The MuLan Collaboration: Improved Measurement of the Muon Lifetime and Determination of the Fermi Constant

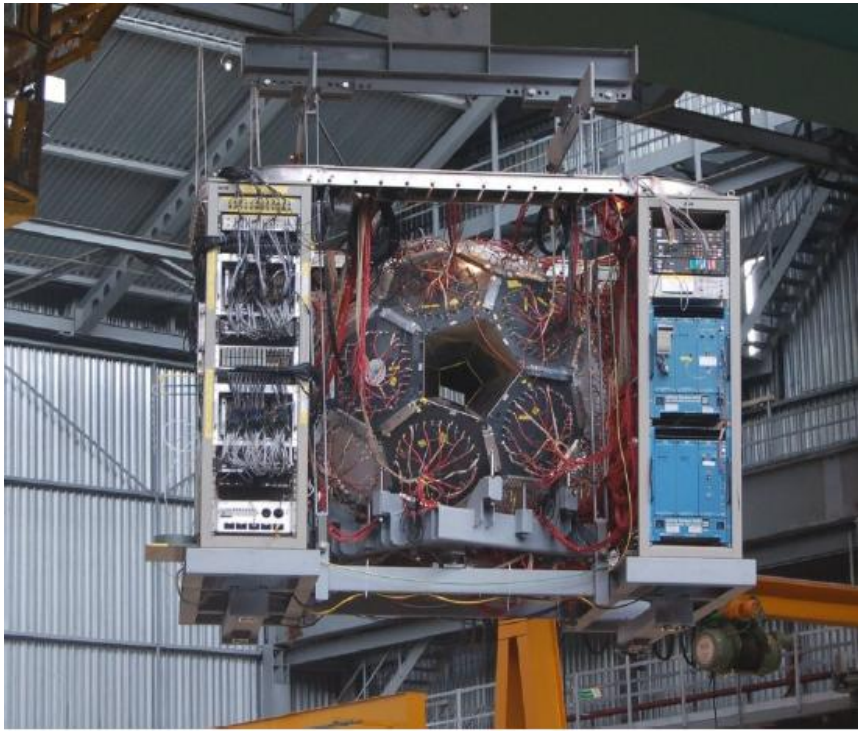
CKM 2010

P. T. Debevec

University of Illinois

MuLan Collaboration

University of Illinois
University of Kentucky
Boston University
James Madison University
Kentucky Wesleyan College
Regis University
Paul Scherrer Institute

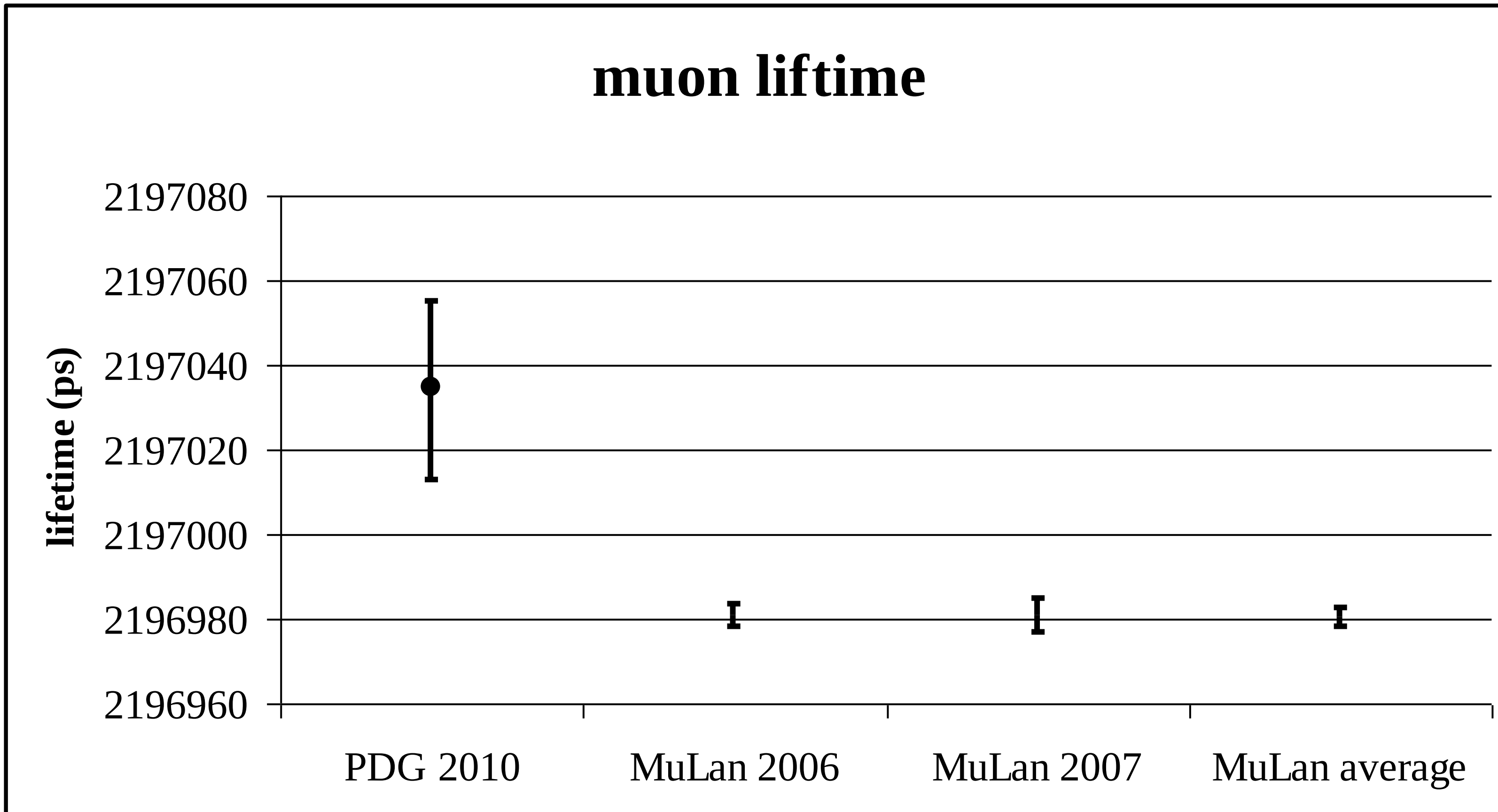


MuLan collaboration acknowledges support from

National Science Foundation
WHERE DISCOVERIES BEGIN

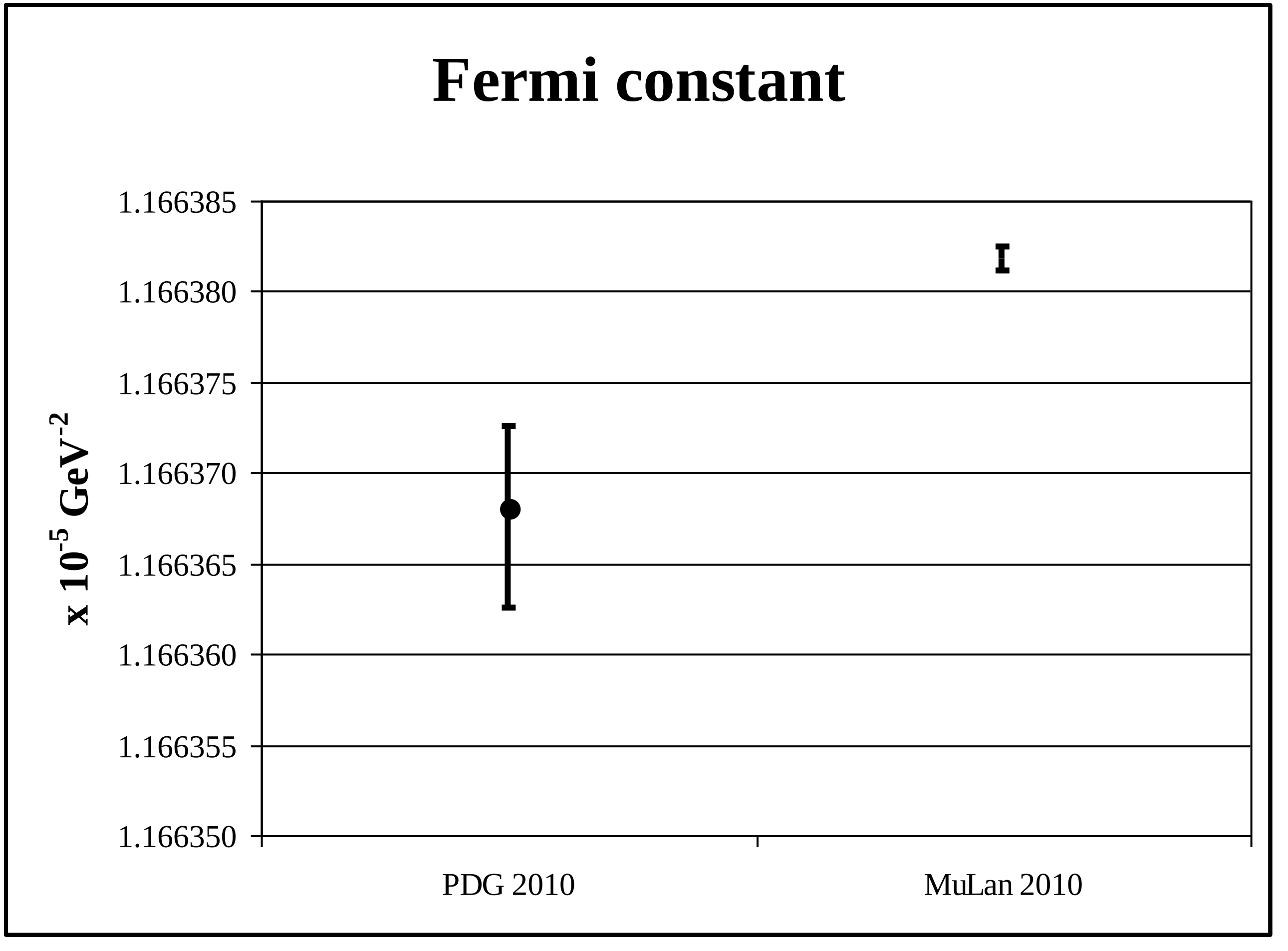
Conclusion, I

In two different experiments, we have measured the muon lifetime to a precision of 1.0 ppm. Our result is 2.6 σ below the current World Average, which has a precision of 9.6 ppm.

