Novel hermetic detector for KAPAE

Darkness on the table

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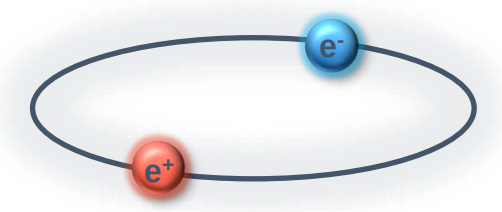
apctp asia pacific center for theoretical physics
KNU KYUNGPOOK NATIONAL UNIVERSITY

Contents

KAPAE

- KNU Advanced Positronium Annihilation Experiment (KAPAE)

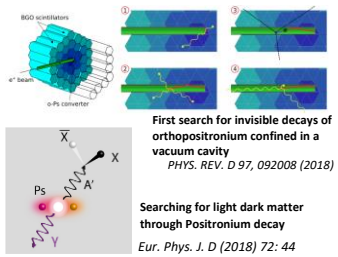
Electron-Positron Pair



- Quasi-stable bound state
- Create energetic photons

($m_{e^+} + m_{e^-}$= 1.022 MeV)

Physics



First search for invisible decays of orthopositronium confined in a vacuum cavity
PHYS. REV. D 97, 092008 (2018)

Searching for light dark matter through Positronium decay
Eur. Phys. J. D (2018) 72: 44

- QED verification
- New Physics (invisible decay…)

Application

- **P**ositron **E**mission **T**omography (PET)

Positronium

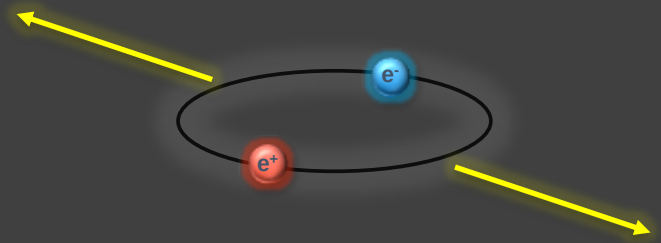
- Unstable hydrogen-like atoms ($M_p \longrightarrow m_{e^+}$)
- The spin state of Ps can be calculated using the hydrogen atom model
- Positronium (Ps)

  - Singlet spin state (para-Positronium, p-Ps)

  - Triplet spin state (ortho-Positronium, o-Ps)

Singlet Spin State (p-Ps)

$[s = 0] \quad |0,0> = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$

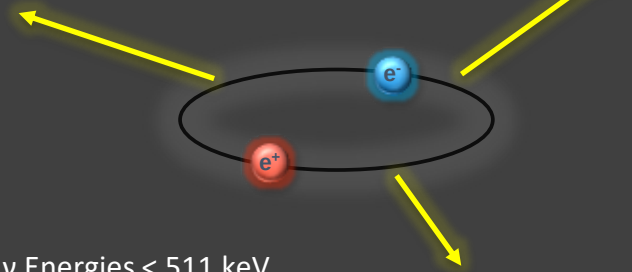


γ Energies = 511 keV

Triplet Spin State (o-Ps)

$[s = 1] \quad |1,1> = \uparrow\uparrow, \; |1,-1> = \downarrow\downarrow$

$|1,0> = \frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow)$



γ Energies < 511 keV

Positronium

- Parity: Flip in sign of spatial coordinates

  → $\hat{P}\psi(x) = \psi(-x), \hat{P}^2\psi(x) = \psi(x)$ → $P = \pm 1$
- Antiparticle & particle pair intrinsic parity : $P_p \cdot P_p = -1$
- $P = (-1)^{l+1}$
- $C = (-1)^{l+s}$

para-Positronium

- The ground state $l = 0,\ s = 0$
- $C = +1$
- Photon $C = (-1)^n$

  - Singlet decay = even photon (2, 4, 6 …)
- Lifetime = 125 ps

ortho-Positronium

- The ground state $l = 0,\ s = 1$
- $C = -1$
- Photon $C = (-1)^n$

  - Triplet decay = odd photon (3, 5, 7 …)
- Lifetime = $142 \pm 0.02\ ns$

New Physics

- Invisible Exotic Decay (Mirror world, Extra dimensions …)
- Visible Exotic Decay (Standard model verification, axion)

Milli-charged particles

- The grand unified theory (GUT) model
- Electric charge particles (”shadow” photon <<<< e^-)

$$\Gamma(o\text{–}Ps \rightarrow X\bar{X}) = \frac{\alpha^5 Q_X^2 m_e}{6} \cdot k \cdot F\left(\frac{m_X^2}{m_e^2}\right)$$

Mirror world

- The mirror universe model
- Vibration of o-Ps and mirror o-Ps

$$\mathrm{Br}(\mathrm{o}\text{–}Ps \rightarrow \text{ invisible}) = \frac{2(2\pi\varepsilon f)^2}{\Gamma^2 + 4(2\pi\varepsilon f)^2}$$

Extra dimensions

- k > 2.7 TeV

$$\mathrm{o}\text{–}Ps \rightarrow \gamma^* \rightarrow \text{ additional dimension(s)}$$

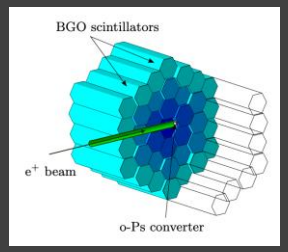
$$\mathrm{Br} = \frac{9\pi}{4(\pi^2 - 9)} \cdot \frac{1}{\alpha^2} \cdot \frac{\pi}{16} \left(\frac{m_0 - Ps}{k}\right)^2 \approx 3 \times 10^4 \left(\frac{m_0 - Ps}{k}\right)^2$$

Axion

- Light pseudoscalar

$$\mathrm{o}\text{–Ps} \rightarrow \gamma X$$

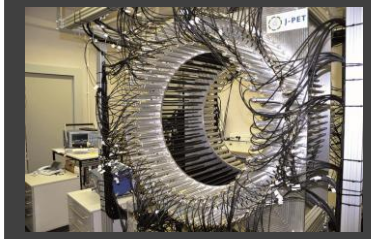
Recently Other Research



- Invisible decay study
- Plastic + BGO + PMT
- 2.1×10^{-8} at 90% C.L.

< 2006

ETH Zurich (Switzerland)

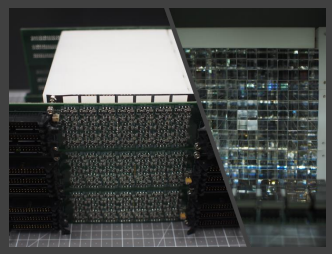


- CPT study
- Plastic + PMT

- Plastic + SiPM (ver. II)

< 2016

J-PET (Poland)
The Jagiellonian University

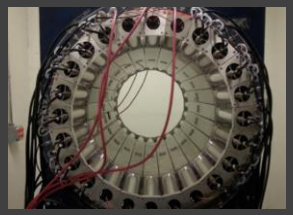


- BGO + SiPM
- CPT study
- ± 0.000142 at 90%CL
- Invisible upper limit sensitivity
- 1.79×10^{-8} at 90% CL

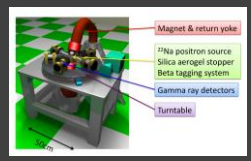
KAPAE (Korea)
Kyungpook Nat'l Univ.

< 2020

- CPT study
- NaI + PMT



APEX (U.S.A.)
Triangle Universities Nuclear Laboratory



- CP & CPT study
- Plastic + NaI + PMT

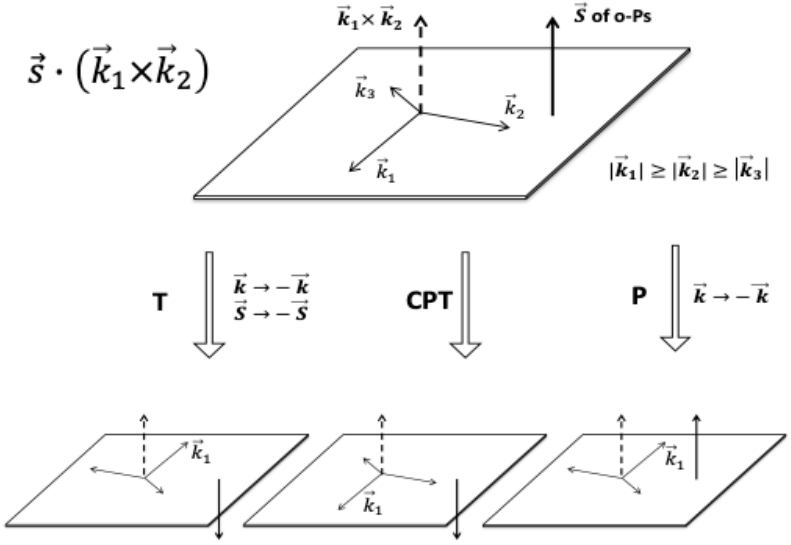
< 2011

ICEPP (Japan)
Univ. of Tokyo

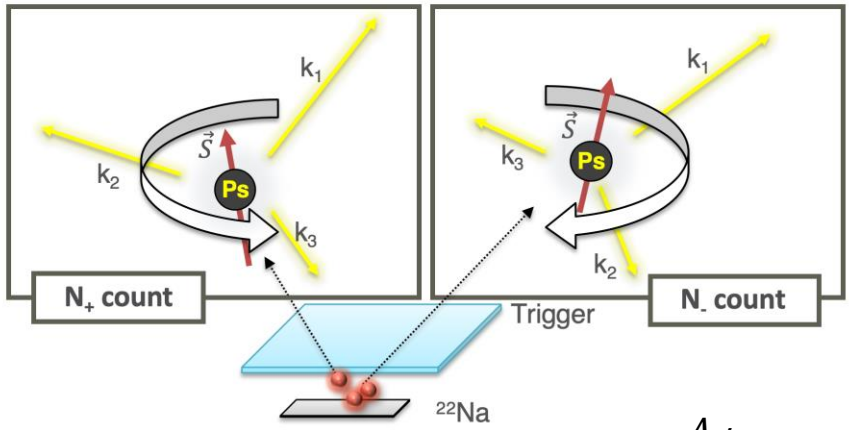
Introduction

CPT-Violation

- Discrete symmetries of positronium
- CPT violation in lepton sector
- CPT violation forbidden



The Ps rest frame



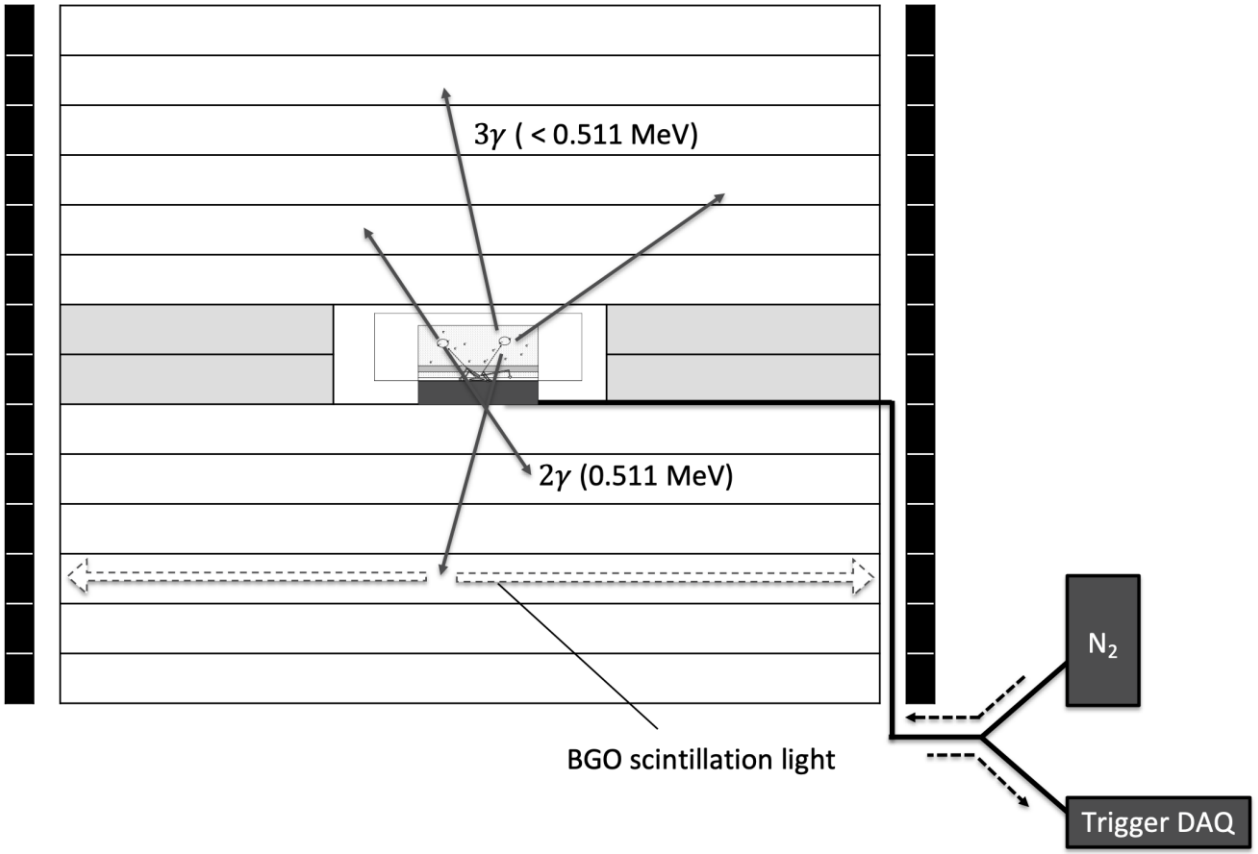
$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

