Development and Beam Test of the ECAL Prototype for STCF

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On behalf of the STCF calorimeter working group

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Outline

- Introduction to STCF and ECAL
- Development of ECAL Prototype
- Beam Test Results
- Summary

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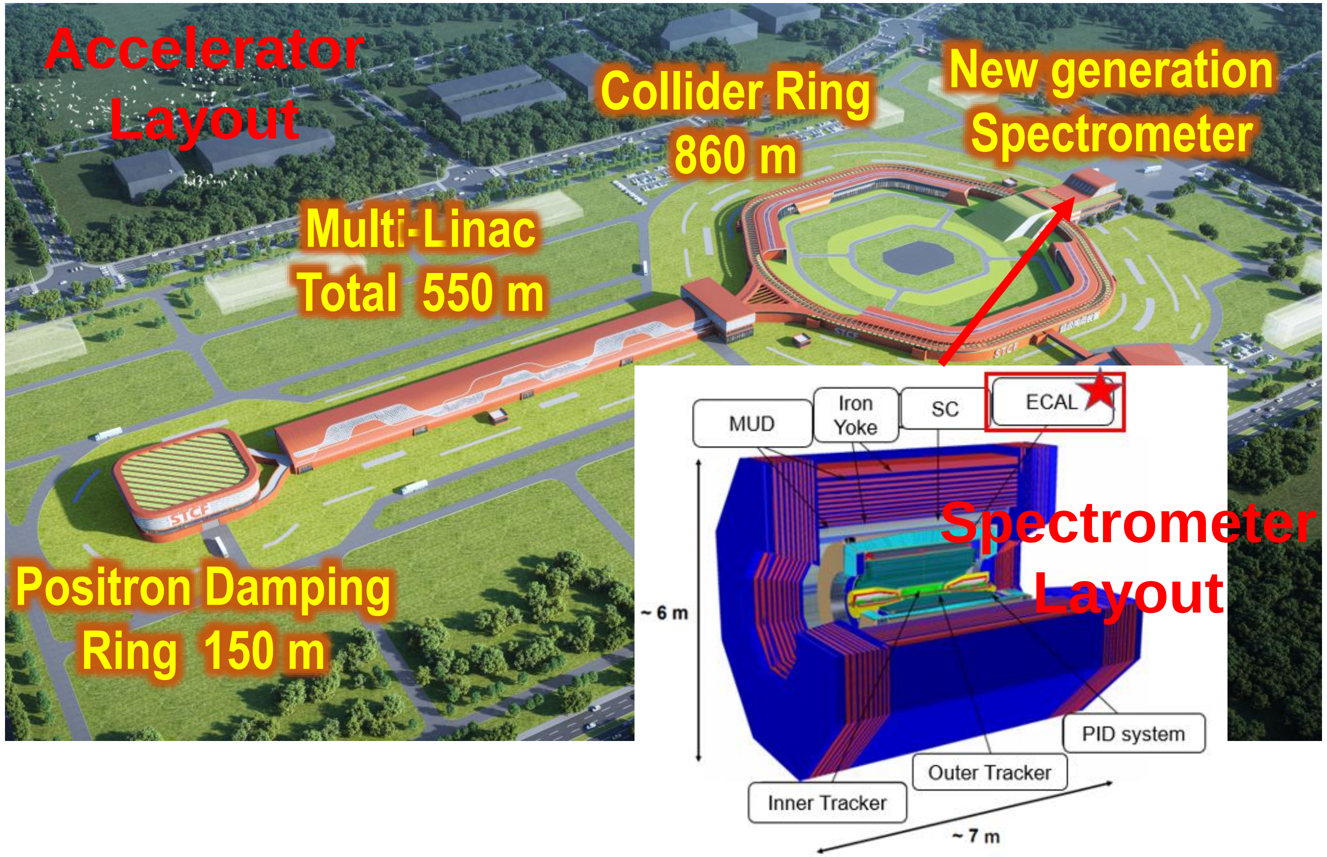
Super Tau-Charm Facility (STCF)

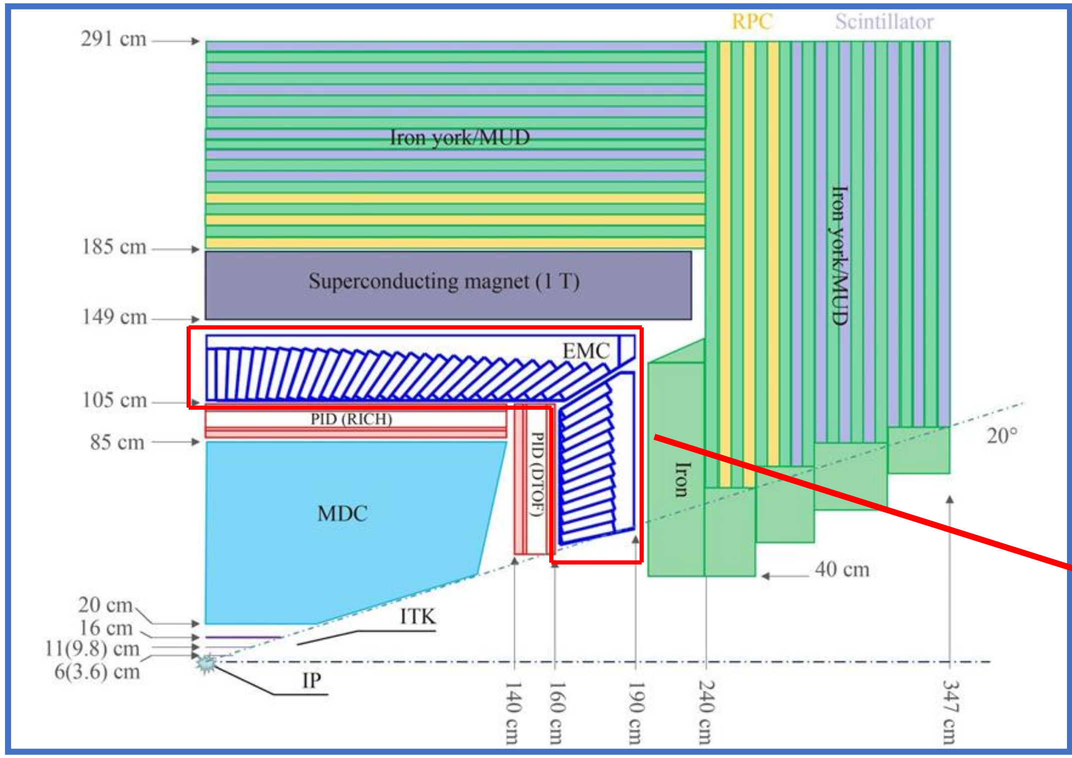
- **Next-generation high luminosity e^+e^- collider in China**
  - ➢ Center-of-mass energy coverage: $\mathbf{2-7\ GeV}$
  - ➢ Peak luminosity $\geq \mathbf{0.5\times10^{35}\ cm^{-2}\ s^{-1}\ @\ 4\ GeV}$
  - ➢ Potential to increase luminosity & realize beam polarization



- **Three-fold physics flagships**
  - ☐ Symmetry tests
    - CPV: $K^0-\bar{K}^0$ system
    - CLFV : Tau, meson decays
  - ☐ QCD nature and confinement
    - Hadron spectroscopy
    - Nuclear structure
  - ☐ Precision measurements
    - R-value, tau mass, CKM elements
    - Running of fine structure constant $\Delta\alpha_{\rm em}$

Requirements and Design of STCF Spectrometer

- **Highly efficient and precise reconstruction of exclusive final states**



Major Performance Requirements

Acceptance:	$94\% \times 4\pi$
Momentum res. :	$\sigma_p/p \sim 0.5\%$ @1 GeV
Energy res. :	$\sigma_E/E \sim 2.5\%$ @1 GeV
Hardon ID:	$\pi/K \sim 4\sigma$ @2 GeV
Muon ID:	eff. $> 95\%$, mis-rate $< 3\%$ @1GeV

Design and Technologies

- Inner Tracker (ITK)
  - MPGD: cylindrical uRGroove, $\sigma_x \sim 100\ \mu m$
  - Silicon: low-mass MAPS, $< 0.3\%\ X_0$/layer
- Central Tracker ($\sigma_p/p \sim 0.5\%$ @1 GeV)
  - Drift chamber with super-small cells, $\sigma_x < 130\mu m$
- PID System ($\pi/K \sim 4\sigma$ @2 GeV)
  - Endcap: DIRC-like TOF – DTOF ($\sigma_t \sim 30$ ps)
  - Barrel: RICH (< 4 mrad) or DTOF ($\sigma_t \sim 30$ ps)
- **ECAL**
  - **pCsI + APD ($\sigma_E/E \sim 2.5\%$, $\sigma_x \sim 5$ mm, $\sigma_t \sim 300$ ps @1 GeV)**
- Solenoid: 1T
- Muon Detector (eff. $> 95\%$, mis-rate $< 3\%$ @ 1GeV)
  - Inner layers: glass RPC ($> 300\ \text{Hz/cm}^2$)
  - Outer layers: scintillation strip + SiPM (~2.4 m)
- Trigger, DAQ, Clock and Data Transmission

Requirements and Challenges of STCF ECAL

- The **e**lectromagnetic **cal**orimeter (**ECAL**) provides energy, position and time measurements for photons

➢ Performance requirements

- Mass reconstruction precision
- Particle reconstruction efficiency
- Neutral particle identification
- Beam background suppression

◆ Large energy dynamic range:
25 MeV ~ 3.5 GeV

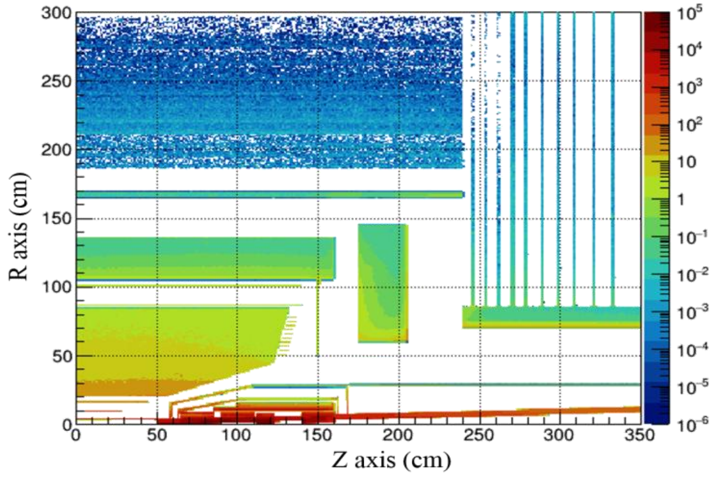
◆ Precise energy resolution :
< 2.5% @ 1 GeV

◆ Good position resolution :
~ 5 mm @ 1 GeV

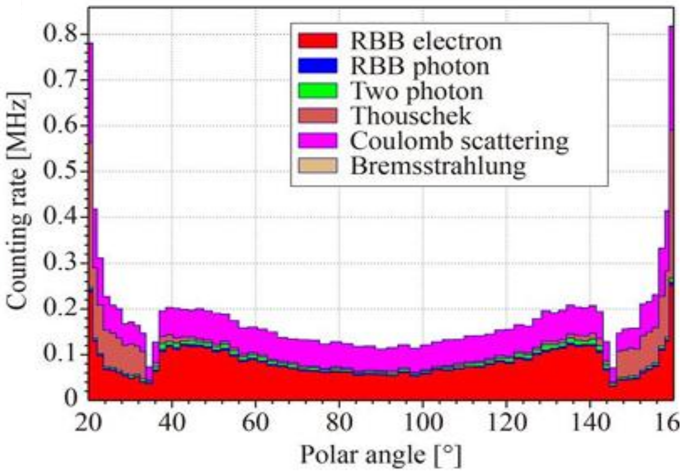
◆ Good time resolution:
~ 300 ps @ 1 GeV

➢ High luminosity challenge

Dose distribution map



Background count rate



Ionization dose ~ 40 krad

Good radiation resistance

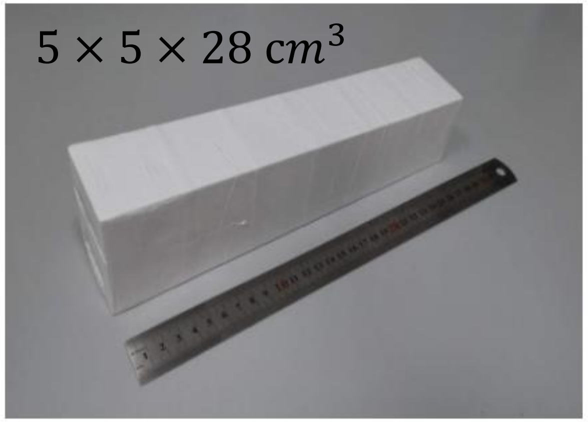
Background level ~1 MHz

Fast time response

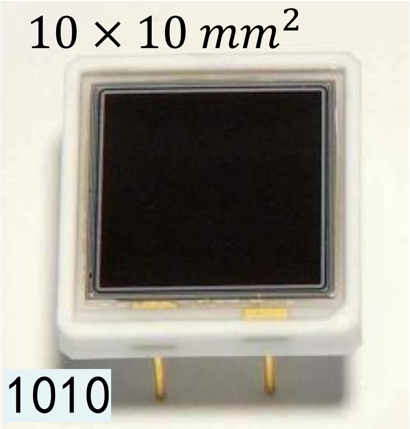
Design of STCF ECAL

- **Design of Sensitive Units**
  - ◆ Pure CsI (pCsI) crystal (28 cm ($15X_0$))
    - ➢ Fast decay time (~30 ns)
    - ➢ Excellent radiation hardness
  - ◆ Avalanche photodiode (APD)
    - ➢ Insensitive to magnetic field
    - ➢ High quantum efficiency (Q.E.)

- **Design of Electronics**
  - ◆ Front-end module (FEM)
    - ➢ Charge-sensitive amplifier (CSA)
    - ➢ High- and low-gain outputs
  - ◆ Signal processing module (SPM)
    - ➢ Waveform sampling readout
  - ◆ Data acquisition system (DAQ)



pCsI crystal

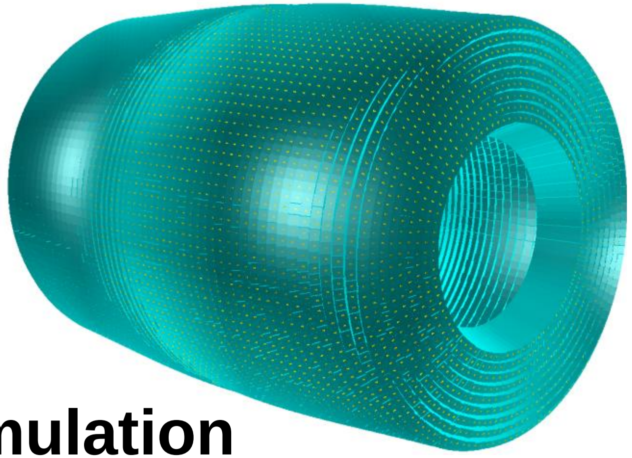


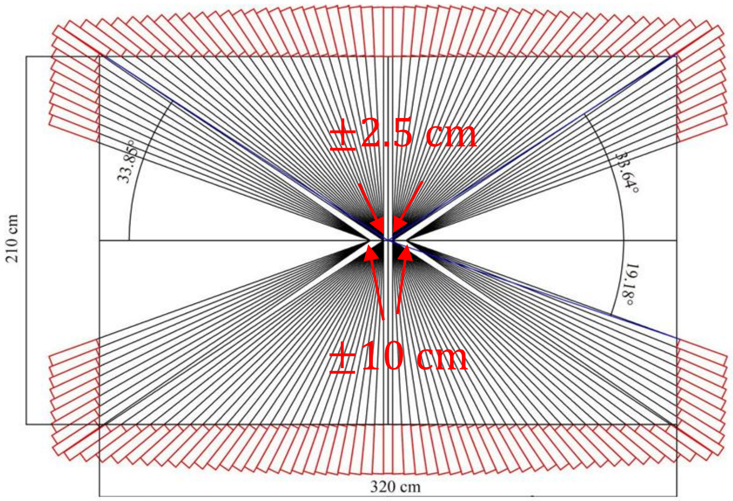
APD (S8664-1010)

