Precise Measurement of the Positive Muon Lifetime at RIKEN-RAL Muon Facility

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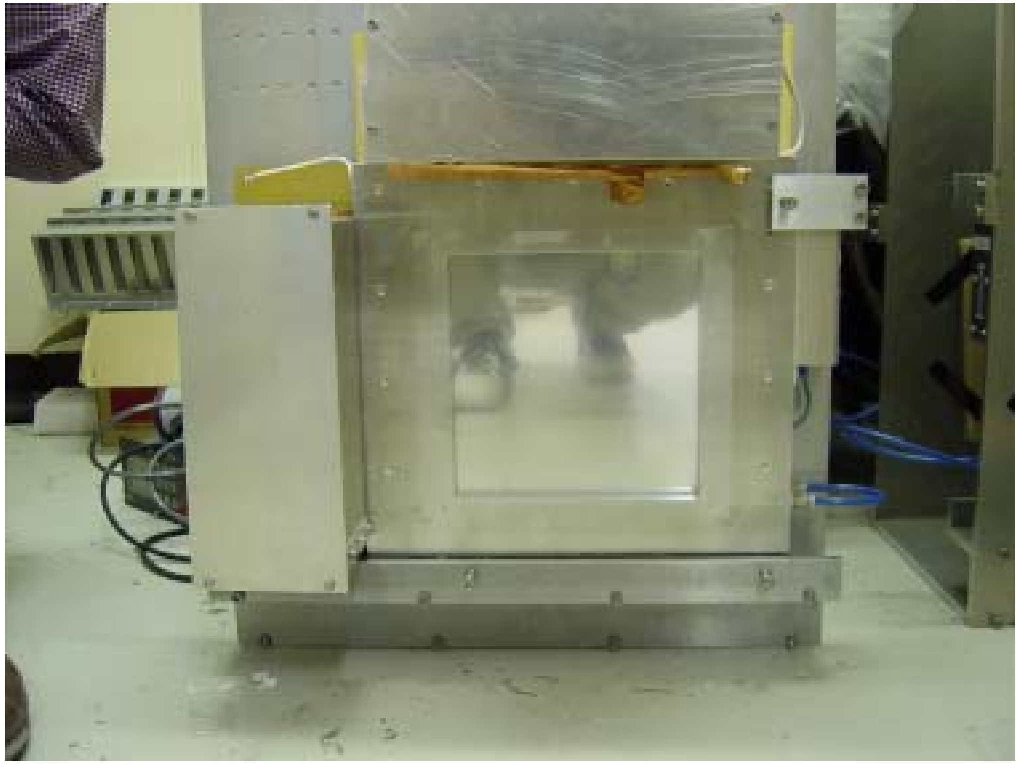
Dai Tomono RIKEN Muon Sci.

S.N. Nakamura Tohoku Univ.
Y. Matsuda RIKEN Muon Sci.
G. Mason Victoria Univ.
M. Iwasaki RIKEN Muon Sci.
K. Ishida RIKEN Muon Sci.
T. Matsuzaki RIKEN Muon Sci.
I. Watanabe RIKEN Muon Sci.
S. Sakamoto KEK Meson Lab.
K. Nagamine KEK Meson Lab.



Motivation

In the electro-weak Standard model Three input parameters

$\Delta\alpha / \alpha \sim 0.045$ ppm **$\Delta G_F / G_F \sim 9$ ppm** **$\Delta M_Z / M_Z \sim 22$ ppm**

Lifetime formula

Muon lifetime τ_μ

- G_F is defined by the muon lifetime
- G_F is one of the input parameters in the Standard Model.
- The error on M_Z will be comparable to the G_F
- Precise test of the Standard Model

Muon lifetime

- Definition of the muon lifetime

$$\boxed{\tau^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left[1 + \frac{3}{5}\frac{m_\mu^2}{m_W^2}\right]\left[1 + \Delta q\right]}$$

T . van Ritbergen and R.G. Stuart
PRL 82(1999)488

$$F(x) = 1 - 8x - 8x^3 - x^4 - 12x^2 \ln(x)$$

$$\alpha^{-1}(m_\mu) = \alpha^{-1} - \frac{2}{3\pi}\ln\left(\frac{m_\mu}{m_e}\right) + \frac{1}{6\pi}$$

$$\Delta q = C_1 \frac{\alpha(m_\mu)}{\pi} + C_2 \frac{\alpha^2(m_\mu)}{\pi^2}$$

$$C_1 = \frac{25}{8} - \frac{\pi^2}{2}$$

$$C_2 = \frac{156815}{5184} - \frac{1036}{27}\zeta(2) - \frac{895}{36}\zeta(3) + \frac{67}{8}\zeta(4) + 53\zeta(2)\ln(2)$$

$$m_\mu \sim 0.3\,ppm$$

$$m_e \sim 0.3\,ppm$$

$$\frac{m_\mu}{m_W} < 1.0\,ppm$$

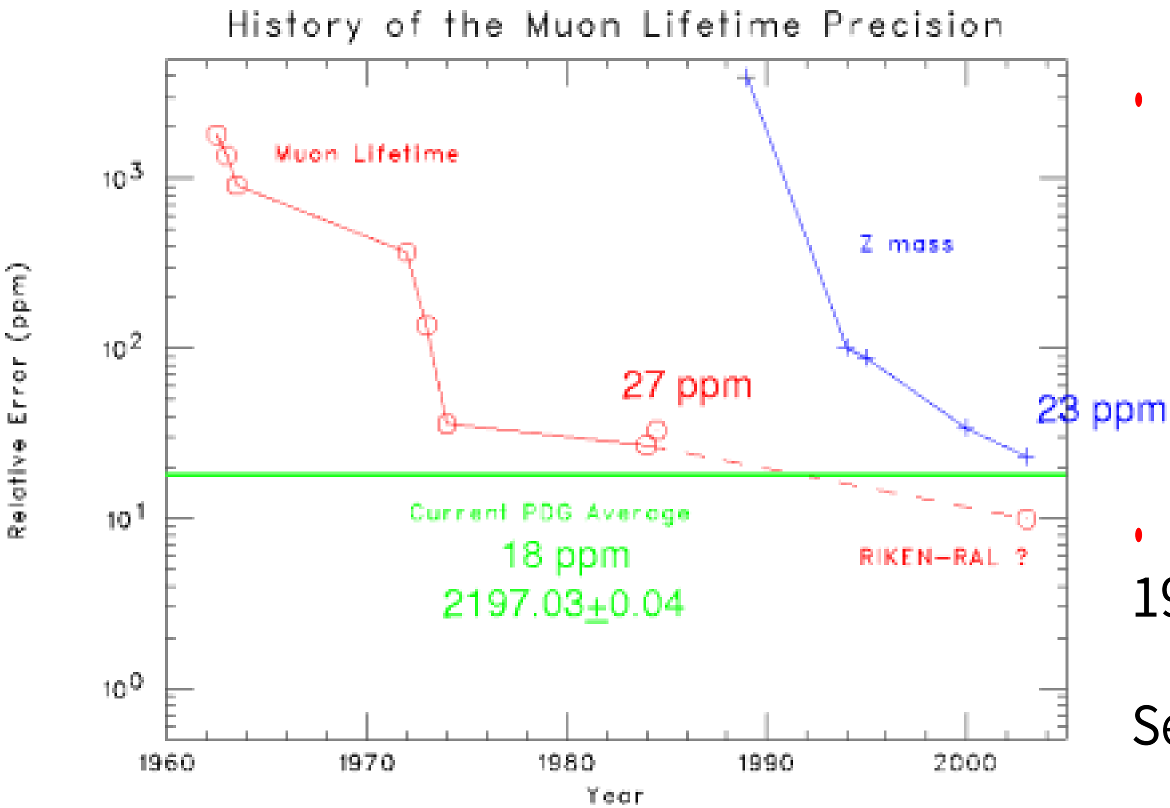
- **Decay mode**

$\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e$ (~ 100%)

