MEG II実験陽電子タイミングカウンターを用いた飛跡再構成手法の開発と応用

宇佐見正志、他MEG IIコラボレーション

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Mu - E - Gamma collaboration

ICEPP The University of Tokyo

Core-to-Core Program

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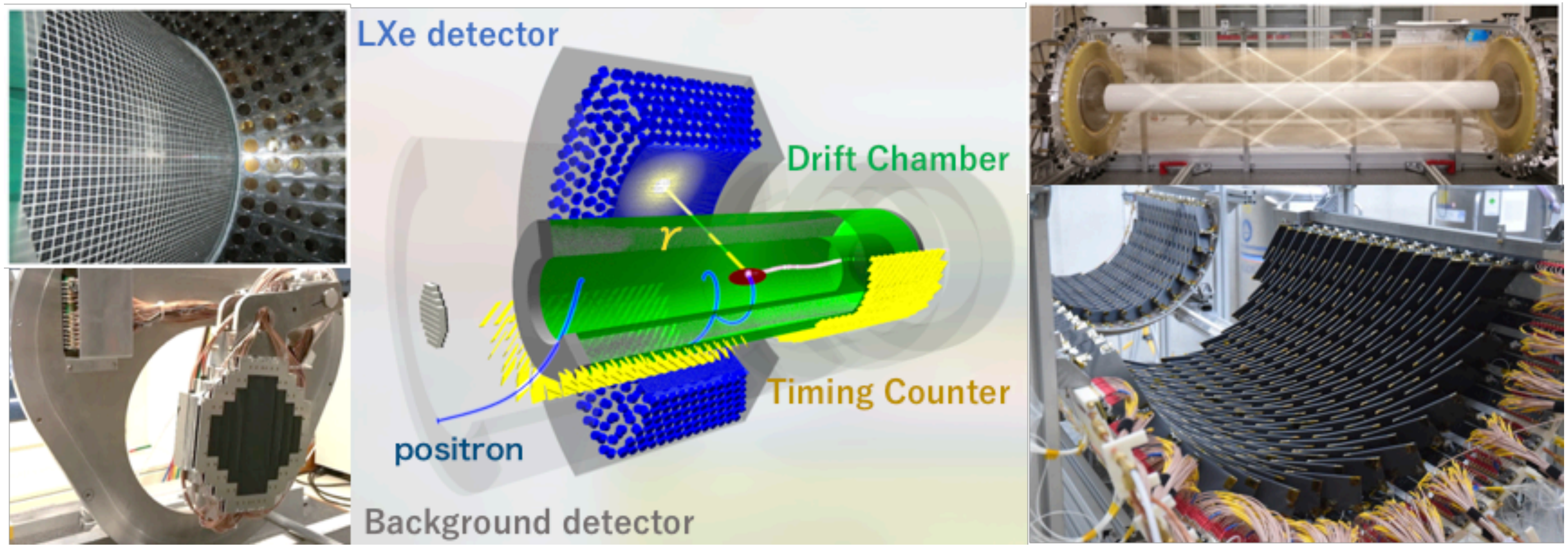
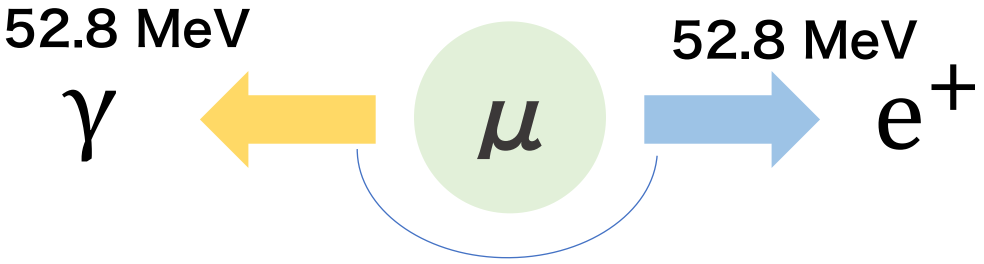
MEG II Experiment

- The most sensitive $\mu \rightarrow e\gamma$ search with the most intense muon beam
- Upgraded experiment from MEG: Positron spectrometer is newly constructed to achieve $\times$ **2** better detector resolution and $\times$ **2** positron reconstruction efficiency under $\times$ **2** higher beam intensity ($7\times10^{7}\ \mu^{+}/s$)



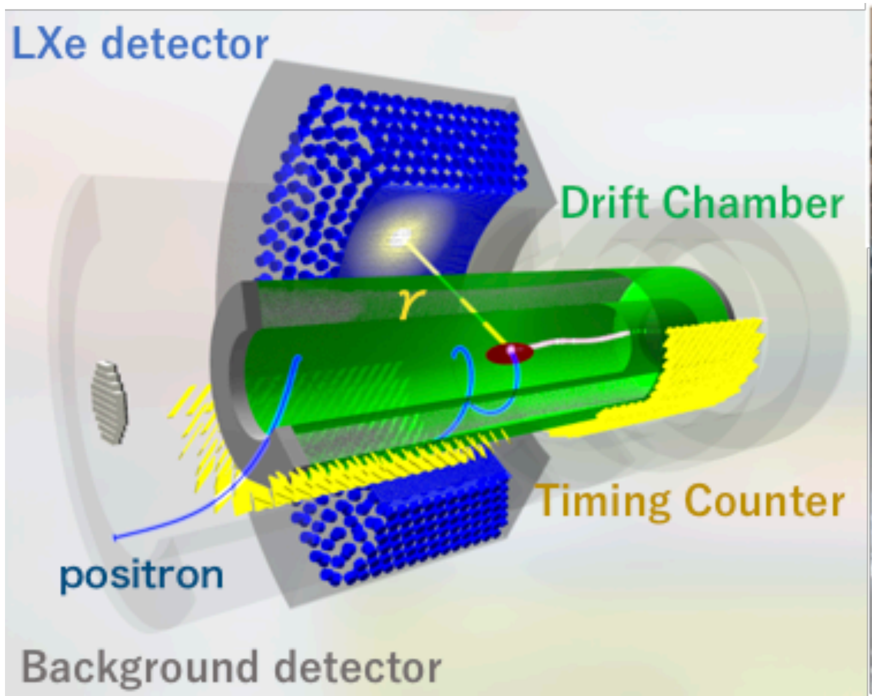
$\mu \to e\gamma$ Decay

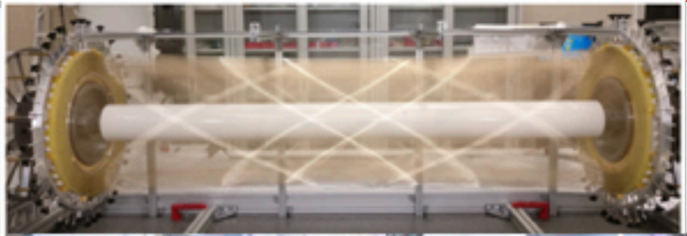
- $\mu \to e\gamma$: charged Lepton Flavor Violation (cLFV)
  - Prohibited in the standard model
  - Predicted in the beyond standard model within experimental reach
  - **To discover $\mu \to e\gamma$ means to discover the new physics!!**
- Signal kinematics of $\boldsymbol{e}$ **and** $\boldsymbol{\gamma}$:
  - Timing, position, and momentum is the key
  - High reconstruction efficiency under the intense μ beam is needed

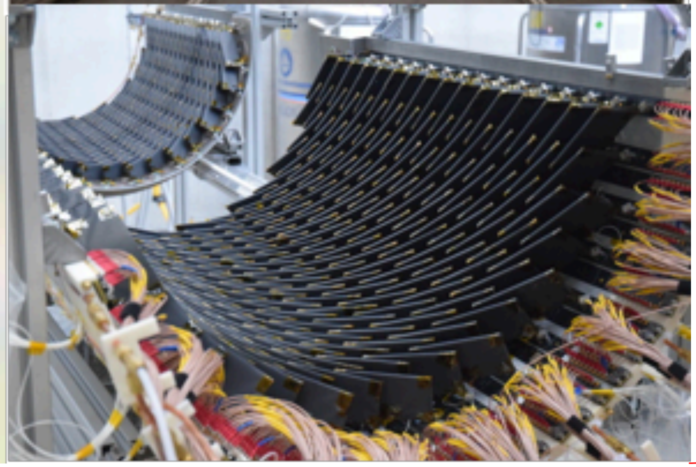


180° (back to back) at the same timing from the same position

Positron Spectrometer





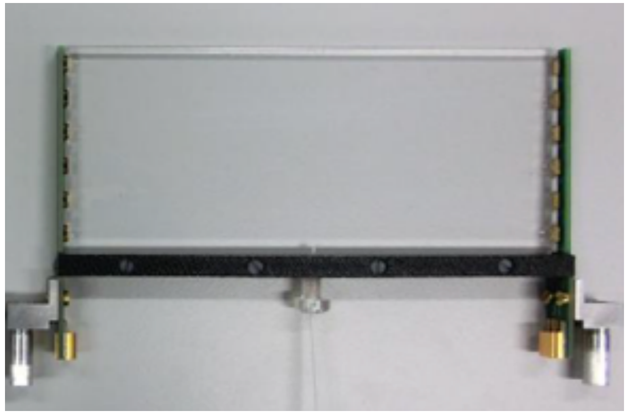


Positron Spectrometer
pTC + CDCH

- Positron Spectrometer:
  - Pixelated timing counter (pTC): measure a positron crossing timing
  - Cylindrical drift chamber (CDCH): detect a positron track as continuous hits
  - Gradient magnetic field: bend the flight path of positron
- **Commissioning with full positron detectors, but partial readout in 2019.**

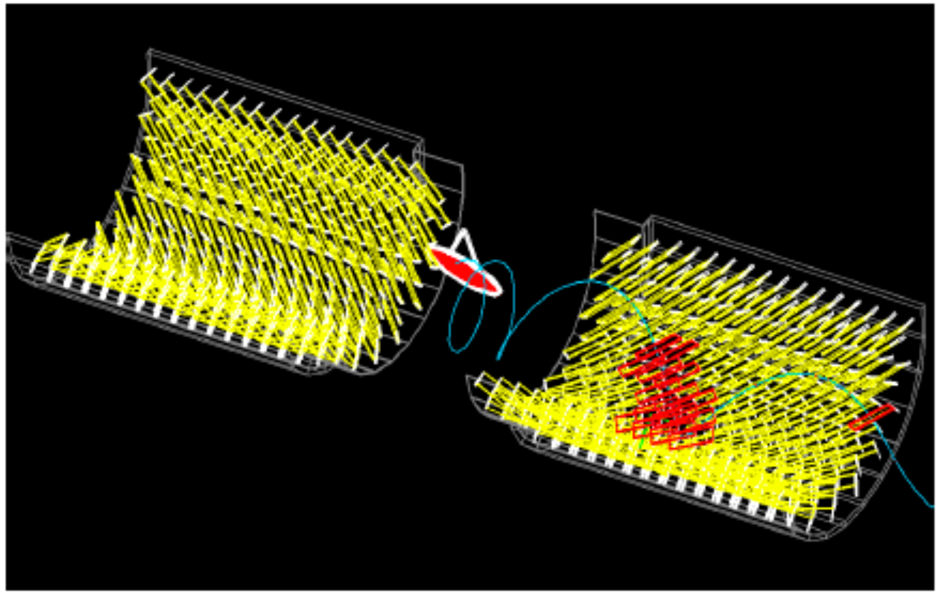
Pixelated Timing Counter (pTC)

