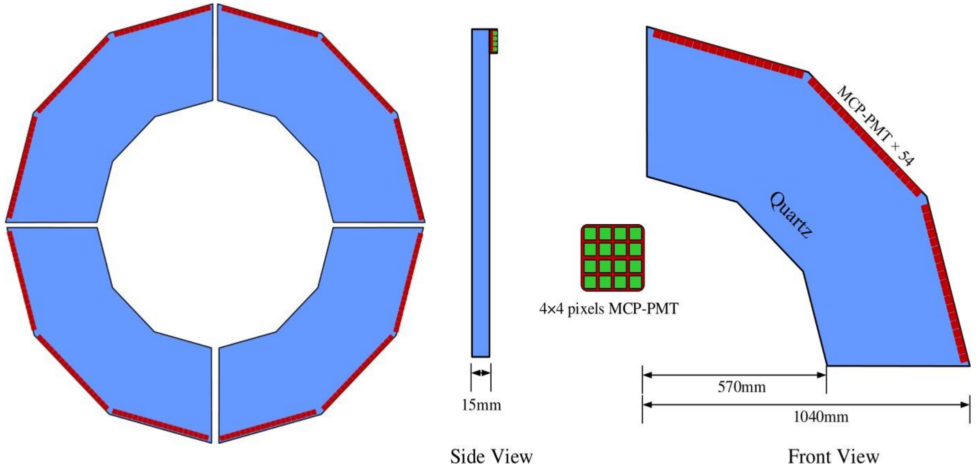


R&D of the STCF DIRC-like TOF detector

Binbin Qi

On behalf of the DTOF group

FTCF2024, Hefei, Jan.14-Jan.18, 2024

- ☐ Detector overview
- ☐ Simulation
- ☐ Prototype development
  - Radiator, MCP-PMT, Electronics
- ☐ Prototype cosmic-ray test
- ☐ Further work

STCF detector

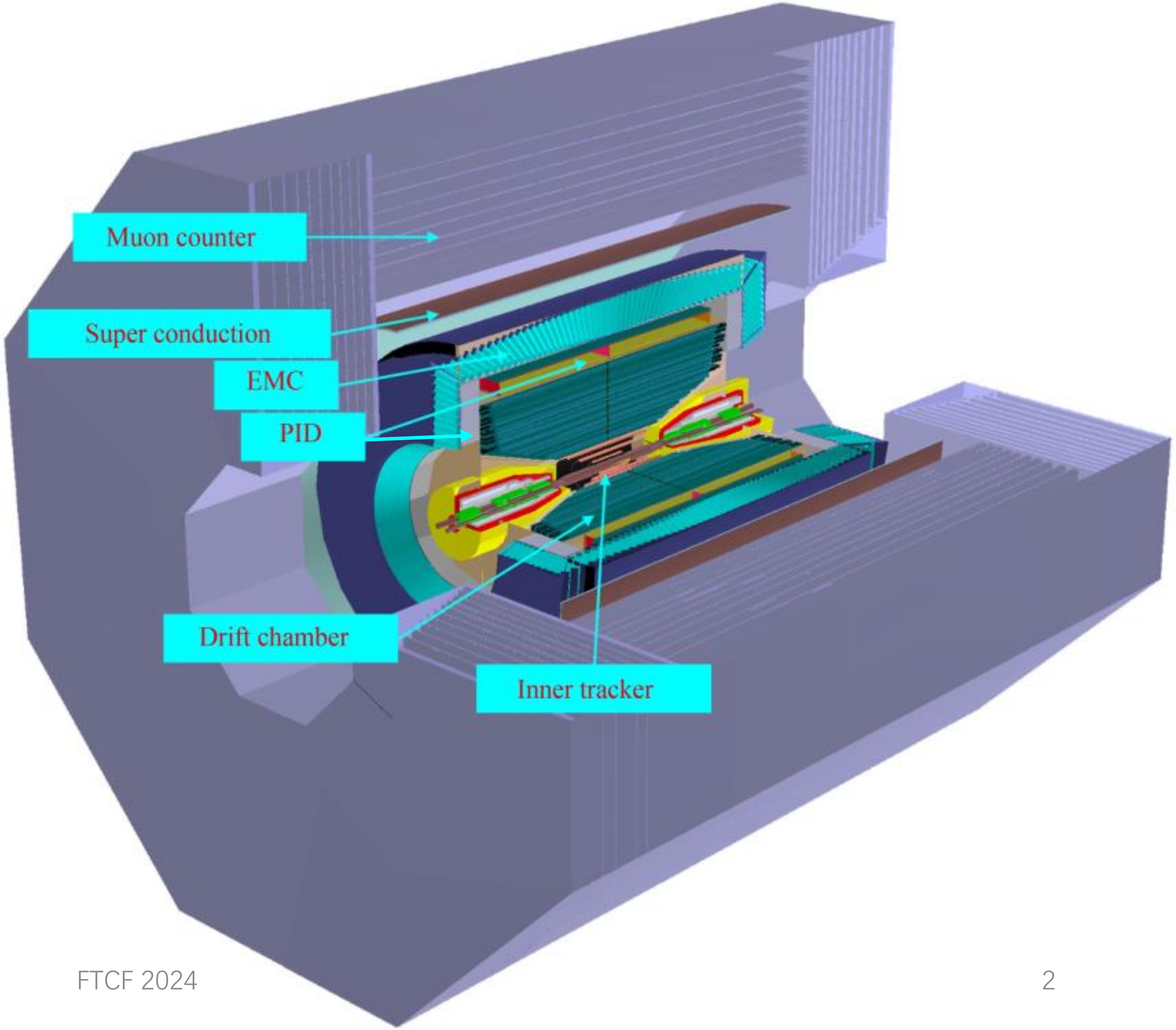
MUD
- μ/π suppression power >30 at $p < 2$ GeV/c

EMC
- Energy range: 25 MeV - 3.5 GeV
- $\sigma_E/E \sim 2.5\%$ at $E = 1$ GeV
- $\sigma_{pos} \sim 5$ mm, $\sigma_T \sim 300$ ps at $E = 1$ GeV

PID
- π/K (and K/p) 4σ separation power up to 2 GeV/c

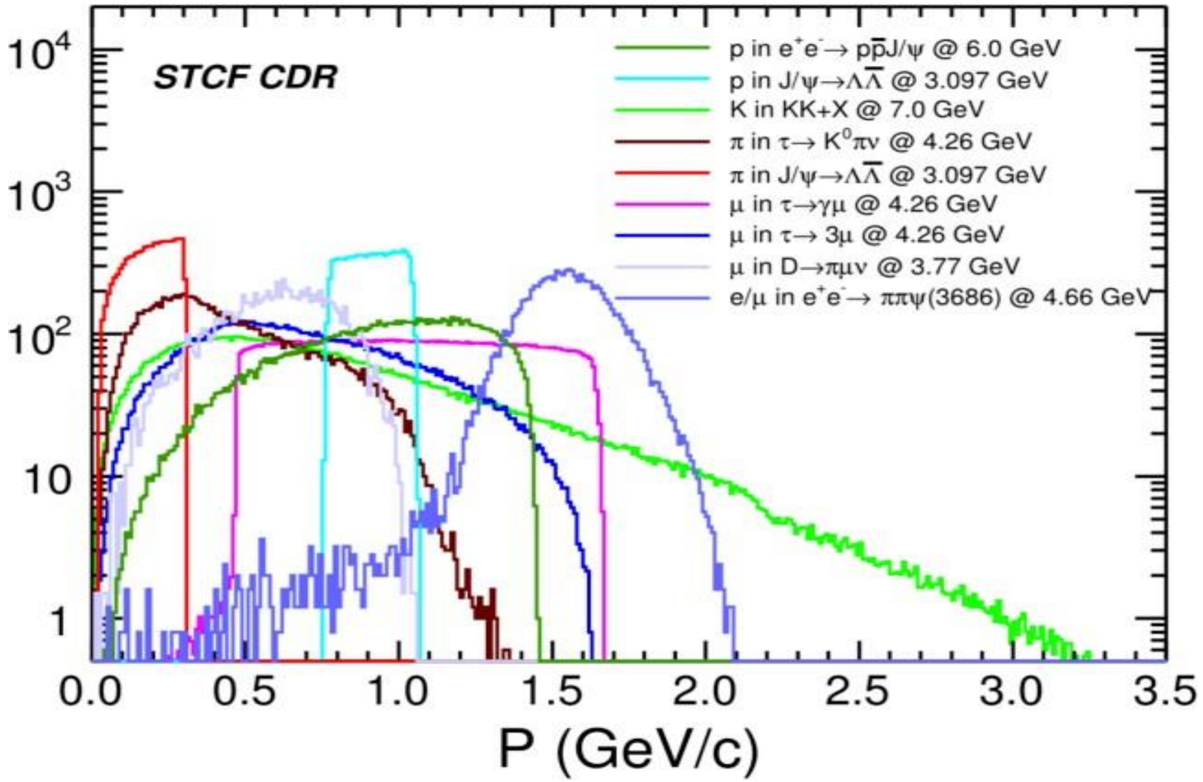
MDC
- $\sigma_{pos} = 130$ μm
- dE/dx ~ 6%, $\sigma_p/p = 0.5\%$ at 1 GeV/c
- Efficiency > 99% at $p_T > 0.3$ GeV/c and >90% at $p_T = 0.1$ GeV/c

ITK
- ~0.25% X_0/layer
- $\sigma_{pos} = 100$ μm for single hit



STCF PID requirement

The momenta of STCF final state particles



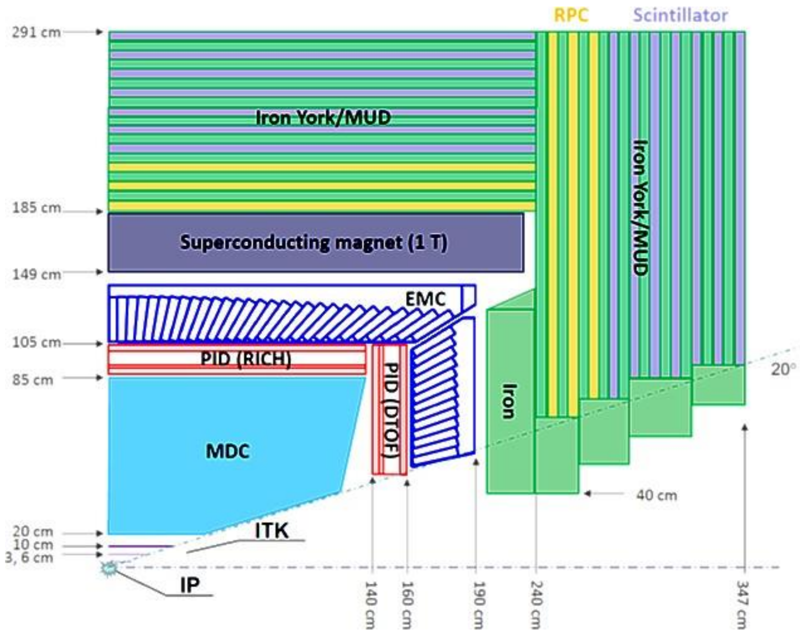
Endcap PID detector requirements

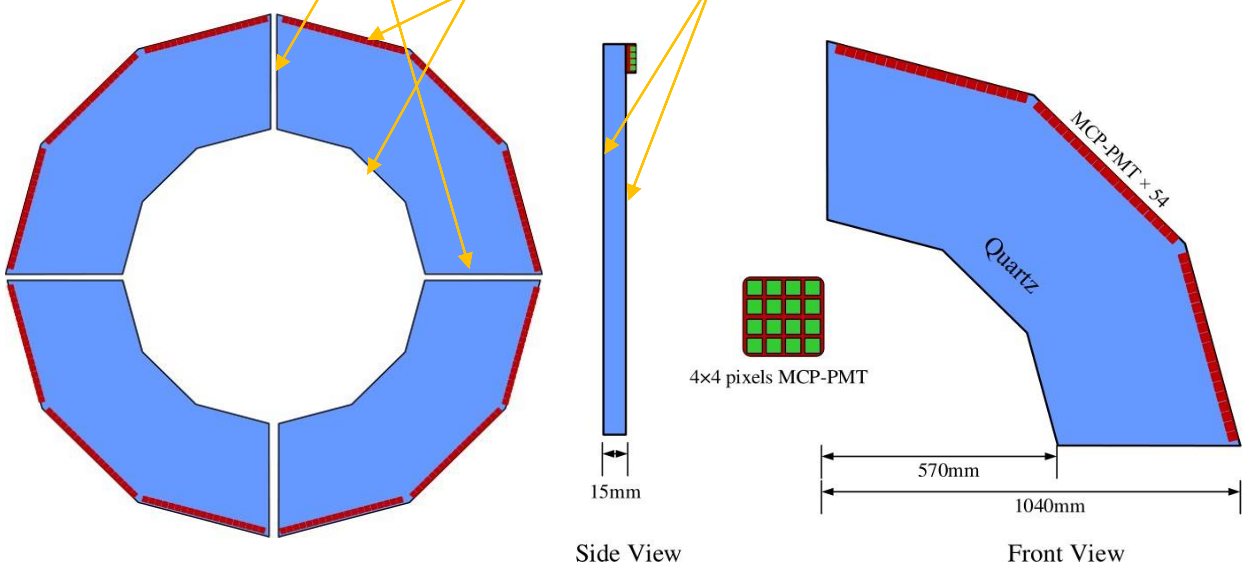
- $>4\sigma$ π/K separation power at $p \leq 2$ GeV/c
- Compact structure, thickness<20 cm
- Low material budget ($<0.5\ X_0$)
- High counting rate capability (~150 kHz/cm^2)
- High radiation tolerance

➢ A **TOF detector** based on **detection of internal reflected Cherenkov light** technology (**DIRC-like TOF**) can meet these requirements.