$$C_{cpt} = {}^{A}/_{\langle P \rangle}$$

$\langle P \rangle$ = 0.41 (^{22}Na)

$$C_{cpt} = 0.0026 \pm 0.0031\ *$$

*Vetter P and J Freedman S 2003 91 263401

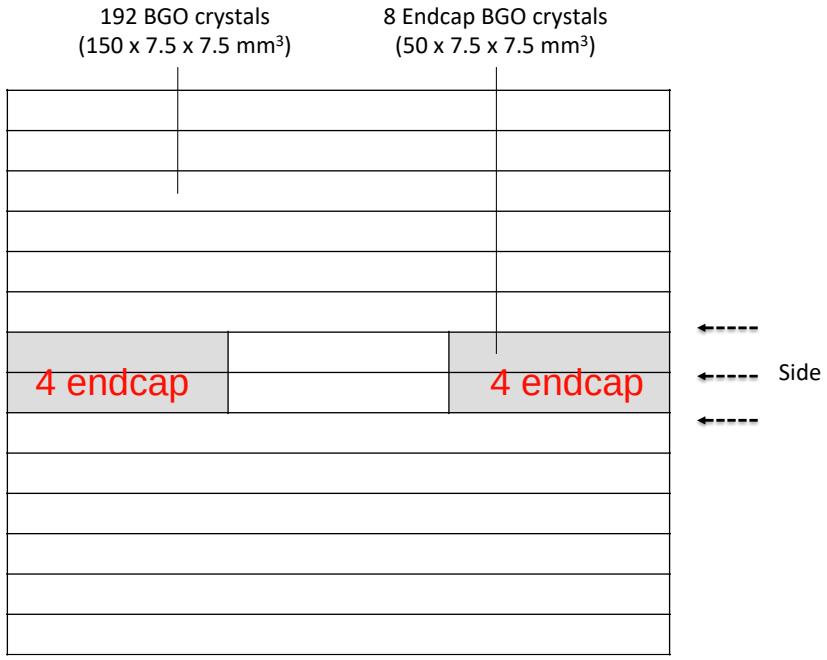


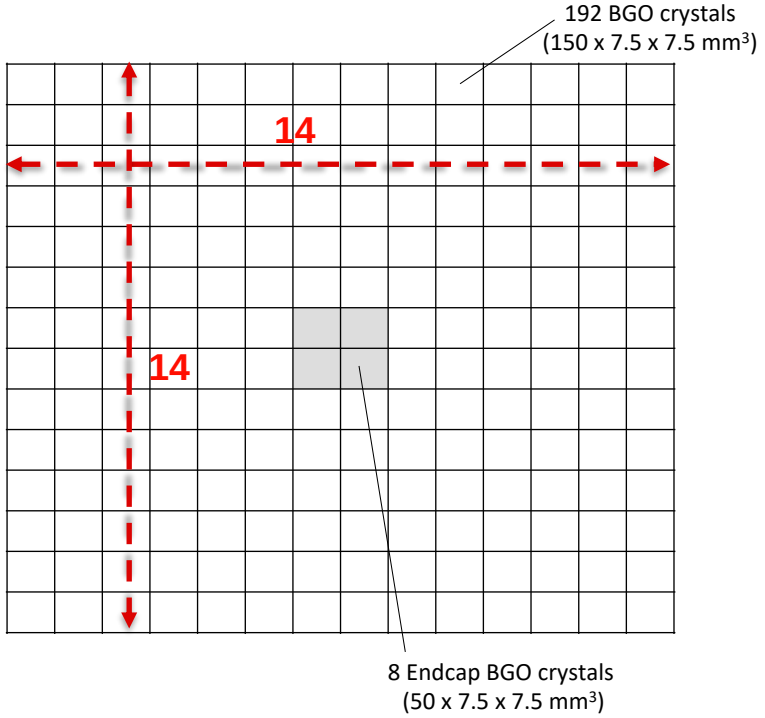
Design of KAPAE Detector

HW Park

Design of hermetic novel detector

- Compact size & multichannel (fine segmentation)
- 192 BGO crystals + 8 endcap BGO crystals = 200 BGO crystals



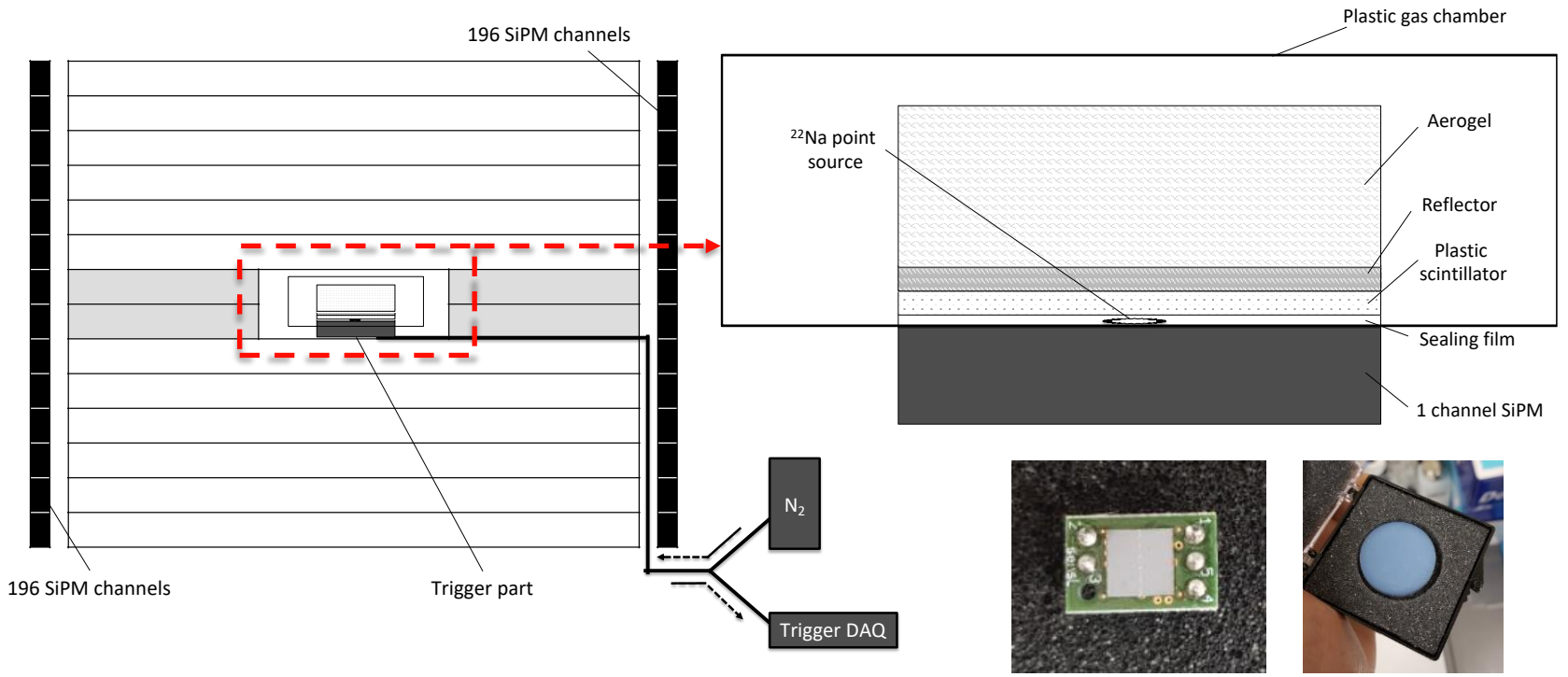


Design of KAPAE Detector

HW Park

Design of hermetic novel detector

- 196 SiPM Channels → Dual readout (392 chaanels)
- New concept of positron trigger (expected to improve trigger efficiency)

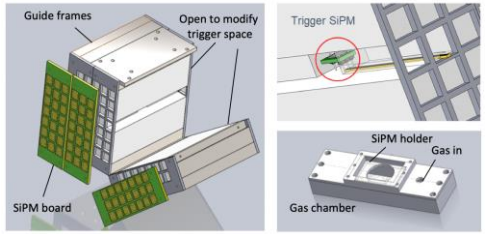


Design of KAPAE Detector

Design of KAPAE Detector

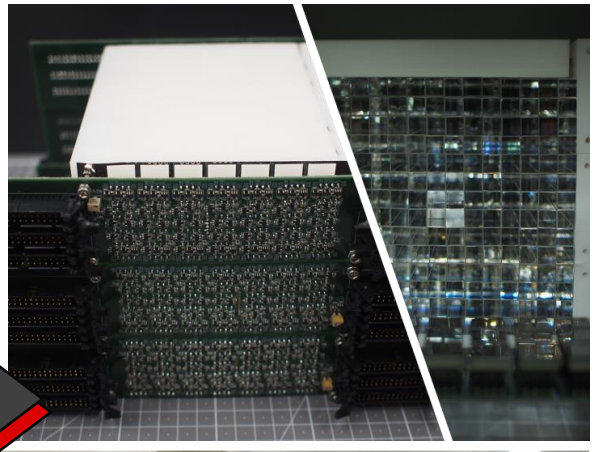
HW Park

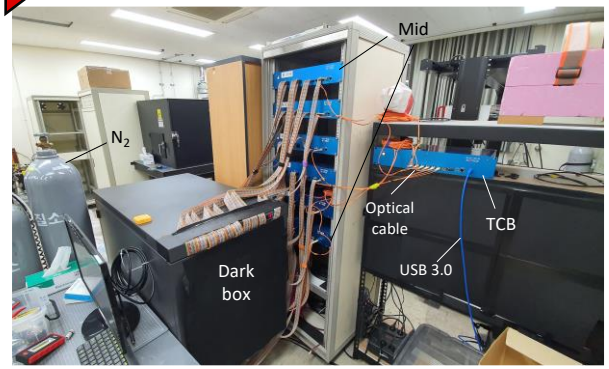
3D CAD design



65 MHz DAQ & 2ns TCB

KAPAE phase I

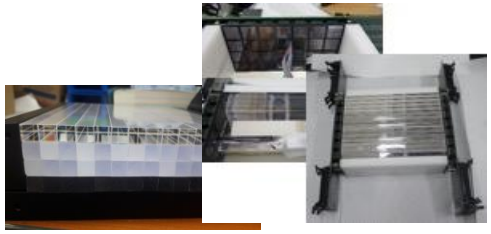




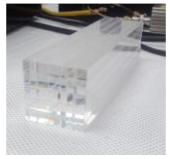
Customized ^{22}Na on trigger

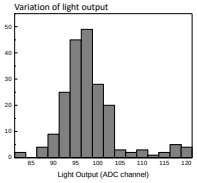
KRISS 한국표준과학연구원 Korea Research Institute of Standards and Science