$\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e \gamma$

$\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e e^+ e^-$ (~ 3.4 x 10^4)

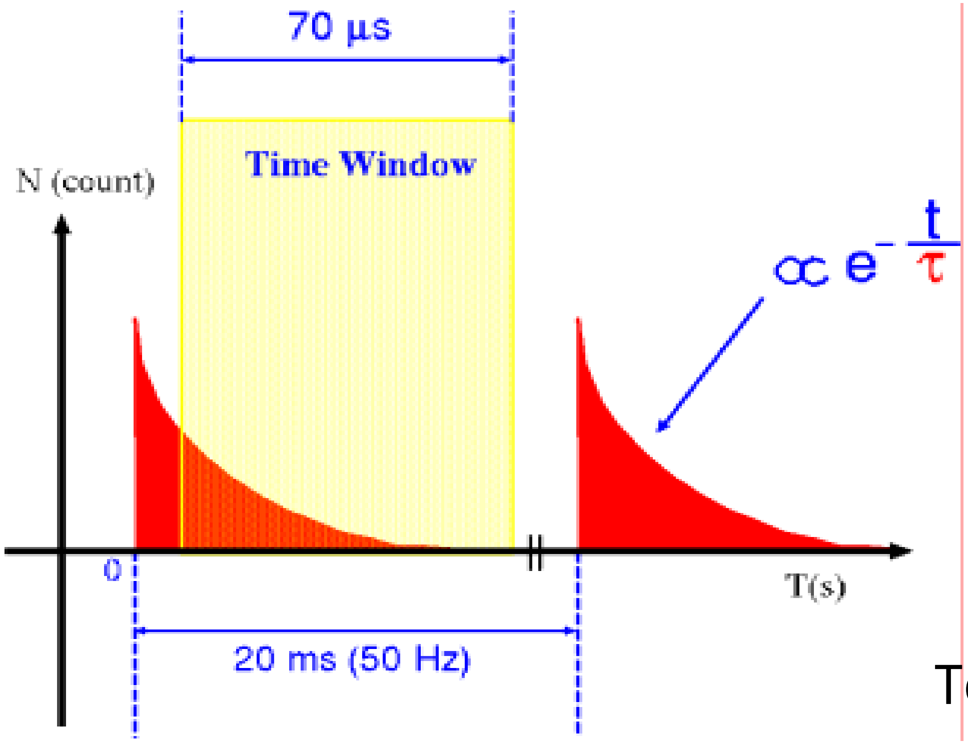
Historical Background



- Experiment
  1984 TRIUMF
  (Giovanetti et.al)
  < 27 ppm

- Theory
  1999 T.van.Ritbergen et.al
  < 1 ppm
  Second order radiative collection

Present Experiment at RIKEN-RAL



- High event rate
  ex. at the RAL
  200 x 50 Hz
  = 10^4 events / sec

- Count loss by the pile-up is a serious problem.

To decrease the count loss

- Fine segmented detector
- Offline correction

Experimental Feature

I. Higher event rate

- Strong pulsed beam at RIKEN-RAL (50 Hz, ～10^6/sec surface $\mu+$)
- Use MWPC for segmented detector （192 segmentations）

  (decrease the pile-up effect)

II Target selection

- Very short spin relaxation time

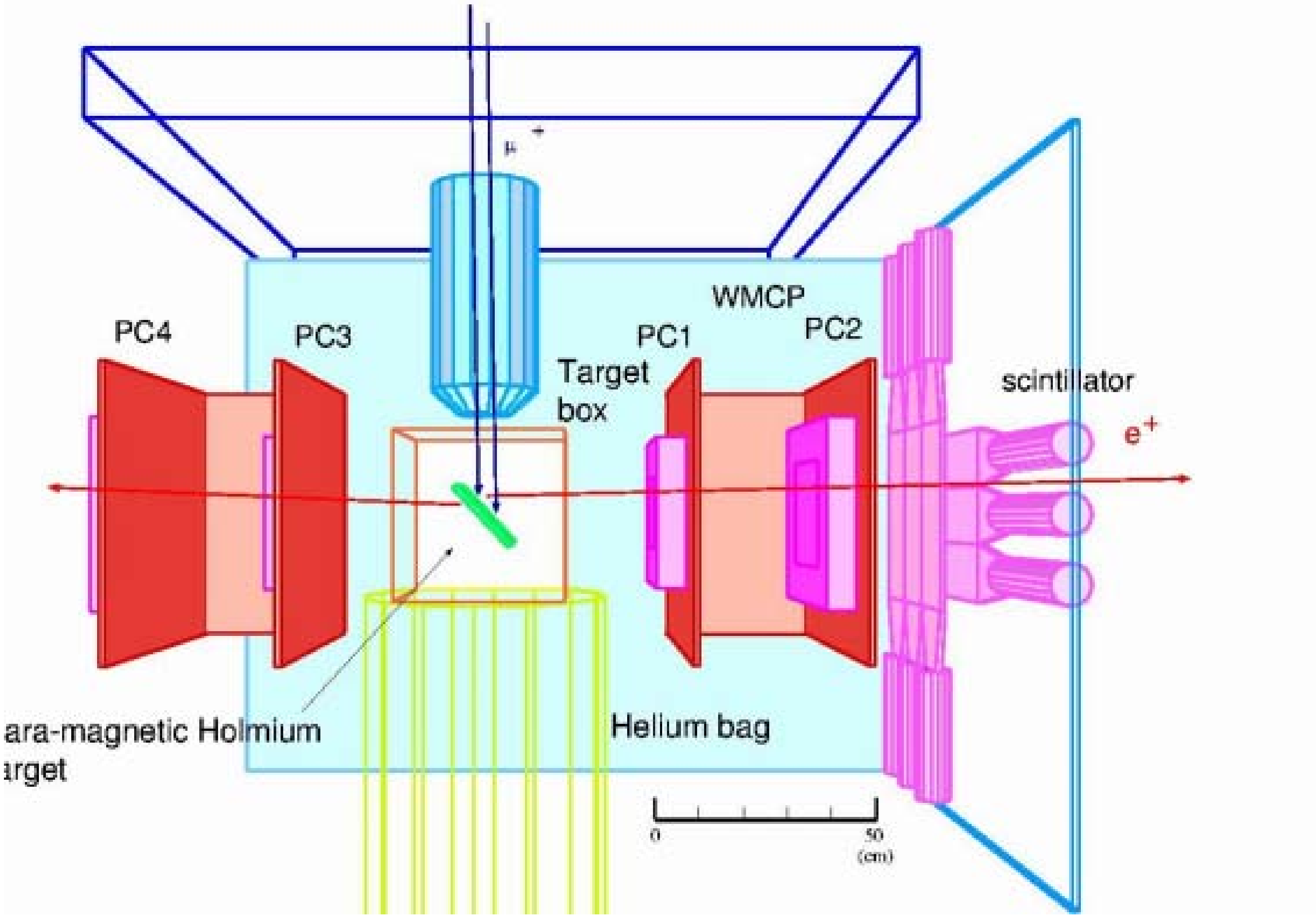
  (reduce distortion of decay spectrum)

