Study of nuclear transmutation by negative muon capture reaction using active target

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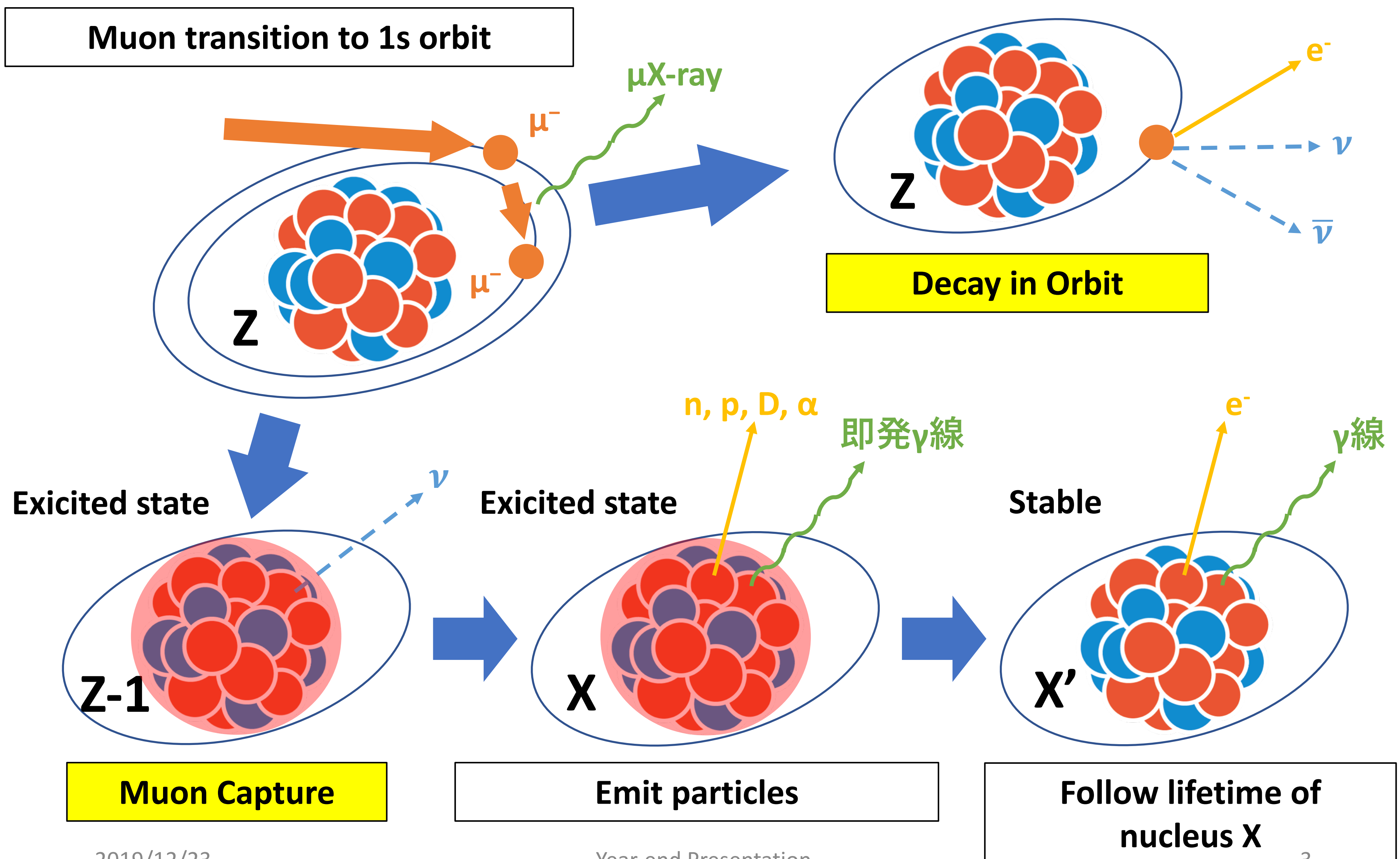
Muon Capture



Motivation

●There is a problem with how to handle radioactive waste generated from nuclear power plants

●One of the candidates is transmutation processing using muon

●However, for heavy nuclei, which are the main fission products, there are not yet theoretical models and sufficient data

Need more basic data for realization

(red box) = 長寿命核分裂生成物(LLFP)

核分裂生成物(FP)

核種	半減期	線量換算係数 (μ Sv/kBq)	含有量 (1トン当たり)
Se-79	29万5千年	2.9	6g
Sr-90	28.8年	28	0.6kg
Zr-93	153万年	1.1	1kg
Tc-99	21万1千年	0.64	1kg
Pd-107	650万年	0.037	0.3kg
Sn-126	10万年	4.7	30g
I-129	1,570万年	110	0.2kg
Cs-135	230万年	2.0	0.5kg
Cs-137	30.1年	13	1.5kg

Major Long-lived nuclides in spent fuel

平成29年8月3日　藤田玲子氏
革新的研究開発推進プログラム(ImPACT)
「核変換による高レベル放射性廃棄物の
大幅な低減・資源化」
進捗状況報告より作成
(https://www8.cao.go.jp/cstp/sentan/kakushintekikenkyu/yusikisha_29/siryo1.pdf)

Previous Research

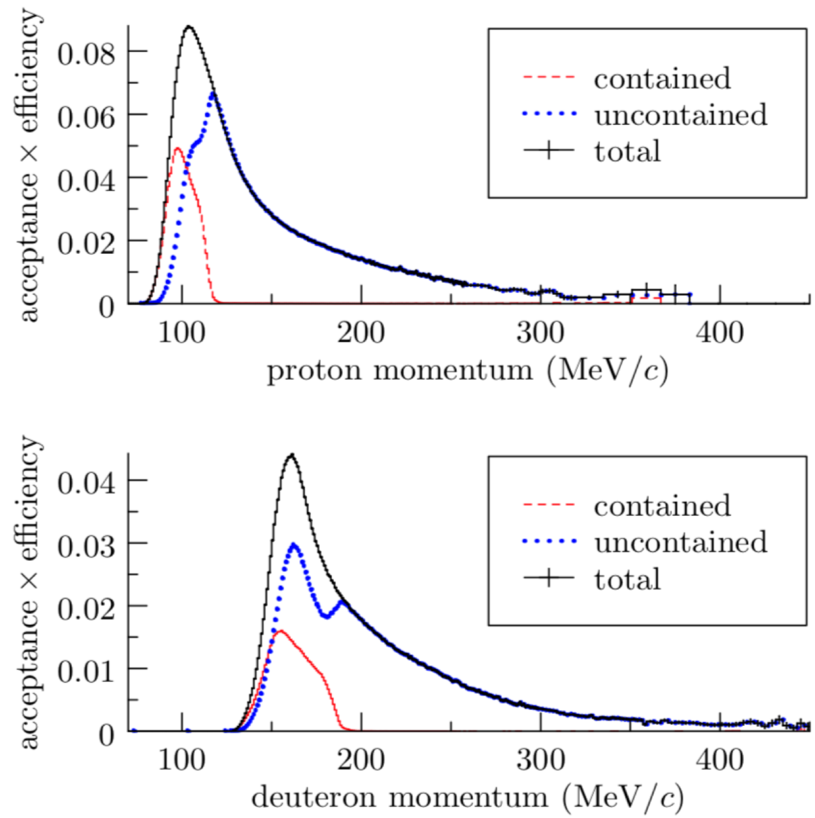
○Nuclear Physics A294 (1974) 278-292
A. Wyttenbach, P. Baertschi, S. Bajo, J. Hadermann, K. Junker, S. Katcoff, E. A. Hermes and H. S. Pruys

Reaction probabilities per captured muon [a]

Target A, Z	Product Reaction Factor / target purity (%)	$A-1, Z-2$ (μ^-, p) (10^{-4})	$A-2, Z-2$ (μ^-, pn) (10^{-3})	$A-3, Z-2$ $(\mu^-, p2n)$ (10^{-3})	$A-4, Z-2$ $(\mu^-, p3n)$ (10^{-3})	$A-4, Z-3$ (μ^-, α) (10^{-3})
$^{23}_{11}Na$	> 99.5					11 ±1.5 (3)
$^{27}_{13}Al$	99.99		28 ±4 (2)			7.6 ±1.1 (2)
$^{31}_{15}P$	99.5		38 ±5 (2)	23 ±3 (2)		13 ±2 (2)
$^{41}_{19}K$	> 99.5		28 ±4 (1)			
$^{51}_{23}V$	99.7	29 ±4 (3)		8.4±1.2 (2)	8.8±1.3 (1)	1.5 ±0.2 (1)
$^{55}_{25}Mn$	99.9	28 ±4 (5)	12 ±2 (5)	11 ±1.5 (5)		1.6 ±0.2 (5)
$^{56}_{26}Fe$	> 99.5					4.6 ±0.7 (1) [b]
$^{59}_{27}Co$	99.5	19 ±2 (4) [c]	24 ±3 (4)	11 ±1.5 (4)		
$^{63}_{29}Cu$	> 99.5	29 ±6 (2) [d]	14 ±3 (1) [e]			
$^{65}_{29}Cu$	> 99.5		8.9±1.6 (2)	14 ±3 (2) [d]	12 ±3 (1) [e]	0.7 ±0,2 (1) [f]
$^{75}_{33}As$	99.999	14 ±2 (3)	7.4±1.1 (3)	5.1±0.7 (3)		*0.28±0.04 (2) [g]
$^{94}_{40}Zr$	> 99.5		4.5±0.9 (1) [h]			
$^{115}_{49}In$	99.99		5.3±0.8 (1)	3.1±0.4 (2)	3.1±0.4 (1)	
$^{121}_{51}Sb$	> 99.5		*2.2±0.3 (2) [i]	*2.4±0.4 (2) [k]	2.8±0.4 (2) [l]	
$^{123}_{51}Sb$	> 99.5				*1.7±0.3 (2) [l]	
$^{133}_{55}Cs$	99.98	4.8±0.7 (1)	2.5±0.4 (1)	1.9±0.3 (2)		
$^{165}_{67}Ho$	99.9	3.0±0.4 (2)	1.5±0.2 (4)	1.6±0.2 (3)		
$^{181}_{73}Ta$	> 99.5	2.6±0.4 (2)		*0.4±0.1 (2) [m]		
$^{208}_{82}Pb$	99.999	1.3±0.2 (3) [n]	1.0±0.2 (3) [o]	1.9±0.8 (3) [p]		
$^{209}_{83}Bi$	99.999	0.8±0.1 (6)				

ミューオン核変換後に出る粒子とその放出確率

○arXiv:1908.06902v1 19 Aug 2019
A. Gaponenko, A. Grossheim, A. Hillaiet, G.M. Marshall, R.E. Mischke and A. Olin



ミューオン核変換後に出る粒子の運動量分布

Active target

● Test experiment we did

Attach PMT to the target CsI(Tl) crystal.
By stopping the negative muon in the crystal
and measuring the waveform and charge directly, we can

Ⅰ) detect low energy particle released after nuclear transmutation

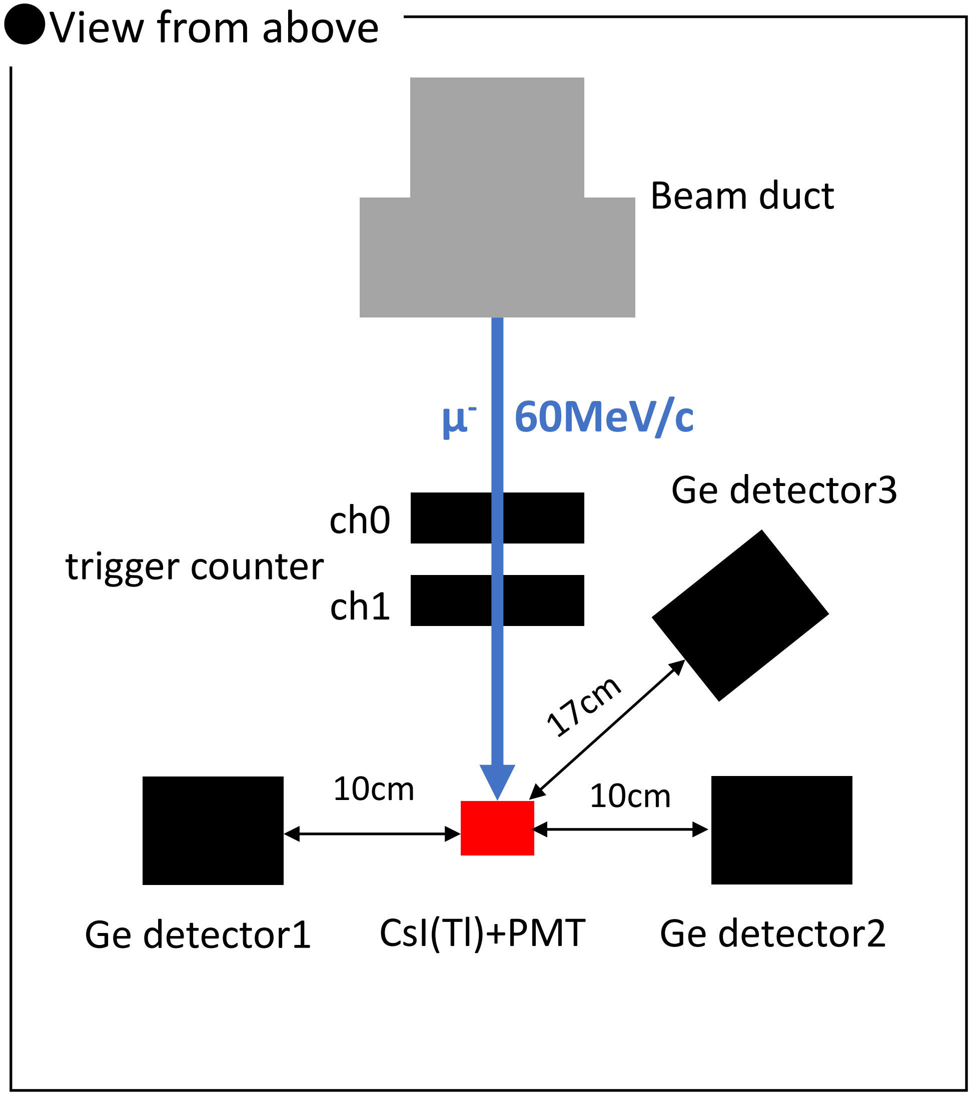
Ⅱ) identify particles and obtain energy distribution by waveform analysis

