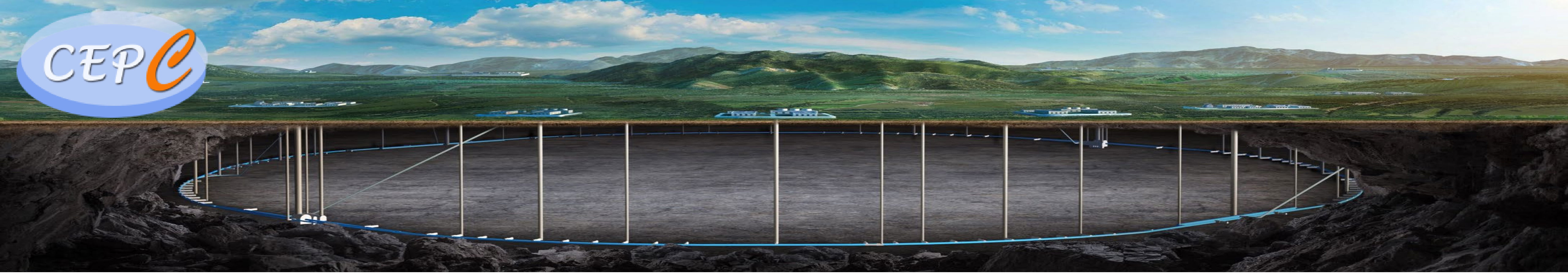
- Institutions (5) and faculties/staff (11)
  - Fudan University (FDU): Xiaolong Wang, Wanbing He, Weihu Ma
  - Shanghai Jiaotong University (SJTU): Jun Guo, Liang Li
  - IHEP: Zhi Wu, Yuguang Xie, Jie Zhang
  - South China Normal University (SCNU): Hengne Li
  - Nankai University: Minggang Zhao, Junhao Yin
- Graduate students: ~15
- Task board:
  - Overall: X.L. Wang
  - Software and simulation: H.N. Li, J.H. Yin, M.G. Zhao
  - R&D on PS scheme: X.L. Wang, Z. Wu, W.B. He, W.H. Ma
  - R&D on PRC scheme: J. Guo, Y.G. Xie
  - Production and testing: Z. Wu, Y.G. Xie
  - Electronics: J. Zhang
  - Radiation hardness test: W.H. Ma
  - LLP search: L. Li

Working plan

- Improvement and optimization of PS bars
  - Increase the light yield to reduce the weight of a long module
- Electronic readout
  - Study of electronics for prototype testing
- Build a prototype module and testing
  - The performance of a module with a length of $5m$: efficiency, time resolution
- Optimization of structure design
- Software and simulation
  - Improvement of muon ID
  - Algorithm for track reconstruction
  - More physics performance study
- Radiation hardness studies.

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: 8 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.
  - $51{,}744$ channels, $5{,}936\ m^2$ area, and $148{,}416\ m$ long fiber, in total.
- Work plan will focus on electronics, software and simulation for performance, prototype modules with long bars.

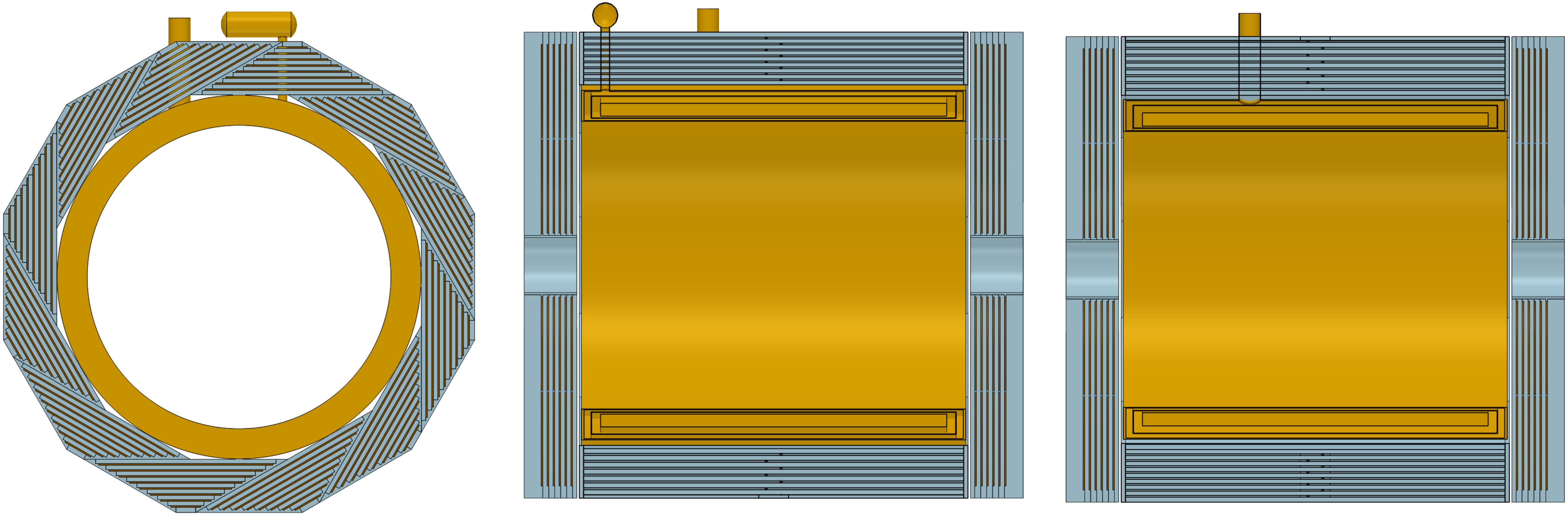


Thank you for your attention!