Review of DIRC Detectors, the talk by Schwiening, Jan 17

DTOF detector





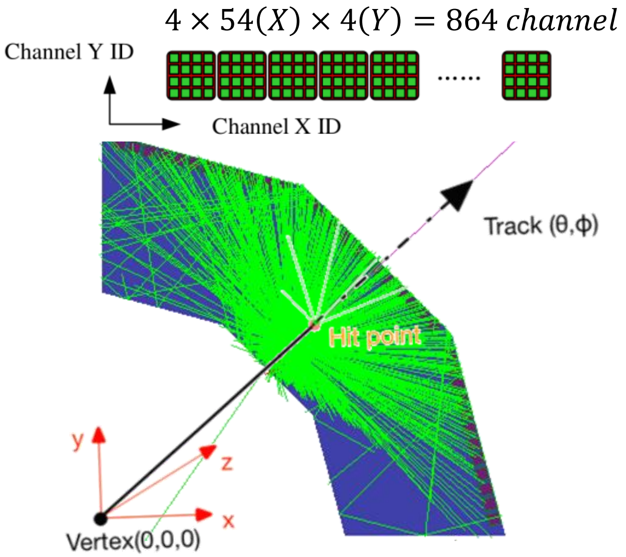
- STCF endcap PID detector
- Polar angle coverage 21°-36°
- Large area fused silica radiator
- Multi-anode MCP-PMT

$$\sigma_{tot}^2 \sim \sigma_{trk}^2 + \sigma_{T_0}^2 + \left(\frac{\sigma_{elec}}{\sqrt{N_{p.e.}}}\right)^2 + \left(\frac{\sigma_{TTS}}{\sqrt{N_{p.e.}}}\right)^2 + \left(\frac{\sigma_{det}}{\sqrt{N_{p.e.}}}\right)^2$$

~40 ps

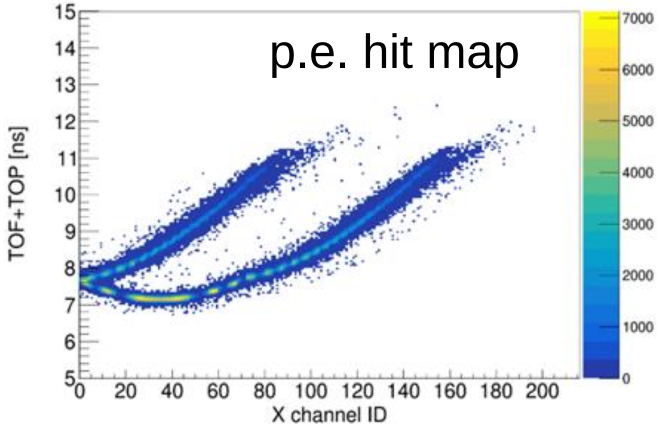
- 4σ π/K separation power at p≤2 GeV/c
  ➔Total time resolution $\sigma_{tot} < 50$ ps
  ➔DTOF intrinsic time resolution $\sigma_{DT} < 30$ ps

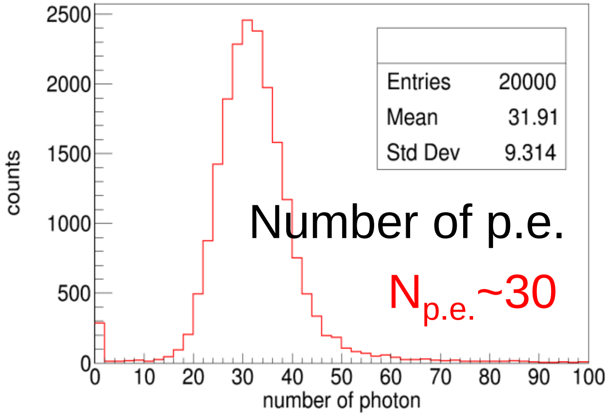
Detector simulation

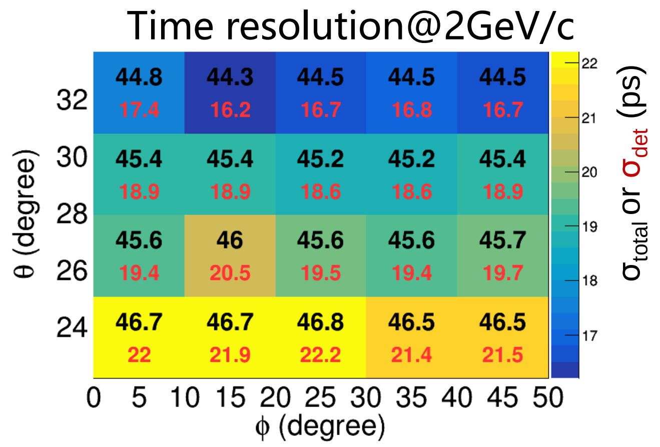


Geant4 simulation setups

- Roughness ~1 nm, Reflection coefficient ~99%
- Mirror reflectivity ~92%
- 4×4 anodes MCP-PMT, 5.5×5.5 mm^2 pixel
- Quantum efficiency ~25%@400 nm
- Considered material budget before DTOF detector





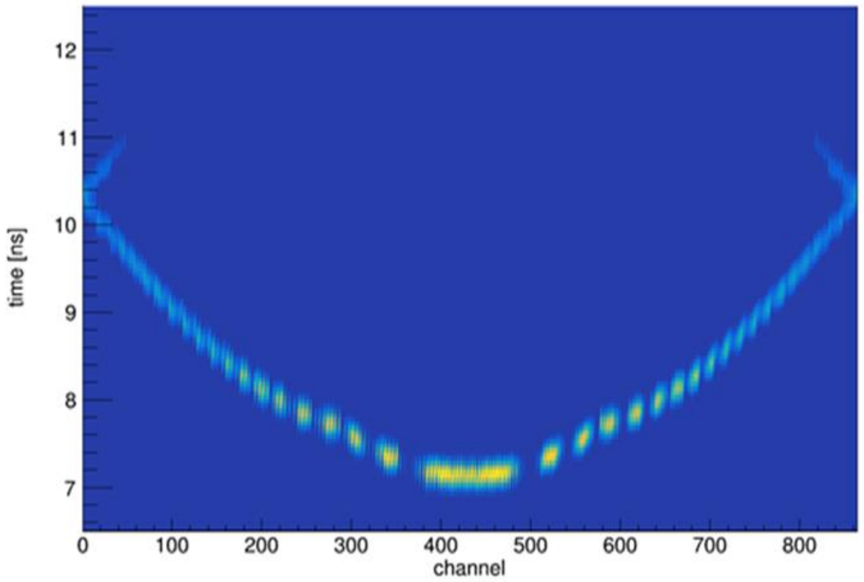


σ_{total} <50 ps, σ_{DTOF} <30 ps

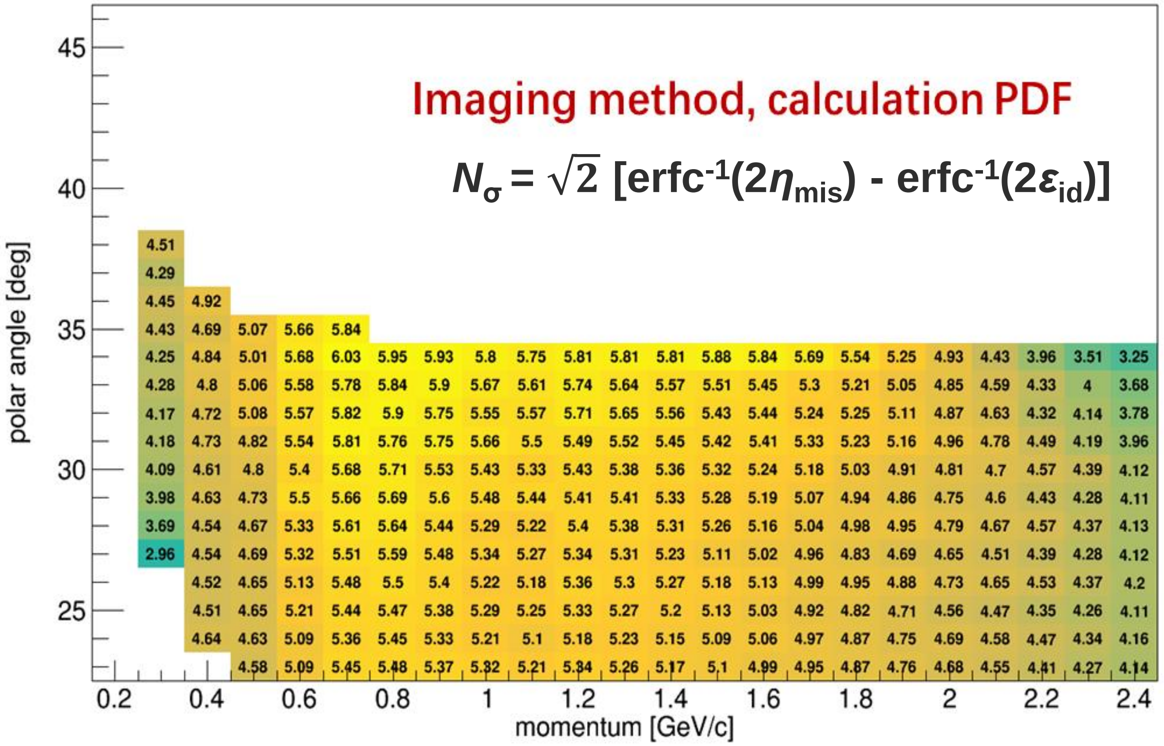
Expected PID performance

Two likelihood methods

1. **Timing method**
   - Reconstruct TOF with different hypothesis
   - $\mathcal{L}_h = p_h(N_{p.e.}) \prod_{i=0}^{N_{p.e.}} f_h(TOF_i)$
2. **Imaging method**
   - 2-D hit maps, channel and photon arrival time
   - $\mathcal{L}_h = p_h(N_{p.e.}) \prod_{i=0}^{N_{p.e.}} f_h(ch_i, t_i)$

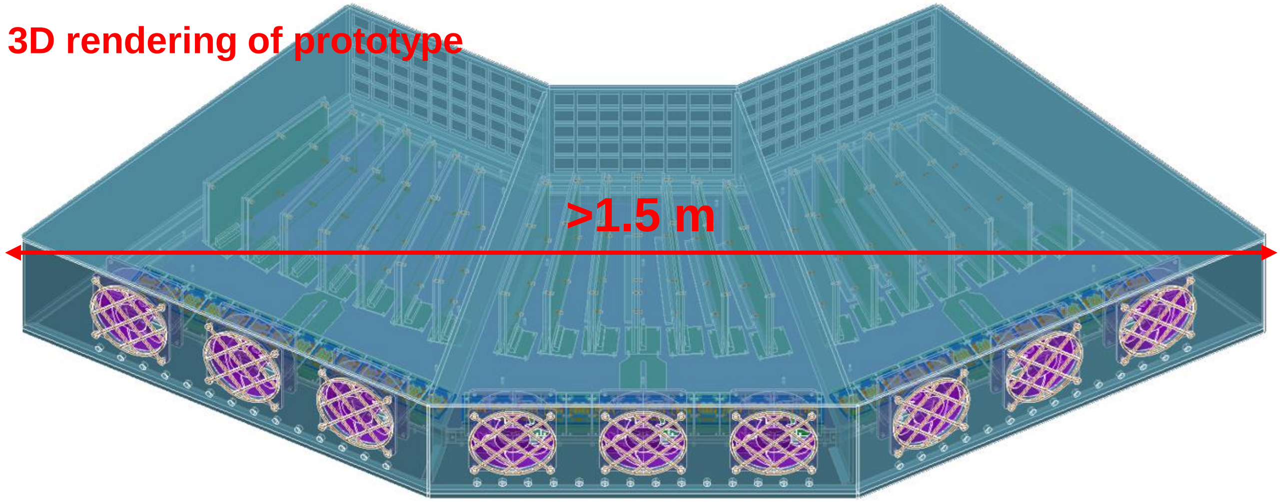


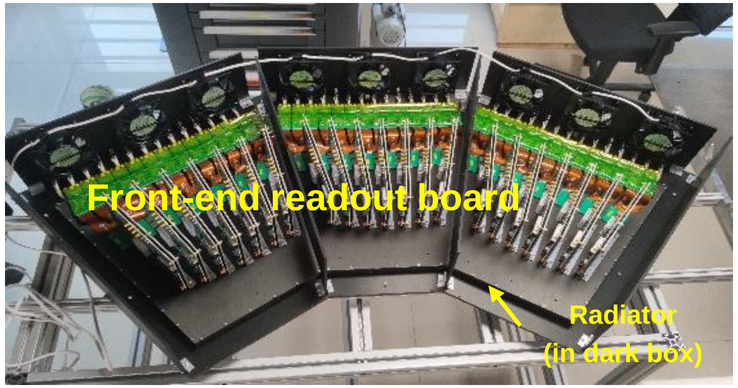
π/K separation power

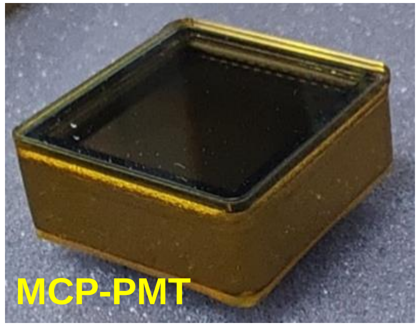


- ✓ It achieved >4σ π/K separation at p≤2 GeV/c
- ✓ Imaging method performed better at p>2 GeV/c

DTOF prototype







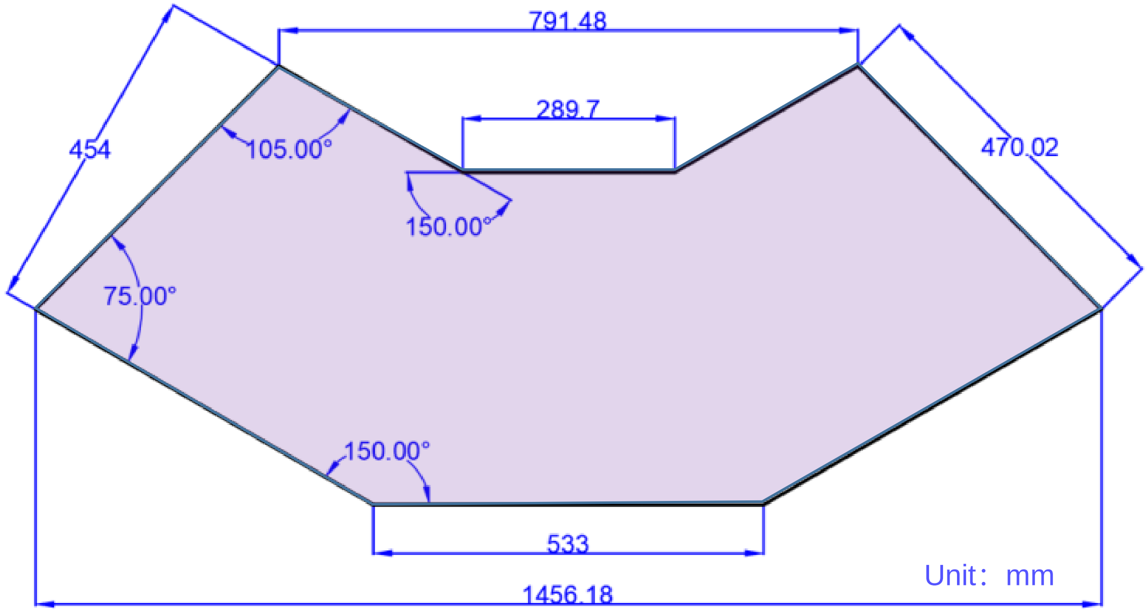
A full-size sector prototype

- **Cherenkov radiator**
  - Heraeus Suprasil 312 synthetic fused silica
  - Thickness = 15 mm, area ≈ 0.56 m^2
  - Roughness < 1 nm
- **Photon readout**
  - Hamamatsu R10754 MCP-PMT×42
  - Sensitive area 23 × 23 mm^2
  - 4×4 anodes, 5.5 × 5.5 mm^2 pixels
  - EJ-550 grease, ~300 nm cutoff
- **Electronics**
  - 672 channels
  - Timing precision < 10 ps
- **Auxiliary systems**
  - Dark box、MCP-PMT installation、cooling、mechanical…

Cherenkov radiator

Heraeus Suprasil 312 synthetic fused silica

- High purity, transparency>99%@200 nm
- High radiation tolerance
- Thickness=15 mm, area ≈ 0.56 m^2



