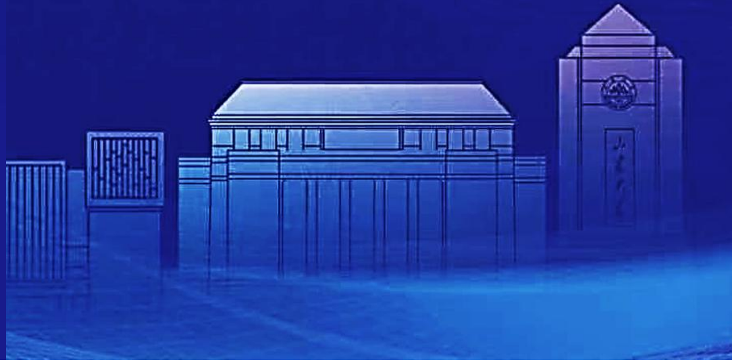
第一届中国电子离子对撞机相关物理年会

The 1st Annual Conference on Electron-Ion Collider Physics in China



Recent advances in DIRC-like TOF detector for STCF

Binbin Qi
University of Science and Technology of China

On behalf of the STCF DTOF working group
2026.04.21

STCF
超级陶粲装置
Super Tau-Charm Facility

Outline

Ⅰ、Introduction

- STCF, DIRC concept, DIRC-like TOF

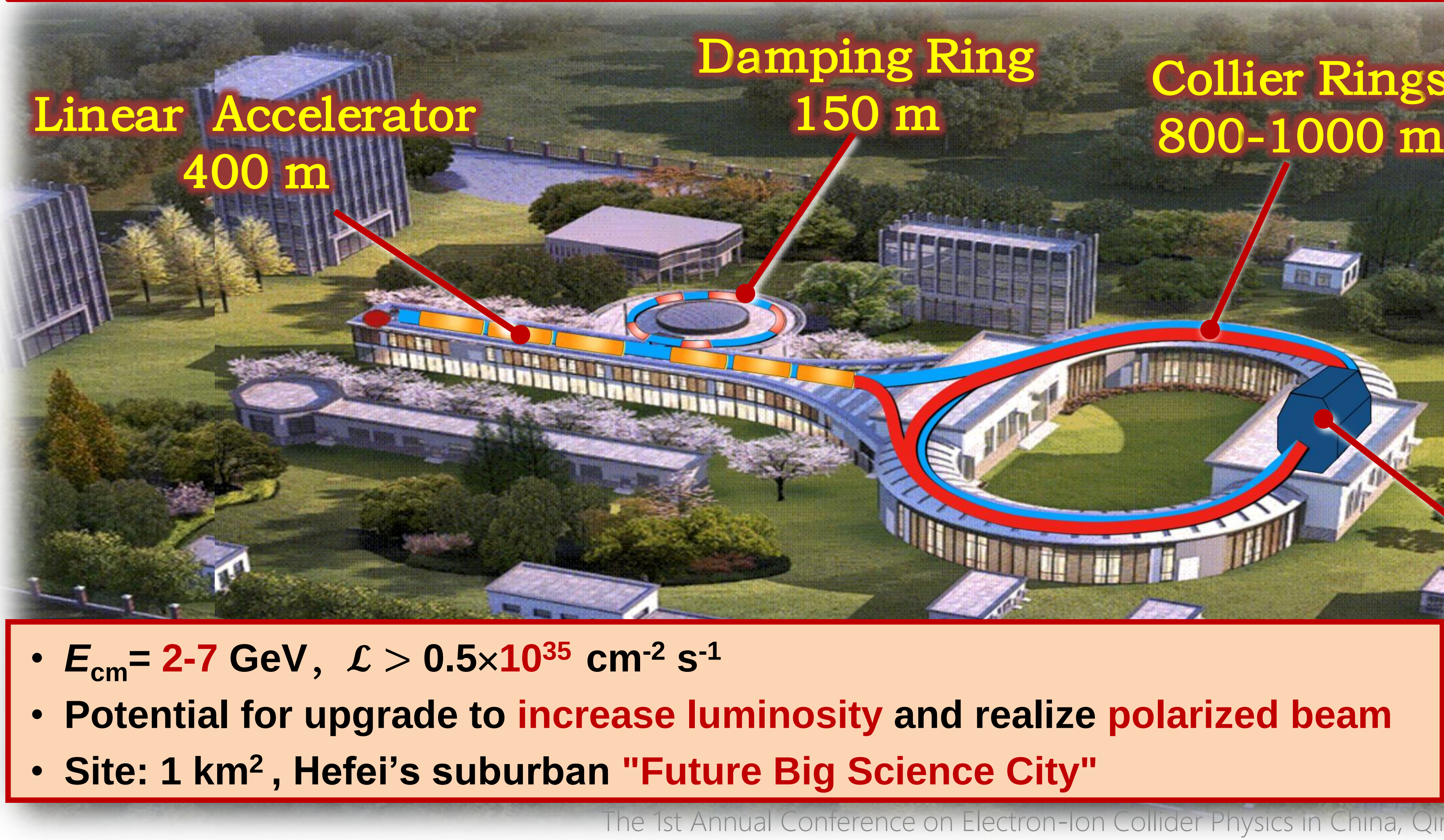
Ⅱ、R&D of DTOF

- Design and simulation
- Prototype and test
- Electronics and MCP-PMT progress

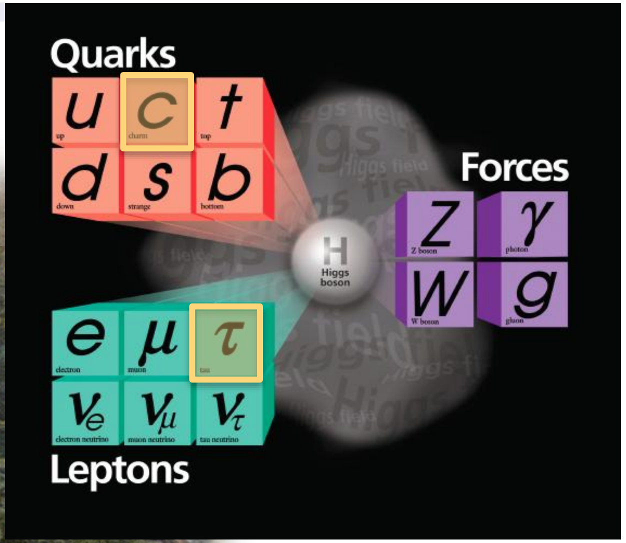
Ⅲ、Summary

Super Tau Charm Facility (STCF)

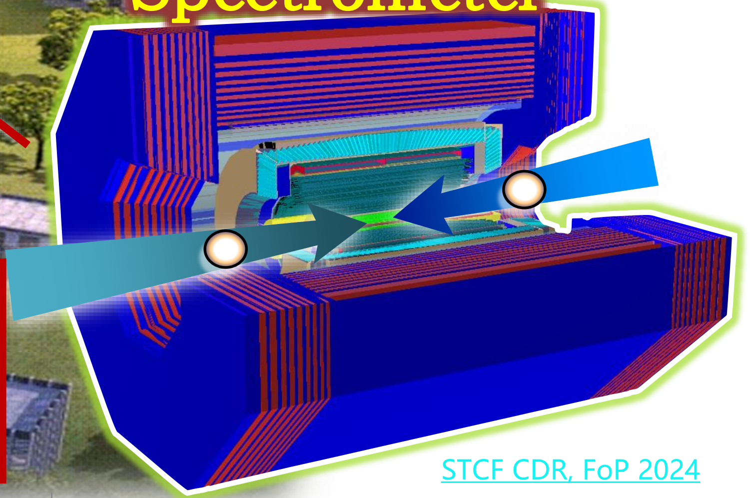
A factory producing massive **tau lepton** and **hadrons**, to unravel the mystery of **how quarks form matter** and the **symmetries** of fundamental interactions



- 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**
- Site: 1 km^2 , Hefei's suburban **"Future Big Science City"**

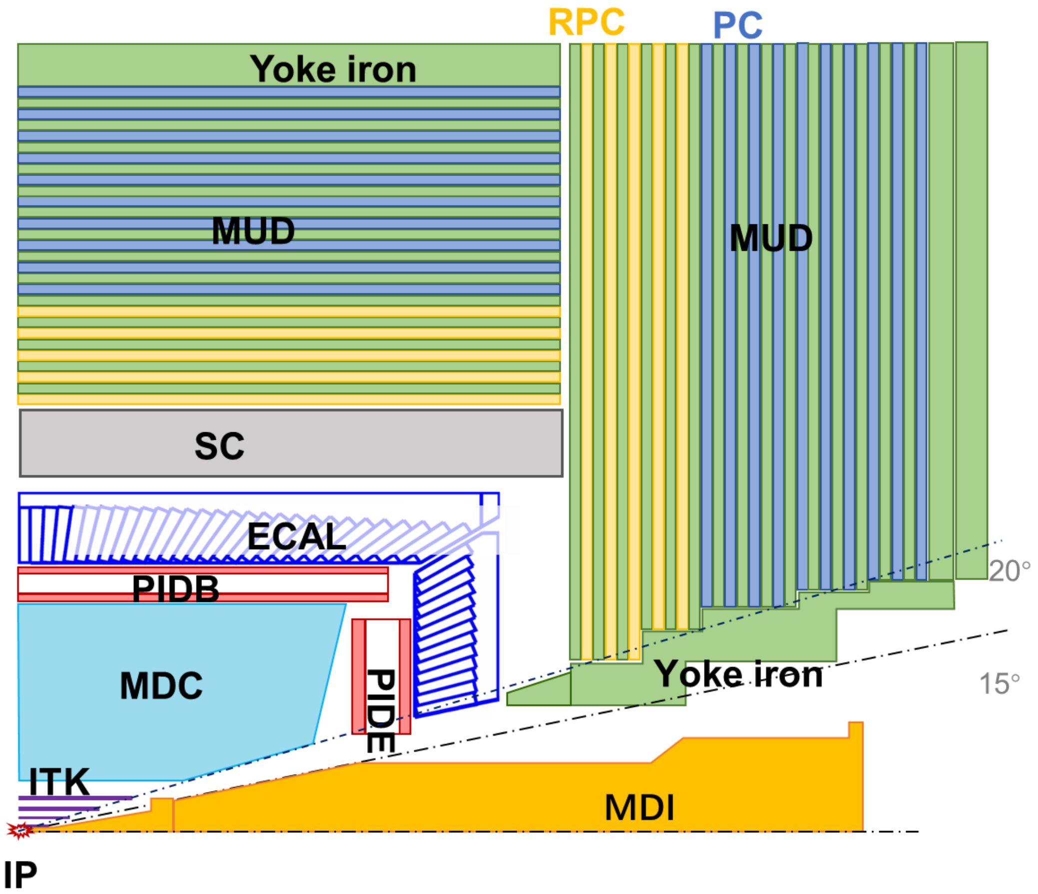


New generation Spectrometer



STCF CDR, FoP 2024

STCF detector

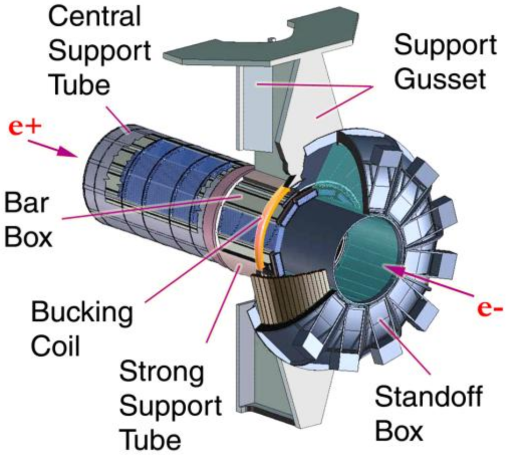


- **PID requirement**: 4σ π/K @ 2 GeV/c
- **Barrel**： DTOF， **endcap**： DTOF/RICH/ASHIPH