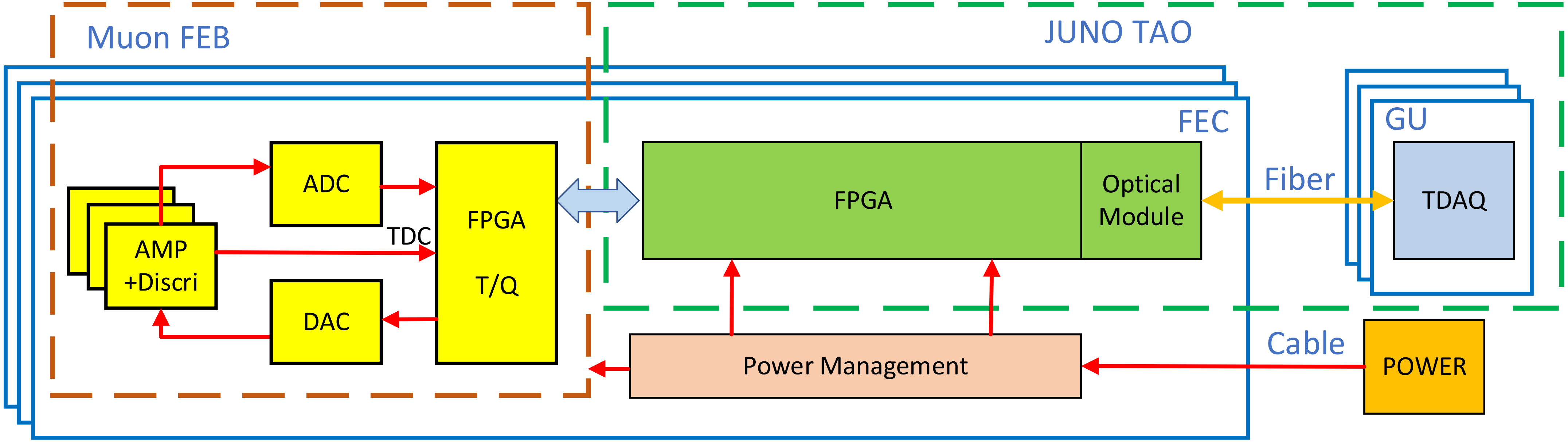
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Add chimneys

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

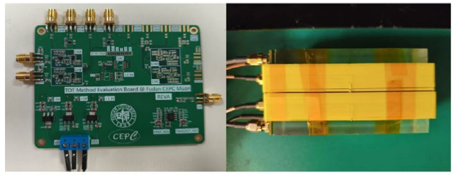


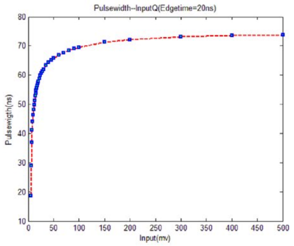
Near-term test environment

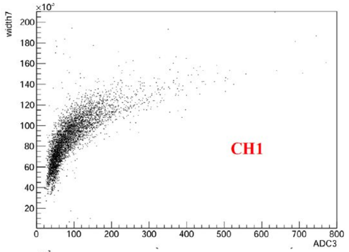


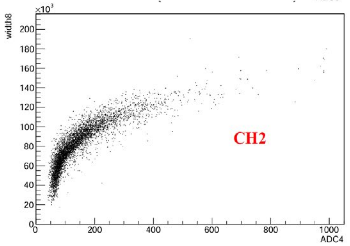
- FEB (Front-end Electronics Board)
  - Commercial chips with radiation tolerance based on past studies for particle physics experiments
  - FPGA based TDC for TOA and TOT measurement with ~1 ns time resolution
  - ADC for charge measurement or TOT calibration
  - DAC for threshold setting or SiPM bias voltage adjustment
- Reuse JUNO-TAO electronics for readout, clock synchronization and TDAQ
  - To accelerate the development schedule

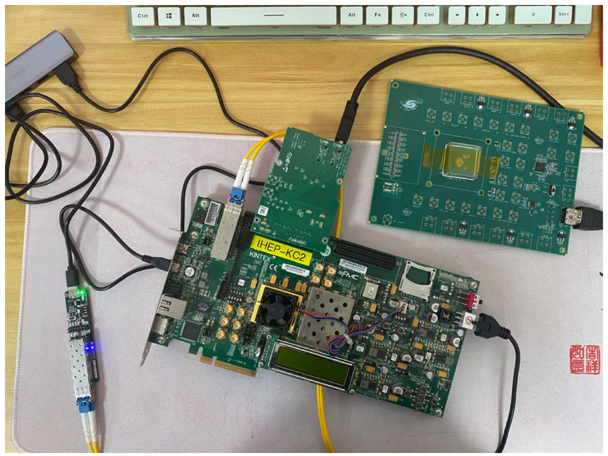
Test for TOT









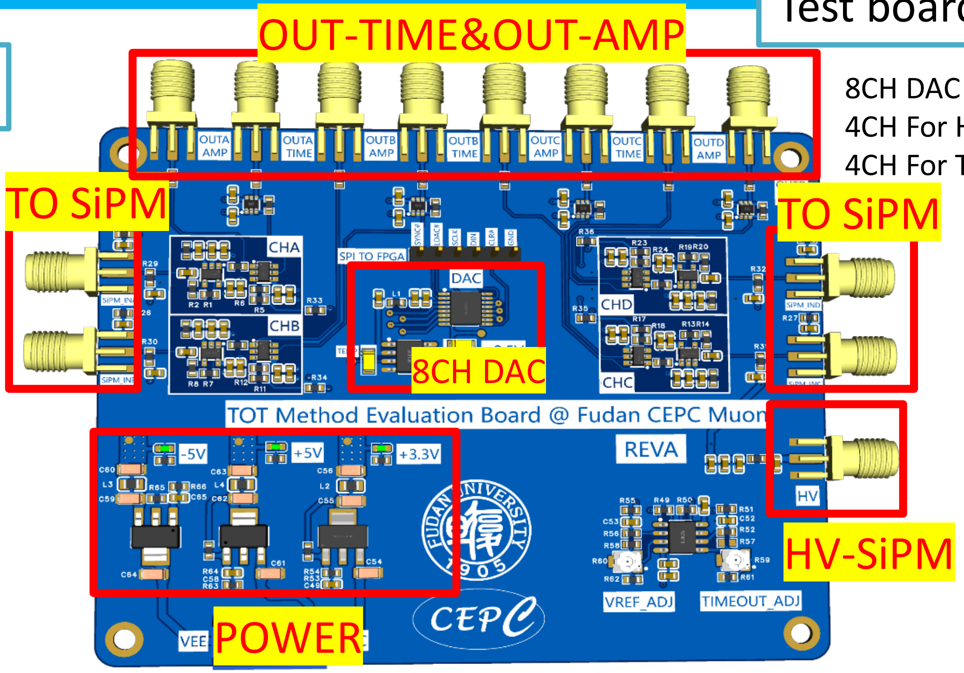


Readout electronics: Time-over-threshold (TOT) scheme

- 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.

