Performance Evaluation of Positron Spectrometer for MEG II Experiment

MEG II実験陽電子スペクトロメータの性能評価

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MEG II
Mu - E - Gamma collaboration
ICEPP
The University of Tokyo
Core-to-Core Program

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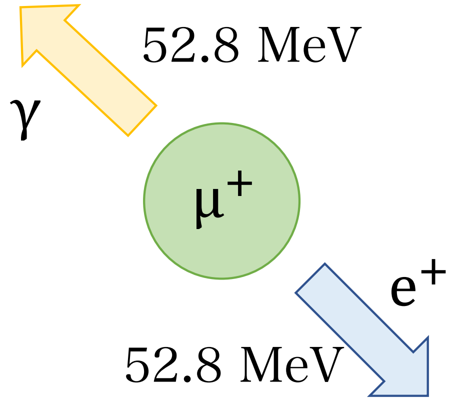
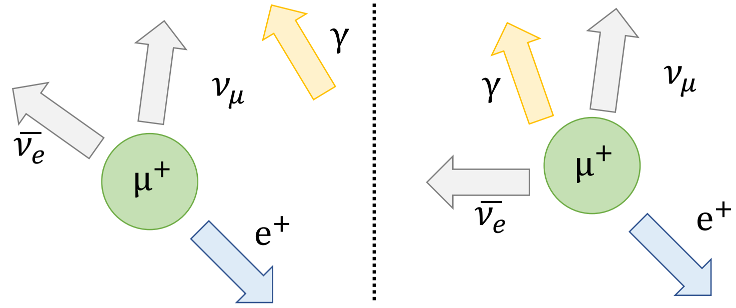
MEG II Experiment -I-

- International particle physics experiment at Paul Scherrer Institut (PSI, Switzerland)
  - Japan, Italy, Switzerland, Russia America
- Search for cLFV ultra-rare muon decay: $\mu \to e\gamma$
  - cLFV: charged Lepton Flavor Violation
    - prohibited in standard model, predicted in the new models
  - To find the $\mu \to e\gamma$ means to find the new physics !
  - Complementary to high-energy frontier (e.g. LHC, ILC)
  - Forerunner to the other cLFV experiment (e.g. COMET, Mu3e)

Signal Kinematics

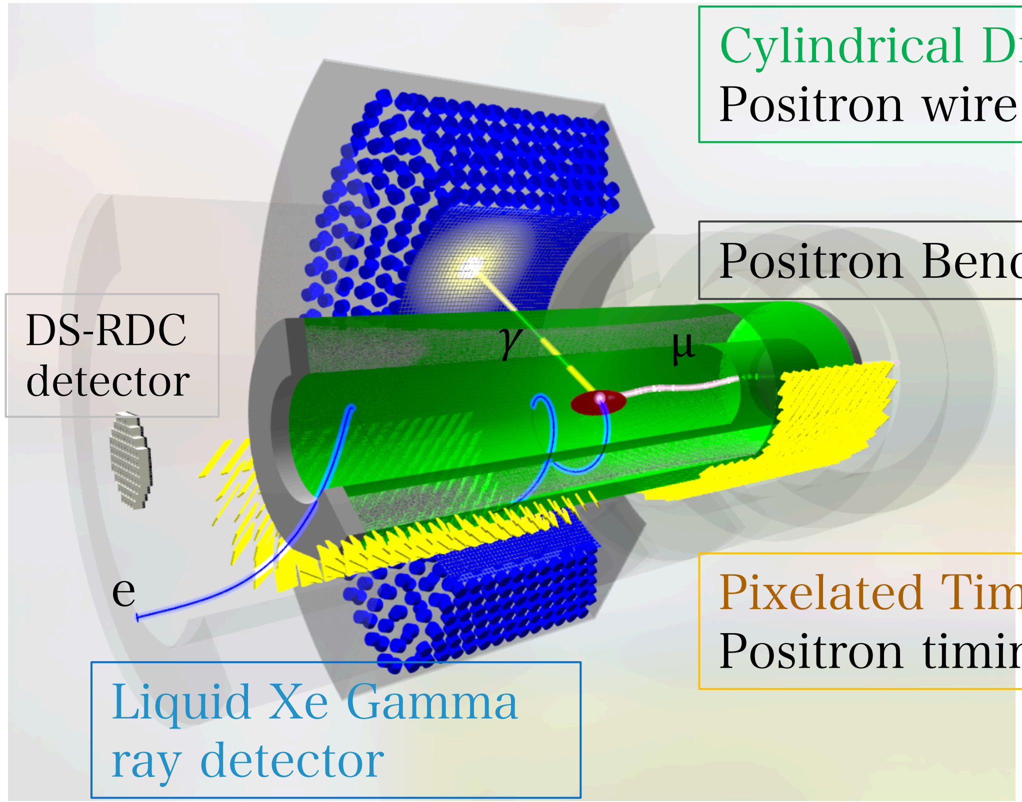
180° (back to back) at the same timing from the same position
-> Timing, Position, Momentum is the key parameters





Background Patterns

MEG II Experiment -II-



The most intense DC muon beam in the world available at PSI
MEG:$3\times10^{7}\mu^{+}/s$ →MEG II $7\times10^{7}\mu^{+}/s$