Mock up & Partial assembly



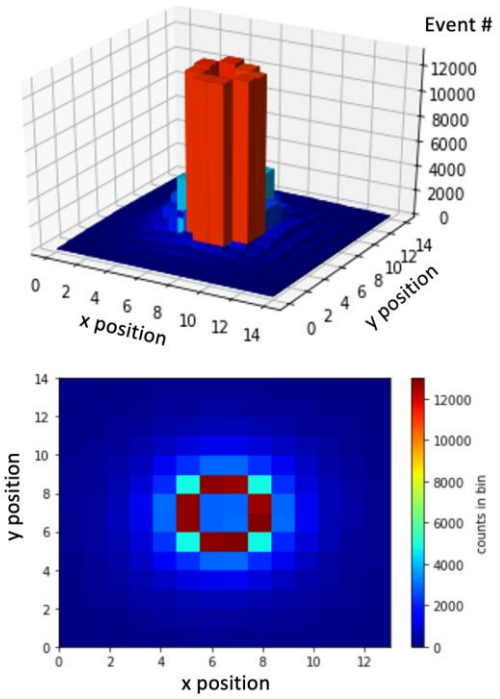
SiPM & BGO optimization



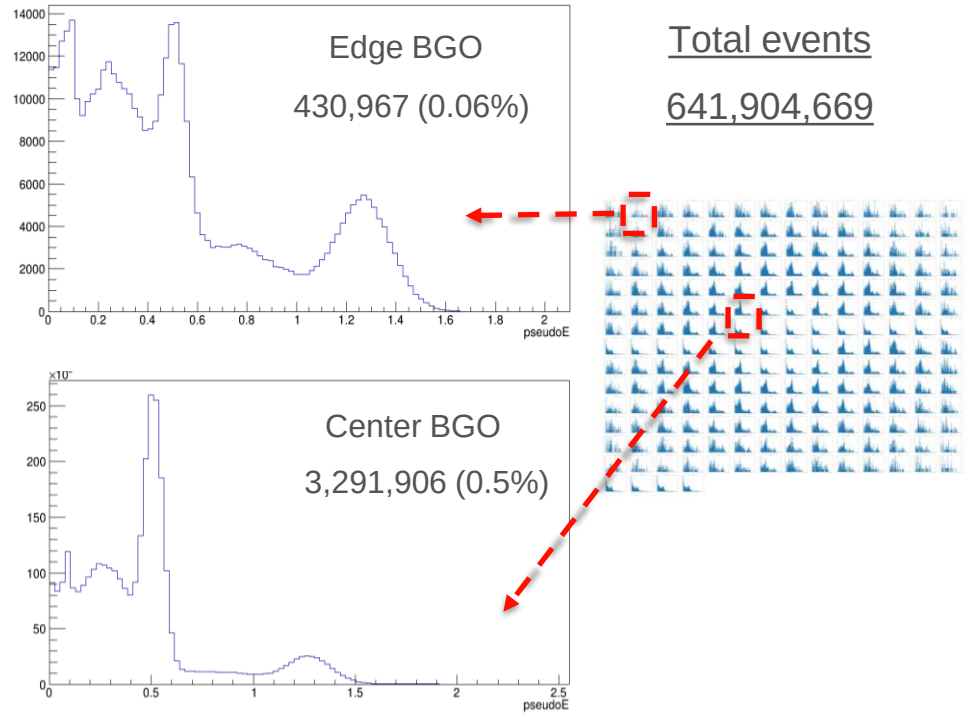


Geant4 Simulation

- Event distributions of BGO location



3D & 2D graph



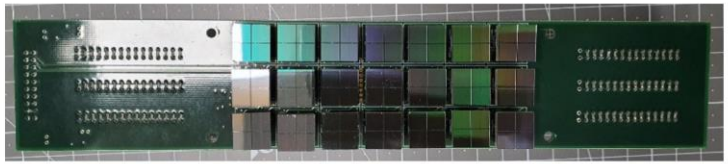
Total events

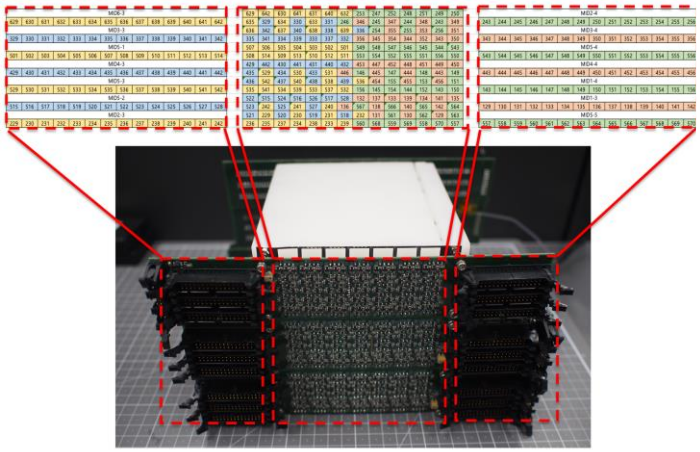
641,904,669

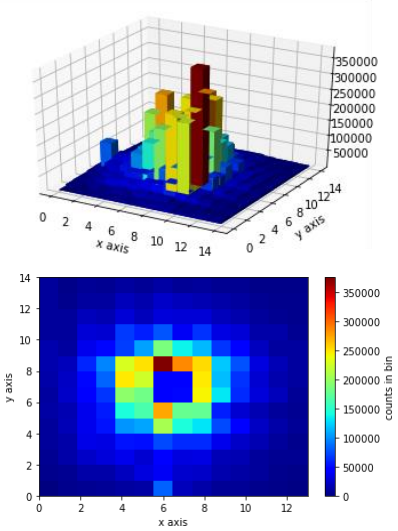
Energy spectrum at different locations

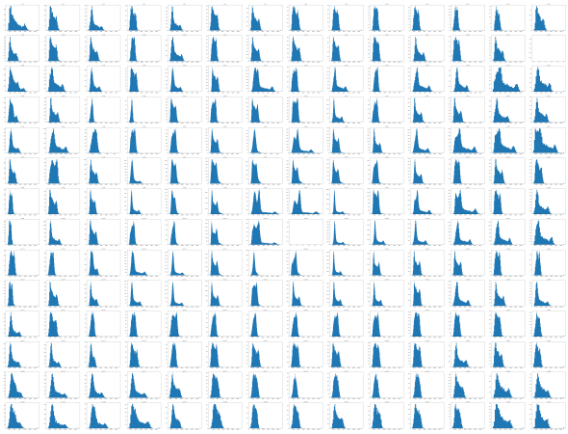
Channel Mapping

- SiPM locations
  ≠ Board number
  ≠ Cable number
  ≠ Channel number



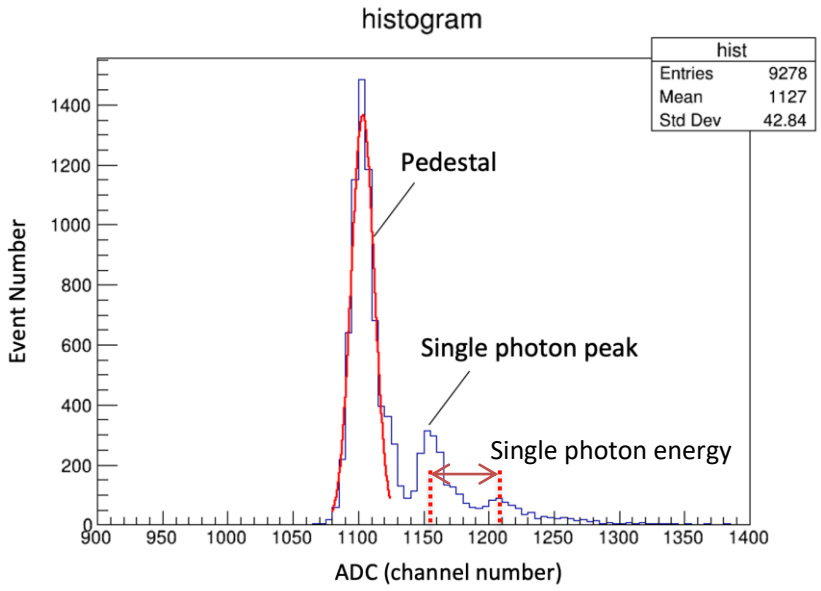


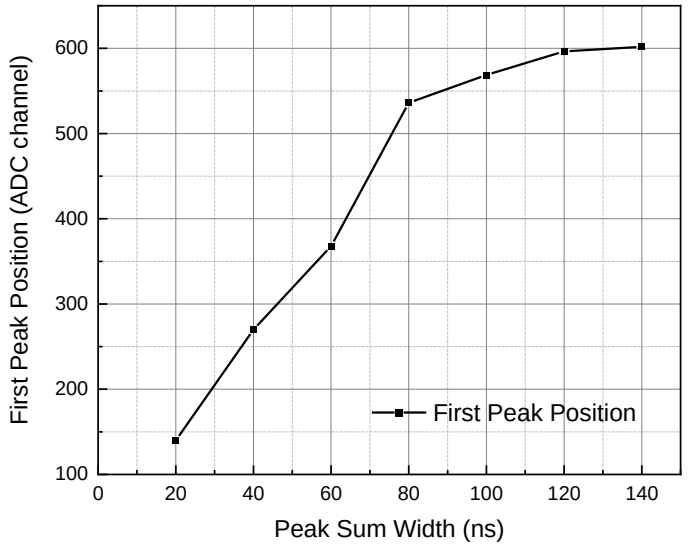




Single photoelectron calibration

- Pedestal & background estimation
- Single photoelectron ~ 40 channels



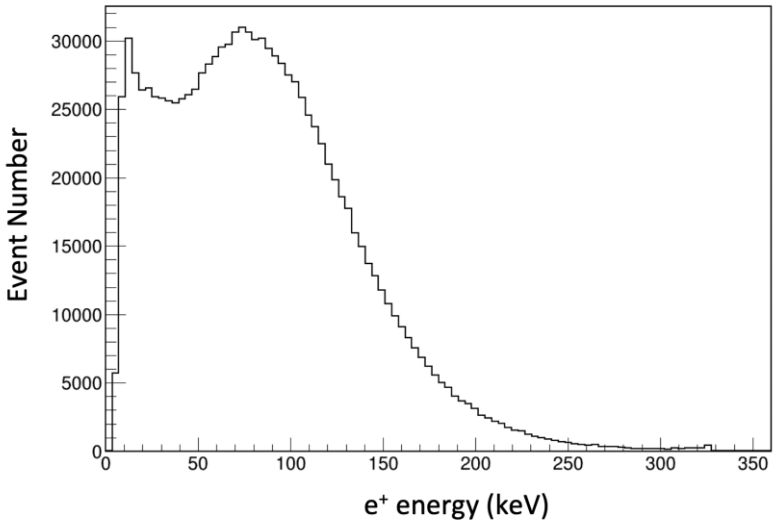


Single photon noise

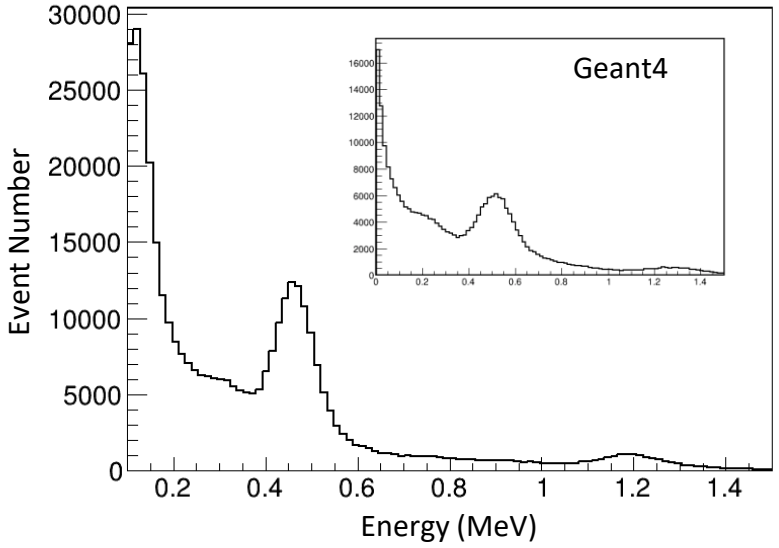
SiPM Manual :::: 50 kHz /mm^2 x 6.07 x 6.07 mm^2 = 1.842 MHz