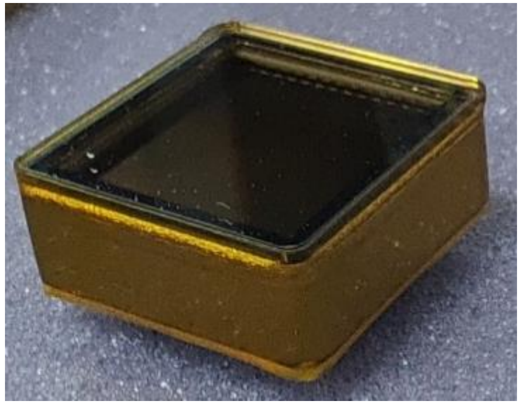
Some requirements

- Front&back surfaces, RMS <1 nm (0.75 nm, ☺)
- Lateral surfaces, RMS <5 nm (not qualified ☹➔absorber)
- Top&button surfaces, absorber
- Thickness=15±0.1 mm, T_{max}-T_{min}<25 μm

Keep Cerenkov photon direction information

Reduce the misidentification of photon paths

MCP-PMT

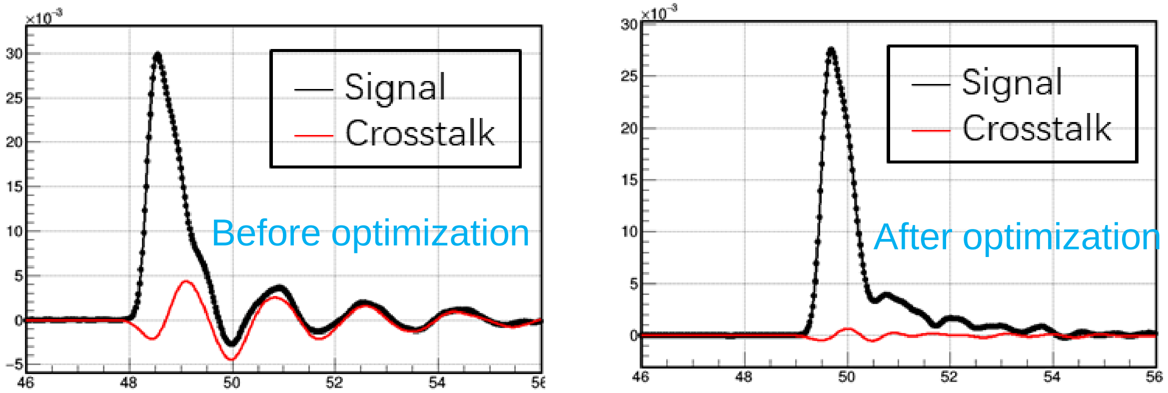


Hamamatsu R10754 MCP-PMT ×42

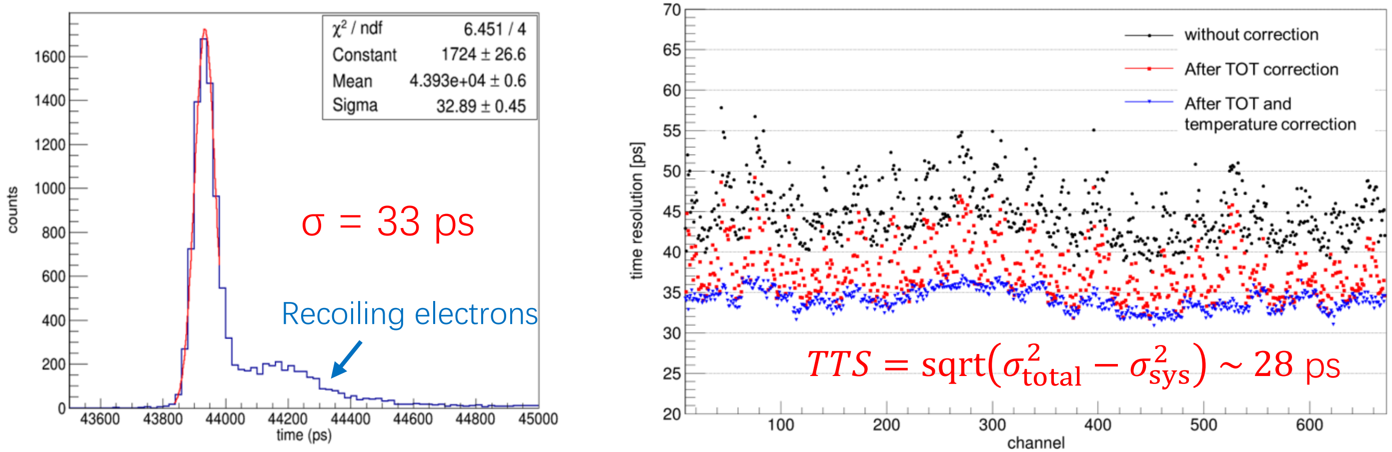
- Sensitive area, 23×23 mm^2
- Segmentation, 4×4 pixels
- Pixel size, 5.5×5.5 mm^2
- spectral response range, 200-850 nm
- Quantum efficiency, ~25%@λ=400 nm
- Gain: >10^6, uniformity~14% (σ/μ)
- Transit time spread: ~28 ps

Readout optimization to reduce crosstalk and ringing

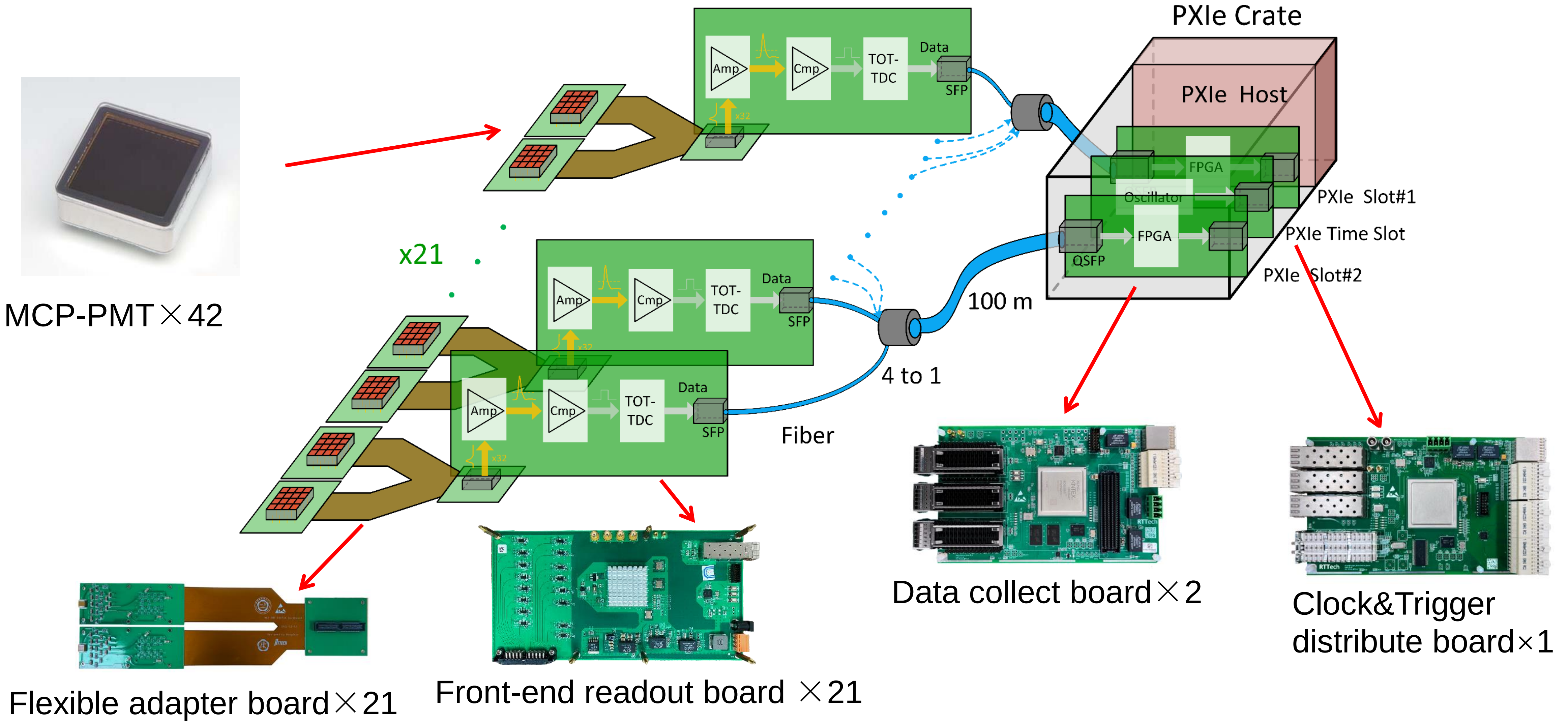
- Optimize PCB routing and ground plane to ensure signal integrity and reduce distributed capacitance
- Separate high-voltage power supply and signal readout
- The decoupling capacitors are distributed around the MCP



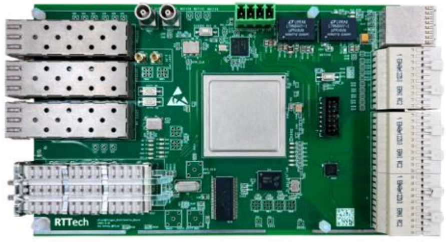
Laser (width=60 ps) test, applying TOT and temperature correction



672-channel electronics system



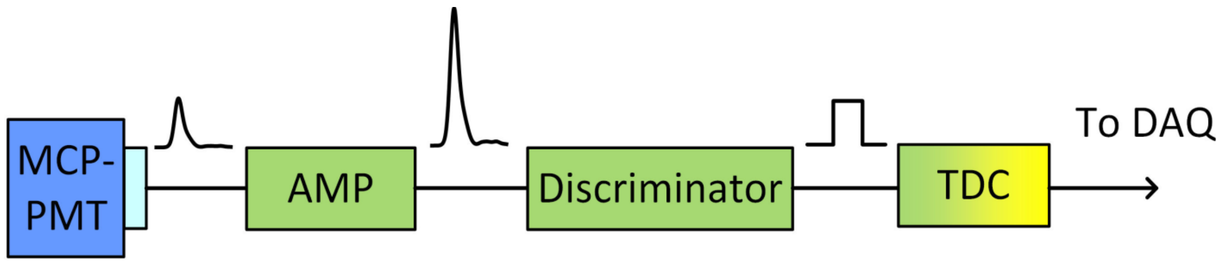
Components of electronics system



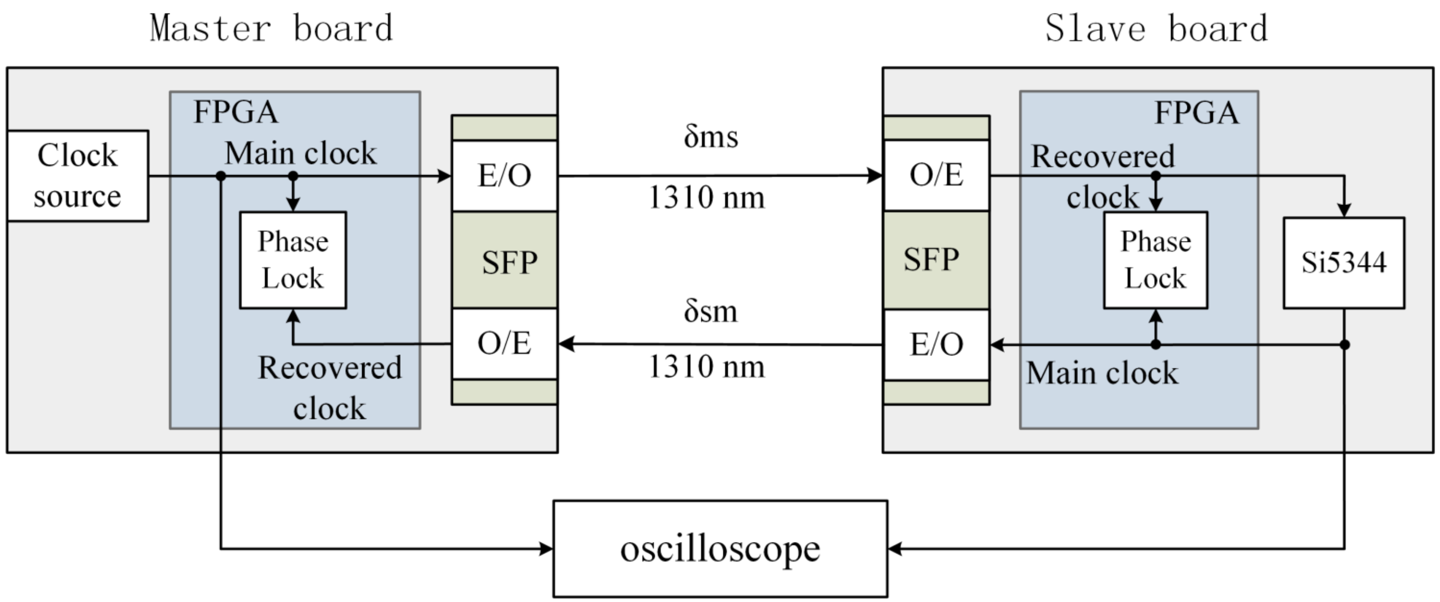
- **Flexible adapter board:** provide high voltage for MCP-PMT and output signals to the front-end readout board.
- **Front-end readout board (FEB):** receive 32-channel signals from 2 MCP-PMTs, and then process them with amplification, discrimination and digitization.
- **Data collect board (DCB):** collect data and distribute system clock to a maximum of 12 FEBs.
- **Clock&Trigger distribute board:** distribute high precision clock and trigger to DCBs.

