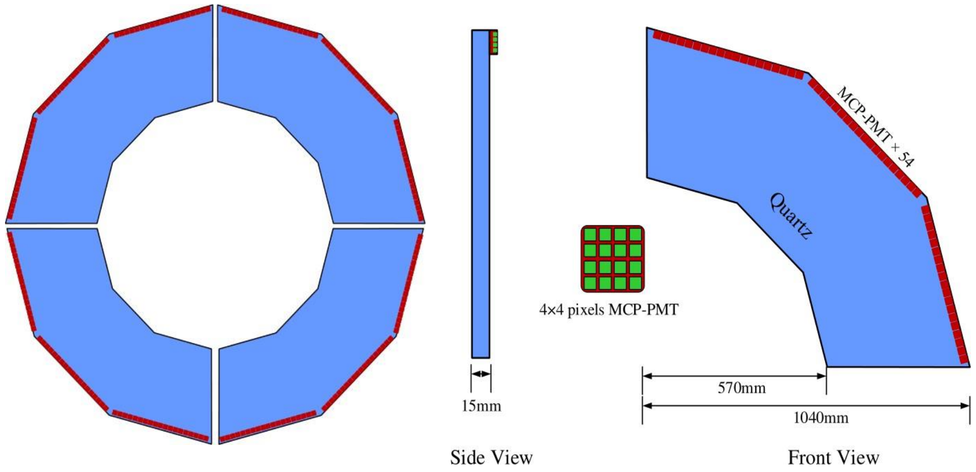


A DIRC-like Time-of-Flight Detector for Particle Identification

Binbin Qi

On behalf of the DTOF group

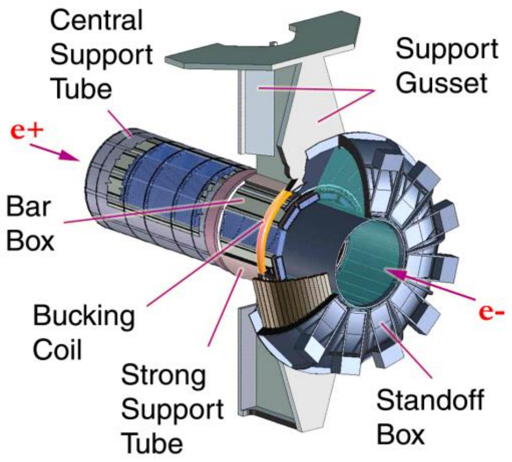
ICHEP 2024, Prague, 2024

- Introduction
  - DIRC concept, DIRC-like TOF
- R&D of DTOF
  - Simulation
  - Prototype (radiator, MCP-PMT, electronics)
  - cosmic-ray test
- Summary and outlook

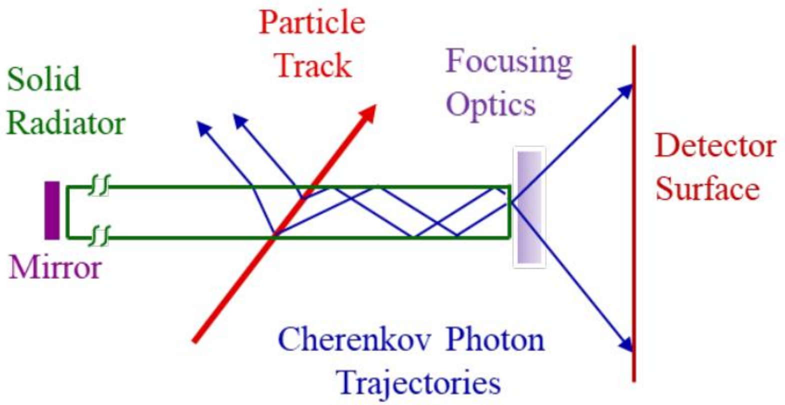
DIRC concept

Detection of Internally Reflected Cherenkov Light

- Used for the first time in BABAR as primary hadronic PID system
  - primary goal: π/K ID to 4 GeV/c
- Charged particle traversing solid radiator, refractive index n
  - Bar or plate radiator, made from Synthetic Fused Silica (Quartz)
- For $\beta>1/n$ tracks, some Cherenkov photons are totally internally reflected
- Quartz bar/plate are both radiator and light guide
  - Cherenkov angle conserved during many internal reflections
- A 3-D device, measuring x, y, and time of Cherenkov photons to defining θ_c, φ_c, $t_{propagation}$ ➔ Ultimate PID performance
  - Defining time of flight (TOF) ➔ DIRC-like TOF detector
- DIRCs requires momentum and position of particle measured by tracking system



BABAR DIRC

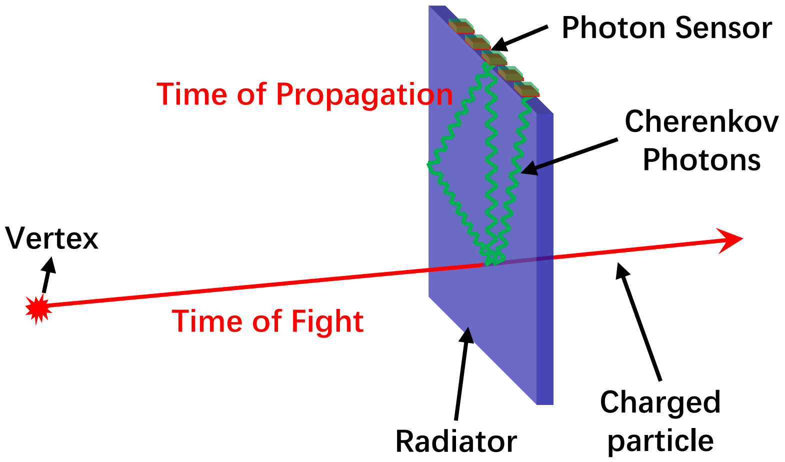


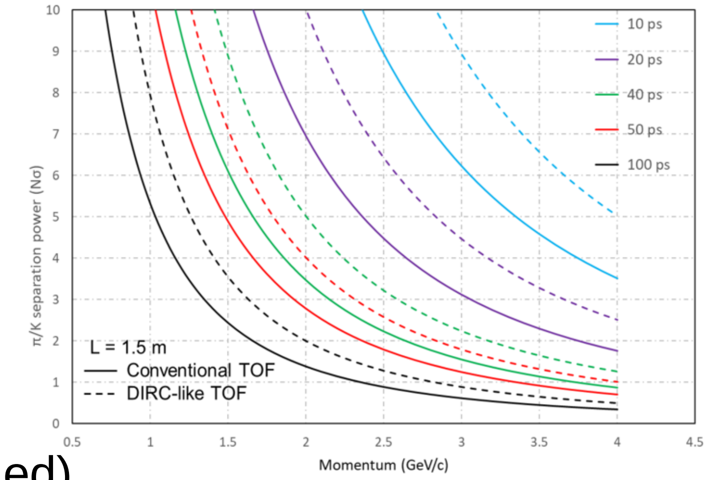
Review of DIRC Detectors by Schwiening

DTOF detector

DIRC-like Time Of Flight detector

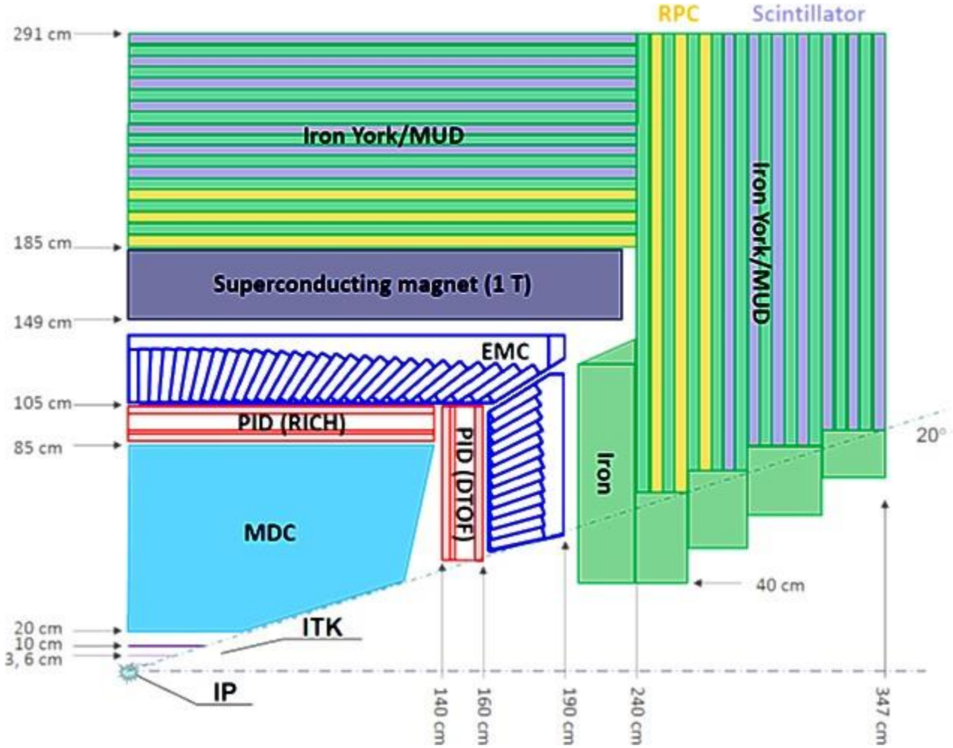
- DTOF: DIRC technique to measure Time Of Flight
  - Large area, ease of operation and maintenance
  - Compact structure, thickness = 1~2 cm
  - High counting rate capability, ~10 MHz/cm^2 for MCP-PMT
  - High radiation tolerance, TID > 5000 Gy
  - Excellent time resolution, σ_{SPE}~100 ps
- The σ_t requirement for 4σ π/K separation at p = 2 GeV/c, assumes length of flight = 1.5 m
  - Conventional TOF (Only TOF), σ_t requirement ≈ 35 ps
  - DIRC-like TOF (TOF+TOP), σ_t requirement ≈ 50 ps
- Some examples of DTOF or similar detectors
  - FTOF (DIRC-like Forward Time-Of-Flight detector) for SuperB (Canceled)
  - TORCH (Time Of internally Reflected CHerenkov light) for LHCb upgrade
  - DTOF for STCF (Super Tau Charm Facility, a future high-luminosity e$^+$-e$^-$ collider proposed in China)

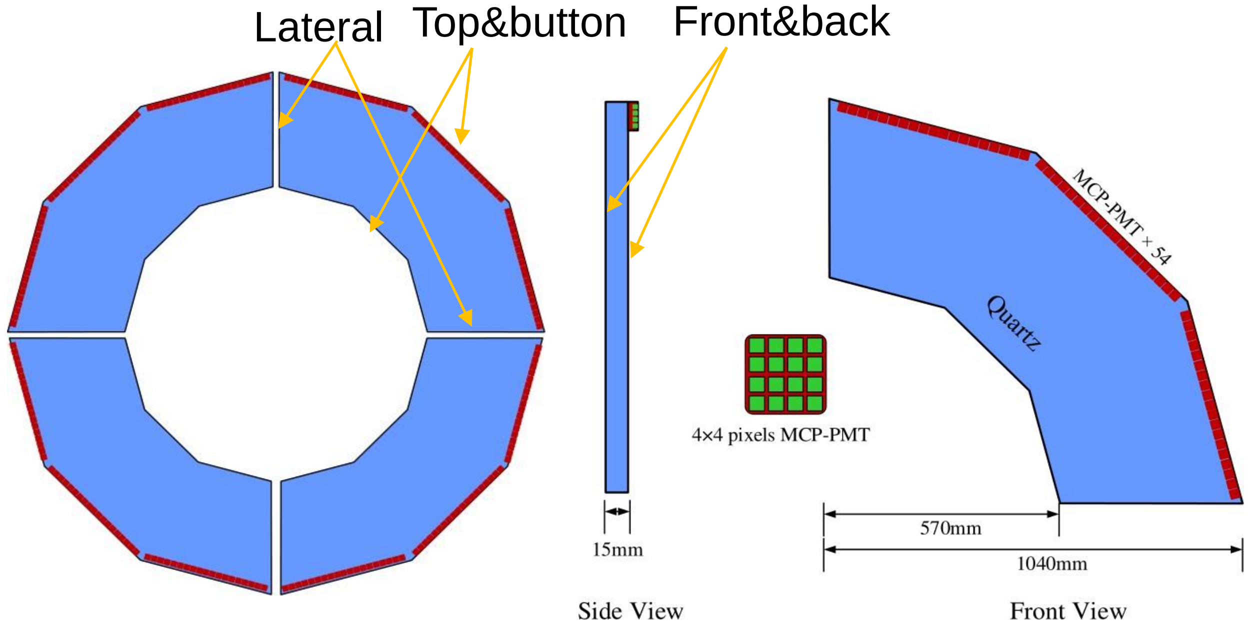




STCF CDR (Volume 1): Physics & detector, 2024

DTOF detector for STCF





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

$\sigma_{trk}^2 + \sigma_{T_0}^2$: ~40 ps

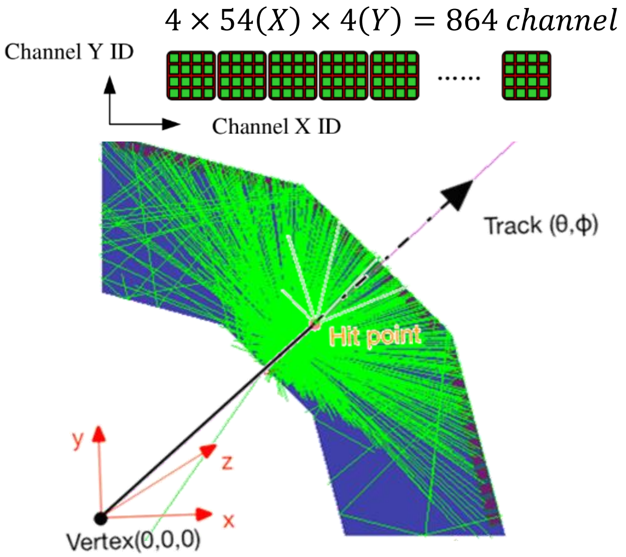
- STCF endcap PID detector
- Polar angle coverage 20°-36°
- Large area fused silica radiator
- Multi-anode MCP-PMT

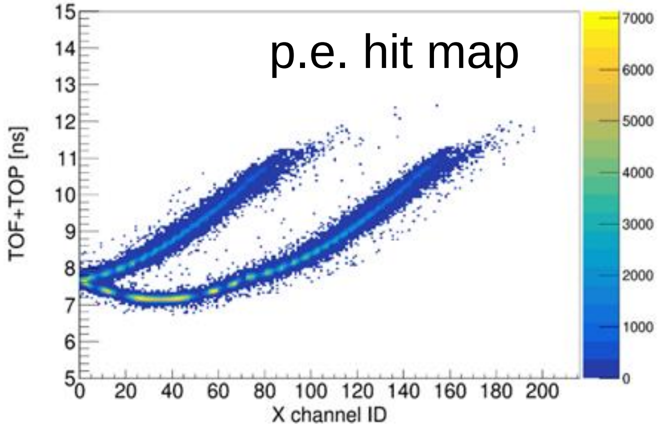
➢ To achieve 4σ π/K separation at p≤2 GeV/c
- Total time resolution $\sigma_{tot} < 50$ ps
- DTOF intrinsic time resolution $\sigma_{\mathrm{DTOF}} < 30$ ps