Result of measurement single photon rate :::: 2.589 MHz

Trigger & Gamma spectrum

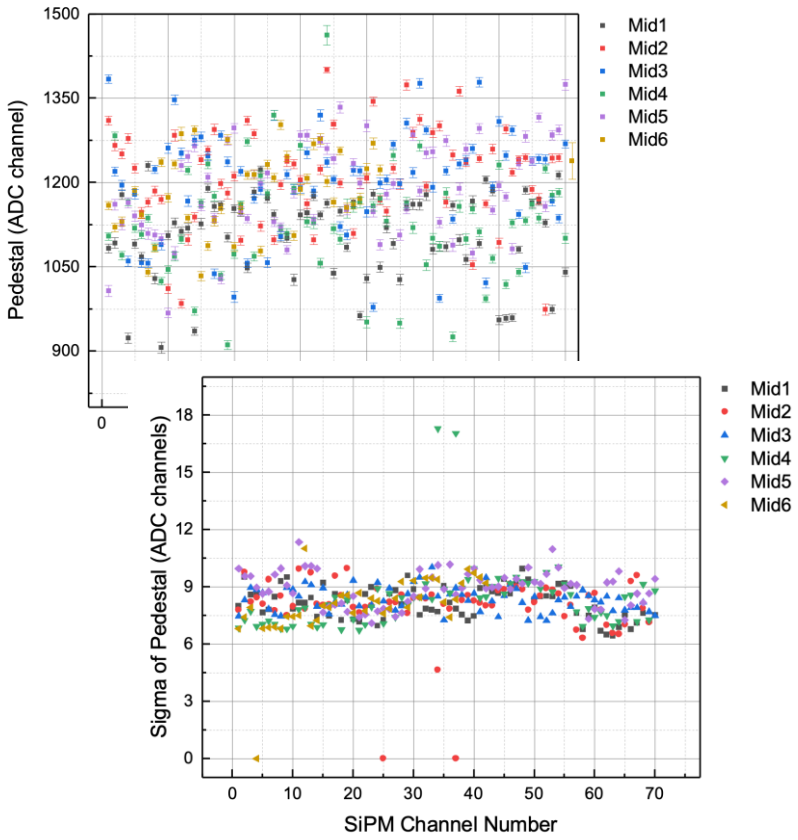


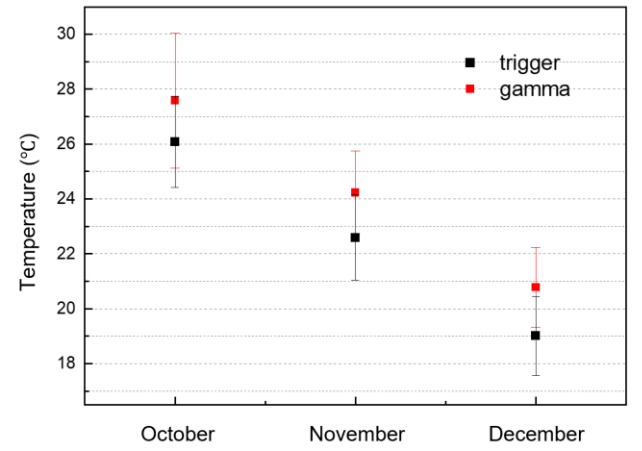
- Positron trigger signal
  - 5.9 x 10^4 Hz positron signal measurement
  - DAQ firmware (Max rate = 2.5 x 10^4 Hz)

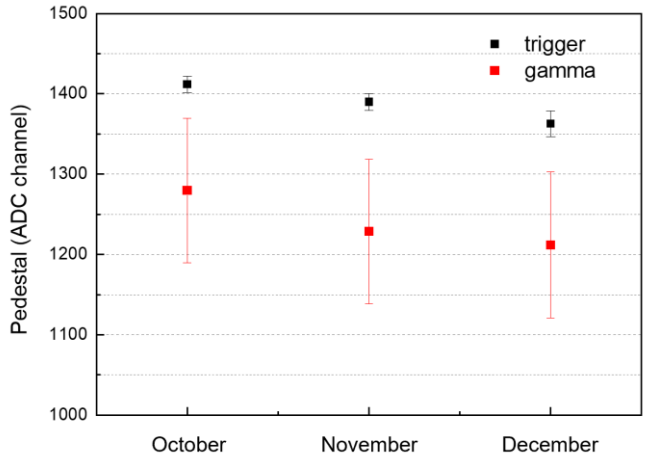


- BGO gamma signal
  - ER 20 ~ 35 % at 511 keV (FWHM)
- 673 photon/MeV (single photon calculation)
  ~ ER 25 %

Monitoring







Pedestal & Temperature monitoring

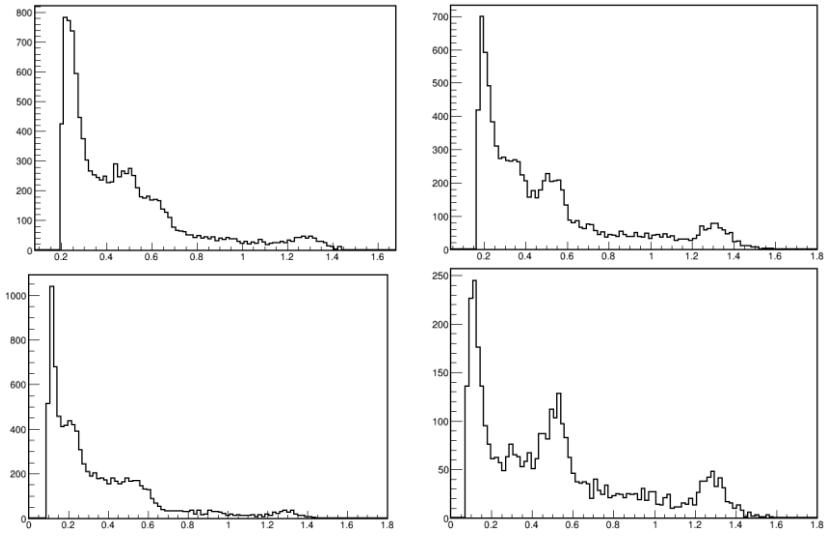
Energy & Time correction

- BGO Left (ER 33%) + Right (ER 38%) → BGO Total (ER 26%) → Correction (ER 25%)
- Adding adjacent BGO energy (ER 63% → 33%)

  - Compton effect, Crosstalk (electronics, optical), Misalignment
- Time correction → leading edge time discrimination

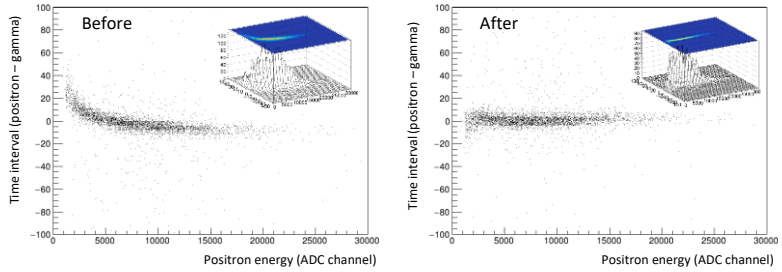
Before correction

After correction

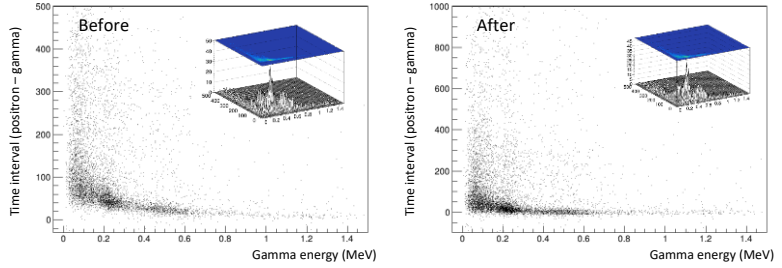


Energy correction

Trigger time correction

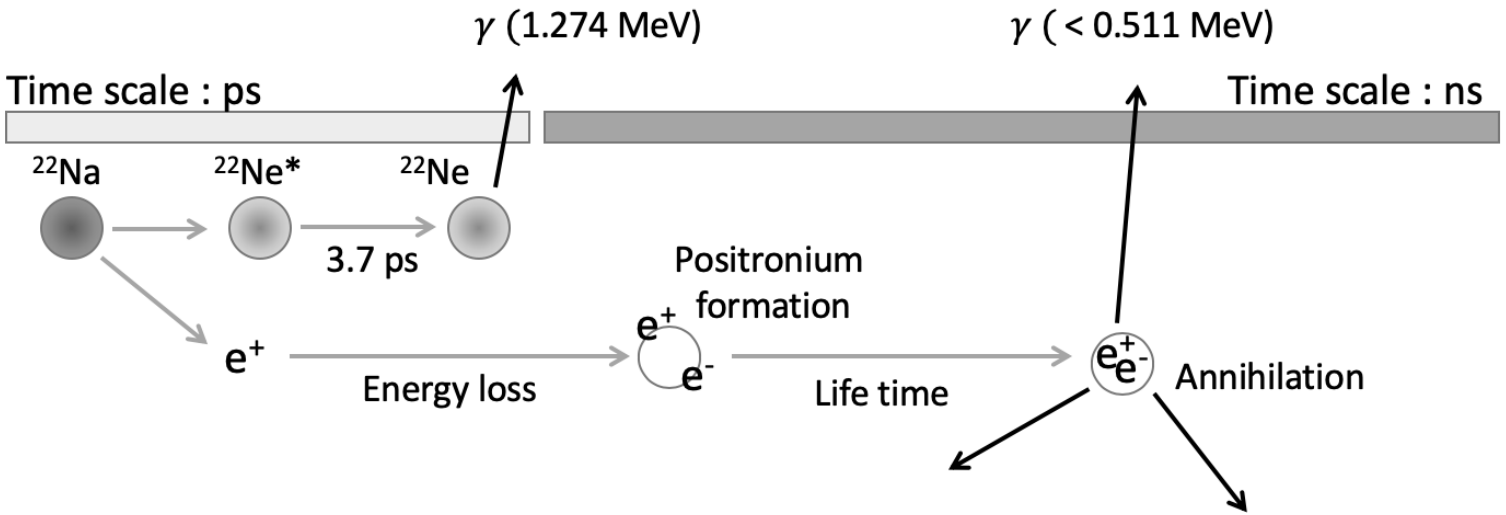


BGO time correction



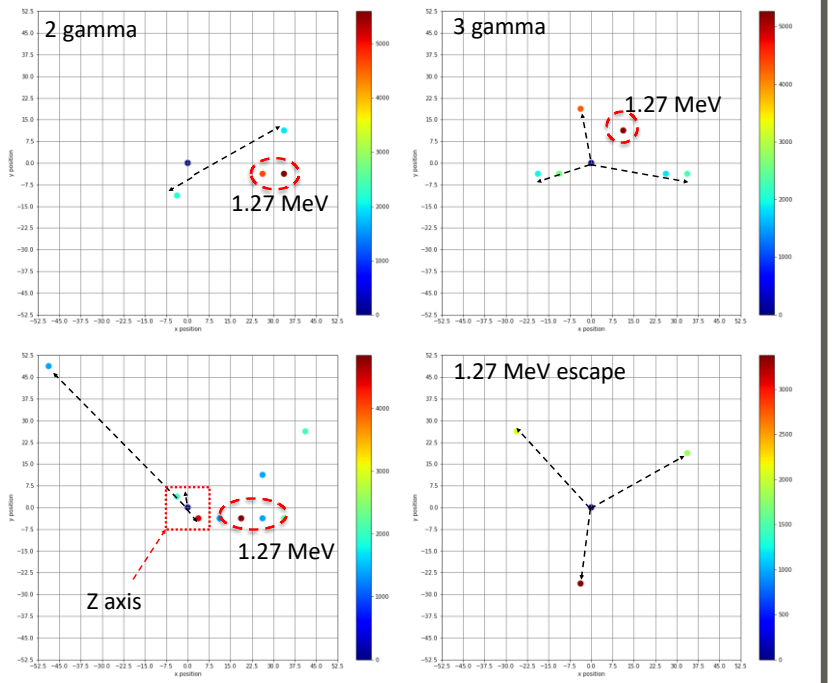
Time correction

Schematic of o-Ps decay

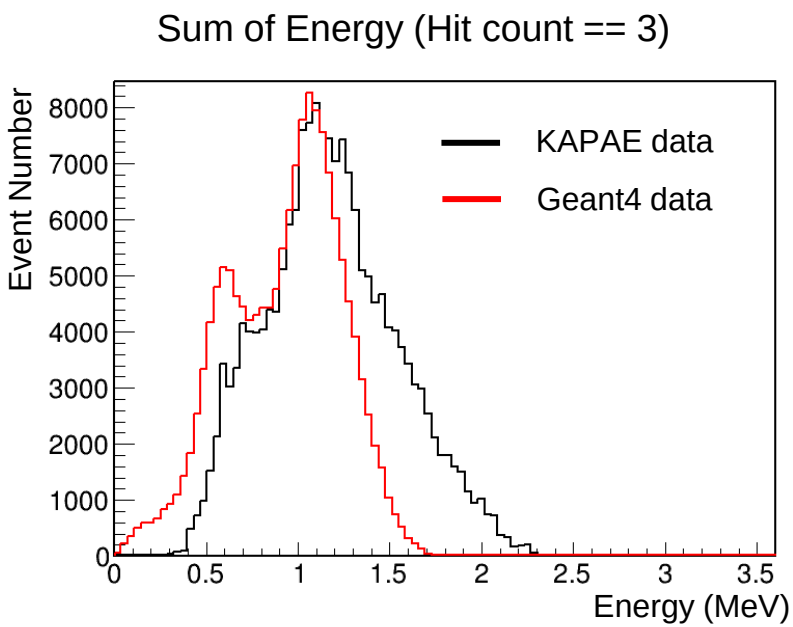


3 Gamma selection

- Total Energy Sum = 1.022 MeV
- Time Cut > 10 ns (exclude 1.274 MeV & p-Ps annihilation)



