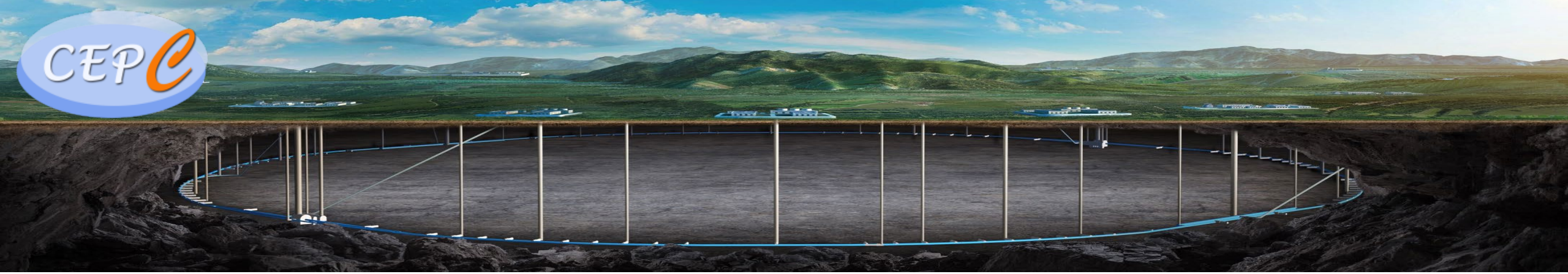


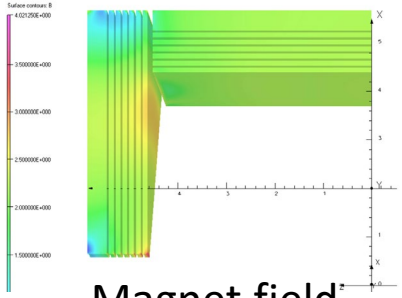
CEPC Muon Detector
--- design and status

Xiaolong Wang
(for the Muon Detector Group)
Fudan University
Tuesday Meeting, 09/24/2024

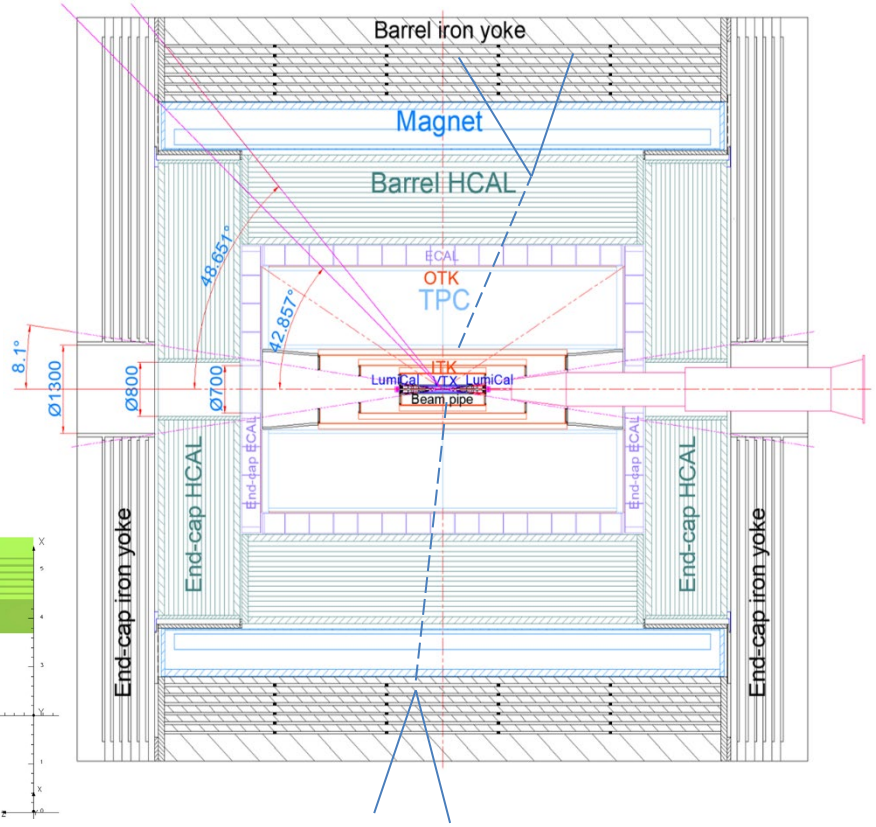
Functions expected from the muon detector

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 $p \approx 40\ \mathrm{GeV}/c$. (High momentum muon)
- Muons provide in many theoretical models a characteristic signature for new physics.
- Muon detector is designed for muon identification, but not limited to this.
  - Could be used to detect the leakage of HCAL.
  - Can be used for trigger, like in ATLAS.
  - Could be useful for additional T0 determination. $\sigma(T0) = \sigma(T_{hit})/\sqrt{n_{hits}}$
  - Can be used to search for Long-lived particles.
- Functions: muon ID, search for NP, leakage of HCAL, trigger and timing information.



Magnet field



Key requirements:

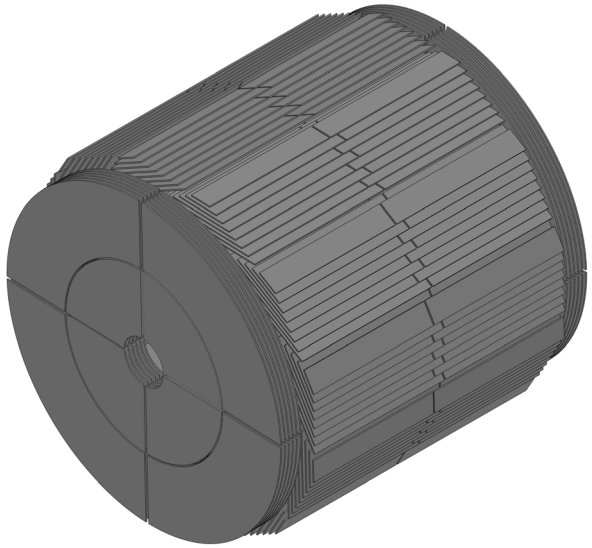
- **Muon ID**
- Track reconstruction

Scenarios

- Scenario #1: 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 budget, but it only works for muon ID, and 50% in barrel has only 3 superlayers. Width of iron plate is ~20cm, too thick.

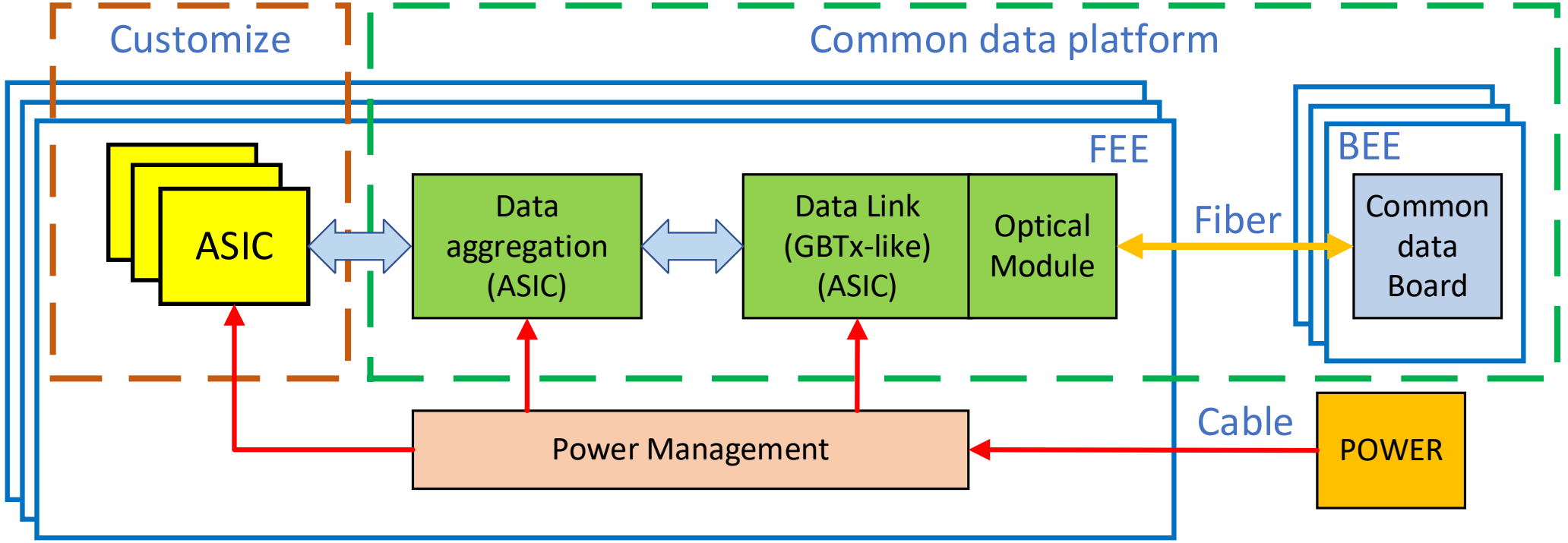
Current emergency for the muon group:

