The MuLan Experiment

Measuring the muon lifetime to 1ppm

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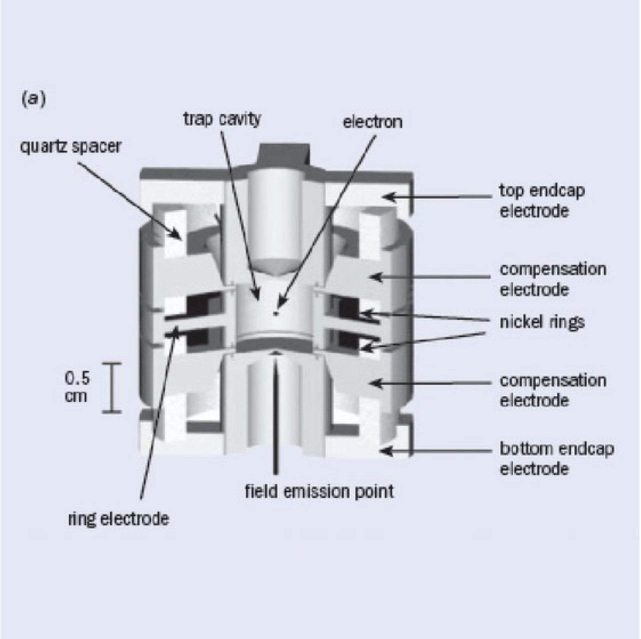
Outline:

- Motivate the measurement
- Describe the experiment
- Past and developing results

Berkeley, Boston, Illinois,
James Madison, Kentucky, KVI, PSI

Precision electroweak predictions rest on three parameters



Fine Structure Constant

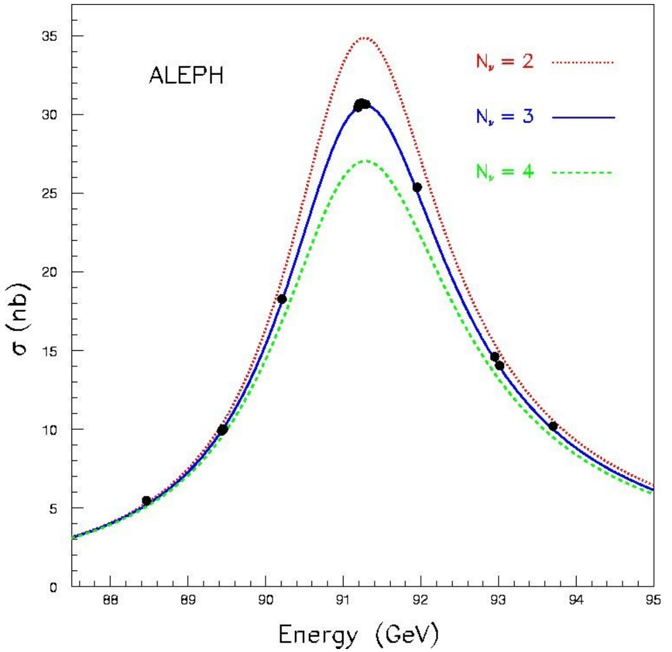
$$\frac{\delta\alpha_{\rm em}}{\alpha_{\rm em}} \approx 0.37\,\mathrm{ppb}$$

Gabrielse *et al* 2008

Mass of the neutral weak boson

$$\frac{\delta M_{Z^0}}{M_{Z^0}} \approx 23\,\mathrm{ppm}$$

LEP EWWG 2005



Fermi Constant

$$\frac{\delta G_{\rm F}}{G_{\rm F}} \approx 4\,\mathrm{ppm}$$

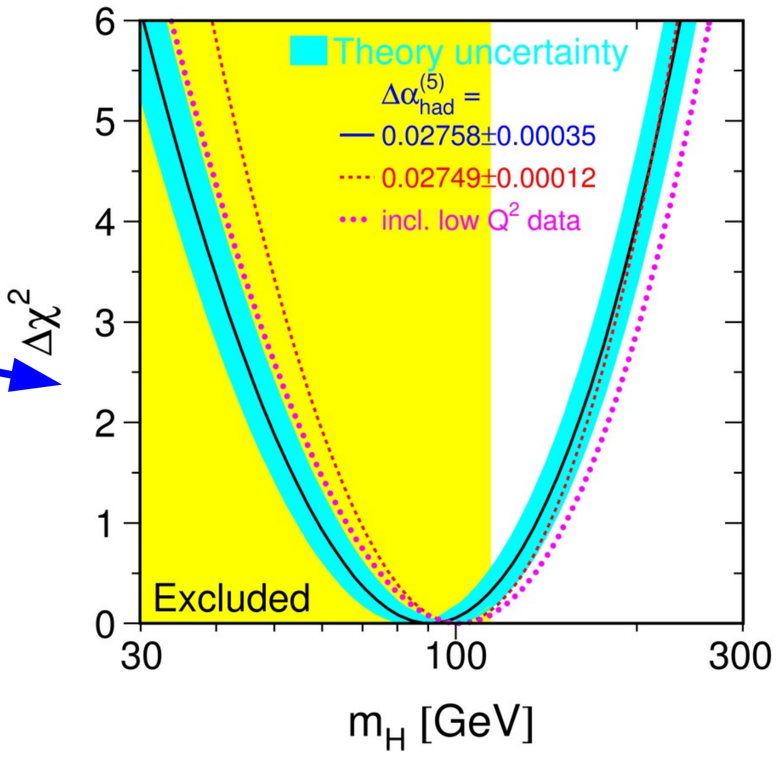
Chitwood *et al* 2006

The Fermi constant is an implicit input to all precision electroweak studies

$$\frac{G_{\mathrm{F}}}{\sqrt{2}} = \frac{g^2}{8M_{\mathrm{W}}^2}\left(1 + \Delta r(m_{\mathrm{t}}, m_{\mathrm{H}}, \ldots)\right)$$

