中国科学技术大学 University of Science and Technology of China

超级陶粲装置 Super Tau-Charm Facility

Progress of the STCF ECAL

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On behalf of the STCF calorimeter working group

International Workshop on Future Tau Charm Facilities (FTCF 2025)
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Outline

- Introduction to STCF ECAL
- Optimization and Development of Prototype
- Beam Test and Performance Study
- Summary

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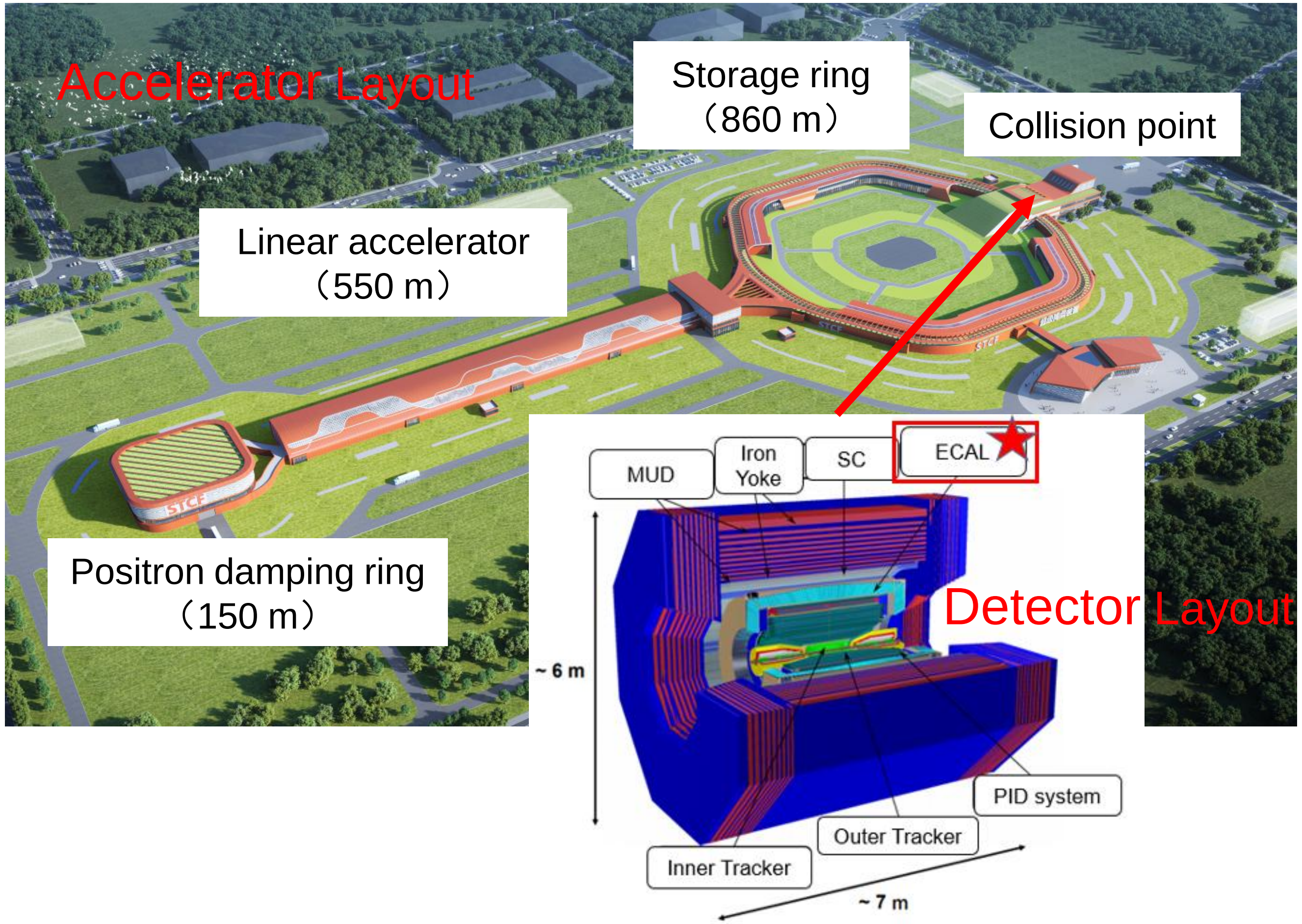
Super Tau-Charm Facility (STCF)

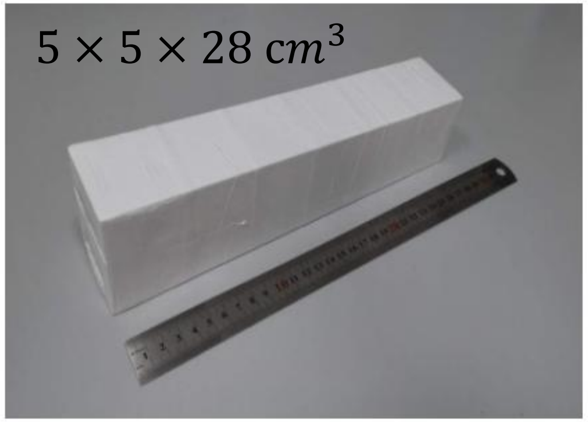
- **Next-generation high luminosity e^+e^- collider in China**
  - Center-of-mass energy: $\mathbf{2-7\ GeV}$
  - Luminosity: $\geq \mathbf{0.5 \times 10^{35}\ cm^{-2}\ s^{-1}}$ **@ 4 GeV**



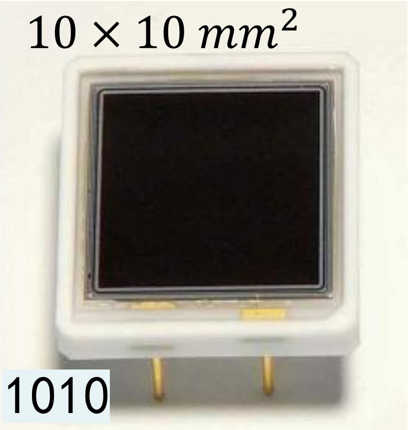
- **Challenges and requirements of ECAL**
  - High event rate (400 kHz)
  - High background level (~MHz)
  - Radiation resistance (40 krad)
  - Large energy dynamic range: 25 MeV ~ 3.5 GeV
  - Precise energy resolution : < 2.5% @ 1 GeV
  - Good position resolution : ~5 mm @ 1 GeV
  - Good time resolution: ~300 ps @ 1 GeV

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.)

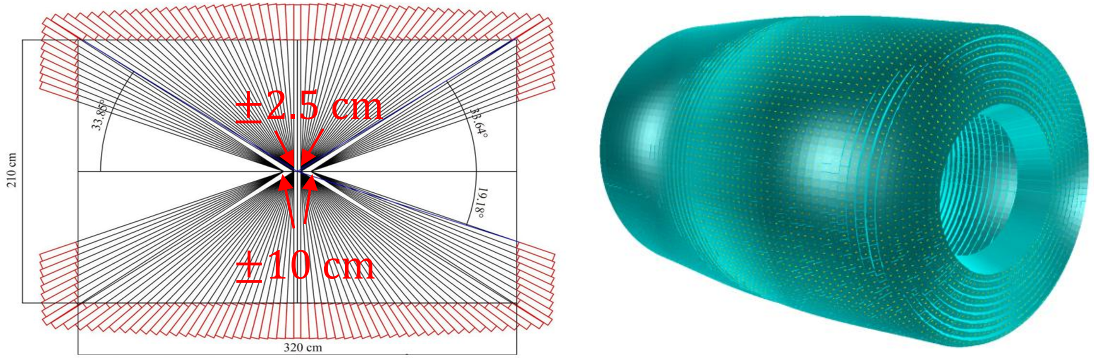


pCsI crystal



APD (S8864-1010)

- **Design of Electronics**
  - Charge-sensitive amplifier (CSA)
  - Waveform sampling readout
- **Design of Geometry**
  - Barrel + Endcap: 8670 crystals
    - ✓ ~95% solid angle coverage
  - Defocus layout
    - ✓ ~6% higher detection efficiency



Crystal arrangement diagram

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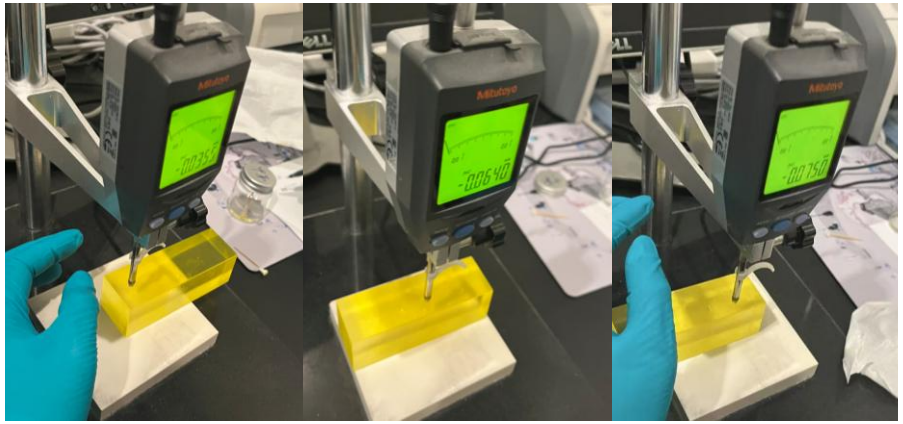
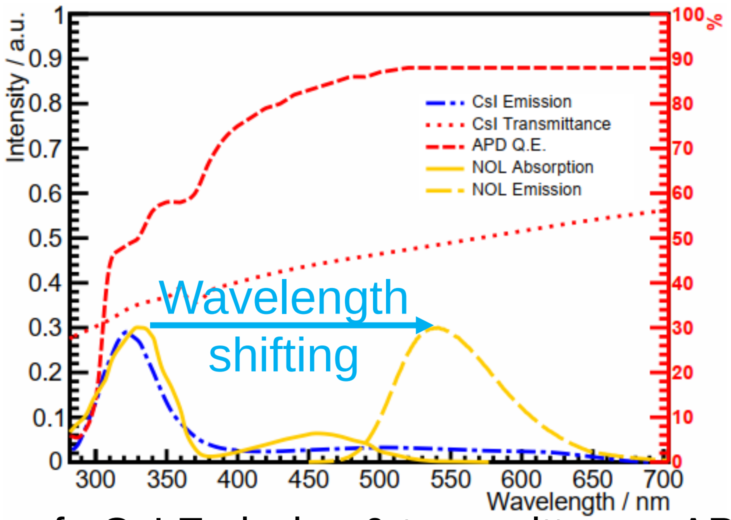
Light output enhancement

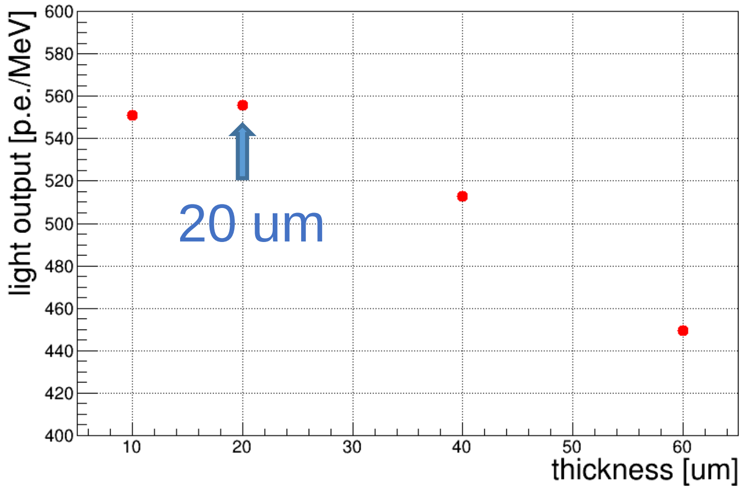
- **Low light collection efficiency**
  - Emission peak of pCsI is ~310 nm
    - Low transmittance
    - Low APD Q.E.
- **WLS coating scheme**
  - Wavelength shifting: ~300 nm → ~550 nm
    - ✓ Transmittance: 30% → 50%
    - ✓ APD Q.E.: 40% → 80%
  - Coating thickness optimization: ~20 um



thickness measurement



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



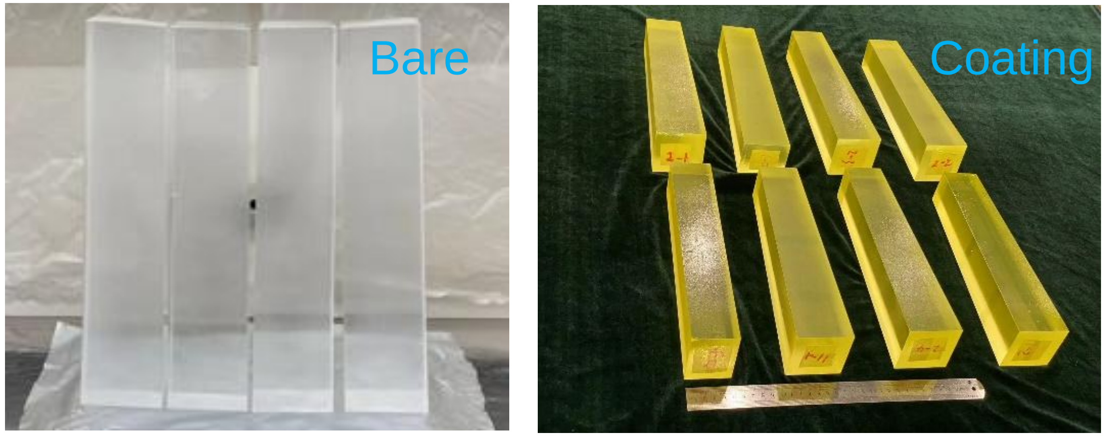
Light output vs. coating thickness

Light output enhancement

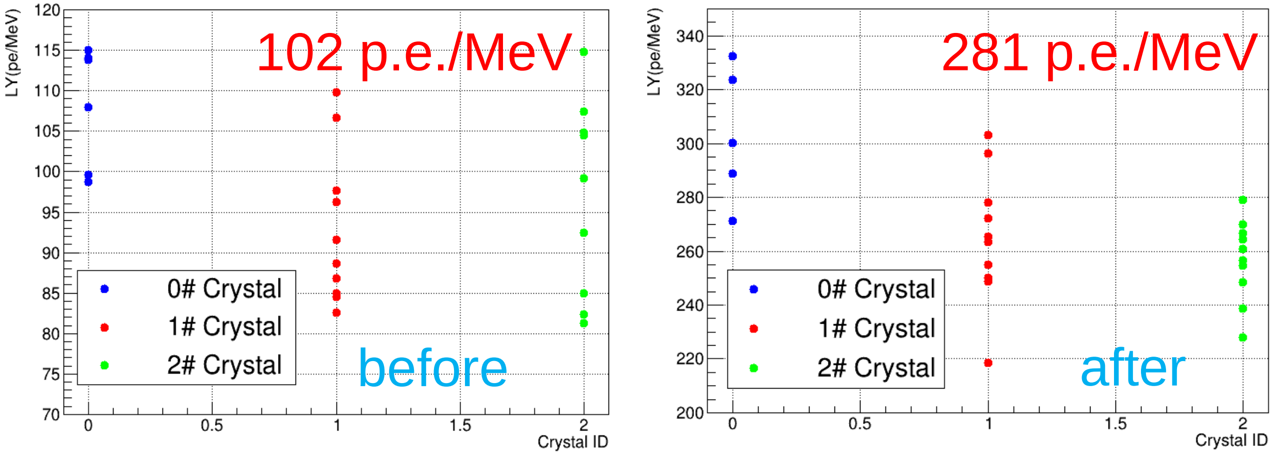
- **Automated coating device**
  - Higher coating efficiency
  - Better thickness uniformity
  - Less harm to humans