+

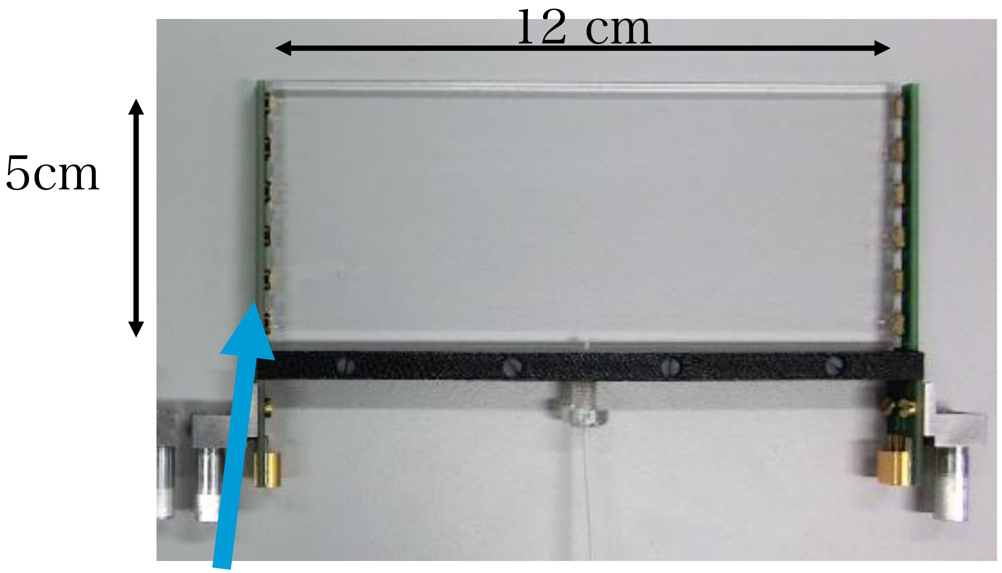
New Positron Spectrometer
Measure positron vertex position momentum and timing

Positron Resolution / Efficiency	MEG	MEG II Design (CDCH 10 layer)
Theta (mrad)	9.4	5.3
Phi (mrad)	8.7	3.7
Momentum (keV)	380	130
Vertex Z (mm)	2.4	1.6
Vertex Y (mm)	1.2	0.7
Positron time (ps)	108	46
Efficiency (%)	30	70

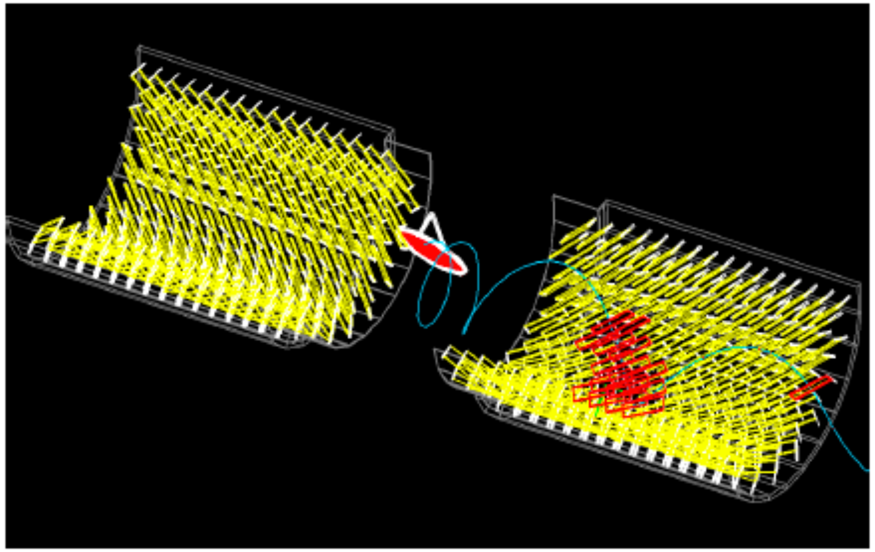
- Upgraded experiment from MEG, ~×10 sensitivity (Br ~ 6×10^{-14} 90% C.L.)
  - 3-year DAQ period (20 week / year)
  - ×2 beam intensity, detector resolution, efficiency with new positron spectrometer

The design and detail: The European Physical Journal C volume 78, Article number: 380 (2018)
The design of the MEG II experiment

pixelated Timing Counter (pTC)



× 512



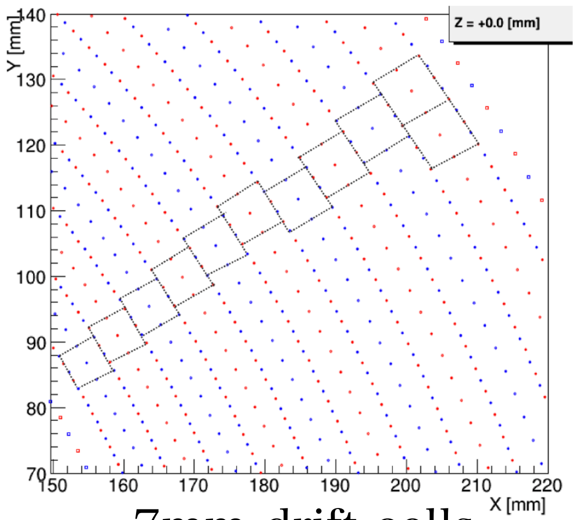
σ (Timing) ~ 80 ps with each counter

~ 8 hits/positron on average

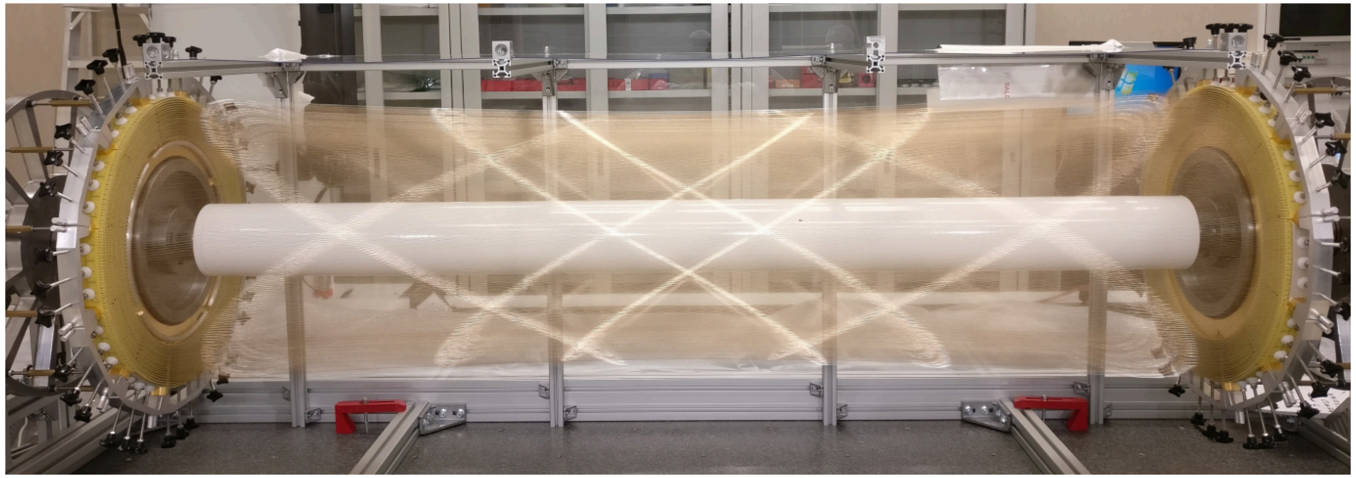
- MEG II pTC measure the positron crossing timing with the precision of O(30 ps)
- 512 "pixelated" design enables the multi-hit information (~8 hits / positron on average)