- Software and simulation → performance study
- Design of electronic system, FEE & BEE
  - Requirements from the detector
  - Design and performance
  - Consistent with the frame of CEPC electronics



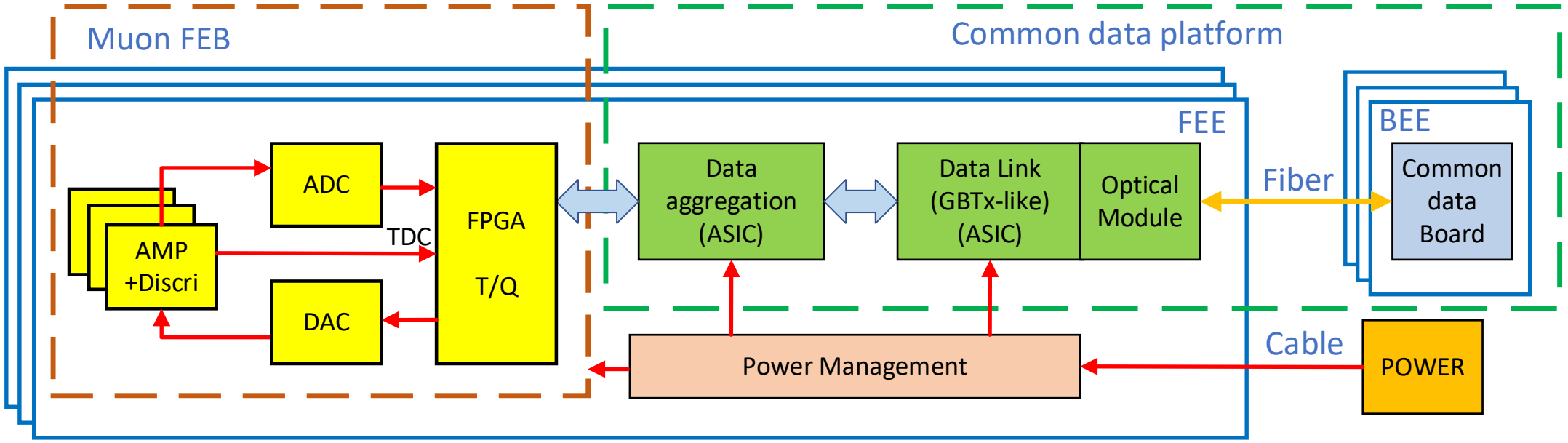
- Design for the electronics

Baseline for SiPM readout



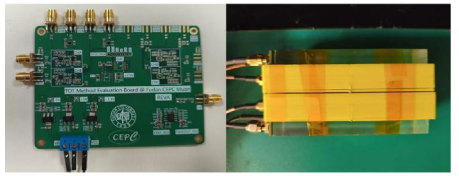
- Reuse the ASIC scheme from ECAL or HCAL
- Revise according to the constraints from cooling and mechanical structure of the detector

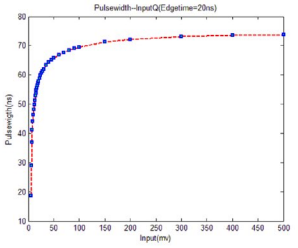
Alternative: discrete device scheme

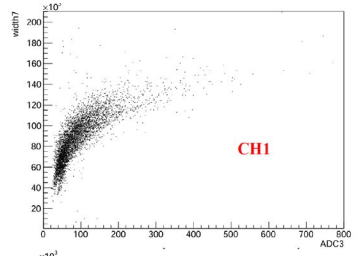


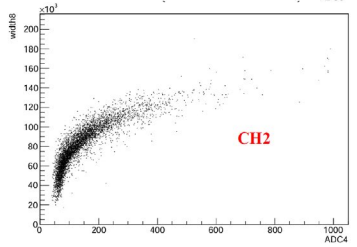
- FEB (Front-end Electronics Board)
  - Commercial chips with radiation tolerance based on past studies for particle physics experiments
  - FPGA based TDC for TOA and TOT measurement with ~1 ns time resolution
  - ADC for charge measurement or TOT calibration
  - DAC for threshold setting or SiPM bias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

