Precision measurement of the positive muon lifetime by the MuLan collaboration

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K. Giovanetti

Contents

- Why?
- How and where?
- Problems / challenges
- Data analysis
- Consistency checks
- Results

Standard Model

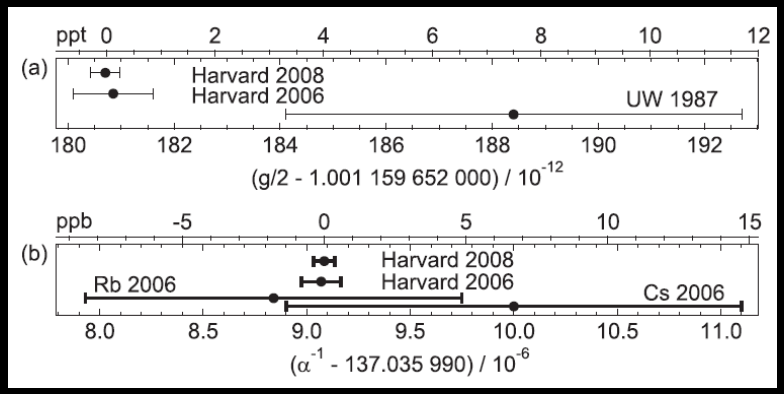
The predictive power of the Standard Model depends on well-measured input parameters

PDG-2010

α^{-1}

0.00037 ppm

137.035999084(51)

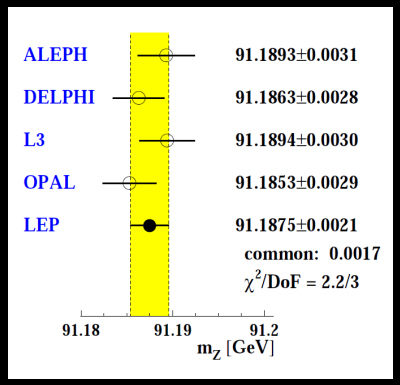


PRL 100 (120801) 2008

M_Z

23 ppm

91.1876(21) GeV

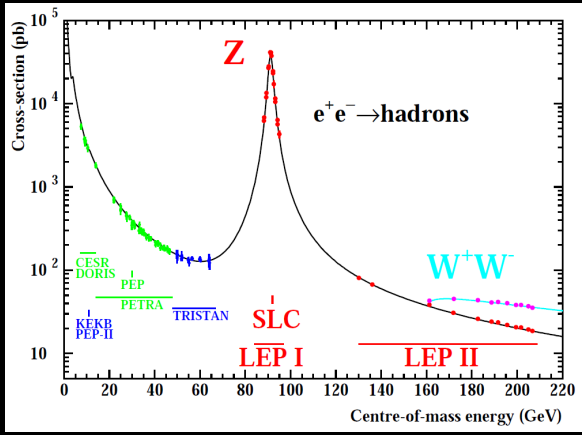


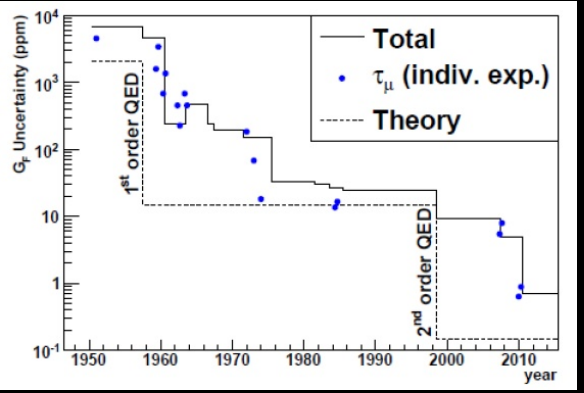
G_F

8.6 ppm

$1.16639(9)\times10^{-5}$* GeV^{-2}

from muon lifetime





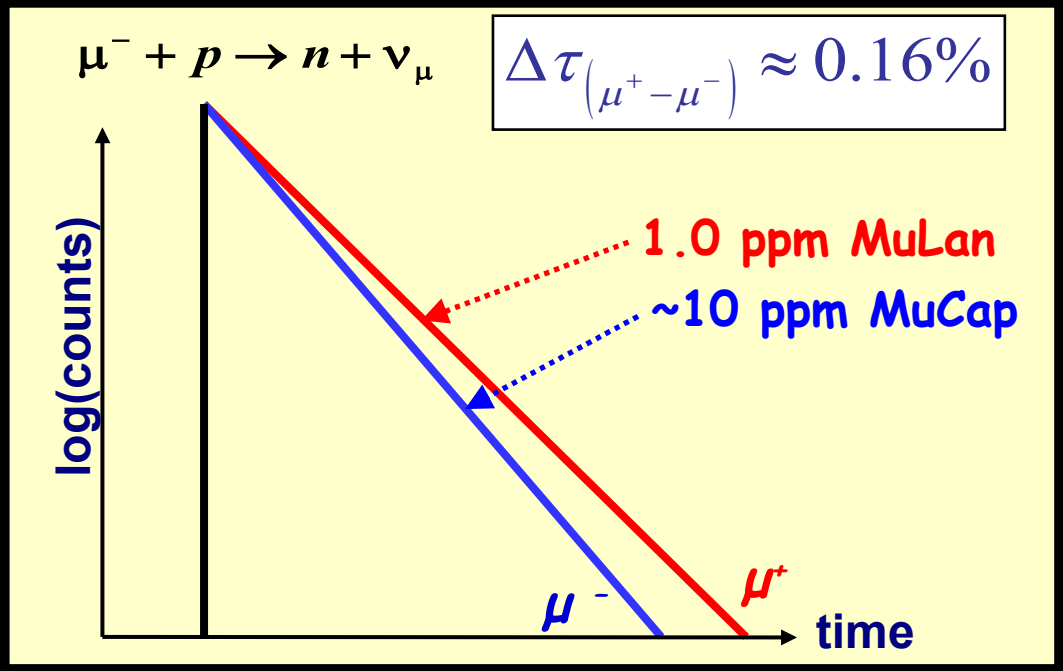
* before MuLan

http://lepewwg.web.cern.ch/LEPEWWG

Motivation

- τ_μ can be used for the most precise determination of Fermi constant G_F
- τ_μ is needed for "reference" lifetime for precision muon capture experiments
  - MuCap: $\mu^- + p$
  - MuSun: $\mu^- + d$

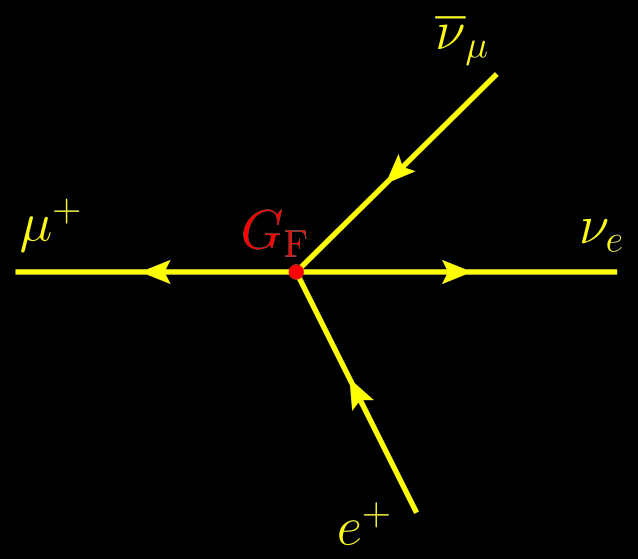
  } capture rate from "lifetime" difference of μ^- and μ^+



The singlet capture rate Λ_S is used to determine g_p and compare with theory

$$\Lambda_S = \frac{1}{\tau^{d}_{\mu^-}} - \frac{1}{\tau_{\mu^+}}$$

Determination of G_F from τ_μ



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

QED, QCD rad. corrections

$$\frac{\delta G_F}{G_F} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)^2 + \left(5\frac{\delta m_\mu}{m_\mu}\right)^2 + \left(\frac{\delta(\Delta q)}{1+\Delta q}\right)^2}$$

mid 90	18 ppm	18 ppm	36 ppb	30 ppm
1999	9 ppm			0.3 ppm

Van Ritbergen and Stuart, 1999

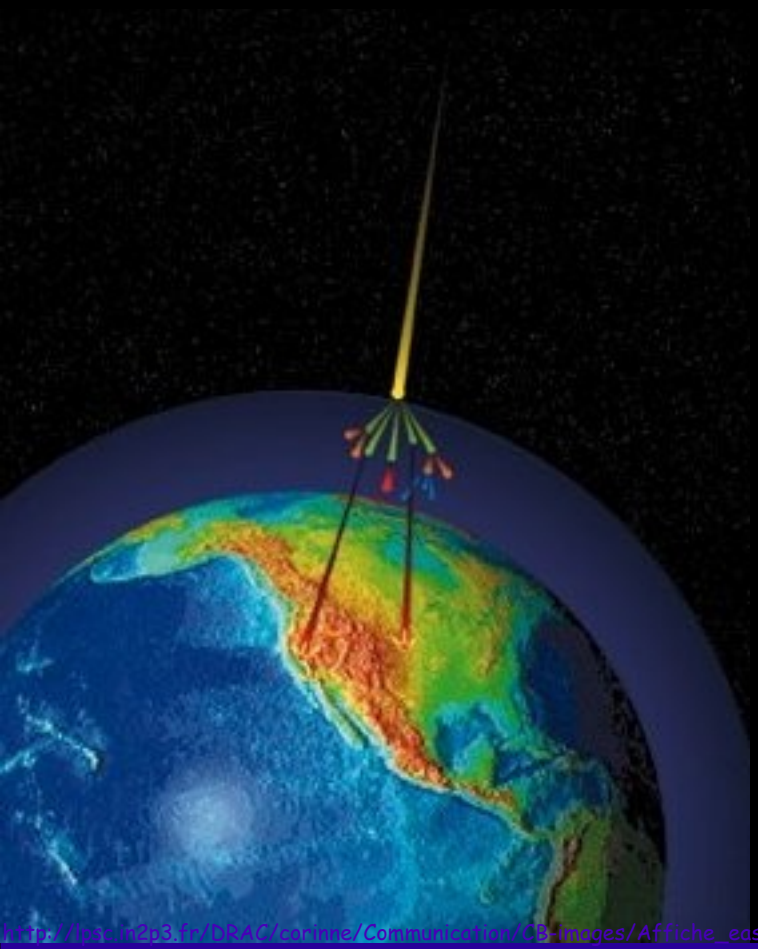
Where to find muons?

$m_\mu = 105.7 MeV$

Cosmic rays:

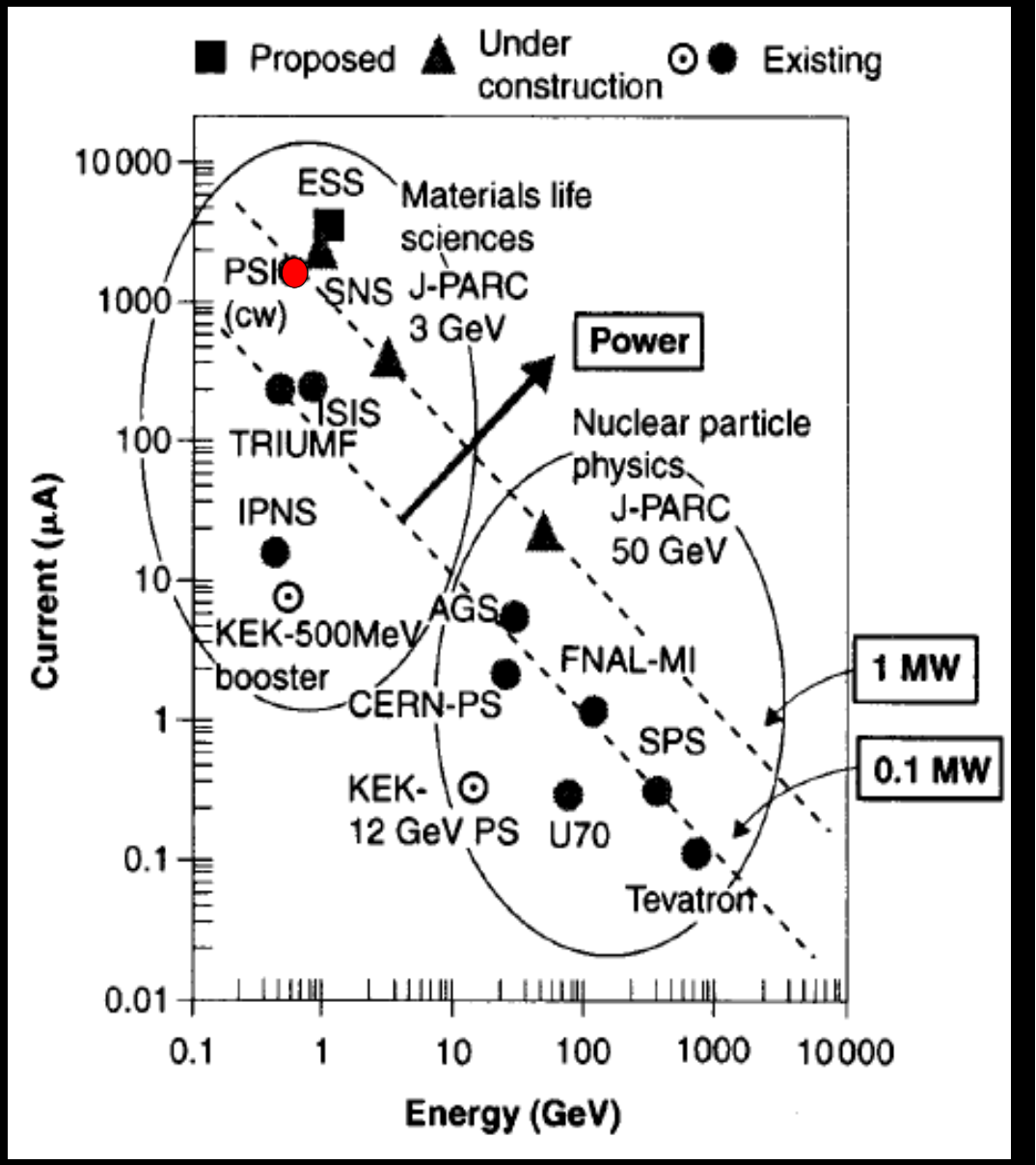
- ~1 muon/(cm^2 min) at sea level
- <E> ~ 4 GeV at sea level

1 ppm ➔ 10^{12} muon decays
➔ 200 years for 10x10 m^2 detector



http://lpsc.in2p3.fr/DRAC/corinne/Communication/CB-images/Affiche_eas.php

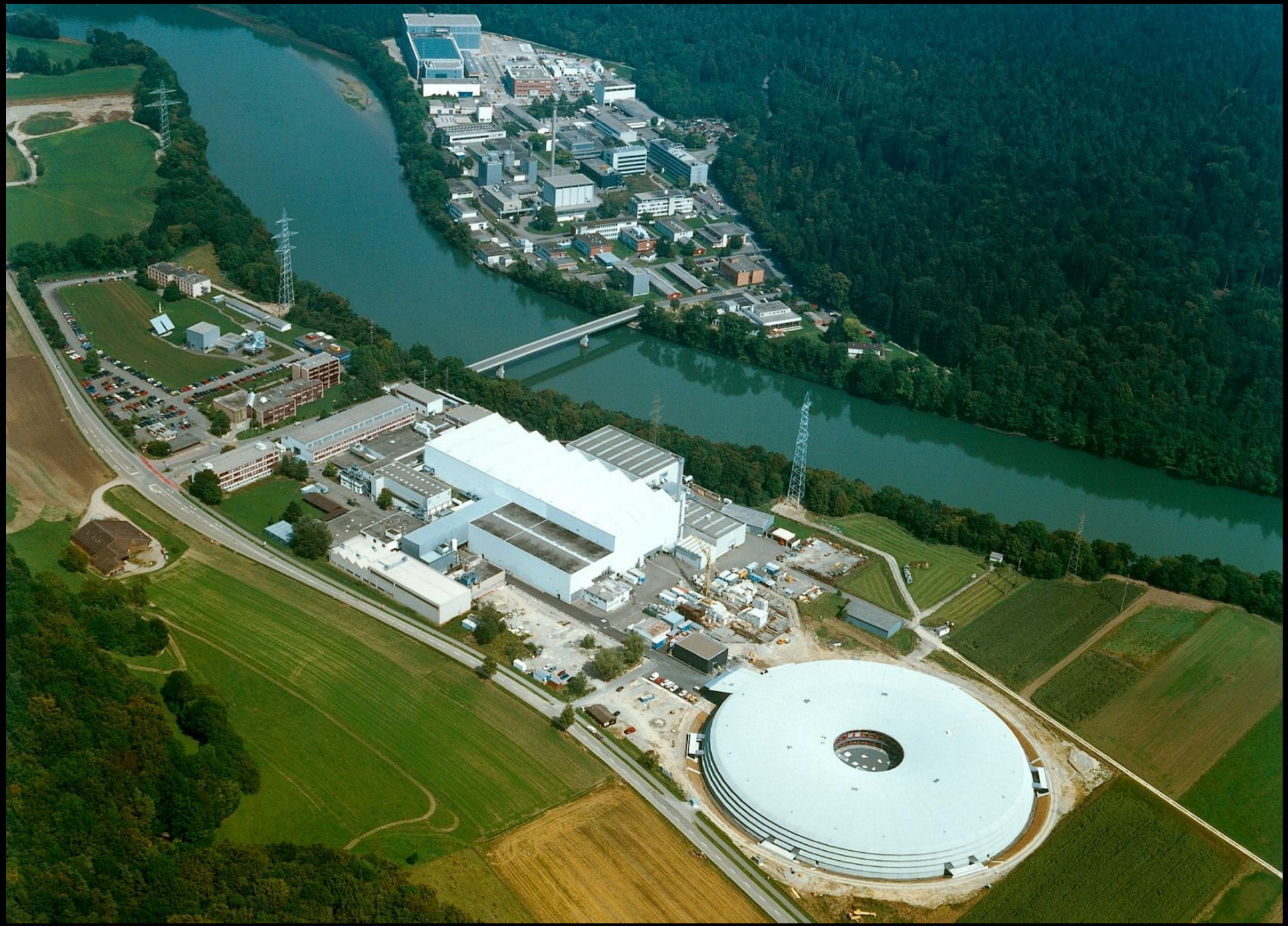
Muon beams worldwide (2007)



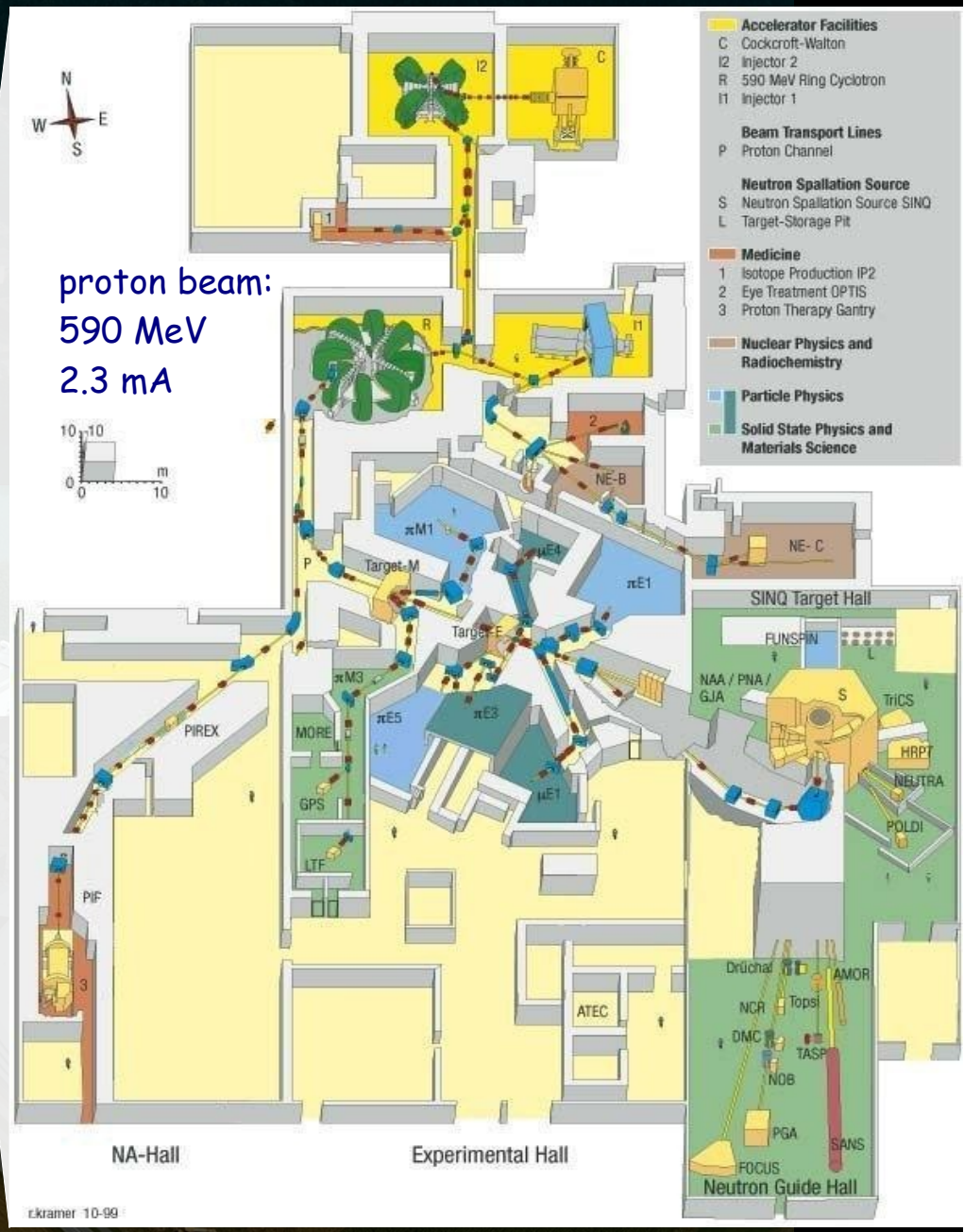
K. Nagamine, "Introductory muon science, Cambridge 2007

We go to Switzerland to find muons

Paul Scherrer Institut, Villigen, Schweiz



πE3 Beamline at PSI



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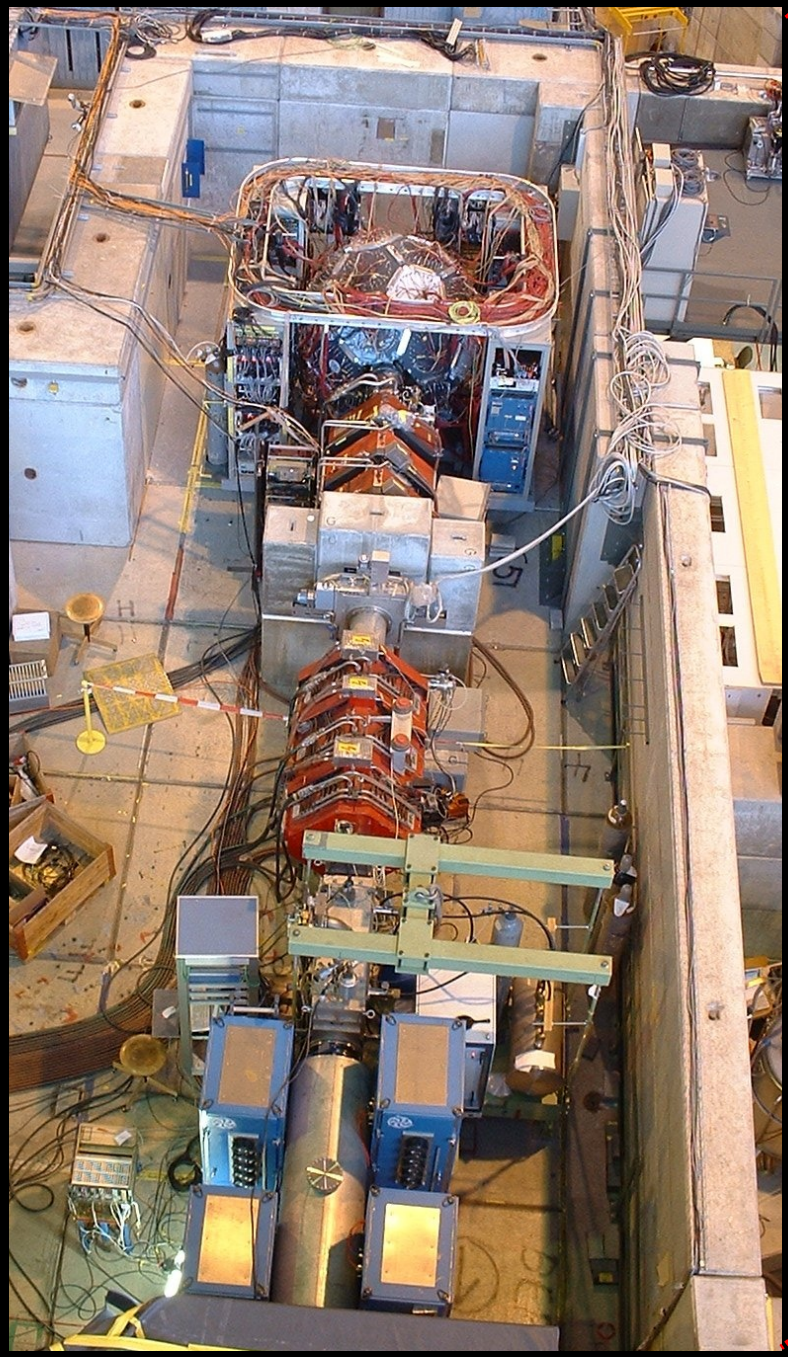