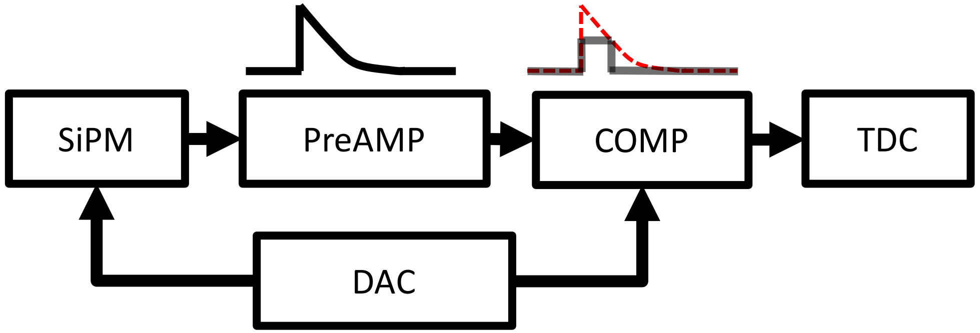
Long cables!

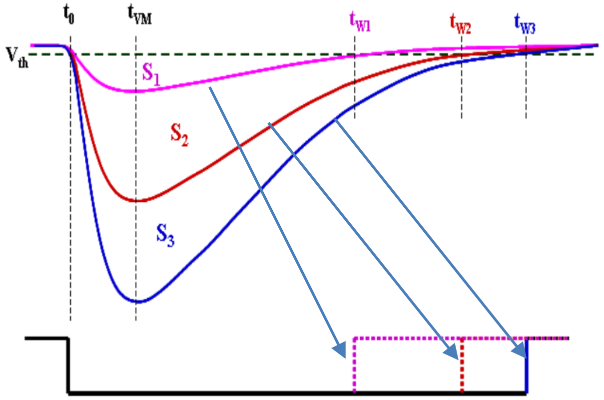
Test board

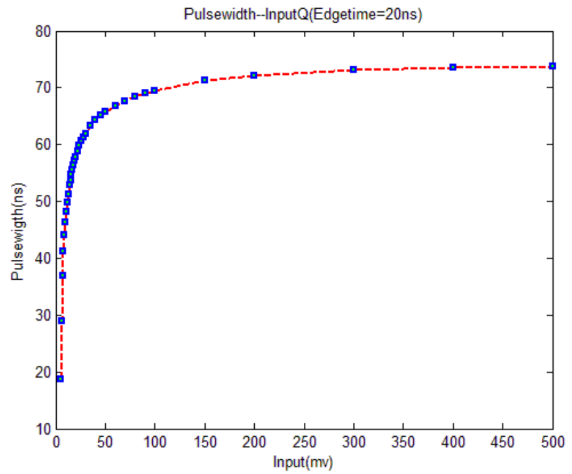


8CH DAC AD562
4CH For HV_ADJ
4CH For TH_ADJ

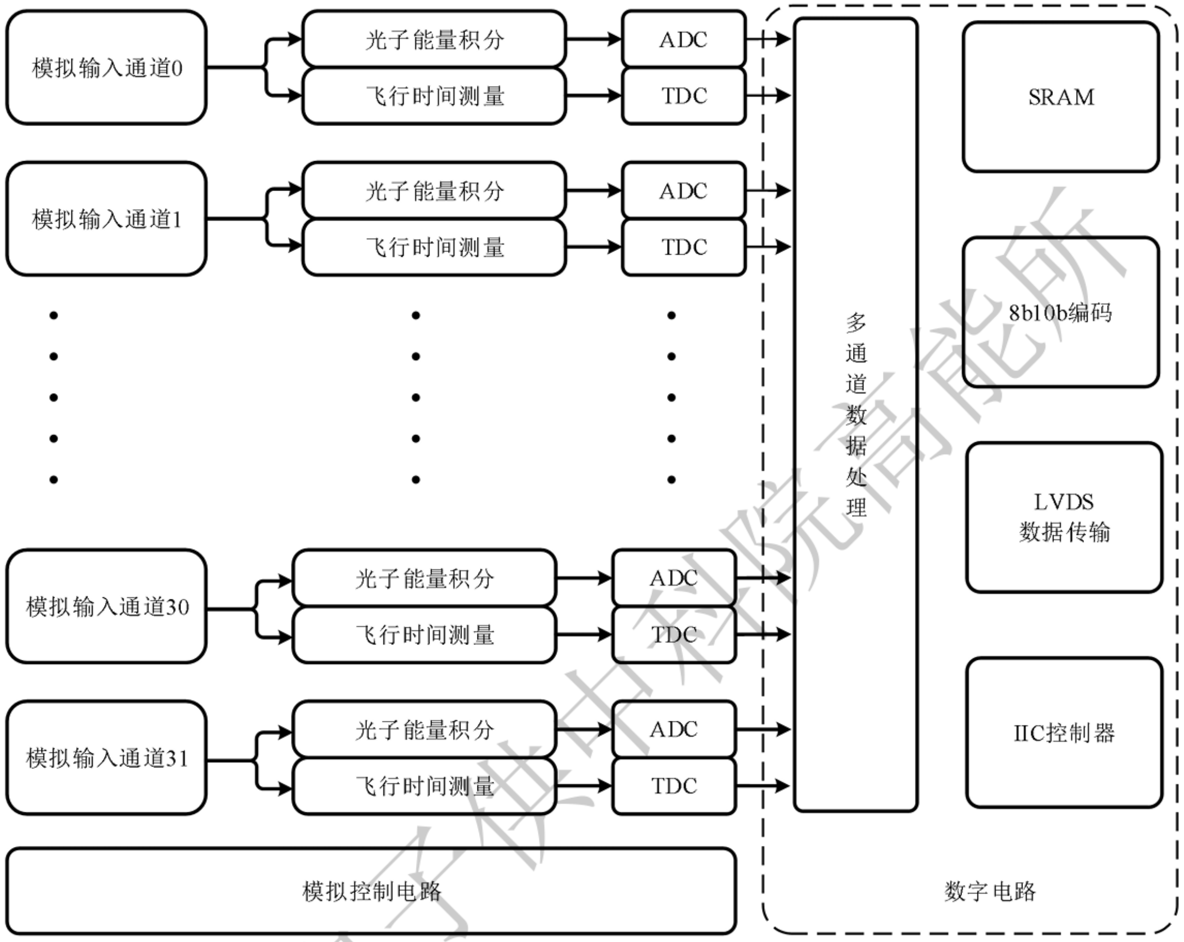
Temperature sensor will be included.