Front-end and signal processing modules

ECAL Geometry and Expected Performance

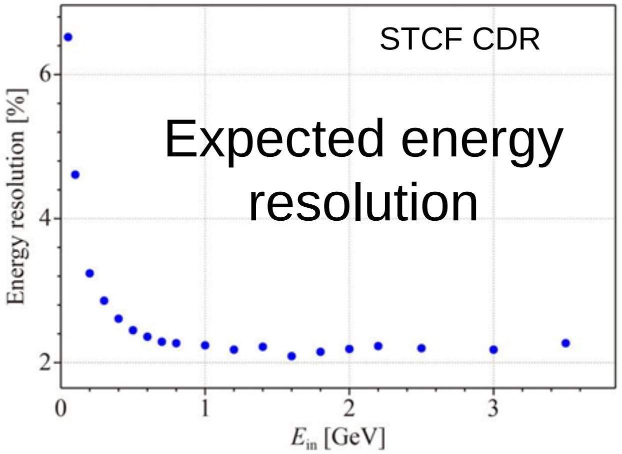
- **Geometry layout**
  - Barrel + Endcap: 8670 crystals
    - ✓ ~95% solid angle coverage
  - Defocus layout
    - ✓ ~6% higher detection efficiency

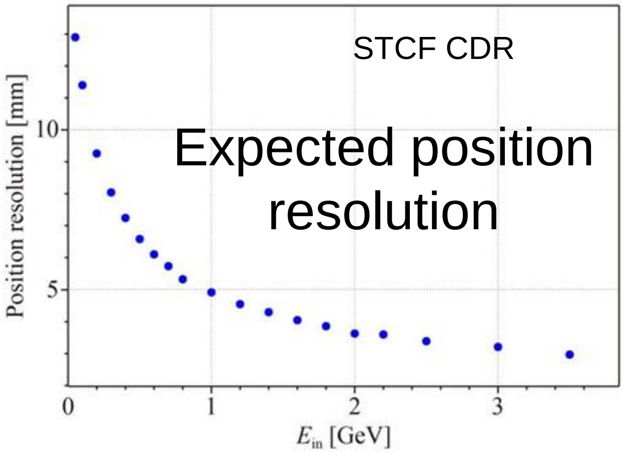


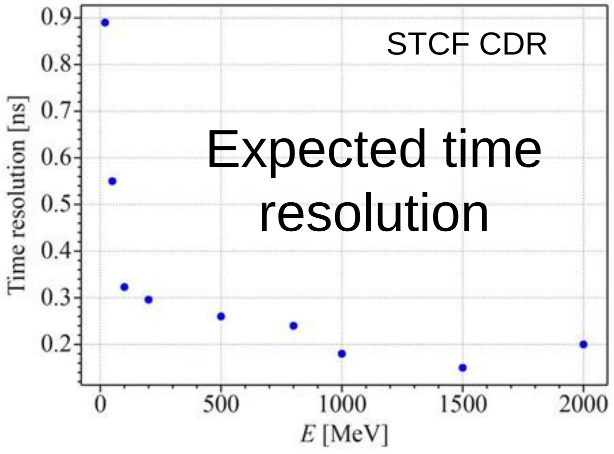


Crystal arrangement diagram

- **Expected performance from simulation**
  - ✓ Energy resolution: 2.27% @ 1 GeV
  - ✓ Position resolution: 4.9 mm @ 1 GeV
  - ✓ Time resolution: 153 ps @ 1 GeV







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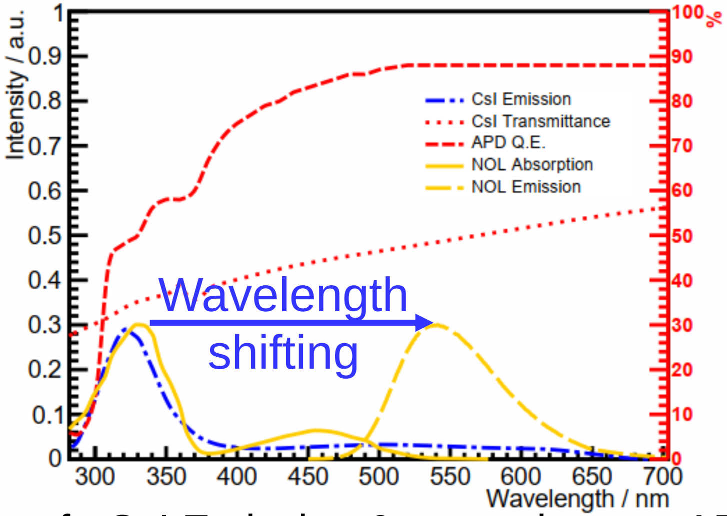
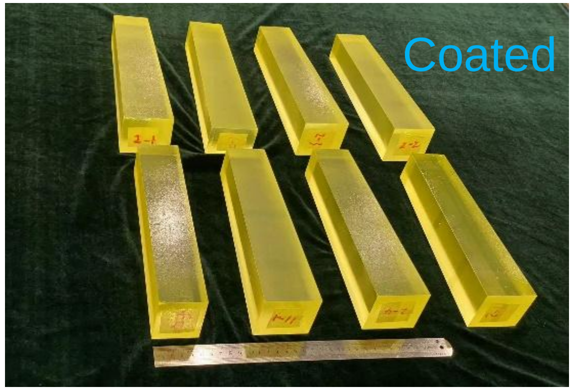
Light Output Enhancement of Sensitive Units

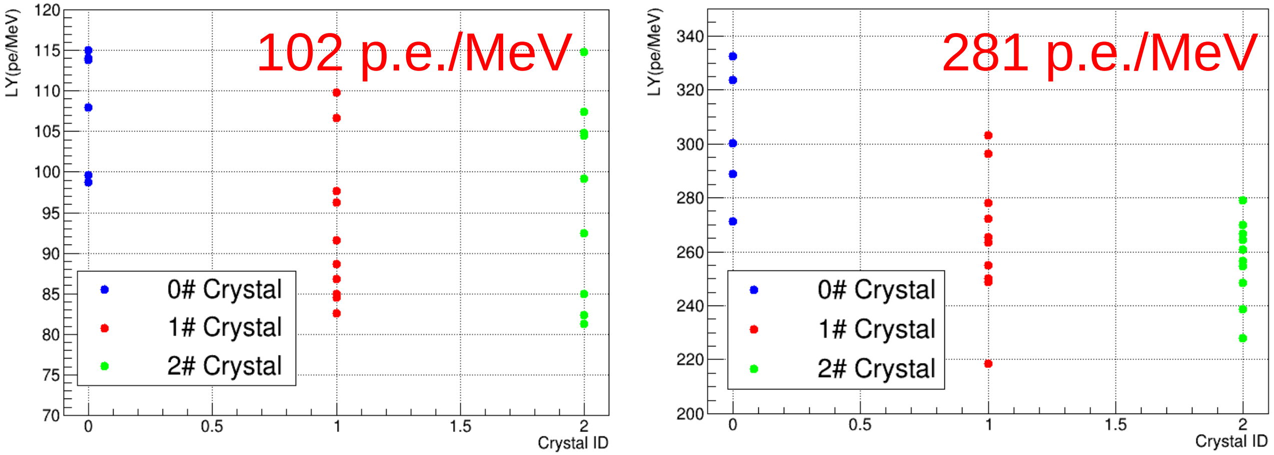
- **Low light collection efficiency**
  - Emission peak of pCsI is ~310 nm
    - Low transmittance
    - Low APD Q.E.
- **WLS coating scheme**
  - Wavelength shifting: ~300 nm → ~550 nm
    - ✓ Transmittance: 30% → 50%
    - ✓ APD Q.E.: 40% → 80%



Spectra of pCsI Emission & transmittance, APD Q.E. and NOL Absorption & emission

- **Light output enhancement**
  - Coat 25 crystals in the prototype
  - Average light output increase: ~175%



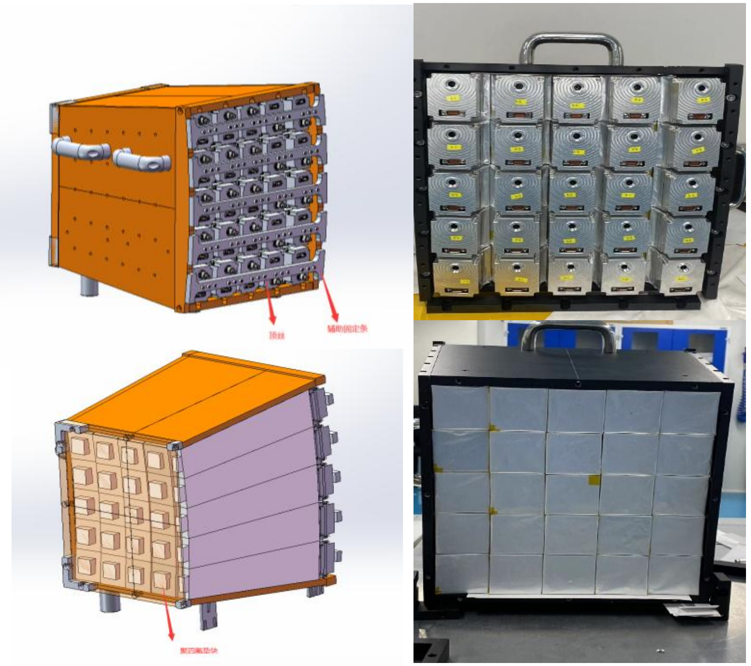


Light output before and after coating

Development of ECAL Prototype

- **Sensitive unit components:**
  ① Crystals with reflective material
  ② 4 APDs
  ③ Front-end electronics

- **ECAL prototype components:**
  - 5 × 5 sensitive unit array
  - Back-end electronics
  - Temperature stabilization system



5 × 5 sensitive unit array

Electronics

Water chiller

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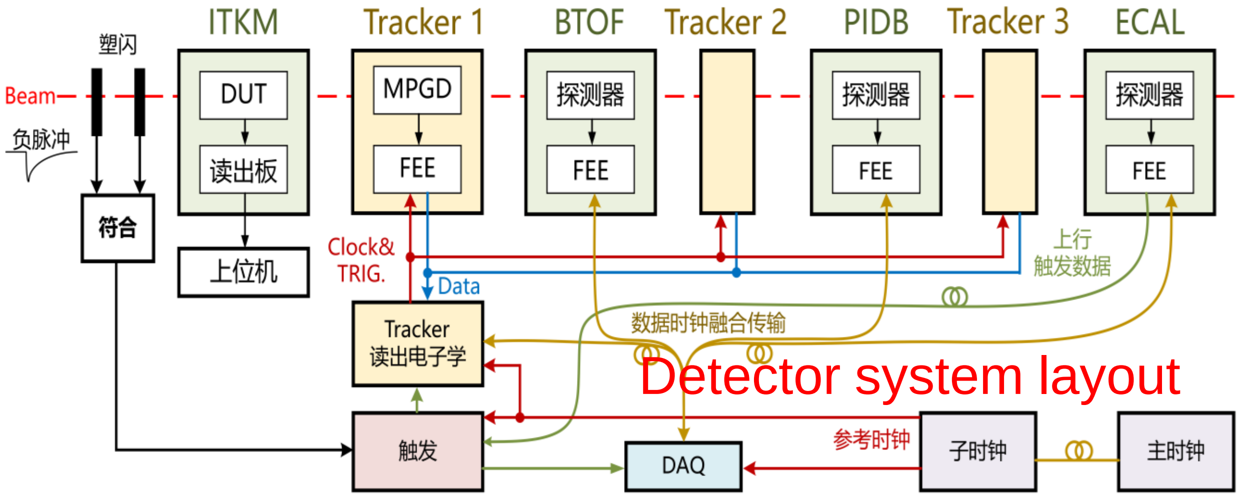
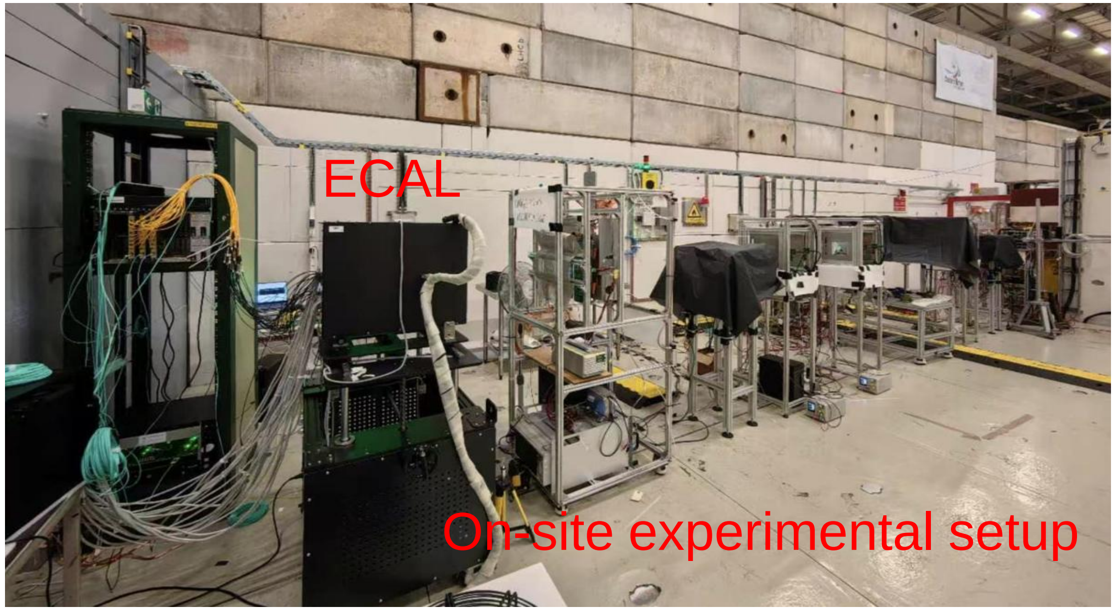
Beam Test Campaign

- **Beam test of the ECAL prototype**
  - ➢ PS T09/T10 beam line at CERN
  - ➢ Multi-system test
    - PID Detector——BTOF&RICH
    - ECAL
    - T0 Detector
    - Tracking Detector
  - ➢ Beam type and momentum

Type	Momentum	Statistics
μ^+	~ 10 GeV/c	~ 20.93 M
e^+	0.2-3.5 GeV/c	~ 11.57 M
$hardon^+$	1-5 GeV/c	~ 33.63 M
$hardon^-$	3 GeV/c	~ 2.18 M





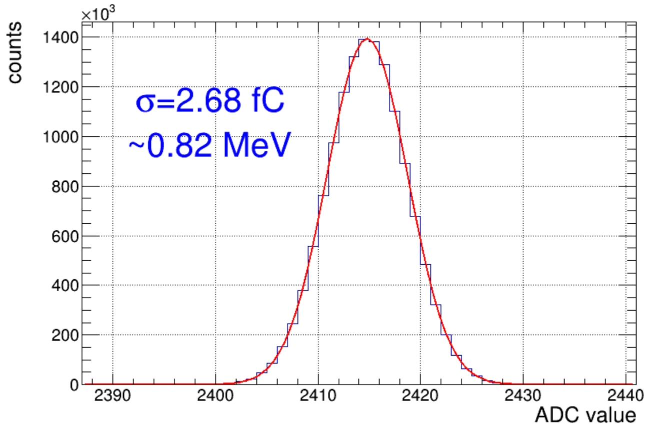
On-site Images

ECAL prototype

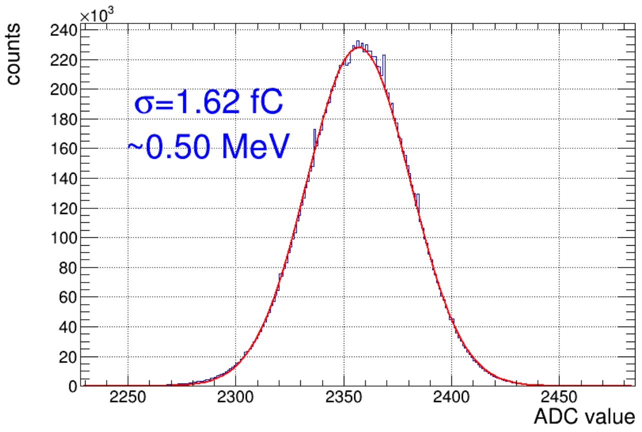
ECAL test team

Operating Status of the Prototype

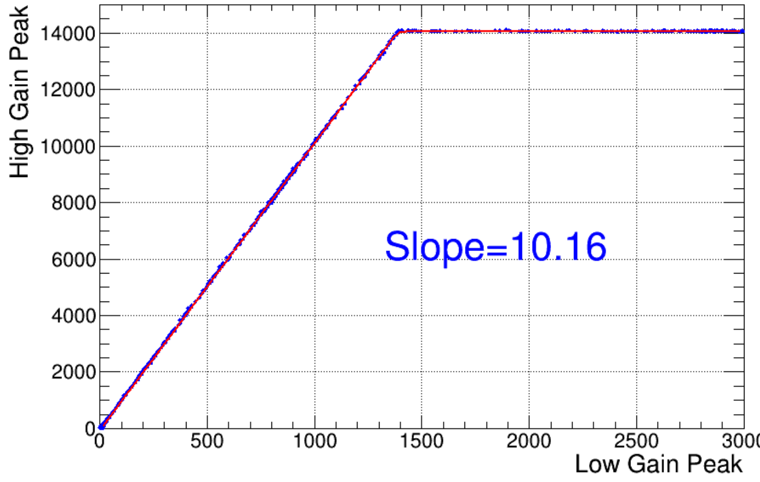
- **Noise level**
  - ➢ Low/High Gain: ~ 2.7/1.6 fC (0.8/0.5 MeV)
- **High-Low gain ratio : ~ 10**
  - ➢ Dynamic range: 3 MeV ~ 3 GeV
- **Stable operating status**
  - ➢ Electronics baseline and noise
  - ➢ Environmental temperature: ~ 29±0.5 ℃