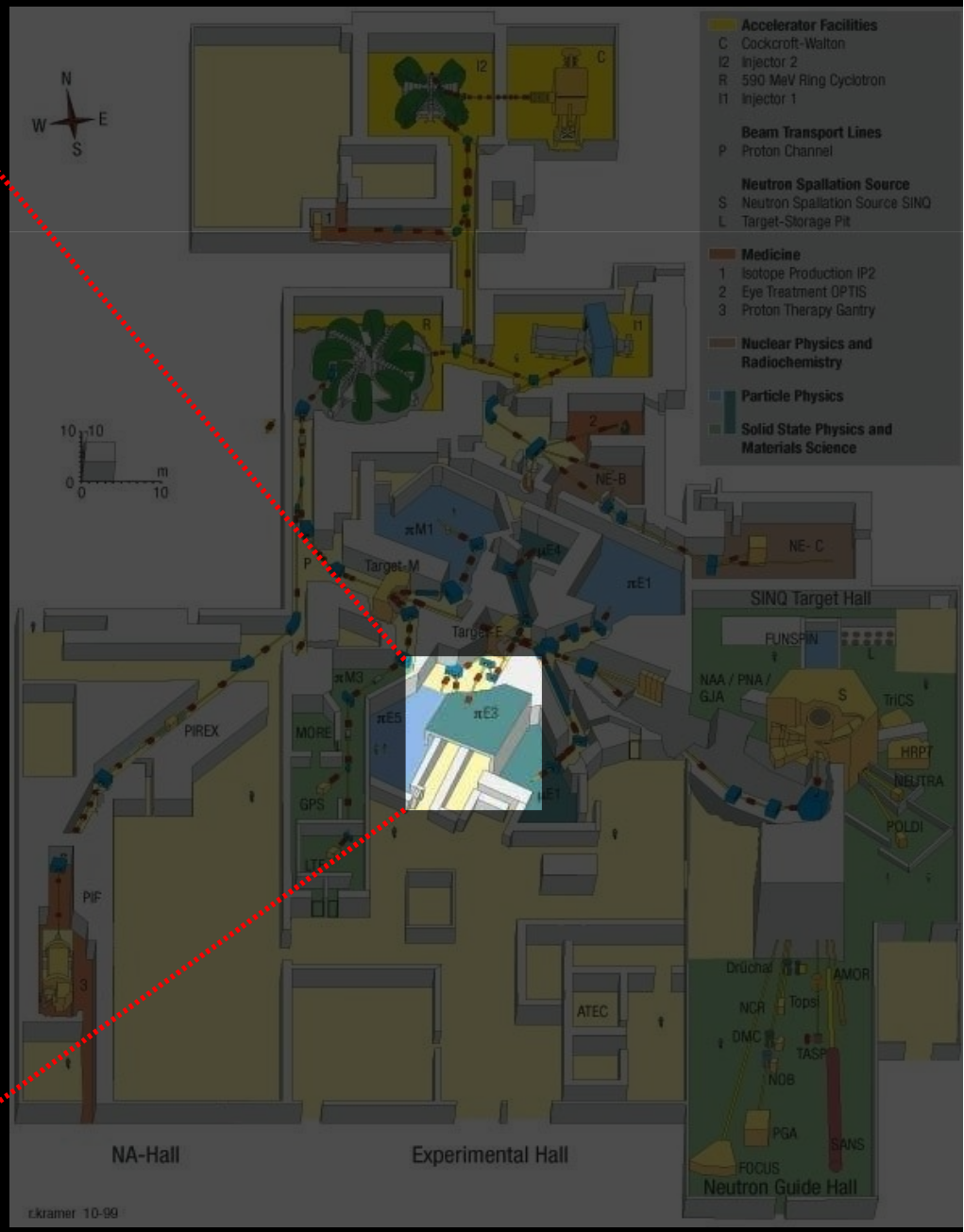

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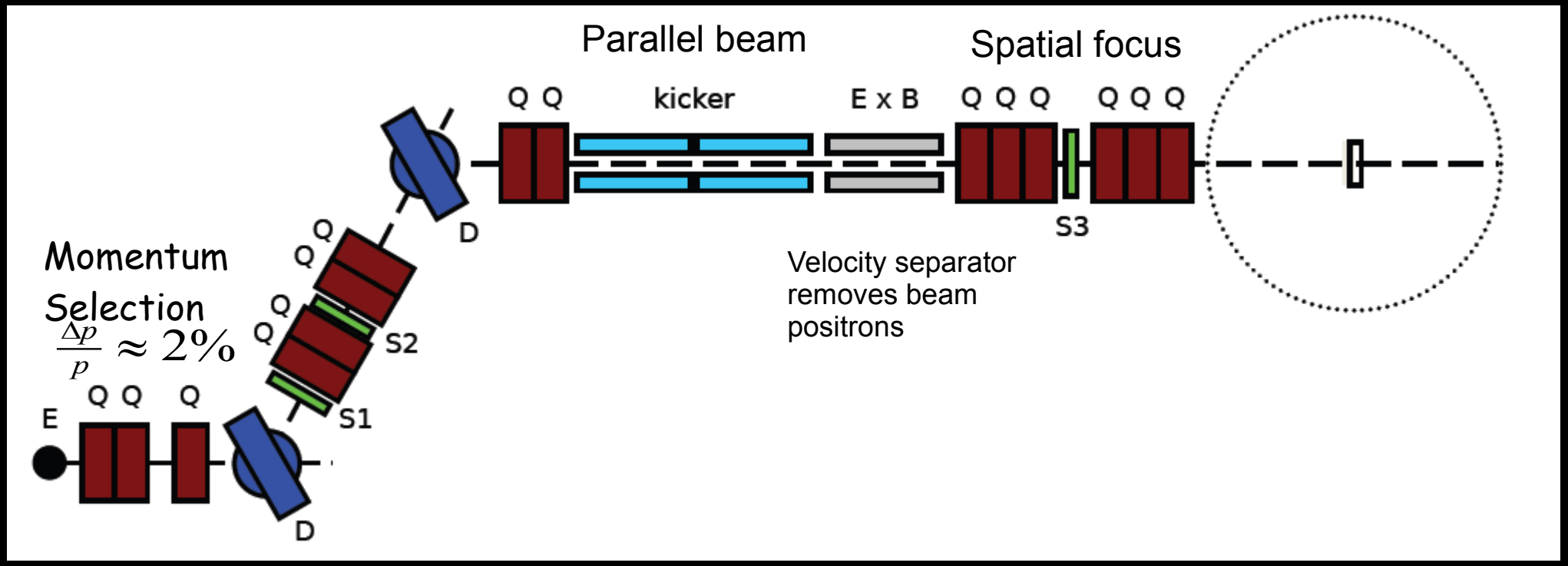
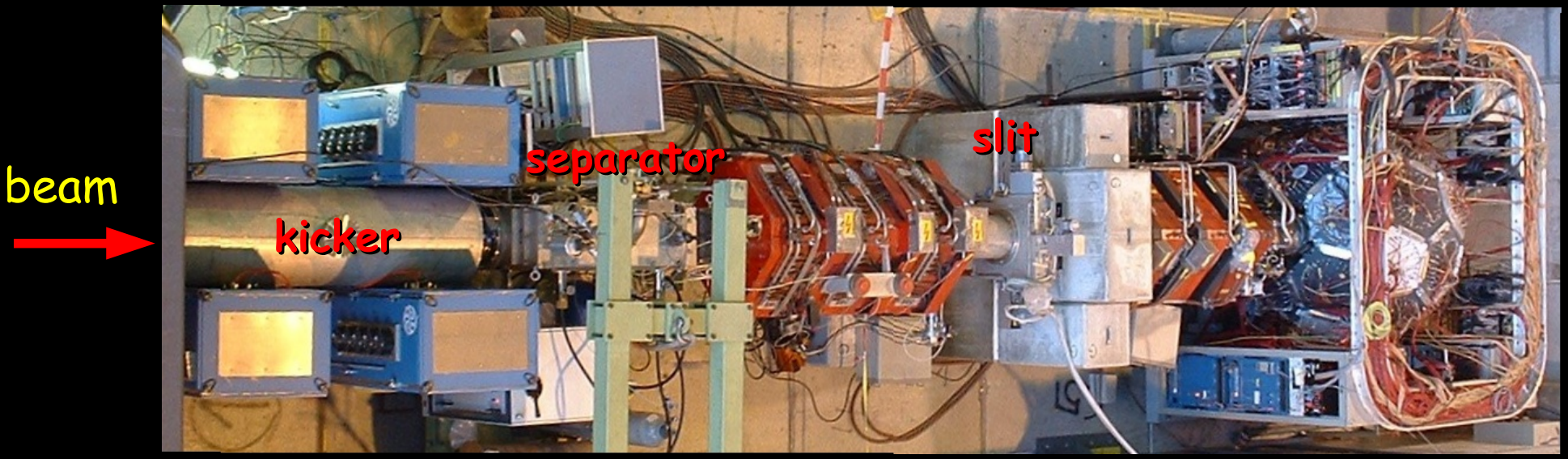
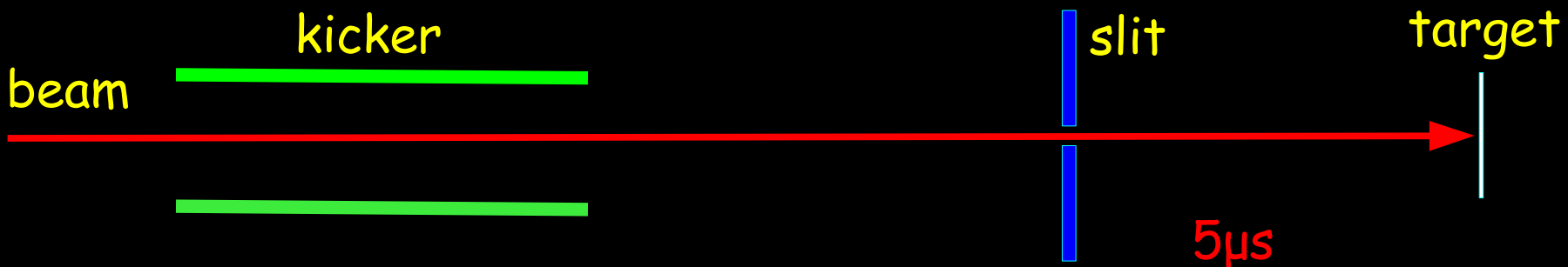
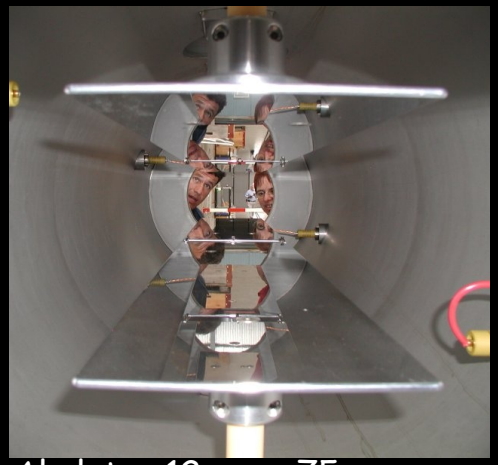


The Kicker is used to create a pulsed beam

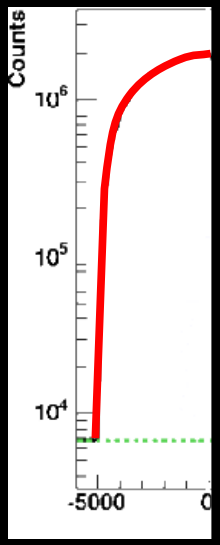






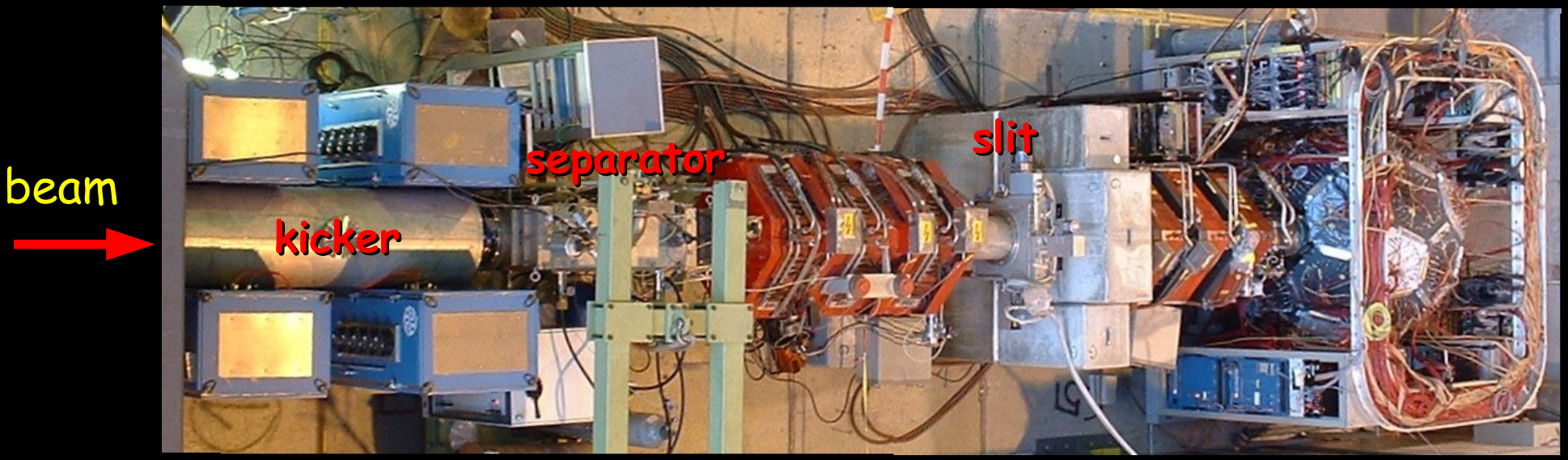
Al plates 12 cm x 75 cm

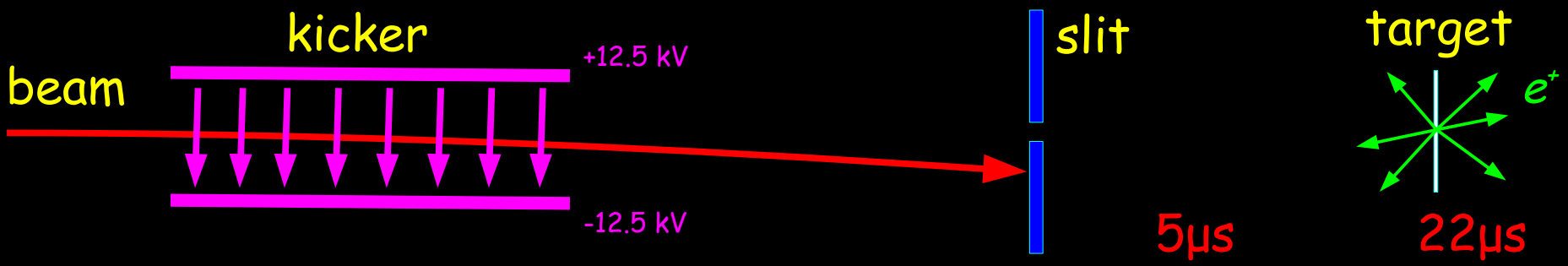
5μs

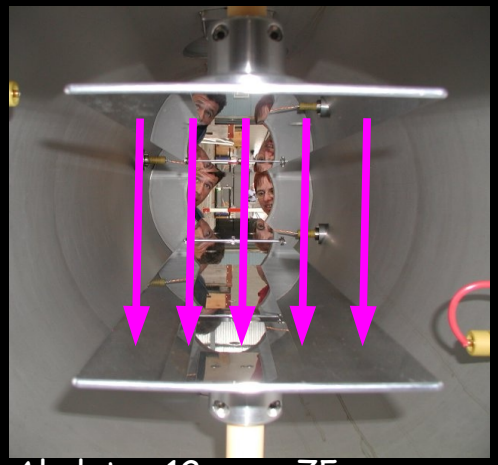


$$N_{\rm in}(t) = \nu_\mu \tau \left(1 - e^{-t/\tau_\mu}\right)$$

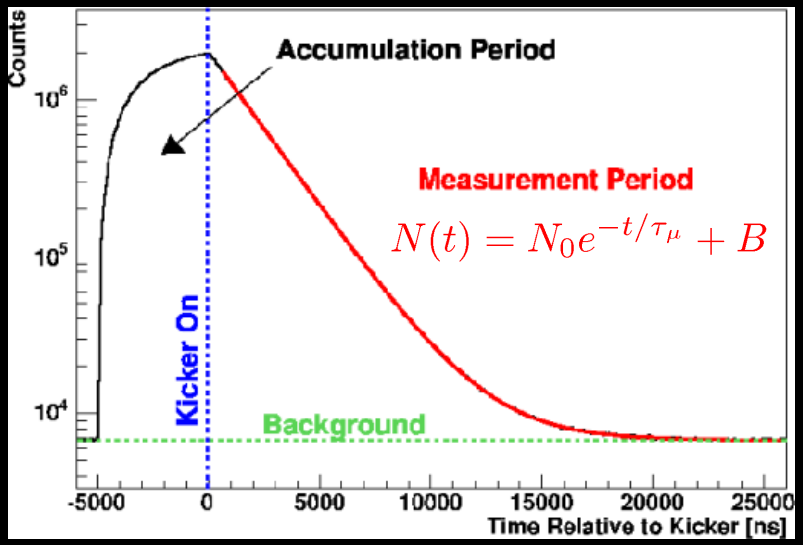
The Kicker is used to create a pulsed beam



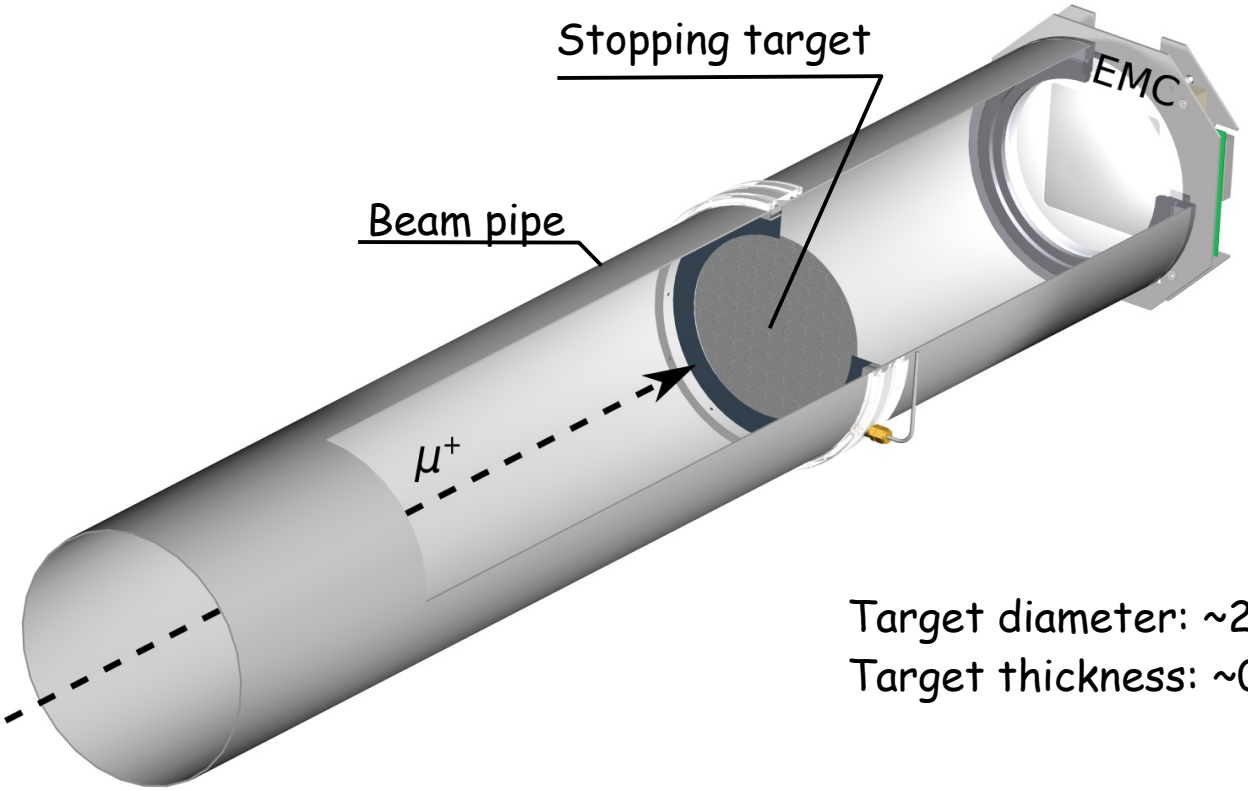




Al plates 12 cm x 75 cm

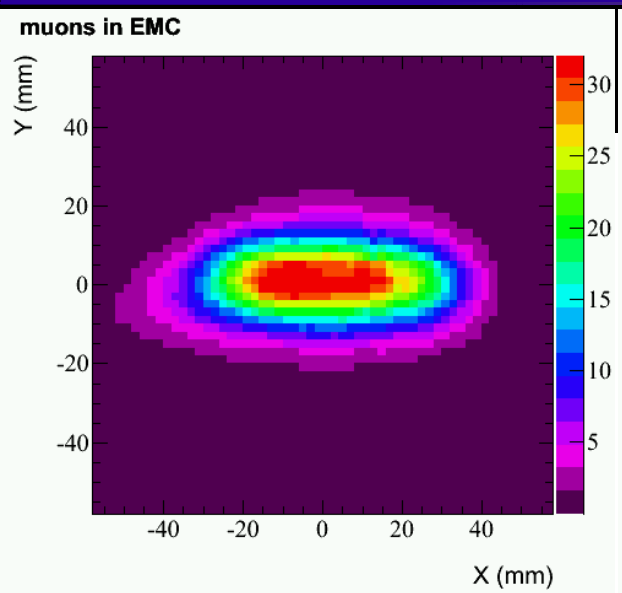


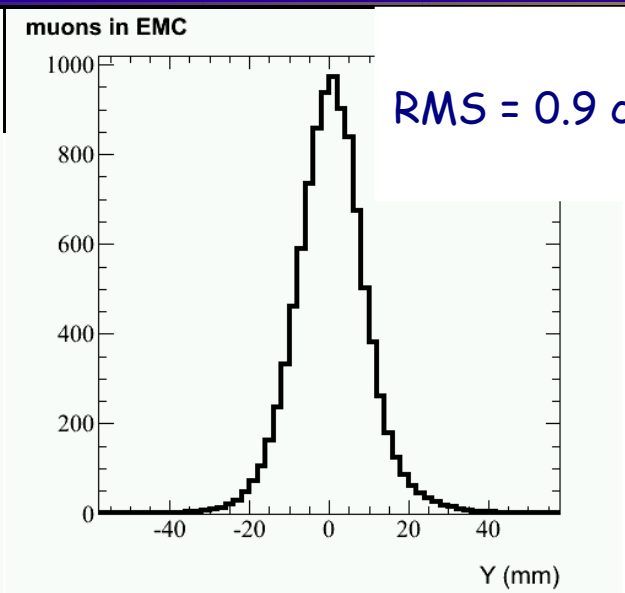
Stopping target



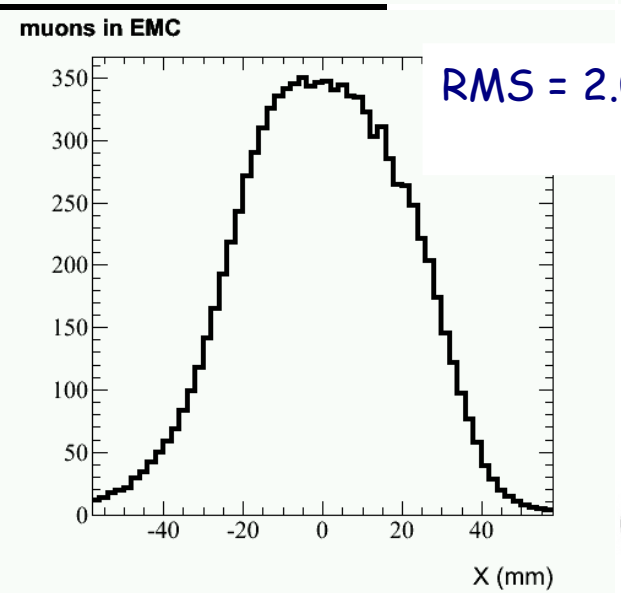
Target diameter: ~20 cm
Target thickness: ~0.5 mm

The target was opened once per day to monitor the beam

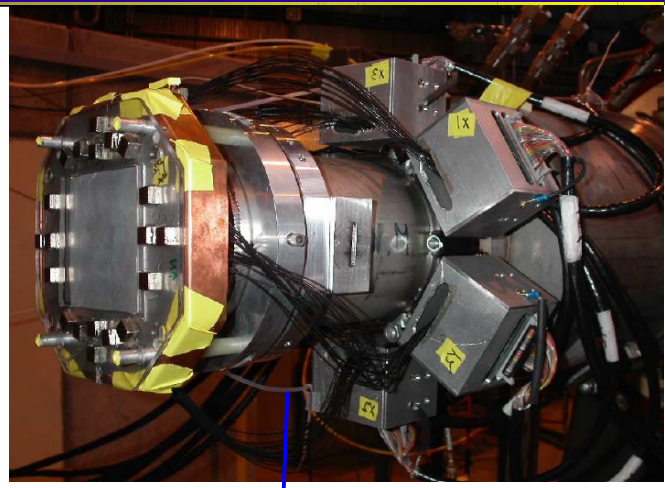


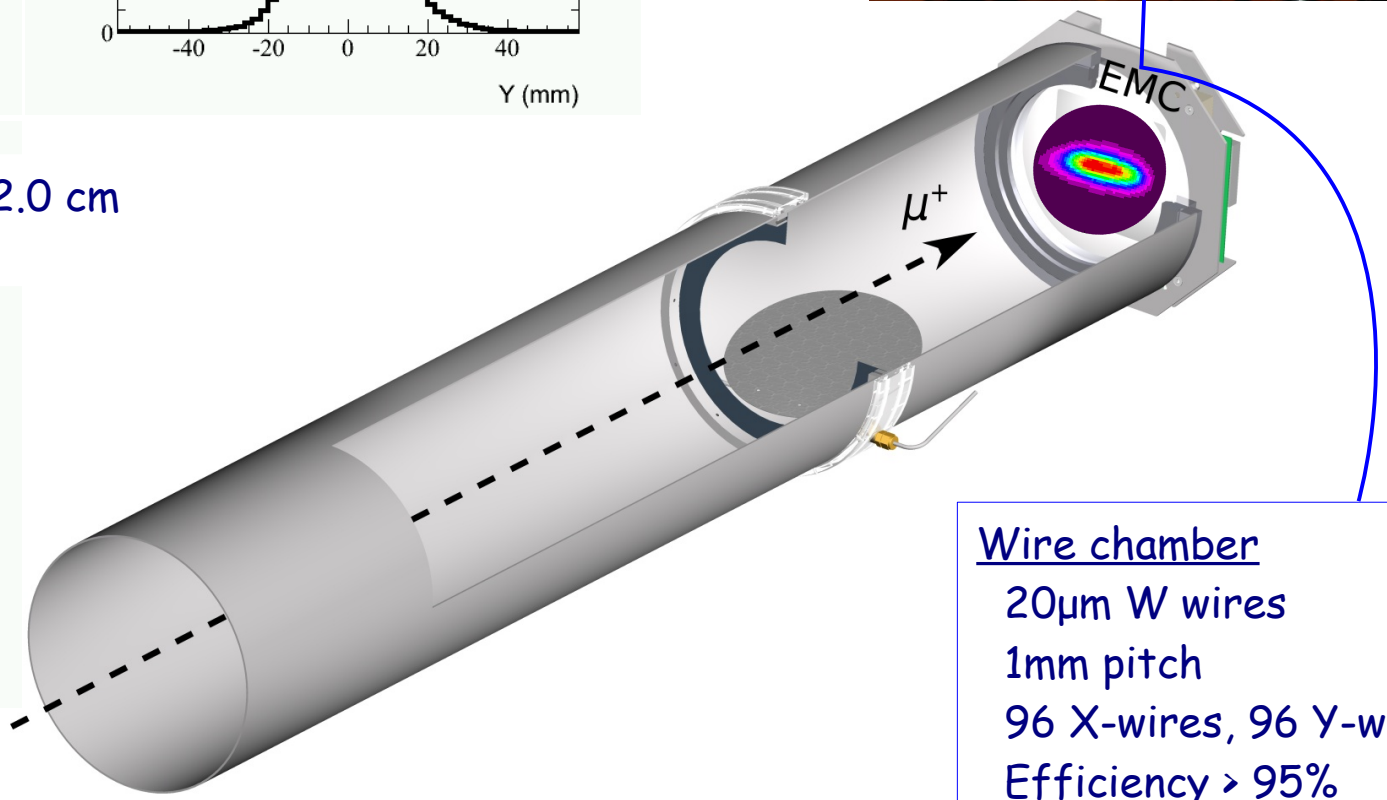


RMS = 0.9 cm



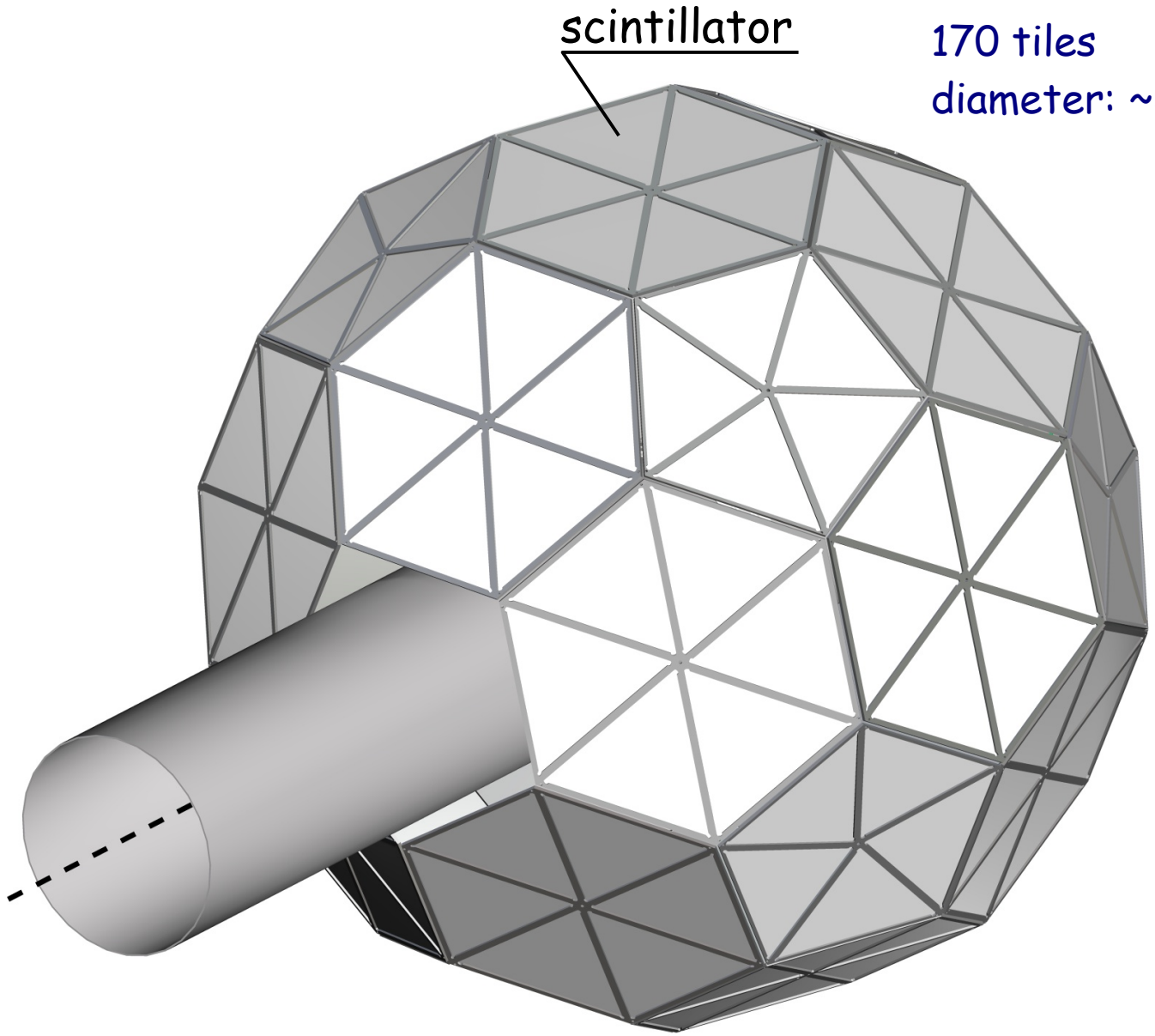
RMS = 2.0 cm





Wire chamber
- 20μm W wires
- 1mm pitch
- 96 X-wires, 96 Y-wires
- Efficiency > 95%