Ref: The European Physical Journal C volume 78, Article number: 380 (2018)
The design of the MEG II experiment

Cylindrical Drift Chamber (CDCH)



~ 7mm drift cells



~2 m

- Ultra-low mass (90% helium-based mixture and 10% isobutane) cylindrical stereo wire chamber to reconstruct the positron track with 2 times better efficiency (~70%) from MEG
- 192 drift cell / layer (7-9mm square shape) x 9 layers

Ref: The European Physical Journal C volume 78, Article number: 380 (2018)
The design of the MEG II experiment

Commissioning Summary

- 2015-2017: pTC commissioning
  - Full detector was tested in 2017
  - Timing resolution below 40 ps was achieved
    - reported in Mar. 2018 JPS by M. Nishimura
- 2018-2019: Spectrometer (pTC + CDCH) commissioning
  - Readout electronics was strictly limited due to the delay of schedule, but many new experience from hardware / software points of view
  - First look of the commissioning data reported in Mar. 2020 by M. Usami
- In this talk, we present the refined algorithms / methods with MC simulation updated based on the commissioning results

Assigned max. readout/year	pTC counters	CDCH cells	note
2017	256	-	Both DS/US pTC tested, mock-up CDCH
2018	128	96 (prototype)	Only DS pTC installed
2019 Oct	128	96 (prototype)	Only US pTC installed
2019 Nov	128	96 (prototype)+ 96	Final version readout for CDCH installed

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Recent Update

Response Simulation Update (CDCH)

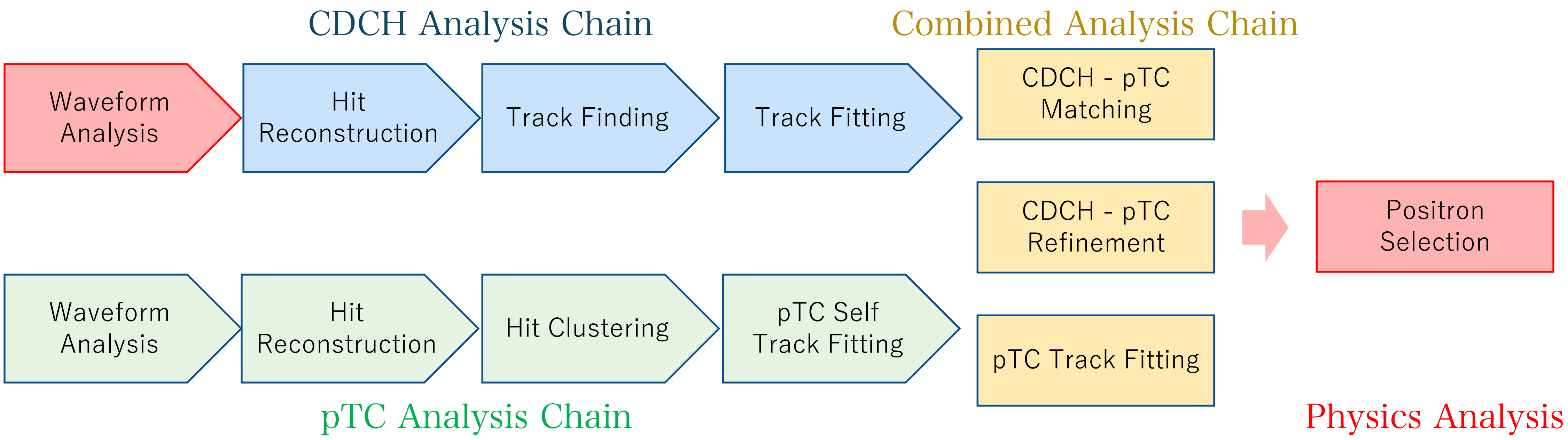
Based on the commissioning data

- Realistic Electronics Gain
  - factor ~ 3.7 decrease of gain
- Realistic Noise Level
  - factor ~ 2 increase
- z dependence of the gain
  - Smaller gain at larger z (edge) due to the large cell size
- Space-Charge Effect
- Realistic CDCH waveform shape by SPICE simulation

Reconstruction Update

- New waveform analysis algorithm
- Set analysis timing window around the signal region
- Positron selection method

Algorithm Overview



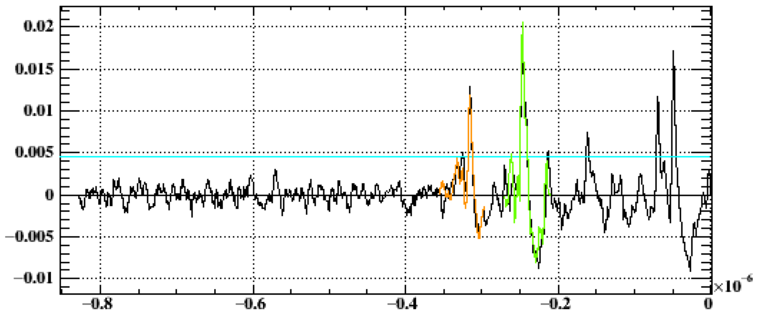
- The major update comes from …
  - Waveform Analysis
  - Positron Selection