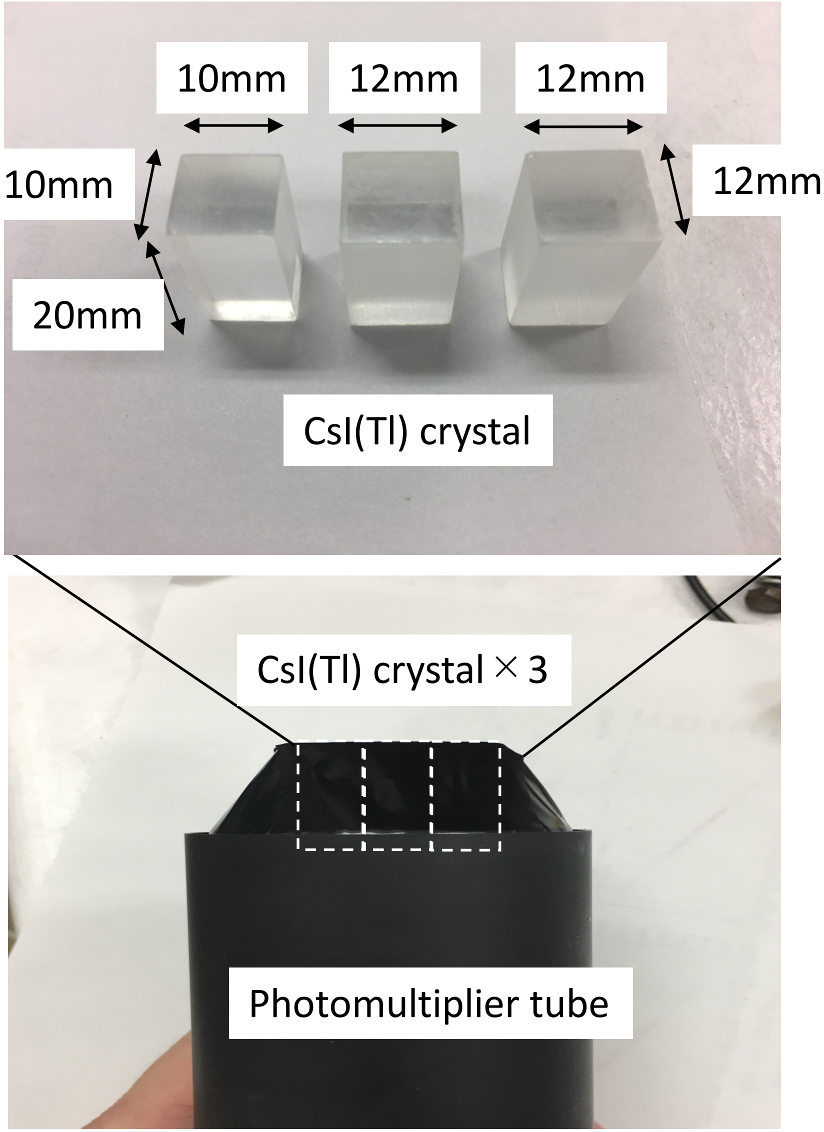
Ⅲ) measure prompt γ-ray and characteristic X-ray simultaneously by using a Ge detector

We can analyze events from more diversified data

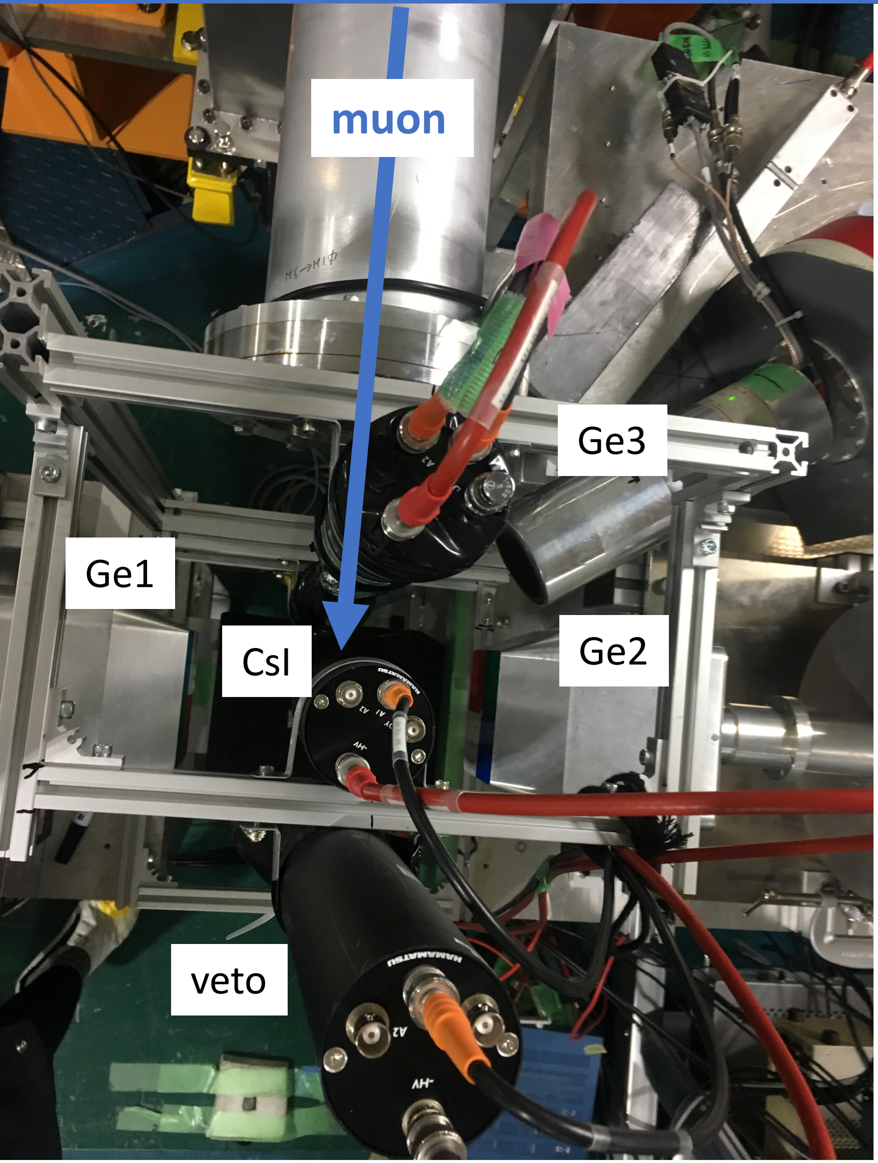
→ **Identify particles and find their emission probability and enrgy distibution**

Setup @ RCNP MuSIC





Setup @ RCNP MuSIC

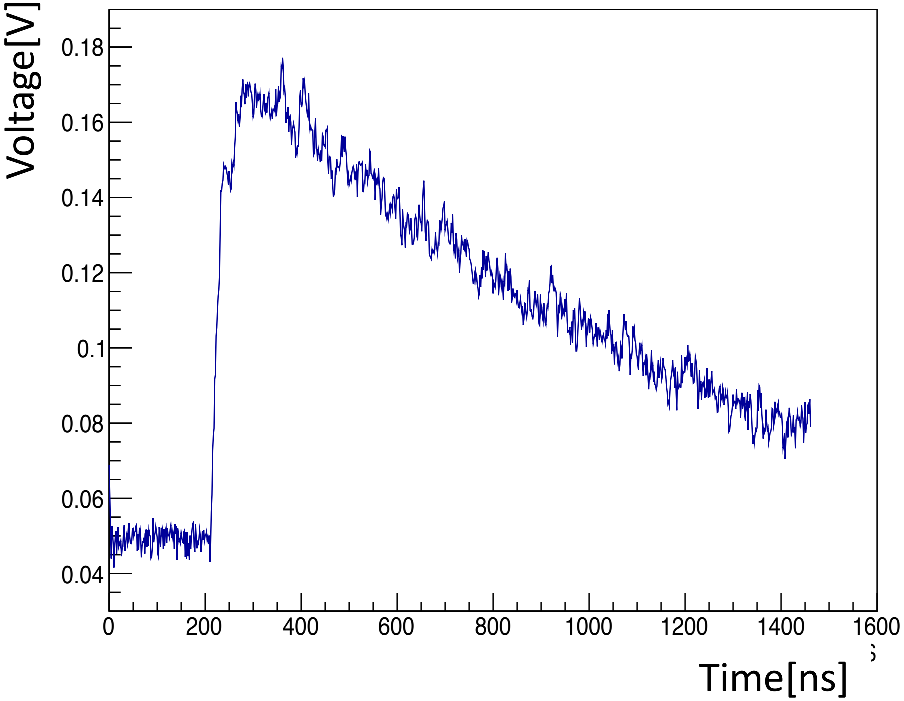


Detector	Measurement data
CsI scintillator veto counter decay electron counter	Waveform DRS4 Wave height Time data A3400
Ge detector1 Ge detector2 Ge detector3	Wave height Time data A3400