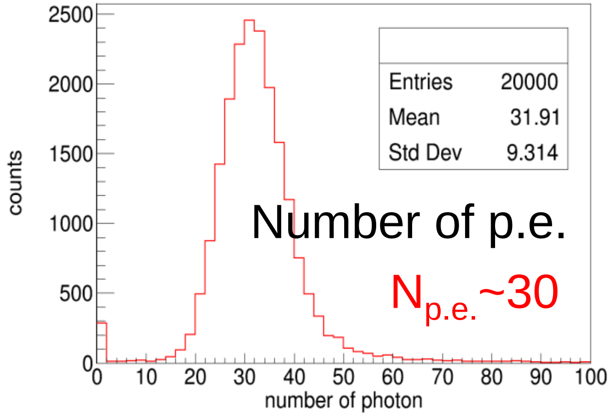
Detector simulation

Geant4 simulation setups

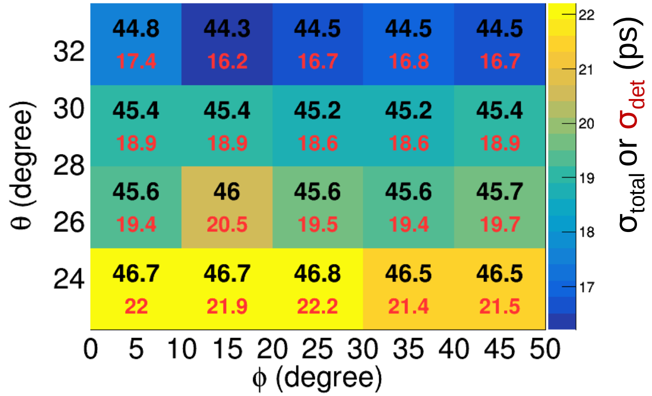
- Roughness ~1 nm, Reflection coefficient ~99%
- 4×4 anodes MCP-PMT, 5.5×5.5 mm^2 pixel
- Quantum efficiency ~25%@400 nm
- Take into considered material budget before DTOF





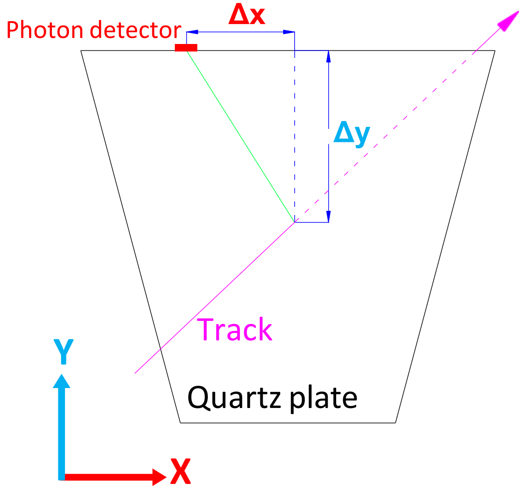


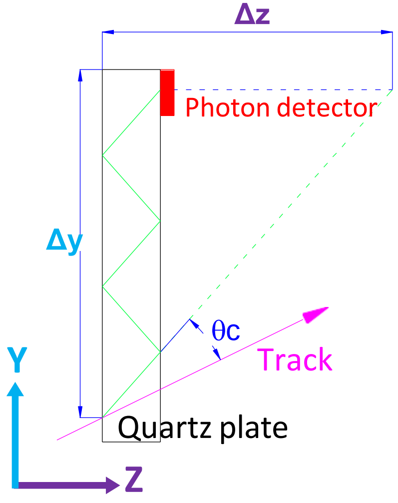
Time resolution@2GeV/c



σ_{total} <50 ps, σ_{DTOF} <30 ps

TOF reconstruction



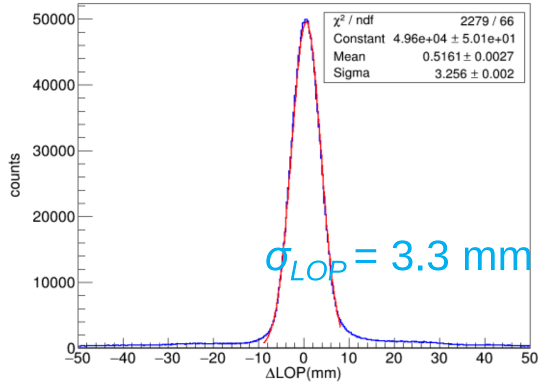


Geometry-based Algorithm

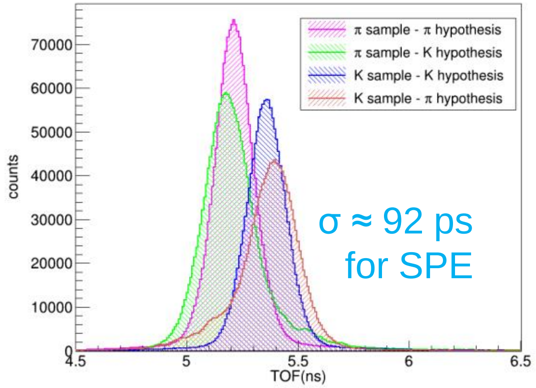
1. Reconstruct light path, including the length of propagation along different direction, i.e. Δx, Δy and Δz
   - Solving equation, $\cos\theta_c = \frac{1}{n_p\beta} = \vec{v_t} \cdot \frac{\vec{v_p}}{|\vec{v_p}|}$
   - $\vec{v_p} = (\Delta x, \Delta y, \Delta z)$
2. Length of propagation $LOP = \sqrt{\Delta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

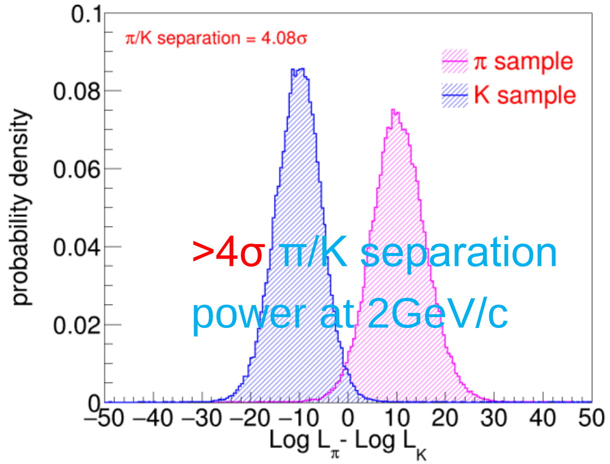
B. Qi et al 2021 JINST 16 P08021

- **LOP precision ~3.3 mm**



- **SPE time resolution ~92 ps**



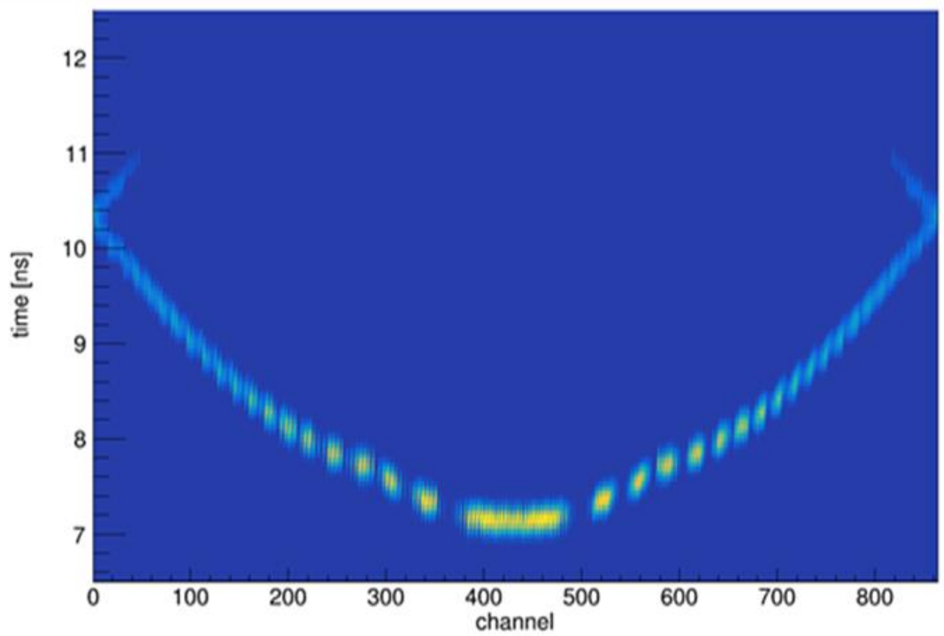


- **π/K separation power**
  - TOF-based algorithm, including TOP differences
  - $TOF_{\text{hypo}} = T - TOP_{\text{hypo}} - T_0$
    $= TOF_{\text{truth}} + TOP_{\text{truth}} - TOP_{\text{hypo}}$

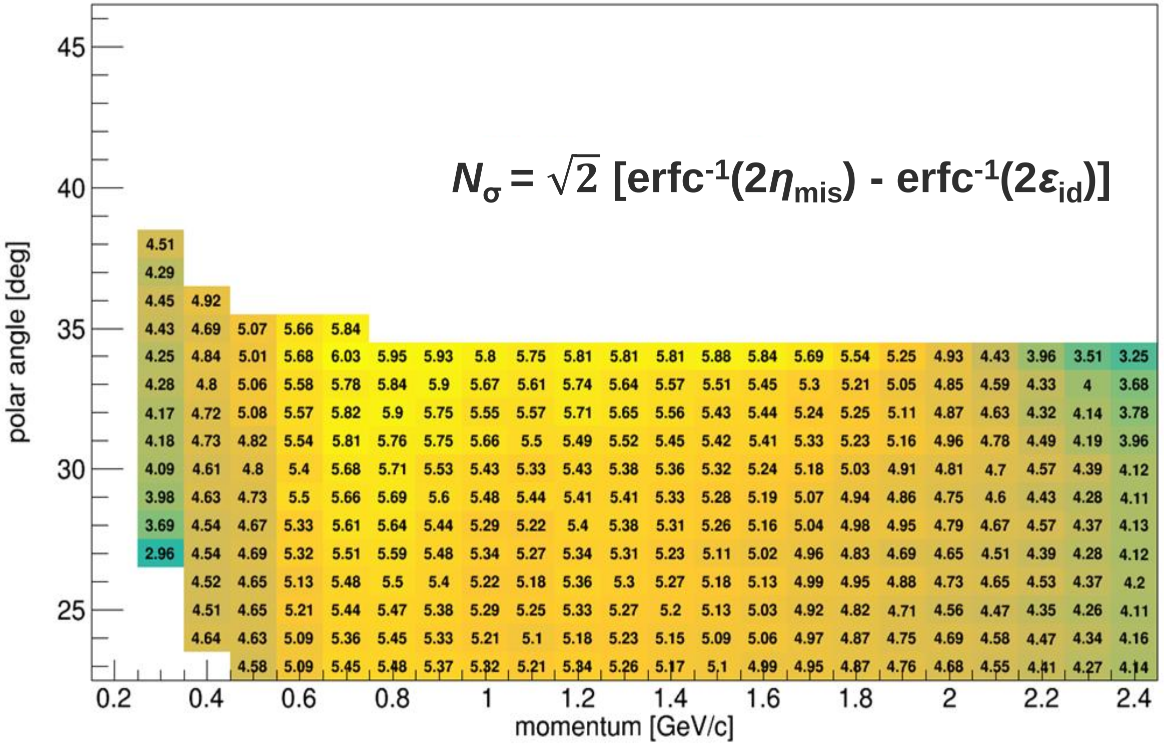
Expected PID performance

Likelihood methods

- 2-D hit maps, channel ID , photon arrival time and number of photons $N_{p.e.}$
- $\mathcal{L}_h = \prod_{hits} N_{p.e.} f_h(ch_i, t_i)$

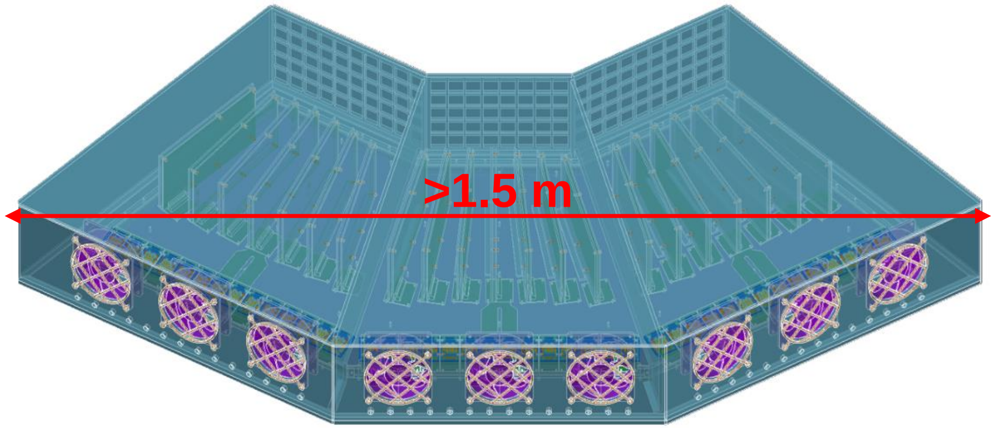


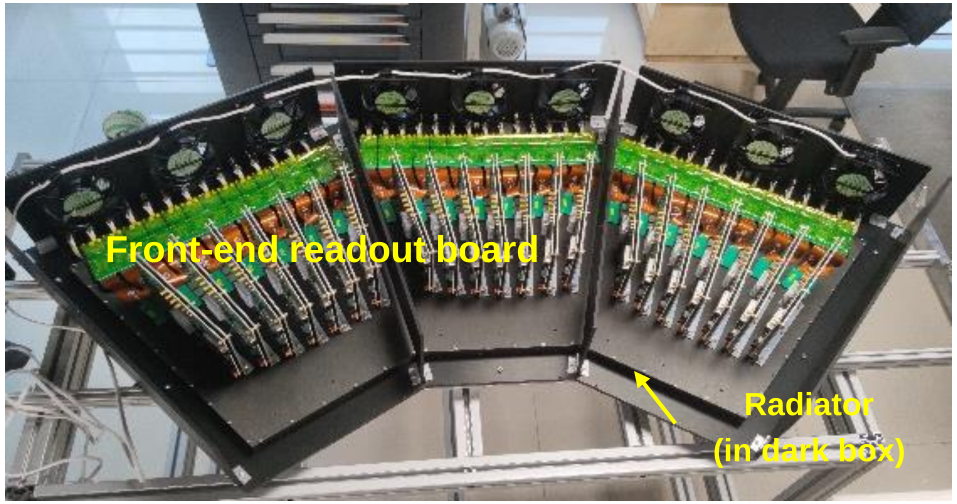
π/K separation power



DTOF can achieved >4σ π/K separation at p≤2 GeV/c.