Case of energy deposit position



Total energy cut

KAPAE Server

- Raw data = 200 TB → After 1st sorting = 41 TB (3 month)
- Storage server and multiple cores for data processing
- 41 TB / 768(Byte/event) = 5.332131 x 10^{10} events → 4% 3gamma select → 2.14 x 10^{9}

64 Core Workstation (x2) + GPU

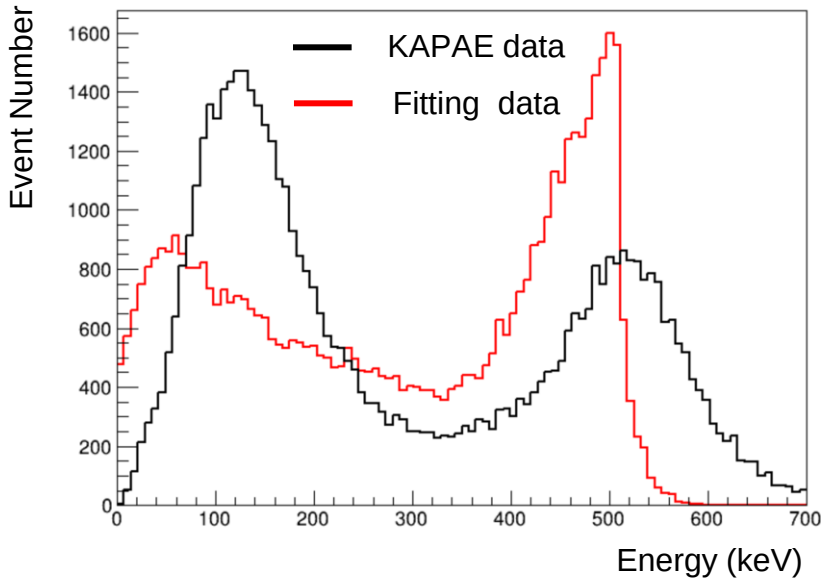
DATA Server (476 TB)

KAPAE Phase I

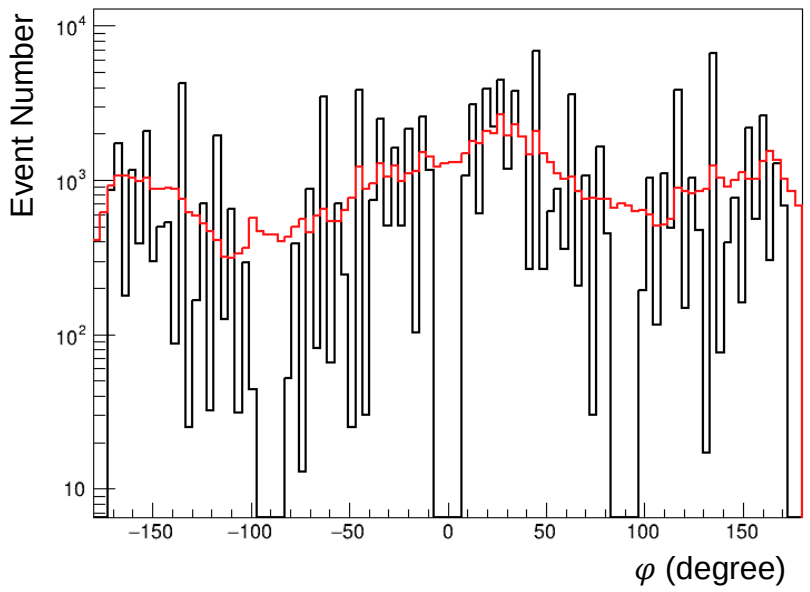
HW Park

Kinematic Fit

- 4 constraint kinematic fitting (BGO attenuation: 0.96 cm^{-1} → θ value is loss)
- The kinematic fitting ROOT code has been converted to Python code



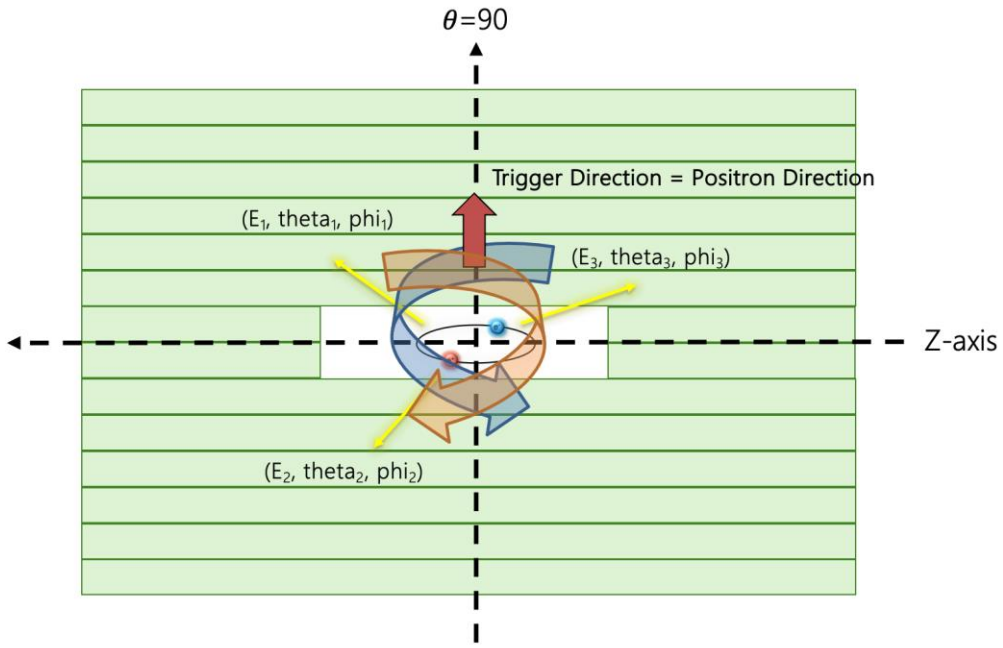
Energy kinematic fitting result



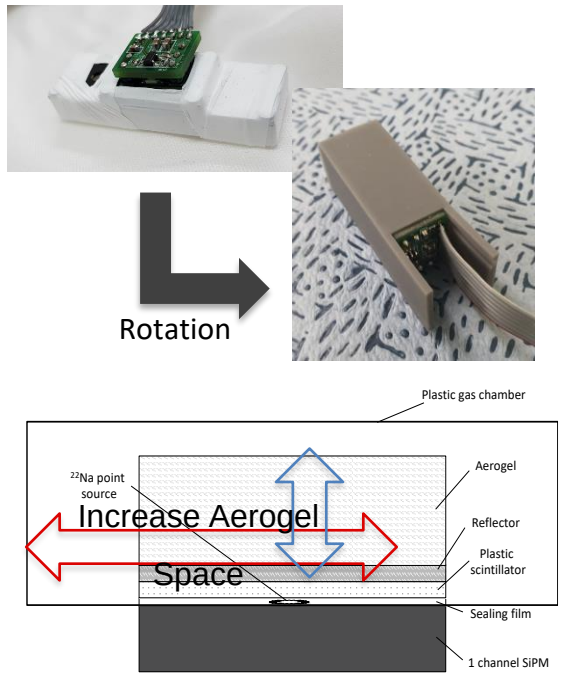
φ kinematic fitting result

Focus on CPT violation

- Rotate the positron trigger direction 90 degrees → θ value is not required
- Enhancing the nitrogen environment → 3 γ efficiency improvement



Current KAPAE Phase I System (θ value is required)



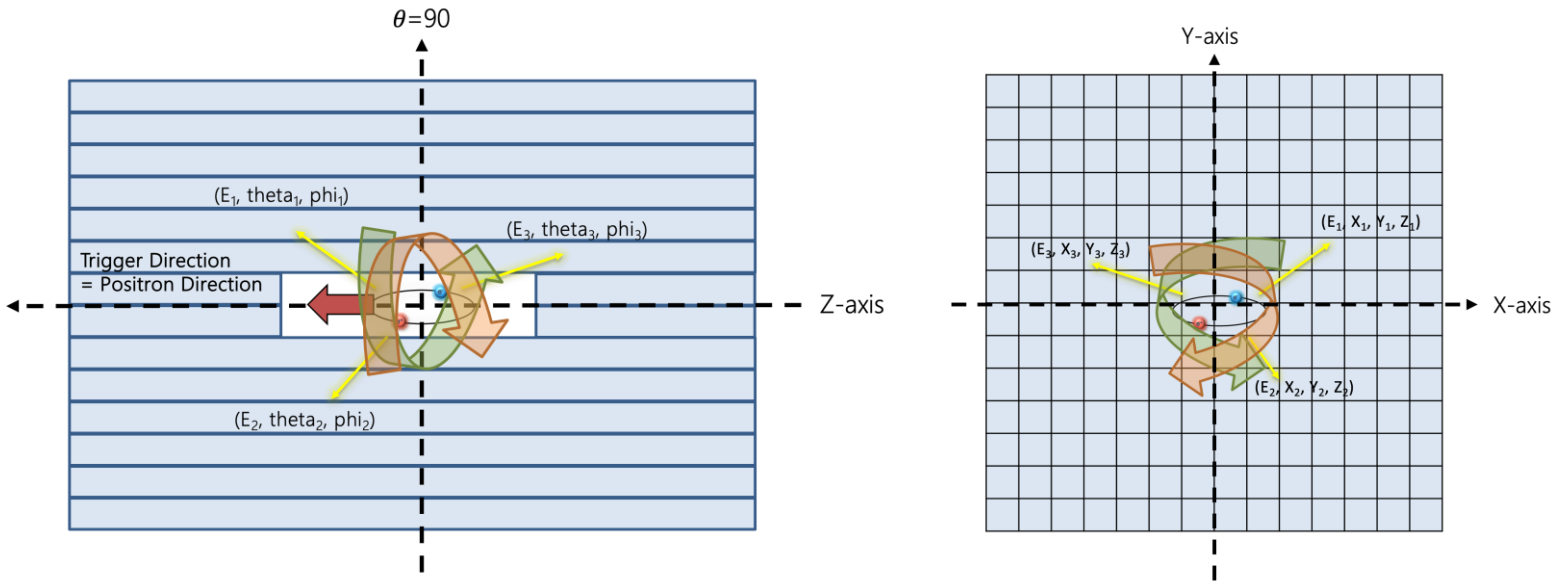
Trigger rotation

KAPAE Phase I System intensification

HW Park

Focus on CPT violation

- Only XY projection data is sufficient to search CPT Violations



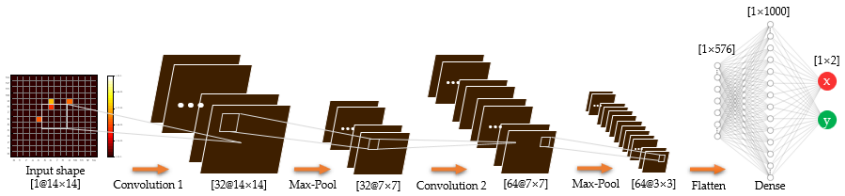
Upgrade KAPAE Phase I System (θ value is not required)

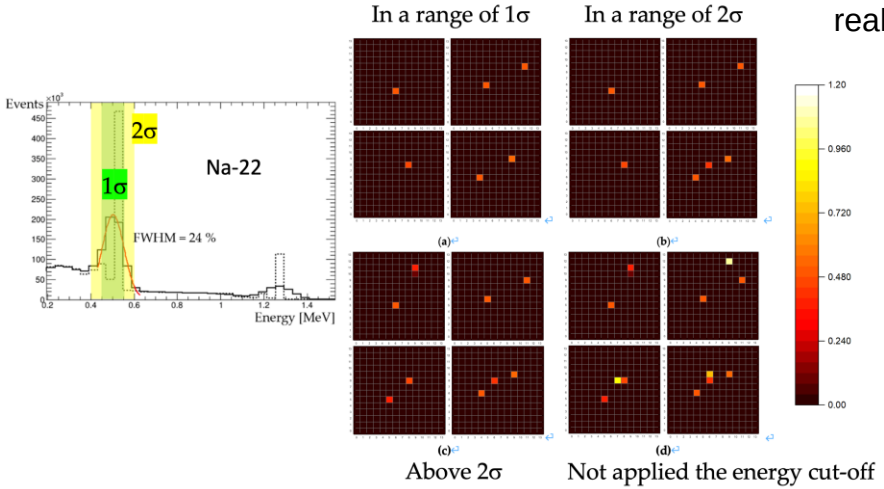
KAPAE Phase I System intensification

HW Park

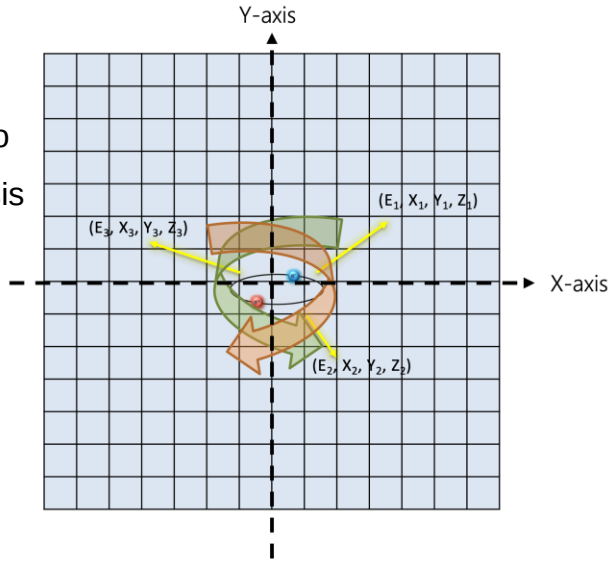
Deep learning

- CNN Deep learning (KAPAE Phase I Geant4 simulation data)
- Positronium annihilation reconstruction (x2 improvement in accuracy)