Test for TOT

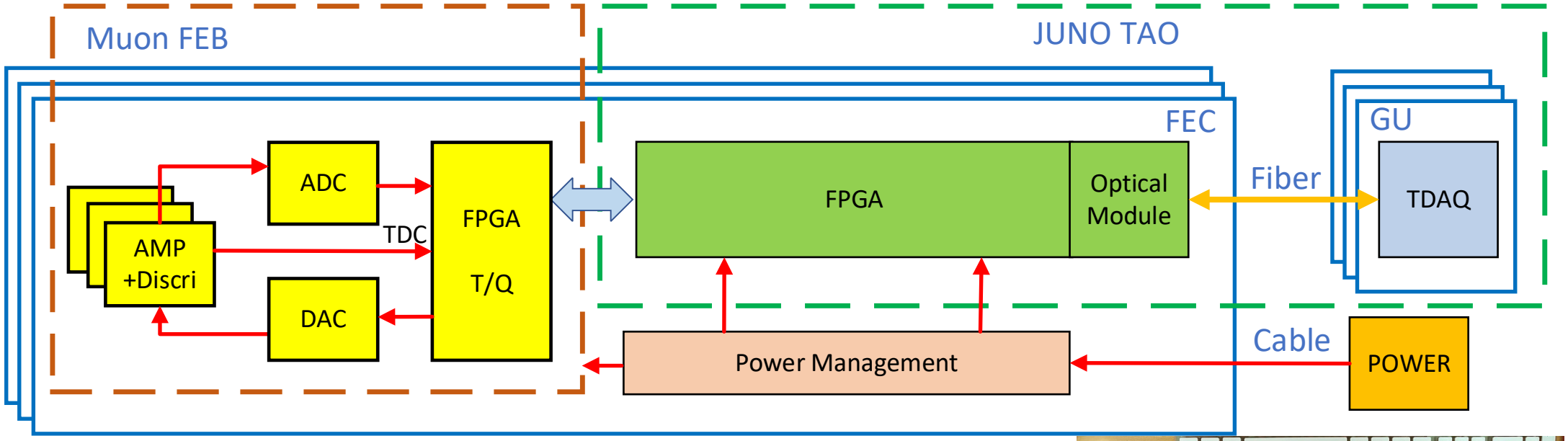




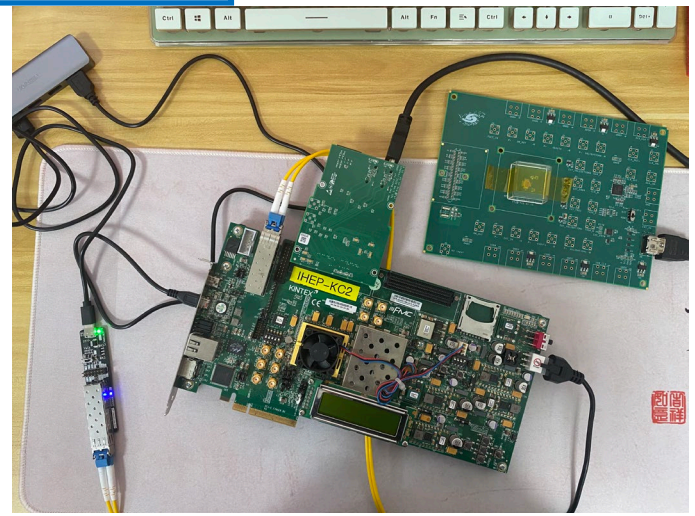




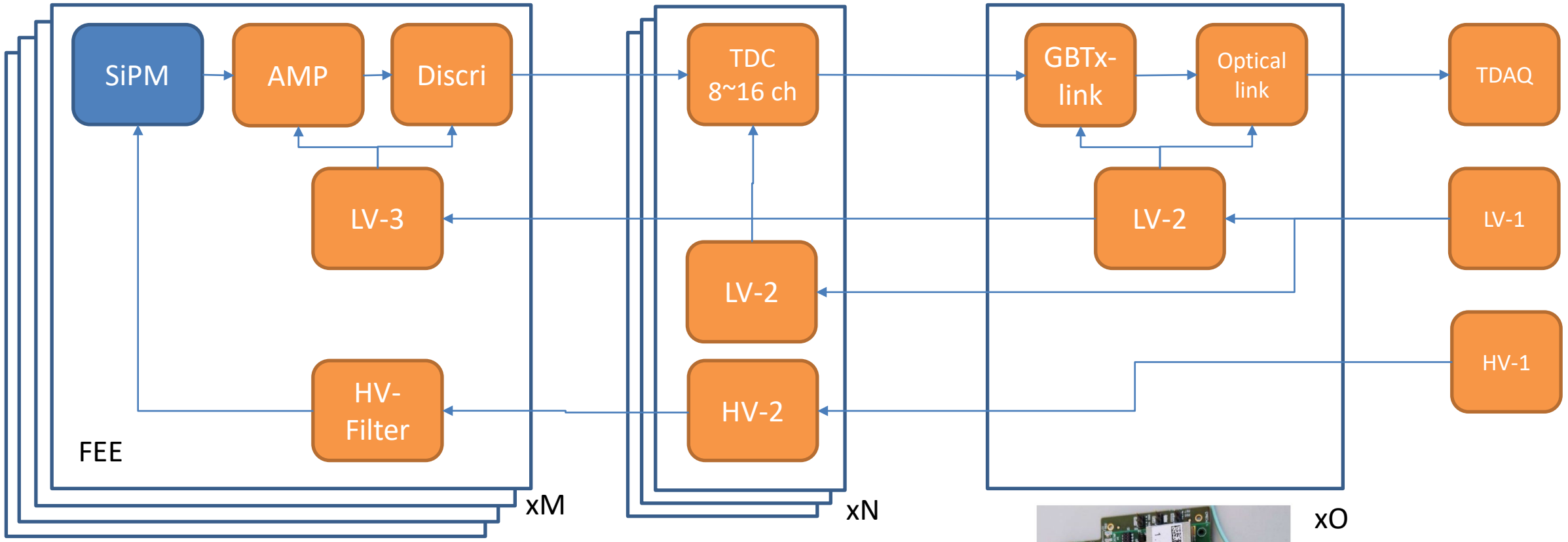
Near-term test environment



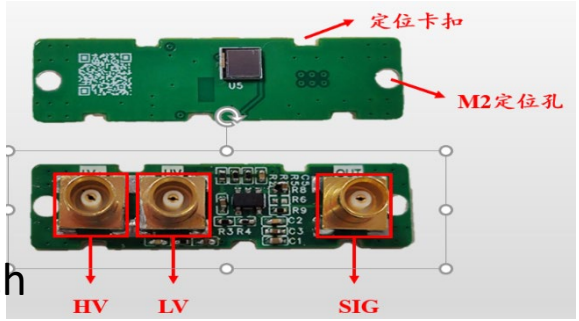
- Reuse JUNO-TAO electronics for readout, clock synchronization and TDAQ
  - To accelerate the development schedule



Stage scheme

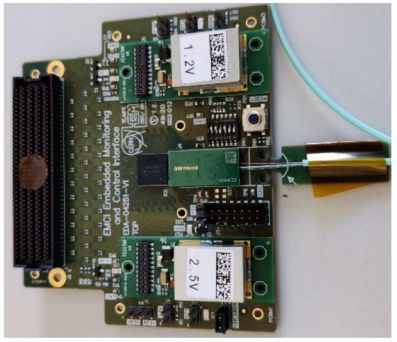


Example:



For each ch

For each module



For each sector

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

Status of software & simulation

Software update

Everything based on CEPCSW framework.

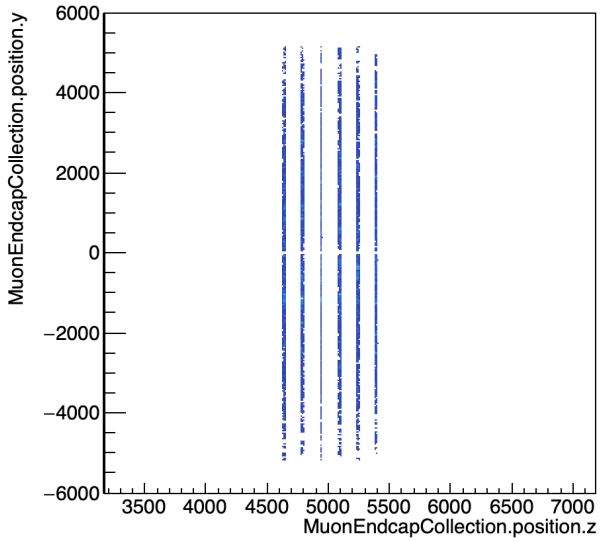
Tasks & Status	3 weeks ago	Today
Geometry: **Update to new baseline geometry:** **Barrel (8-layers) / Endcap (6-layers)**	Bug fix for output sim hits, merge request ready.	**Merged and tested.**
Digitization: **from "Sim. Hit" (GeV)** **to "Raw Hit" (ADC counts)**	Preliminary implementation strategy proposed.	**A first experimental version implemented:** - **A simplified model from GeV to ADC counts directly.** - **A more realistic model is almost ready** - **Merge Request in CEPCSW is almost ready** - **Only for barrel at the moment.**
Detector Optimisation **& Physics Performance**	Not started.	**Preliminary optimisation of:** - **the muon tracker hit vs. energy threshold** - **Muon id efficiency vs. momentum**

Software update: simulation

Everything based on CEPCSW framework.

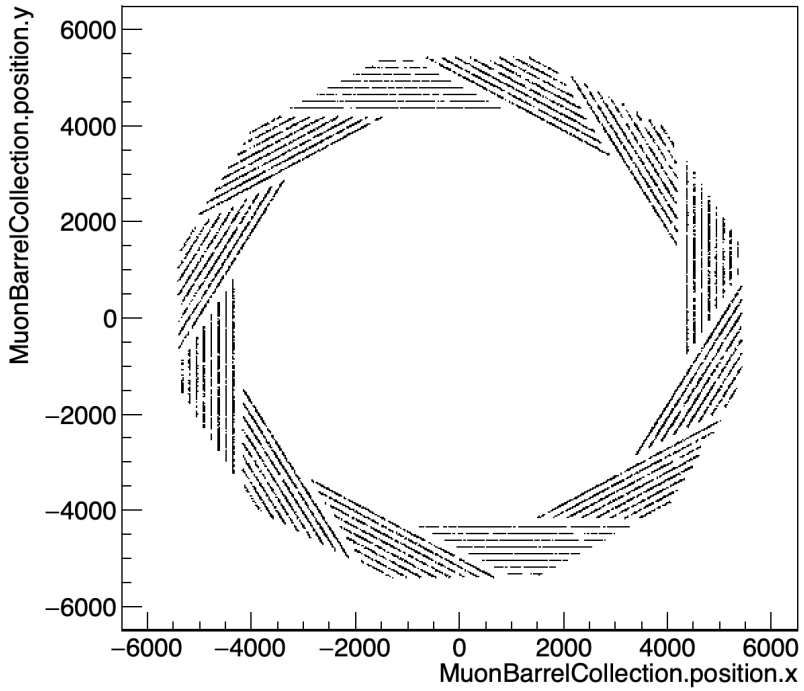
Muon Sim Hit positions

z-y position map in Endcap



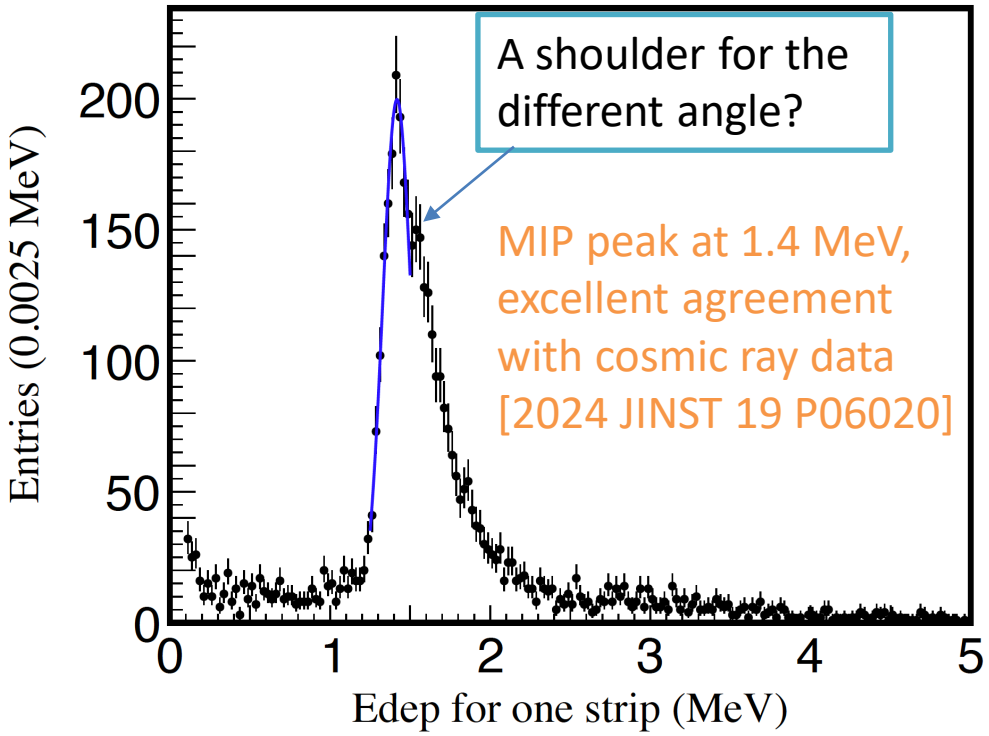
1k muons with 10 GeV/c

x-y position map in Barrel



Muon detector geometry is clearly visible!