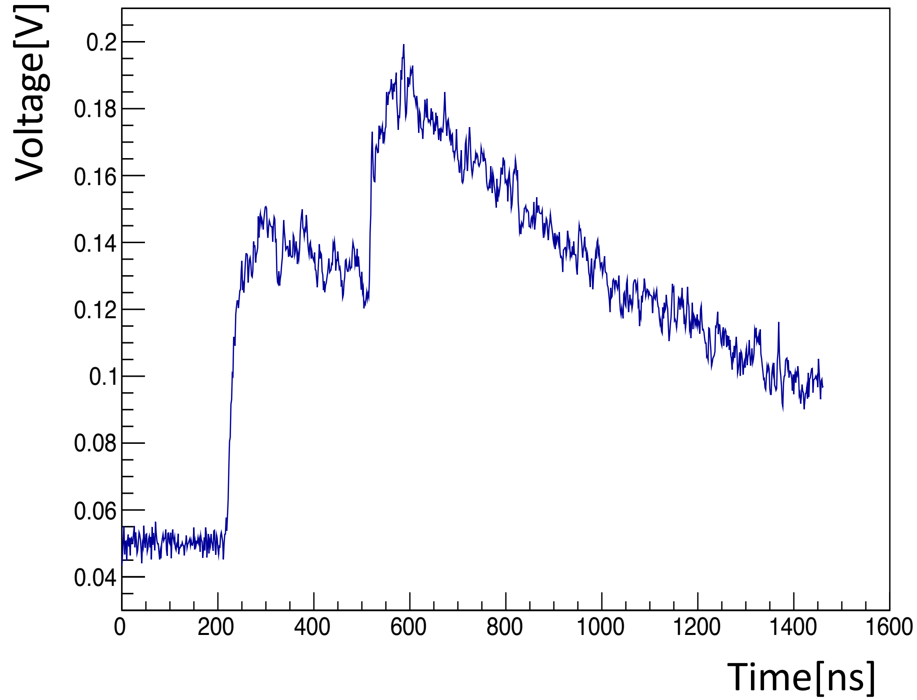
Waveform Analysis

waveform of CsI(Tl) scintillator

Waveform when one muon stops



Waveform when releasing second particle



The waveform is different due to the difference in dE/dx of each particles

Create and fit template waveform of muons, electrons and protons

Determine the protons emission rate and energy distribution

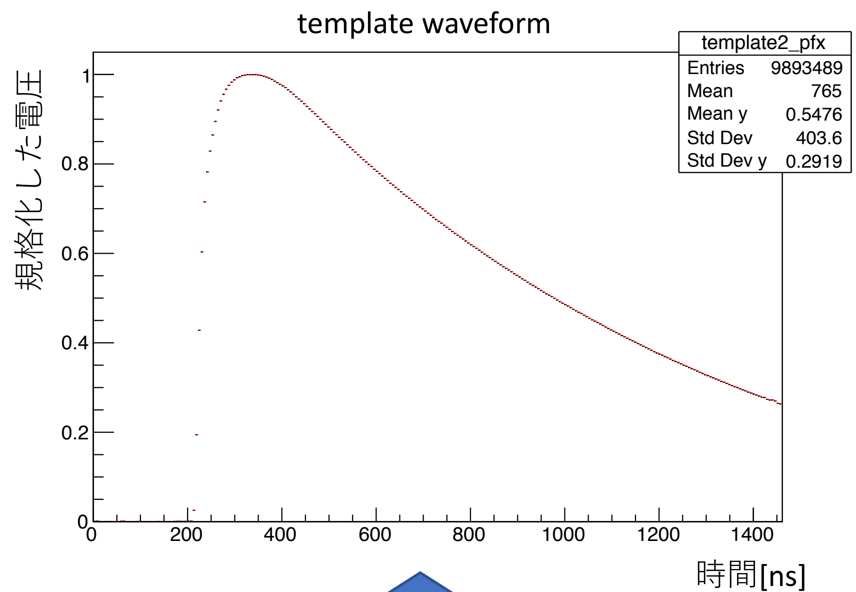
Making Template

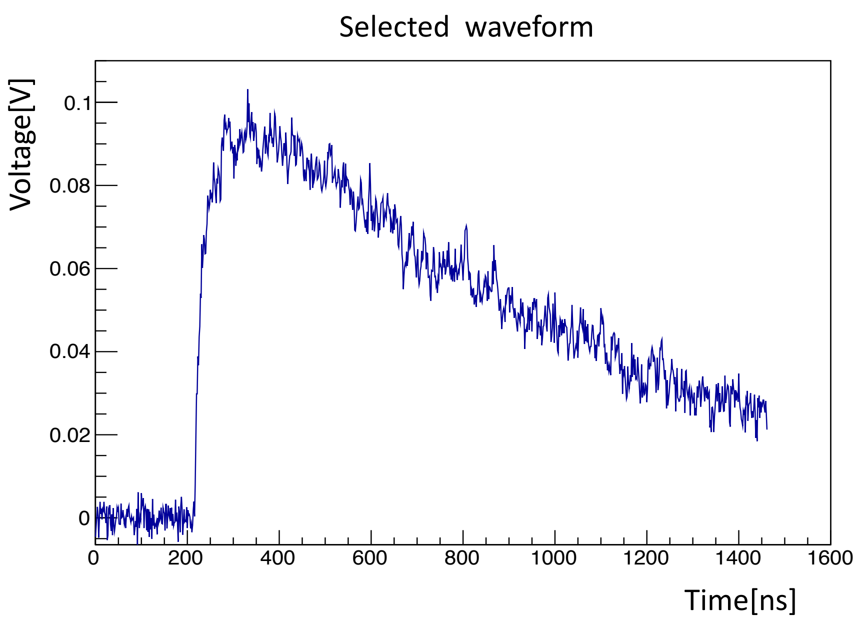
Ⅰ) Fit the 400-1500ns range of each waveform
with $f(t) = \color{red}{N}exp\left(-\frac{t}{\color{red}{\tau}}\right) + \color{red}{B.G.}$

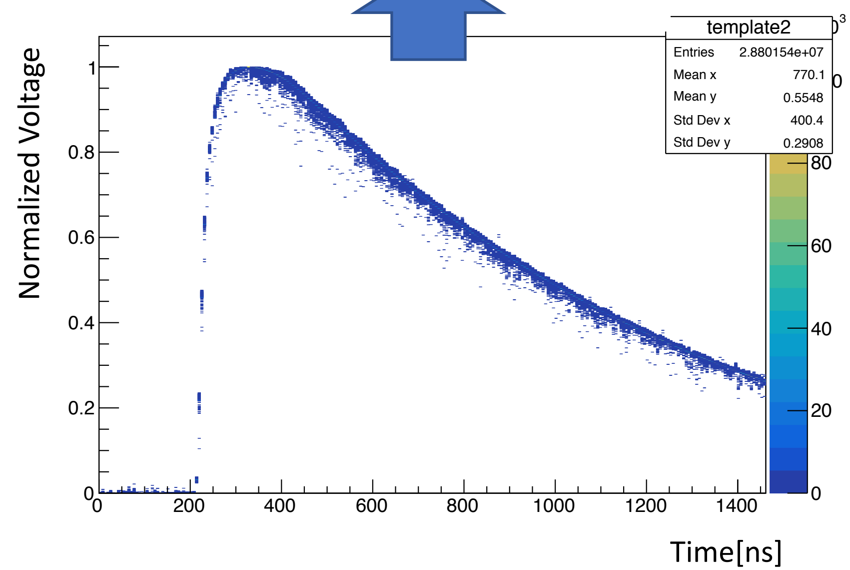
Ⅱ) Select waveforms with good χ^2/ndf and superimposed them normalized by wave height

Ⅲ)Profile the 2D histgram

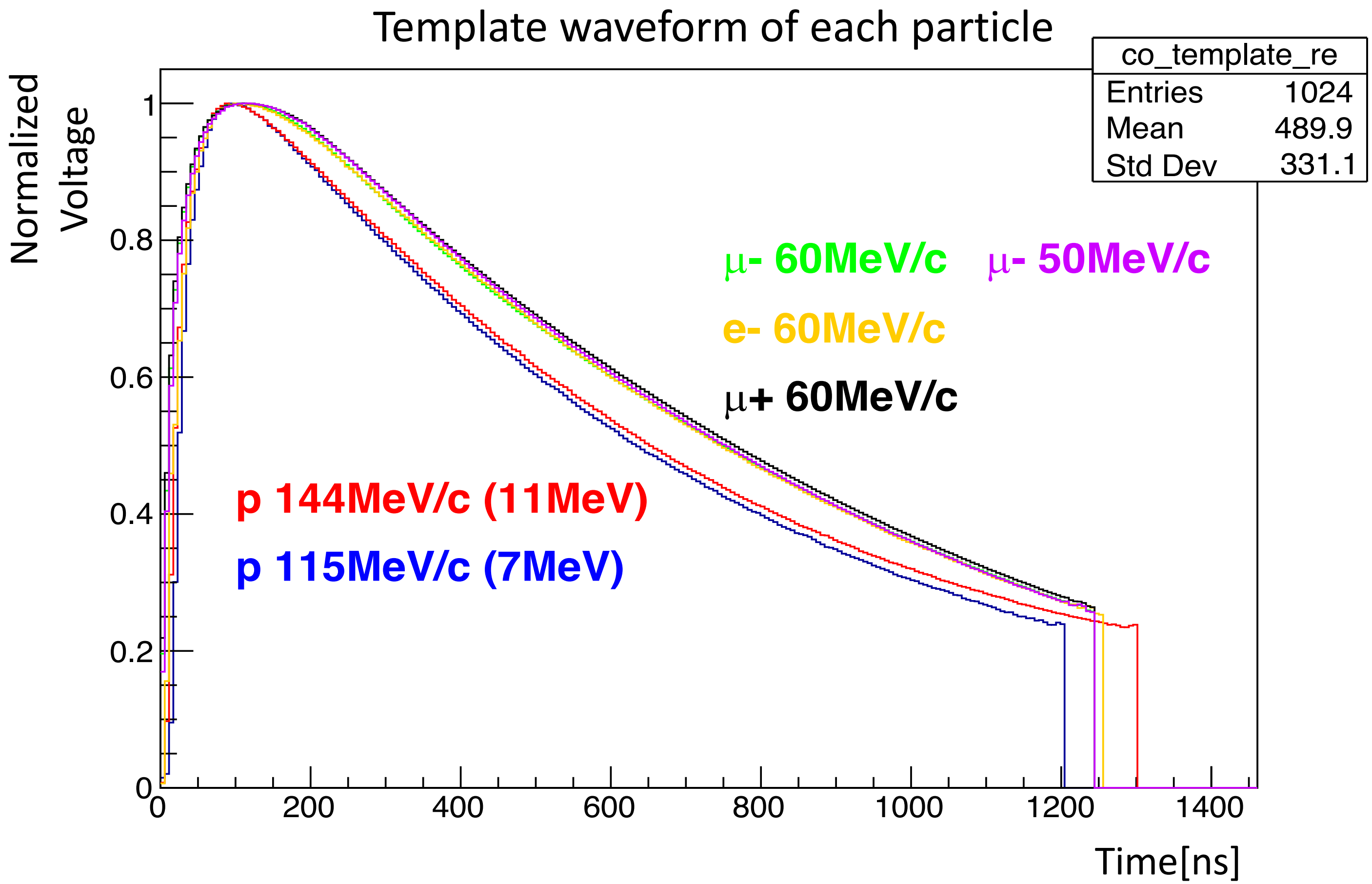
Ⅳ) Do the same for each particle







Template Waveform

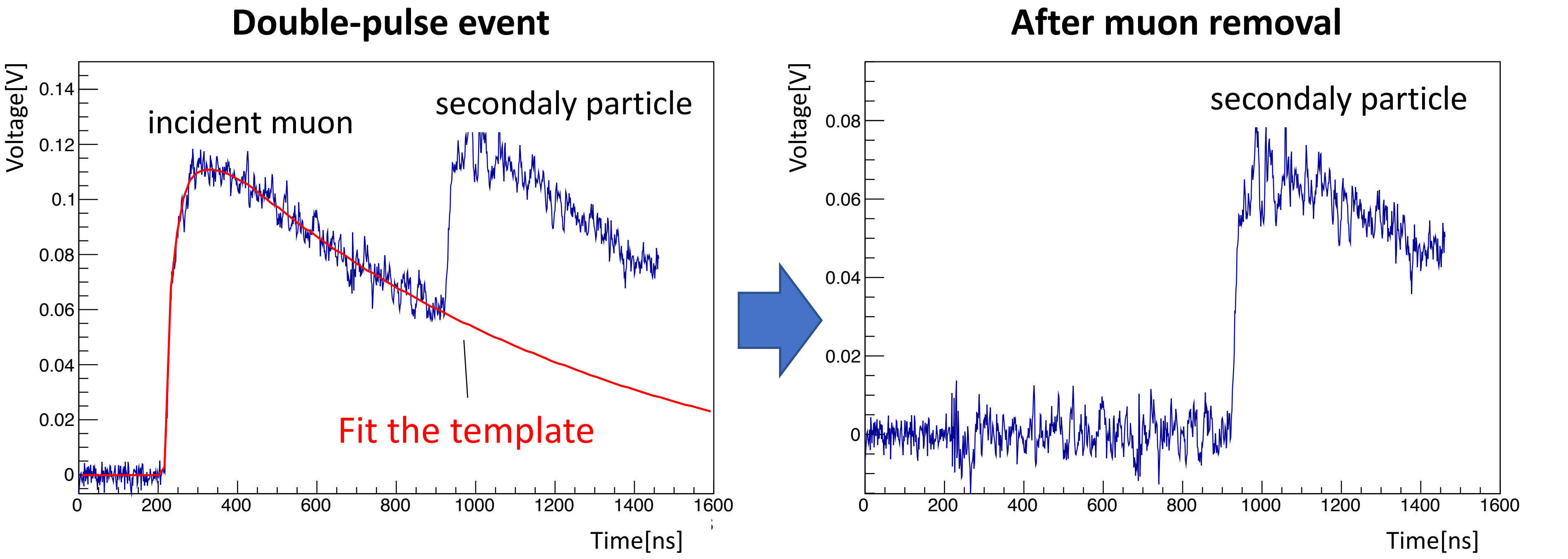


Muon and electron waveforms are almost the same in this energy region

The waveform of particles with large dE/dx is significantly different from the muon electron waveform

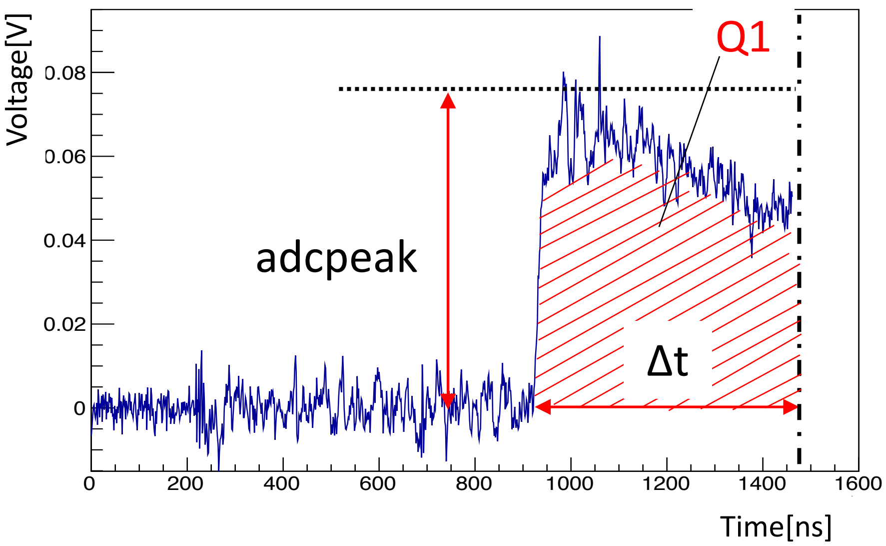
Acquisition of secondary particle waveform