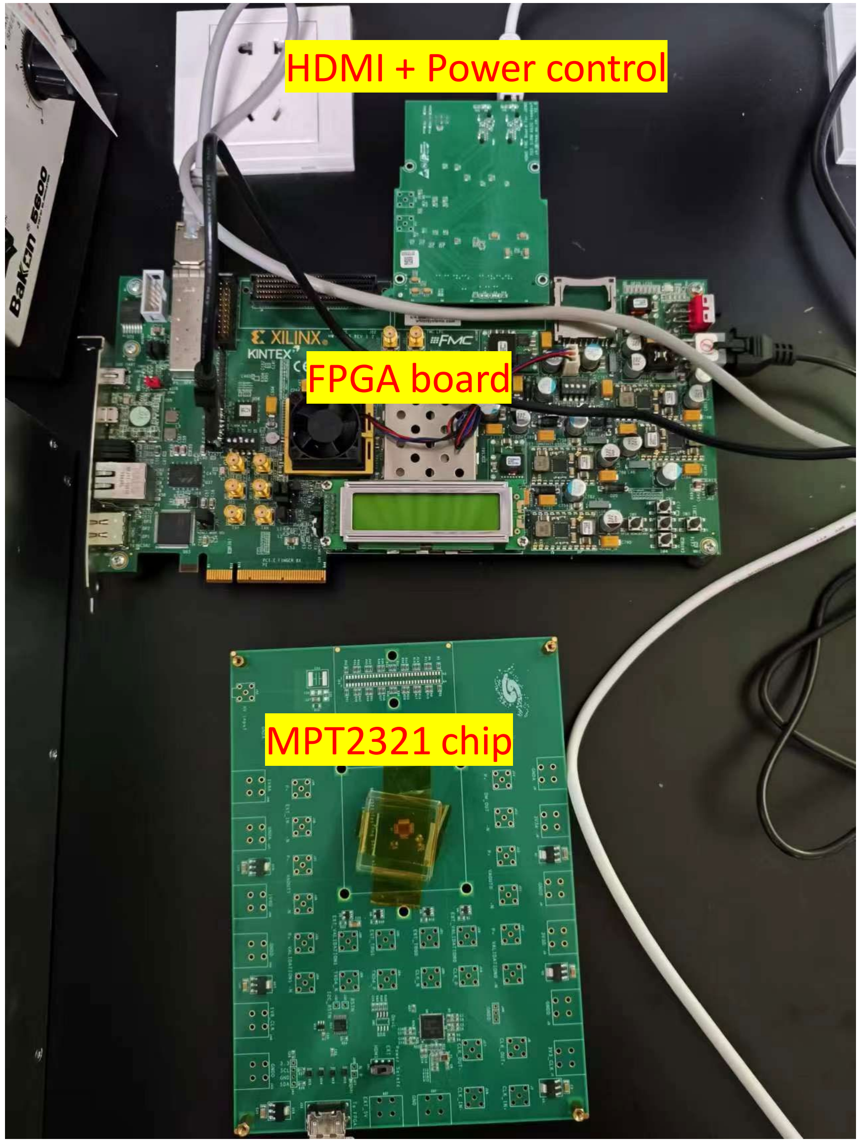






SiPM – ASIC MPT2321





MPT2321, made in China

32CH ADC (12bit) + TDC(50ps)

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.

