

The R&D of the Fast MCP-PMTs for High Energy Physics Detectors

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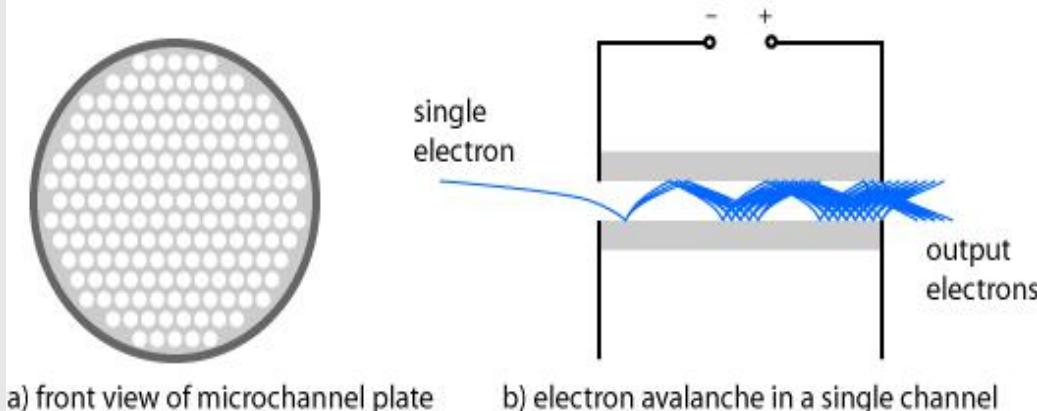
CEPC Workshop 2023. Nanjing, 2023-Oct-26

Outline

- 1. The Conventional PMTs
- 2. The 20 inch Large MCP-PMT (LPMT)
- 3. The 2 inch Fast timing MCP-PMT (FPMT)
- 4. Summary

1.1 The Conventional -- Small-MCP-PMT

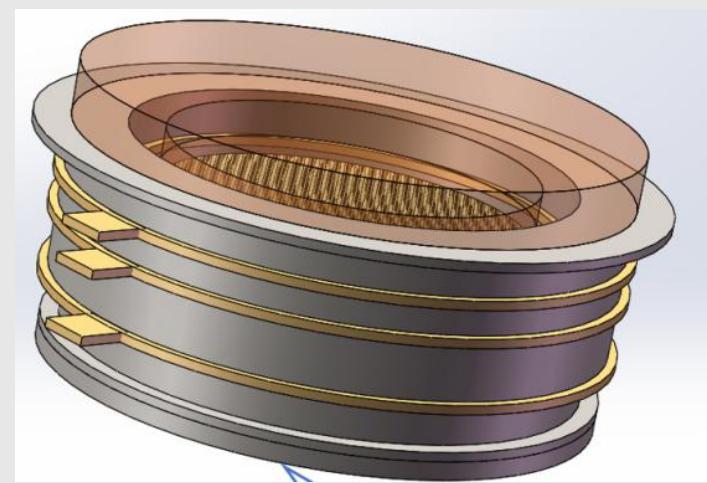
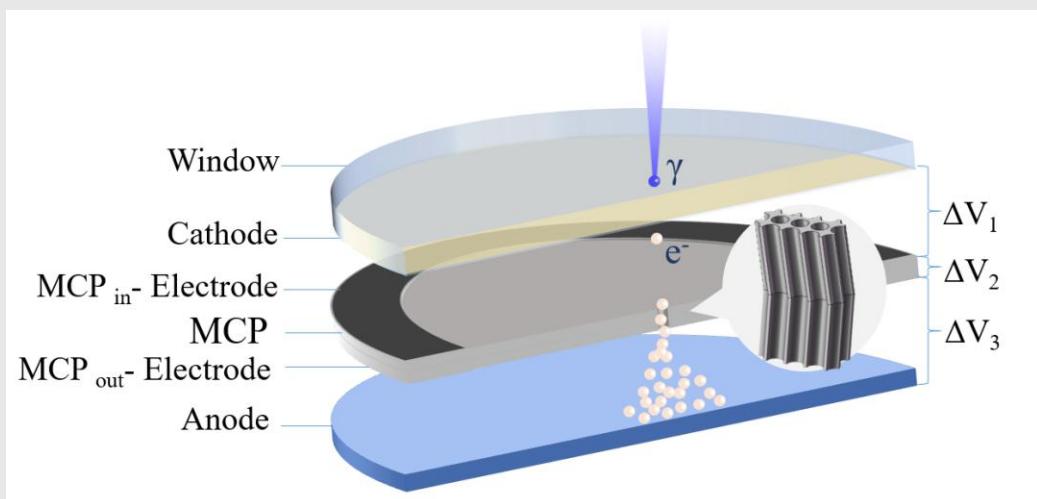
➤ The Microchannel Plate MCP



performance of the MCP:

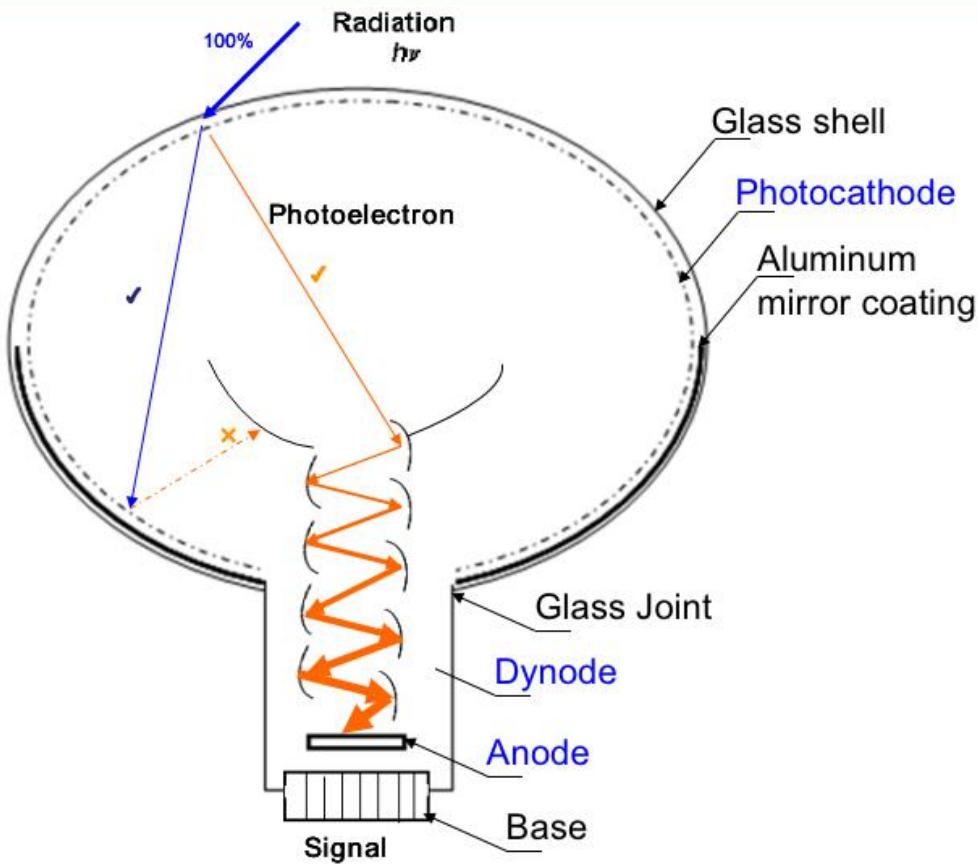
- High Gain: 1×10^4 / 1 pic
- Small Size: Diameter=50mm
- Fast Signal: Rise time < 1ns
- TTS@SPE: ~30ps

➤ The Conventional small, fast timing MCP-PMT, FPMT



1.2 The Conventional -- Dyonde-PMT

➤ The 20 inch Dynode PMT



The first PMT in the world in 1933
“Kubetsky’ s tube”



How to improve the PDE of PMT?

Quantum Efficiency (QE) :

20%

Collection Efficiency (CE) of Anode:

70%

$$\text{Photon Detection Efficiency (PDE)} = \text{QE}_{\text{Trans}} * \text{CE} = 20\% * 70\% = 14\%$$

Outline

- 1. The Conventional PMTs
- 2. The 20 inch Large MCP-PMT (LPMT)
 - 2.1 The Design of LPMT;
 - 2.2 The Roadmap for the R&D of LPMT;
 - 2.3 The HPD LPMT for JUNO;
 - 2.4 The Fast LPMT for LHAASO;
- 3. The 2 inch Fast timing MCP-PMT (FP)
- 4. Summary



2.1 the design of a Large MCP-PMT (2009)