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

Automated coating device



pCsI crystals before and after coating

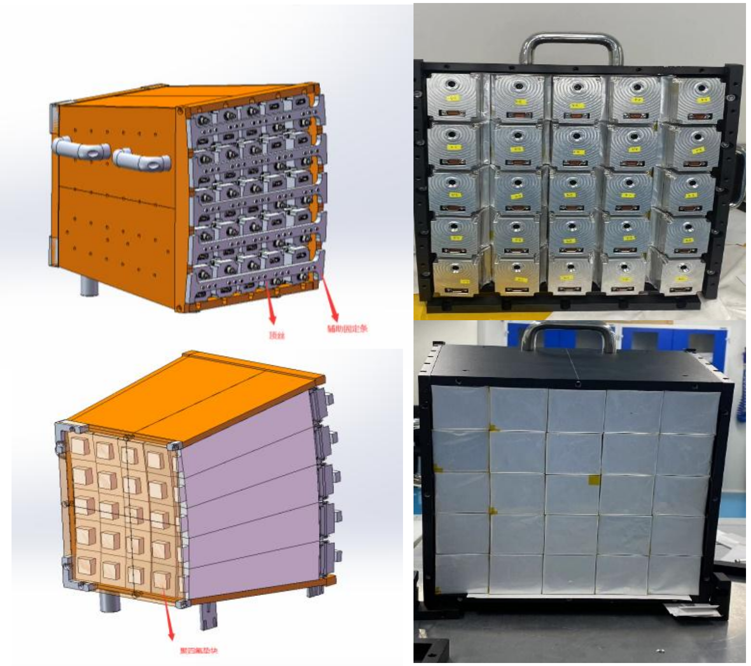


Light output before and after coating

Development of 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

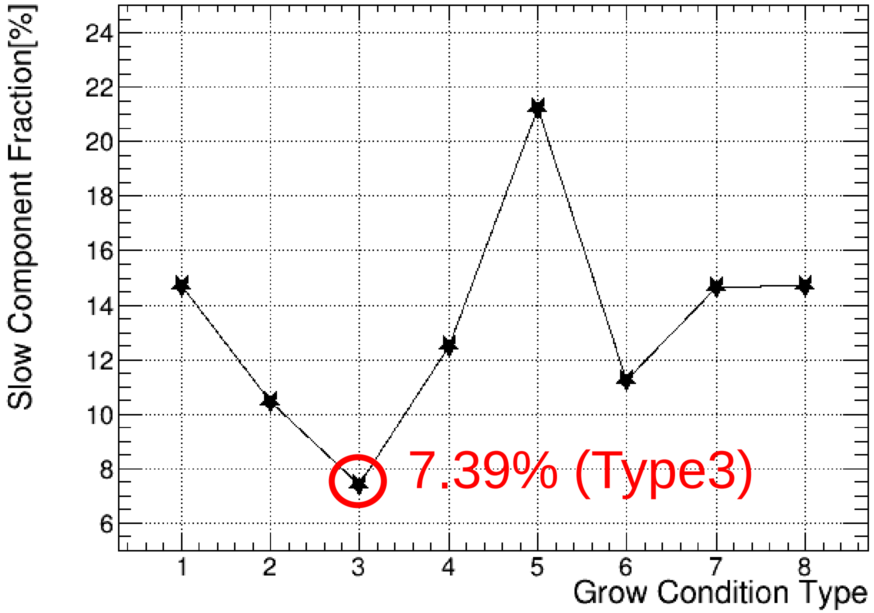
Optimization of Crystal Growth Conditions

- **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

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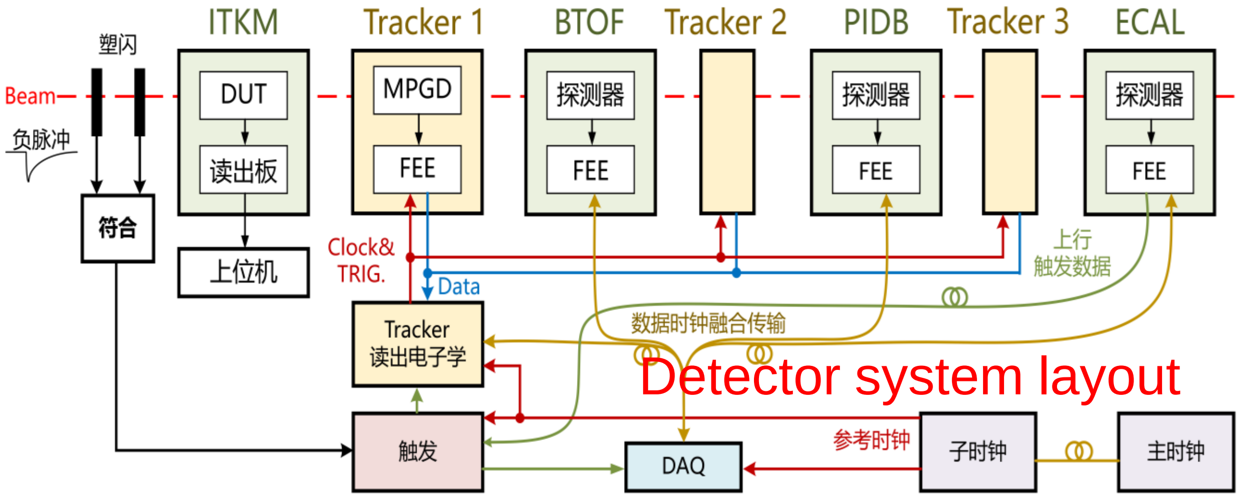
Beam Test

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

Type	Momentum
μ^+	~ 10 GeV/c
e^+	0.2-3.5 GeV/c
$hardon^+$	1-5 GeV/c



Detector system layout

On-site setup

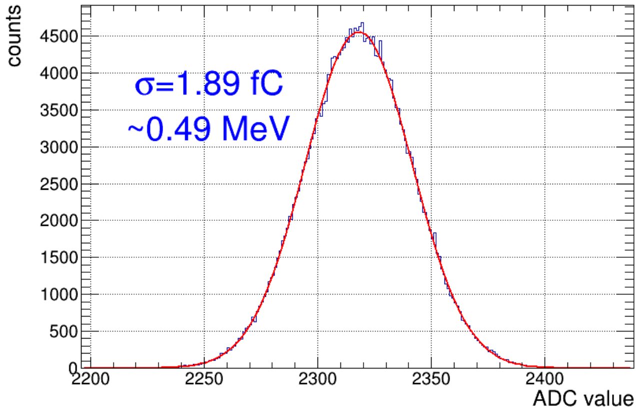
Beam Test

ECAL prototype

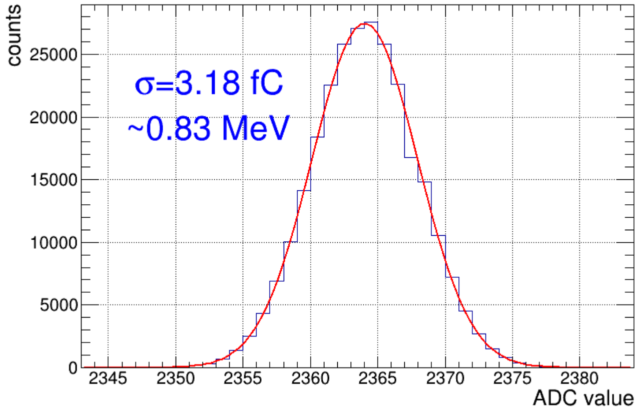
ECAL test team

Operating status of Prototype

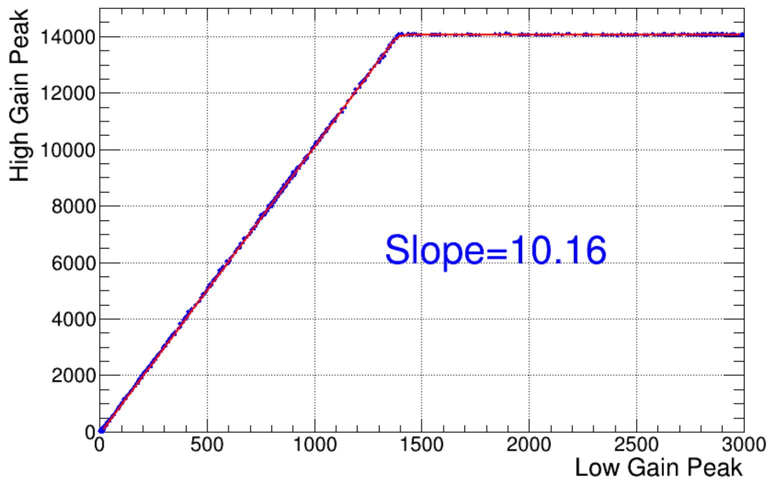
- **Noise level**
  - ➢ Low Gain : ~3.2 fC (ENE: ~ 0.8 MeV)
  - ➢ High Gain: ~1.9 fC (ENE: ~0.5 MeV)
- **High-Low gain ratio : ~ 10**
- **Calibration with μ^+: ~180 MeV**
- **Temperature is stable: ~30$\pm$0.5 ℃**



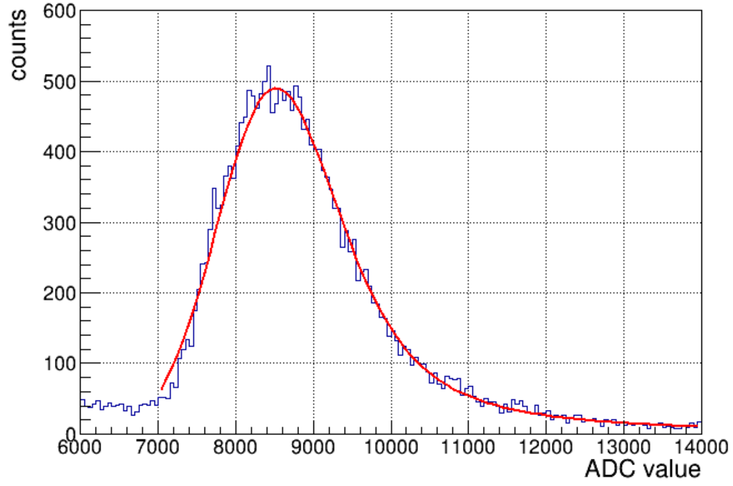
High gain noise



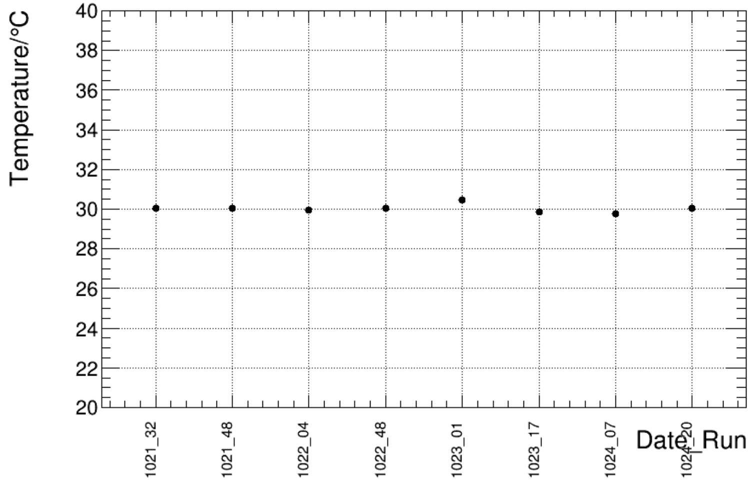
Low gain noise



High-Low gain ratio



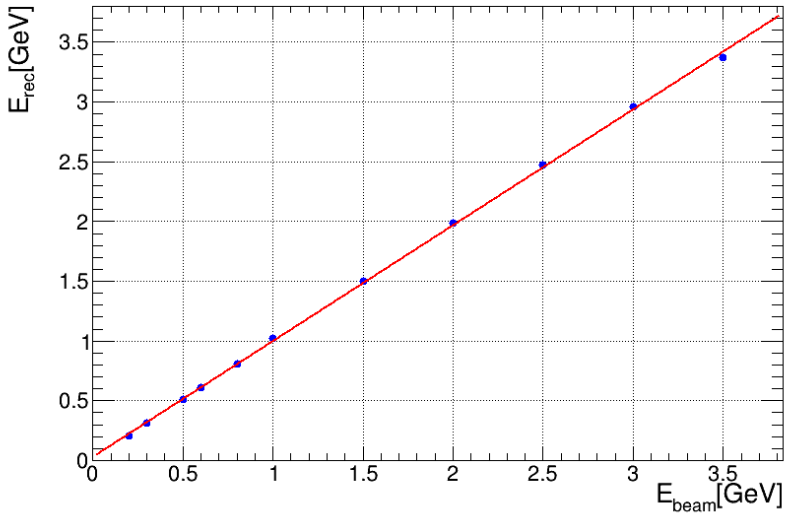
Energy spectrum of MIPs



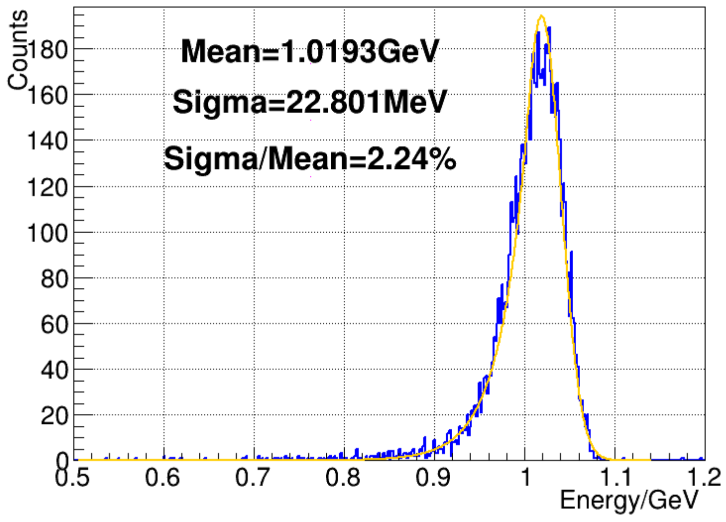
Temperature stability

Energy Reconstruction Performance

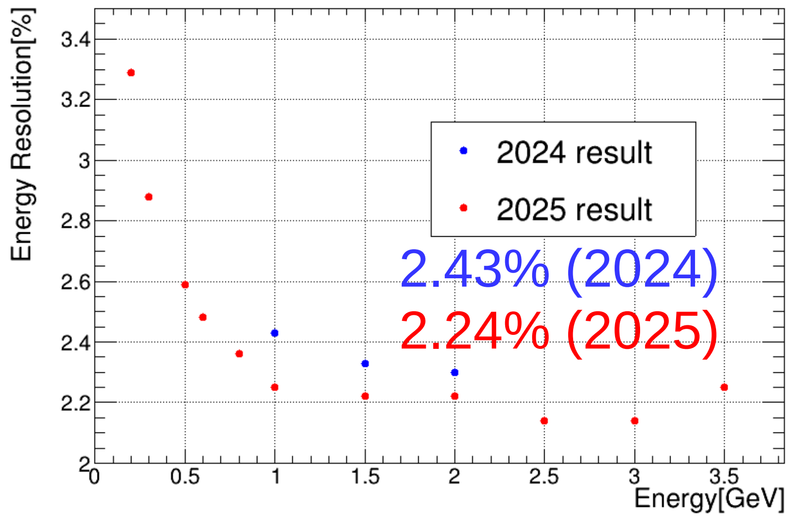
- **Good Energy linearity**
  - From 0.2 GeV to 3.5 GeV
- **Energy resolution for 1 GeV e^+ is 2.24% (better than 2024)**
  - Higher dynamic range of low-noise HG channel
  - Less material budget in front of ECAL