- **Inner tracker (ITK, two options)**
  - MPGD: cylindrical MPGD
  - Silicon: CMOS MAPS
- **Central tracker (MDC)**
  - Main drift chamber
- **Particle identification (Cherenkov)**
  - **DTOF (DIRC-like TOF)**
  - RICH (C_6F_{14} + CsI-MPGD)
  - ASHIPH (Aerogel + Shifter + SiPM)
- **Electromagnetic calorimeter (EMC)**
  - pure CsI + APD
- **Muon detector (MUD)**
  - RPC + scintillator strips
- **Magnet**
  - Super-conducting solenoid, 1 T

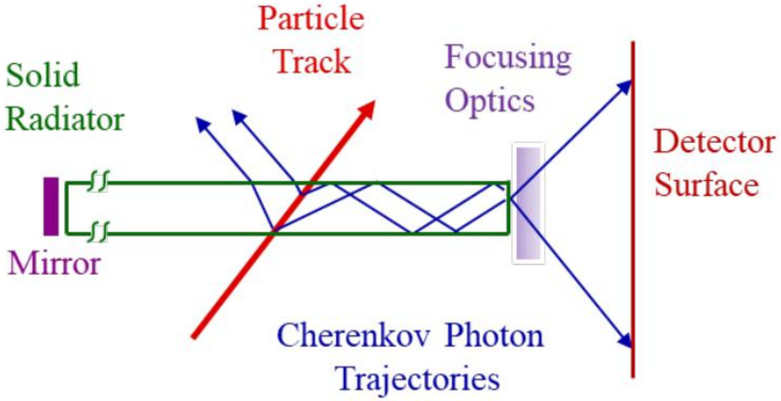
DIRC concept

- 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



BABAR DIRC

- 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_p ➔ Ultimate PID performance
  - Defining time of flight (TOF) ➔ DIRC-like TOF detector

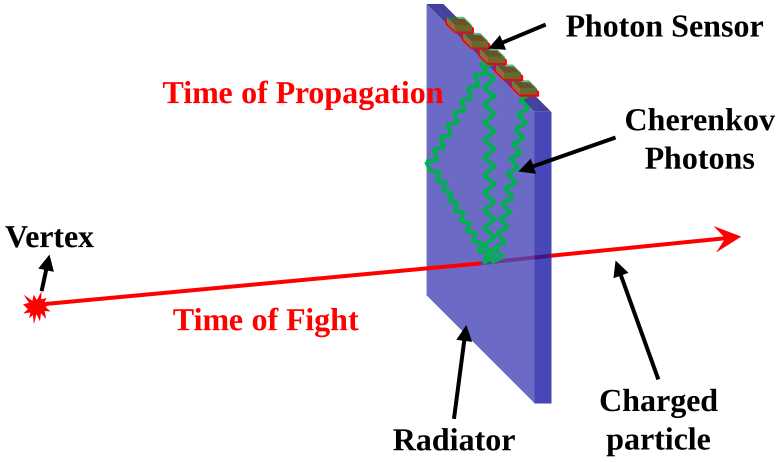


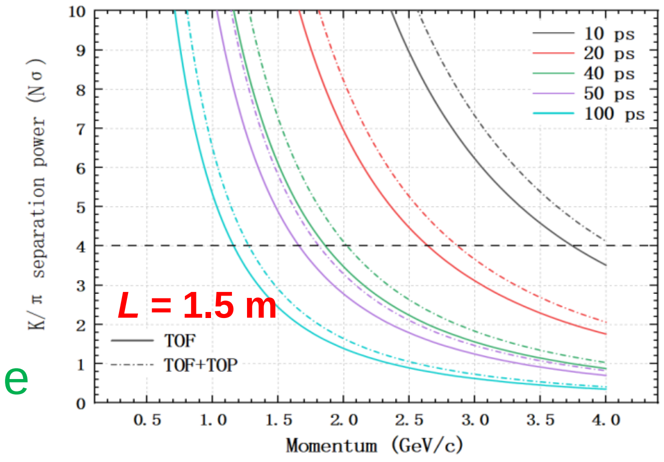
- DIRCs requires momentum and position of particle measured by tracking system

DTOF 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
  - Only TOF, σ_t requirement ≈ 35 ps
  - TOF+TOP, σ_t requirement ≈ 50 ps
- Some examples of DTOF or similar detectors
  - TORCH (Time Of internally Reflected CHerenkov light) for LHCb upgrade
  - DTOF for both barrel and endcap of STCF (Super Tau Charm Facility)

DIRC-like Time Of Flight detector





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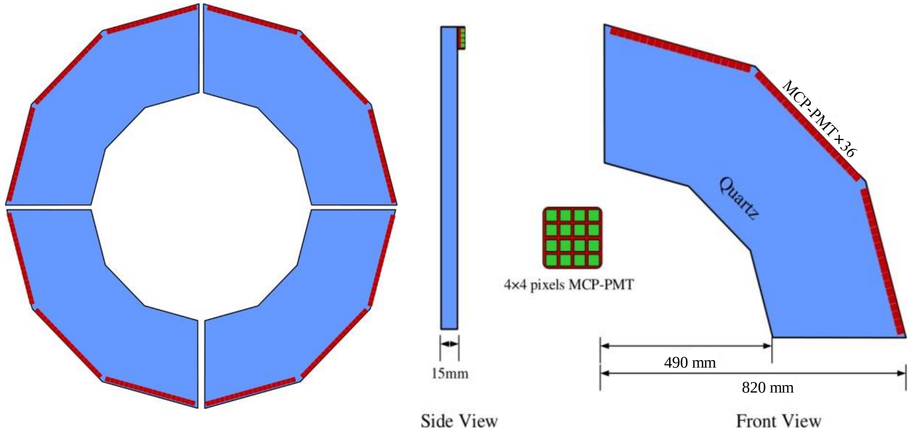
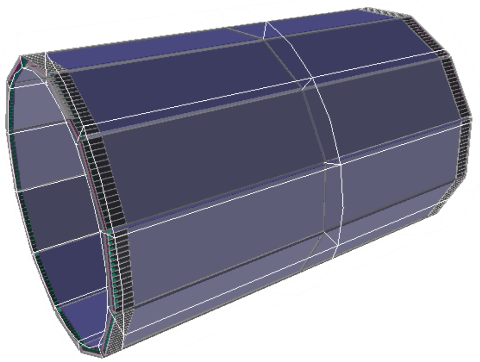
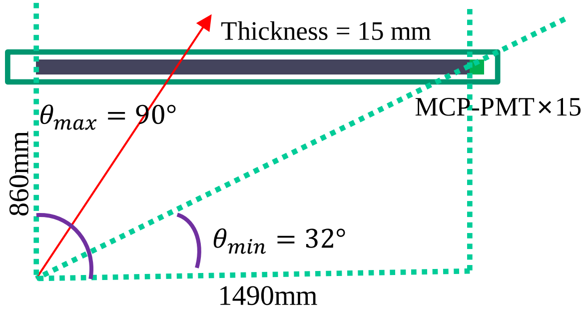
DTOF design

DTOF (endcap)



Barrel-DTOF (BTOF)





☐ STCF PID detector

☐ Polar angle coverage 20°-160°

☐ Large area of fused silica

☐ Multi-anode MCP-PMT

$$\sigma_{tot}^2 \sim \underbrace{\boxed{\sigma_{trk}^2 + \sigma_{T_0}^2}}_{\sim 40\ \text{ps}} + \boxed{\left(\frac{\sigma_{elec}}{\sqrt{N_{p.e.}}}\right)^2 + \left(\frac{\sigma_{TTS}}{\sqrt{N_{p.e.}}}\right)^2 + \left(\frac{\sigma_{det}}{\sqrt{N_{p.e.}}}\right)^2}$$

- 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

TOF reconstruction

Geometry-based Algorithm

- Reconstruct light path
- How to get **Δz**?
- Use average n with different particle hypothesis

$$\frac{(\Delta x, \Delta y, \Delta z) \cdot (t_x, t_y, t_z)}{\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}} = cos(\theta_c)$$

$$\Downarrow$$

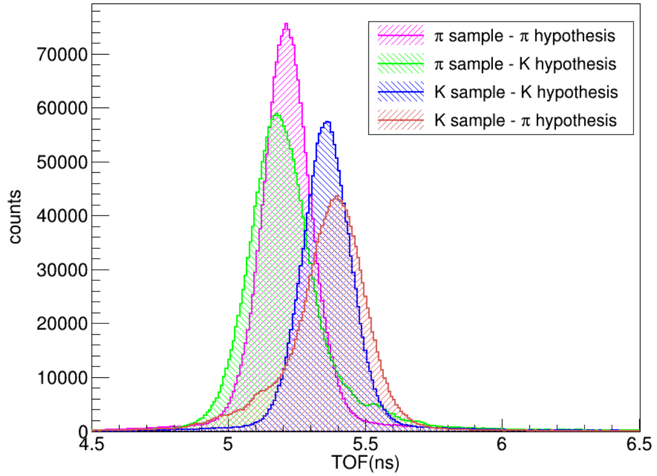
$$\mathrm{LOP} = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$$

$$\Downarrow$$

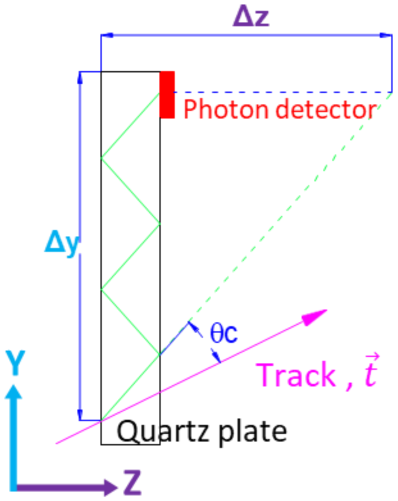
$$\mathrm{TOP} = \frac{LOP}{n_g \cdot c}$$

