# STCF endcap PID detector R&D Progress

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On behalf of the DTOF group

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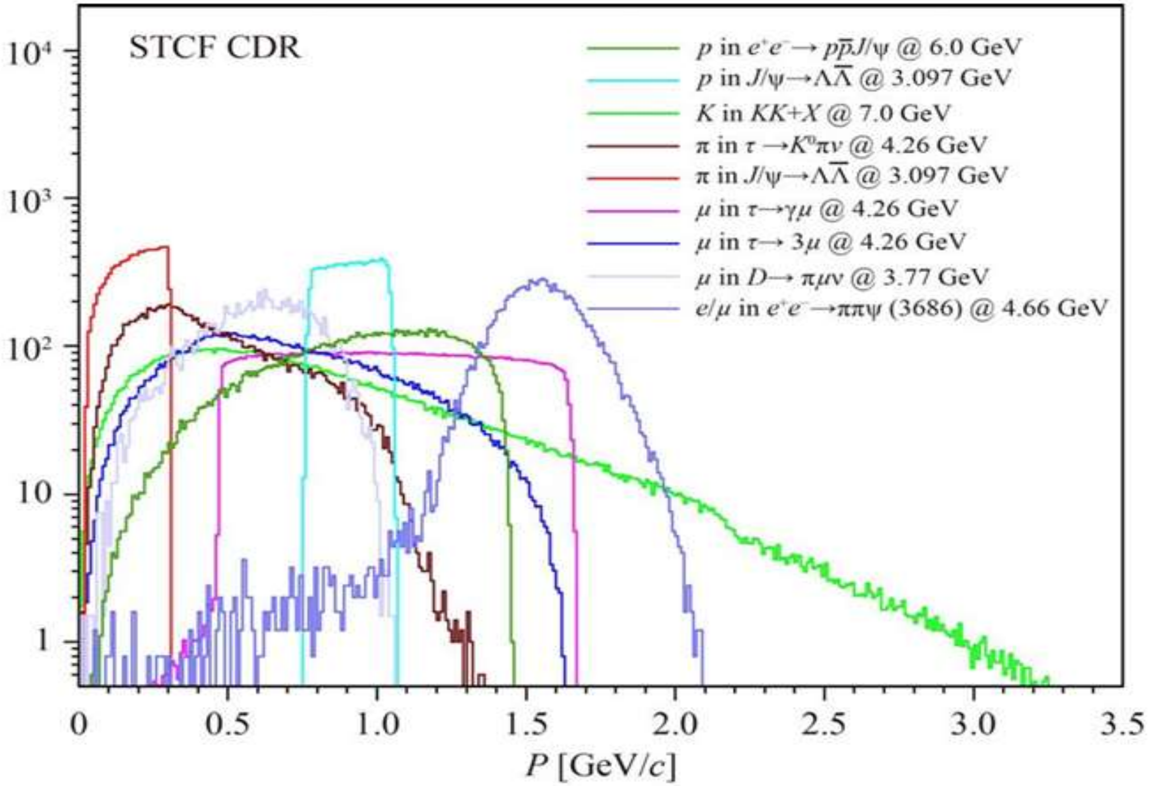
# Detector Overview-STCF PID requirement

The momenta of STCF final state particles

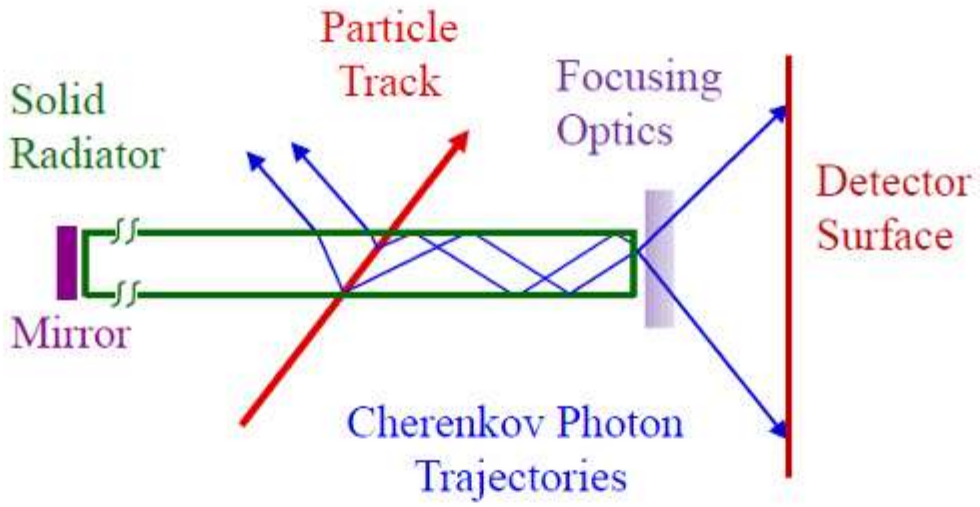



## Endcap PID detector requirements

- >4σ $\pi$/K separation power at p≤2 GeV/c
  - Equivalent to 2% misidentification while over 97% corresponding identification for particles(Pi/K)
- Compact structure, thickness<20 cm
- Low material budget (<0.5 $X_0$)

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

# Detector overview



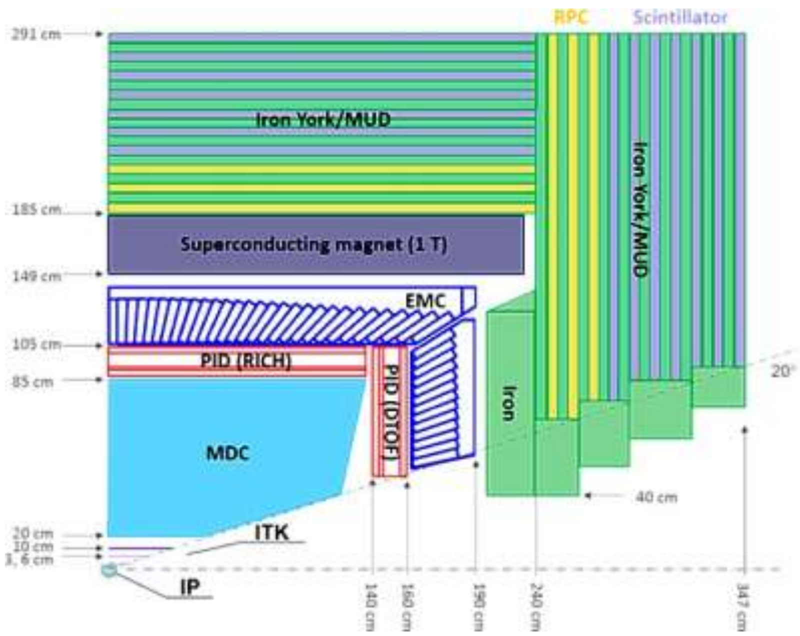

**Detector feature**

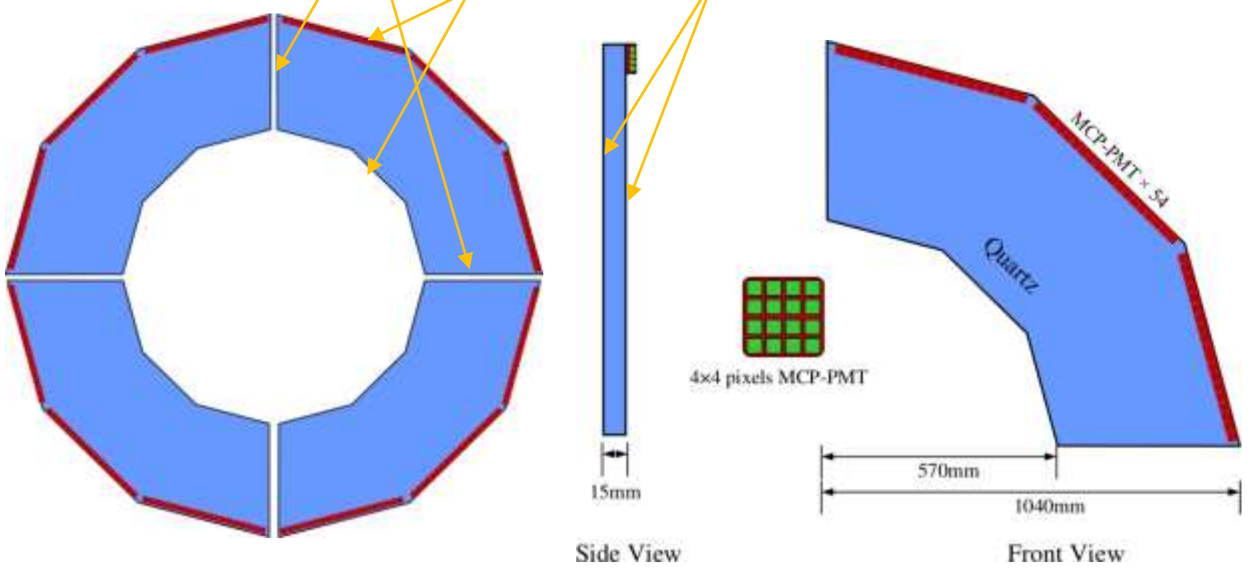
- Radiator as light guide
- Very smooth surface to keep the light direction
- Use Cherenkov angle and hit time information to separate particles

Good direction property

=> need a VERY smooth light guide

# Detector Overview-DTOF detector




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

~40 ps

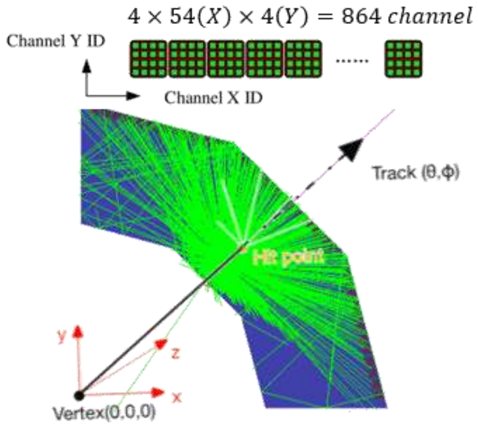
- STCF endcap PID detector
- Polar angle coverage 21°-36°
- Large area fused silica radiator
- Multi-anode MCP-PMT

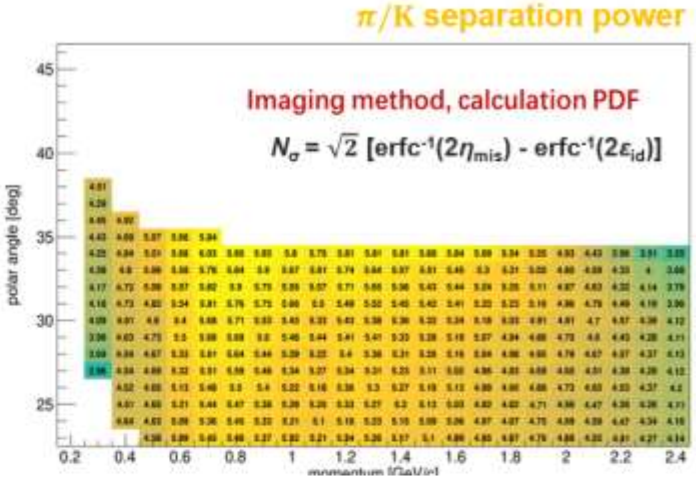
- 4σ $\pi$/K separation power at p≤2 GeV/c
  ➔Total time resolution $\sigma_{tot} < 50$ ps
  ➔DTOF intrinsic time resolution $\sigma_{DT} < 30$ ps

# Detector overview

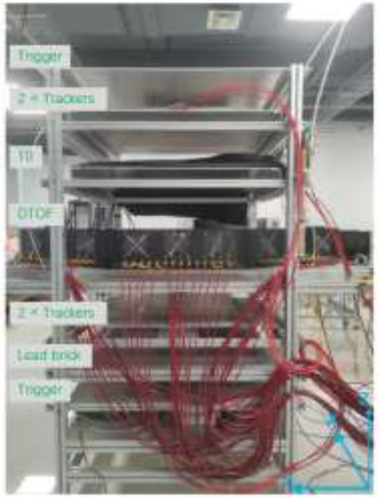
## Previous work

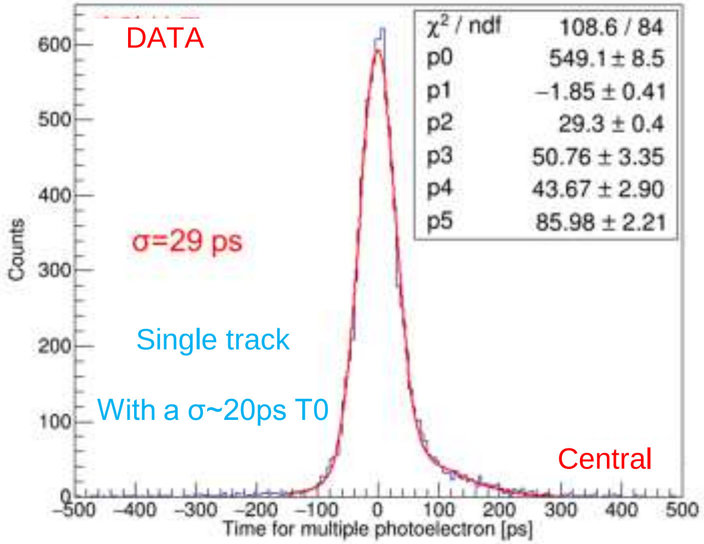
- Simulation work
    - Time & Separation performance
- Full size prototype
    - Production
    - Cosmic ray test (and simulation)




| 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 |






$$\sigma_{intrinsic} \sim \sqrt{29^2 - 20^2} \sim 21ps$$

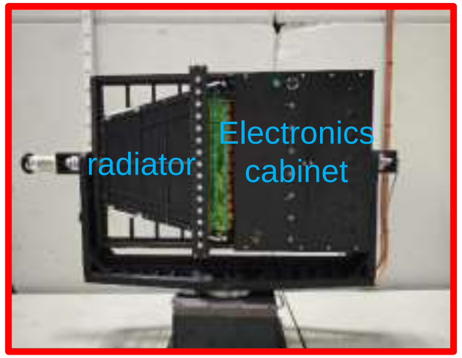
Time performance consistent well with simulation!

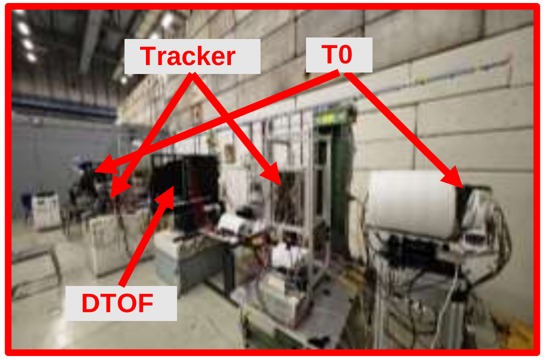
# DTOF prototype for Beam Test

**DTOF beam test prototype:**

- A trapezoid Heraeus Suprasil 312 synthetic fused silica
  - Thickness = 15 mm
  - Roughness < 1 nm for front & back surfaces
  - Top & bottom surfaces blackened
  - Lateral roughness not so good
- 14 MCP-PMTs :Hamamatsu R10754
  - 4*4 channels
  - 27.5mm*27.5mm
  - 33 ps time resolution
- PMT-silica coupled by EJ550 silicon grease
- A rotatable designed mechanical structure

top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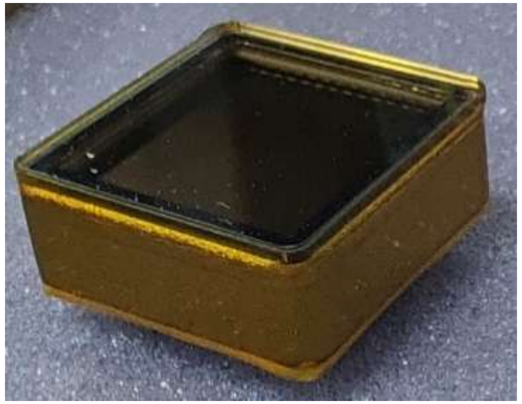
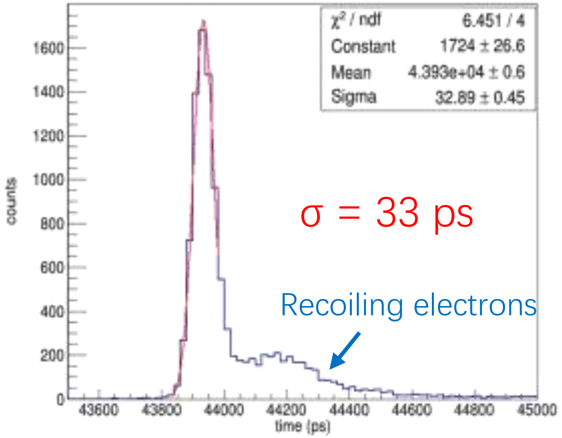
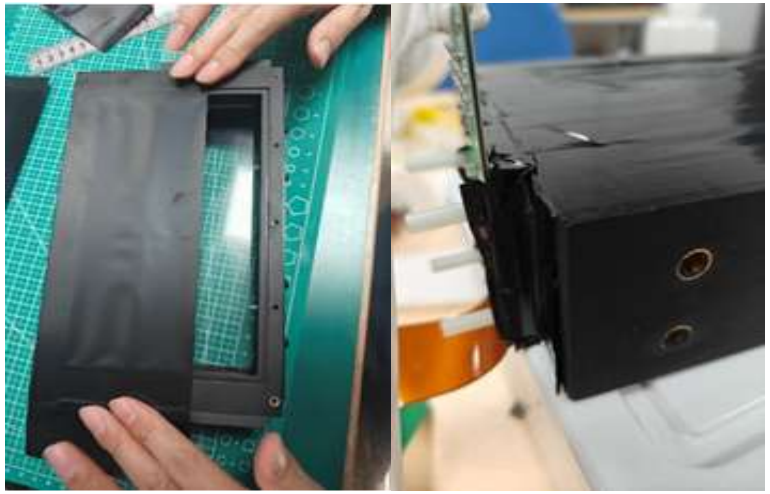