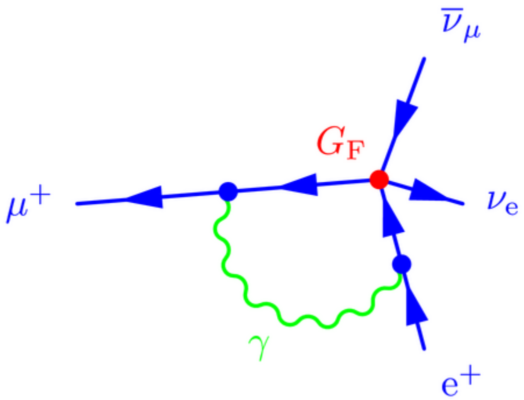


Conclusion, II

From our lifetime measurement, we determine the Fermi constant to a precision 0.6 ppm. Our determination is 12 ppm greater than the current World Average.



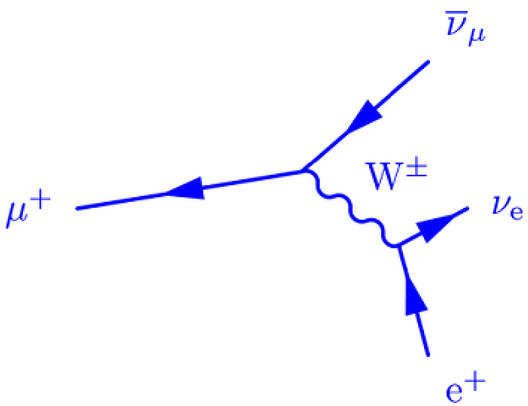
τ_μ G_F and g



In Fermi theory muon decay is a contact interaction

$$\frac{1}{\tau_\mu} = \frac{G_F^{\,2} m_\mu^{\,5}}{192\pi^3}\ 1+\Delta q \qquad \left[G_\mu \rightarrow G_F\right]$$

Δq QED radiative corrections *



The Fermi constant is related to the electroweak gauge coupling by

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^{\,2}}\ 1+\Delta r$$

Δr weak interaction loop corrections

* We use van Ritbergen & Stuart, Nucl. Phys. B564 (2000) 343.

G_F and CKM matrix elements

$$V_{ud}{}^2 = \frac{G_V{}^2}{G_F{}^2}$$

G_V is the vector coupling constant determined 9for example) from superallowed nuclear beta decay

$$\mathcal{F}t = \frac{K}{2G_V{}^2 \; 1+\Delta_R^V}$$

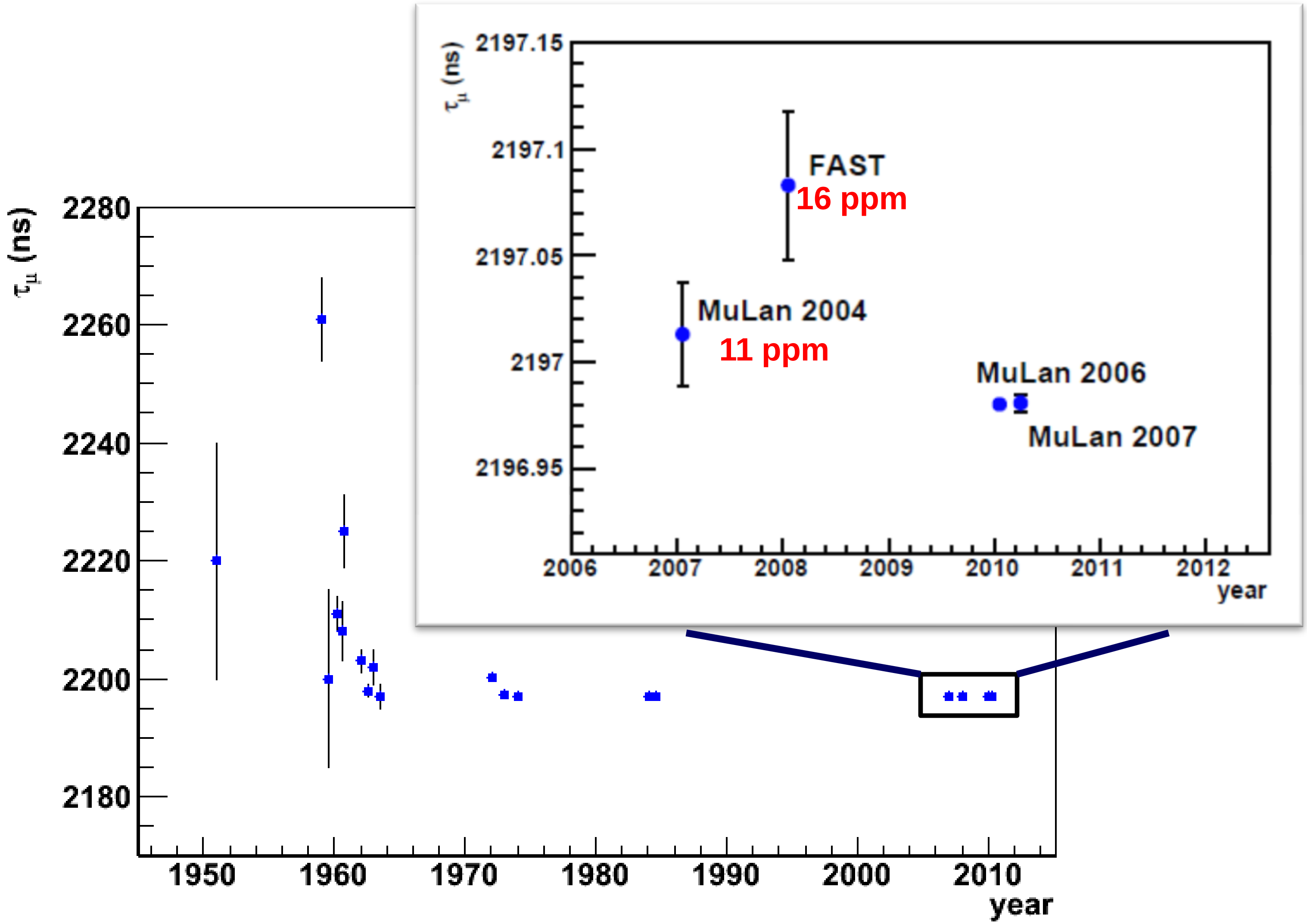
see Towner & Hardy, Rep. Prog. Phys. 73(2010)046301

$$V_{us}{}^2 = \frac{\Gamma_{K\to\ell 3}}{G_F{}^2 \left[\frac{m_K{}^5}{192\pi^3} S_{EW} \;\; 1+\delta_K^\ell + \delta_{SU2} \;\; C^2 f_+^2 \;\; 0 \;\; I_K^\ell \right]}$$

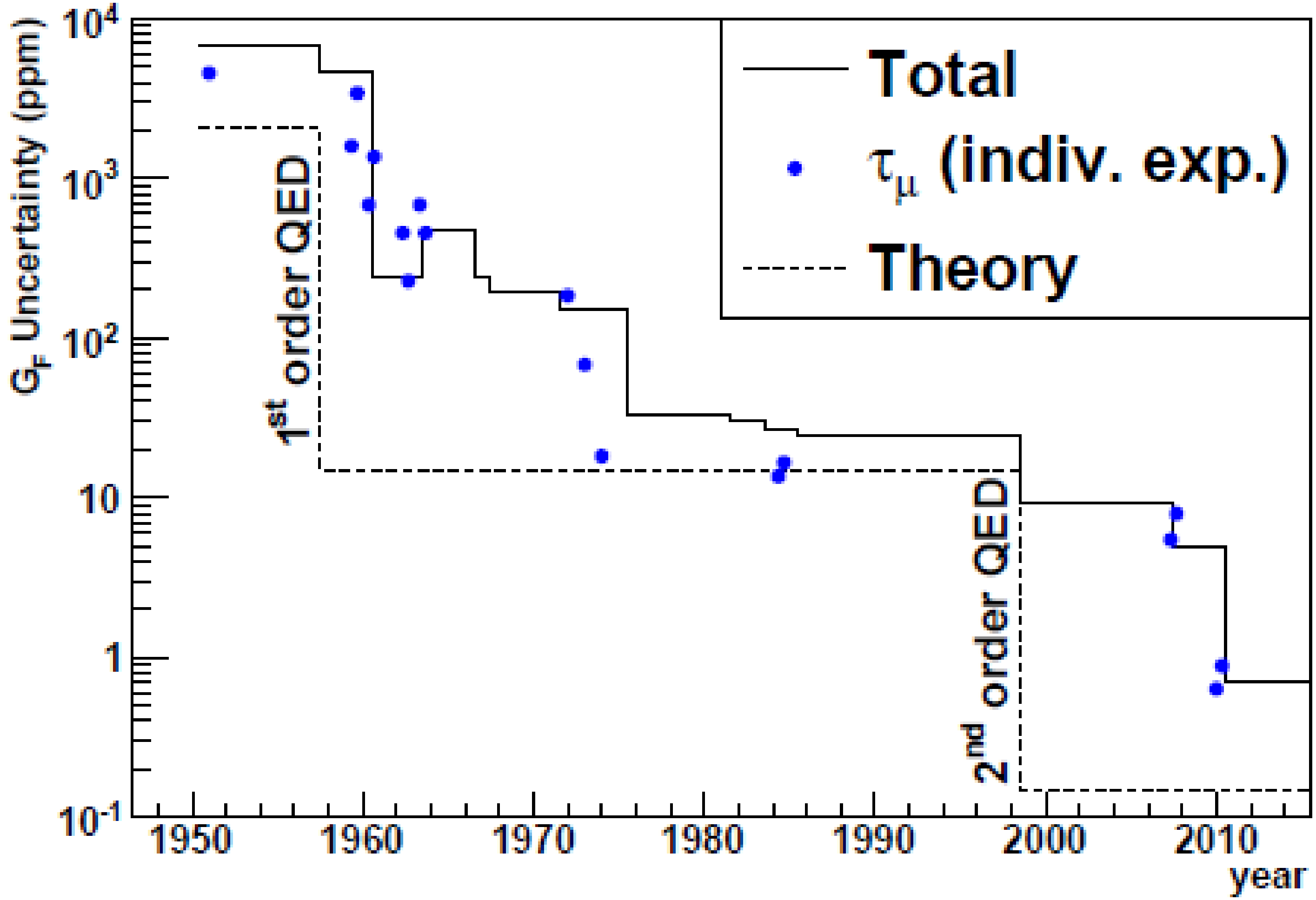
$\Gamma_{K\to\ell 3}$ is a kaon decay rate