MuLan Ball

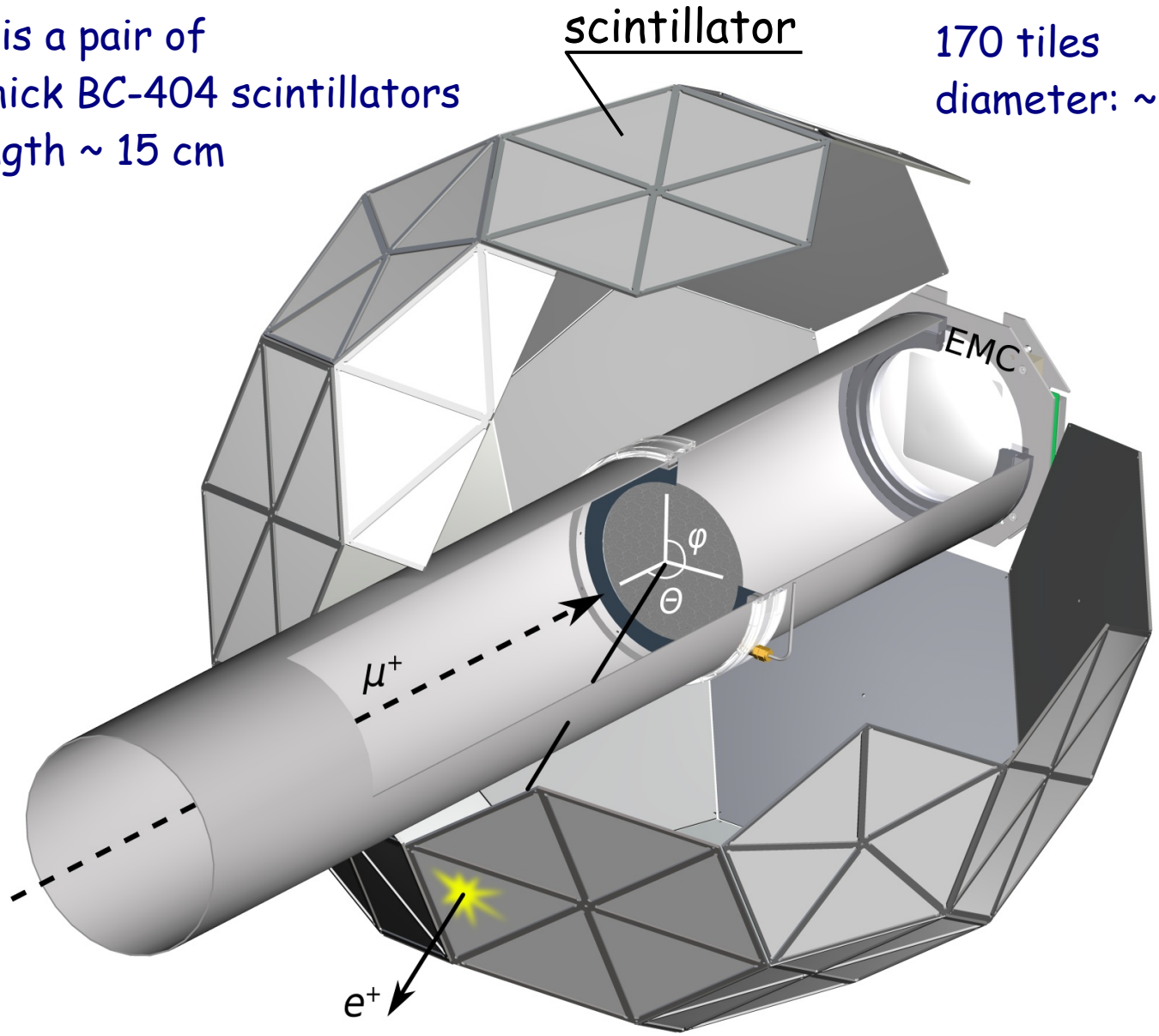


170 tiles

diameter: ~80 cm

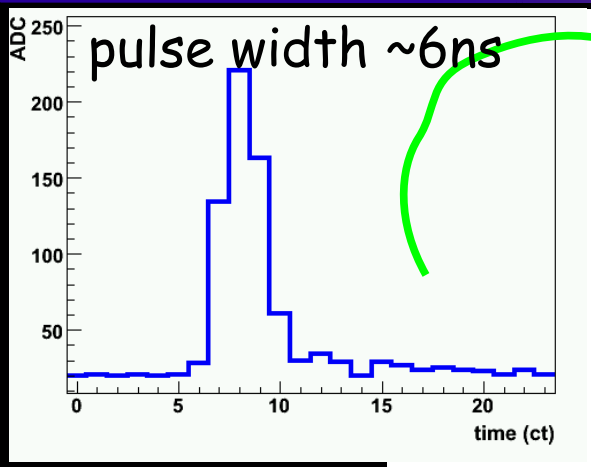
MuLan ball

one tile is a pair of
3-mm thick BC-404 scintillators
base length ~ 15 cm

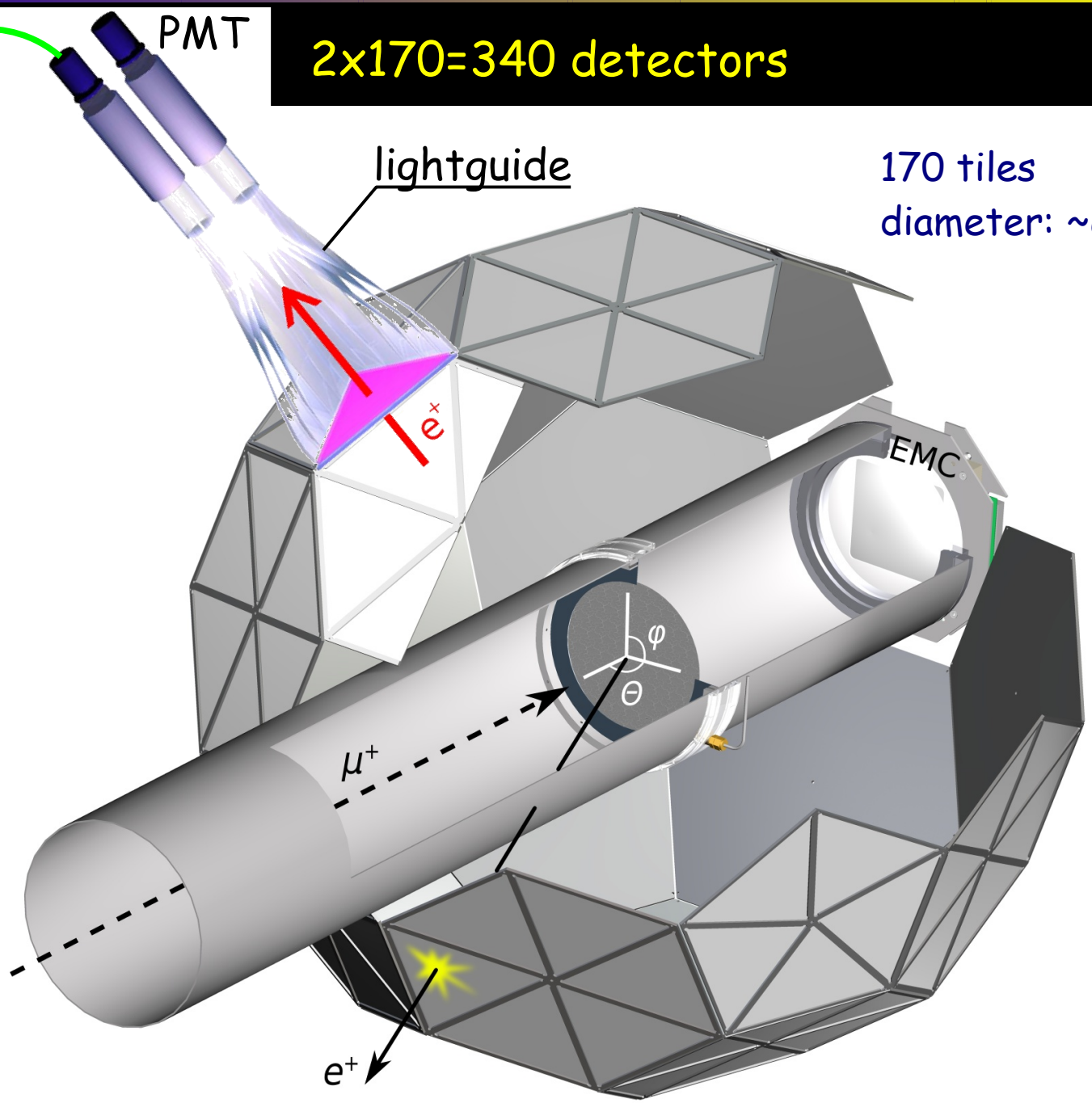


170 tiles
diameter: ~80 cm

MuLan Ball



2x170=340 detectors



170 tiles
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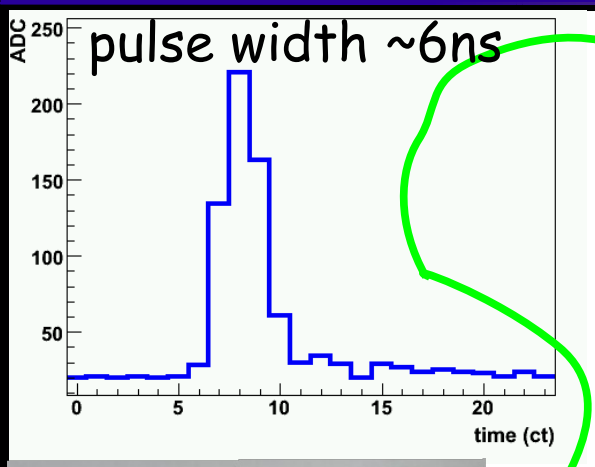
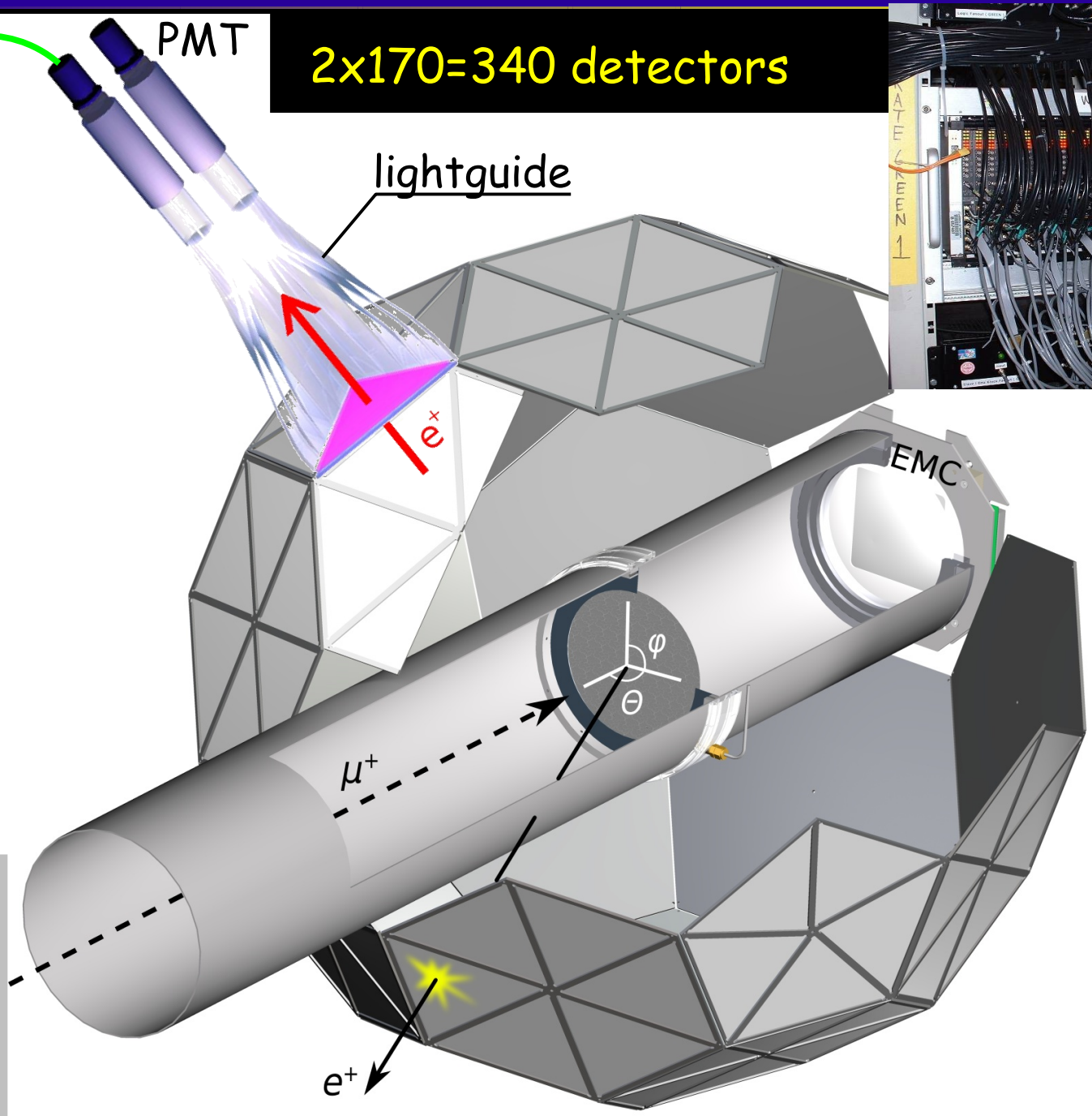
MuLan Ball



Boston 500MHz WFD
- 4 channels/board
- Inner and outer tile as well as opposite tiles on one board
- 64 bit wide data bus to VME
- total rate ~40 MB/s
- ~ 2×10^{12} pulses recorded



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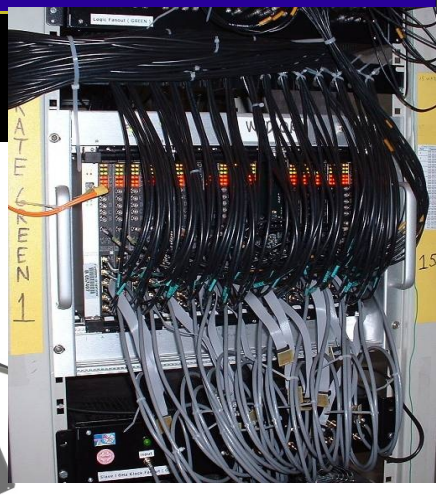
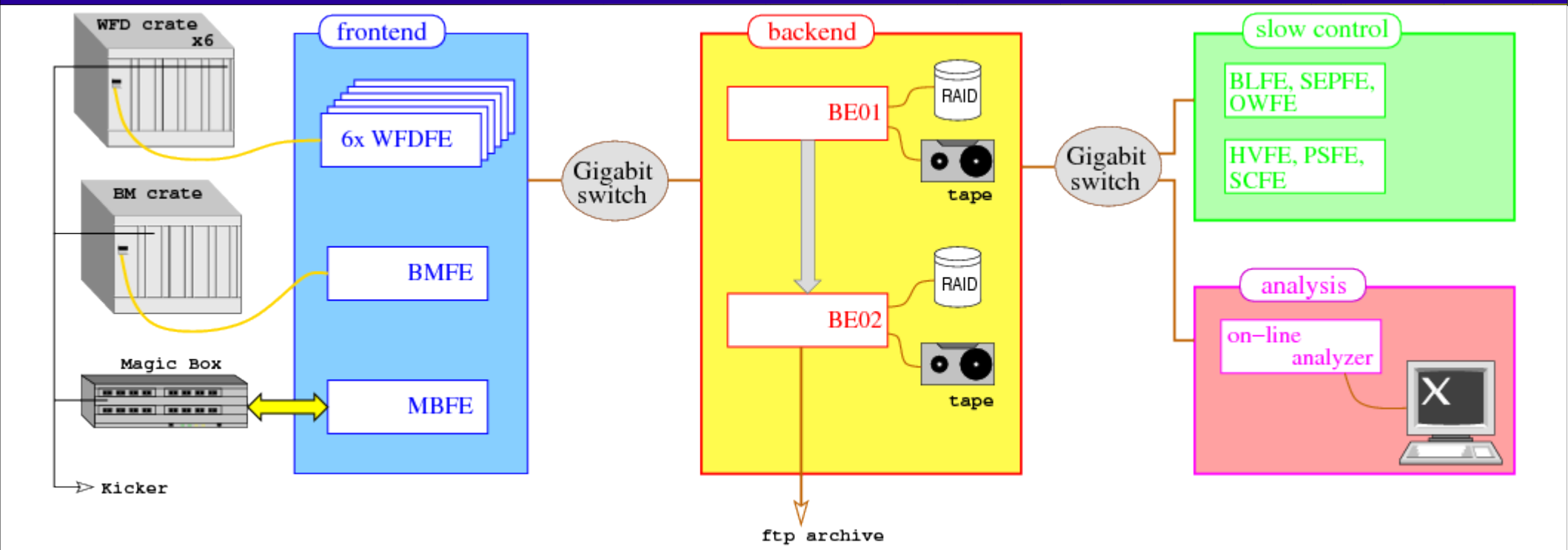
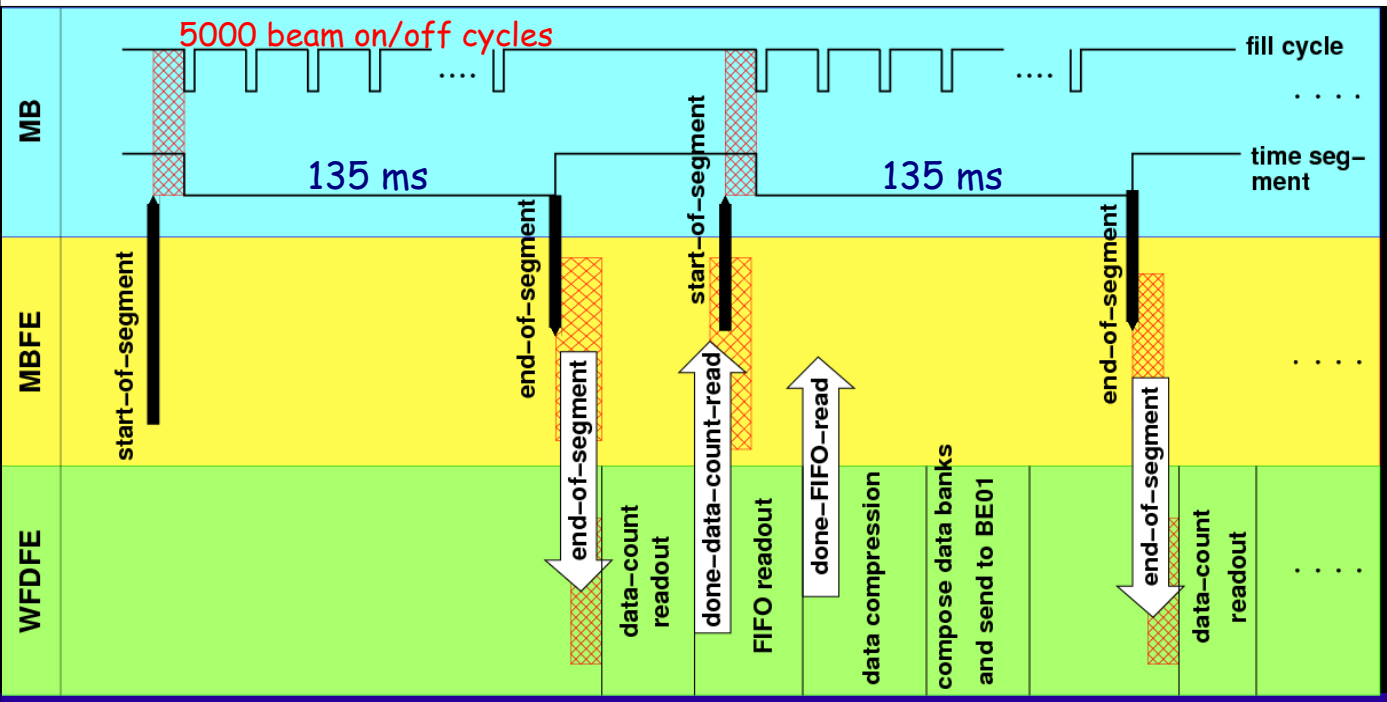


x6

Data Acquisition System (DAQ)

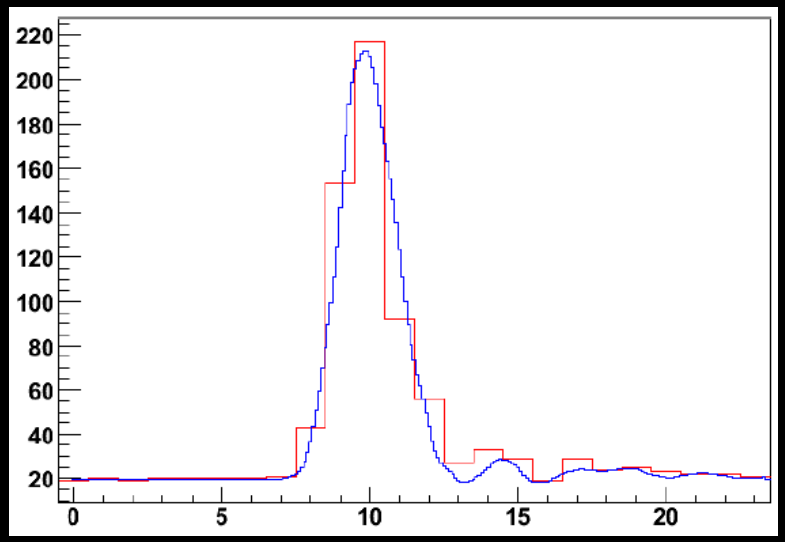




1 ppm -> 10^{12} muon decays

- ~50 MB/s raw data stream
- ~ 130 TB of data collected
- deadtime-free data segments
- ~97% DAQ livetime
- On-line data compression
- Double-core Intel™ Xion two-CPU PCs
- Multi-threading

Data Analysis Flow

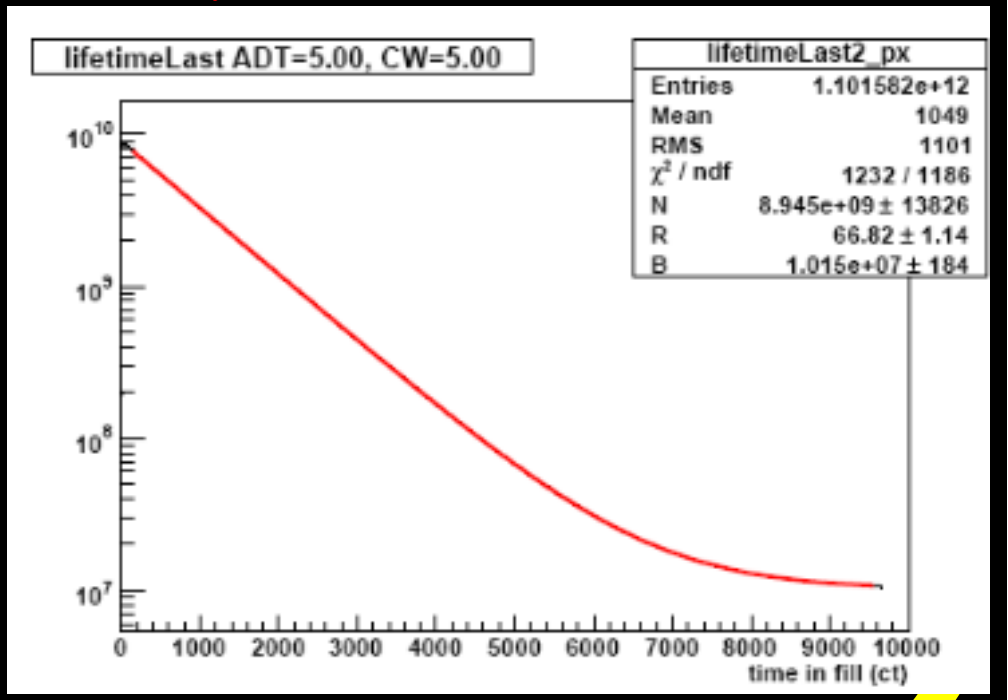


raw waveforms are fit with templates to find pulse amplitudes and times

histogram times

fit for τ_μ

$$f(t) = N_0 e^{-t/\tau_\mu} + B$$



check consistency,
study systematic errors

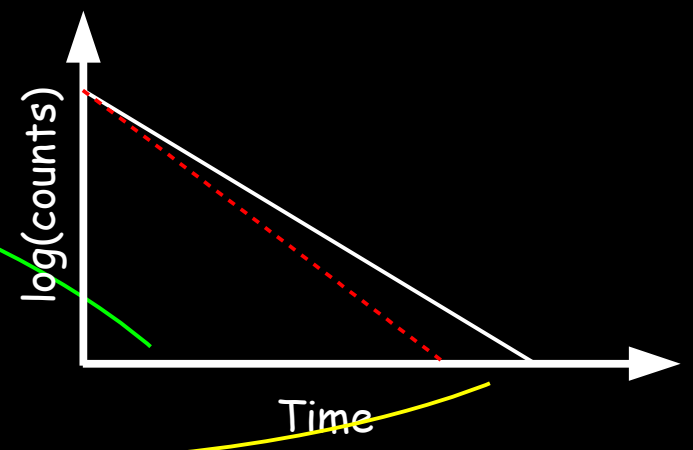
Blind analysis

- Exact clock frequency kept secret
- Muon lifetime is reported is reported with the value R with units of ppm defined as

$$\tau_\mu = \tau_{\text{secret}}(1 + R/10^6)$$

only analyzer knows

What can go wrong?