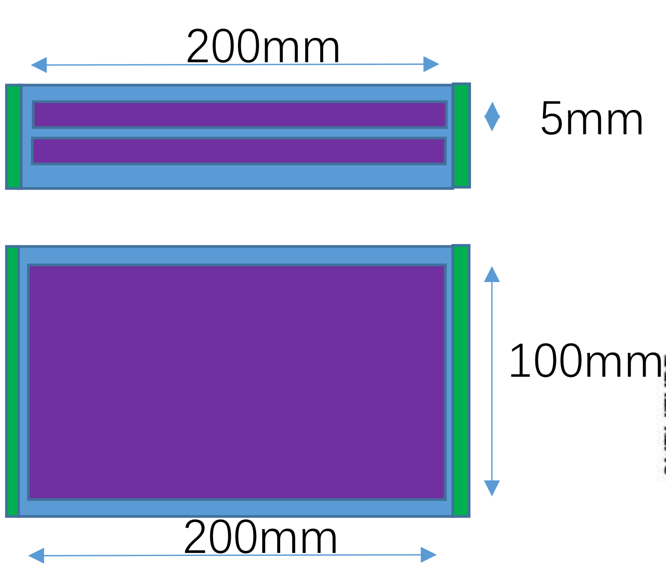


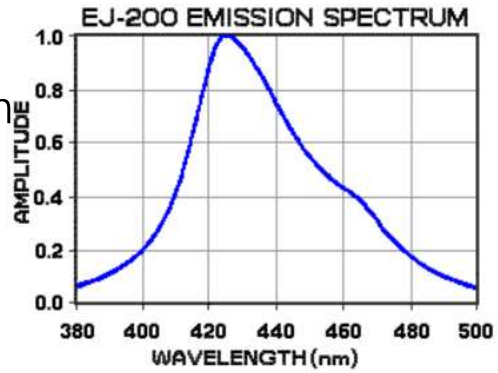
# T0 for Beam Test

**T0 detector:**

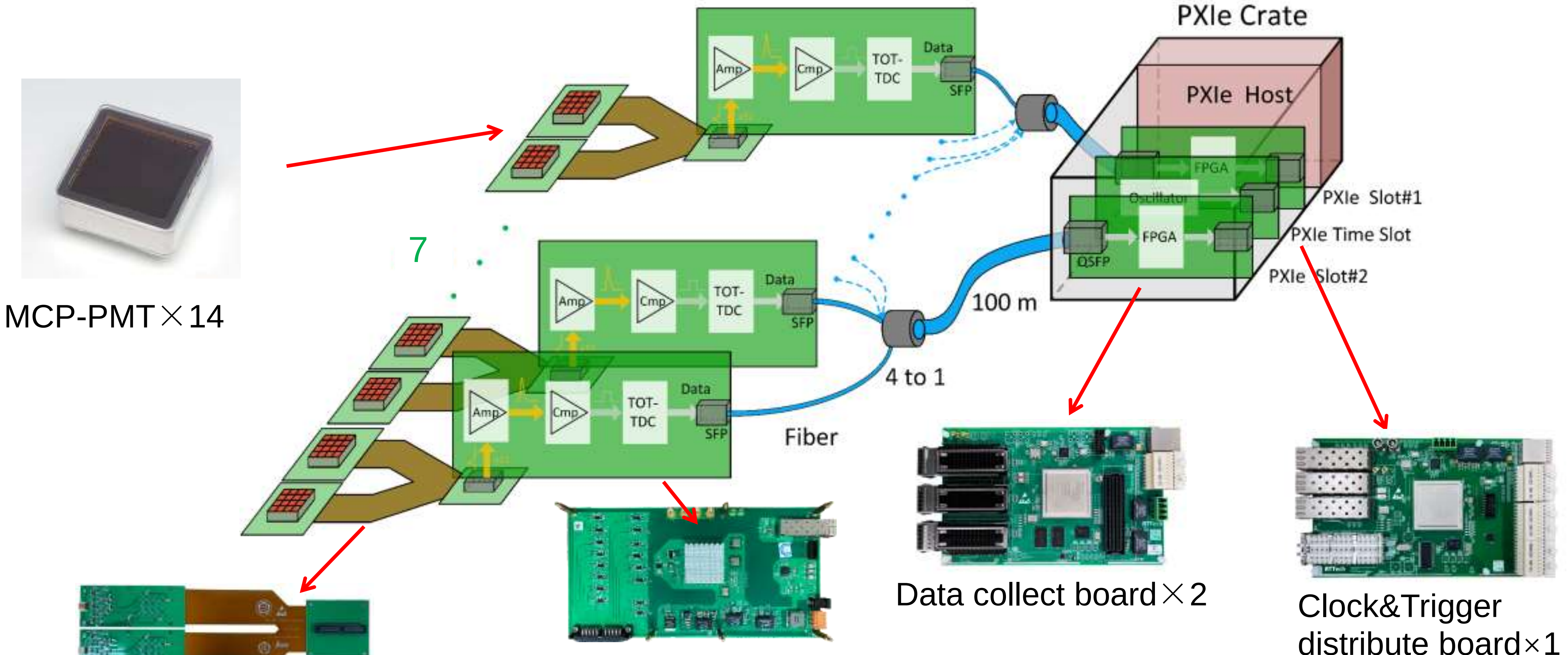
- 2 modules
- Each module
  - 2 pieces of 10cm*20cm EJ200 scintillators
    - Rise time ~0.9ns Decay time ~2.1ns
  - 2*3 MCP-PMT
  - Coupling by EJ550 silicon grease
  - Thin black Kapton tape for light shield and low material budget
- Good time resolution ~ 60ps/module, 45ps for T0(~STCF T0 40ps)
- Also serves as TOF for hadron PID up to 5 GeV/c (flight length ~8 m)





# Electronics system for DTOF & T0




Front-end readout board ×(7+8)

Flexible adapter board×(7 for DTOF+8 for T0)

10ps time precision !

# Beam test - Introduction

**Basic Information**

- CERN PS T9
- 4GeV Pi/P~2GeV Pi/K
- 2 T0 modules
- 2 group of trackers(each 2 Micromegas)
- A trapezoid DTOF prototype

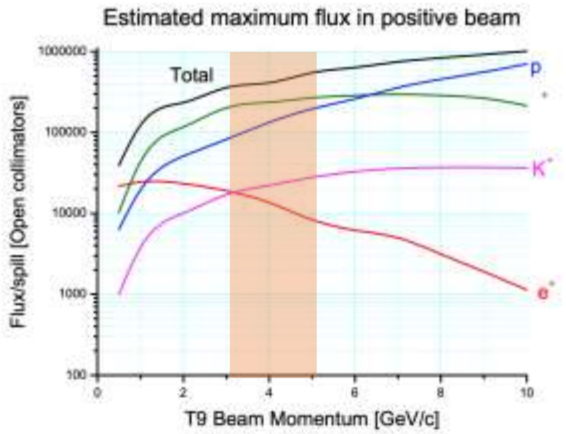
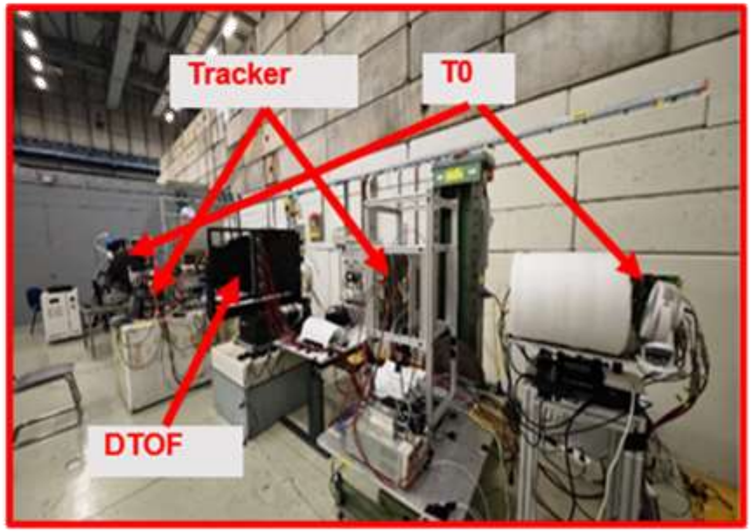



Fig. 5. Beam composition of the positive beam at the T9 beam line. Flux/spill describes the number of particles per burst. As for the positive beam, there are no muons present right after the target, but they appear when pions or kaons decay.[7]

| ParticleType/L=1450mm | TOF/DeltaTOF:ps | Beta |
|---|---|---|
| Pi@2GeV | 4839.6 | 0.9975 |
| K@2GeV | 4967.9 | 0.9709 |
| TOF Difference Pi/K@2GeV | 128.3 | |
| Pi@4GeV | 4848.4 | 0.9994 |
| P@4GeV | 4981.4 | 0.9736 |
| TOF Difference Pi/P@4GeV | 133.0 | |



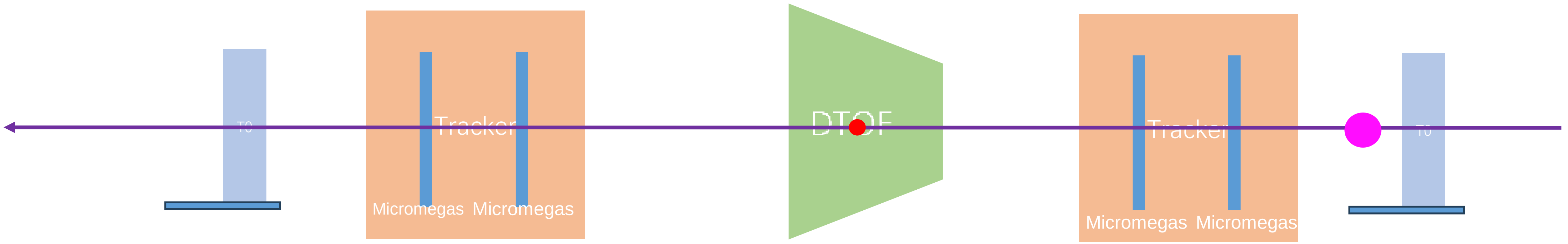

Pi/P@4GeV are equivalent to Pi/K@2GeV!

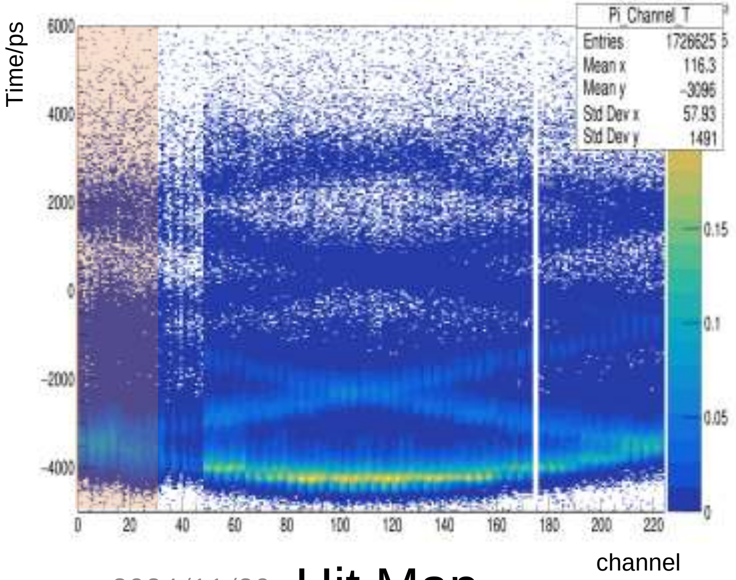
# Beam test  Introduction

Hit point:

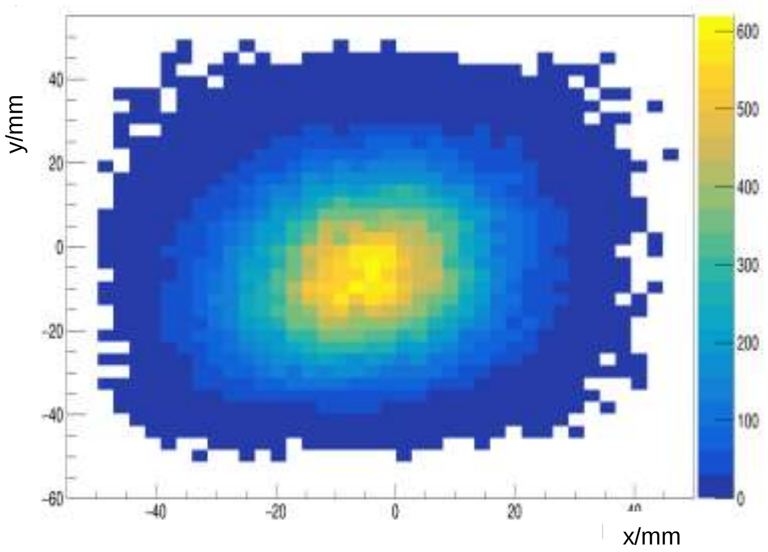
$TOF = reference\ time + 1450mm/(\beta c)$

Reference point:
1450mm to DTOF



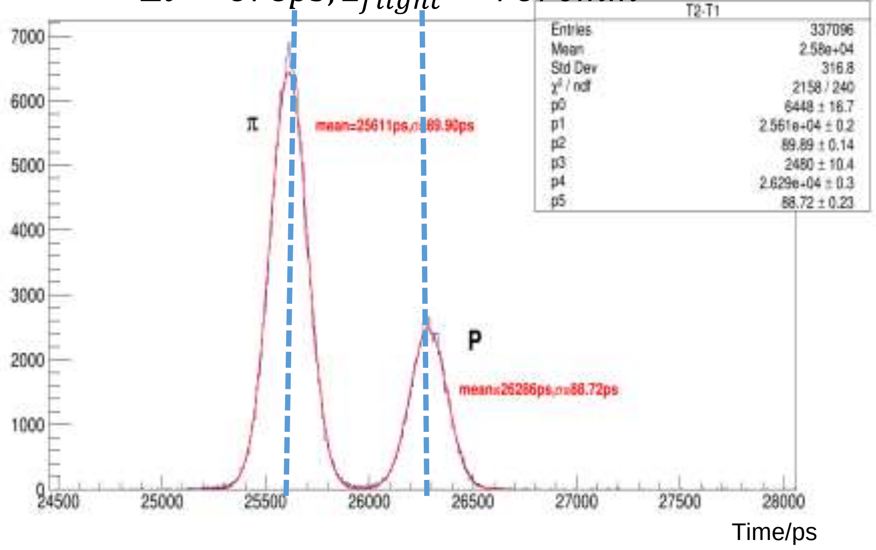




 Hit Map



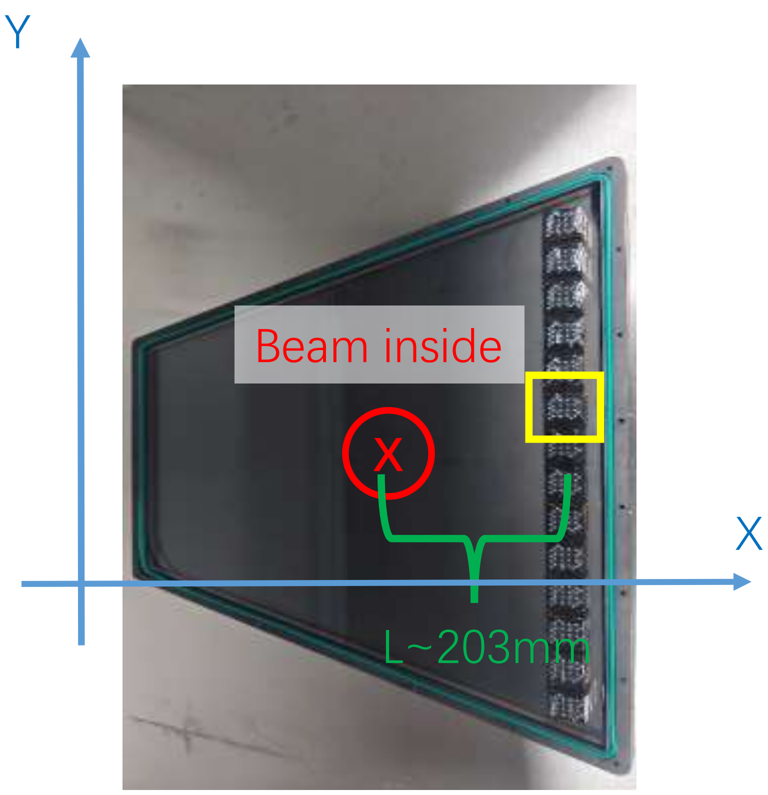

Tracker extrapolate point @DTOF

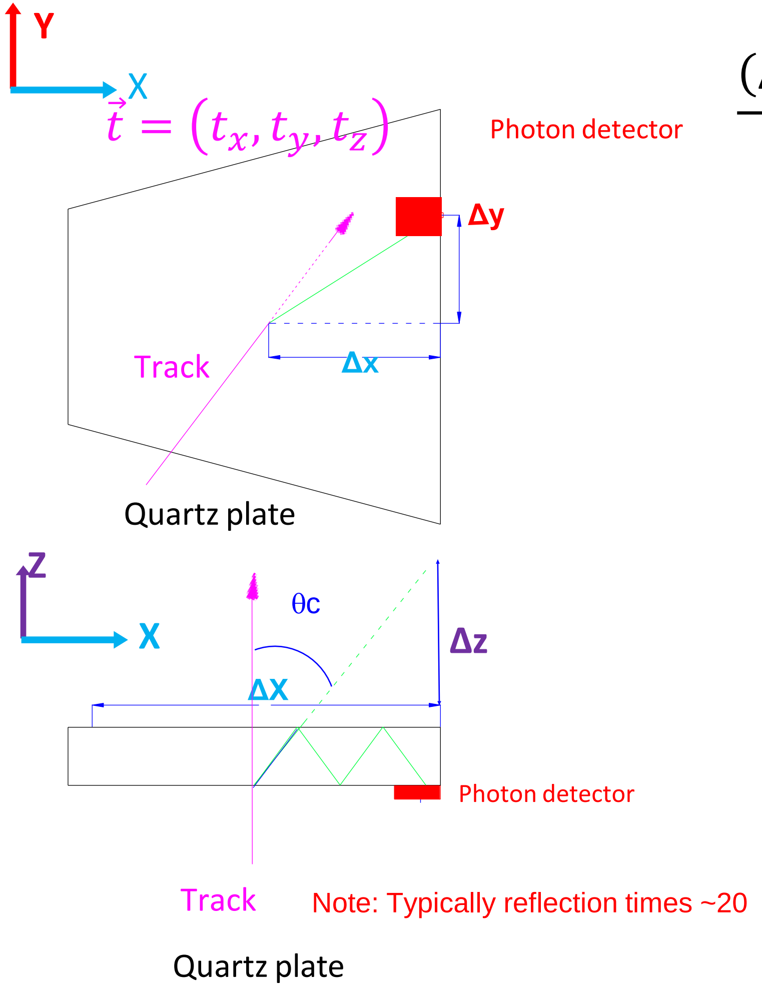
$\Delta t = 678ps, L_{flight} = 7670mm$




T0 separation for $\pi$/P

# Time reconstruction algorithm



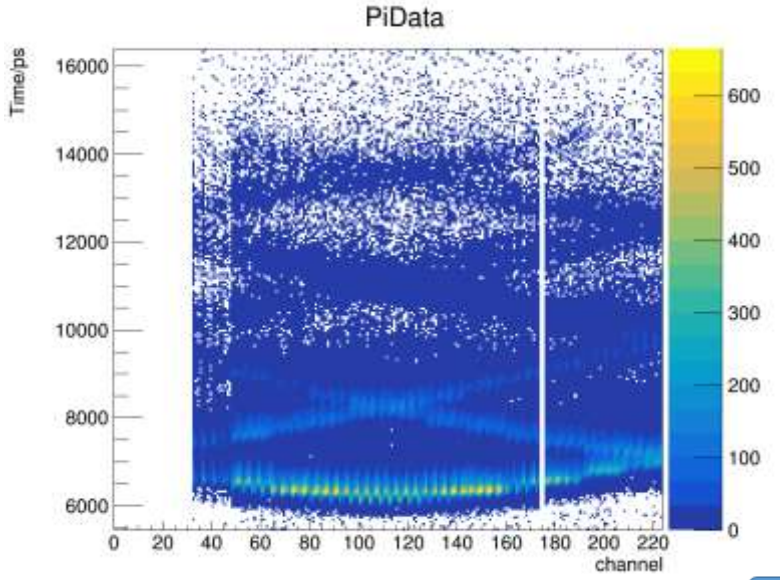

$$\frac{(\Delta x, \Delta y, \Delta z) \cdot (t_x, t_y, t_z)}{\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}} = cos(\theta_c)$$

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

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

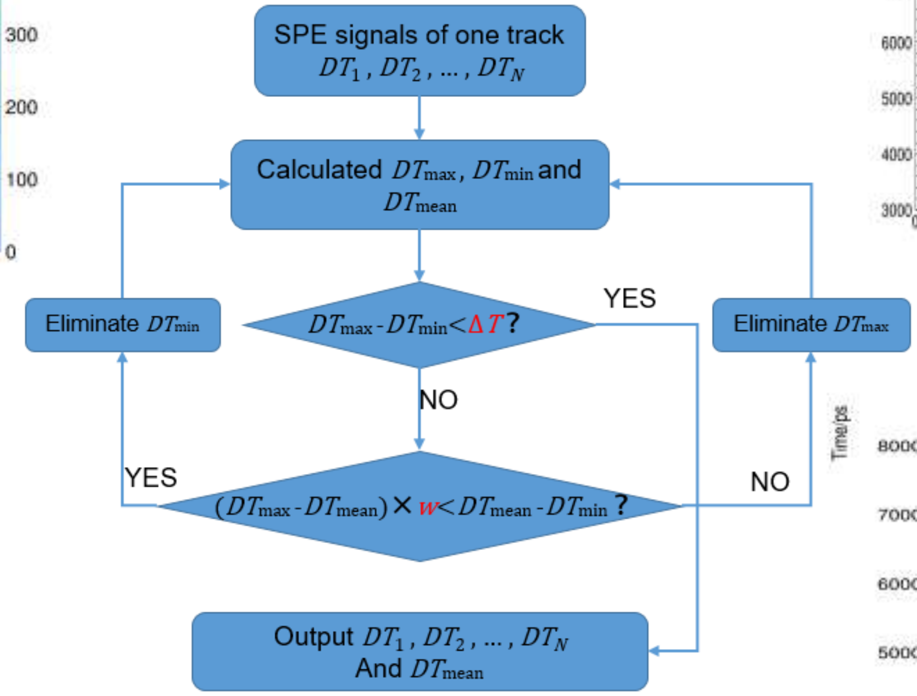
$$\mathrm{Time} = \mathrm{T_{ch}} - \mathrm{TOP}$$