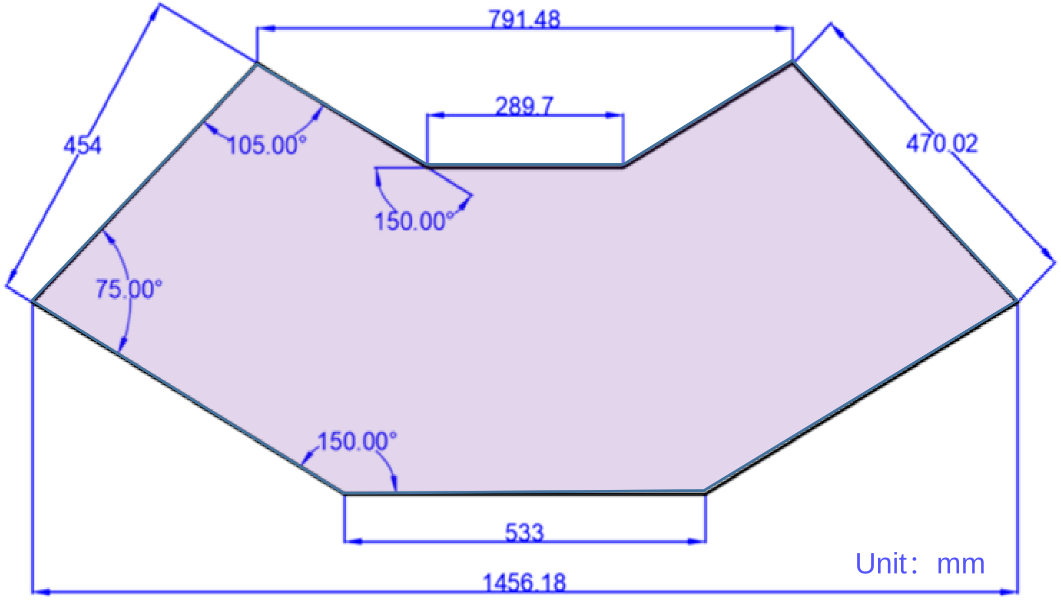
DTOF prototype





- **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
  - 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

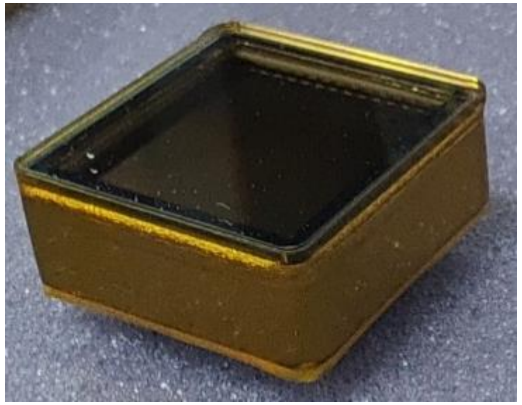
- High purity, transparency>99%@200 nm
- High radiation tolerance
- Thickness=15 mm, area ≈ 0.56 m^2

- Processed by **Beijing Glass Research Institute** (BGRI)
- 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 angle during propagation

Reduce the misidentification of photon paths

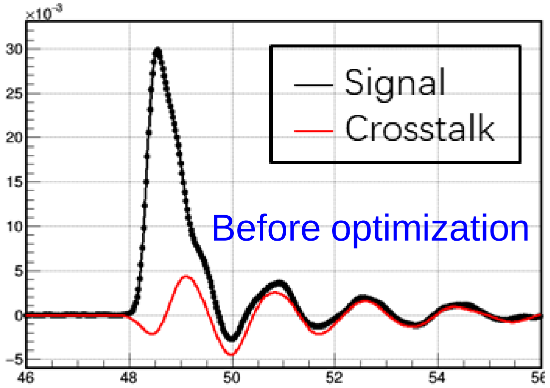
MCP-PMT

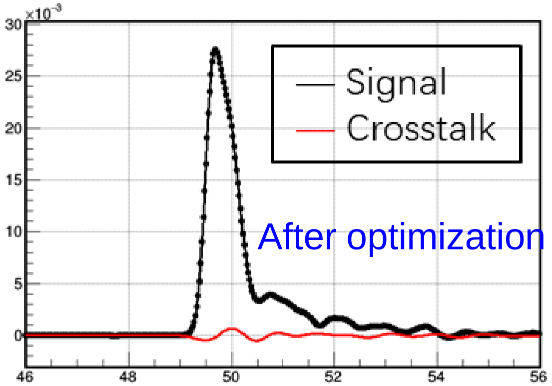


Hamamatsu R10754 MCP-PMT ×42

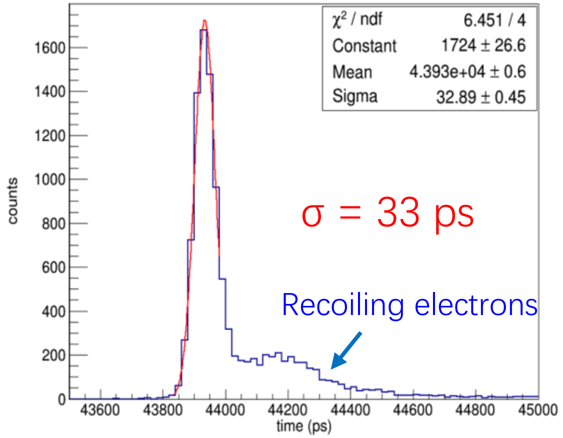
- Sensitive area, 23×23 mm^2
- Segmentation, 4×4 pixels
- Pixel size, 5.5×5.5 mm^2
- spectral response range, 200-850 nm
- Quantum efficiency, ~25%@λ=400 nm
- Gain： $>10^6$, uniformity~14% (σ/μ)
- Transit time spread： ~28 ps

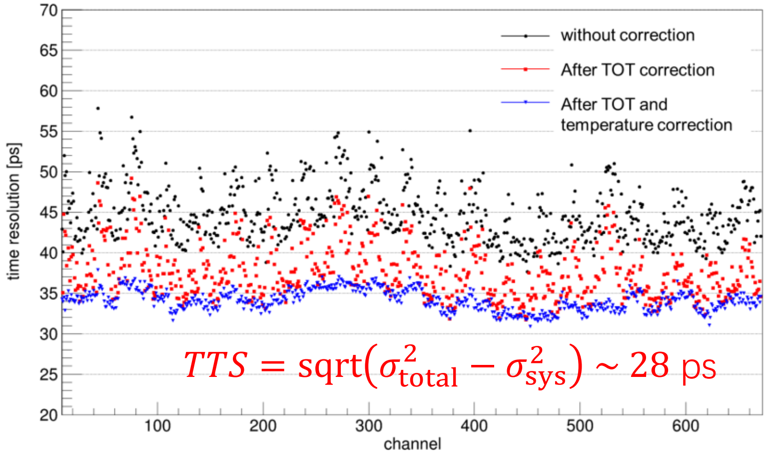
- **Readout optimization to reduce crosstalk and ringing**
  - Optimize PCB routing and ground plane to ensure signal integrity and reduce distributed capacitance
  - Separate high-voltage power supply and signal readout
  - The decoupling capacitors are distributed around the MCP



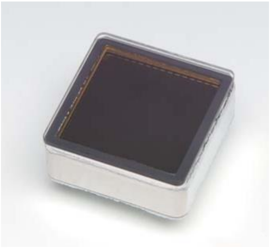


- **Laser (width=60 ps) test, applying TOT and temperature correction**

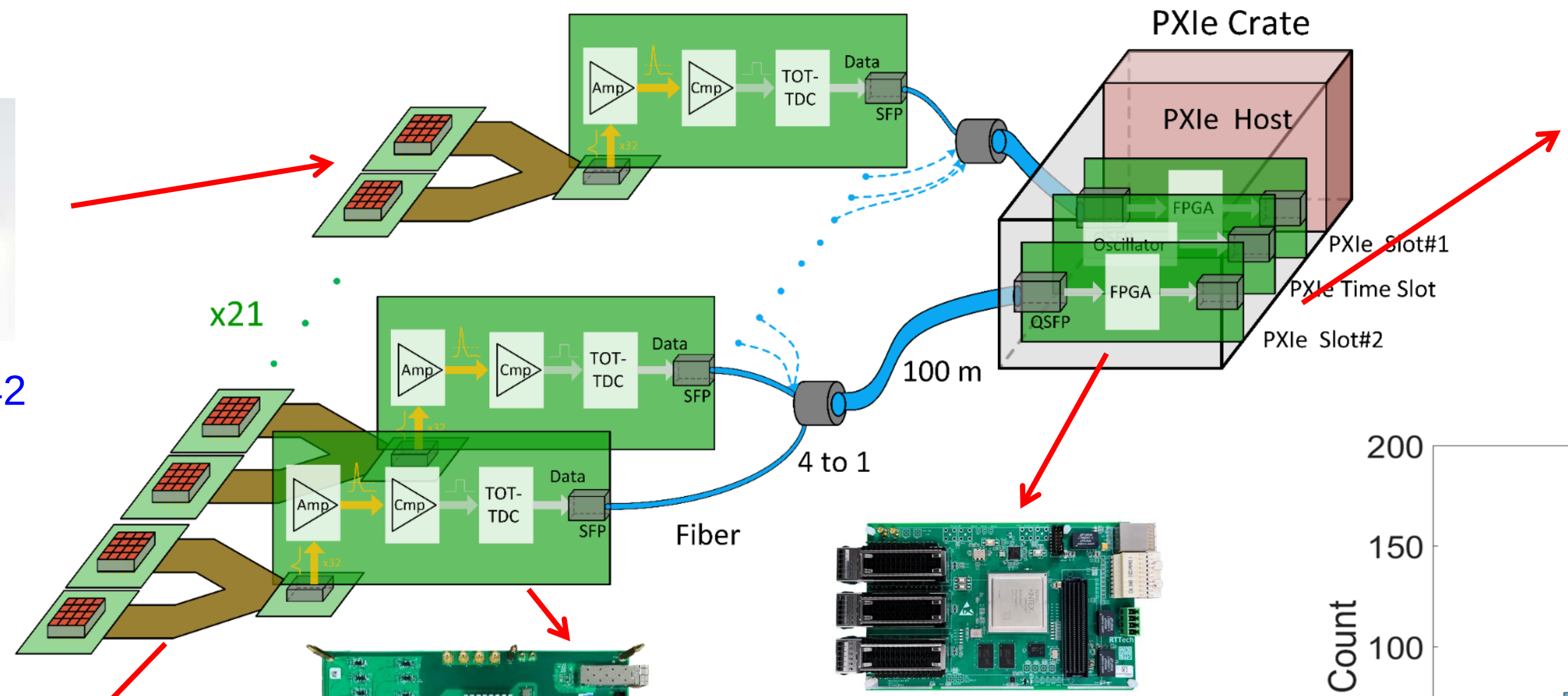




672-channel electronics system



MCP-PMT×42

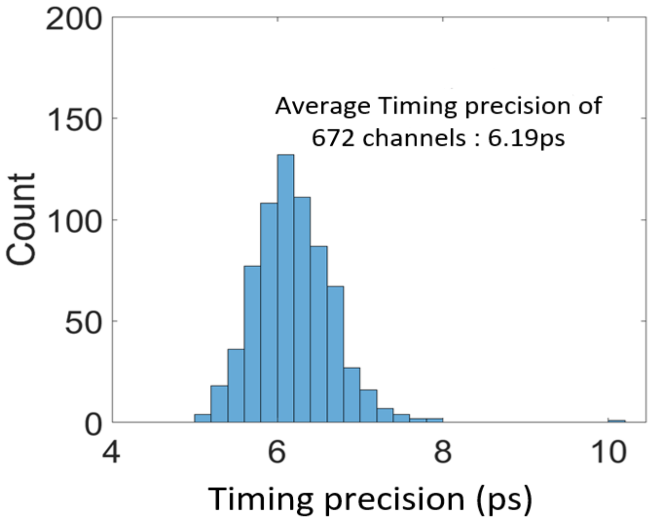


Clock&Trigger distribute board×1

Flexible adapter board×21

Front-end readout board ×21

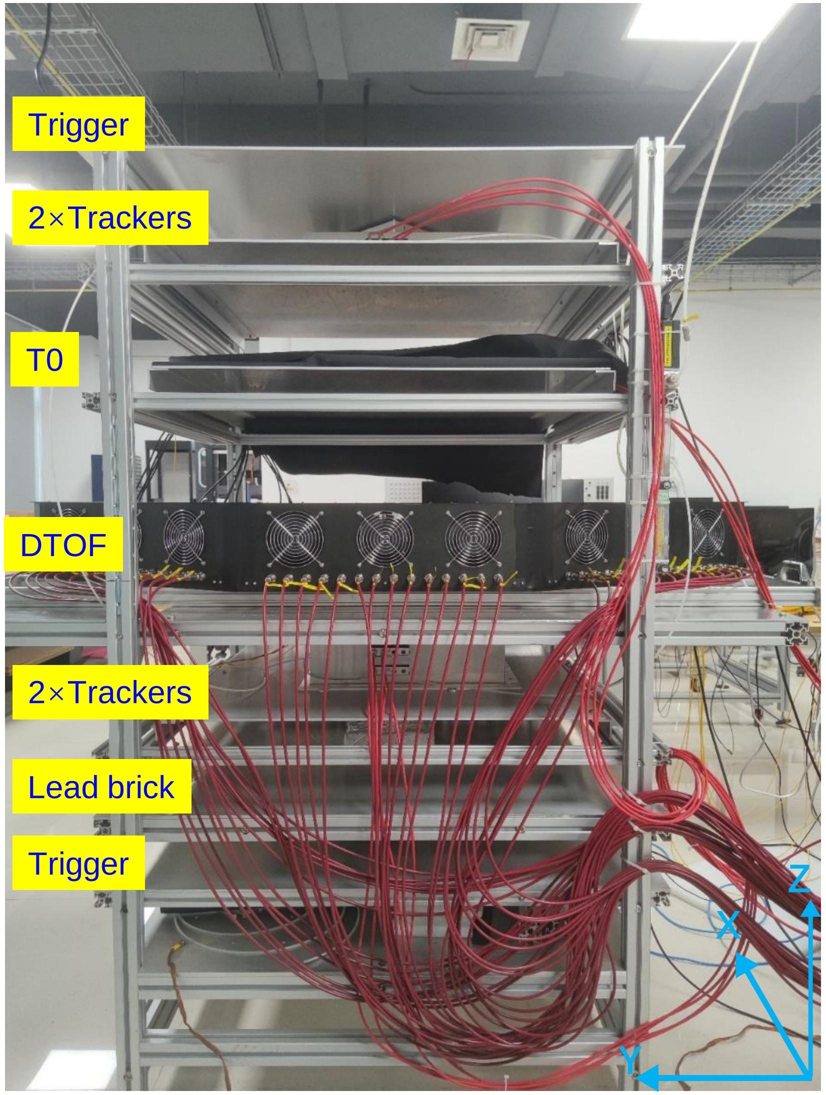
Data collect board×2



✓ **timing precision <10 ps**

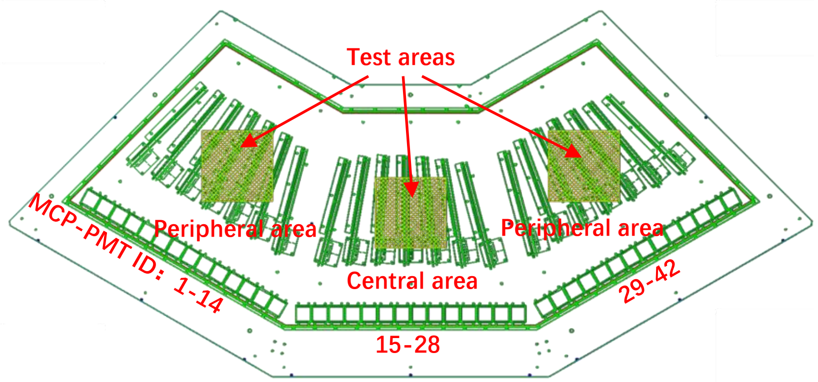
(more details in backup slides)