see Blucher and Marciano in Nakamura et al., J. Phys. G37(2010)075021

Chronology of muon lifetime measurements



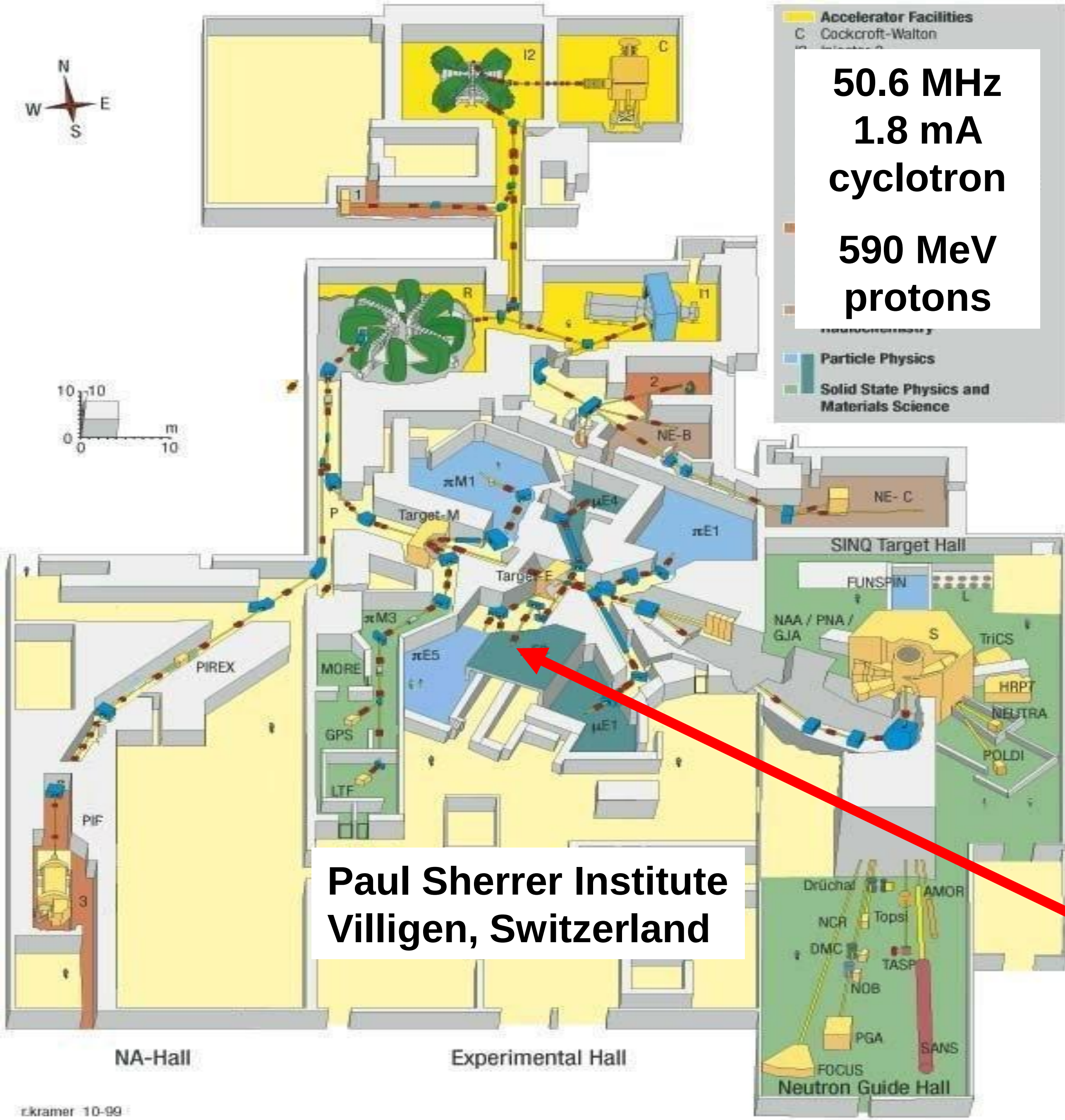
Chronology of muon lifetime experiments and G_F theory precision



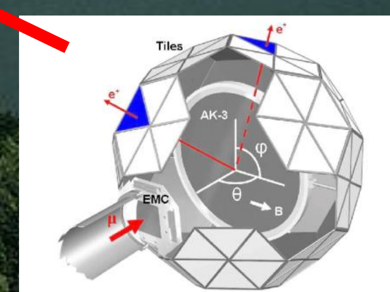
MuLan experiment

50.6 MHz
1.8 mA
cyclotron

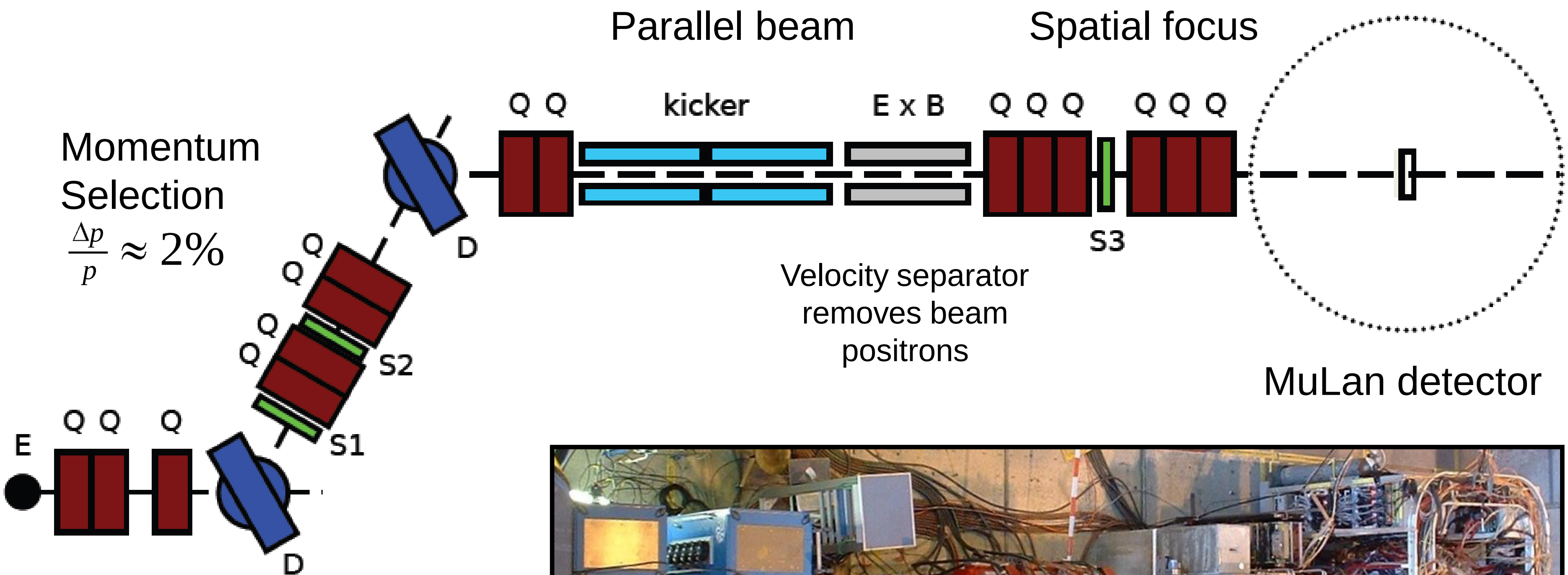
590 MeV
protons

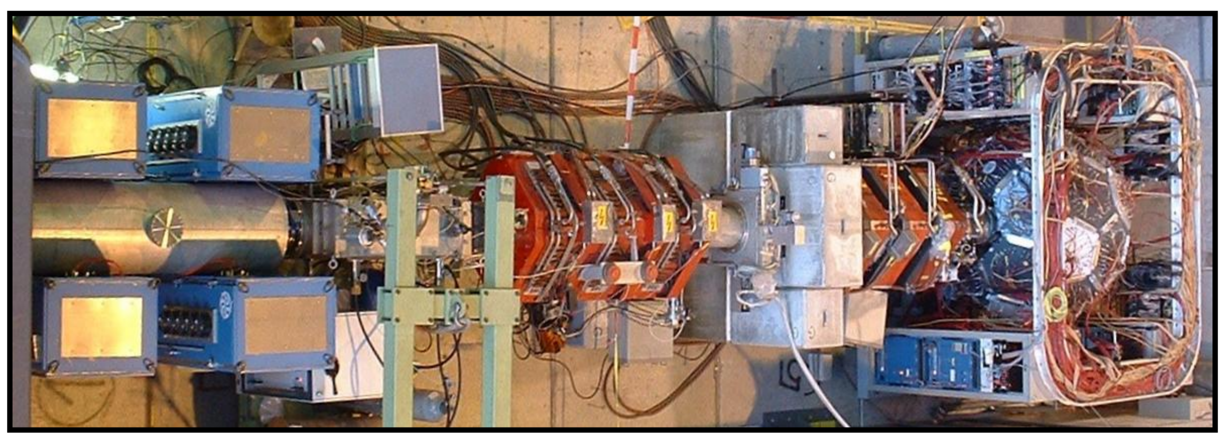


Paul Sherrer Institute
Villigen, Switzerland



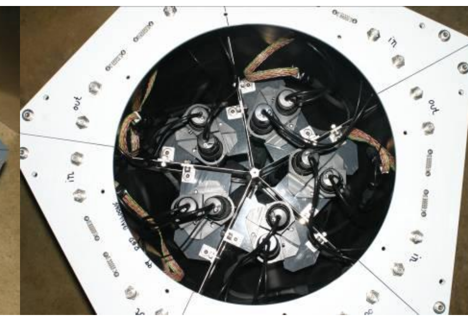
The beamline transports ~10^7 “surface” muons per second to the experimental area.