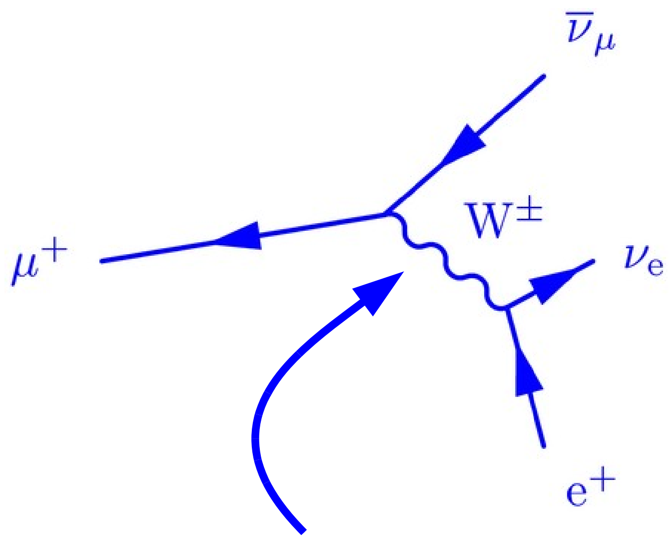
Contains all weak interaction loop corrections.

Example: the “blue band” Higgs limit plot.



Plot borrowed from LEP Electroweak Working Group publications

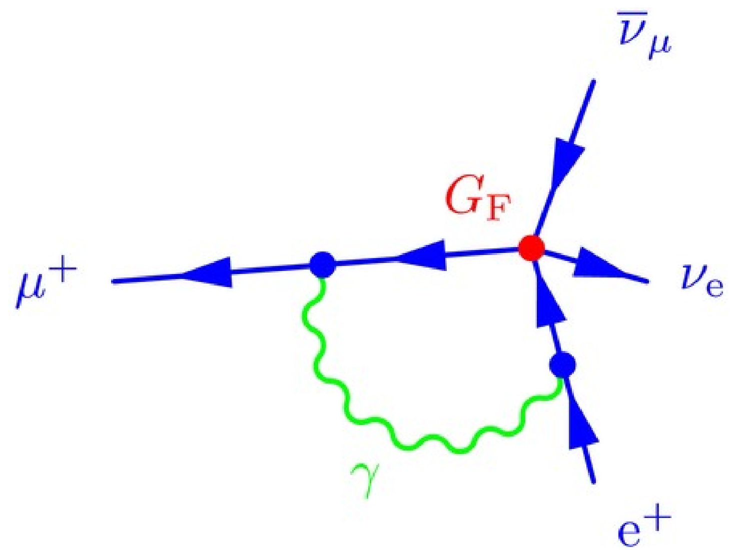
Muon decay gives us unique access to the electroweak scale



The muon *only* decays via the weak interaction, which gives it a very long lifetime.

The V-A theory factorizes into a pure weak contribution, and non-weak corrections, essentially uncontaminated by hadronic uncertainties.

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



All relevant weak interaction physics confined to one easily measured parameter with a clean theoretical interpretation.

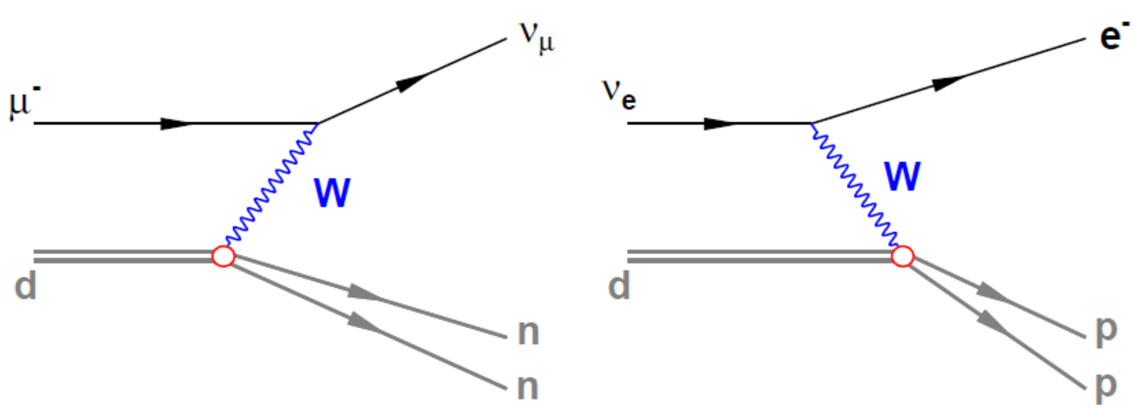
Additionally, the free muon lifetime is a precision reference for nuclear capture measurements

$$\mu^- + p \to \nu + n$$ MuCap

$$\mu^- + d \to \nu_\mu + n + n$$ MuSun

These are the simplest weak interaction processes in nuclei with precise theoretical predictions in QCD (EFT, χPT, pQCD)