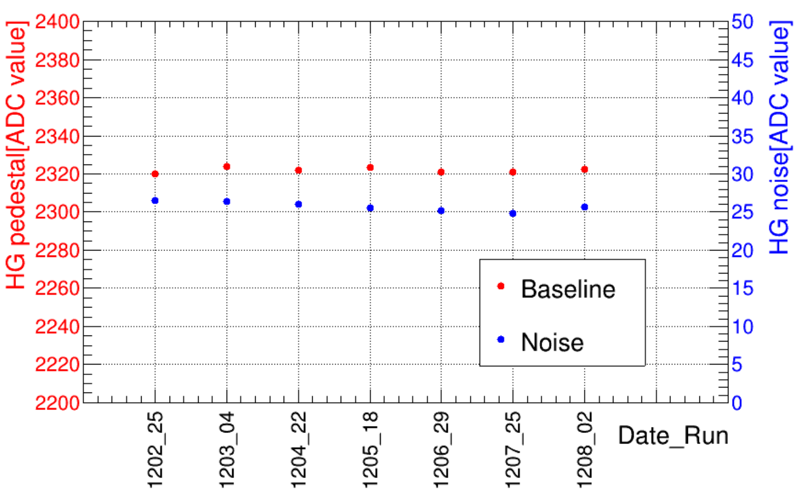
Low gain noise



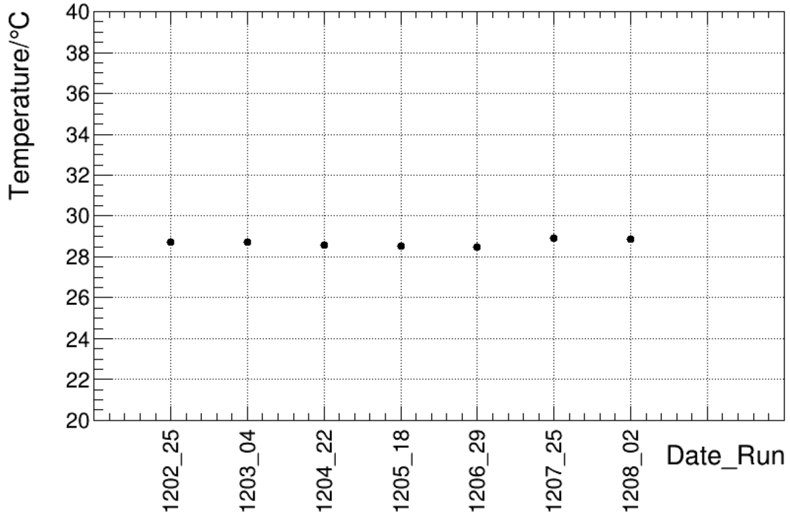
High gain noise



High-Low gain ratio



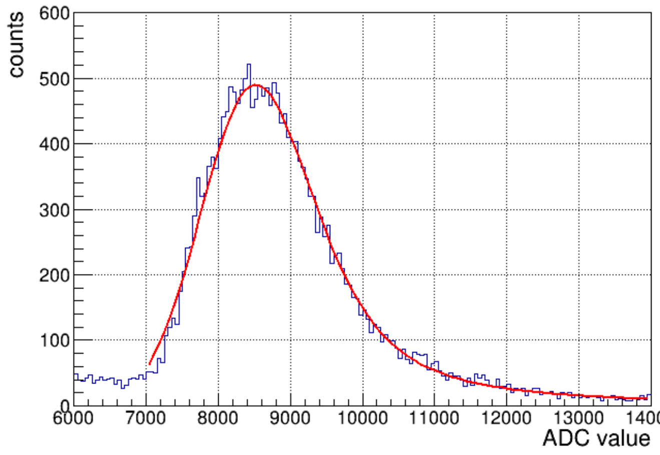
Baseline and noise stability



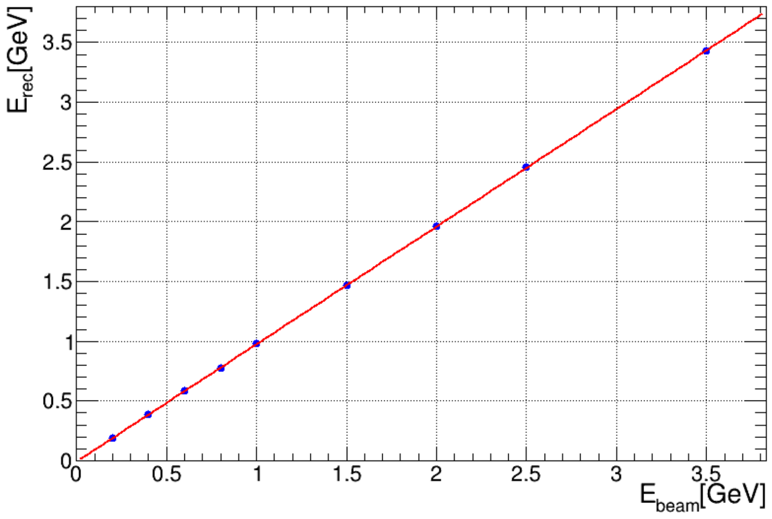
Temperature stability

Energy Reconstruction Performance

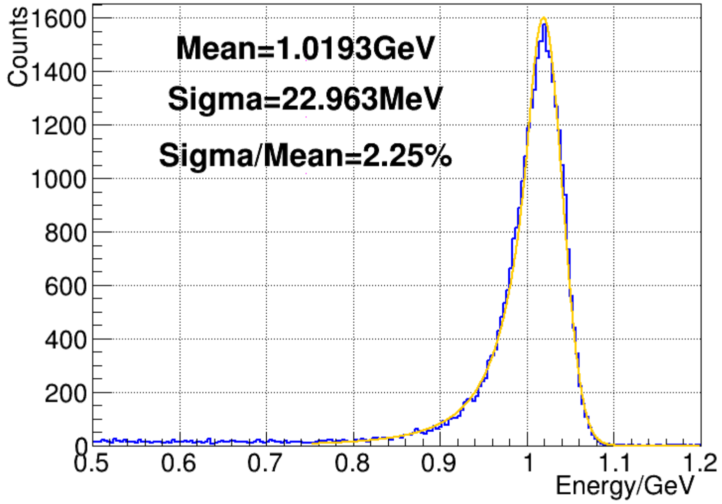
- **Calibration with μ^+: ~ 180 MeV**
- **Good Energy linearity**
  - From 0.2 GeV to 3.5 GeV
- **Energy resolution for 1 GeV e^+ is 2.25%**
  - ~ 1% beam momentum spread contributed



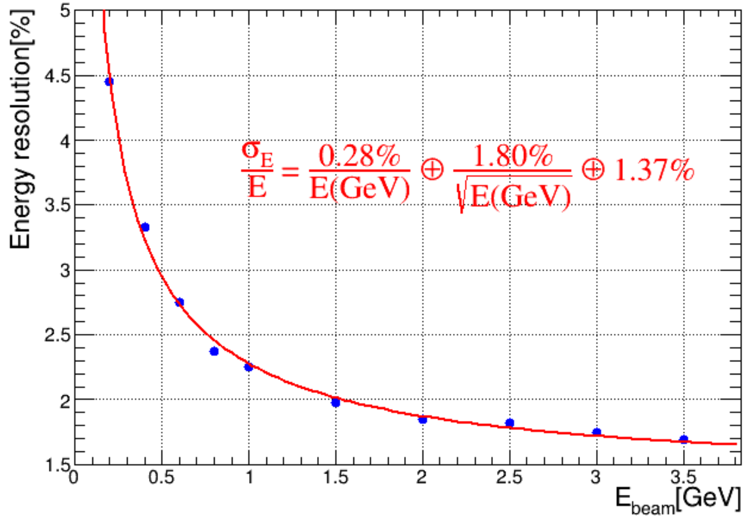
Energy spectrum of MIPs



Energy linearity



Energy spectrum of 1 GeV e^+



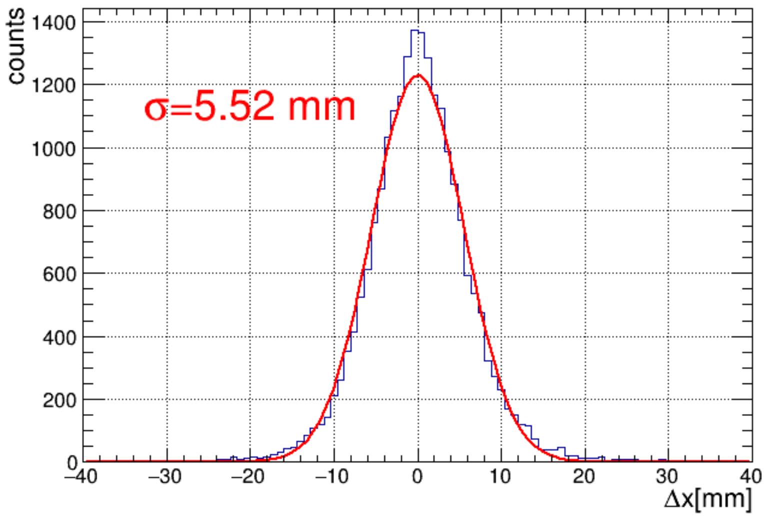
Energy resolution vs. beam energy

Position Reconstruction Performance

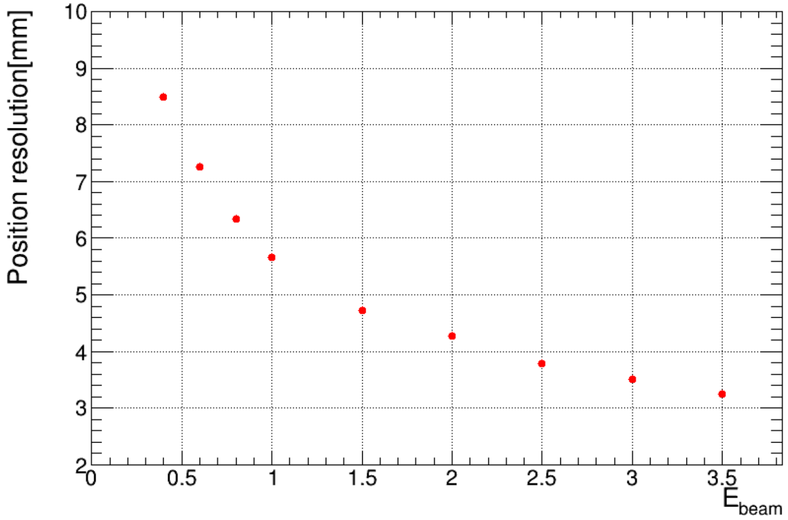
- **Position resolution for 1 GeV e^+ is ~5.5 mm ($\Delta_x = x_{ECAL\_Rec} - x_{Incident}$)**
  - Logarithmic-weighted barycenter method
- **Limitations on ECAL position resolution**
  - Track extrapolation accuracy
  - Non-uniform beam hit distribution

$$x_{rec} = \frac{\sum_j^N w_j(E_j) \cdot x_j}{\sum_j^N w_j(E_j)}$$

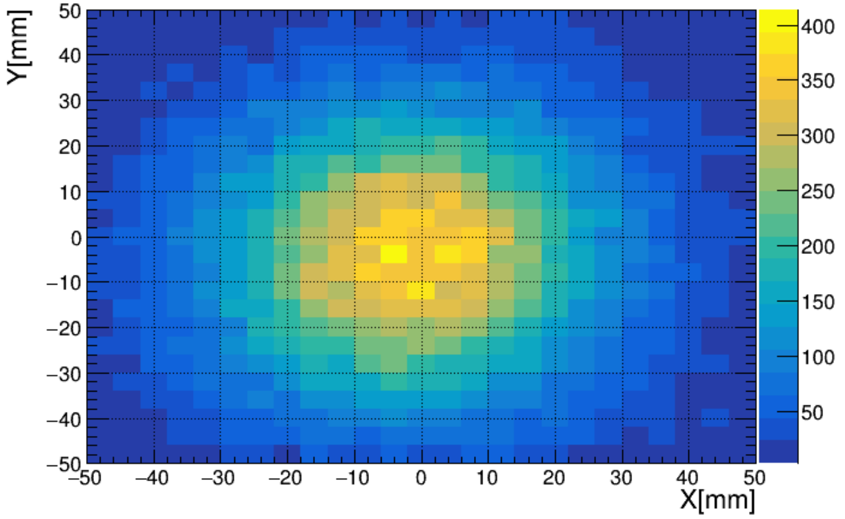
$$w_j(E_j) = max\{0, a + ln(\frac{E_j}{\sum_j^N E_j})\},\ a = 4.2$$



Position reconstruction for 1 GeV e^+



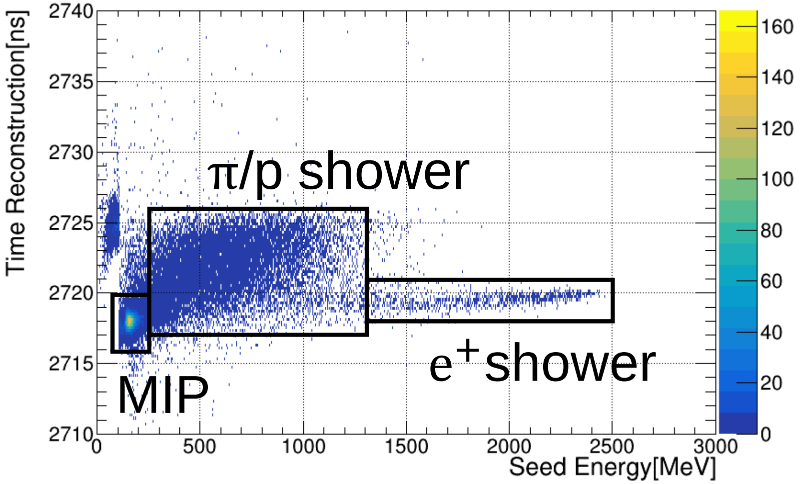
Position resolution vs. beam Energy



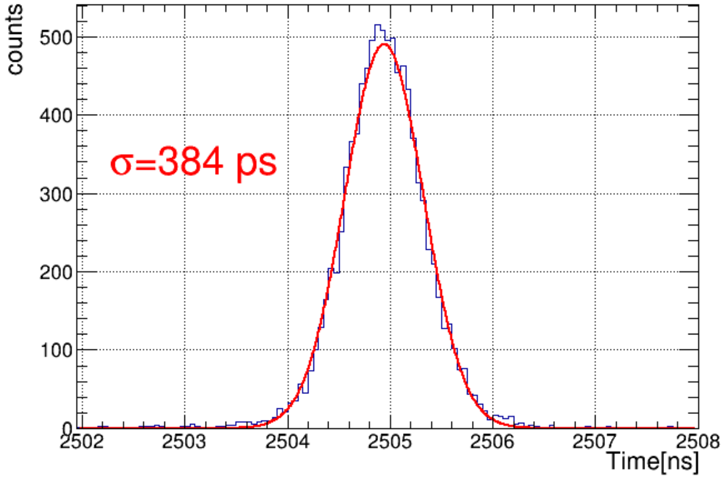
Distribution of beam incidence positions

Time Reconstruction Performance

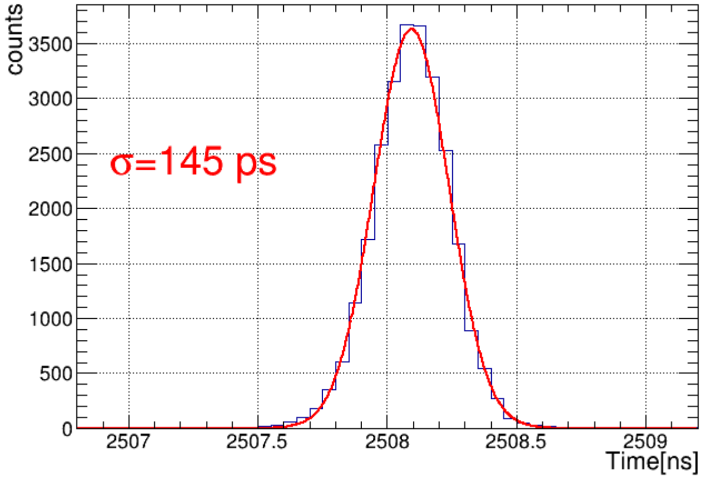
- **Time reconstruction ($\Delta_T = T_{ECAL\_Rec} - T_0$) for different particles ($\pi^+/p^+/\mu^+/e^+$)**
  - Time resolution for MIP is 384 ps
  - **Time resolution for 1 GeV e^+ is 145 ps**
  - Hadronic showers show time delay and spread (large pulse shape differences)