High photon detection efficiency



Single photoelectron Detection

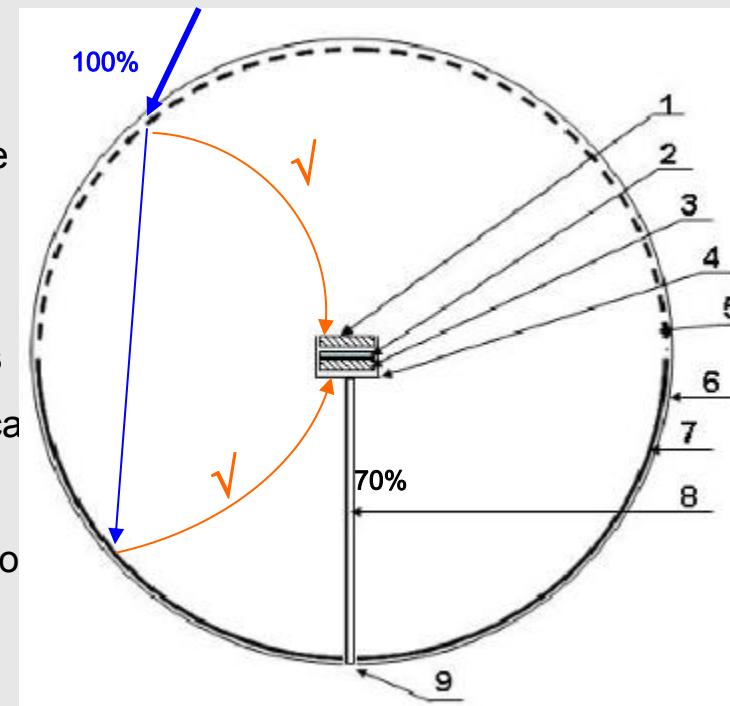
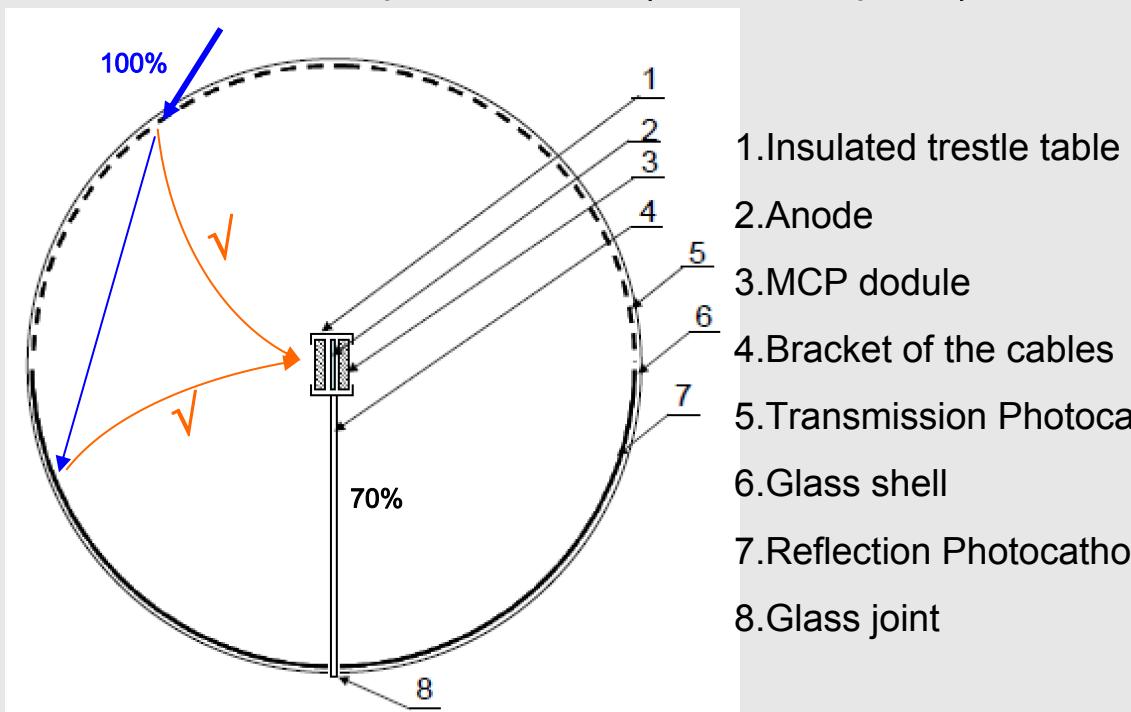


Low cost

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain

2) Using transmission photocathode (front hemisphere)
and reflection photocathode (back hemisphere)

~ 4π viewing angle!



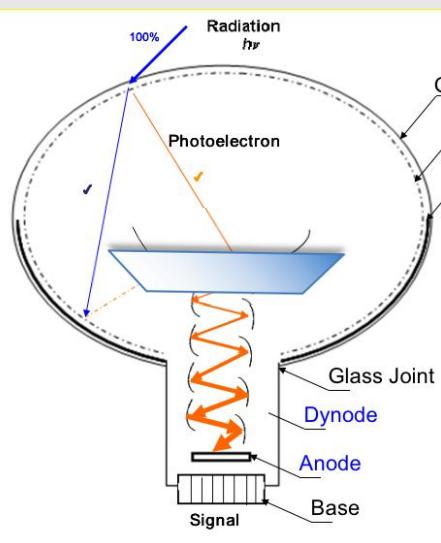
$$PD = QE_{Trans} * CE + TR_{Photo} QE_{Ref} * CE$$

Photon Detection Efficiency: 15% → 30% ; $\times \sim 2$ at least !

2012 NIMA 695

2.2 The Roadmap -- (1) Technology

➤ Dynode-PMT



- new tech. for the Photocathode

① MCPs for the SPE test

2016 NIMA 824

② QE=30%

2020 NIMA 971

③ CE=100%

2017 NIMA 868

- ALD coating for the MCP

Detection Eff.=14%

④ DE=30%

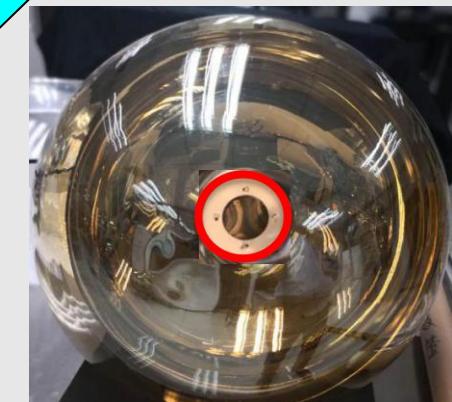
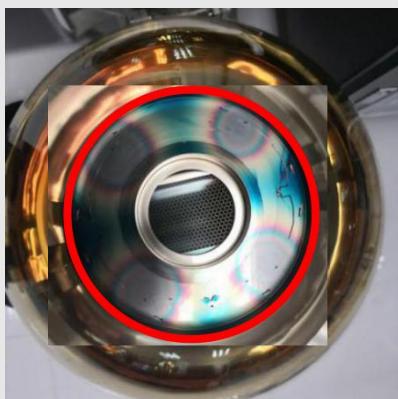
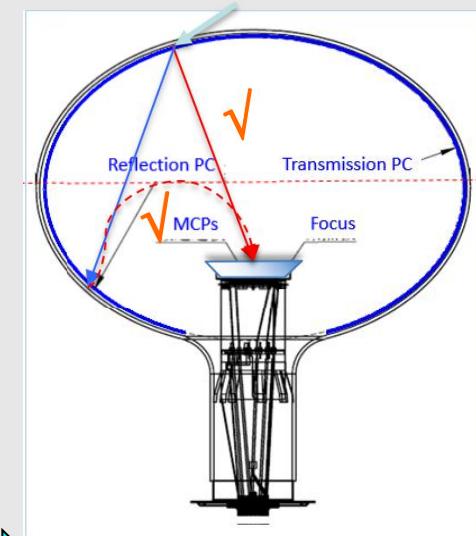
2021 JINST 16 T05007

⑤ Low-Potassium Glass

2018 NIMA 898

⑥ Low cost (3000\$, 20KRMB)

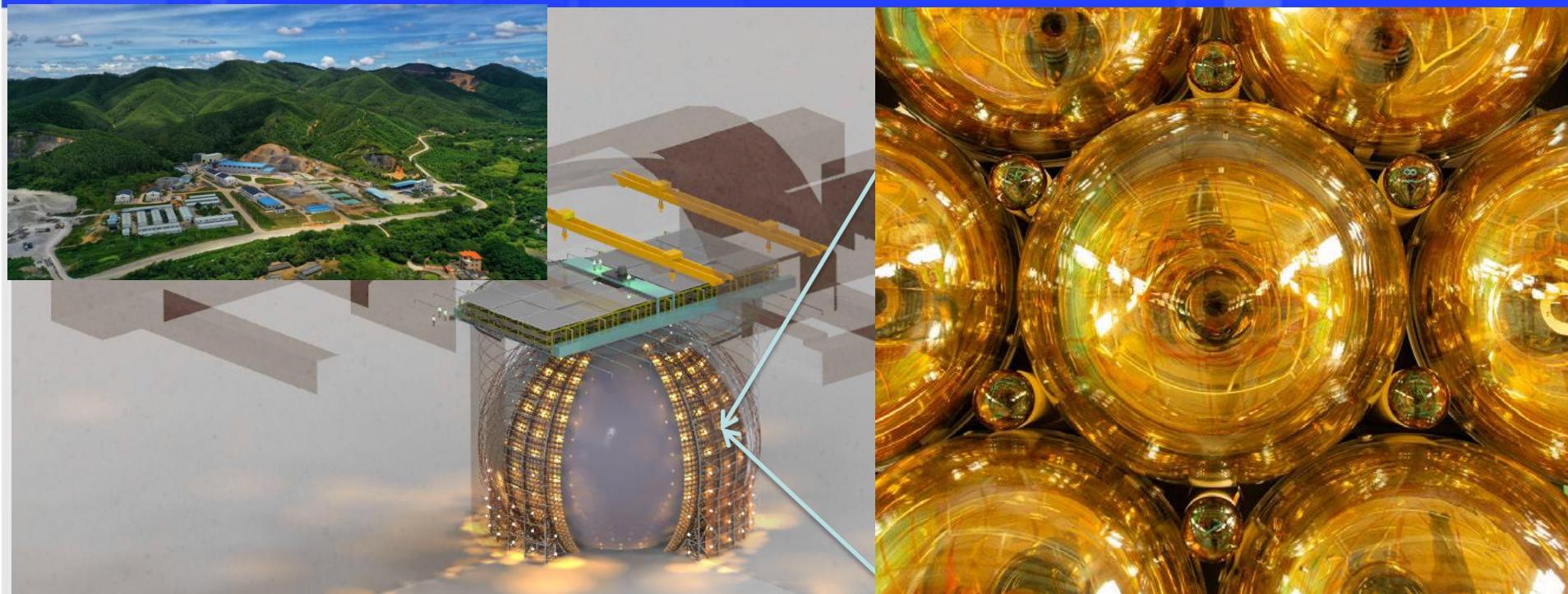
➤ MCP-PMT



2.2 The Roadmap -- (2) Parameters

Characteristics (20inch)	unit	MCP-PMT Prototype (IHEP)	MCP-PMTs 15K pieces (NNVT)
Electron Multiplier	--	MCP	MCP
Photocathode Mode	--	reflection+ transmission	reflection+ transmission
Quantum Efficiency (400nm)	%	26 (T), 30 (T+R)	32%
Collection Efficiency		~99%	99%
Detection Efficiency (400nm)	%	~ 27%	31.5%
Detection Efficiency (420nm)	%	--	28.3%
P/V of SPE		> 5	7.1
TTS on the top point	ns	~15	~ 20
Rise time/ Fall time	ns	R~2 , F~20	R~1.4 , F~24
Anode Dark Rate	Hz	~30K	40K
After Pulse Time distribution	us	0.1, 4.5	0.2 , 0.8 , 3 , 4.5, 17
After Pulse Rate	%	2.5%	5.2%
Glass	--	Low-Potassium Glass	Low-Potassium Glass

2.3 The High PDE 20" MCP-PMT for JUNO



—JUNO (Jiangmen Underground Neutrino Observatory), has already supported the MCP-PMT collaboration group to R&D the 20 inch MCP-PMT from 2009 to 2020.