MuLan “3π” detector truncated icosahedron with point symmetry

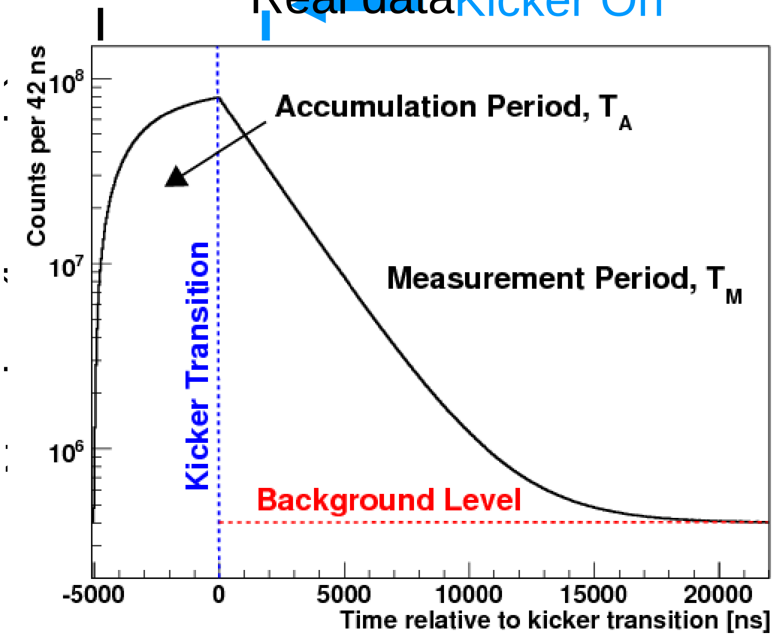
Each section contains either 6 or 5 tile elements



Each element is made from two independent scintillator tiles with light guides and photomultiplier tubes.

The experimental concept in one animation …

Real data Kicker On



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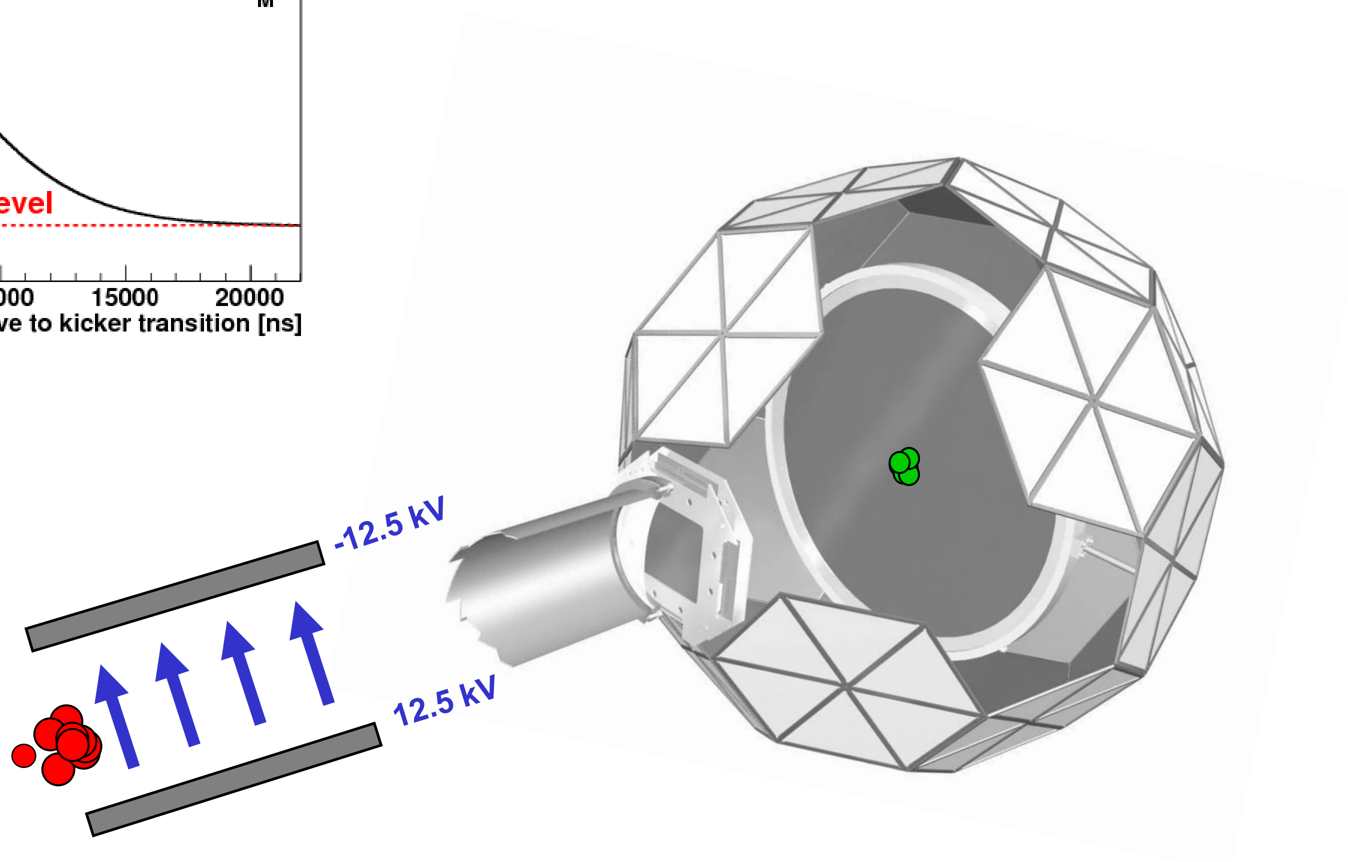
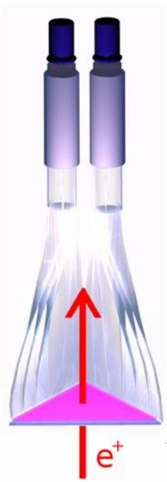
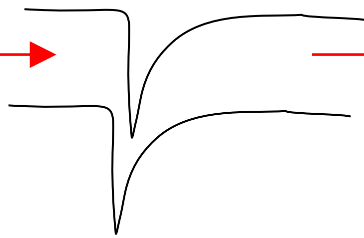


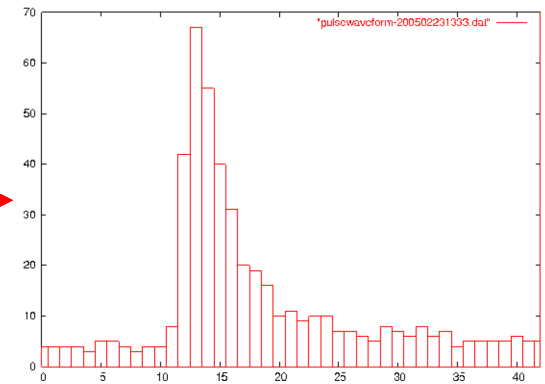
170 scintillator tile pairs readout using 450 MHz custom waveform digitizers.

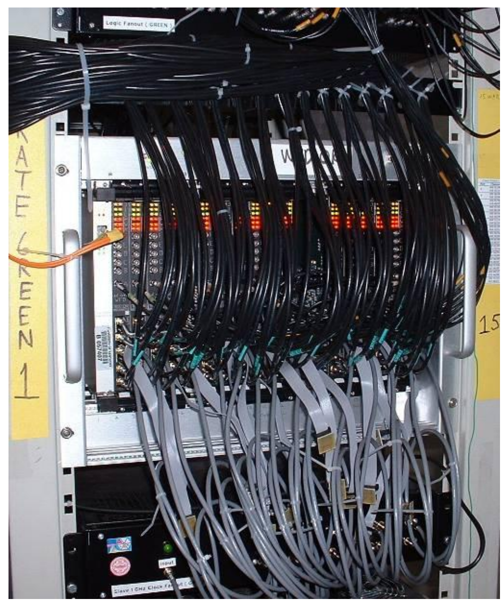


2 Analog Pulses

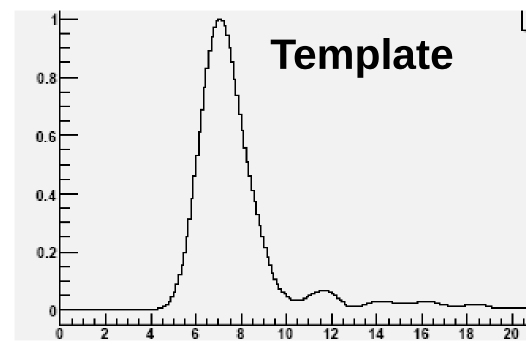


Waveform Digitizers





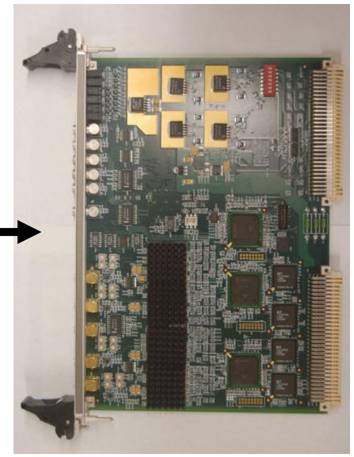
1/6 of system



1 clock tick = 2.2 ns

The clock was stable to 0.010 ppm during the two runs and accurate to 0.025 ppm.

Agilent E4400 Function Generator



1 ct = 2.217???