Remove the incident muon waveform from the double-pulse event and make it a secondary particle-only waveform

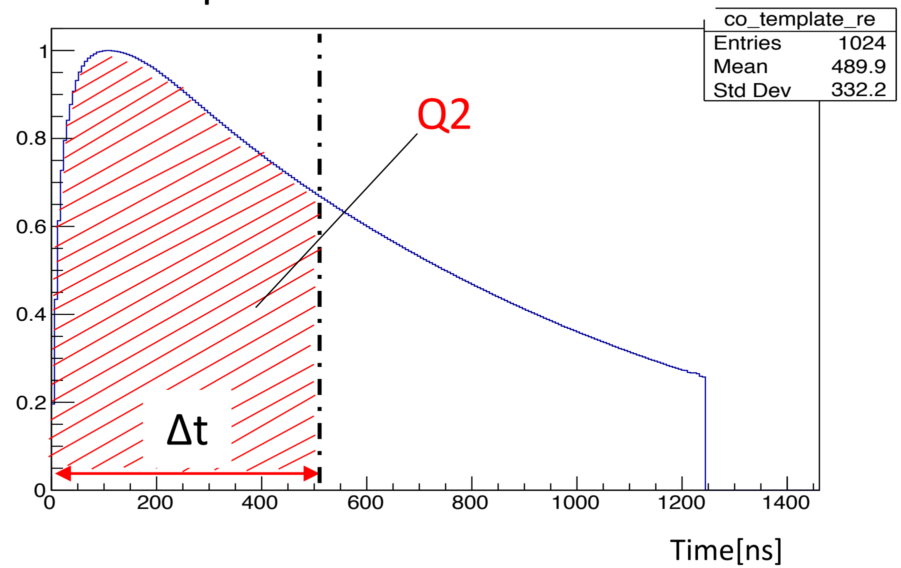


Particle Identification by Waveform Analysis

Residual waveform



Template waveform of Muon

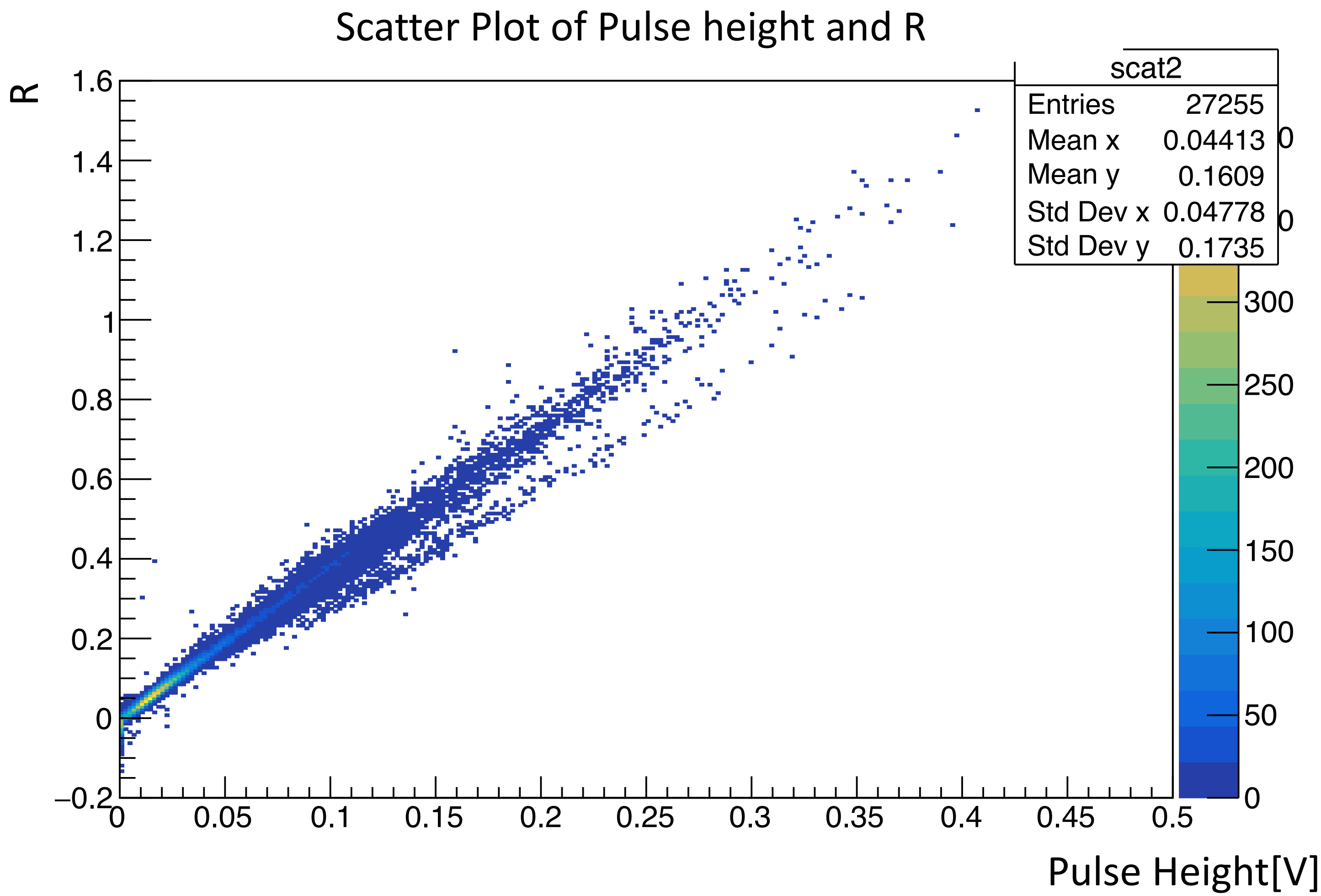


Define $R = Q1/Q2$

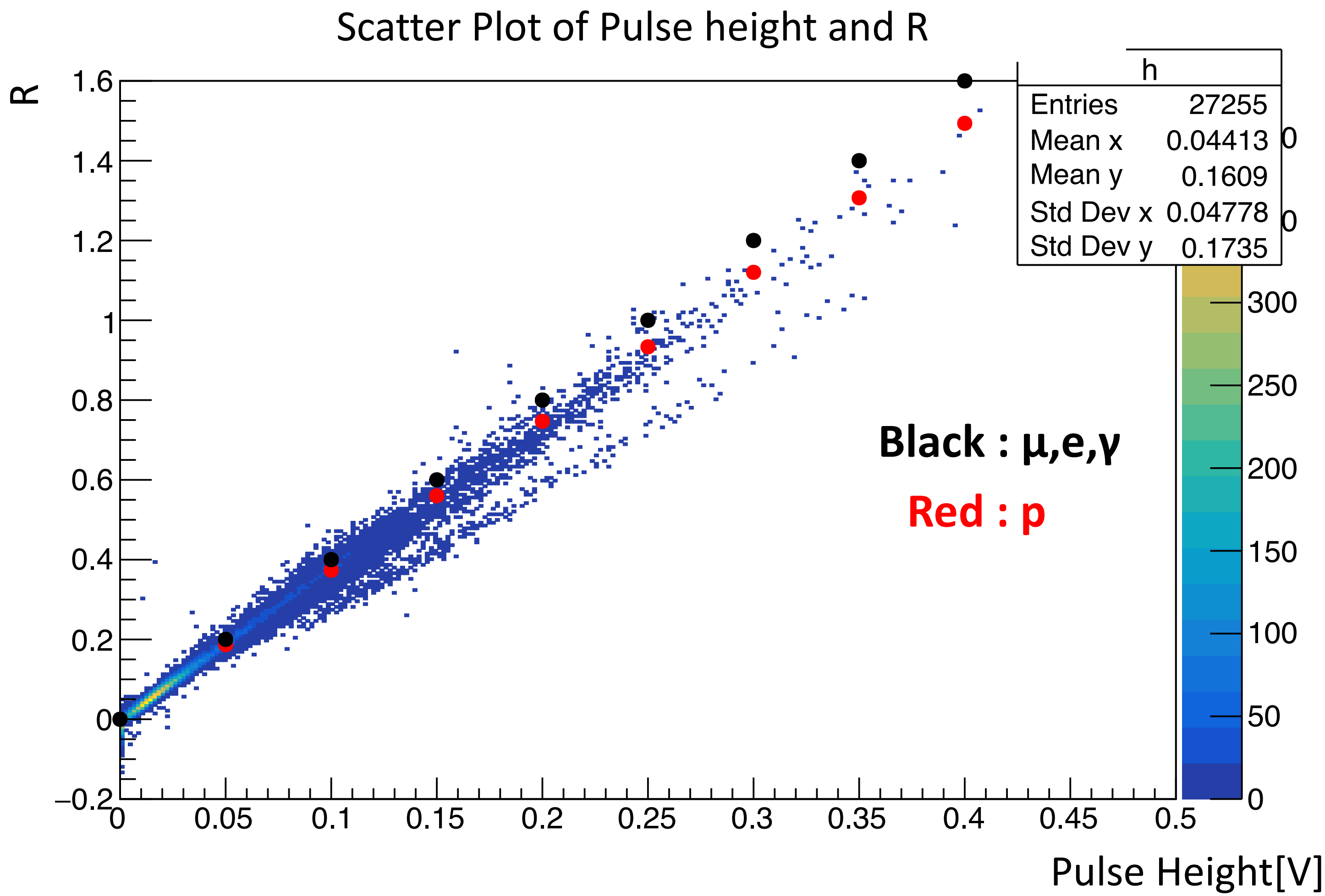
R∝ adcpeak if the template and waveform are the same

Check the correction between pulse height and R
by fitting all residual waveforms with muon template

Particle Identification by Waveform Analysis



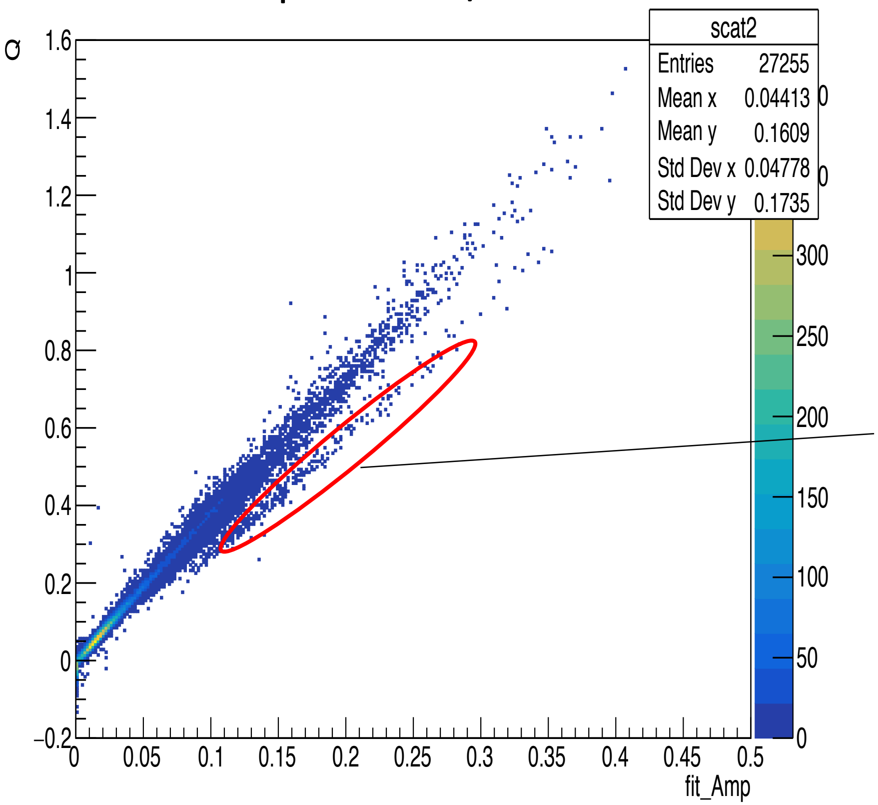
Particle Identification by Waveform Analysis