- Select the decay positron from the target

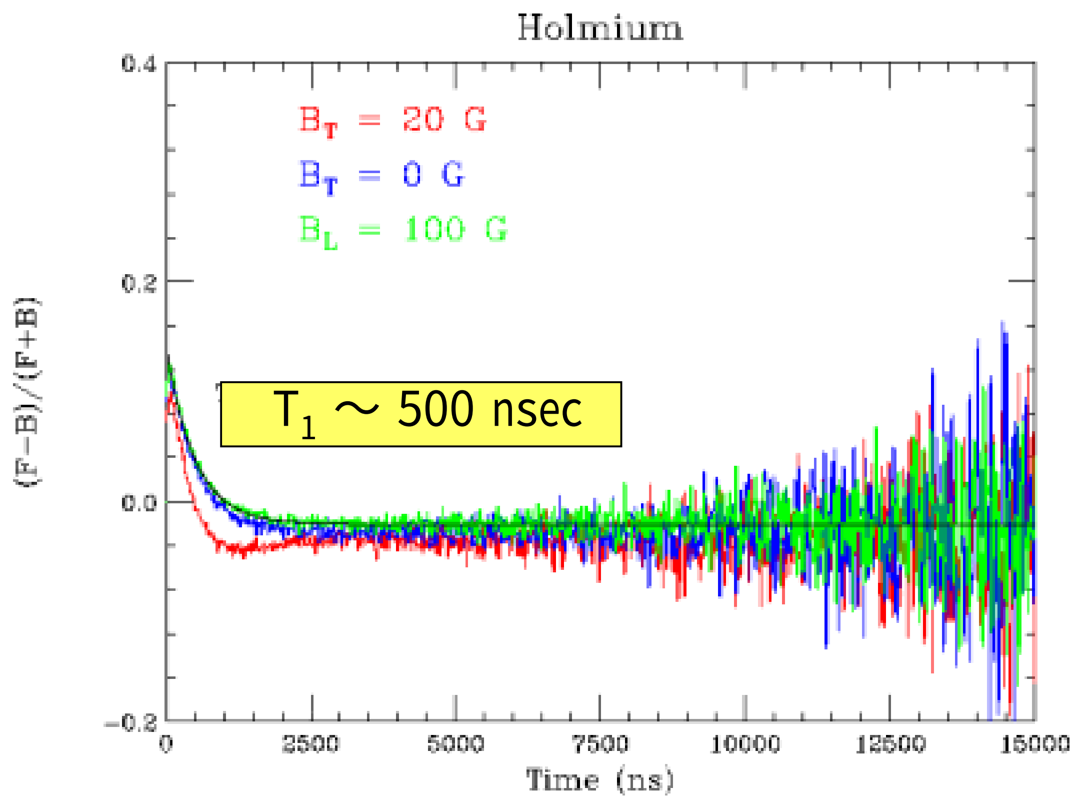
III Very accurate and multi-stop clock

- Synchronize GPS and Latching Memory every 100 nsec
- Monitor same signal with multi-stop TDC (500 psec bin)

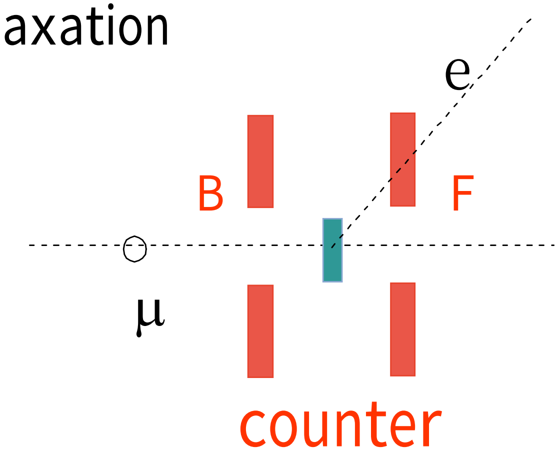
Experimental Set-up



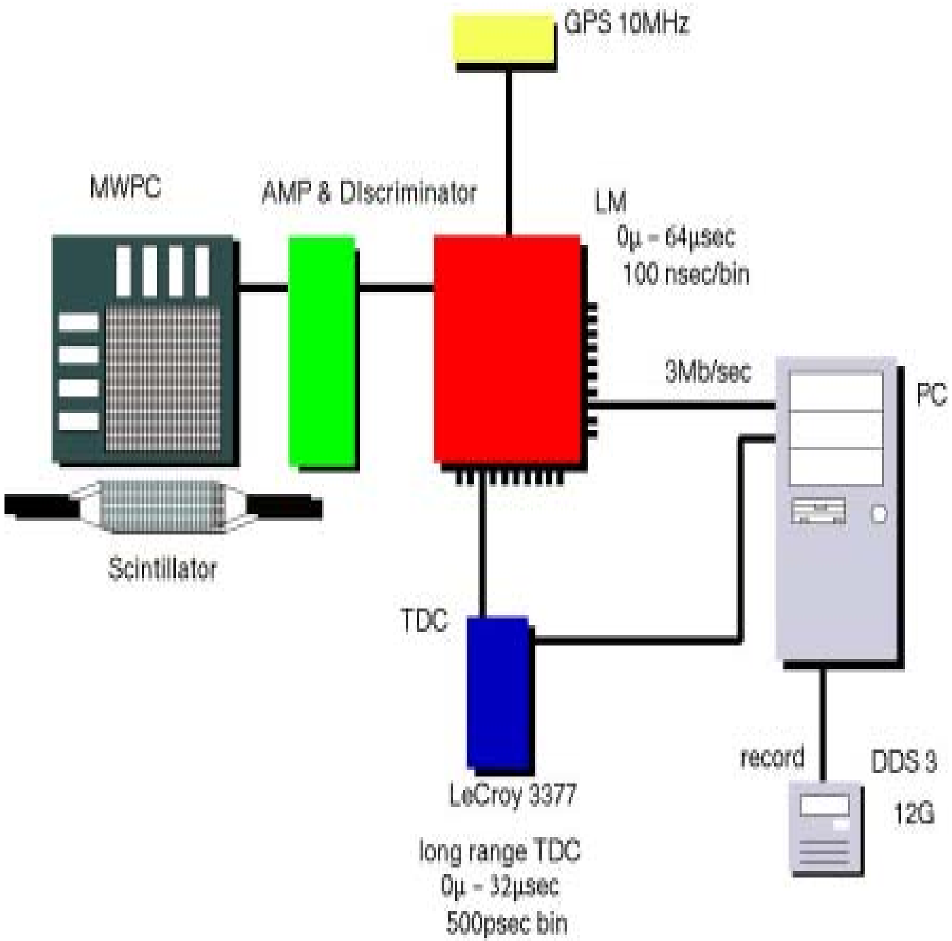
Spin relaxation in para-magnetic Holmium



- Spin assymmetry was measured
- Zero, Transverse and Longitudinal field were applied (independent of the magnetic field)
- Rapid and exponential relaxation