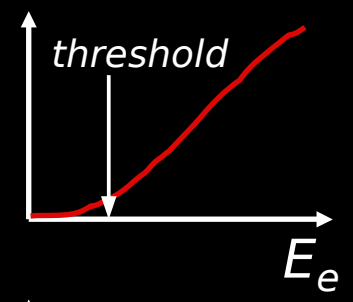
Early-to-late changes, for instance:

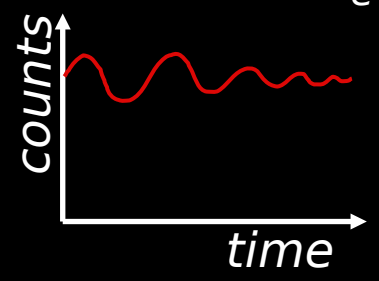
<u>Instrumental issues</u>

- PMT gains
- Discriminator threshold walk
- Kicker voltage sag
- Pileup

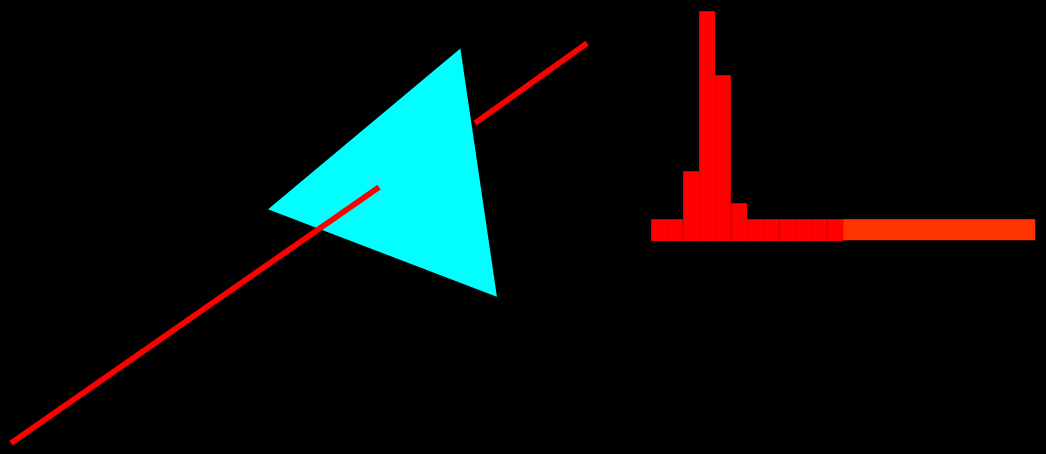
<u>Physics issues</u>

- Spin polarization
- Non-flat background sources



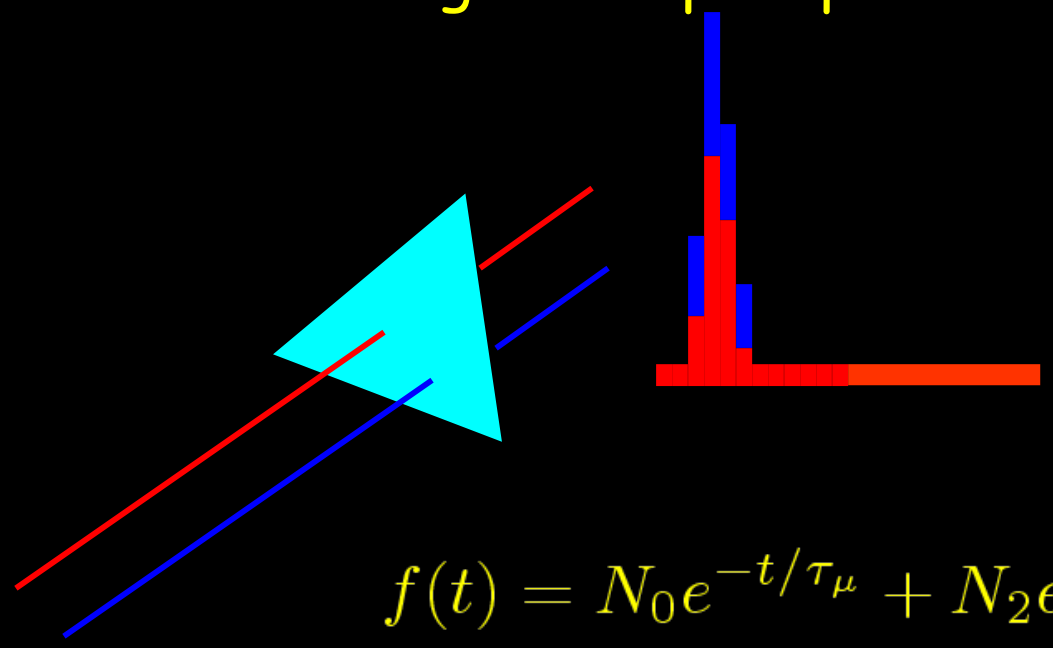


Pileup

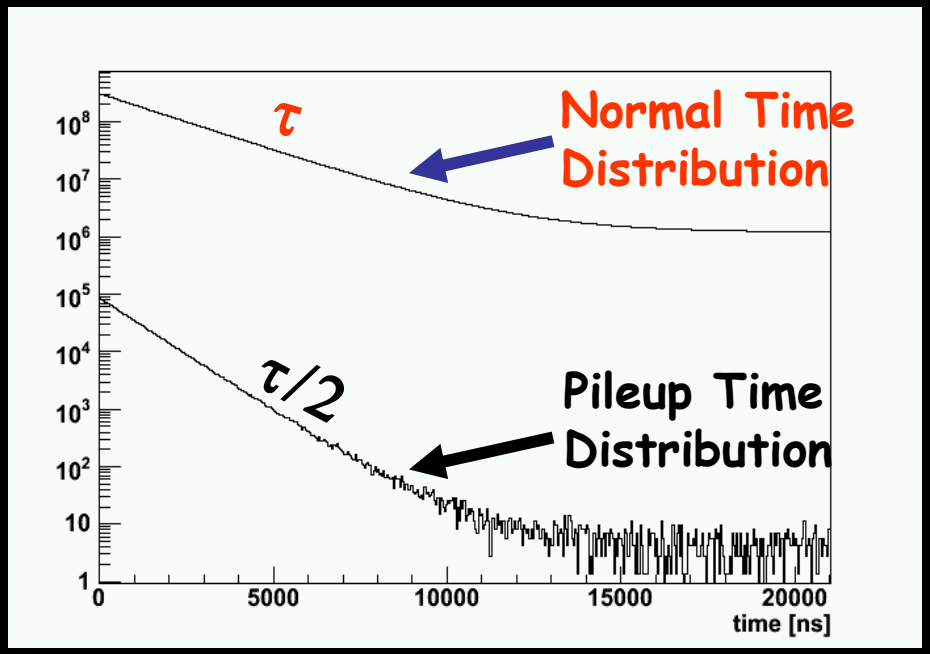


Pileup

Leading order pileup to a ~5x10^{-4} effect

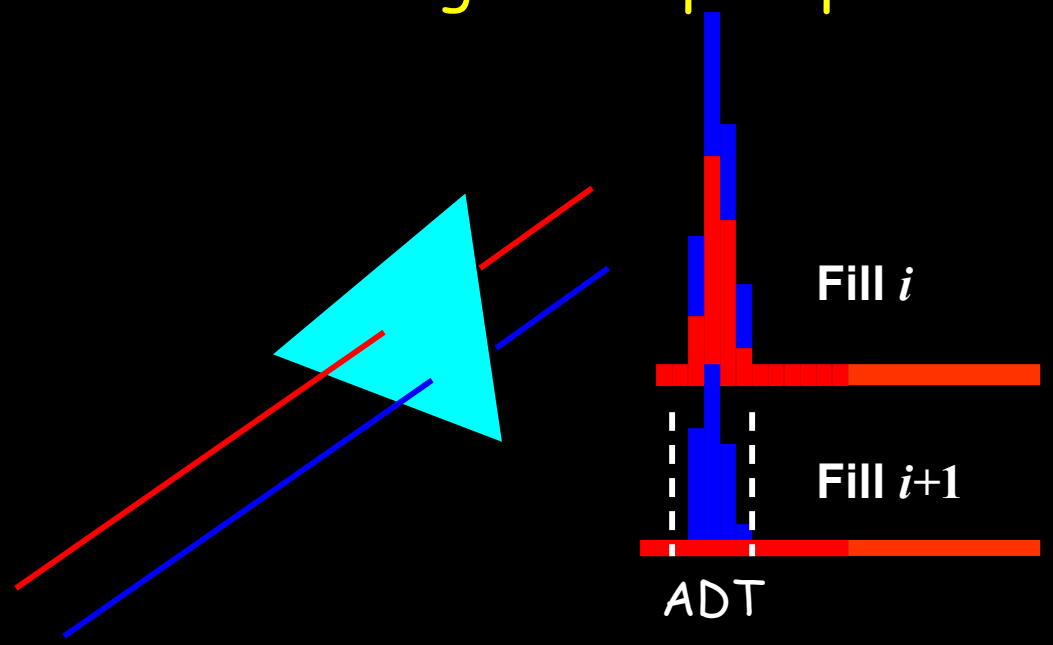


$$f(t) = N_0 e^{-t/\tau_\mu} + N_2 e^{-2t/\tau_\mu} + N_3 e^{-3t/\tau_\mu} + \cdot + B$$

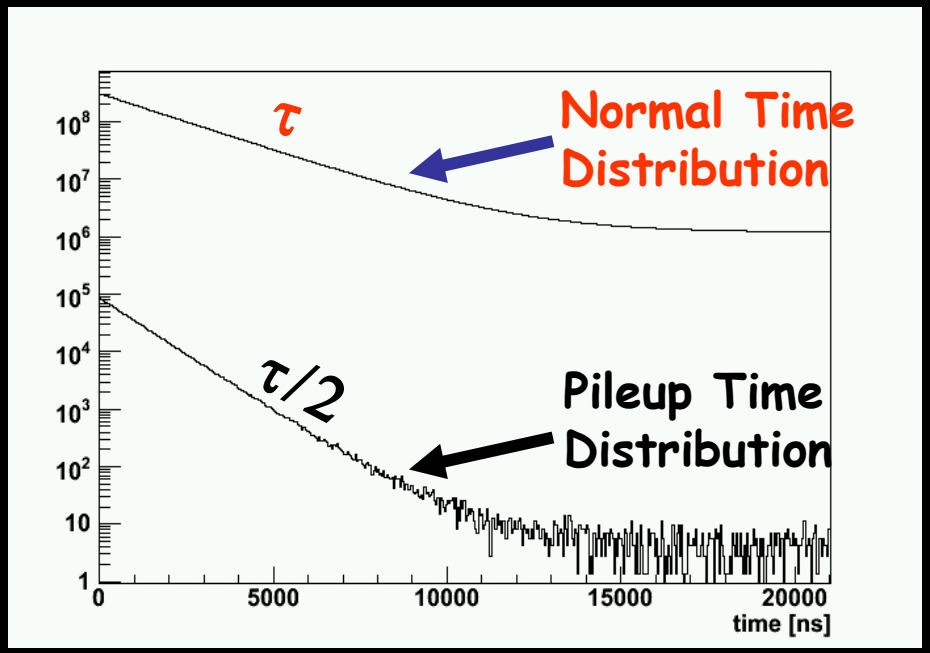


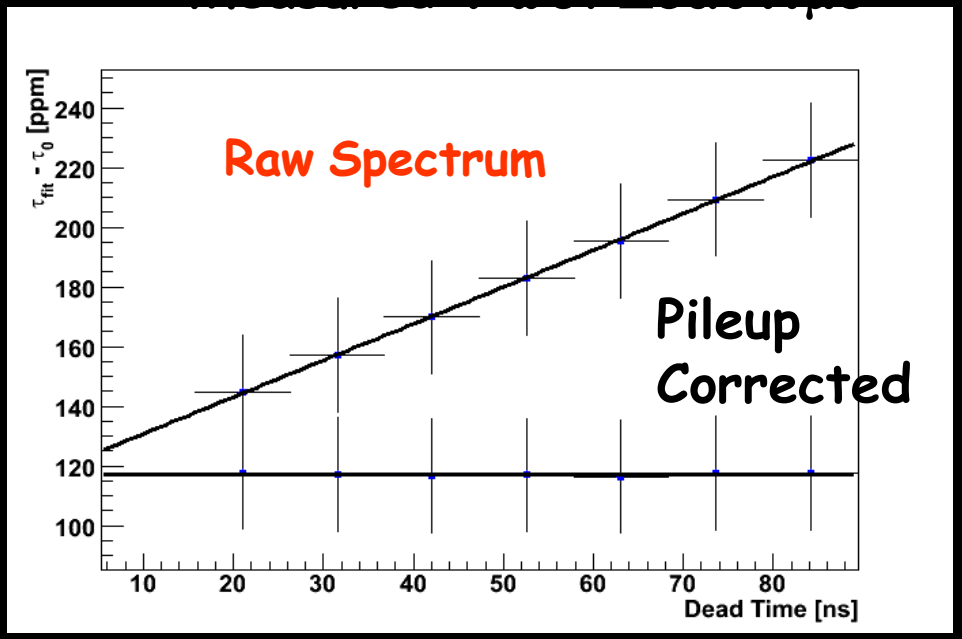
Pileup

Leading order pileup to a ~5x10^{-4} effect



- Statistically reconstruct pileup time distribution
- Fit corrected distribution



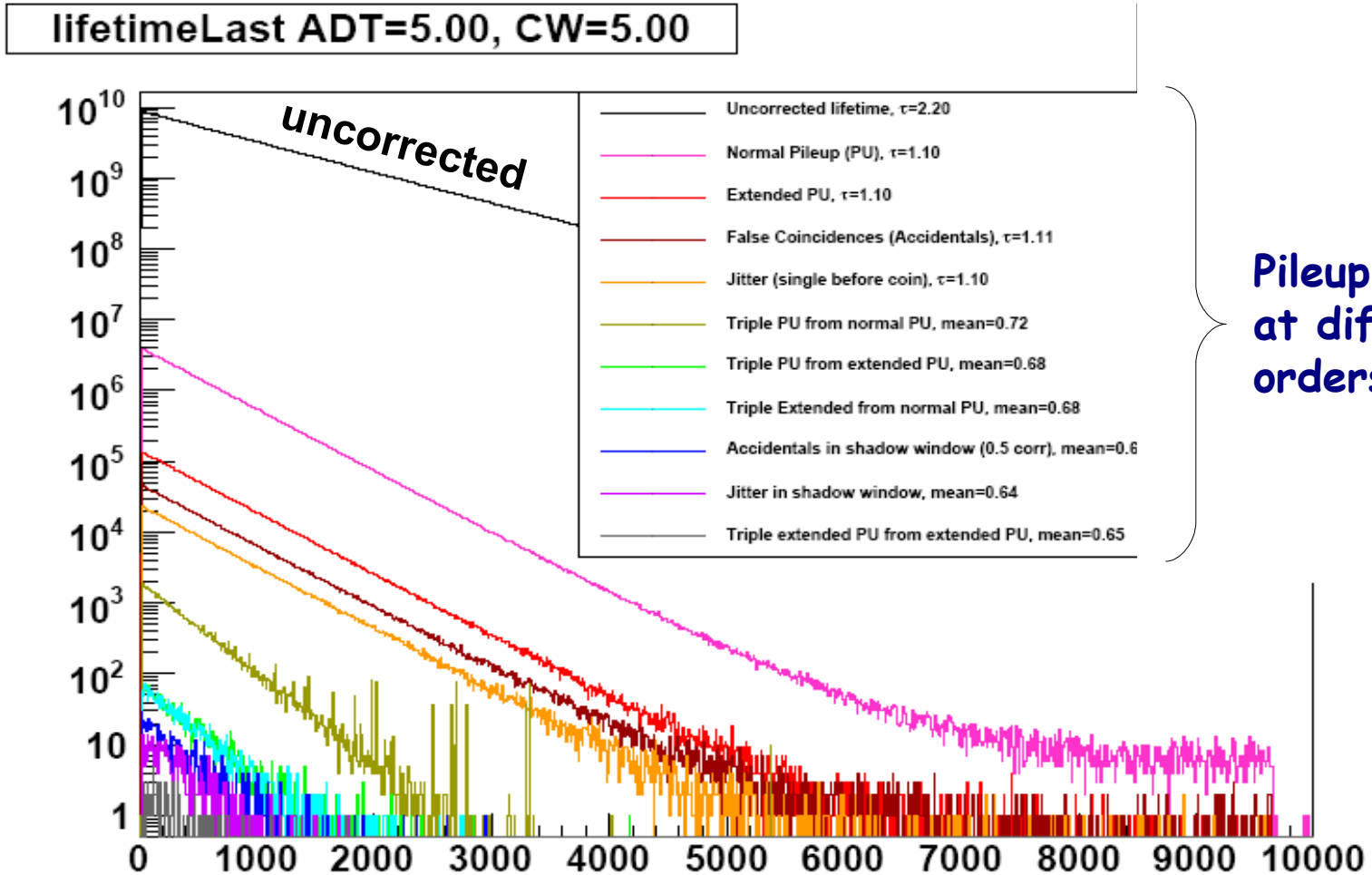


Pileup to sub-ppm requires higher-order terms

12 ns deadtime, pileup has a 5 x 10^{-4} probability at our rates

Left uncorrected, lifetime wrong by 100's of ppm

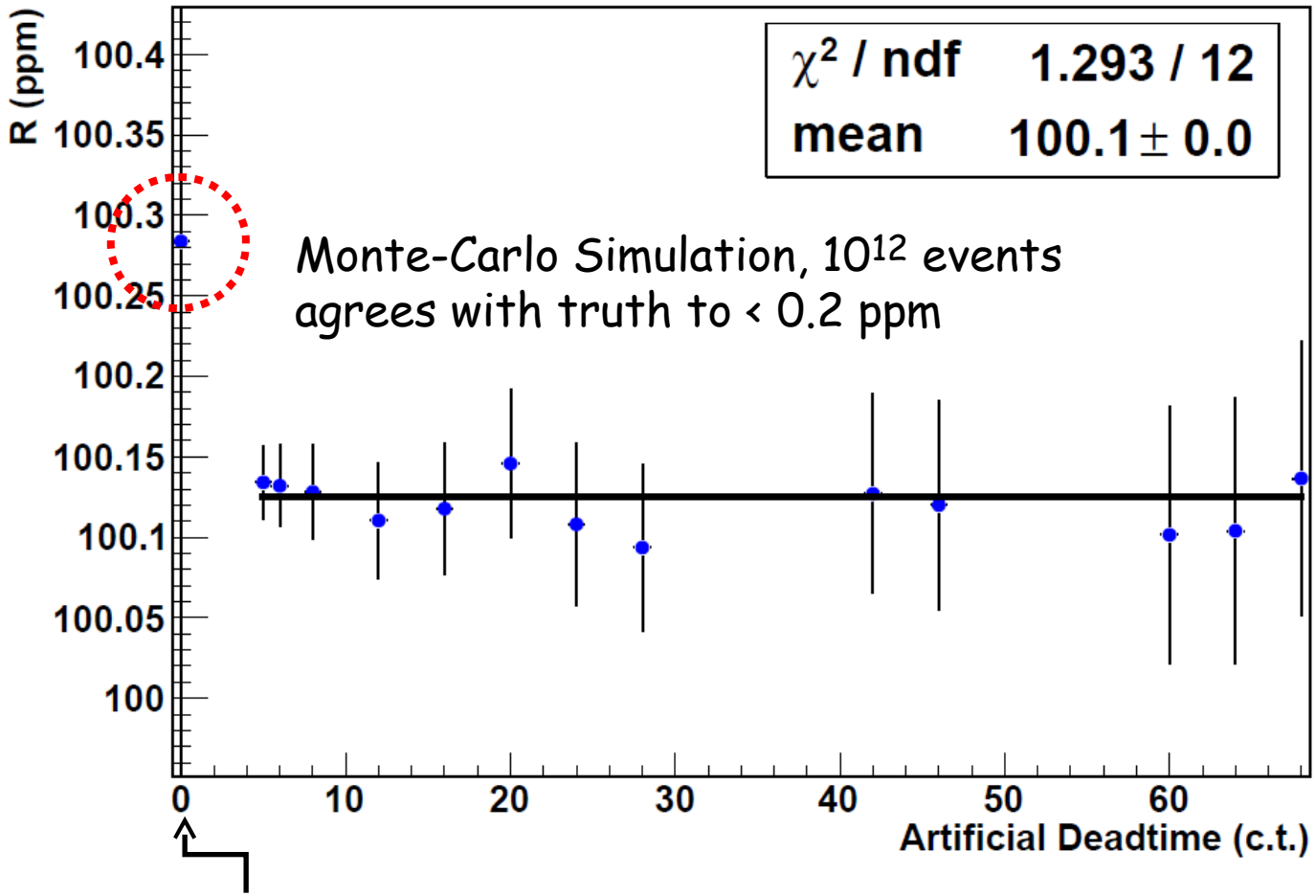
Proof of procedure validated with detailed Monte Carlo simulation



Pileup terms at different orders …

D. M. Webber

The pileup corrections were tested with Monte-Carlo.

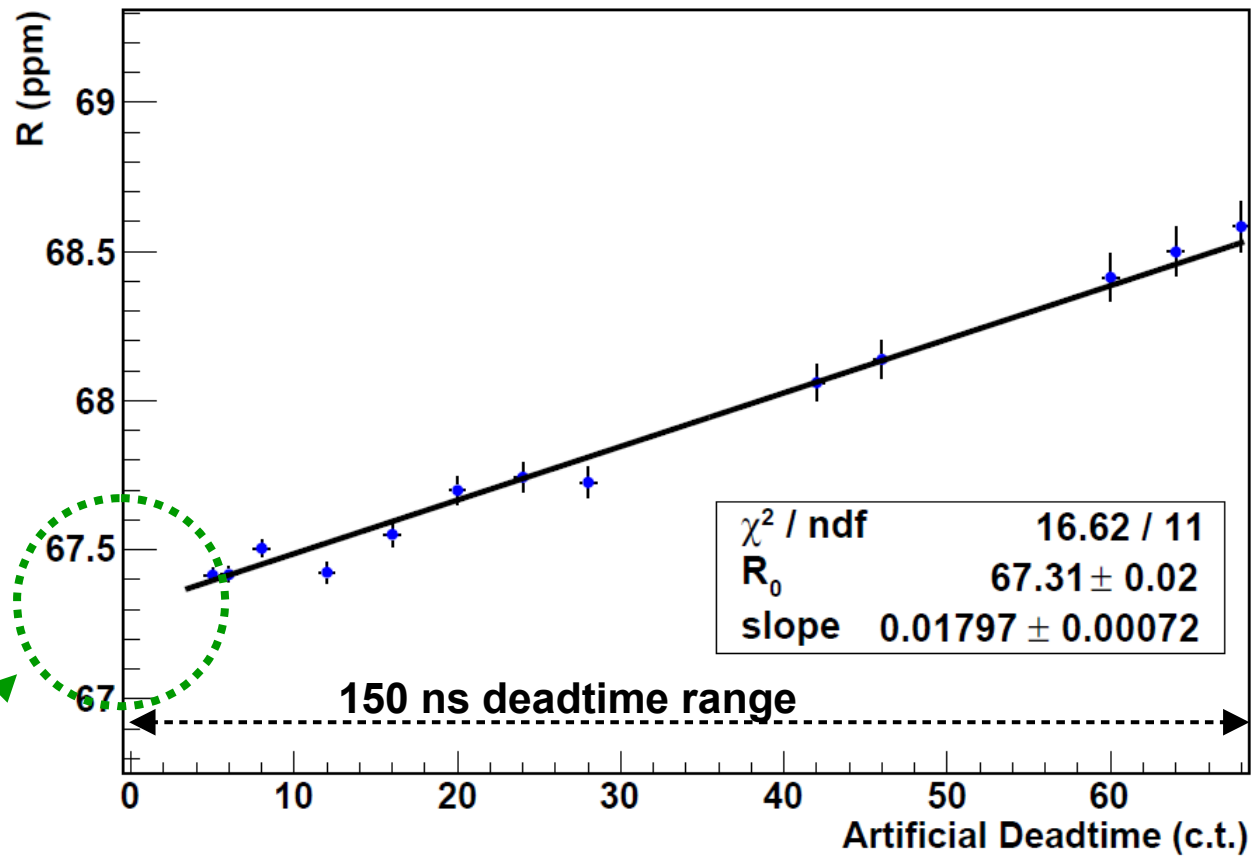


1.19 ppm statistical uncertainty

D. M. Webber

Lifetime vs. artificially imposed dead time diagnostics

A slope exists due to a pileup undercorrection



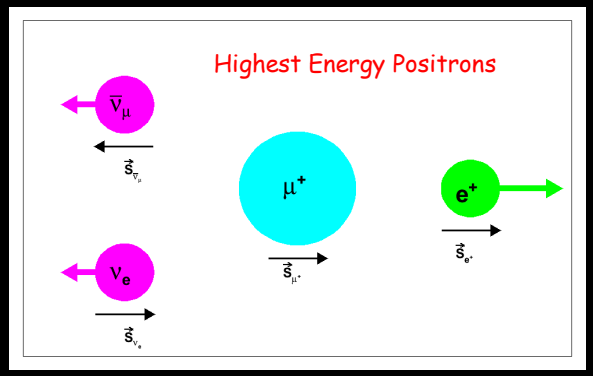
Extrapolation to 0 deadtime is correct answer

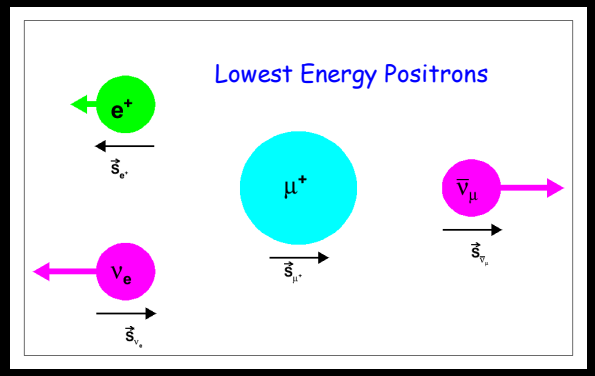
Pileup Correction Uncertainty: 0.2 ppm

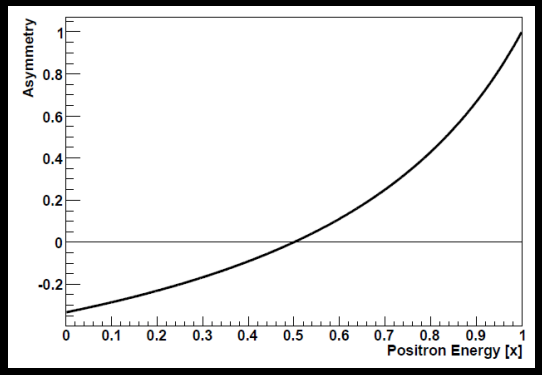
D. M. Webber

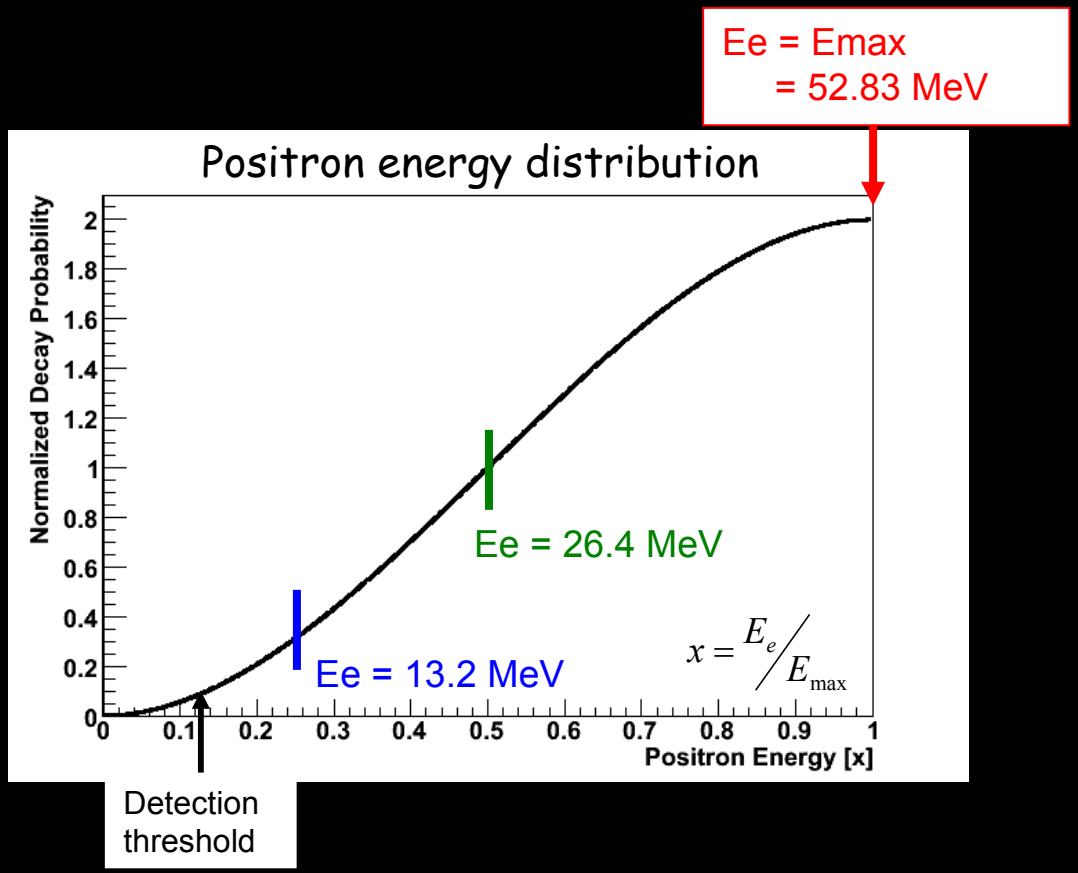
μSR

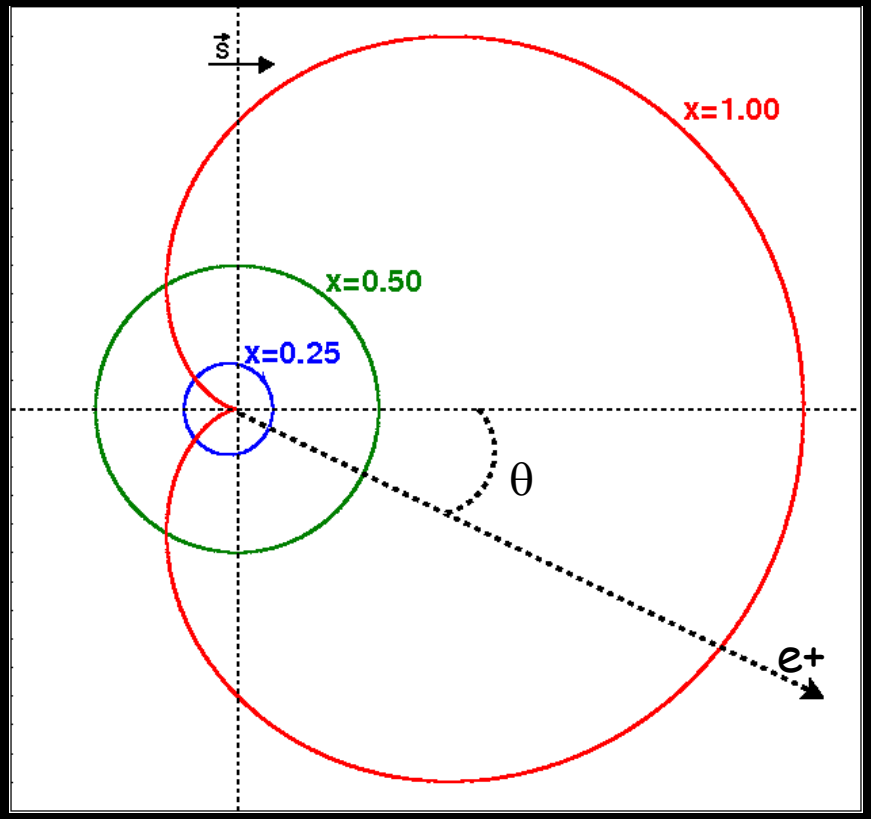
The decay positron energy and angular distributions are not uniform, resulting in position dependent measurement rates.