These measurements also calibrate some processes of astrophysical interest



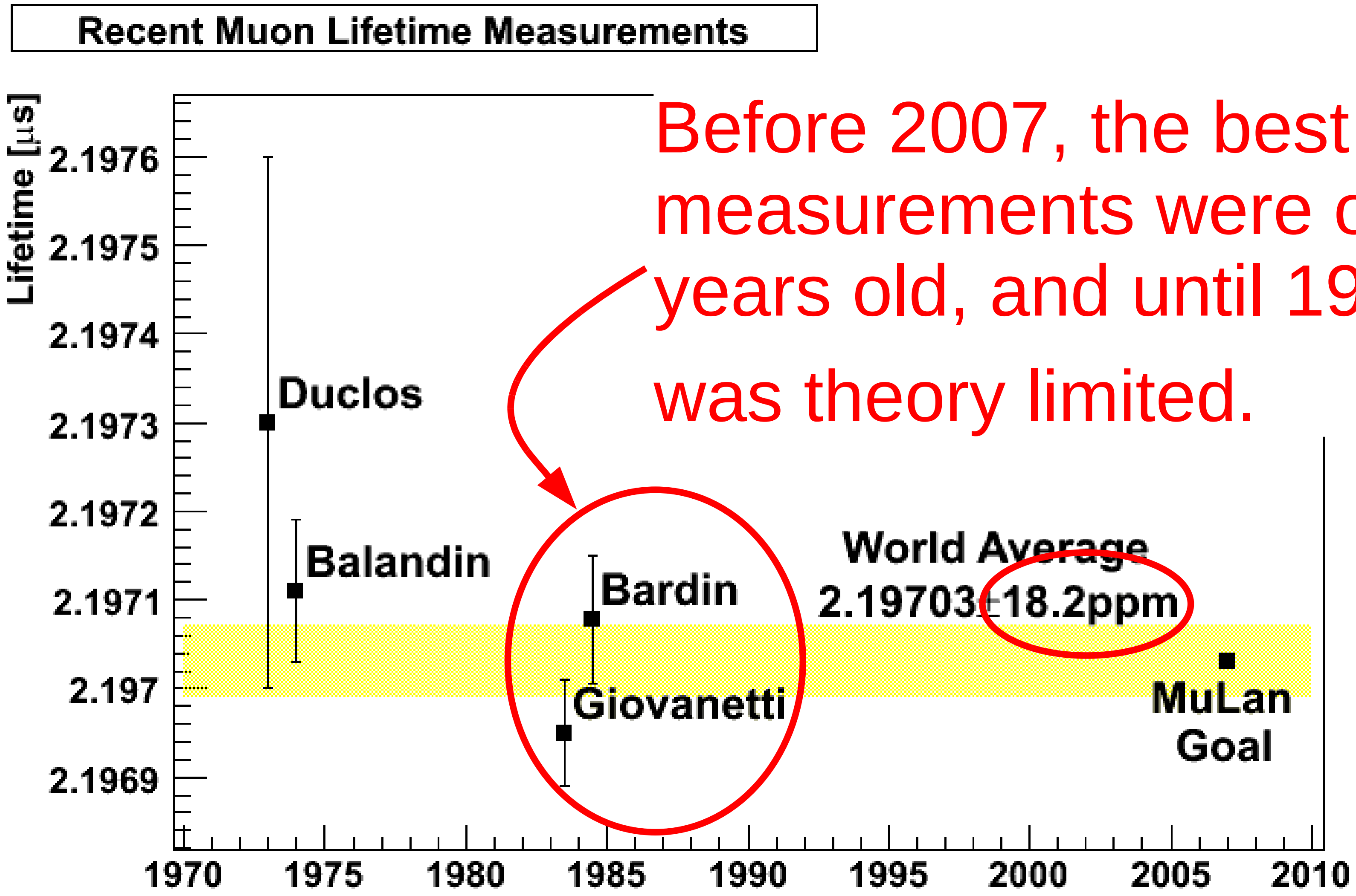
Solar pp fusion cycle

$$p + p \to d + e^- + \bar{\nu}_e$$

νd scattering in SNO

$$\nu_\mu + d \to \mu^- + n + n$$

A brief history...



Before 2007, the best measurements were over 20 years old, and until 1999 G_F was theory limited.

G. Bardin et al., Phys. Lett. B 137, 135 (1984)
K. Giovanetti et al., Phys. Rev. D 29, 343 (1984)

The Standard Model Fermi extraction is no longer theory limited

$$\frac{\delta G_{\mathrm{F}}}{G_{\mathrm{F}}} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)^2 + \left(5\frac{\delta m_\mu}{m_\mu}\right)^2 + \left(\frac{\delta\mathrm{theory}}{\mathrm{theory}}\right)^2}$$

Mid 90s: 17 ppm 18 ppm 90 ppb 30 ppm

The Standard Model Fermi extraction is no longer theory limited

$$\frac{\delta G_{\mathrm{F}}}{G_{\mathrm{F}}} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau_\mu}{\tau_\mu}\right)^2 + \left(\frac{\delta\mathrm{theory}}{\mathrm{theory}}\right)^2}$$

Future: 0.5 ppm 1 ppm < 0.3 ppm

Lifetime error now limits the Fermi constant

van Ritbergen and Stuart: 2-loop QED corrections (massless electrons)

T. van Ritbergen and R. G. Stuart, Nucl. Phys. B564, 343 (2000)

What exactly is the “lifetime” of a particle?

