Muon lifetime measurement at J-PARC muon g-2/EDM experiment

S.Ogawa (Kyushu Univ.)
H.Iinuma, T.Mibe, T.Yamanaka, Y.Sato

220829, SJTU-KEK workshop

Muon lifetime measurement

- Muon lifetime is the best way to determine the Fermi coupling constant G_F, which is an important input for the weak interaction tests (such as M_W) .

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left(1 + \sum_i \Delta q^{(i)}\right),$$

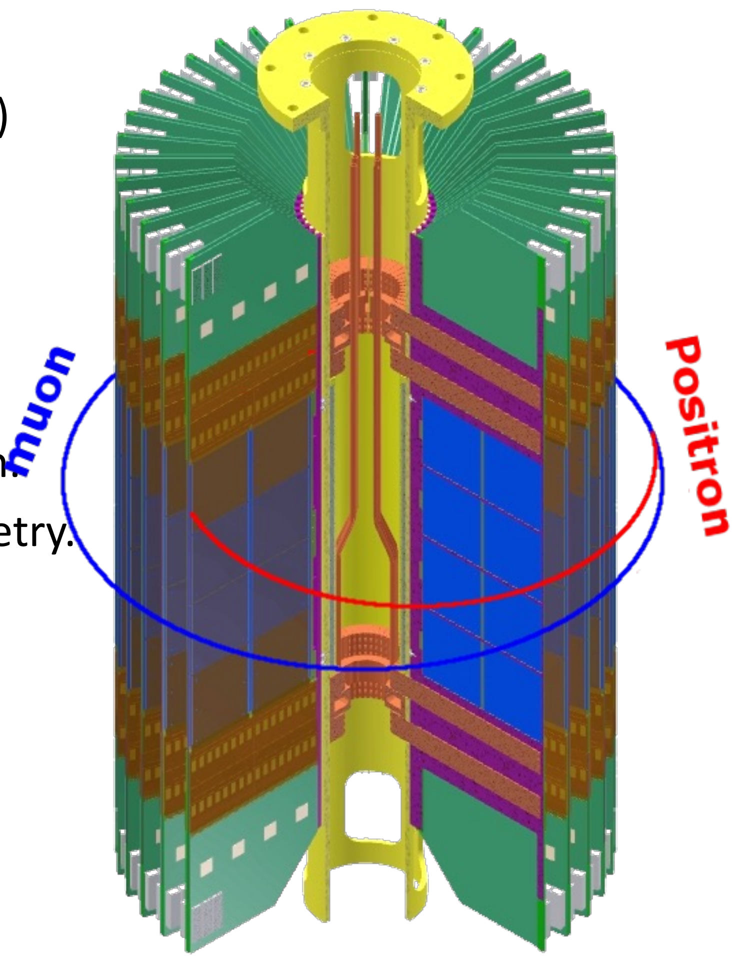
  - Δq : correction from electron mass, QED 1st and 2nd order radiative correction. Its theoretical uncertainty is 0.14ppm
  - m_μ : Muon mass. Measured to be 105.6583755(23) MeV (0.02ppm).
  - τ_μ : Muon life time.
- Most precise value of τ_μ is given by the MuLAN experiment at the precision of (1.0ppm).
  - $\tau_\mu = 2196980.3 \pm 2.1\ (\mathrm{stat}) \pm 0.7(\mathrm{syst})\ \mathrm{ps}$
- Experimental error on τ_μ limits the precision of G_F.

- Comparison with the MuLAN result may be a test of time dilation in special and general relativity.

Muon storage region in E34 experiment

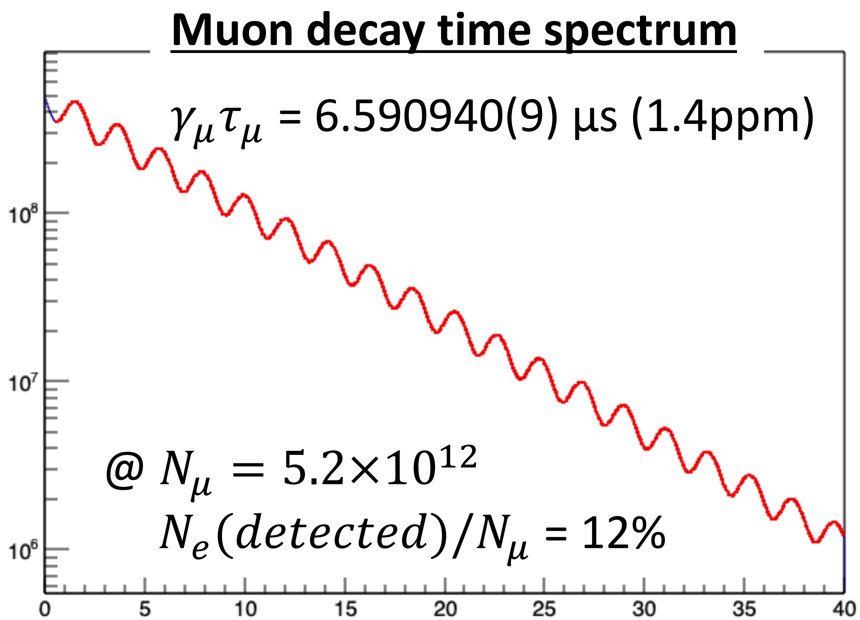
- Muons are injected into the storage region, and follows a cyclotron motion.
- Storage region:
  - Beam profile
    - Z : ~ ±10 mm (VBO amplitude)
    - Lorentz factor γ: 3.0 (spread: 0.04% in rms)
  - B_z: 3T (uniformity: 0.1ppm)