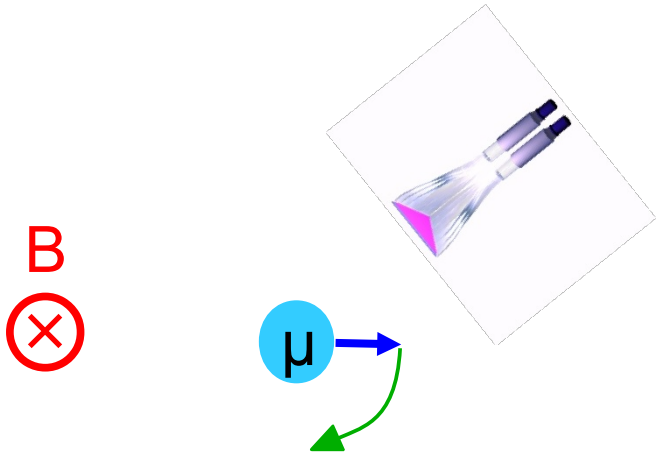


Precession of the muon spin distorts lifetime histogram

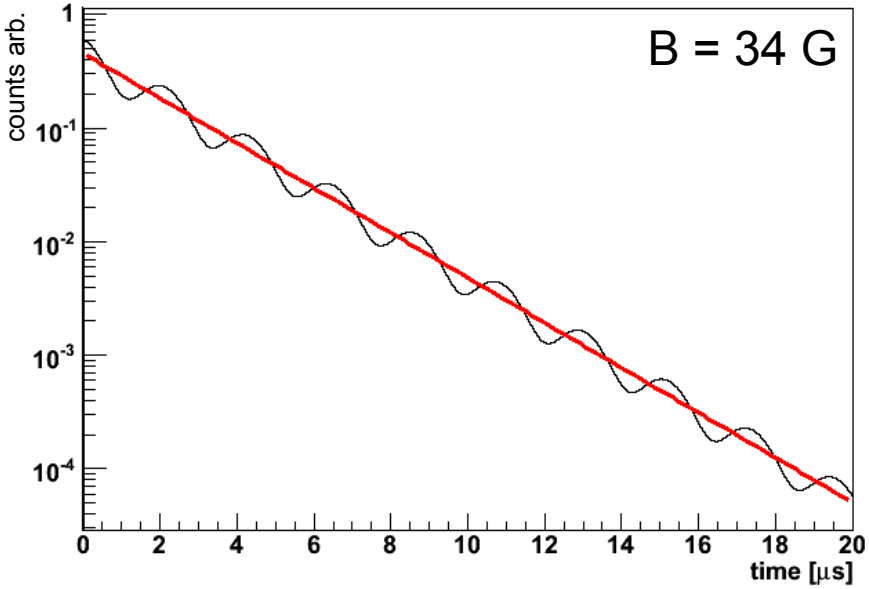
$$\omega = g_\mu \frac{eB}{2m_\mu c}$$

$$g_\mu \approx 2$$

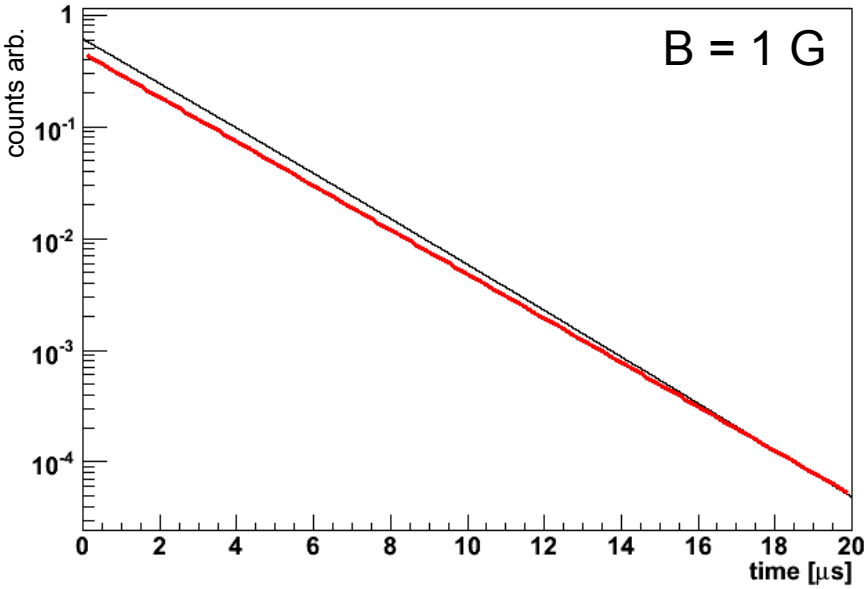
$$\omega \sim 135 \text{ MHz/T}$$



$$N(t) = N_0 e^{-t/\tau_\mu} \left[1 + AP_2 \cos(\omega t + \phi_0)\right]$$

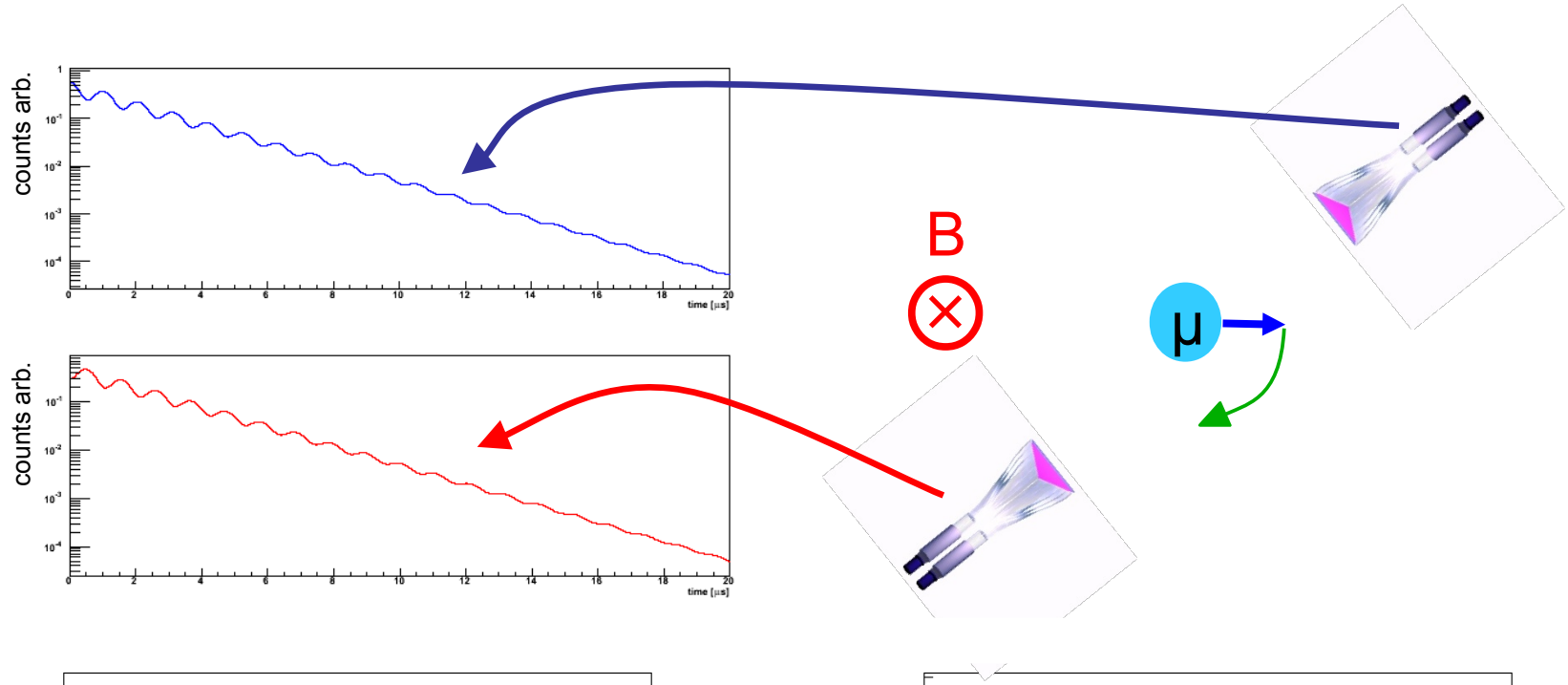


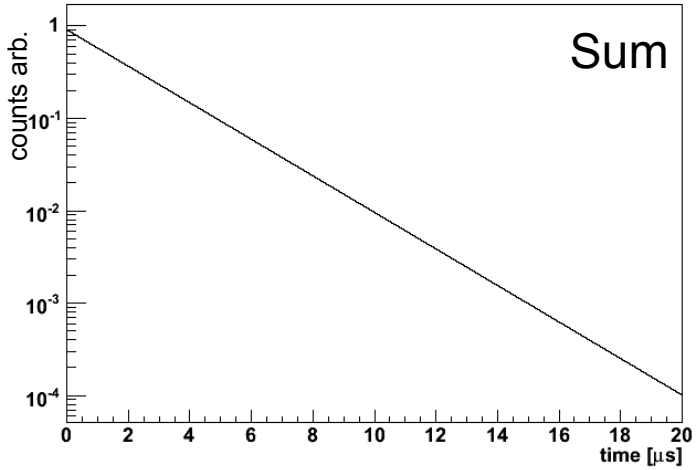
This oscillation is easily detected



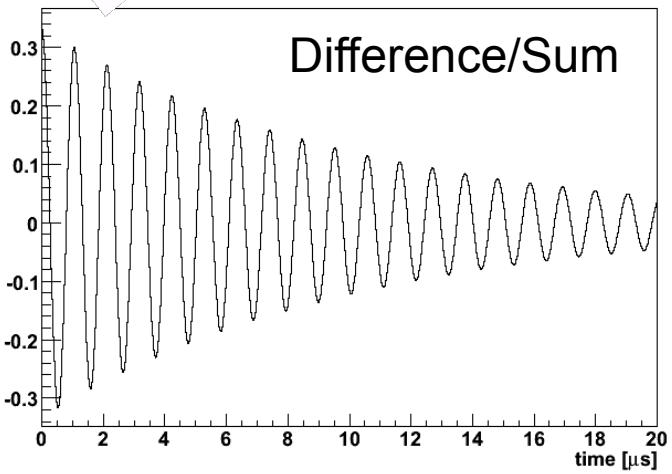
This oscillation is not easily detected and systematic errors may arise

μSR signal in opposite detectors





The sum cancels μSR effects



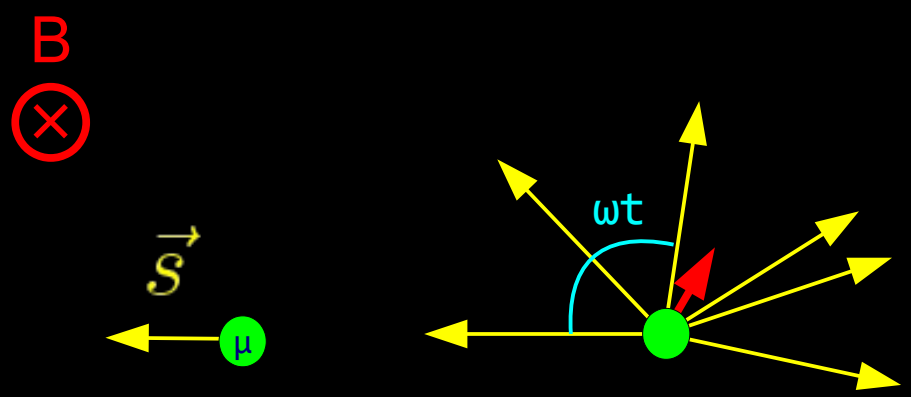
The difference accentuates μSR effects

MuLan strategy – reduce polarization!

- Dephasing
- Polarization destroying targets

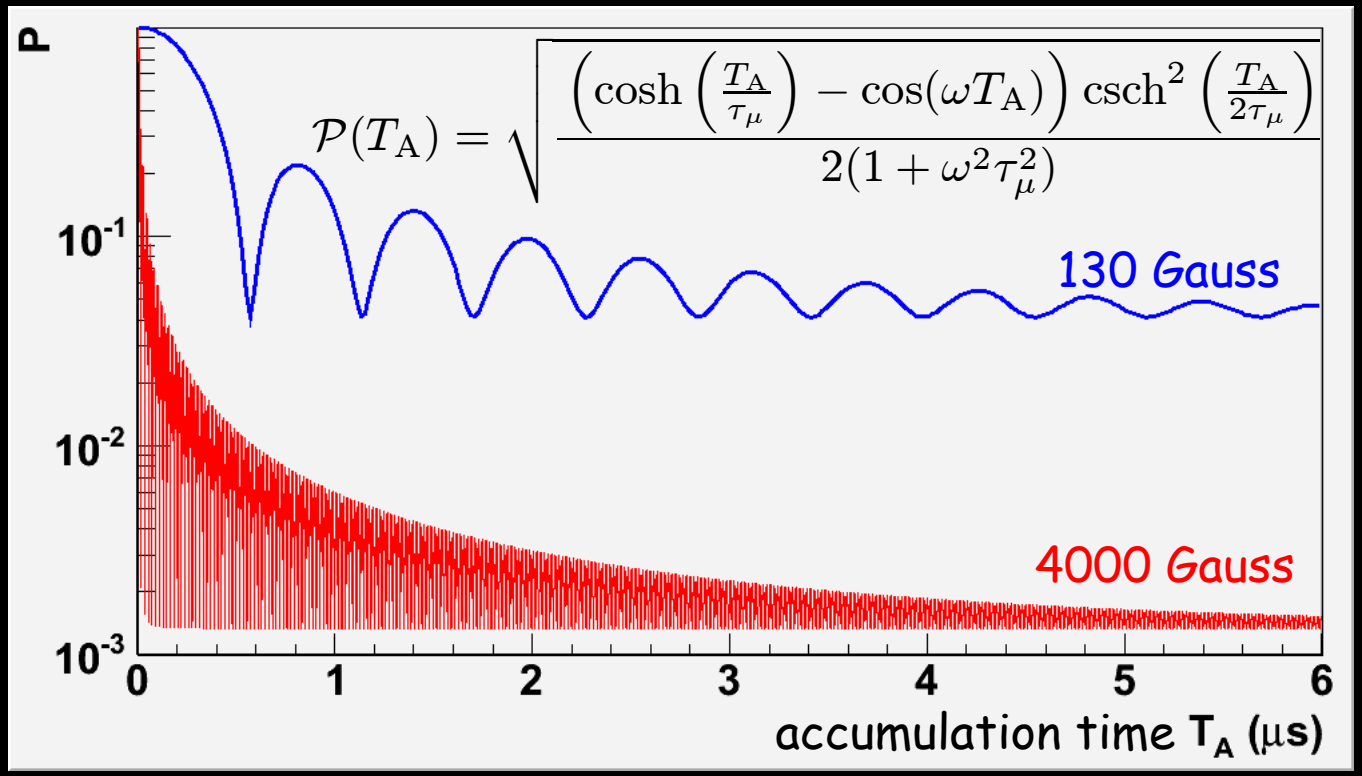
Dephasing

Muons arrive randomly during 5μs accumulation period



Polarization of a muon ensemble

$$\vec{\mathcal{P}}(t) = \frac{1}{n}\sum^{n}\vec{s}(t)$$



Muon stopping targets

2006

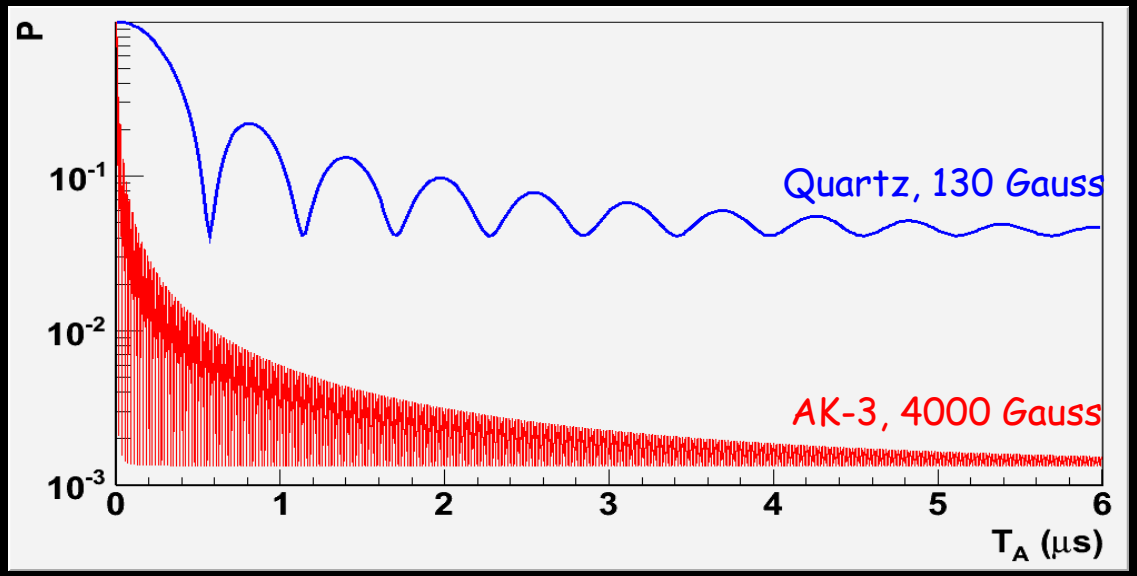
Arnokrome-3 (AK-3) target
(~28% chromium, ~8% cobalt, ~64% iron)
0.4 T transverse field rotates muons with 18 ns period

Muons precess by 0 to 350 revolutions
DEPHASED small ensemble avg. polarization

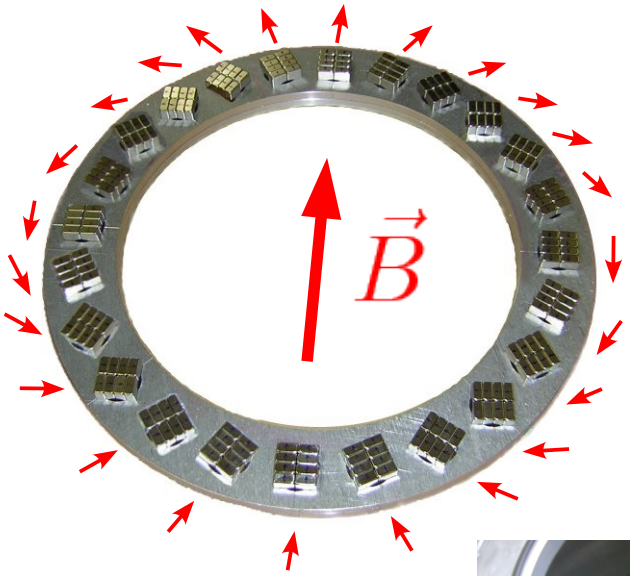
2007

Crystalline quartz target
90% muonium formation
- 50% depolarization (Mu in singlet state)
- Fast precession of Mu in triplet state

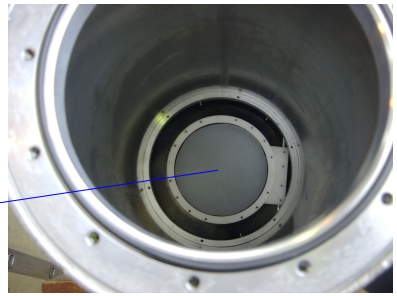
10% "free" muons
- Noticeable precession
- Relaxation of longitudinal polarization



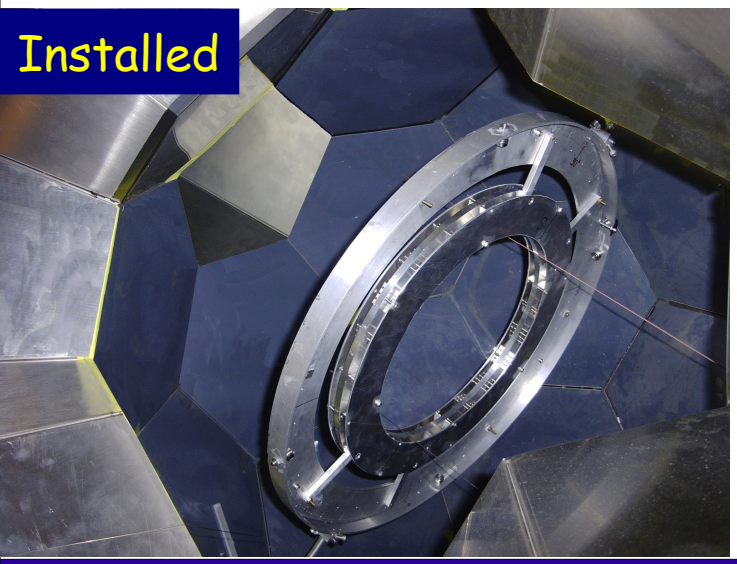
μSR magnet for Quartz target



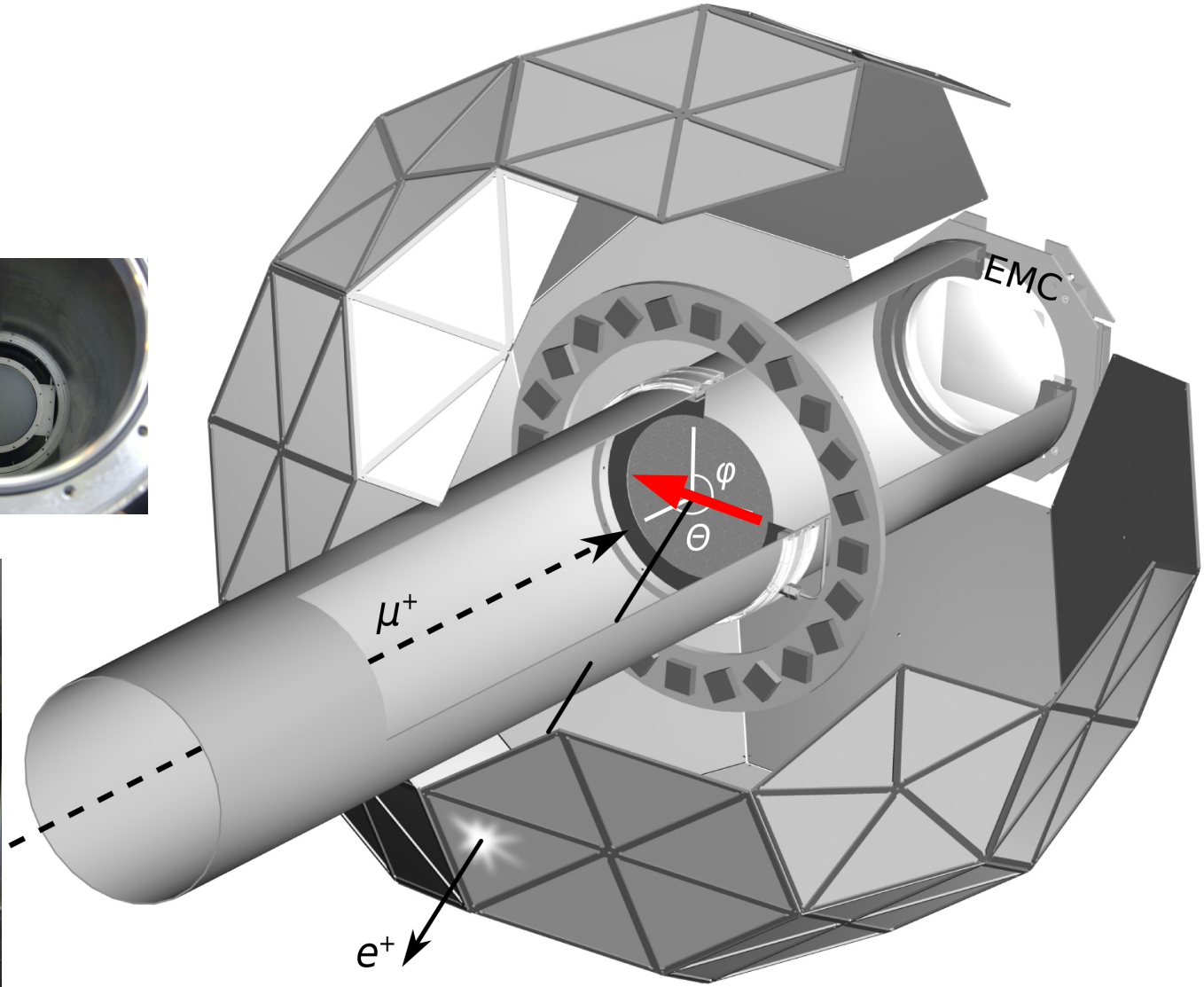
Halbach array of permanent magnets to produce ~130 G field in the target plane



Quartz target



Installed



Two targets, two analysis strategies

AK-3

(strongly suppressed μSR)

Sum time histograms from all detectors and fit for τ_μ

Quartz

(noticeable μSR)

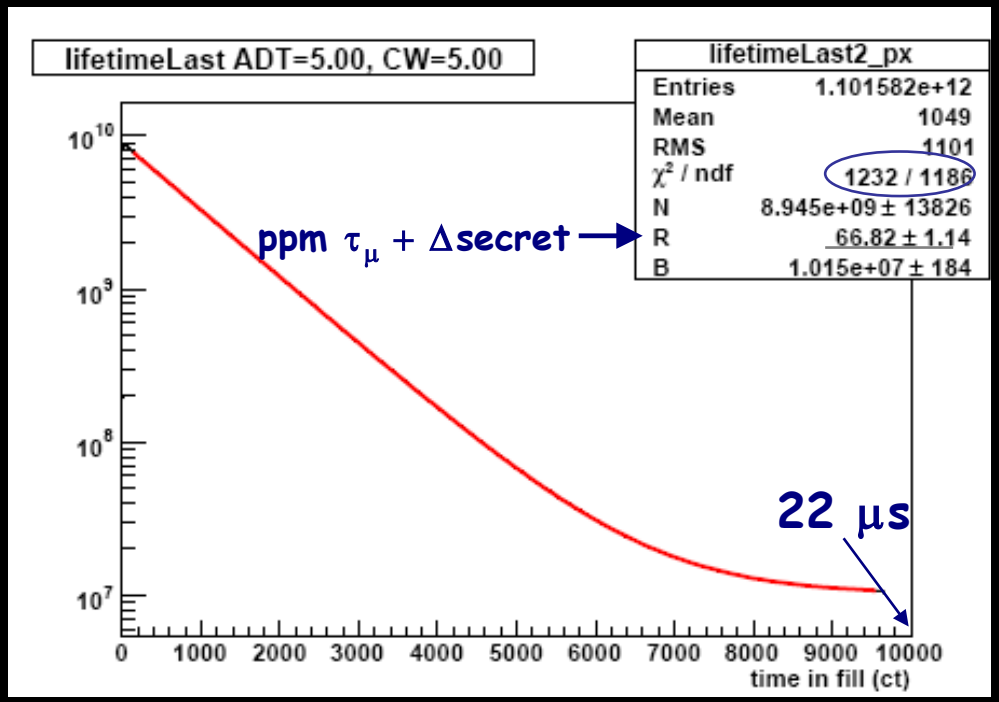
Incorporate μSR effects into the fit function. Fit each detector individually.