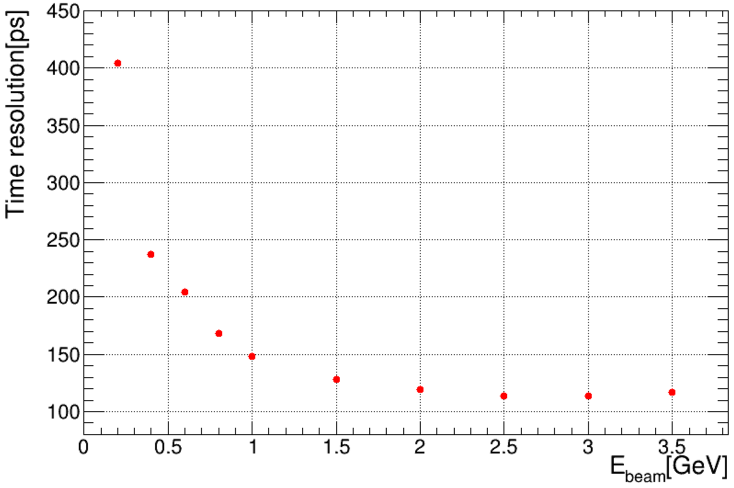
Time reconstruction vs. energy



Time reconstruction for MIPs



Time reconstruction for 1 GeV e^+



Time resolution vs. beam energy

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Summary

- **STCF can produce massive tau leptons and hadrons**
  - ➢ Unravel how quarks form matter and fundamental symmetries
- **Development of ECAL prototype**
  - ➢ 5×5 sensitive unit array (pCsI + APD design)
- **Beam test of ECAL prototype**
  - ➢ Performance meets the design requirements
    - 2.25% (energy), 5.5 mm (position), 145 ps (time)

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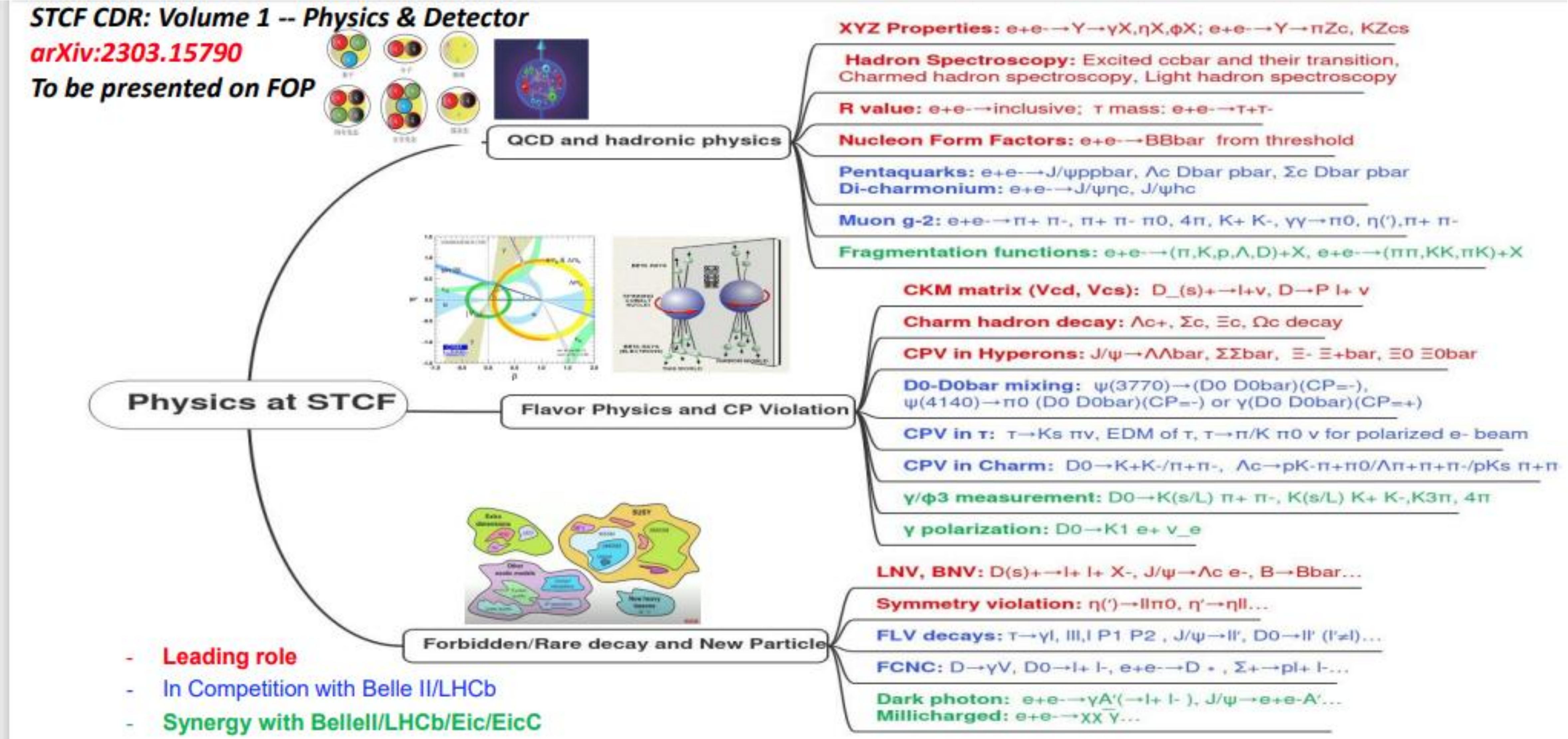
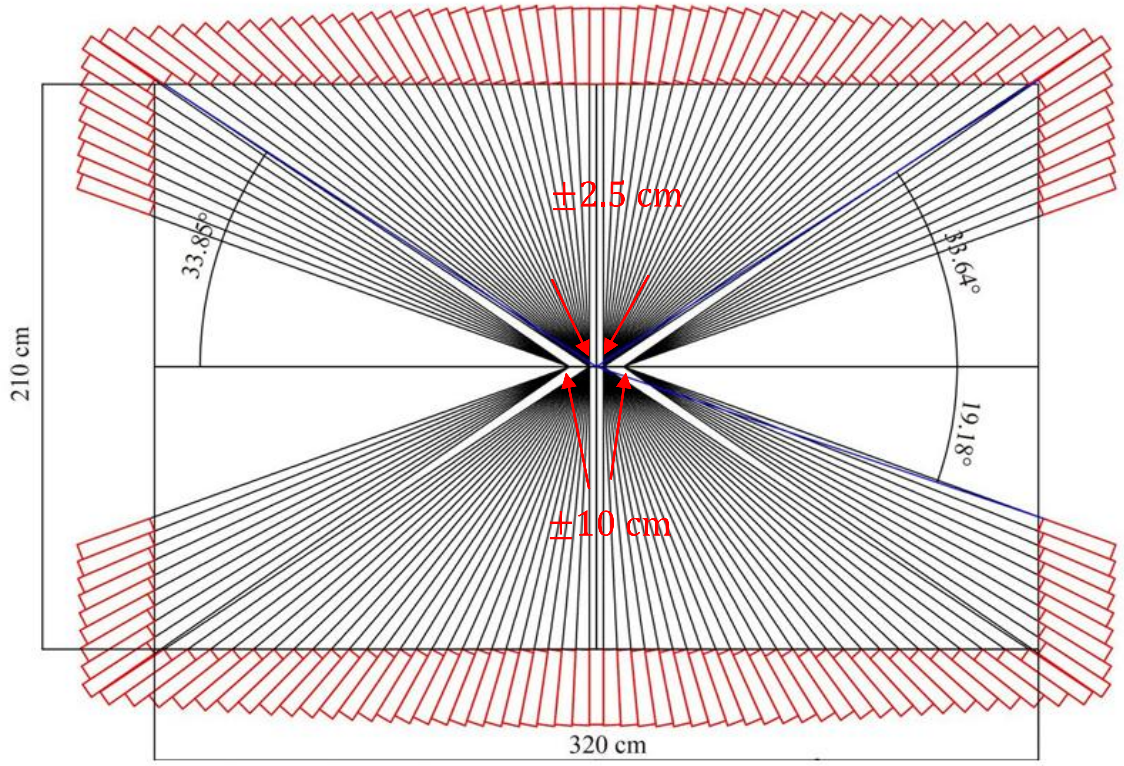
Thanks!

Back Up

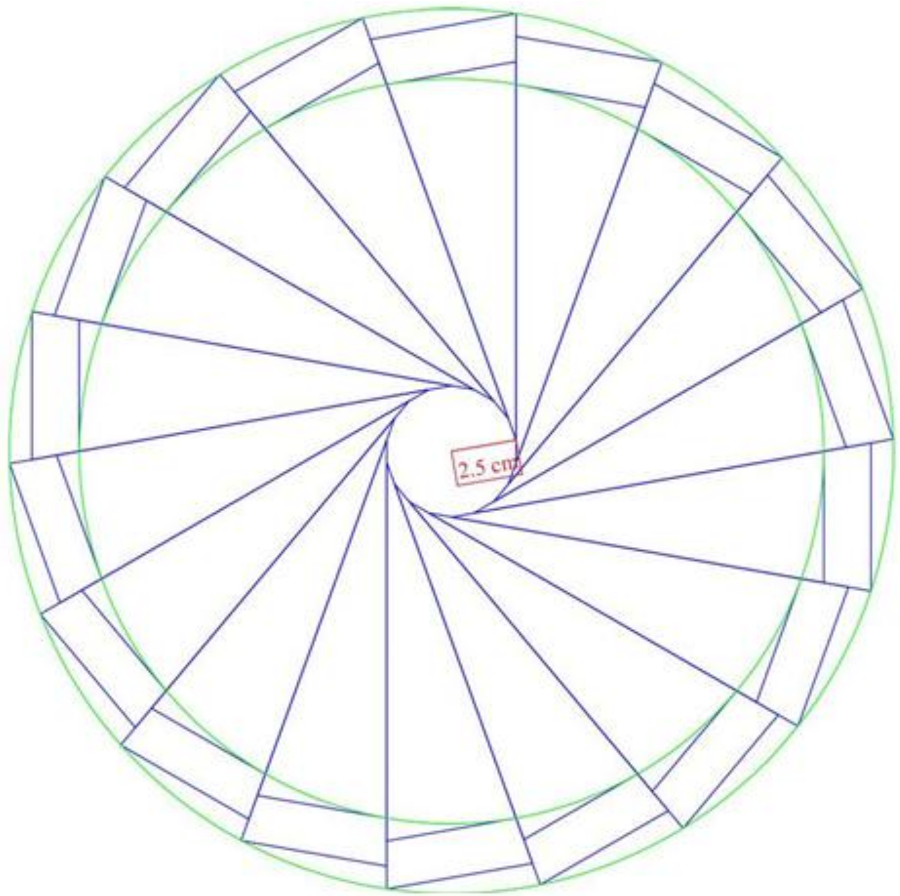
STCF Physical Topics



Defocused Layout



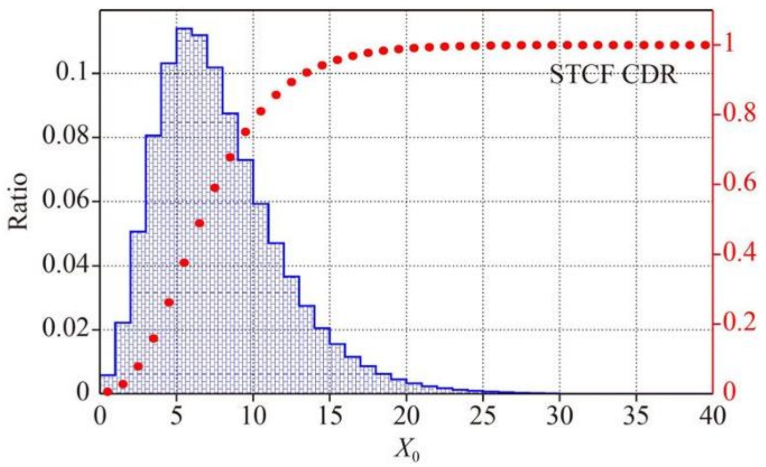
θ-direction arrangement

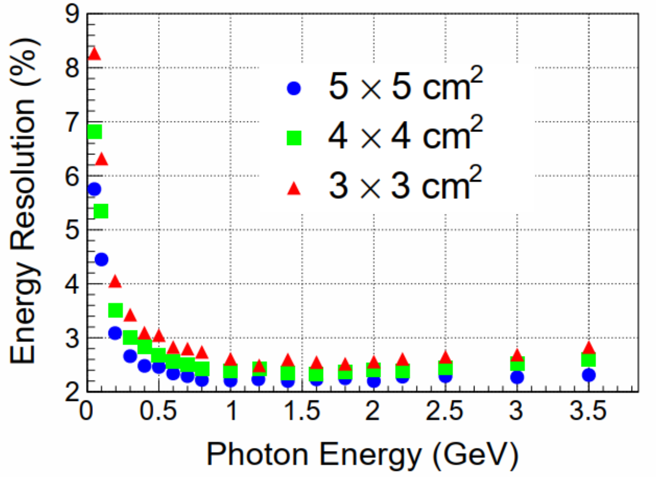


φ-direction arrangement

Crystal Size Optimization

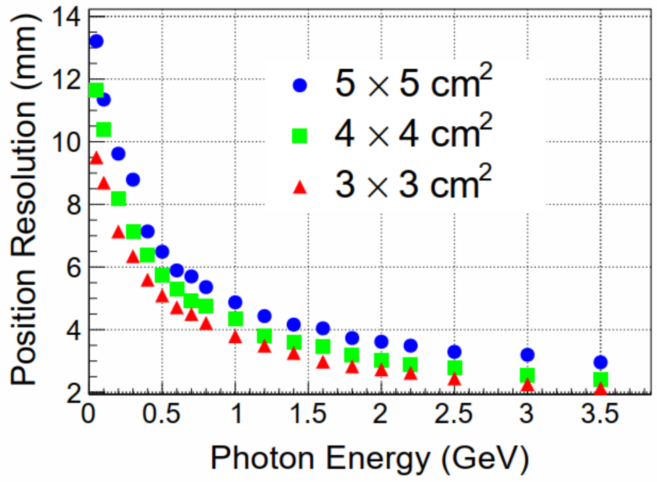
- Longitudinal size: $15X_0$ (28 cm)
  - ➢ 95% energy deposits for 3 GeV photons





Energy resolution vs. lateral size

- Lateral size: 5×5 cm2
  - ➢ The minimum angle of the two photons from the π⁰ decay is about 10° (~5.5 × 3 cm)
  - ➢ Smaller size leads to poor energy resolution but better position resolution.