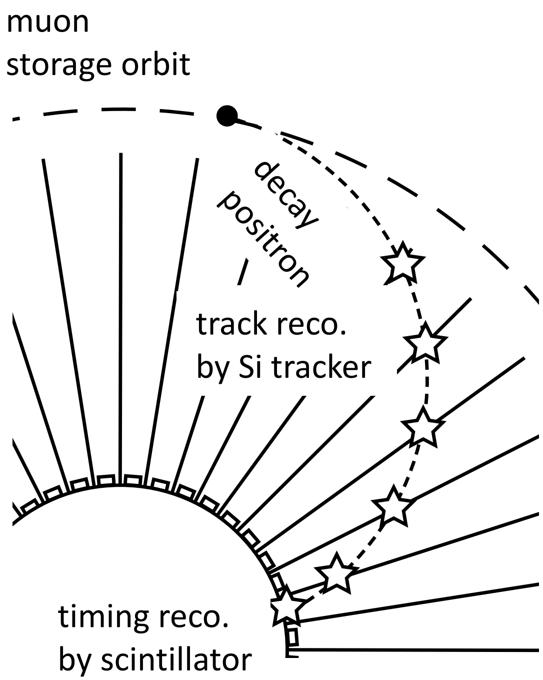
- Decay positrons are measured by a silicon strip detector.
  - g-2 meas. by a wiggle of decay time distribution.
  - EDM meas. by a wiggle in the up-down asymmetry.



Muon lifetime meas. at E34

- This setup can also be used for muon lifetime measurement.
- Dilated lifetime of muon $\gamma_\mu \tau_\mu$ from decay time spectrum of positron
- Lorentz factor of muon γ_μ from cyclotron period measured from muon bunch motion.

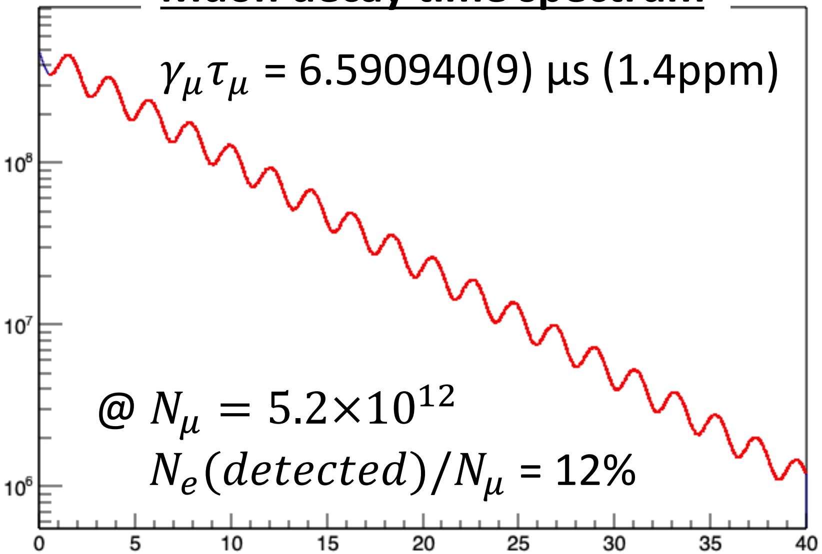




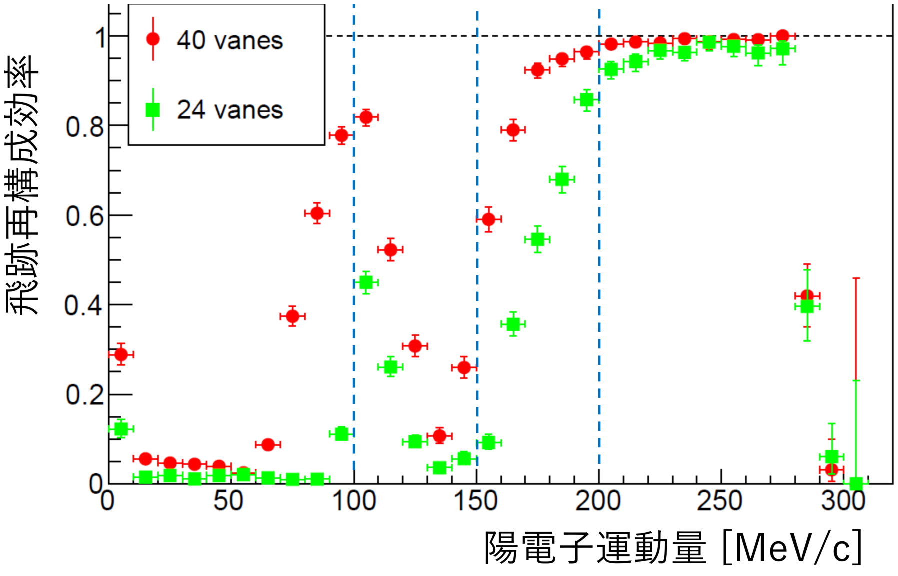
Dilated lifetime $\gamma_\mu \tau_\mu$ measurement

- Dilated muon lifetime $\gamma_\mu \tau_\mu$ can be obtained from the Wiggle plot.
- Expected statistical uncertainty is 1.4ppm (comparable to MuLAN.)
  - assuming $N_\mu = 5.2 \times 10^{12}$, and positron detection efficiency of 12 % (TDR statistics)
- Further improvement may be possible by efficiency enhancement by detecting the decay positrons with lower momentum.
  - Increase number of vane
  - Track finding algorithm improvement