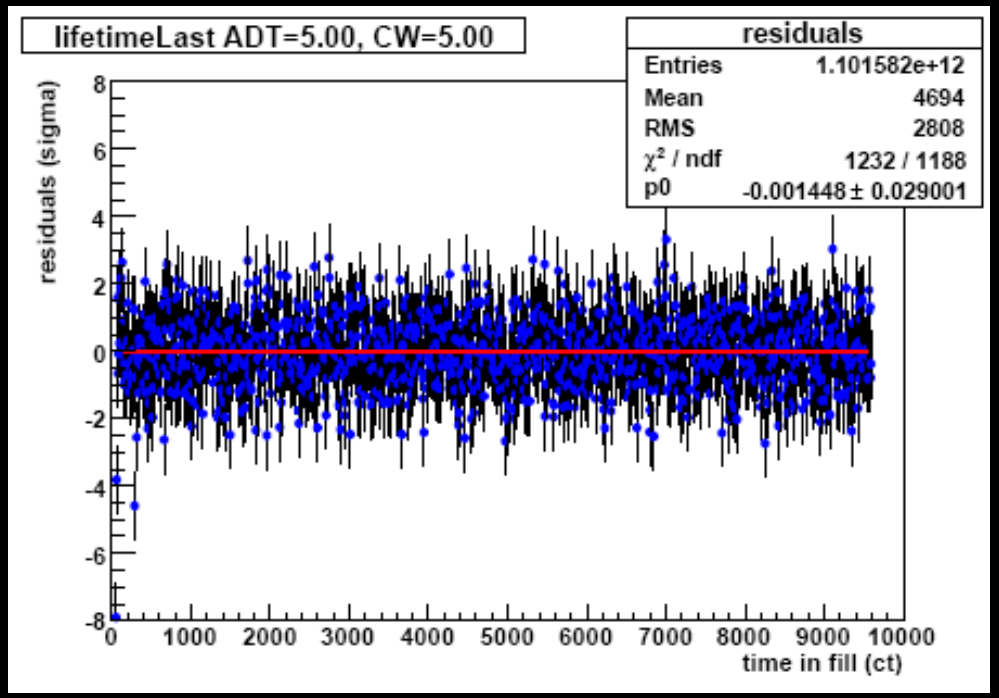
AK-3, Sum of all detectors, sum of all 30000 runs

fit function

$$f(t) = N_0 e^{-t/\tau_\mu} + B$$

$$\tau_\mu = \tau_{\text{secret}}(1 + R/10^6)$$





Quartz target, fit individual detectors

<u>fit function</u>
(most general form)

$$f(t) = N_0 \left[1 + A\vec{\mathcal{P}}(t)\hat{r}_{\mathrm{D}} \right] e^{-t/\tau_\mu} + B$$

decay asymmetry

ensemble polarization

unit vector to detector

Quartz target, fit individual detectors

fit function
(most general form)

$$f(t) = N_0 \left[1 + A\vec{\mathcal{P}}(t)\hat{r}_{\mathrm{D}}\right] e^{-t/\tau_\mu} + B$$

decay asymmetry

ensemble polarization

unit vector to detector

resolve $\mathcal{P}$ into two components relative to B-field

$$f(t) = N_0 \left[1 + A(\vec{\mathcal{P}}_1(t) + \vec{\mathcal{P}}_2(t))\hat{r}_{\mathrm{D}}\right] e^{-t/\tau_\mu} + B$$

transverse (precession+relaxation)

longitudinal (relaxation)

Quartz target, fit individual detectors

fit function
(most general form)

$$f(t) = N_0 \left[1 + A\vec{\mathcal{P}}(t)\hat{r}_{\mathrm{D}}\right] e^{-t/\tau_\mu} + B$$

decay asymmetry

ensemble polarization

unit vector to detector

resolve $\mathcal{P}$ into two components relative to B-field

$$f(t) = N_0 \left[1 + A(\vec{\mathcal{P}}_1(t) + \vec{\mathcal{P}}_2(t))\hat{r}_{\mathrm{D}}\right] e^{-t/\tau_\mu} + B$$

transverse (precession+relaxation)

longitudinal (relaxation)

$$\mathcal{P}_1(t) = P_1 e^{-t/T_1}$$

P_1 ~ 0.0015, T_1~28μs

$$\mathcal{P}_2(t) = P_2 e^{-t/T_2} \cos(\omega t + \phi_0)$$

P_2 ~ 0.0025, T_2~4μs

Quartz target, fit individual detectors

fit function
(most general form)

$$f(t) = N_0 \left[1 + A\vec{\mathcal{P}}(t)\hat{r}_{\mathrm{D}}\right] e^{-t/\tau_\mu} + B$$

decay asymmetry

ensemble polarization

unit vector to detector

resolve $\mathcal{P}$ into two components relative to B-field

$$f(t) = N_0 \left[1 + A(\vec{\mathcal{P}}_1(t) + \vec{\mathcal{P}}_2(t))\hat{r}_{\mathrm{D}}\right] e^{-t/\tau_\mu} + B$$

transverse (precession+relaxation)

longitudinal (relaxation)

$$\mathcal{P}_1(t) = P_1 e^{-t/T_1}$$

P_1 ~ 0.0015, T_1~28μs

$$\mathcal{P}_2(t) = P_2 e^{-t/T_2} \cos(\omega t + \phi_0)$$

P_2 ~ 0.0025, T_2~4μs

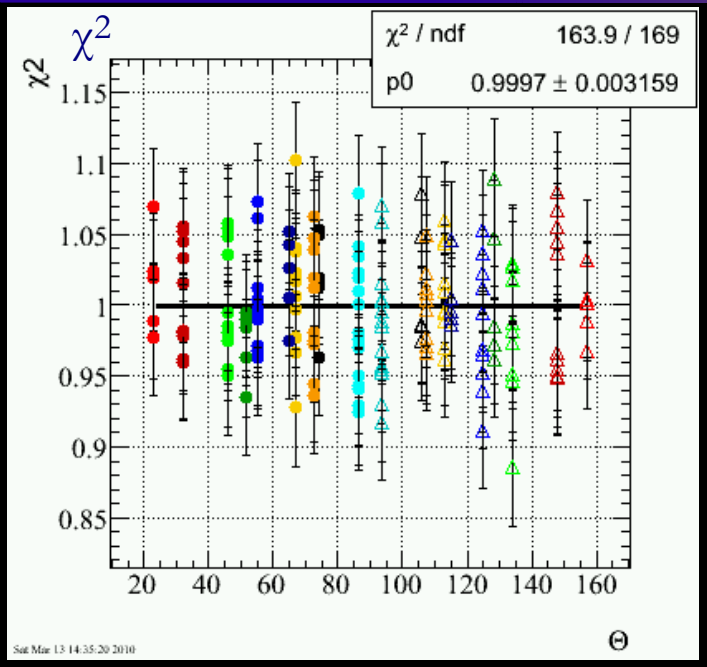
practical realization fit for muon disappearance time, then fit for τ_μ

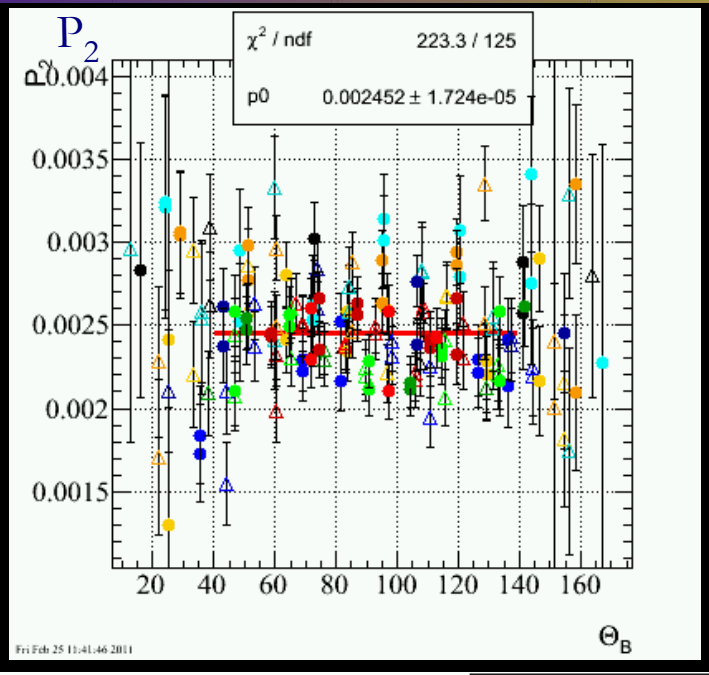
$$f(t) = N_0 \left[1 + AP_2 e^{-t/T_2} \cos(\omega t + \phi_0)\right] e^{-t/\tau_{\mathrm{d}}} + B$$

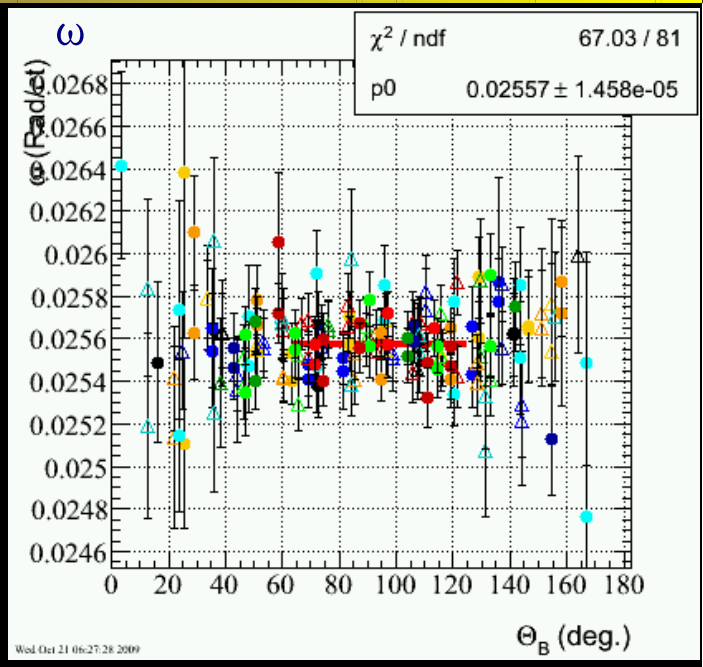
→ 170 values of τ_{d}

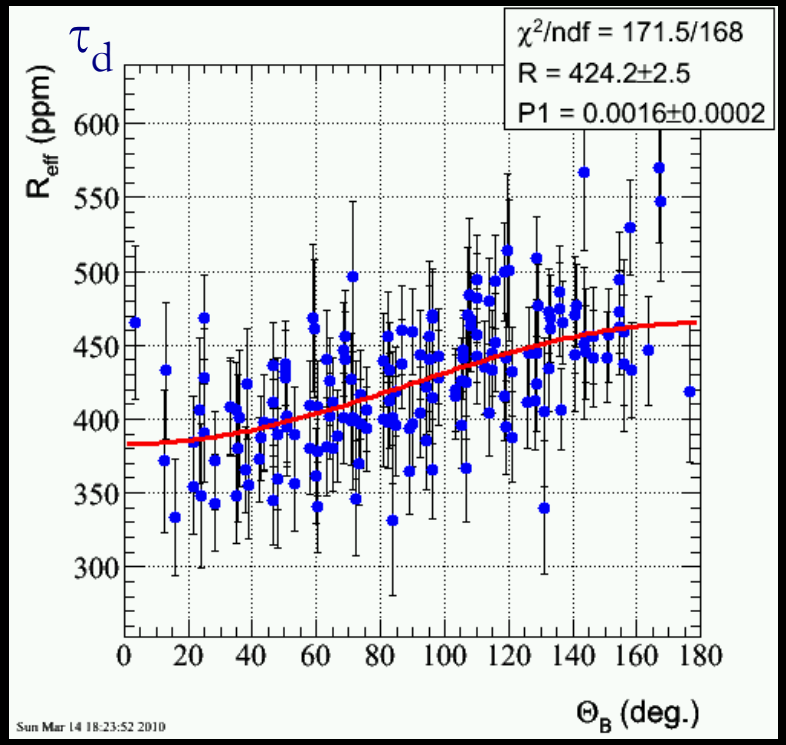
$$\tau_{\mathrm{d}} = \tau_\mu \left(1 - A\frac{\tau_\mu}{T_1}\vec{P}_1\hat{r}_{\mathrm{D}}\right)$$

fit results vs. detector position relative to B-field







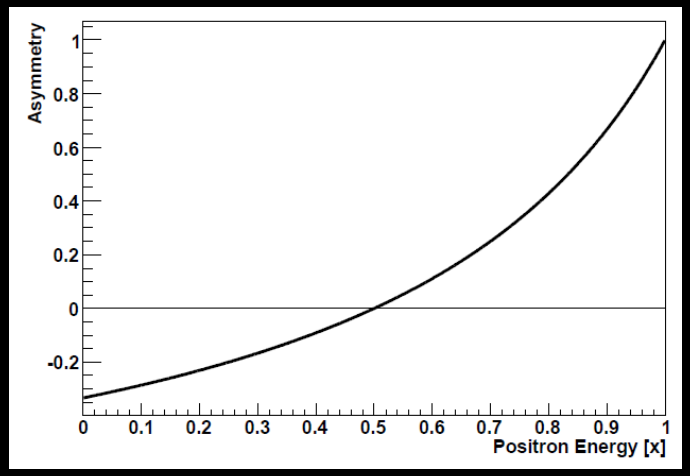


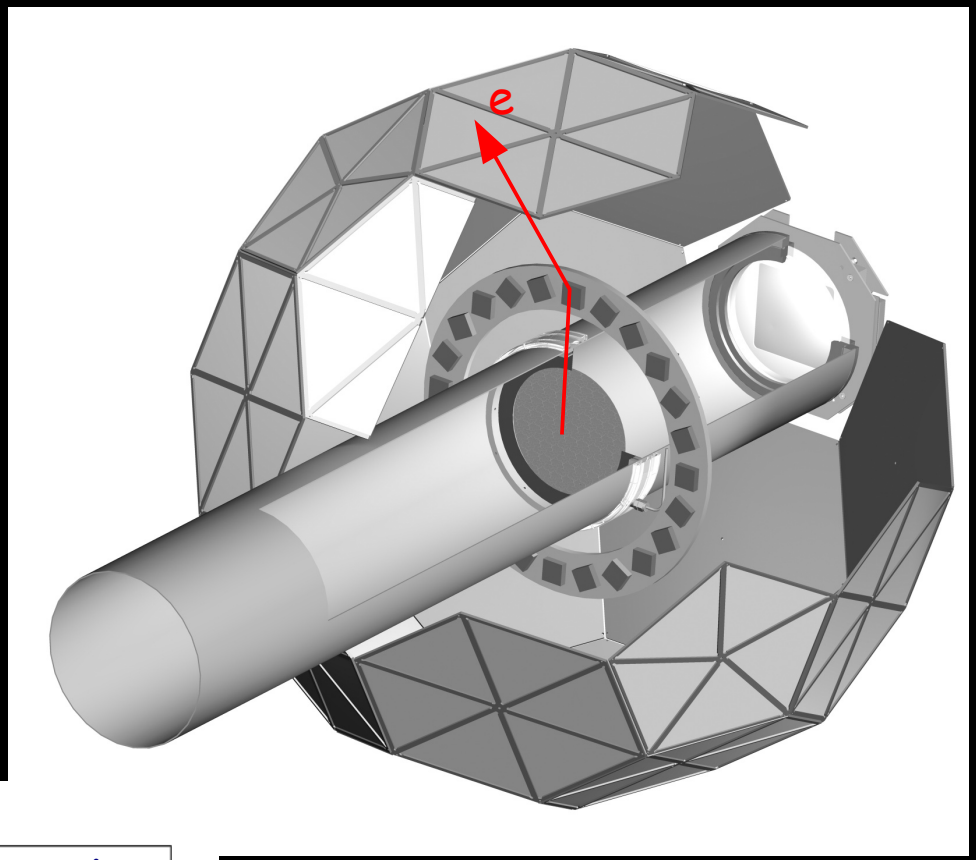
$$\tau_{\mathrm{d}} = \tau_{\mu}\left(1 - A\frac{\tau_{\mu}}{T_1}\vec{P}_1\hat{r}_{\mathrm{D}}\right)$$

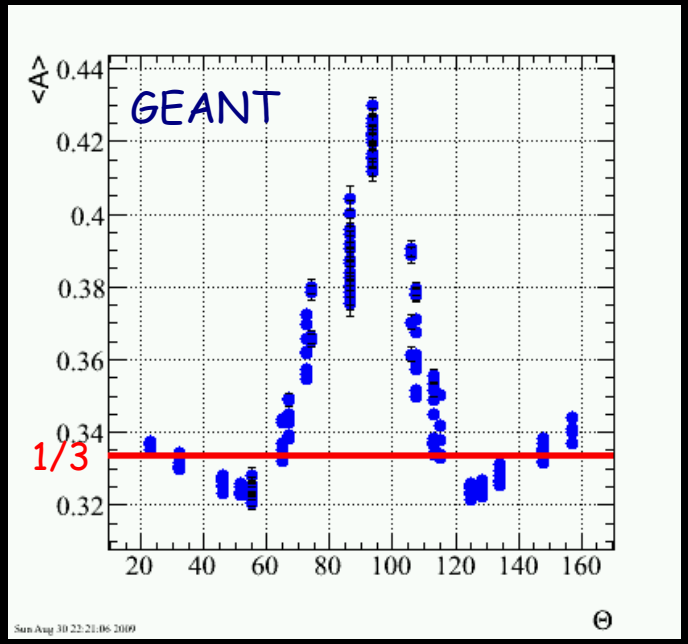
A small complication: decay asymmetry

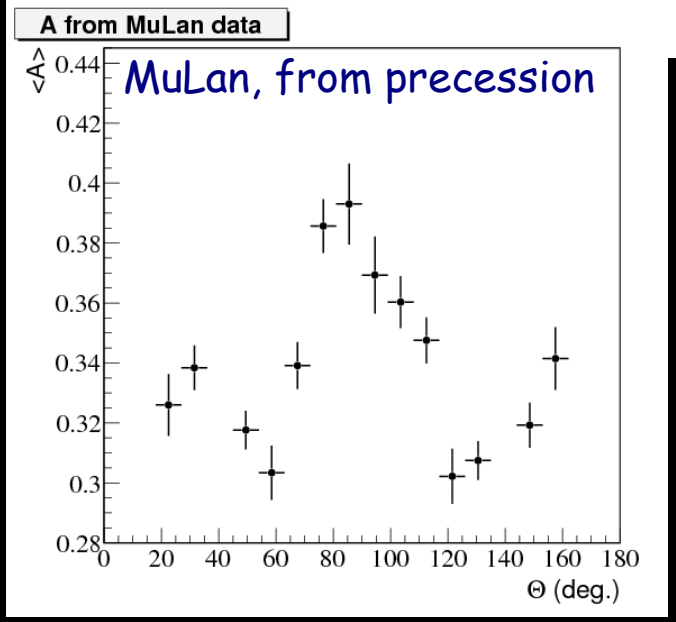
$$f(t) = N_0 \left[1 + AP_2 e^{-t/T_2} \cos(\omega t + \phi_0)\right] e^{-t/\tau_d} + B$$

Energy-integrated A = 1/3



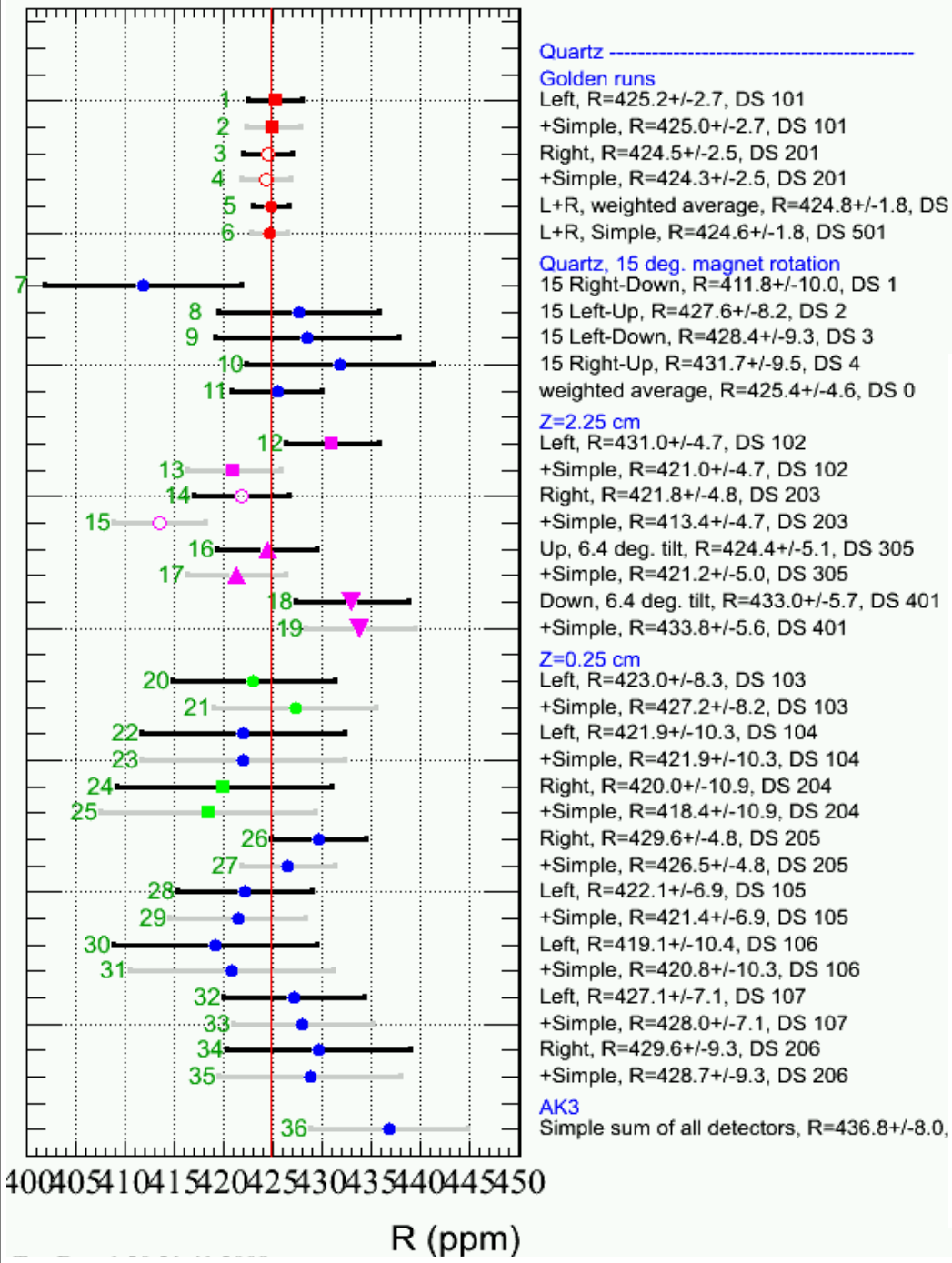




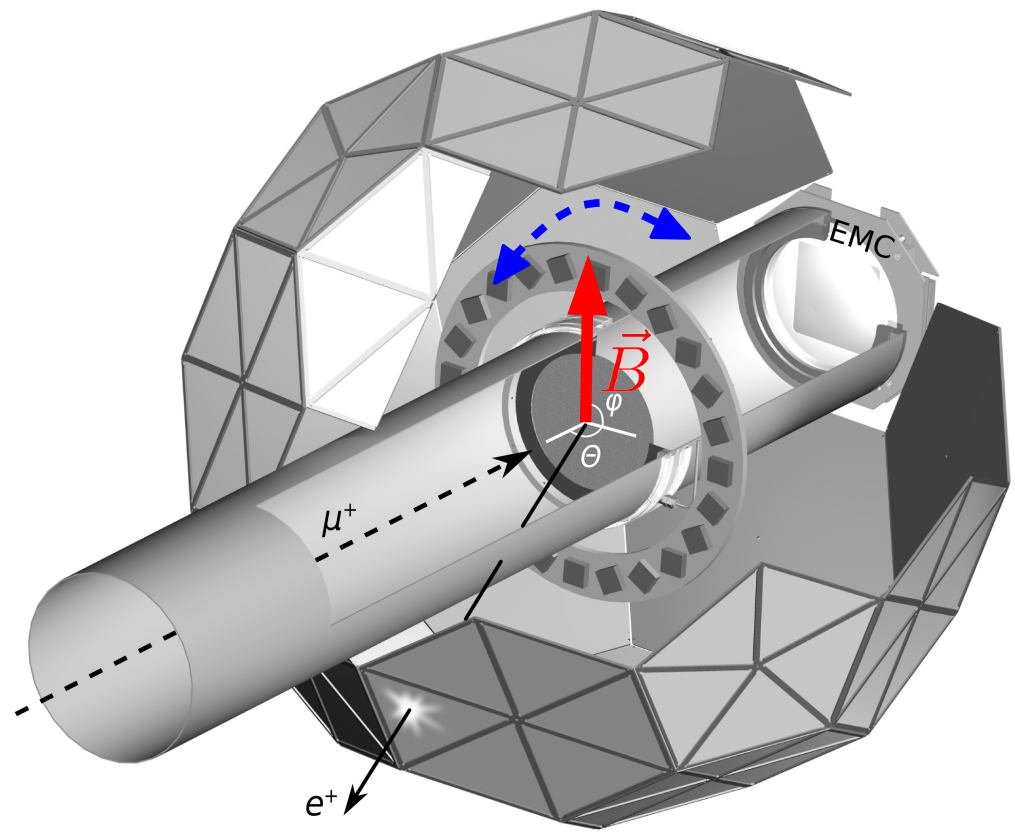


Plugging in GEANT asymmetries instead of a common A=1/3 asymmetry changes muon lifetime by 0.1 ppm

Consistency checks

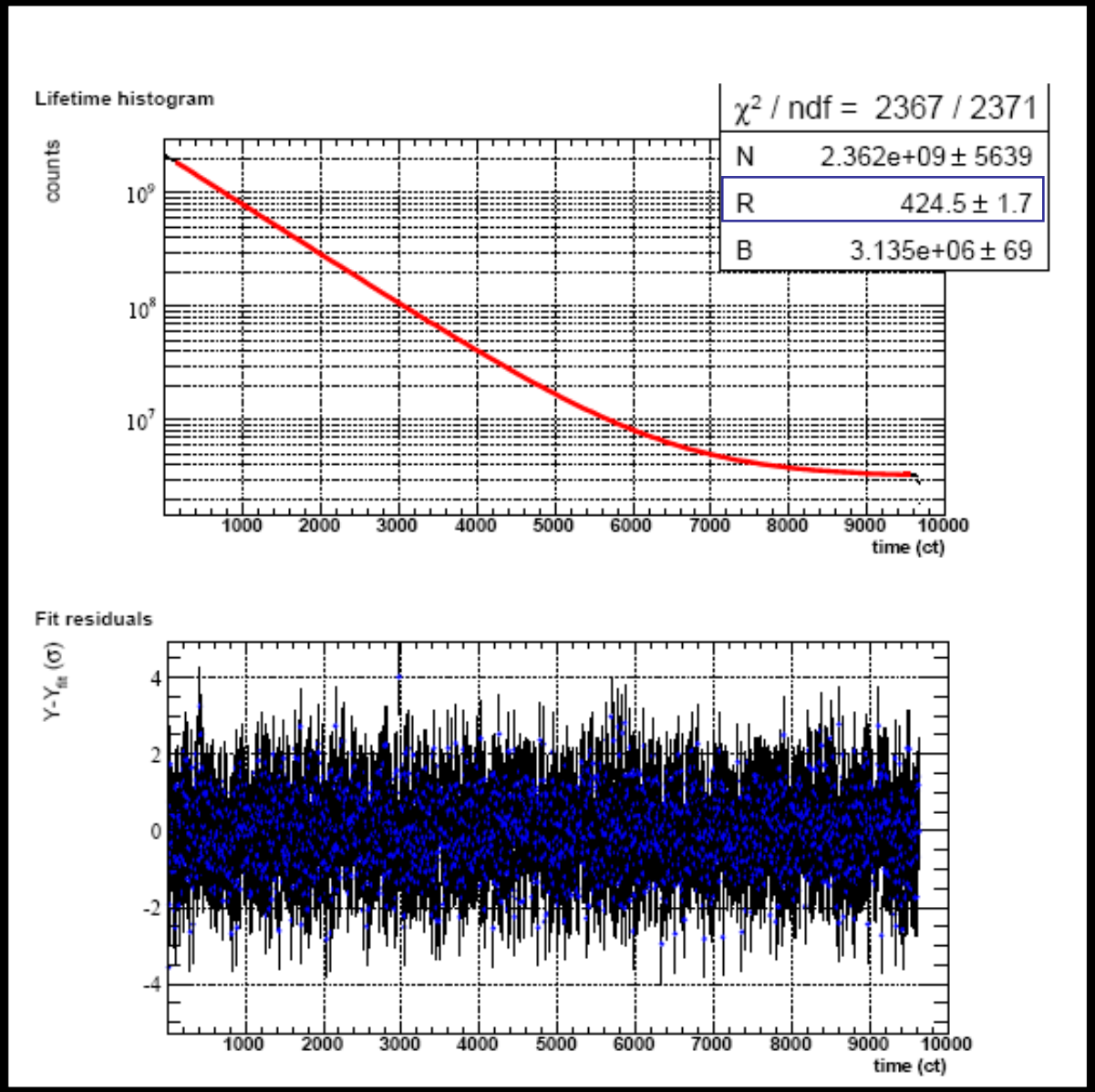


Consistency against MANY special runs, where we varied target, magnet, ball

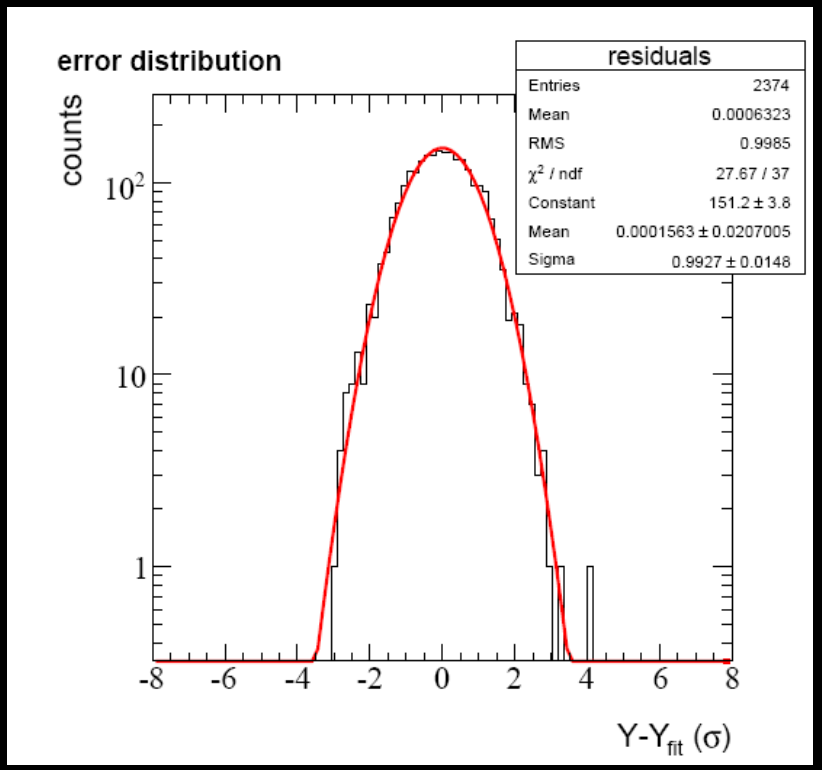


Quartz target: fit the sum...

Quartz data fits well as a simple sum, exploiting the symmetry of the detector.