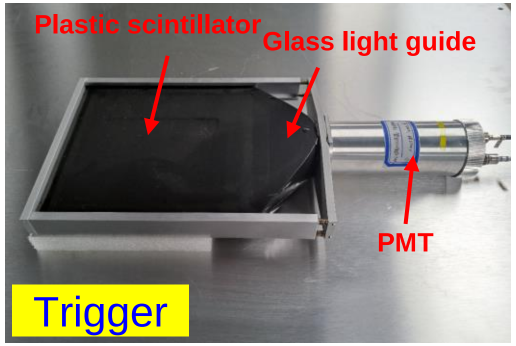
Cosmic-ray test

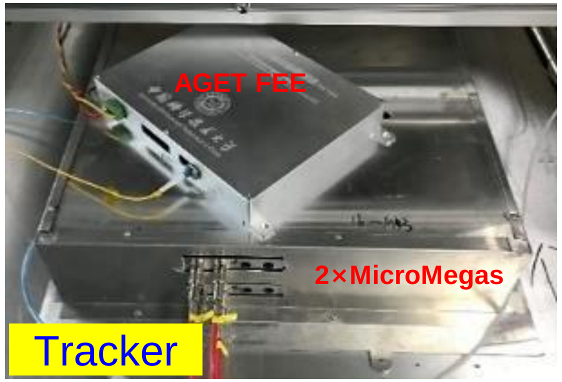


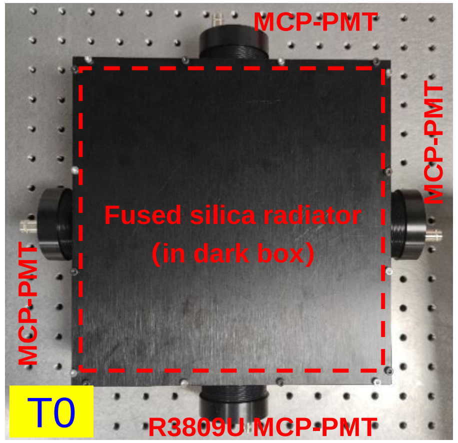
- **Trigger counters**
  - Plastic scintillator + PMT, 220 × 220 mm^2
  - Coincidence of two trigger counters
- **Trackers**
  - 4 × MicroMegas, 150×150 mm^2
  - Efficiency ~90%, σ_{pos} < 200 μm
- **Reference time detector (T0)**
  - 180×180×10 mm^3 fused silica
  - 4 × MCP-PMT, Φ = 10 mm
  - $\sigma_{T0}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

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

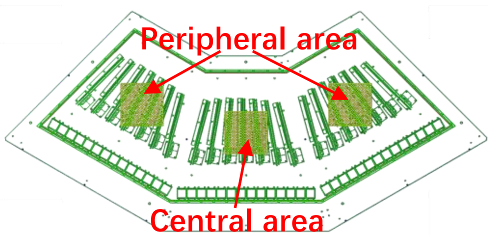


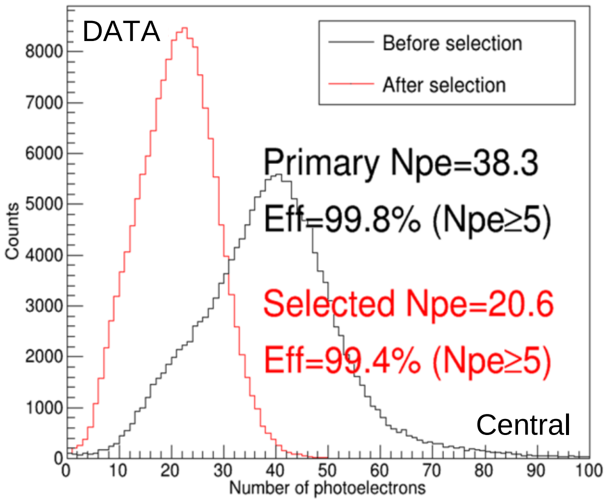


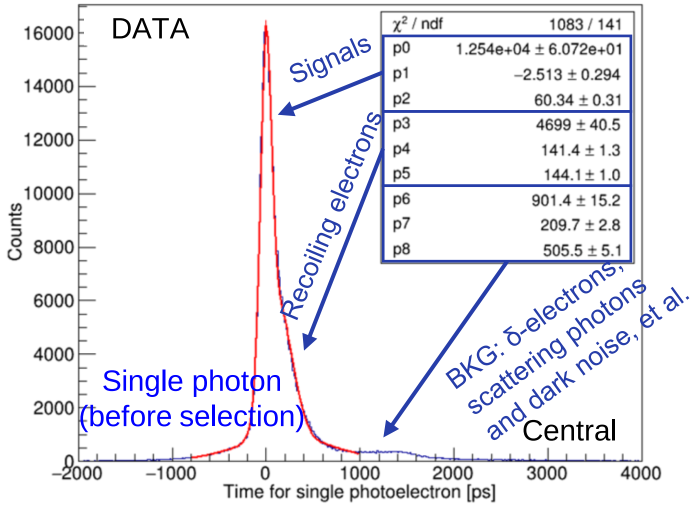


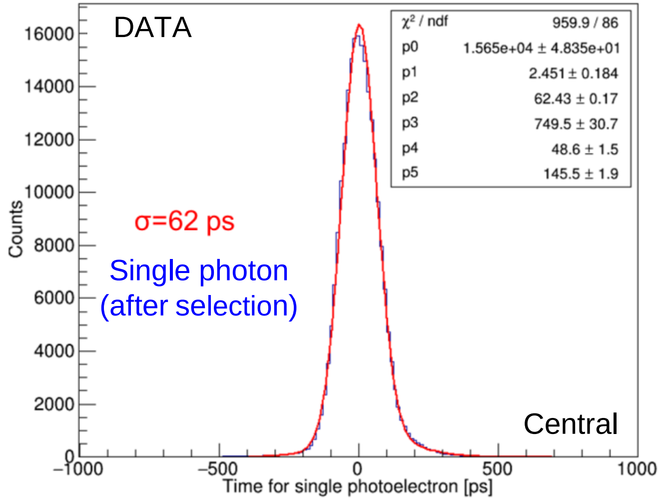


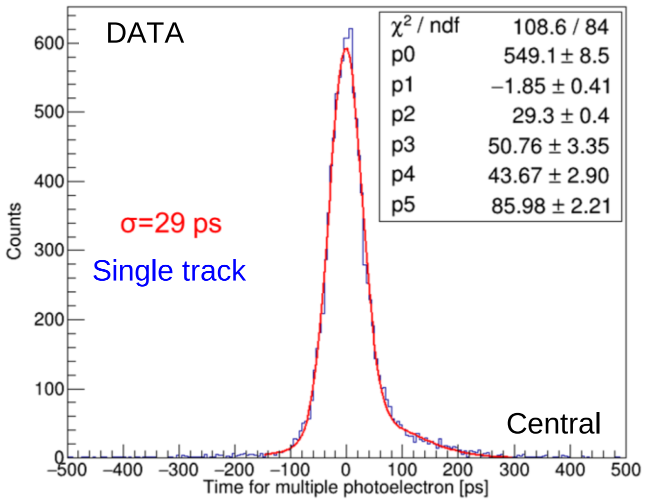
Prototype performances







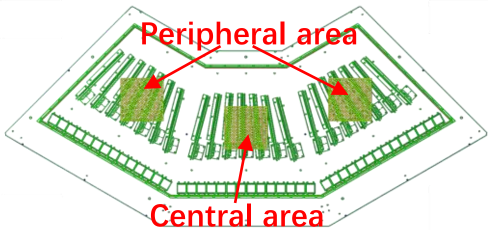


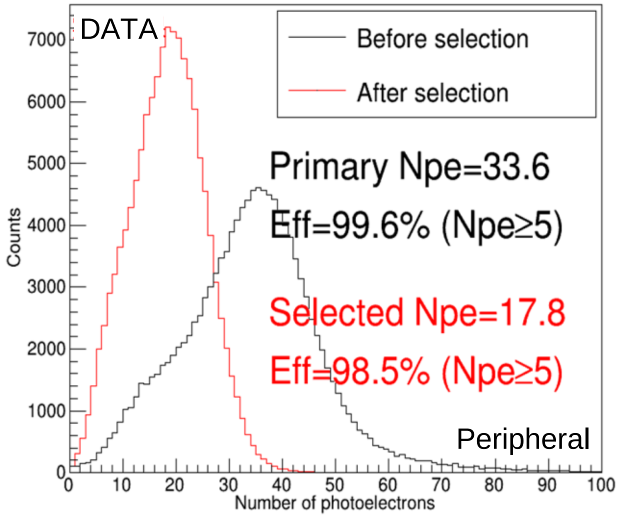


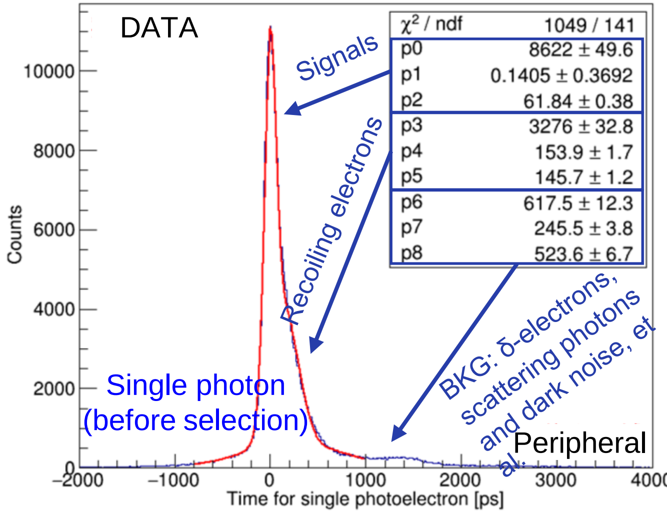
Central area

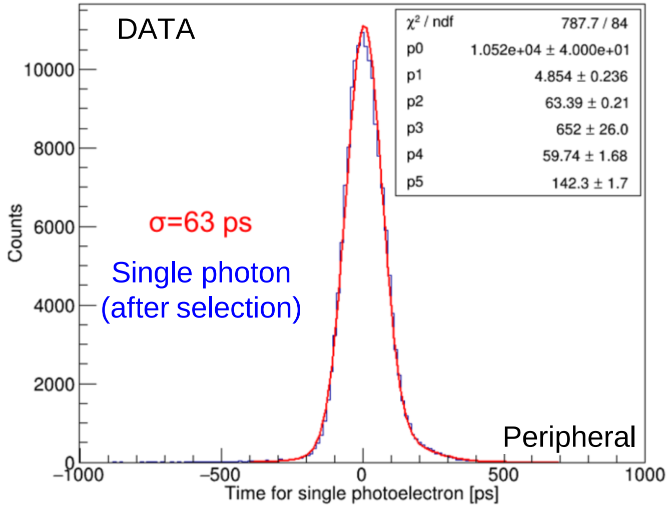
- Detection efficiency = 99.4%
- Single photon, $\sigma_{SPE} = \sqrt{62^2 - 20^2} \approx$ 59 ps
- Single track, $\sigma_{DTOF} = \sqrt{29^2 - 20^2} \approx$ 21 ps

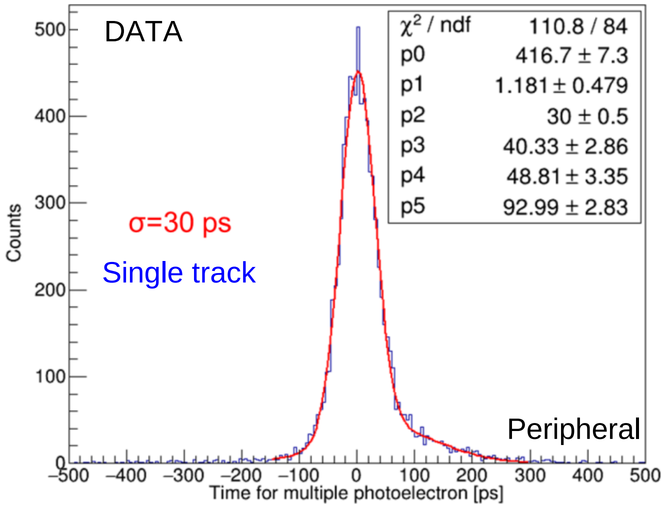
Prototype performances











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

Results 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

Due to the signal selection algorithm to eliminate timing tails, there is a little correlation between each p.e. hit, $r \approx 0.1$

- ► **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 ➔ great potential for amplification in future collider experiments.**

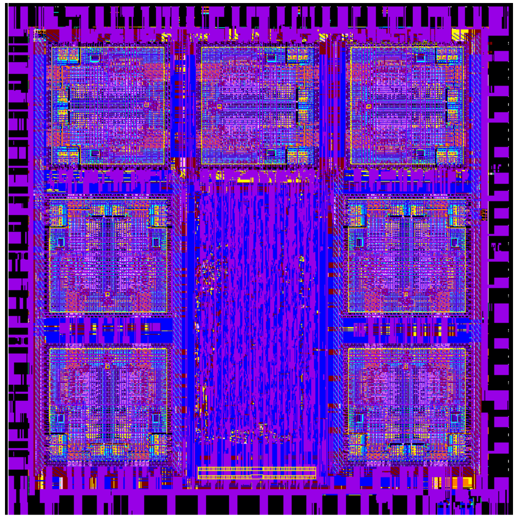
Summary

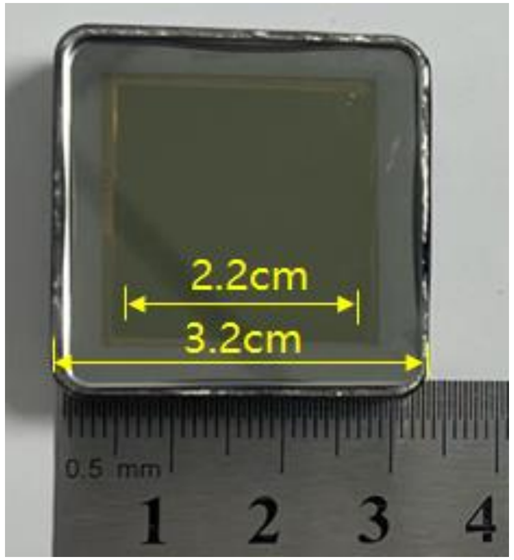
- The DIRC-like Time-of-flight (DTOF) detector was proposed for Particle Identification.
- The expected performance of the DTOF detector was studied in simulation, achieved a >4σ π/K separation power at 2GeV/c for STCF.
- A full-size DTOF prototype was developed and tested using cosmic-ray. The results are consistent with MC.
    - Single track time resolution is approximately 22 ps .

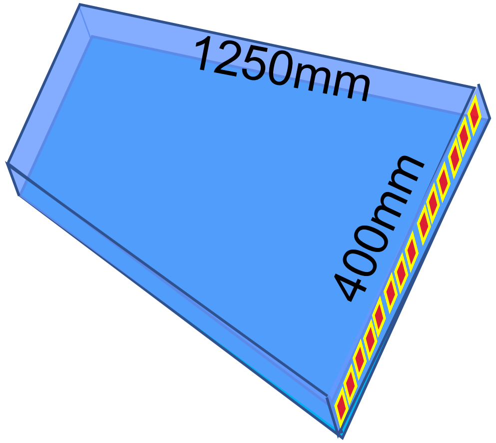
Outlook

- ASIC R&D, to replace the electronics based on the discrete components.
- Life-extended multi-anode MCP-PMT is under developing by Xi'an Institute of Optics and Precision Mechanics, CAS.
- DTOF for PID in the barrel of STCF, and more (radiator, integration etc.)
- The beam test for DTOF prototype will take place at the end of this month at CERN PS T9 beam line.