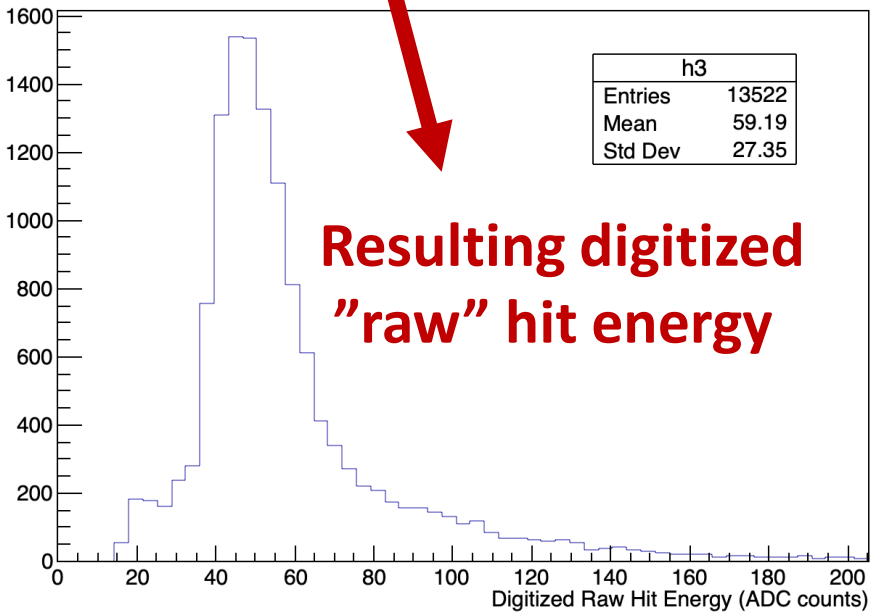
Muon Sim Hit Energy deposition



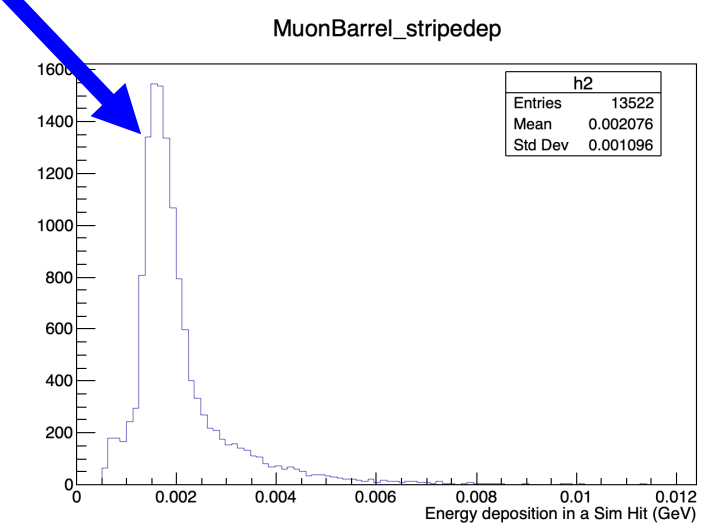
Software update: digitization

- 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.

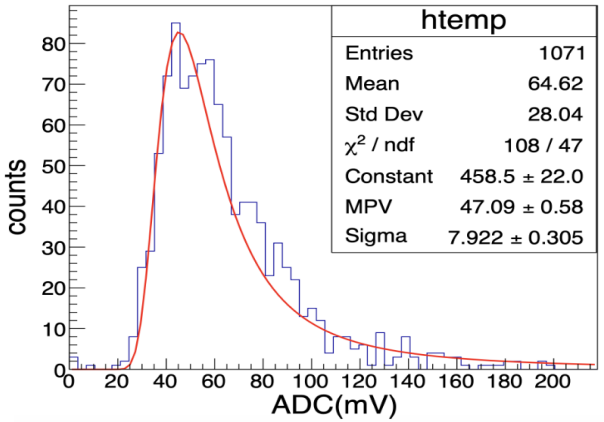
$E_{digi.}$ (ADC counts) = $E_{sim.}$ (MeV) ÷ 1.4 MeV ⊗ MIP



Resulting digitized ”raw” hit energy



MIP peak distribution in unit of ADC counts

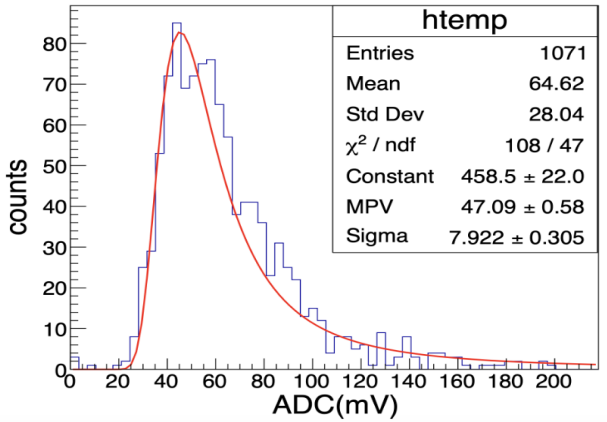


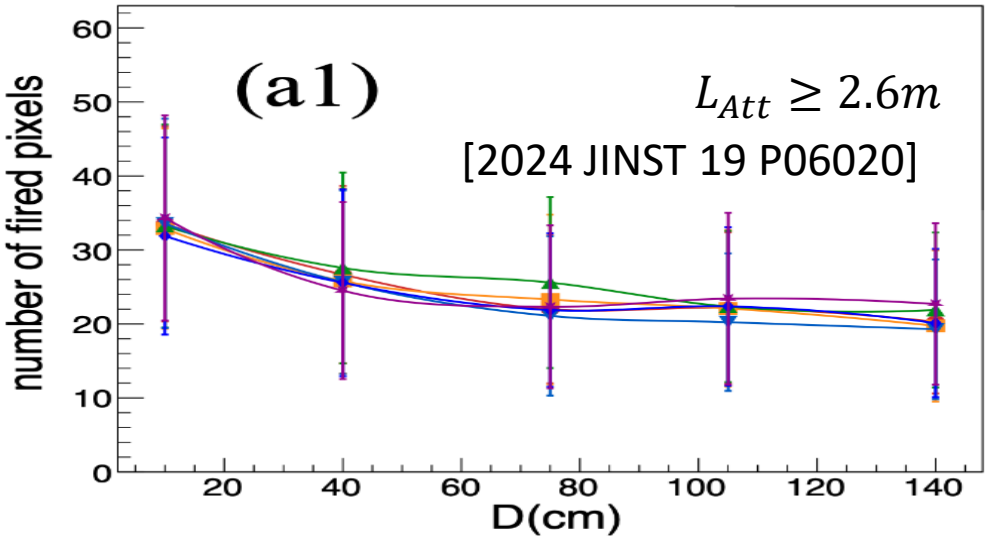
[2024 JINST 19 P06020]

Software update: digitization

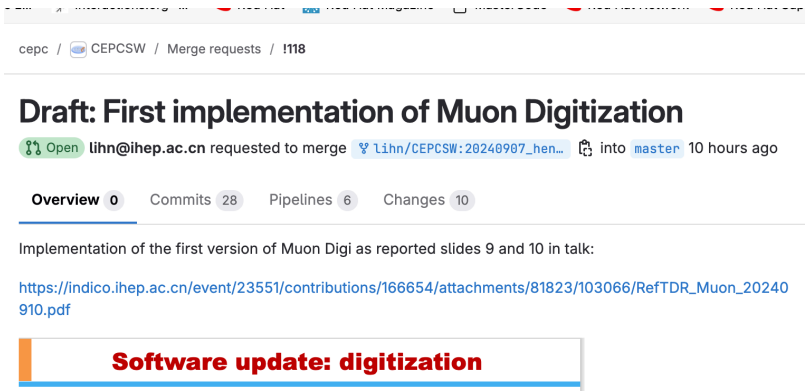
- Digitization from “Sim. Hit” (GeV) to “Raw Hit” (ADC counts)
- A first experimental version implemented:
  - A simplified model from GeV to ADC counts directly.
  - Only for barrel at the moment.
- A more realistic model with N_{pe} per MIP attenuated along the strip is to be ready this week: →

MIP peak distribution in unit of ADC counts





Merge Request in CEPCSW is almost ready.