The deviation from the "fit each detector method" is 0.3ppm



Summary of μSR systematics

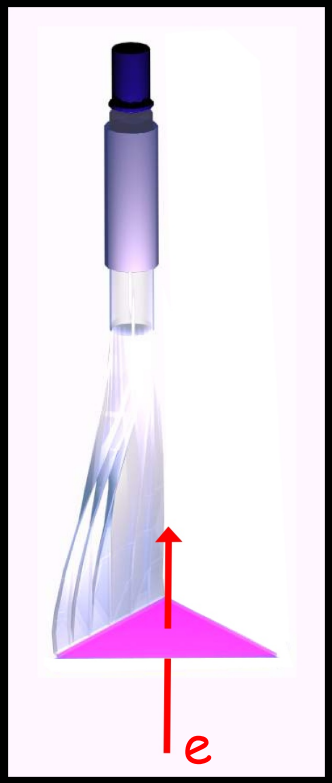
$$f(t) = N_0 \left[1 + AP_2 e^{-t/T_2} \cos(\omega t + \phi_0)\right] e^{-t/\tau_\mathrm{d}} + B$$

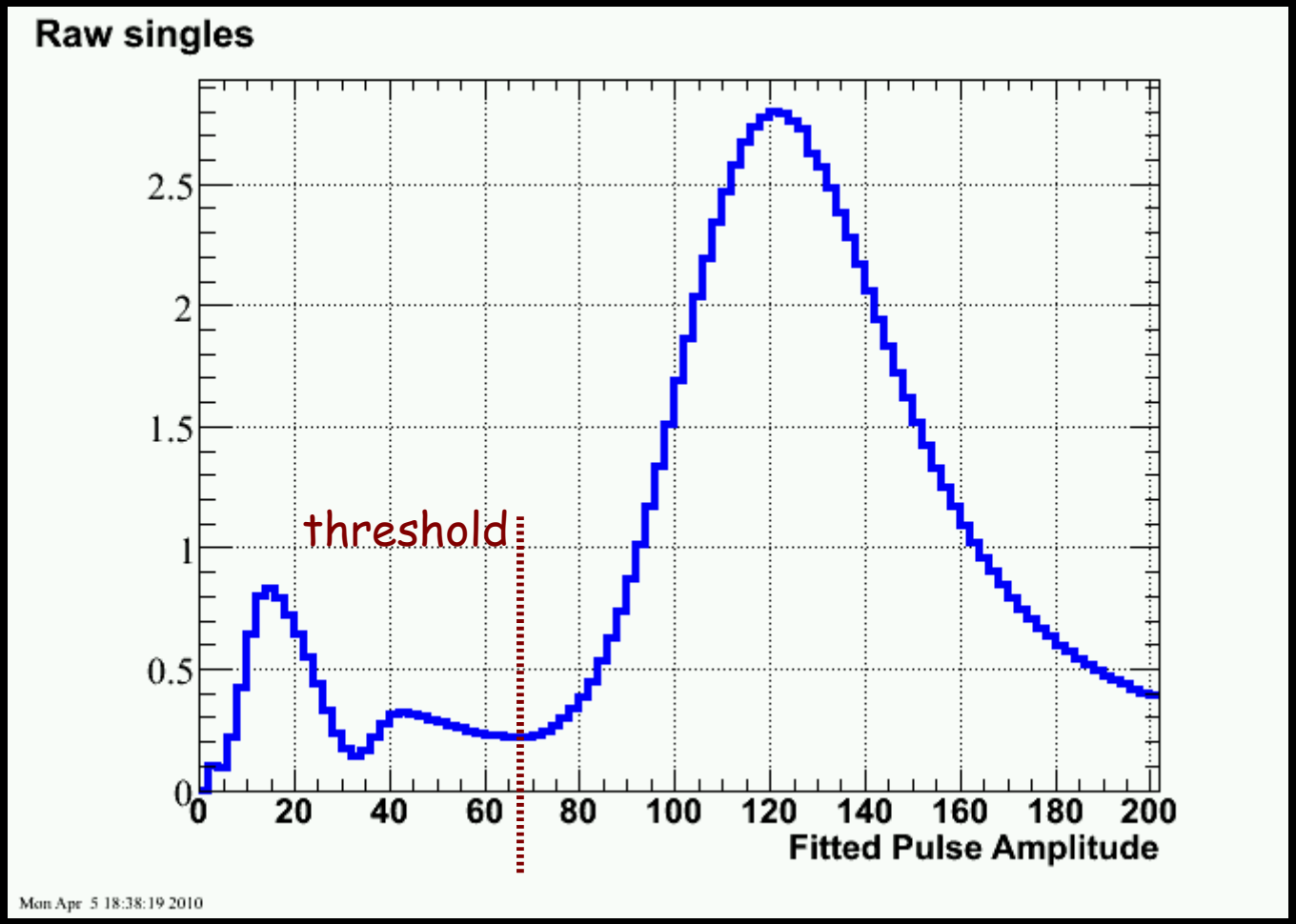
$$\tau_\mathrm{d} = \tau_\mu \left(1 - A\frac{\tau_\mu}{T_1}\vec{P}_1 \hat{r}_\mathrm{D}\right)$$

parameter	$\delta\tau_\mu$ (ppm)
ω	0.003
T_2	0.001
$\hat{P}_1$ [1)]	0.004
beam x [2)]	0.18
beam y [2)]	<0.001
beam z [2)]	<0.001
A [3)]	0.05
total error	0.20

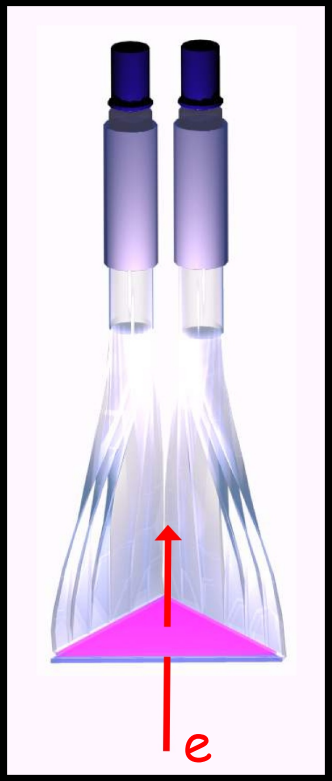
[1)] for $\pm 2°$ variation of the direction of vector $\hat{P}_1$
[2)] for ± 2 mm variation of the position of the beam
[3)] change between GEANT4 or MuLan asymmetries

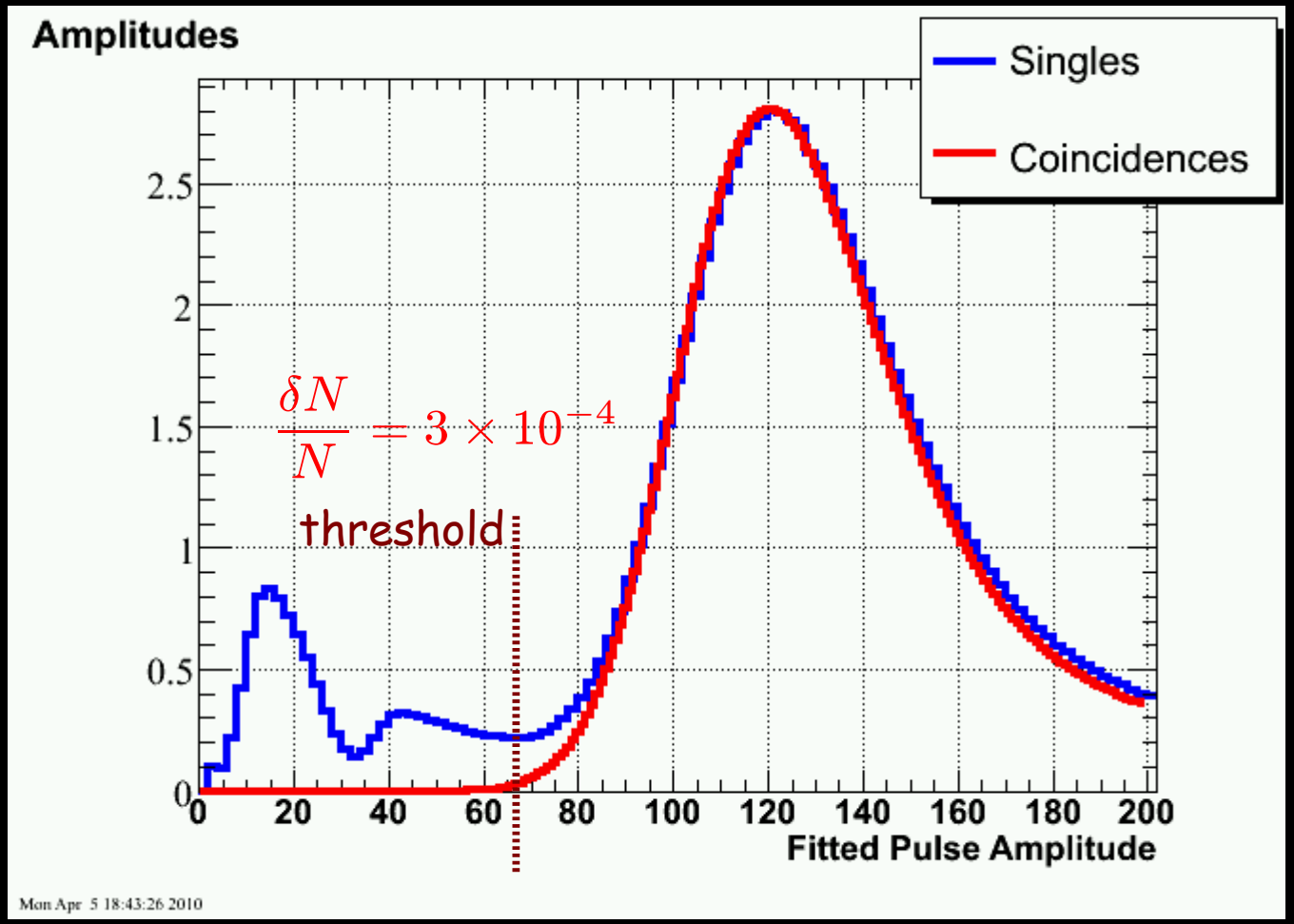
Gain stability



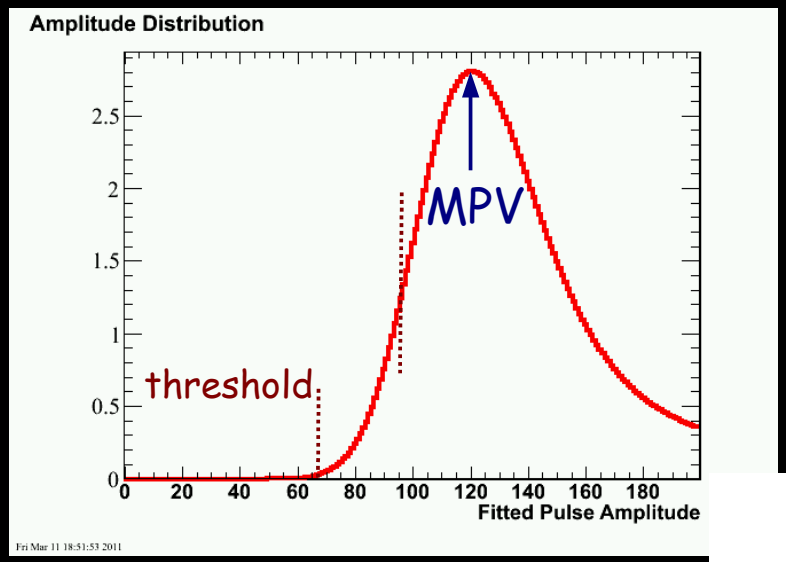


coincidences suppress background





Correction for early-to-late gain variation



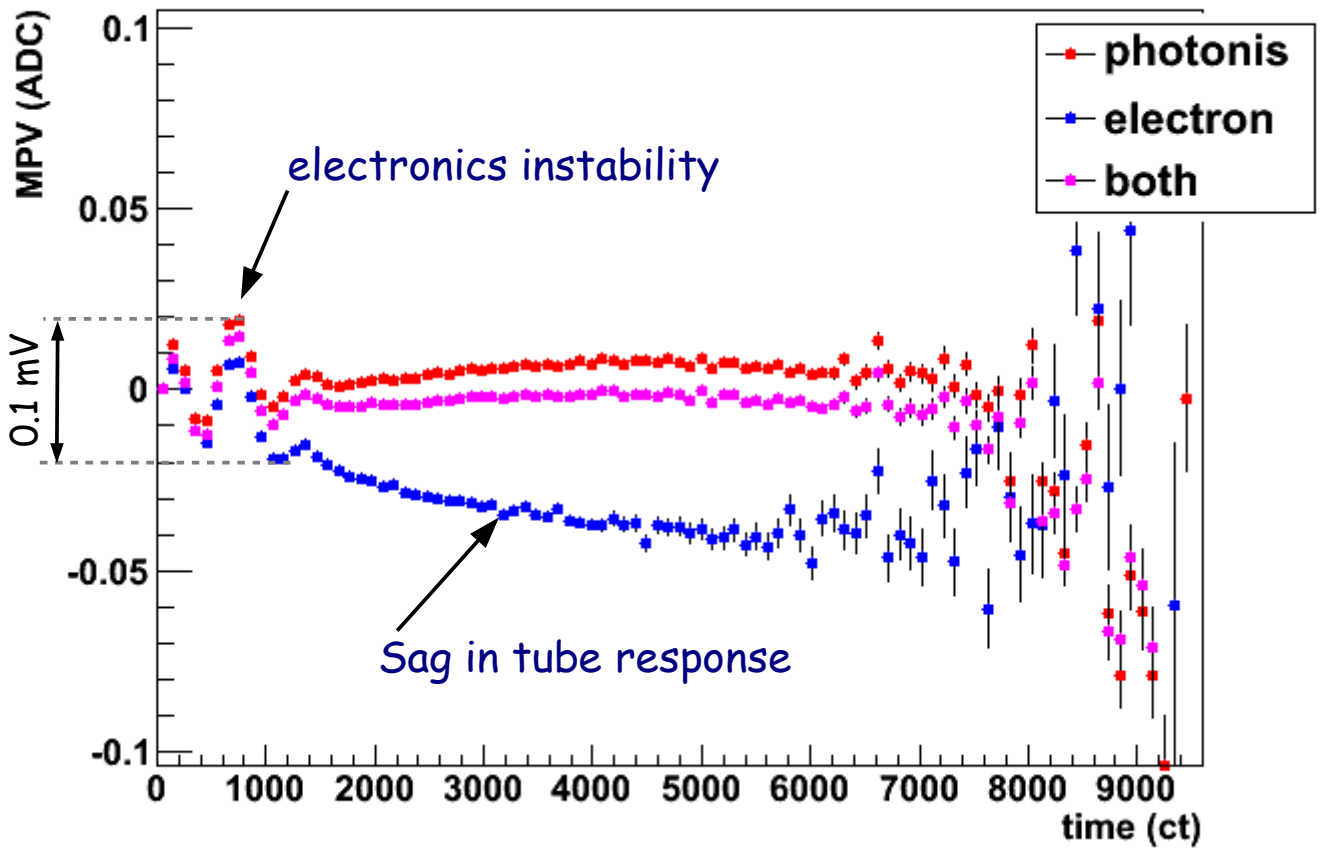
Correction

1) Gain vs. time variation is derived from the stability of the peak of the fit to pulse amplitude distribution
2) Extrapolate from MPV to threshold

Consistency check

Raise the threshold to amplify the effect

Gain is photomultiplier tube type dependent



Gain correction is 0.5 ppm shift with 0.25 ppm uncertainty.

Timing stability

Master clock

The clock was provided by an Agilent E4400B RF Signal Generator, which was stable during the run and found to be accurate to 0.025 ppm.

Agilent E4400 RF Signal Generator

f = 450.87649126 MHz

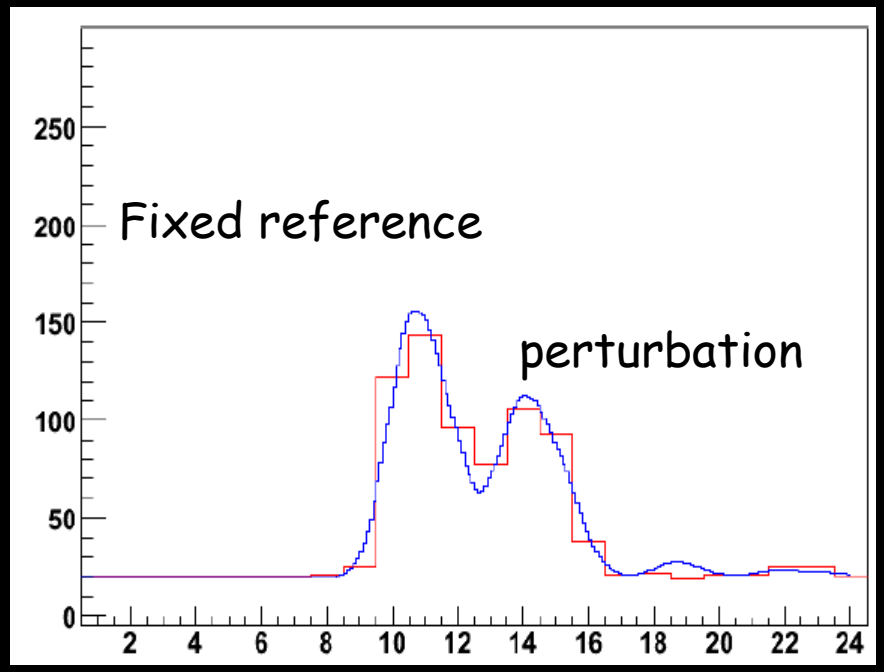
- Checked for consistency throughout the run.
- Compared to Quartzlock A10-R rubidium frequency standard.
- Compared to calibrated frequency counter
- Different blinded frequencies in 2006 and 2007

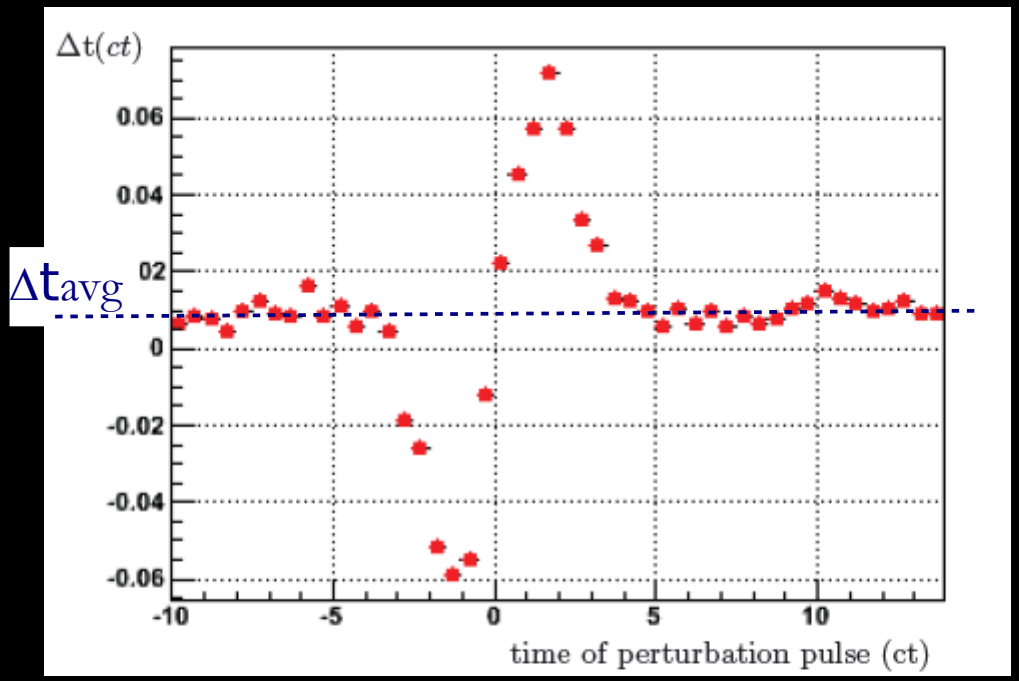
Comparison	10 MHz	60 MHz
Frequency counter	1×10^{-8}	2×10^{-8}
Rubidium atomic clock	4×10^{-8}	3×10^{-8}

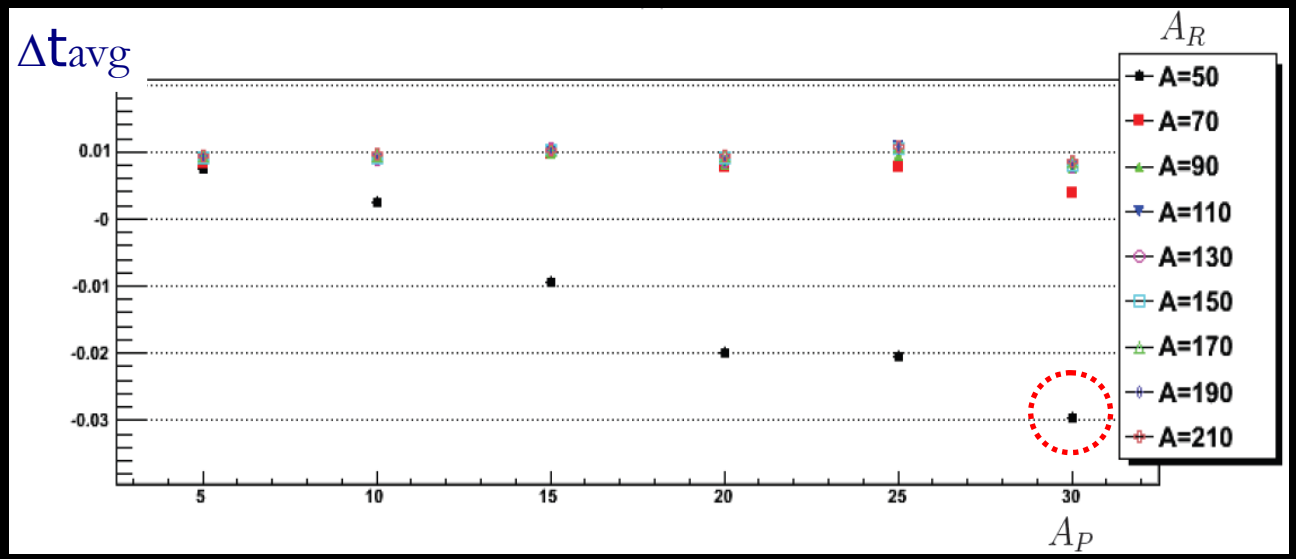
Average difference = 0.025 ppm

Nearby unseen pulses perturb the time of main pulses

software stability studied with simulations





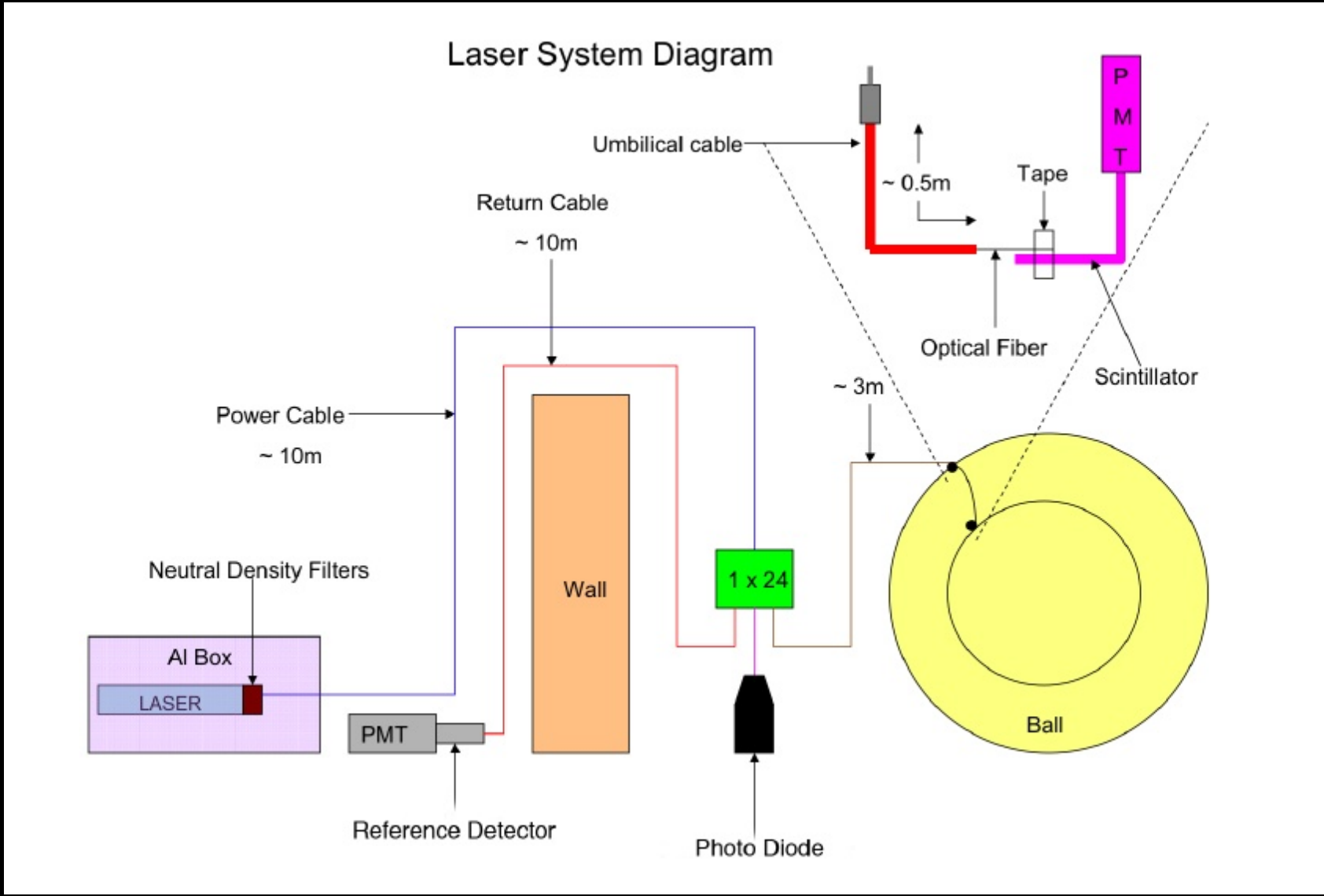


Estimated pull:

$$\frac{(0.03\ \text{ct})\times(0.25\%\ \text{pileup})}{(1000\ \text{ct}/\tau_\mu)} = 0.075\ \text{ppm}$$

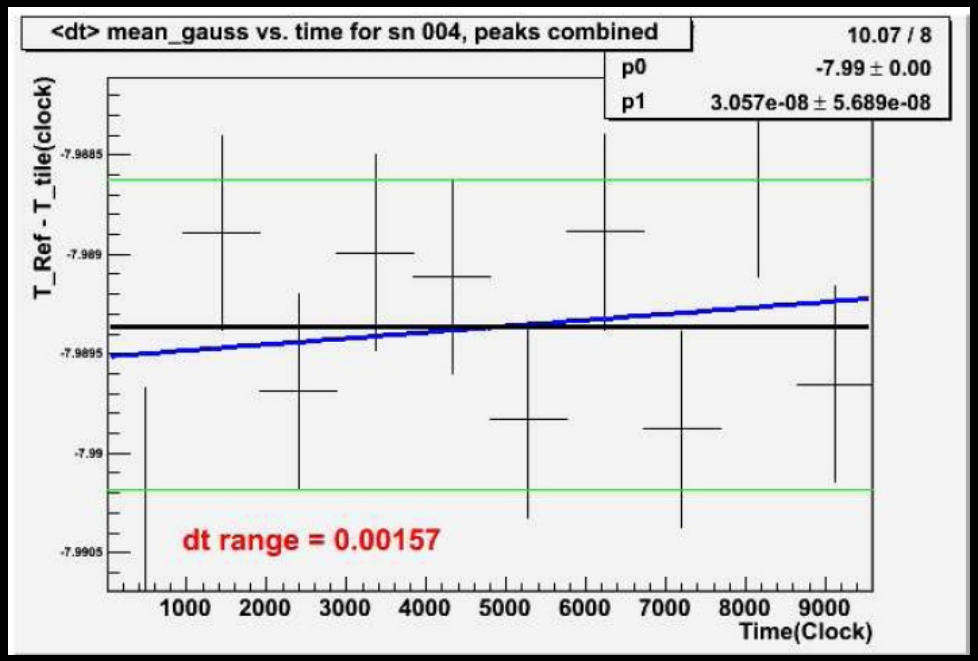
D. M. Webber

Hardware stability studied with Laser pulses



Laser: LN203C sealed nitrogen/dye laser made by Laser Photonics Inc.
Peak power 167kW, spectral output 337.1nm; pulse width: 600 ps (FWHM)