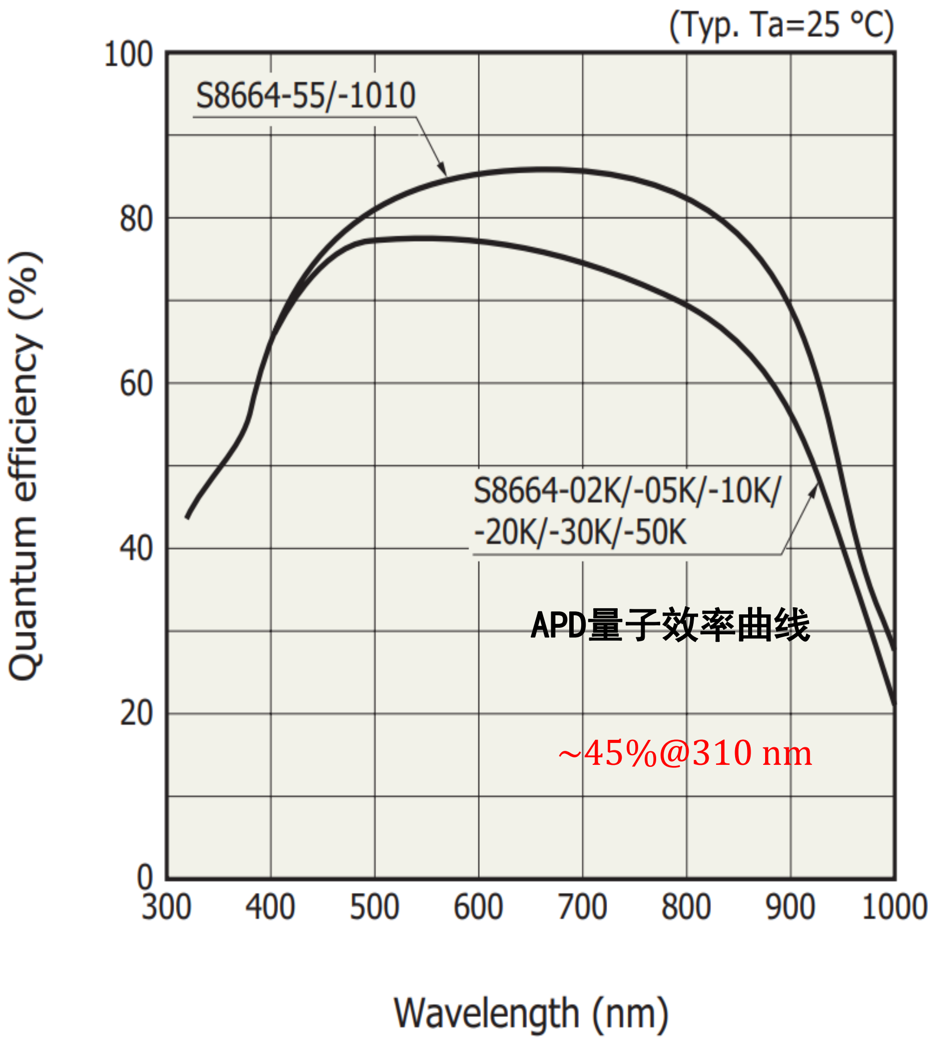


Position resolution vs. lateral size

Crystal Selection - pCsI

Crystal	pure CsI	LYSO	GSO	PWO	BaF_2
Density (g/cm^3)	4.51	7.40	6.71	8.30	4.89
Radiation Length (cm)	1.86	1.14	1.38	0.89	2.03
Moliere Radius (cm)	3.57	2.07	2.23	2.00	3.10
Hygroscopicity	Slight	No	No	No	No
Luminescence (nm)	310	402	430	425(s) 420(f)	300(s) 220(f)
Decay time (ns)	30(s) 6(f)	40	60	30(s) 10(f)	600(s) 0.6(f)
Light output* (%)	3.6(s) 1.1(f)	85	20	0.3(s) 0.1(f)	36(s) 4.1(f)
Dose rate dependent	No	No	-	Yes	No
Reasons for not being selected	-	Cost is too high	Unable to produce large crystals	Too low light yield	Slow component is hard to suppress

f = fast component, s = slow component.

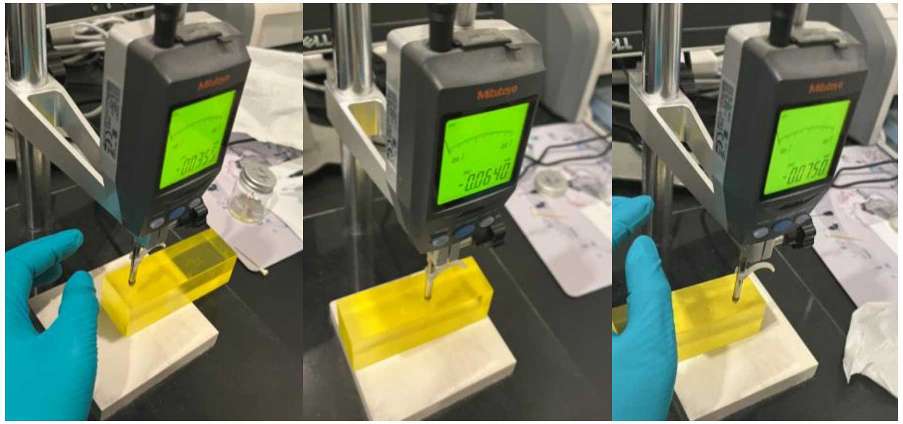


Light output enhancement

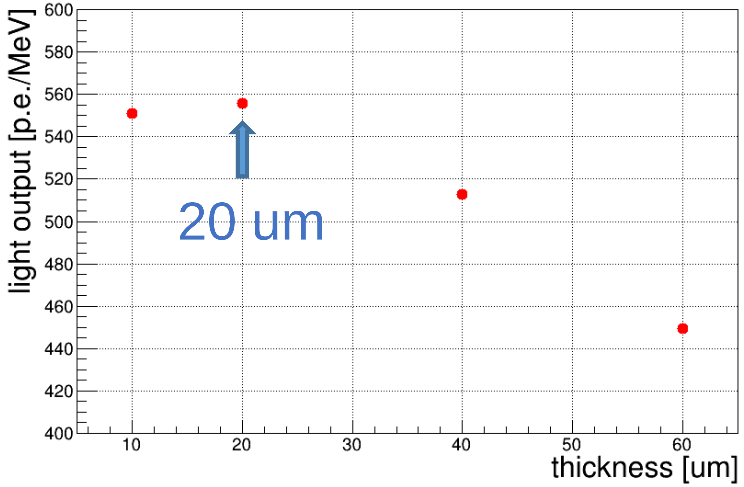
- **Automated coating device**
  - Higher coating efficiency
  - Better thickness uniformity
  - Less harm to humans

Automated coating device

- **WLS coating scheme**
  - Coating thickness optimization: ~20 um



thickness measurement



Light output vs. coating thickness

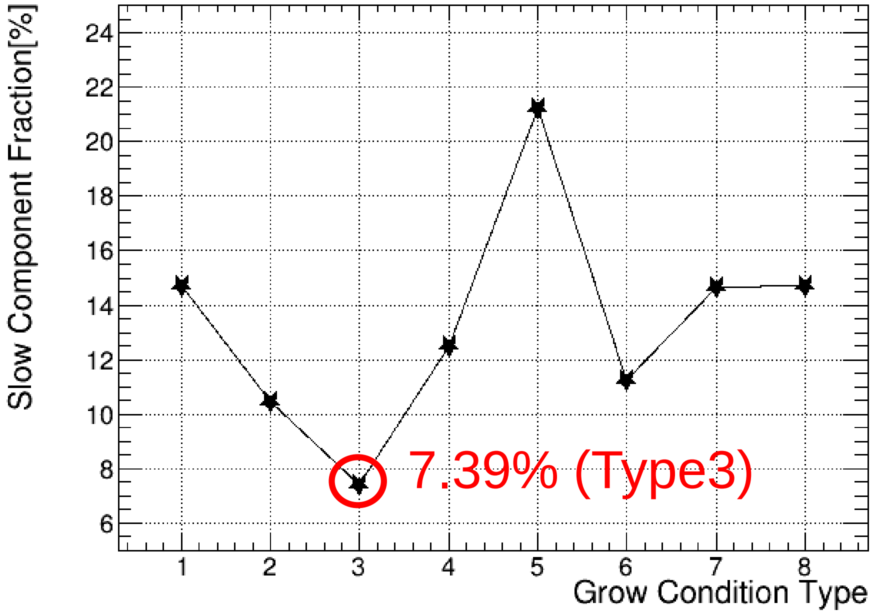
Optimization of Crystal Growth Conditions

- **Requirements of pCsI crystals**
  - Radiation hardness: >70% L.Y. (100 krad)
  - Slow component fraction: <10%
- **Performance vs. growth conditions**
  - ✓ 7.4% slow component fraction
  - ☐ Radiation hardness test in the future

Crystal samples

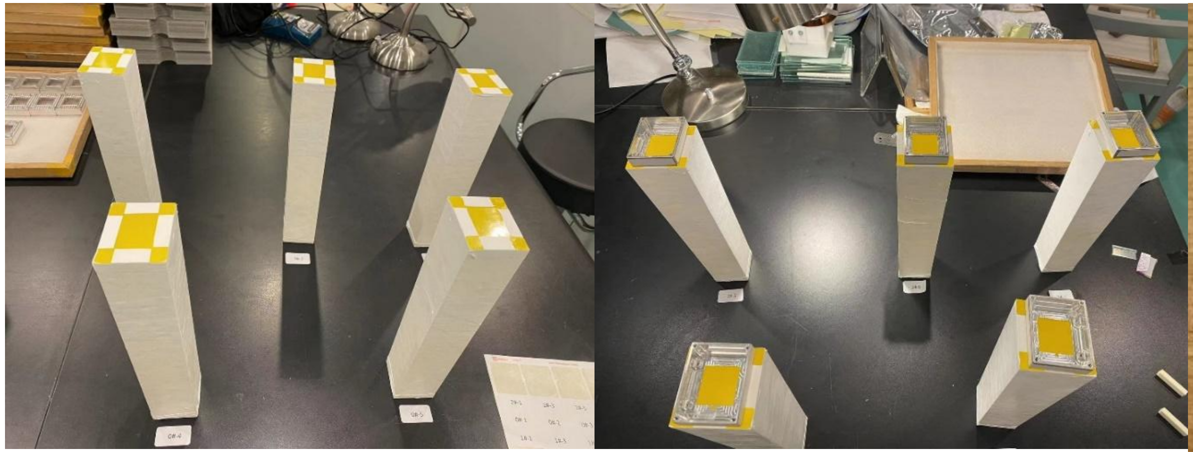
Growth condition	Baking environment	Annealing	Deoxidizing
Type 1	Vacuum	No	Yes
Type 2	Vacuum	No	No
Type 3	Air	No	Yes
Type 4	Air	No	No
Type 5	Vacuum	Yes	Yes
Type 6	Vacuum	Yes	No
Type7	Air	Yes	Yes
Type 8	Air	Yes	No

8 types of growth condition

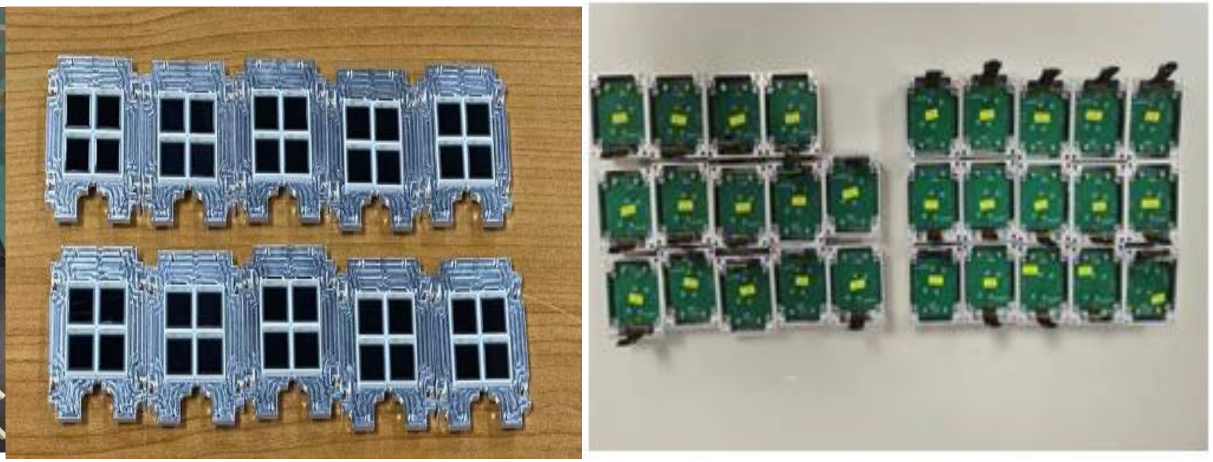


Slow component fraction vs. growth conditions

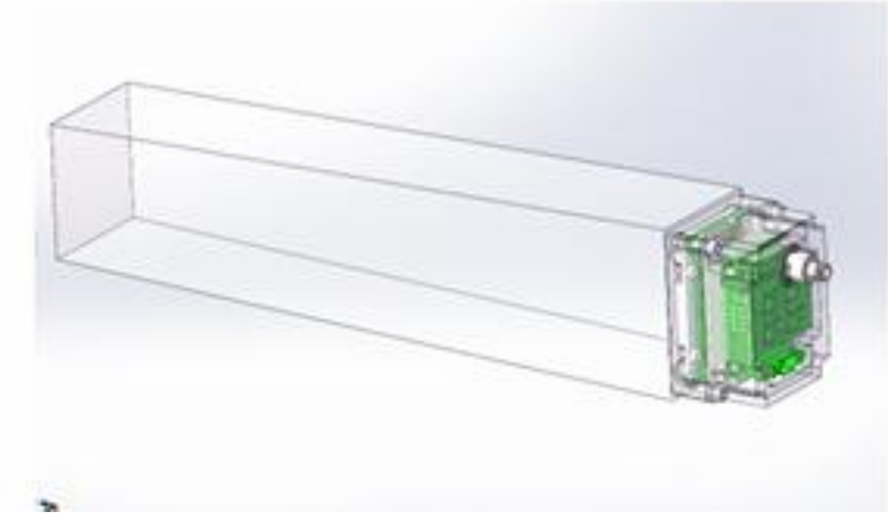
Batch assembly of sensitive units



Glue the APD box to pCsI crystal



The APD and FEM boxes



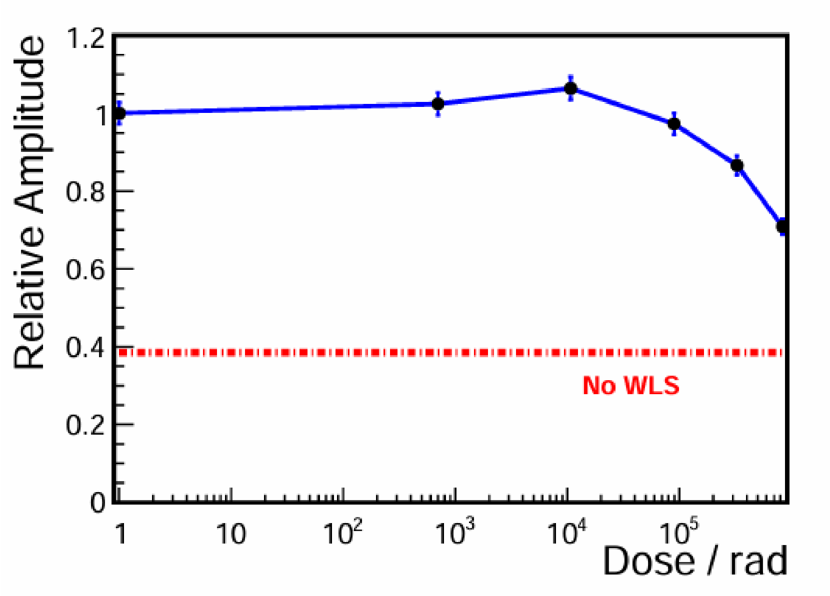
Schematic diagram of the sensitive unit

Photograph of the sensitive unit

WLS Coating Stability

➢ Irradiation test

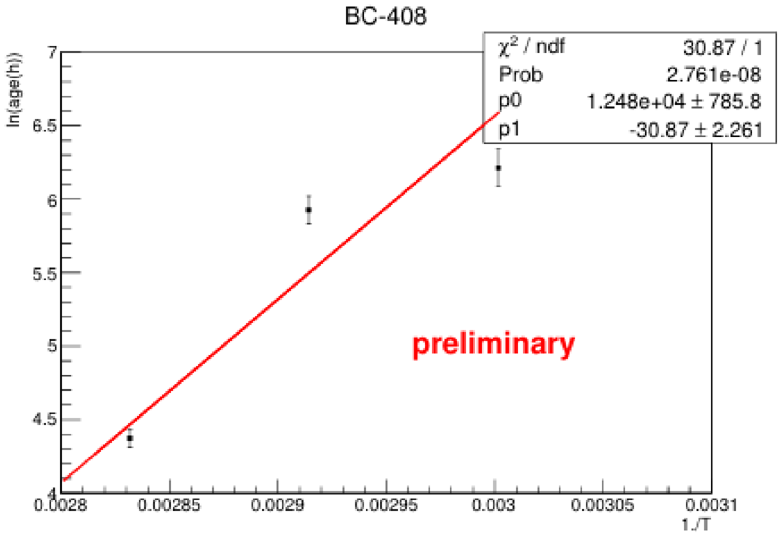
- Irradiate WLS with ^{60}Co source：
  - 90 krad： no obvious decline
  - 833 krad： decrease by 30%
- Good radiation hardness of WLS