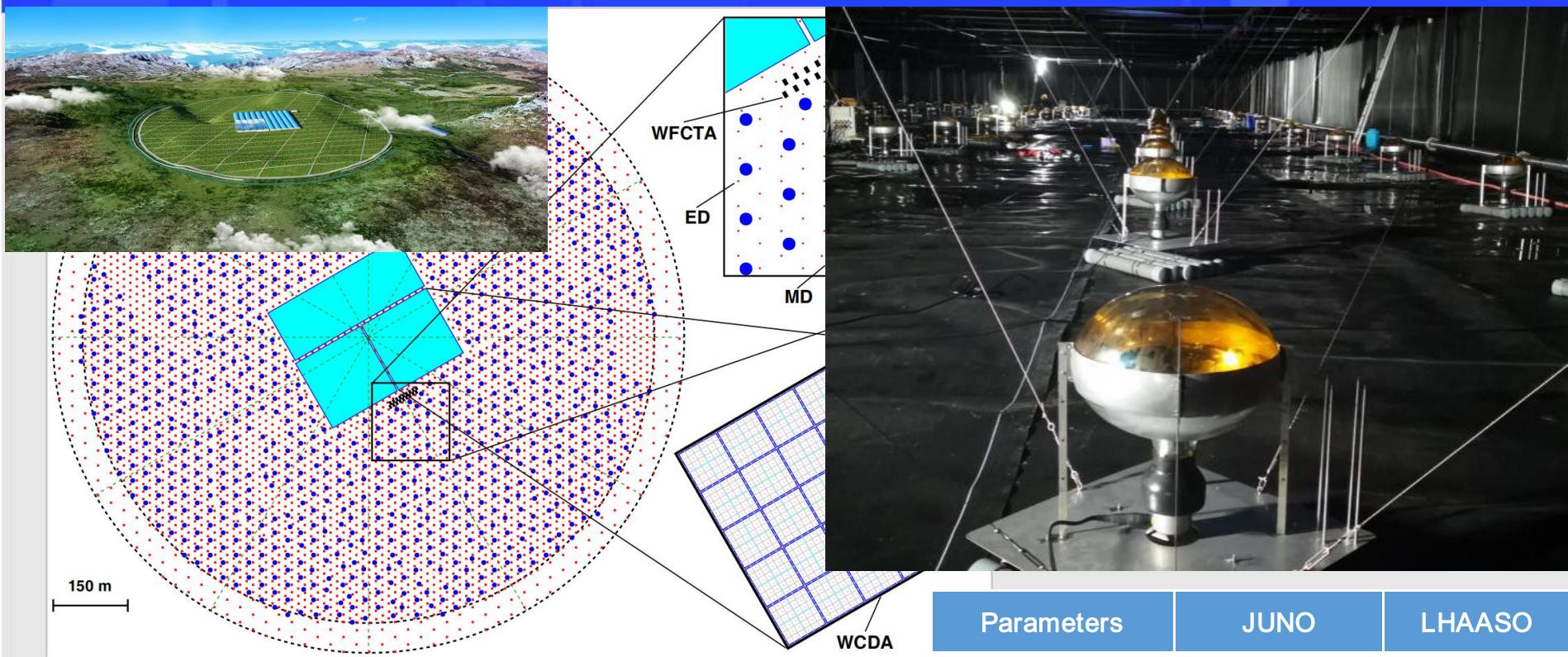
—Yifng Wang in IHEP is our group leader for this type of MCP-PMT development and the company NNVT is the one to do the mass production work.

Parameters	MCP-PMT	Dynode-PMT
Total number	15000	5000
DE@420nm	28.3%	27.6%
Dark Rate	~ 40KHz	~ 17KHz
P/V	~7	~3

2020 NIMA 952;

2021 JINST 16 C11003

2.4 The FAST 20" MCP-PMT for LHAASO

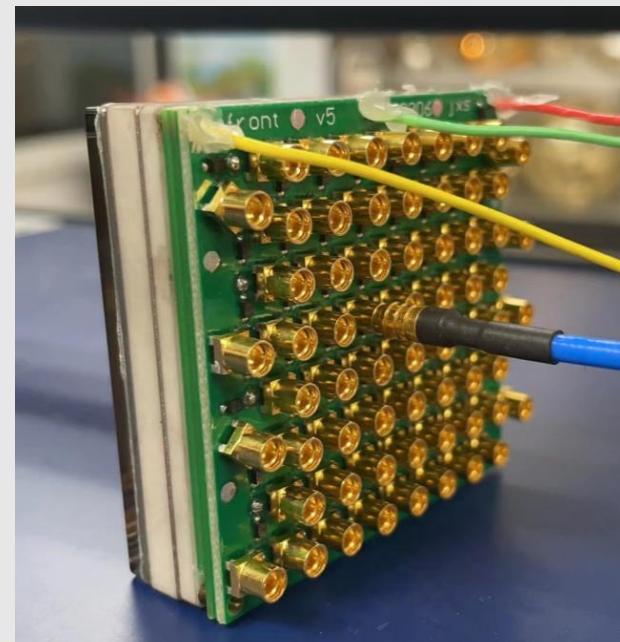


- LHAASO (Large High Altitude Air Shower Observatory), has already ordered 2270 pics 20" Flower-like-MCP-PMT.
- The 20 inch Prototype with potting has also post to the HyperK PMT Group in Tokyo University for the testing.
- The performance are different from the tubes for JUNO.

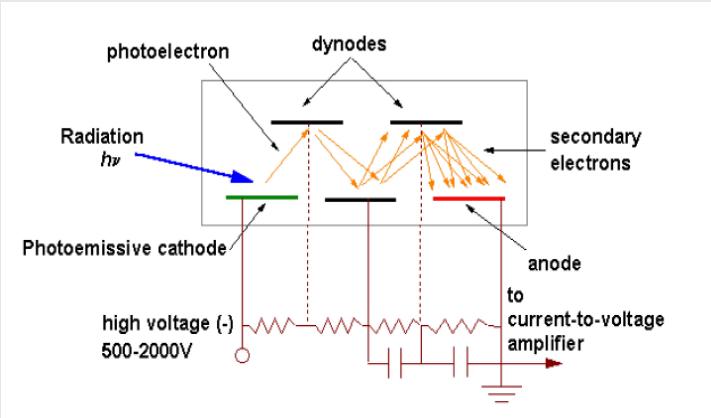
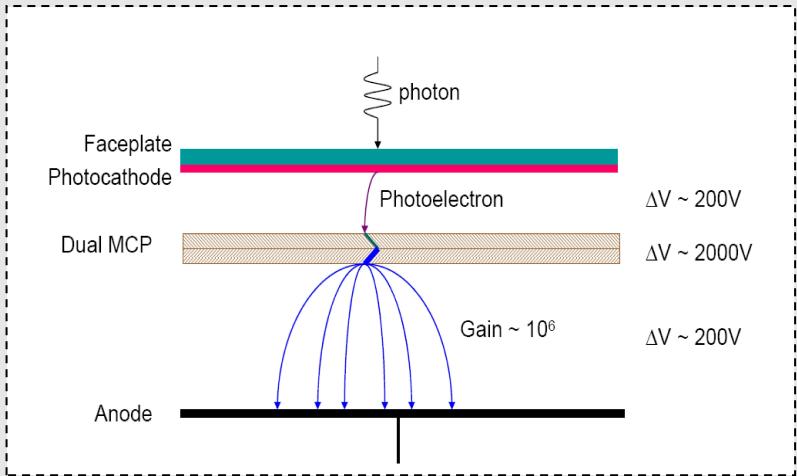
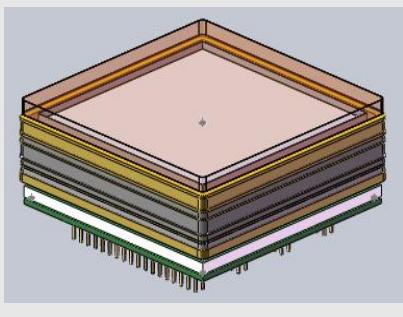
Parameters	JUNO	LHAASO
Total number	15000	2270
DE@400nm	30%	26.8%
Dark Rate	~ 40KHz	~ 20KHz
TTS	~20ns	~5.5ns