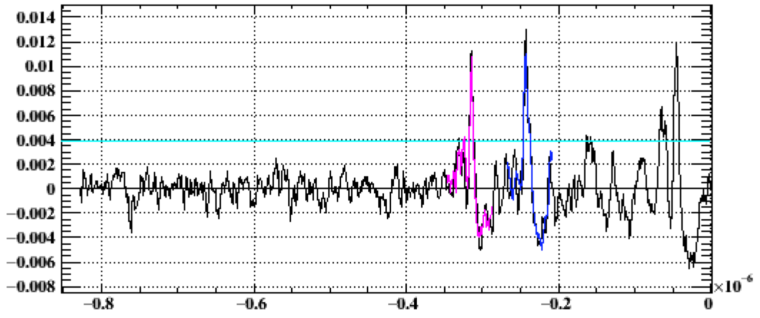
Waveform Analysis

- Previous algorithm does not work well with severe S/N
- Cross-Fitting Algorithm
  - Assumption: Waveforms at the both end of a wire are the same shape except for the amplitude
  - If a waveform is observed at the one side, we try fitting at the other end to find the signal
    - Minimize the following with MINUIT:

$$\chi^2 = \int \frac{(f(t) - c \times g(t+\tau))}{\sigma^2} dt$$

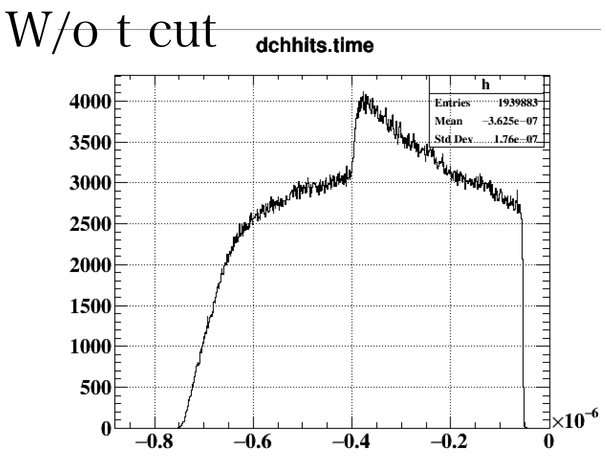
f(t): fit function (the waveform of one side)
g(t): waveform from the other end
c, τ : constant value to adjust the fitting

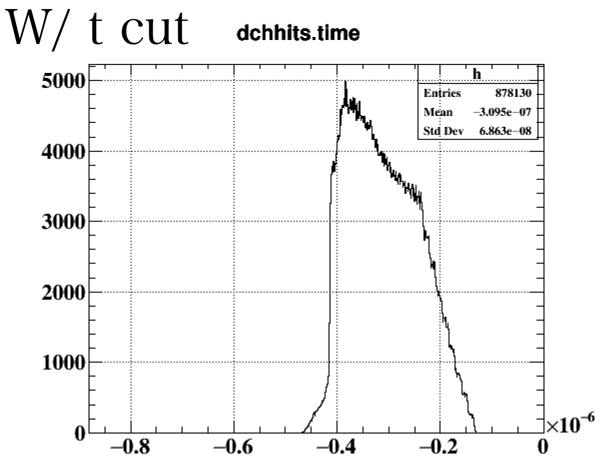


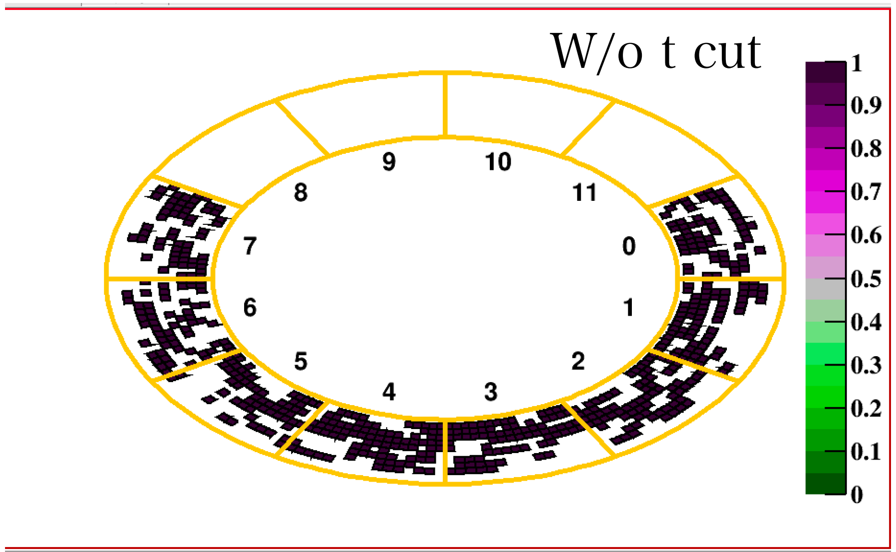


Timing Window

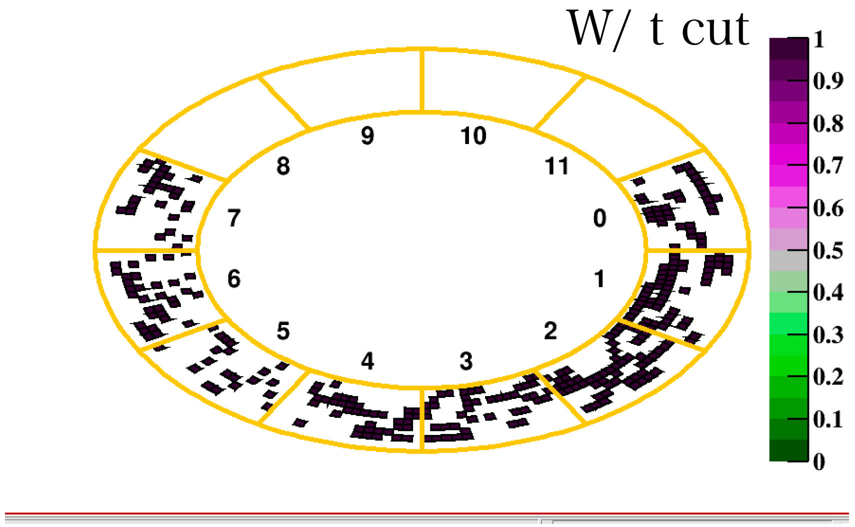
- Timing window for waveform analysis
  - $T_{\text{signal}} - 7.5\ \text{ns} < t_{\text{hit}} < T_{\text{signal}} + 282.5\ \text{ns} - 12.5\ \text{ns} \times \text{iPlane}$
    - No interests on pile up hits, skip the record
    - Efficient and precise reconstruction of track with interest
      - Efficiency: + ~5%