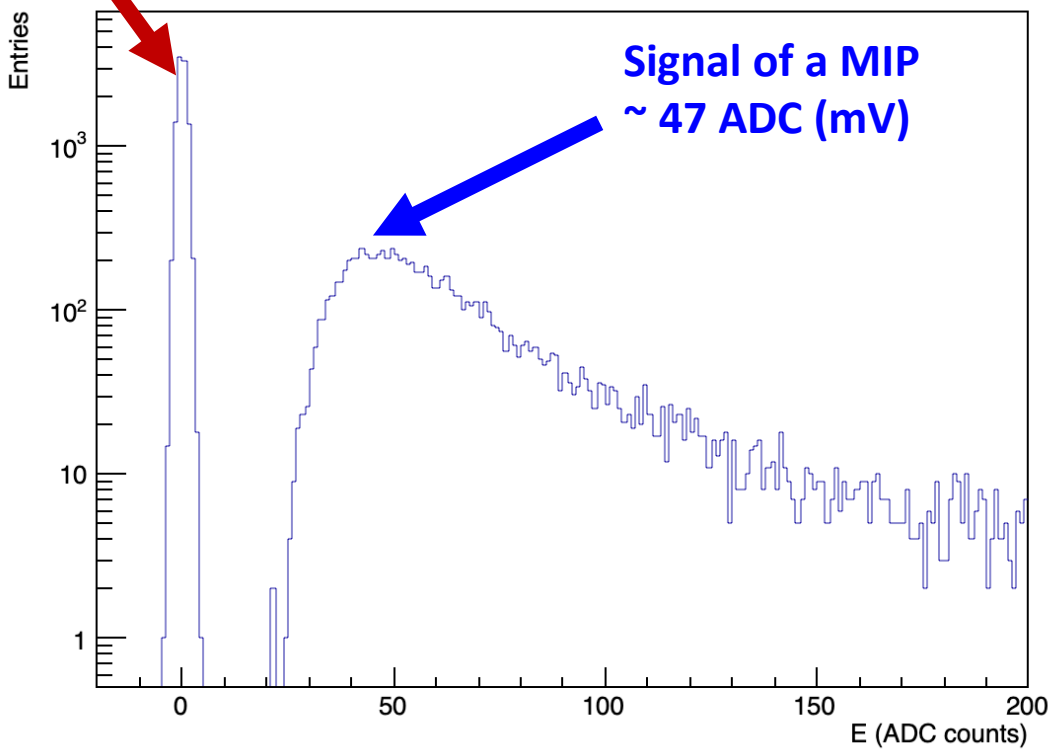


Software update: Optimization

- The muon tracker hit vs. energy threshold:

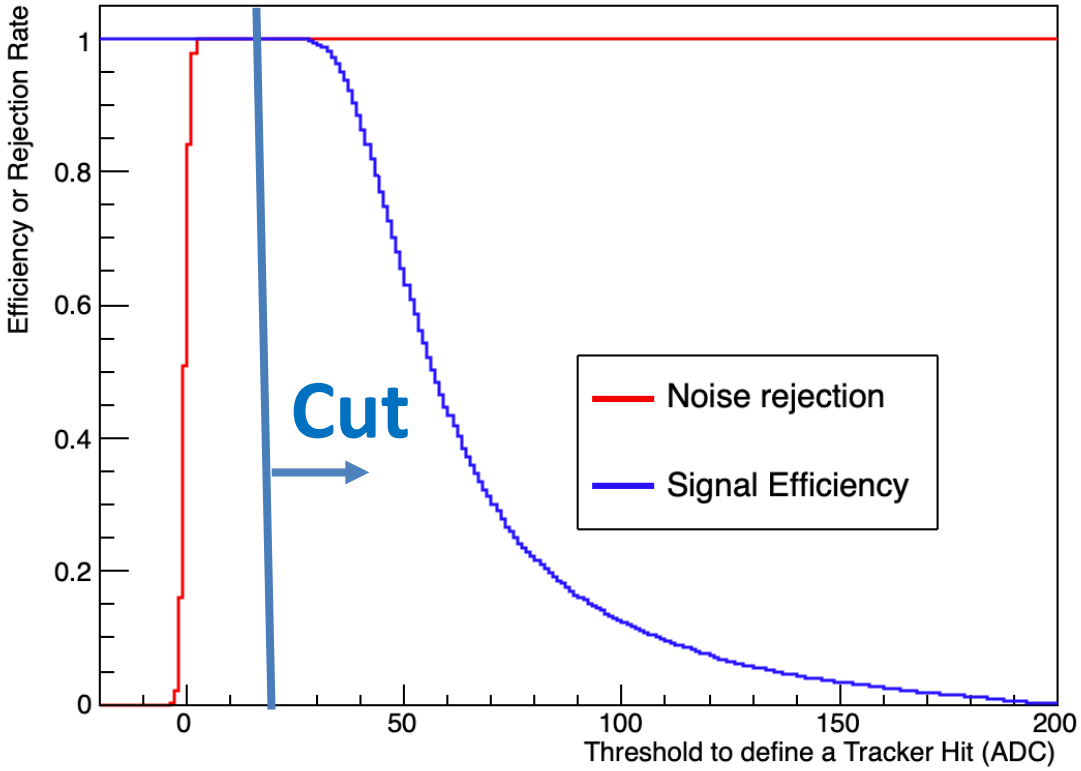
Pedestal peak, width ~ 1 ADC (mV)

Signal and electronic noise are well separated.



[2024 JINST 19 P06020]

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

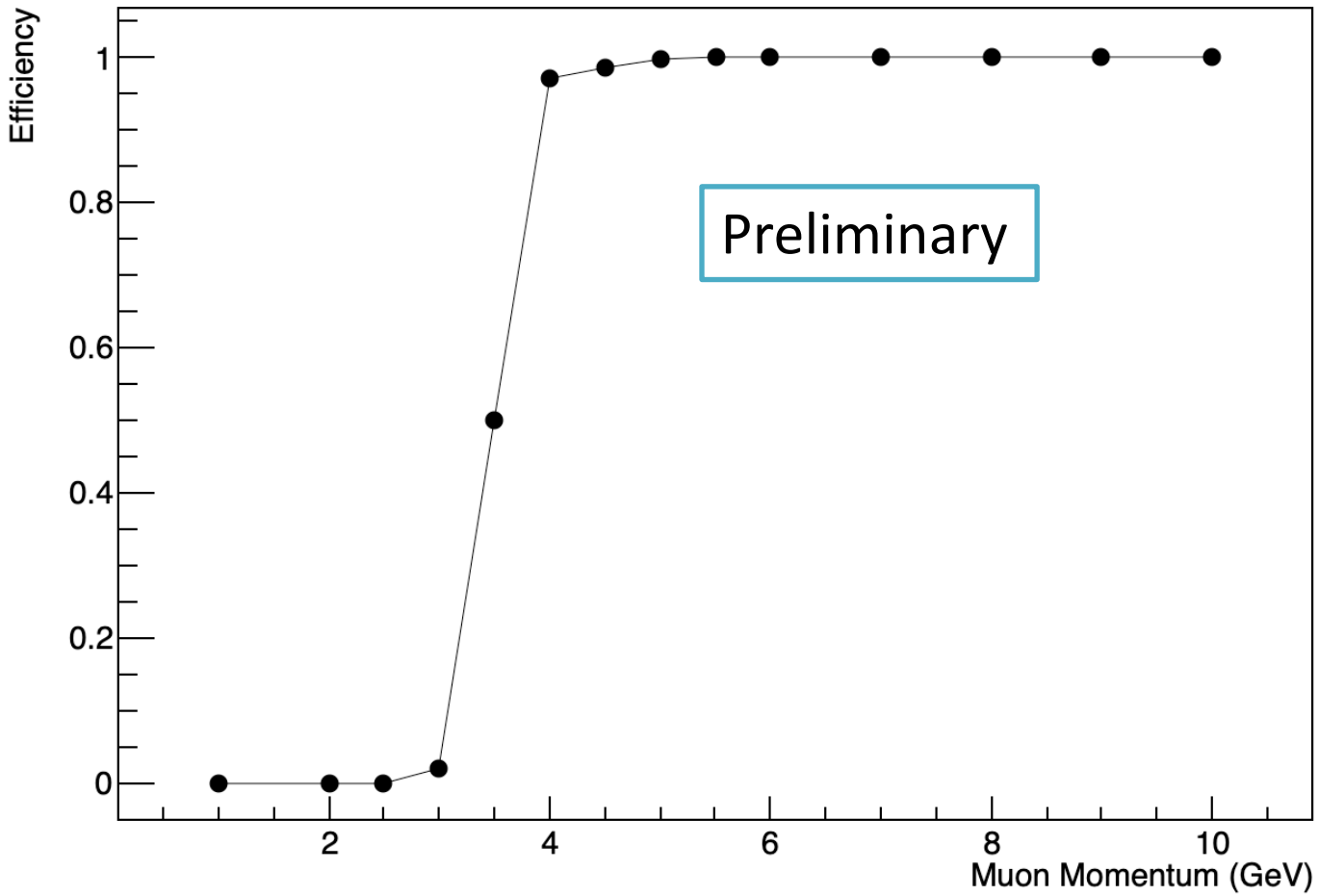


Assuming pedestal : signal = 1:1

Software update: Optimization

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

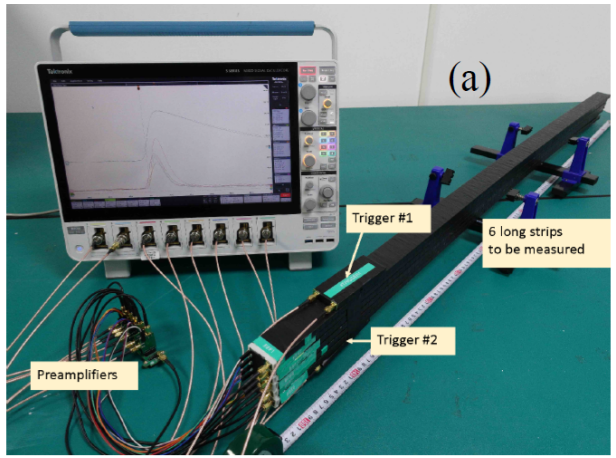
  If a muon candidate has 3 or more hits reconstructed in the muon detector, it is identified as a muon.