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- 1. The Conventional PMTs
- 2. The 20 inch Large MCP-PMT (LPMT)
- 3. The 2 inch Fast timing MCP-PMT (FPMT)
 - 3.1 The Roadmap for FPMT;
 - 3.2 The Performance of FPMT;
 - 3.3 The CTR of FPMTs;
 - 3.4 The Beam Test Results;
 - 3.5 The FPMT-PID Detector;
- 4. Summary



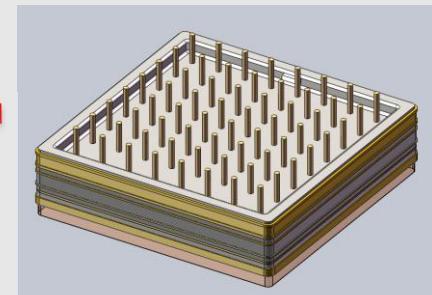
3.1 The Roadmap for FPMT-- (1) Purpose

	Operation Principle	Small Size (proximity focusing)	Large Size (electrostatic focusing)
Dynode	 <p>Diagram illustrating the operation principle of a Dynode-PMT:</p> <ul style="list-style-type: none"> Radiation $h\nu$ strikes the Photoemissive cathode. Photoelectrons are emitted from the cathode. The photoelectrons are accelerated towards the dynodes by a high voltage (-) of 500-2000V. At the dynodes, the photoelectrons release secondary electrons. The secondary electrons are collected by the anode. The signal is sent to a current-to-voltage amplifier. 	<p>2" Dynode-PMT </p> 	<p>20" Dynode-PMT </p> 
MCP	 <p>Diagram illustrating the operation principle of an MCP-PMT:</p> <ul style="list-style-type: none"> A photon hits the Faceplate Photocathode. A photoelectron is emitted from the photocathode. The photoelectron is accelerated through the Dual MCP stage with high voltage differences ($\Delta V \sim 200V$, $\Delta V \sim 2000V$). The photoelectron is collected by the Anode. The signal is amplified with a gain of $\sim 10^6$. 	<p>2" MCP-PMT </p> 	<p>20" MCP-PMT </p> 

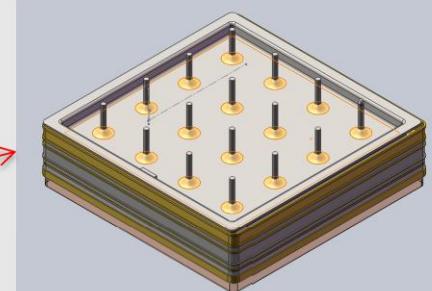
3.1 The Roadmap for FPMT -- (2) Technology

- Five Core technologies are needed to produce this new type of 2 inch Fast MCP-PMT;
- We have the experience of the PC, MCP production, but need do more research on the sealing, the anode, and the electronics.

➤ 2 inch - 8X8 ch.



➤ 2 inch - 4X4 ch.



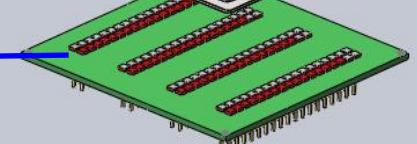
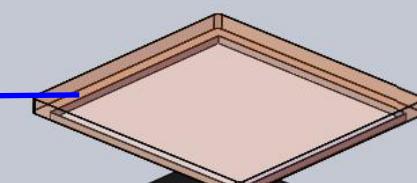
High QE Photocathode

High Gain Low Noise MCP

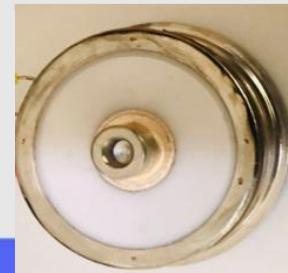
High Vacuum Sealing

Crosstalk-free Array Anode

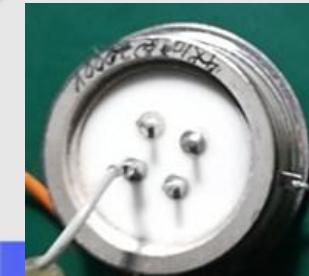
High-density Electronics



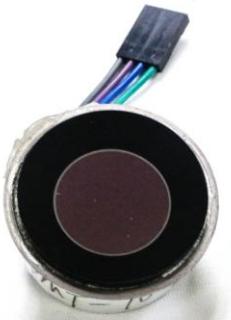
➤ 1inch- 1ch.



➤ 1 inch- 4ch.



3.1 The Roadmap for FPMT -- (3) Prototypes



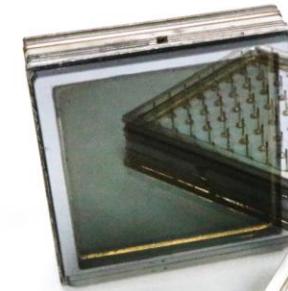
➤ Single Anode FPMT



➤ 2*2 Anodes FPMT



➤ 4*4 Anodes FPMT

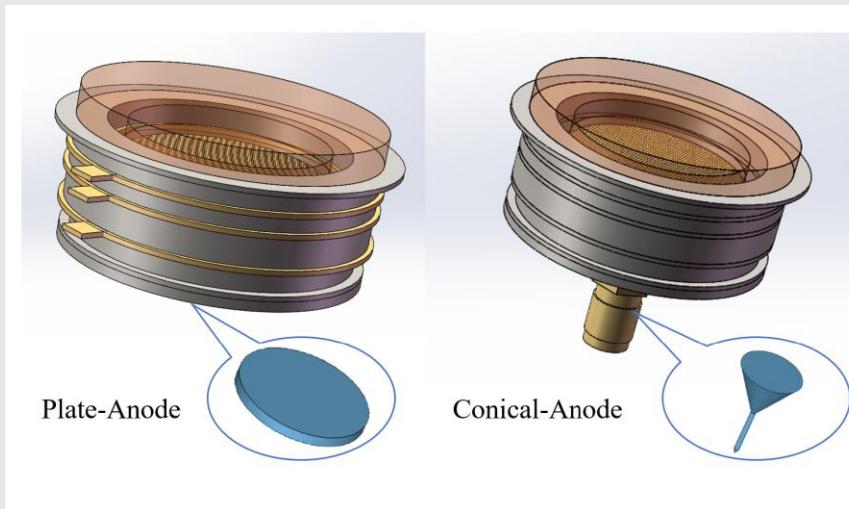


➤ 8*8 Anodes FPMT

FPMTs developed in IHEP+NNVT

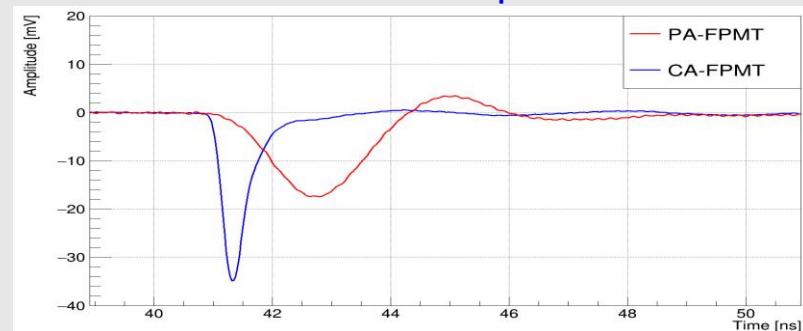
3.2 The Performance -- (1) Single Anode FPMT

➤ Anode Optimization

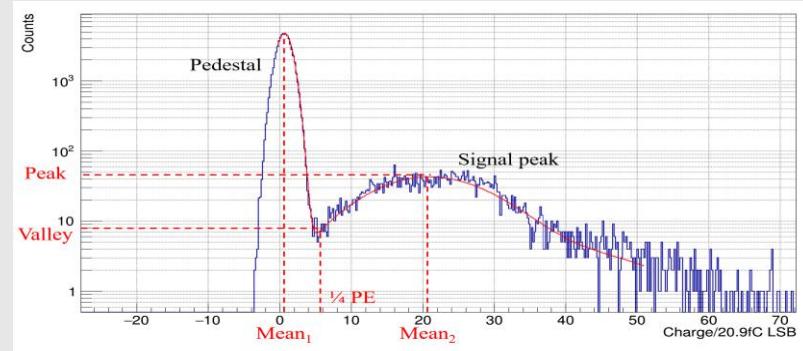


2022 NIMA 1041

➤ Waveform comparison

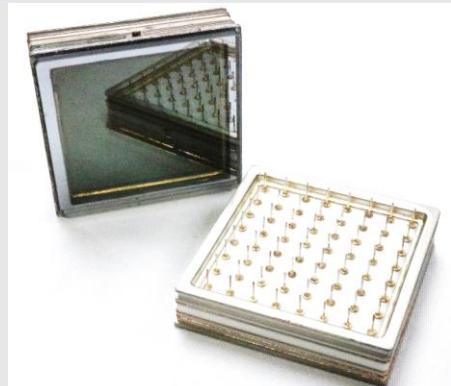


➤ SPE Spectrum



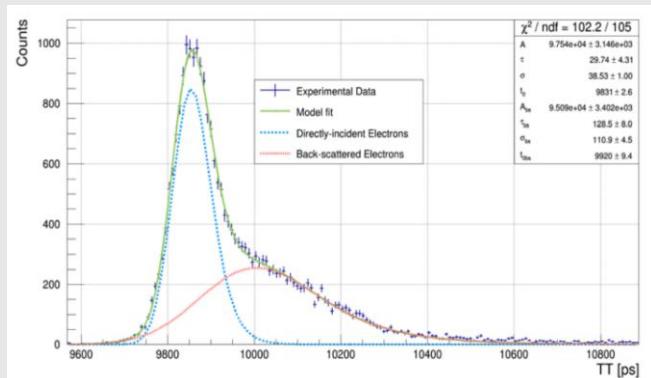
	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek 210	-4700	2.9E6	2.0	93 mV	96 ps	350 ps	190ps	45 ps	10 ps
Plate-Anode	-2000	1.9E6	28.8	7 mV	1.4 ns	1.4 ns	1.8 ns	70 ps	25 ps
Conical-Anode	-3181	2.6E6	6.3	53 mV	150 ps	420 ps	330 ps	27 ps	5 ps