ASIC TDCv1





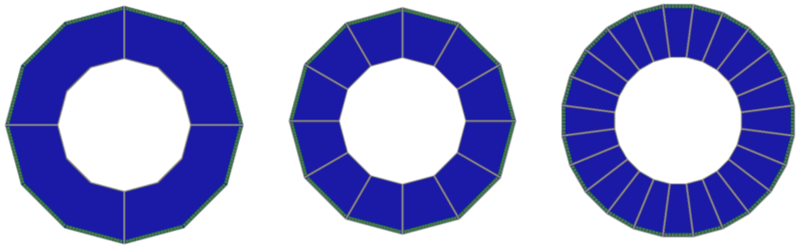


Beijing Glass Research Institute had processed fused silica plate of 1050mm*1050mm and 1250mm*400mm. Larger plate can be handled (e.g. 2500mm*700mm).

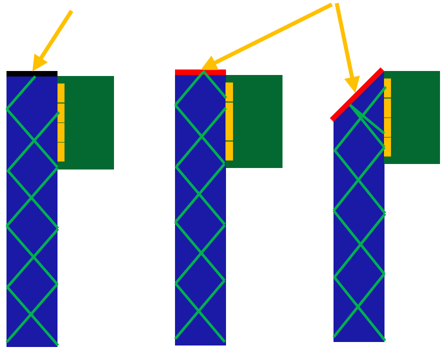
BACK UP

Geometry 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)	**pion**	**21.8**	21.4	16.3	15.5	25.5	32.7	37.2
	kaon	**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

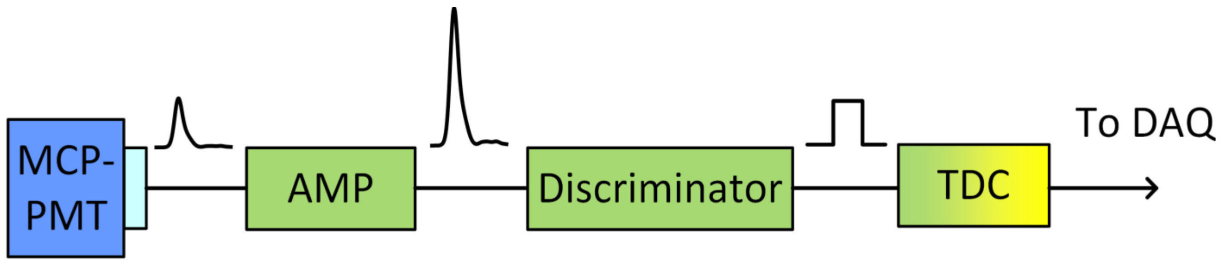
- Thick radiator increases material, and thin radiator degreases performance.
  - A right thickness is better
- Large area radiator reduces the number of lateral reflections, causing less hit map's overlaps and better π/K separation power
- Adding mirrors on the top surface will increase Np.e., but cause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

Components of electronics system

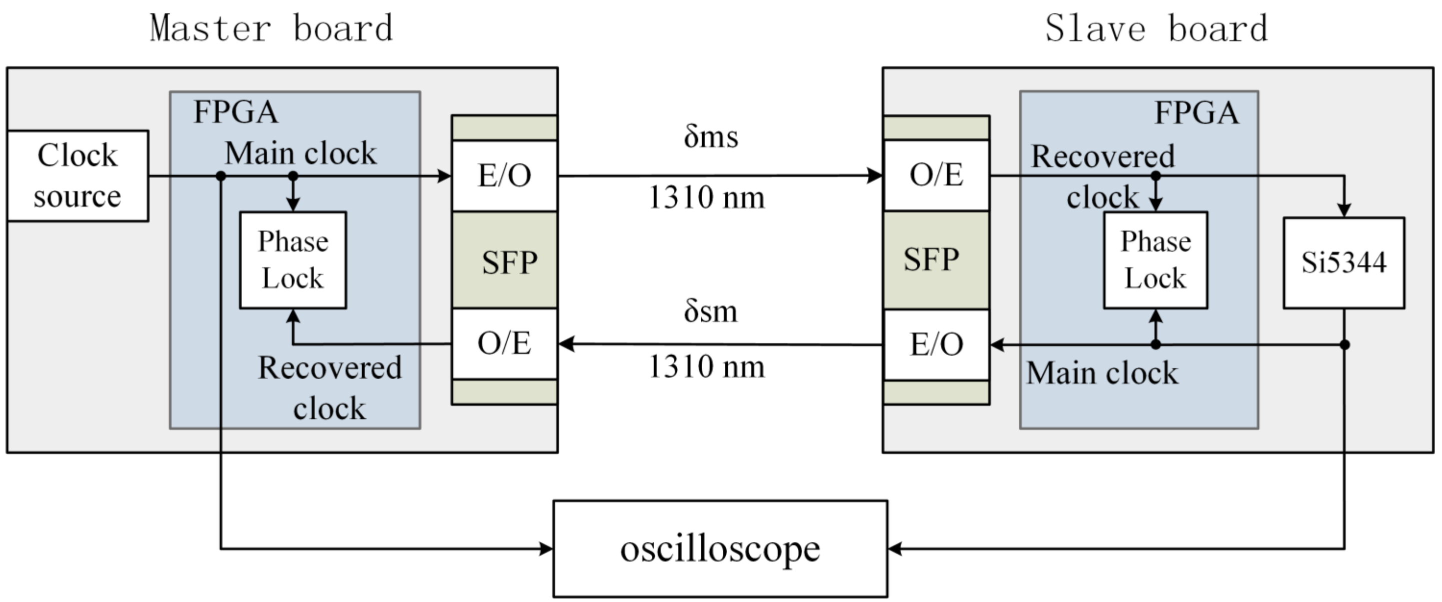
- **Flexible adapter board:** provide high voltage for MCP-PMT and output signals to the front-end readout board.
- **Front-end readout board (FEB):** receive 32-channel signals from 2 MCP-PMTs, and then process them with amplification, discrimination and digitization.
- **Data collect board (DCB):** 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

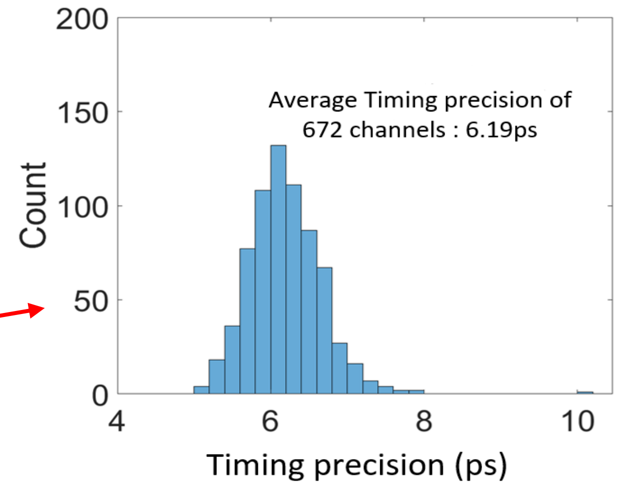


Timing circuit structure



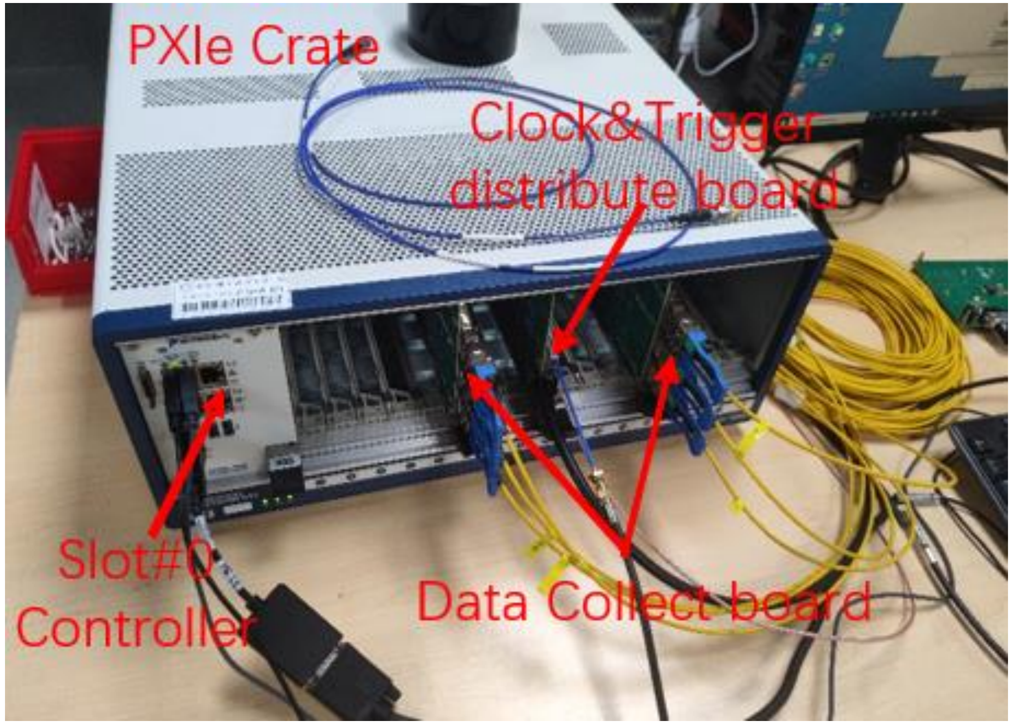
Distribute the clock via fibers

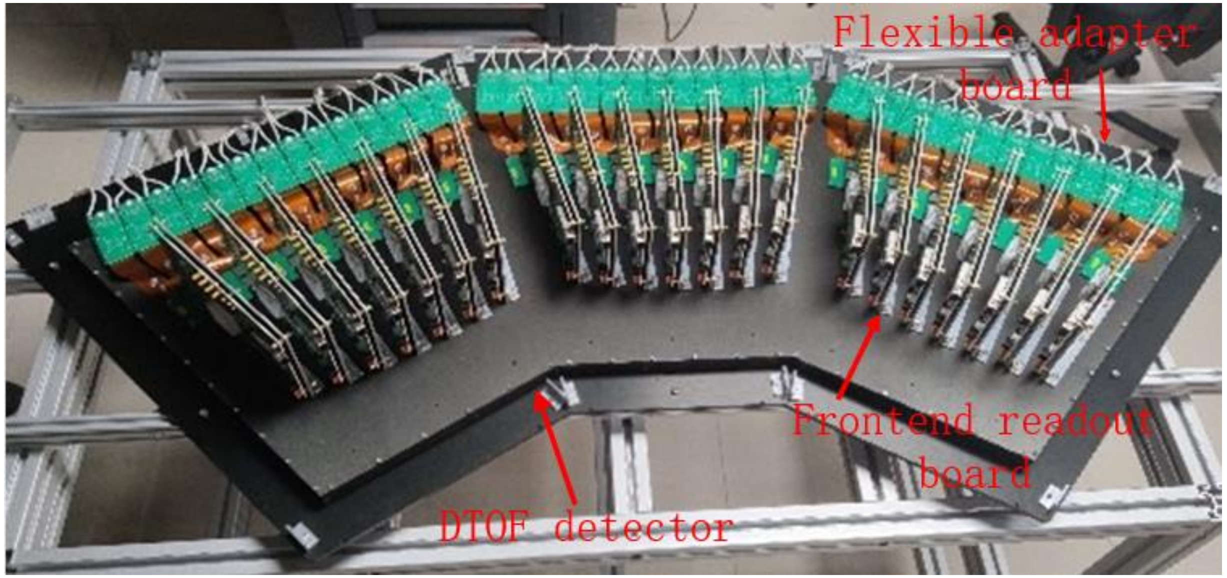
Summary of electronics system



	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)