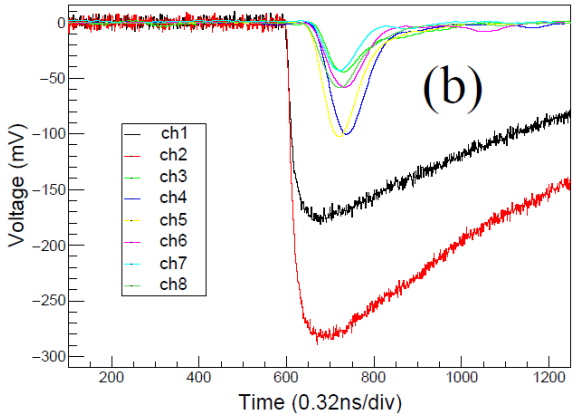


Efficiency in barrel

Next improvements

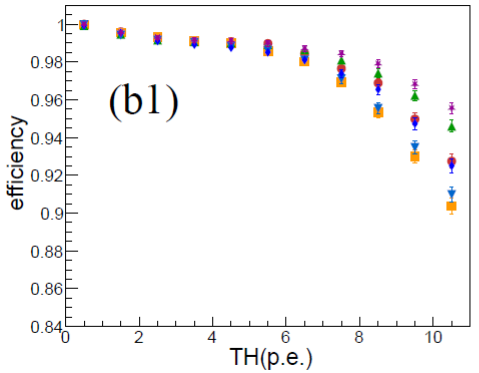
- According to the tests in lab.
  - Channel efficiency from ~100% → 90-95%.
  - Number of active channels

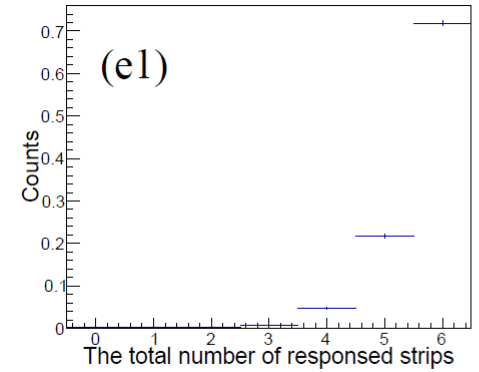




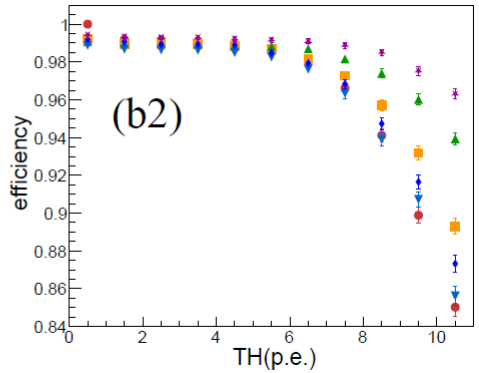
[2024 JINST 19 P06020]

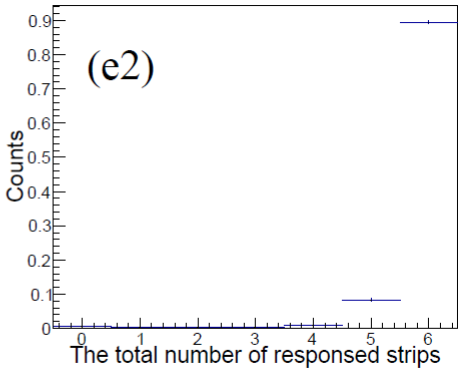
NDL SiPM





HPK MPPC

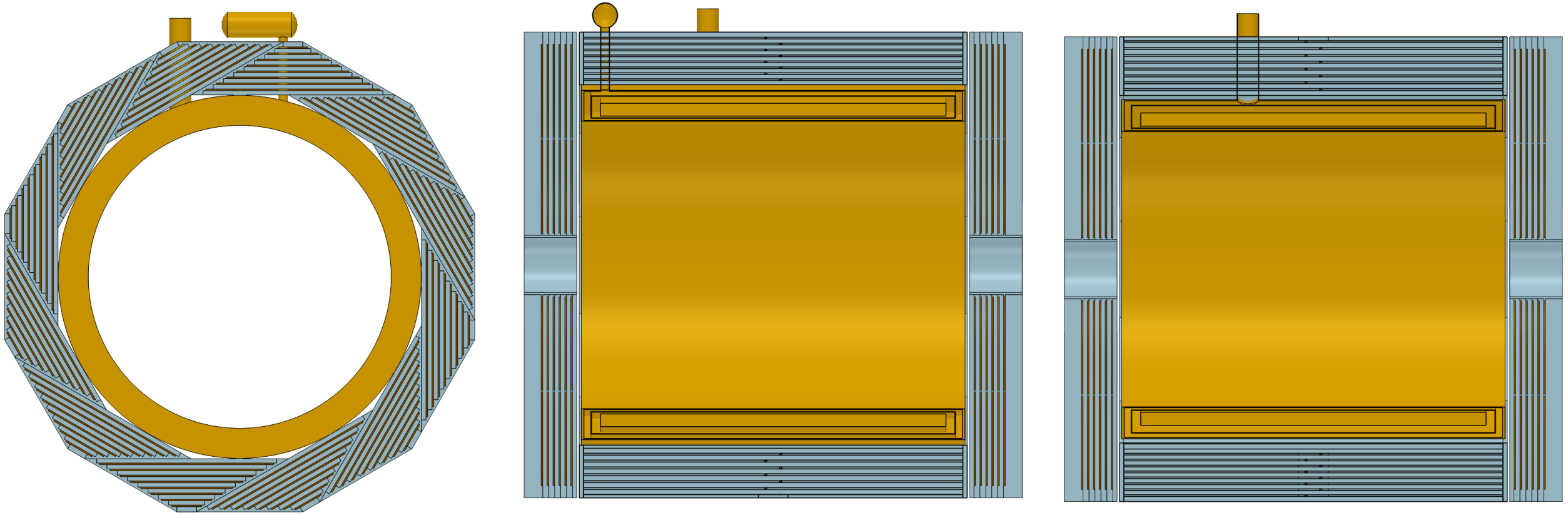




- Study of the overall performance is ongoing, including tracking.

Update on geometry/mechanics

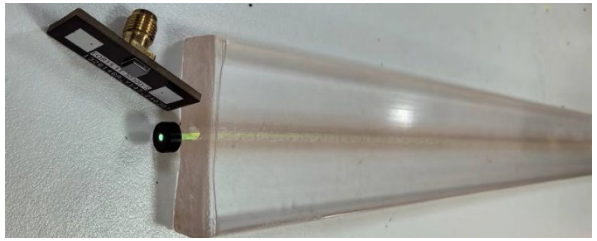
- Input the chimneys of the magnet system.
- It may contribute a dead zone of <0.4%.