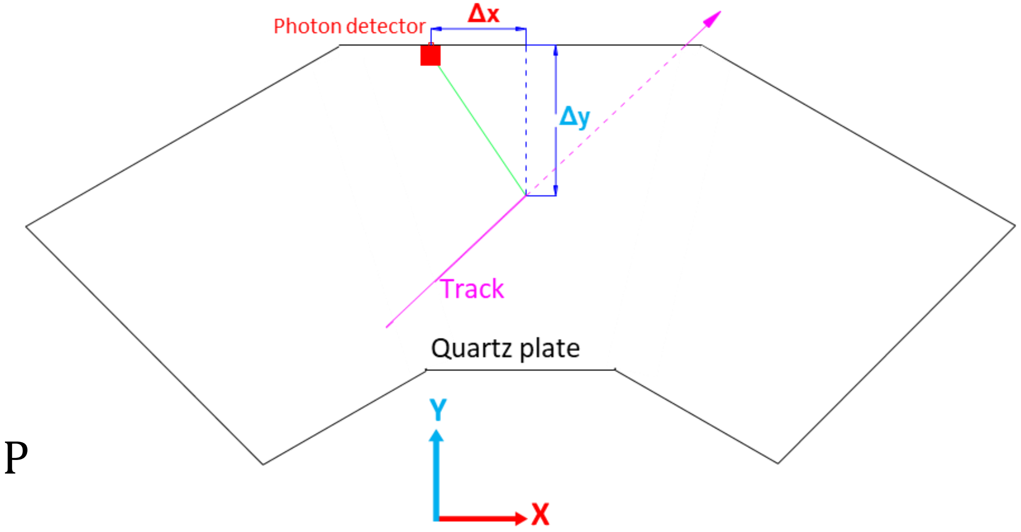
$$\Downarrow$$

$$\mathrm{Time} = \mathrm{T_{ch}} - \mathrm{TOP}$$



SPE time resolution ~100 ps

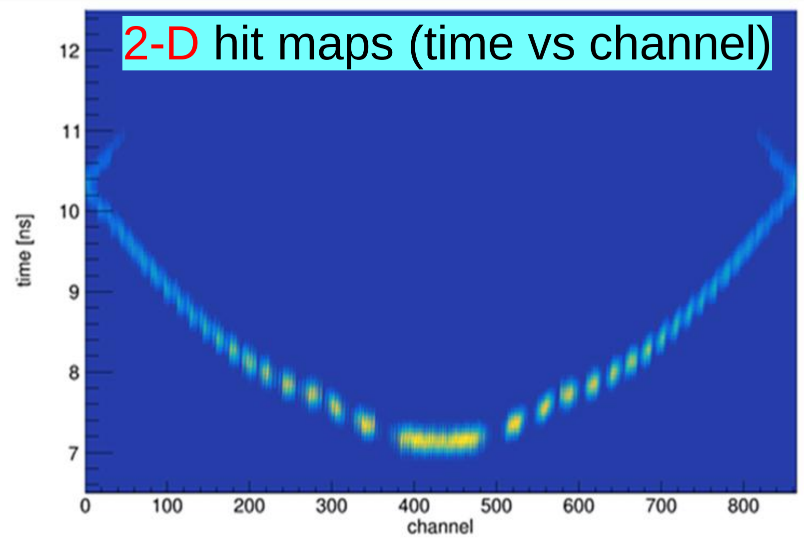


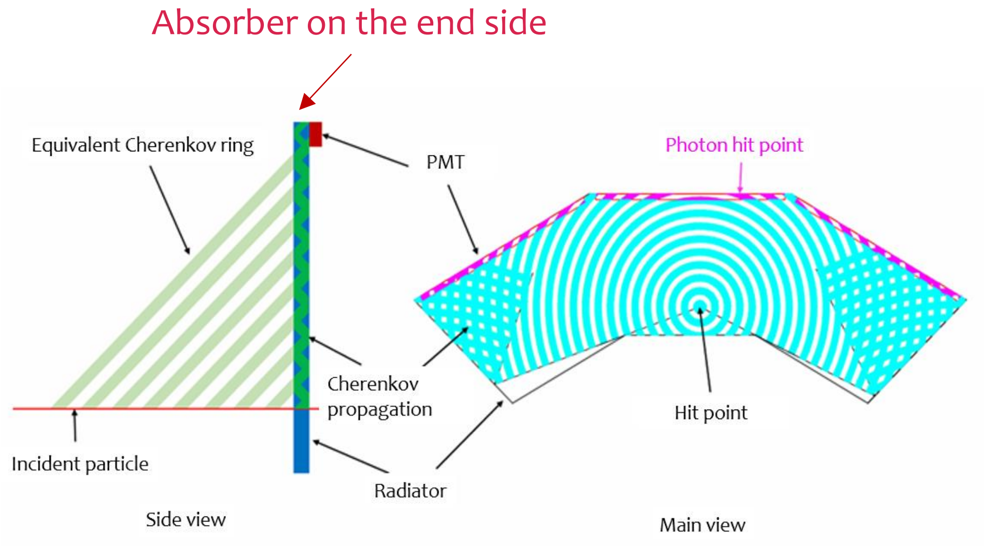


B. Qi, JINST 2021

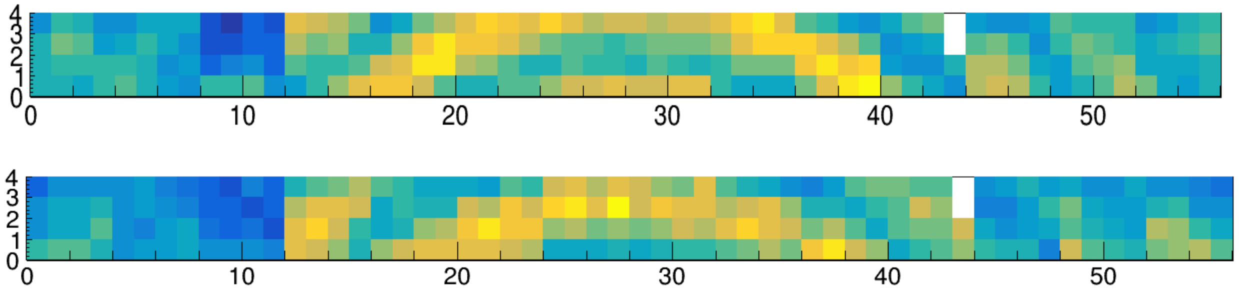
Pattern reconstruction

- **What does pattern look like?**
  - Photons propagate like “water wave”
- **Reconstruction concept**
  - Calculate the photon propagation vector using hit point and the channel information


2-D hit maps (time vs channel)


Absorber on the end side

Cherenkov ring propagation in radiator



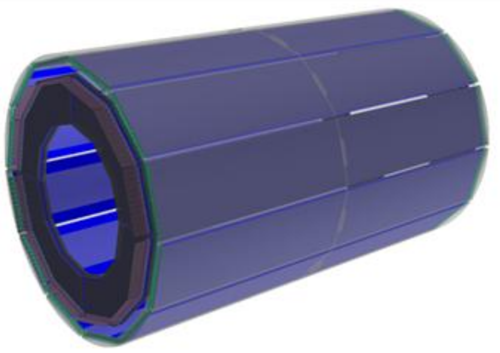
Cherenkov ring for **π/K** at 2 GeV/c

B. Qi, NIMA 2023

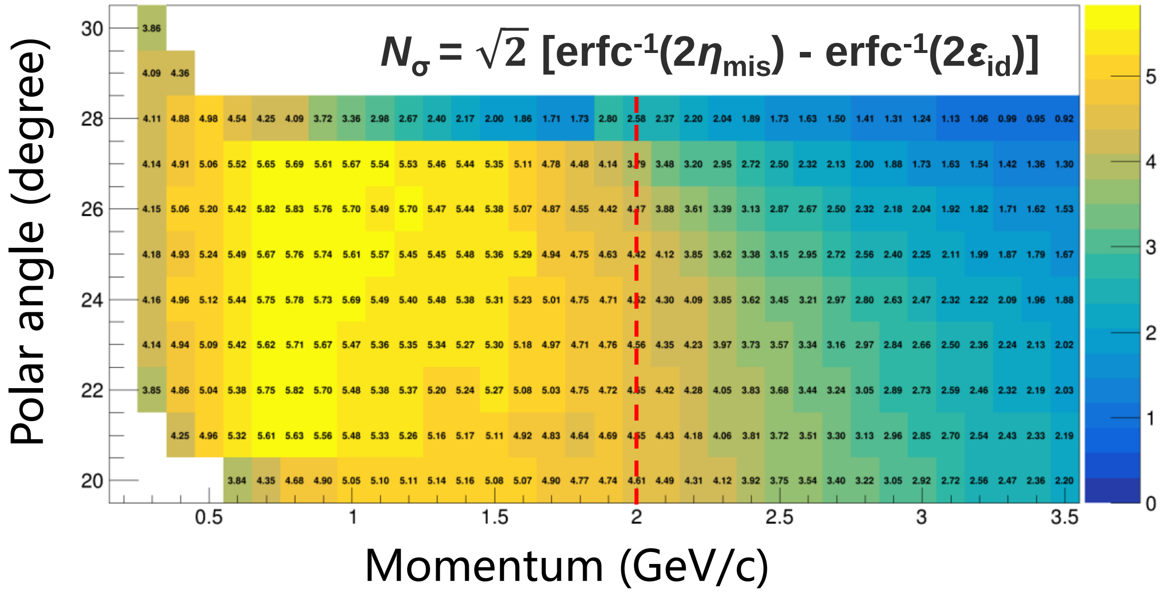
- **Likelihood function:** $\mathcal{L}_h = p_h(N_{p.e.})\prod_{hits} f_h(ch_i, t_i)$

Expected performance

- A full simulation within **OSCAR** (The Offline Software of Super Tau-Charm Facility)
- **Reconstructed track** information was used for DTOF reconstruction
- π/K separation power was estimated using **single particles** with different θ and p
- DTOF can achieved **>4σ** π/K separation at p≤2 GeV/c.

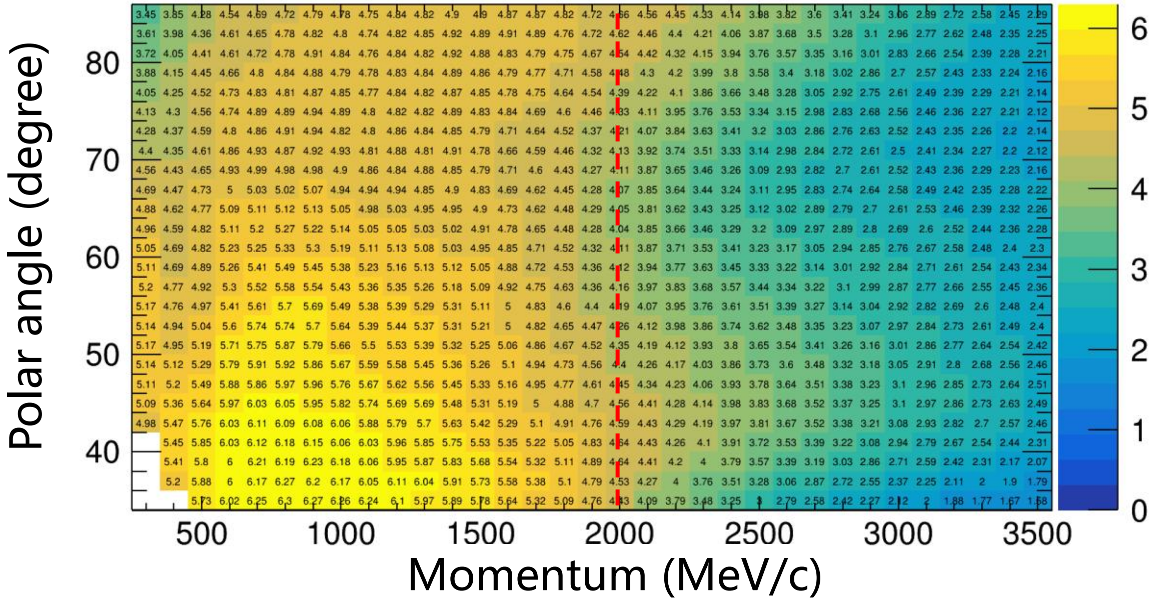


DTOF (endcap)