# Beam test result - time reconstruction

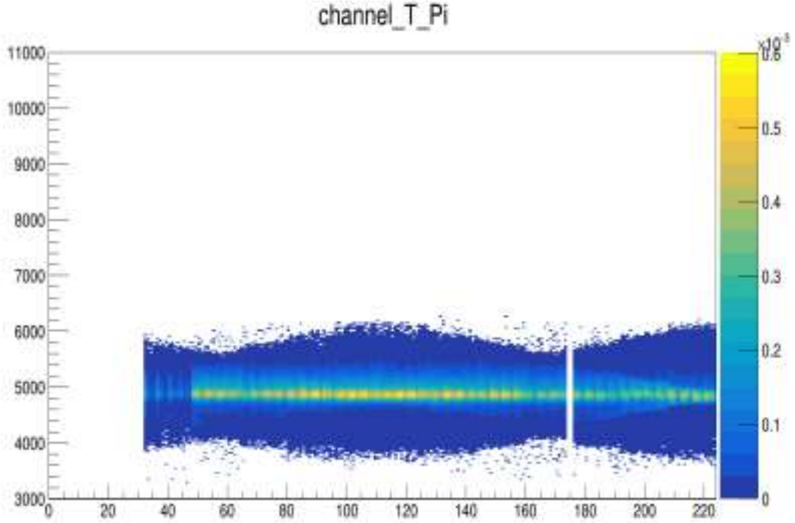



Hit Map

Reconstruction

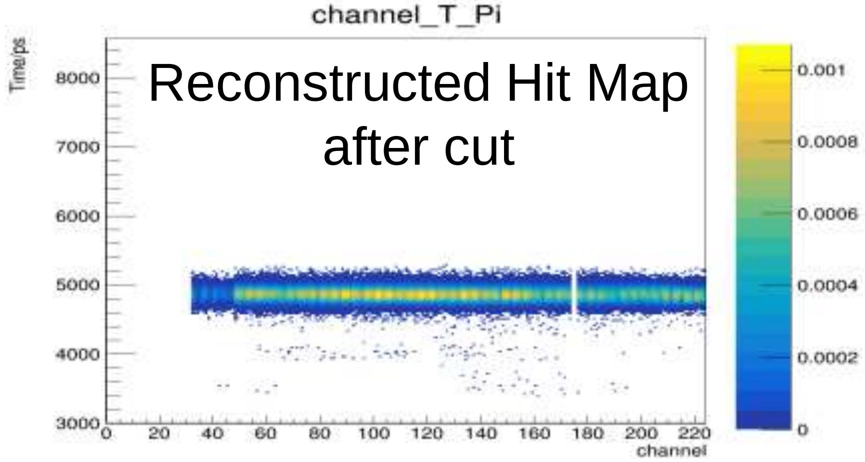



Two parameters, **$\Delta t$** and ***w***




Reconstructed Hit Map

Self-filtering




**Time reconstruction:**

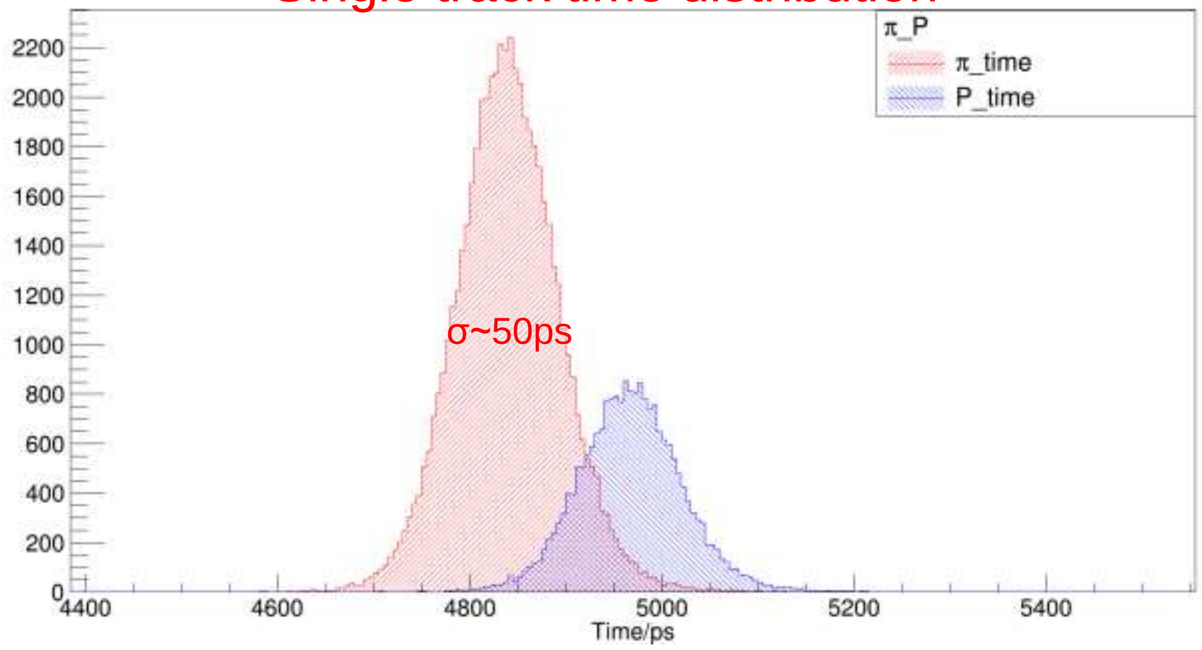
- A 200 ps time window cut for reconstructed data set

# Beam test result - time reconstruction

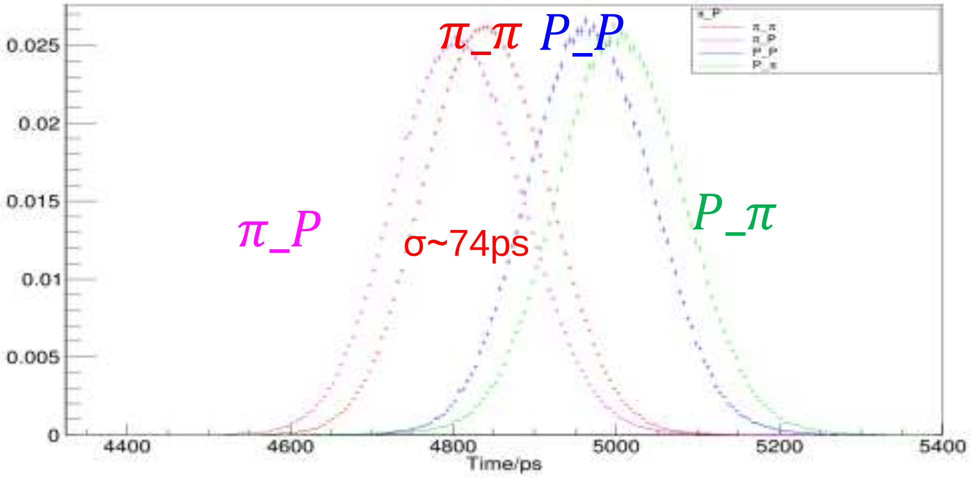
**Timing result :**

- For Pi/P, use Pi/P assumption separately

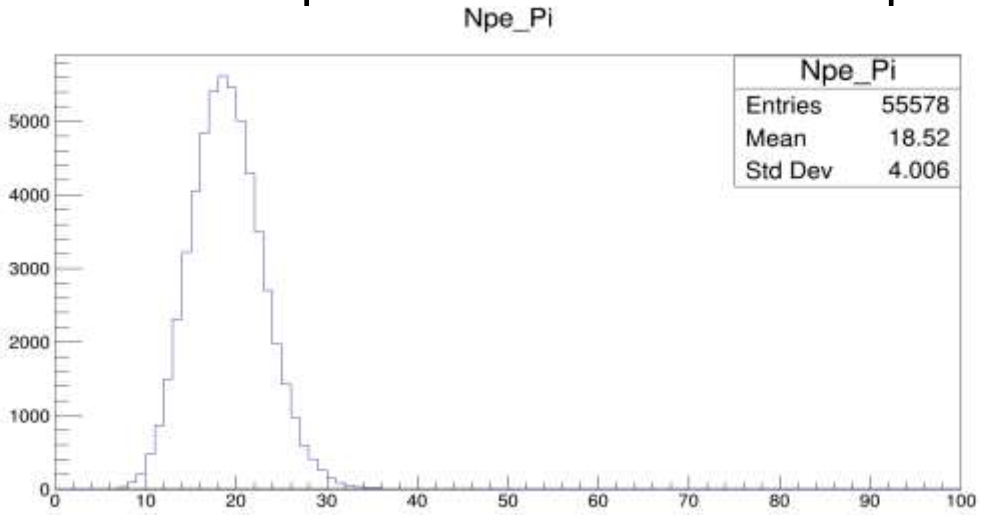
Single track time distribution




| L=1450mm | Exp/ps | Cal/ps |
|---|---|---|
| Pi | 4839.2 | 4839.6 |
| P | 4967.1 | 4967.8 |




Single photon time distribution result
for different particle with each assumption




Number of photons(Pi after cut)



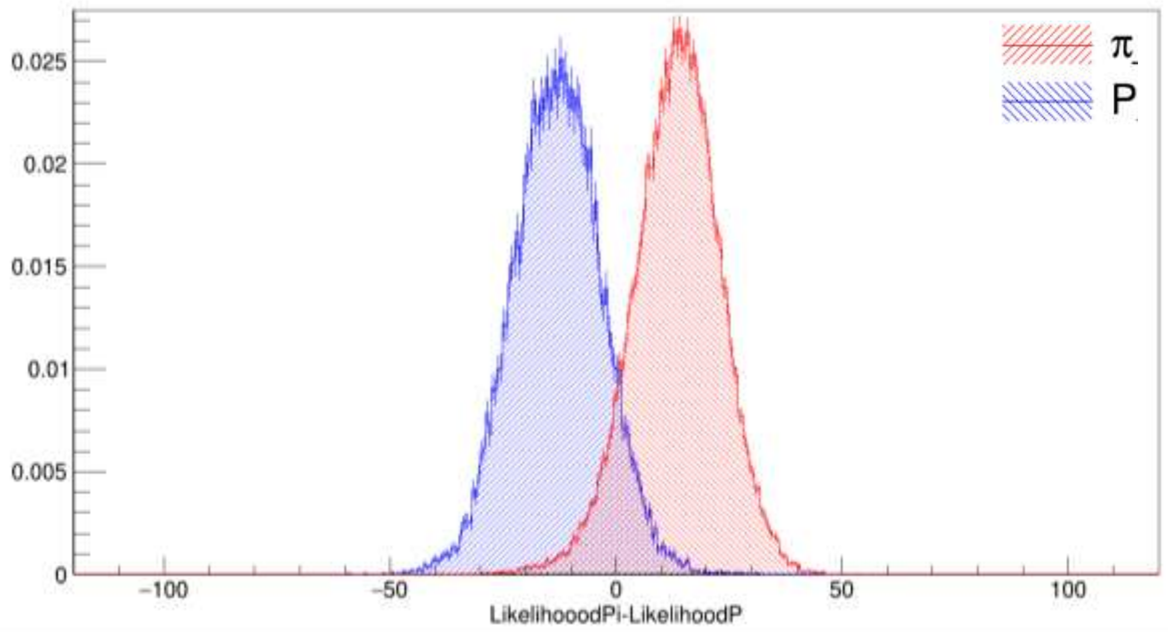
Considering the time $\sigma_t \sim 45ps$,the intrinsic $\sigma_{DTOF} \sim 23ps$

# Beam test result - time reconstruction

**Timing likelihood :**

- For each event: calculate the likelihood

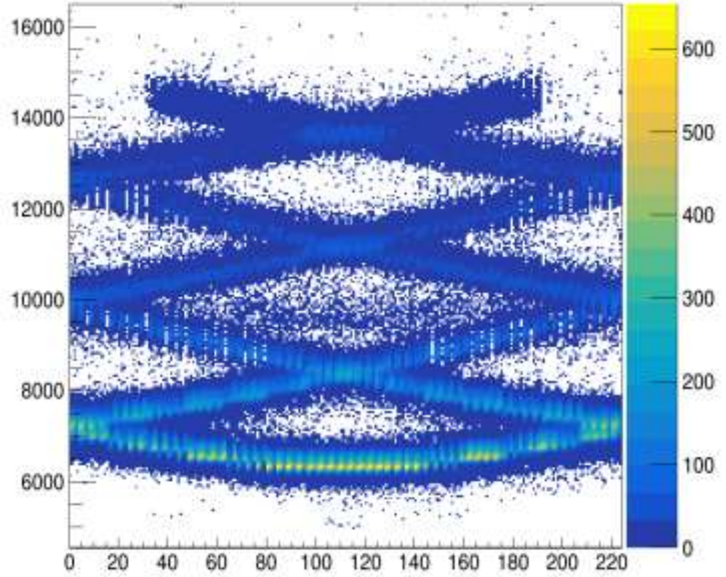
$$\mathcal{L}_h^{TL} = p_h(N)\prod_{i=0}^{N} f_h(TOF_i)$$



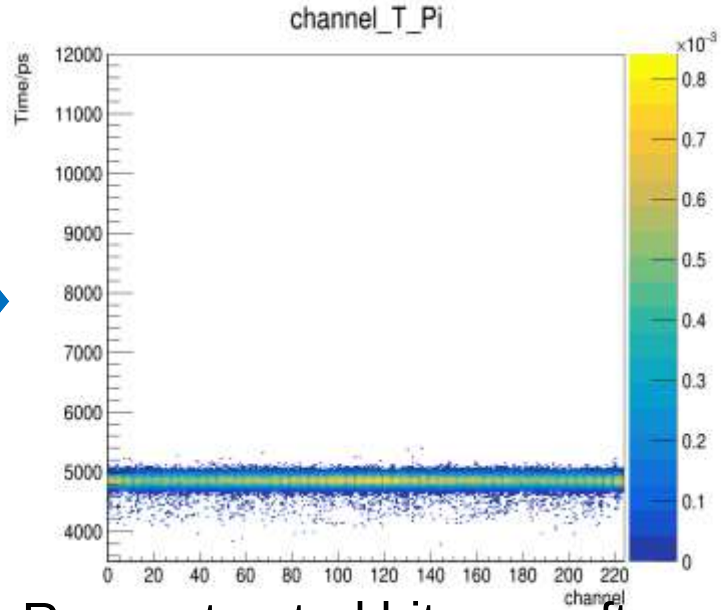

Likelihood Pi/P distribution

Separation power~3.25σ

# Simulation result

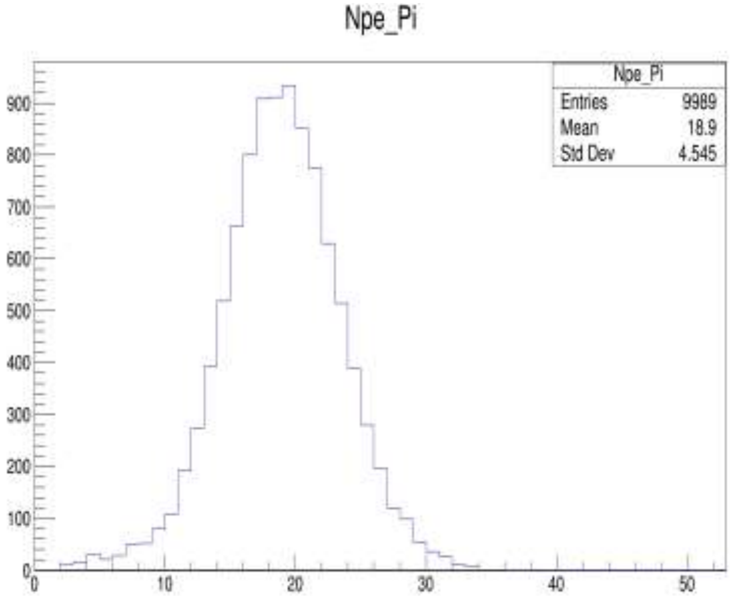



Hit Map

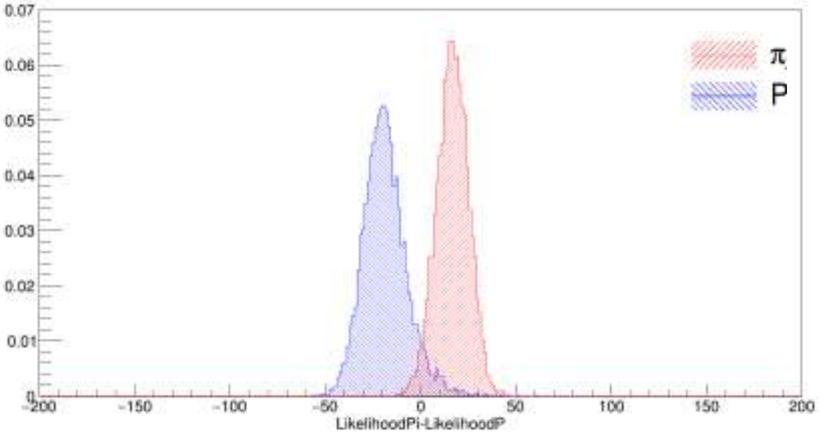


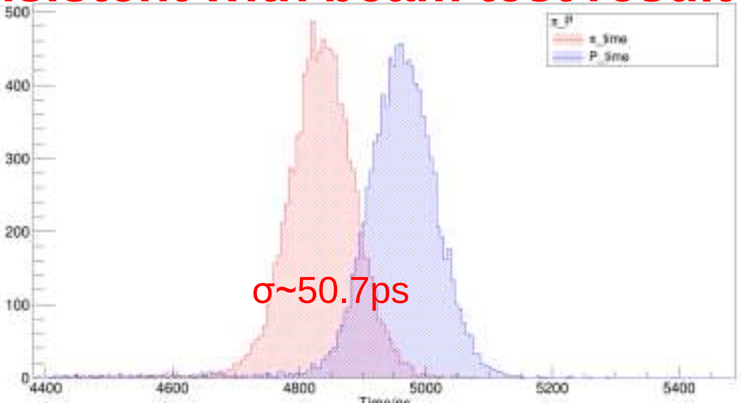

Reconstructed hit map after cut

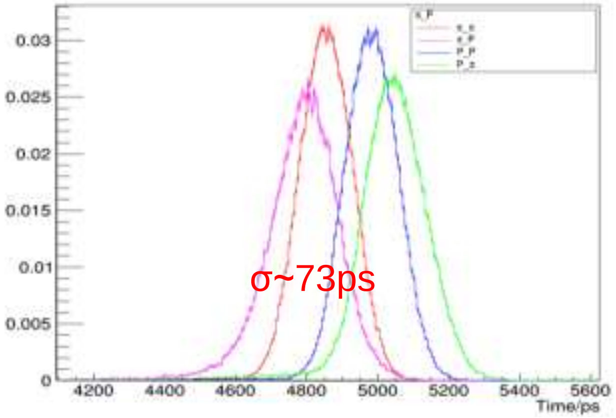
**Consistent with beam test result!**




Number of PE distribution






Separation power~3.2σ

Single track distribution

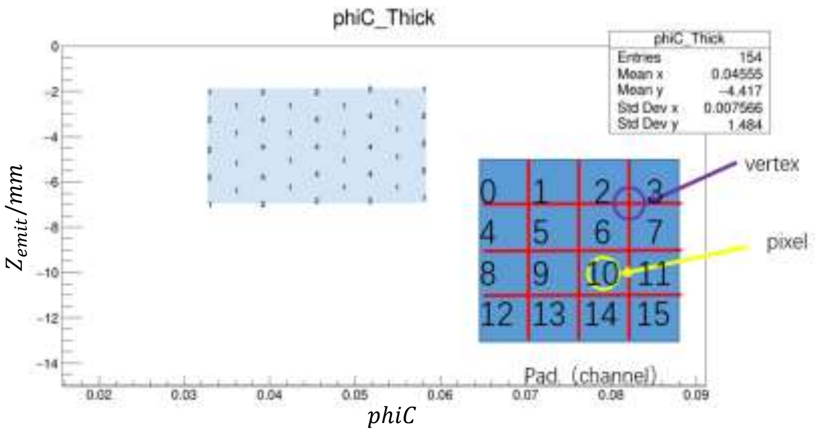
Single Photon distribution

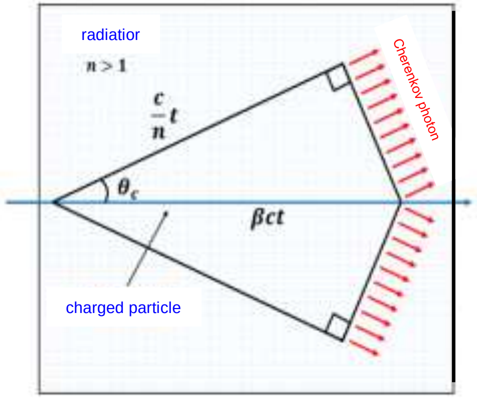
# 2D likelihood algorithm-Imaging algorithm