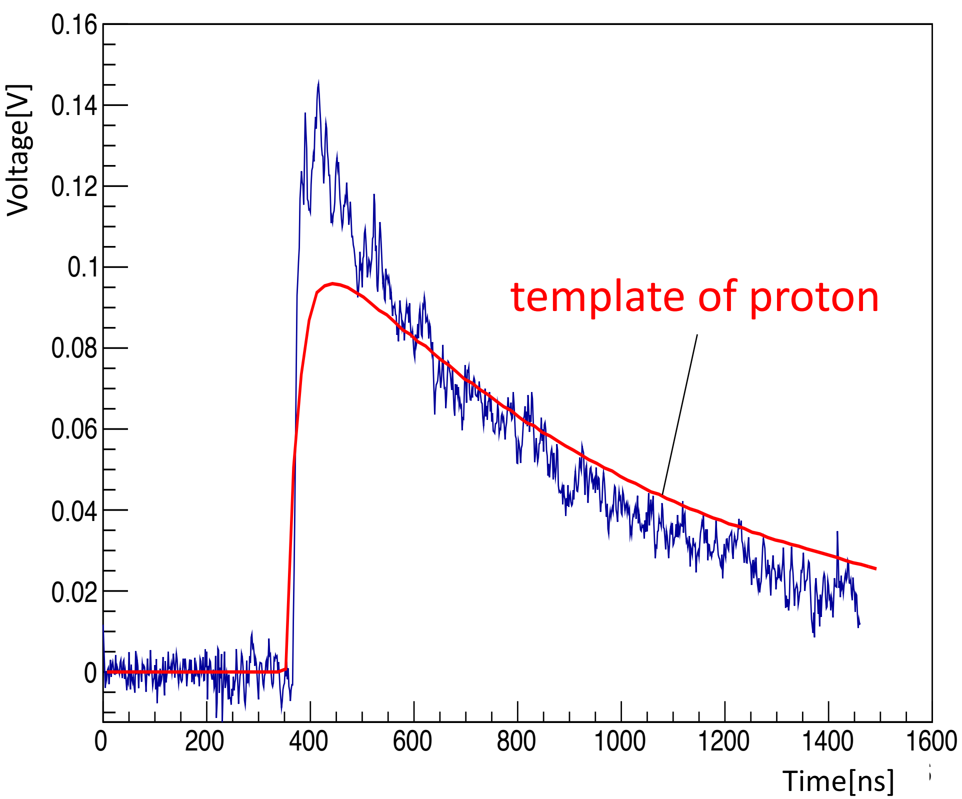
This method makes it difficult to distiguish between proton and muon(also e,γ)

Particle Identification by Waveform Analysis

μ- 60MeV/c



Selected residual waveform

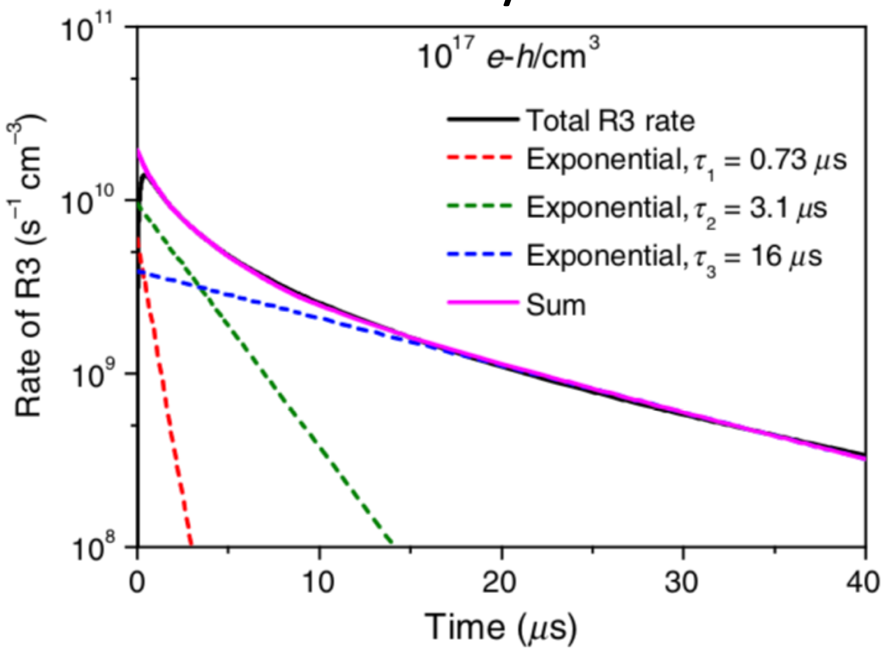


This waveform has a sharper rise than the proton waveform and decays faster

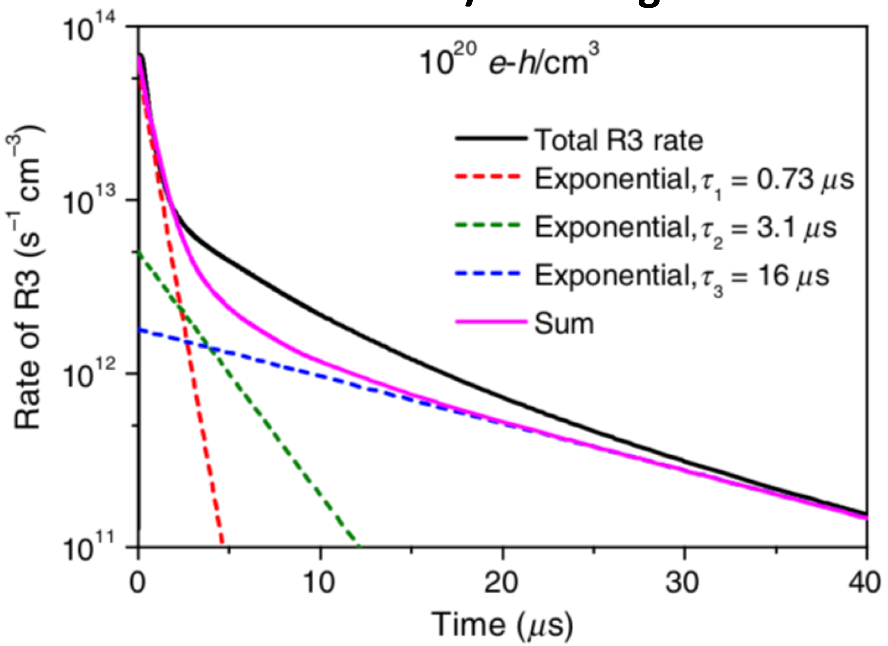
The relationship between dE/dx and waveform

○Phys. Rev. Applied 7,014007(2017)
X. Lu, S. Gridin, and R. T. Williams

When dE/dx is small



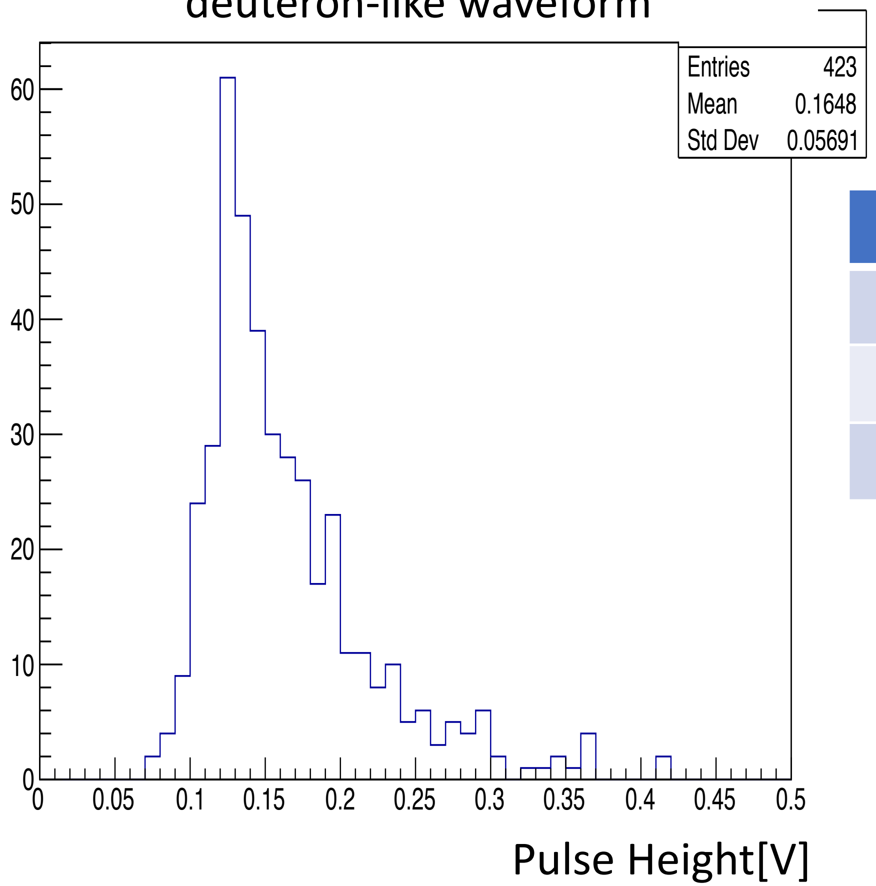
When dE/dx is large



Particle with larger dE/dx than proton ⇨ **Deuteron??**

Deuteron??

Pulse height distribution of deuteron-like waveform



The number of events is not significantly different from expected

Number of muon capture events	1627479
Emission probability of deuteron	$\approx 6\times10^{-4}$
Time cut correction	$\approx$0.4
Expected number of events	390

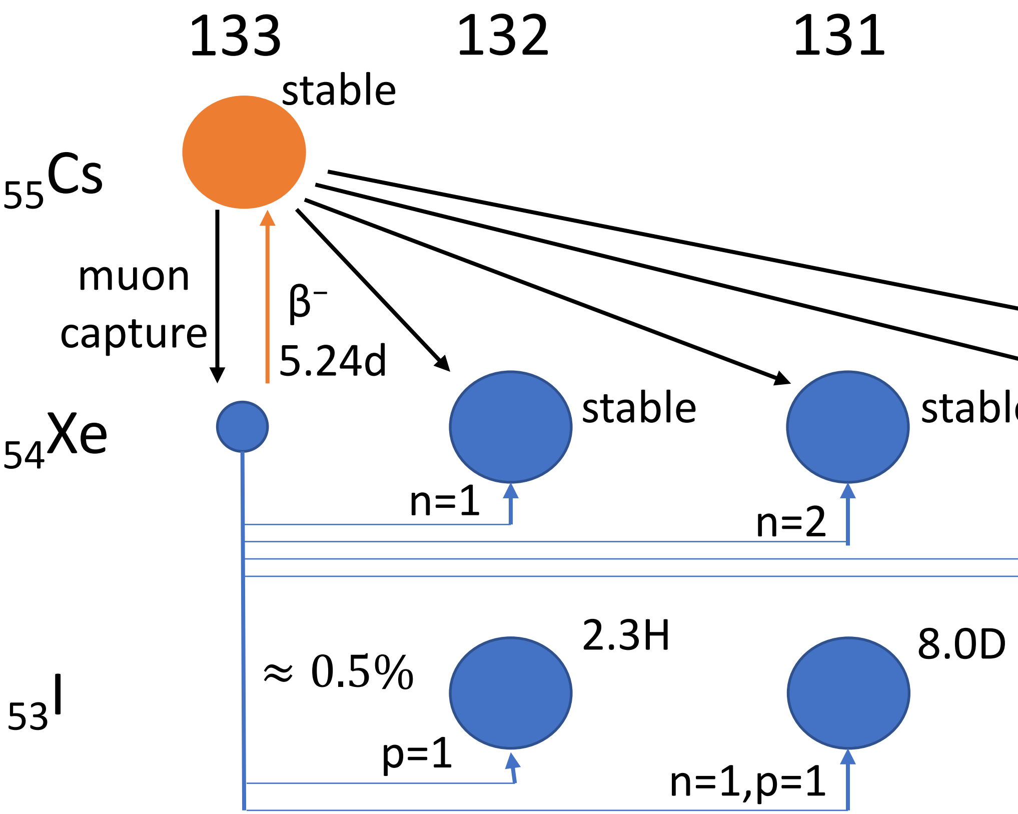
I will identify from the relationship between waveform and dE/dx

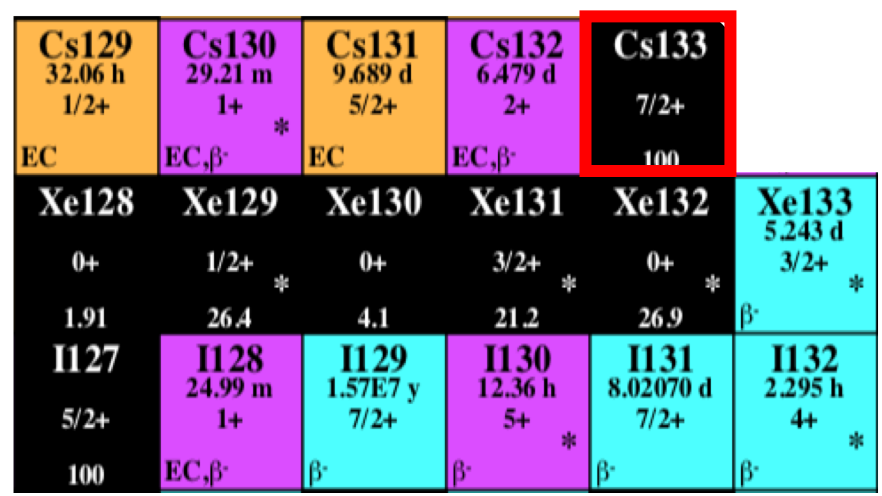
Summary

- Muon transmutation is considered as one of the new disposal methods of radioactive waste, and collection of basic data is urgently required for its realization.
- As a new approach to nuclear reaction research, we are considering a research method using active target that can also observe low energy emission particles directly.
- A test experiment using CsI(Tl) crystal as an active target was performed with RCNP MuSIC M1 beamline.
- As a result of waveform analysis, deuteron-like particle can be separated.
- In the future, we will investigate the usefulness of the active target by conducting waveform analysis and wave height analysis and comprehensively comparing with results of Ge detector.