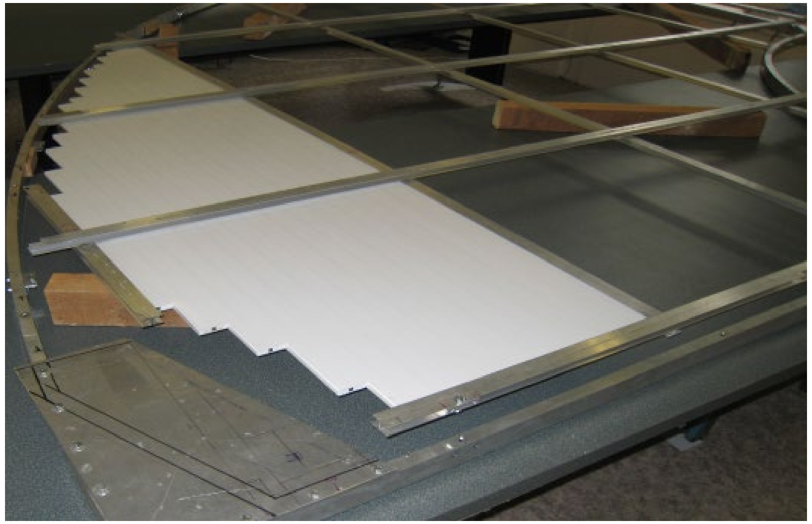
Bandwidth requirement

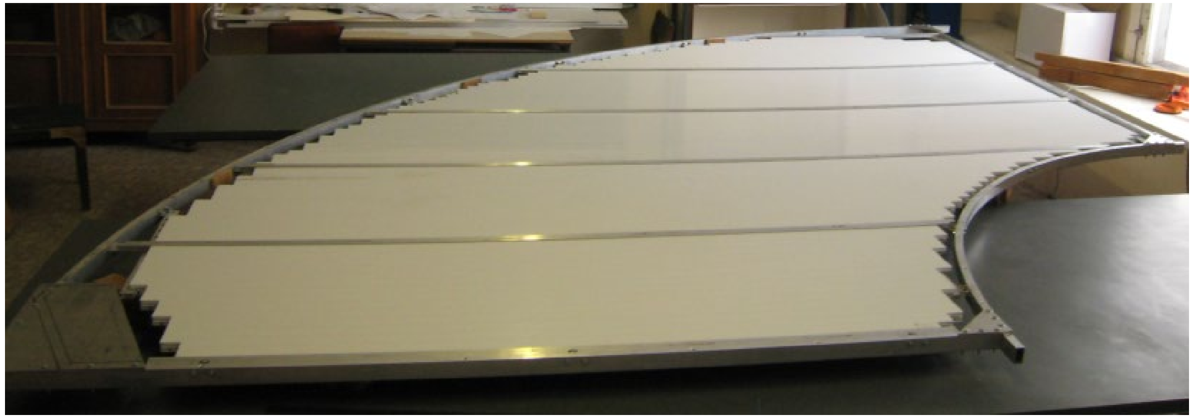
Requirement from Sub-Detector

	Vertex	Pix(ITKB)	Strip (ITKE)	TOF (OTK)	TPC	ECAL	HCAL	Muon
Channels per chip	512*1024 Pixelized	512*128 (2cm*2cm@34um*150um)	512	128	128	8~16	8~16	8~16
Ref. Signal processing	XY addr + BX ID	XY addr + timing	Hit + TOT + timing	ADC+TDC/TOT+TOA	ADC + BX ID	TOT + TOA/ ADC + TDC	TOT + TOA/ ADC + TDC	TOT+TOA/ ADC+TDC
Data Width /hit	32bit (10b X+ 9b Y + 8b BX + 5b chip ID)	48bit （9b X+7b Y +14b BX + 6b TOT + 5TOA + 4b chip ID）	32bit (10b chn ID + 8b BX + 6b TOT + 5b chip ID)	40~48bit （7b chn ID + 8b BX + 9b TOT + 7b TOA+5b chip ID)	48bit (7b chn ID + 8b BX + 11b chip ID + 12b ADC + 10b TOA)	48bit (8b BX+ 10b ADC + 2b range + 9b TOT + 7b TOA+ 4b chn ID + 8b chip ID)	48bit (8b BX+ 10b ADC + 2b range + 9b TOT + 7b TOA+ 4b chn ID + 8b chip ID)	48bit (8b BX+ 10b ADC + 2b range + 9b TOT + 7b TOA+ 4b chn ID + 8b chip ID)
Data rate / chip	1Gbps/chip@ Triggerless@ Low LumiZ Innermost	640Mbps/chip Innermost	Avg. 1.01MHz/chip Max. 100MHz/chip	Avg：26kHz/chip @ z pole Max：210kHz/chip @z pole	~70Mbps/module Inmost	<4.8Gbps/module	<4.8Gbps/module	<1 Gbps/module
Data aggregation	10~20:1, @1Gbps	1. 1-2:1 @Gbps; 2. 10:1@O(10Gbps)	1. 10:1 @Gbps 2. 10:1 @O(10Gbps)	1. 10:1 @1Mbps 2. 10:1 @O(10Mbps)	1. 279:1 FEE-0 2. 4:1 Module	1. 4~5:1 side brd 2. 7*4 / 14*4 back brd @ O(10Mbps)	< 10:1 (40cm*40cm PCB – 4cm*4cm tile – 16chn ASIC)	<= 256:1
Detector Channel/module	2218 chips @long barrel	30,856 chips 2204 modules	22720 chips 1696 modules	41580 chips 1890 modules	258 Module	1.1M chn	6.7M chn	~58.2 k chn
Data Volume before trigger	2.2Tbps	2Tbps	22.4Gbps	1Gbps	18Gbps	164.8Gbps	14.4Gbps	~32.4 Gbps