8,9,10,11: not used for readout



Positron Selection

Event Pre-Selection

Rough cut for the latter analysis
e.g. (for signal) 40 MeV < Pe < 65 MeV
-1 < $\cos\theta_{e\gamma}$ < -0.9
-12 ns< $t_{e\gamma}$ < 12 ns

Quality Cut

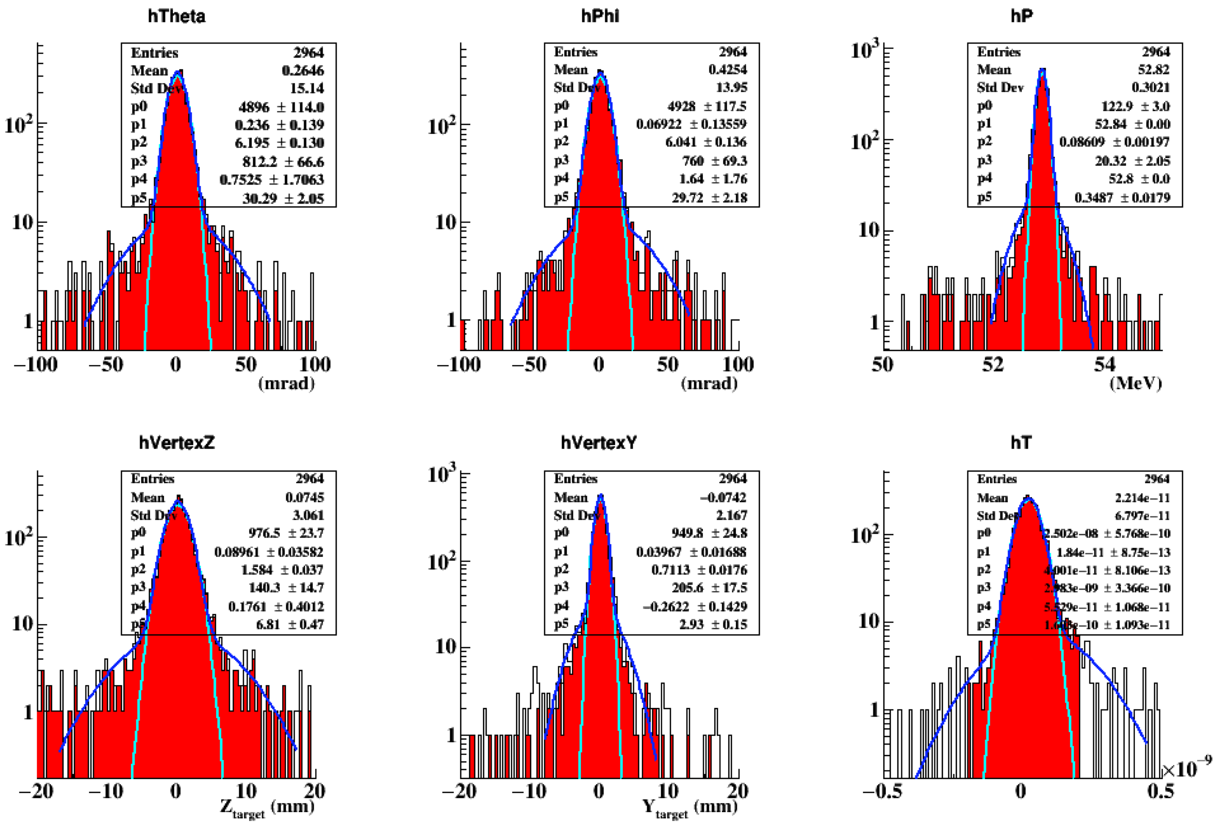
Check the tracking quality
independent criteria of michel / signal
e.g. χ^2, covariance from KF (cov_θ < 20 mrad etc …)
$0 \leq n_{\mathrm{turn}} \leq 9$

Track Selection

Select a good track for physics analysis / michel analysis
e.g. Propagation to fiscal target volume, Matching to pTC cluster,
covariance, propagation length, etc …
Selection based on χ^2/dof

- Efficiency and performance should be evaluated with the same condition to the physics analysis – One track must be picked up from one event
  - Also, the acceptance is checked before the pre-selection
  - The criteria can be tuned for michel / signal / other analysis

MC Evaluation



	Design	2018 JPS Autumn	7e7 beam
theta [mrad]	5.3	5.9	6.8
phi [mrad] ※1	3.7	5.3	6.5
momentum [keV]	130	83	93
z [mm]	1.6	1.3	1.7
y [mm]	0.7	0.72	0.8
time [ps] ※2	46	49	51
Efficiency [%] (W/ Tail)	70%	60%	70.0% (74%)

※ Correlation b/w thata / phi is included in design value
※ $\sigma(T_{calib})$~10 ps, $\sigma(T_{sync})$~25 ps added, 1-year radiation effects for JPS reports

- Though the hardware situation becomes severe (especially S/N ~ 1/10), the efficiency is recovered by software side
  - Resolution becomes slightly worse because of the worse S/N

Evaluation Method

- The positron reconstruction algorithm has been developed and established
- Realistic and reconstructed data-driven performance evaluation must be prepared
  - Positron Momentum: Michel Fit / Double Turn
  - Positron Tracking: Double Turn
  - Positron Timing: Even-Odd
    - Already reported in Mar. 2018 by M. Nishimura, Sep 2019 by M. Usami, Sep 2019 by K. Yanai …

Michel Fit

- The theoretical Michel Spectrum is well known
  - Kinoshita & Sirlin 1959 (implemented in RooFit package)
- The reconstructed energy at the vertex can be fitted with the following formula:

$$S_{\mathrm{rec}}(E_e^{\mathrm{rec}}) = \sum (S_{\mathrm{theo}} \times F_{\mathrm{Acceptance}})(E_e^{\mathrm{param}}) * R_{\mathrm{response}}$$