Light output vs. radiation dose

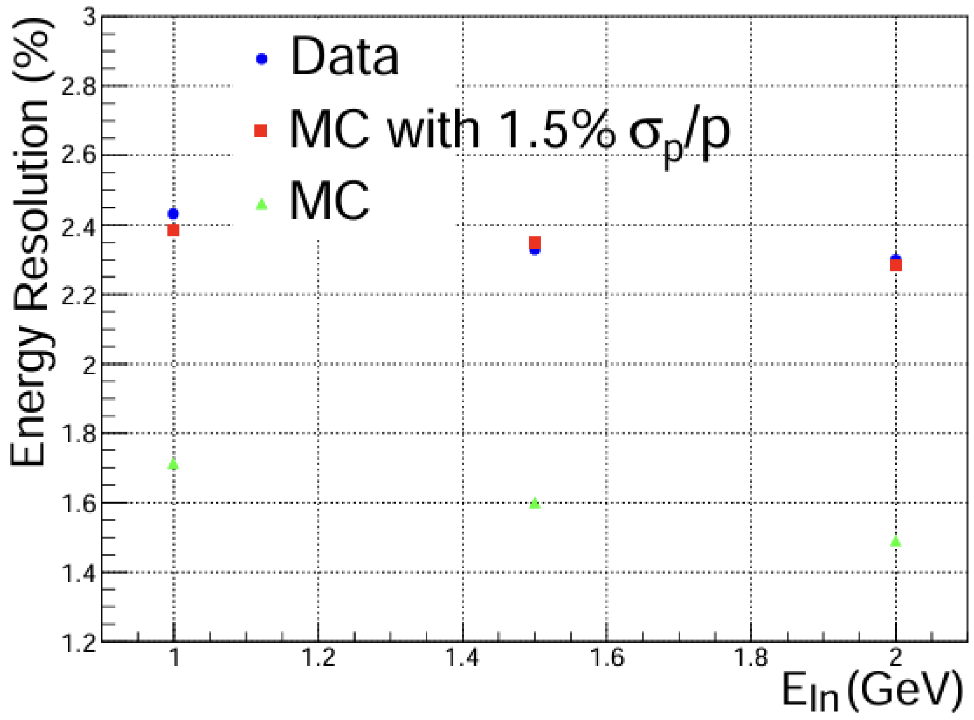
➢ Aging test in the future

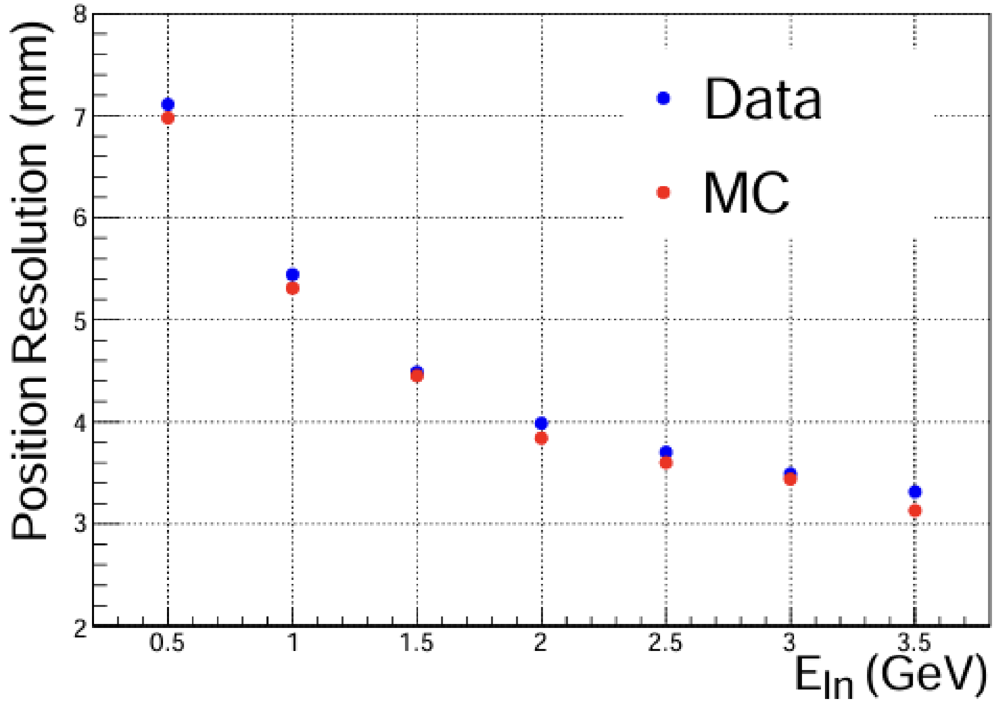
- Aging study of WLS is tested in high temperature environment
- The relationship is described by Arrhenius formula： $\ln(t) = \frac{A}{T} + B$。



Aging effect of PS is described by Arrhenius formula

Performance vs. Simulation

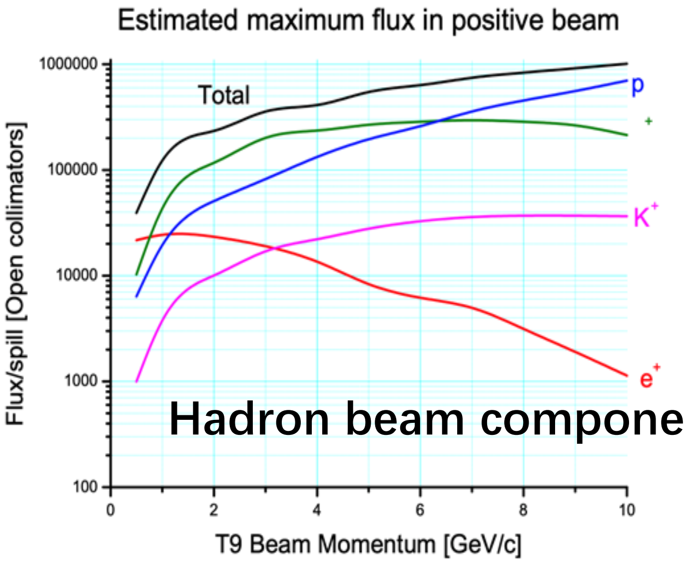




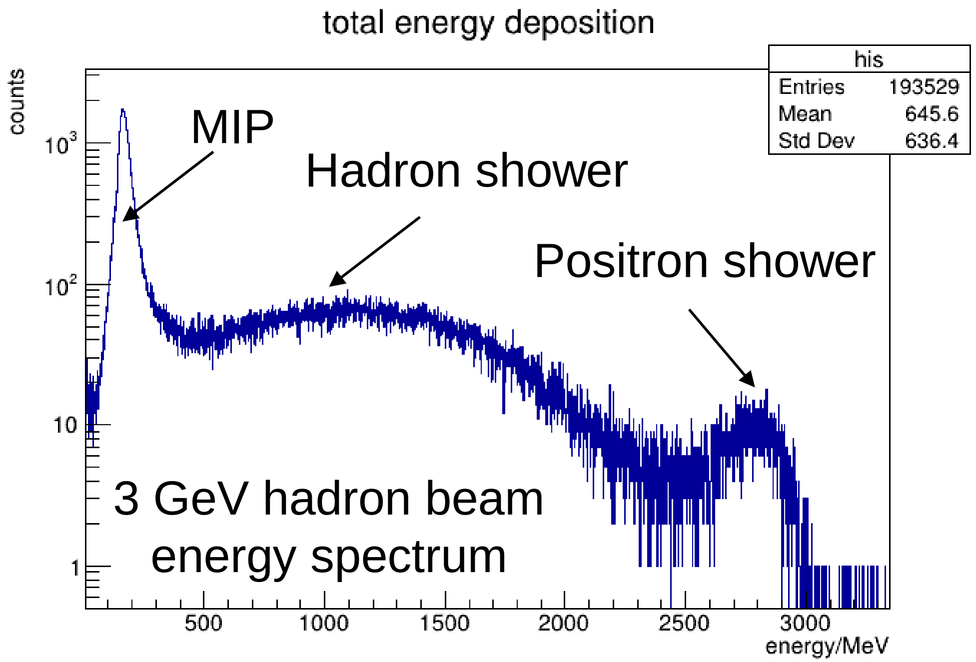
- Energy and position resolution vs. e^+ beam momentum

Hadron beam components

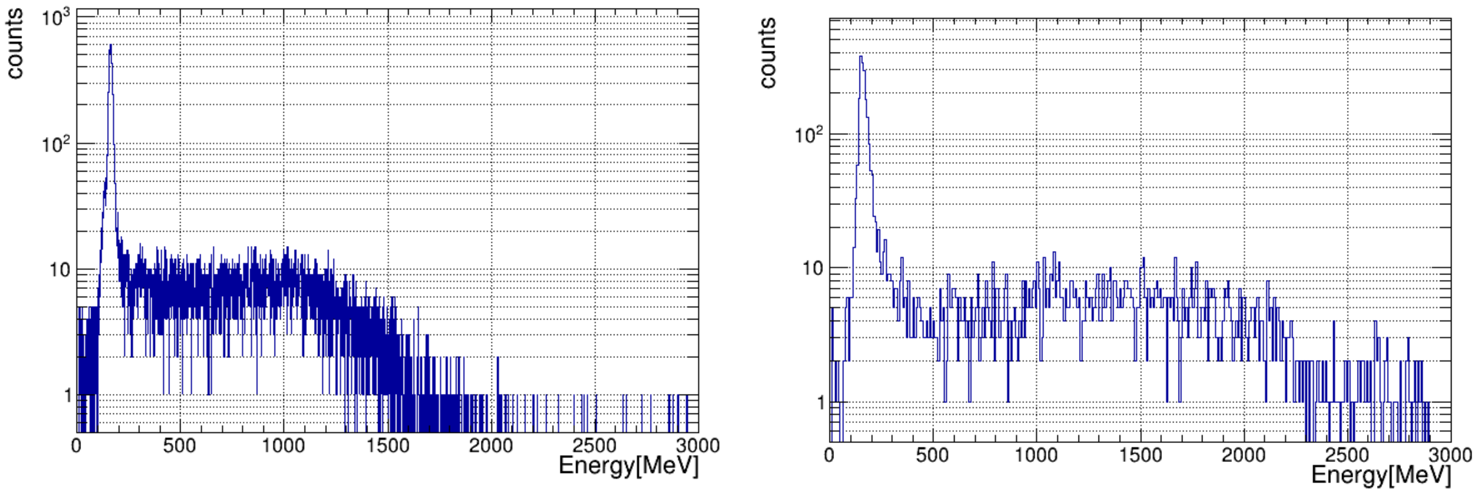
- Hadron beam consists of p、π、K、e。



Hadron beam components



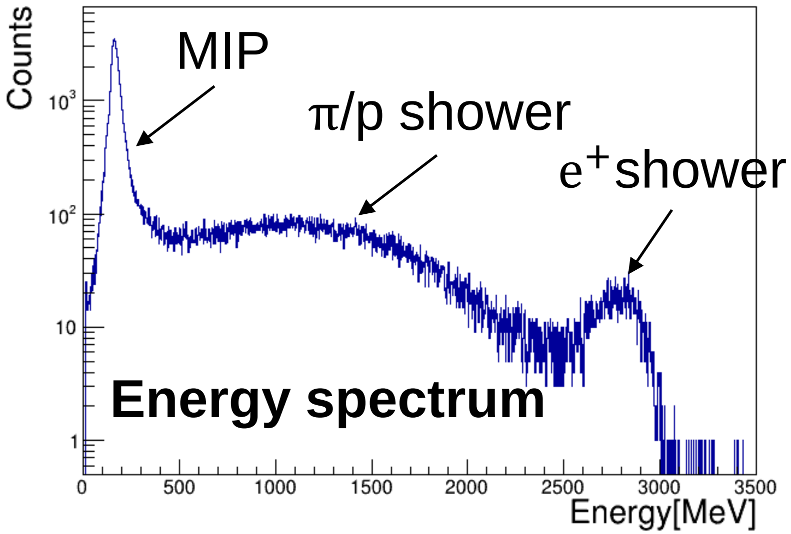
3 GeV hadron beam energy spectrum

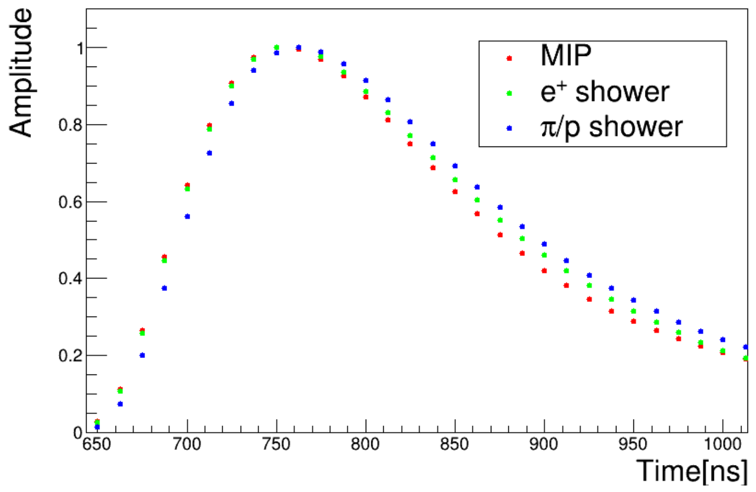


3 GeV proton(left) and anti-proton(right) energy spectra

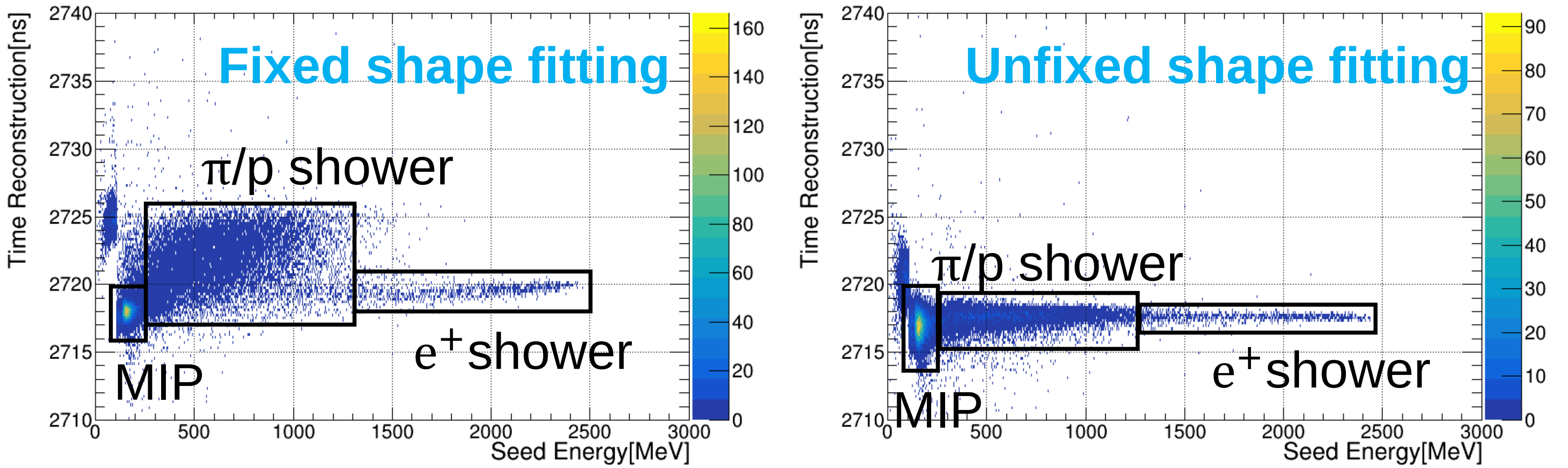
Time Reconstruction Performance

- **Time reconstruction ($\Delta_T = T_{ECAL\_Rec} - T_0$) for hadron beam ($\pi^+/p^+/e^+$)**
  - ➢ Pulse shape differences result in a nonuniform time response
  - ✓ A good uniformity is achieved with an “unfixed shape” fitting method