Energy linearity



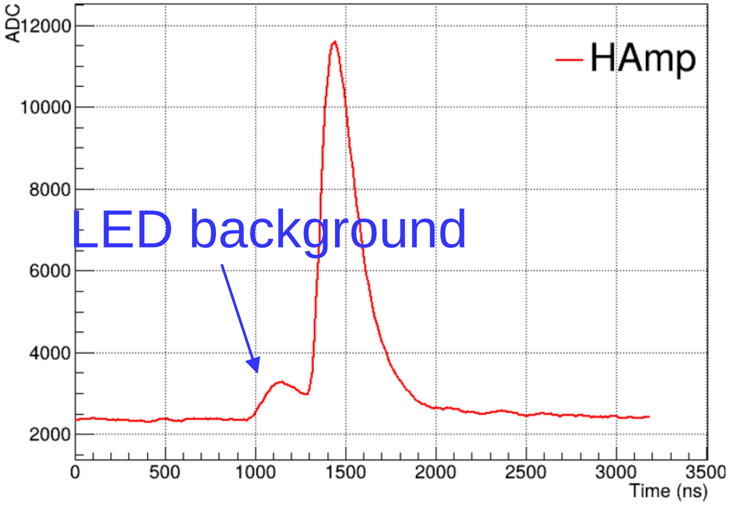
Energy spectrum of 1 GeV e^+



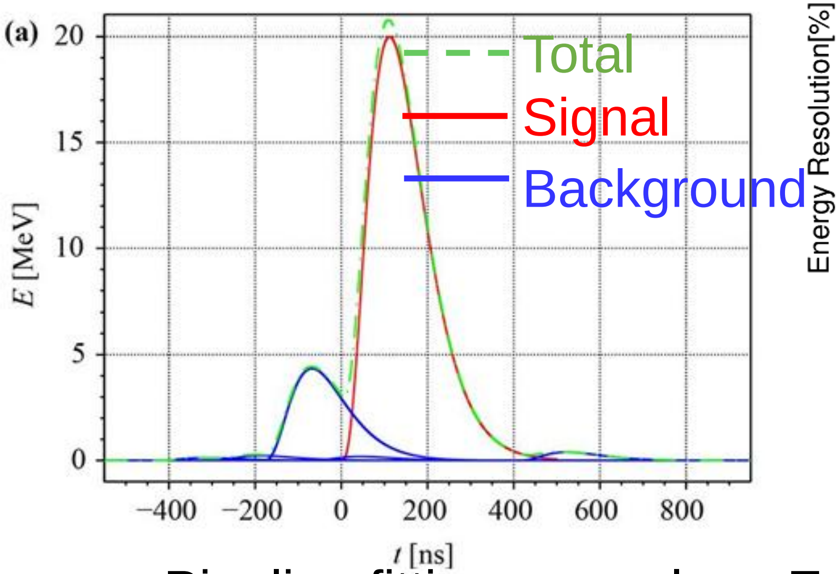
Energy resolution vs. Energy

Pileup Mitigation

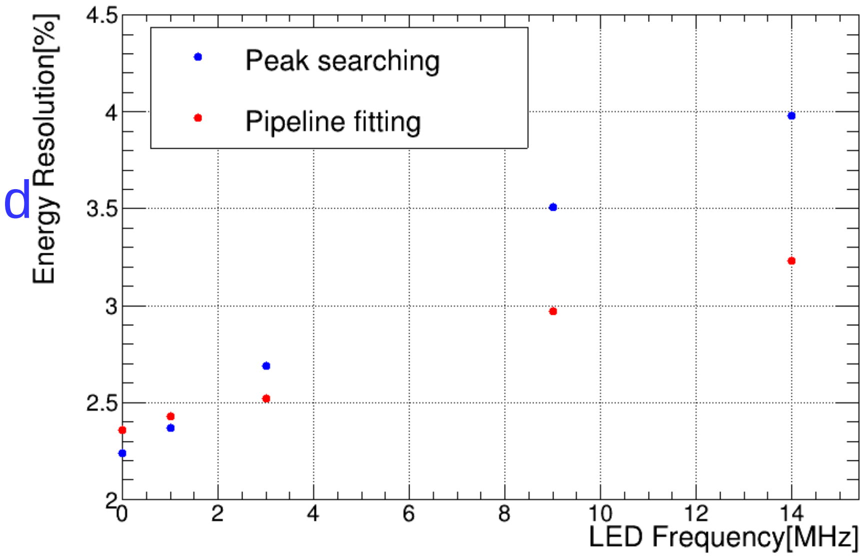
- **LED light is introduced to simulate high background in STCF**
  - Energy spectrum similar to background
  - Frequency up to 14 MHz
- **Pileup mitigation with "pipeline fitting" method**
  - ~2.5% energy resolution under 3 MHz background level



Signal with LED background



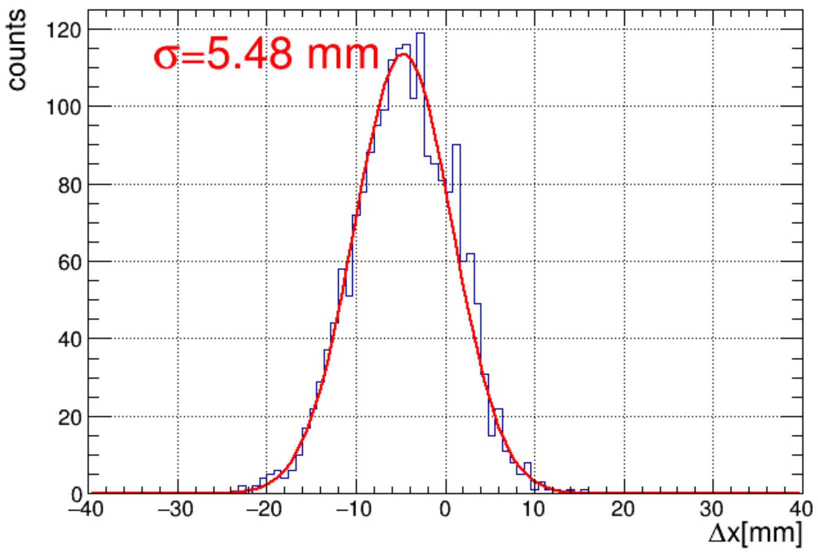
Pipeline fitting example



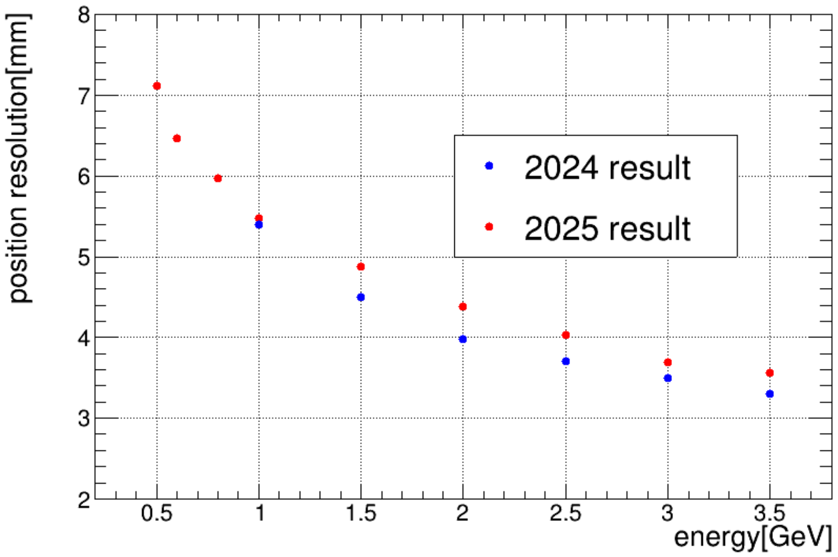
Energy resolution degradation with LED

Position Reconstruction Performance

- **Position resolution for 1 GeV $e^+$is ~5.5 mm ($\Delta_x = x_{ECAL_Rec} - x_{Incident}$)**
- **Limited by the track extrapolation accuracy**
  - ➢ Unable to perform tracking goodness-of-fit selection
  - ➢ Next beam test is scheduled for December



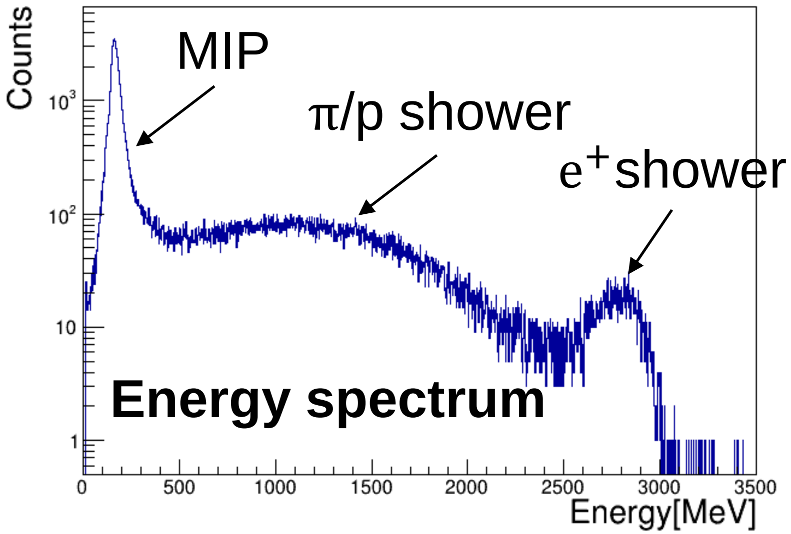
Position reconstruction results of 1 GeV e^+

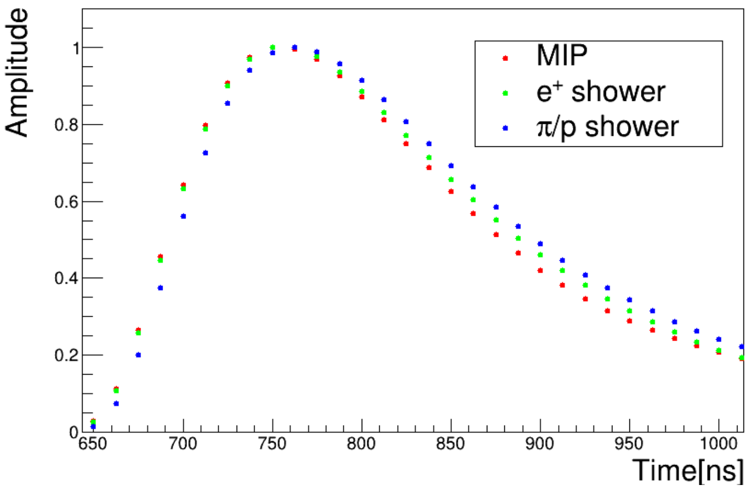


Position resolution vs. Energy

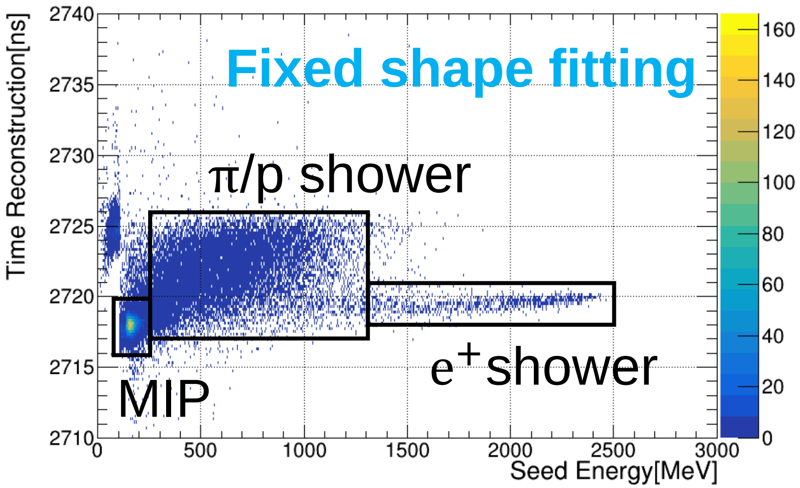
Time Reconstruction Performance

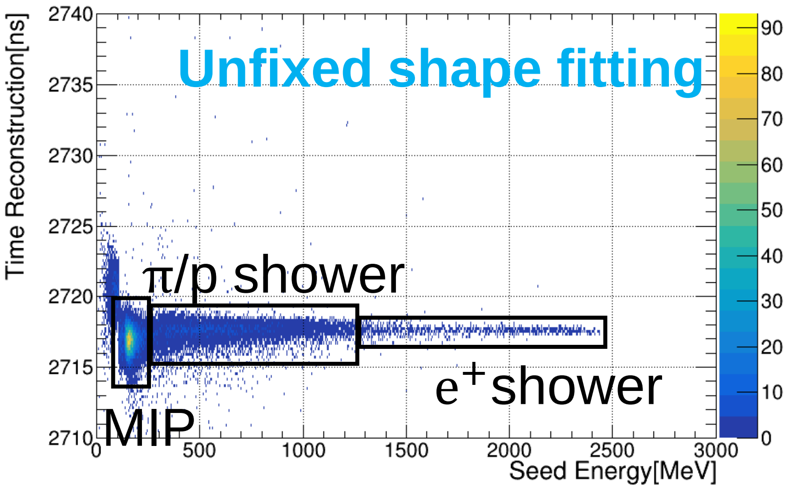
- **Time reconstruction ($\Delta_T = T_{ECAL\_Rec} - T_0$) for hadron beam ($\pi^+/p^+/e^+$)**
  - ➢ Pulse shape differences result in a nonuniform time response
  - ✓ A good uniformity is achieved with an "unfixed shape" fitting method





Pulse shape differences

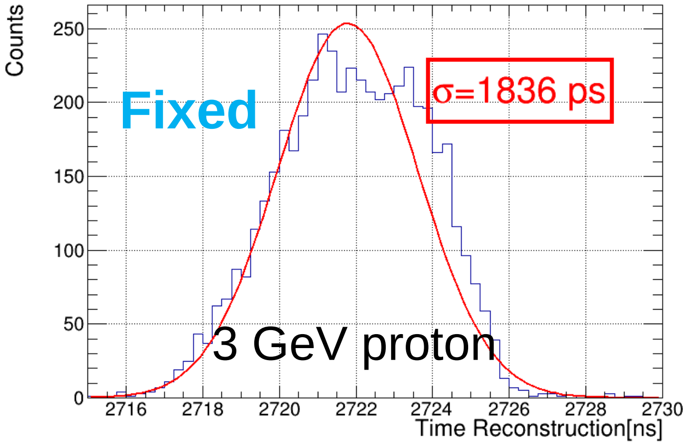


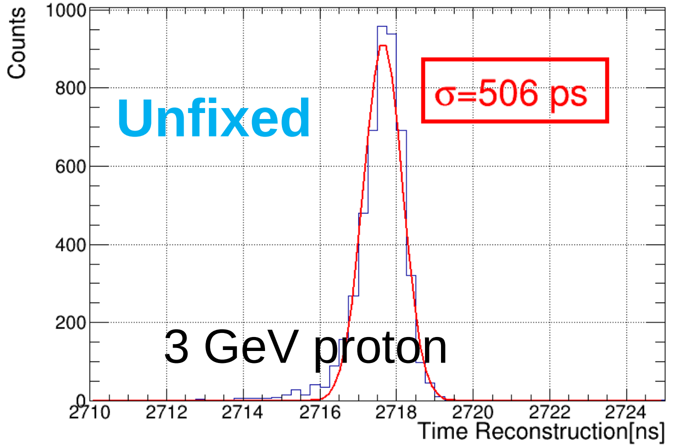


Time reconstruction vs. Energy for 3 GeV hadron$^+$ beam

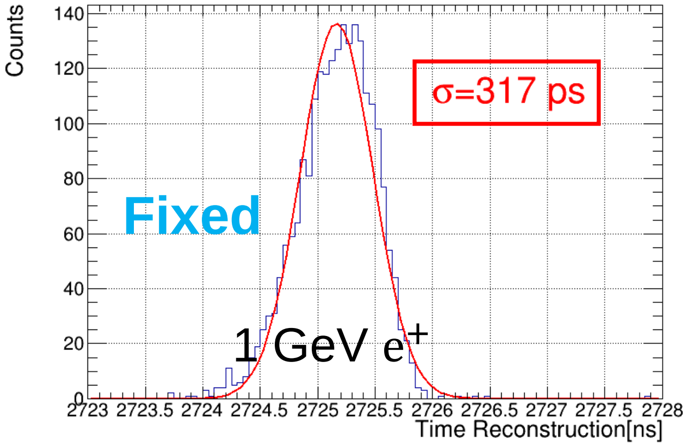
Time Reconstruction Performance

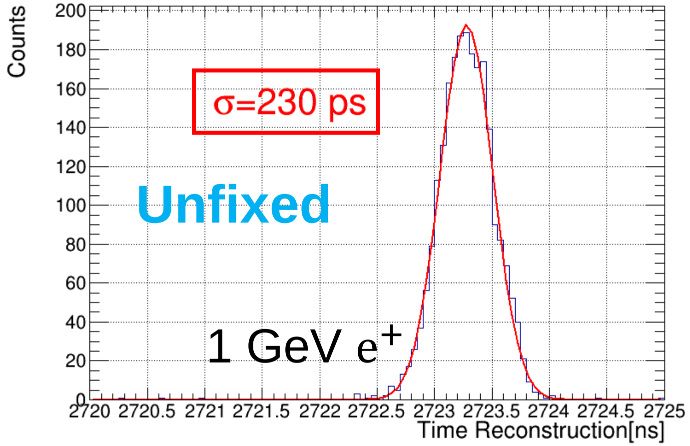
- **Time resolution significantly improved for hadrons**





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





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Summary

- **Optimization of sensitive units**
  - ➢ Significant increase in light output (~175%)
  - ➢ Growth of low slow-component fraction pCsI (~7.4%)
- **Development of ECAL prototype**
- **Beam test of ECAL prototype**
  - ➢ Performance meets the design requirements
    - 2.24% (energy), 5.5 mm (position), 230 ps (time)
    - Pileup mitigation of background