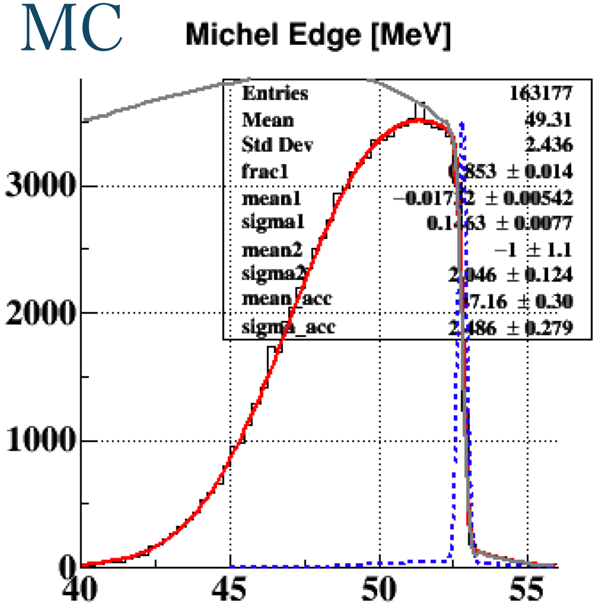
  - $R_{\mathrm{response}} = f_{\mathrm{core}} \times \mathrm{gaus}_{\mathrm{core}} + (1 - f_{\mathrm{core}}) \times \mathrm{gaus}_{\mathrm{tail}}$ (Double Gaussian)
  - $F_{\mathrm{Acceptance}} = \dfrac{1 + \mathrm{erf}\left(\dfrac{E_e^{\mathrm{param}} - \mu}{\sqrt{2}\,\sigma}\right)}{2}$ (Acceptance Function)

※Scaling parameter omitted

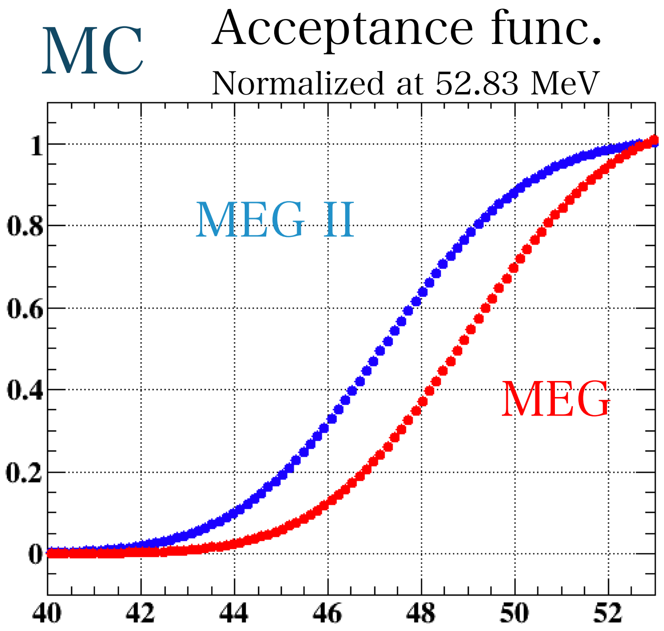
Michel Fit

Work In Progress

MC



MC



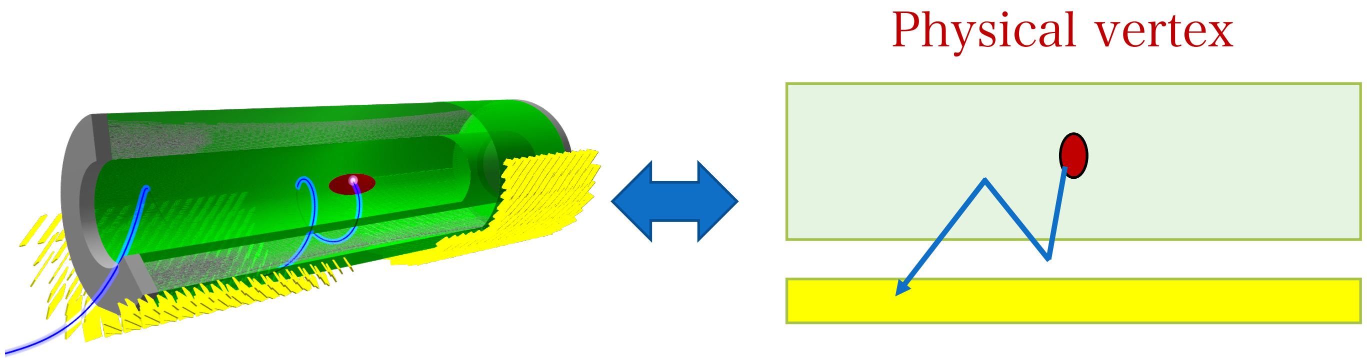
	2013 Data MEG I	MEG II MC (7e7)
σ_{core}	325 keV	146 keV
σ_{tail}	1.91 MeV	2.05 MeV
f_{core}	0.852	0.853
μ_{acc}	49 MeV	47.2 MeV
σ_{acc}	2.5 MeV	2.48 MeV

MEG I value from: Ph.D thesis by D. Kaneko (2016)

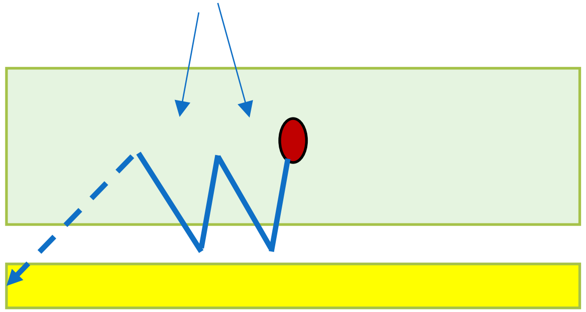
- Compared with MEG-I,
  - The Michel Edge becomes x2-3 sharper
  - The acceptance around the signal region becomes flat
- Preliminary results
  - Selection criteria for Michel fit are under studying
    - Currently I did not use "timing window" written in P. 12 for this analysis
  - Fit results are sensitive to fit range, initial parameter, limit range etc...