3.2 The Performance -- (2) 8X8 Anode FPMT

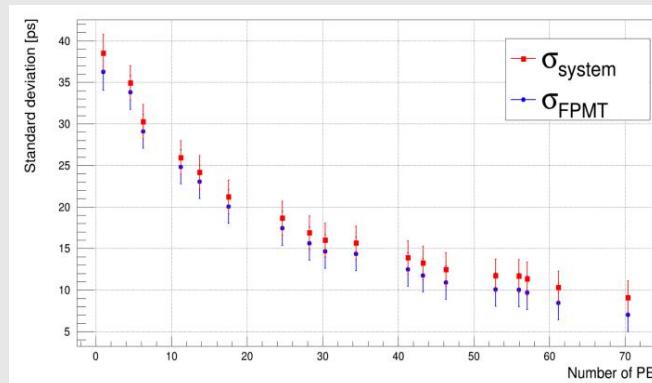


2022 JINST 17 T04002

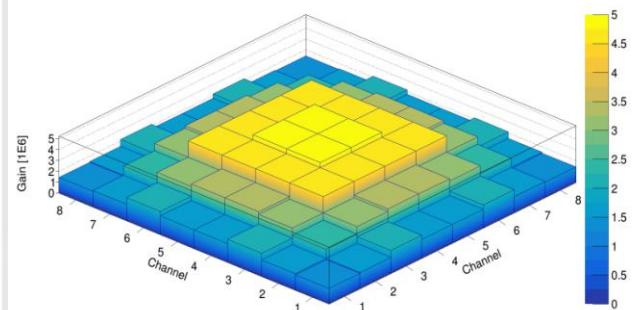
➤ TTS Spectrum



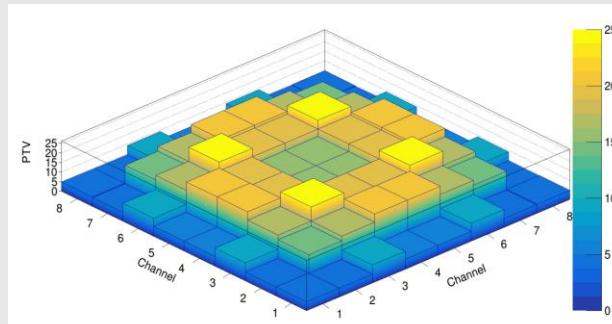
➤ TTS Variation with light intensity



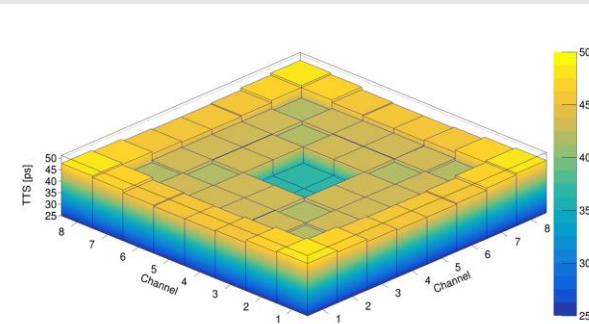
➤ Uniformity of Gain



➤ Uniformity of P/V

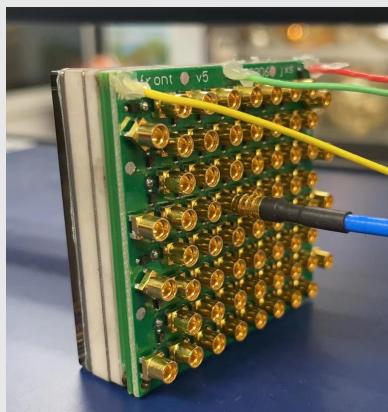
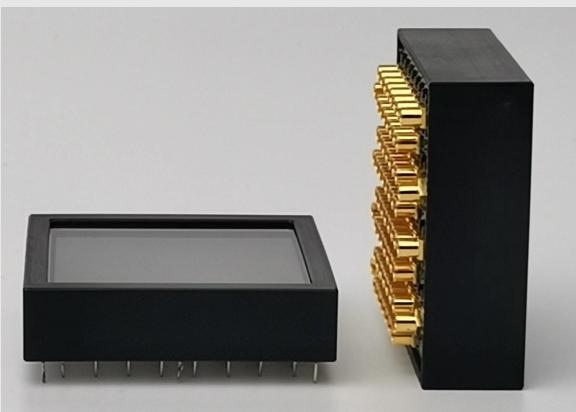
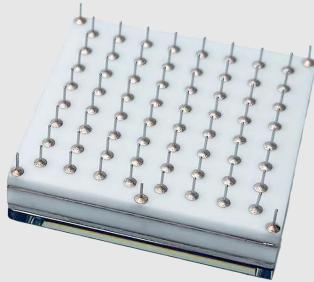


➤ Uniformity of TTS



	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek-253	-2600	1.2E7	11.2	113 mV	490 ps	1.1 ns	~1ns	45 ps	16 ps
8*8 Anodes	-1500	3.9E6	18.6	45 mV	334 ps	660 ps	~900ps	40 ps	10 ps

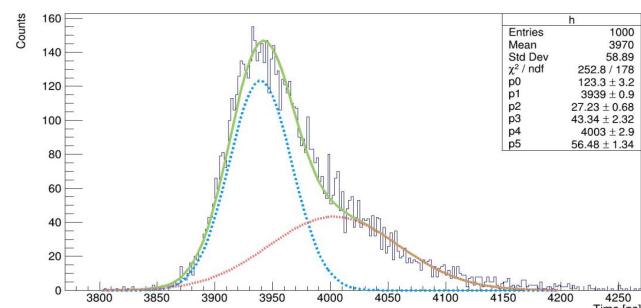
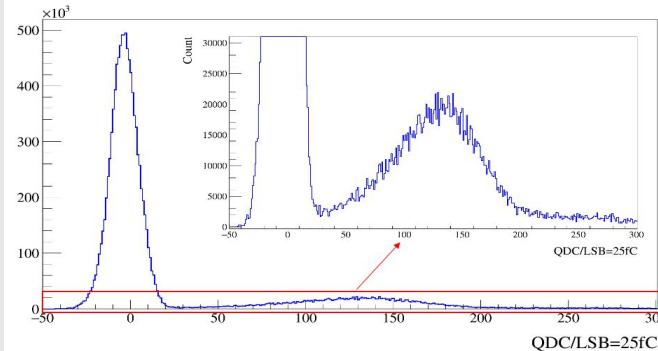
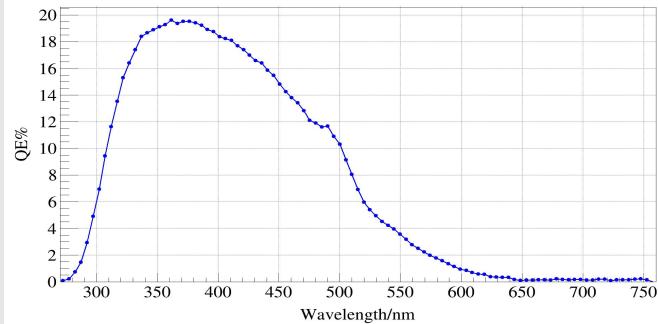
3.2 The Performance -- (3) 8X8 Anode FPMT



➤ QE
@400nm
~20%

➤ P/V
@SPE
>4

➤ TTS
@SPE
< 30ps

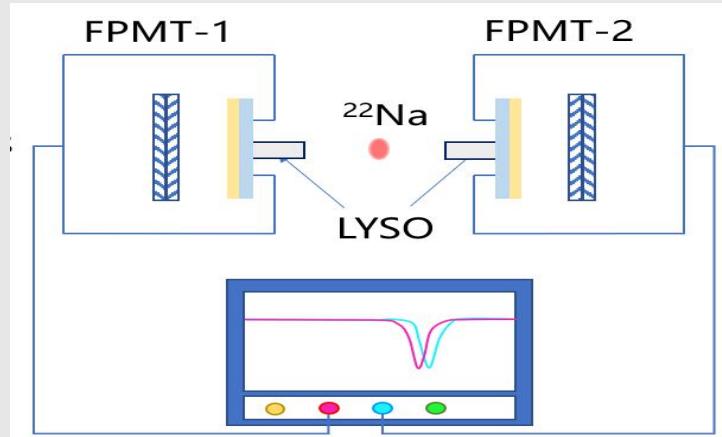


	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
8*8 Anodes	-1500	6E6	4	100 mV	250 ps	400ps	~500ps	30 ps	10 ps

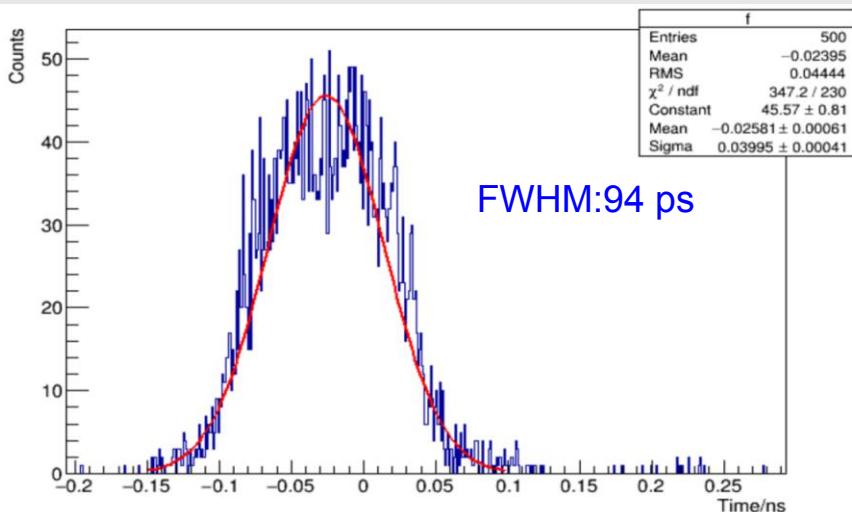
3.3 The CTR of FPMTs

- ✓ Radioactive sources: Sodium (^{22}Na) ,
- ✓ Crystal: LYSO / Lead Fluoride (PbF_2)
- ✓ DAQ: Oscilloscope~25ps
- ✓ FPMT: 1CH- Anodes FPMT*2