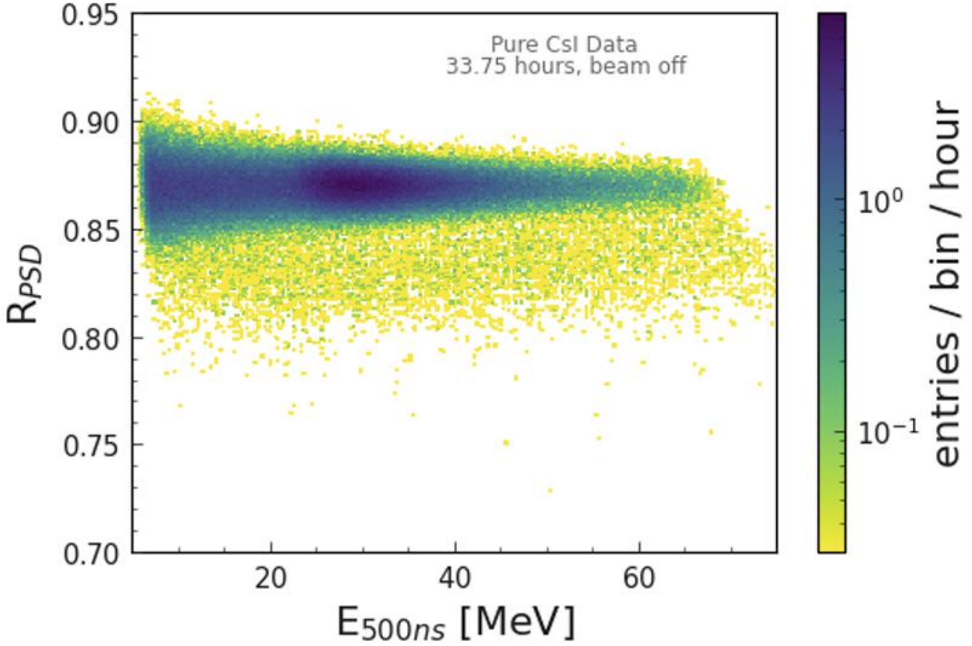


Pulse shape differences

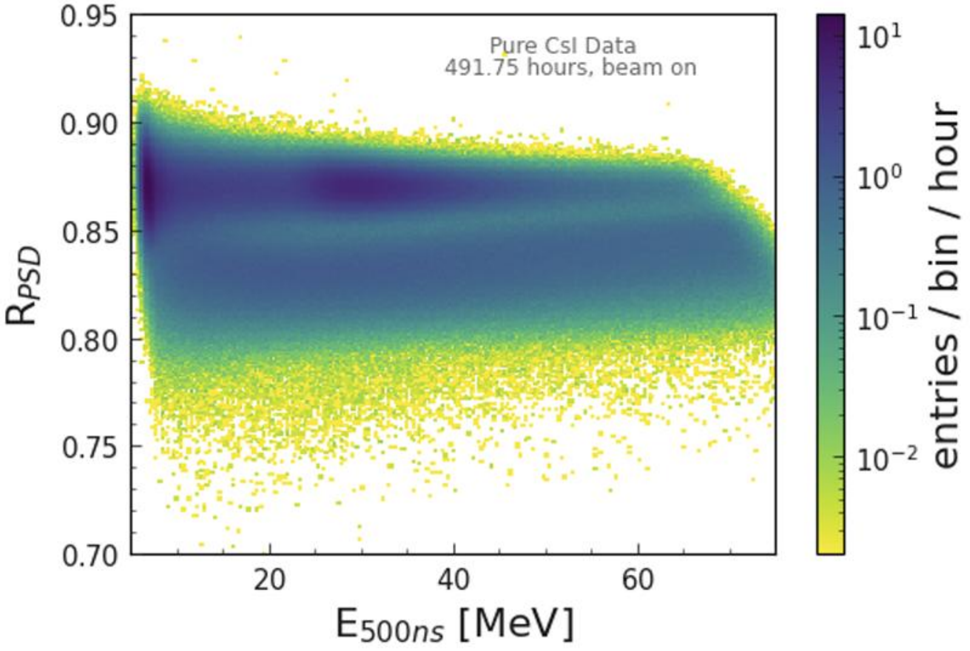


Time reconstruction vs. Energy for 3 GeV hadron$^+$ beam

Time Response Non-uniformity



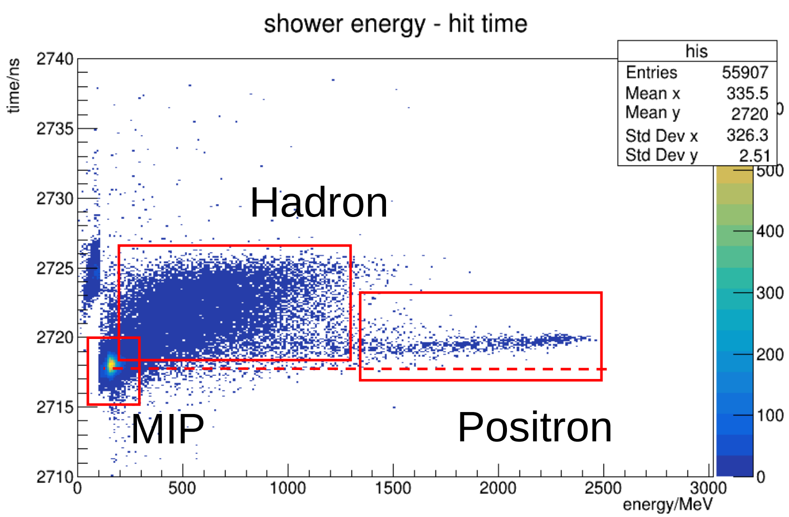
R_{psd} vs. Energy in cosmic-ray test



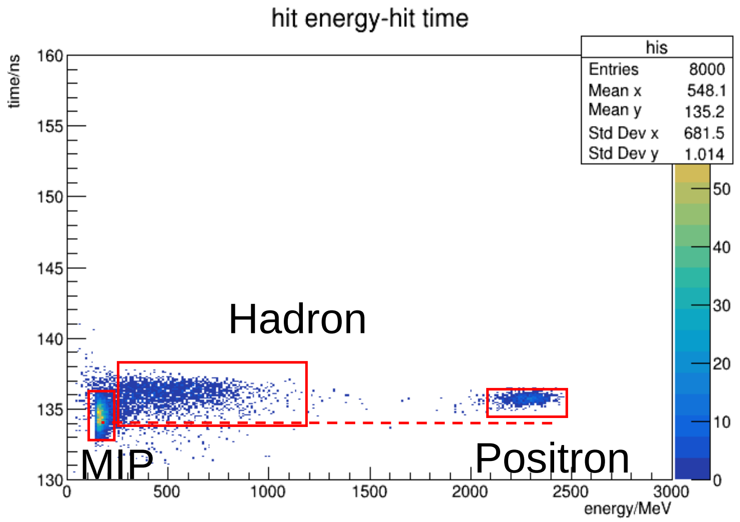
R_{psd} vs. Energy in neutron beam test

- Low R_{psd} events in neutron beam indicate a slower scintillation component of pCsI crystals

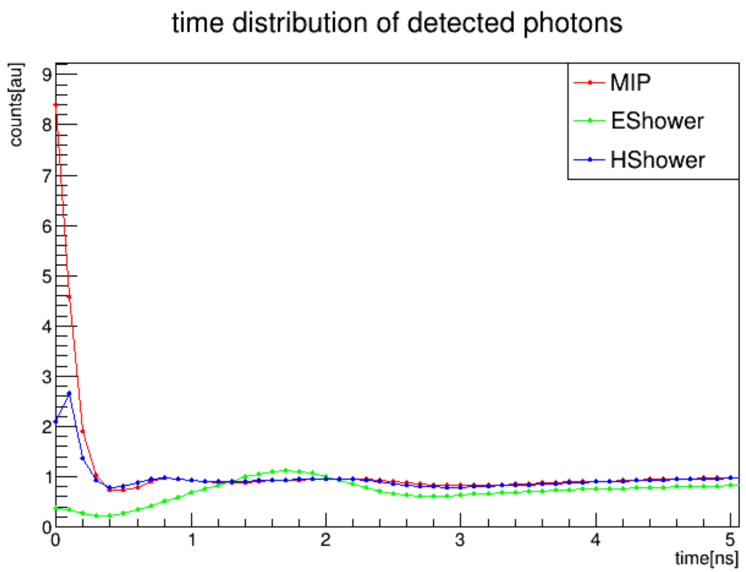
Time Response Non-uniformity



Time response vs. energy deposition for 3 GeV hadron beam (data)



Time response vs. energy deposition for 3 GeV hadron beam (simulation)



time distribution of photons detected in the simulation

- In the simulation, positrons are also slightly slower than MIPs (~1 ns), originating from the spatial distribution of energy loss

Unfixed-shape fitting

- Form of the template fitting function:

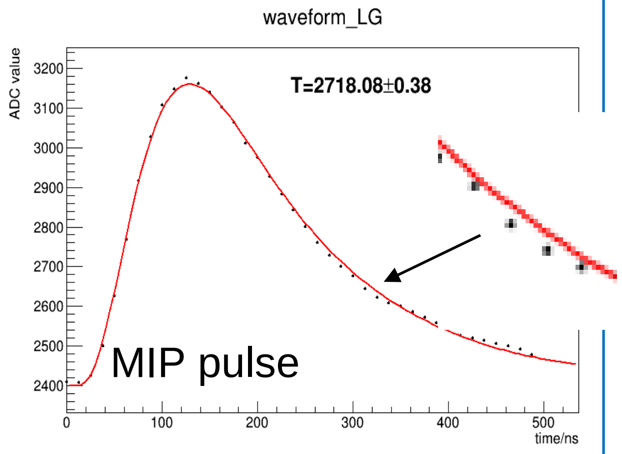
$$f(t) = \begin{cases} \{\sum_{i=0}^{5} A_i e^{-\frac{t-T_0}{\tau_i}}\} \cdot (t-T_0)^k + ped & t \geq T0 \\ ped & t < T_0 \end{cases}$$

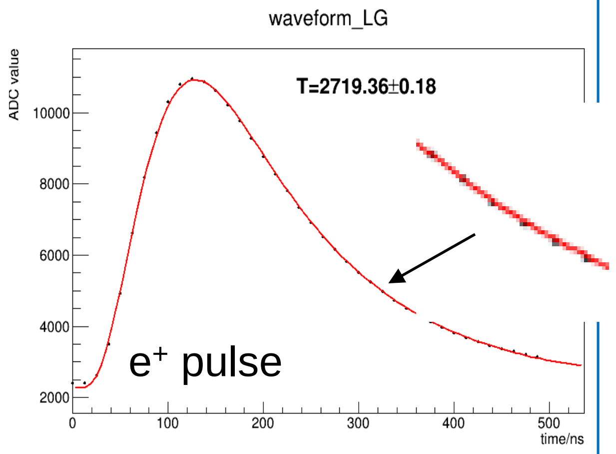
5 Exponential ×1 Power

- Only two free parameters: ped(pedestal) and T0(time)

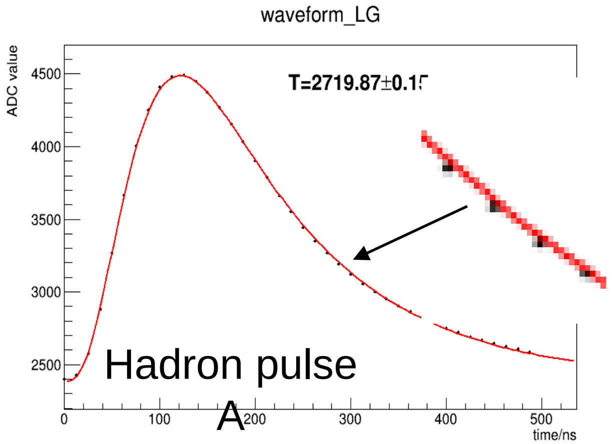
- Template does not fit MIP and hadron pulses well

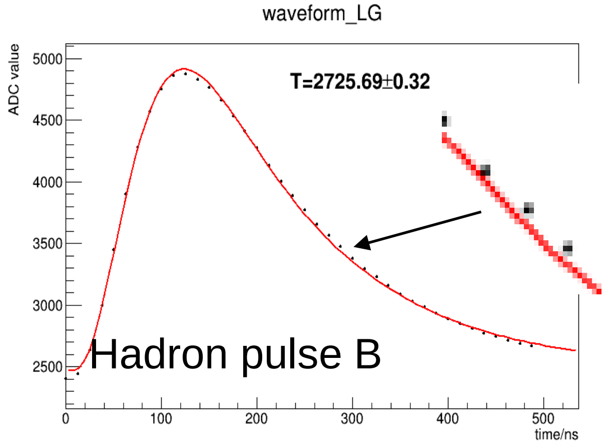
➢ MIP and e^+





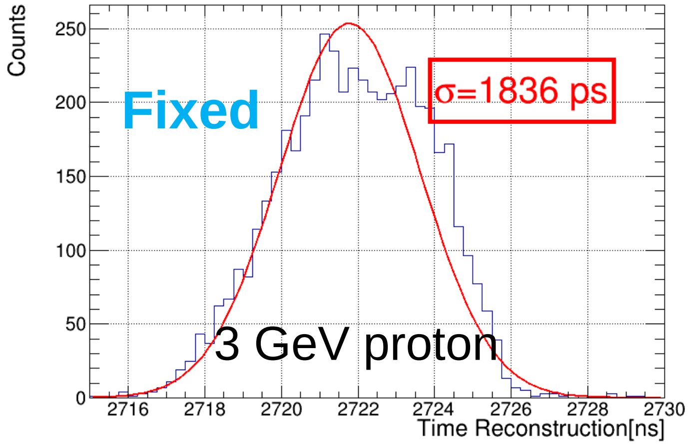
➢ Hadron showers

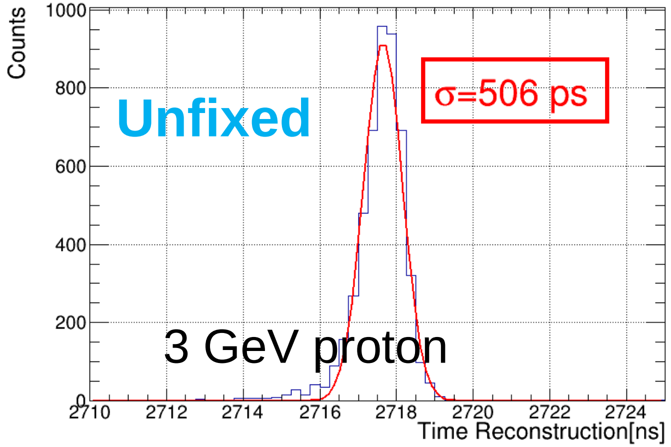




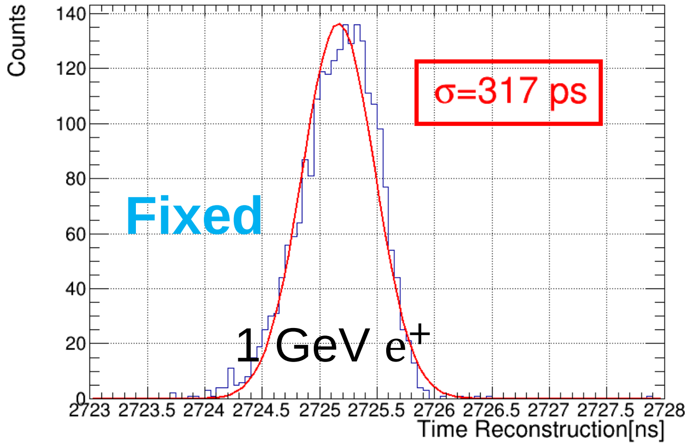
Time Reconstruction Performance

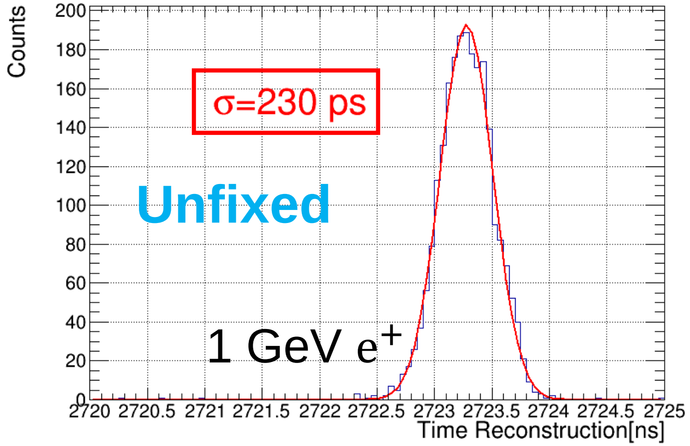
- **Time resolution significantly improved for hadrons**





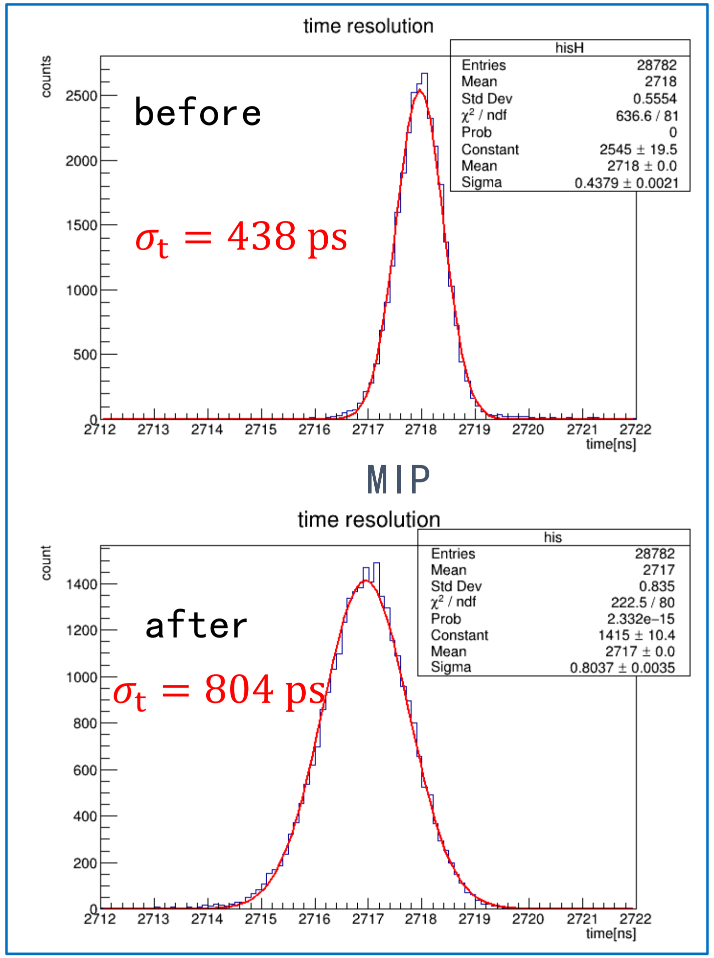
- **Time resolution for 1 GeV e^+ reaches 230 ps**