If an unstable particle exists at a certain time, then it has a fixed (history independent) probability of decaying in the next “clock tick”.

$$p_d(\mathrm{d}t) = \frac{1}{\tau}\mathrm{d}t$$

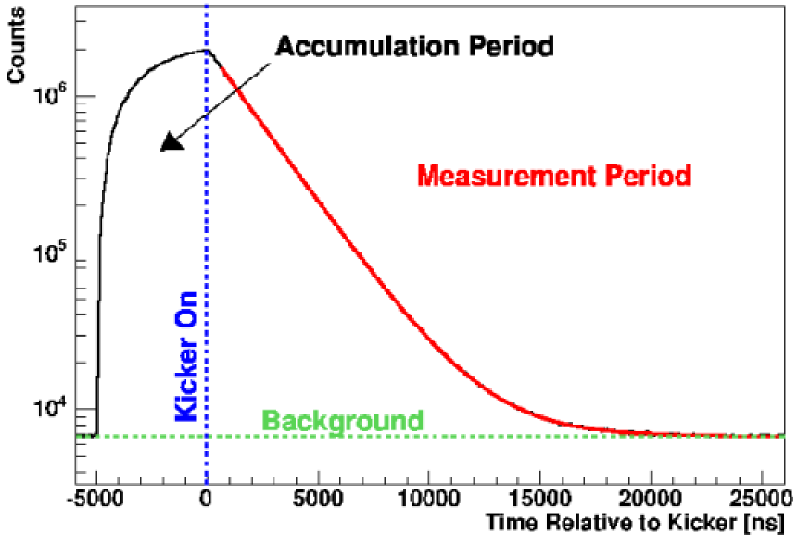
Not normalized!

$$p_s(t + \mathrm{d}t) = p_s(t)\left(1 - p_d(\mathrm{d}t)\right)$$

$$\frac{\mathrm{d}p_s(t)}{\mathrm{d}t} = -\frac{1}{\tau}p_s(t)$$

$$p_s(t) = \frac{1}{\tau}e^{-t/\tau}$$

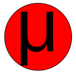
Normalized!

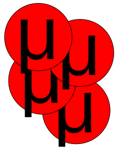


τ is called the lifetime.

How do you measure the muon lifetime?

One-at-a-time



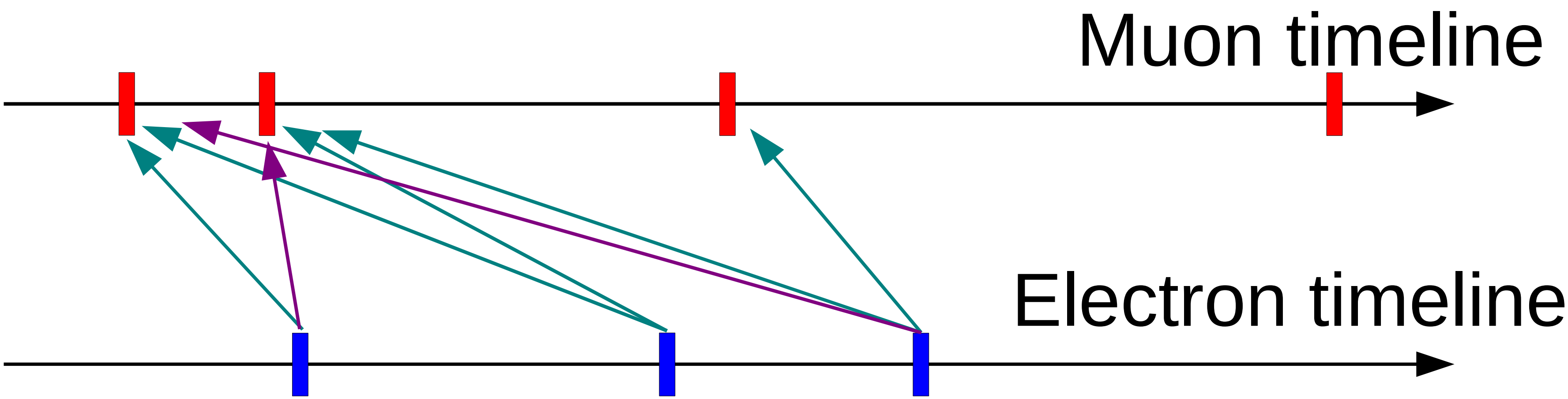


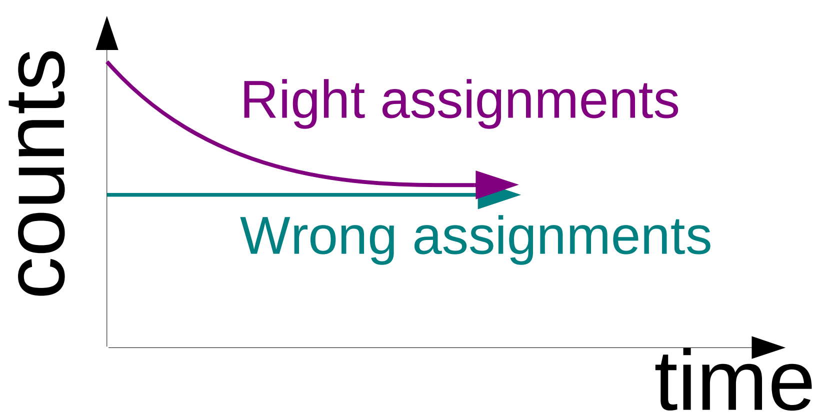
Many-at-once

$$\tau_\mu = 2.197\,\mu\mathrm{s}$$

One-at-a-time

Can't really do one-at-a-time, the next best thing is a low rate, DC beam.