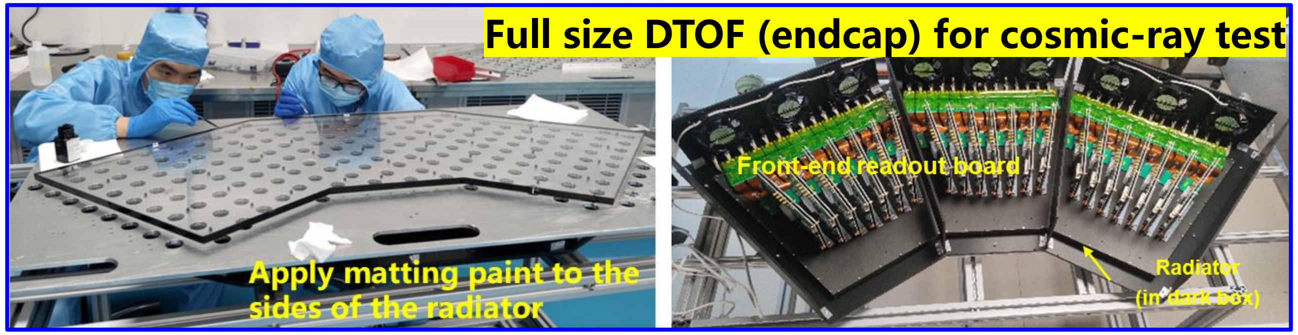
$$N_\sigma = \sqrt{2}\,[\mathrm{erfc}^{-1}(2\eta_{mis}) - \mathrm{erfc}^{-1}(2\varepsilon_{id})]$$

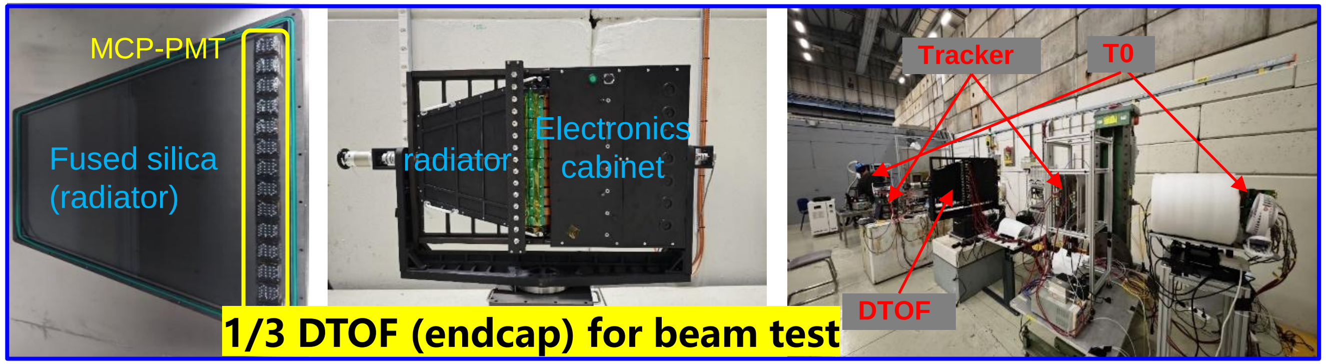
DTOF (barrel)



DTOF prototype

- **Heraeus synthetic fused silica radiator (Suprasil 312)**
  - Thickness = **15 mm** for endcap and **20 mm** for barrel
  - Surface roughness **< 1nm**
  - Lateral surface roughness **> 5nm** (**need improved**)
- **MCP-PMTs: Hamamatsu R10754**
  - 27.5mm*27.5mm, 4*4 channel
  - TTS **< 30 ps**
  - **14/42** for endcap and **10** for barrel
- **Coupled PMT with radiator by EJ550 silicon grease**
  - **~ 300 nm** cutoff
- **Electronics**
  - Time precision **< 10 ps**
  - Record TOA and TOT
  - Dead time < 10 ns

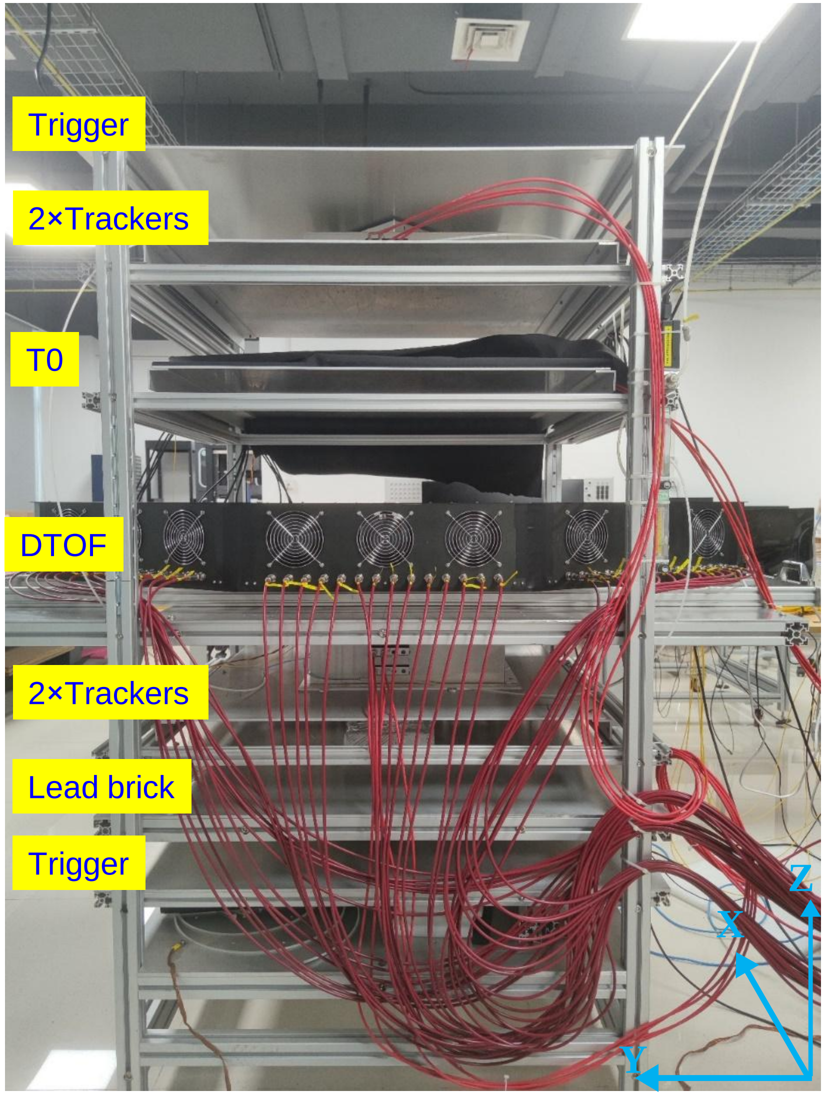

Full size DTOF (endcap) for cosmic-ray test


1/3 DTOF (endcap) for beam test


Hamamatsu R10754

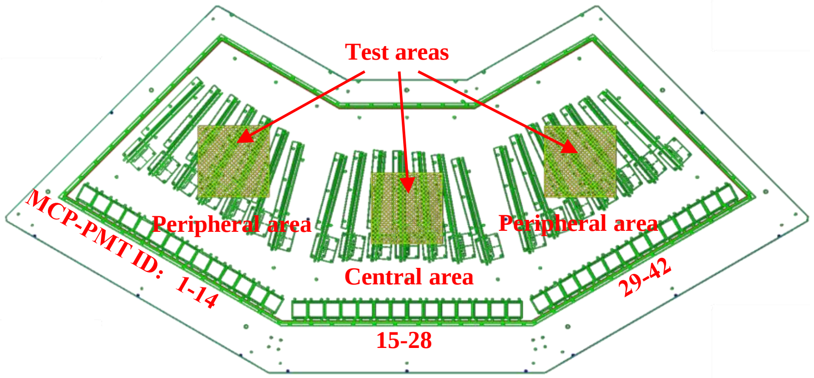

DTOF (barrel) for beam test

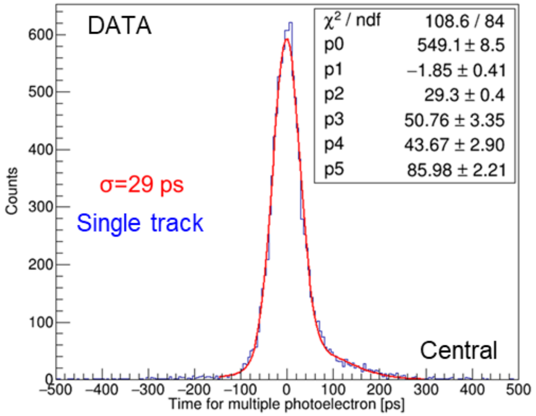
Cosmic-ray test



- **Trigger counters**
  - Plastic scintillator + PMT, 220 × 220 mm^2
  - Coincidence of two trigger counters
- **Trackers**
  - 4 × MicroMegas, 150×150 mm^2
  - Efficiency ~90%, $\sigma_{pos} < 200$ μm
- **Reference time detector (T0)**
  - 180×180×10 mm^3 fused silica
  - 4 × MCP-PMT, $\Phi = 10$ 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



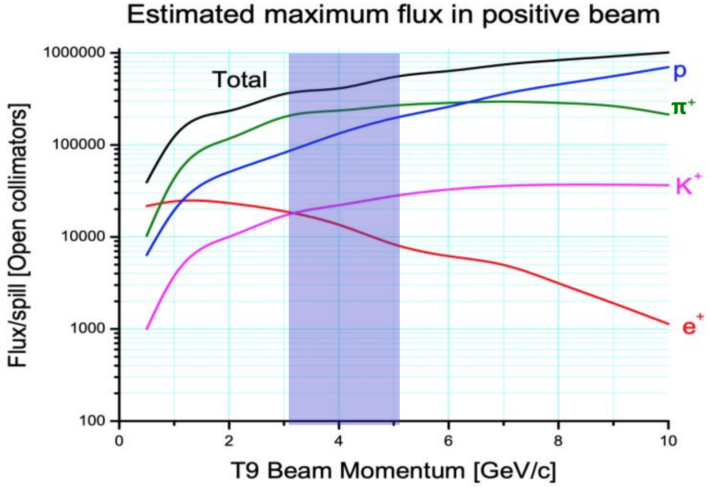


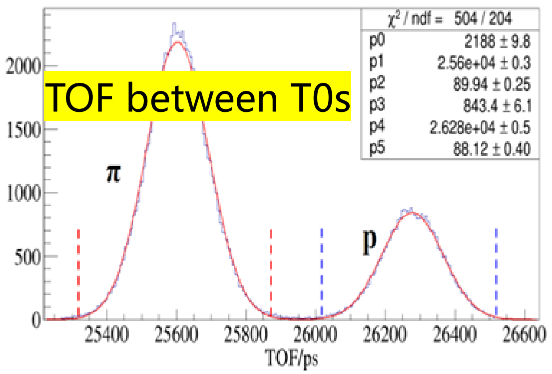
Test areas			Central area	Peripheral area
Number of photon electrons		DATA	20.6	17.8
		MC	20.3	17.6
Time resolution of the DTOF prototype	DATA	Single photon	59 ps	60 ps
		Single track	21 ps	22 ps
	MC	Single photon	54 ps	57 ps
		Single track	18 ps	22 ps