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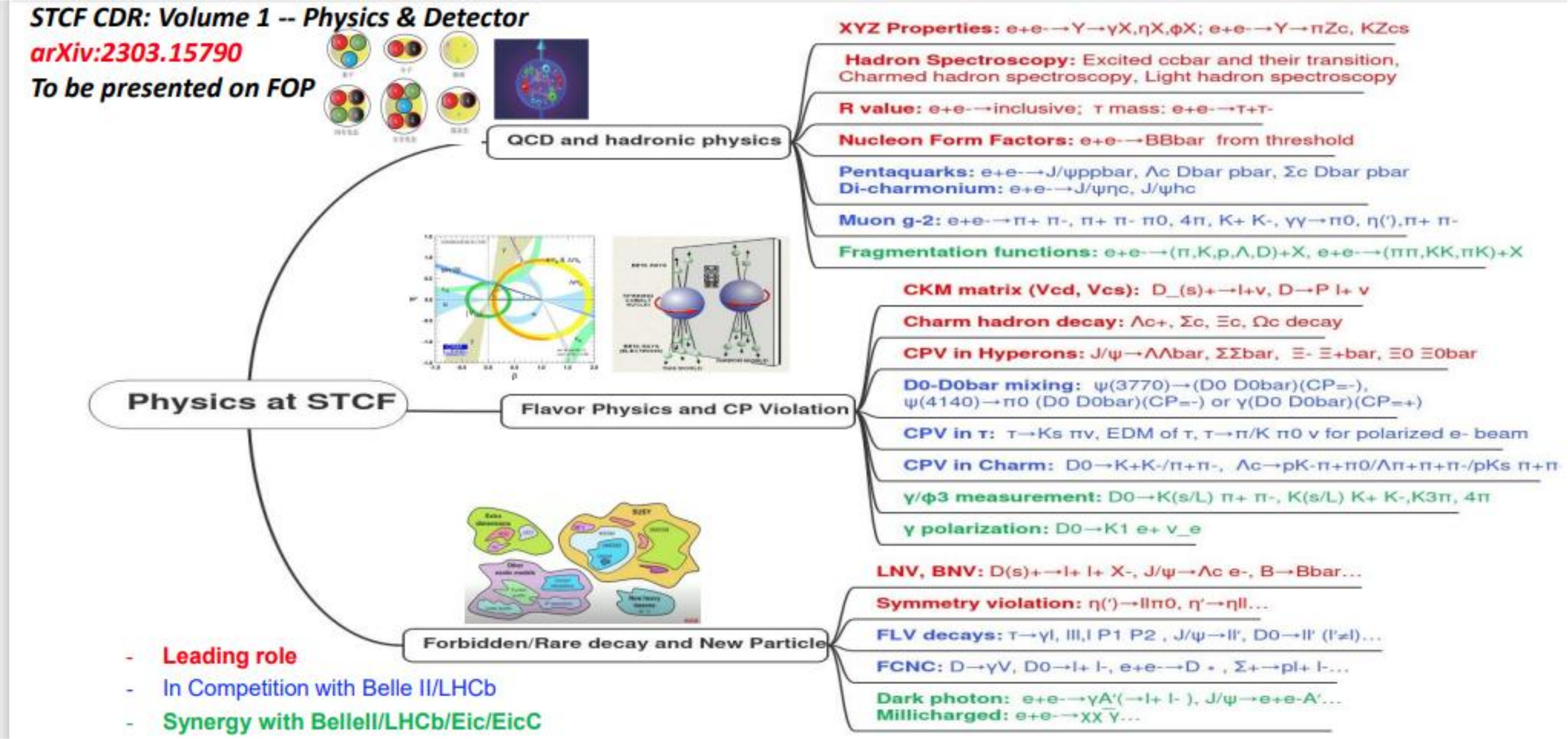
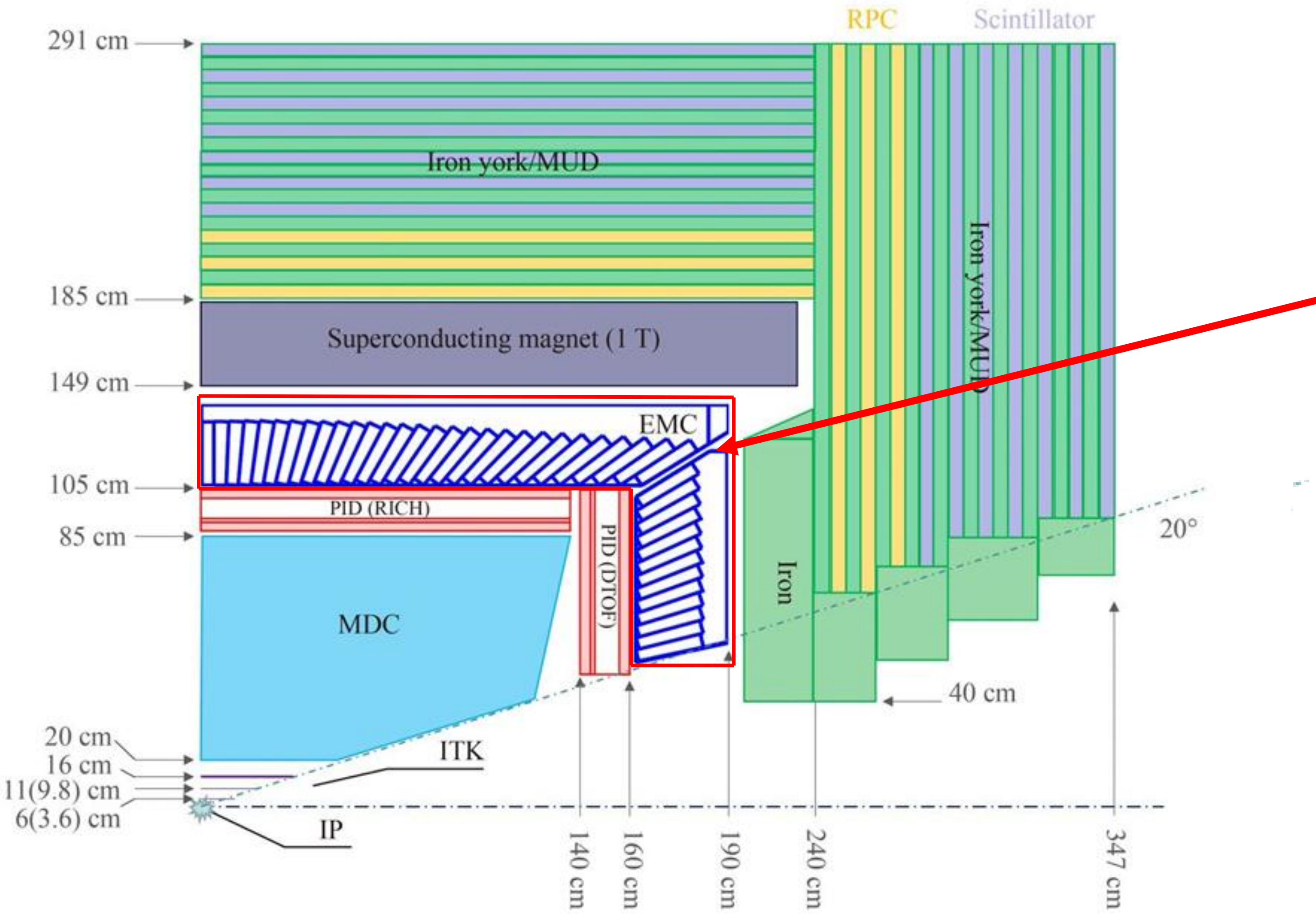
Thanks!

Back Up

STCF Physical Topics



STCF Spectrometer



STCF spectrometer layout

MUD

- μ/π suppression power >30 at $p < 2$ GeV/c

ECAL

- Energy range: 25 MeV - 3.5 GeV
- σ_E/E ~ 2.5% at E = 1 GeV
- σ_{pos} ~ 5 mm, σ_T ~ 300 ps at E = 1 GeV

PID

- π/K (and K/p) 4σ separation power up to 2 GeV/c

MDC

- σ_{pos} = 130 μm
- dE/dx ~ 6%, σ_p/p = 0.5% at 1 GeV/c
- Efficiency > 99% at p_T > 0.3 GeV/c and >90% at p_T = 0.1 GeV/c

ITK

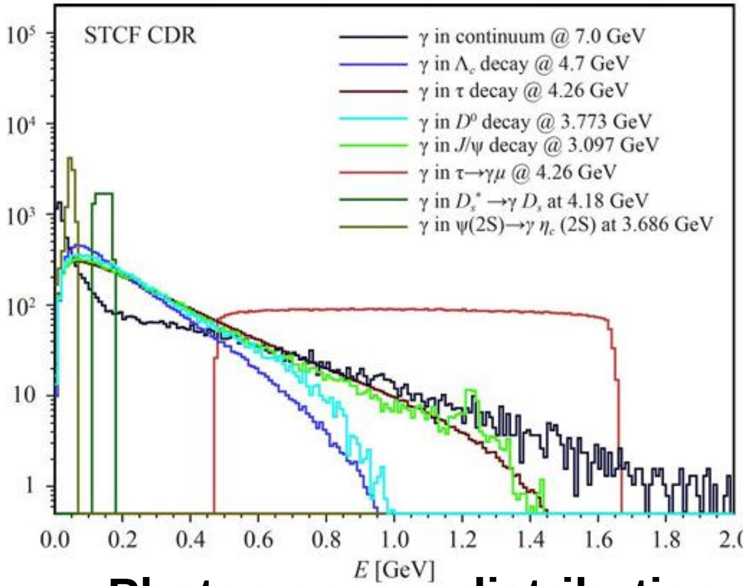
- ~0.25% X_0/layer
- σ_{pos} = 100 μm for single hit

Required performances

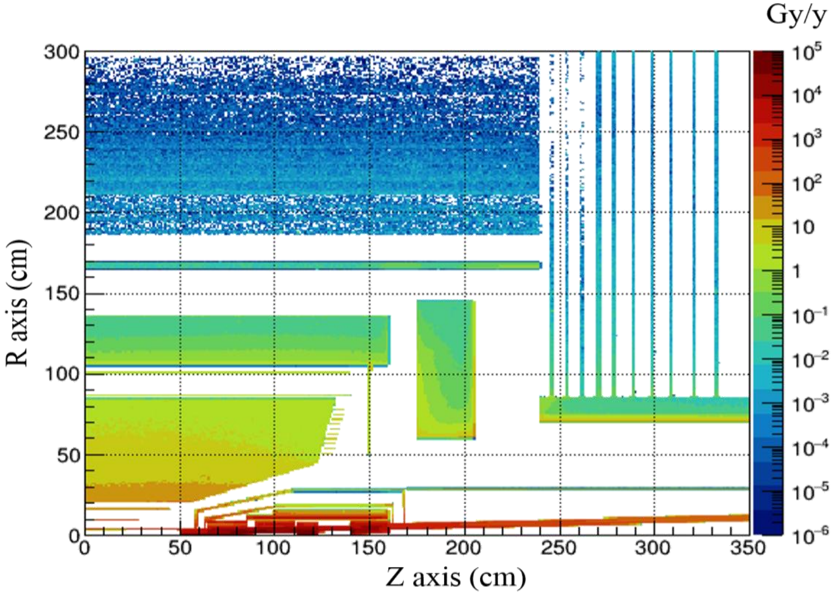
Performance requirements for ECAL

- Measurement requirements
- Working environment

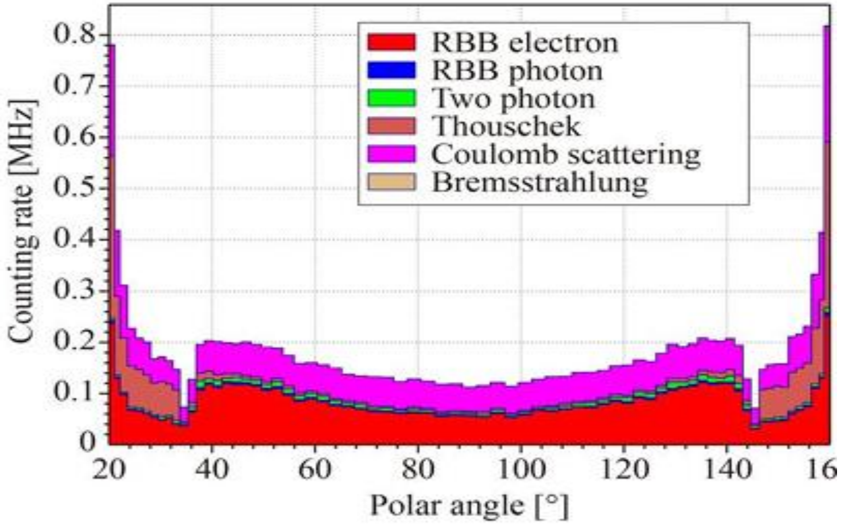
➢ Energy: **< 2.5% @ 1 GeV**
➢ Position: **~5 mm @ 1 GeV**
➢ Time: **~300 ps @ 1 GeV**



Photon energy distribution



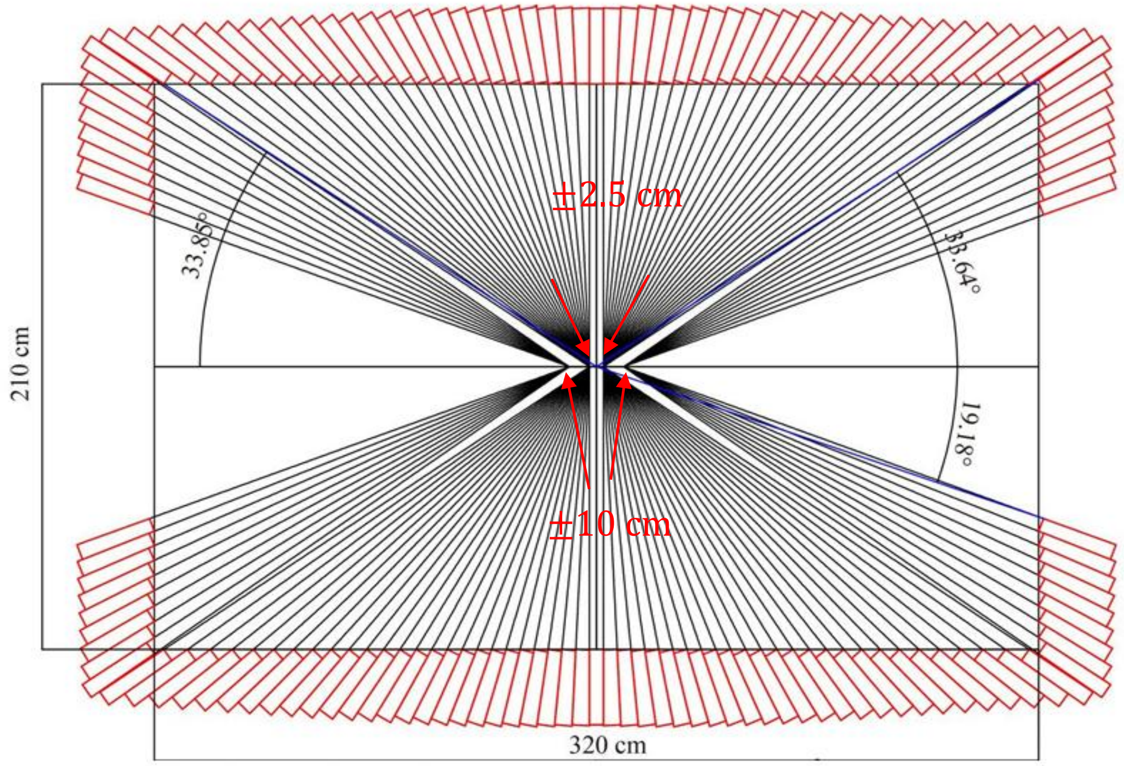
Irradiation dose distribution



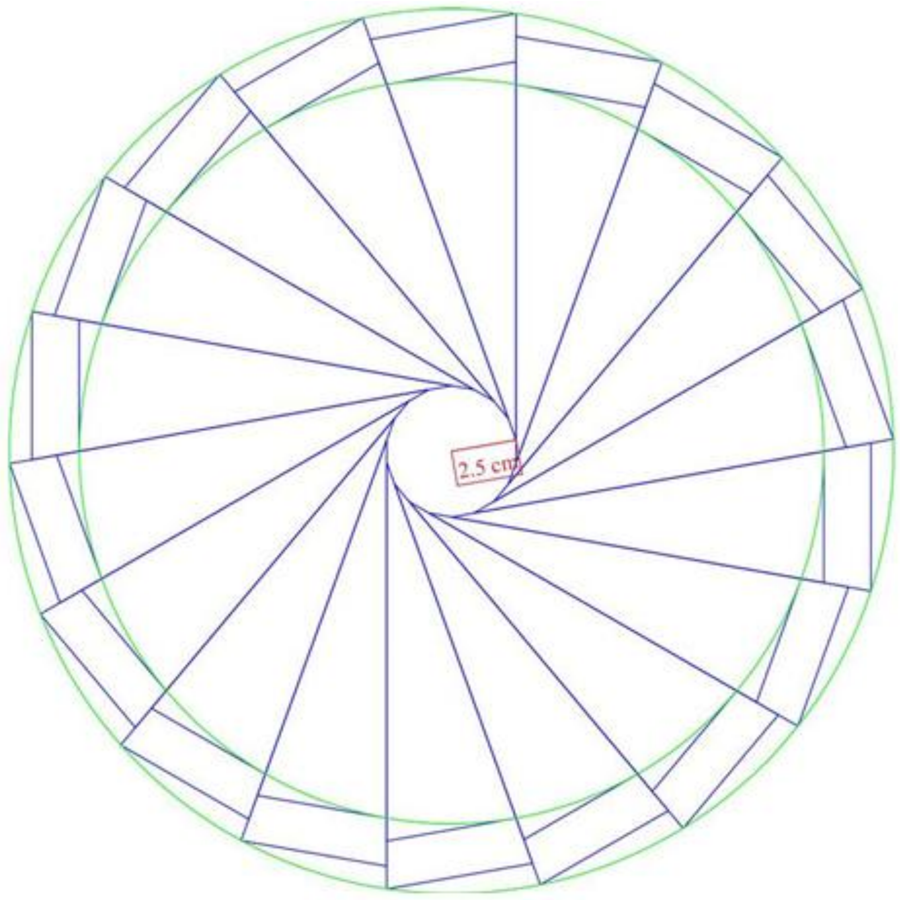
Background counts

$E_\gamma = 25$ MeV - 3.5 GeV	Peak TID> 400 $Gy \cdot y^{-1}$	Background level~1 MHz
Dynamic range	Radiation tolerance	Fast response