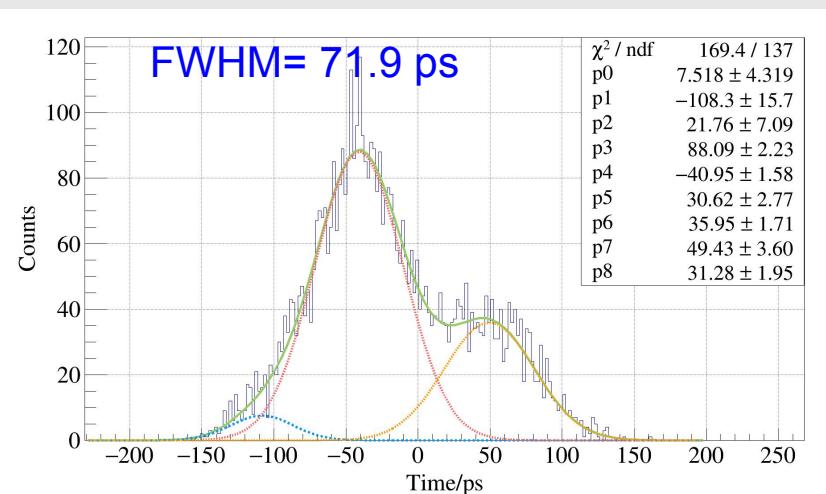
The Best Coincidence Time Resolution:



➤ CTR :FPMT+LYSO (3*3*5mm³)

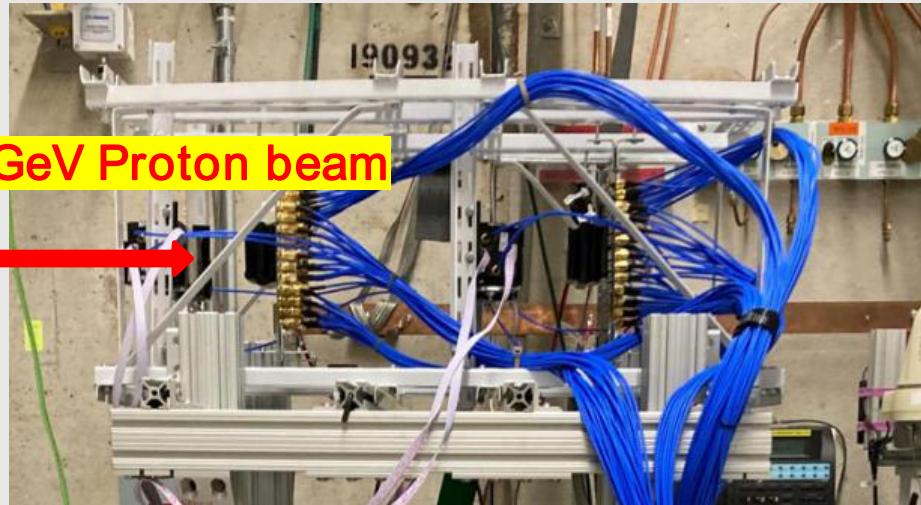


➤ CTR: FPMT+PbF₂ (3*3*5mm³)



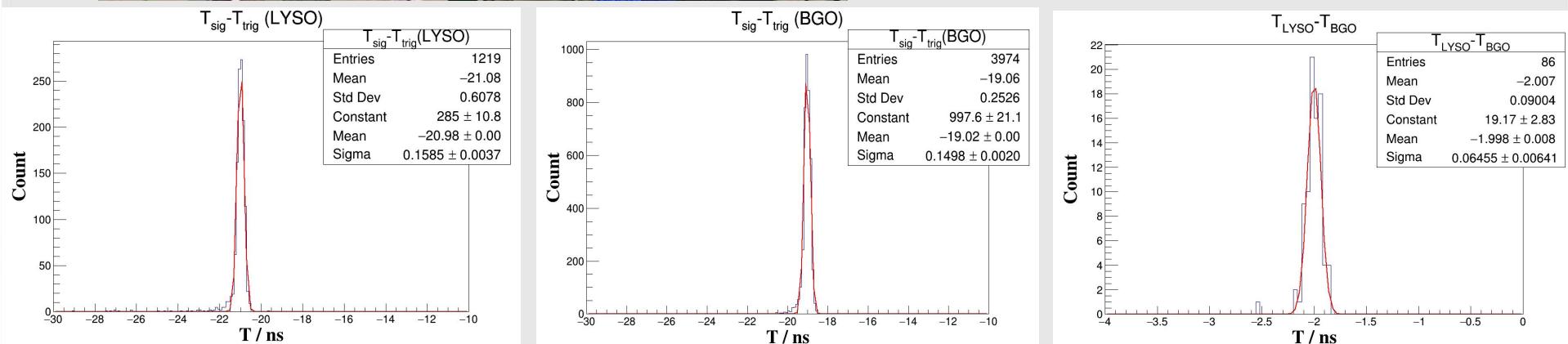
Ref: Lishuang Ma et al 2022 J. Phys.: Conf. Ser. 2374 012132

3.4 The Beam Test -- (1) Proton



- Beam: 120GeV Proton (Fermi)
- Crystal: LYSO & BGO
- PMT: 8*8 FPMT
- DAQ: CAEN V1742~50ps;
- Carried out by Zhenyu Ye (UIC)

Zhihong Ye (THU)

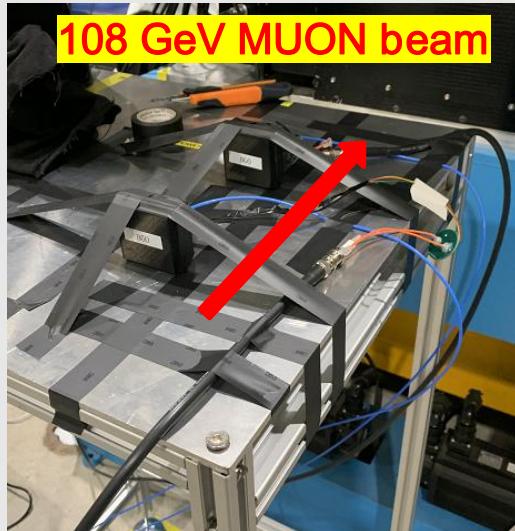


➤ LYSO single channel
Time Resolution
Sigma: 158.5 ps

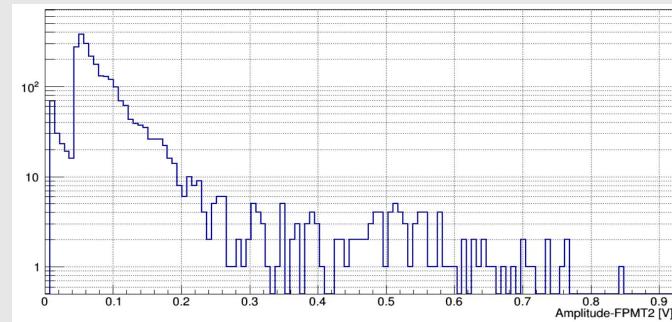
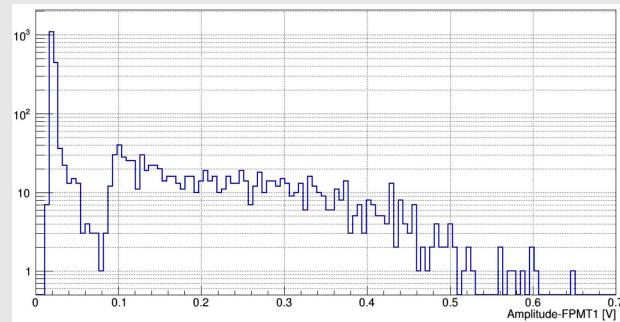
➤ BGO single channel
Time Resolution
Sigma: 149.8 ps