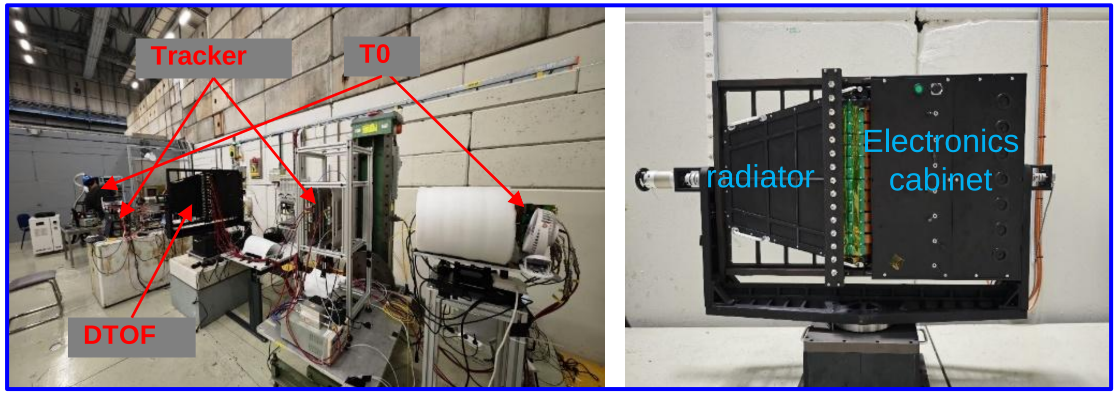
B. Qi, NIMA 2025

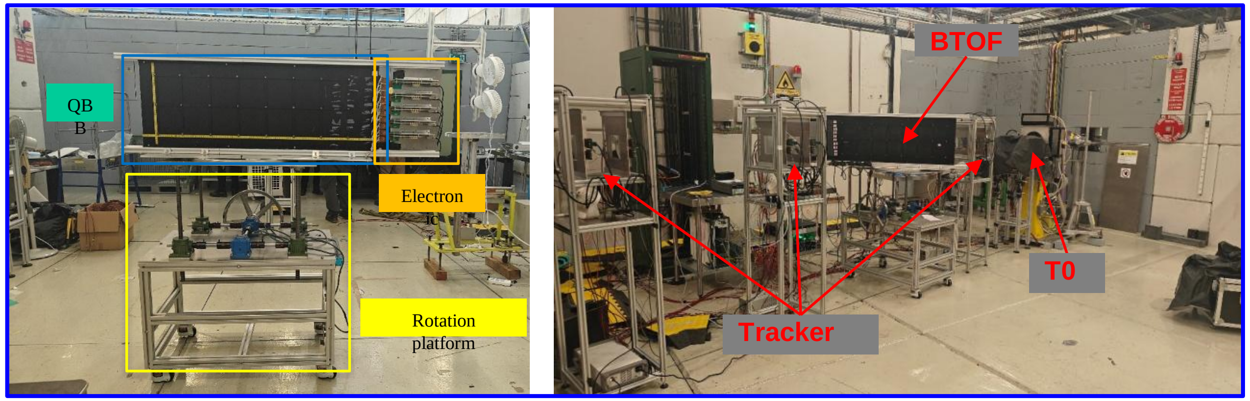
Beam test

- CERN PS T9 and T10, 2-5 GeV/c π/p
  - 4 GeV/c π/p ➔ 2 GeV/c π/K
- 2 T0 detectors (each ~ 60 ps)
- 4 MM @2024 and 6 MM @2025
- 1/3 DTOF and full-sized BTOF prototype







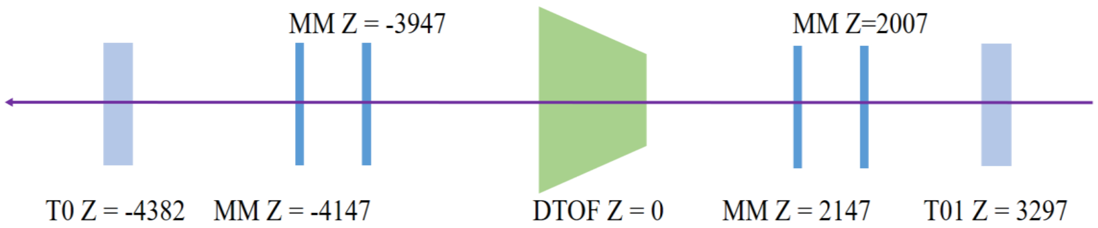


Beam test @2024 with a **1/3 DTOF** prototype

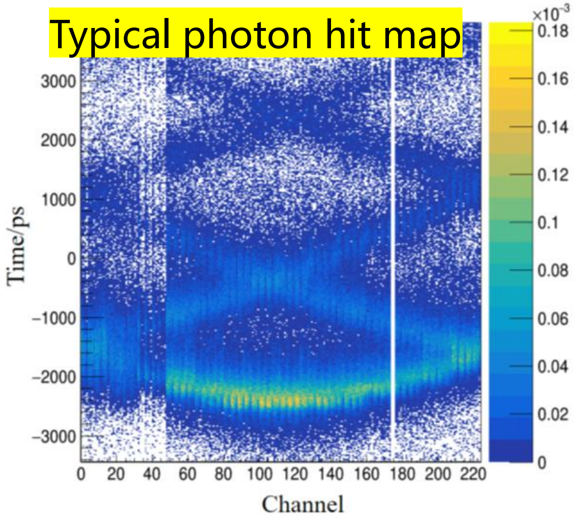
Beam test @2025 with a **full-sized BTOF** prototype

Beam test result of endcap DTOF @2024

Beam setup

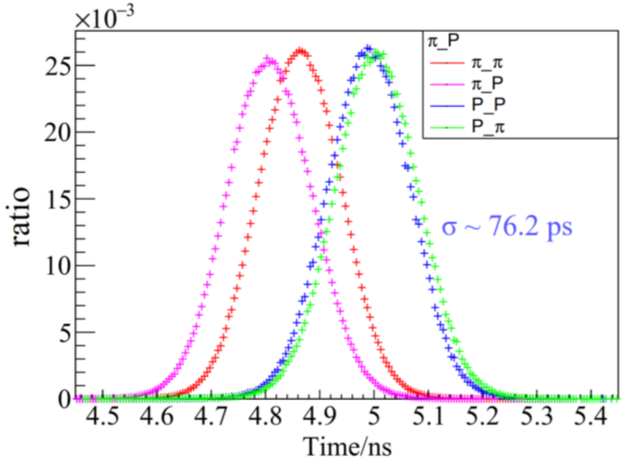


Typical photon hit map

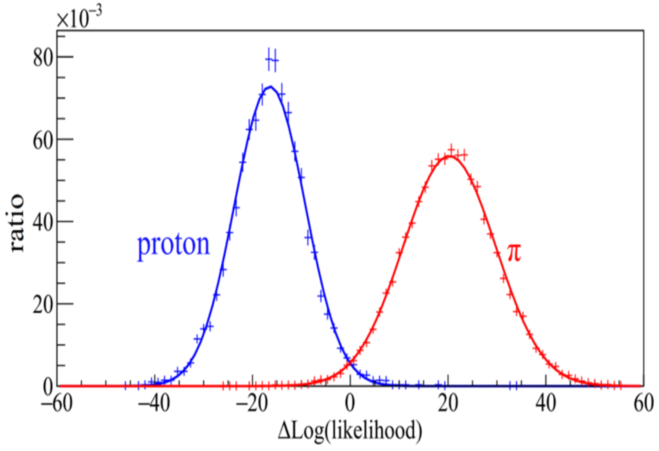


- **Electronics channel malfunction**
- **Poor optical coupling**
- **Poor lateral surface roughness**
- **Improved performance is expected once these issues are resolved**

Timing performance



π/p separation power @4GeV/c

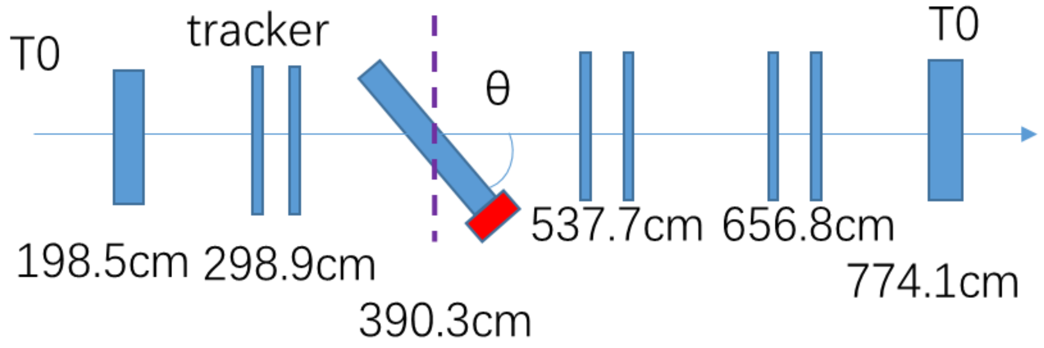


Beam choices	Npe	Separation power
3 GeV/c π/p, normal incidence	36.0	4.96σ
4 GeV/c π/p, normal incidence	36.6	4.4σ
5 GeV/c π/p, normal incidence	37.2	2.53σ
4 GeV/c π/p, $\theta_y = 30°$	25.9	3.85σ
4 GeV/c π/p, $\theta_y = 22°$, Δy=+66 mm	29.4	3.95σ

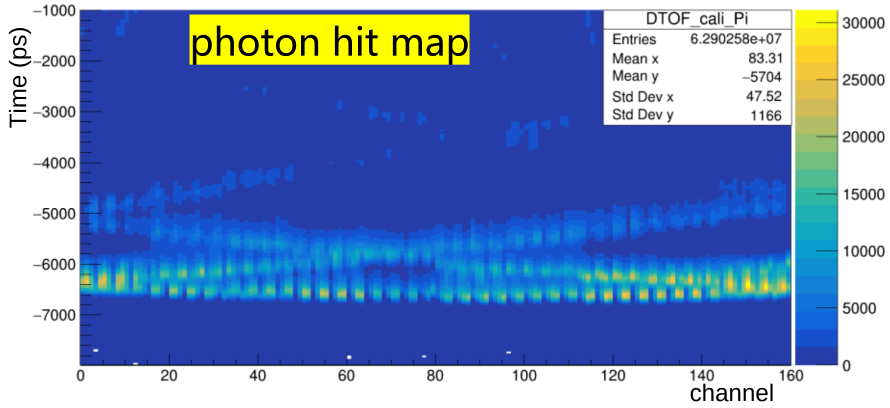
X. Li, NIMA 2026

Preliminary analysis on Beam test @2025

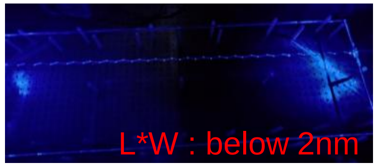
Beam setup



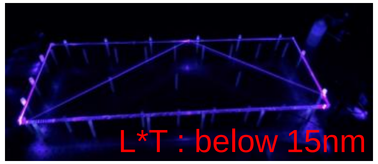
photon hit map



Surface roughness test



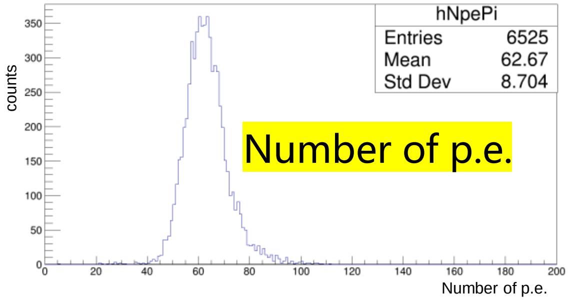
L*W : below 2nm



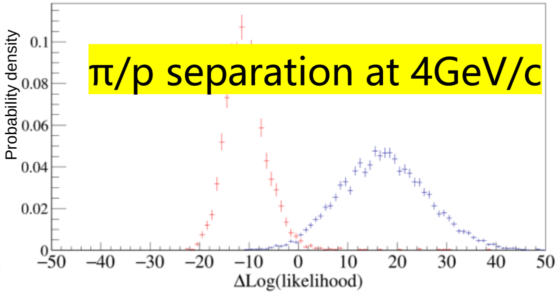
L*T : below 15nm

- **Lateral surface roughness is poor and requires improvement.**
- **Average NPE varies with angle as predicted by the model.**
- **A data-driven PDF is employed to estimate PID performance.**
- **Fine alignment is necessary to enhance performance.**
- **Further analysis is still needed.**

Number of p.e.