Muon decay time spectrum



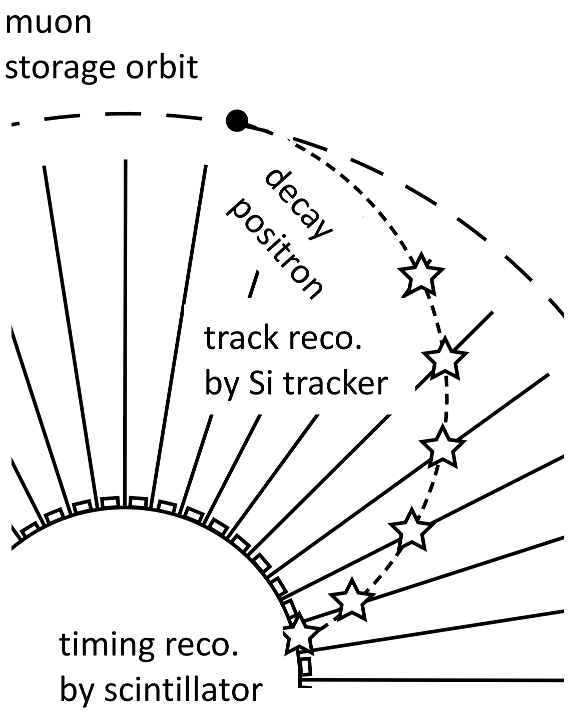
Detection efficiency vs. positron momentum



Lorentz factor γ_μ measurement

- Lorentz factor of muon γ_μ will be measured from its cyclotron period τ_c , which can be measured from the muon bunch position.
  - $\gamma_\mu = eB/(\tau_c m_\mu 2\pi)$

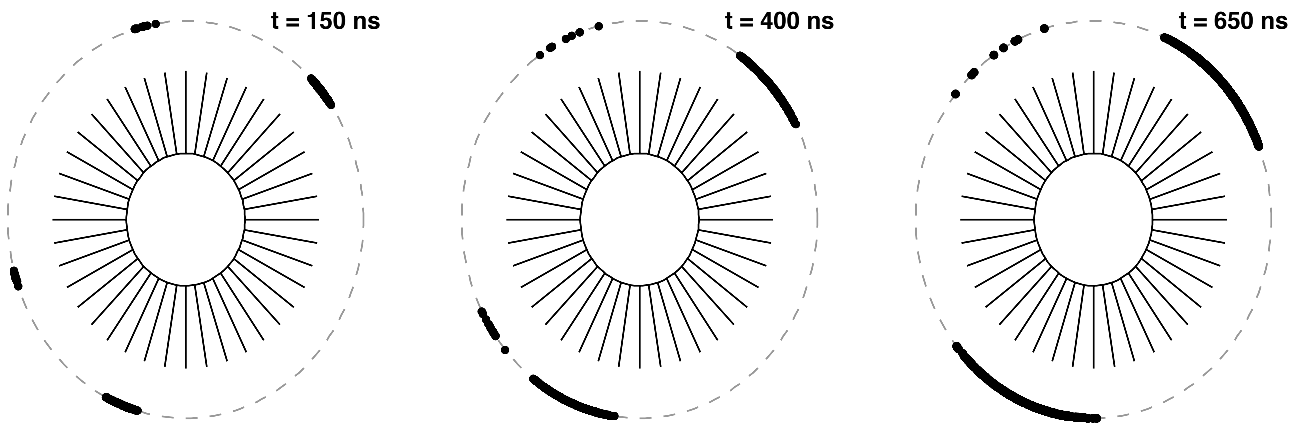
- Cyclotron period is measured from the motion of muon bunch.
  - Motion of each muon bunch can be measured from reconstructed decay vertex and timing.
  - decay vertex : intersection of muon storage orbit and measured positron track.
  - decay timing: measured timing of positron track



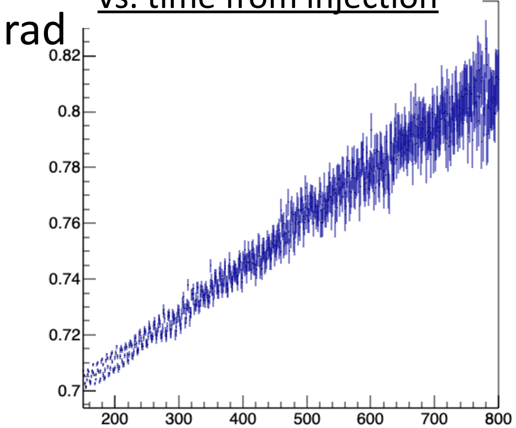
Lorentz factor γ_μ measurement

- In reality, distribution of γ_μ has also to be measured.
  - Design value of γ_μ distribution : 0.04% rms.
- This should be possible from the "de-bunching speed" of muon beam.

Simulated muon position (as a function of time from injection)