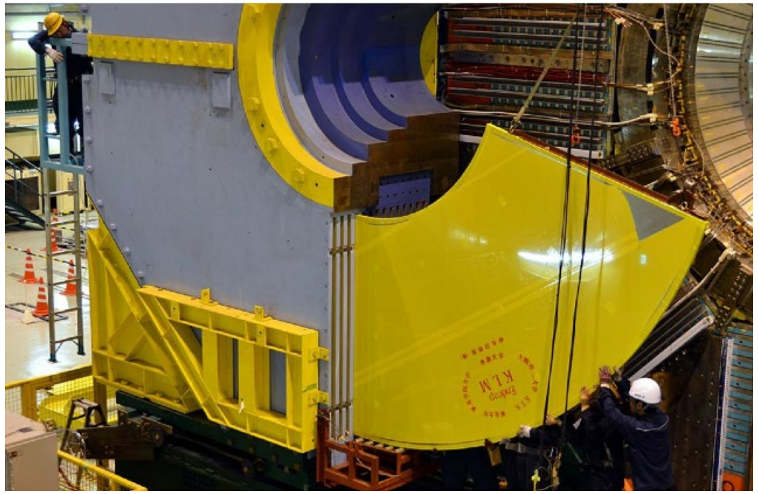
Reference for endcaps

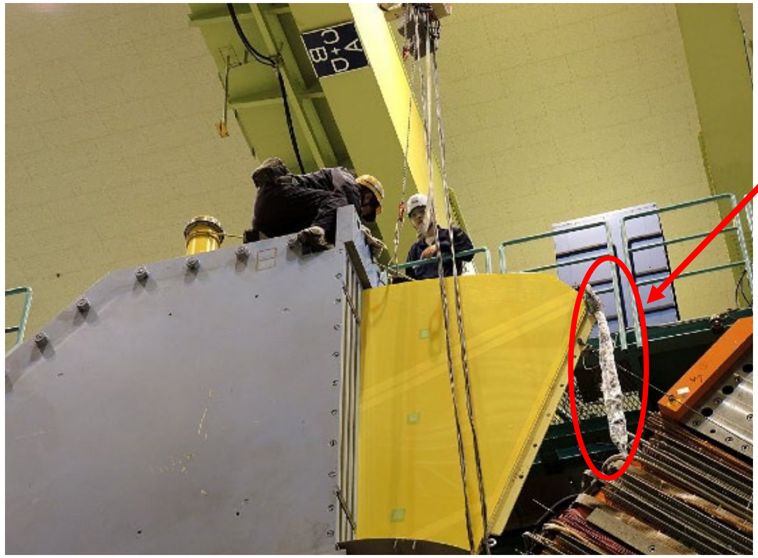
- Structure of a module



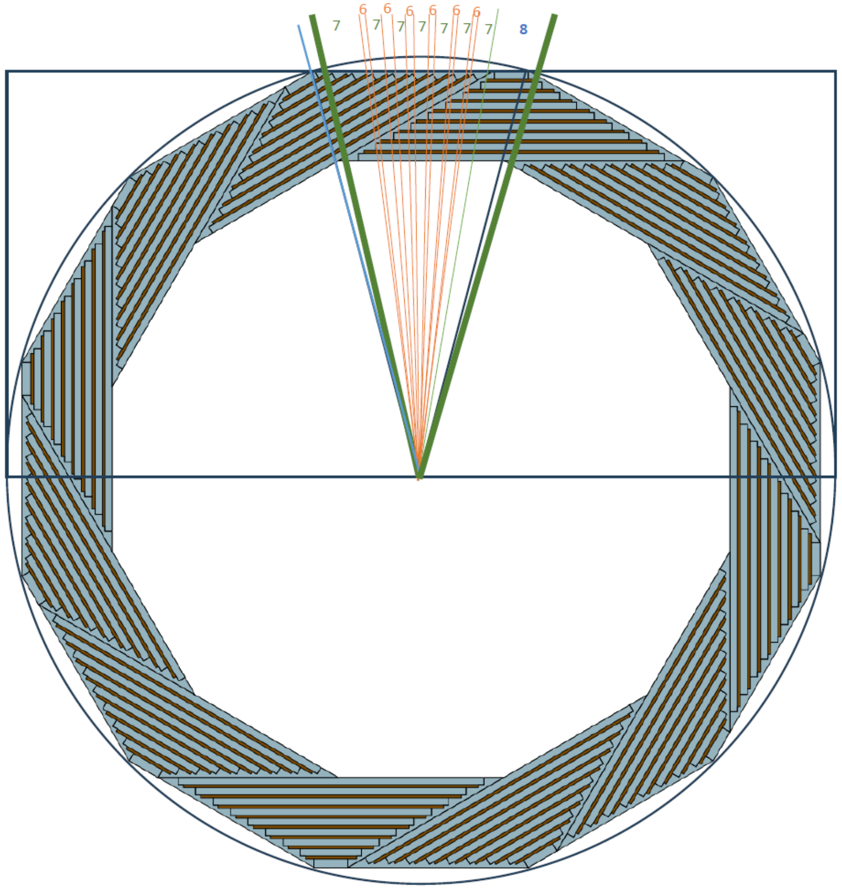


- Installation

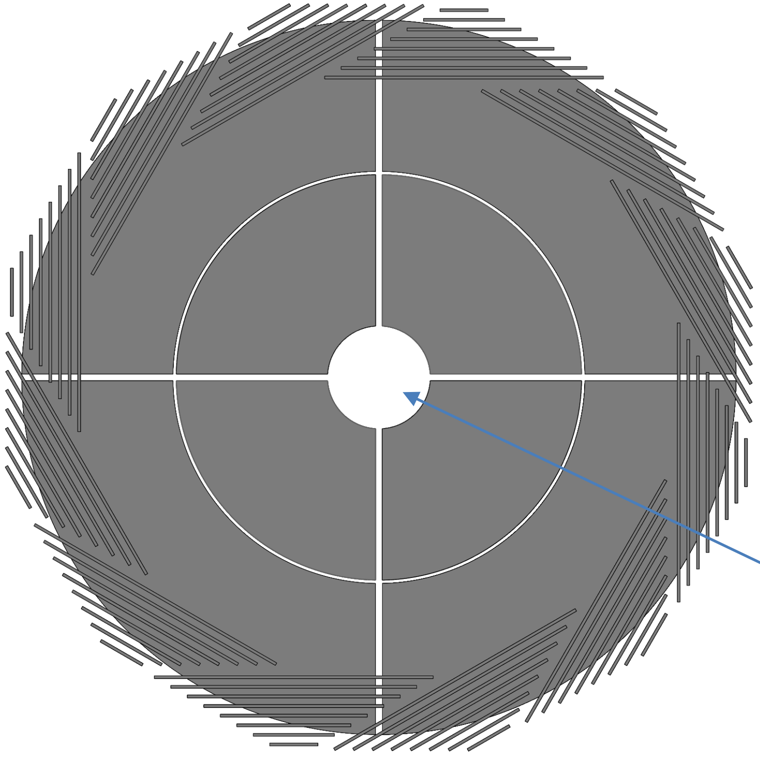




Estimation of dead zone



Tracks passing 6, 7, or 8 layers.
6-layers: ~25%, 7-layers: ~50%, 8-layers: ~25%



- Cross (+) = dead zone
- Width of the cross: $10\ cm$

For beam pipe,
$R = 75cm$

Conclusion:

There is no dead zone in the barrel.