Data Acquisition System



- Very Accurate Clock (< 10^{-12})
  Synchronized
  GPS and LM(10MHz)
- Examine MWPC hit pattern
  Multi-hit TDC(500 psec)
- DAQ system
  4 CAMACs in parallel (3Mb/sec)
- Scintillators
  calibration purpose

Analysis

- Examine event structure （MWPC）、event selection
  Examine Multiplicity, Cluster size, Beam current
- Time calibration
  LM analysis (Mainly used)
  Determine dead-time in the off-line analysis (d=200)
- Estimate count loss by pile-up event
  Establish the correction method
- Fitting
- Estimate systematic error

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Count loss correction (Scheme)

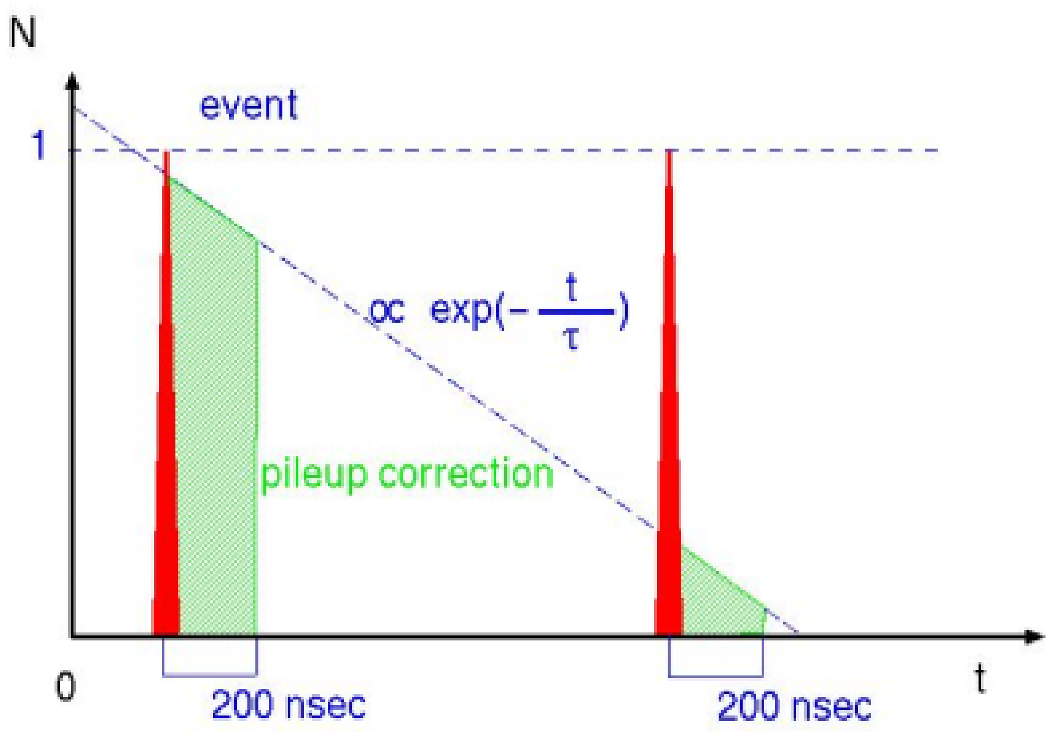
I, Restore "distribution before count-loss(Poisson)"

(Observed mean value)

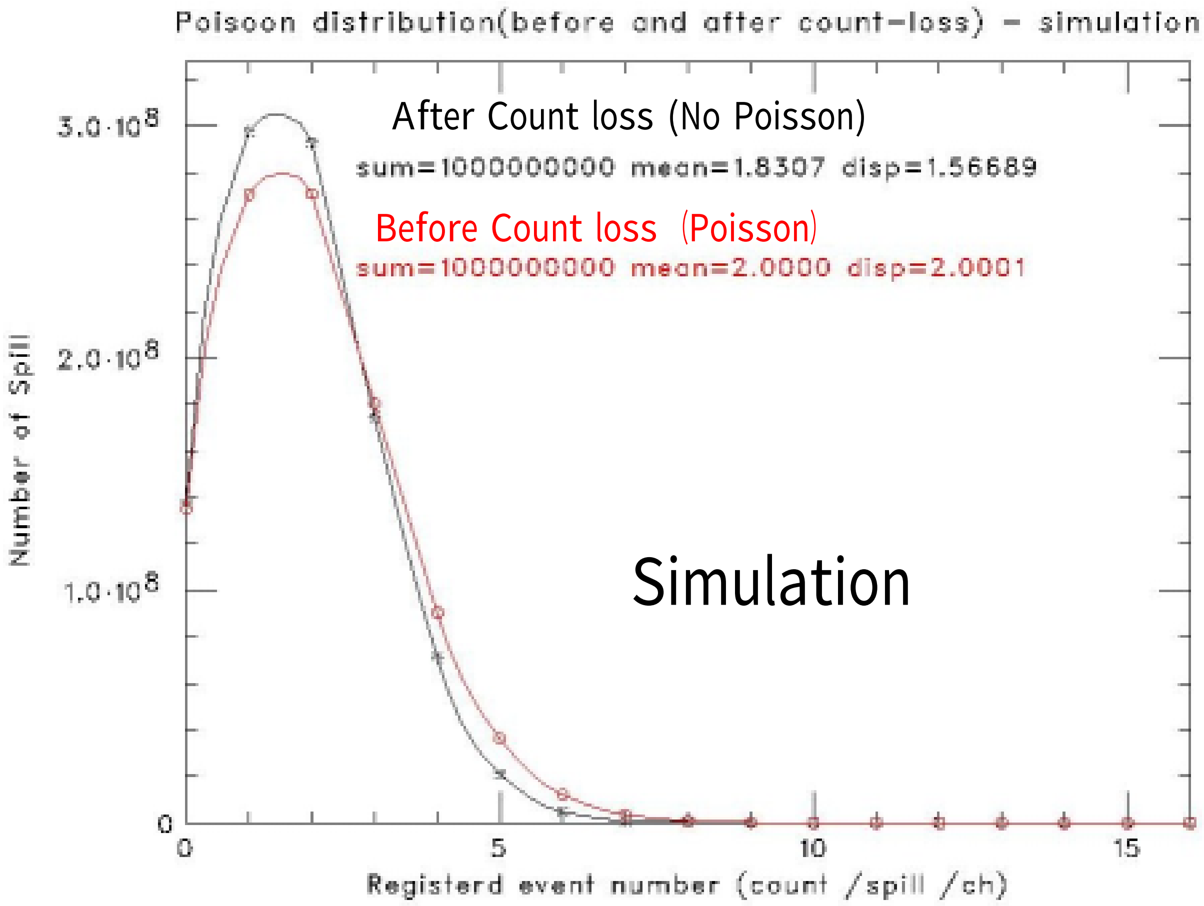
→ (Mean value given by Poisson distribution)

II, Calculate the correction

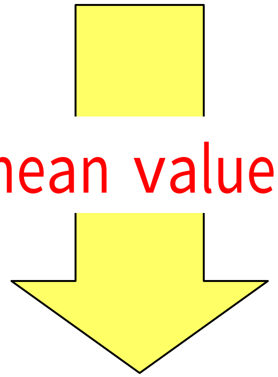
III, Add the correction to a observed time spectrum during the dead-time by "event by event" method