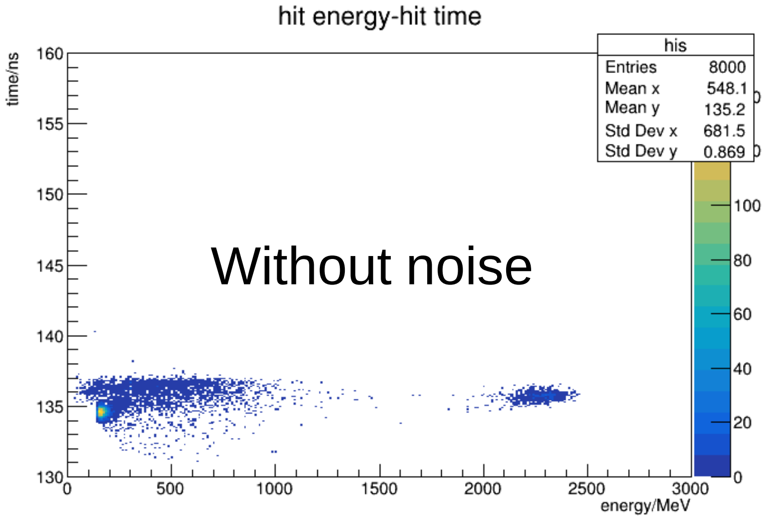


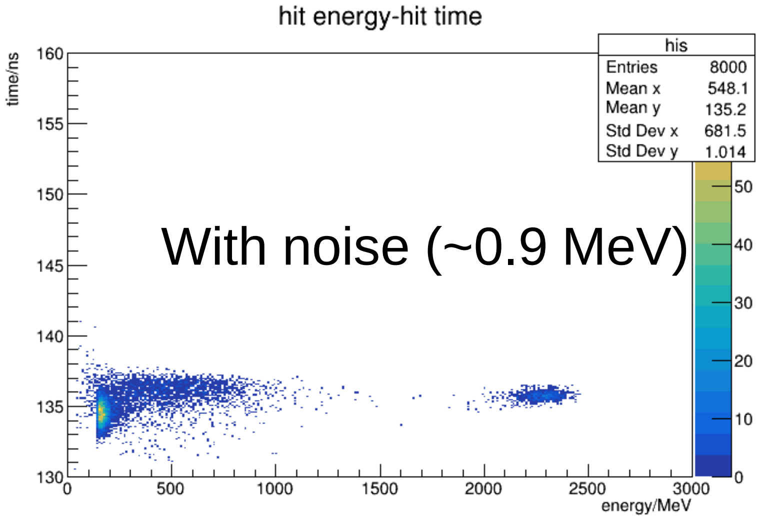


Unfixed-shape fitting

- Time resolution of MIP gets worse because of electronic nose

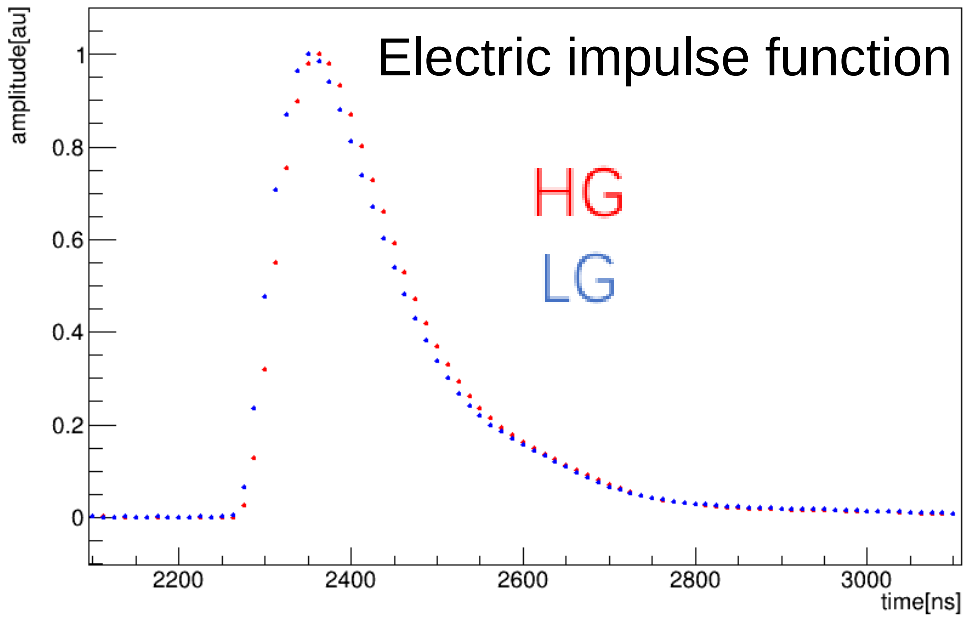




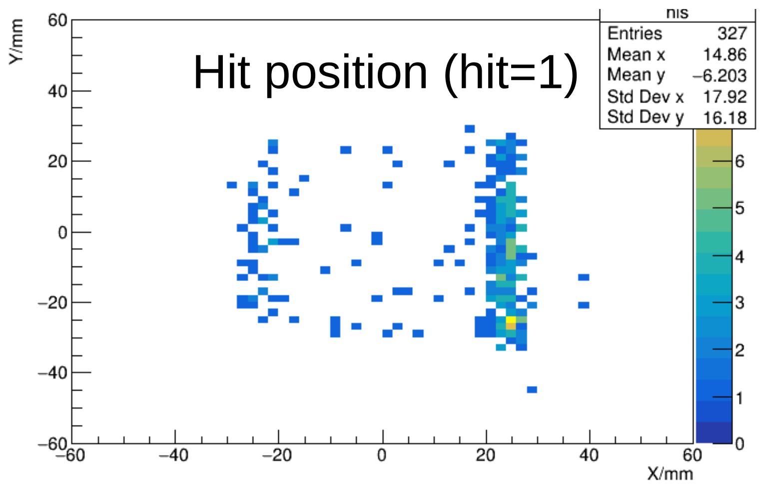


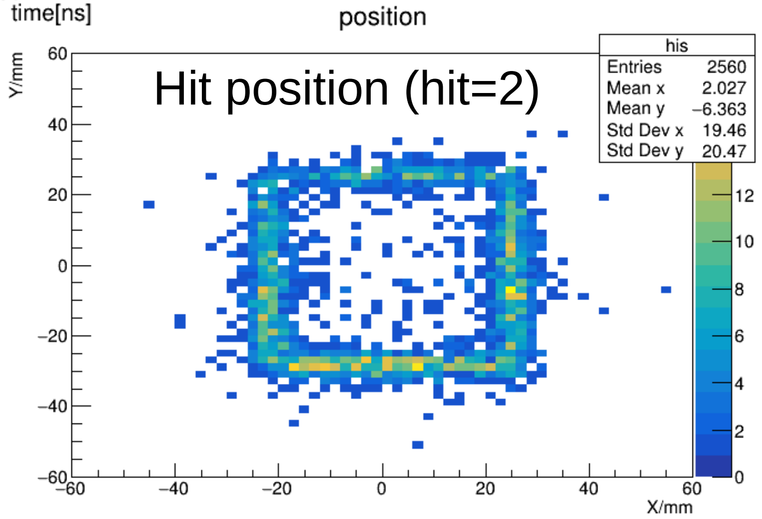
- Fitting result is affected by pulse shape perturbation from electronic noise

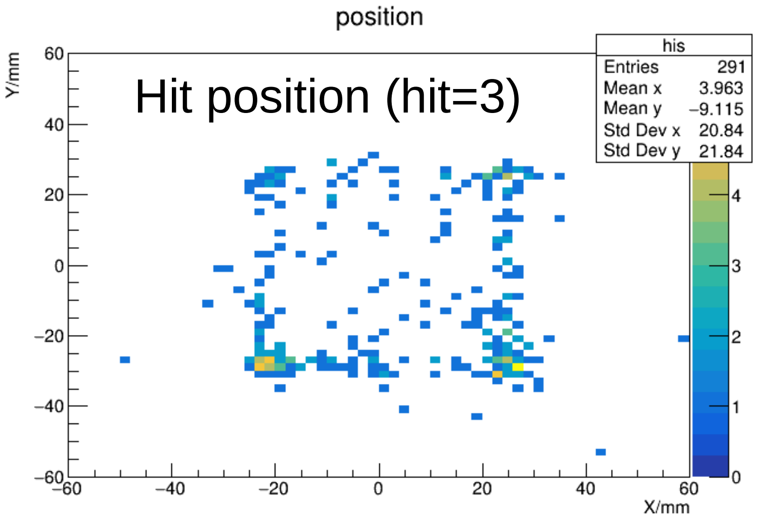
HG Channel Events



- Hit=1: pass through a single crystal and its gap
- Hit=2: pass through two crystals and the gap
- Hit=3: pass through three crystals and the gap







Pipeline fitting

Pipeline fitting method

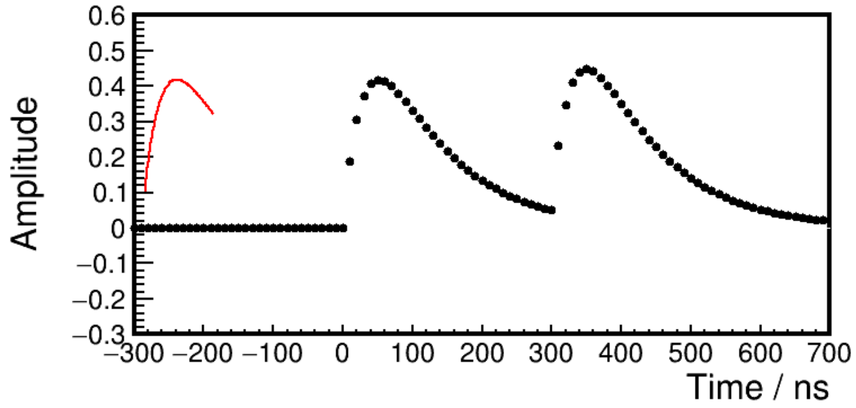
- Real-time online processing
- Template fit once for each fitting
  - Each fitting begin with different ADC point
  - Add one more fitting between two ADC points
- Fit successful
  - $A > E_{thr}$
  - $\triangle T < 12.5/2$
  - $\chi^2/ndf < 3$:

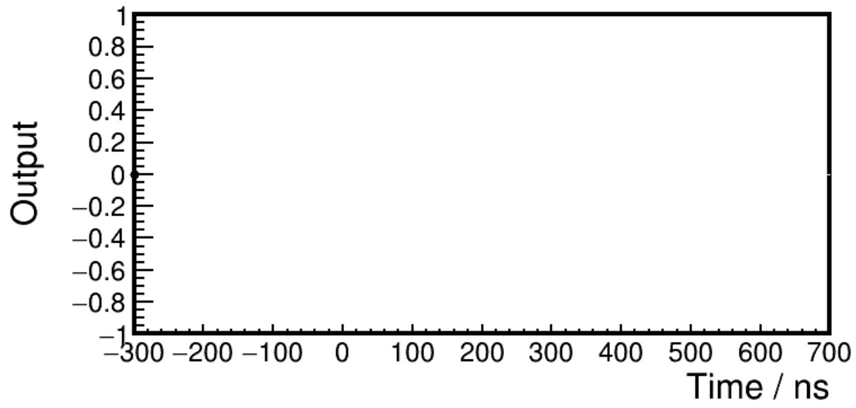
$$\chi^2/ndf = \left[\sum_{i,j}\left(y_i - A\cdot f(t_i-\tau) - p\right)\cdot S_{ij}^{-1}\cdot\left(y_j - A\cdot f\left(t_j-\tau\right)-p\right)\right]/\left((n-2)\cdot\left(\sigma_{nos}^2 + (A\cdot 0.01)^2\right)\right)$$

→ Cache and compared with next fit

→ Remove template

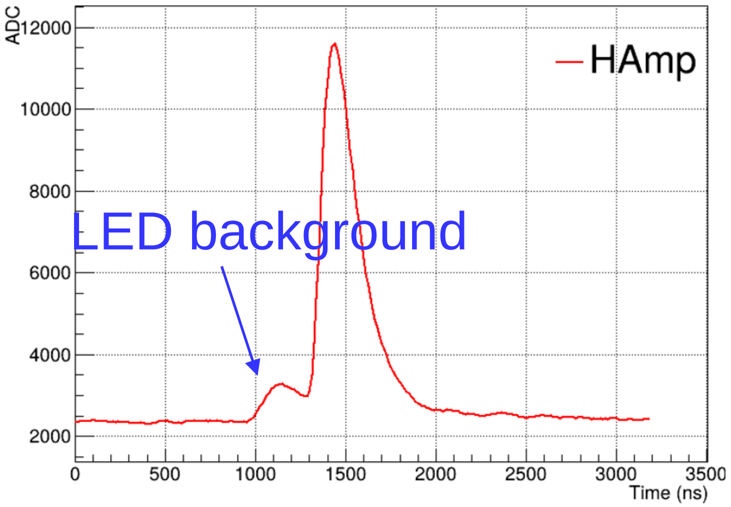
→ Ongoing processing



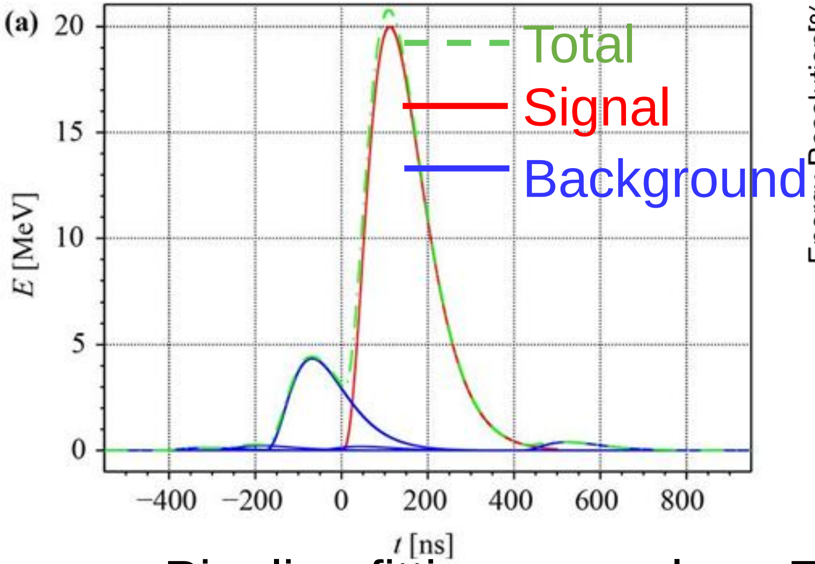


Pileup Mitigation

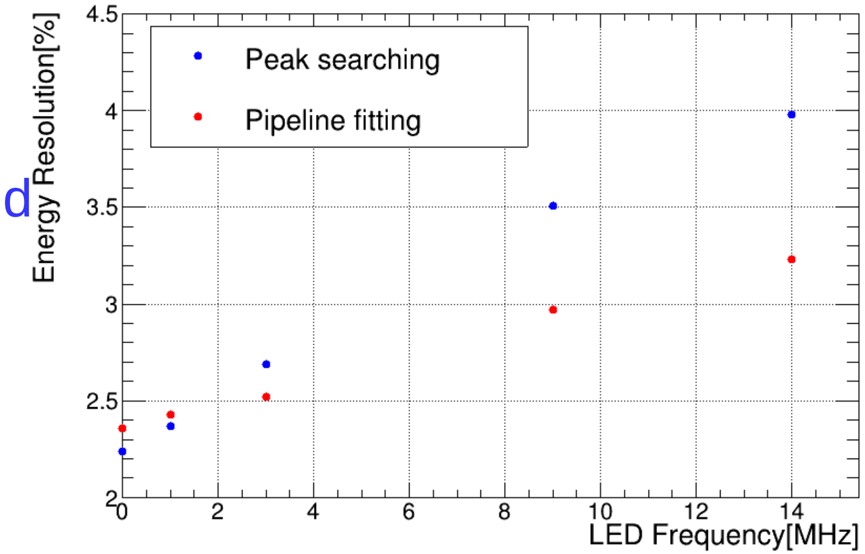
- **LED light is introduced to simulate high background in STCF**
  - ➢ Energy spectrum similar to background
  - ➢ Frequency up to 14 MHz
- **Pileup mitigation with "pipeline fitting" method**
  - ➢ ~2.5% energy resolution under 3 MHz background level



Signal with LED background



Pipeline fitting example



Energy resolution degradation with LED