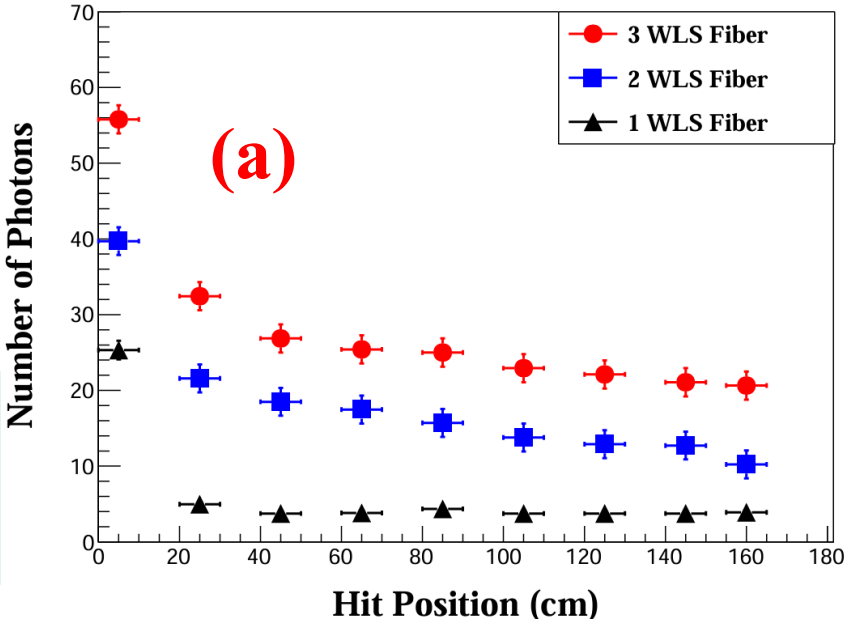
- Status of others

Improvements on the scint. strip

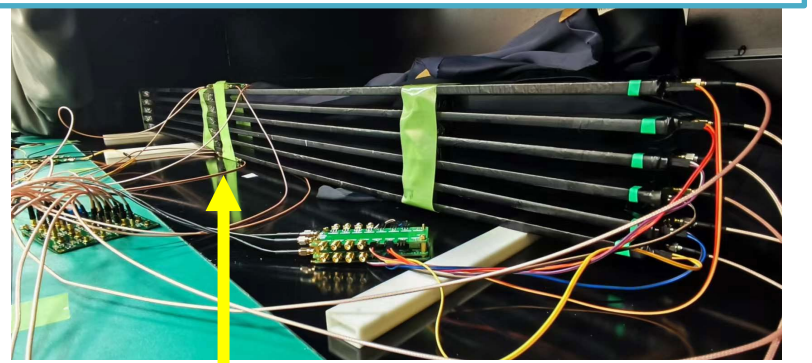
- Fiber embedding: Groove → hole
- Diameter: $1.2mm$ → $2.0mm$



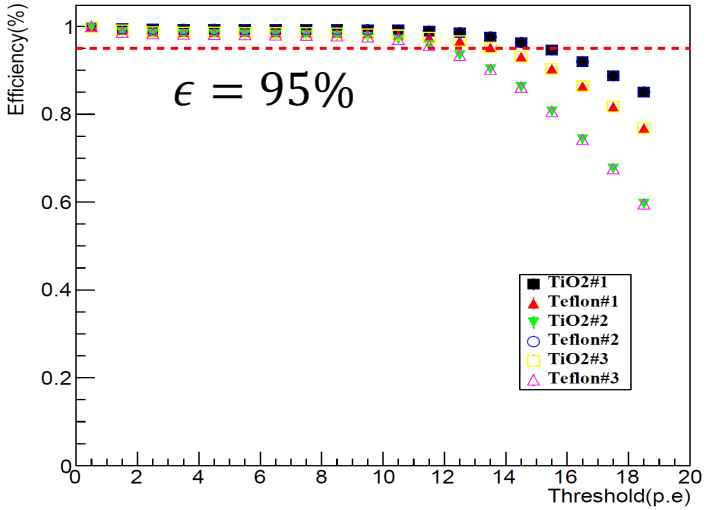
New performance!!!
Very positive to the design of very long module (>4m).

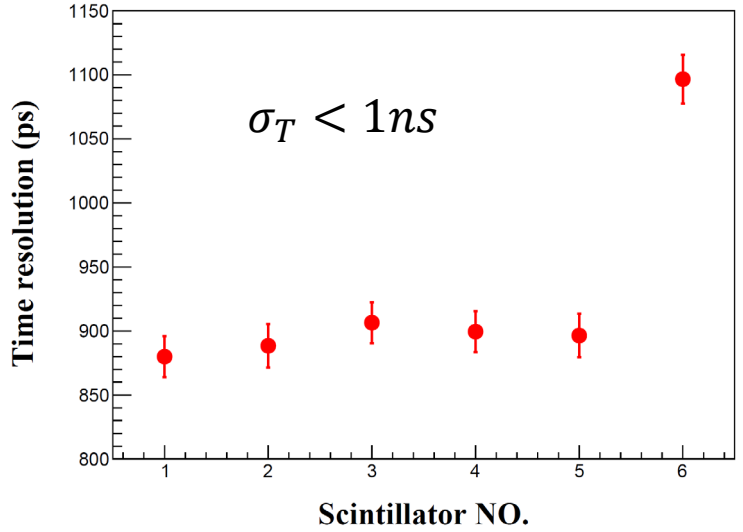


1.65m new scint with 2.5mm diameter

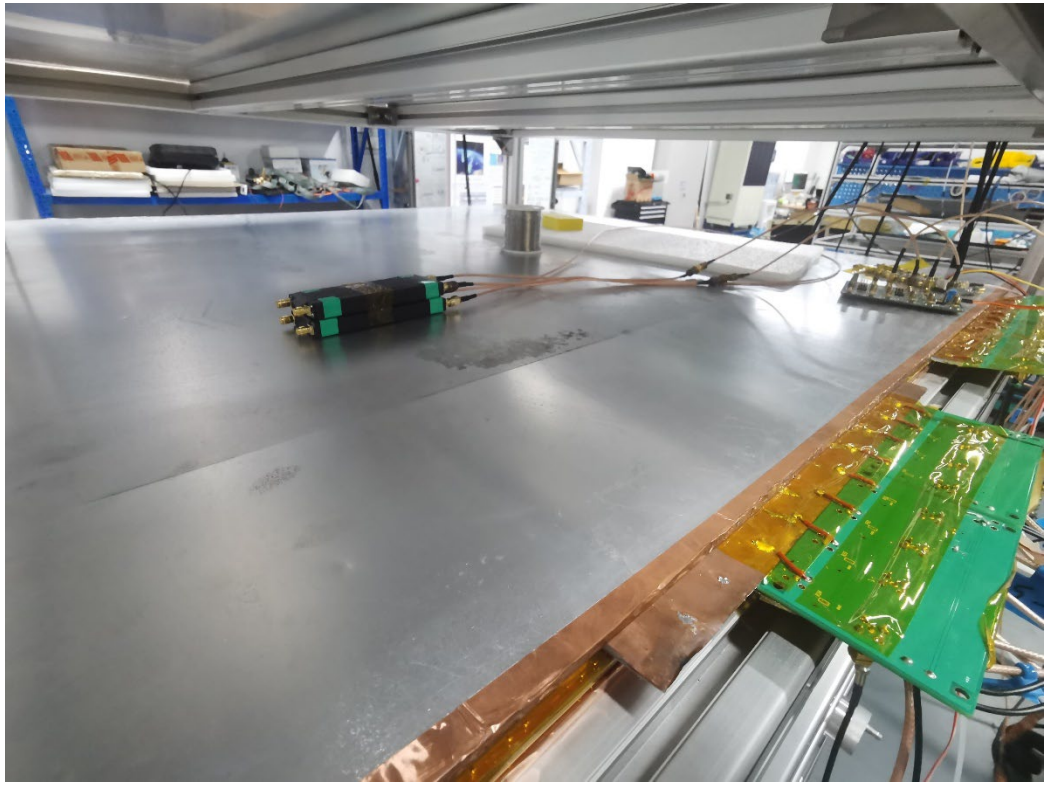


Trigger at middle





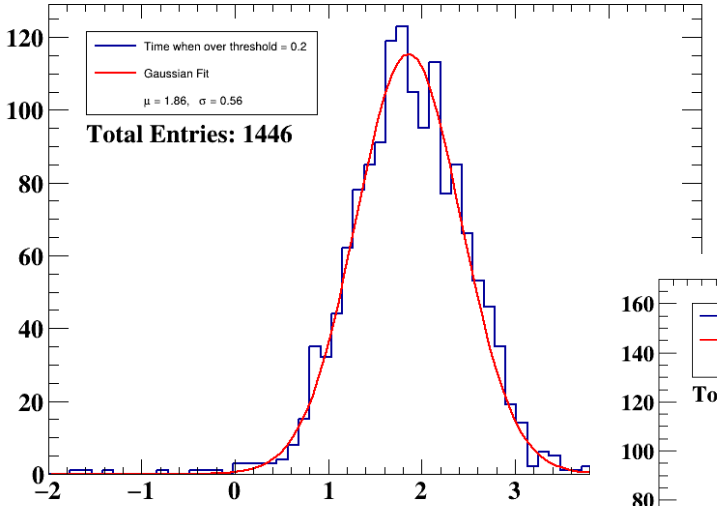
Setup of RPC@SJTU



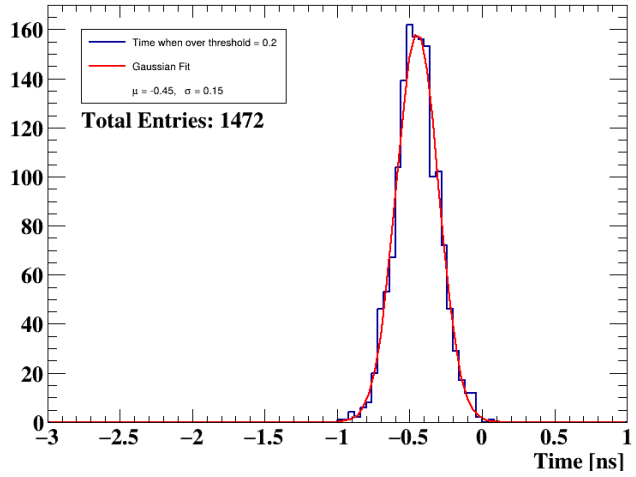
Scintillator 1

Scintillator 2

RPC



Δt_{RPC}



Δt_{12}

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

Thank you!