Due to the cross： $0.00214 * 2.09829 * 2/4\pi$=0.07%

Due to the beam pipes： $2 * \Omega_1 = 0.173$; $2 * \frac{\Omega_1}{4\pi} = 1.4\%$

Cost estimation – PS scheme

Unit: CNY

SiPM+FEE:

- Number of detector channels: 51,744
  - Endcaps:
    - Inner modules: $72 \times 2 \times 4 \times 6 \times 2 = 6{,}912$
    - Outer modules: $128 \times 2 \times 4 \times 6 \times 2 = 12{,}288$
  - Barrel: $1356 \times 2 \times 12 = 32{,}544$
- Cost: $51{,}744ch \times 80/ch = 4.14\ M$

SiPM: ￥50/ch
Preamp: ￥30/ch (could be ￥10)

PS + fiber

- Sensitive length: 148,416 m
  - Endcaps: $(154.83 + 343.73) \times 2 \times 4 \times 6 \times 2 = 47861.76\ m$
  - Barrel: $4189.76 \times 2 \times 12 = 100{,}554.24\ m$
- Sensitive area: $5936.64\ m^2$
- Scintillator volume: $59.3664\ m^3$

Cost for fiber: $148{,}416m \times 45/m = 6.68\ M$
Cost for scintillator: $59.3664m^3 \times 200/L = 11.87\ M$

Total cost: $\mathbf{4.14 + 6.68 + 11.87 = 22.69\ M}$
Consider 20% is for additional costs, like the module structure, wastage, etc.

$$22.69 \times 1.2 = 27.228\ M$$

➢ CEPC RPC Muon cost

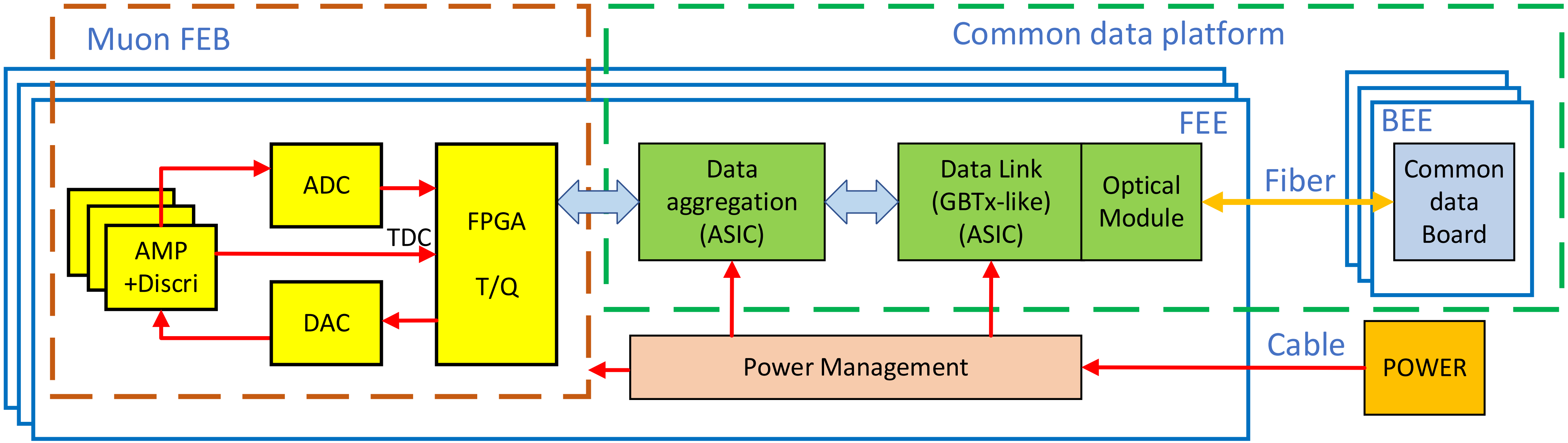
A previous estimation

Bare RPCs (Bakelite)	5080 m^2	2200/m^2	11.18 +0.6 = 11.78M	From GNKD
Bare RPCs(glass)	5080 m^2	1000/m^2	5.08+0.6=5.68M	Estimated
Box	280	3500/module	0.98 M	Estimated
Readout strip & insulation materials	5080 m^2	1000/m^2	5.08 M	Ref to DYB
Subtotal			17.84(Bakelite)/11.74(glass)	
Electronics (discrete)	31100 ch	~200/ch	6.22 M	From USTC
Electronics (ASIC)	31100 ch	~146.5/ch	4.55M	From USTC
HV system			1.5M	Estimated
Gas system			1.0M	Estimated
Total	Bakelite RPC: 26.56M(discrete)/2.489(ASIC); Glass RPC: 20.46M(discrete)/18.79(ASIC)			

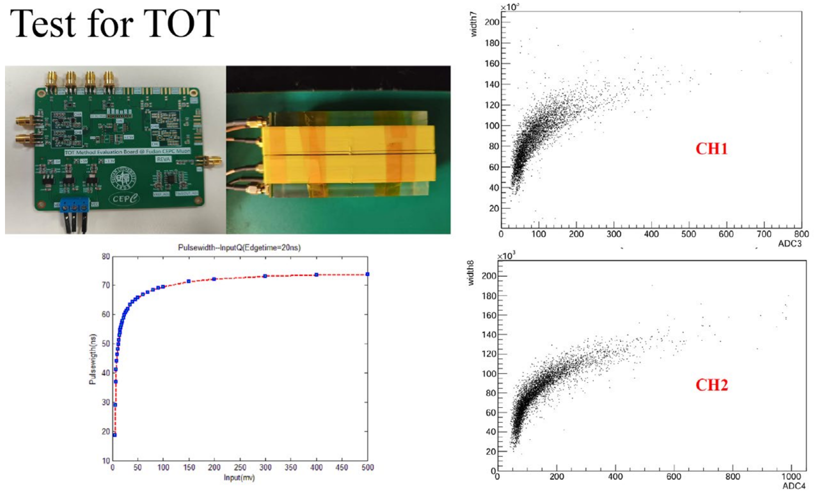
➢ RPC mass production condition

Vendor: GaoNengKeDi co.ltd only, currently; glass RPC no problem. A new clean room is needed. Raw materials are not an issue. (Bakelite, graphite, glass, glue, strips of insulation film, etc.)