Double Turn Method

- Most of positrons has "1.5" turn in CDCH before pTC
- Sometimes positrons has < 2 turns, and these positrons can be used for Double Turn Analysis
  - Split "2-turn track" to "2 single-turn tracks"
  - Extrapolate the both tracks to the imaginary plane
  - Compare the state

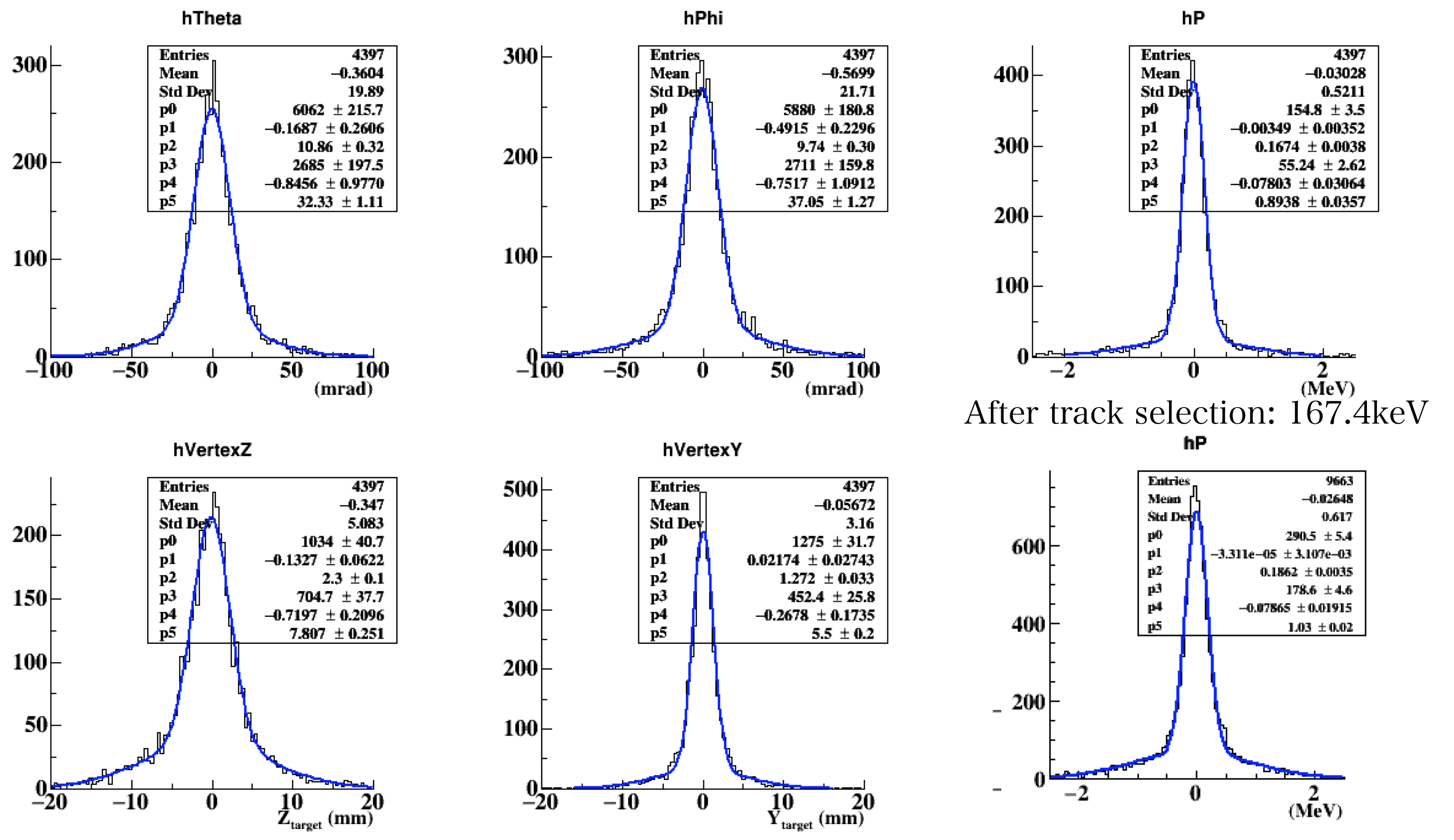


Typical Event (1.5 turn)



Double turn event

Double Turn Analysis



After track selection: 167.4keV

Before track selection: 186.2 keV

MC results

	7e7 signal MC true	7e7 michel Double turn
theta [mrad]	6.8	7.7 (10.86)
phi [mrad]	6.5	6.9 (9.74)
momentum [keV]	93	118 (167.4)
z [mm]	1.7	1.6(2.3)
y [mm]	0.8	0.85(1.2)

- Comparable results obtained from Double turn analysis
  - The discrepancy and tail events will be checked

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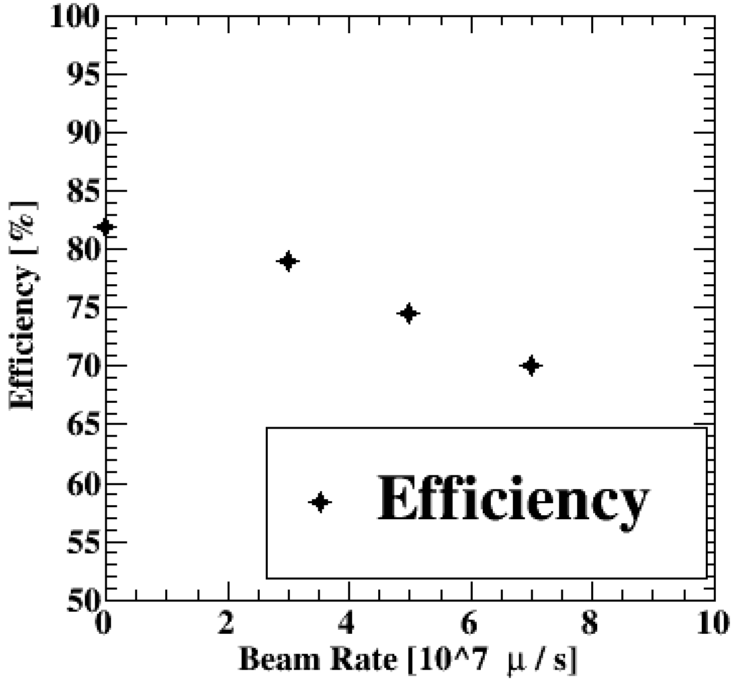
Summary and Prospect