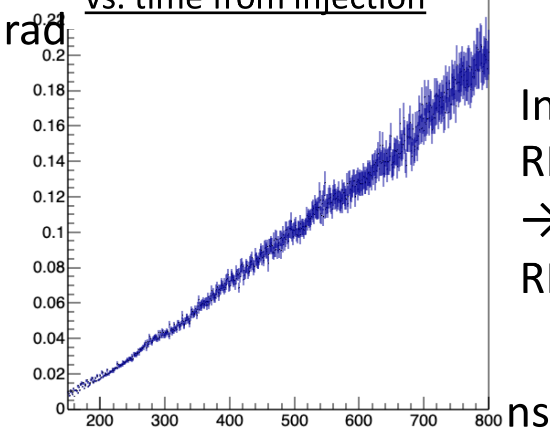


Mean position of bunch vs. time from injection



Circulation period of center of each bunch
→
Mean of γ_μ

"Width" of bunch vs. time from injection

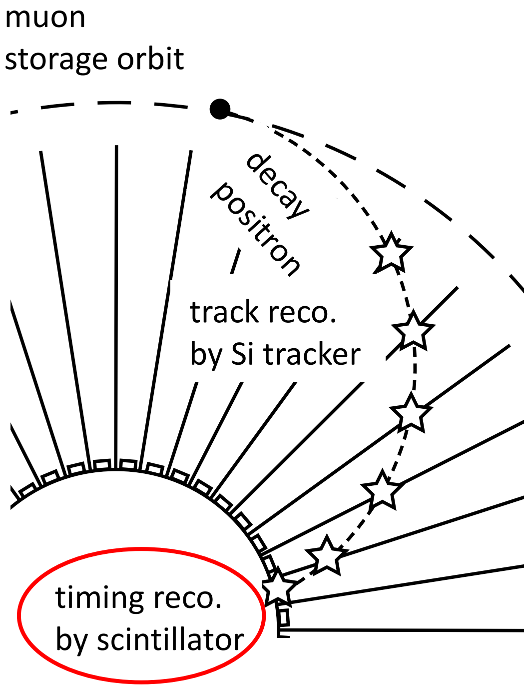


Increase on the RMS of each bunch
→
RMS of γ_μ

New timing counter

- Timing resolution of the silicon strip detector may not be sufficient for γ_μ measurement.
  - Expected timing resolution is limited for ~ 1.2ns.
    - Depending on the number of vane hit by each positron
  - Minimum interval between bunches is ~ 1ns.
    - Bunch by bunch separation is difficult with this timing resolution.

- A new detector dedicated for the timing measurement is under consideration.
  - Fast plastic scintillator + SiPM readout
  - ~ 100 small scintillator blocks ($3\times3\times20$ mm^3) mounted on the center pole of silicon tracker
  - 100ps timing resolution should be achievable.
    - Based on the technology adopted in MEG II/Mu3e experiment.



Summary

- A possibility of a precise muon lifetime measurement in J-PARC E34 experiment is discussed.

- The dilated muon lifetime $\gamma_\mu \tau_\mu$ is obtained from the decay time spectrum.
- The Lorentz factor γ_μ is obtained from the cyclotron period, which is reconstructed from the decay positron tracks. A new additional detector for timing measurement is being discussed.

- Statistical uncertainty will be ~ 1ppm, which is better or comparable to the current upper limit given by the MuLan experiment.
- Systematic uncertainty has to be investigated, especially on the pileup effect on efficiency, the muon loss, the precision of γ_μ measurement, and the effect of VBO/CBO etc...

We start thinking about this possibility recently, and we would appreciate it if you could give us some comments and advices based on your experience at BNL/FNAL.

BACKUP

MuLAN result

$$\tau_\mu(\text{R06}) = 2196979.9 \pm 2.5(\text{stat}) \pm 0.9(\text{syst})\ \text{ps} \quad (20)$$

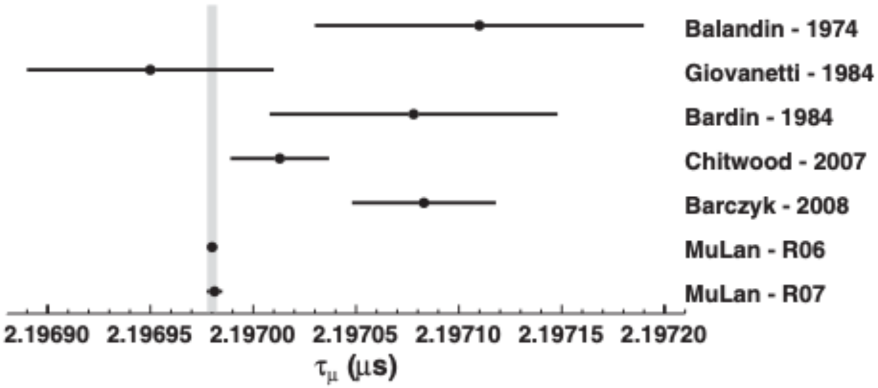
and

$$\tau_\mu(\text{R07}) = 2196981.2 \pm 3.7(\text{stat}) \pm 0.9(\text{syst})\ \text{ps}. \quad (21)$$

The combined result

$$\tau_\mu(\text{MuLan}) = 2196980.3 \pm 2.1(\text{stat}) \pm 0.7(\text{syst})\ \text{ps} \quad (22)$$

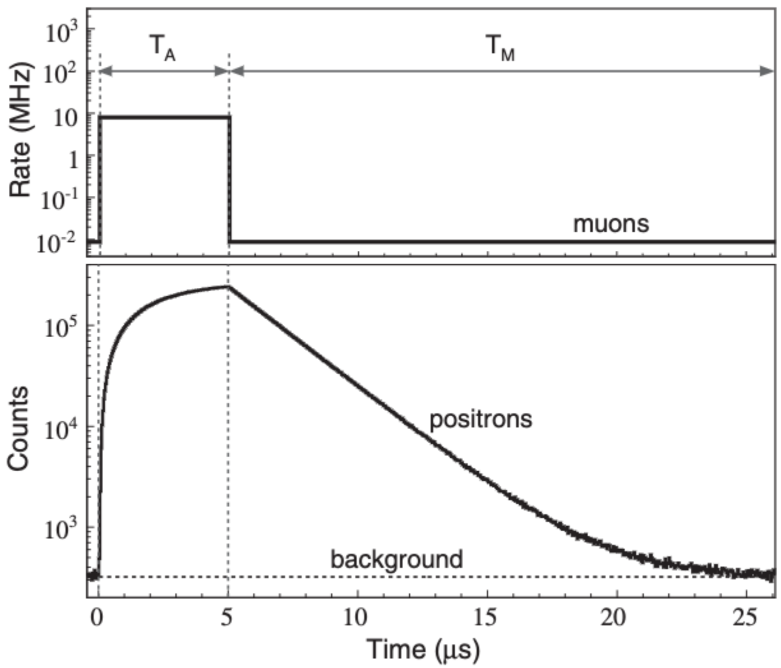
<table>
<tr><th>Uncertainty</th><th>R06 (ppm)</th><th>R07 (ppm)</th></tr>
<tr><td>Kicker stability</td><td>0.20</td><td>0.07</td></tr>
<tr><td>μSR distortions</td><td>0.10</td><td>0.20</td></tr>
<tr><td>Pulse pileup</td><td colspan="2">0.20</td></tr>
<tr><td>Gain variations</td><td colspan="2">0.25</td></tr>
<tr><td>Upstream stops</td><td colspan="2">0.10</td></tr>
<tr><td>Timing pick-off stability</td><td colspan="2">0.12</td></tr>
<tr><td>Master clock calibration</td><td colspan="2">0.03</td></tr>
<tr><td>Combined systematic uncertainty</td><td>0.42</td><td>0.42</td></tr>
<tr><td>Statistical uncertainty</td><td>1.14</td><td>1.68</td></tr>
</table>