**2D likelihood:**

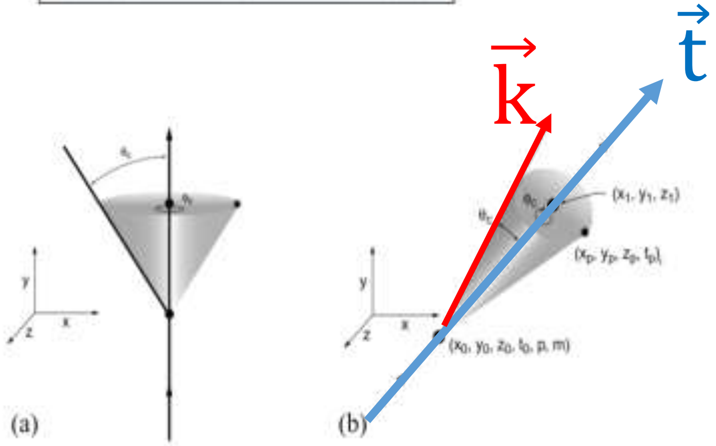
- Time algorithm cannot meet the requirement~3.3σ
- Use the channel information
- But Geant4 need over $10^5$ s to form a hit template

- Project channel vertexs to 2 dimension coordinate (phiC , Zemit)
- Pad area and hit time for each pad=>2D channel-Time map



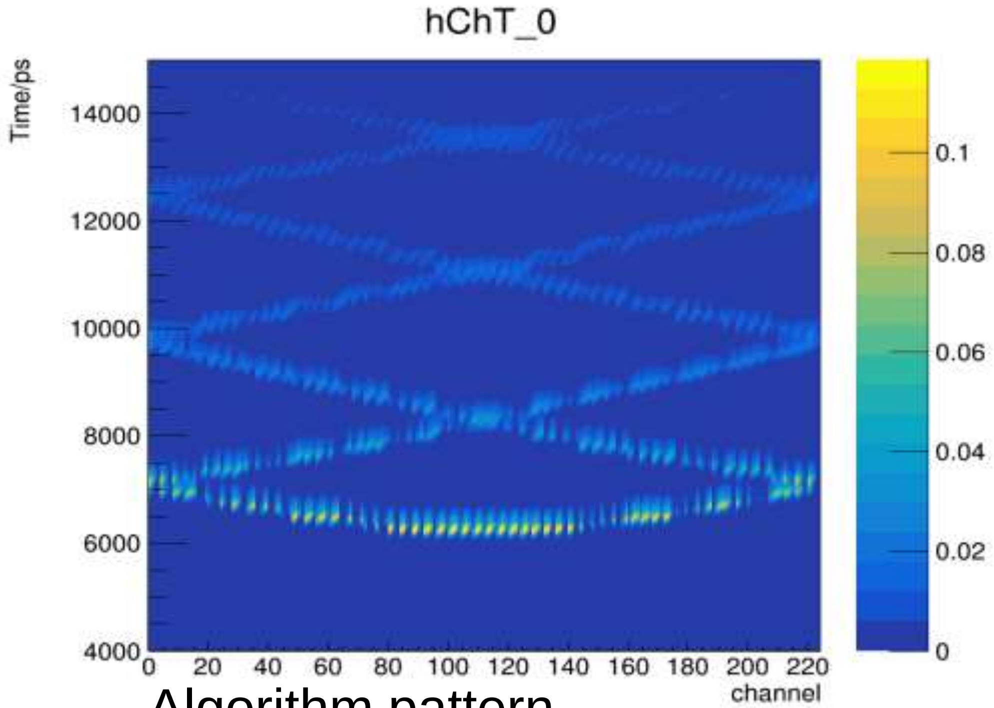




$$\vec{t} = \begin{cases} t_x = \sin\theta\cos\phi \\ t_y = \sin\theta\sin\phi \\ t_z = \cos\theta \end{cases}.$$

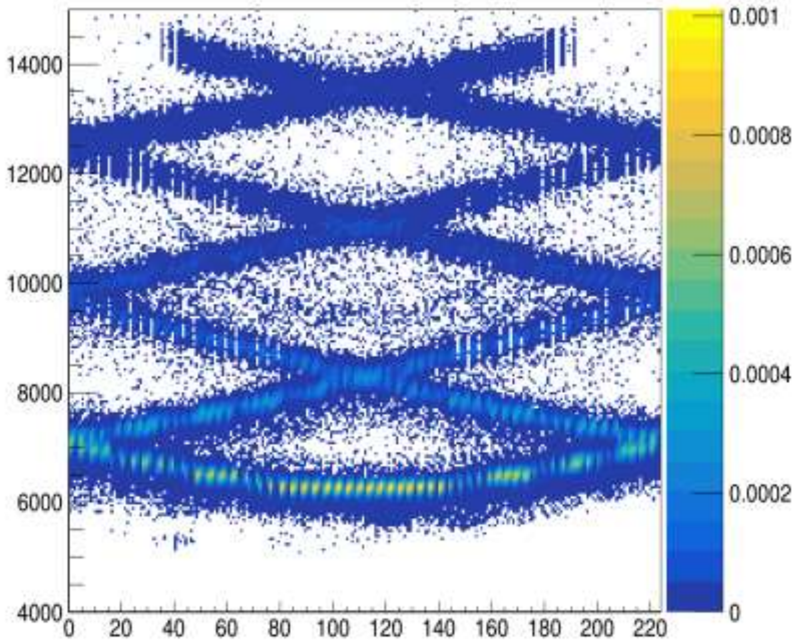



Cherenkov photons are uniformly distributed in phiC and transportation dimension!

# 2D likelihood algorithm-Imaging algorithm




Algorithm pattern



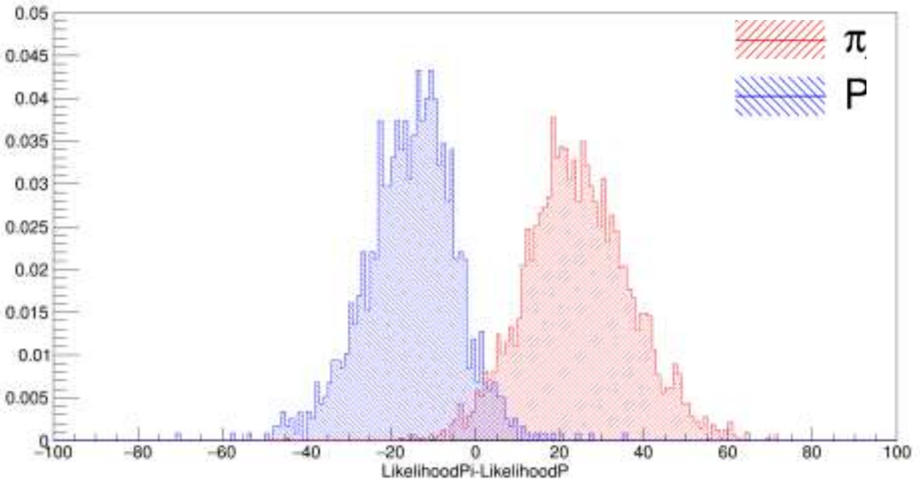

Geant4 simulation pattern

**2D likelihood:**

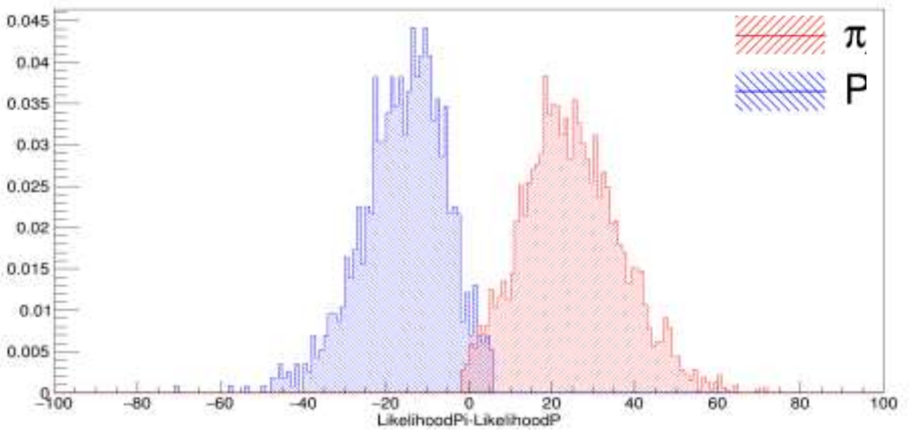
- Compare with Geant4 Simulation for fixed hit point (0mm,0mm) and perpendicular to the DTOF prototype
- Patterns are consistent well

Can reduce the process time to 2s/event!

# 2D likelihood result-Imaging likelihood




2D likelihood result ~3.5σ@ 99.93% efficiency




2D likelihood result ~4.0σ@ 98.4% efficiency

**Result:**

- ~3.5/4.0 σ separation (at 99.9%/98.4% efficiency)
- Slightly worse than simulation, Possible reasons
  - PMT crosstalk
  - Tracker calibration
  - Alignment
  - Average flight distance for Pi/K in STCF is 1650mm, which is set to 1450mm in beam test (in order to accord with the z-dimension distance)

# Summary

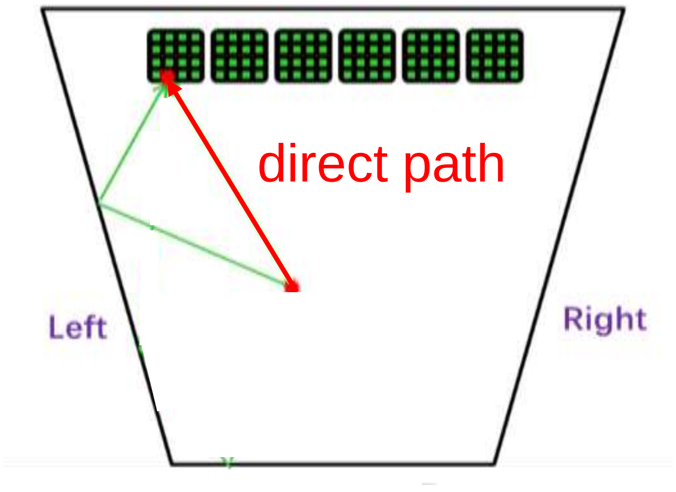
- We proposed the 1/3 DIRC-like TOF (DTOF) detector for beam test @CERN
- The expected performance of the DTOF detector was simulated, and compared with the beam test result, the result agreed with each other.
- Time reconstruction method was used to separated Pi/P@4GeV. A 3.3σ separation was achieved.
- Imaging reconstruction achieved 4σ separation power for Pi/P@4GeV, with an efficiency of 98.4%.
- More detailed study and calibration ongoing…

Thanks for your attention!

# BACK UP

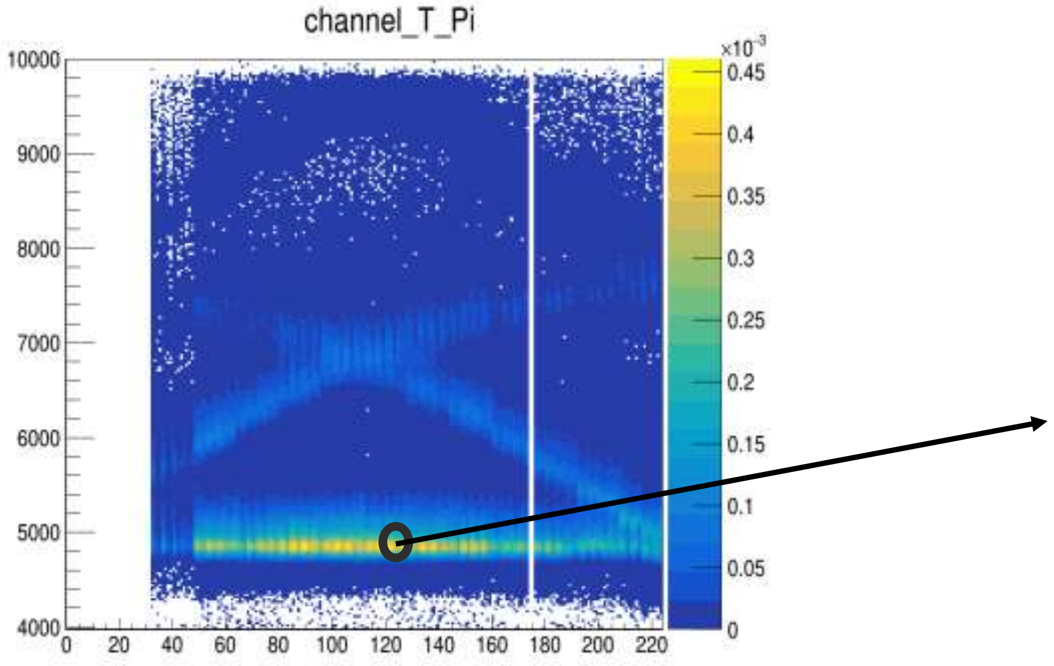
BACKUP

# System calibration

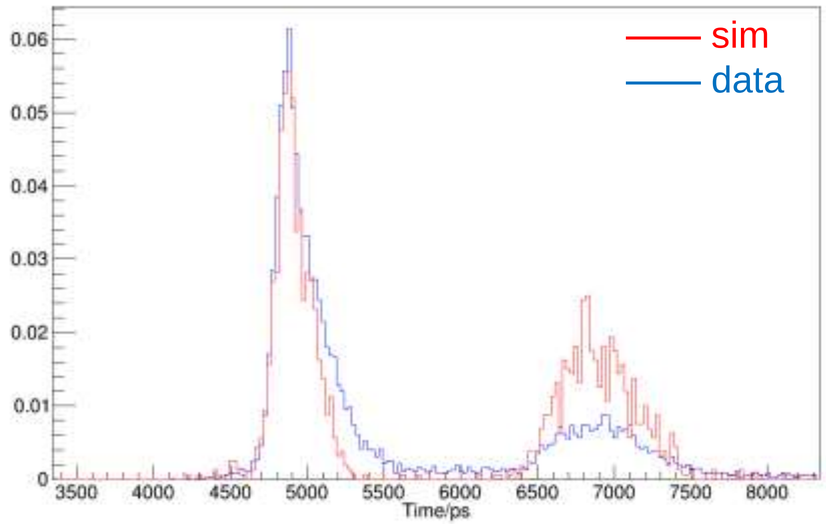



**Calibration for channels:**

- For each channel, use the "direct path" reconstruction

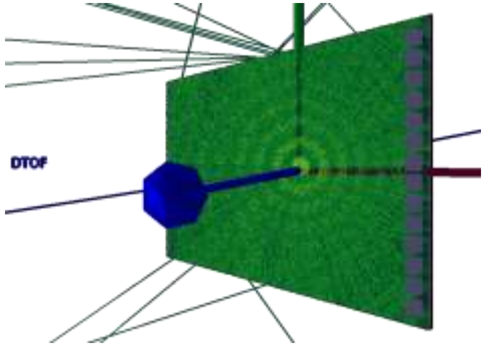



Beam test data



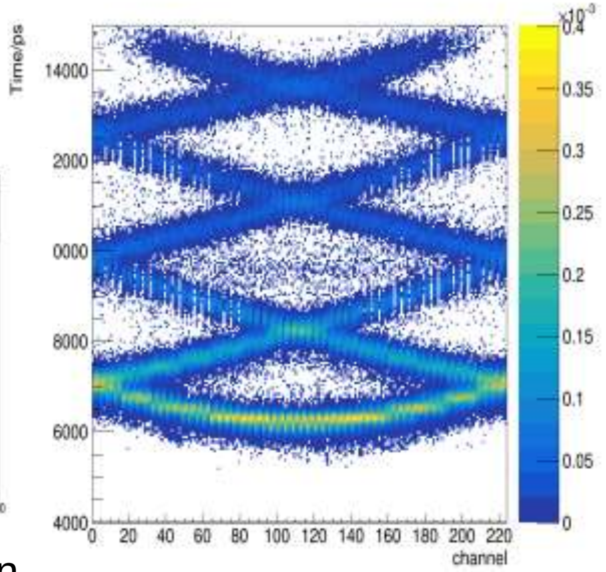

Channel 126 (as example)

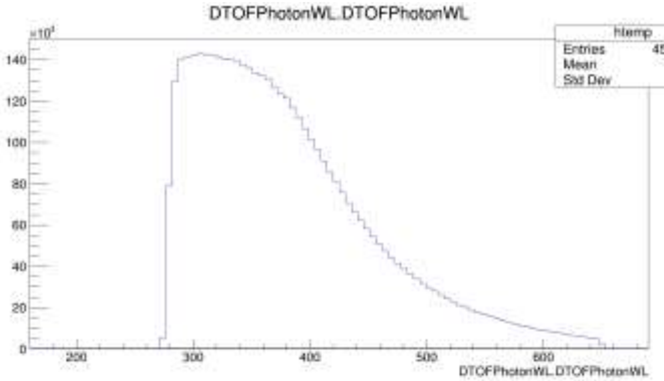
# Beam test Simulation



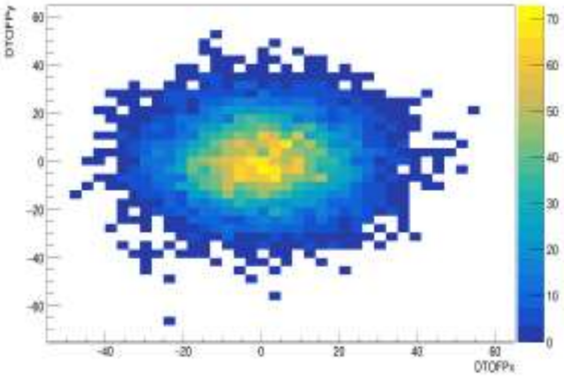

**Geant4 Simulation setup:**

- 4GeV Pi/P from $z = -1450mm$
- Wavelength:280-600nm
- A 8mm thickness shell
- Surface roughness SigmaAlpha ~ 0.1deg
- Track hit point ~2D Gaus(mean=0,sigma=14mm)
- PMT time response function:
  - 67%*Gaus(t,0ps,28ps)+33%*Gaus(t,135ps,135ps)