Plan to apply to real data analysis



CNN Deep learning

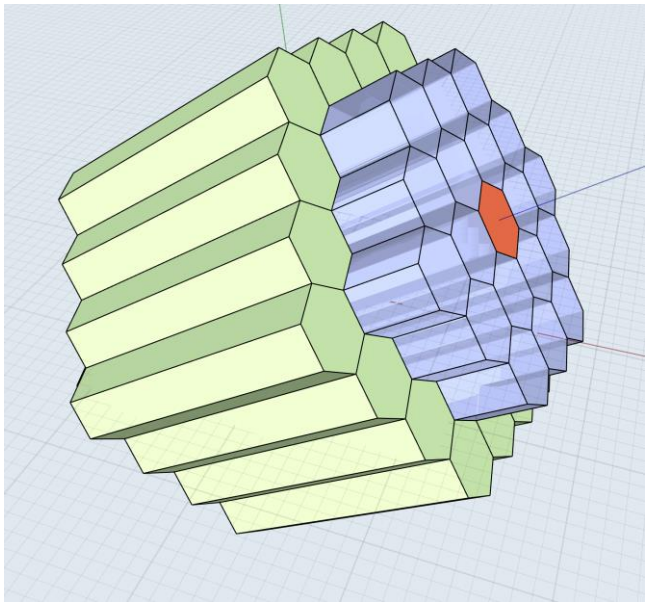
KAPAE Phase I System intensification

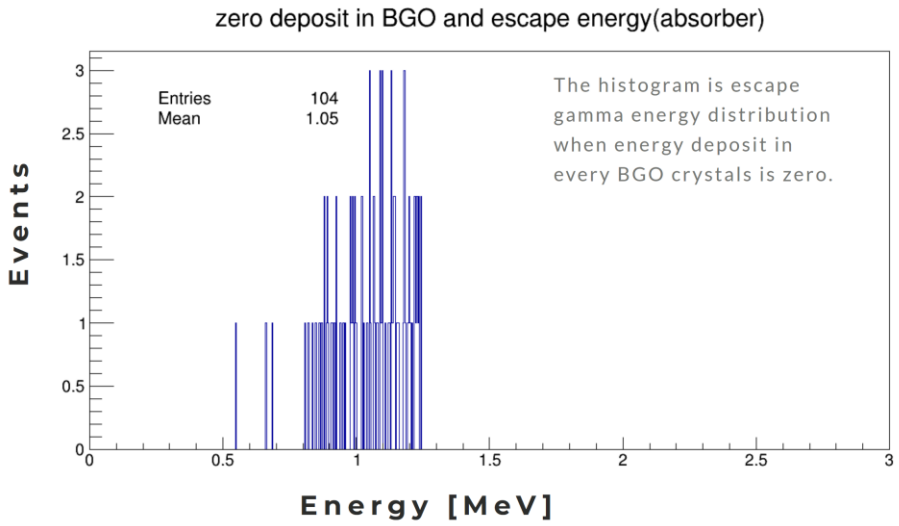
Jin Jegal

Design & Simulation

- Invisible upper limit sensitivity
- KAPAE phase II (Minimize dead area, Thicker BGO system)

  KAPAE phase I → 1.778×10^{-8} at 90% CL, KAPAE phase II → **1.728×10^{-9} at 90% CL**

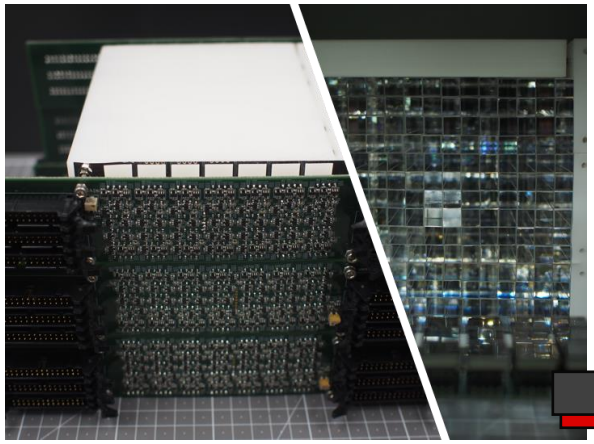




3D design & GEANT4 simulation

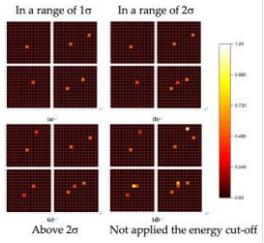
KAPAE Phase II

KAPAE phase I



Trigger upgrade

Deep learning



CPT Violation

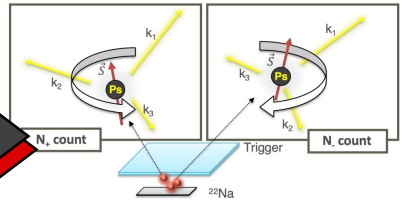
- CPT Violation sensitivity

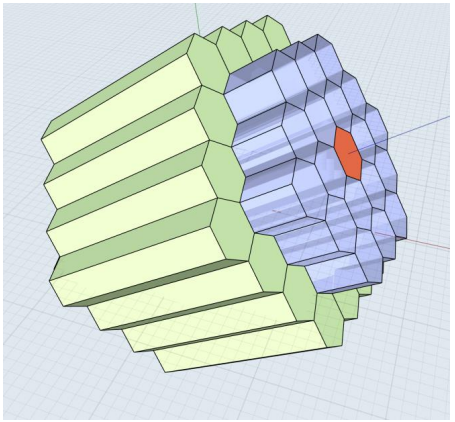
  ± 0.000142 at 90%CL

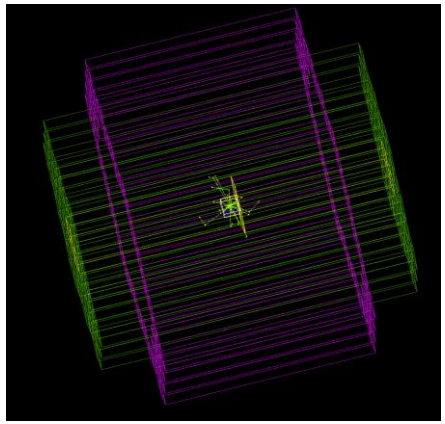
→ ± 0.000086 at 90%CL

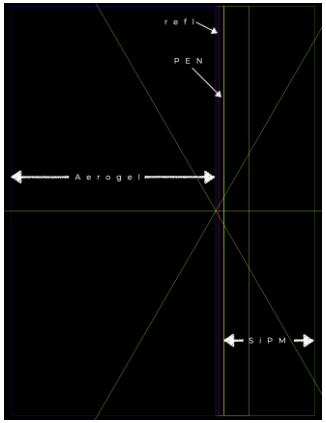
- Invisible upper limit

1.778 × 10^{-8} at 90% CL









KAPAE phase II (Design & Simulation)

- Invisible upper limit sensitivity

1.778 × 10^{-8} at 90% CL

→ 1.728 × 10^{-9} at 90% CL

0.0073 % → 0.000069%

Zero deposit events improve

Invisible Decay

Summary

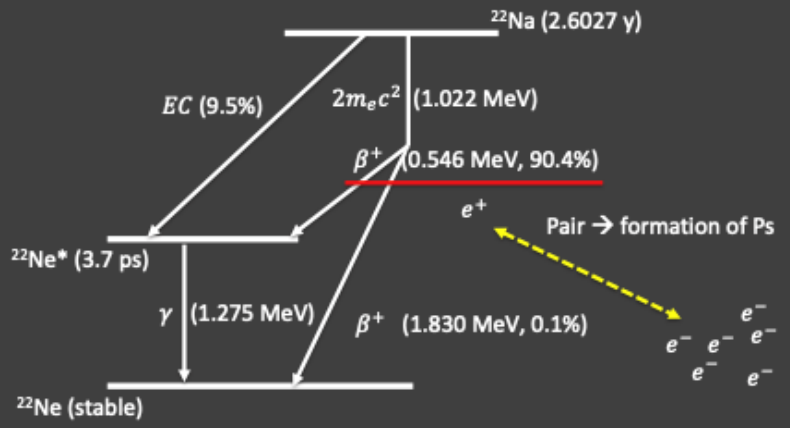
HW Park

Thank You !

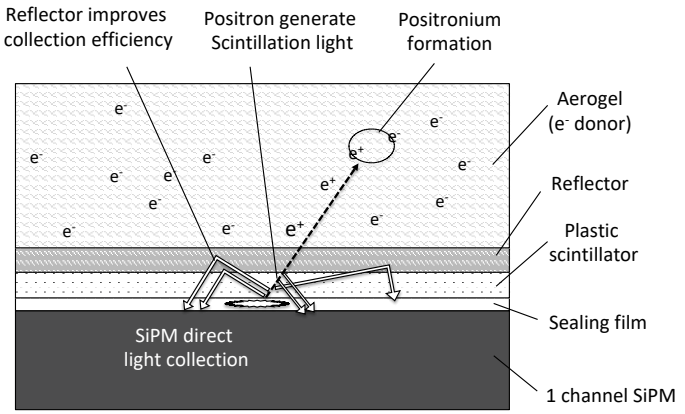
BACK UP

The concept of detector for KAPAE

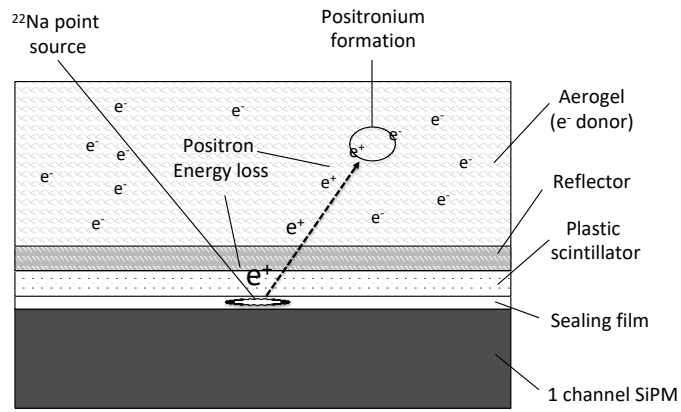
- Positronium = Electron + Positron
  - Positron → β^+ decay (^{22}Na)
  - Electron → aerogel
- Trigger signal
  → Plastic scintillator