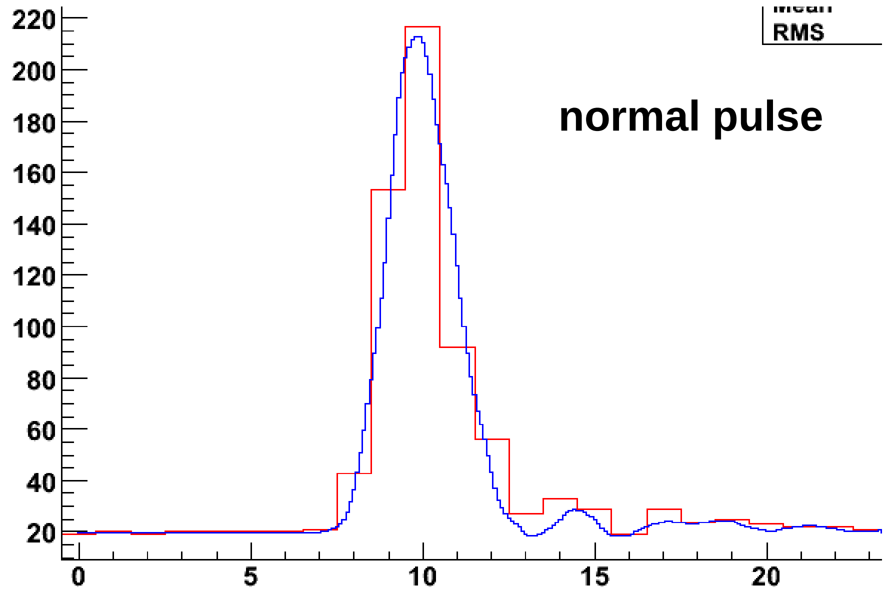
- **The MuLan experiment is doubly blinded.**
- **During the runs and throughout the analysis, the two absolute clock frequencies for the 2006 and 2007 data sets were only known to the collaboration to 0.2 MHz.**
- **When relative blinding between the two data sets was removed, it was found that they agreed to 0.3 ppm.**

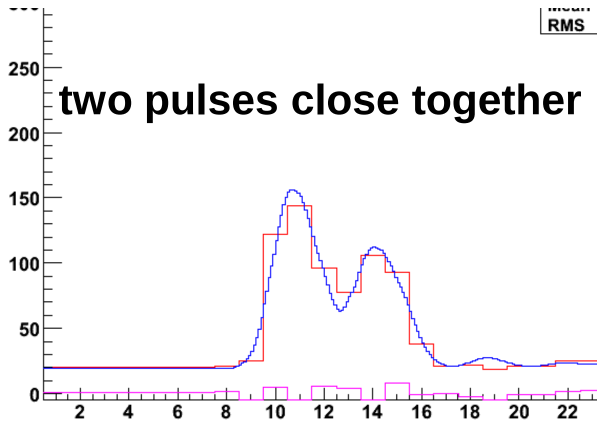
Fit raw waveforms to pulse templates to obtain amplitude and time

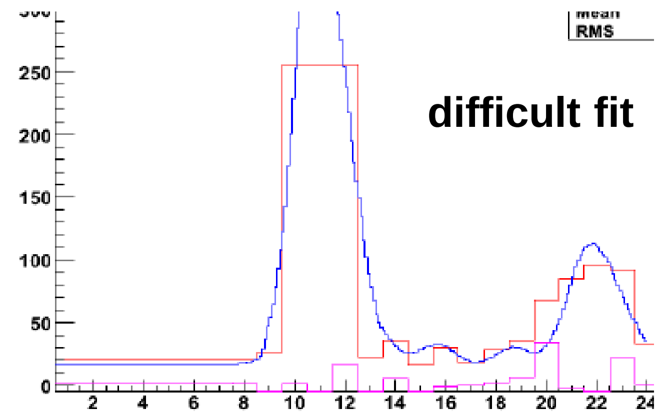
>2 x 10^{12} events in each data set

225 terabytes data

analyzed at NCSA

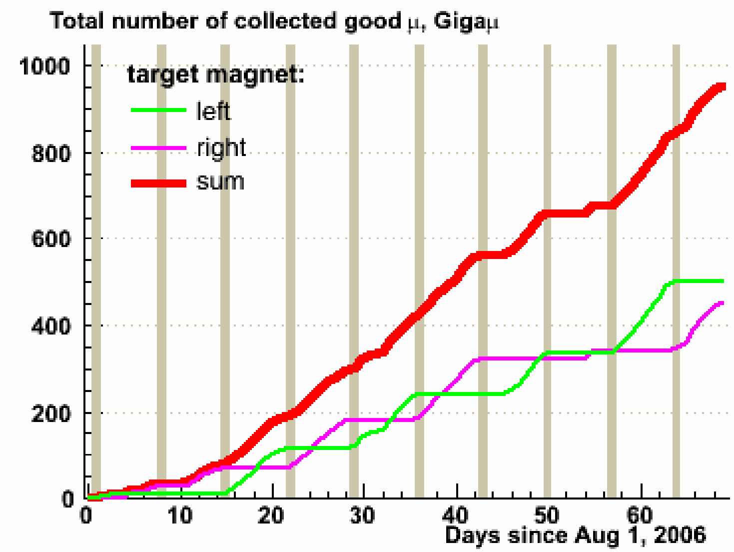




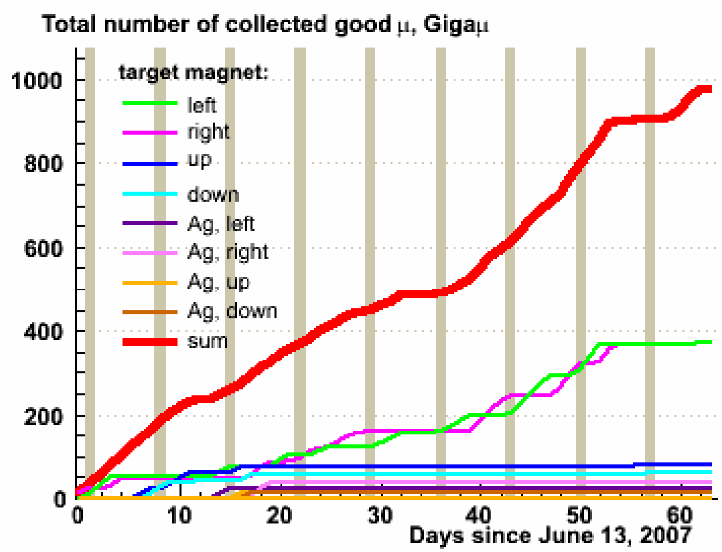


MuLan collected two datasets, each containing 10^{12} muon decays.

Ferromagnetic Target, 2006



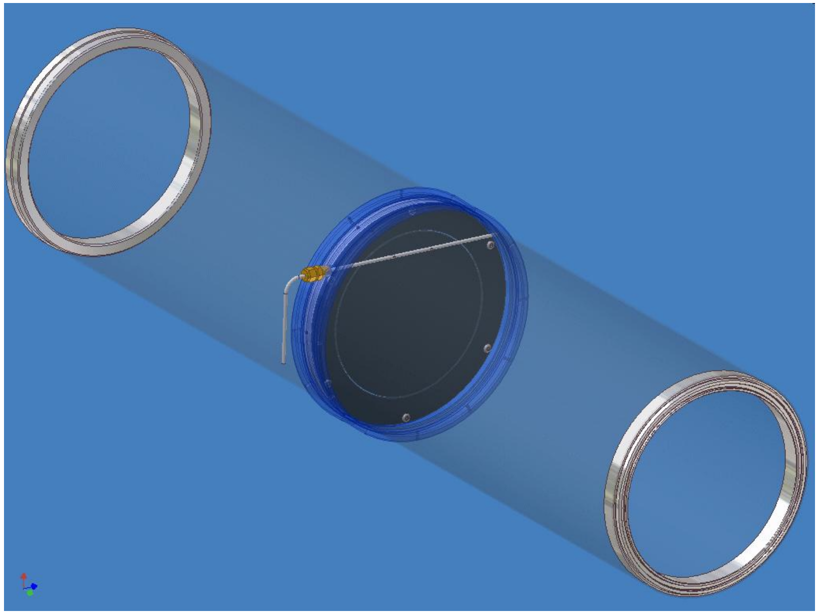
Quartz Target, 2007

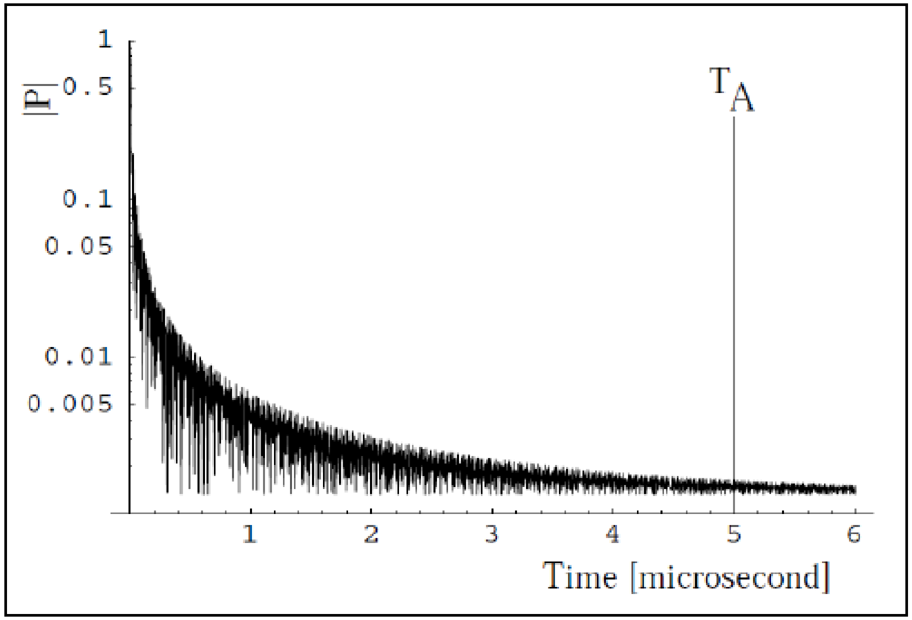


- Two (very different) data sets
  - 2006:
    - Ferromagnetic target dephases muon ensemble
    - 1.2 ppm statistical uncertainty
  - 2007:
    - Quartz target forms 90% muonium, 10% free (precessing) muons
    - 1.7 ppm statistical uncertainty (part of data used as misalignment check)

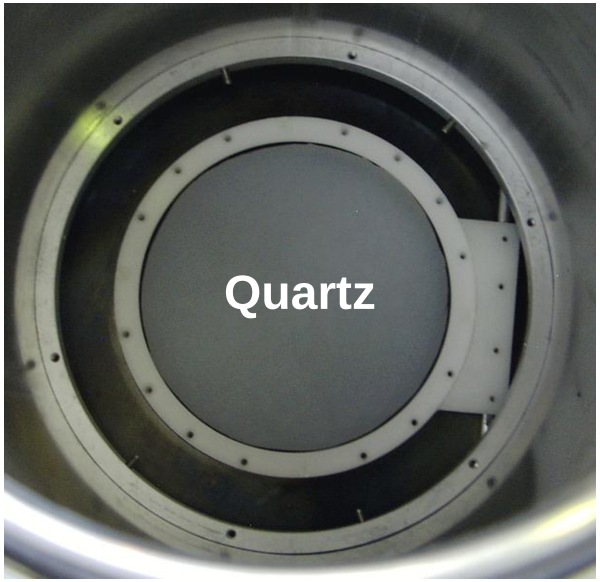
The ferromagnetic target (2006 data) dephases the muons during accumulation.