➤ LYSO & BGO
Coincidence Time jitter~64 ps
Single tube Time jitter ~45ps

3.4 The Beam Test -- (2) Muon

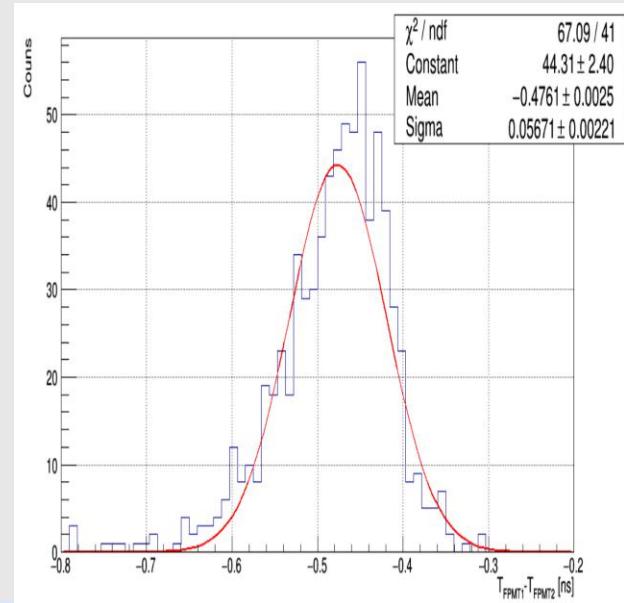
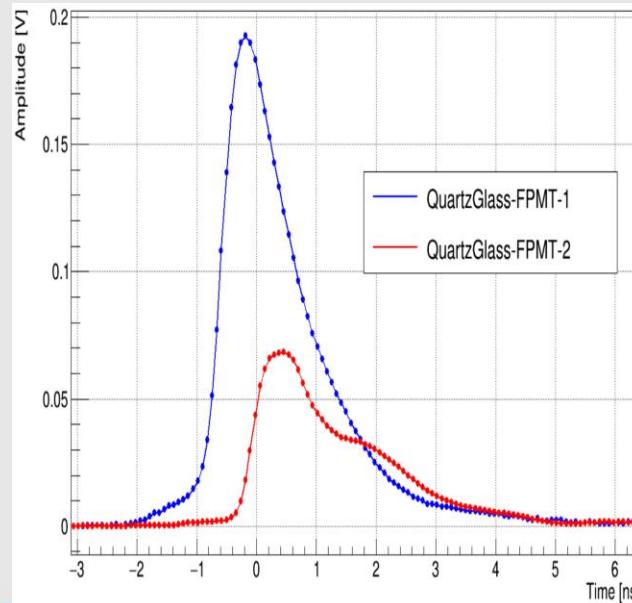


➤ Quartz Glass + FPMT

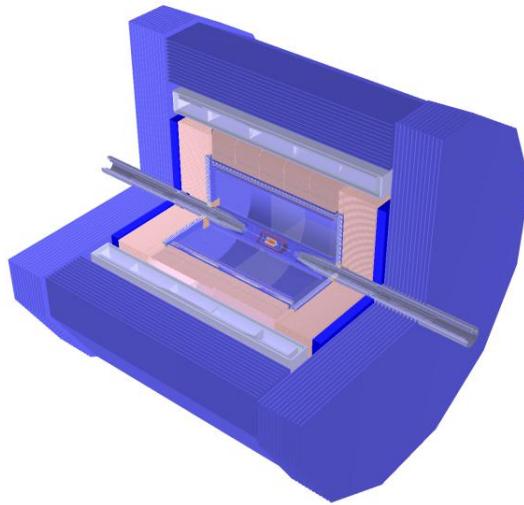


Coincidence time jitter~ 56ps
Single tube Time jitter ~40ps

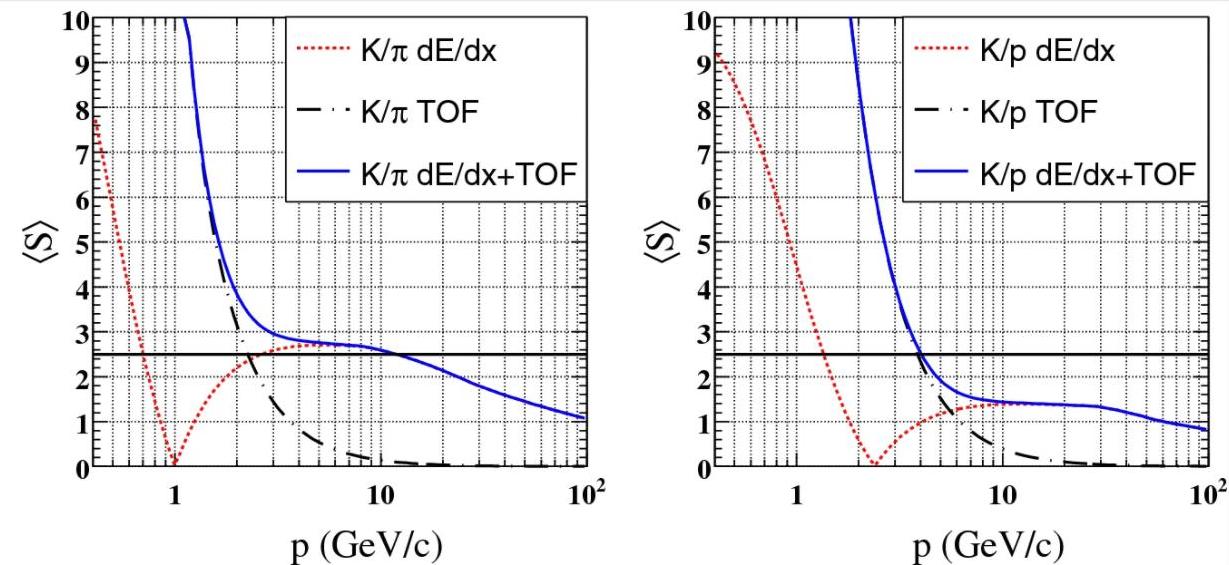
- **Beam:** (CERN)
108GeV Muon
- **Scintillator:**
Quartz Glass;
- **PMT:** 8*8 FPMT
TTS = 50ps@SPE;
- **DAQ:** 15 GSa/s \sim 25ps



3.5 Potential Applications -CEPC-PID

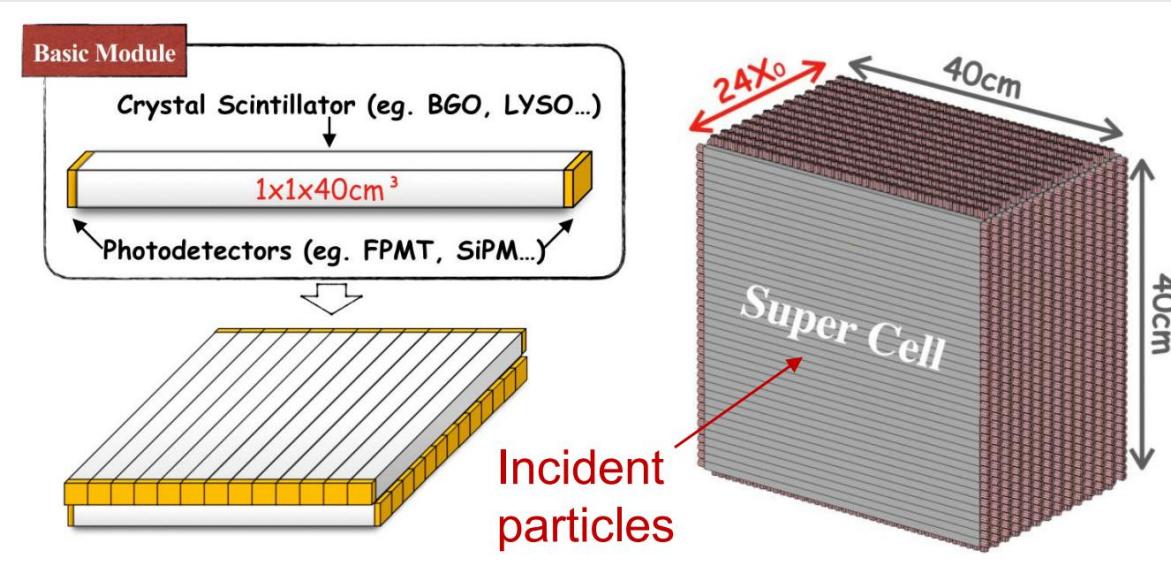


CEPC Detector



Supposing TOF information with a 50 ps time resolution, accounting for the time resolution and the location of the ECAL, the TOF information can provide K/π (K / p) separation better than 2.5σ up to 2.1 (4.0) GeV/c. By combining TOF and dE / dx , more than 2.0 (1.4) σ K/π (K / p) separation can be achieved up to 20 GeV/c.

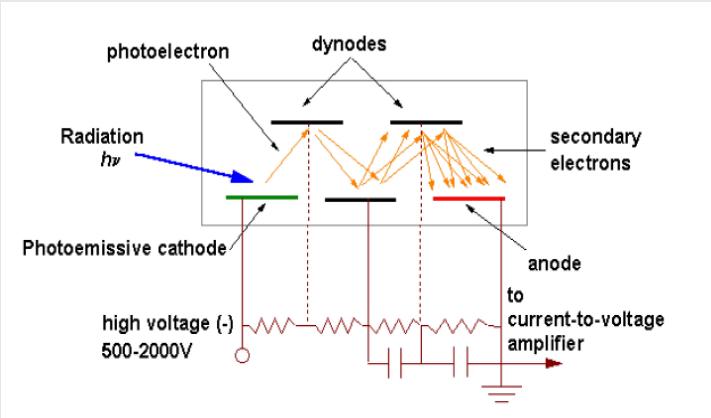
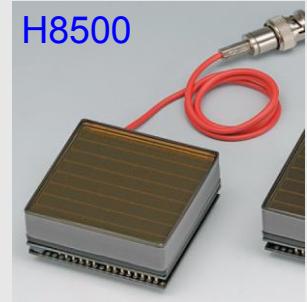
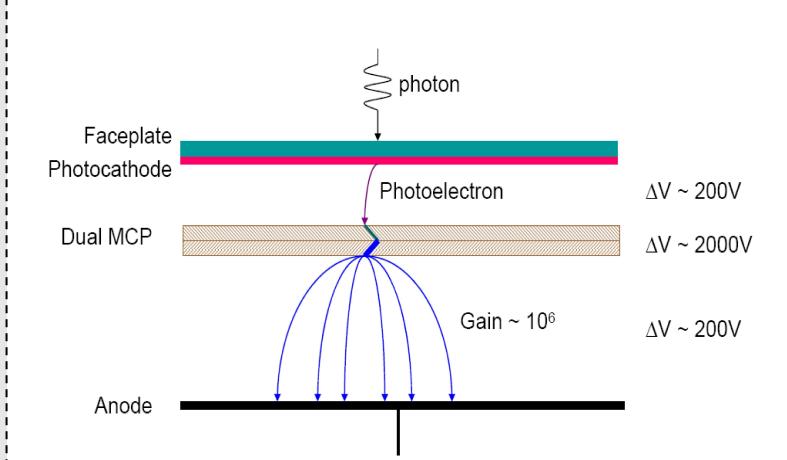
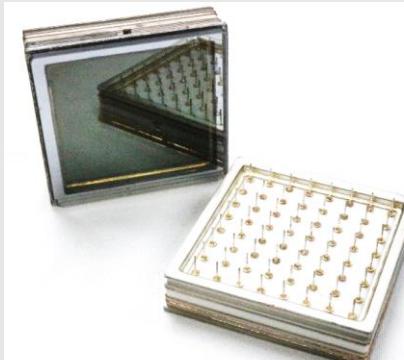
3.5 Potential Applications -CEPC-TOF-ECAL