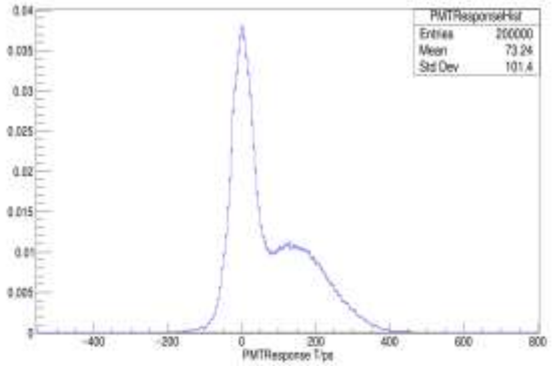



Wavelength distribution@sim

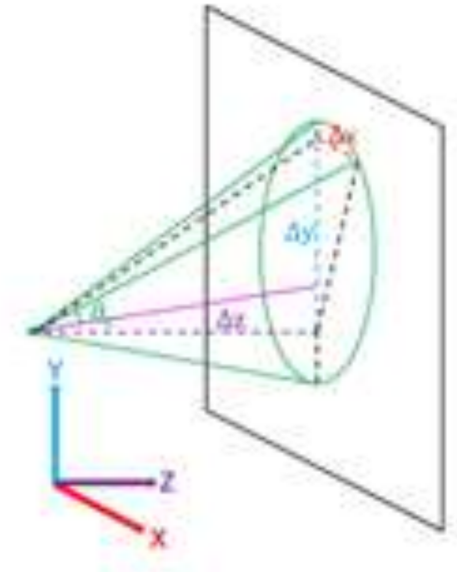


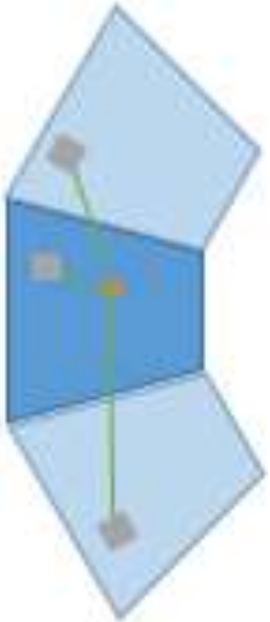

Hit x-y@sim

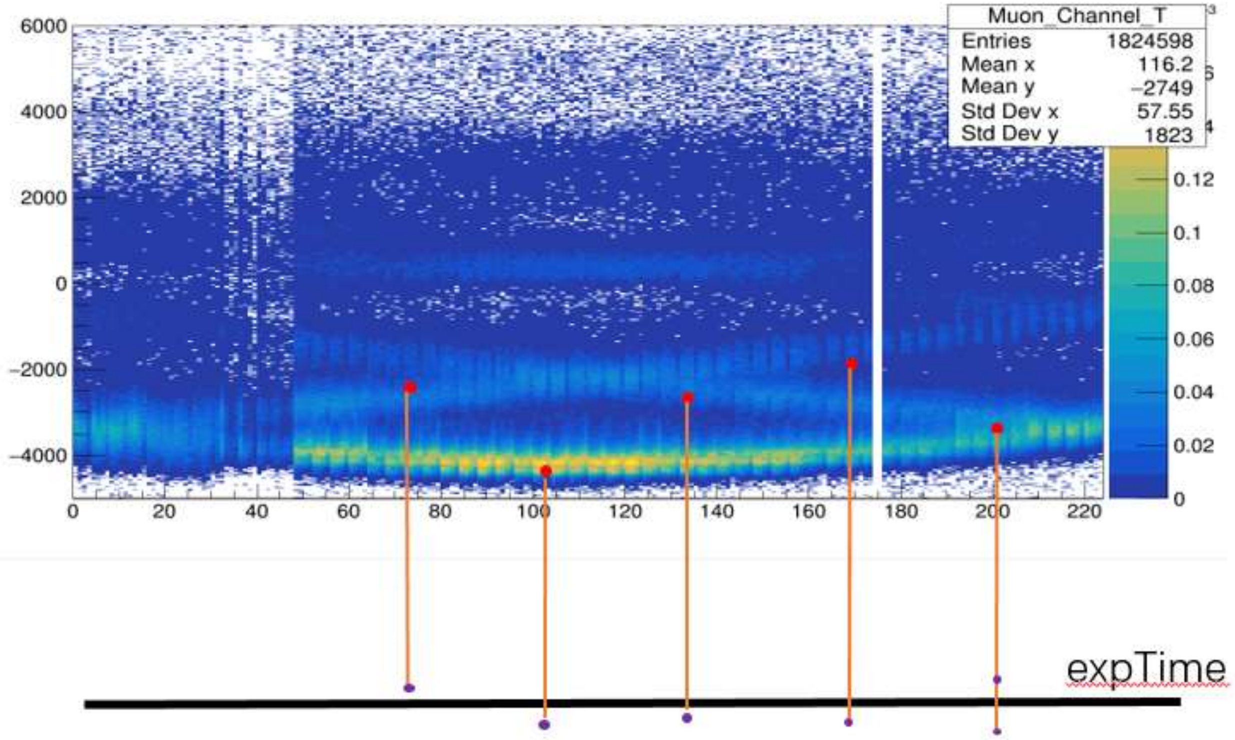


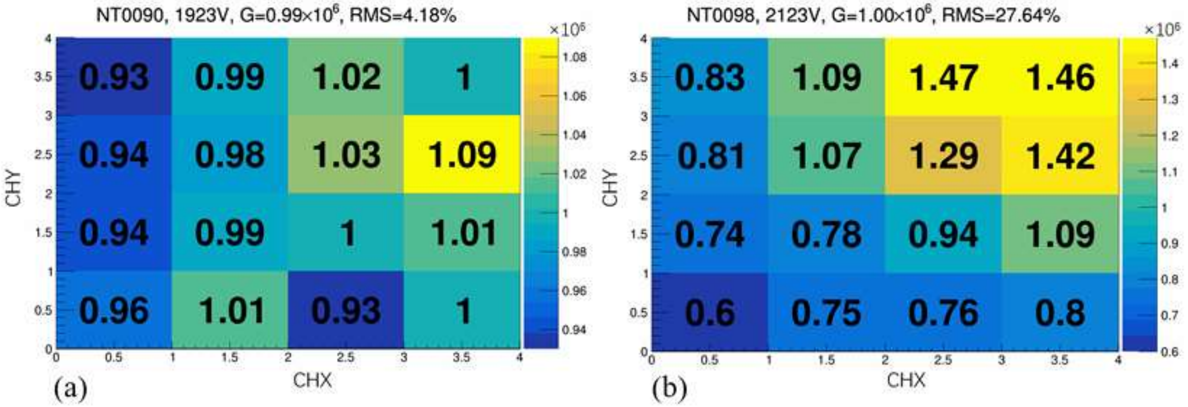

PMT response Time distribution

Hit map@sim

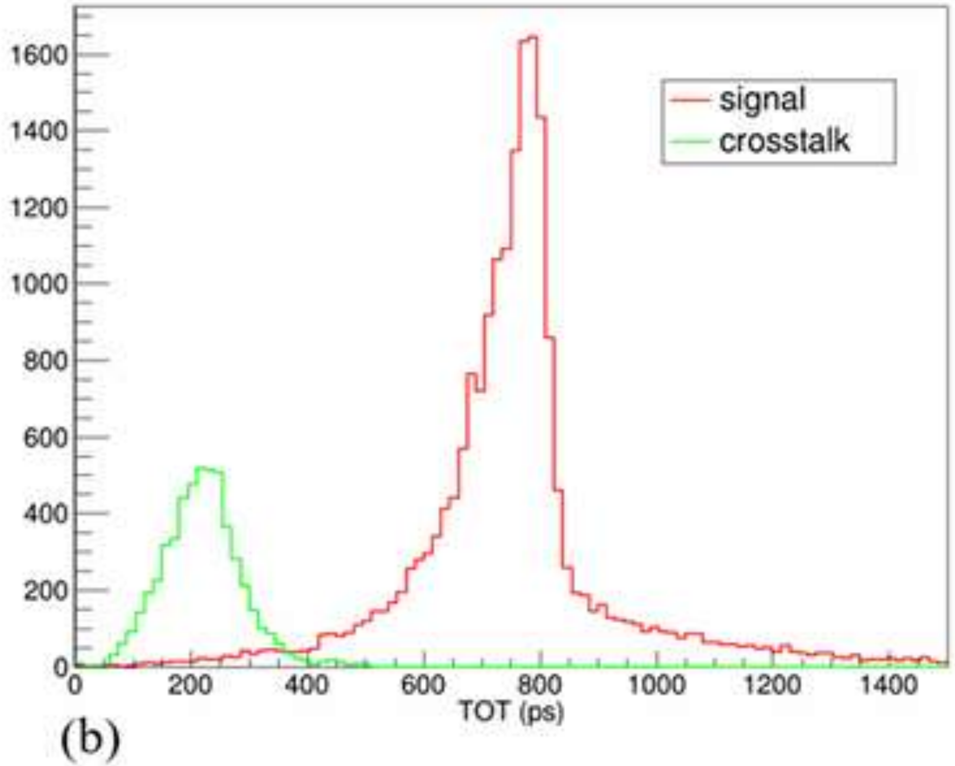

Y
Z
X



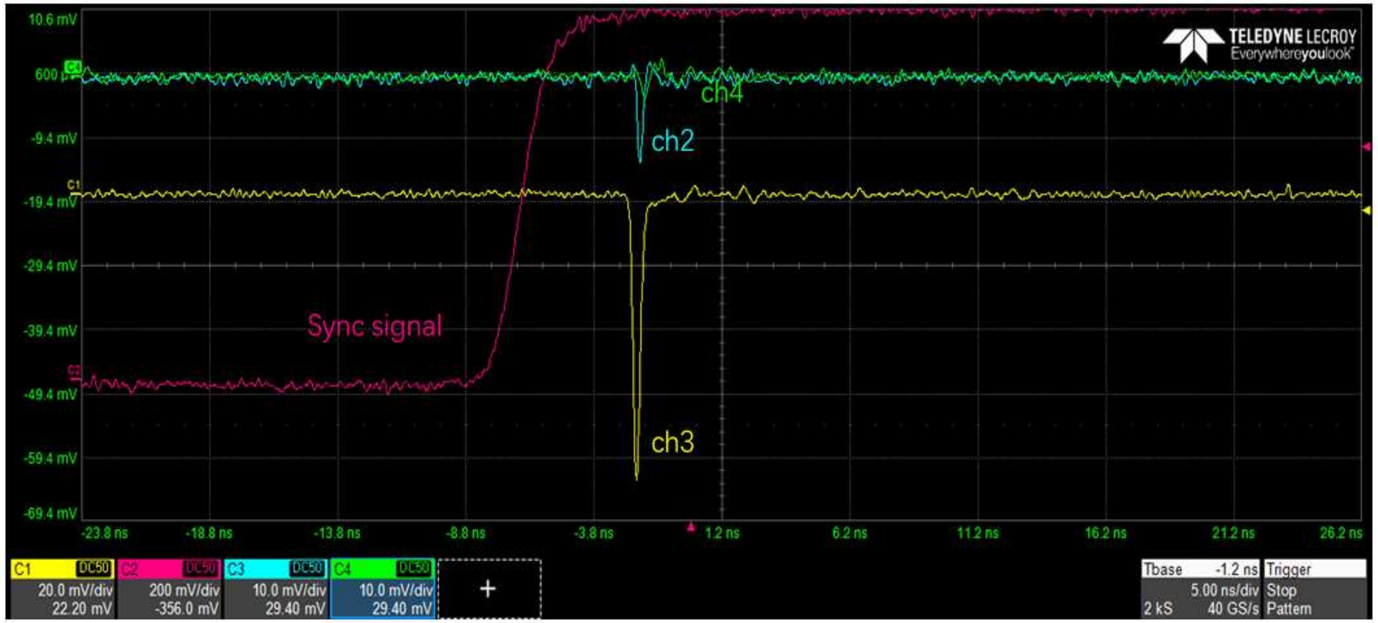

Muon_Channel_T
Entries 1824598
Mean x 116.2
Mean y -2749
Std Dev x 57.55
Std Dev y 1823
6000
4000
2000
0
−2000
−4000
0
20
40
60
80
100
120
140
160
180
200
220
0.12
0.1
0.08
0.06
0.04
0.02
0
expTime

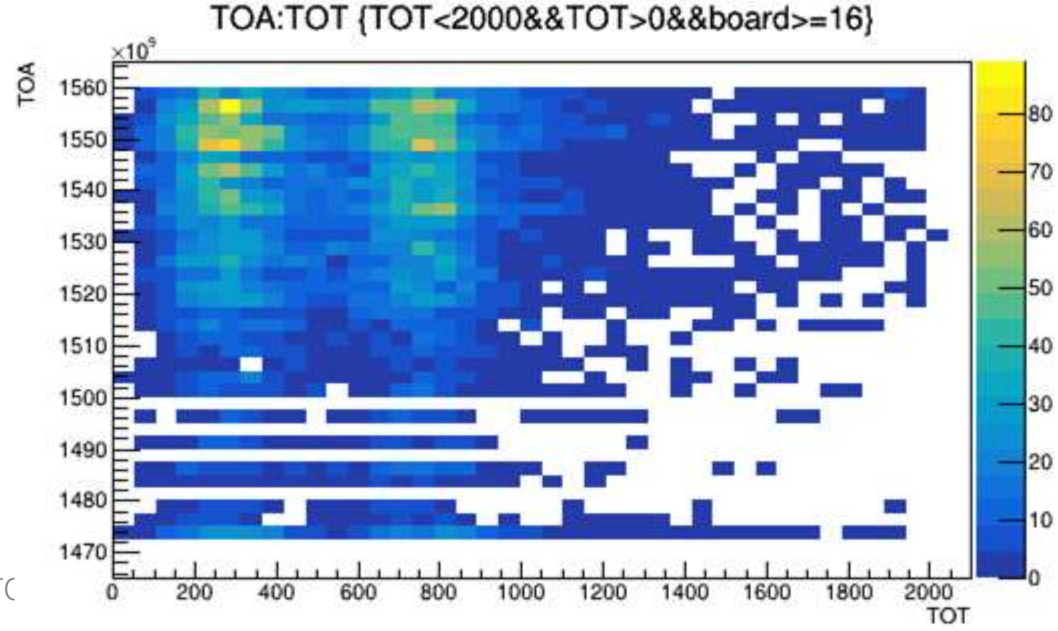

Gain Uniformity for MCP-PMT
($1{:}10^6$)