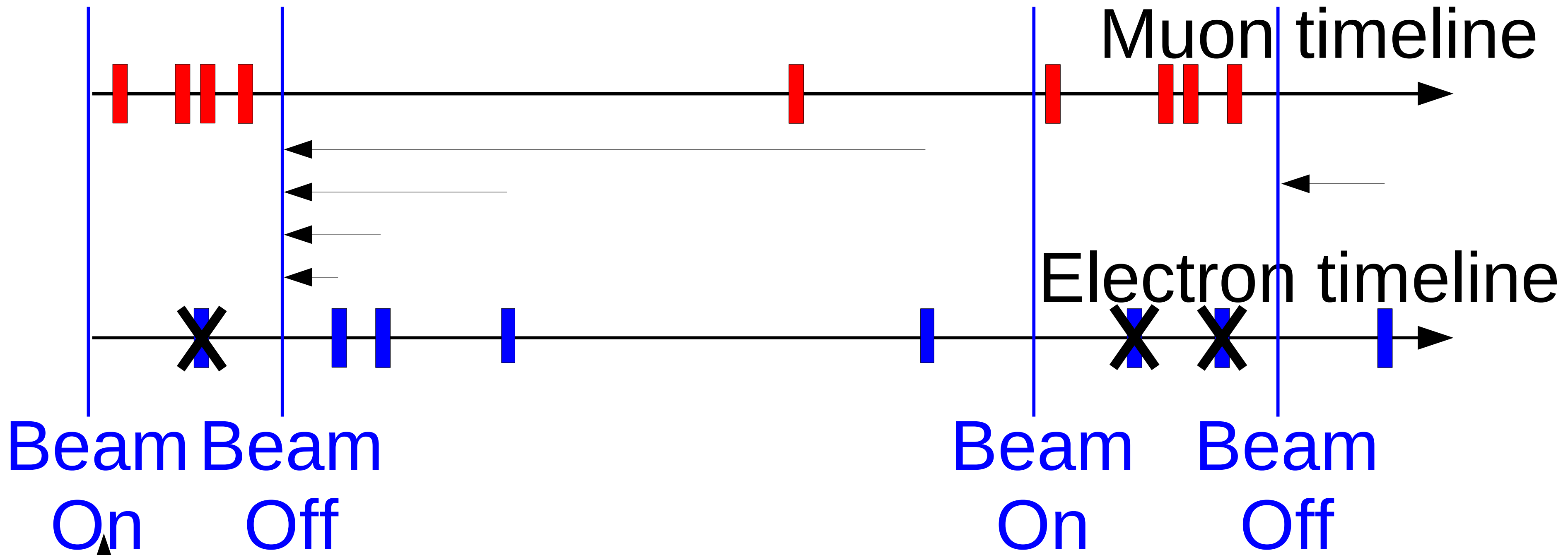


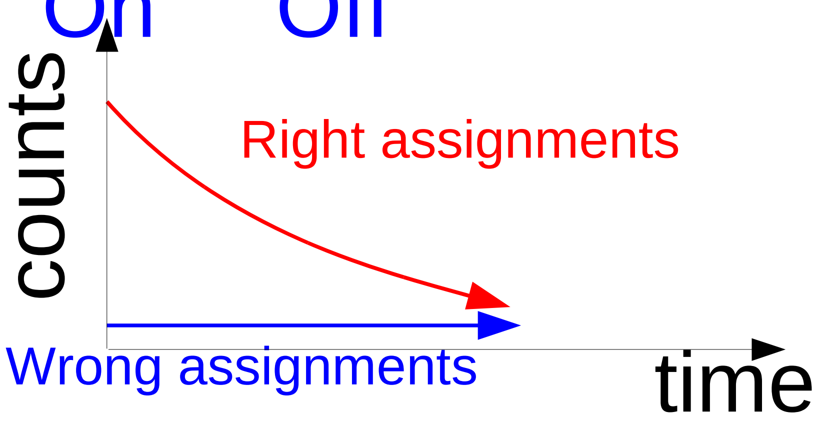
$$\frac{S}{B} \propto \frac{N}{N^2} = \frac{1}{N}$$