High precision timing technique

- **Timing circuit**
  - Leading-edge discrimination and TOT correction
  - Bandwidth: ~2 GHz
  - Gain: 24dB
- **TDC**
  - FPGA-based Tapped Delay Line TDC
  - Average bin width: ~ 6.5 ps
  - Timing precision < 10 ps
  - Dead time: 3 ns (two cycles)
- **Clock distribute**
  - FPGA SerDes based clock distribution
  - Main clock: 160 MHz
  - Compensate transmission delay with phase interpolator(PI)
  - Clock synchronization accuracy <10 ps

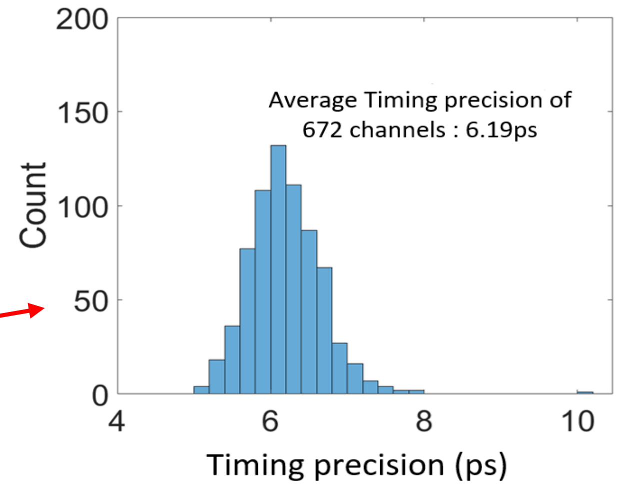


Timing circuit structure



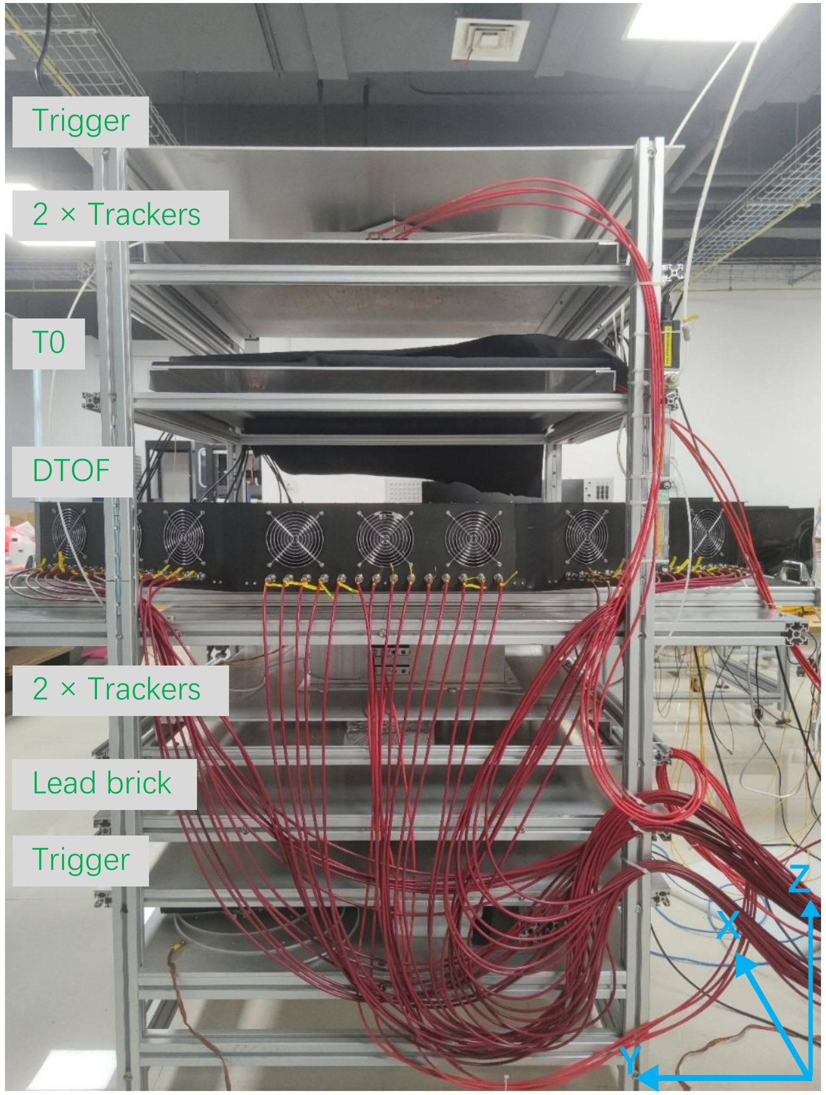
Distribute the clock via fibers

Summary of electronics system



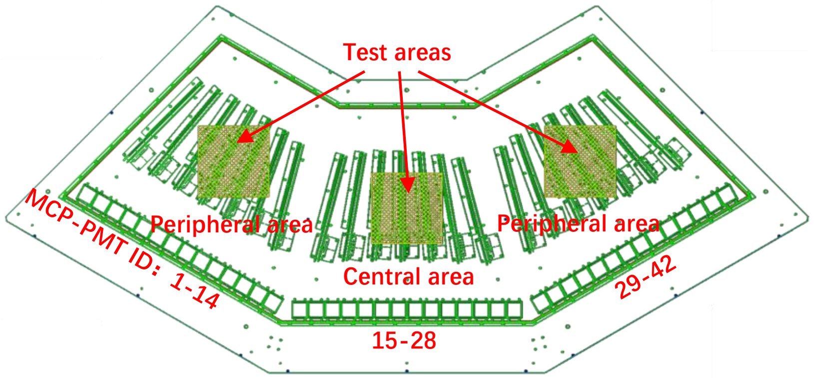
	value
Channel number	672
Electronics timing precision	<10 ps
Single-photon time resolution	~30 ps (including MCP-PMT TTS contribution)
Signal timing method	Leading-edge discrimination + FPGA-based TDC (correct leading-edge error by TOT)
Dead time	3 ns
Data transmission bandwidth	~ 6 GB/s
Power consumption	600 mW/channel (estimate based on the total power consumption of front-end board)

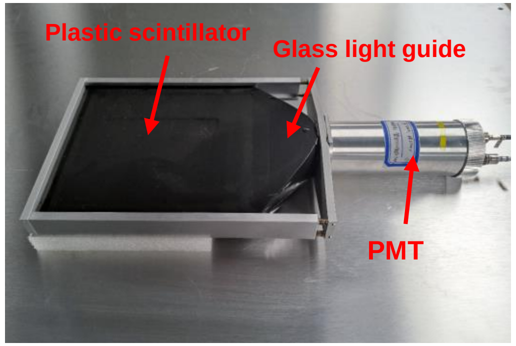
Cosmic-ray test

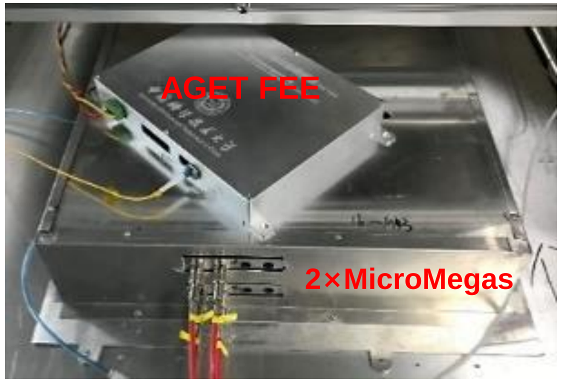


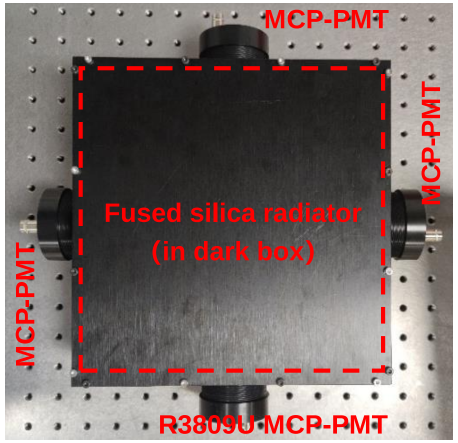
- **Trigger counters**
  - Plastic scintillator + PMT, 220 × 220 mm^2
  - Coincidence of two trigger counters
- **Trackers**
  - 4 × MicroMegas, 150×150 mm^2
  - Efficiency ~90%, σ_{pos} < 200 μm
- **Reference time detector (T0)**
  - 180×180×10 mm^3 fused silica
  - 4 × MCP-PMT, Φ = 10 mm
  - $\sigma_{T0} \approx$ 20 ps
- **5 cm lead absorber**
  - Remove soft muons (p < 200 MeV/c)

- **Platform for detectors under test**
  - Test different areas

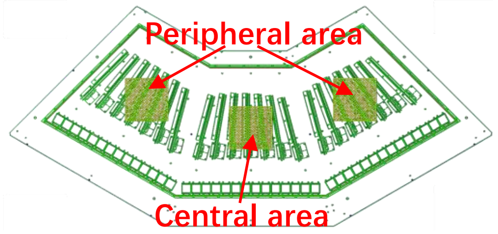


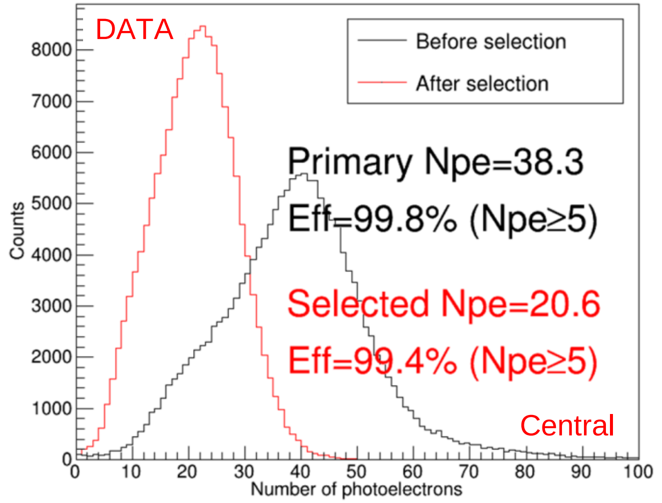






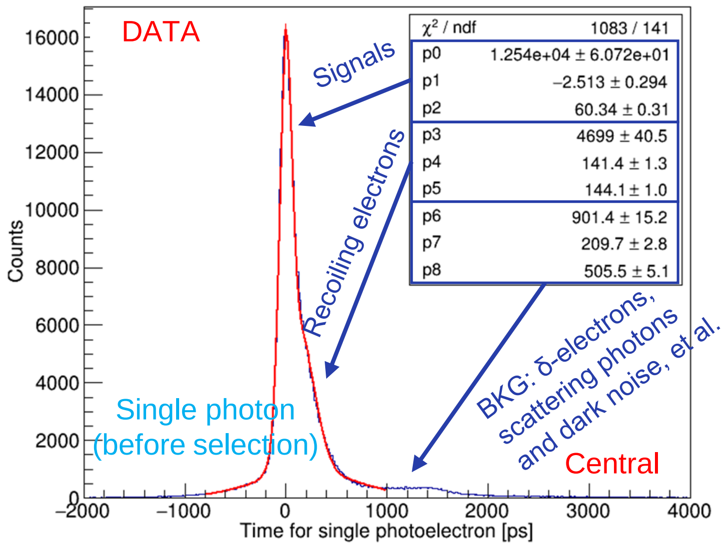
Prototype performances

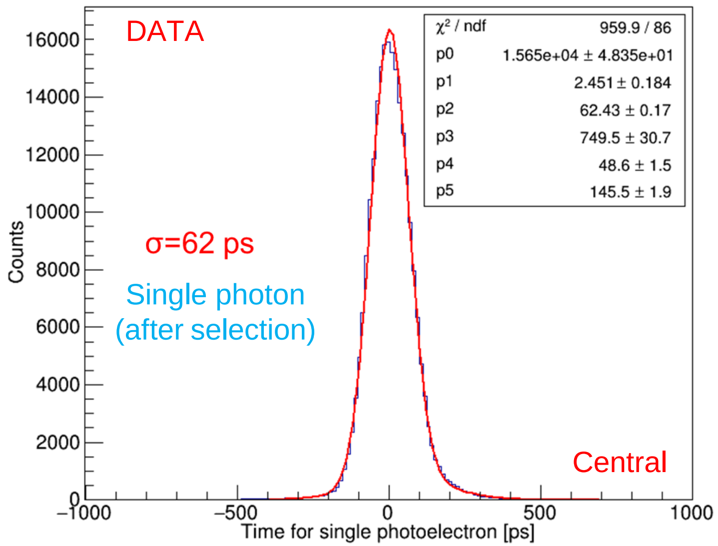


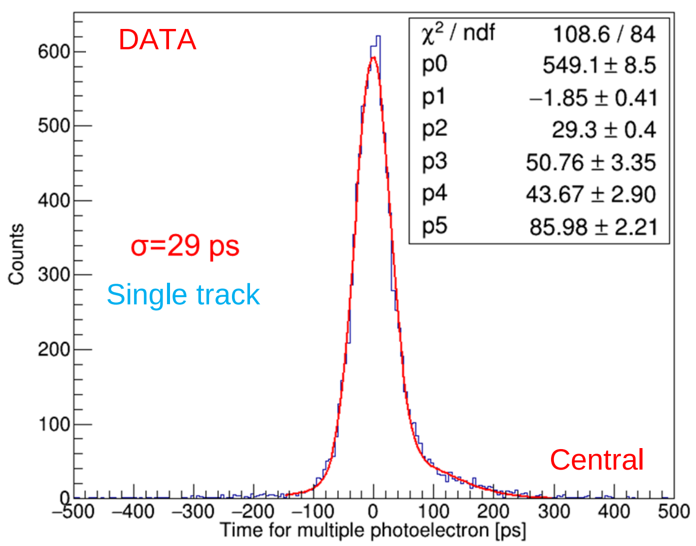


Central area

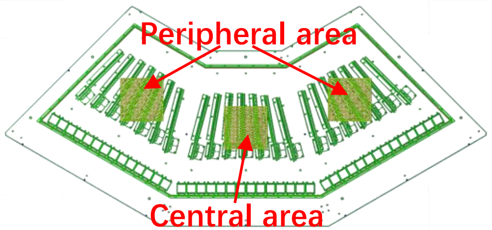
- Detection efficiency = 99.4%
- Single photon, $\sigma_{SPE} = \sqrt{62^2 - 20^2} \approx 59$ ps
- Single track, $\sigma_{DTOF} = \sqrt{29^2 - 20^2} \approx 21$ ps