Back up

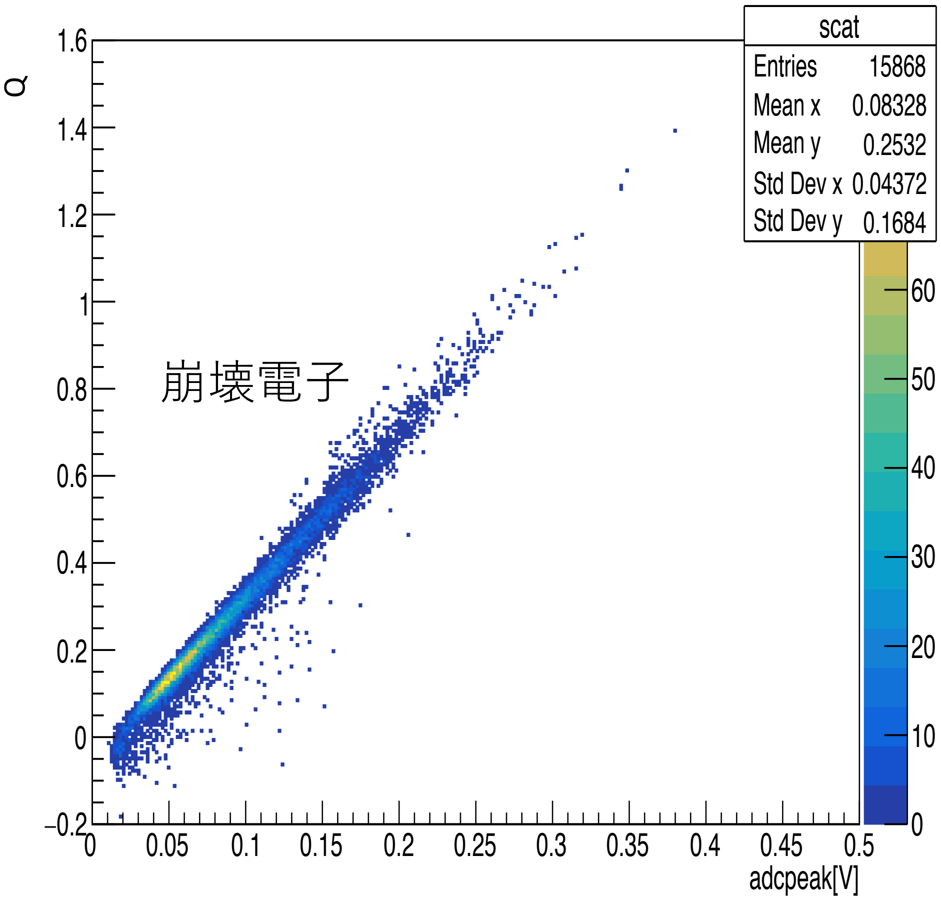
133Cs


133
132
131
130
129
stable
$_{55}$Cs
muon capture
β⁻ 5.24d
$_{54}$Xe
stable
stable
stable
stable
n=1
n=2
n=3
n=4
$_{53}$I
≈ 0.5%
2.3H
8.0D
p=1
n=1,p=1

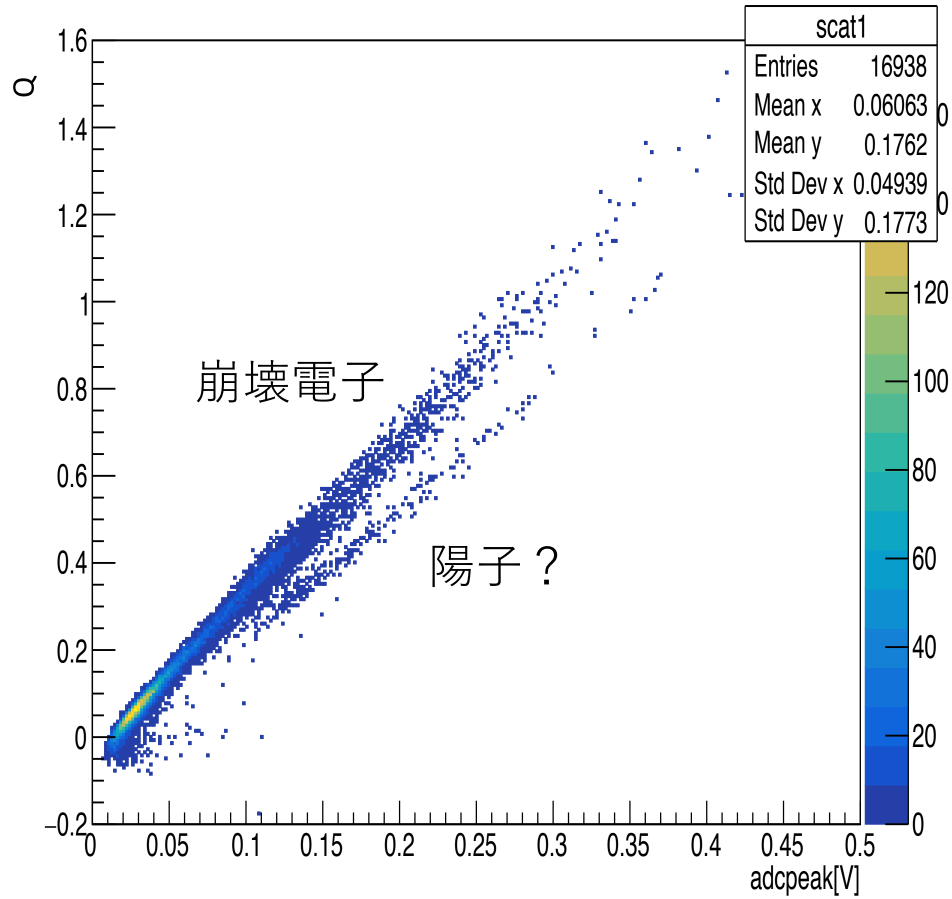

Cs129 32.06 h 1/2+ EC
Cs130 29.21 m 1+ EC,β-
Cs131 9.689 d 5/2+ EC
Cs132 6.479 d 2+ EC,β-
Cs133 7/2+ 100
Xe128 0+ 1.91
Xe129 1/2+ 26.4
Xe130 0+ 4.1
Xe131 3/2+ 21.2
Xe132 0+ 26.9
Xe133 5.243 d 3/2+ β-
I127 5/2+ 100
I128 24.99 m 1+ EC,β-
I129 1.57E7 y 7/2+ β-
I130 12.36 h 5+ β-
I131 8.02070 d 7/2+ β-
I132 2.295 h 4+ β-