Defocused Layout



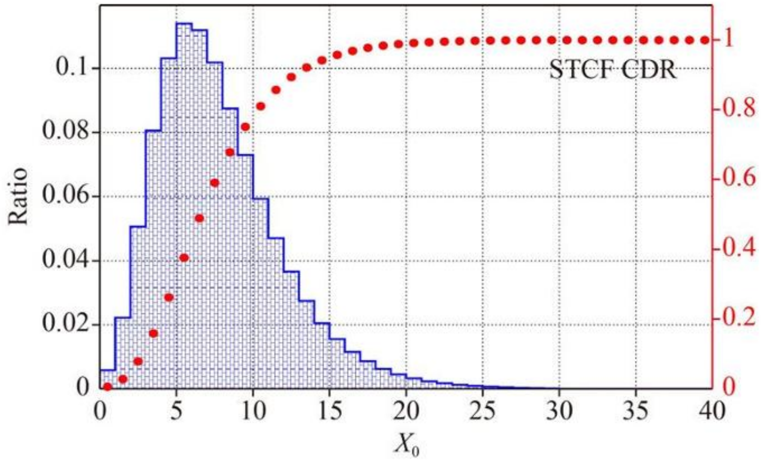
θ-direction arrangement



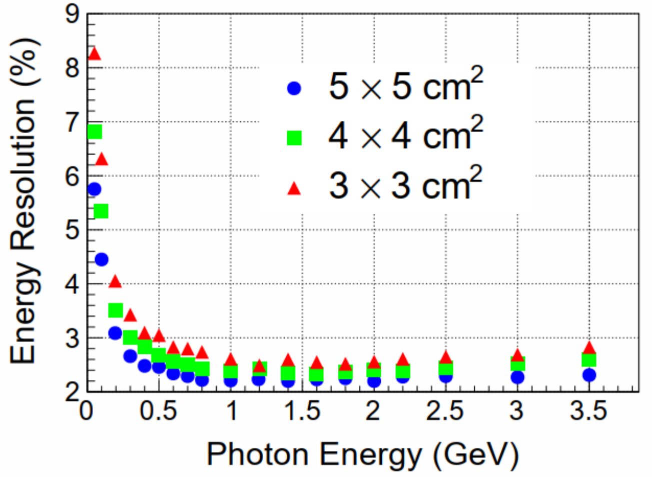
φ-direction arrangement

Crystal Size Optimization

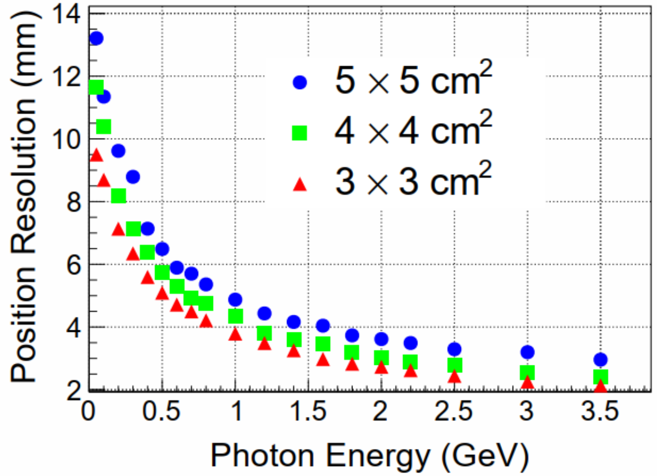
- Longitudinal size: $15X_0$ (28 cm)
  - ➢ 95% energy deposits for 3 GeV photons



- 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.



Energy resolution vs. lateral size

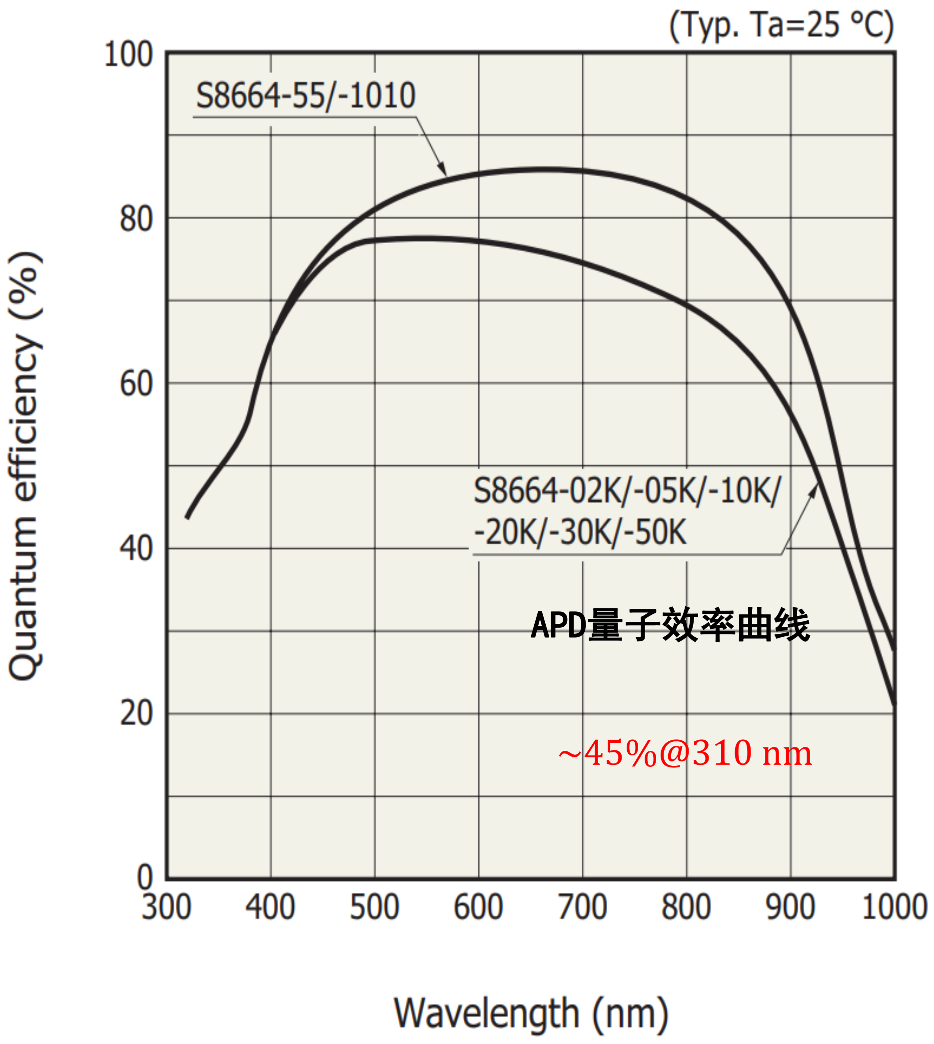


Position resolution vs. lateral size

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

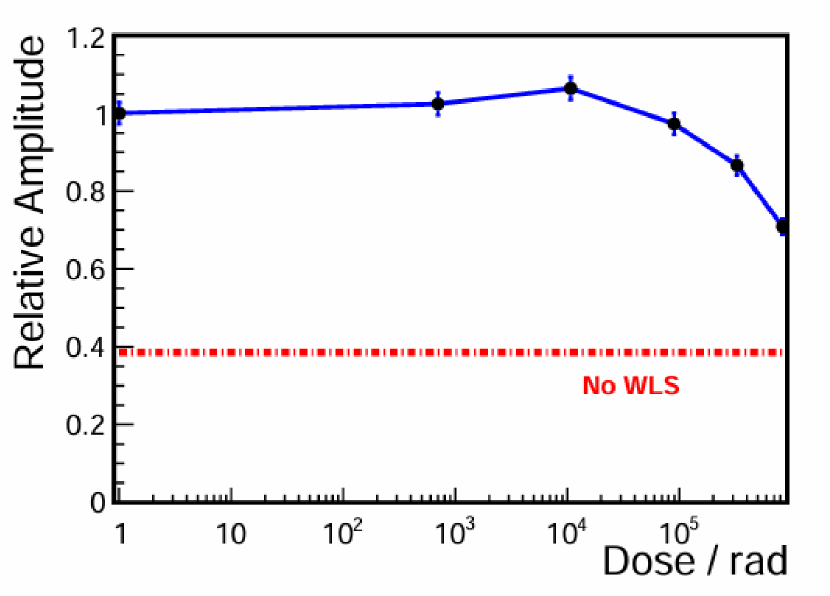
f = fast component, s = slow component.



WLS Coating Stability

➢ Irradiation test

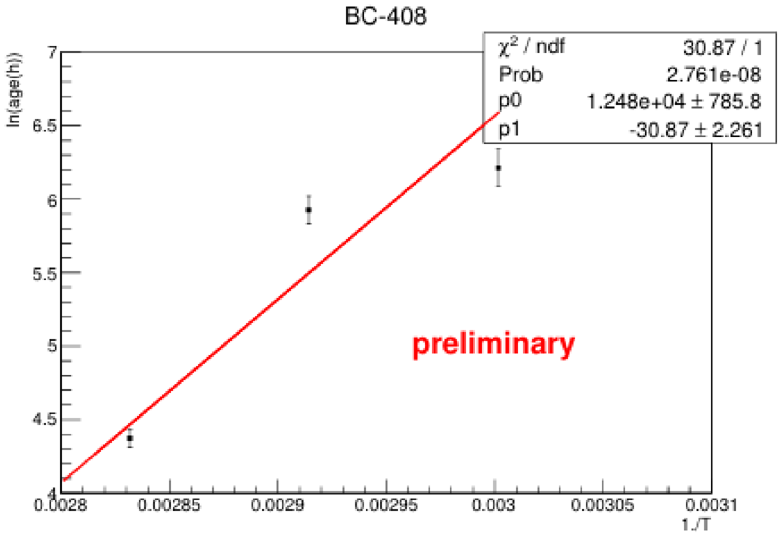
- Irradiate WLS with ^{60}Co source：
  - 90 krad：no obvious decline
  - 833 krad：decrease by 30%
- Good radiation hardness of WLS