$$30\,\mathrm{kHz} \rightarrow 385\,\mathrm{d} \text{ for } 10^{12}\mu^+$$

Many-at-once

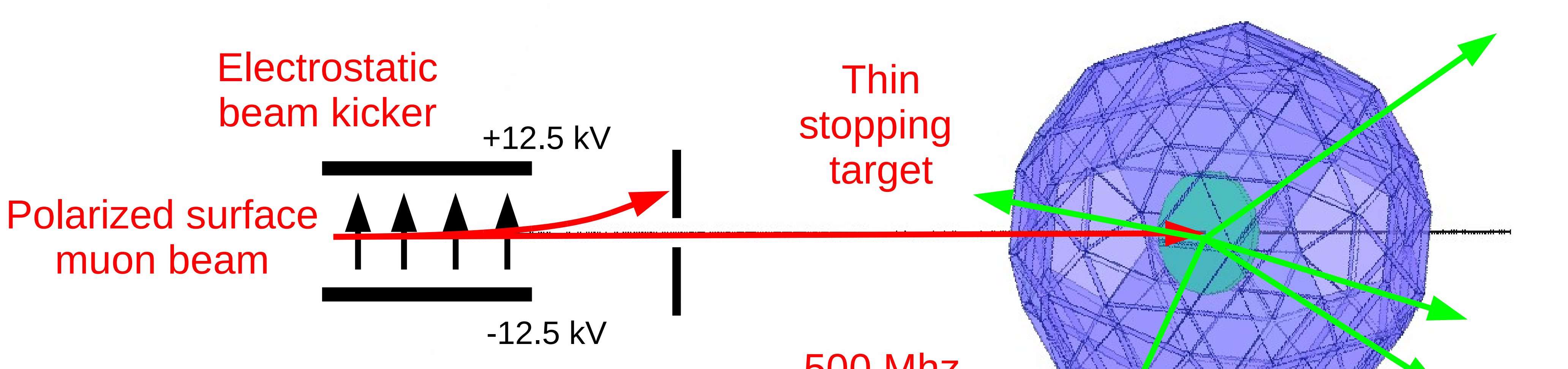
Need time structured (AC) beam, not a continuous (DC) beam