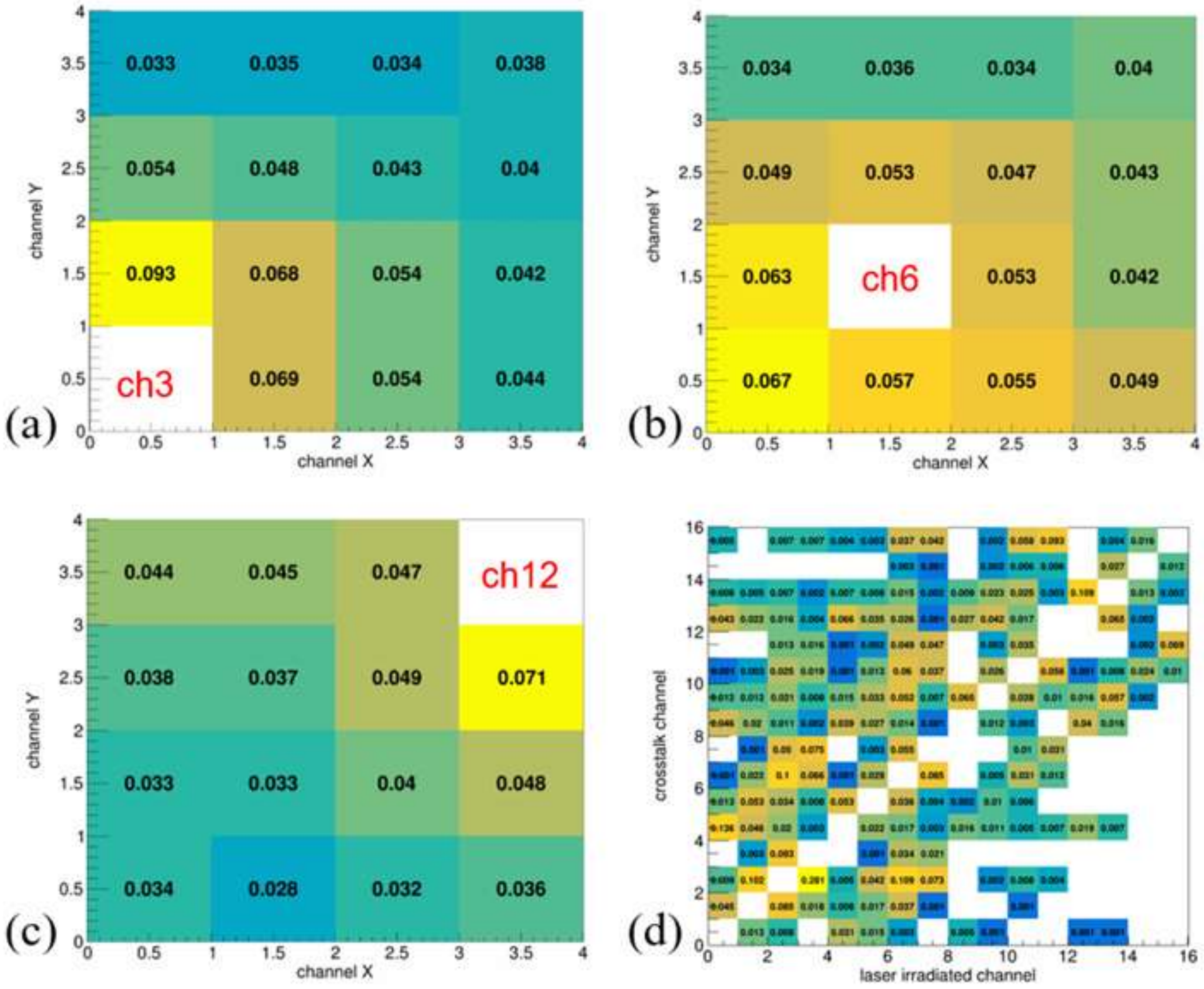



MCP-PMT TOT and cross talk

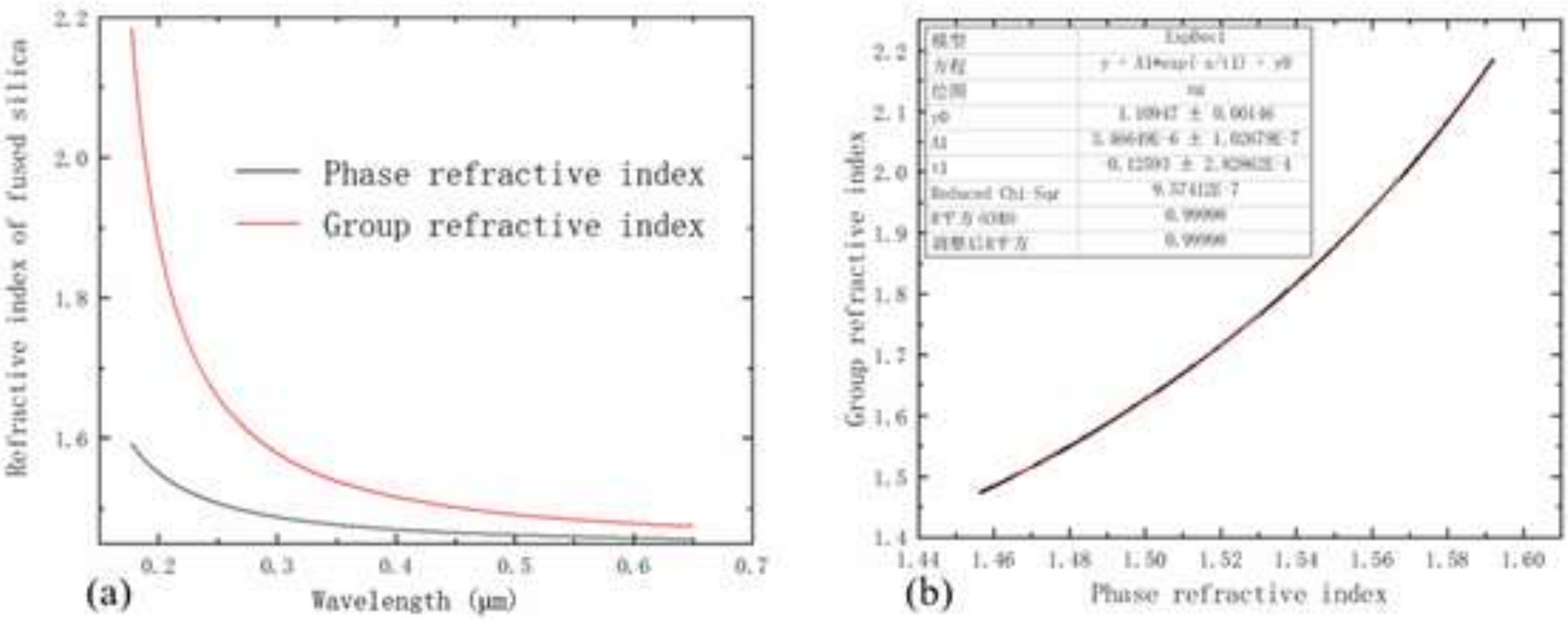


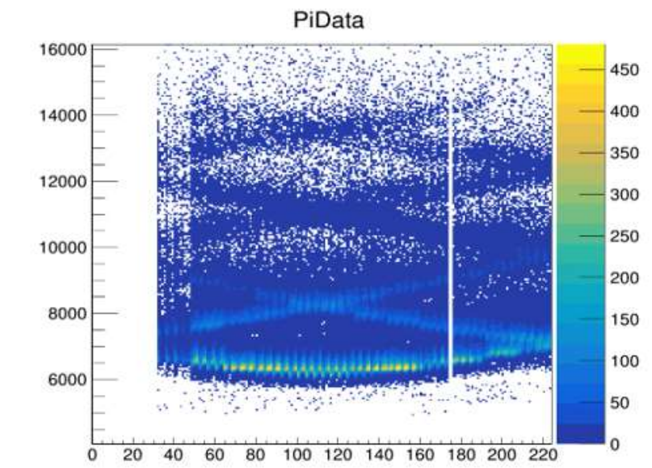

cross talk channel 4

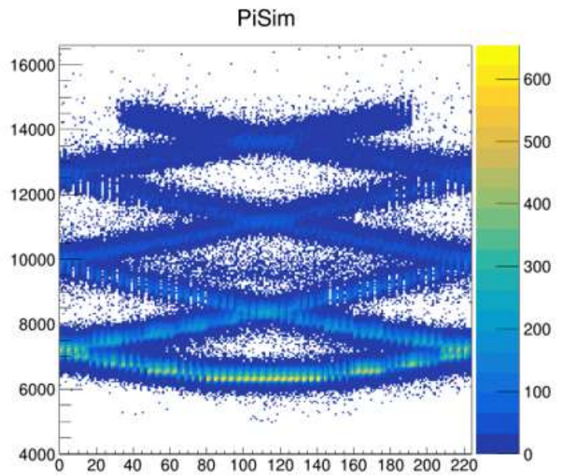


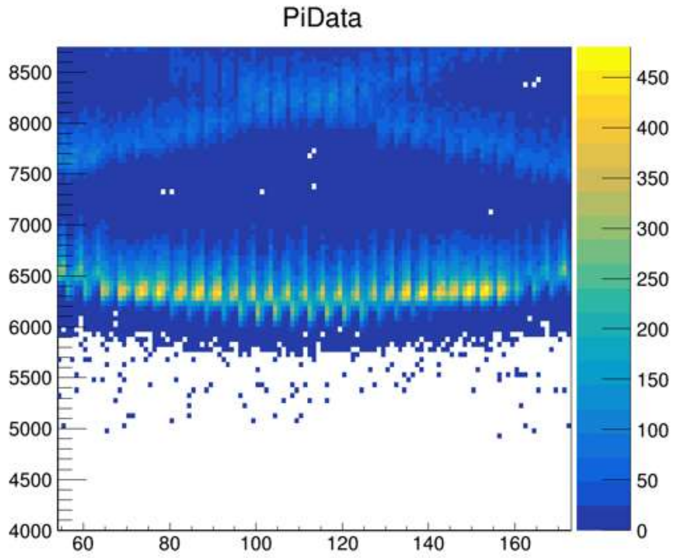


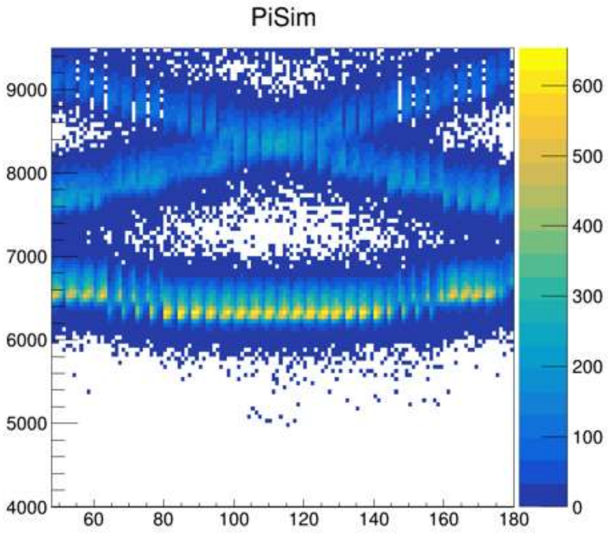

signal/cross talk amplification ratio

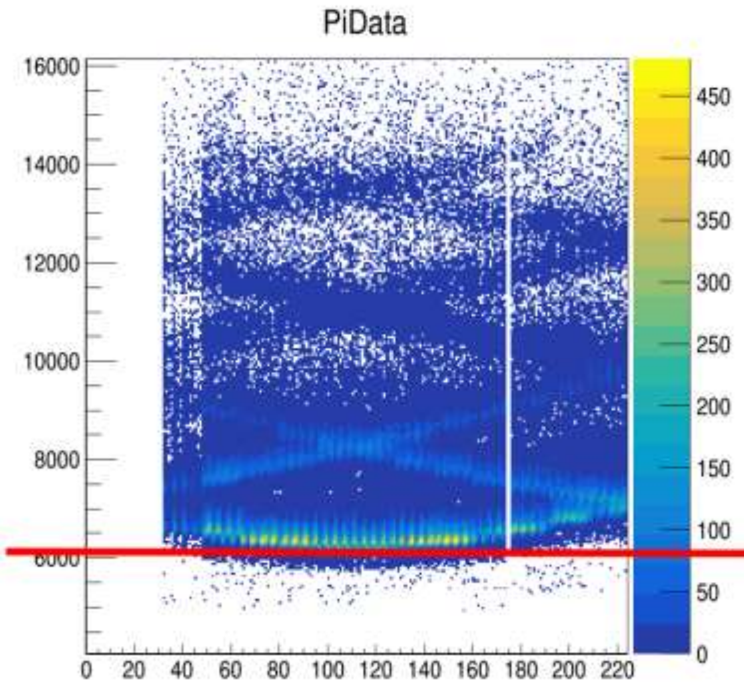

Refractive index of fused silica
Phase refractive index
Group refractive index
Wavelength (μm)
(a)
Group refractive index
Phase refractive index
(b)
模型
方程
Reduced Chi-Sqr

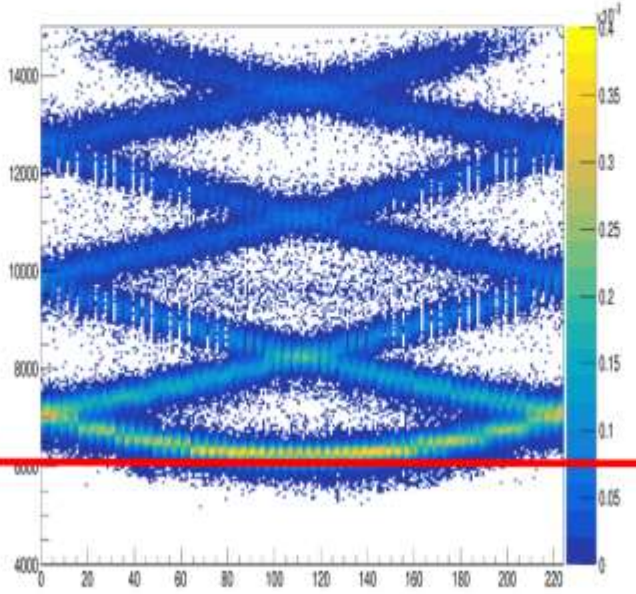

PiData
16000
14000
12000
10000
8000
6000
0 20 40 60 80 100 120 140 160 180 200 220
450
400
350
300
250
200
150
100
50
0


PiSim
16000
14000
12000
10000
8000
6000
4000
0 20 40 60 80 100 120 140 160 180 200 220
600
500
400
300
200
100
0

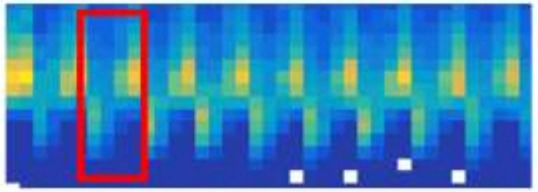

PiData
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
60 80 100 120 140 160
450
400
350
300
250
200
150
100
50
0

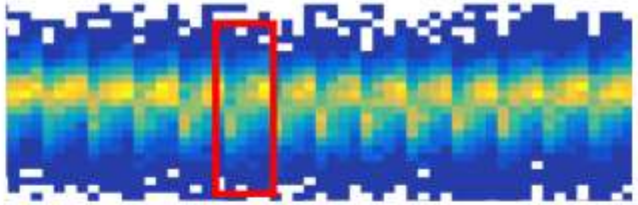

PiSim
9000
8000
7000
6000
5000
4000
60 80 100 120 140 160 180
600
500
400
300
200
100
0


PiData
16000
14000
12000
10000
8000
6000
0 20 40 60 80 100 120 140 160 180 200 220
450
400
350
300
250
200
150
100
50
0

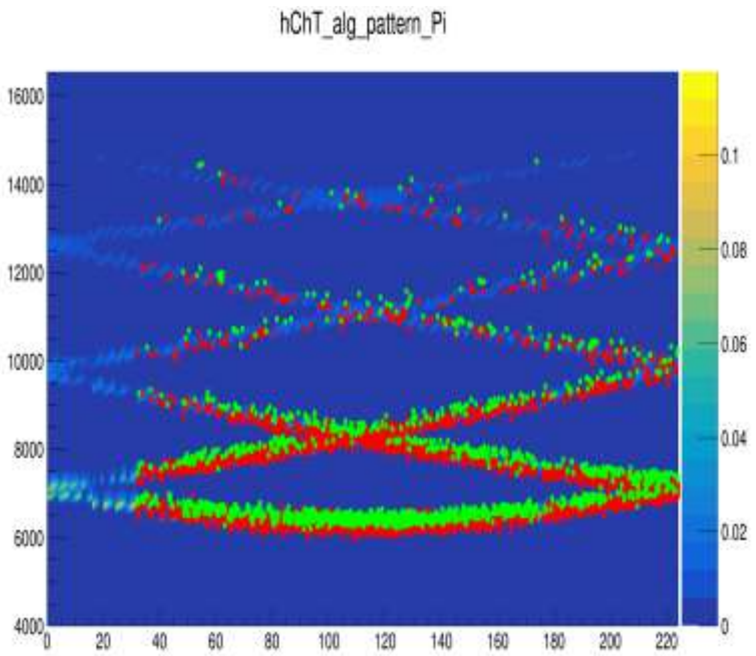

14000
12000
10000
8000
4000
0 20 40 60 80 100 120 140 160 180 200 220
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