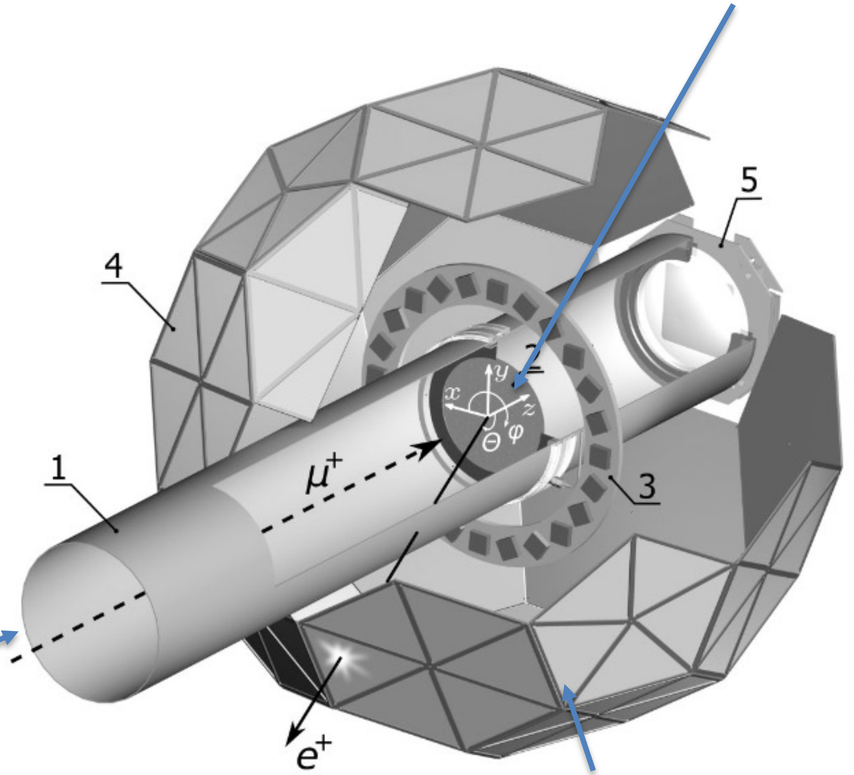


$$G_F(\text{MuLan}) = [1.1663787(6) \times 10^{-5}]\ \text{GeV}^{-2}\ (0.5\ \text{ppm}).$$