π/p separation at 4GeV/c

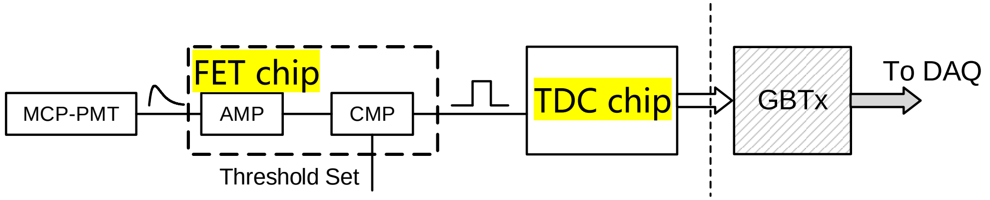


	38deg(2)	53deg(1)	74deg(3)
Npe	62.6	53.3	36.5
Sep/σ	4.2	3.6	2.5
Npe-sim	75.4	62.7	43.7

Preliminary results

DTOF electronics

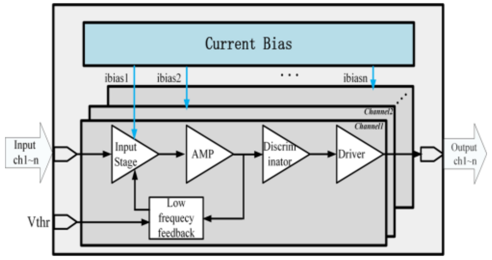
- **Discrete component circuit ➔ ASICs**
  - FET ASIC: signal amplification and discrimination
  - TDC ASIC: edge timing measurement



- **FET ASIC**: signal amplification and discrimination
  - Based on ASIC **NINO** structure, CMOS 130nm
  - **8-16 channels** per chip
  - Timing precision: **~ 3-10ps**
  - Power consumption: **18mW/ch**

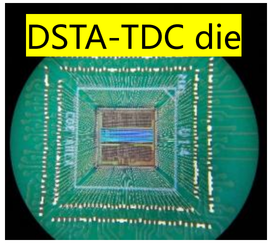

FET test board


FET die

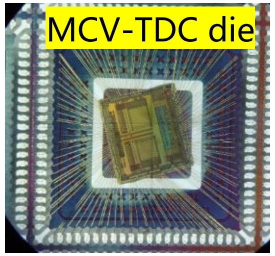


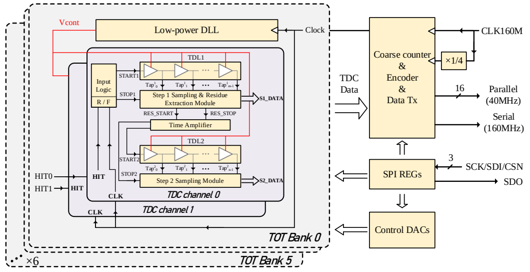
FET chip structure

- **DSTA-TDC**: Double Slope Time-Amplifier TDC
  - **8-16 TDC channels**
  - Timing precision: **~12 ps**
  - Dead Time: **~60 ns**
  - Power consumption: **~25 mW/ch**

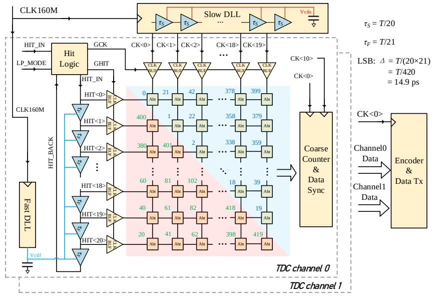

DSTA-TDC die

- **MCV-TDC**: Multiphase clock 2D-Vernier TDC
  - **2 TDC channels**
  - Timing precision: **~15 ps**
  - Dead Time: **~20 ns**
  - Power consumption: **~30 mW/ch**


MCV-TDC die



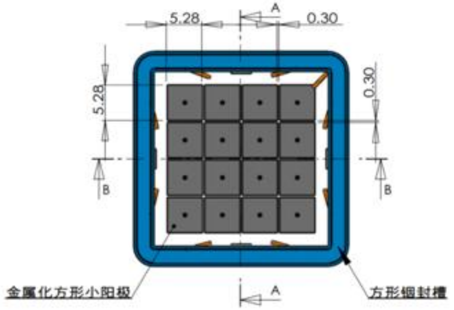
DSTA-TDC chip structure

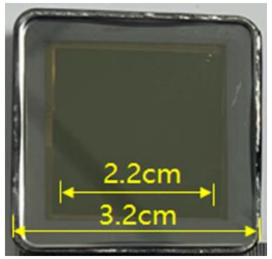


MCV-TDC chip structure

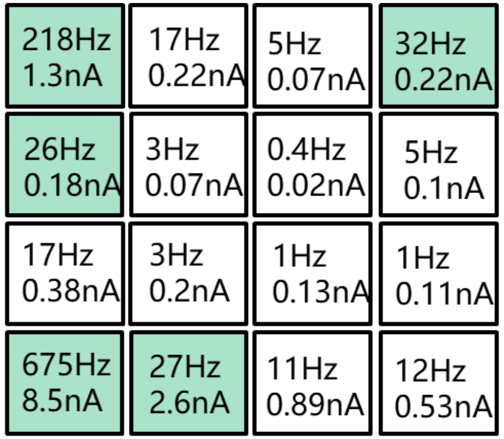
maMCP-PMT @ XIOPM

- **maMCP-PMT: a critical component of the DTOF technology**
- **Intensive R&D on techniques (ALD and electron scrubbing) to produce long-life MCP-PMT (target Q > 10 C/cm^2).**
- **Designed and produced 1-inch maMCP-PMT prototypes with 16 annodes each.**
- **Carried out various tests of the MCP-maPMT prototypes**
  - **TTS<40 ps, QE>20%, G>10^6**
  - **Aging : <10% gain drop when Q>11C/cm^2**



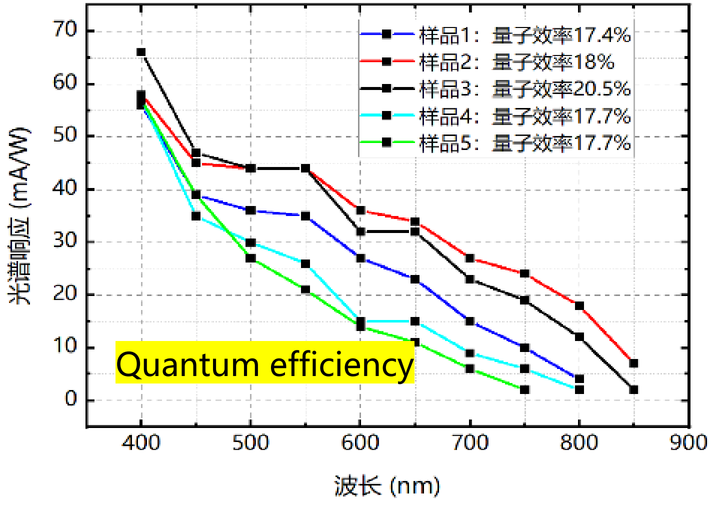


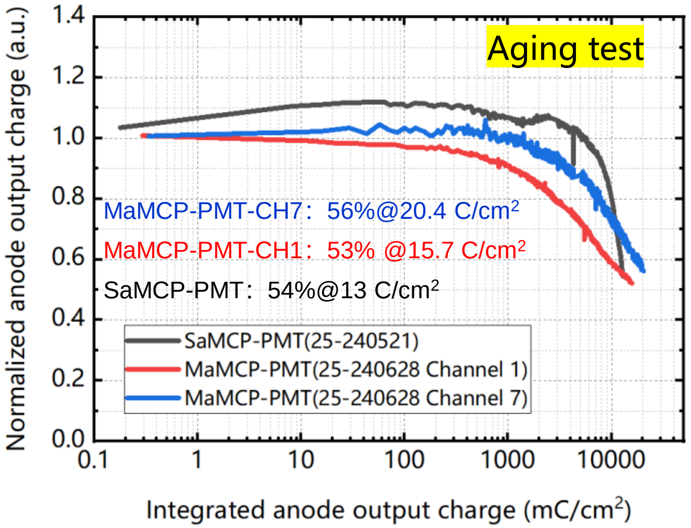
MCP-PMT编号	25-240507	25-240521	25-240605	25-240620
MCP类型	ALD-MCP，ALD镀膜厚度：D2			
MCP厂家	厂家1	厂家1	厂家2	厂家2
MCP电子清刷剂量	0.75 uA·h/cm^2	0.87 uA·h/cm^2	0.75 uA·h/cm^2	0.87 uA·h/cm^2



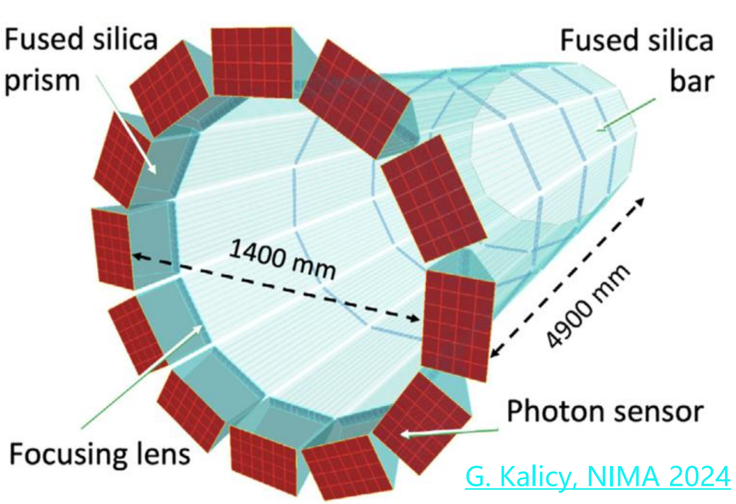
218Hz 1.3nA	17Hz 0.22nA	5Hz 0.07nA	32Hz 0.22nA
26Hz 0.18nA	3Hz 0.07nA	0.4Hz 0.02nA	5Hz 0.1nA
17Hz 0.38nA	3Hz 0.2nA	1Hz 0.13nA	1Hz 0.11nA
675Hz 8.5nA	27Hz 2.6nA	11Hz 0.89nA	12Hz 0.53nA