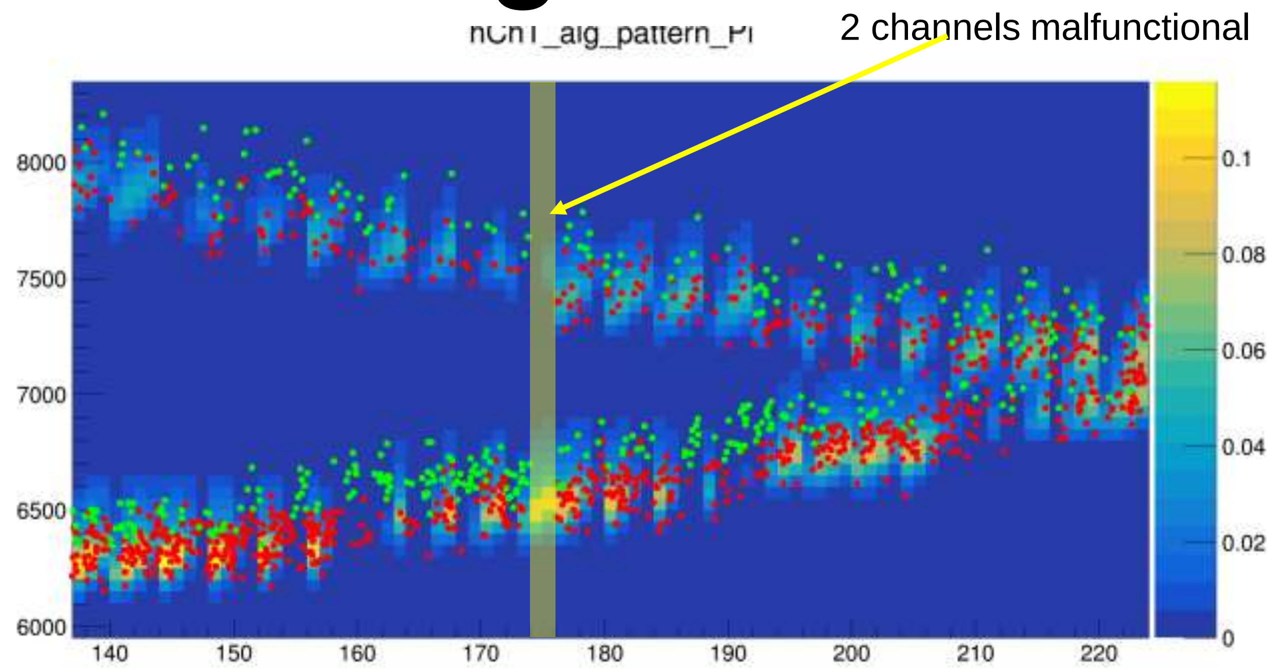
1.5*deg

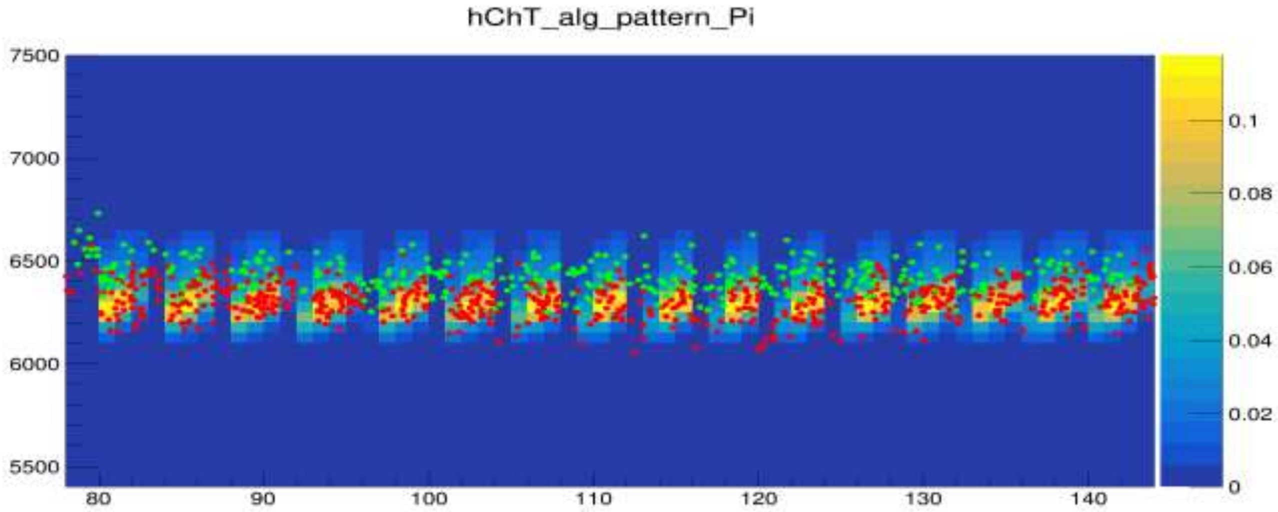




# Beam test 2D likelihood algorithm

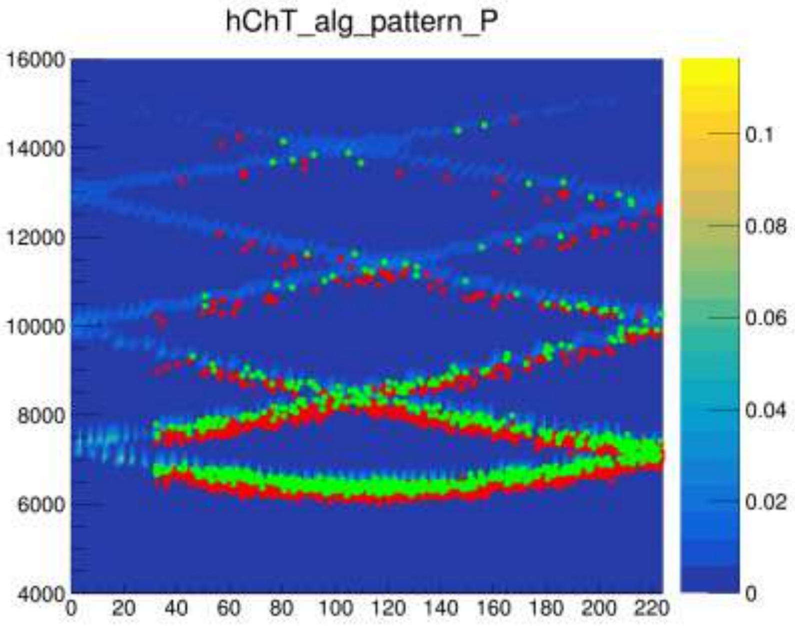


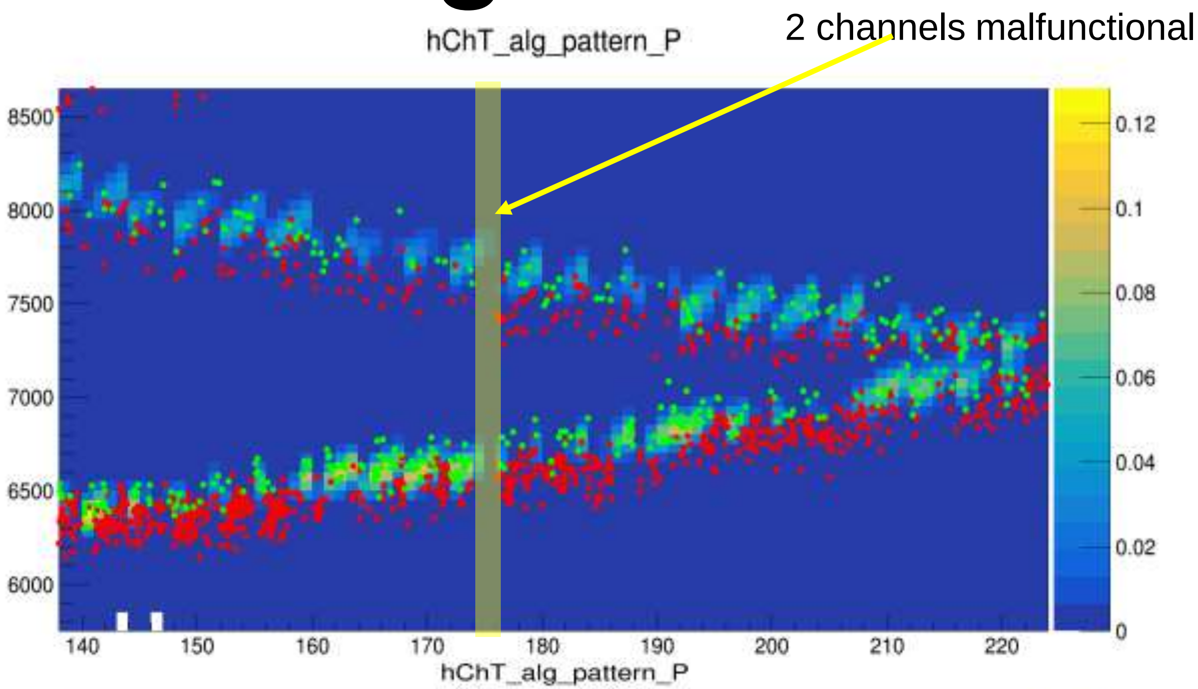



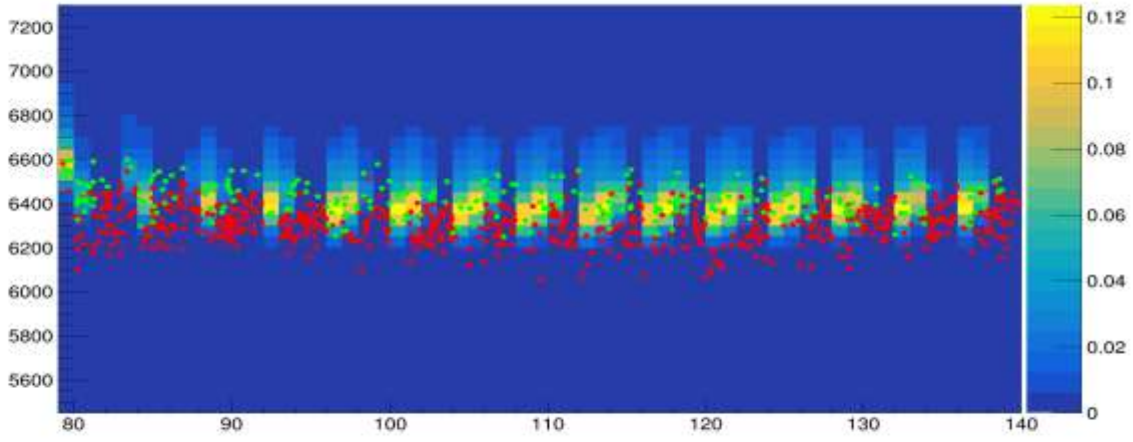




Red dot : Pi
Green dot : P as Pi

# Beam test 2D likelihood algorithm

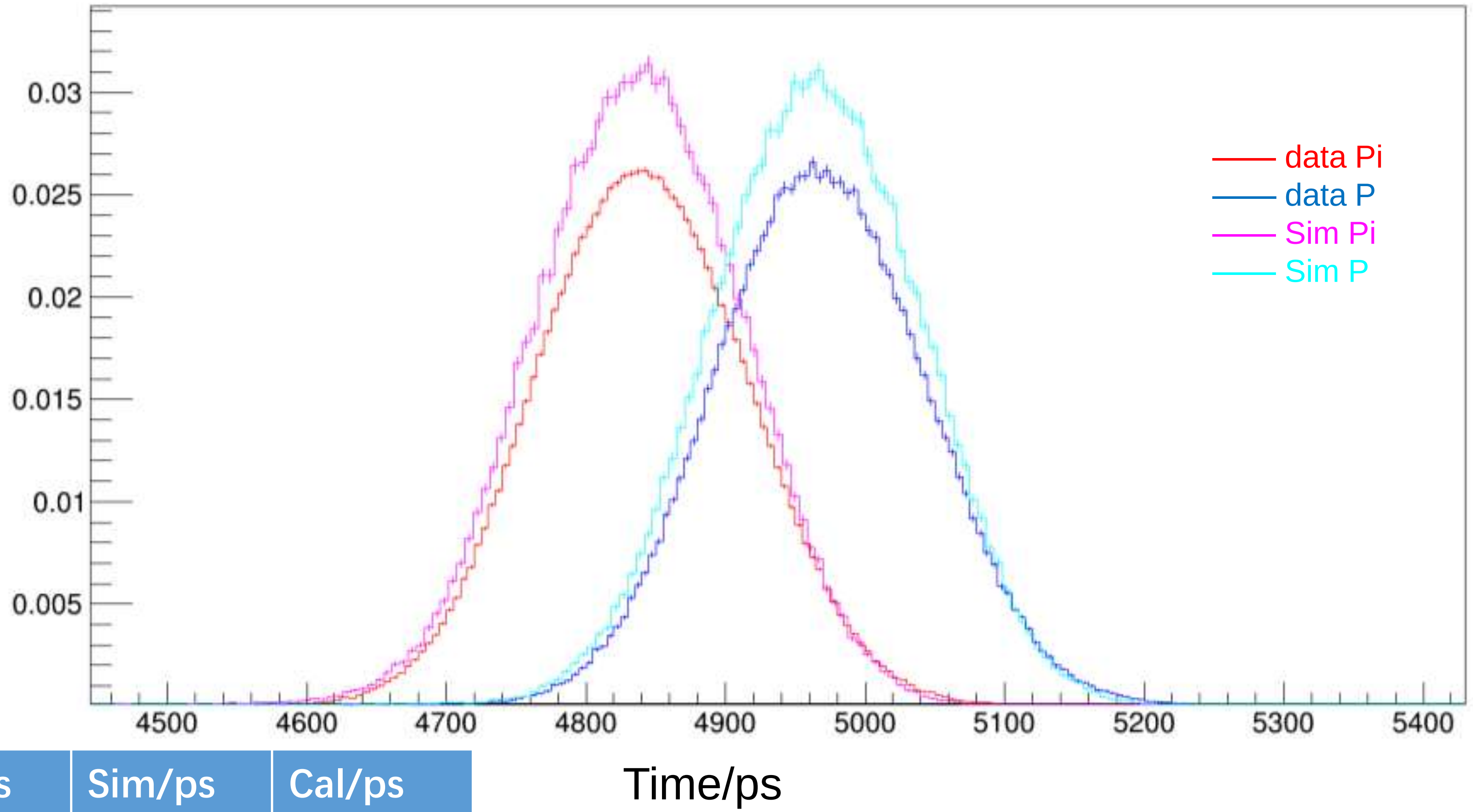



Red dot : Pi as P
Green dot : P

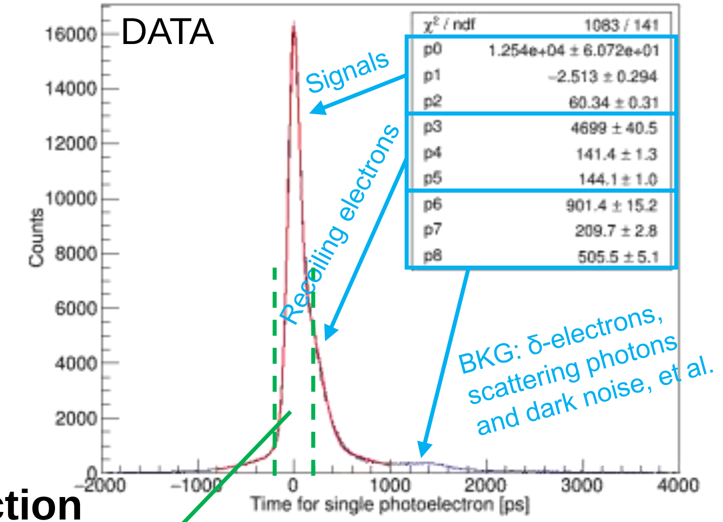
# Beam test Sim and Data comparason



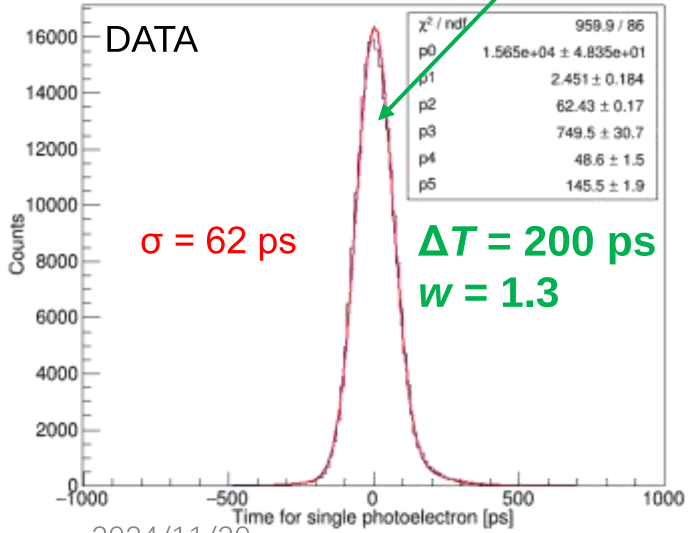

| L=1450 mm | Exp/ps | Sim/ps | Cal/ps |
|---|---|---|---|
| Pi | 4839.2 | 4838.7 | 4839.6 |
| P | 4967.1 | 4965.9 | 4967.8 |

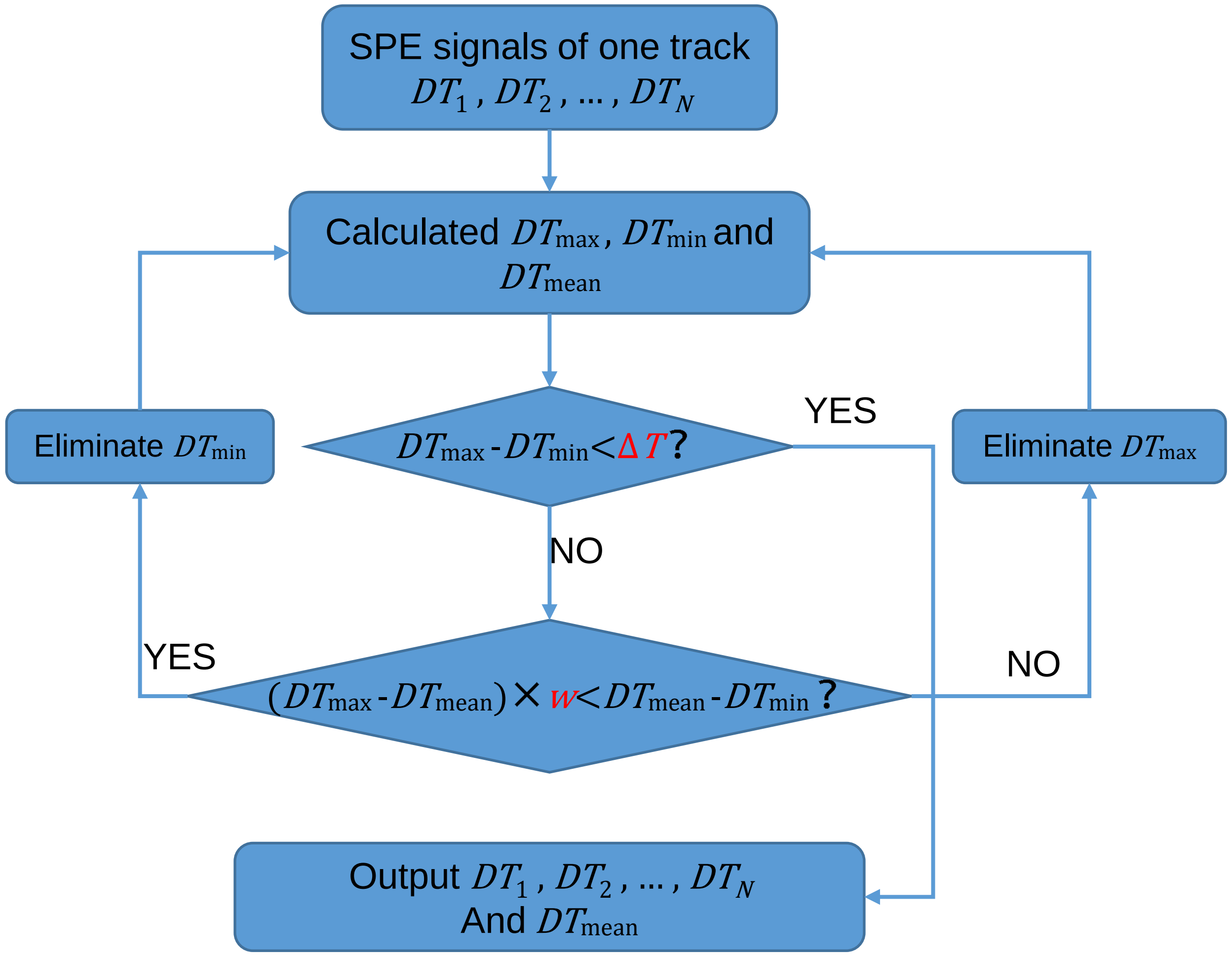
# Signal selection

- **Before selection**



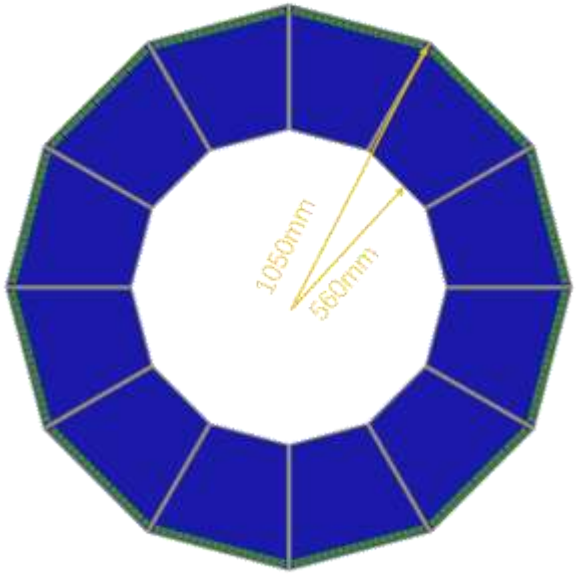

- **After selection**

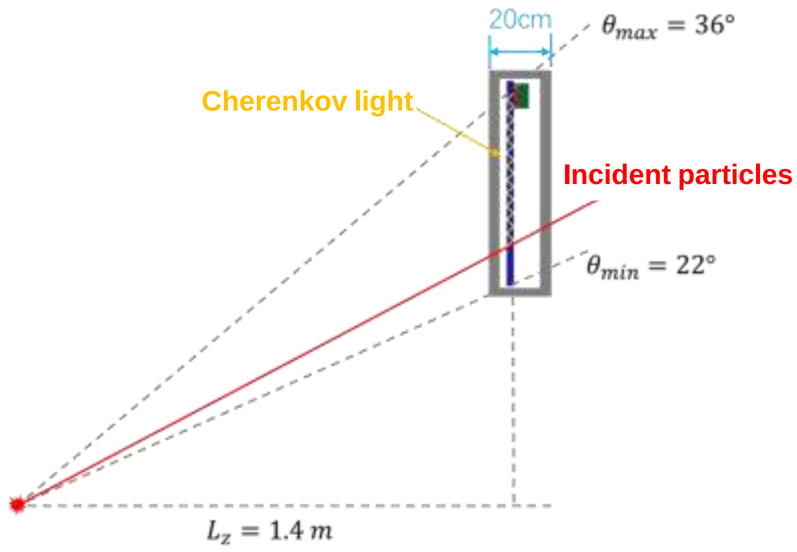


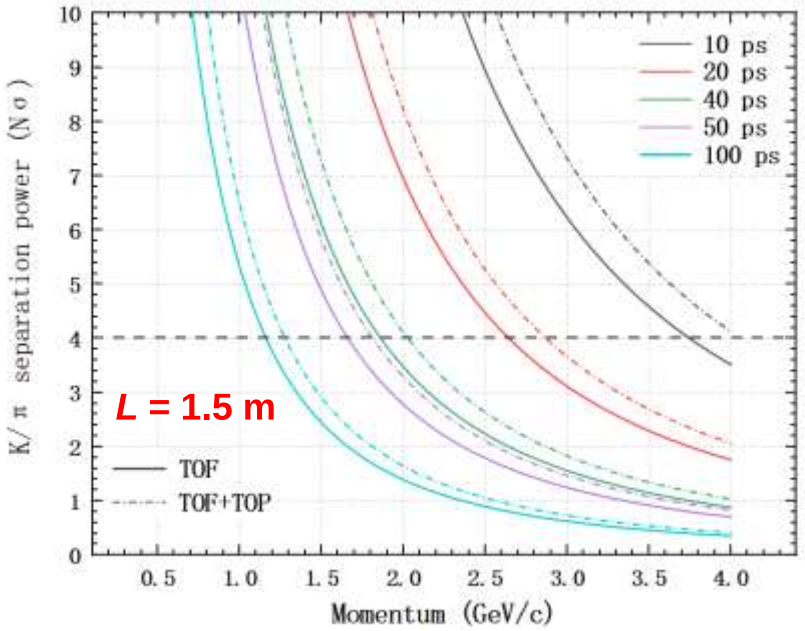




Two parameters, **Δt** and ***w***

# DTOF detector



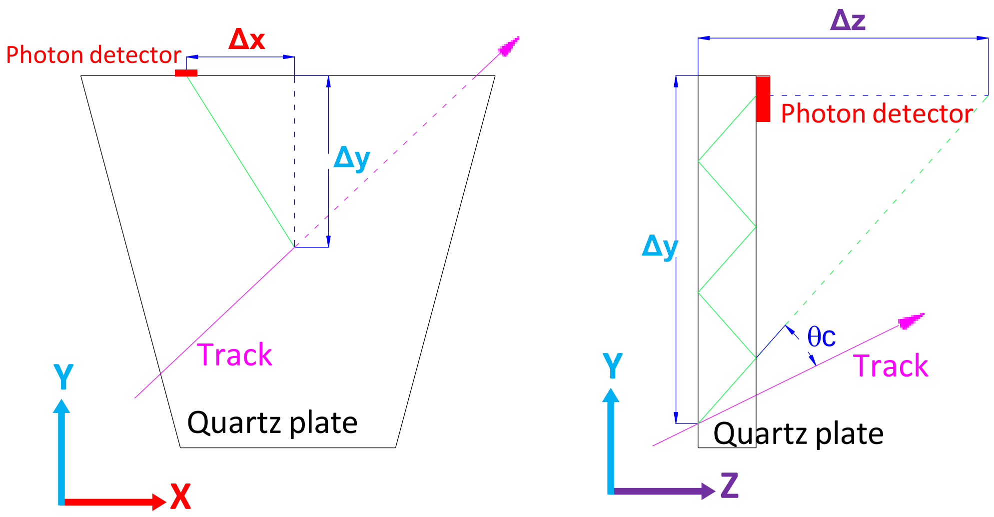



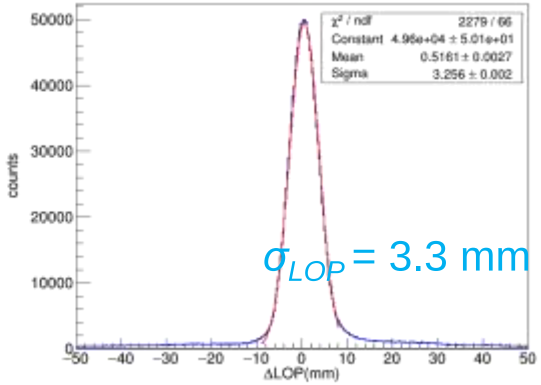

- **fused silica radiator and MCP-PMT**
- **4σ π/K separation at *p* = 2 GeV/*c*** **($\sigma_{T0} \approx$ 40 ps)**
  - Only ***TOF***, time resolution **~35 ps**
  - ***TOF+TOP***, time resolution **~50 ps**

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

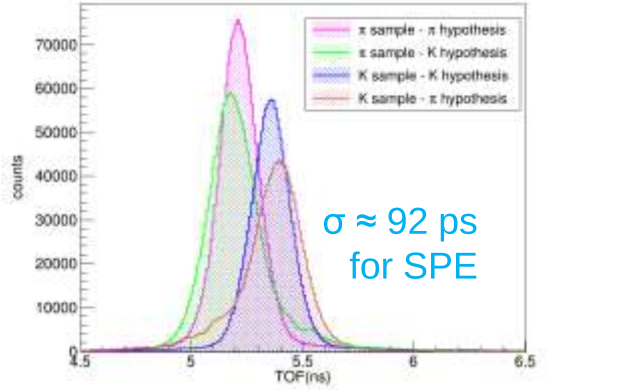
# TOF reconstruction




- **LOP precision ~3.3 mm**



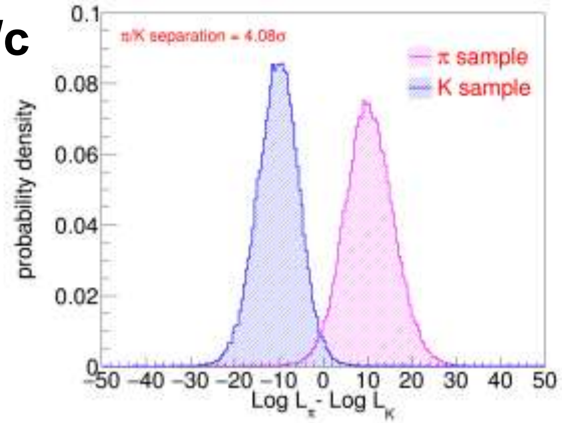

- **SPE time resolution ~92 ps**




## Algorithm

1. Reconstruct light path, including the length of light transmission along different direction, i.e. $\Delta x$, $\Delta y$ and $\Delta z$
   - 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** $TOF = T - \frac{LOPn_g}{c} - T_0$

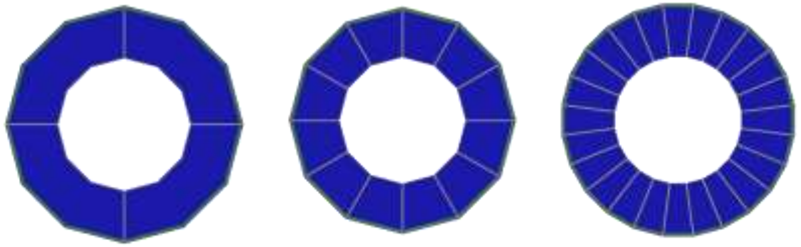
- **π/K separation power at 2 GeV/c**
  - TOF-based algorithm, including TOP differences
  - $TOF_{\mathrm{hypo}} = T - TOP_{\mathrm{hypo}} - T_0$
    $= TOF_{\mathrm{truth}} + TOP_{\mathrm{truth}} - TOP_{\mathrm{hypo}}$