- Positron timing is determined by pixelated Timing Counter (pTC)
  - 512 scintillation counter with 6 series connected SiPMs
  - 1 positron crosses multiple counters
  - pTC achives ~ 35 ps with 8 hits (average # of hits)



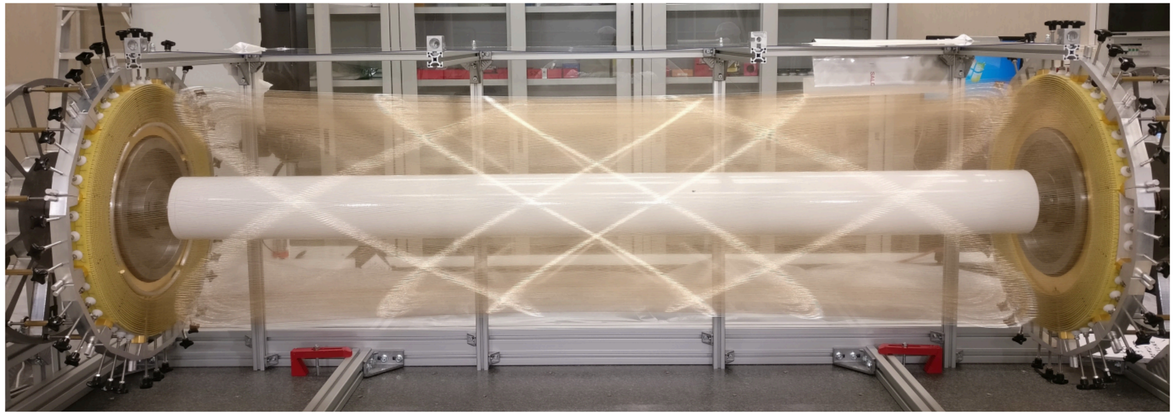
σ (t) ~ 80 ps at each single counter

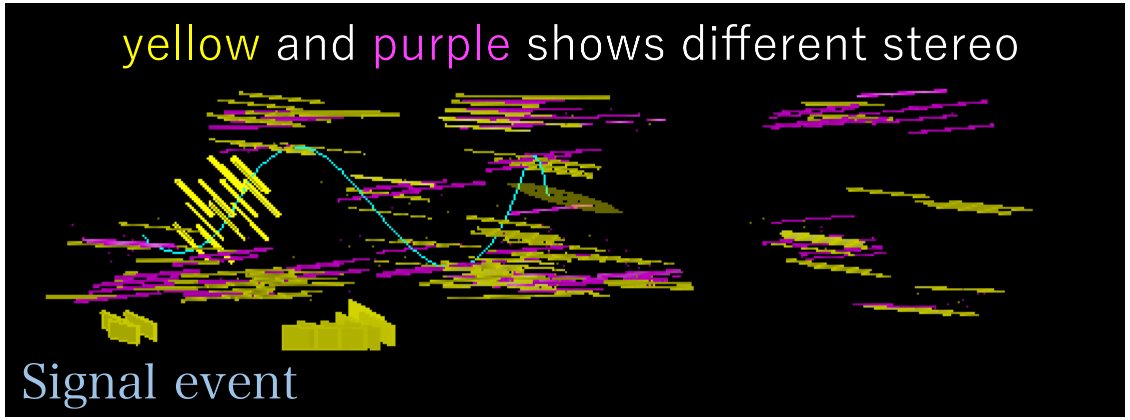
× 512 ➡



Cylindrical Drift Chamber (CDCH)

- Ultra-low mass (90% helium based gas mixture + 10% isobutene) cylindrical drift chamber with stereo wires
- 192 drift cell (~7mm × 7mm) per layer (9 layers)
  - 1.7—0.8 MHz/cell
  - <Nhit> ~ 650 in event in 250 ns
- Tracking done based on Kalman Filter technique (with GENFIT)
  - Track seeds are made with outer layer hits





MEG II Positron Analysis Status

From the previous JPS report (2018年9月15日)

Positron Resolution	MEG	Design (10 layer)	Updated (9 layer)
Theta (mrad)	9.4	5.3	5.9
Phi (mrad)	8.7	3.7	5.3 ※A
Momentum (keV)	380	130	83
Vertex Z (mm)	2.4	1.6	1.3
Vertex Y (mm)	1.2	0.7	0.72
Positron time (ps)	108	46	49 ※B

※A. Correction based on theta and phi correlation is not applied, though expected value include it.
※B. 1 year radiation damage effect is roughly simulated, w/o cooling condition. $\sigma(T_{calib})$ ~10 ps, $\sigma(T_{WDB\_sync})$ ~25 ps is added.
(Baldini, A.M., Baracchini, E., Bemporad, C. et al. Eur. Phys. J. C (2018) 78: 380.)

Signal only case
Efficiency: 80±1%
9 layer configuration

Signal + BG
Efficiency: 60±1%
9 layer configuration

- MC : We have not yet achieved the target efficiency (70%)
  - Current algorithm is not enough to achieve the target sensitivity
  - Tracking quality is not enough- > becomes inefficiency events (tail)
- Data : We do not have enough data to estimate the track quality
  - Limited readout is now available, CDCH tracking is difficult this year
- Analysis breakthrough is now needed to take a step !!!

pTC Self-Tracking

- We have developed new tracking idea: pTC self-tracking
  - Track reconstruction with pTC hits, without CDCH information
- With this algorithm,
  - Improve the positron reconstruction quality and efficiency
    - pTC track gives CDCH for the initial position, momentum, time etc …
    - Those additional information will help to improve tracking (LR ambiguity, 1st turn & 2nd turn combine, z determination etc …)
  - Detector response study with the commissioning data in 2019
    - We want to reconstruct "track" even with the strictly limited readout
    - This partial track can pick up CDCH hits and combine those as track

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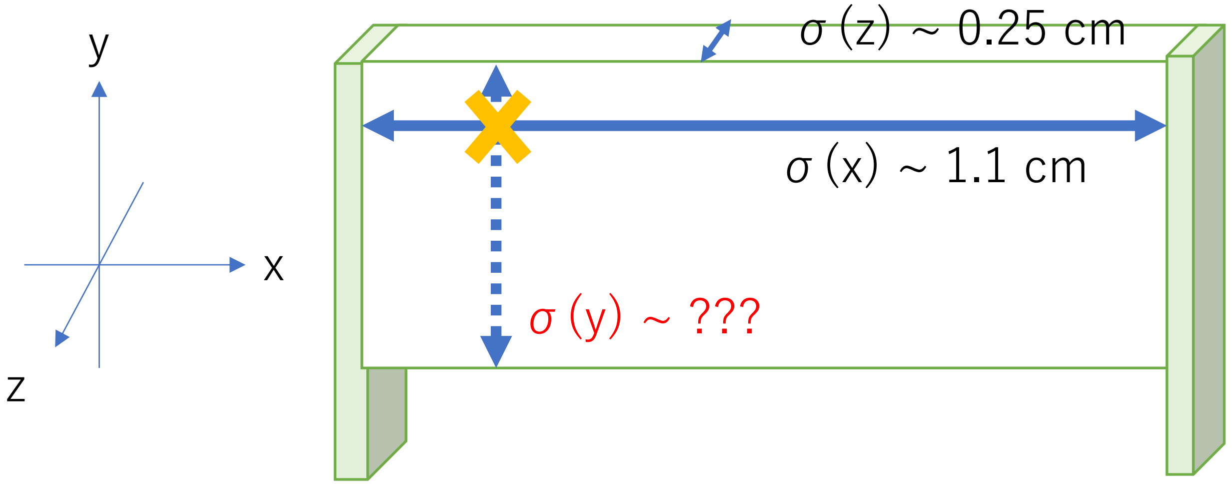
- Introduction
- Positron Track Reconstruction with pTC
- Application to pTC analysis
- Summary

Positron Tracking in pTC

- <u>Track reconstruction</u>: estimate the positron's momentum, path-length, and position etc from detector's hits
- We have to estimate the momentum and y-position information to make a good track
  - Initial momentum is around the signal value : ~ 45 ± 8 MeV
    - This is determined by our gradient magnetic field's characteristics



○ x from arrival time difference (σ ~ 1.1 cm)

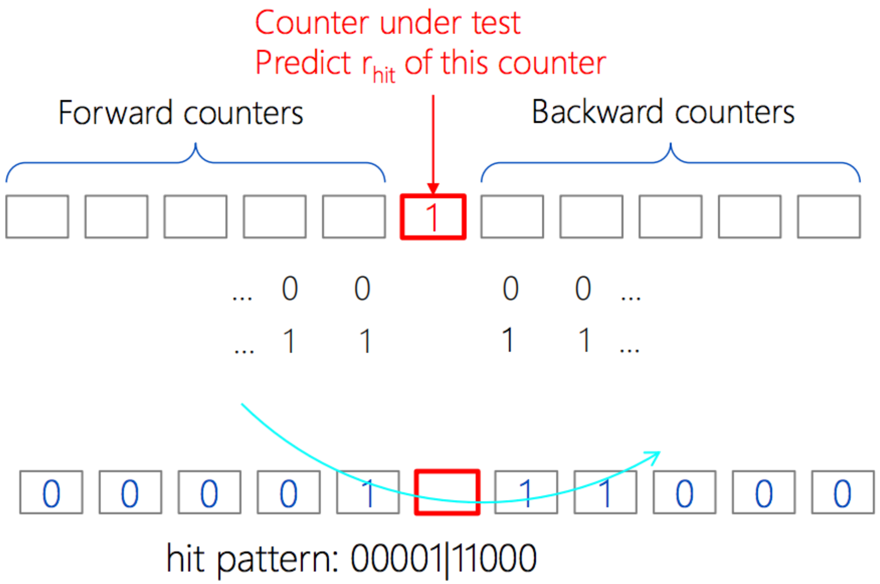
○ z from counter position (σ ~ 0.25 cm)

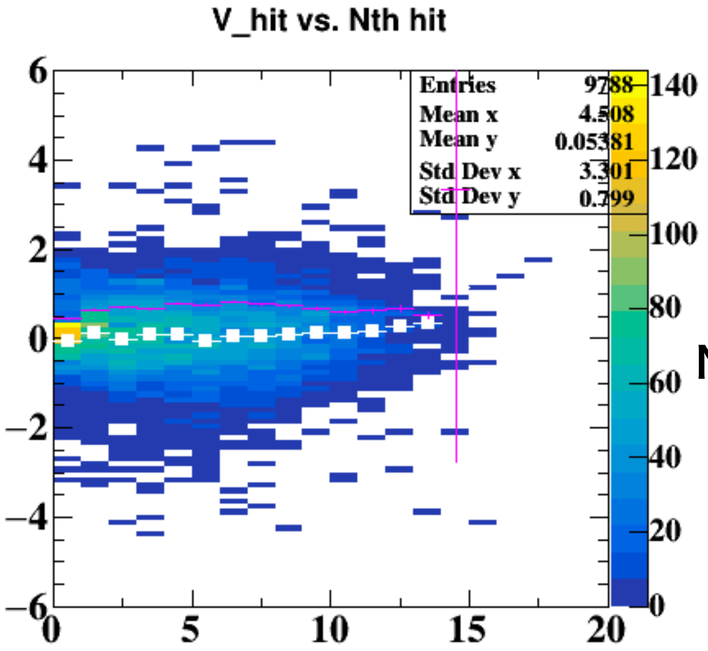
✖ y information

✖ momentum information

Parameter Estimation

- y-position from the segmented design of pTC
  - We list up all possible patterns of cluster hits pattern
  - 8 mm resolution on y direction