Timing stability from laser data

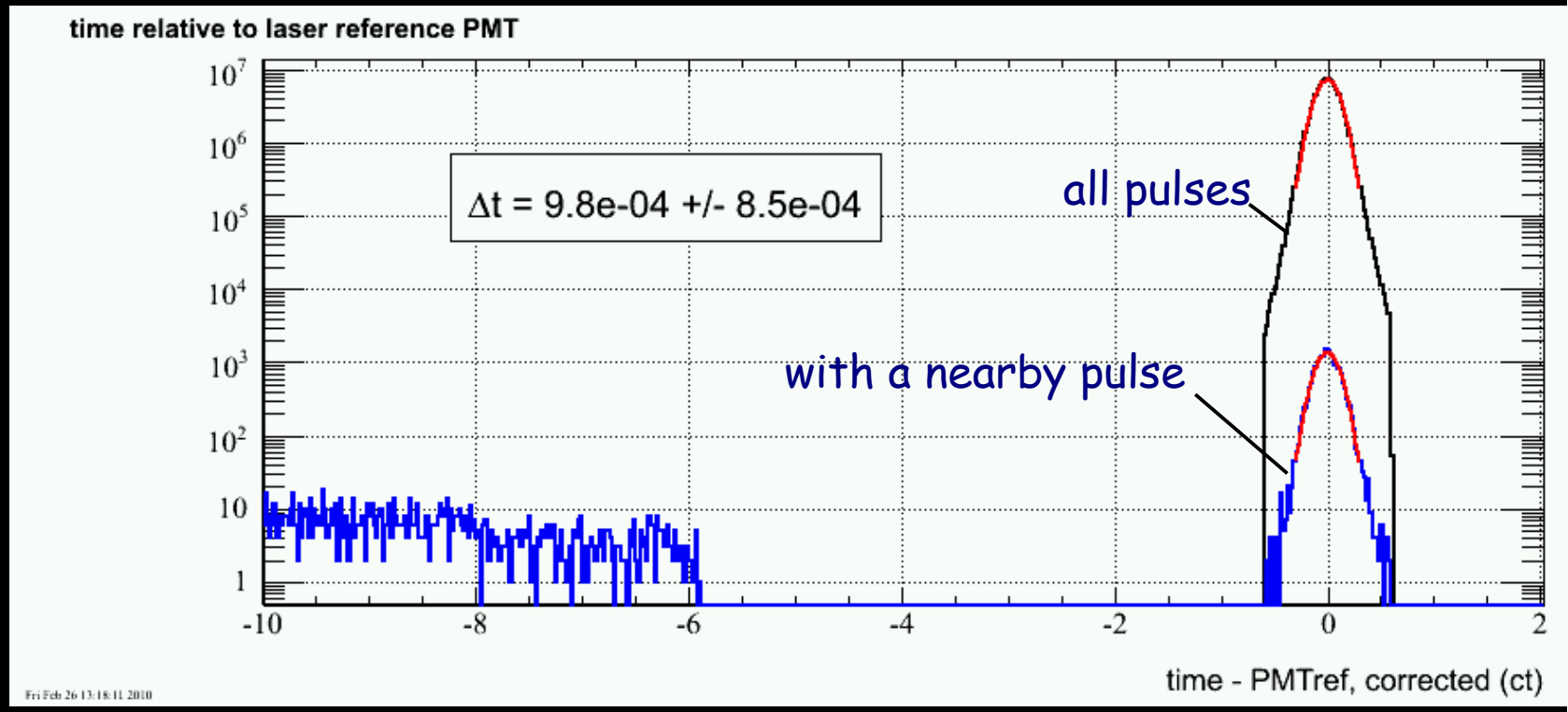


early-to-late timing shifts

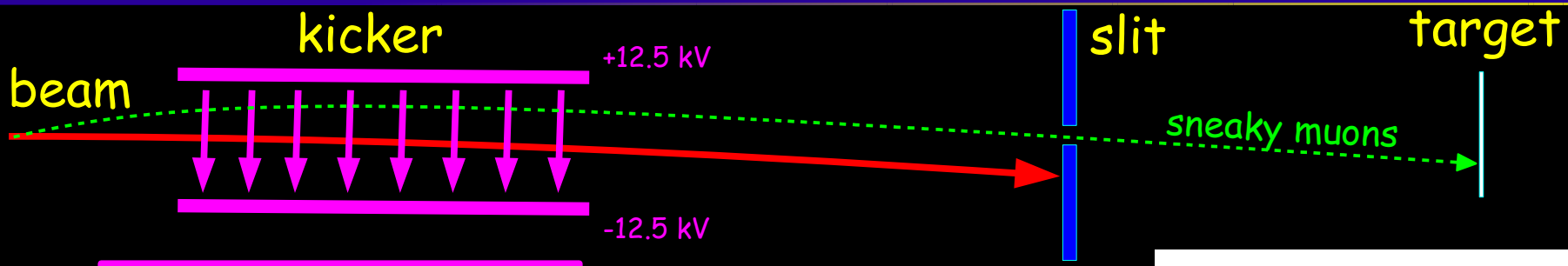
0.1 ppm, limited by statistics

timing shifts due to nearby pulses

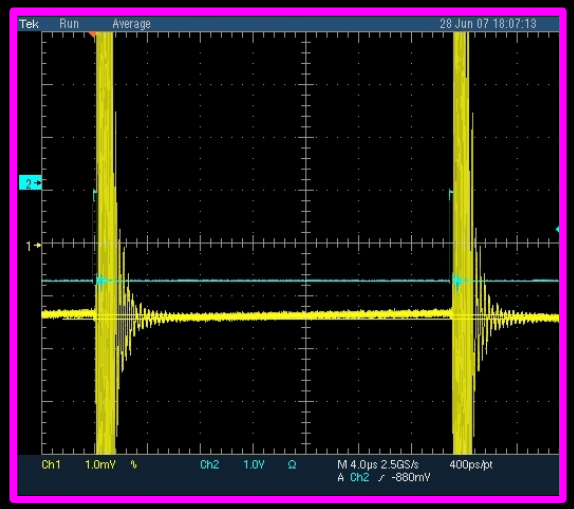
tiny



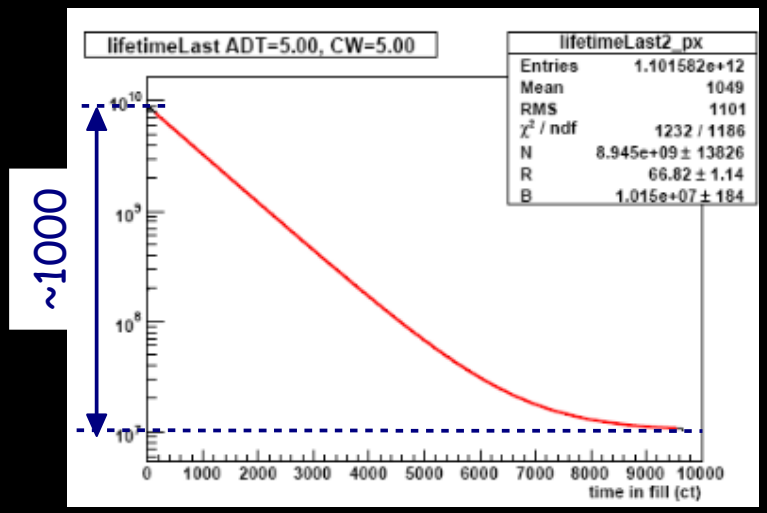
Background stability

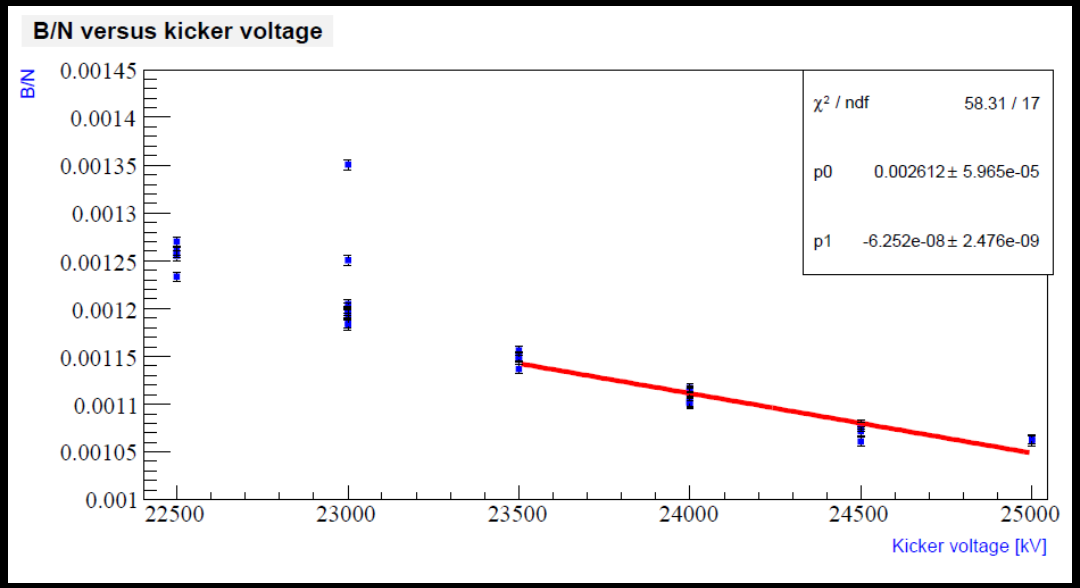


HV



any variation of the plate high voltage during the measurement period leads to a deviation of a flat accidental background.

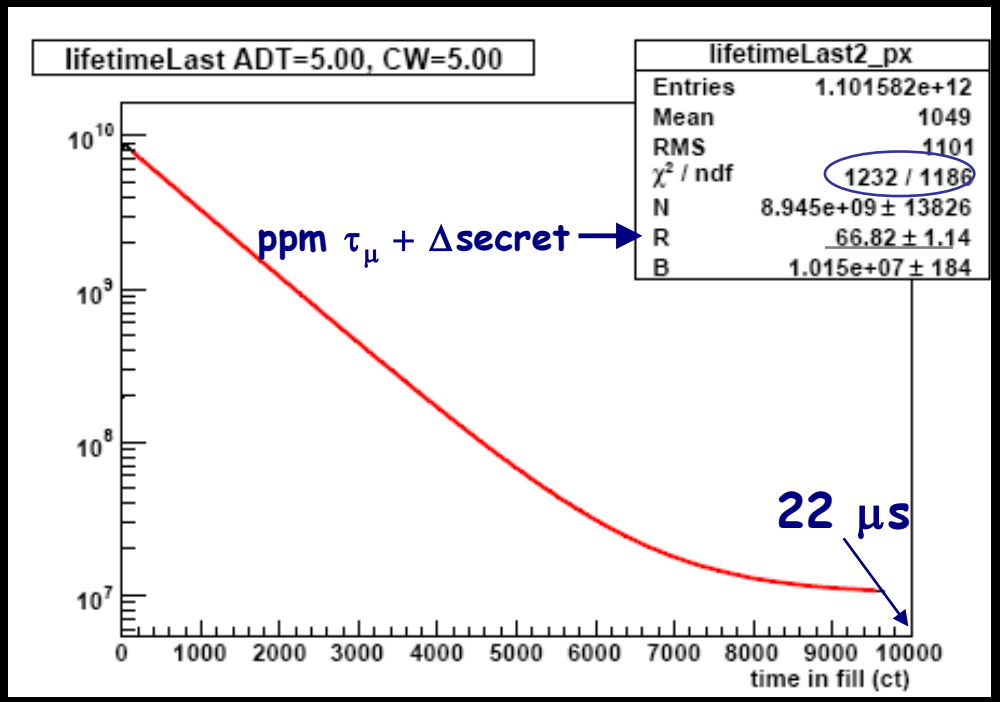


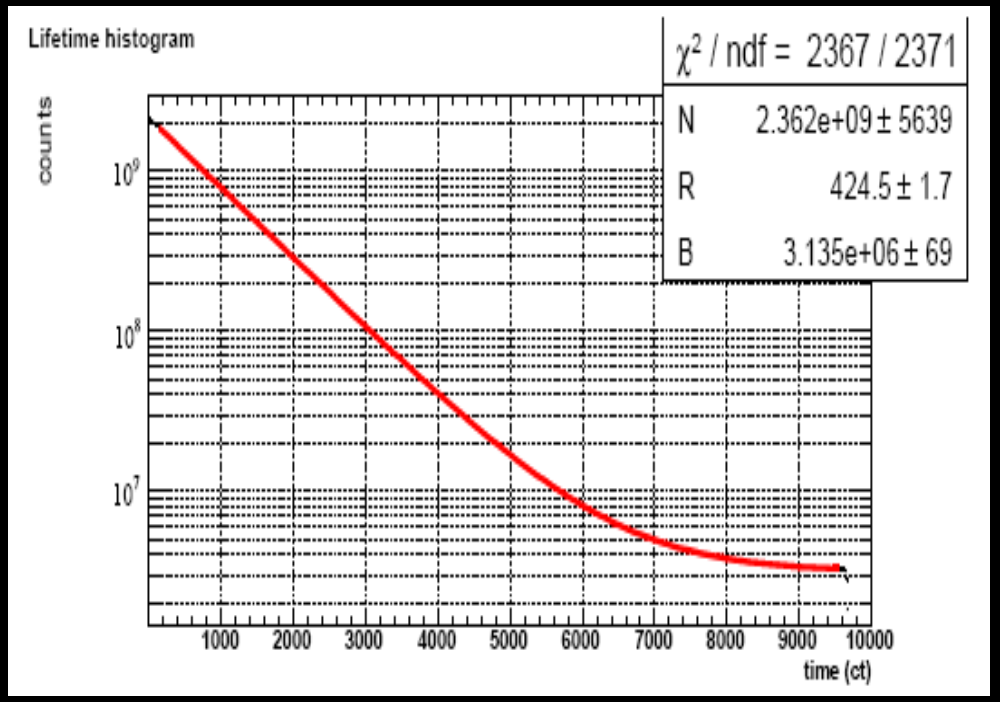


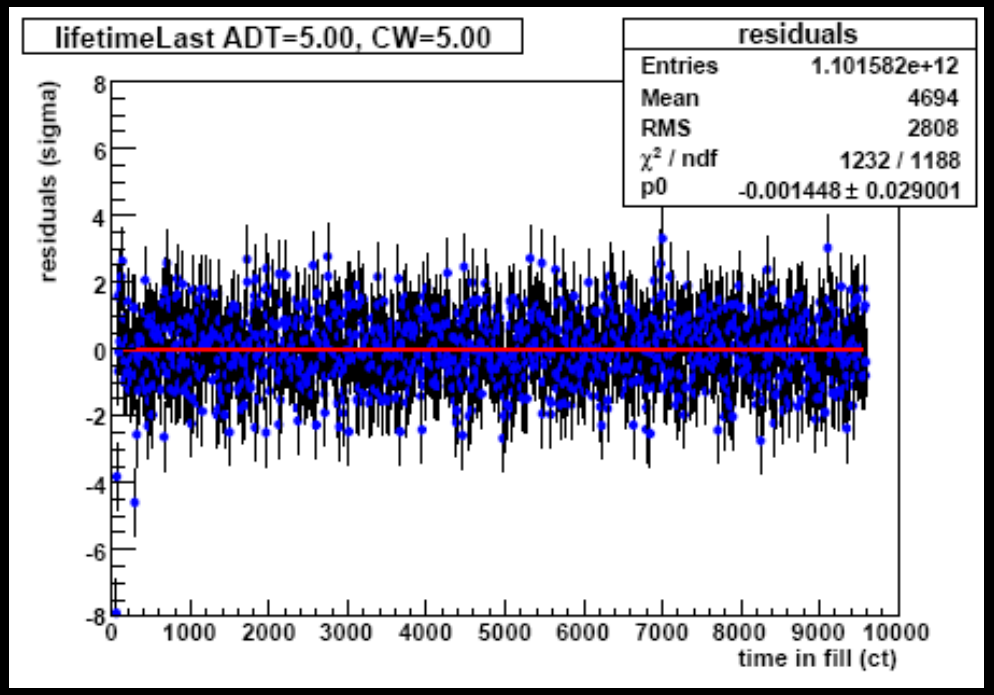
Systematic error stemming from a potential voltage drift on the kicker deflector plates

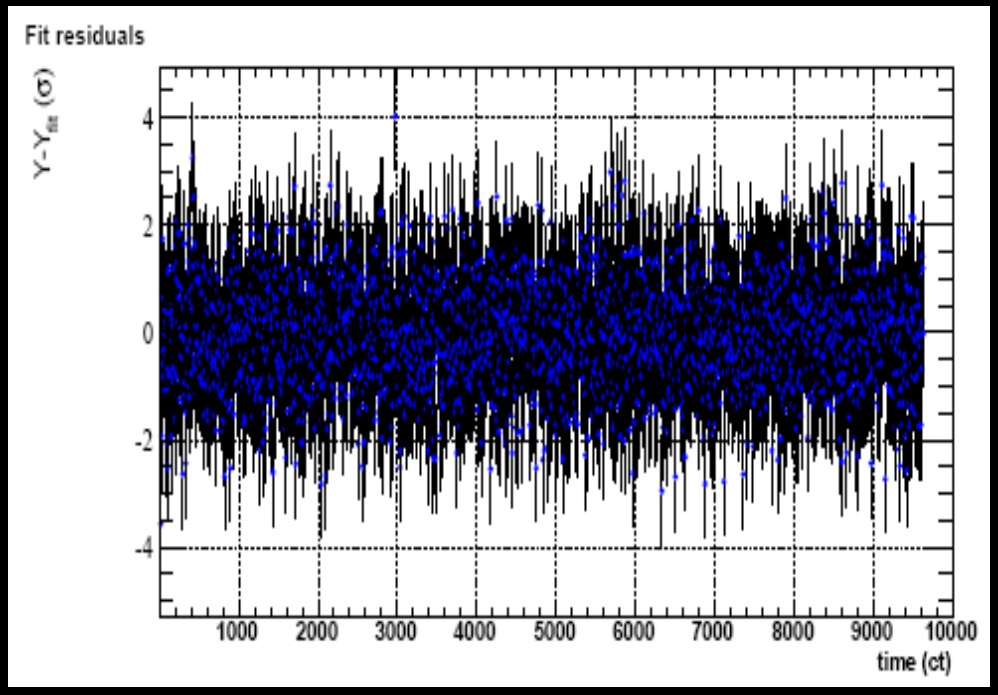
2006: 0.2 ppm
2007: 0.07 ppm

Consistency checks: fit quality

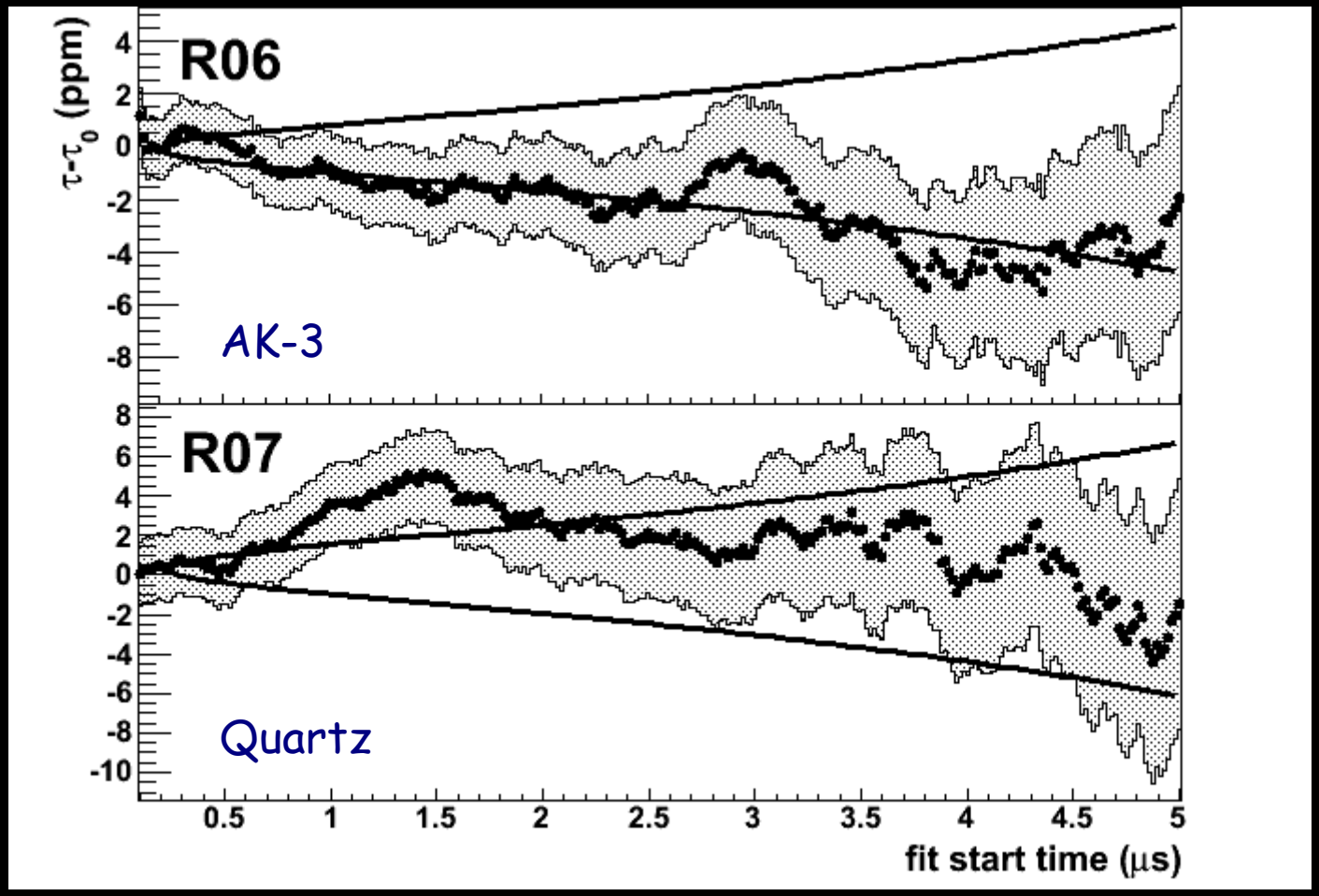








Consistency checks: Fit start time scan



Final Errors and Numbers

ppm units

Effect	2006	2007	Comment
Kicker extinction stability	0.20	0.07	Voltage measurements of plates
Residual polarization	0.10	0.20	Long relax; quartz spin cancelation
Upstream muon stops	0.10		Upper limit from measurements
Overall gain stability:	0.25		MPV vs time in fill; includes:
Short time; after a pulse			MPVs in next fill & laser studies
Long time; during full fill			Different by PMT type
Electronic ped fluctuation			Bench-test supported
Unseen small pulses			Uncorrected pileup effect → gain
Timing stability	0.12		Laser with external reference ctr.
Pileup correction	0.20		Extrapolation to zero ADT
Clock stability	0.03		Calibration and measurement
Total Systematic	**0.42**	**0.42**	**Highly correlated for 2006/2007**
Total Statistical	**1.14**	**1.68**	

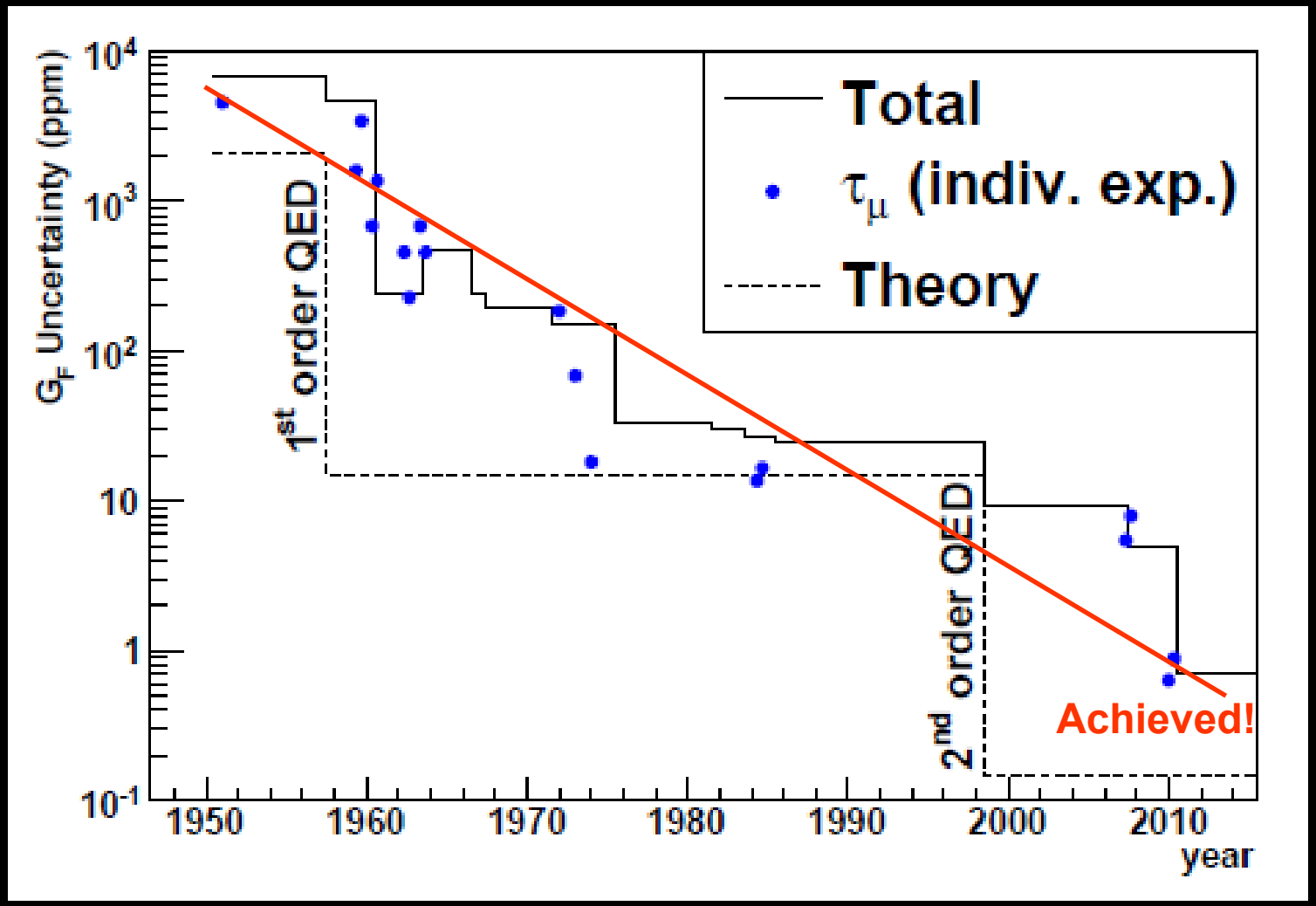
τ(R06) = 2 196 979.9 ± 2.5 ± 0.9 ps
τ(R07) = 2 196 981.2 ± 3.7 ± 0.9 ps

τ(Combined) = 2 196 980.3 ± 2.2 ps (1.0 ppm)
$\Delta\tau$(R07 – R06) = 1.3 ps

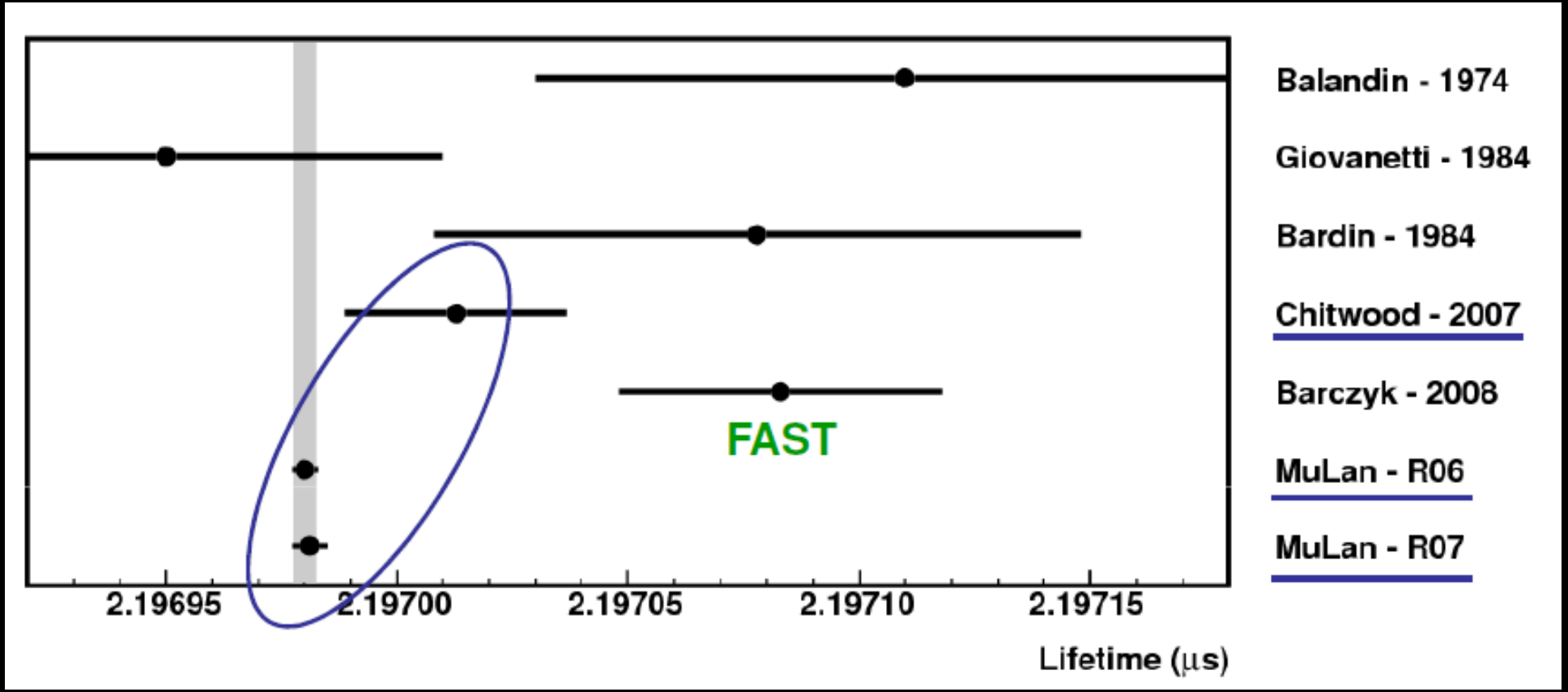
New G_F

G_F(MuLan) = 1.166 378 8(7) x 10^{-5} GeV^{-2} (0.6 ppm)

G_F & τ_μ precision has improved by ~4 orders of magnitude over 60 years



Lifetime "history"



MuLan Collaborators

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Thank you!
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HOFBRÄU MÜNCHEN
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Weissbier
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