Conversion the Mean value



Observed distribution
(Not Poisson)



Distribution before
Count-loss
(Poisson distribution)

Count-loss Correction Calculation

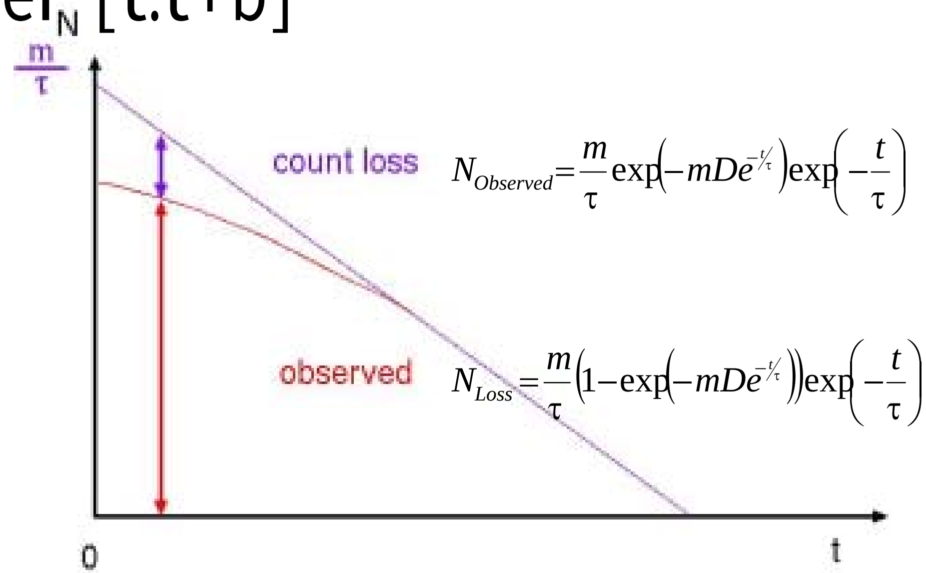
- Follow Poisson distribution
- Limit positrons less than 2 counts / spill /channel
- calculate the expected event number registered in the dead-time
- Integrate this function over [t:t+b]

(count loss) : (observed)