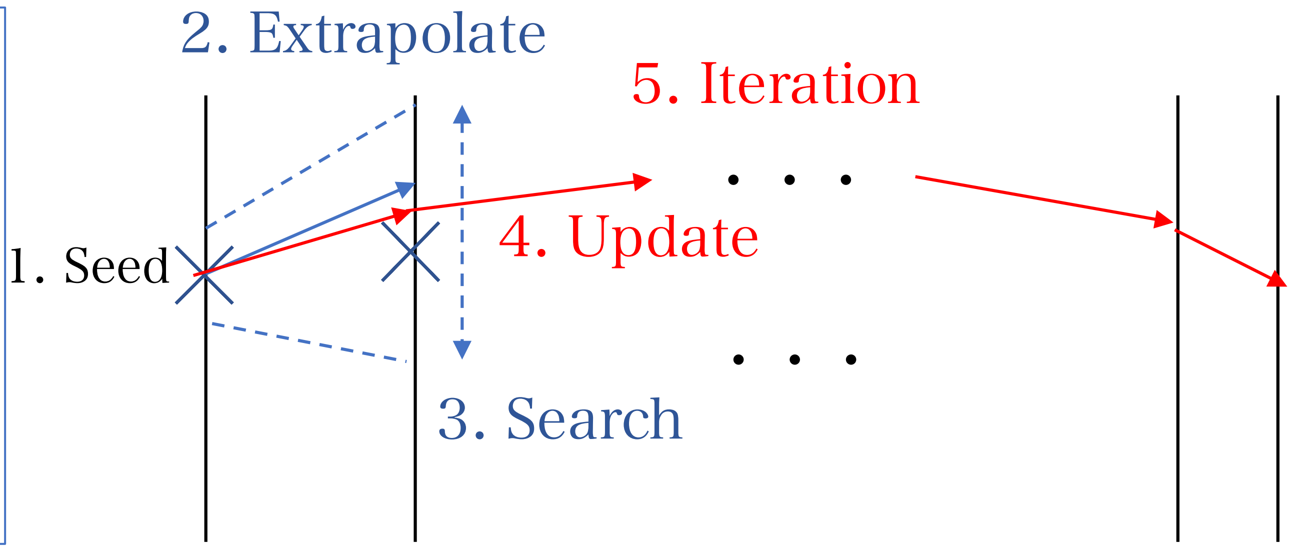
~ 8 mm resolution at each # of hits

No bias for mean value

Track Reconstruction

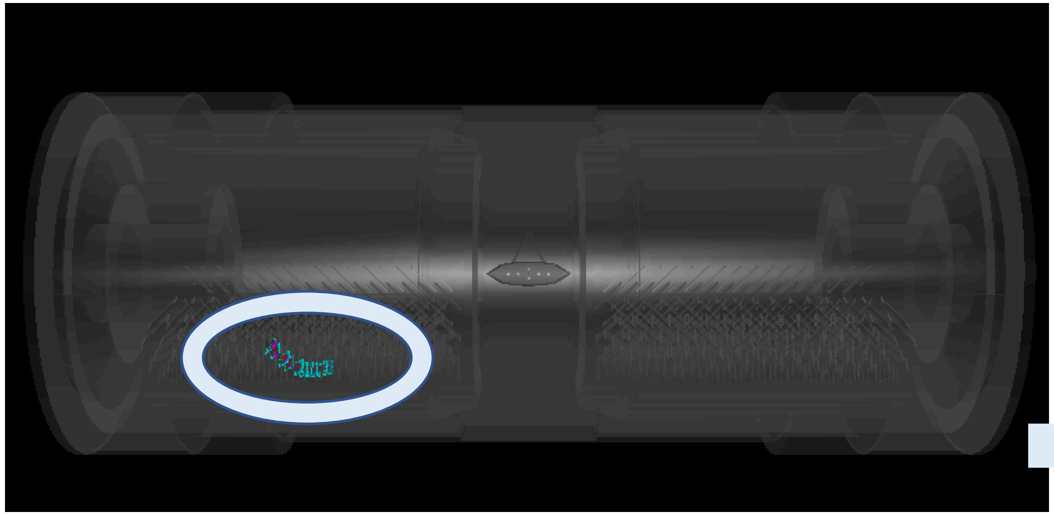
- Track reconstruction with Kalman Filter technique
  - We use GENFIT package for calculation
  - Outlier can be rejected by using DAF option (extension of kalman filter)

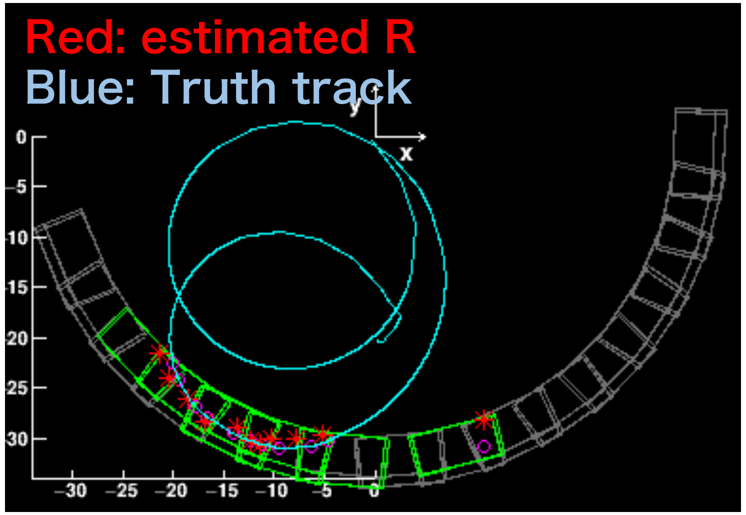
Kalman Filter
Efficient recursive algorithm to estimate the state vector and its covariance matrix based on previous states.
GENFIT
A generic toolkit for track reconstruction for experiments in particle and nuclear physics.

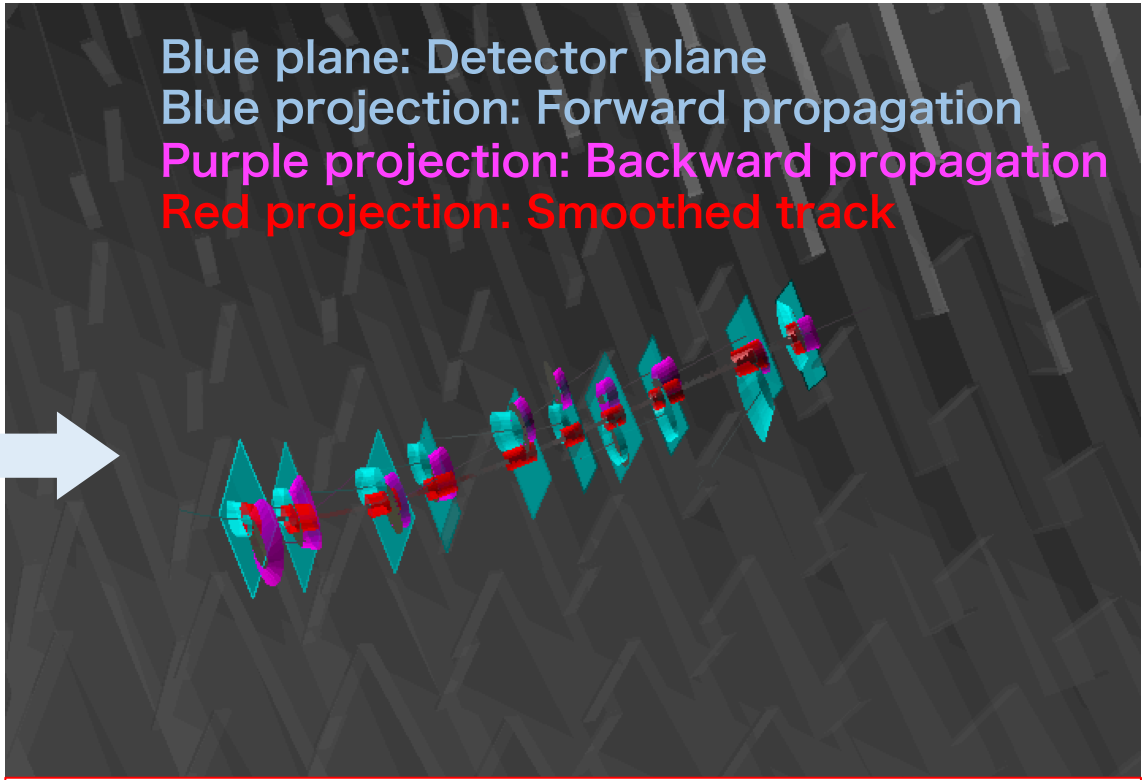


About GENFIT: http://genfit.sourceforge.net/Main.html

Track Reconstruction (MC)





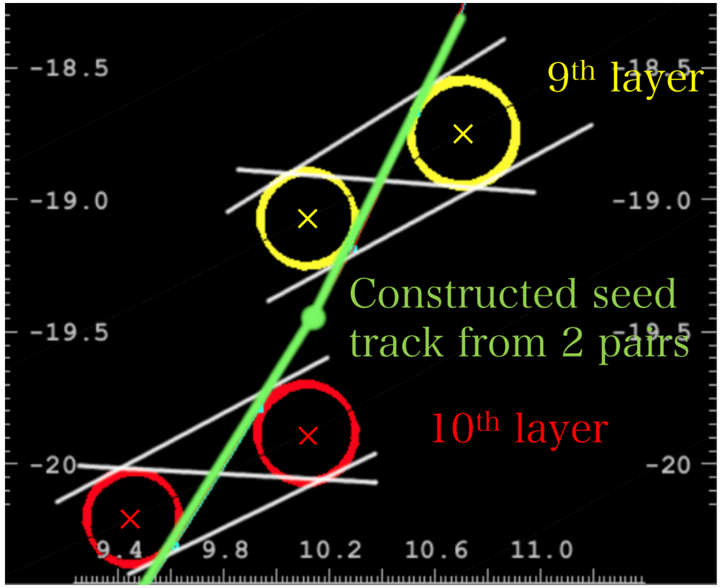


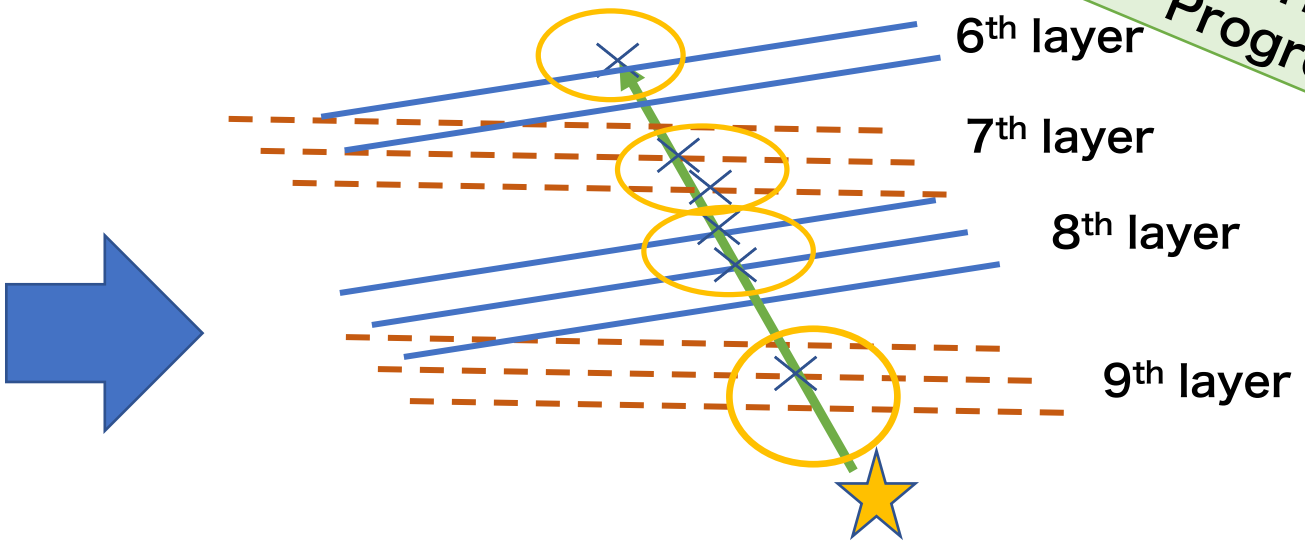
<u>Expected Performance (MC)</u>

Efficiency: 90%
R position resolution on each counter: ~5mm
Momentum resolution: 5 MeV
Angle resolution: 100 mrad
TOF b/w adjacent counters: 5 ps

pTC-CDCH Combined Tracking (MC)