Generation of trigger signal



Positronium formation in aerogel

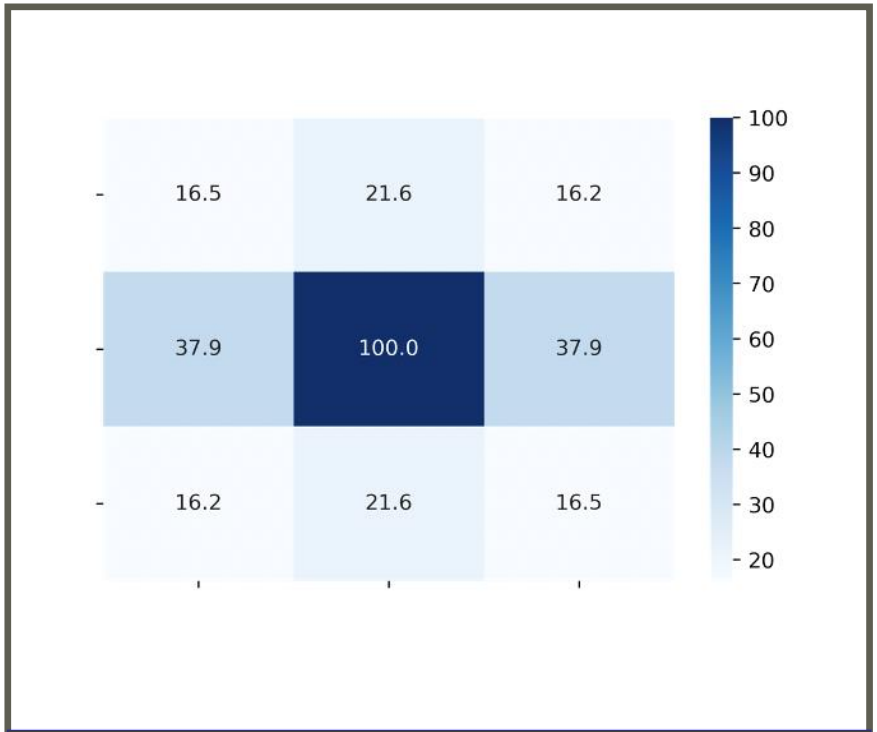


Design of KAPAE Detector

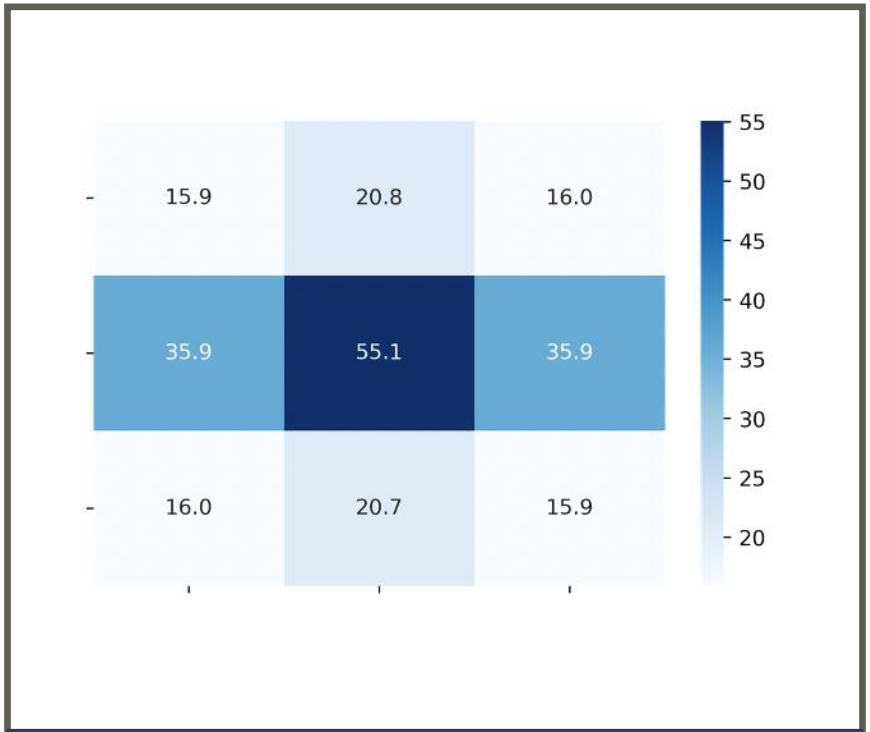
HW Park

Light loss in KAPAE

- Near coincidence events check
- 44.9% light loss at other side direction light (BGO optimization ER = 12% → KAPAE 20~35%)



Near coincidence events



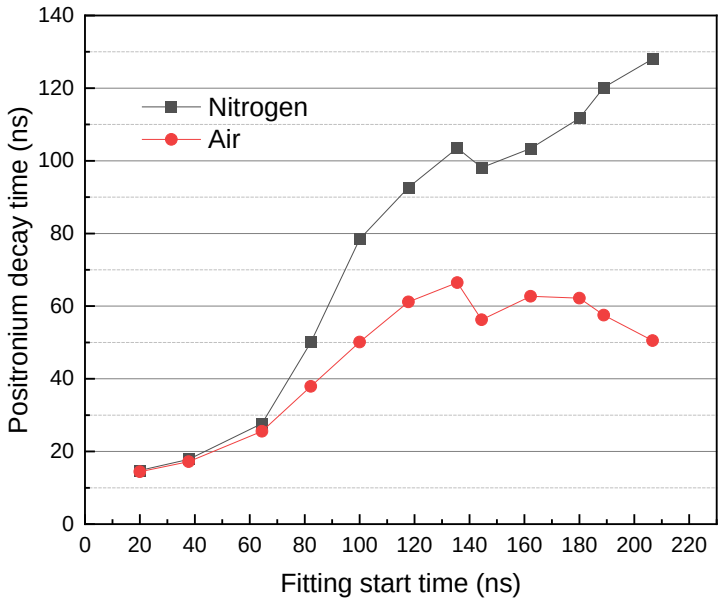
The other side coincidence events

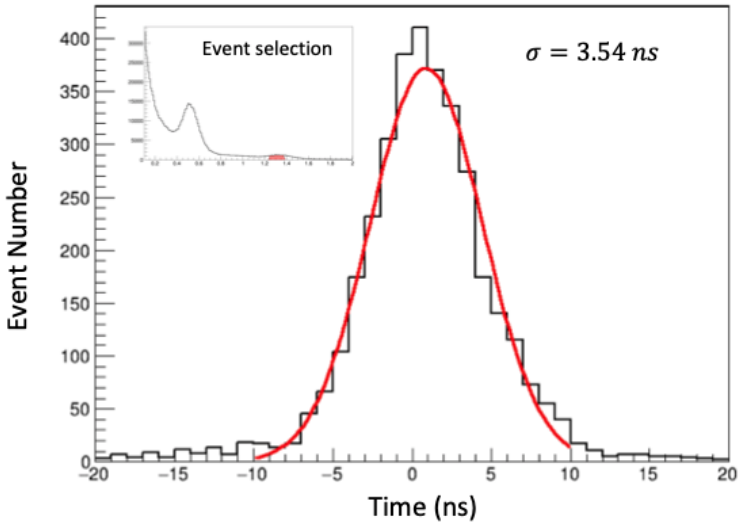
Analysis of preliminary data

- Accidental γ-ray → exponential fitting include constant term

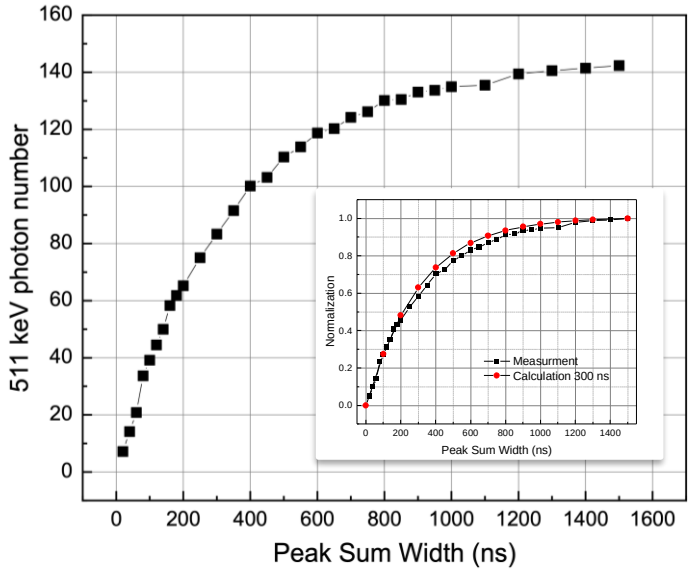
  - Lifetime: 62.4 $\pm$ 0.25 ns in air & 111.7 $\pm$ 8.44 ns in N_2

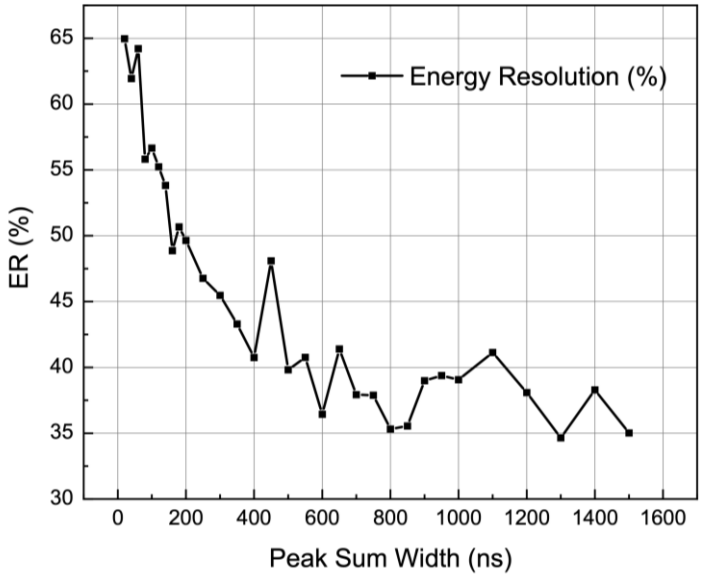
Positronium decay time





Analysis of preliminary data





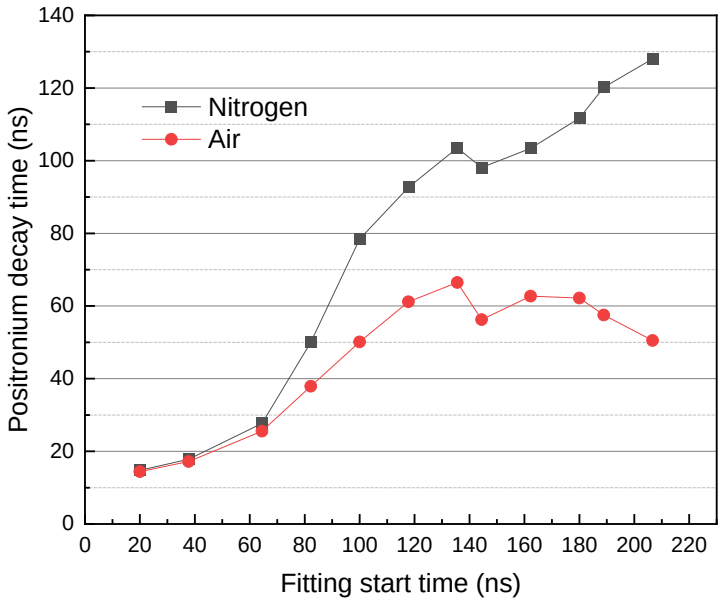
- Optimization of peak sum width
  - BGO decay time 300 ns
  - Peak sum width (PSW) = 1000 ns

Analysis of preliminary data

- Accidental γ-ray → exponential fitting include constant term

  - Lifetime: 62.4 $\pm$ 0.25 ns in air & 111.7 $\pm$ 8.44 ns in N_2

Positronium decay time



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Analysis of preliminary data

- 3 γ events selection

  - Detector efficiency → 0.86 % 511 keV gamma loss

- - BGO Compton

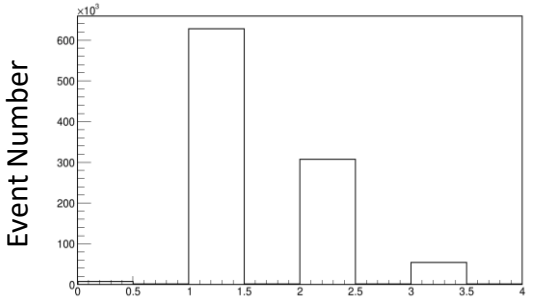
  - 3 γ deposit at 3BGO crystal = 34.8%

The number of hit	Compton Events	Adjacent Events Sum
Total	100.00%	100.00%
0	0.86%	0.86%
1	62.78%	84.77%
2	30.65%	13.37%
3	5.29%	0.36%
4	0.57%	–

The number of hit	Compton Events	0.4 ~ 0.5 MeV select	Adjacent Events Sum	0.4 ~ 0.5 MeV select
1	62.78%	51.89%	84.76%	70.34%

3 Gamma

→ 3 hit < 34.8%



Geant4 Simulation data analysis

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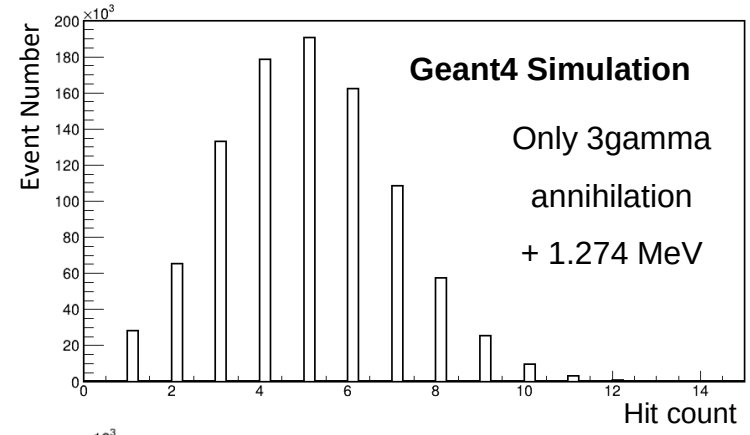
Analysis of preliminary data