$$= \sum_{i=1}^{\infty} P(i; m_d) : P(0; m_d)$$

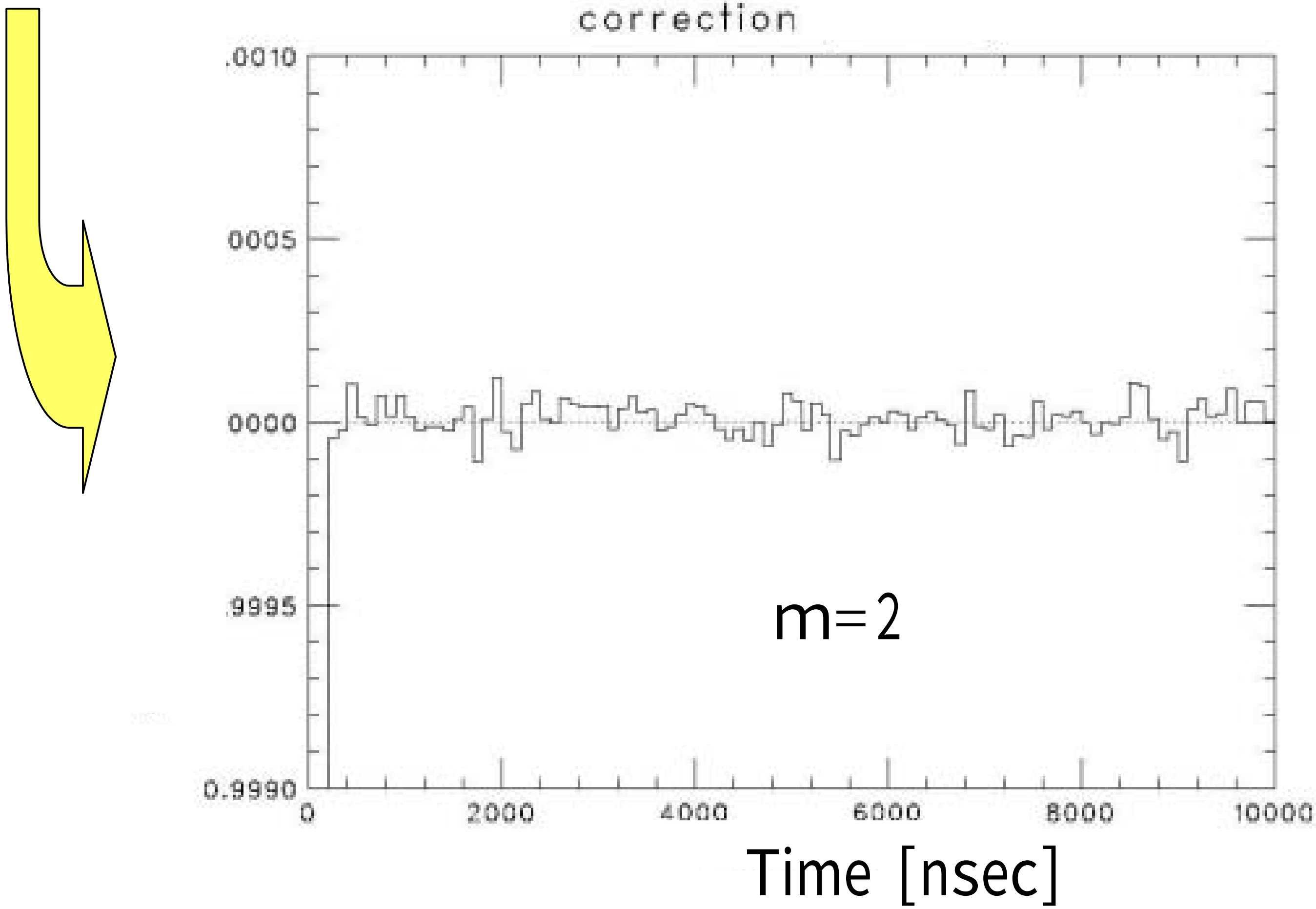
$$= 1 - \exp(-m_d) : \exp(-m_d)$$

$$m_d = mDe^{-t/\tau} = 1/\tau \int_t^{t+d} e^{-t/\tau}\, dt$$

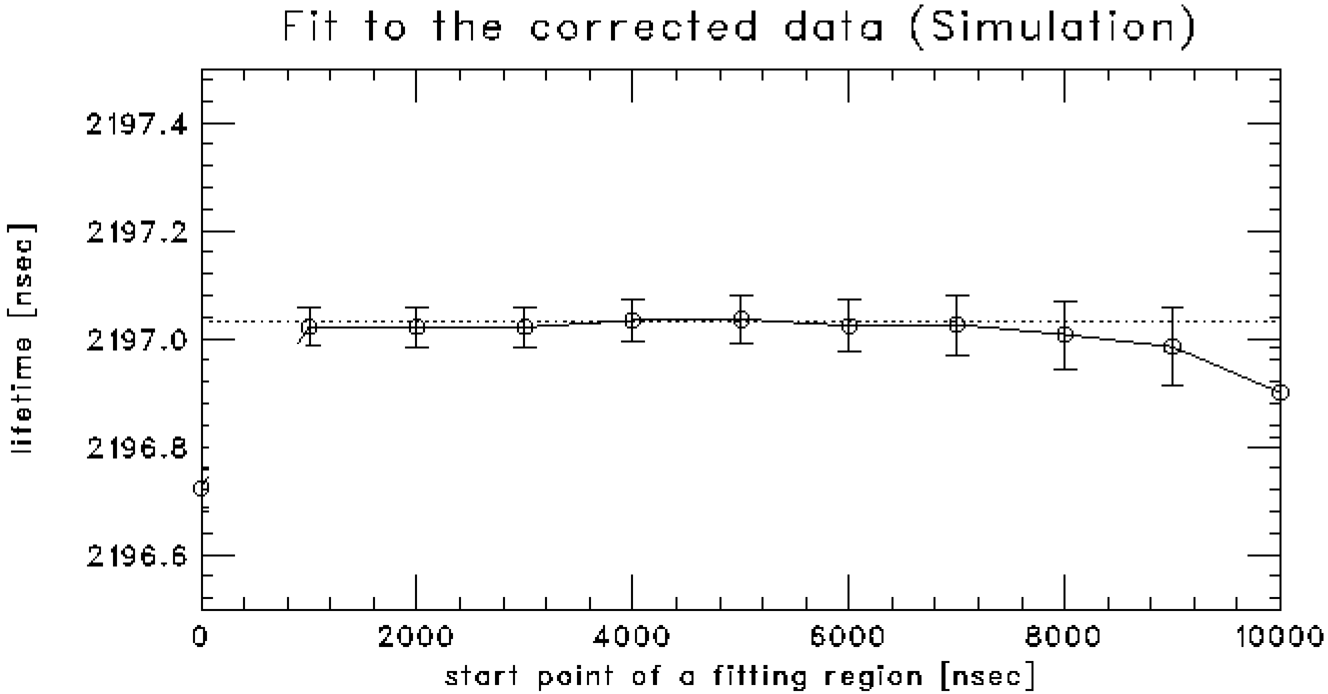


Count loss correction (Monte Carlo Simulation)

{ (observed spectrum) + (correction) } / (no loss spectrum)



Count Loss Correction (Simulation)



Fitting region
[t : 22000]

- Valid if consistent lifetime values are obtained
  in any time region within the statistical error
- tried m<2 (consistent in any mean value)
- Consistent correction after 1 μs for m=2
- Apply this method to a real data set

Difference between “Correction” and “Fitting” to the treatment of the pile-up

Merits for the count loss correction

- Event rate fluctuation is taken into accounted in the long time (event by event method)
- Count-loss correction is flexible to the dead-time determined by the offline analysis (now d= 200 nsec)
- Less parameter fitting (3 parameters)

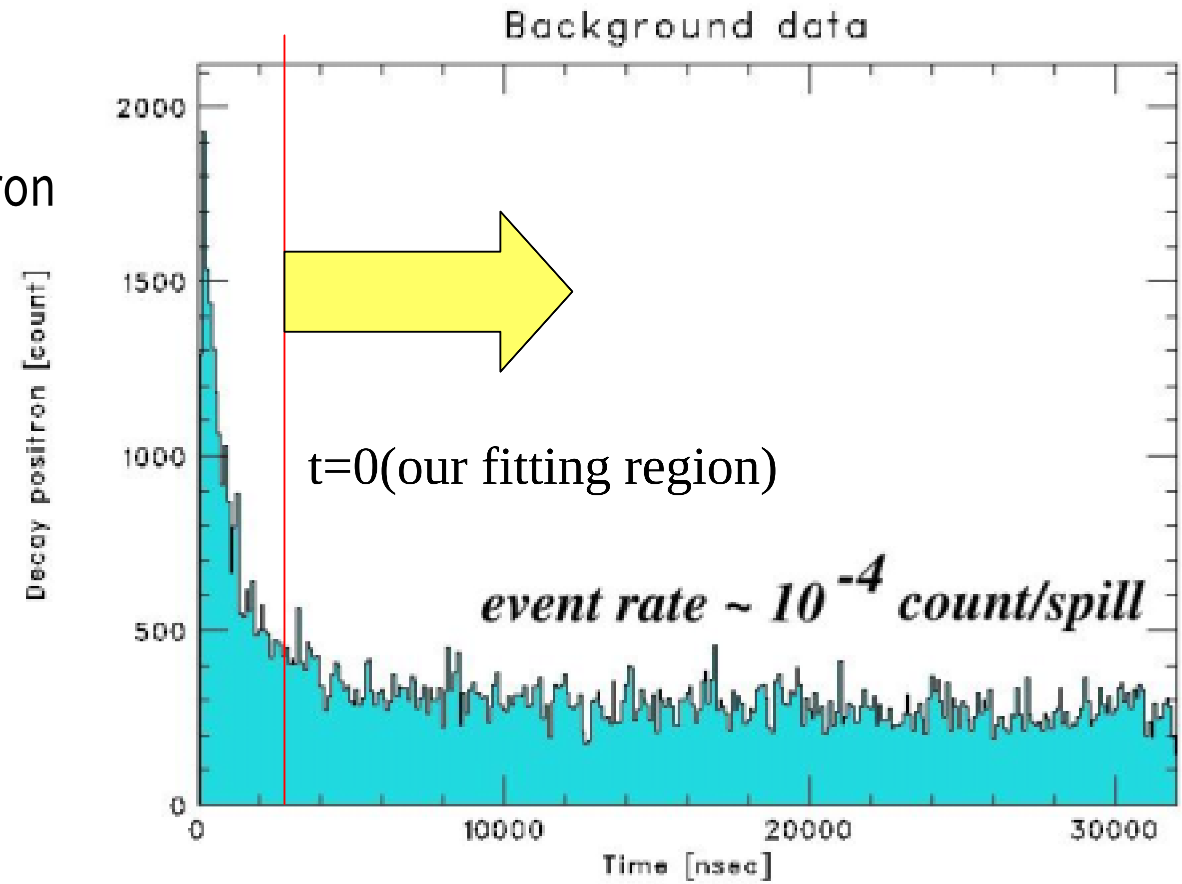
Points

- Correction parameters, mean value (m) and dead-time (d) should be taken precisely into the correction scheme.
- Consistency check by iterating the lifetime value

  because of using a known lifetime value (known precision) in the correction

Background Component

- Event rate
  ～10^4 counts/spill
- Cosmic ray and neutron from the beam-line
- Constant