5D crystal ECAL
(3D spatial
+
Energy
+
Time)

- FPMT has **good single-photon detection capability**
- FPMT has **big sensitive area**
- One FPMT can achieve a maximum of **64*64 channels of readout**
- **FPMT+LYSO ->excellent time resolution**
- **Low noise**

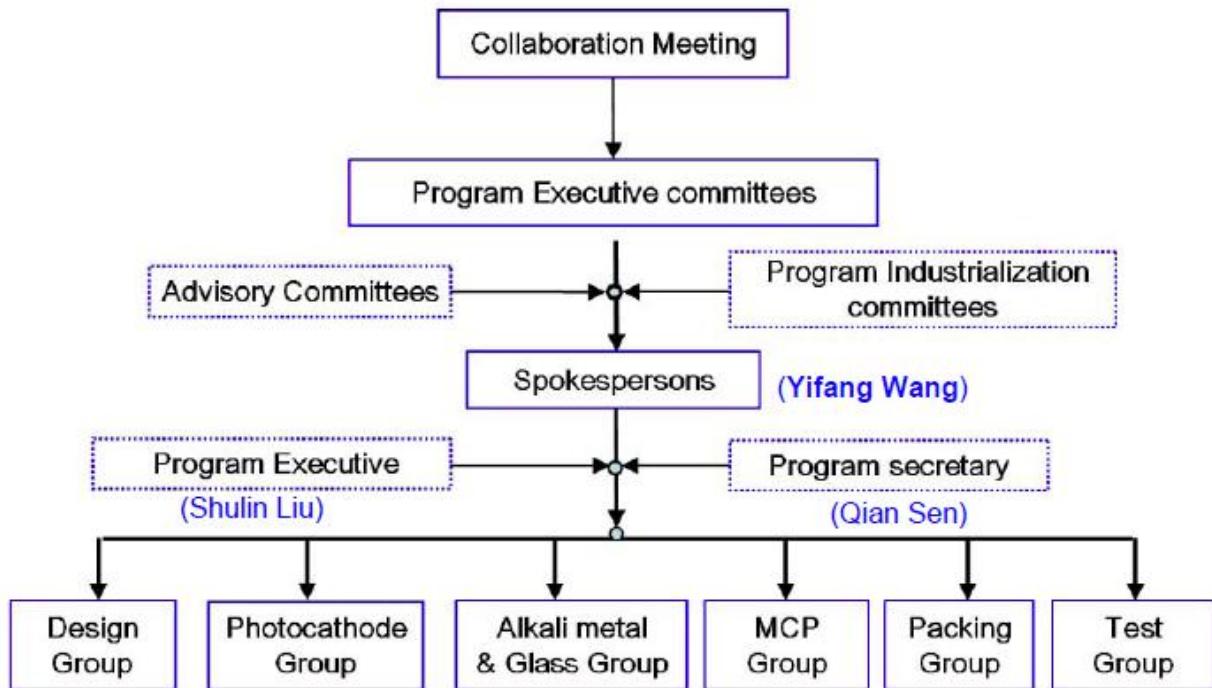
4. Summary-- (1) The PMTs

	Operation Principle	Small Size (proximity focusing)	Large Size (electrostatic focusing)
Dynode	 <p>Diagram illustrating the operation principle of a Dynode PMT:</p> <ul style="list-style-type: none"> Radiation $h\nu$ strikes the Photoemissive cathode. Photoelectrons are emitted from the cathode. The photoelectrons are accelerated towards the dynodes by a high voltage (-) of 500-2000V. The photoelectrons are reflected off the dynodes. Secondary electrons are emitted from the dynodes. The secondary electrons are collected by the anode. The signal is sent to a current-to-voltage amplifier. 	2" Dynode-PMT ✓ 	20" Dynode-PMT ✓ 
MCP	 <p>Diagram illustrating the operation principle of an MCP PMT:</p> <ul style="list-style-type: none"> A photon hits the Faceplate Photocathode. A photoelectron is emitted from the photocathode. The photoelectron passes through the Dual MCP stage. The photoelectron is accelerated by a high voltage (ΔV) of approximately 200V. The photoelectron undergoes a gain of $\sim 10^6$. The photoelectrons are collected by the Anode. The signal is sent to a current-to-voltage amplifier. 	2" MCP-PMT ✓ 	20" MCP-PMT ✓ 

4. Summary-- (2) The Group



Microchannel-Plate-Based Large Area Photomultiplier Collaboration (MLAPC)

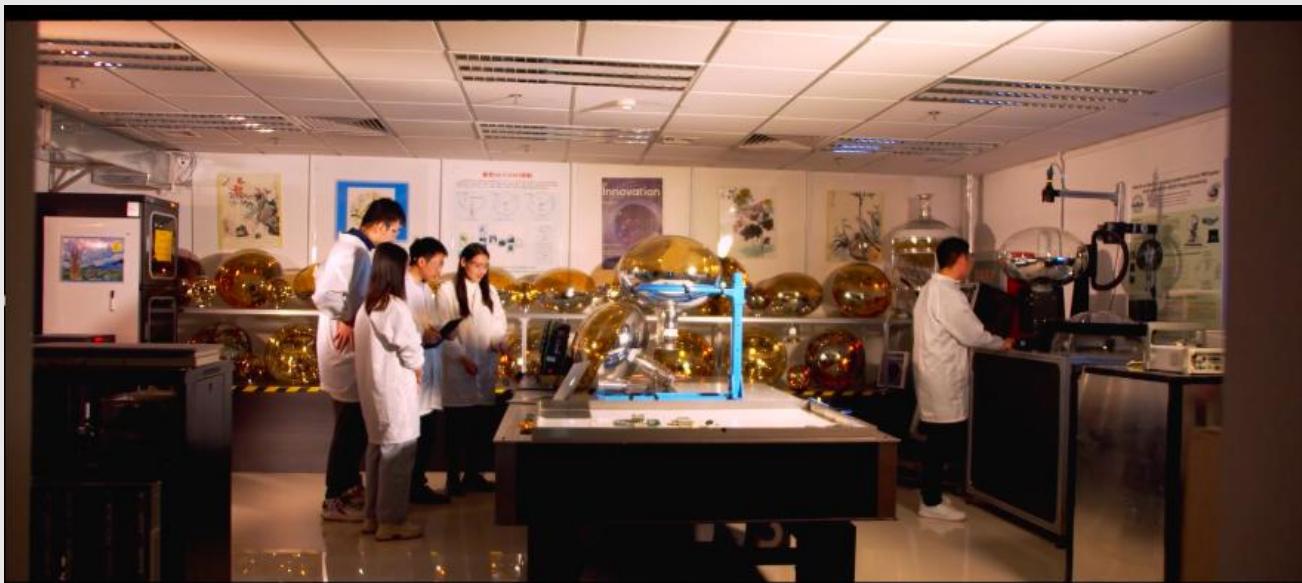


effort by Yifang Wang

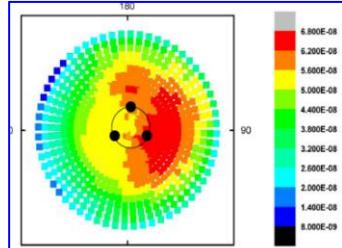
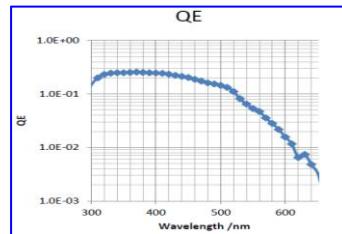
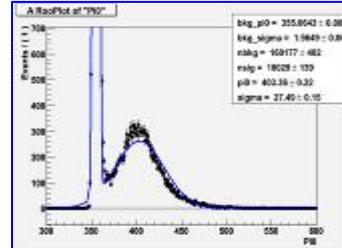
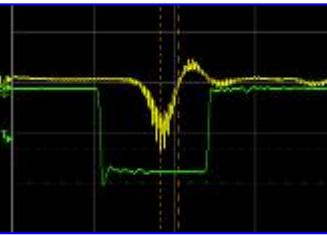


4. Summary--(3) The Photodetector Lab in IHEP

工欲善其事必先利其器 = Work must first of its profits



4. Summary-- (4) The PMT Test Facility



Others
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- Anode Pulse Rise Time;
- Pre/Late/After Pulse;
- Dark Count
- The Single Photoelectron Spectrum;
- The voltage distribution (BASE) ;
- The Supply voltage;
- Typical Gain Characteristic;
- Anode Dark Current
- Spectral Response;
- Wavelength of Maximum Response;
- Cathode Sensitivity: Luminous(2856K);
- Quantum efficiency with λ
- Photocathode efficiency Area;
- Photocathode efficiency Uniform;
- The position of the Sb, K, Cs;
- The linearity of the PMT
- Magnetic characteristics;
- Transit Time Spread (FWHM)

谢谢！



Thanks for your attention!

Any Comment & Suggestion are welcomed!



The PMT Family in NNVT in China

THANKS



See the unseen
change the unchanged



The Innovation