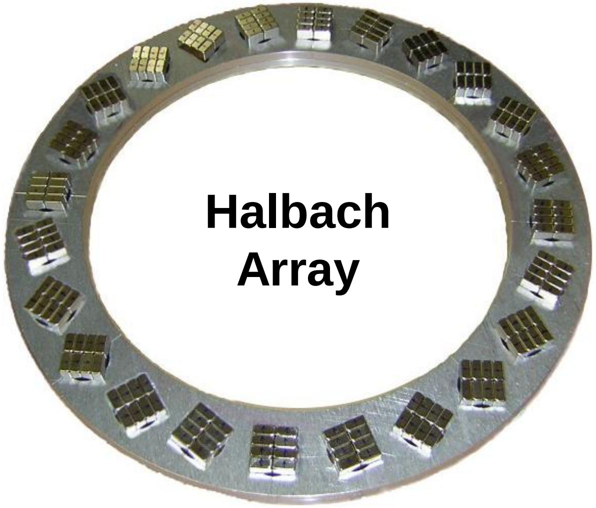
- Arnokrome-3 (AK3) Target (~28% chromium, ~8% cobalt, ~64% iron)
- 0.5 T internal magnetic field
- Muons arrive randomly during 5 μs accumulation period
- Muons precess by 0 to 350 revolutions

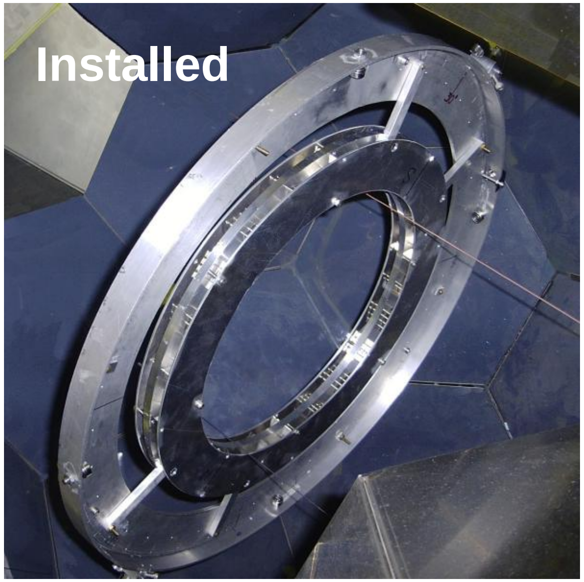




90% of the muons form muonium in the quartz target (2007 data). The remainder precess in an ~135 G quasi-uniform external field.







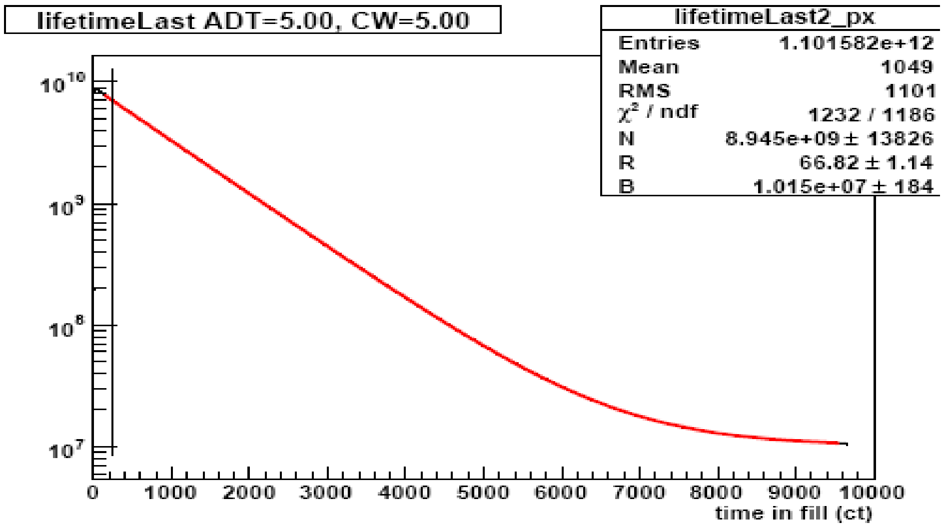
Point symmetry of the detector largely removes the precession signal.

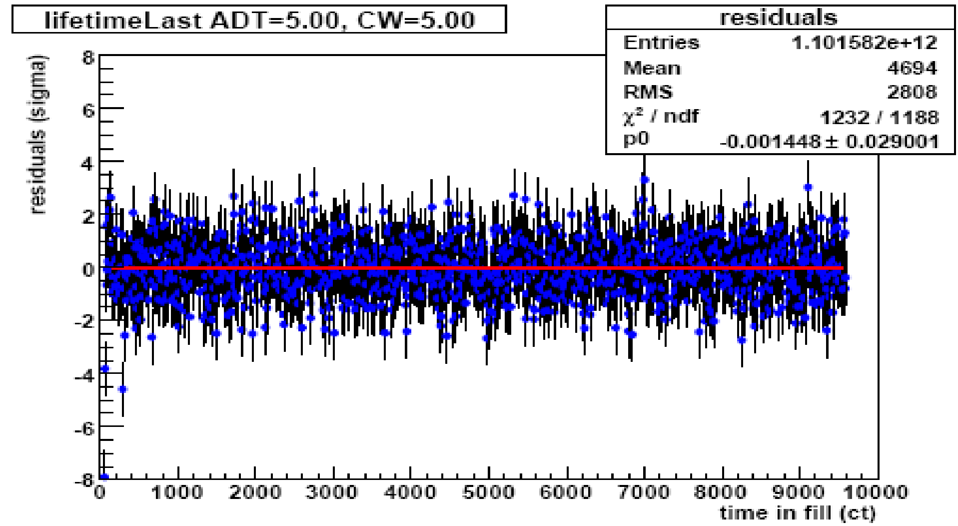
Leading systematic error considerations

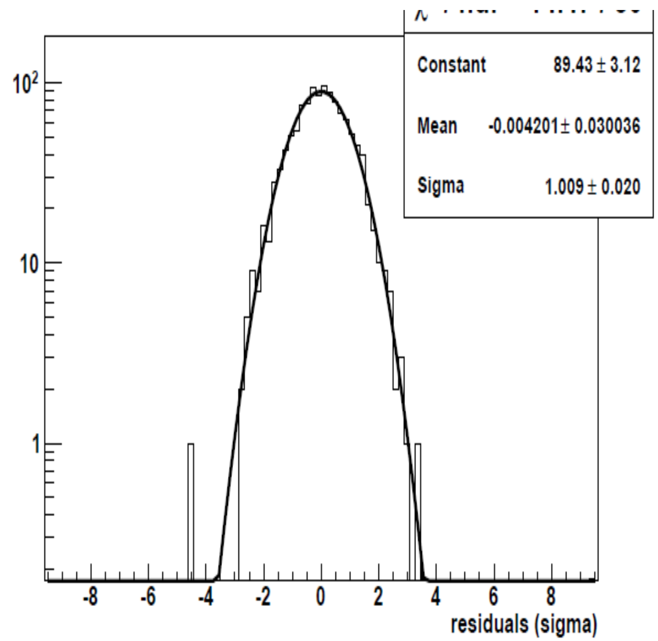
- “early-to-late” change in extinction
- change in source residual polarization
- counting loses from pile-up
- “early-to-late” change in detection efficiency from gain, threshold or timing instabilities

Each systematic error reduced to sub-ppm level.

Three parameter fit of pile-up corrected AK-3 data.