Fitting Procedure

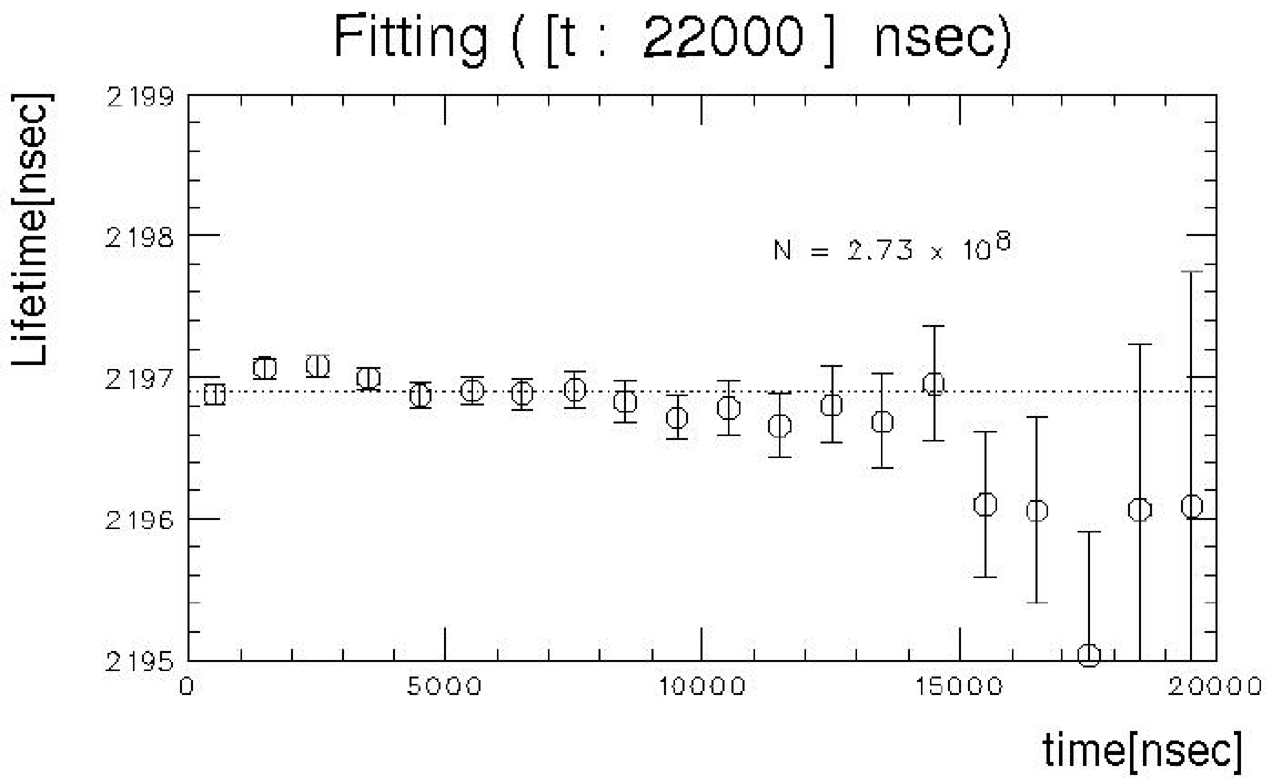
Fitting Function

$$N(t) = Ae^{-\frac{t}{\tau}} + B$$

A : Amplitude B : Background τ : Lifetime

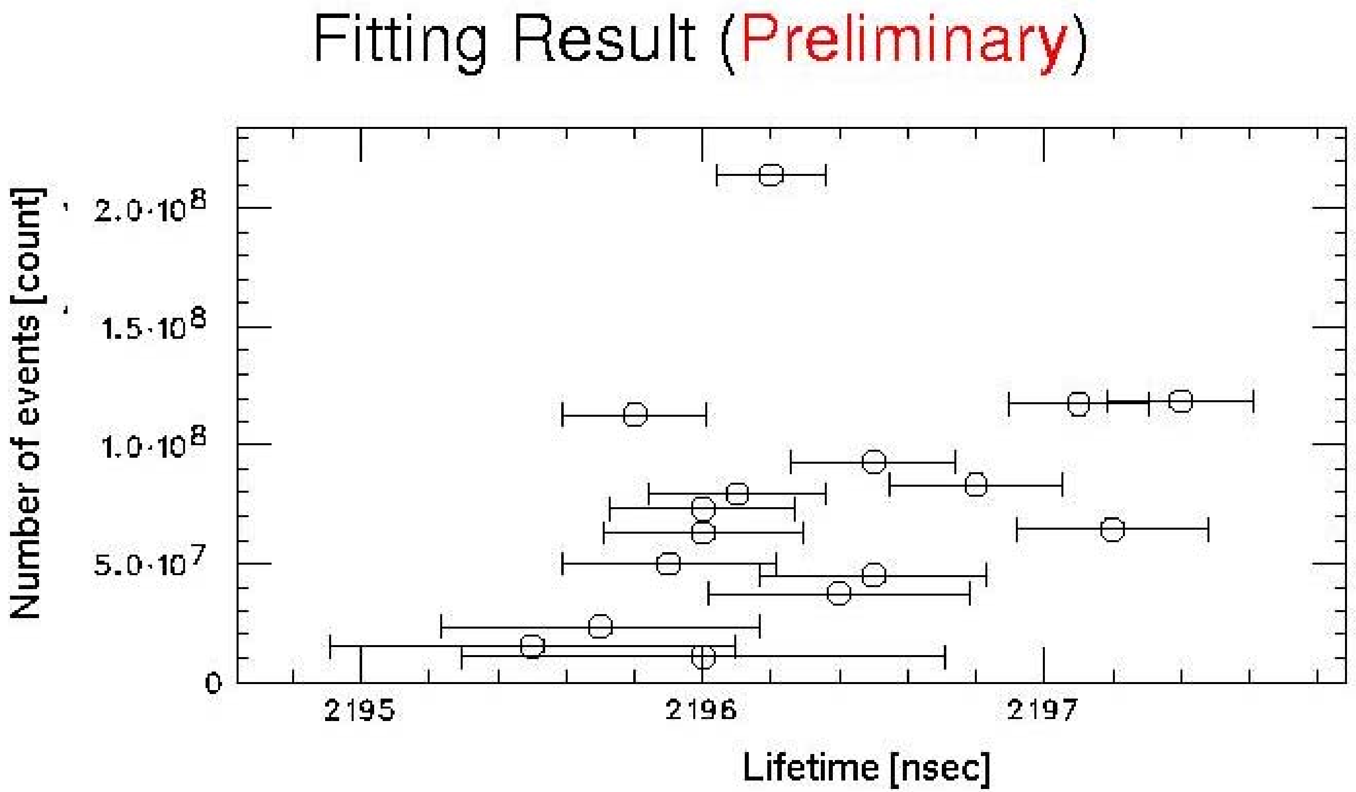
- 3 parameters fitting (Less parameters)
- Using Minuit