波形による粒子識別

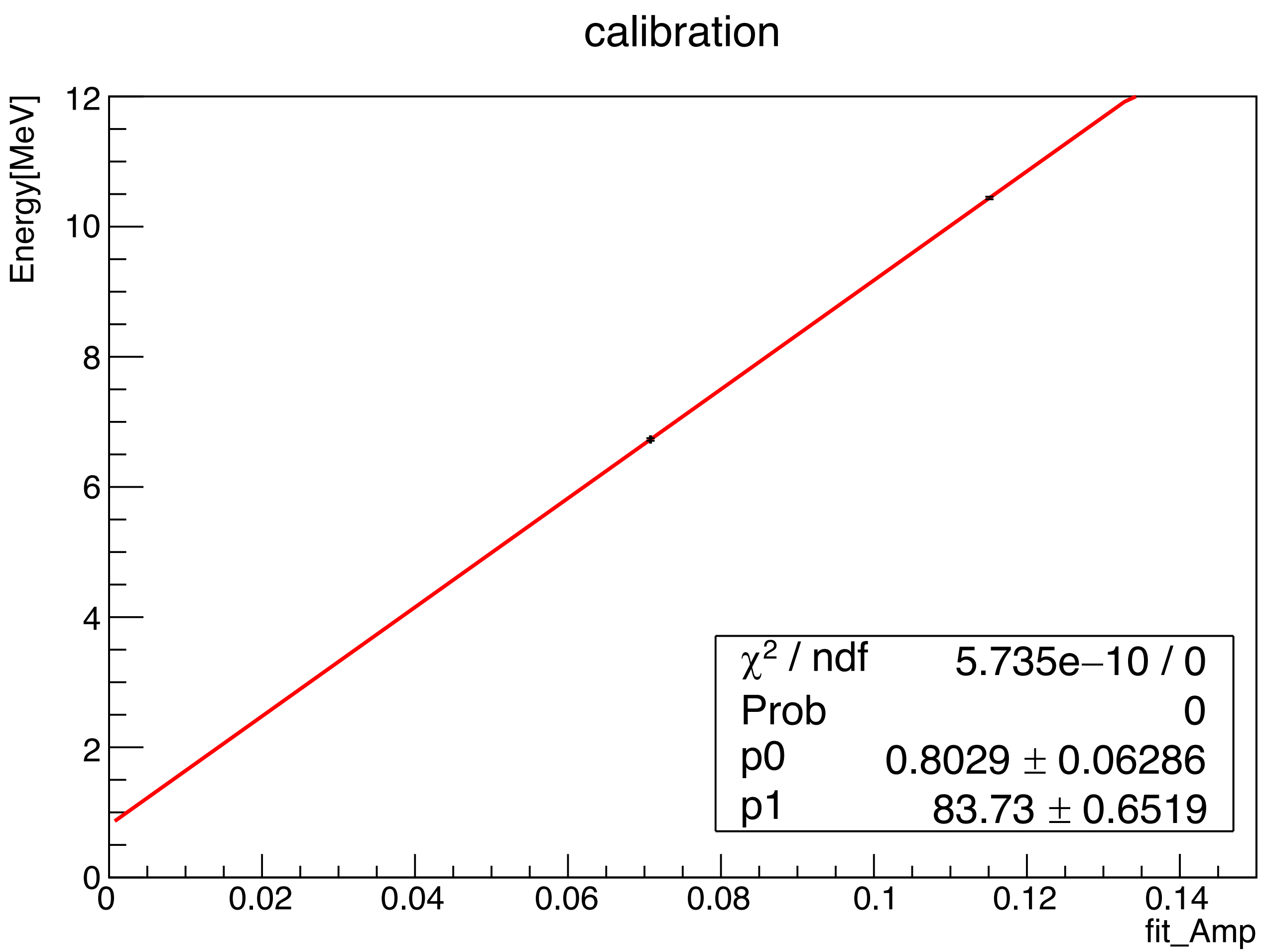
μ+ 60MeV/c



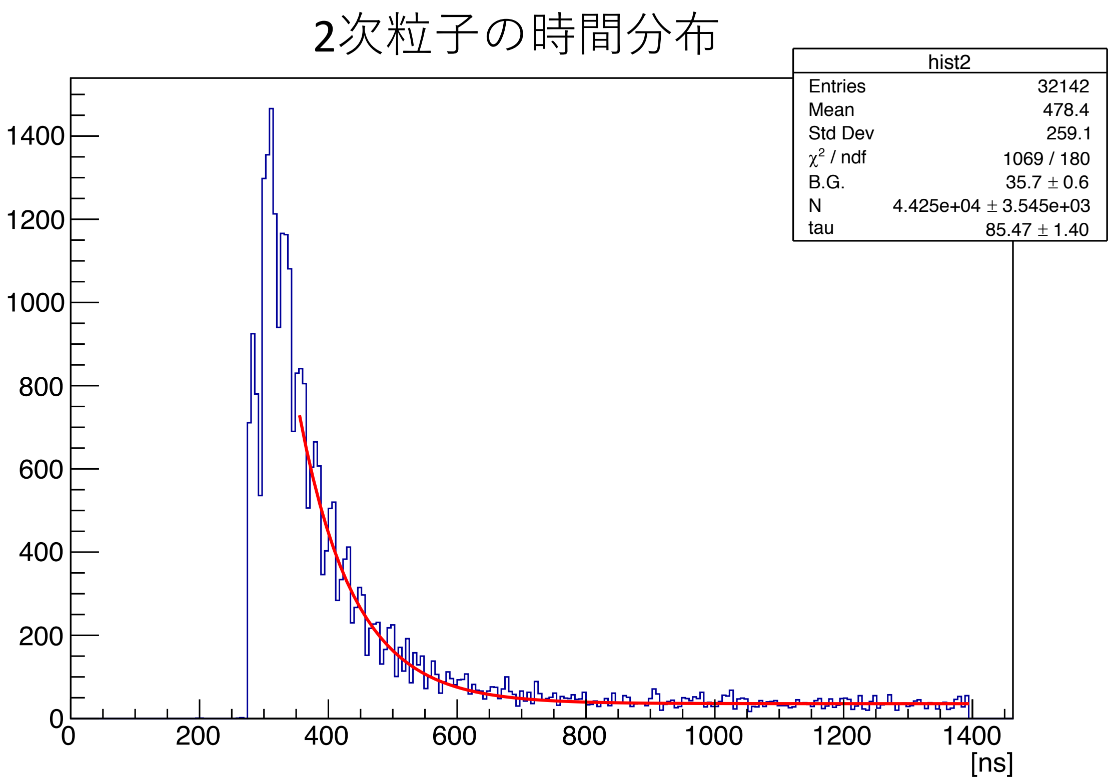
μ- 60MeV/c



熊取ビームを使った較正



2次粒子の時間分布



$f(t) = Nexp\left(-\frac{t}{\tau}\right) + B.G.$ でFit

Fit結果

τ = 85.47 ± 1.40 ns

Cs及びI中での

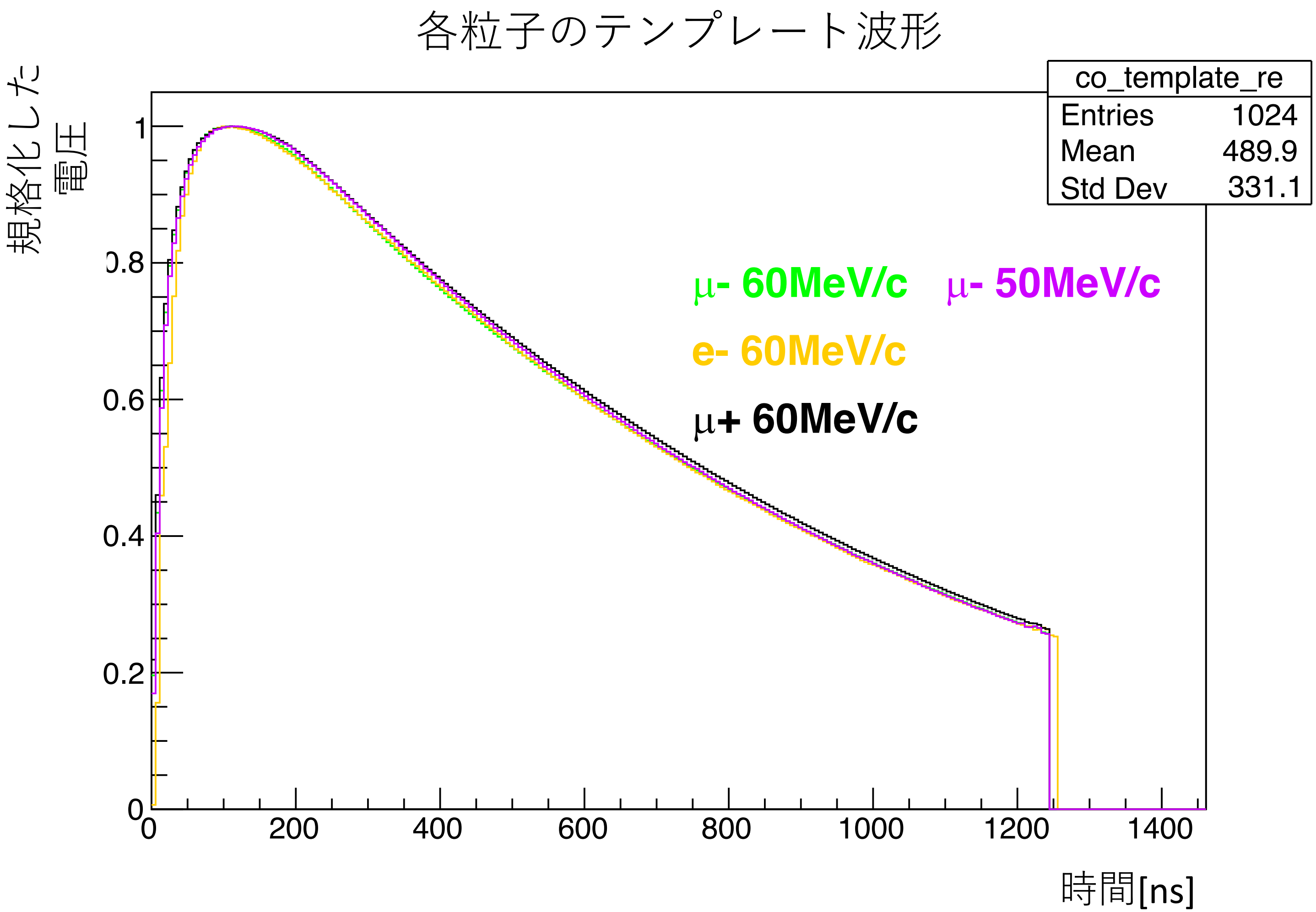
負ミューオンの寿命

τ_{Cs} = 87.8 ± 1.9

τ_{I} = 83.4 ± 1.5

見ている2次粒子はミューオン捕獲イベント由来であると思われる

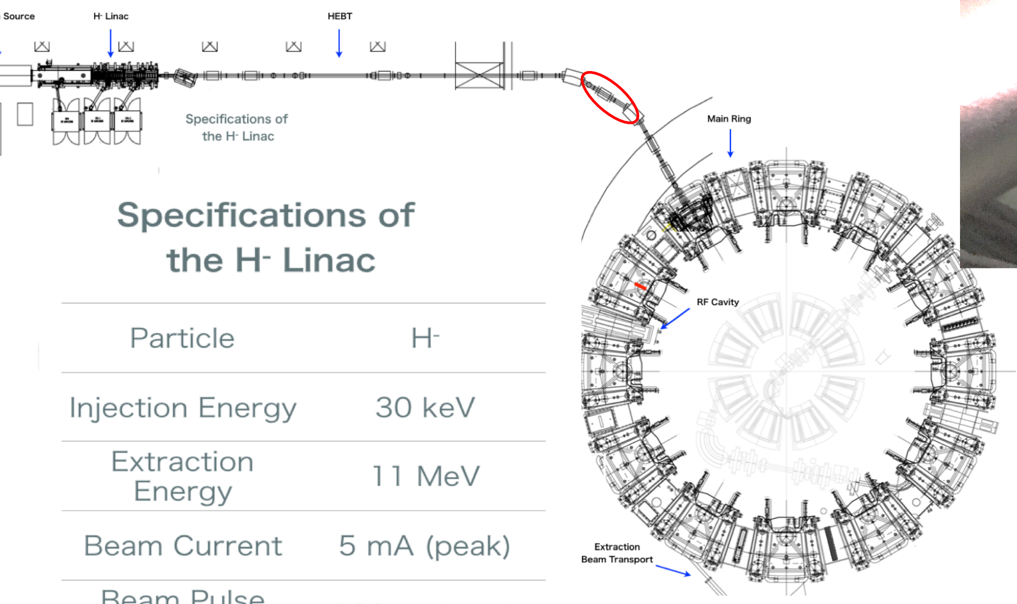
テンプレート波形



このエネルギー領域ではミューオンと電子の波形はほぼ同じ。

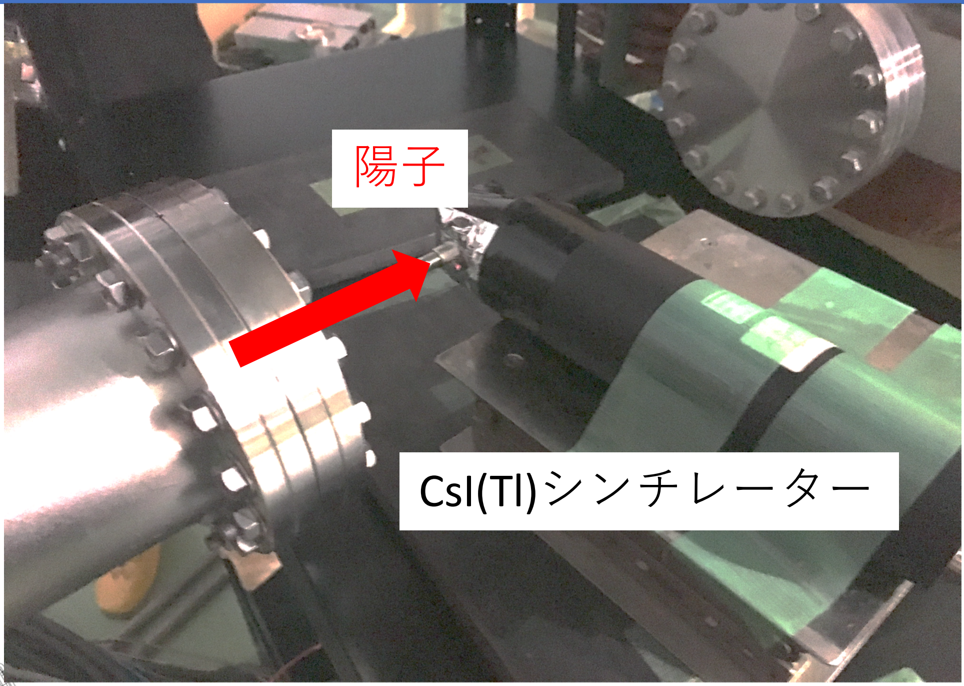
低エネルギー陽子のCsI(Tl)波形測定

- 京都大学複合原子力科学研究所イノベーションリサーチラボにて行った
- 負水素イオンビーム線形加速器を用い、11MeV,7MeVのprotonビームで実験した



Specifications of the H- Linac

Particle	H-
Injection Energy	30 keV
Extraction Energy	11 MeV
Beam Current	5 mA (peak)
Beam Pulse Width	100 μs (max)
Repetition Rate	1 - 200 Hz



共同研究者

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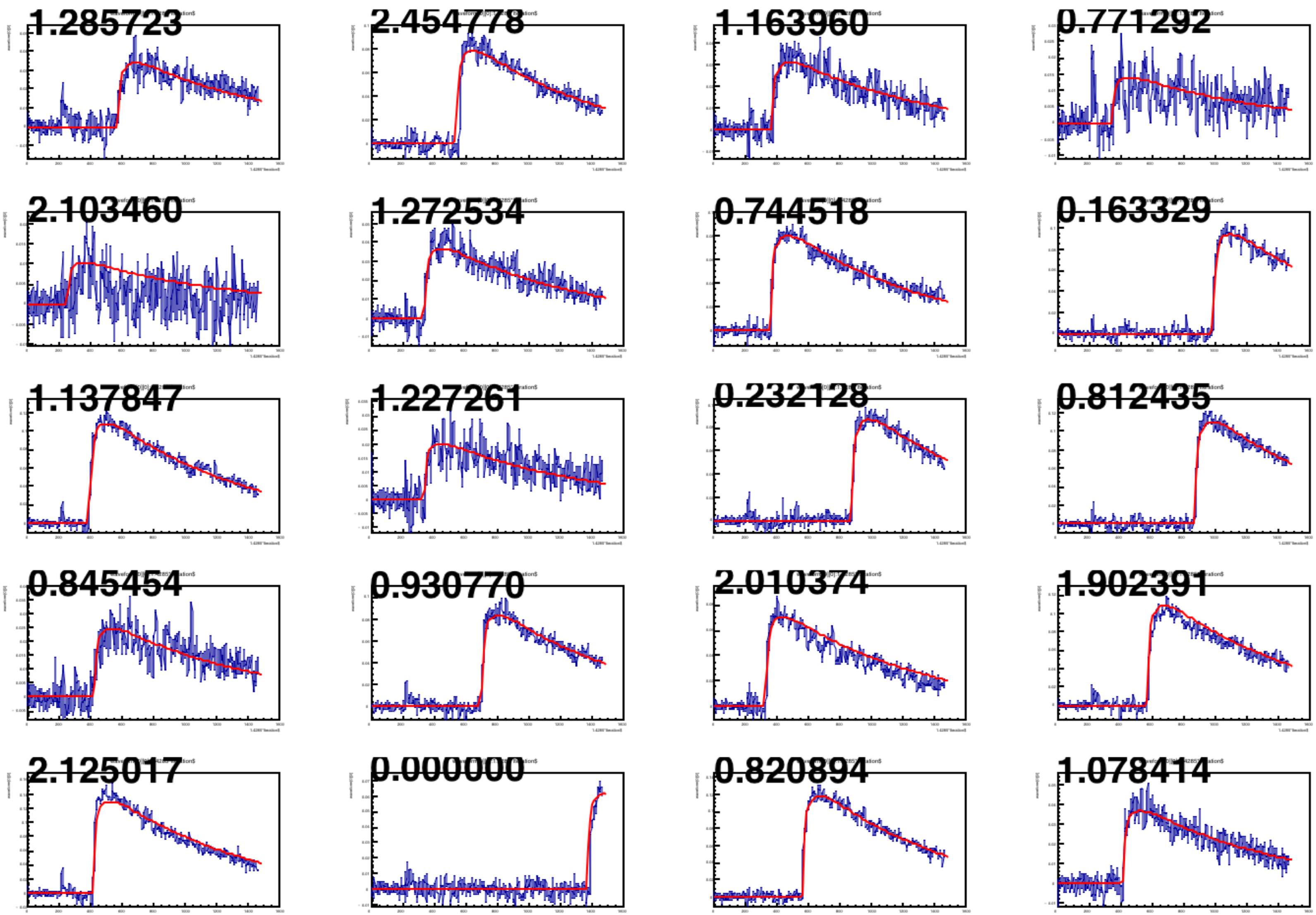
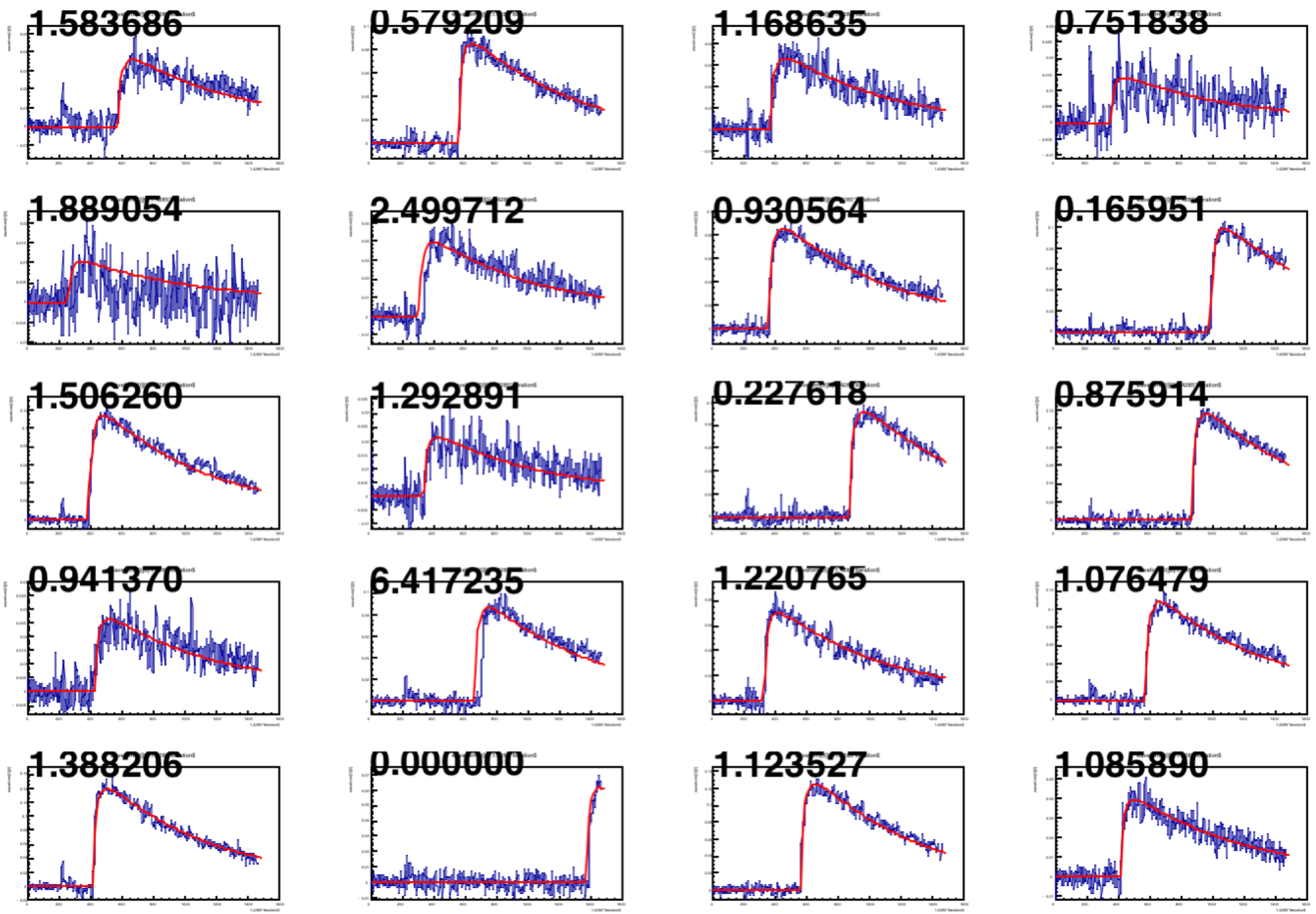
- 上杉 智教
- 栗山 靖敏