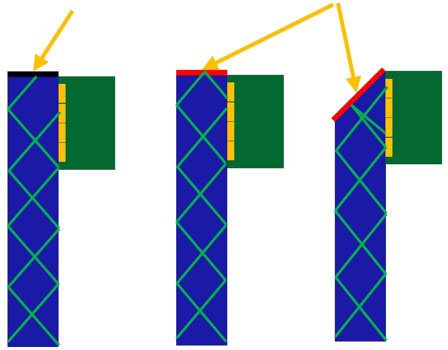

**>4σ π/K separation power**

# Optimization

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



- Absorber or mirror



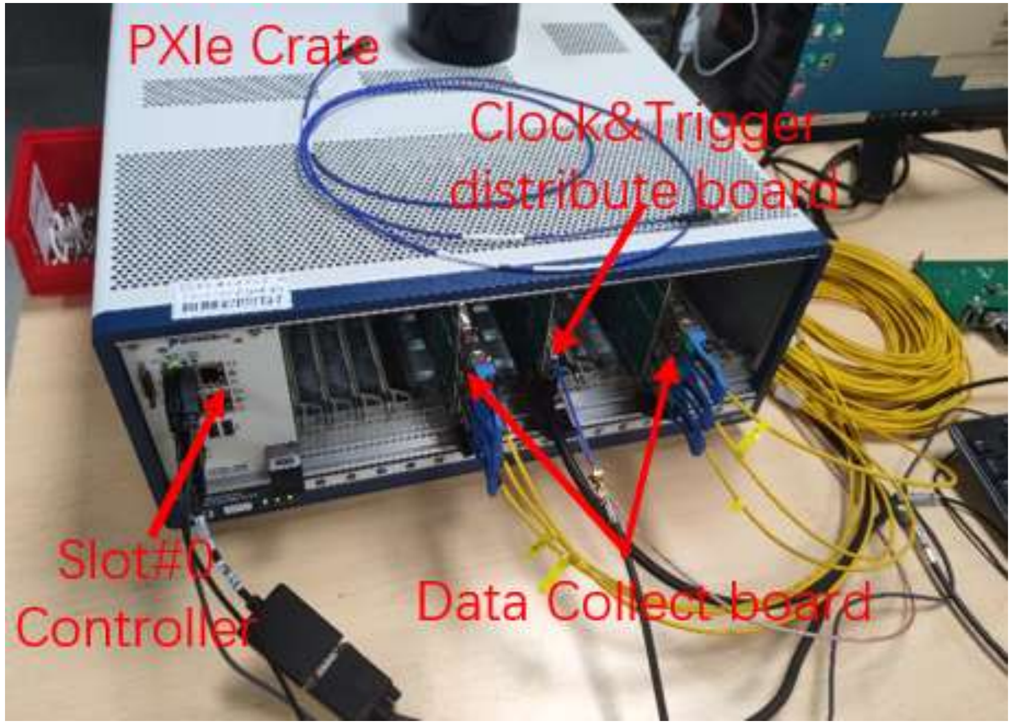
| Geometry ID | | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|---|
| Sector number | | **4** | 12 | 24 | 4 | 4 | 4 | 4 |
| Radiator thickness | | **15 mm** | 15 mm | 15 mm | 10 mm | 20 mm | 10 mm | 10 mm |
| Top surface | | **A** | A | A | A | A | M | 45° M |
| Button surface | | **A** | 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 ($N_\sigma$)** | | **4.17** | 4.08 | 3.66 | 3.99 | 4.27 | 4.26 | 4.19 |

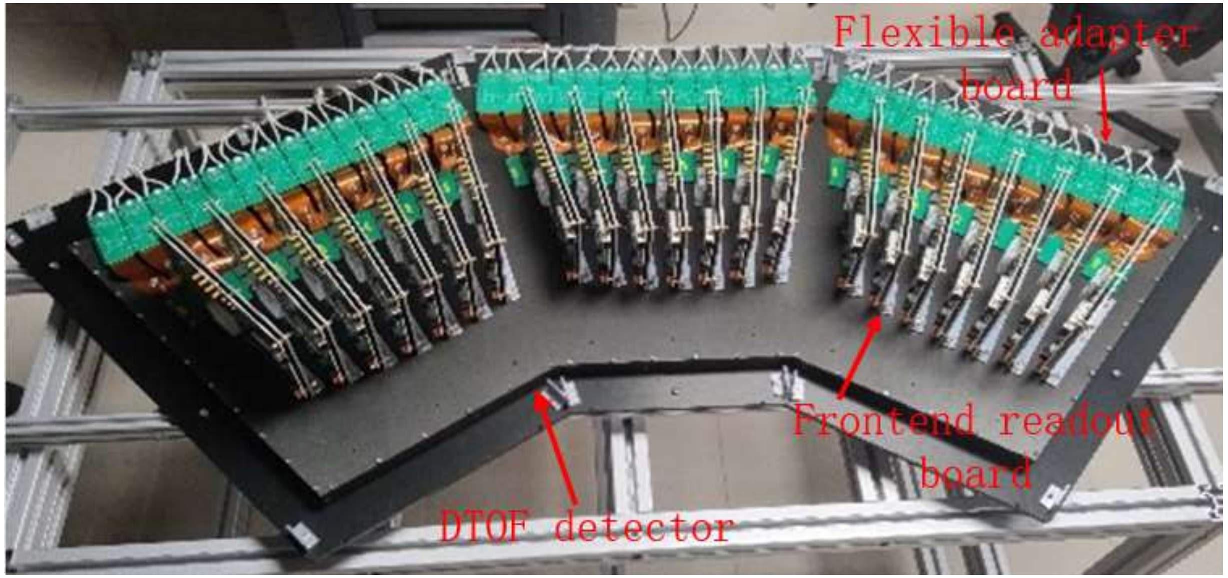
## Some conclusions

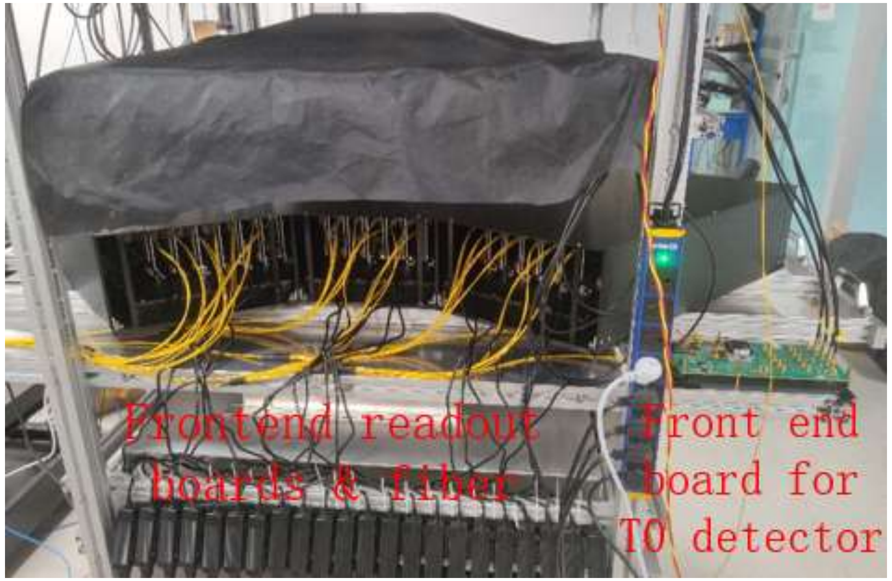
1. Thick radiator increases material, and thin radiator degrases performance ➔ a right thickness is better
2. Large area radiator reduces the number of lateral reflections, causing less hit map's overlaps and better π/K separation power
3. Adding mirror on the top surface will increase Np.e., but cause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

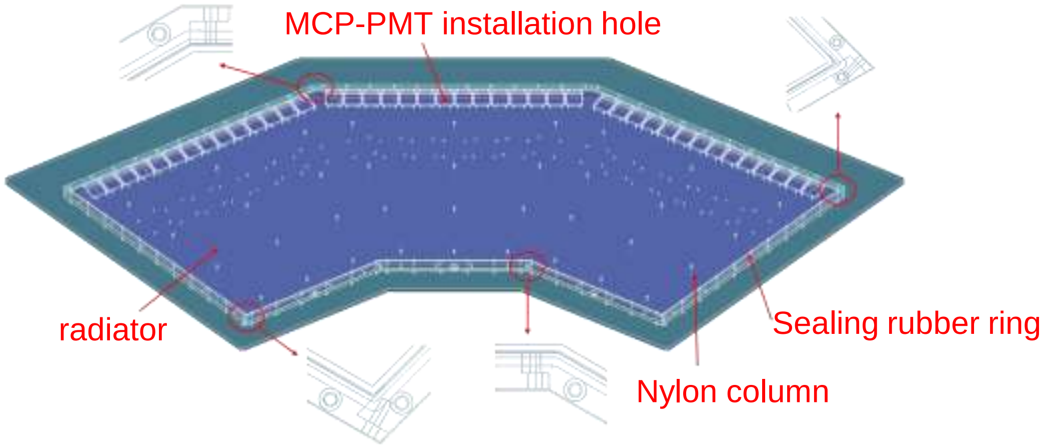


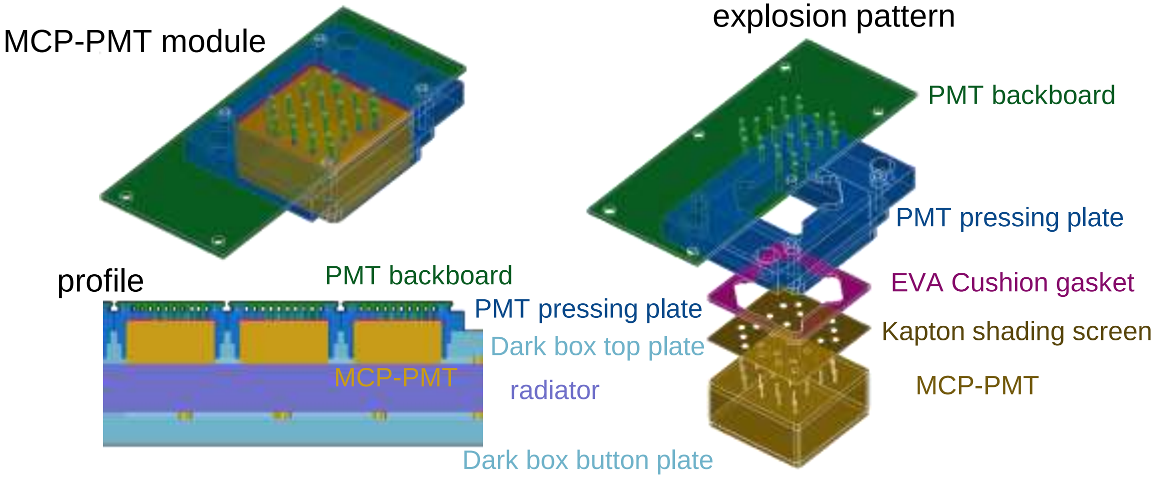



# DTOF prototype Auxiliary systems

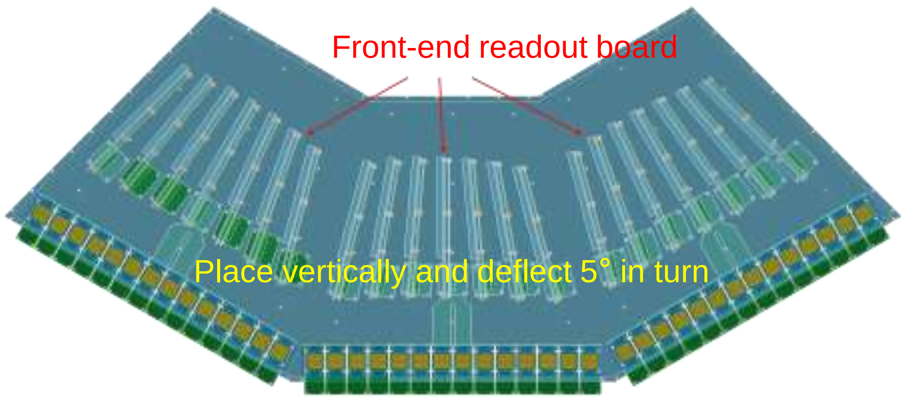
- **Dark box**



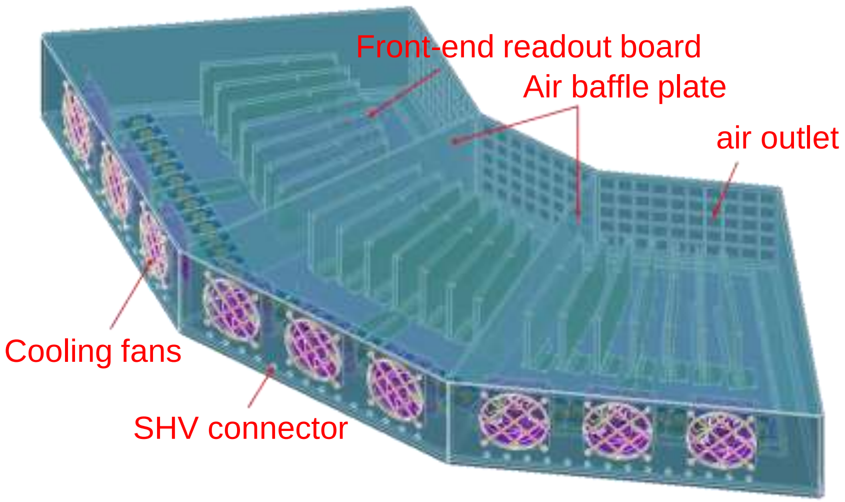

- **MCP-PMT installation**




- **Electronics module**

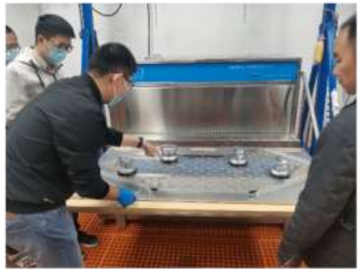



- **Cooling**



# DTOF installation and system integration

- Clean radiator and apply matting paint


晶体放入清洗装置


组装清洗装置


吊装搬运晶体

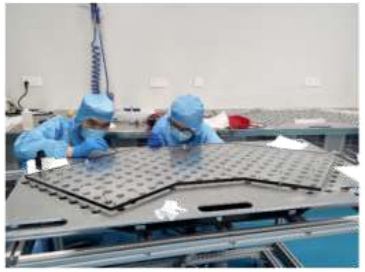

放入超声水箱


超声清洗


搬运转移出水箱


搬运至洁净间


洁净室拆卸清洗装置


晶体侧边涂黑

- Installation


安装晶体


安装PMT


PMT安装完成后转移至实验室


安装柔性读出板

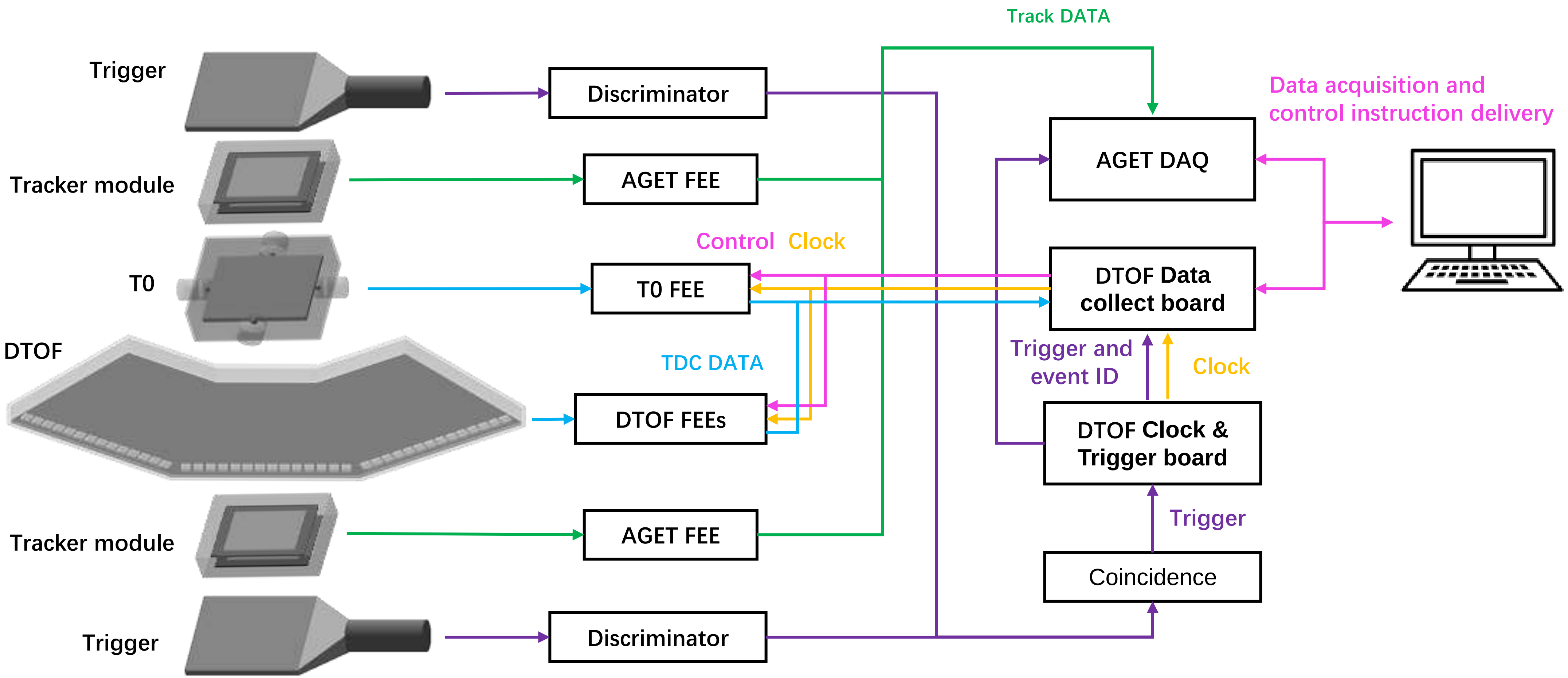

安装前端读出版

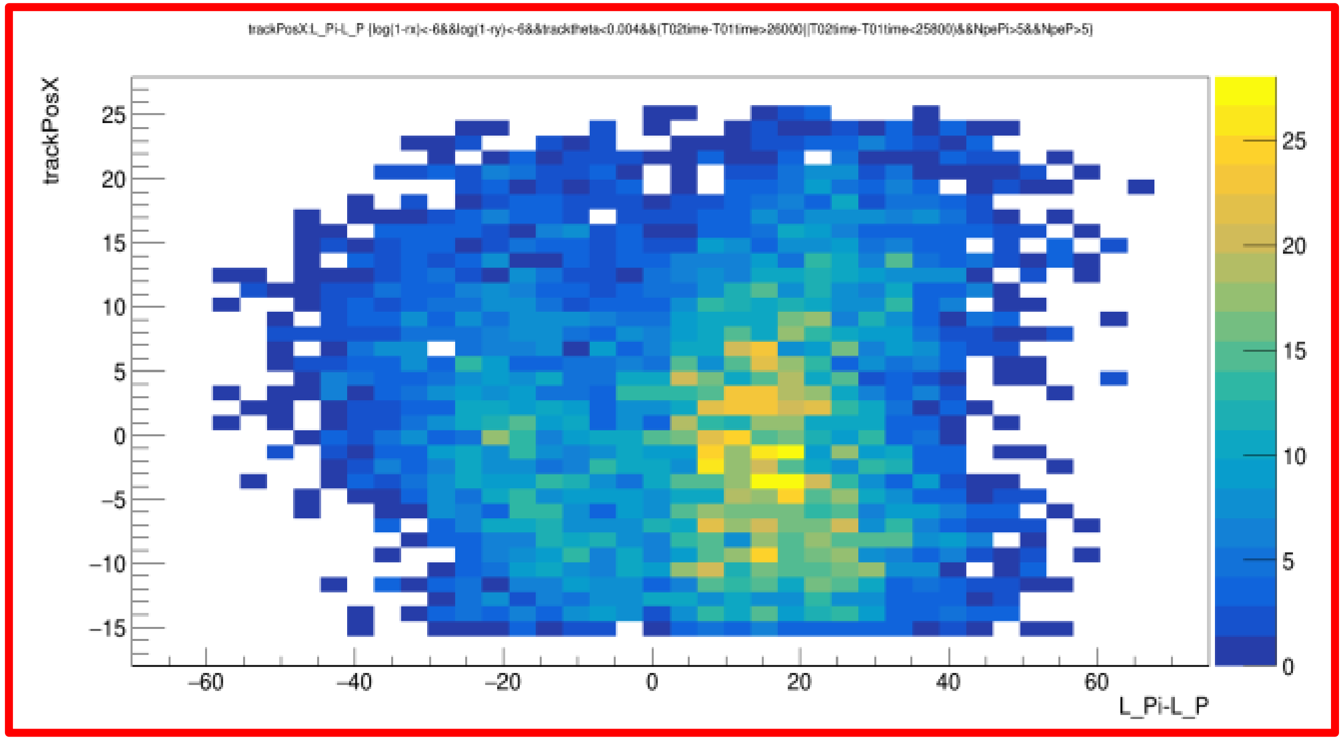

安装风扇和探测器外壳


探测器安装完毕


搭建测试平台

# Cosmic ray test data acquisition system

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trackPosX
L_Pi-L_P