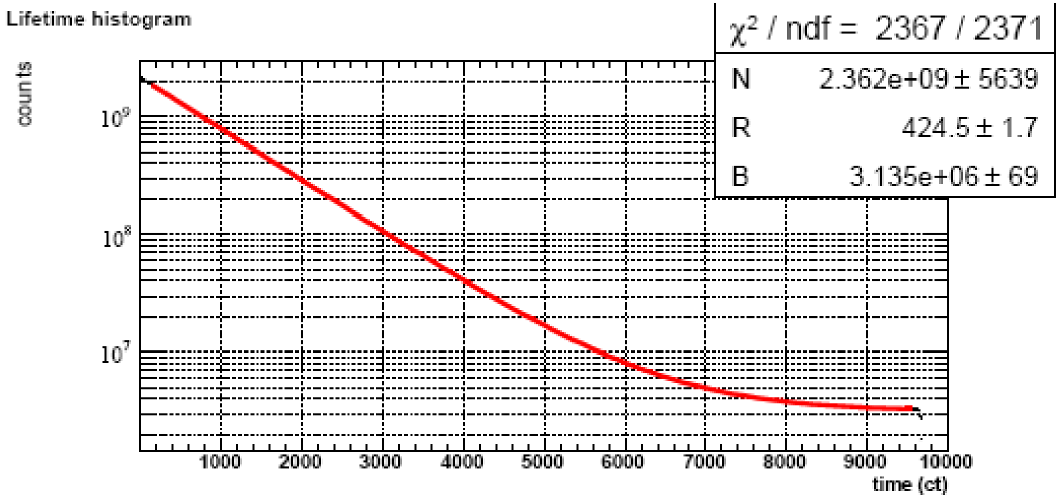


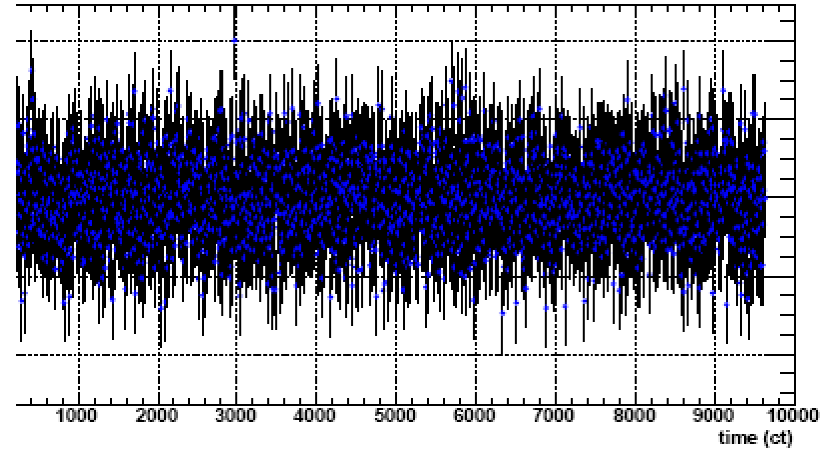


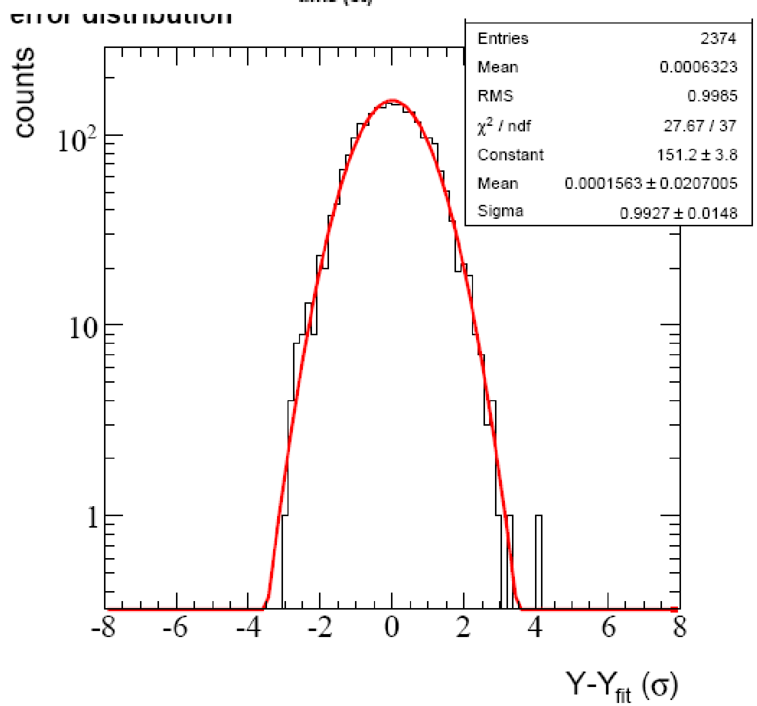


(b)

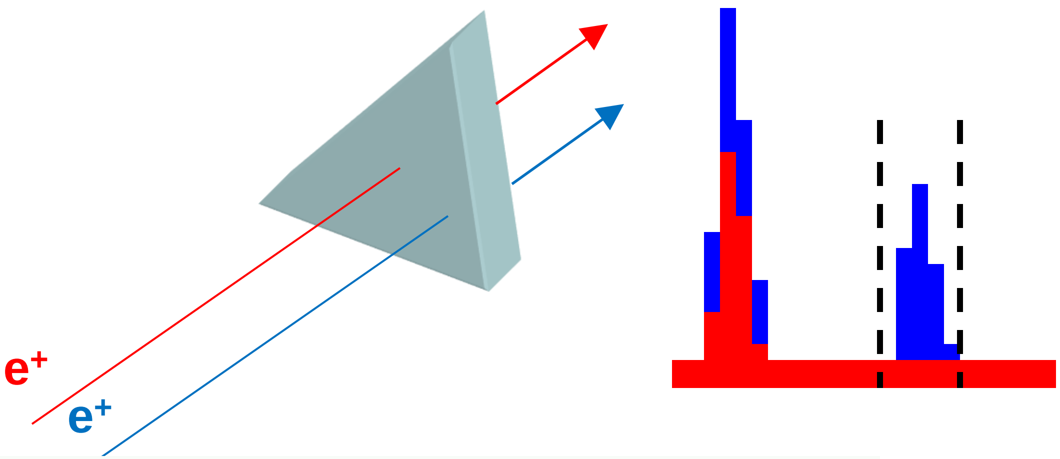
Three parameter fit of quartz data.
Detector symmetry removes precession.



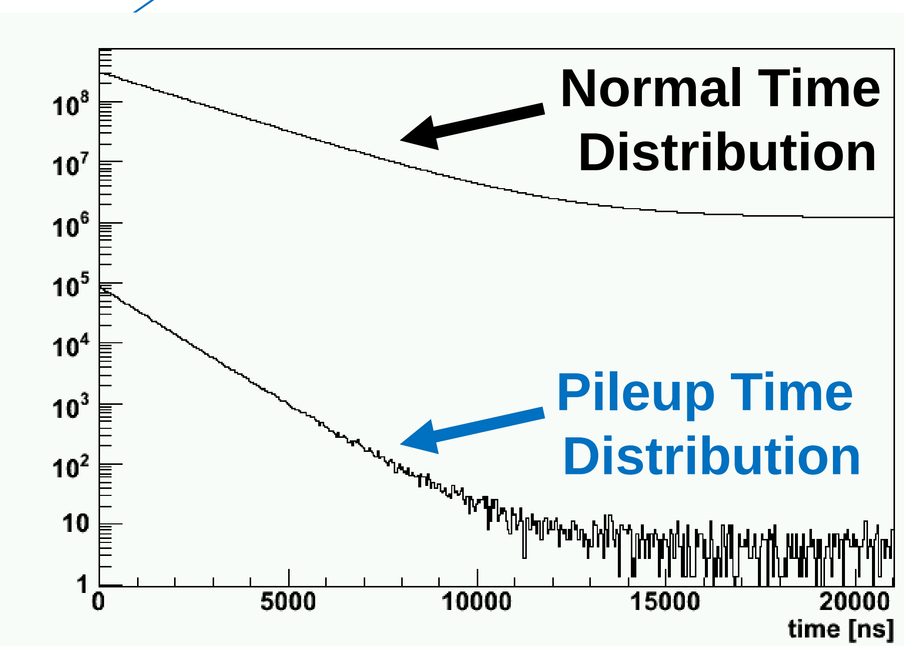


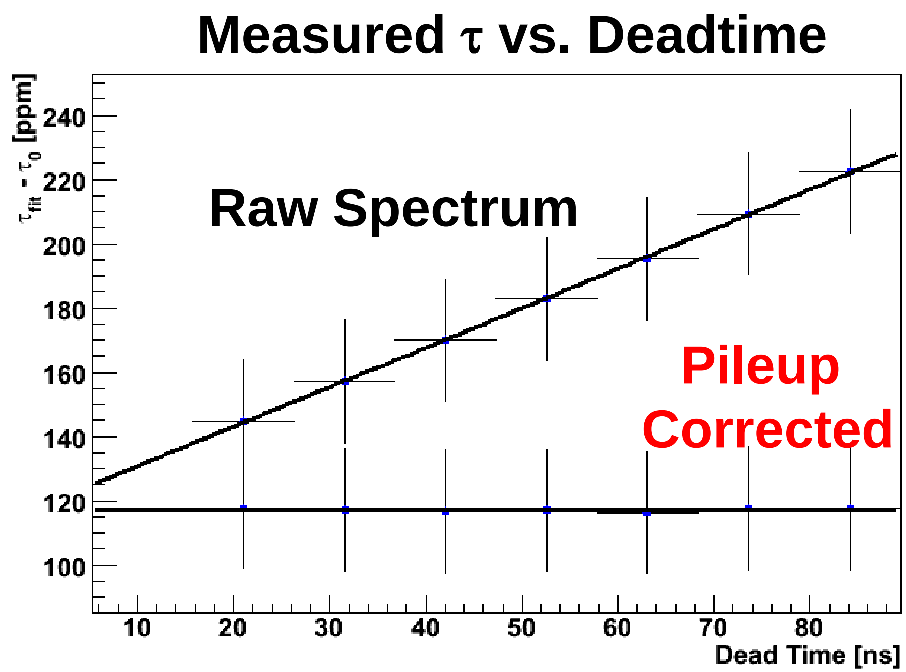


Leading order pileup is a 500 ppm effect



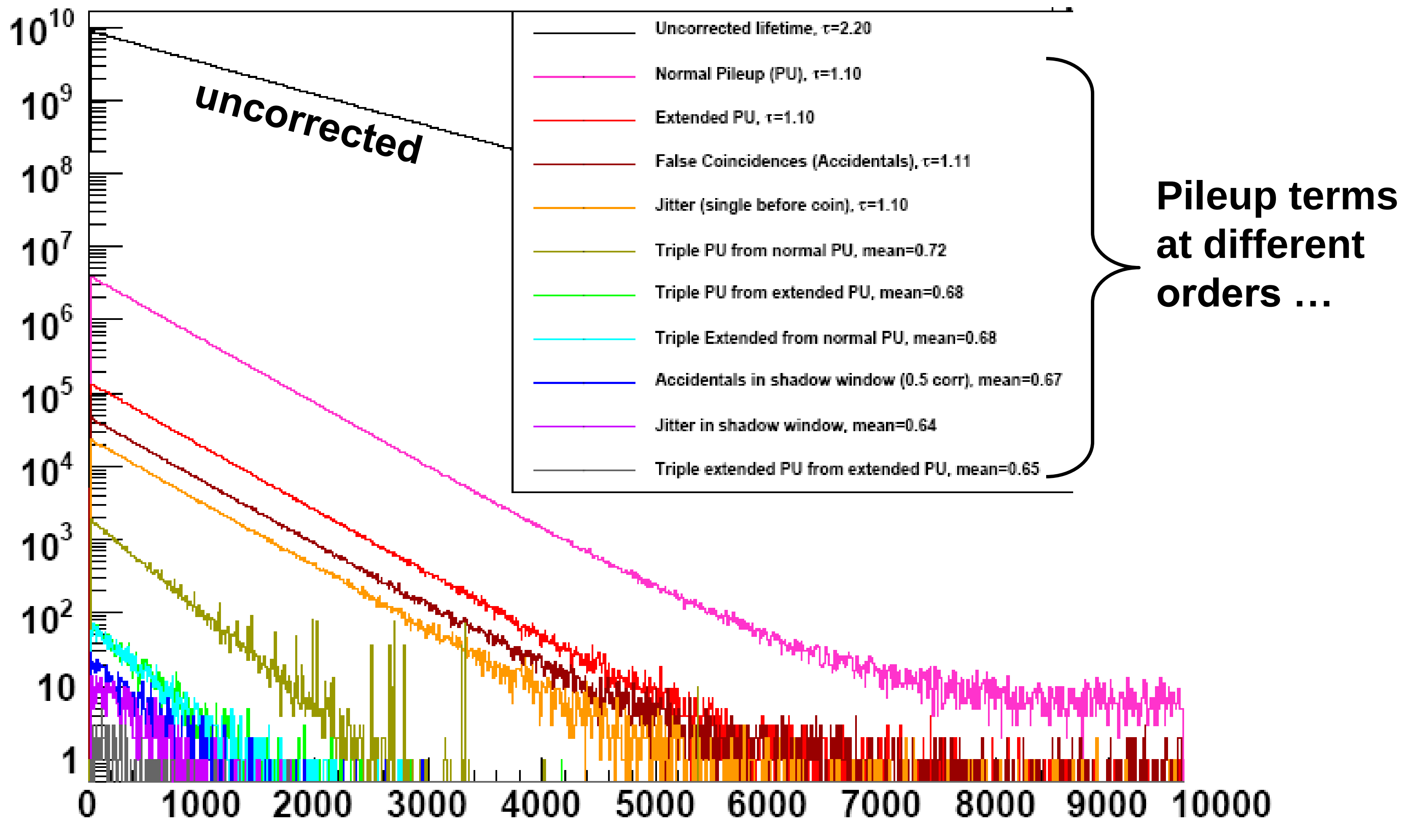
- Same probability
- Statistically reconstruct pileup time distribution
- Fit corrected distribution