●阪大
- 能町正治
- 嶋達志
- 高久圭二
- 佐藤朗
- 宮元幸一郎

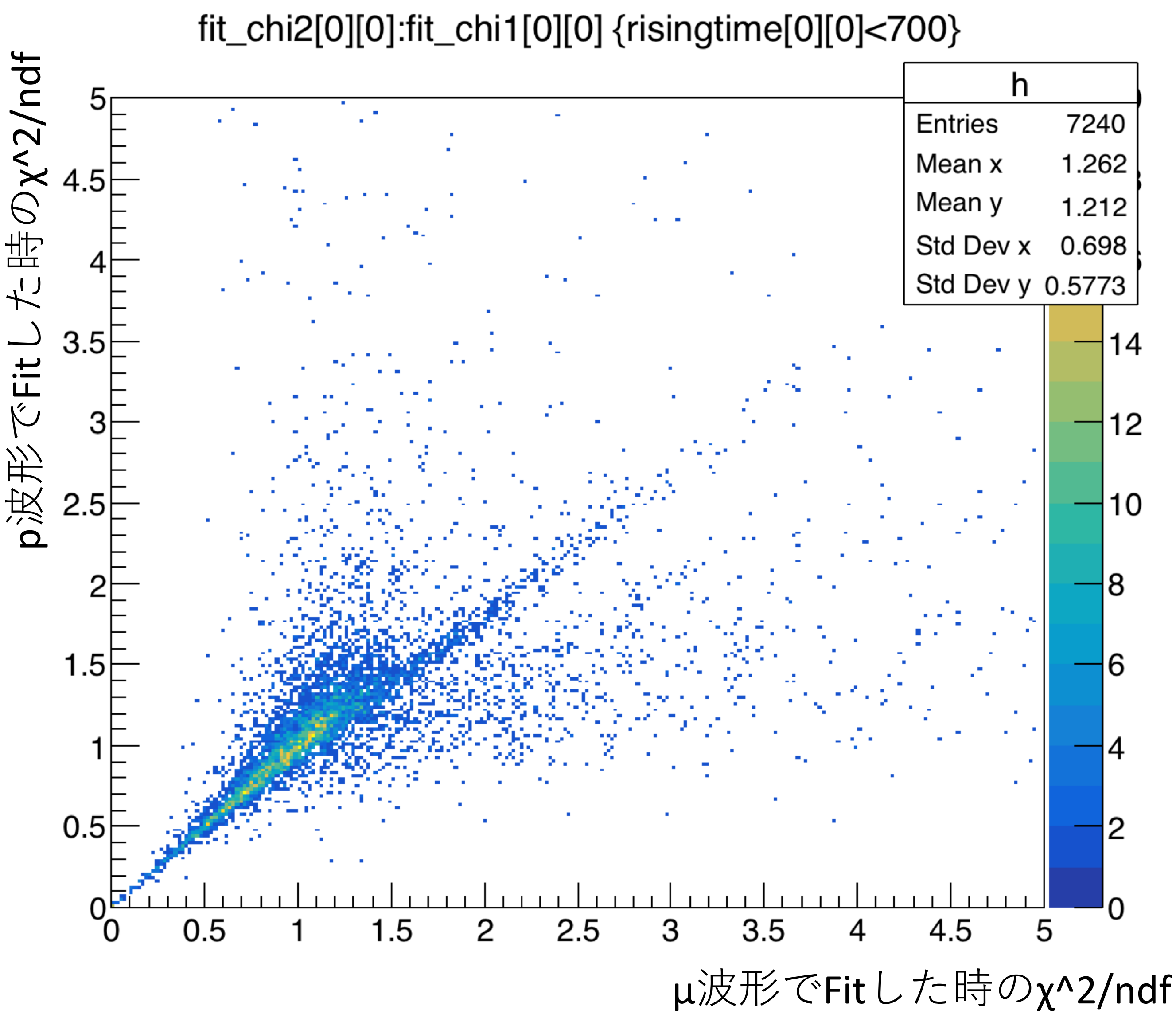
ミューオン波形でFitした時



プロトン波形でFitした時

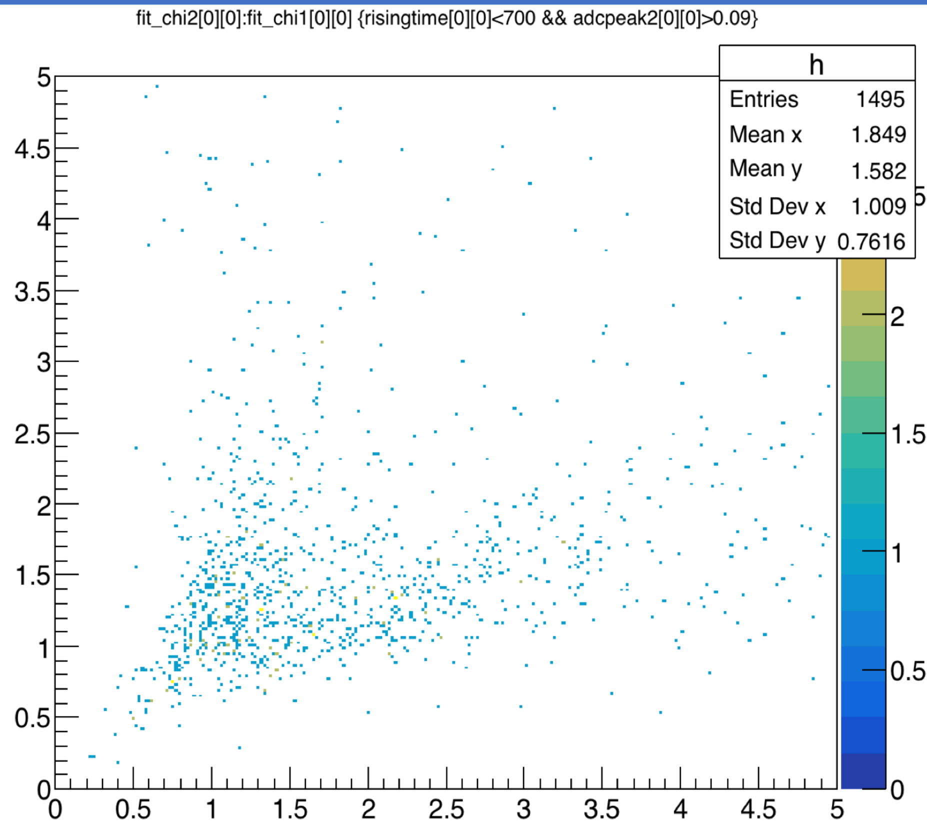


chi^2/ndf 分布

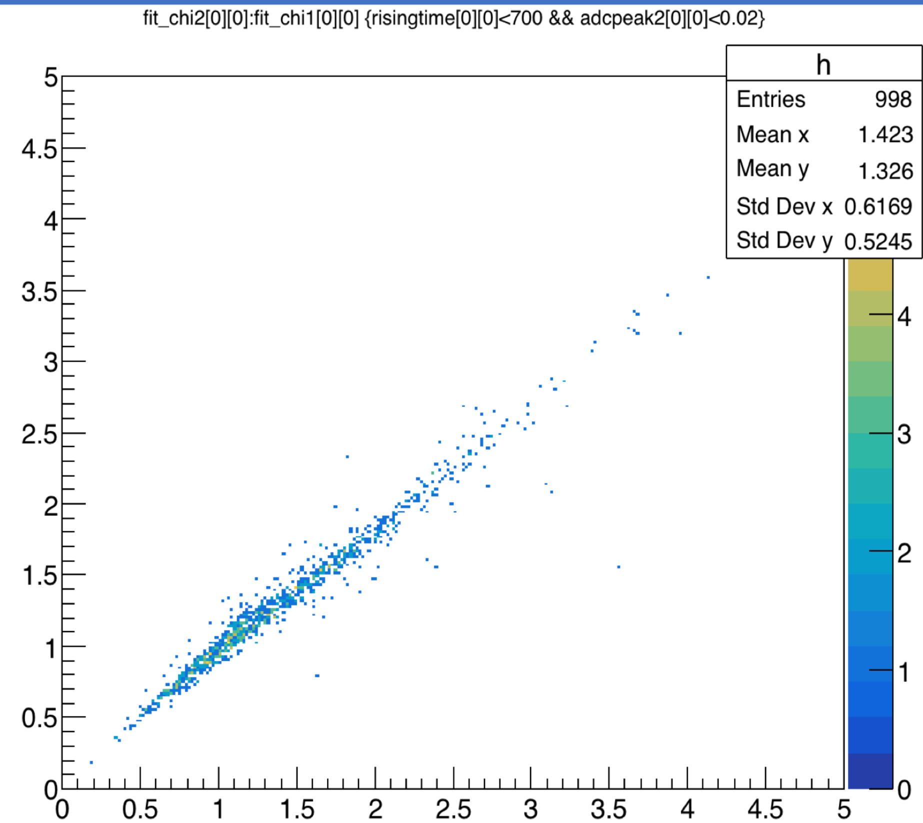


fit_chi2[0][0]:fit_chi1[0][0] {risingtime[0][0]<700}
h
Entries 7240
Mean x 1.262
Mean y 1.212
Std Dev x 0.698
Std Dev y 0.5773
pで波形でFitした時のχ^2/ndf
μ波形でFitした時のχ^2/ndf
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14

chi^2/ndf 分布



adcpeak>0.09の時



adcpeak<0.02の時

adcpeakが低い時、Fitによるpとμ,e,γとの判別は難しい？？