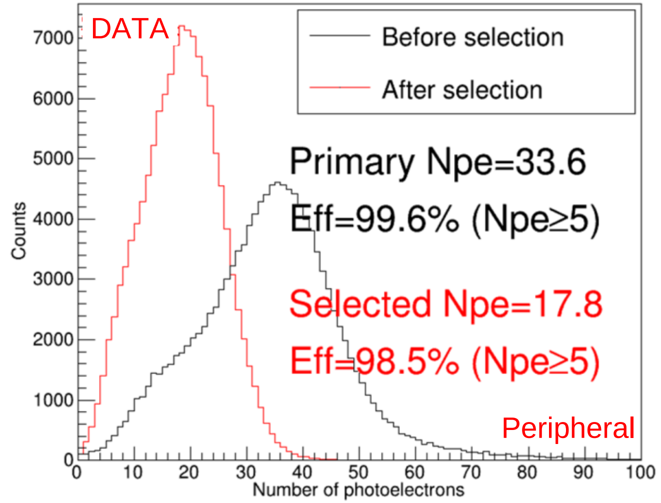






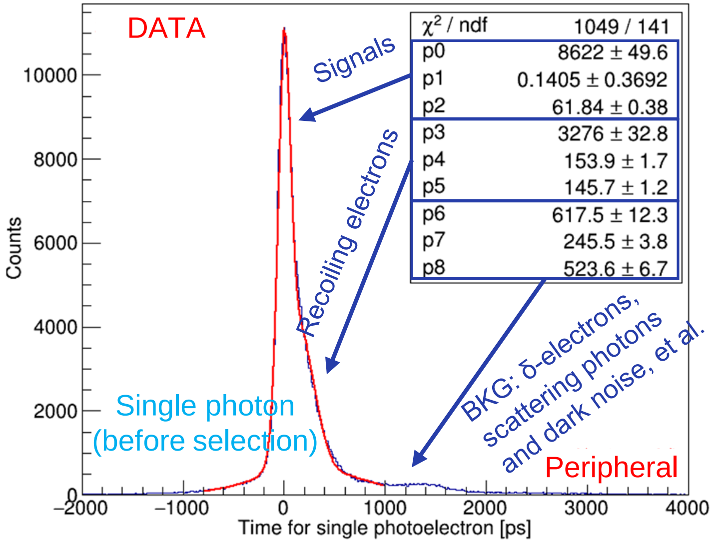
Prototype performances

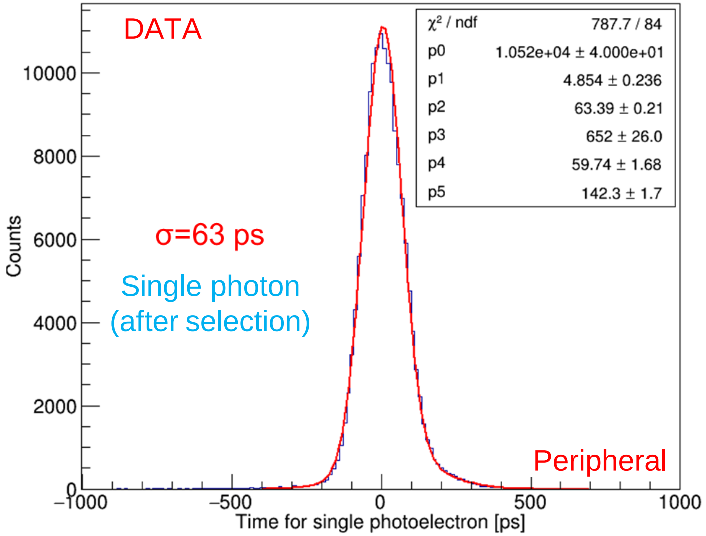


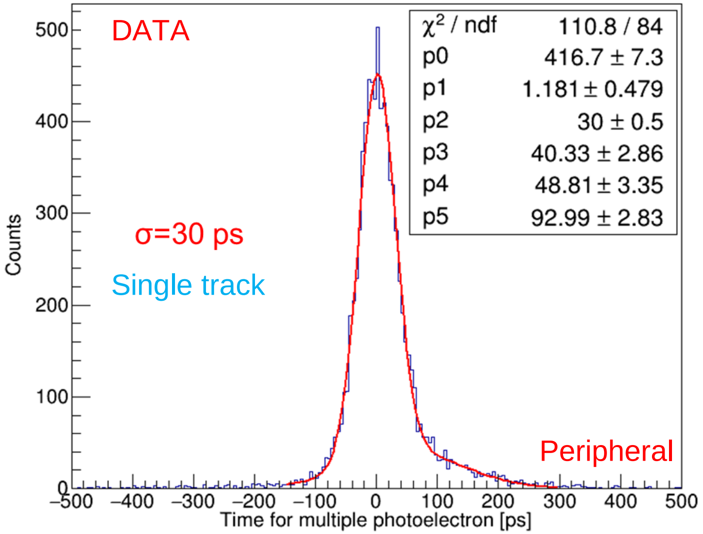


Peripheral area

- Detection efficiency = 98.5%
- Single photon, $\sigma_{SPE} = \sqrt{63^2 - 20^2} \approx 60$ ps
- Single track, $\sigma_{DTOF} = \sqrt{30^2 - 20^2} \approx 22$ ps







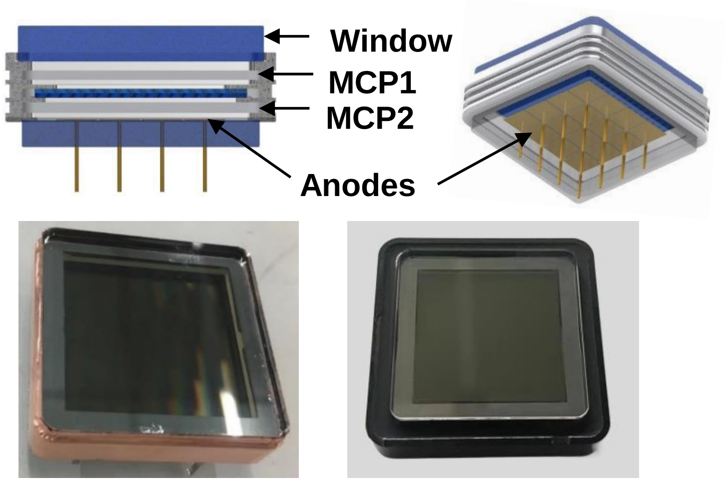
Summary of cosmic-ray test

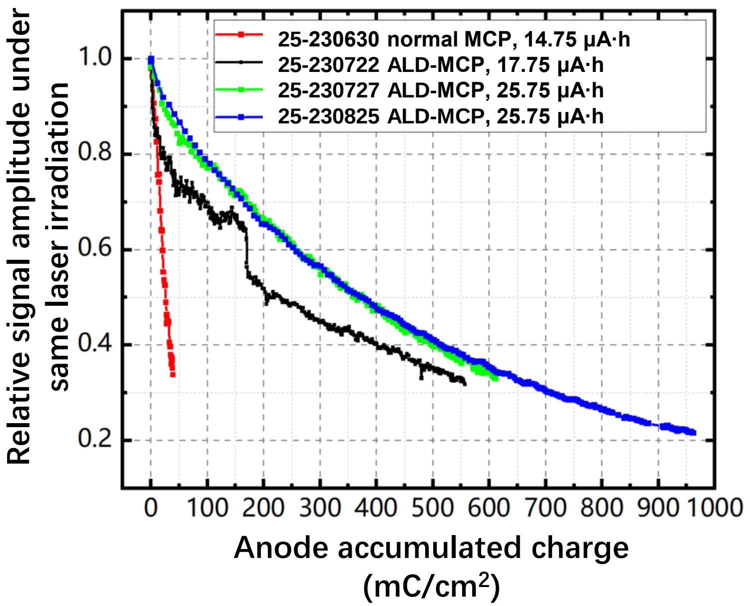
Test areas			Central area	Peripheral area
Number of photon electrons		DATA	20.6	17.8
		MC	20.3	17.6
Time resolution of the DTOF prototype	DATA	Single photon	59 ps	60 ps
		Single track	21 ps	22 ps
	MC	Single photon	54 ps	57 ps
		Single track	18 ps	22 ps

- **A Geant4-based simulation was been done to check the experimental results.**
- **The experimental DATA are consistent with the MC results.**
- **The time resolution of the DTOF prototype is ~22 ps, which meets the performance requirements of the DTOF detector (σ_{DTOF} < 30 ps).**

Further work – MCP-PMT development

Lifetime extended MCP-PMT development at XIOPM



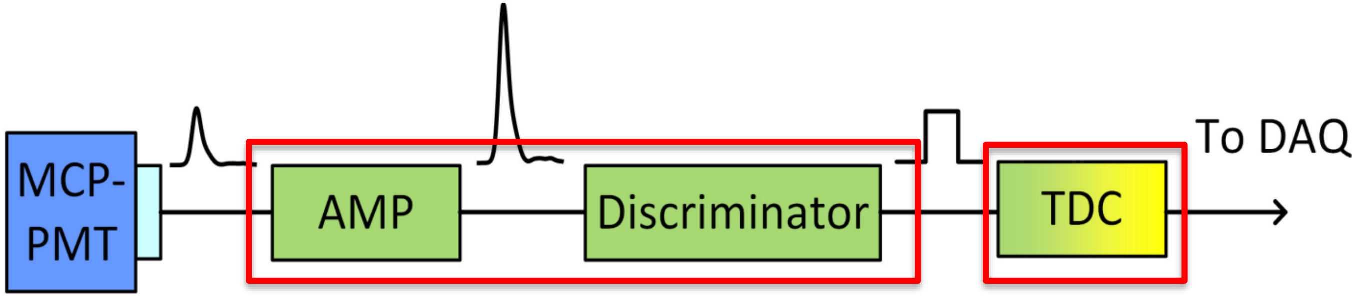


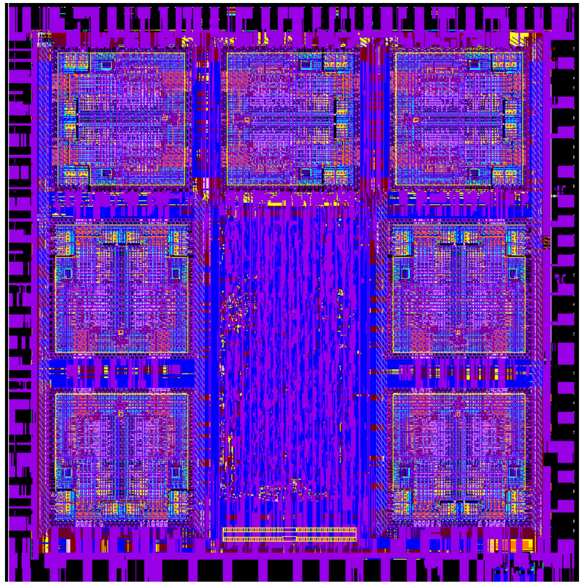
- multi-anode MCP-PMT using ALD-MCP
- Use mass spectrometer to monitor gas composition during tube manufacturing process
- optimize the ALD-MCP cleaning process (including electron scouring dose and high temperature baking time) to improve the vacuum level in the tube
- Monitor the after pulse of MCP-PMT (time measurement) to evaluate the neutral gas/ion composition in the tube

- ALD-MCP has better performance than normal MCP, but it has not yet met the DTOF requirement (>10 C/cm^2).
- Further work is ongoing.
- More details can be found in the talk by Ping Chen, Jan 17, 2024, 10:05 AM.

Further work – ASIC development

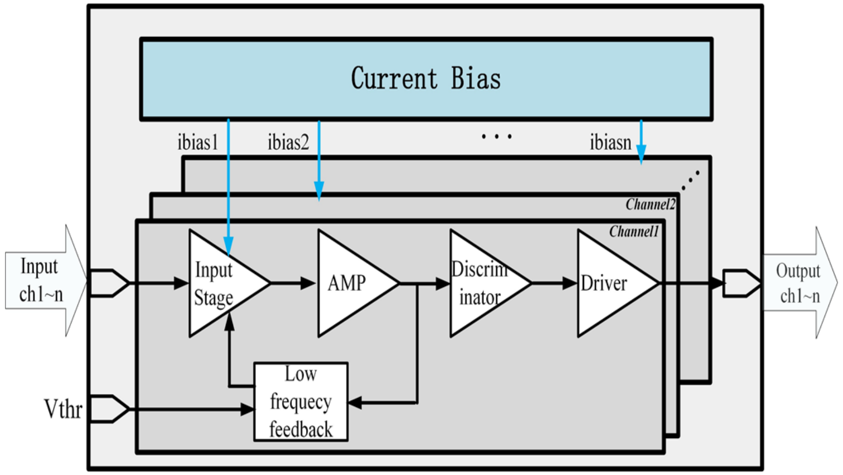
- Design Front-end timing ASIC and TDC ASIC
- Total timing precision of the circuit < 30 ps
- Power <150 mW/ch





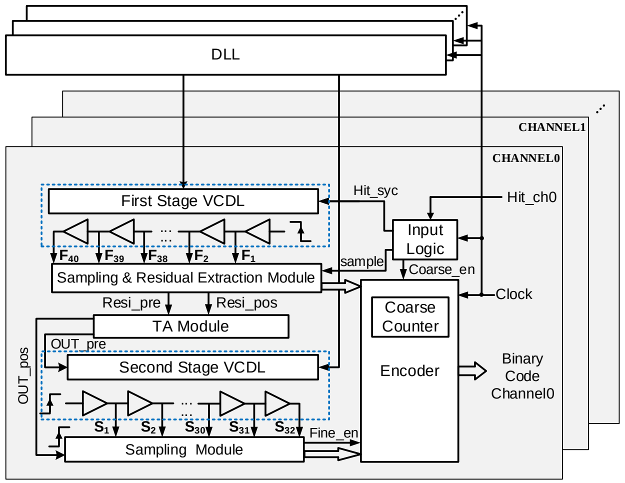
TDC ASIC layout
(unfinished)

Front-end timing ASIC



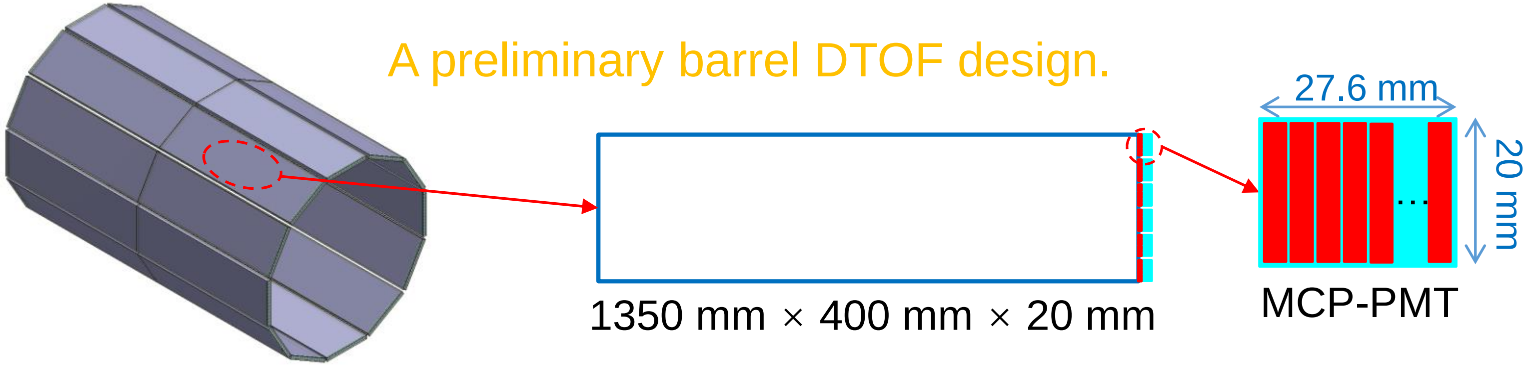
High bandwidth cascade amplifier + comparator
Design target: timing precision < 15 ps