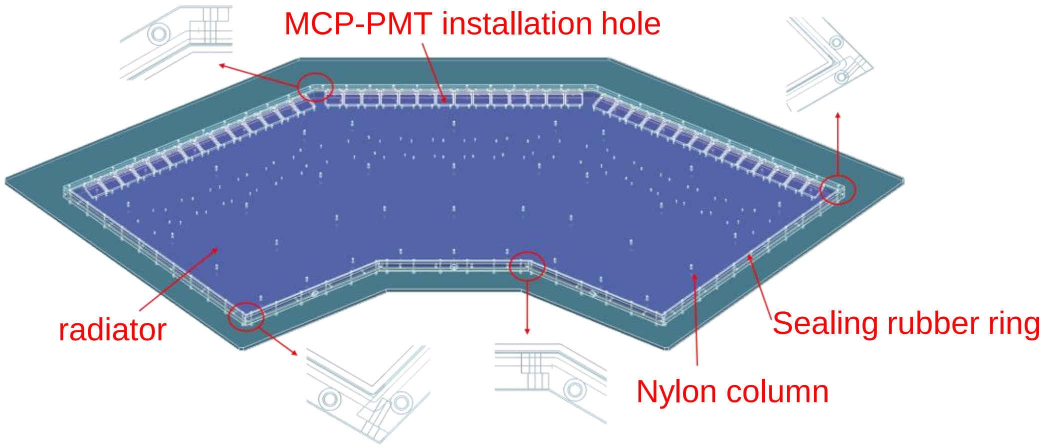
672-channel electronics system of DTOF



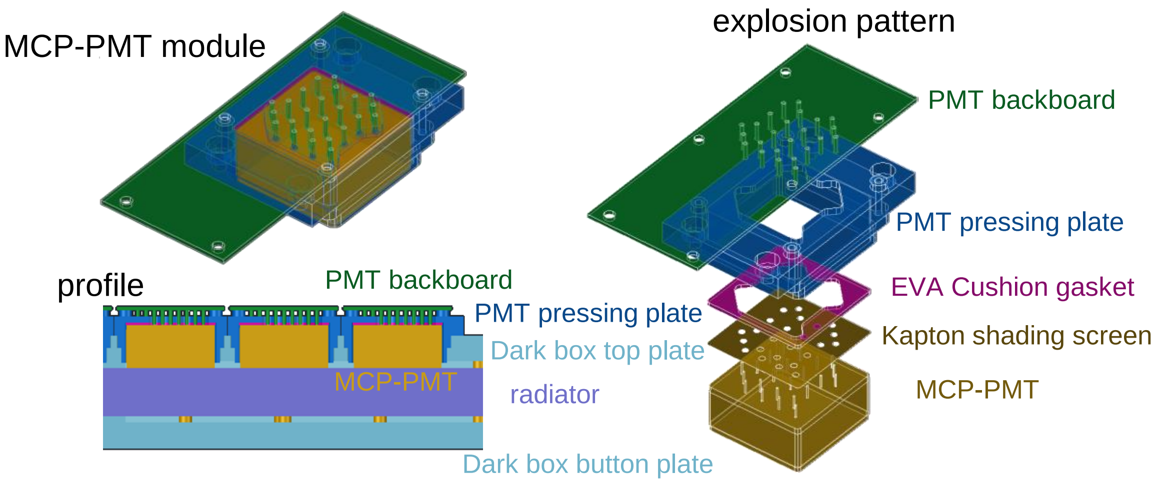


DTOF prototype Auxiliary systems

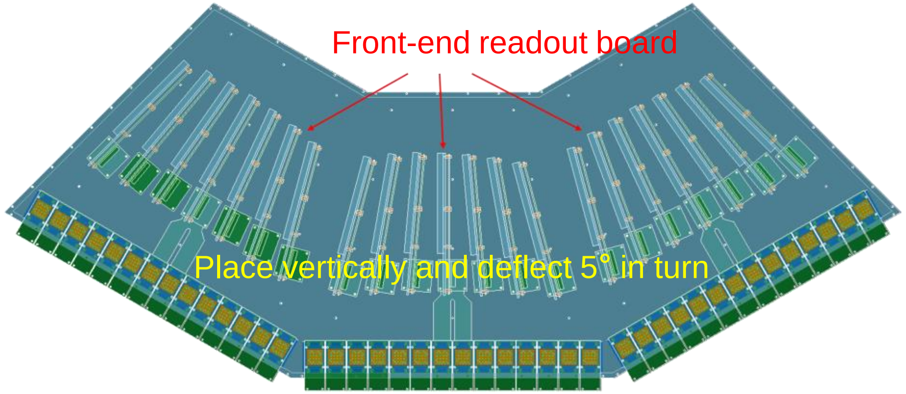
- **Dark box**



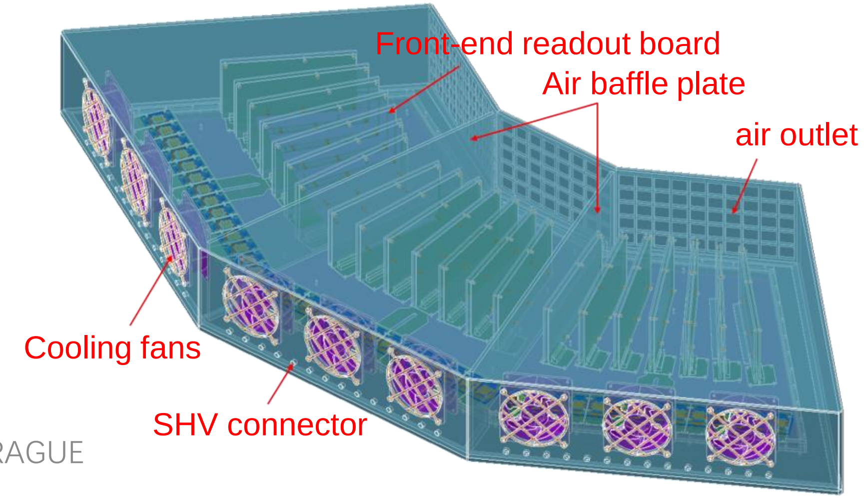
- **MCP-PMT installation**



- **Electronics module**

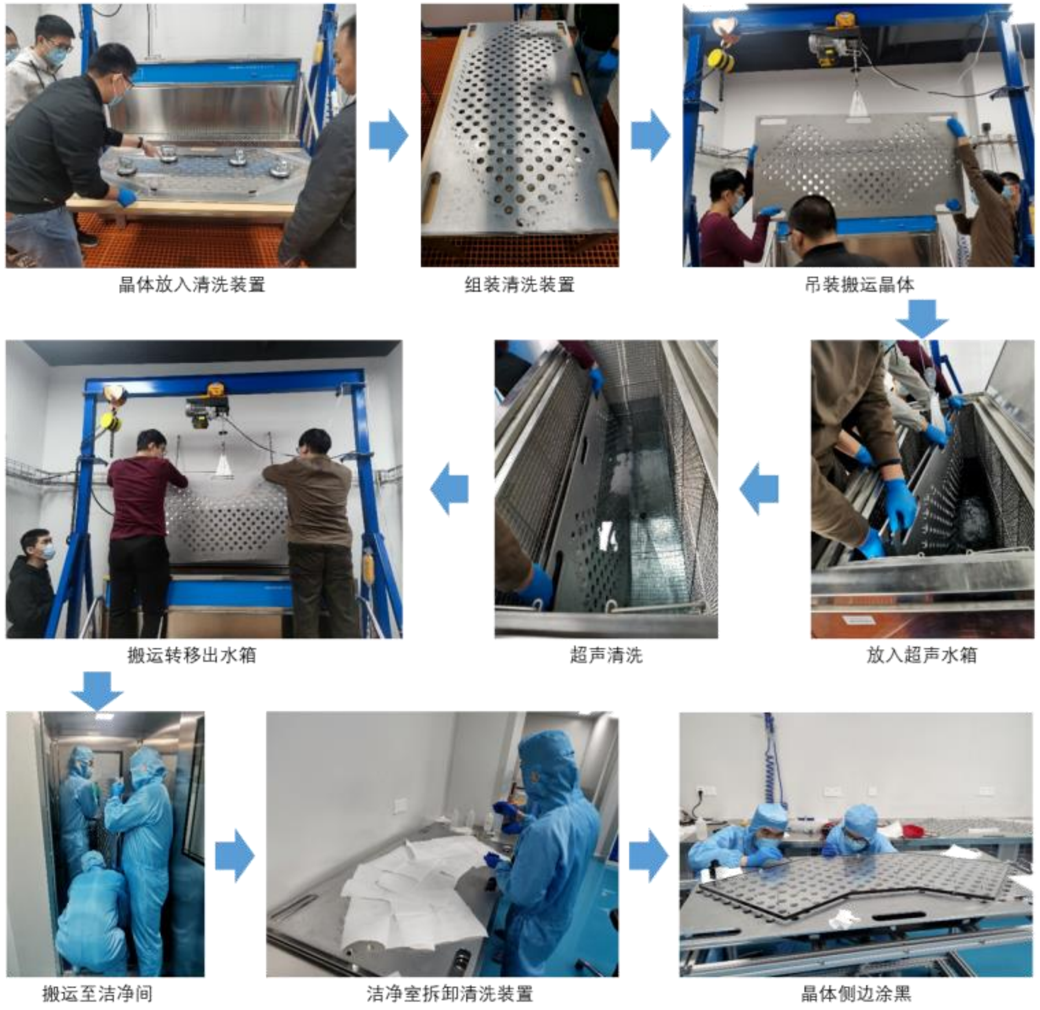


- **Cooling**

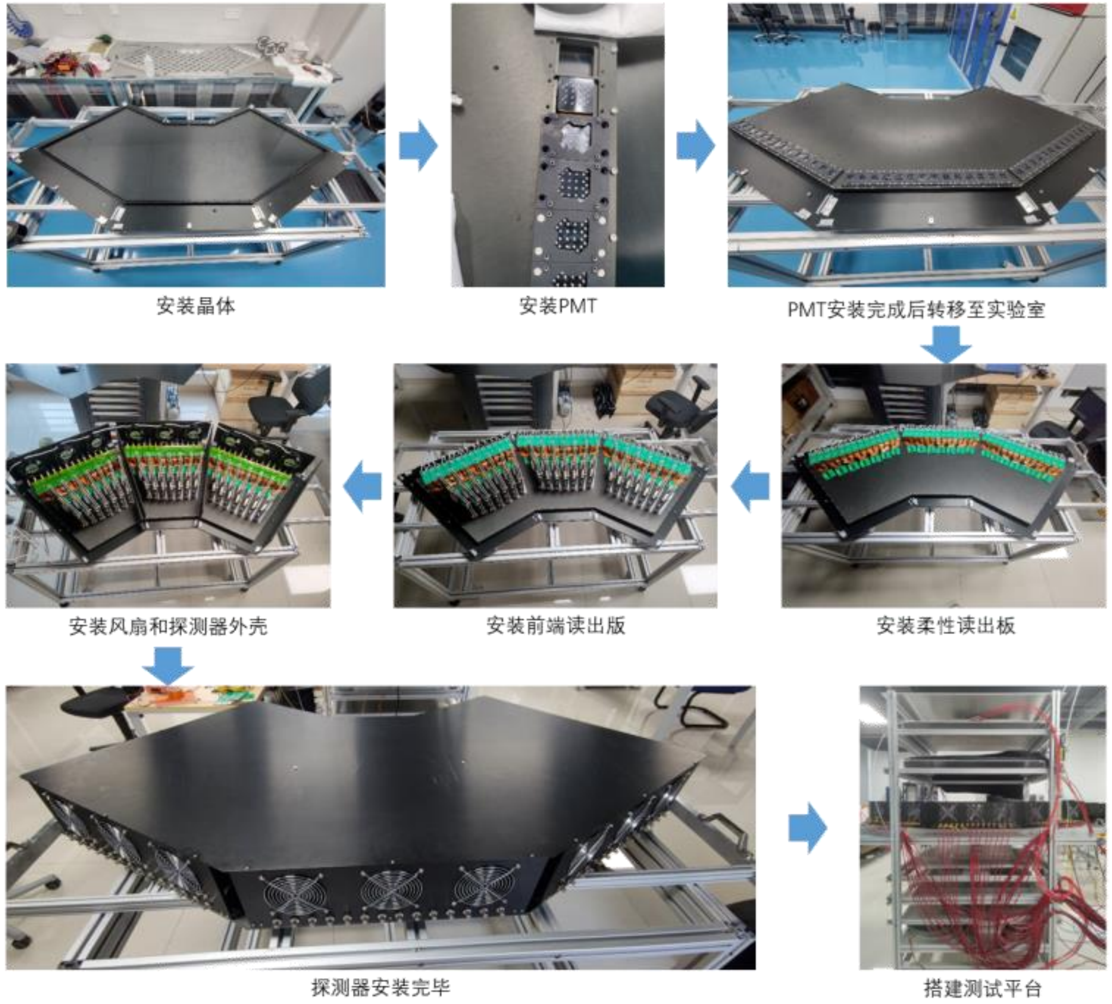


DTOF installation and system integration

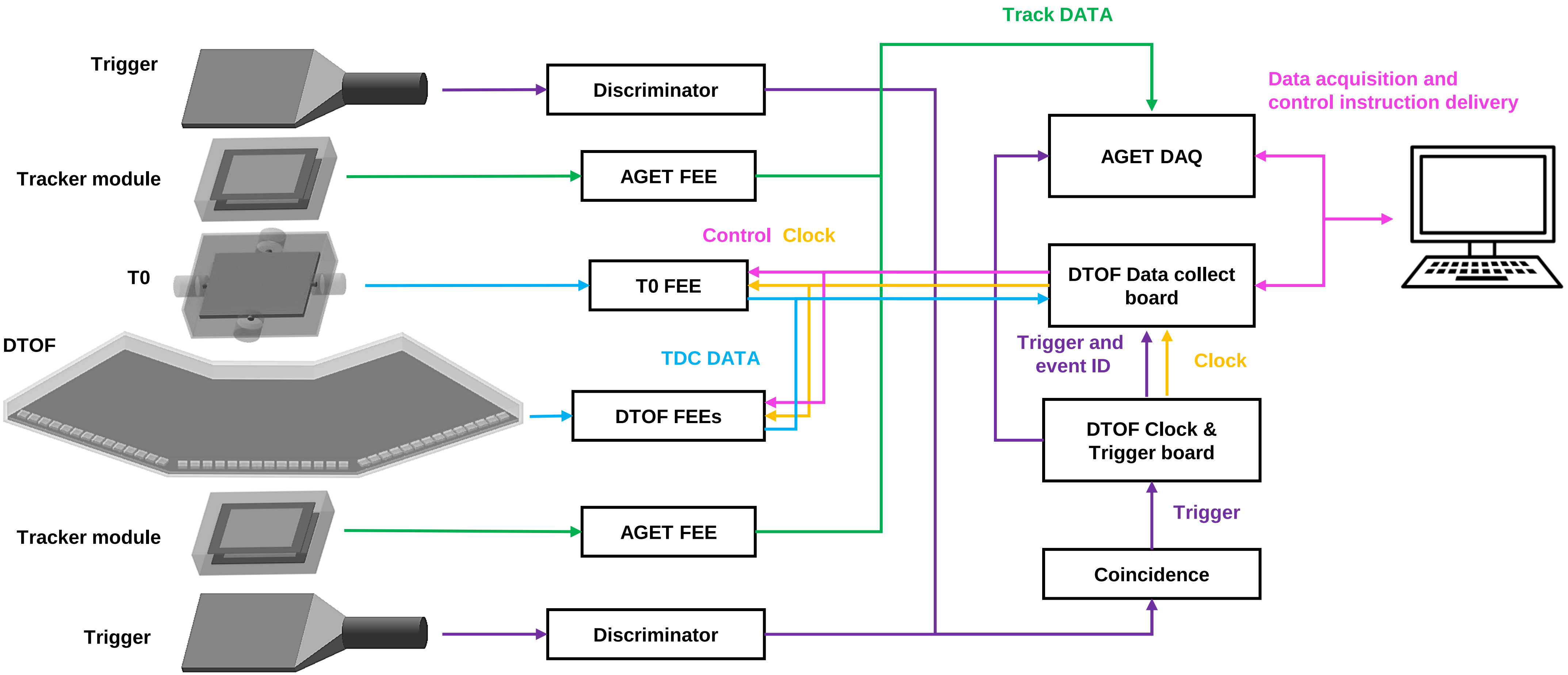
- Clean radiator and apply matting paint