Light output vs. radiation dose

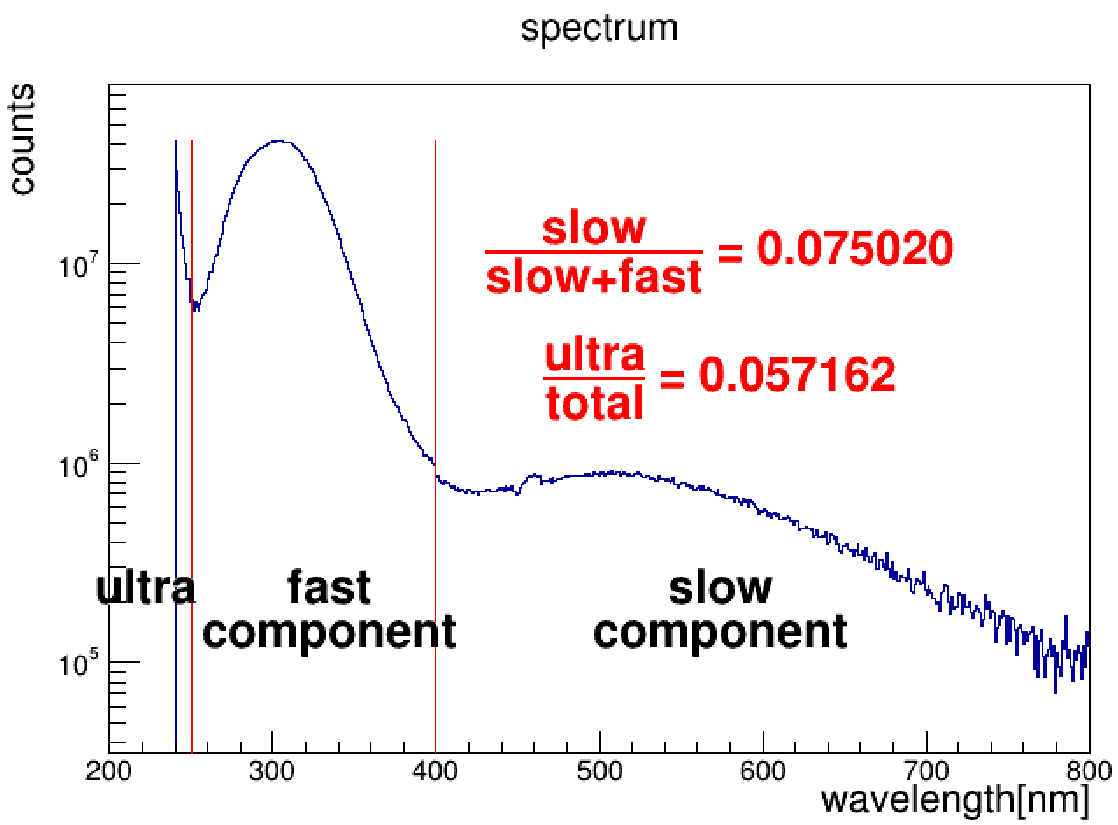
➢ Aging test in the future

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

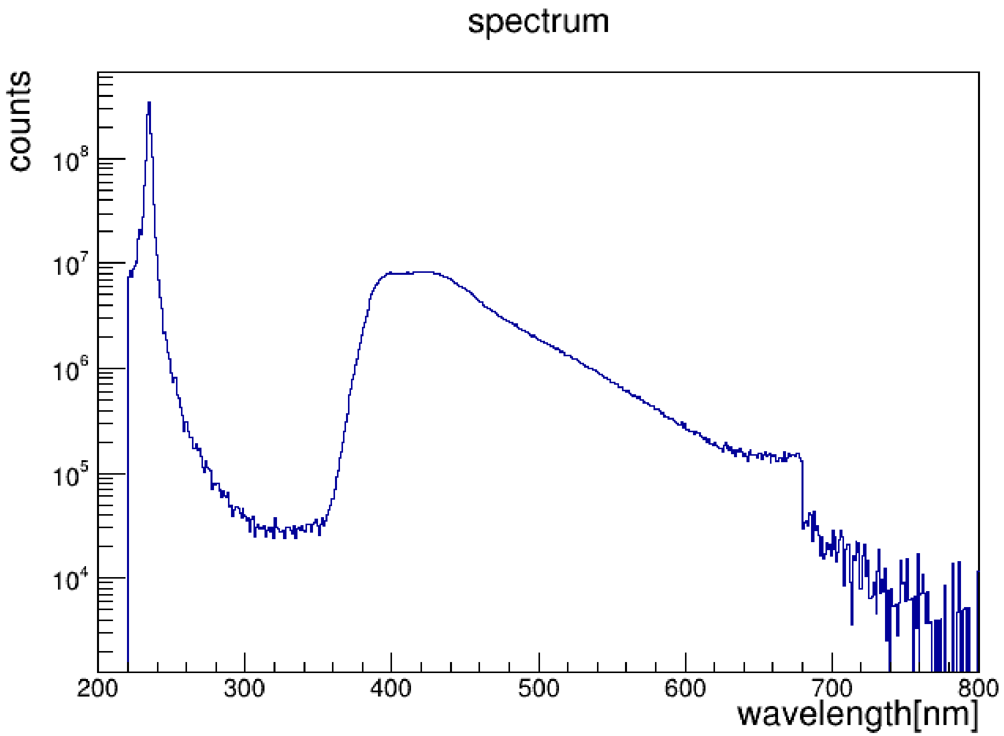


Aging effect of PS is described by Arrhenius formula

Slow Component Fraction



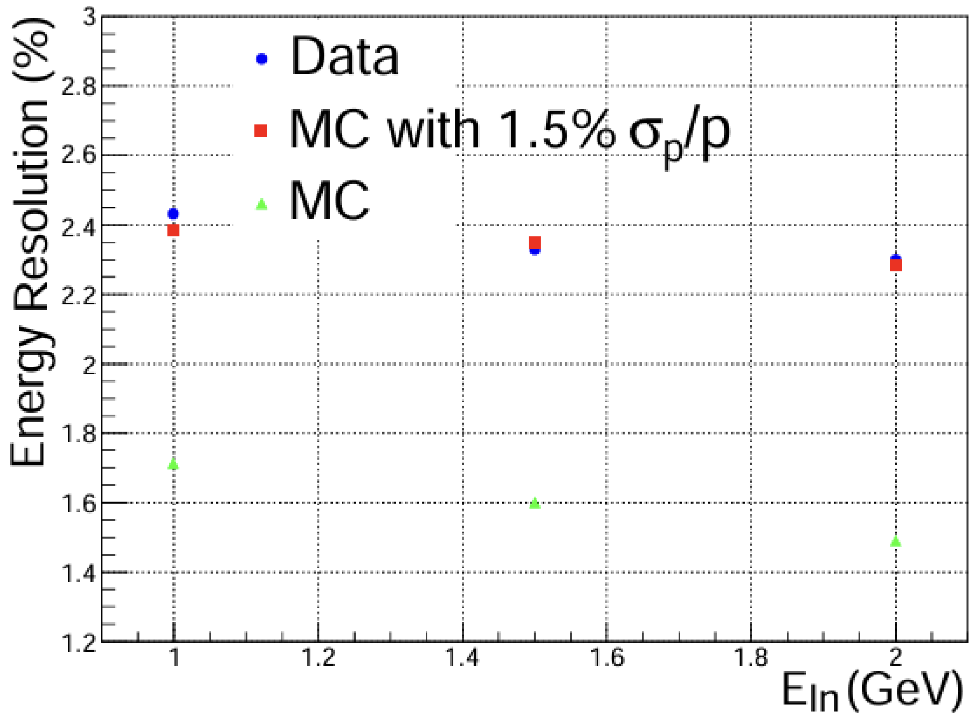
pCsI emission spectrum

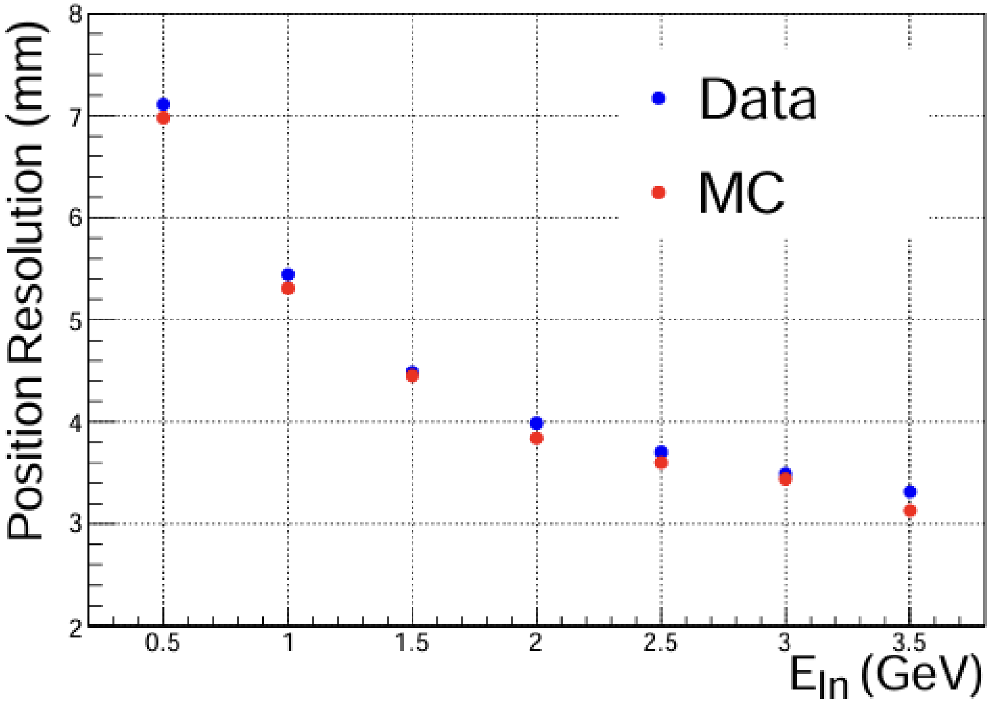


LYSO emission spectrum

- Fast component [250 nm, 400 nm], slow component [400 nm, 800 nm]
- The short-wave component with a peak ~235 nm is caused by the instrument

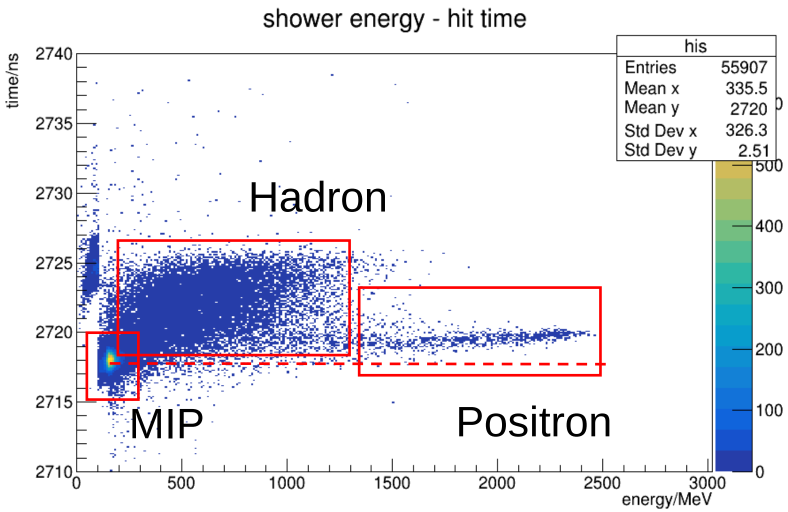
Performance vs. Simulation



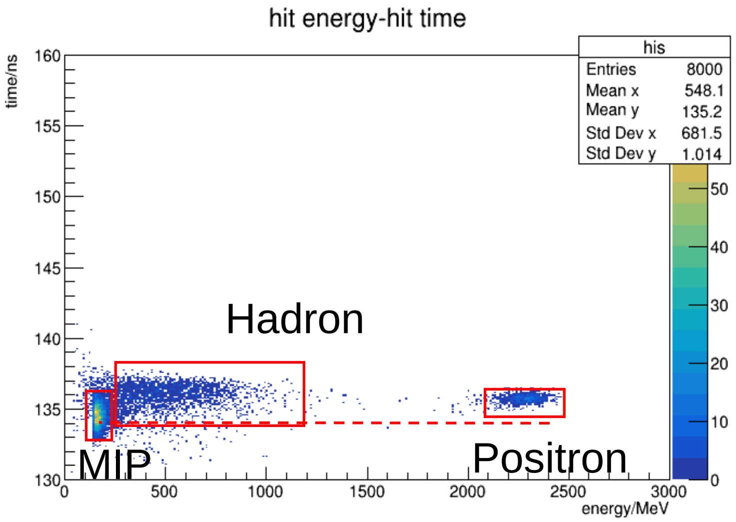


- Energy and position resolution vs. e^+ beam momentum

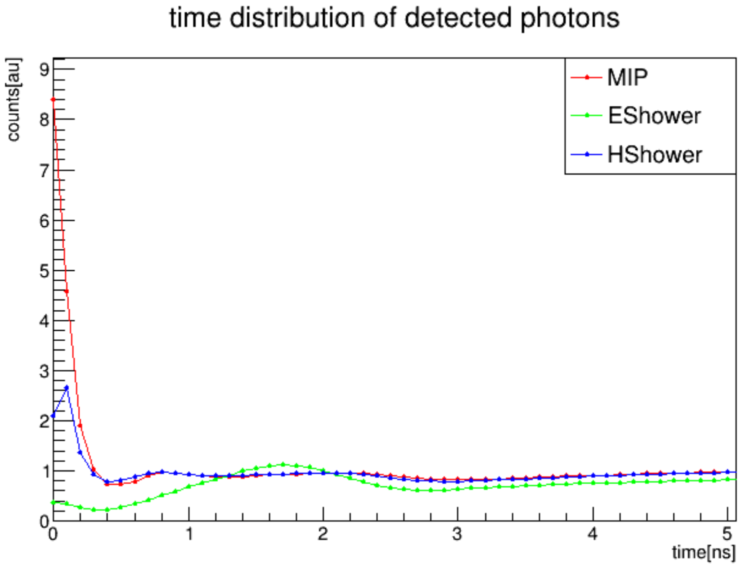
Time Response Non-uniformity



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



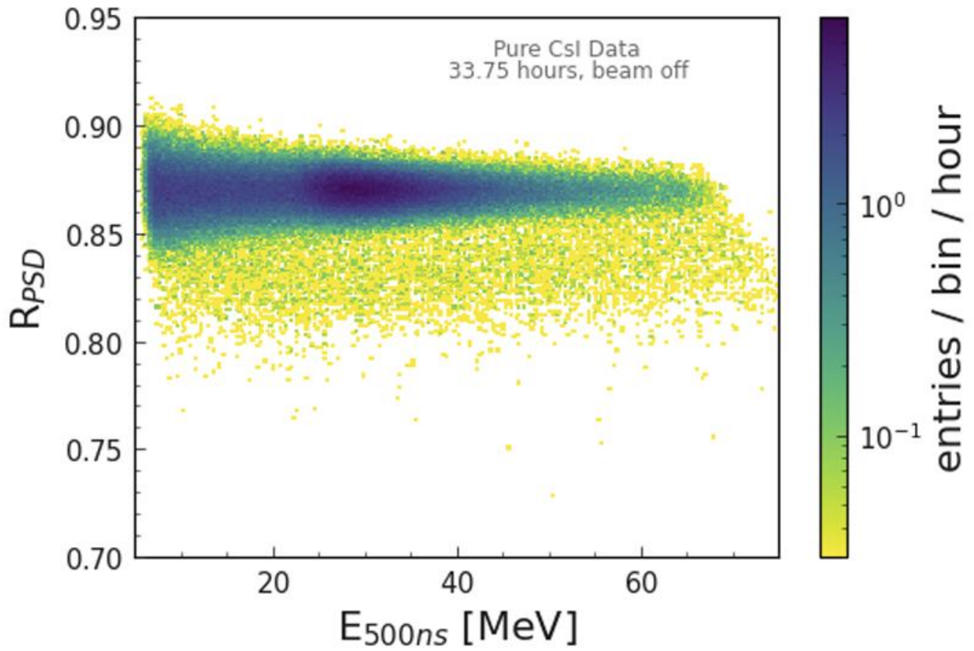
Time response vs. energy deposition for 3 GeV hadron beam (simulation)



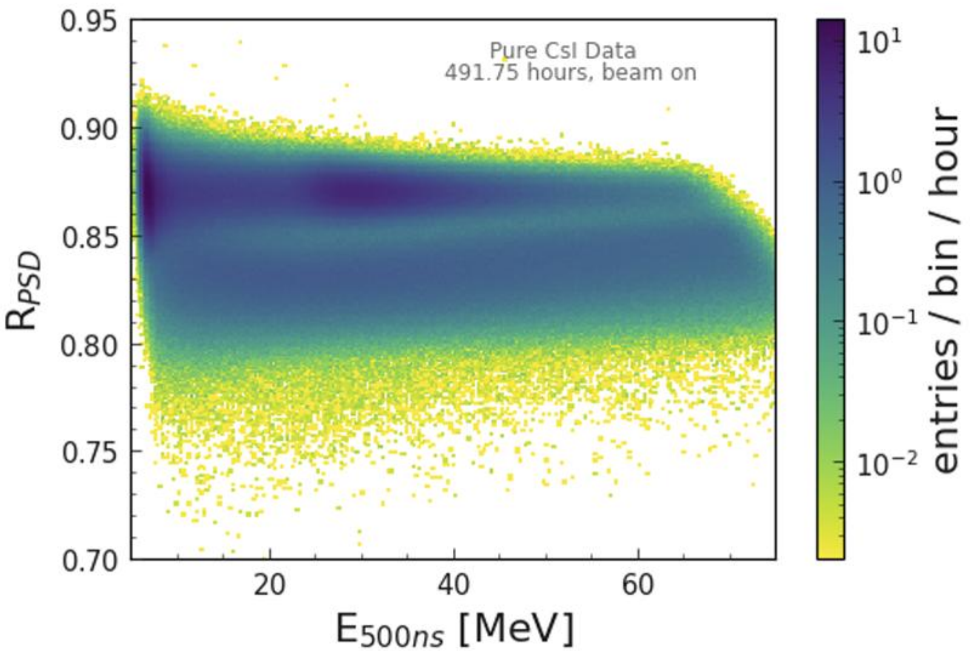
time distribution of photons detected in the simulation

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

Time Response Non-uniformity



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

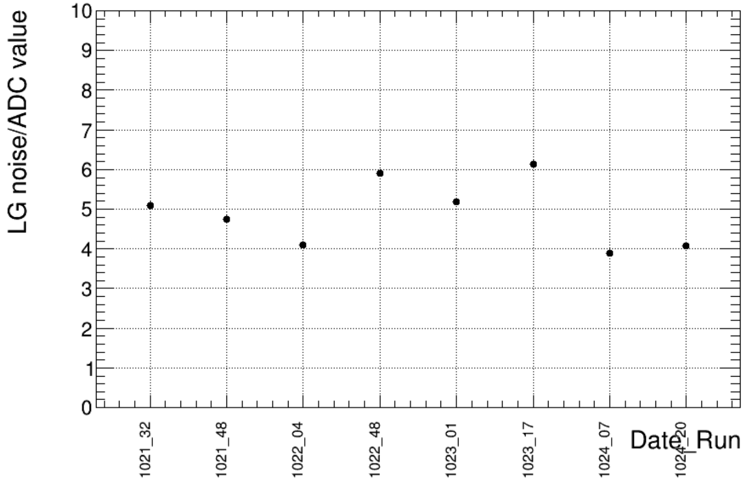


R_{psd} vs. Energy in neutron beam test

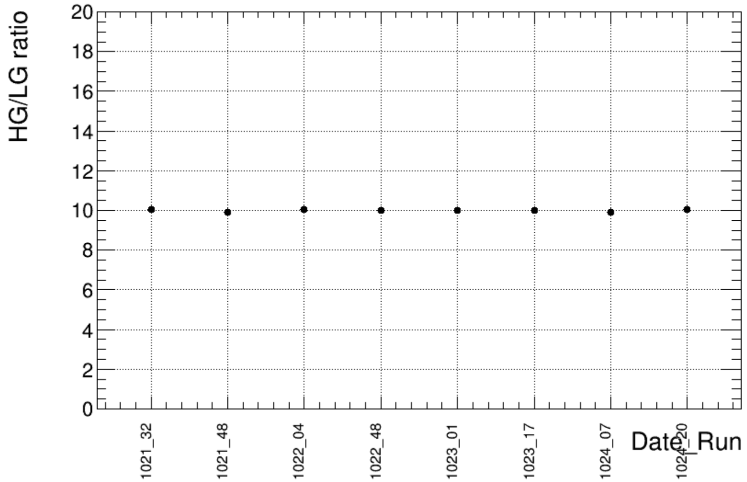
- Low R_{psd} events in neutron beam indicate a slower scintillation component of pCsI crystals