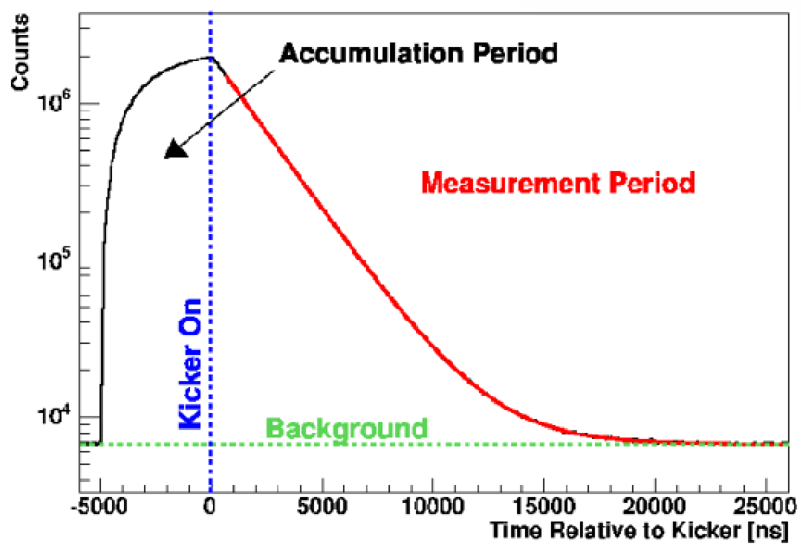


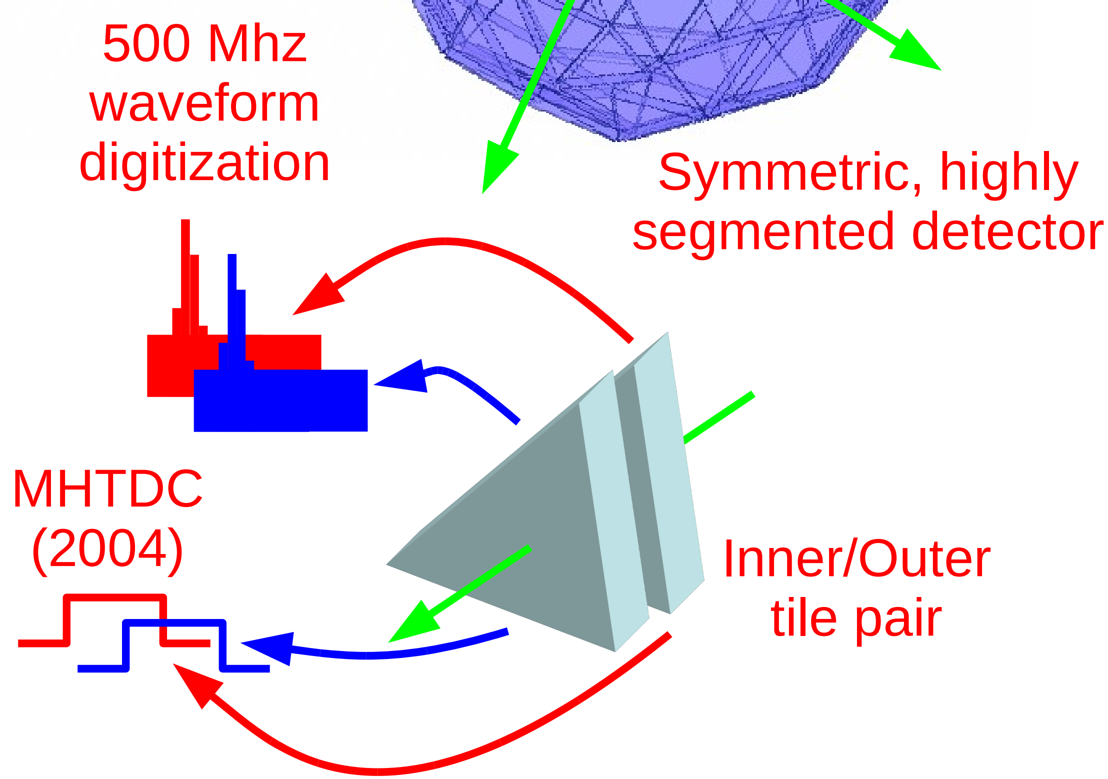


Much higher rates, but much harder experiment R&D and construction

We will reach our goal by running many muon decay experiments simultaneously





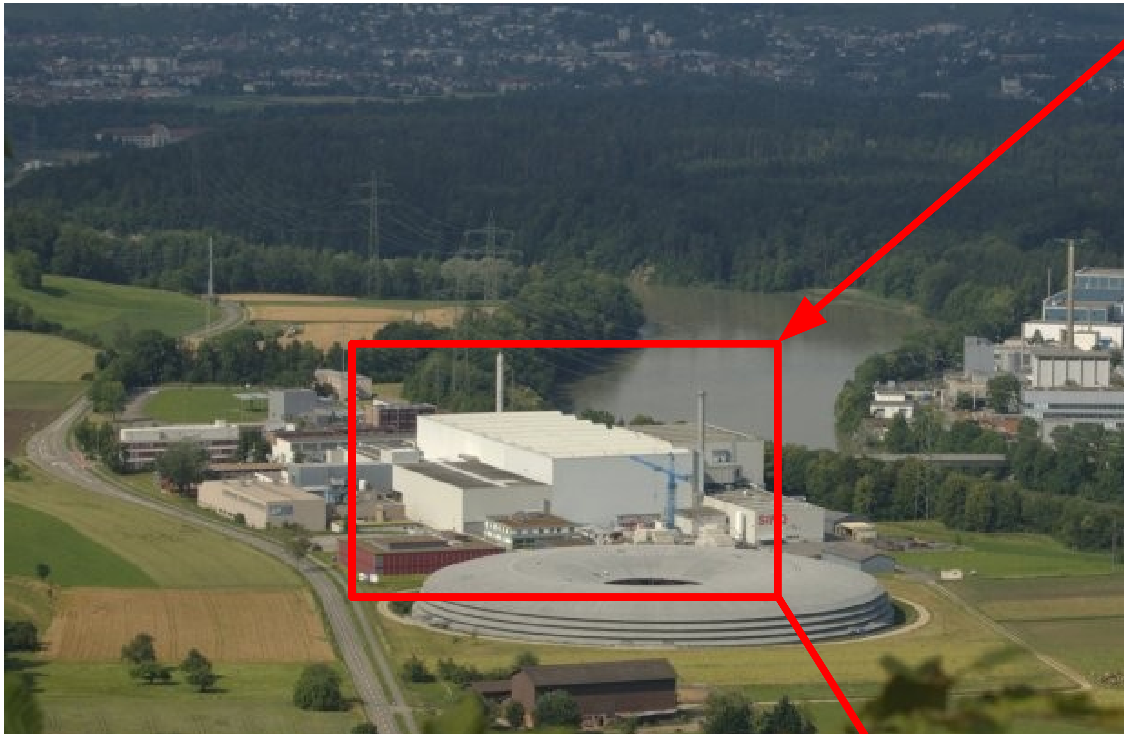