- Installation

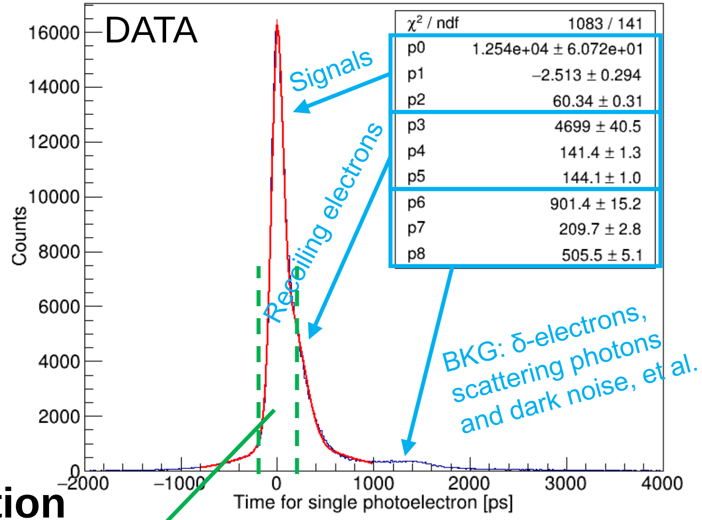


Cosmic ray test data acquisition system

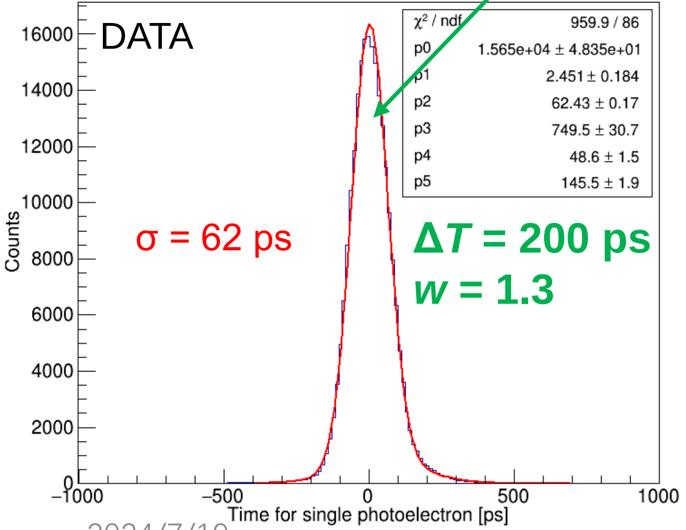


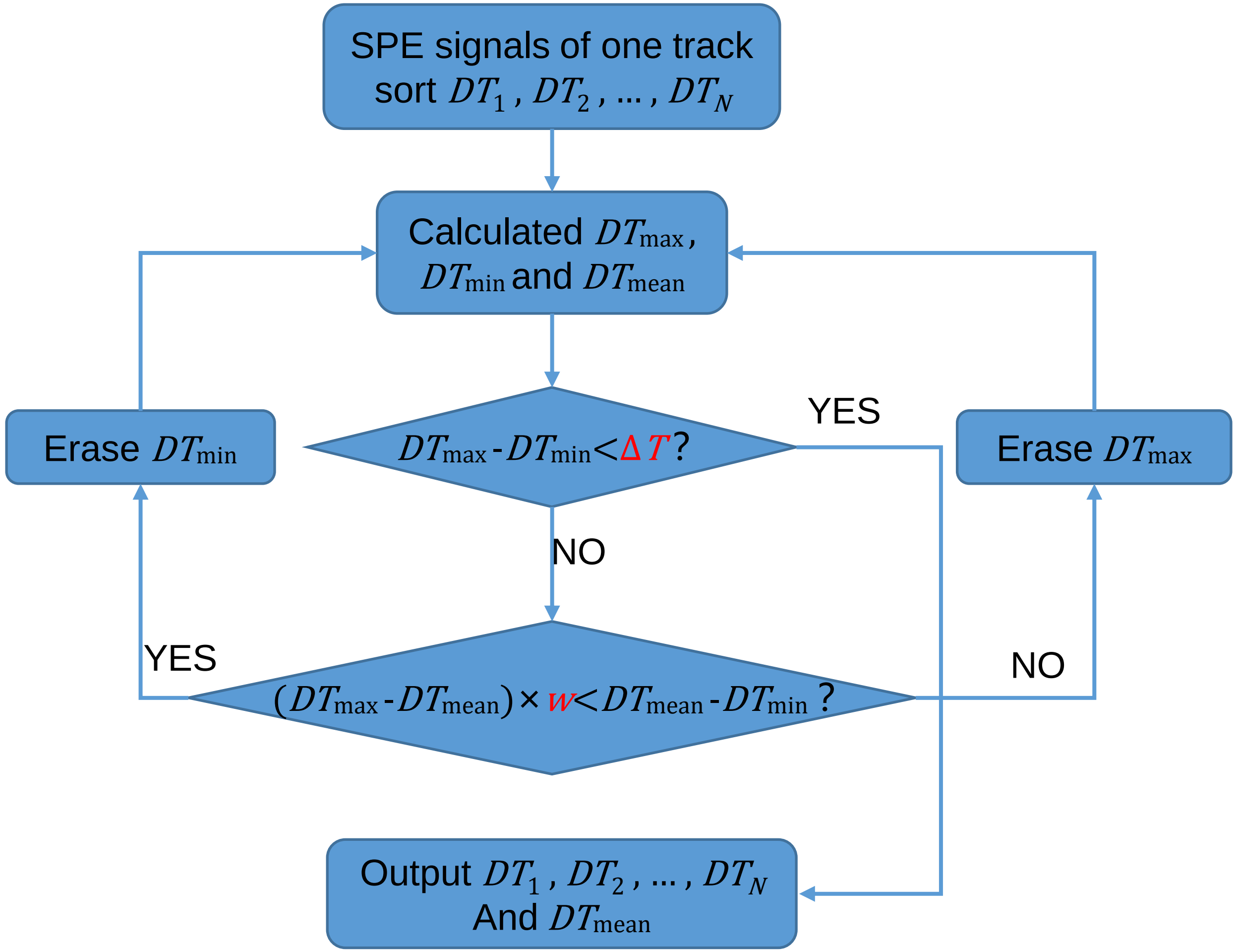
Signal selection

- **Before selection**

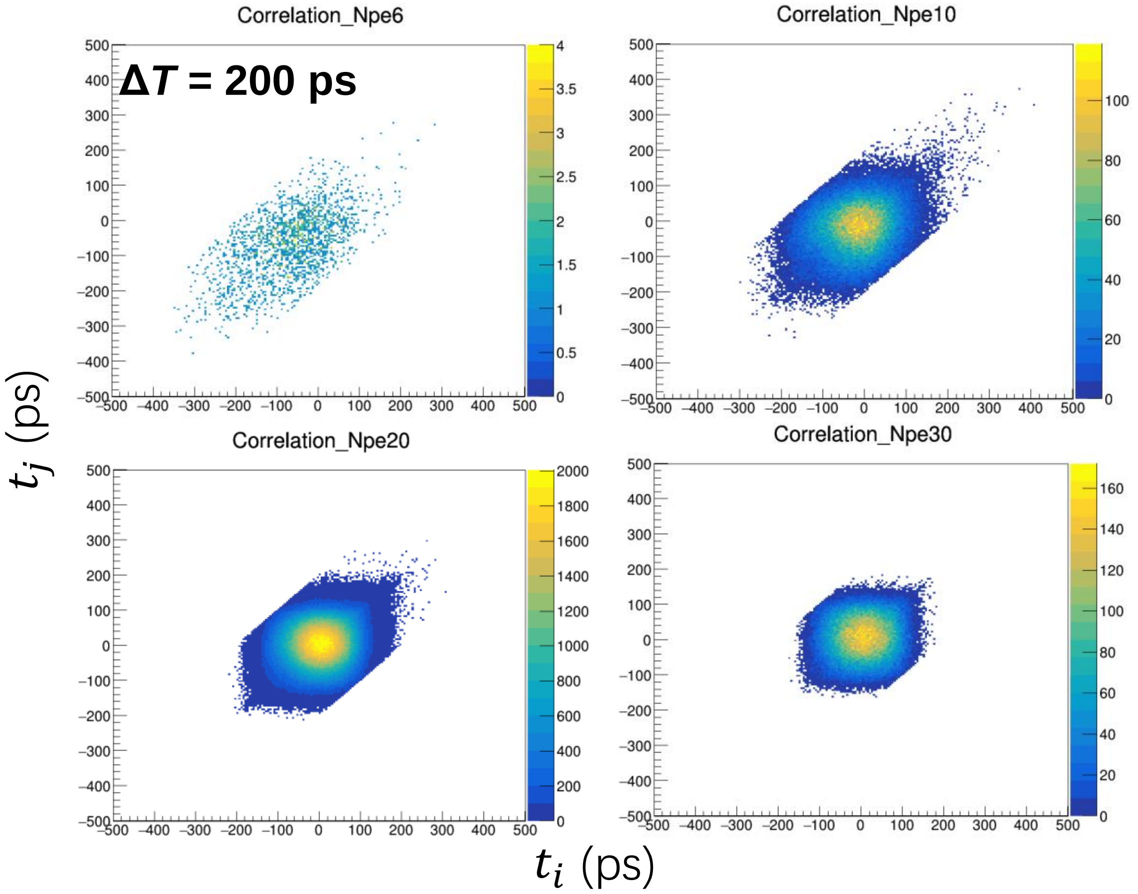


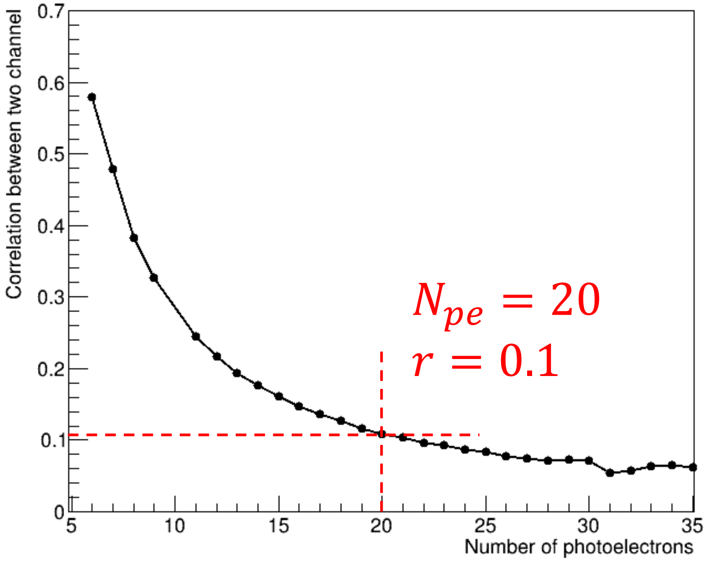
- **After selection**

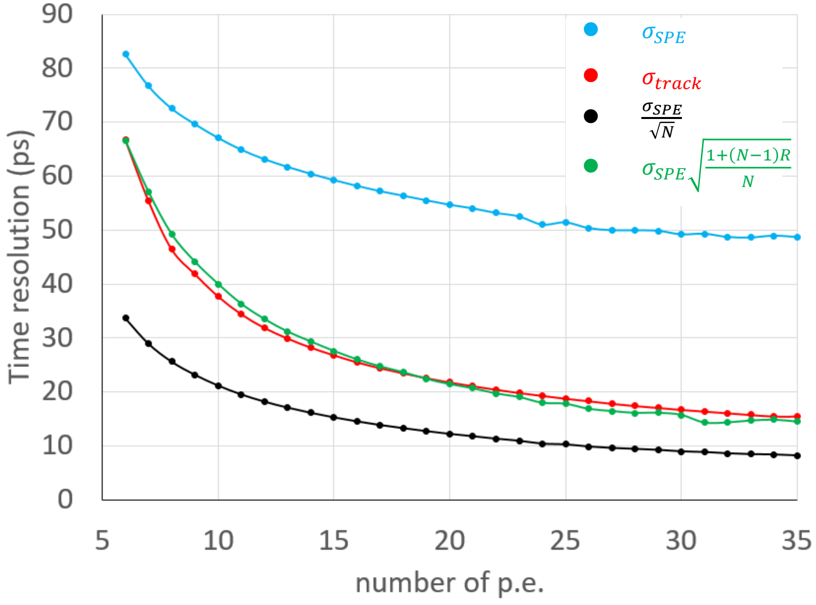




Correlation check



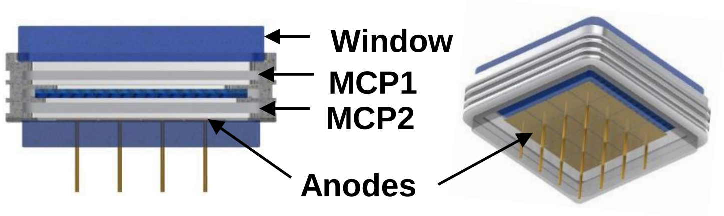


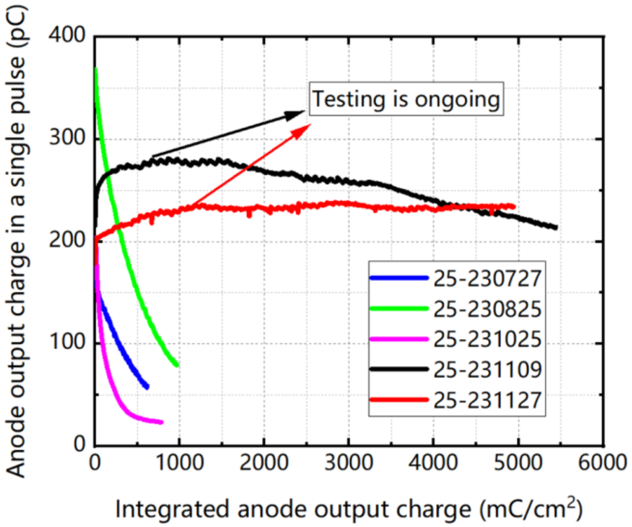


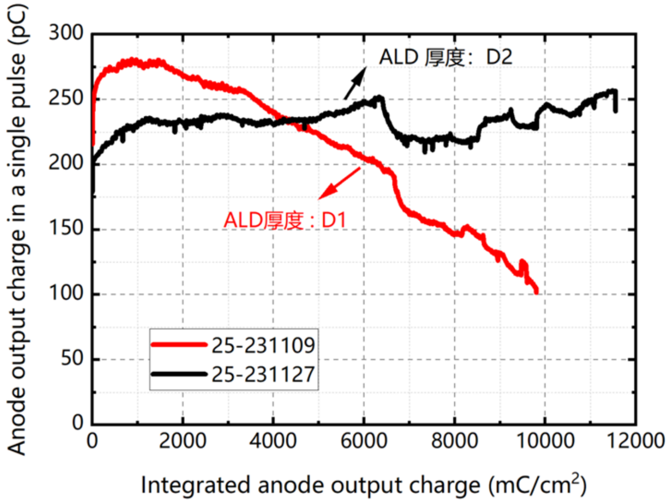
- **Time resolution,** $\sigma_{track} = \sigma_{SPE}\sqrt{\frac{1+(N_{pe}-1)r}{N_{pe}}}$
- **Correlation coefficient,** $r = \frac{\mathrm{Cov}(t_i, t_j)}{\sigma_{t_i} \cdot \sigma_{t_j}}$

MCP-PMT development

Lifetime extended MCP-PMT development at XIOPM





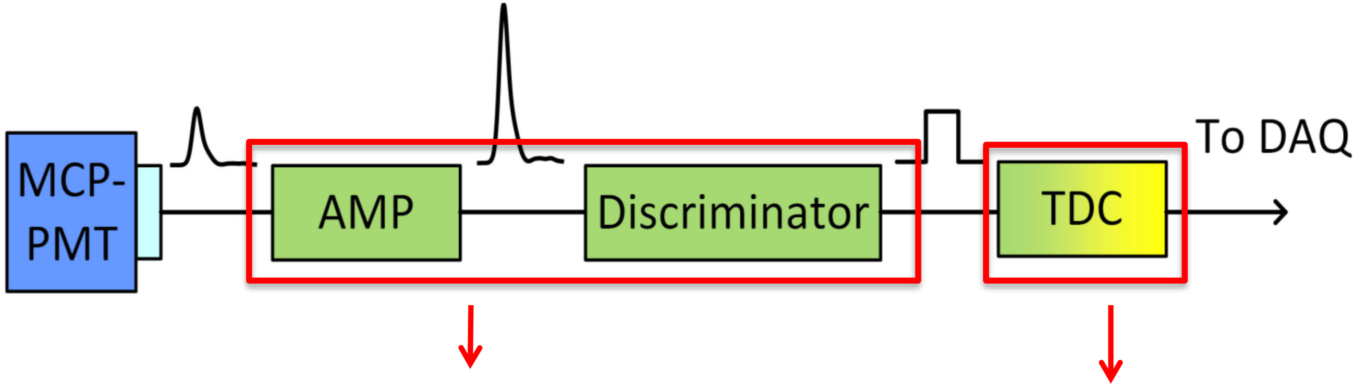


- Multi-anode MCP-PMT using ALD-MCP
- Use mass spectrometer to monitor gas composition during tube manufacturing process
- optimize the ALD-MCP cleaning process (including electron scouring dose and high temperature baking time) to improve the vacuum level in the tube
- Monitor the after pulse of MCP-PMT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

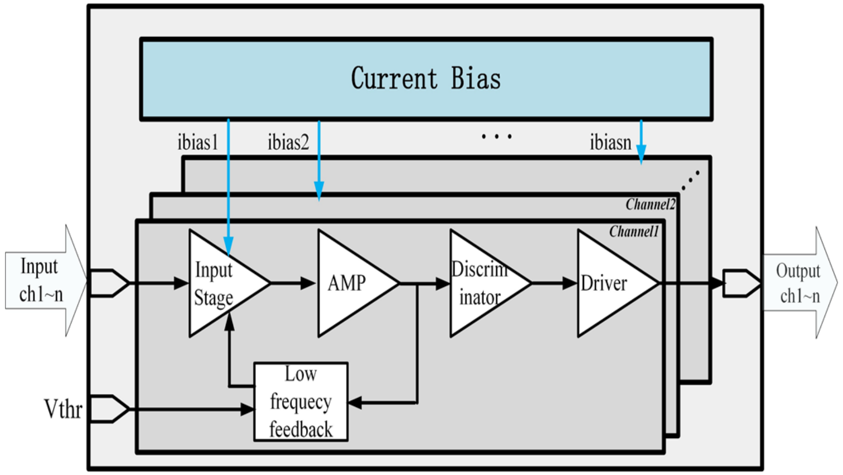
- ALD-MCP has better performance than conventional MCP, met the DTOF requirement (>10 C/cm^2).