Operational status stability

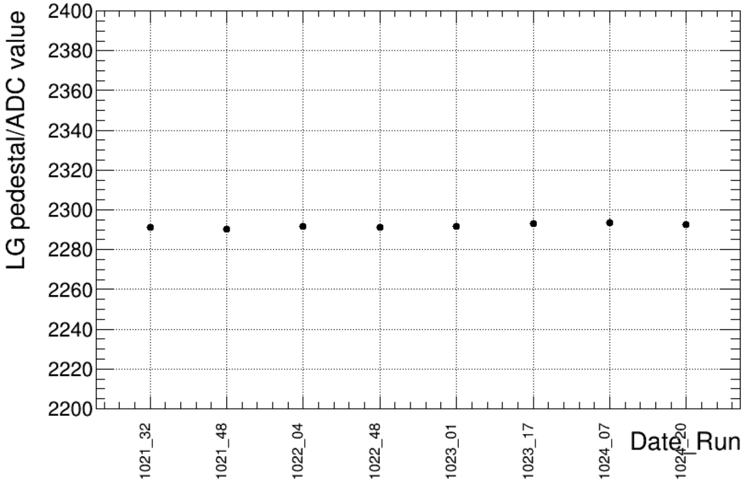
- Stability of LG noise



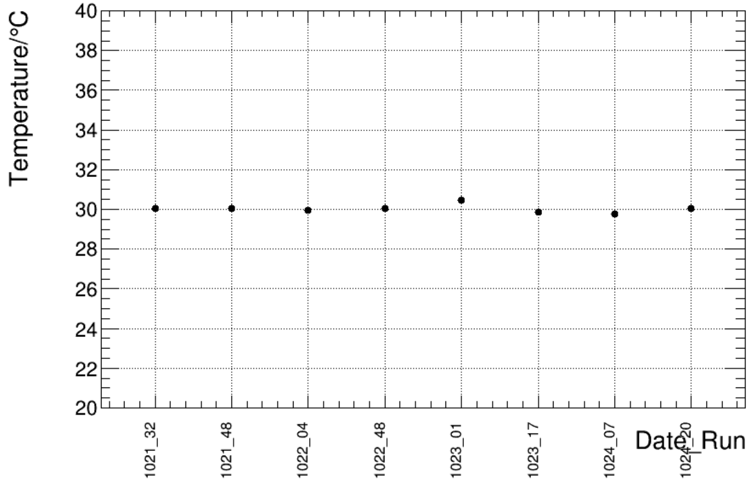
- Stability of HG-LG gain ratio



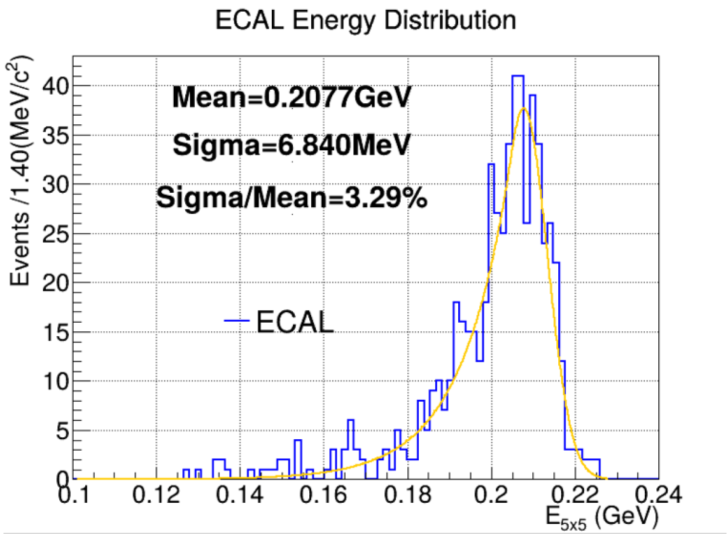
- Stability of LG pedestal

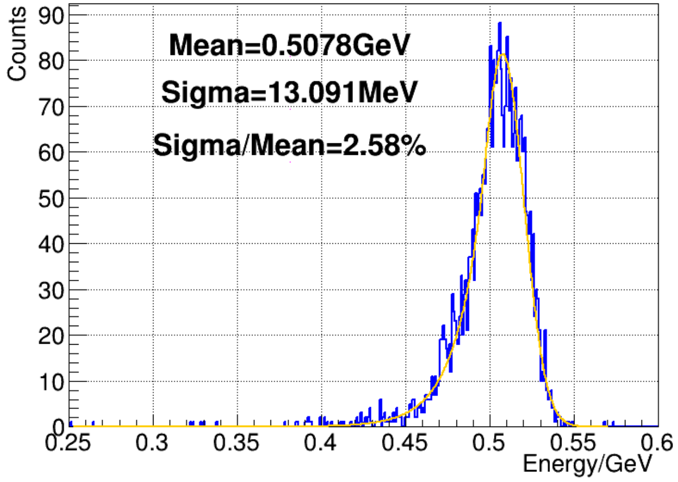


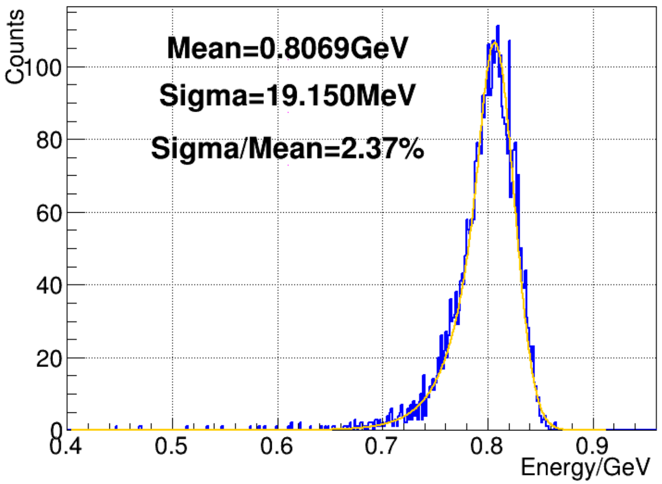
- Stability of temperature

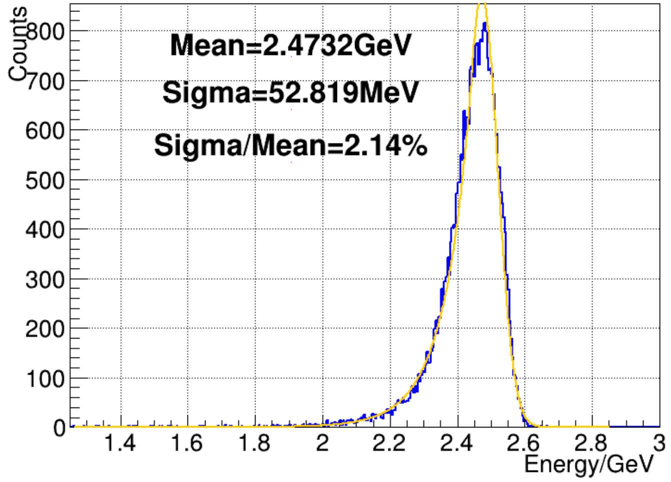


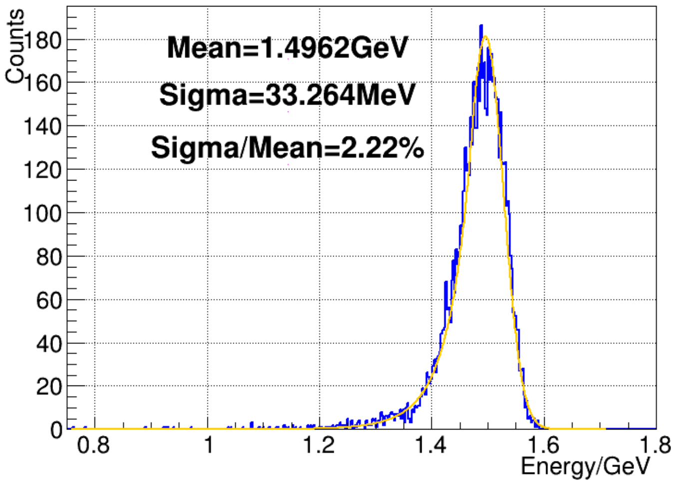
Energy spectra of e^+

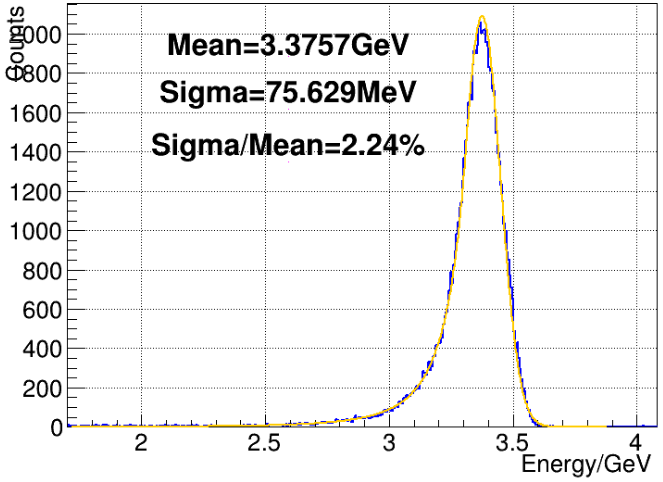












Pipeline fitting

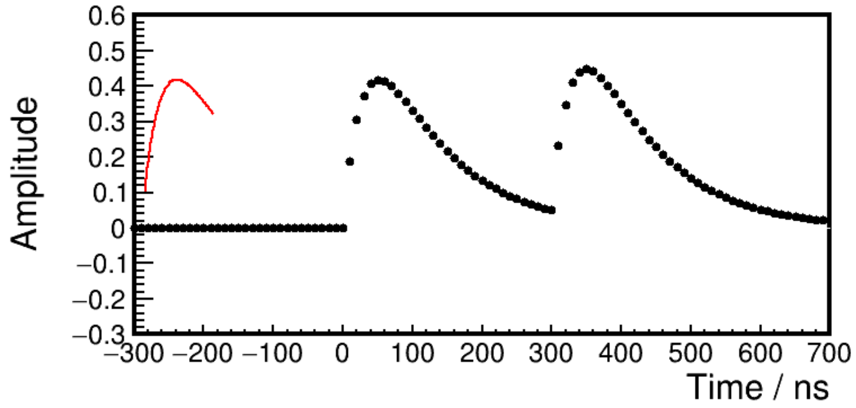
- **Pipeline fitting method**
  - Real-time online processing
  - Template fit once for each fitting
    - Each fitting begin with different ADC point
    - Add one more fitting between two ADC points
  - Fit successful
    - $A > E_{thr}$
    - $\triangle T < 12.5/2$
    - $\chi^2/ndf < 3$:

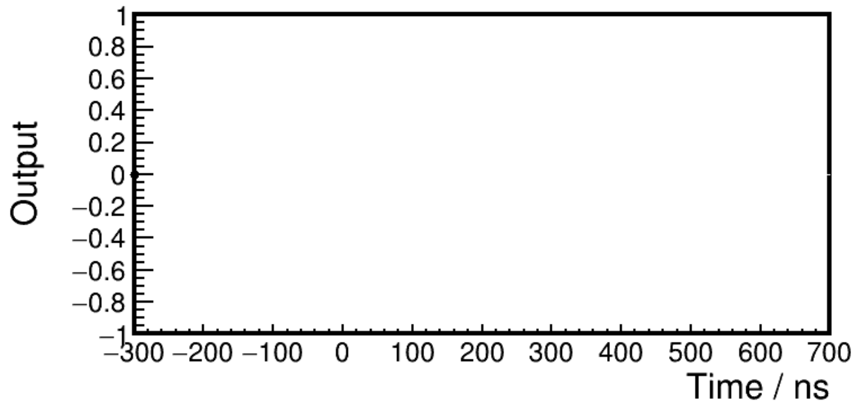
$$\chi^2/ndf = \left[\sum_{i,j}\left(y_i - A\cdot f(t_i-\tau) - p\right)\cdot S_{ij}^{-1}\cdot\left(y_j - A\cdot f\left(t_j-\tau\right) - p\right)\right]/\left((n-2)\cdot\left(\sigma_{nos}^2 + (A\cdot 0.01)^2\right)\right)$$