dark count rates and dark currents



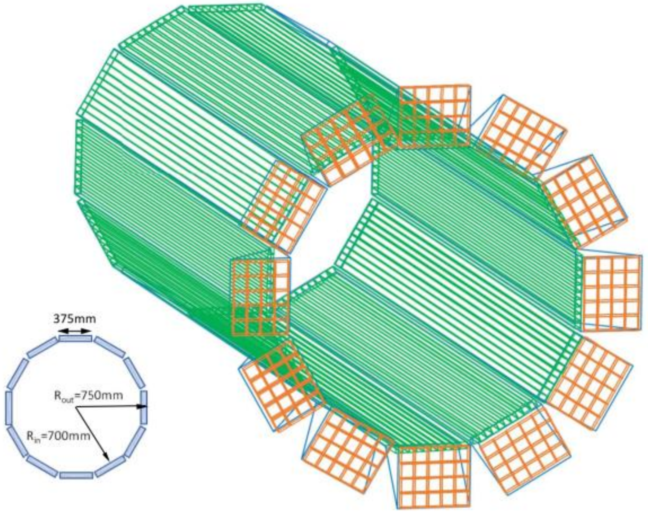


DIRC for EIC and EicC



G. Kalicy, NIMA 2024

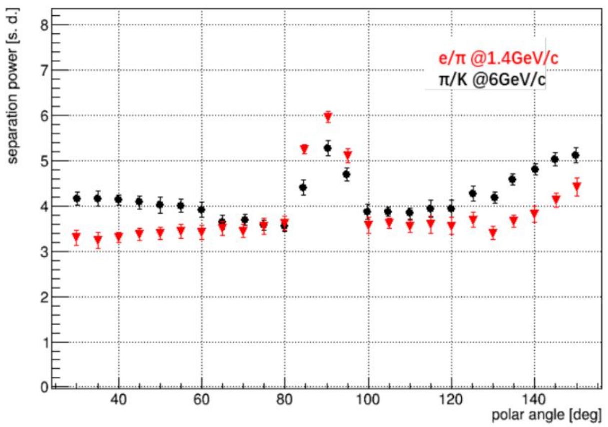
Baseline design of the hpDIRC for EIC



Xin Li, JINST 2025

Concept design of barrel DIRC for EicC

Expected PID performance of EicC DIRC



- **DIRC for EIC and EicC barrel** – provides 3σ π/K/p separation at 6 GeV/c
- **Commonalities between EicC DIRC & STCF DTOF** – radiator manufacturing, electronics, MCP-PMT
- **Lessons from STCF DTOF** – can be leveraged for EicC DIRC
  - **Time vs. angle measurement** – time is more robust due to MCS; track precision becomes critical for DIRC at high momenta;
  - **Radiator fabrication challenge** – polish a narrow surface is much harder than a wide one

Summary

- **STCF DTOF detector**
  - used for both barrel and endcap regions
- **Performance estimation**
  - evaluated within the **OSCAR** framework
  - achieves **4σ π/K** separation at **2 GeV/c**
- **Prototype development & tests**
  - **Full-size endcap DTOF** – cosmic-ray test: **σ_t~ 22 ps**
  - **1/3 endcap DTOF** – beam test: **4σ π/p** separation at **4 GeV/c**
  - **Full-size barrel DTOF** – analysis ongoing
- **Key technology developments**
  - DTOF ASIC chips (**FET** ASIC, **TDC** ASIC)
  - Long-lifetime maMCP-PMT: **>10 C/cm²**

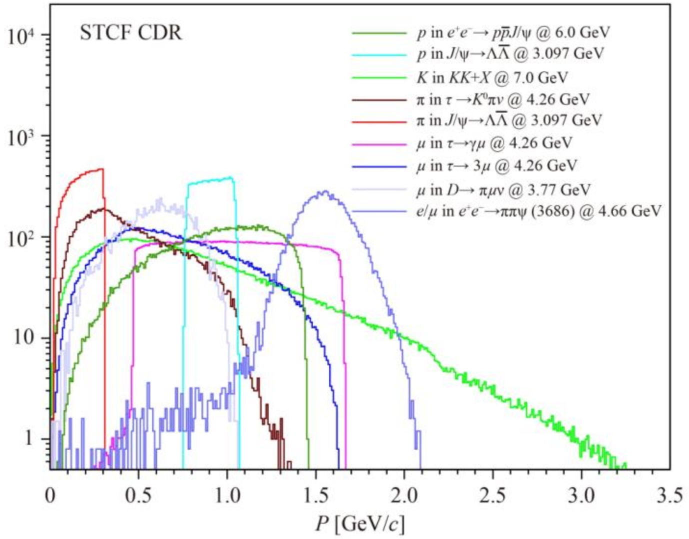
Thanks for your attention!

backup

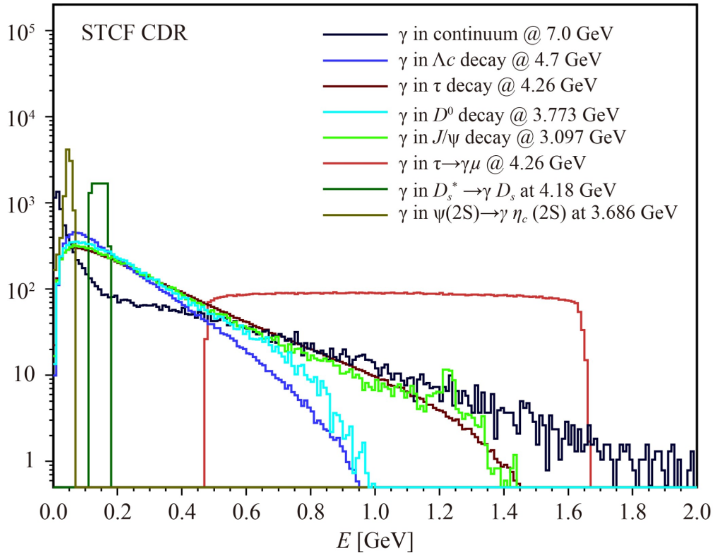
STCF final state particles

- **Charged particles**（e、μ、π、K、p）
  - Most particles have momentum < 2 GeV/c, with an upper limit of 3.5 GeV/c
- **Neutral particles**（γ、K_L、n）
  - Energy of gamma from 25 MeV to 3.5 GeV， momenta of K_L and n up to 1.6 GeV/c

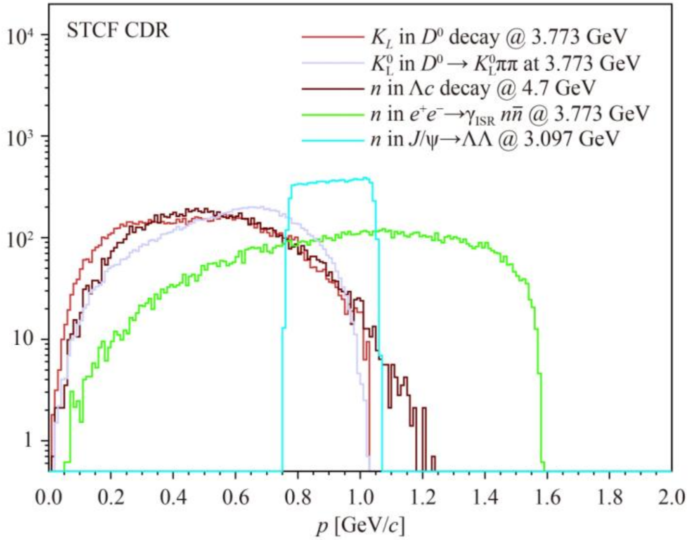
Charged particles



Photons



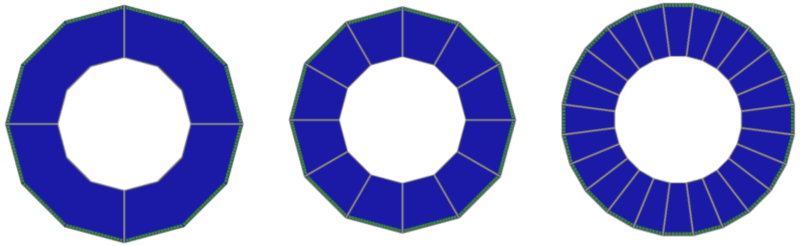
K_L和neutron



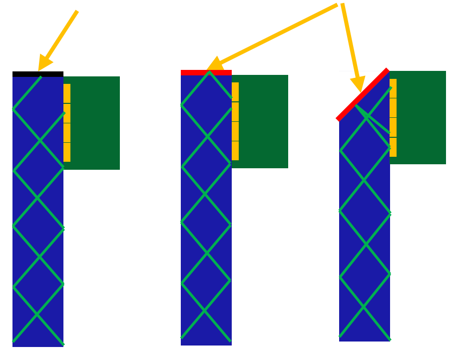
DTOF Geometry Optimization

☐ Radiator thickness (10, 15, 20 mm)

☐ Radiator shape (4, 12, 24 sectors)



☐ Absorber or mirror

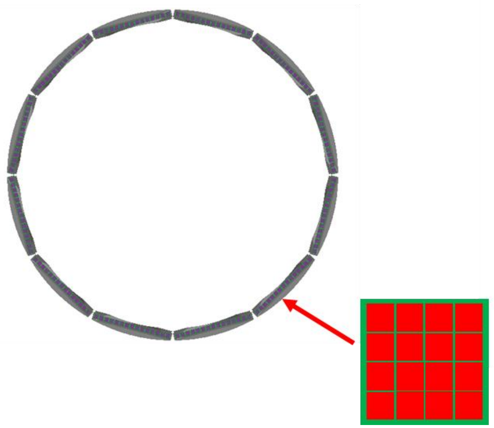


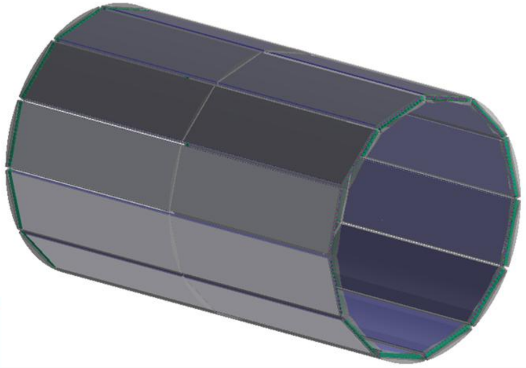
Geometry ID		0	1	2	3	4	5	6
Sector number		**4**	12	24	4	4	4	4
Radiator thickness		**15 mm**	15 mm	15 mm	10 mm	20 mm	10 mm	10 mm
Top surface		**A**	A	A	A	A	M	45° M
Button surface		**A**	A	A	A	A	A	A
Lateral surface		**M**	M	M	M	M	M	M
Number of p.e. (w/o BKG)	**pion**	**21.8**	21.4	16.3	15.5	25.5	32.7	37.2
	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

Some conclusions

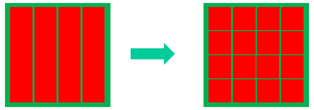
1. **Thick radiator increases material, and thin radiator degreases performance ➔ a right thickness is better**
2. **Large area radiator reduces the number of lateral reflections, causing less hit map’ s overlaps and better π/K separation power**
3. **Adding mirror on the top surface will increase Np.e., 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**