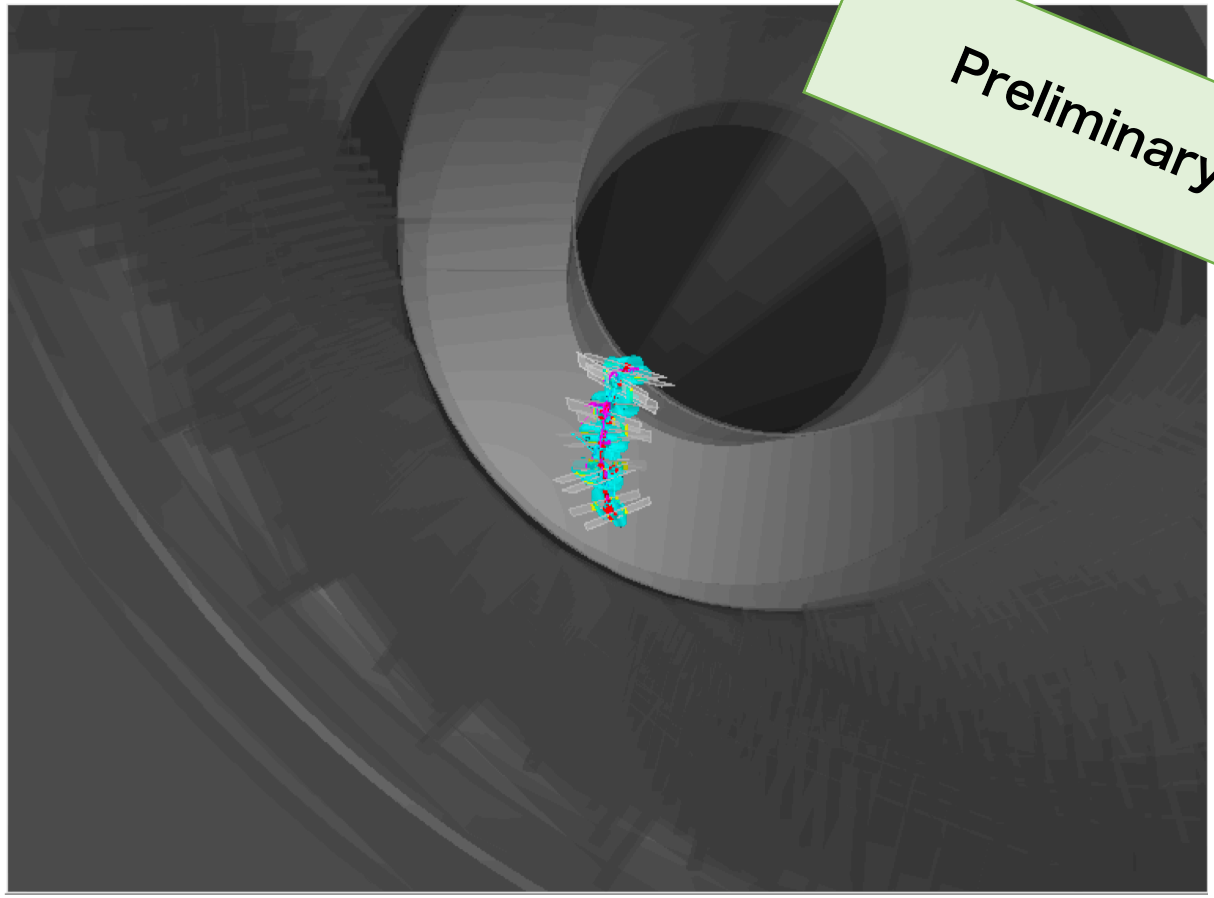
Work in Progress





- pTC self track gives CDCH for the initial position, momentum, time etc…
  - Current CDCH seeding starts from 2 x 2 hits in 2 layer
  - Especially direction information (momentum) is the key for improvement
- Improve the positron tracking quality by combining two detectors

pTC-CDCH Combined Tracking (MC)



Preliminary

Intermediate Summary

We established pTC-self tacking algorithm

- This algorithm can give additional information for CDCH tracking
  - Initial momentum (direction), position, timing etc…
  - Momentum (direction), z information is the key to improvement
- CDCH detector study in 2019 commissioning with limited channel
- Application:
  - Track based calibration / performance study in the pTC
  - Resolution improvement study / Outlier rejection with DAF
  - CDCH detector response study in 2019 commissioning with limited channel

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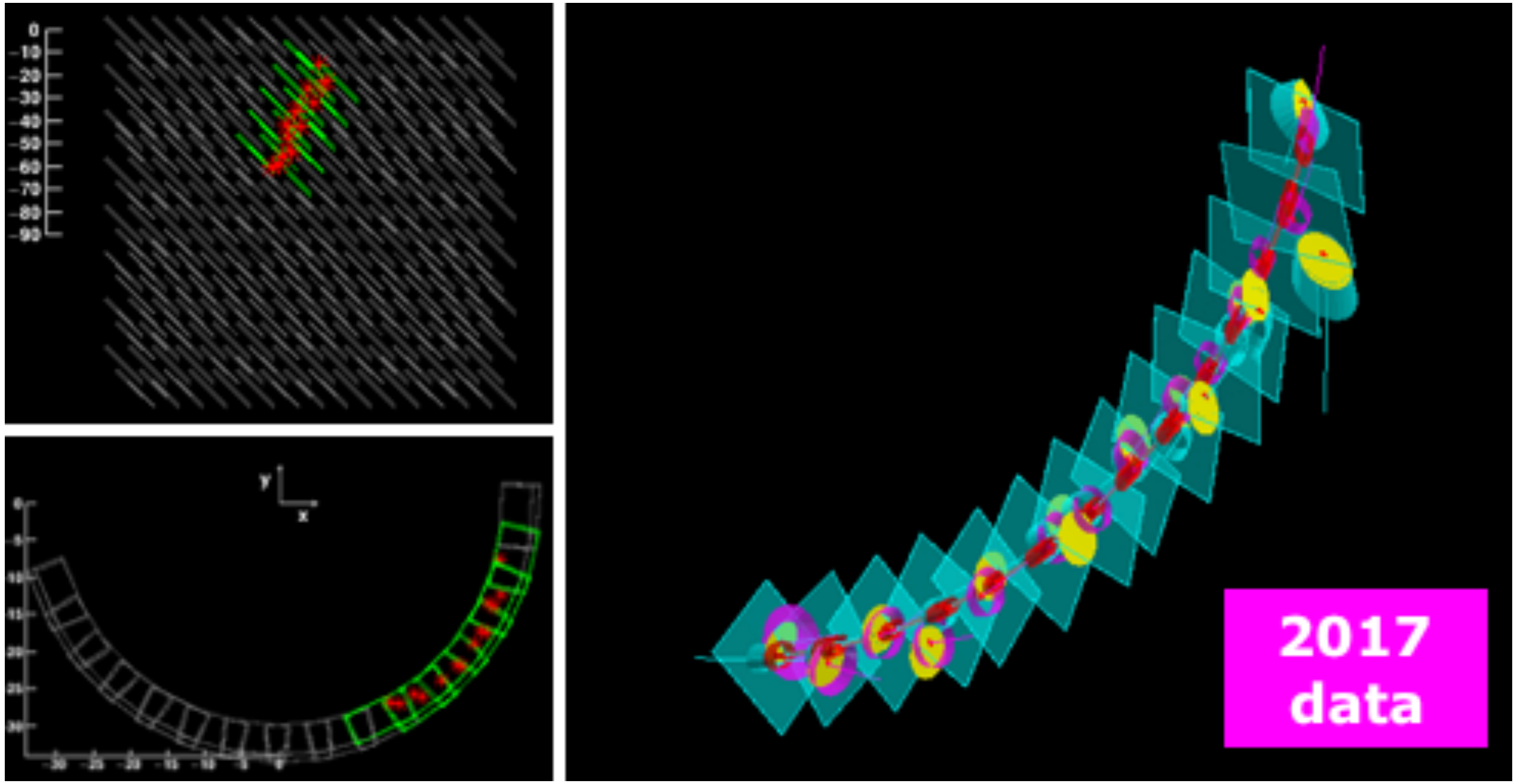
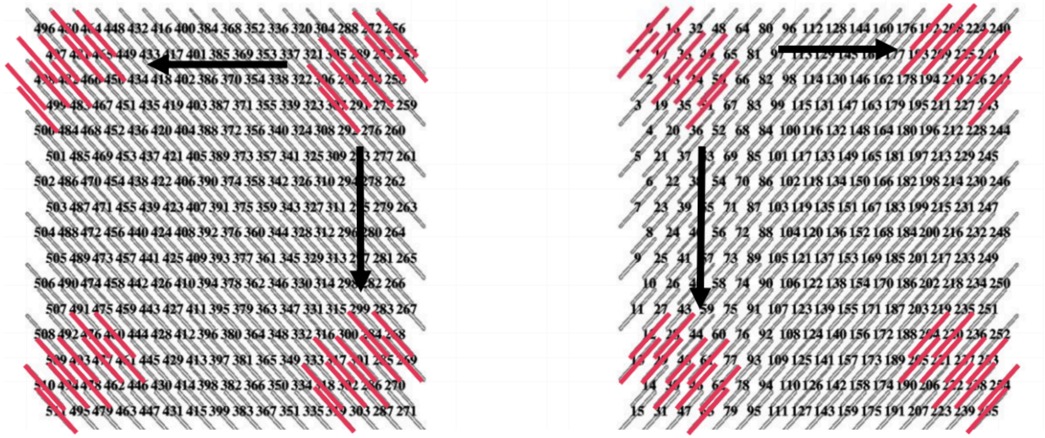
Application for pTC analysis



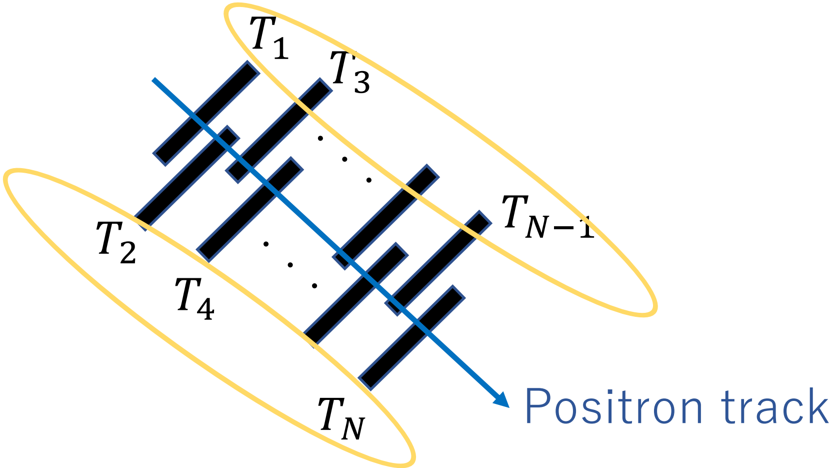
Application for pTC analysis

Check the all geometrically same combinations

US DS



(Notice that counters are used twice or more.)