→ Cache and compared with next fit

→ Remove template

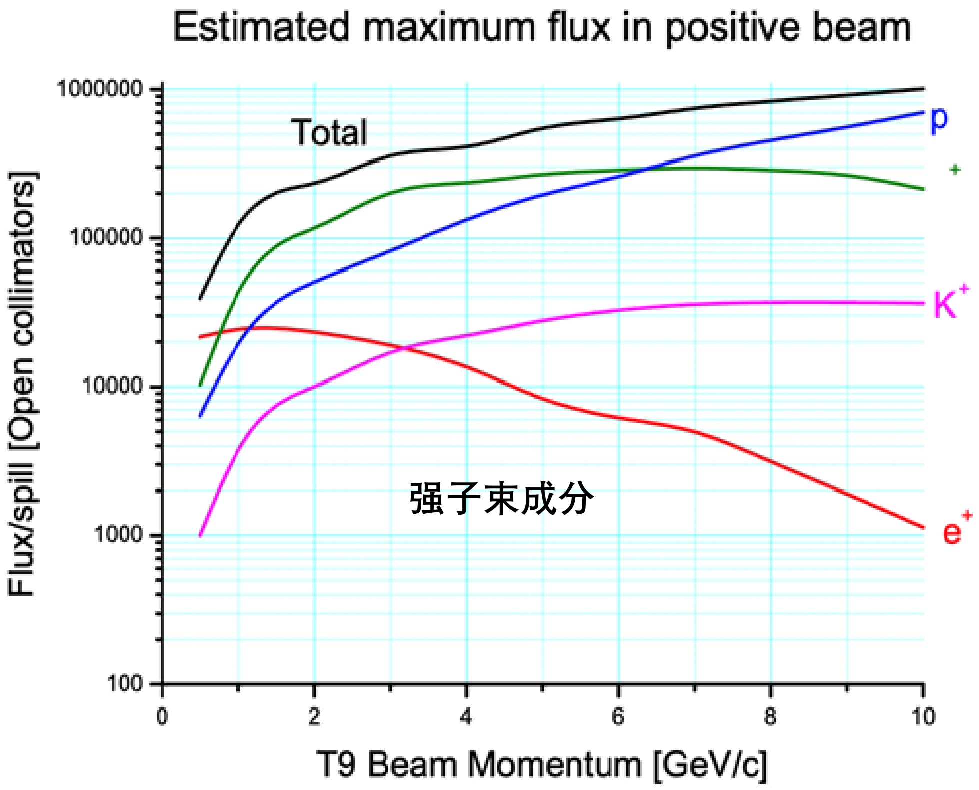
→ Ongoing processing

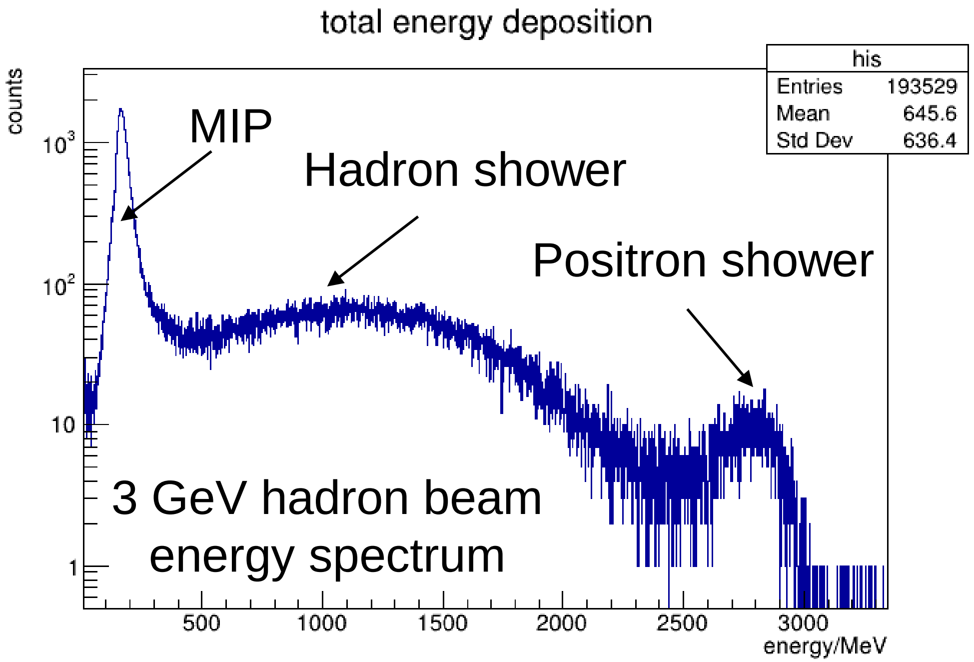


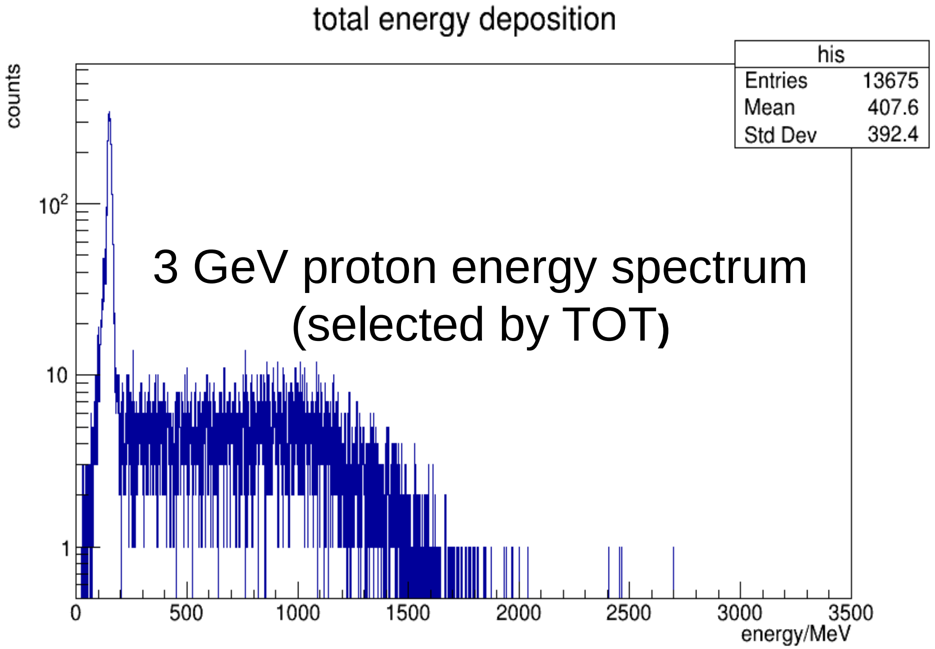


Hadron beam components

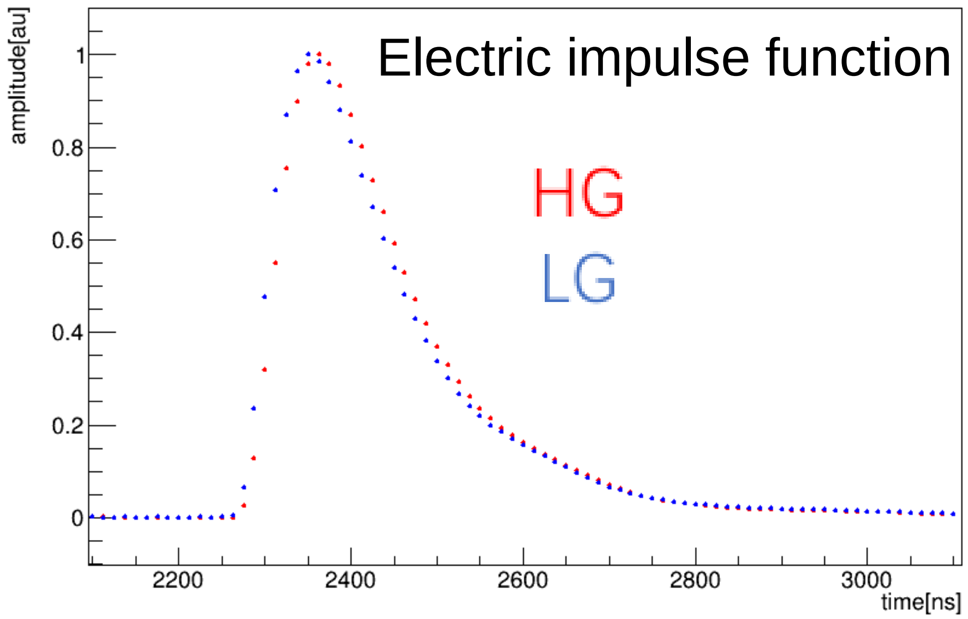
- Hadron beam consists of p、π、K、e。



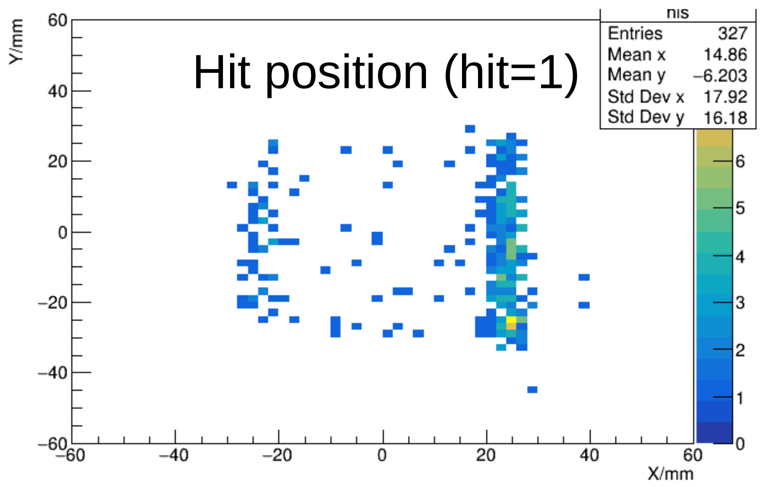


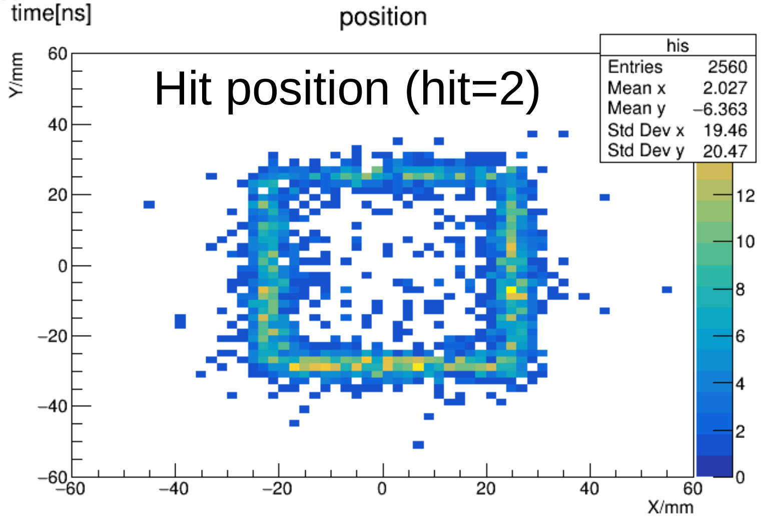


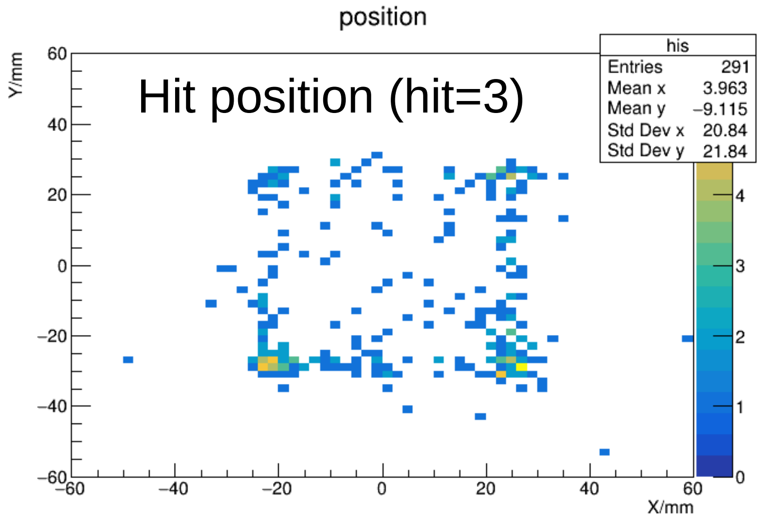
HG Channel Events



- 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







Unfixed-shape fitting

- Form of the template fitting function:

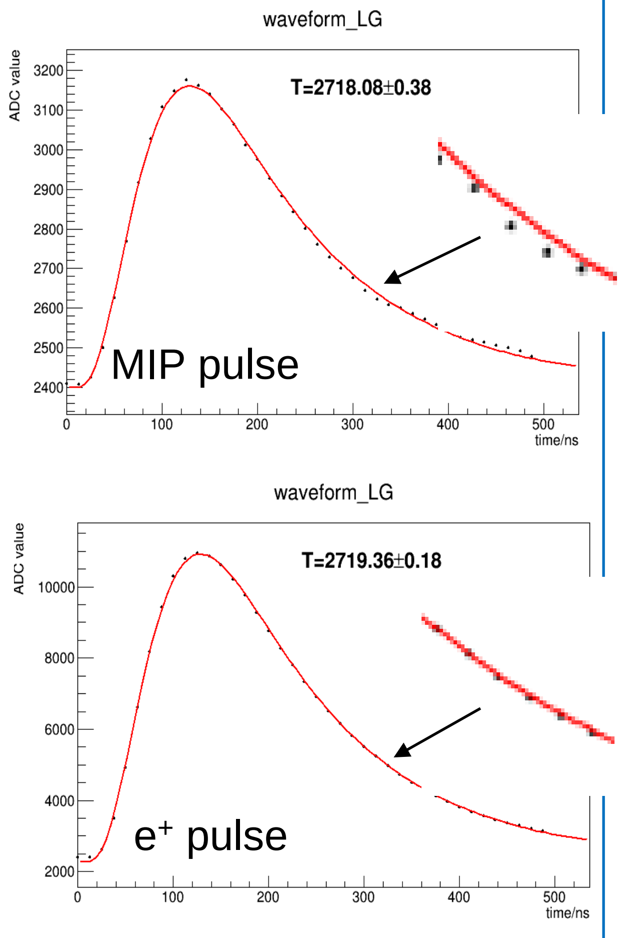
$$f(t) = \begin{cases} \{\sum_{i=0}^{5} A_i e^{-\frac{t-T_0}{\tau_i}}\} \cdot (t-T_0)^k + ped & t \geq T0 \\ ped & t < T_0 \end{cases}$$

5 Exponential ×1 Power

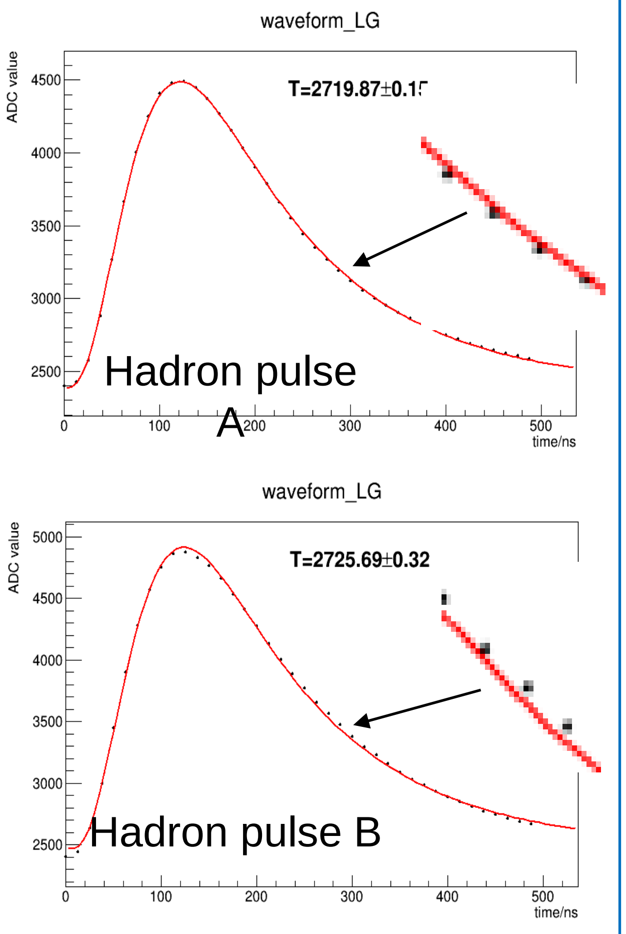
- Only two free parameters: ped(pedestal) and T0(time)

- Template does not fit MIP and hadron pulses well

➢ MIP and e$^+$

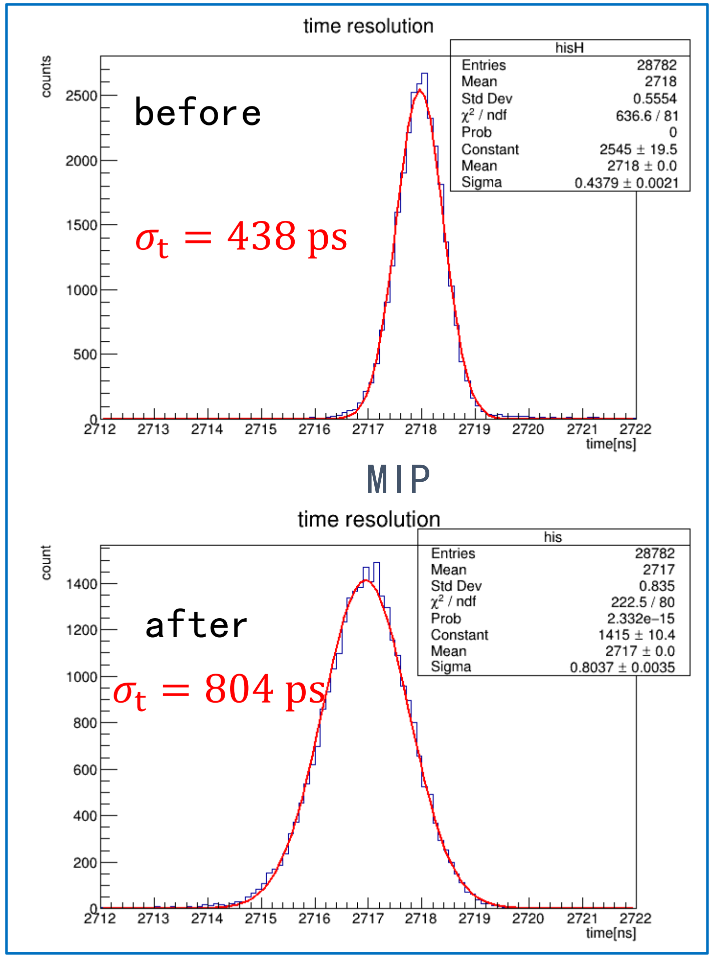


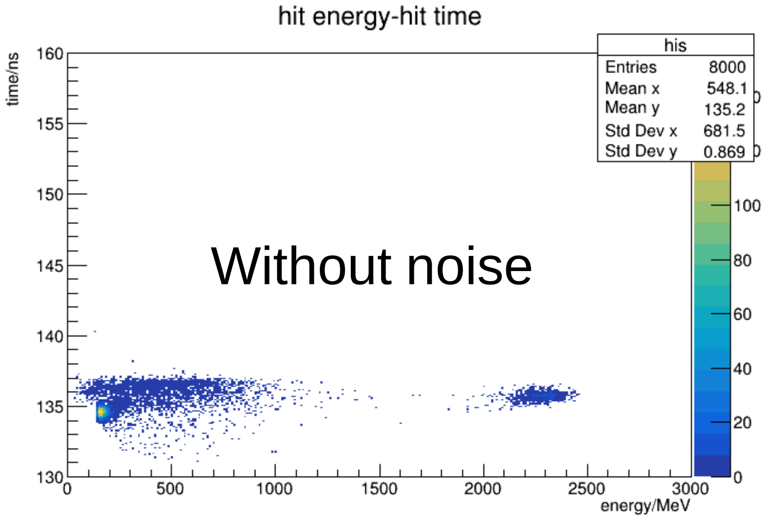
➢ Hadron showers

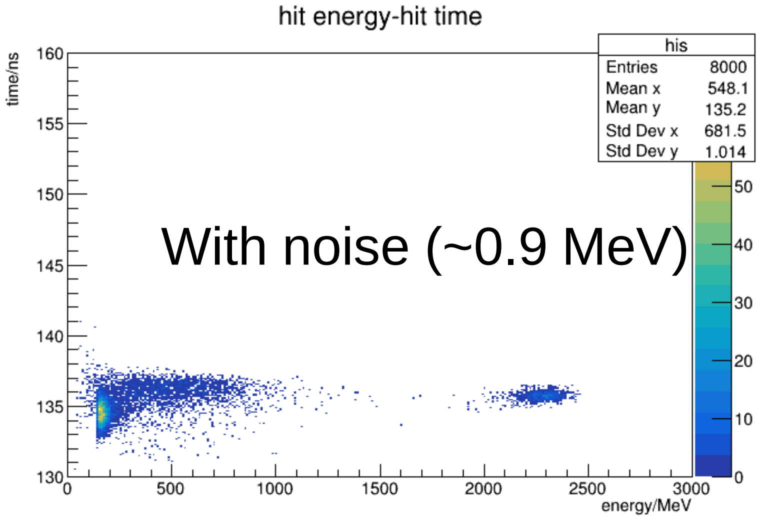


Unfixed-shape fitting

- Time resolution of MIP gets worse because of electronic nose







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