Fitting



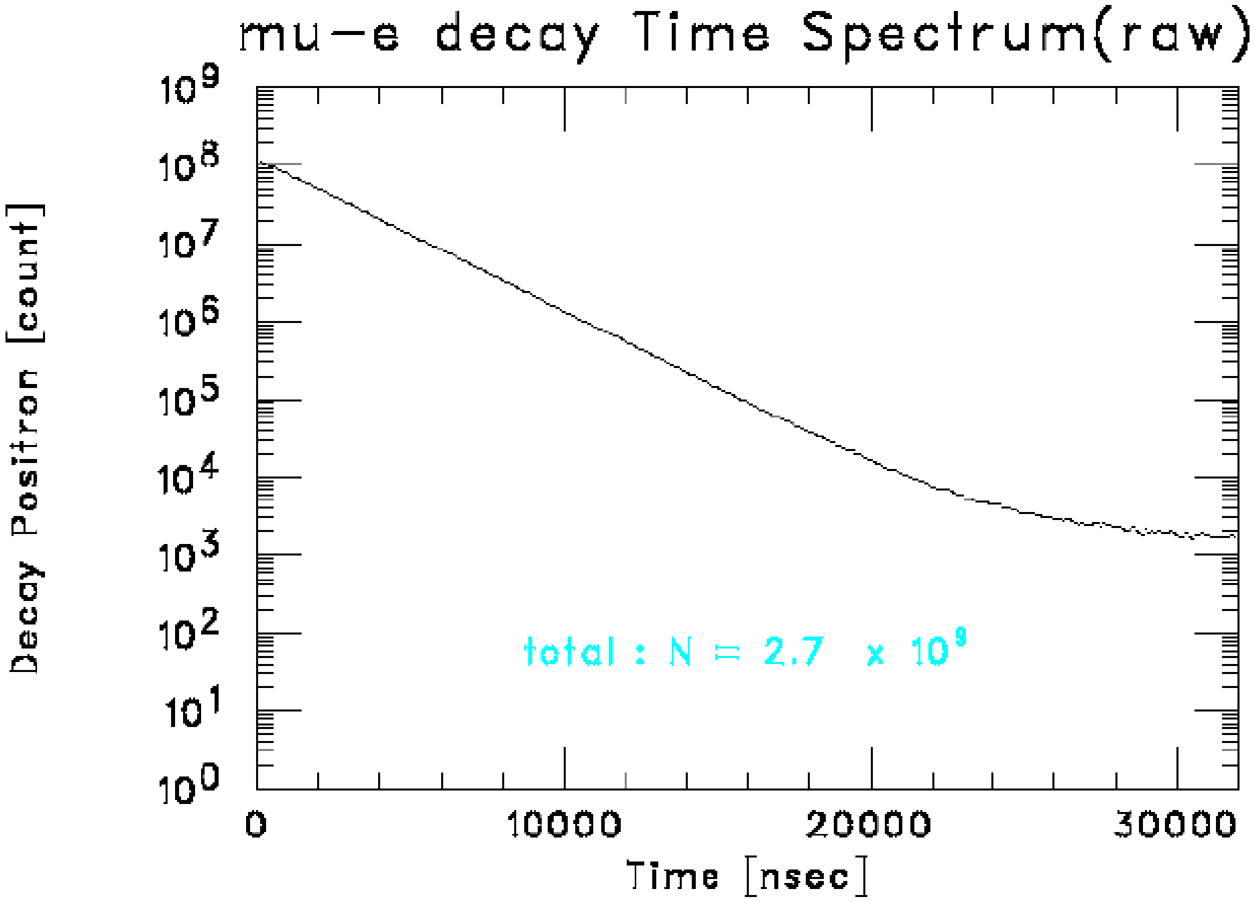
- Determine the amplitude to distribute the lifetime at the constant level.
- Should check all data in the analysis

Fitting Results (Preliminary)

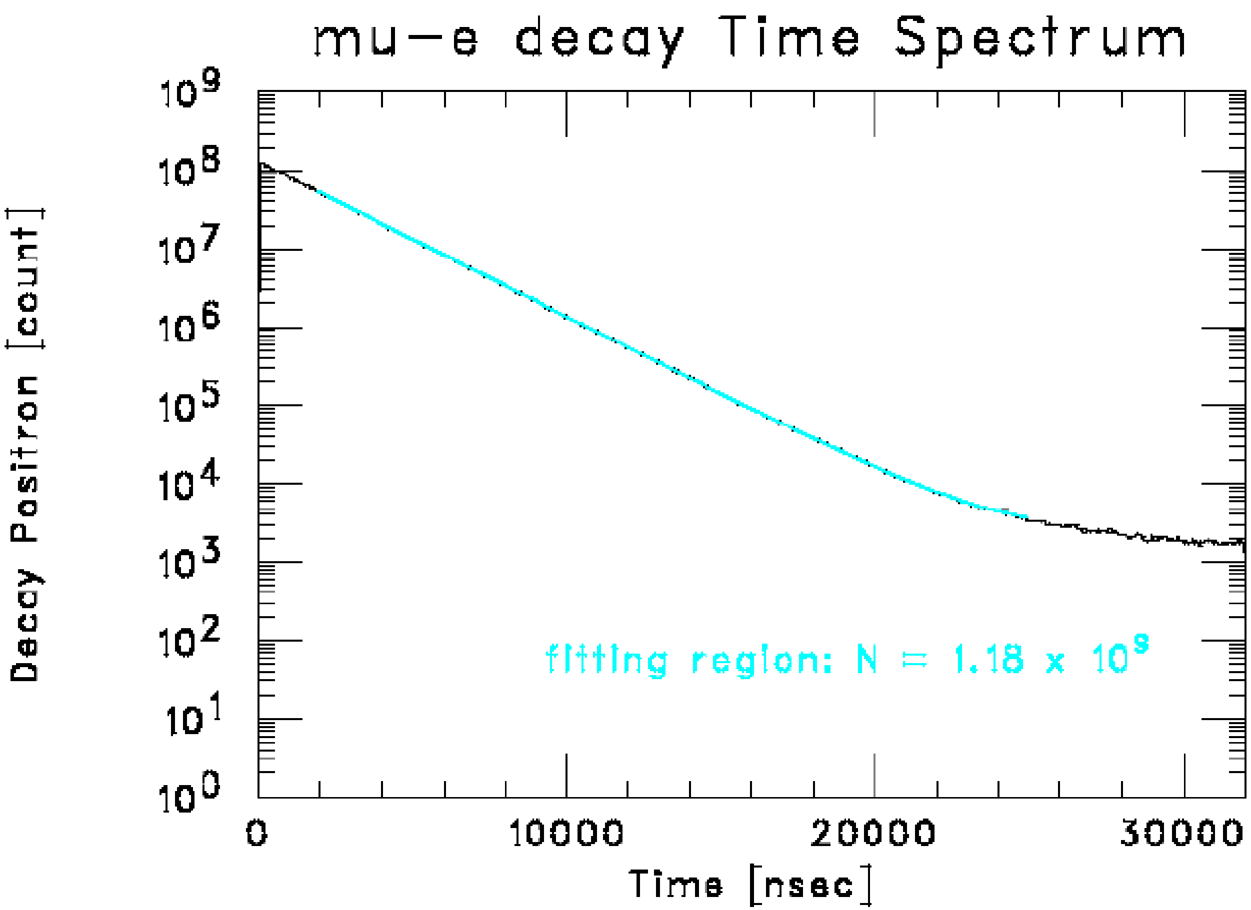


- 1 set has half-day data
- Fitting region 2 μs - 22 μs

Raw spectrum (Preliminary)



Fitting results (Preliminary)



- Not all data set
- Fitting region
  2 μs – 22 μs
- Data
  2.5 x 10^9
  (in the fitting region)
  1.18 x 10^9

Expected Error

- Systematic error

GPS Clock (Synchronized Latching Memory)	<1ppm
Background(Charged particles)	< 10ppm
Muon stopping target(Polarization effect)	< 1ppm
MWPC multiplicity cut	<10ppm
Bin size(100nsec LM)	1ppm

+ expected count loss correction < 10 ppm?

- Statistical error

- All data $< 10^{11}$

Analysis efficiency

Event selection	~ 75 – 80 %
Fitting region limit	~ 65 %
MWPC multi-hit effect	< 30 %

Total $\sim 10^{10}$

Summary

- Data analysis is now in the last stage
- Count loss correction method was developed.
- We determined the lifetime by fitting LM data (preliminary).
- Statistics by the analysis efficiency is the key point to determine the statistical error.
- Iteration should be done to obtain the self-consistent lifetime value (now doing)
- Systematic error should be determined.