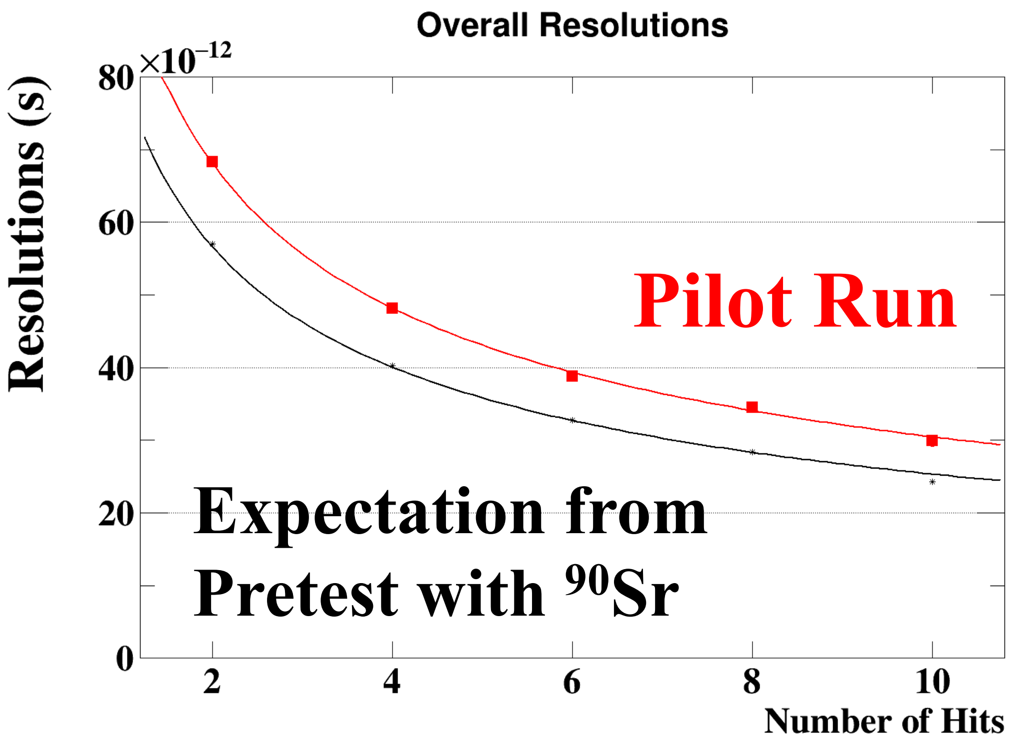


With <u>any</u> combination

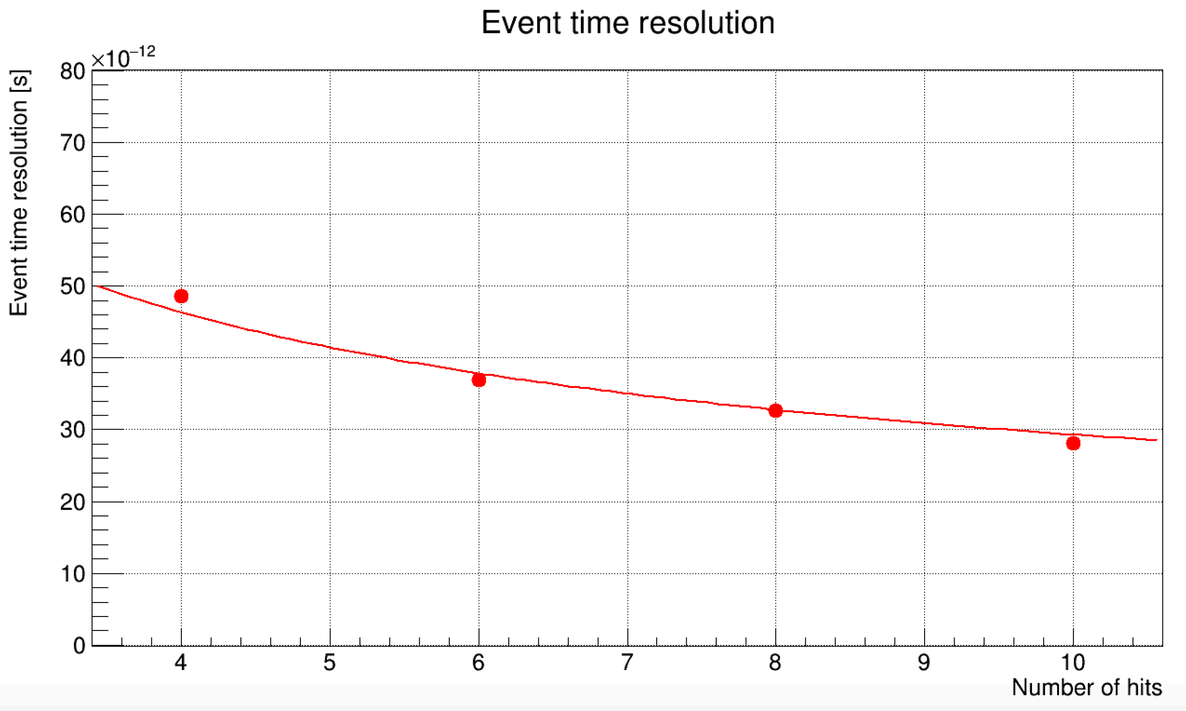
Even-Odd Analysis: $\sum_i^{\frac{N}{2}} \frac{T_{2i}}{N} - TOF_{2i} - \sum_i^{\frac{N}{2}} T_{2i+1} - TOF_{2i+1}$

- Until 2017, we used fixed counter combination to evaluate the pTC's timing resolution
- With this track, we can use any combination with TOF correction

Application for pTC analysis



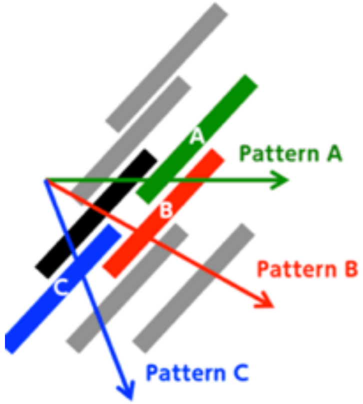
2017, fixed combination



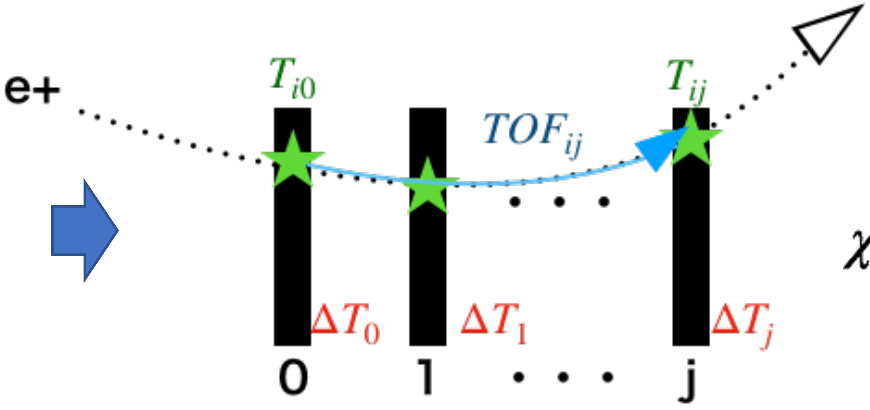
2018, any combination

Reported by M.Nishimura @ VCI 2019

Track Based Calibration



TOF estimation from 3 pattern



TOF estimation from track

Measured time at j-th counter

TOF b/w first and j-th

$$\chi^2 = \Sigma_i^{event}\Sigma_j^{hit}\left(\frac{\boxed{T_{ij}} - \boxed{(T_{i0}^{true}} + \boxed{TOF_{ij}} + \boxed{\Delta T_j)}}{\sigma}\right)^2$$

True hit time at first counter

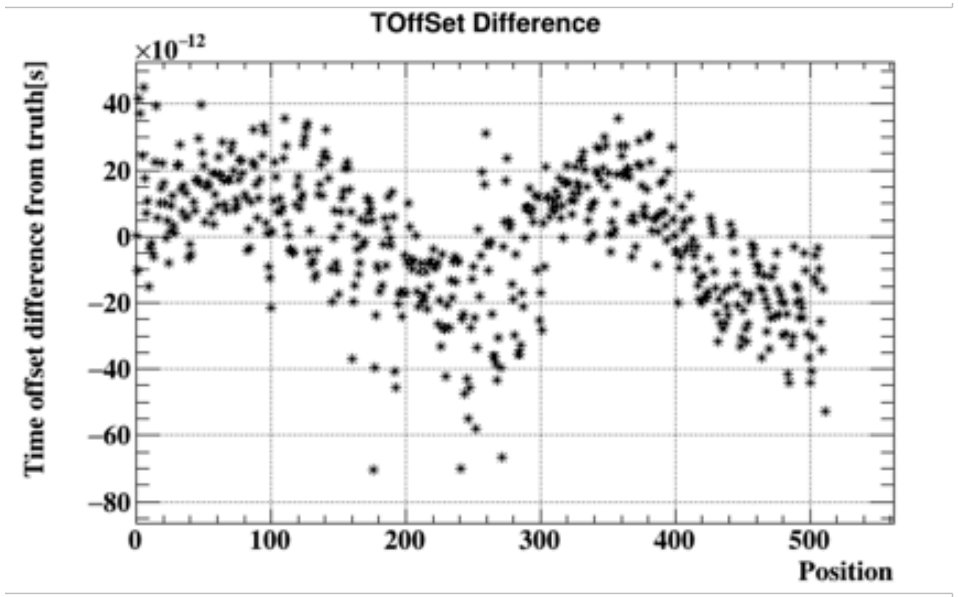
Time offset

What we want to know!