MuLan実験概要

- 「5us beamを標的に当てる→22us 崩壊用電子数を測る」を繰り返す。



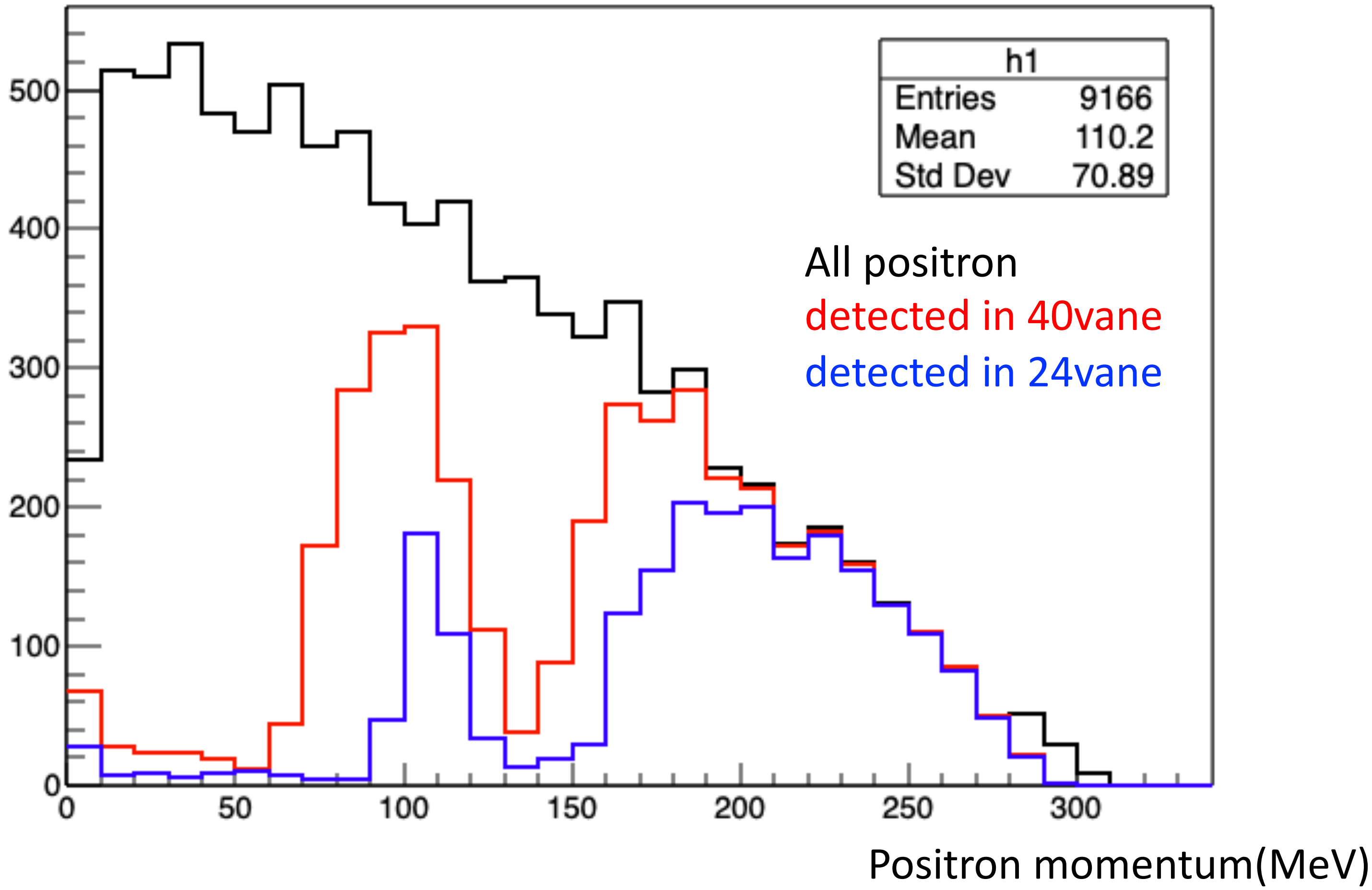


標的で止める
止めた後のPolarizationを制御

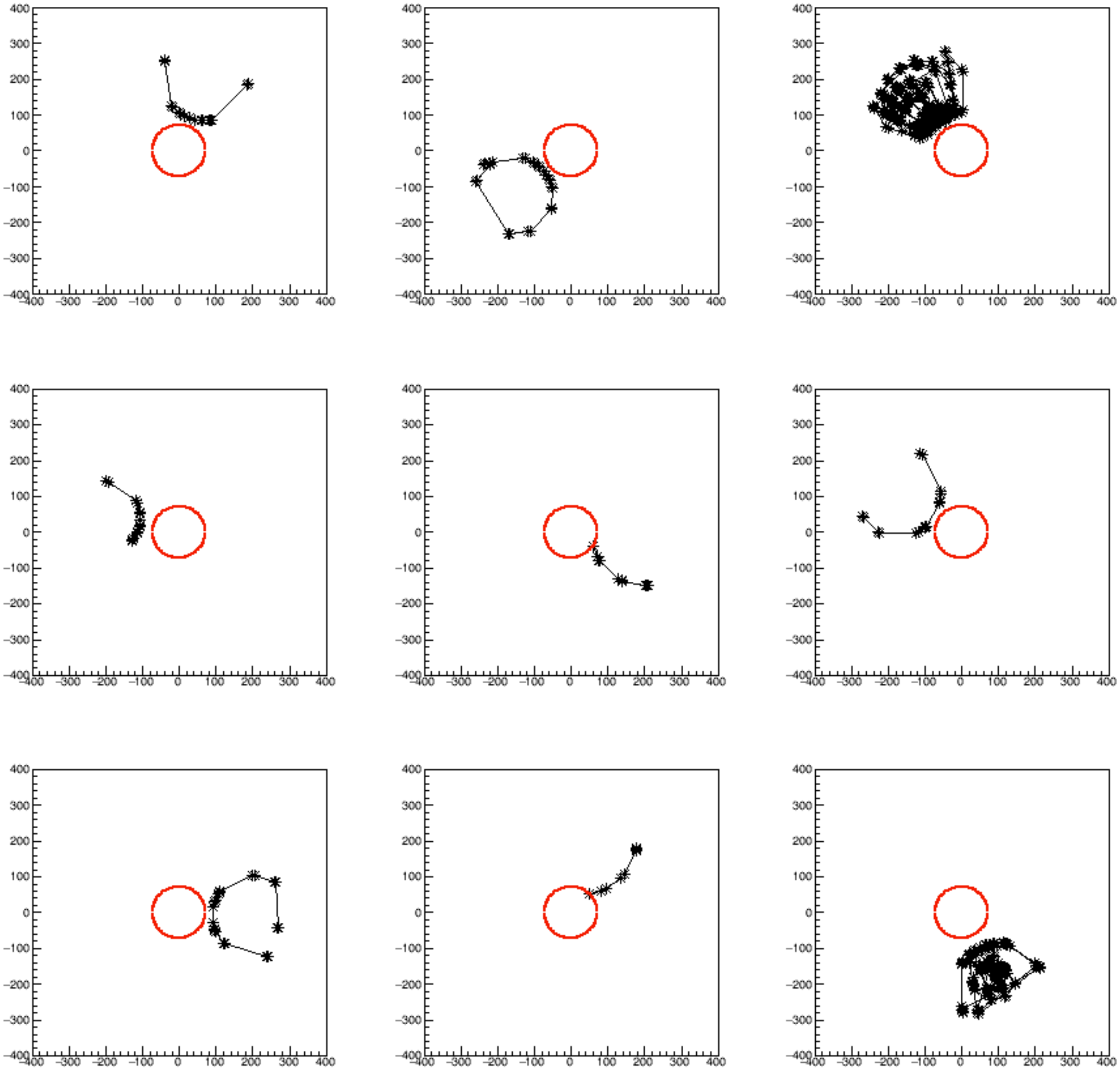
Surface DC muon beam
をKickerでpulse化

崩壊陽電子をシンチで測定
立体角70%でカバー
Pileup対策 (Early-to late effect)