The number of hit	Simulation Events	Measurement Events
1	2.94%	1.00%
2	6.77%	7.94%
3	13.83%	14.87%
4	18.54%	23.99%
5	19.80%	24.28%
6	16.87%	14.57%
7	11.24%	6.47%
8	5.96%	2.89%
9	2.62%	1.70%
10	0.97%	1.09%
11	0.33%	0.63%
12	0.09%	0.32%
13	0.02%	0.14%
14	0.01%	0.07%

Comparison of Geant4 and measurement data (3 gamma)

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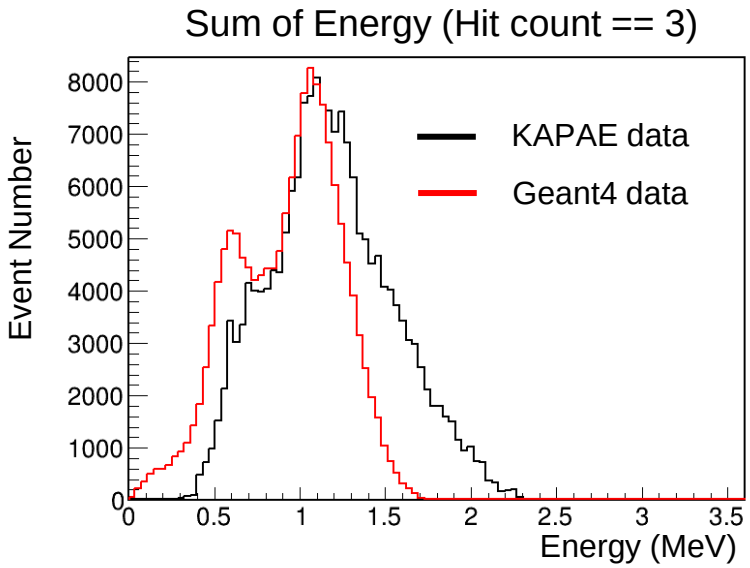
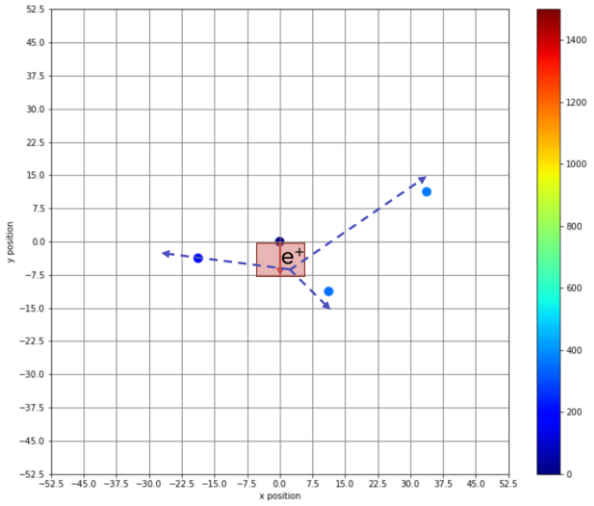
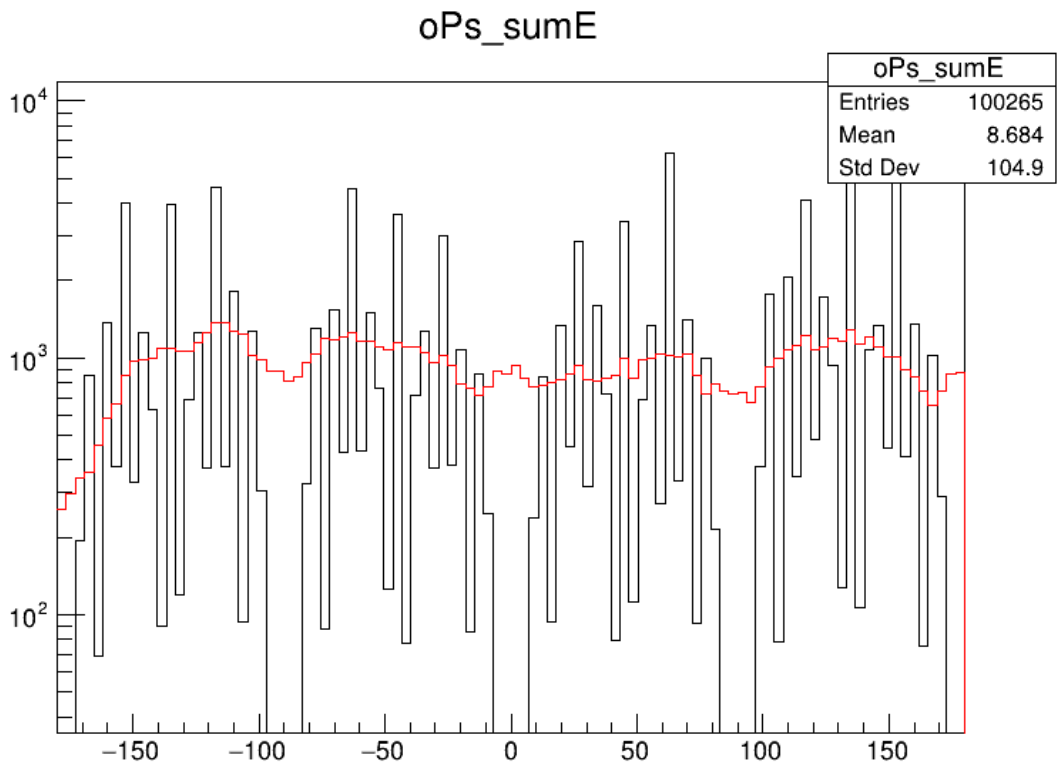
Analysis of preliminary data

- 3 gamma events selection
  - BGO Hit Count > 3 (include Compton scattering)
  - Total Energy Sum = 1.022 MeV
  - Time Cut = 160 ns ~ 800 ns (exclude 1.274 MeV & p-Ps annihilation)
  - Accidental gamma depress





Partial Assembly Results



preliminary

VI Conclusion

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Summary

- Development of a Hermetic Novel Detector for KAPAE
- The new concept of trigger part offers high performance of positron trigger efficiency
  - KAPAE trigger maximum counting rate 59 kHz
  - 20 times better than ETH Zurich trigger counting rate 3.2 kHz
- CPT asymmetry sensitivity is $\pm$ 0.000058 at 90% C.L. (confidence level)
  - 5.5 times improvement over reported papers.
- Invisible upper limit sensitivity is 1.79×10^{-8} at 90% C.L. for new physics
  - 2.1×10^{-8} at 90% C.L. (ETH Zurich)
- Positronium decay time increase under N_2 condition
- Geant4 simulation include 3 gamma annihilation
- Python based → machine learning

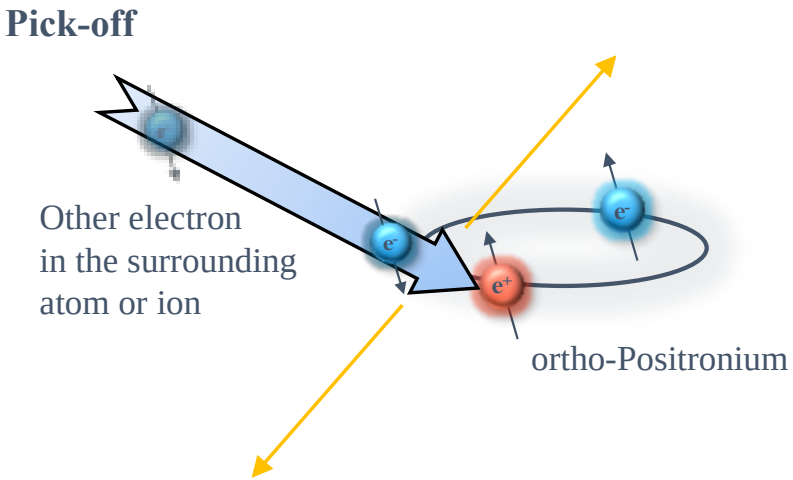
→

- CPT violation study
- Invisible decay
- PET medical application

Pick-off process

Pick-off Process

$$\Gamma_{pick-off} = 4\pi r_0^2 c \rho_0 Z_{eff} P_0$$



Pick-off process

SiPM (SensL spec.)

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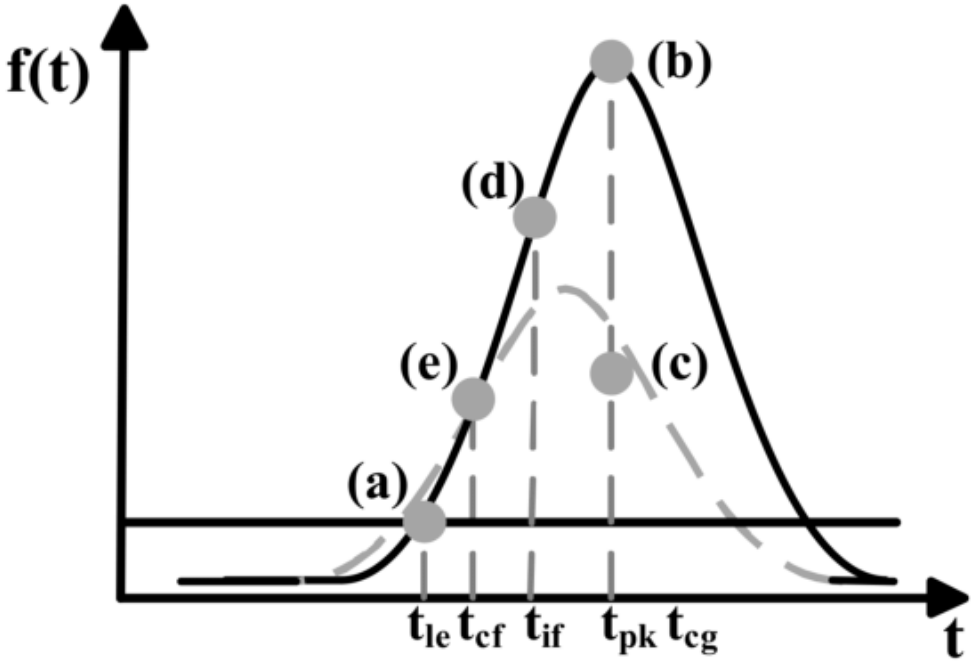
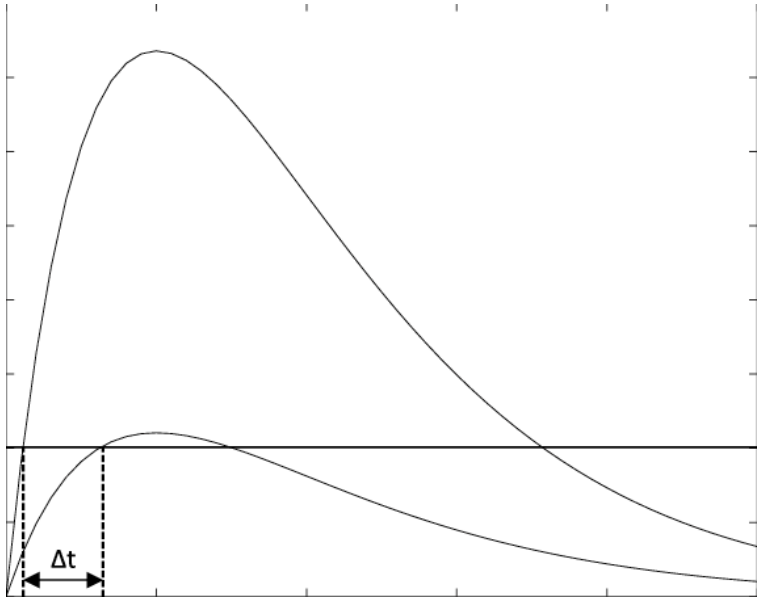
Table 3.1: The basic properties of SiPM.

Parameter	J-Series 60035	
Active area	6.07 x 6.07 mm^2	
No. of microcells	22,292	
Microcell fill factor	75%	
Microcell recharge time	50 ns	
Breakdown Voltage	24.7 V	
Spectral Range	200 – 900 nm	
Capacitance	4140 pF	
Overvoltage properties	+ 2.5V	+ 5V
➢ PDE	38%	50%
➢ Dark count rate	50 kHz/mm^2	150 kHz/mm^2
➢ Gain	2.9 x 10^6	6.3 x 10^6
➢ Rise time	180 ps	250 ps
➢ Crosstalk	8%	25%
➢ Afterpulsing	0.75%	5%

Time leading edge problem





Time discrimination methods: (a) Leading edge, (b) peak, (c) center of gravity, (d) inflection, (e) constant fraction.

511 keV Hit of BGO