ASIC development

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

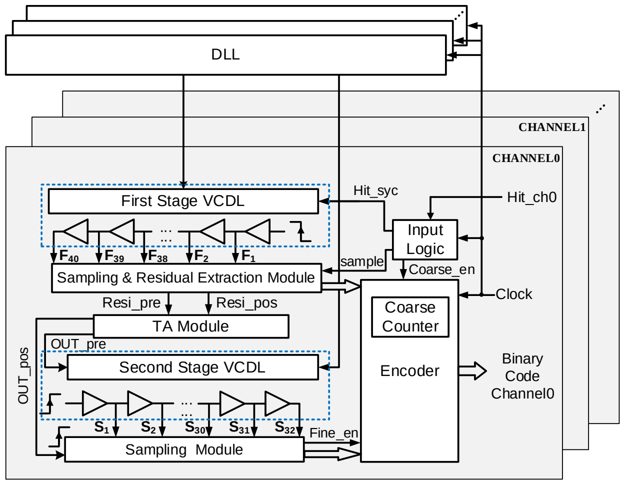


Front-end timing ASIC

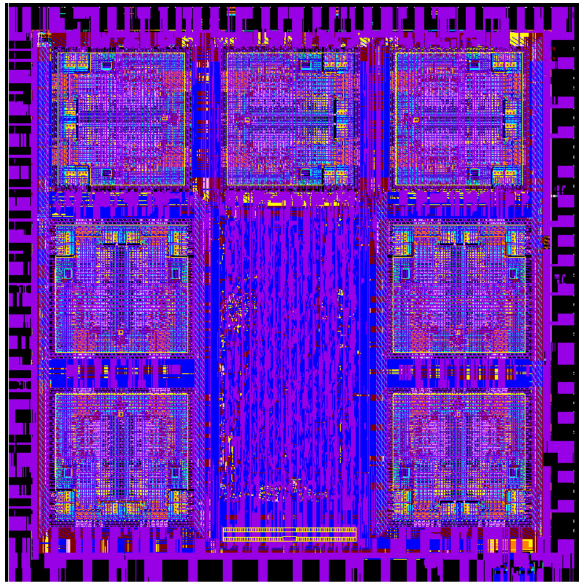


High bandwidth cascade amplifier + comparator
Design target: timing precision < 15 ps

TDC ASIC

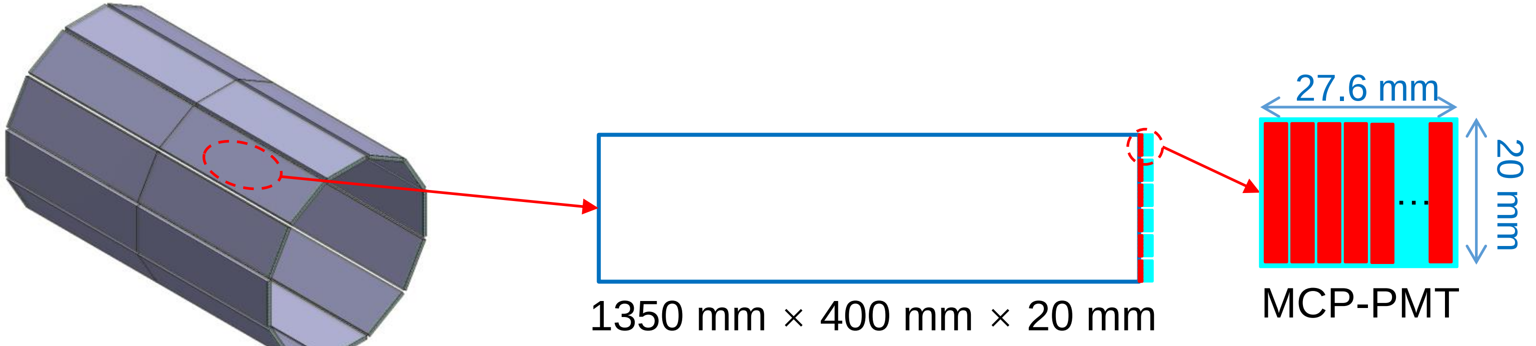


Delay lock ring (DLL) + two stage interpolation
Design target: timing precision < 20 ps

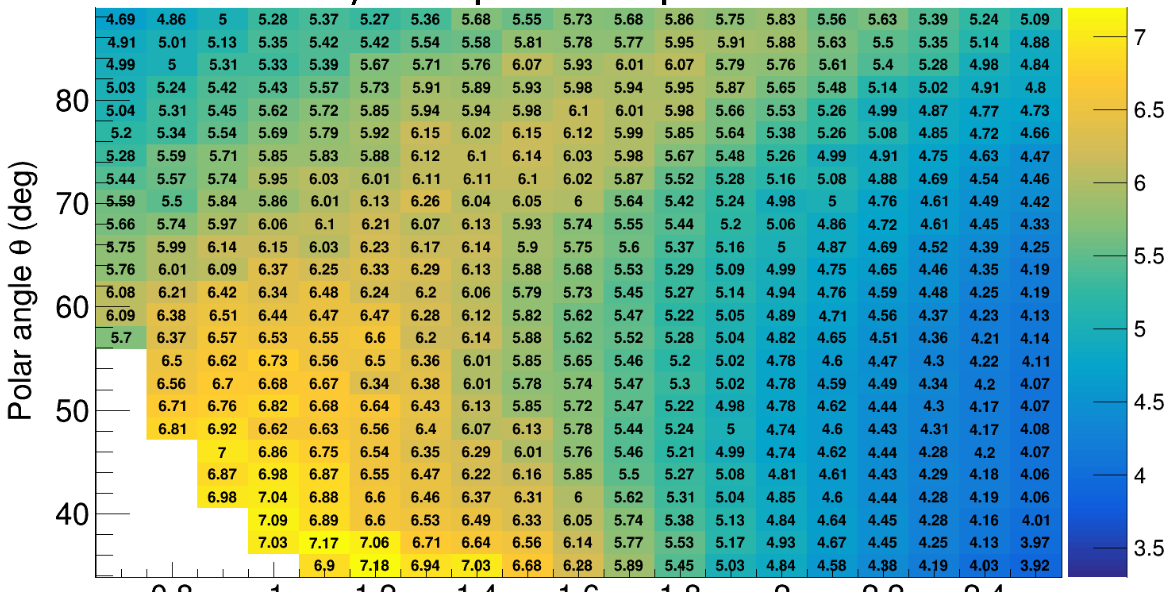


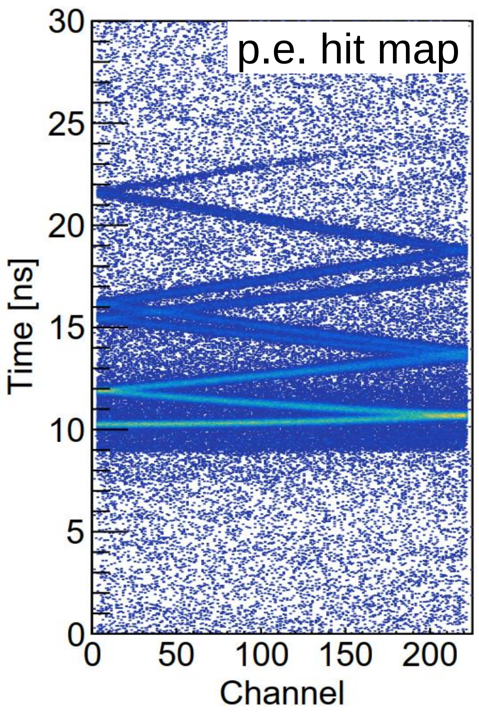
TDC ASIC layout (unfinished)

Barrel DTOF study



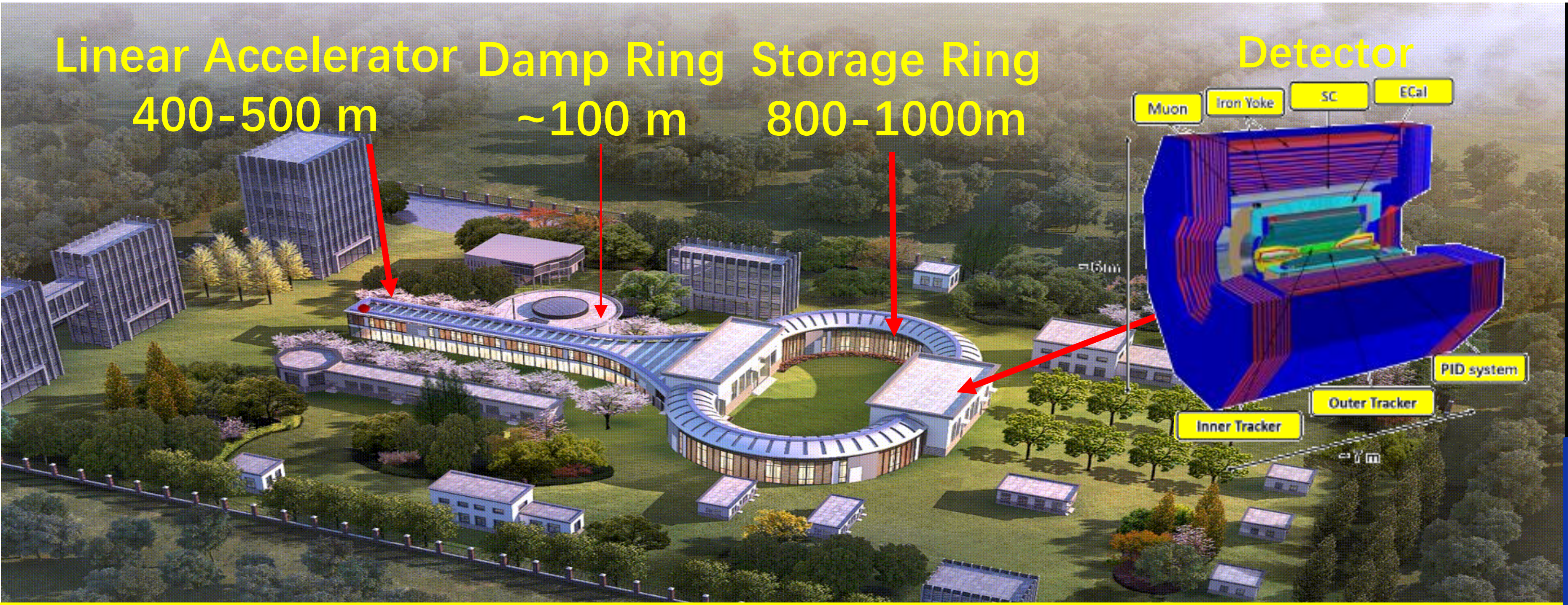
π/K separation power

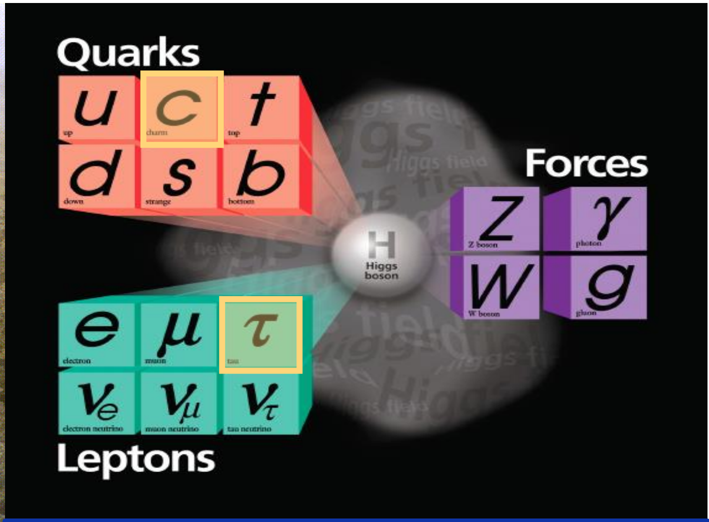




A preliminary simulation results indicate that its performance meets the STCF PID requirements.

Super Tau Charm Facility (STCF)





Deliver a massive amount of tau-leptons and composed of charm quarks, to study the composition of particles, the deep structure of matter, as well as the basic interaction forces

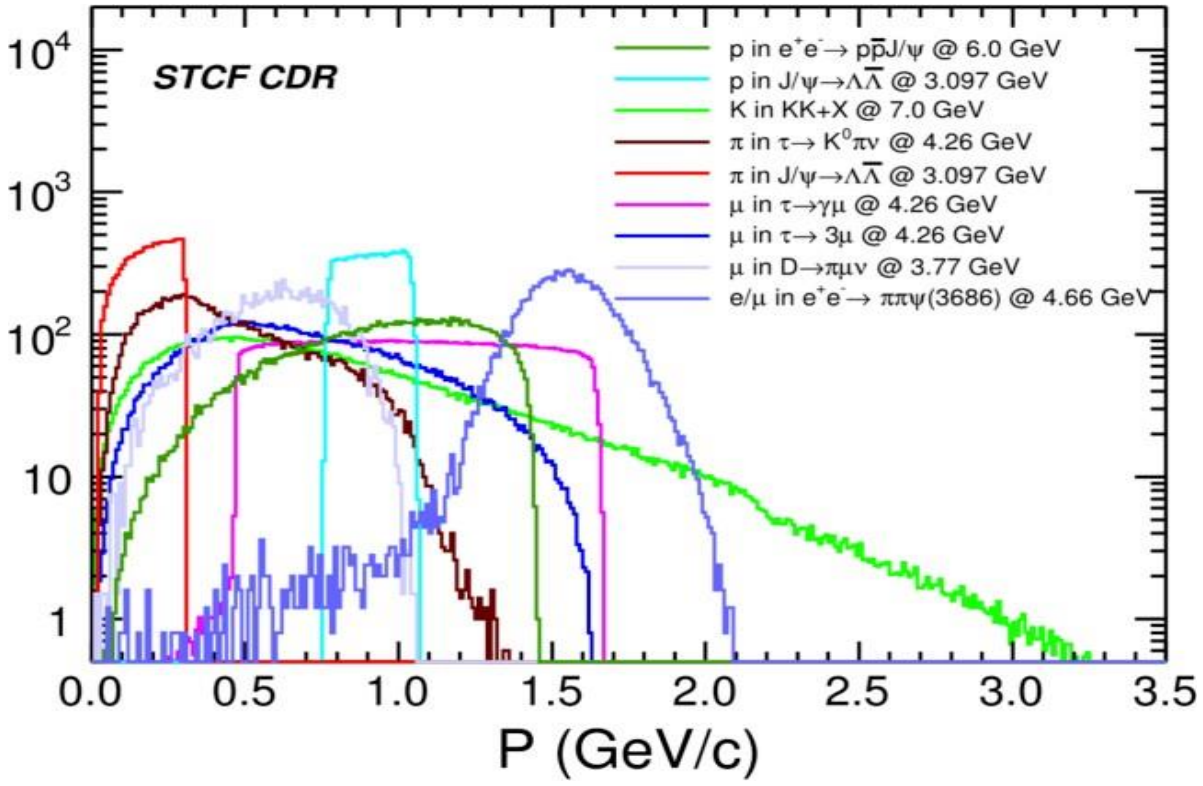
- A future e^+-e^- collider in China
- E_{cm}= 2-7 GeV， $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1}
- Potential for upgrade to increase luminosity and realize polarized beam

- 2021-2026： Conceptual design and R&D of Key technologies, 0.42 B CNY
- 2026-2031： Construction, 4.5 B CNY
- Operating for 15 years (may undergo upgrade).

STCF CDR (Volume 1): Physics & detector, 2024

STCF PID requirement

The momenta of STCF final state particles



Endcap PID detector requirements

- >4σ π/K separation power at p≤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 **DIRC-like TOF** detector was proposed for these requirements.