Alternative: discrete device scheme



Test for TOT



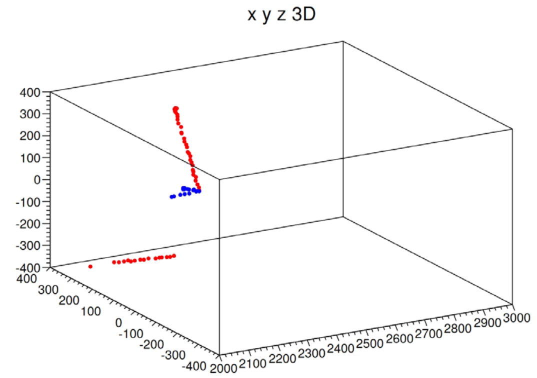
- FEB (Front-end Electronics Board)
  - Commercial chips with radiation tolerance based on past studies for particle physics experiments
  - FPGA based TDC for TOA and TOT measurement with ~1 ns time resolution
  - ADC for charge measurement or TOT calibration
  - DAC for threshold setting or SiPM bias voltage adjustment

Requirements according to functions

- Muon ID: passing >= 3 superlayers of the muon detector.
- Leakage of hadronic shower from HCAL: muon ID and/or standalone tracking.
- Search for NP, such as LLP: tracking to find the common vertex, and momentum measurement.
- Trigger: rough tracking and timing information.
- Additional T0 determination: timing information.
- Background veto at high luminosity: timing is useful.

Key requirements:

- Muon ID
- Track reconstruction

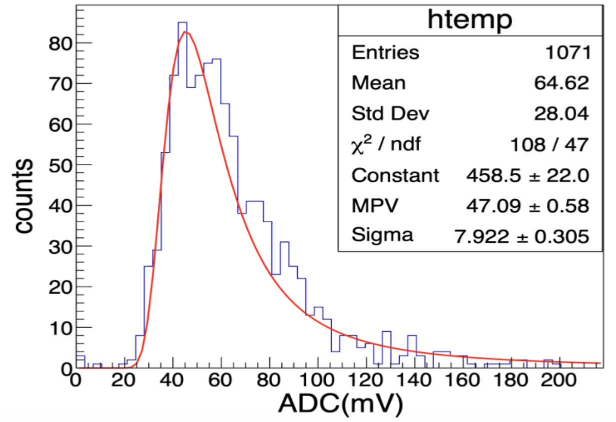


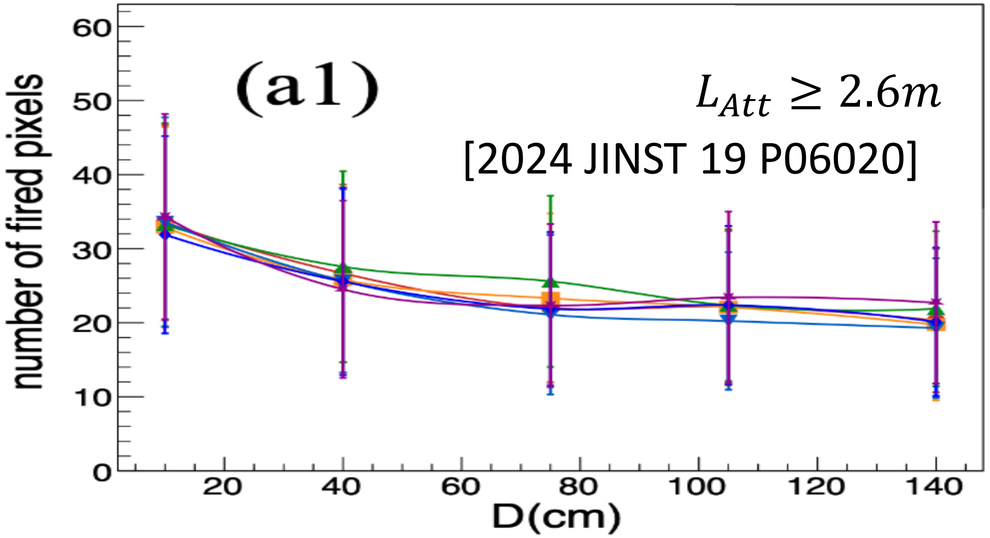
There will be background due to KL in searching for LLP, especially from the hadronic shower.

Detector Simulation

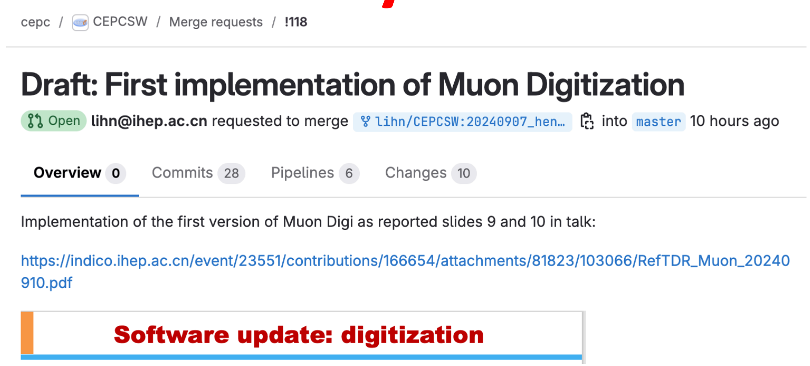
- Digitization from “Sim. Hit” (GeV) to “Raw Hit” (ADC counts)
- A first experimental version implemented:
  - A simplified model from GeV to ADC counts directly.
  - Only for barrel at the moment.
- A more realistic model with N_p.e. per MIP attenuated along the strip is to be ready this week: →

MIP peak distribution in unit of ADC counts





Merge Request in CEPCSW is almost ready.



cepc / CEPCSW / Merge requests / !118

Draft: First implementation of Muon Digitization

Open lihn@ihep.ac.cn requested to merge lihn/CEPCSW:20240907_hen… into master 10 hours ago

Overview 0 Commits 28 Pipelines 6 Changes 10

Implementation of the first version of Muon Digi as reported slides 9 and 10 in talk:

https://indico.ihep.ac.cn/event/23551/contributions/166654/attachments/81823/103066/RefTDR_Muon_20240910.pdf

Software update: digitization