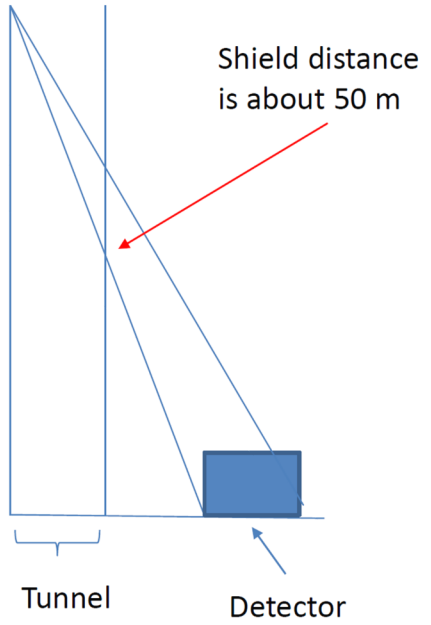
Considerations of the backgrounds

- Very low level of the CR backgrounds, with the earth shield of > 50m.
- Reference to the beam backgrounds in Belle II.

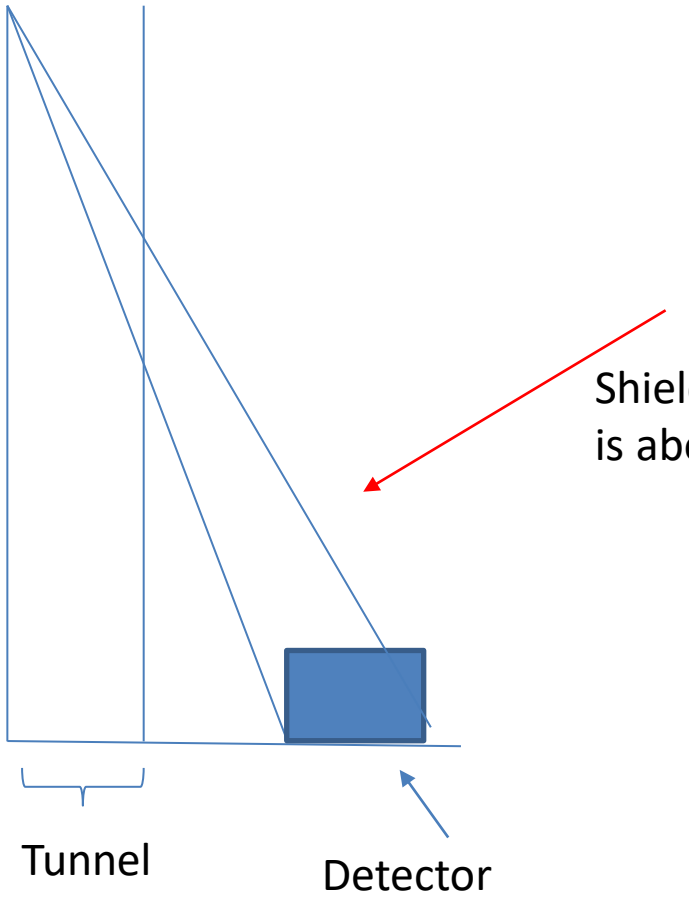
Barrel Layer	Expected Hit Rate (Hz/cm^2)	Expected RPC Efficiency	Bad-case Hit Rate (Hz/cm^2)	Bad-case RPC Efficiency	Worst-case Hit Rate (Hz/cm^2)	Worst-case RPC Efficiency
0	—scintillators—		—scintillators—		—scintillators—	
1	—scintillators—		—scintillators—		—scintillators—	
2	2.6	0.86	26	0.00	260	0.00
3	1.7	0.91	17	0.14	170	0.00
4	0.9	0.95	9	0.54	90	0.00
5	0.5	0.97	5	0.54	50	0.00
6	0.5	0.97	5	0.54	50	0.00
7	0.3	0.98	3	0.84	30	0.00
8	0.5	0.97	5	0.54	50	0.00
9	0.2	0.98	2	0.89	20	0.00
10	0.2	0.98	2	0.89	20	0.00
11	0.1	0.99	1	0.94	10	0.49
12	0.1	0.99	1	0.94	10	0.49
13	0.1	0.99	1	0.94	10	0.49
14	0.2	0.98	1	0.94	10	0.49

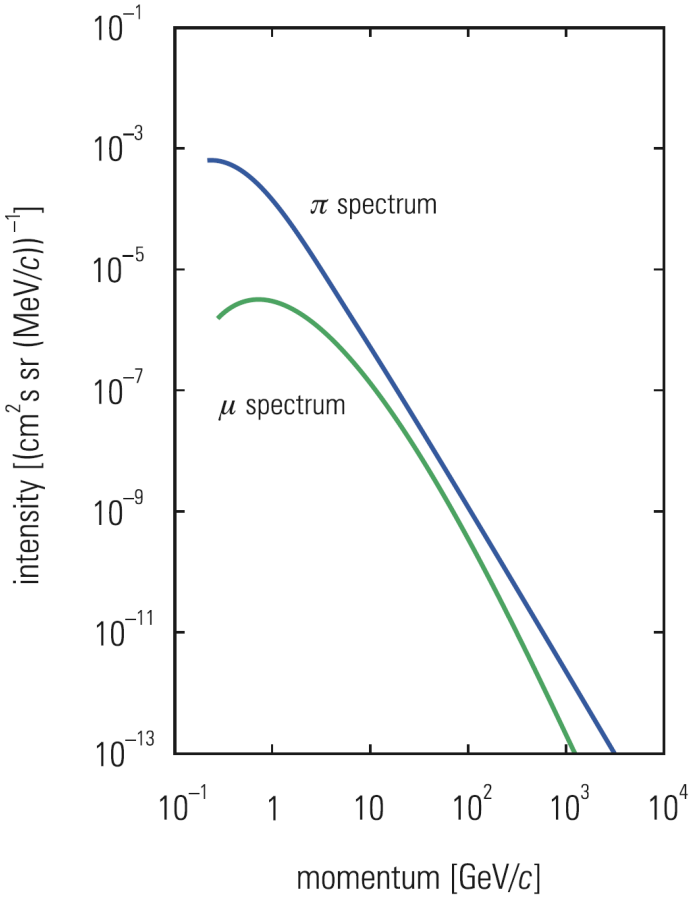
Table 2: *Neutron flux, hit rate per unit area, and instantaneous efficiency in each layer of the barrel KLM from the late-2020 simulations of beam-induced neutron backgrounds at the SuperKEKB design luminosity of* $6 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. *Here, the Belle II hybrid configuration replaces the RPCs in the two innermost layers with scintillators and neutron-absorbing polyethylene sheets.*

For a 4m long bar, the hit rate might be 160Hz. For the 'bad-case', it would be 1.6kHz!



Backgrounds from CR





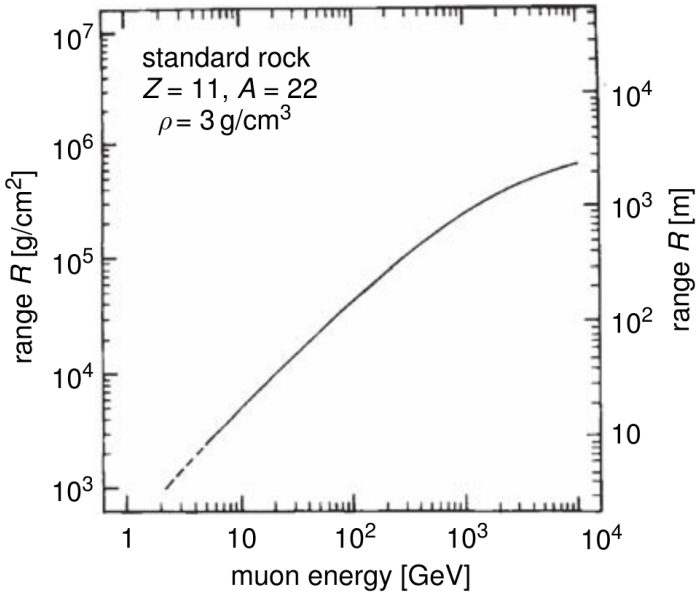


Fig. 1.12. Range of muons in rock [51].