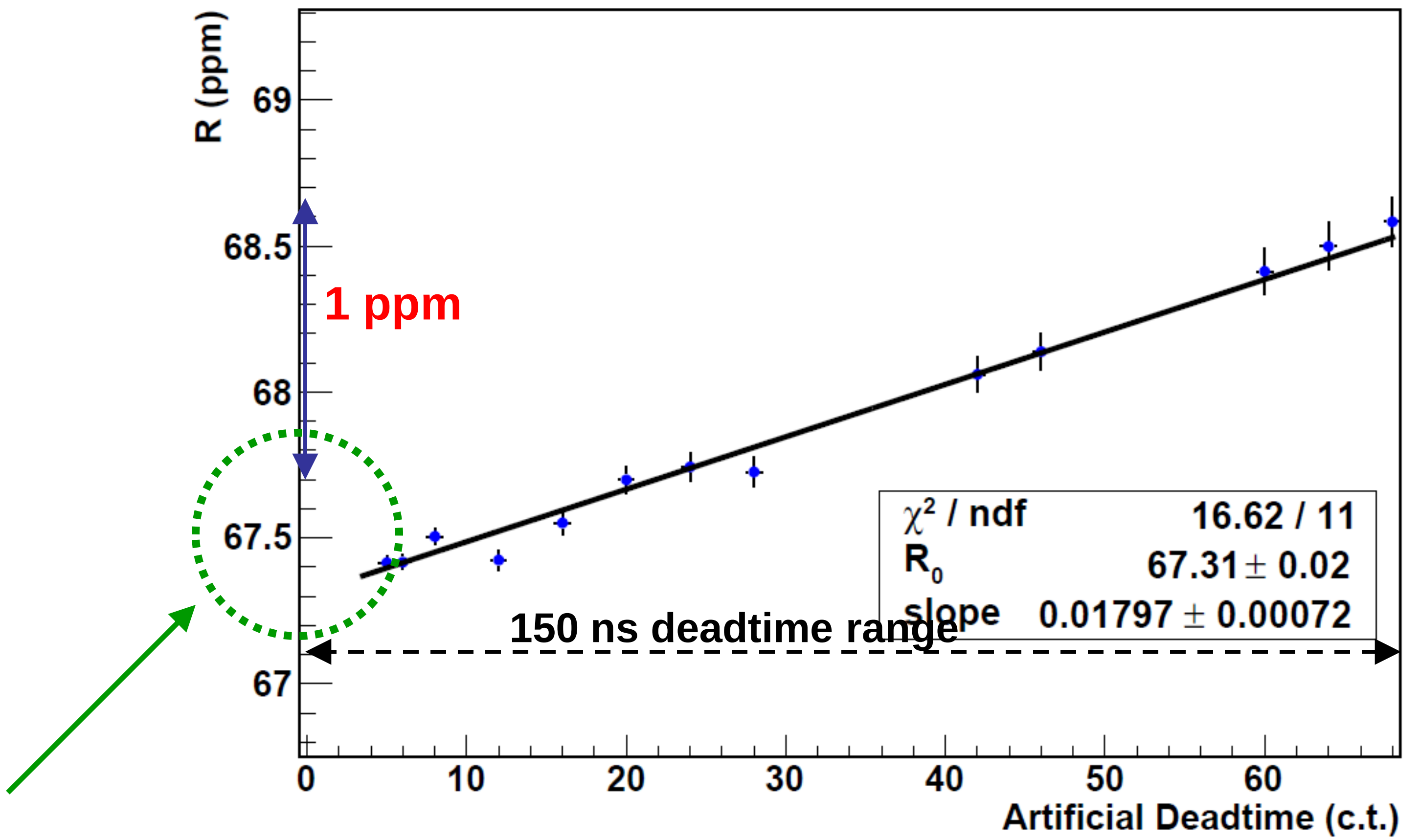
Pileup to sub-ppm requires higher-order terms

- 12 ns deadtime, pileup has a 5 x 10^{-4} probability at our rates
- Proof of procedure validated with detailed Monte Carlo simulation



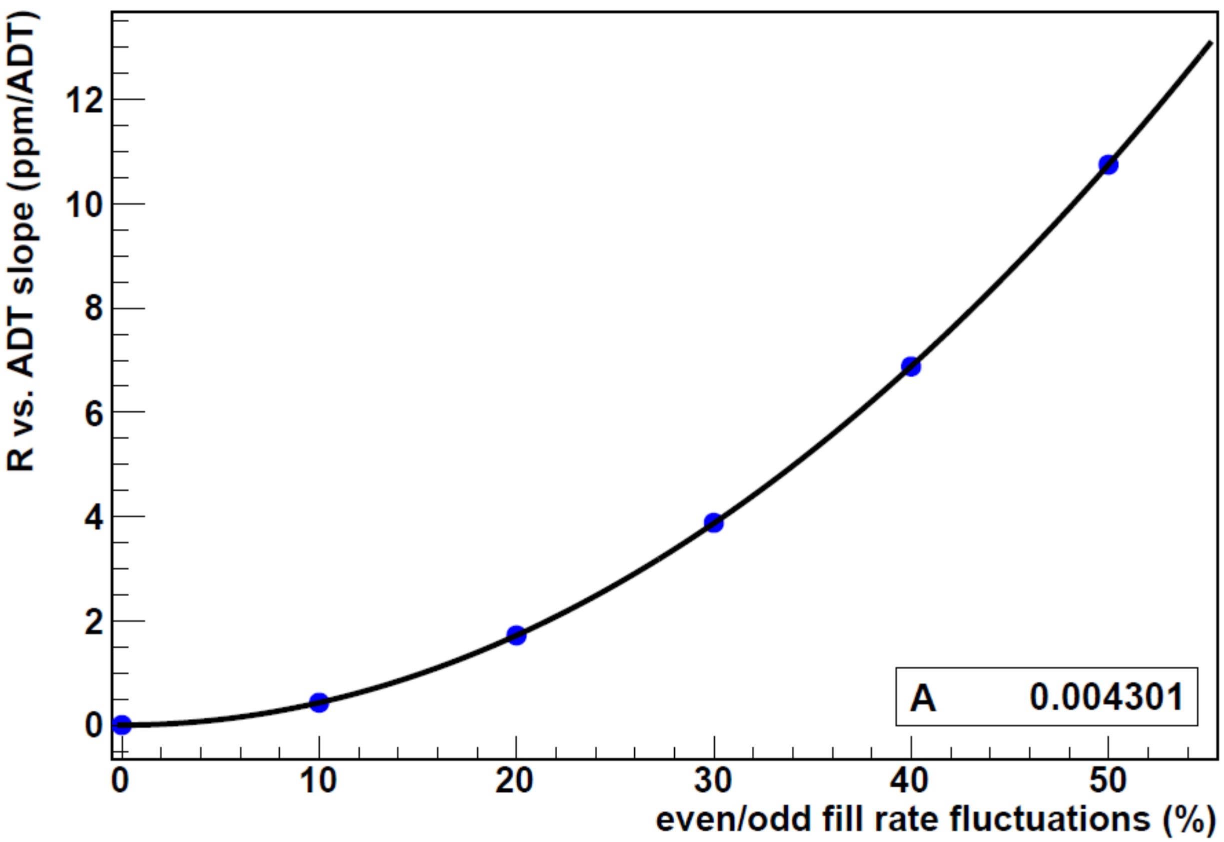
Lifetime versus artificially imposed deadtime window is an important diagnostic.

A slope indicates a pileup under correction. However, extrapolation to 0 deadtime still gives the correct lifetime.



Slope in pileup correction yields 0.2 ppm uncertainty.

Monte-Carlo shows that fill-to-fill rate fluctuations give a pileup under correction.



A 2% fluctuation in beam rate fill-to-fill would account for the R vs. ADT slope.
The PSI beam staff report 4-10% fluctuations are expected on μs timescales.

Systematic and Statistical Uncertainties

Source	2006 (ppm)	2007 (ppm)
Kicker stability	0.22	0.07
Spin precession / relaxation	n/a	0.20
Pileup	0.20	
Gain stability	0.25	
Unseen pulses	0.15	
Upstream muon stops	0.10	
Timing stability	0.12	
Clock calibration	0.03	
Total systematic (0.38 common)	0.41	0.41
Statistical uncertainty	1.14	1.67
Combined total uncertainty	**1.05**	

New MuLan Result

MuLan 2006: τ_μ = 2196979.9 2.5(stat) 0.9(sys) ps

MuLan 2007: τ_μ = 2196980.9 ± 3.7(stat) ± 0.9(sys) ps

2006 & 2007 avg: τ_μ = 2196980.3 2.2 ps (1.0 ppm)

G_F = 1.166 381 8(7) x 10^{-5} GeV^{-2} (0.6 ppm)*

*We use van Ritbergen & Stuart, Nucl. Phys. B564 (2000) 343.
Following Pak & Czarnecki, Phys. Rev. Lett. 100(2008)241807,
we include 0.43 ppm shift in Δq from linear m_e term.

MuLan Collaborators