- The simulation settings for MEG II experiment is updated more realistic based on the data taken in 2018-2019
  - S/N of CDCH waveform: roughly ~1/10, z-dependence etc...
- The reconstruction algorithm is refined, especially
  - New CDCH waveform analysis
  - Positron Selection task
  - Reached the target efficiency: 70%
- The realistic and data-driven performance evaluation
  - Double turn analysis : Tracking
  - Michel fit : Momentum
  - Even-Odd : Timing

Toward Further Optimization

- The reduced muon beam may be a realistic option of MEG II
  - PDE decrease of XEC MPPC
- Positron spectrometer situation with several beam intensities:
  - The accumulated statistics become smaller, but the reconstruction efficiency will be better
  - Resolution becomes slightly better
  - Less radiation damage (pTC) / pile up (CDCH)
- Updated sensitivity value with several scenario from positron side will come soon
  - Hopefully at the next JPS ...

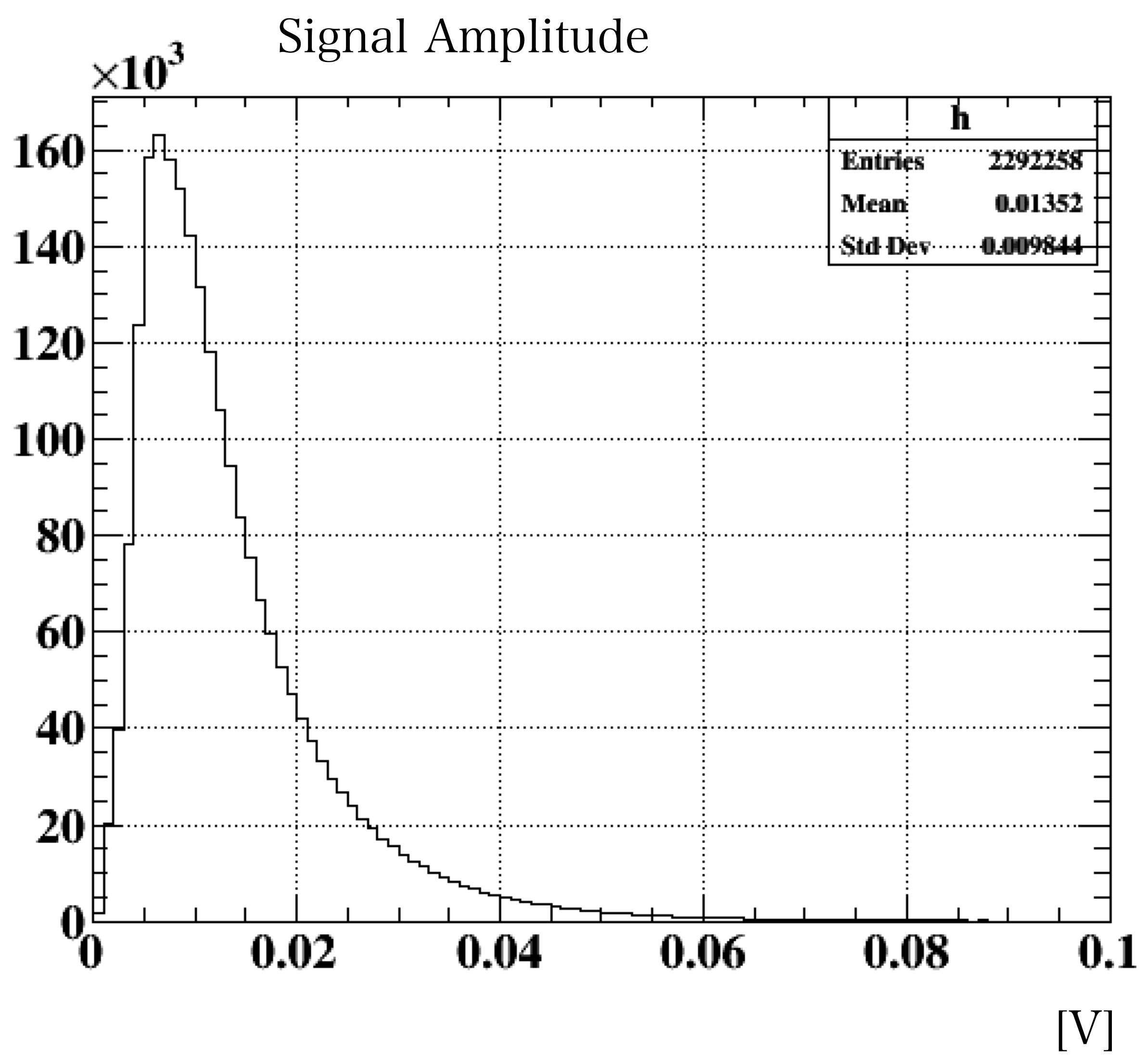


~10% efficiency recovery at the MEG I intensity
Resolutions are in backup

Backup

MC Evaluation

	No pile up (Signal Only)	3e7 beam	5e7 beam	7e7 beam
theta [mrad]	6.3	6.4	6.7	6.8
phi [mrad]	5.8	6.0	6.1	6.5
momentum [keV]	79	85	89	93
z [mm]	1.4	1.6	1.6	1.7
y [mm]	0.7	0.7	0.8	0.8
time [ps]	41	41	43	43
Efficiency [%] (Core)	85.0% (82.0%)	82.7% (79.0%)	79.1% (74.5%)	74% (70.0%)


Signal Amplitude
×10^3
160
140
120
100
80
60
40
20
0
0
0.02
0.04
0.06
0.08
0.1
[V]
h
Entries 2292258
Mean 0.01352
Std Dev 0.009844