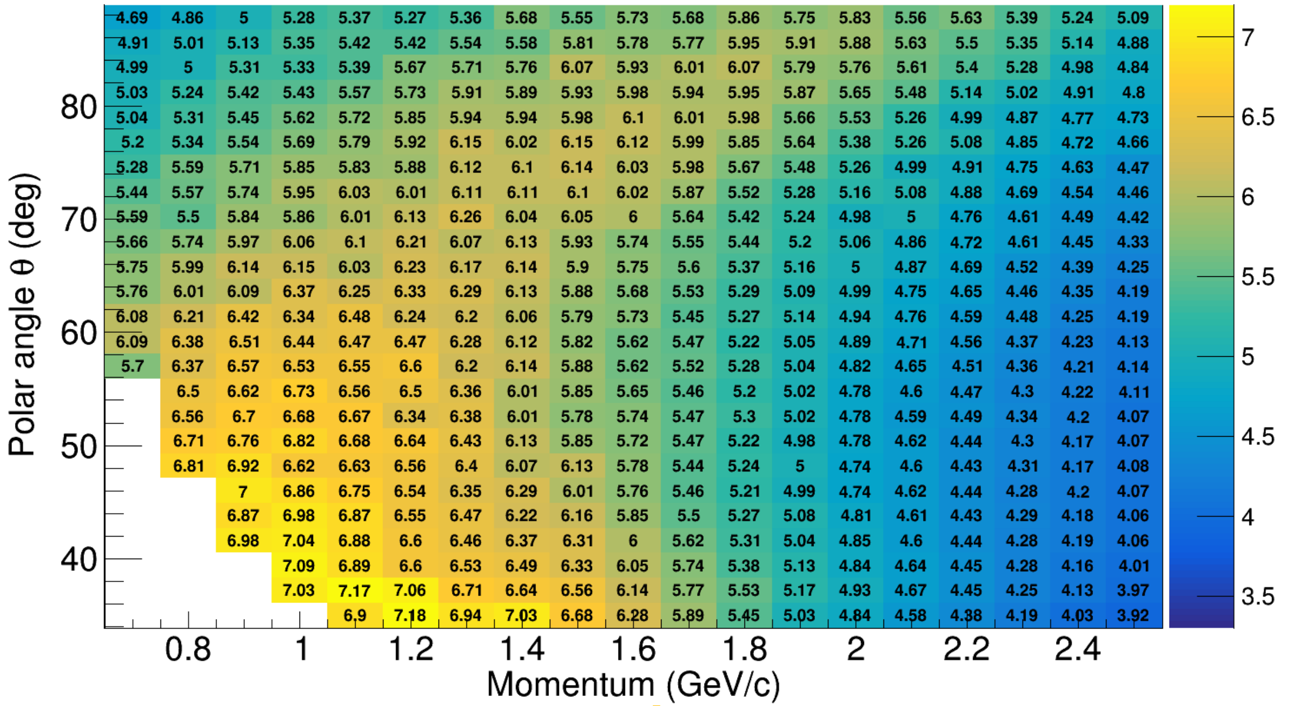
TDC ASIC



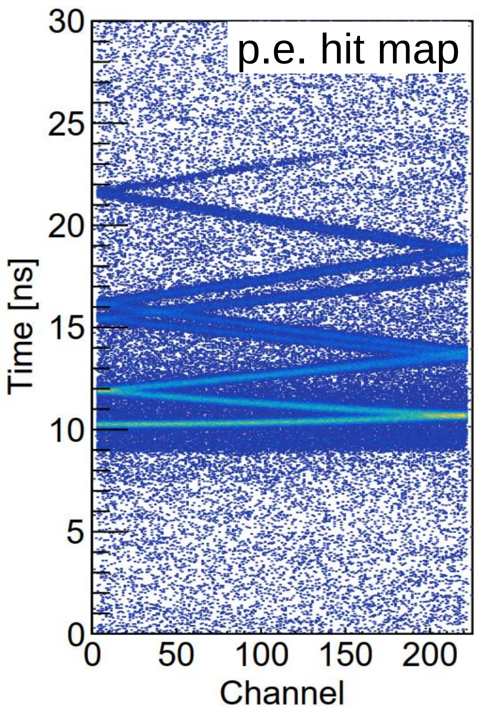
Delay lock ring (DLL) + two stage interpolation
Design target: timing precision < 20 ps

Further work – barrel DTOF study





π/K separation power



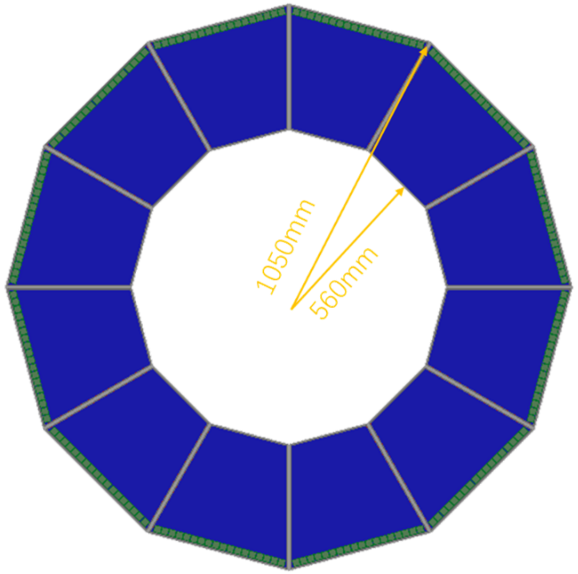
A preliminary simulation results indicate that its performance meets the STCF PID requirements.

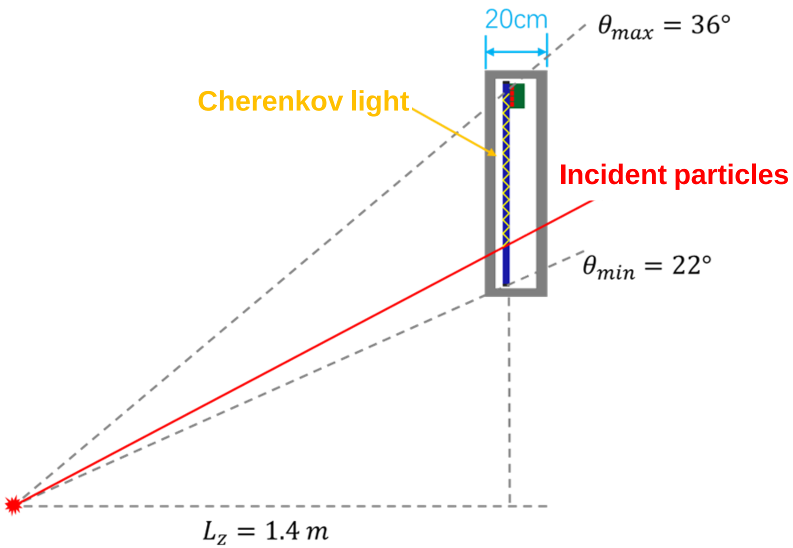
Summary

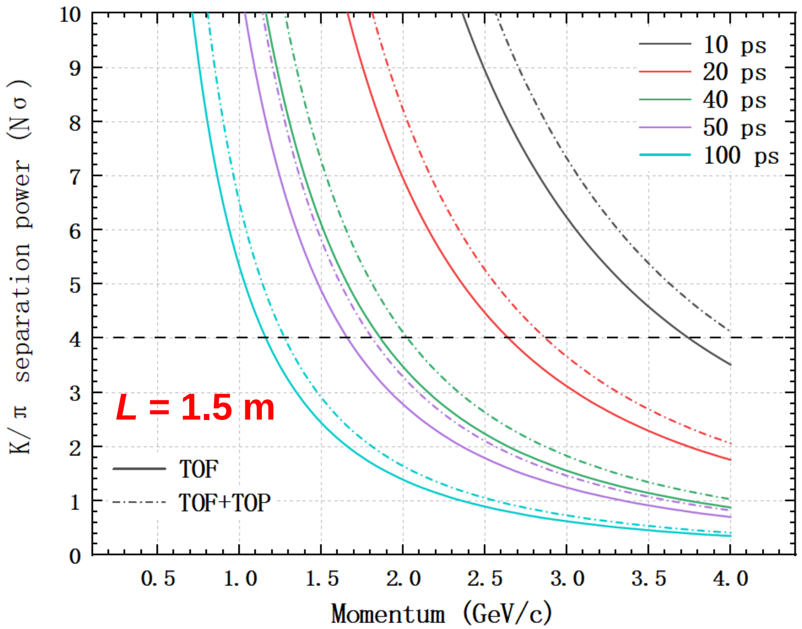
- We proposed the DIRC-like TOF (DTOF) detector as STCF end-cap PID detector.
- The expected performance of the DTOF detector was simulated, showing its performance met the STCF PID requirement.
- A full-size DTOF prototype was developed and tested using cosmic-ray.
  - Single track time resolution is approximately 22 ps .
- Some further work is ongoing, including lifetime extended MCP-PMT development, ASIC development, and the barrel DTOF study…

BACK UP

DTOF detector



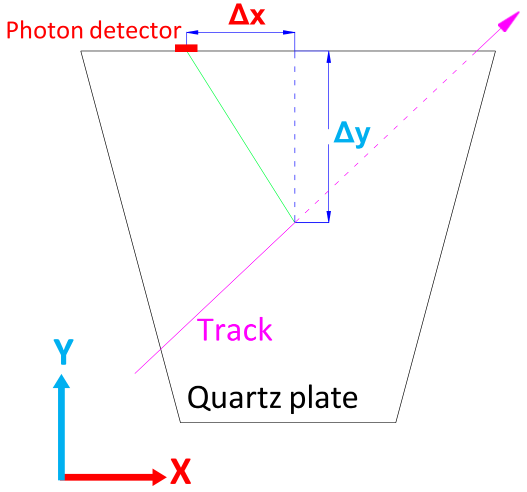


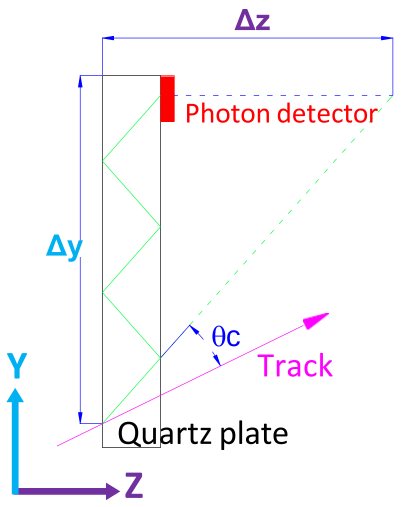


- **fused silica radiator and MCP-PMT**
- **4σ π/K separation at *p* = 2 GeV/*c*** **(**$\sigma_{T0} \approx 40$ **ps)**
  - Only ***TOF***, time resolution **~35 ps**
  - ***TOF+TOP***, time resolution **~50 ps**

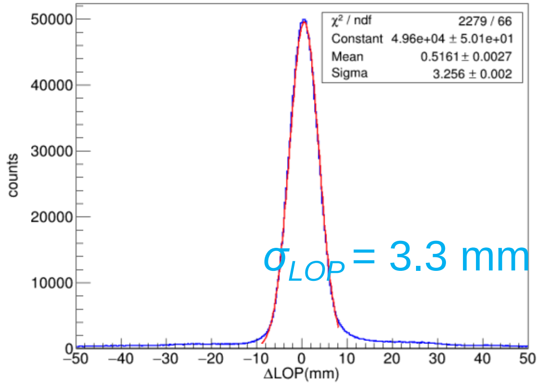
- ✓ **Large area**
- ✓ **ease of operation and maintenance**
- ✓ **Compact structure, T=1-2 cm**
- ✓ **Excellent time resolution, σ_{SPE}~100 ps**
- ✓ **High counting rate capability, ~10 MHz/cm² for MCP-PMT**
- ✓ **High radiation tolerance, TID>5000 Gy**

TOF reconstruction

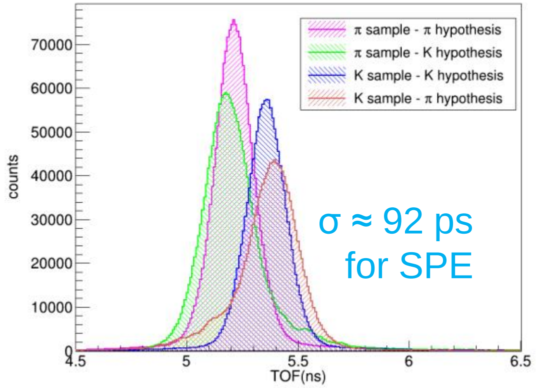




- **LOP precision ~3.3 mm**



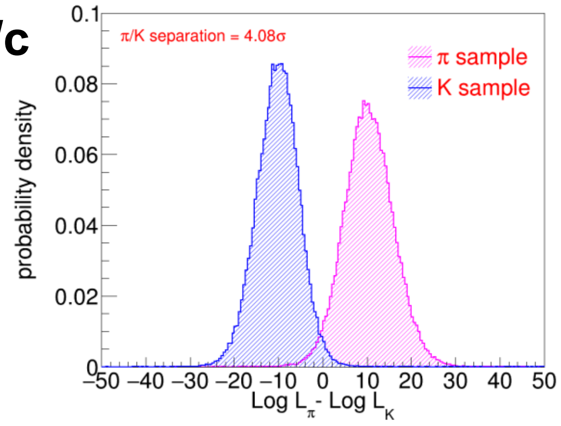
- **SPE time resolution ~92 ps**



Algorithm

1. Reconstruct light path, including the length of light transmission along different direction, i.e. Δx, Δy and Δz
   - Solving equation, $\cos\theta_c = \frac{1}{n_p \beta} = \vec{v_t} \cdot \frac{\vec{v_p}}{|\vec{v_p}|}$
   - $\vec{v_p} = (\Delta x, \Delta y, \Delta z)$
2. **Length of propagation** $LOP = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$
3. **Time of flight** $TOF = T - \frac{LOP n_g}{c} - T_0$

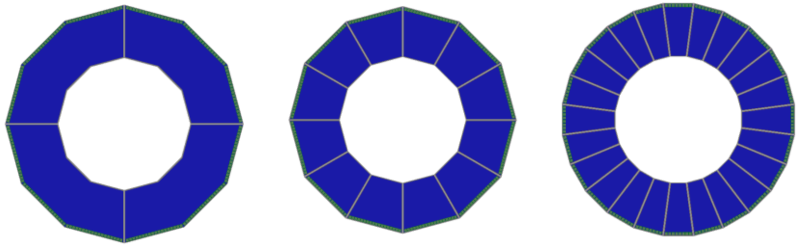
- **π/K separation power at 2 GeV/c**
  - TOF-based algorithm, including TOP differences
  - $TOF_{\text{hypo}} = T - TOP_{\text{hypo}} - T_0$
    $= TOF_{\text{truth}} + TOP_{\text{truth}} - TOP_{\text{hypo}}$



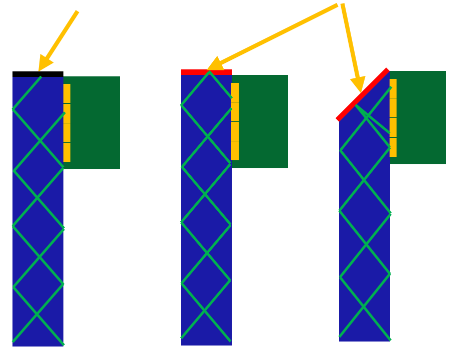
>4σ π/K separation power

Optimization

- ☐ Radiator thickness (10, 15, 20 mm)
- ☐ Radiator shape (4, 12, 24 sectors)