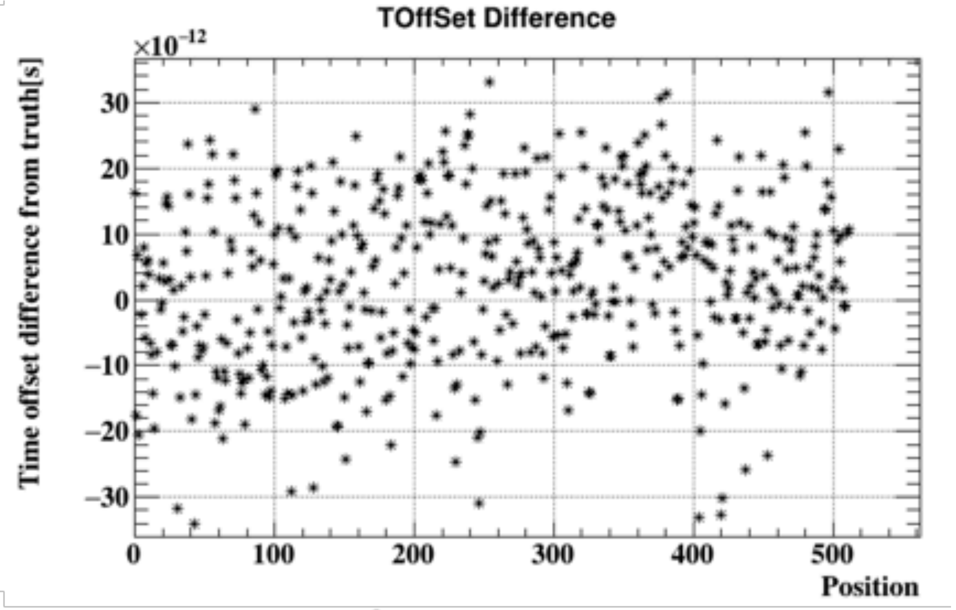
Calculation with Millepede II
A software provided by DESY to solve the linear squares problems, such as detector alignment and calibration based on track fits.
(www.desy.de/~kleinwrt/MP)

- Calibration with michel positron track by minimizing the chi2
  - Important point is TOF (path length) calculation b/w counters
  - Until 2017, we used the flight pattern classification

Track Based Calibration (MC)



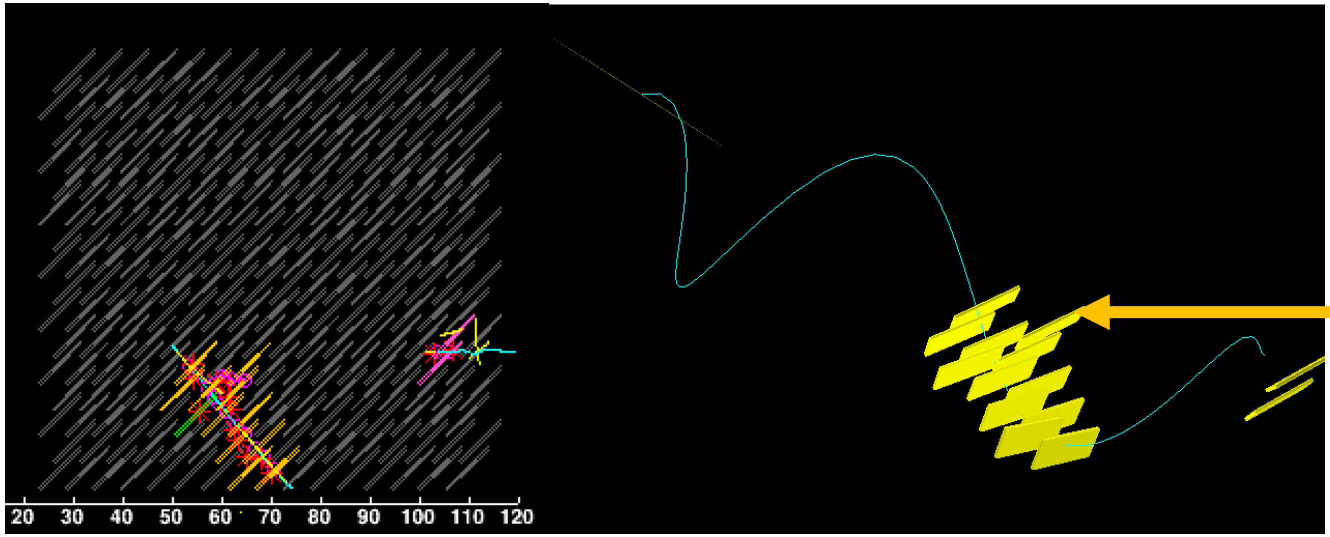
σ~19.6 ps
with 3 tof patterns



σ~13.5 ps
with Independent track

Outlier Rejection

- Sometimes outlier hits in a cluster make a tail event (timing tail or position tail in tracking) and may cause inefficiency
- DAF computes the "weight" in each detector layer, and rejects the outliers
  - Based on "position" (calculated by GENFIT) and "timing" (Added manually)
  - Slight improvement with 2018 commissioning data (36.7 ps -> 36.1 ps on average)



The signal positron does not pass through this counter, but a "hit" is reconstructed (secondary particle entered) -> Strange hits are rejected by the position DAF weight (threshold: 0.5)

MC Event Monitor

event 96, spxhit 123

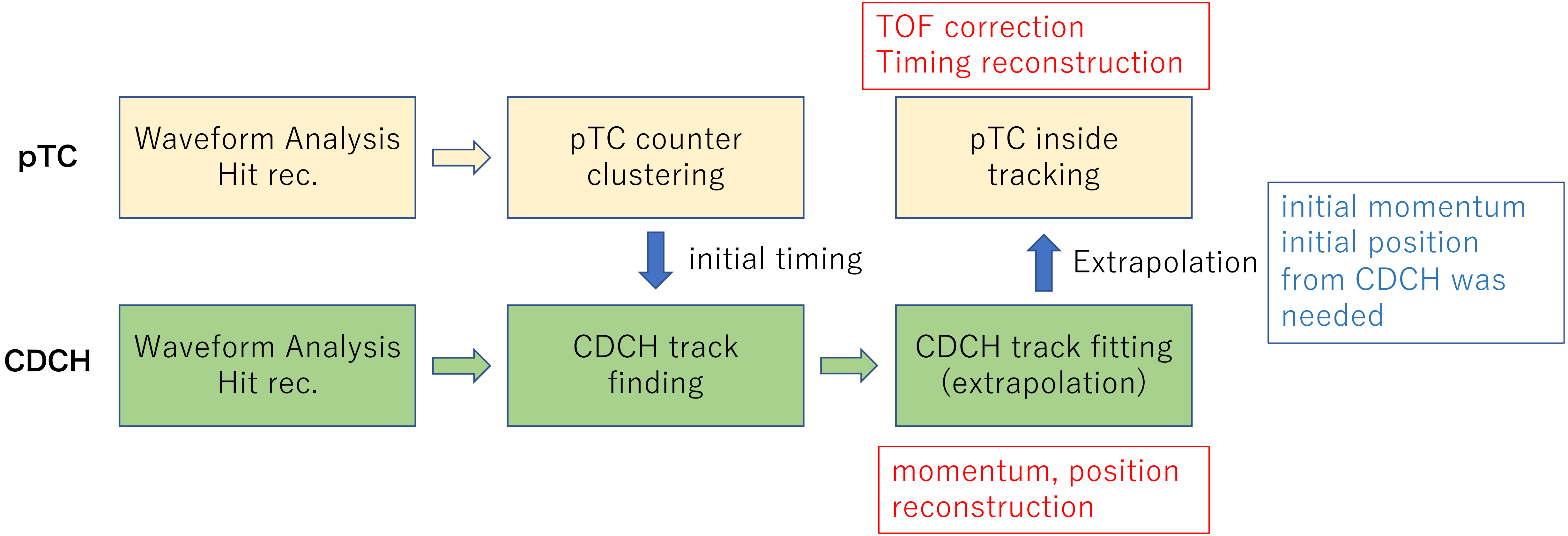
Summary

- Positron reconstruction algorithm for MEG II experiment has been developed. And new idea with pTC self-tracking is implemented
  - High efficiency (90%), relatively good resolution on position (~5 mm), and momentum (~ 5 MeV)
- Combined algorithm with pTC self-track reconstruction and CDCH track reconstruction started to be developed
  - To achieve the target efficiency (70%) and target resolution of positron reconstruction
  - Application to 2019 commissioning to try the CDCH detector response study (e.g. hit reconstruction efficiency, z resolution)

Back up

MEG II Positron Analysis Framework

- What we want: positron timing, momentum, position
- Analysis framework with pTC and CDCH has been developed



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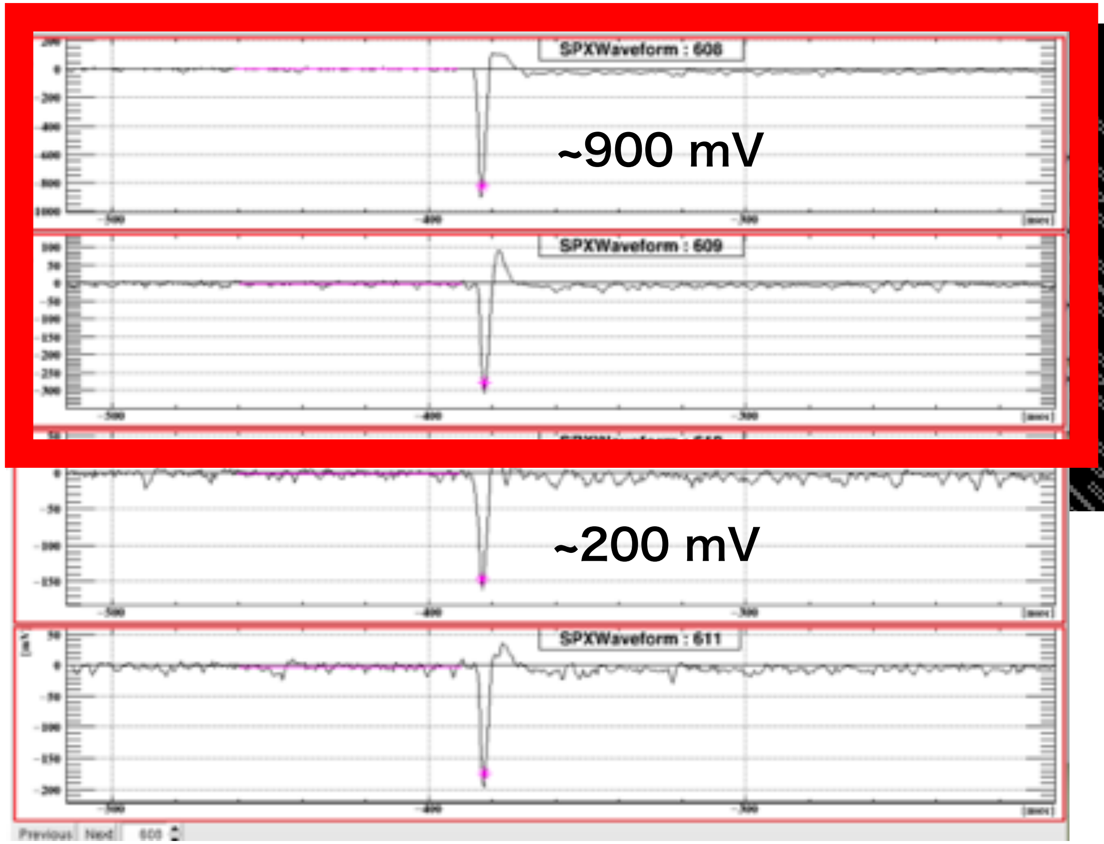
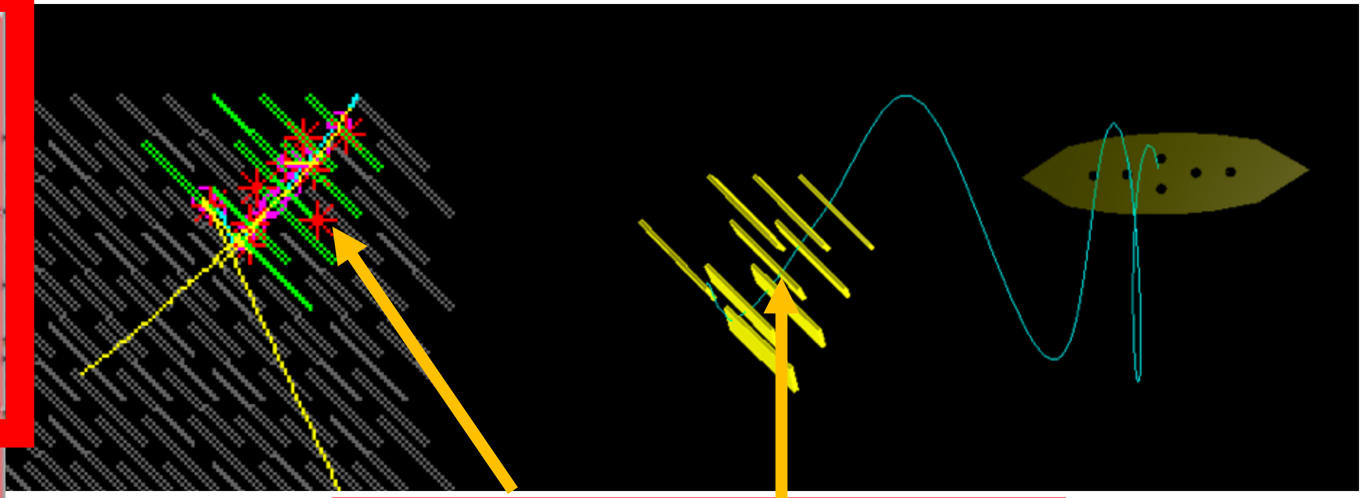