muon lifetime stat

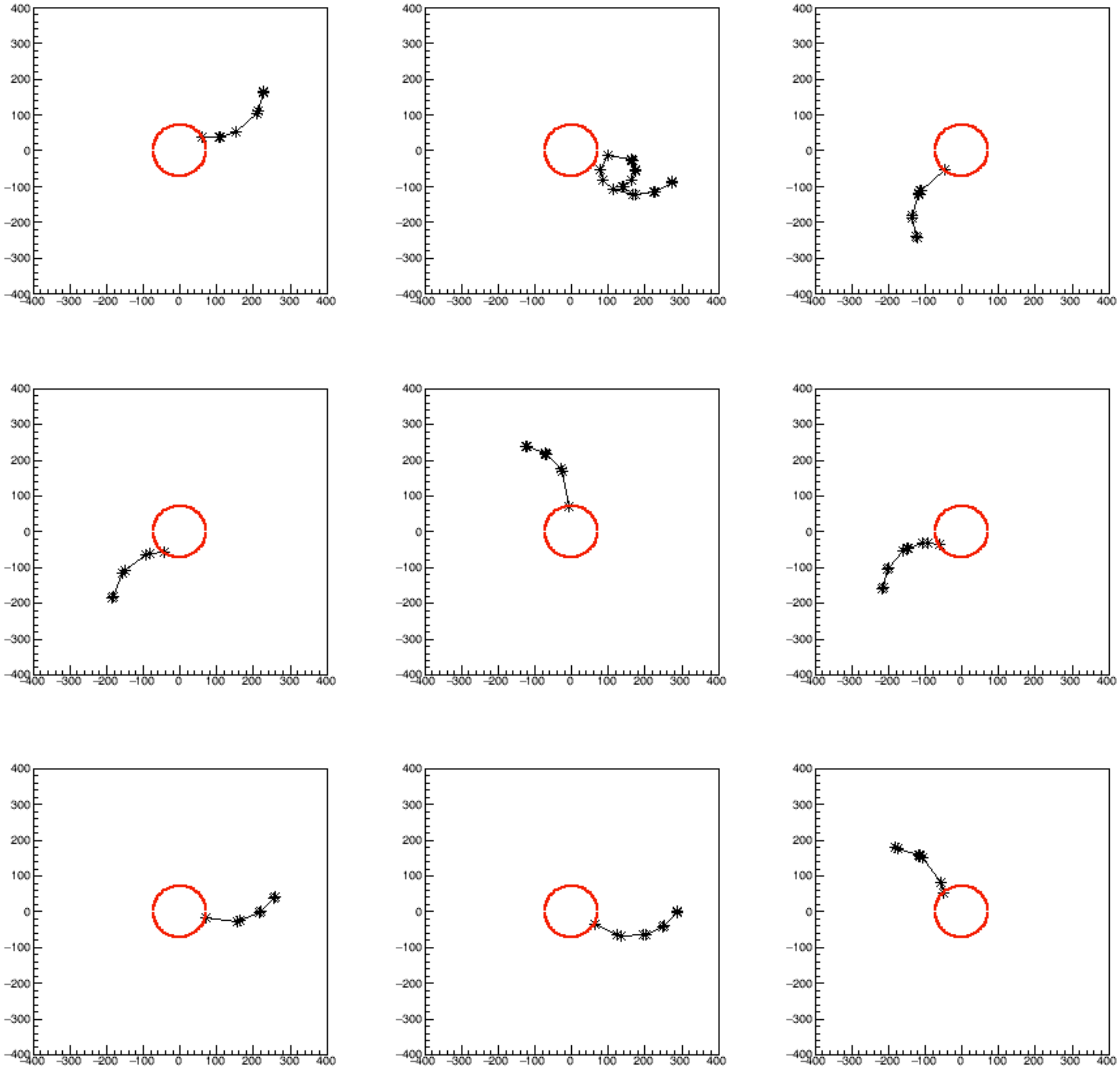


110-130 MeV

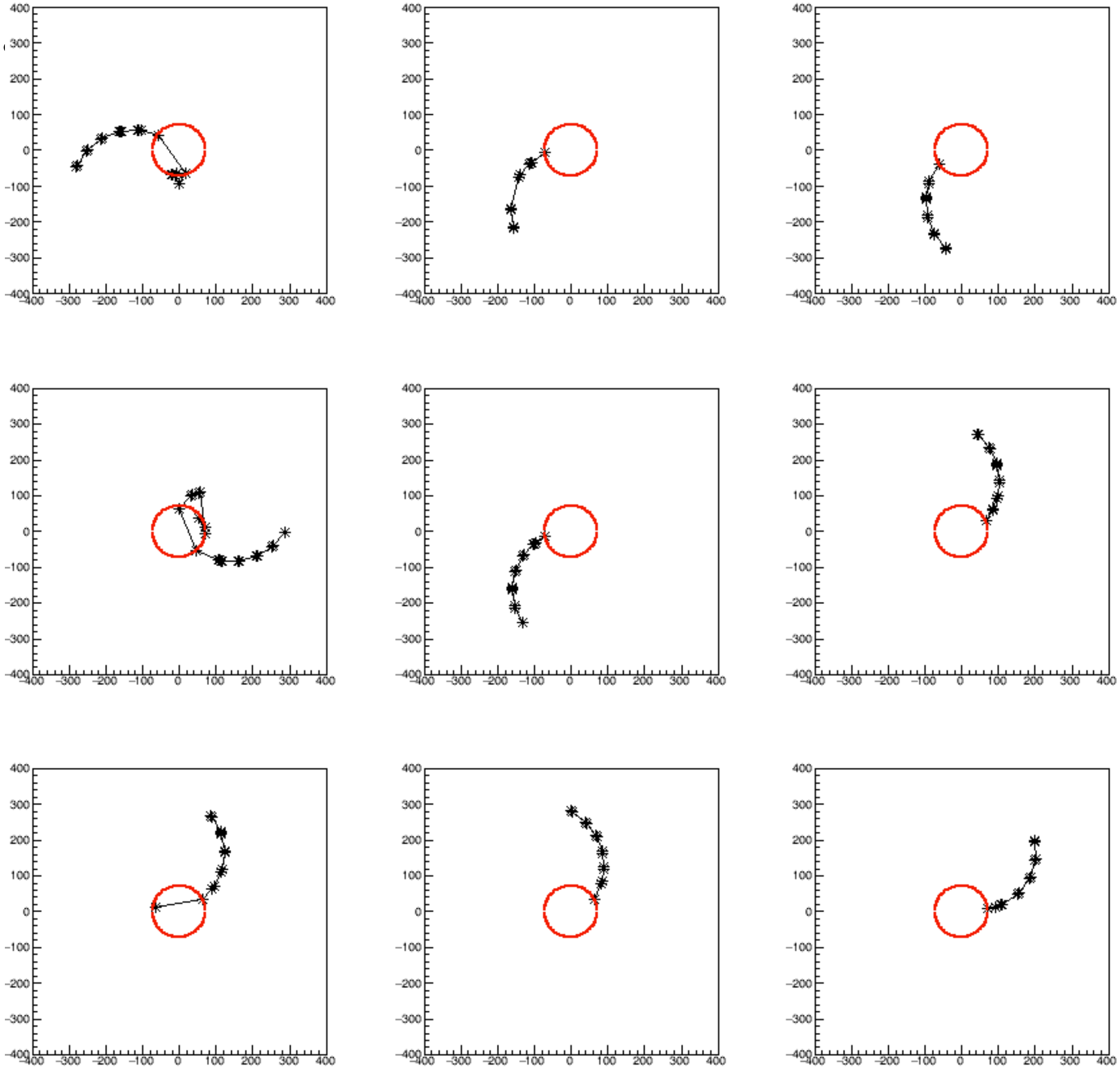


400
300
200
100
0
−100
−200
−300
−400
−400 −300 −200 −100 0 100 200 300 400

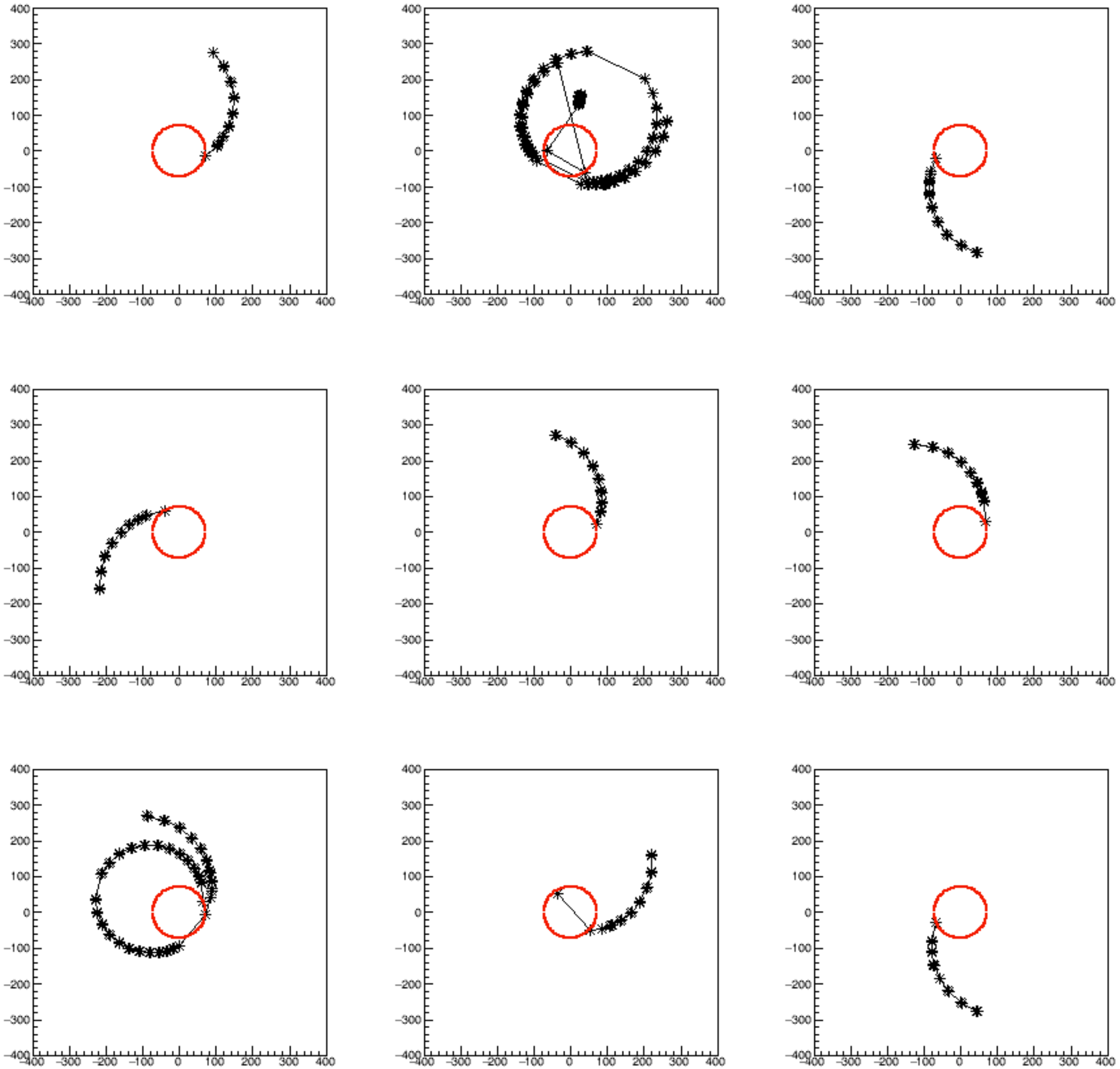
130-150 MeV


400 300 200 100 0 −100 −200 −300 −400
−400 −300 −200 −100 0 100 200 300 400

150-170 MeV


400
300
200
100
0
-100
-200
-300
-400
-400 -300 -200 -100 0 100 200 300 400

170-190 MeV


400 300 200 100 0 −100 −200 −300 −400
−400 −300 −200 −100 0 100 200 300 400