- ☐ Absorber or mirror



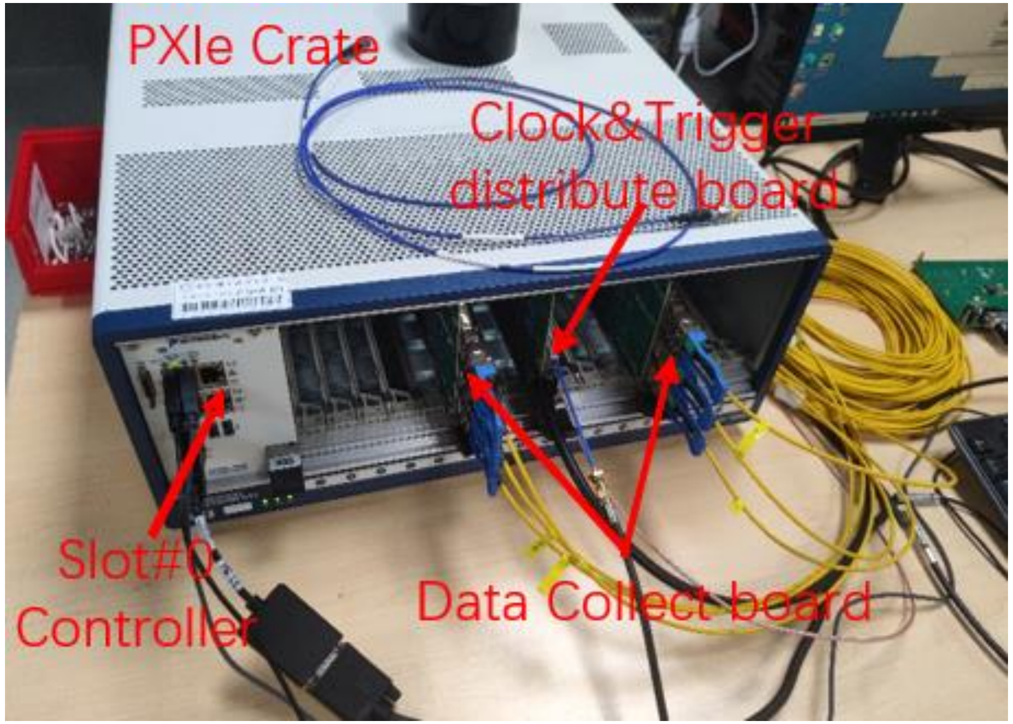
Geometry ID		0	1	2	3	4	5	6
Sector number		**4**	12	24	4	4	4	4
Radiator thickness		**15 mm**	15 mm	15 mm	10 mm	20 mm	10 mm	10 mm
Top surface		**A**	A	A	A	A	M	45° M
Button surface		**A**	A	A	A	A	A	A
Lateral surface		**M**	M	M	M	M	M	M
Number of p.e. (w/o BKG)	**π**	**21.8**	21.4	16.3	15.5	25.5	32.7	37.2
	K	**17.6**	17.8	14.3	13.2	22.1	27.6	33.7
Anode accumulated charge (C/cm^2)		**10.8**	10.5	9.6	8.8	11.8	17.0	25.6
π/K separation power (N_σ)		**4.17**	4.08	3.66	3.99	4.27	4.26	4.19

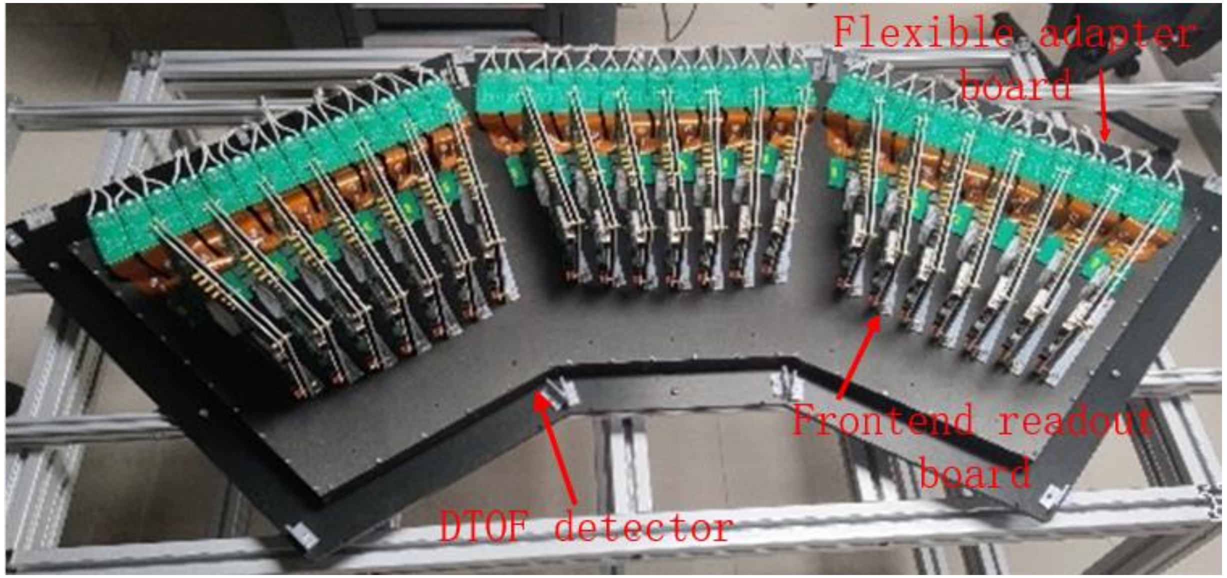
Some conclusions

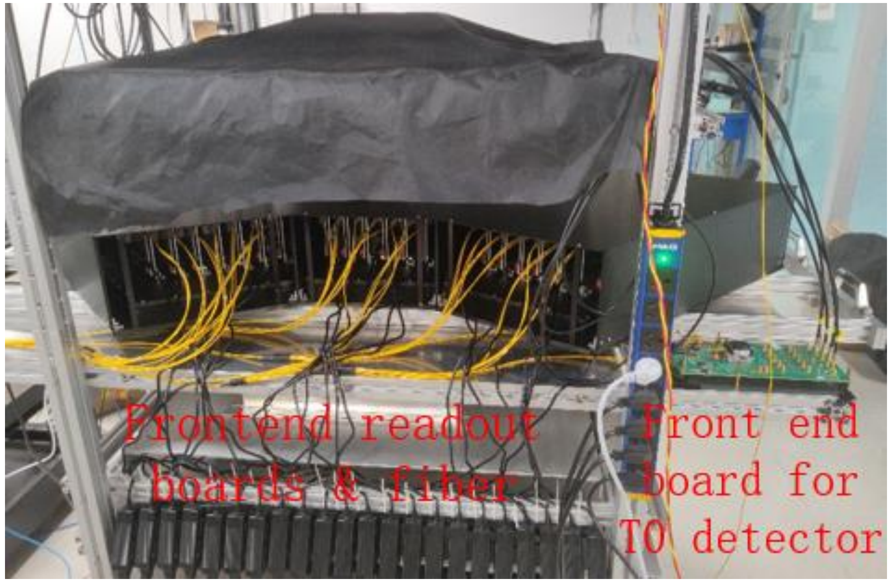
1. Thick radiator increases material, and thin radiator degreases performance ➔ a right thickness is better
2. Large area radiator reduces the number of lateral reflections, causing less hit map's overlaps and better π/K separation power
3. Adding mirror on the top surface will increase Np.e., but cause more overlaps on the photon hit maps. As results, no obvious performance improvement and great attenuation of MCP-PMT's lifetime ➔ Reducing the misidentification of photon paths is more important than increasing the number of photons

Optimal design: Large area (4 sectors), 15 mm radiator, with absorber on top and button surfaces