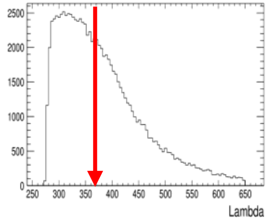
BTOF design and optimization

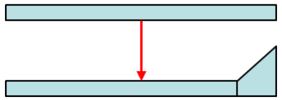


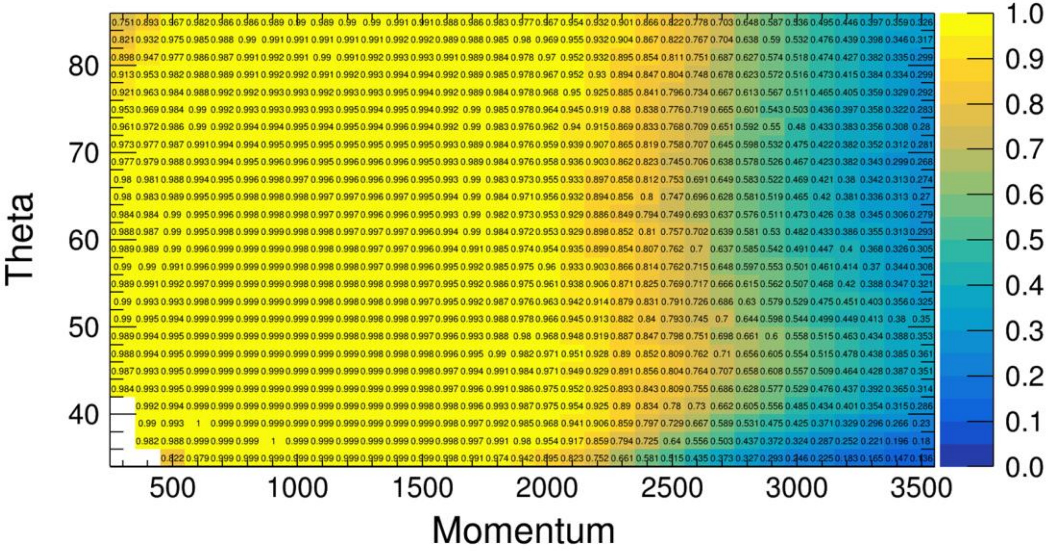


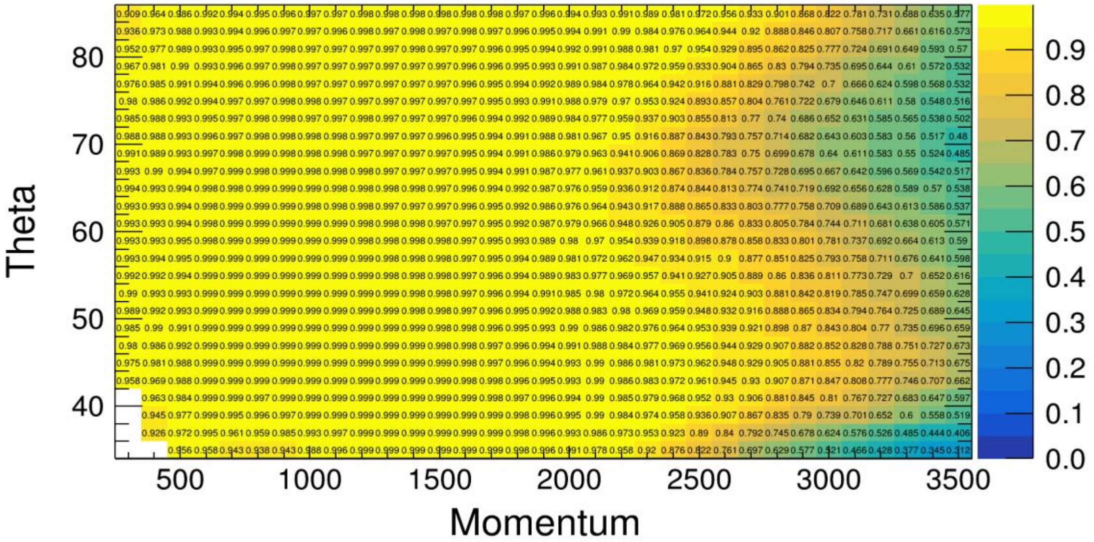
- **Bonding radiator**
- **Radiator size （thickness10-20 cm)**
- **MCP-PMT anode segmentation （1×16 vs 4×4)**
- **Optical grease （cut wavelength)**
- **Expand volume**





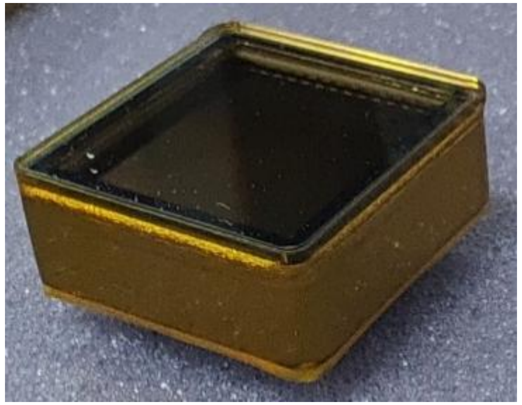






Comparison of pion efficiency with 2% kaon mis-identification before and after optimization.

MCP-PMT

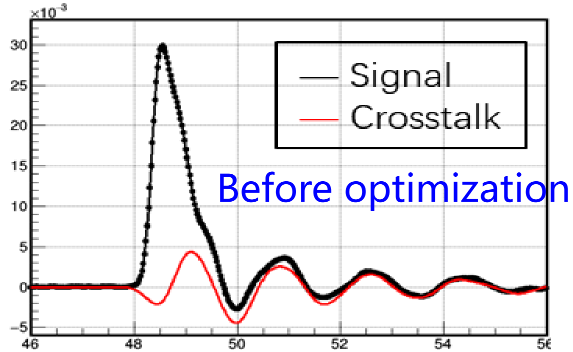


Hamamatsu R10754 MCP-PMT

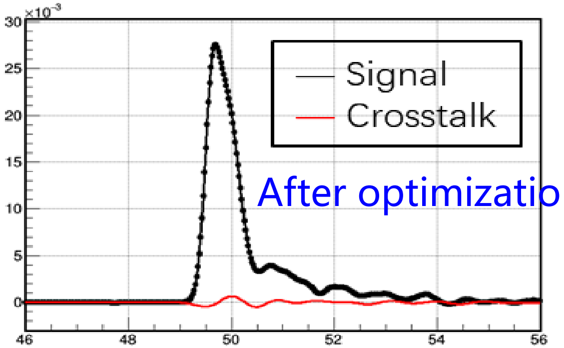
- Sensitive area, 23×23 mm^2
- Segmentation, 4×4 pixels
- Pixel size, 5.5×5.5 mm^2
- spectral response range, 200-850 nm
- Quantum efficiency, ~25%@λ=400 nm
- Gain: >10^6, uniformity~14% (σ/μ)
- Transit time spread: ~28 ps

➢ 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

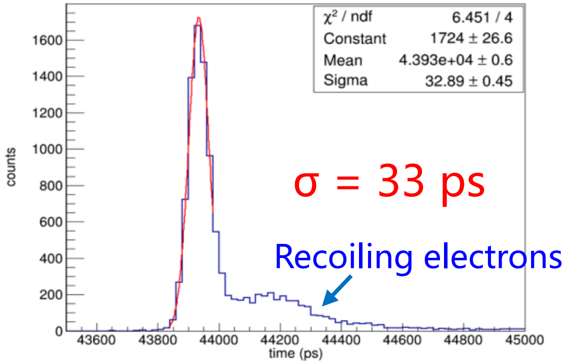


Before optimization



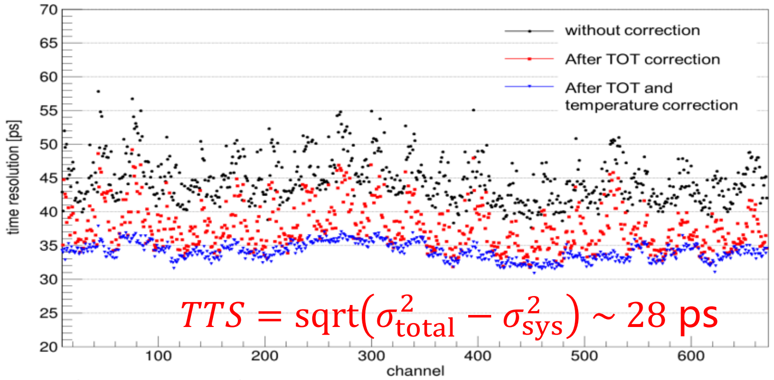
After optimization

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



σ = 33 ps

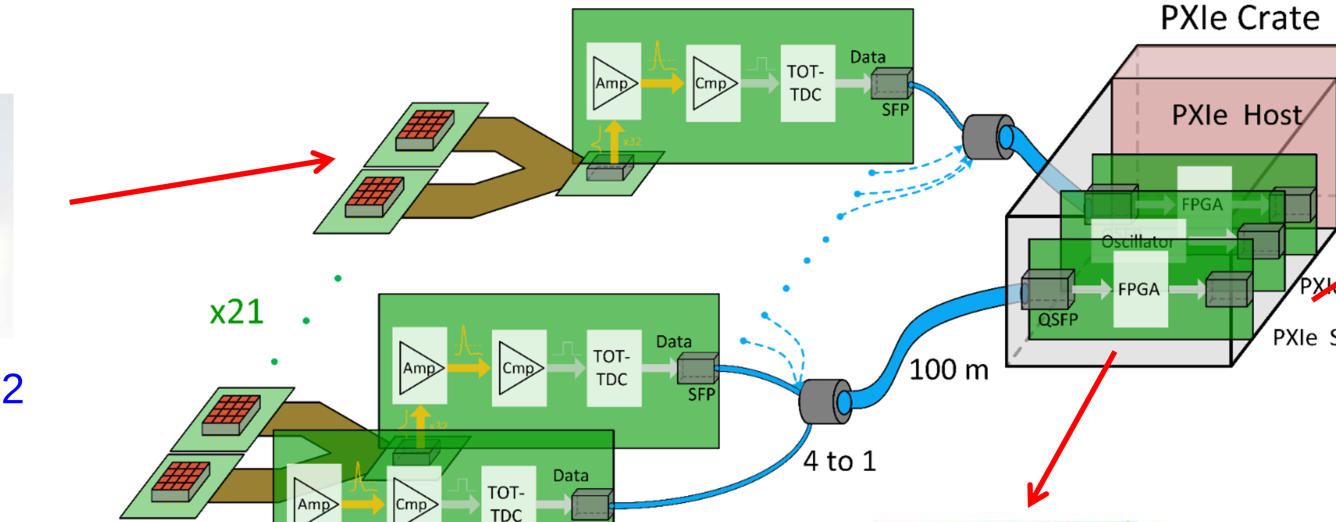
Recoiling electrons



$TTS = \mathrm{sqrt}\left(\sigma_{\mathrm{total}}^2 - \sigma_{\mathrm{sys}}^2\right) \sim 28$ ps

electronics system

MCP-PMT×42

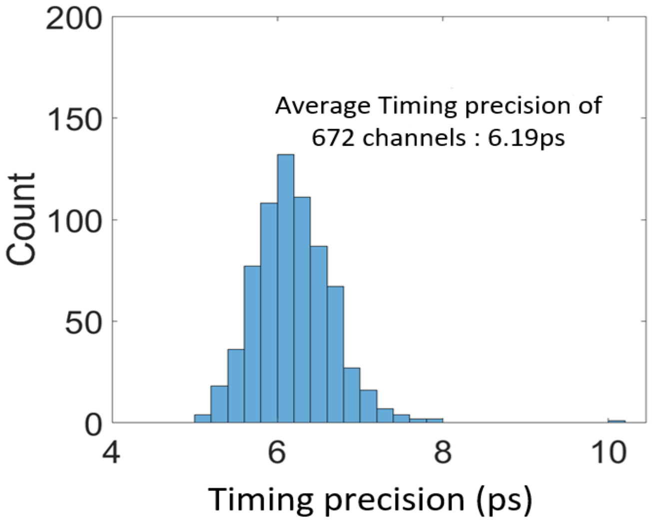


Clock&Trigger distribute board×1

Data collect board×2

Front-end readout board ×21

Flexible adapter board×21



✓ **timing precision <10 ps**