This counter has very large waveform (~900mV) compared to normal counters (~200-400mV)
-> Strange reconstruction, rejected in pTC tracking

event 432, index 4

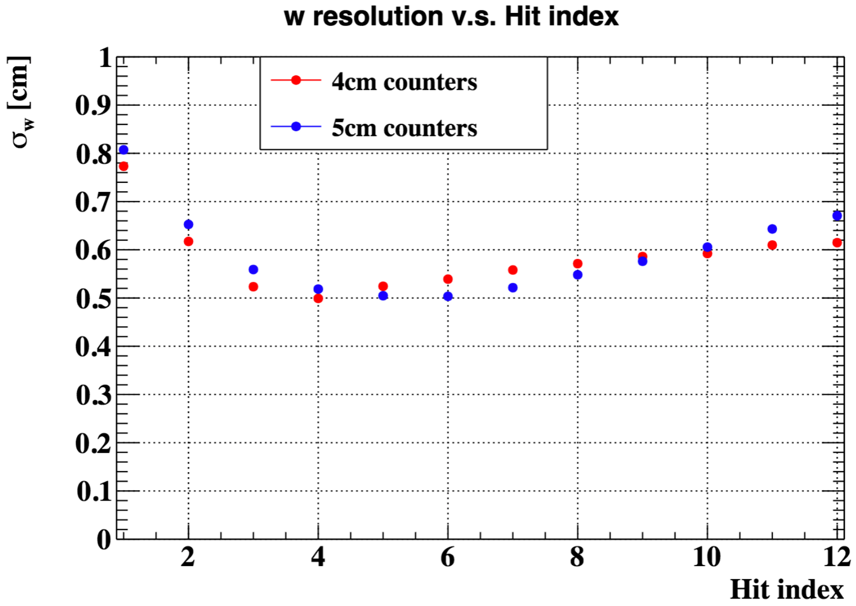
想定質問

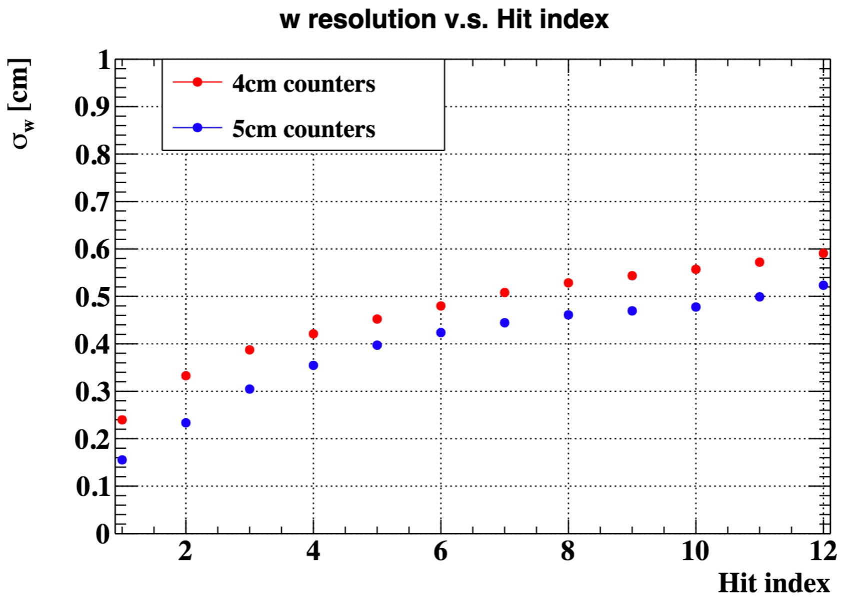
- CDCHありの時のresolution/効率は？
- 効率：97%
- Resolution

Positron inefficiency

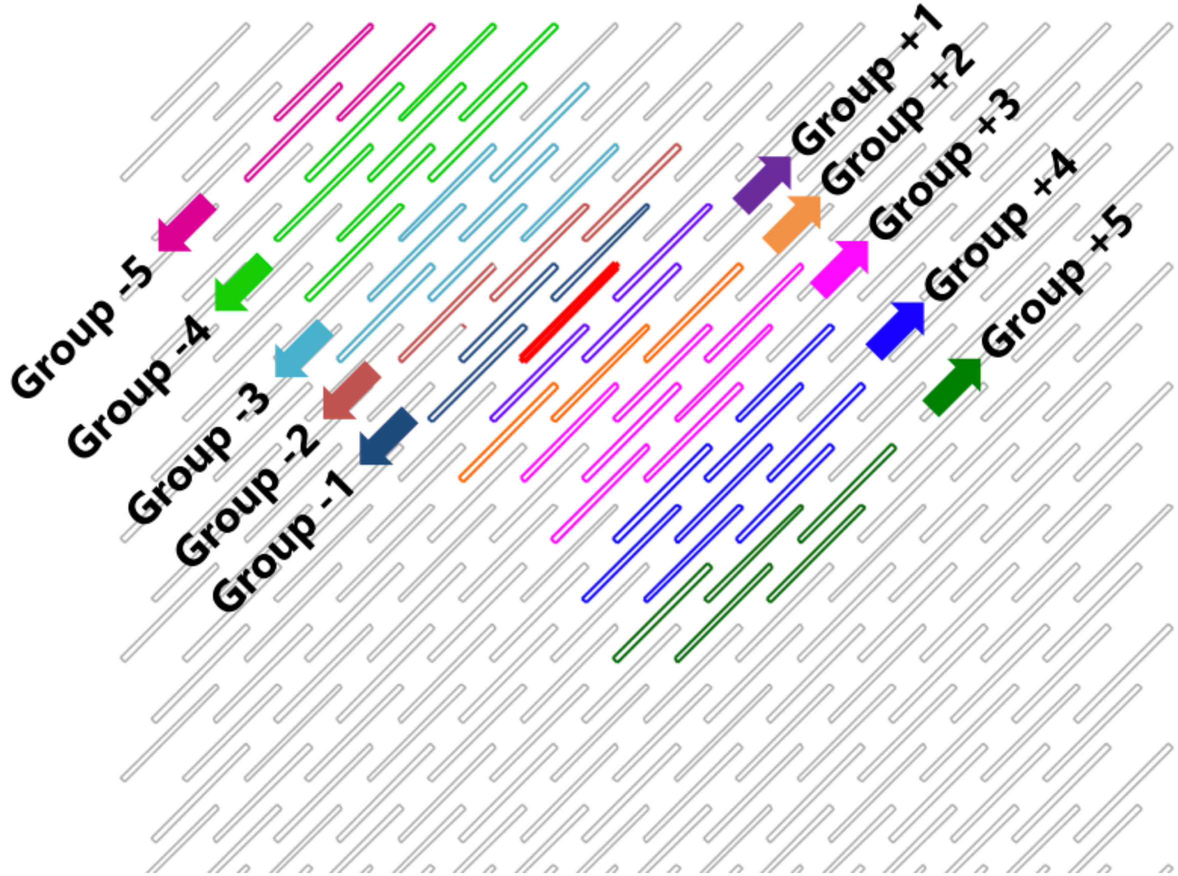
on 6511 events in LXE acceptance

	9 layer configuration at 25.06.2018	From git At 19.10.2018 (Many TC improvements)
SPX acceptance(crossing) :	: 88.97 %	: 88.97 %
DCH tracking(fakes hit) :	: x94.99 %	: x94.63 %
Quality cut :	: x98.78 %	: x98.74 %
Target propagation :	: x99.28 %	: x99.39 %
Tail cuts :	: x76.30 %	: x76.41 %
To TC propagation :	: x98.74 %	: x98.97 %
TC matching :	: x91.83 %	: x98.01 %
TC fake hits contamination :	: x99.49%	: x99.85%
Time tail cut :	: x94.72%	: x97.01%
SPX :	: 76.0 %	: 83.6 %
DCH :	: 71.1 %	: 71.0 %
Sum :	: 54.0 +- 0.6 %	: 59.3 +- 0.6 %