672-channel electronics system of DTOF

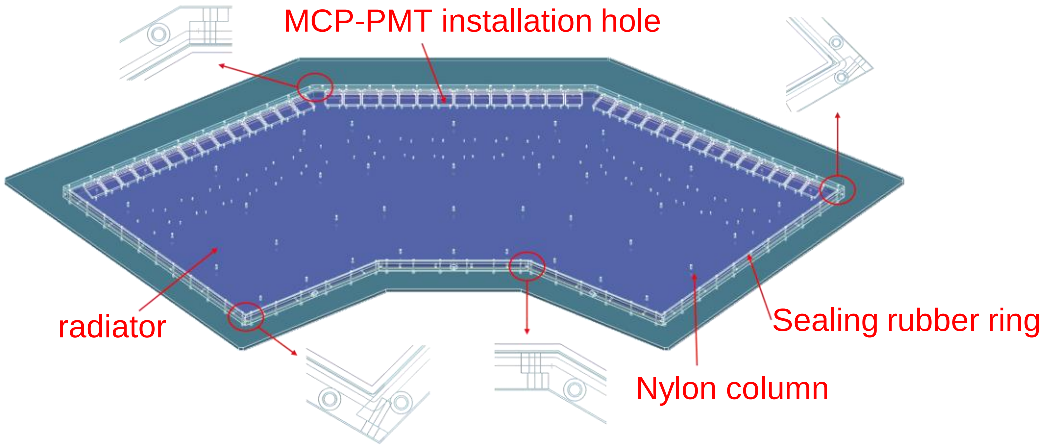




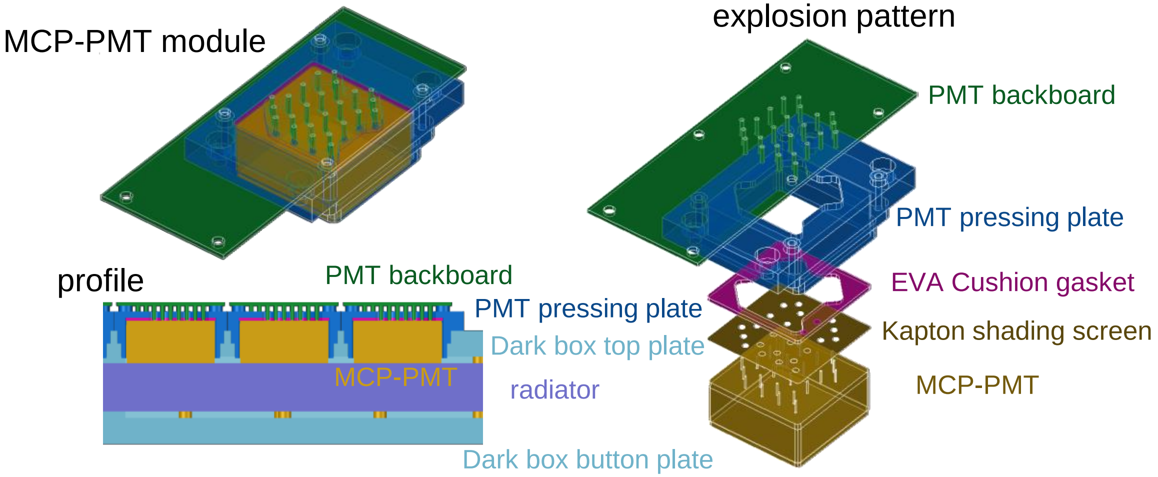


DTOF prototype Auxiliary systems

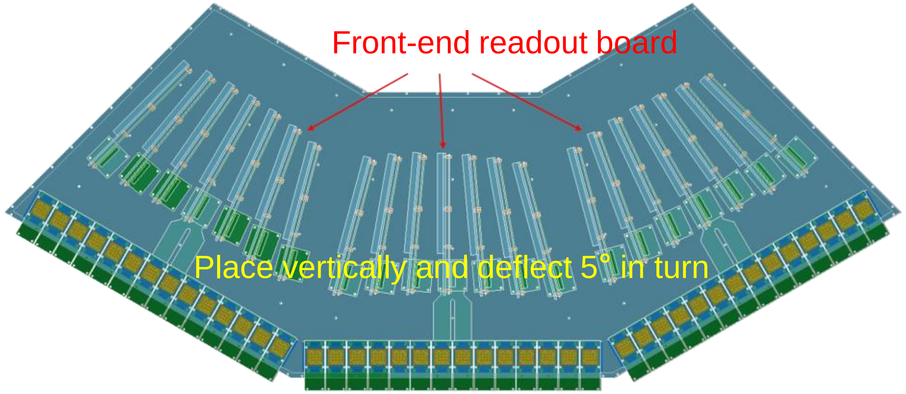
- **Dark box**



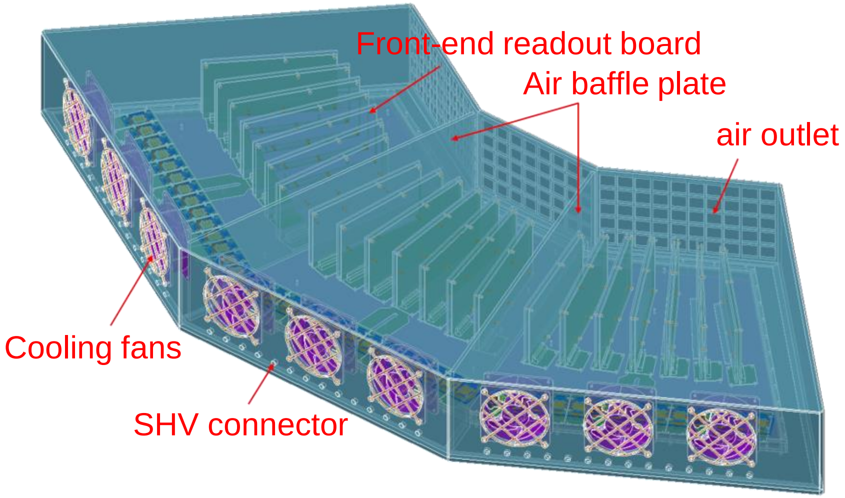
- **MCP-PMT installation**



- **Electronics module**

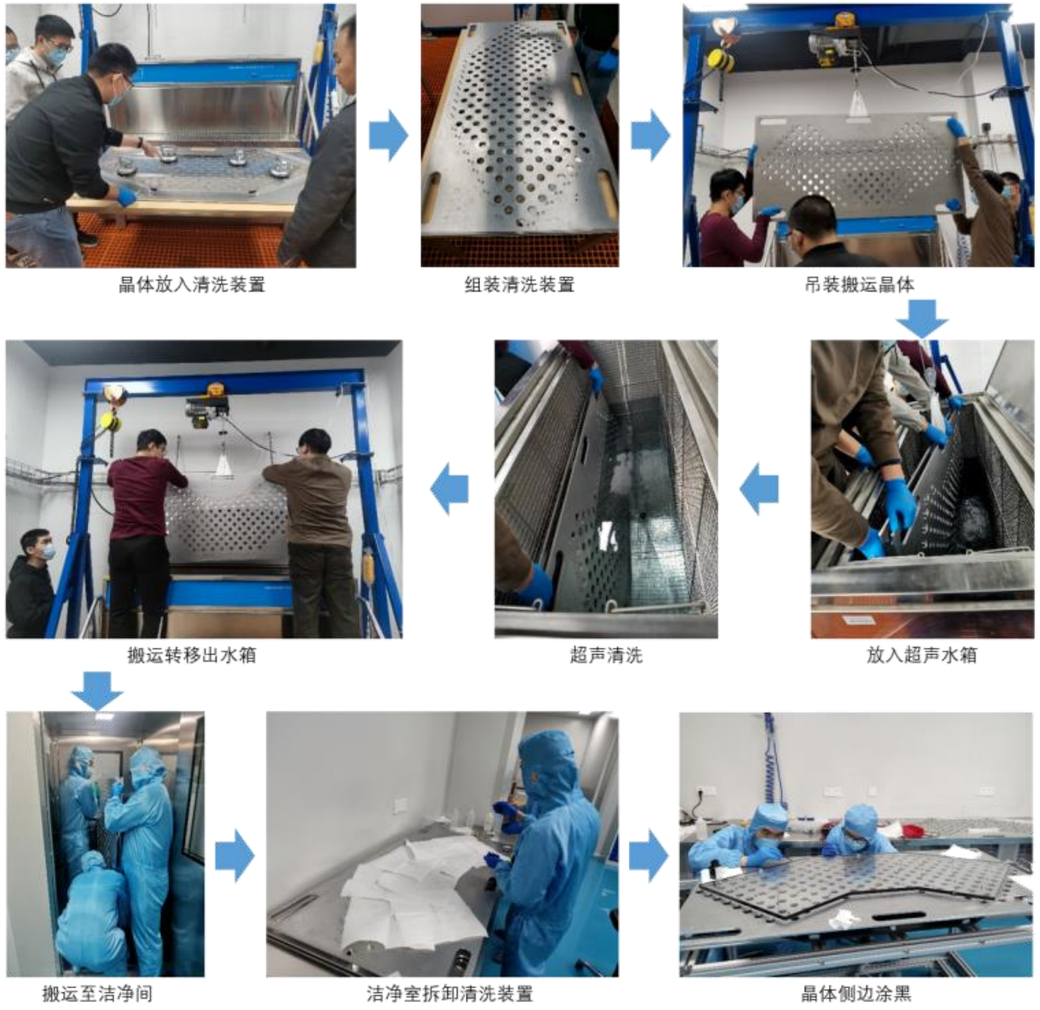


- **Cooling**

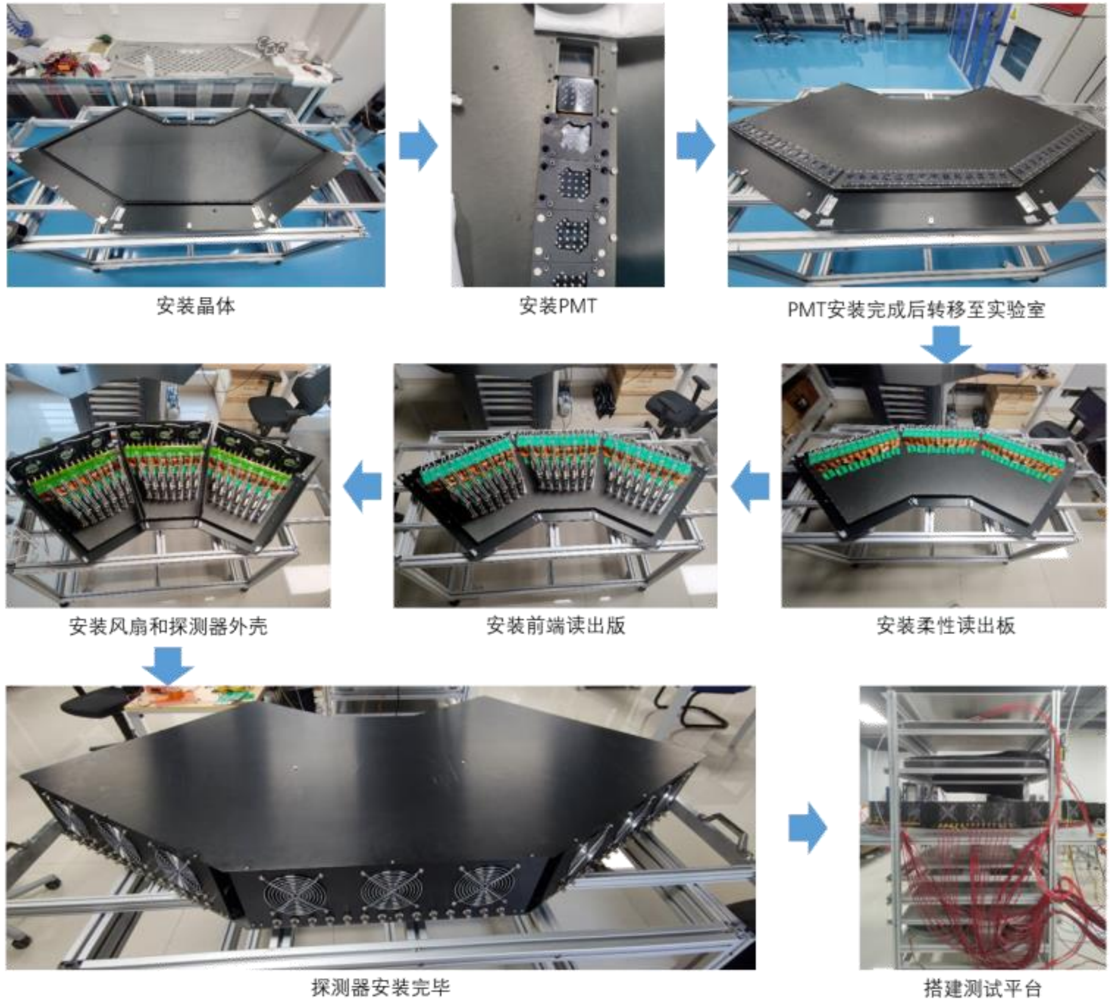


DTOF installation and system integration

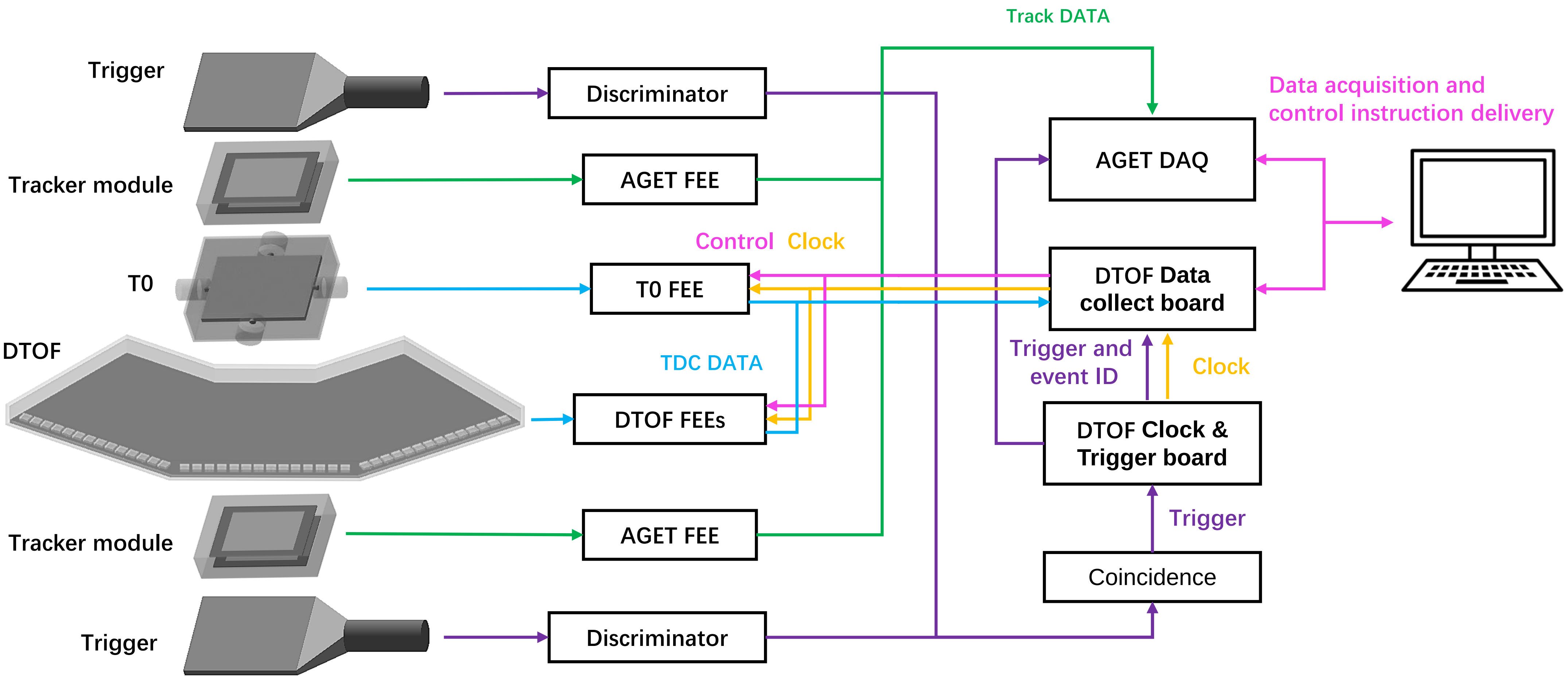
- Clean radiator and apply matting paint



- Installation

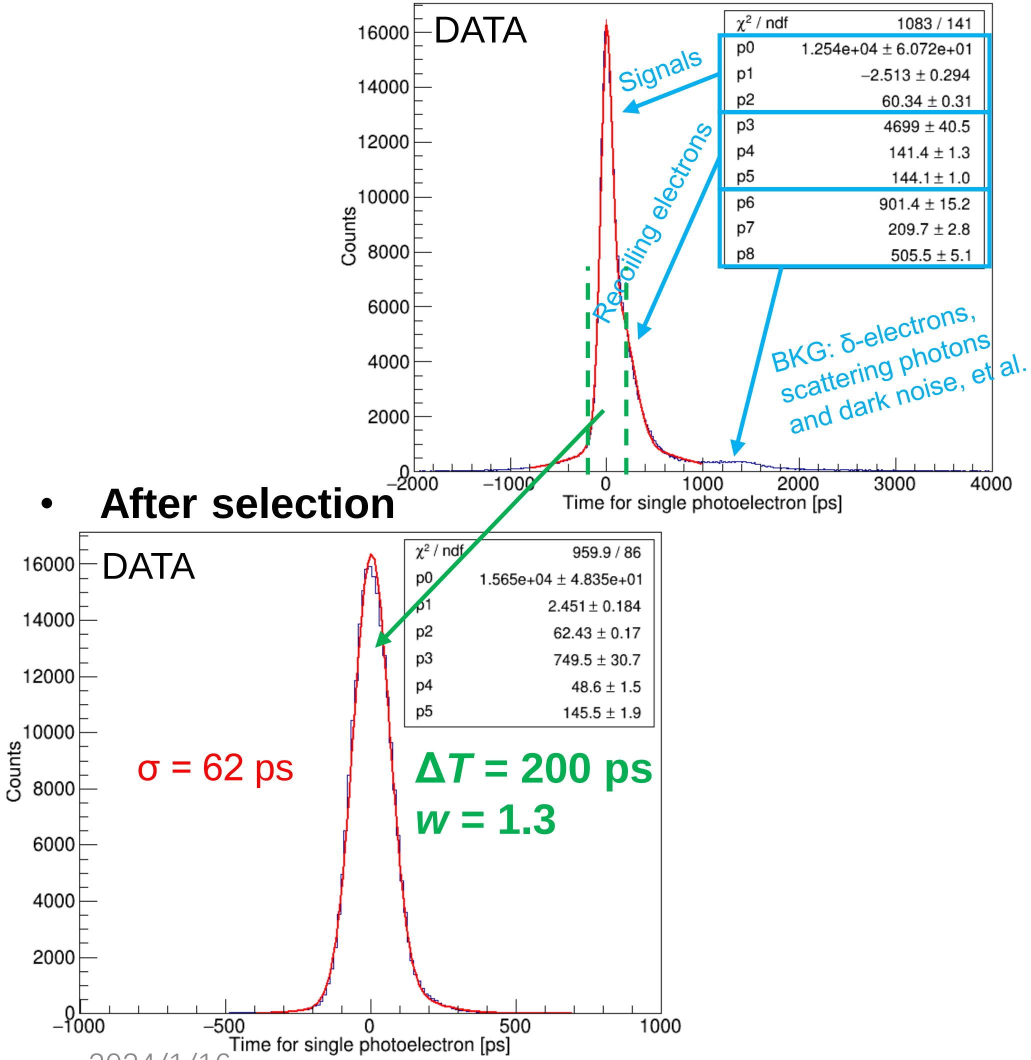


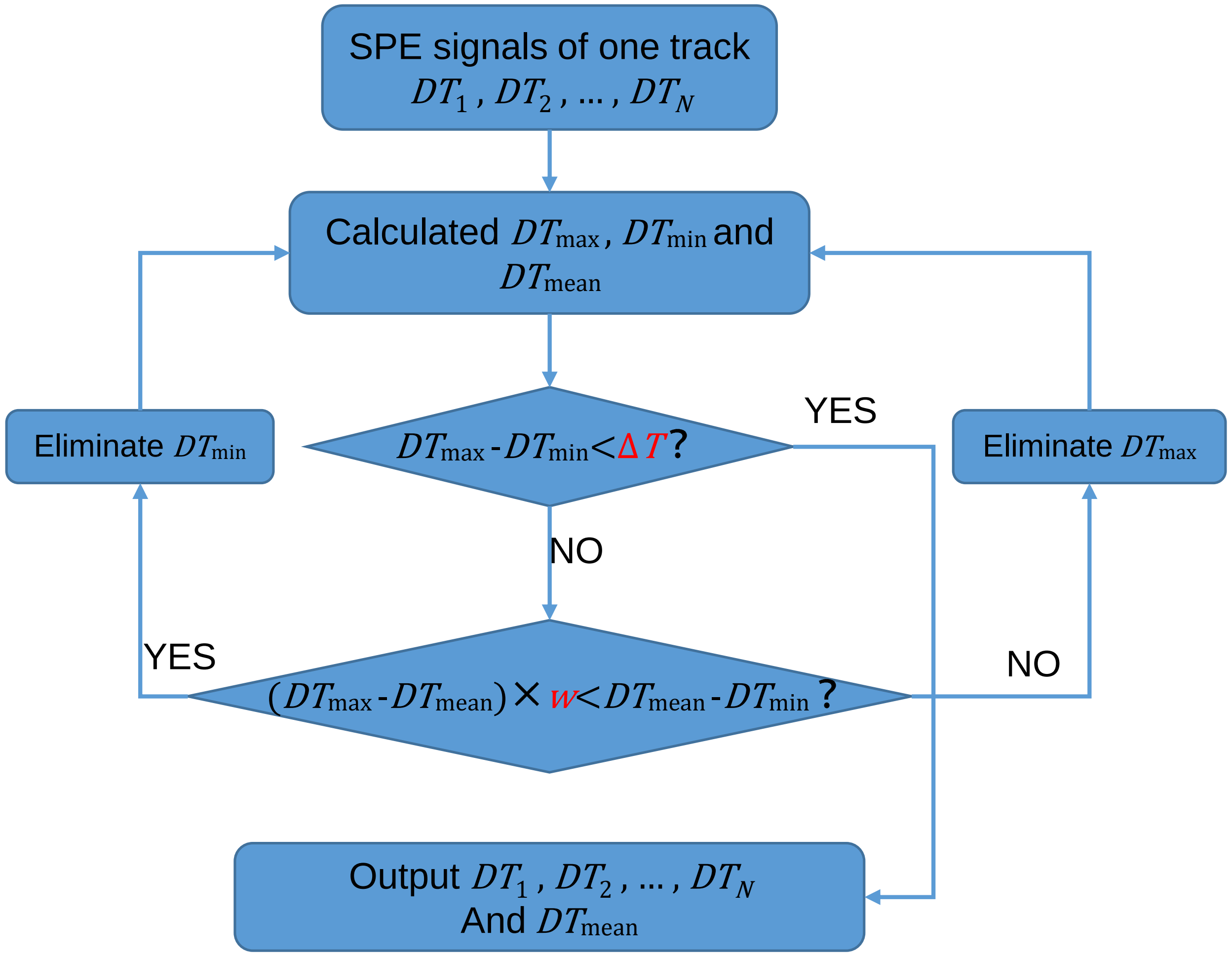
Cosmic ray test data acquisition system



Signal selection

- **Before selection**
- **After selection**





Two parameters, **Δt** and **w**