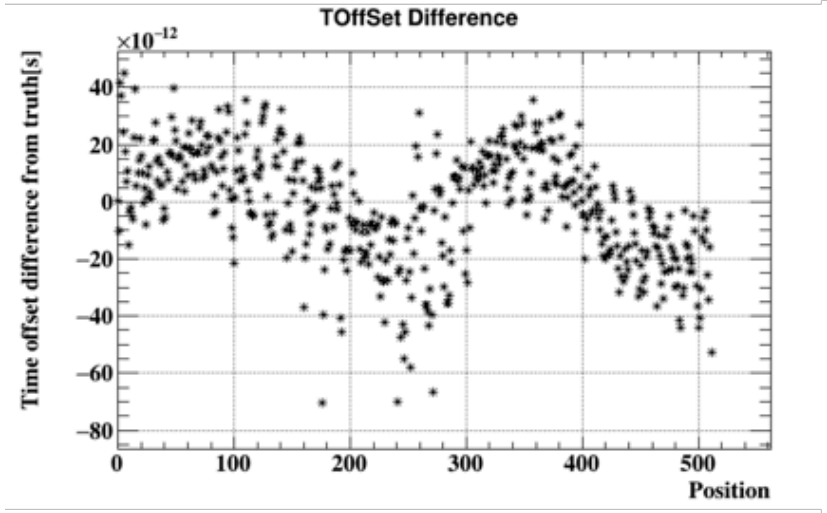


Grouping of r-estimation

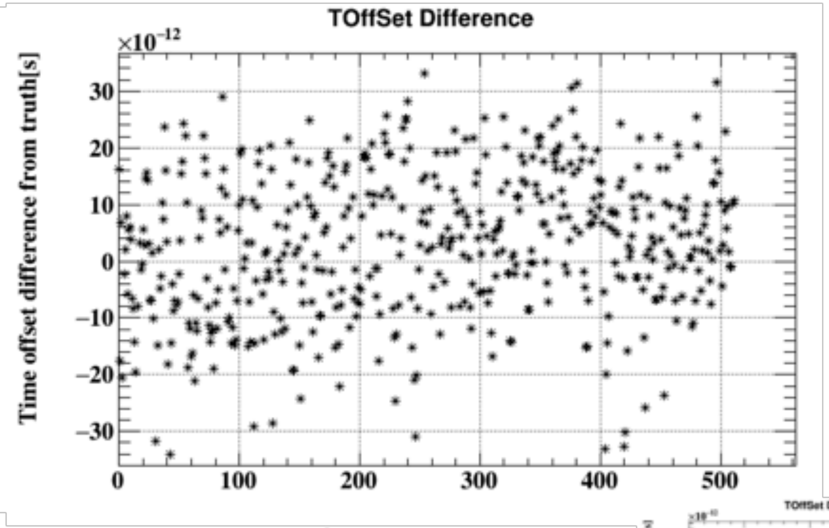


Mica

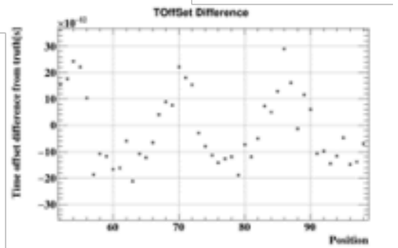
- z position bias has been solved by independent tracking
- But still there remains phi-direction dependence?
    - caused by algorithm itself? or something other problem?



σ~19.6 ps
with 3 tof patterns



σ~13.5 ps
with Independent track

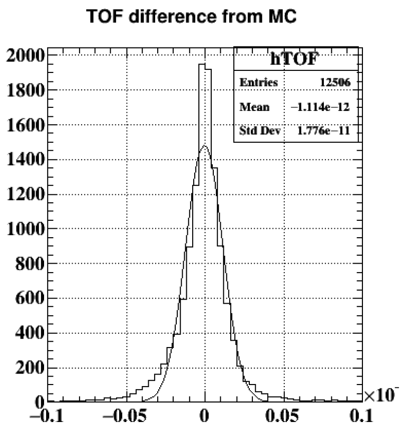


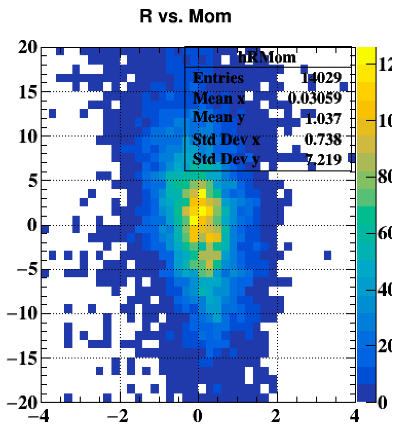
pTC Tracking with CDCH information

TOFの確認

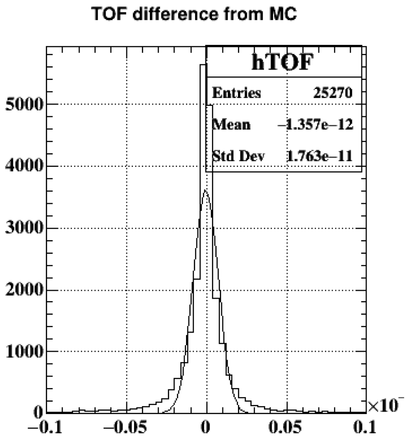
- TOFの精度は全部合わせてstv ~ 17.6 ps
  - IndependentTrackingとさほど変わらない(若干悪い？)
  - gaussianの幅は明らかに細い一方で、外れ値が増加している。
  - 若干ではあるが、Rを小さく見積もりがちな傾向。

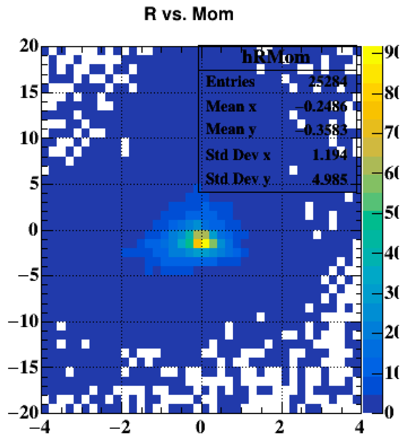
Independent



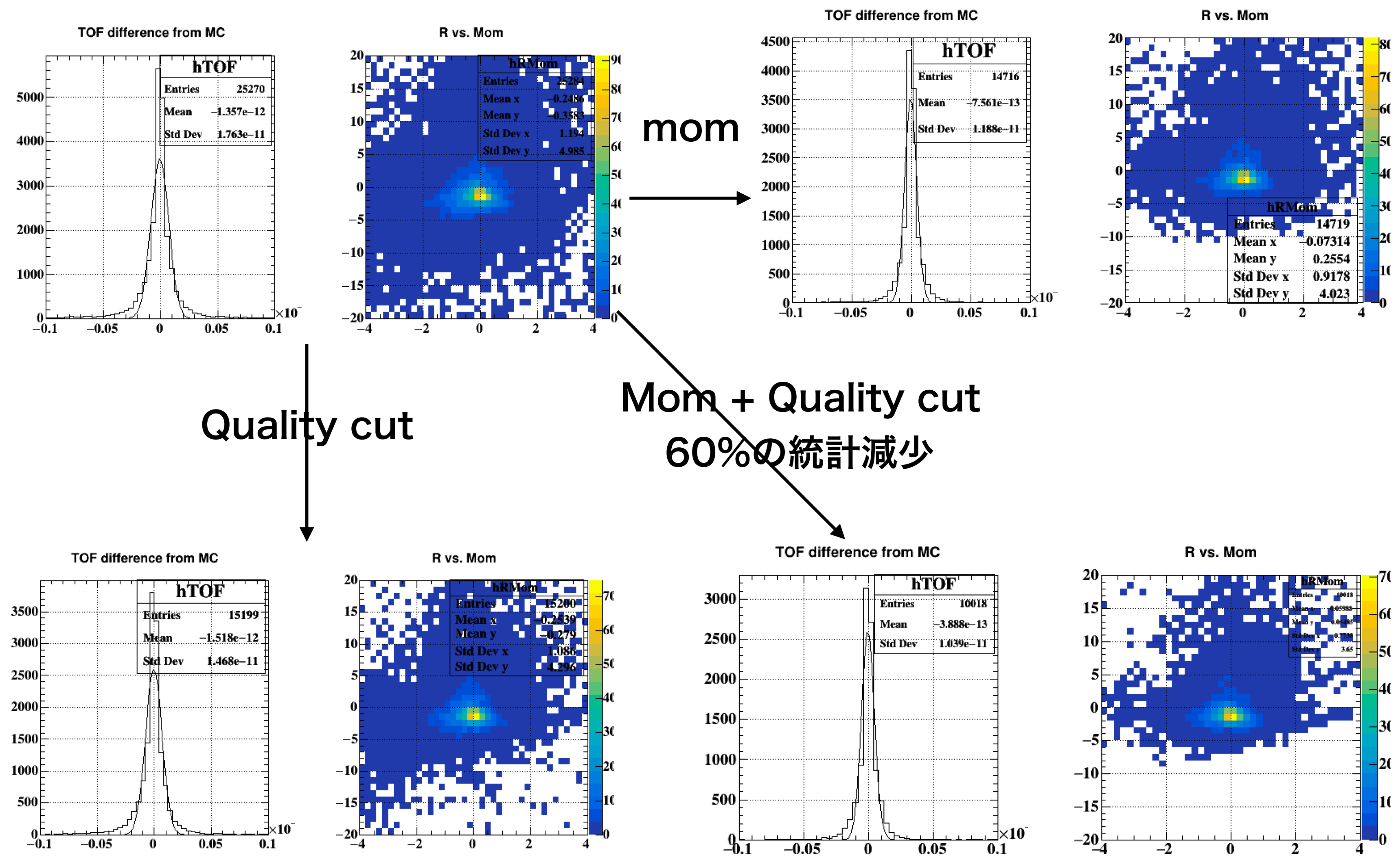


with CDCH



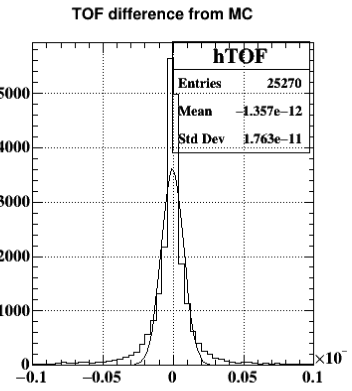


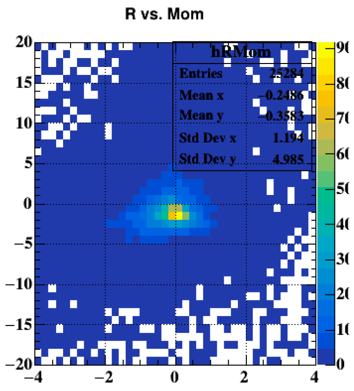
TOF の確認


TOF difference from MC
hTOF
Entries 25270
Mean −1.357e−12
Std Dev 1.763e−11
R vs. Mom
hRMom
Entries 25284
Mean x 0.2486
Mean y 0.3583
Std Dev x 1.194
Std Dev y 4.985
mom
TOF difference from MC
hTOF
Entries 14716
Mean −7.561e−13
Std Dev 1.188e−11
R vs. Mom
hRMom
Entries 14719
Mean x −0.07314
Mean y 0.2554
Std Dev x 0.9178
Std Dev y 4.023
Quality cut
Mom + Quality cut
60%の統計減少
TOF difference from MC
hTOF
Entries 15199
Mean −1.518e−12
Std Dev 1.468e−11
R vs. Mom
hRMom
Entries 15200
Mean x 0.2539
Mean y 0.279
Std Dev x 1.086
Std Dev y 4.296
TOF difference from MC
hTOF
Entries 10018
Mean −3.888e−13
Std Dev 1.039e−11
R vs. Mom
hRMom

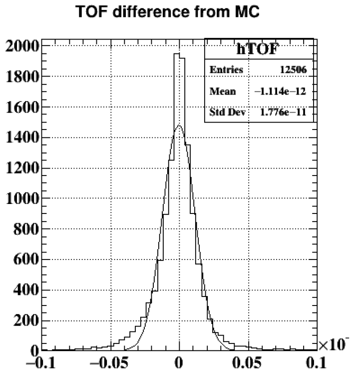
Event Selection

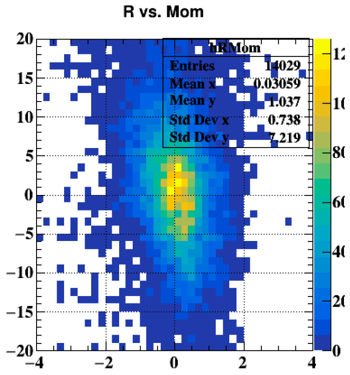
SPXTracking





IndependentTracking





40 MeV<mom<55 MeV

明らかにtail eventの減少

40 MeV<mom<55 MeV

Propagation to cyl

10%程度の統計減少

改善は小さい