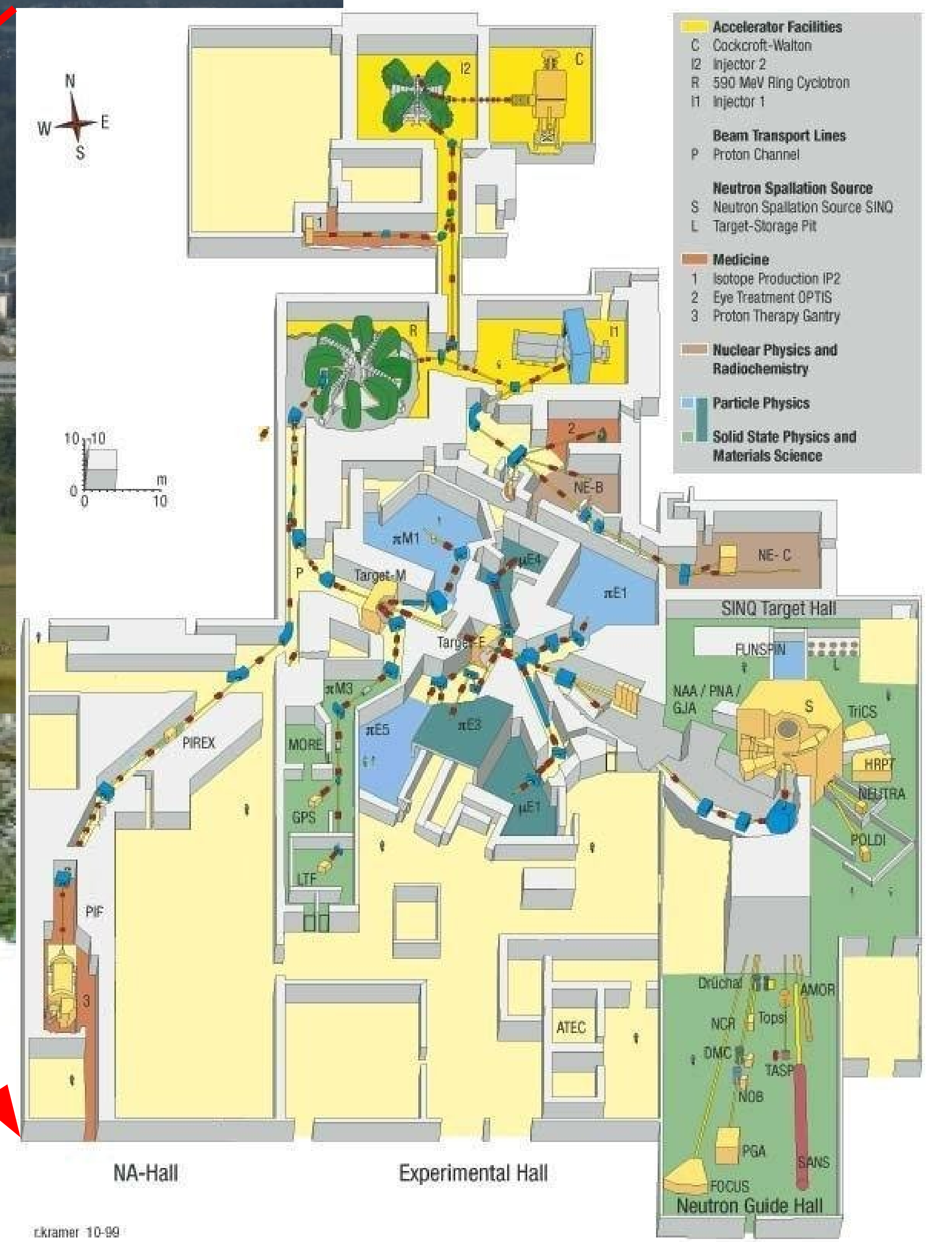
$$N(t) = N_0 e^{-t/\tau} + B$$

Finding muons isn't such a problem

πE3 Beamline,
Paul Scherrer Institut,
Villigen, Switzerland

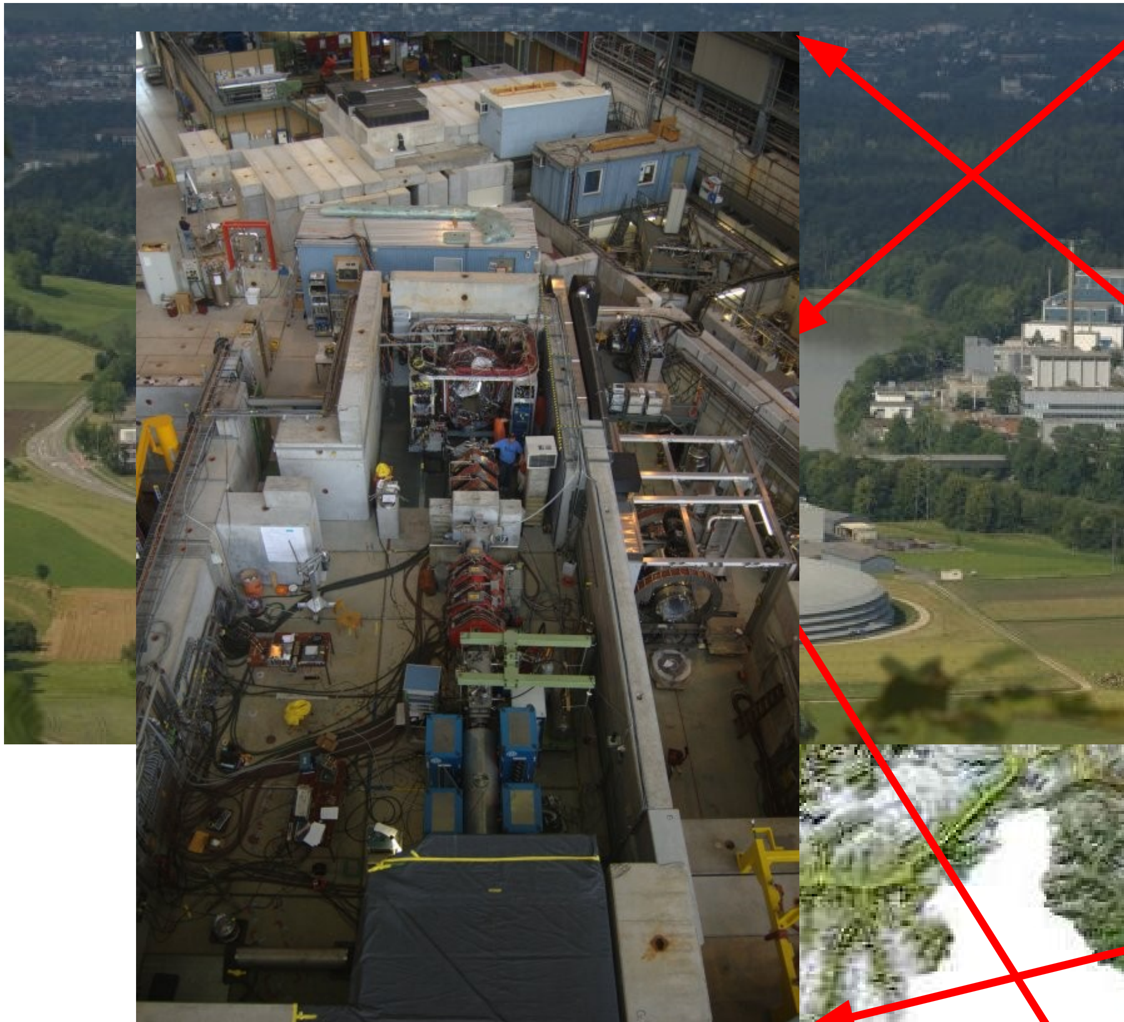
Finding muons isn't such a problem

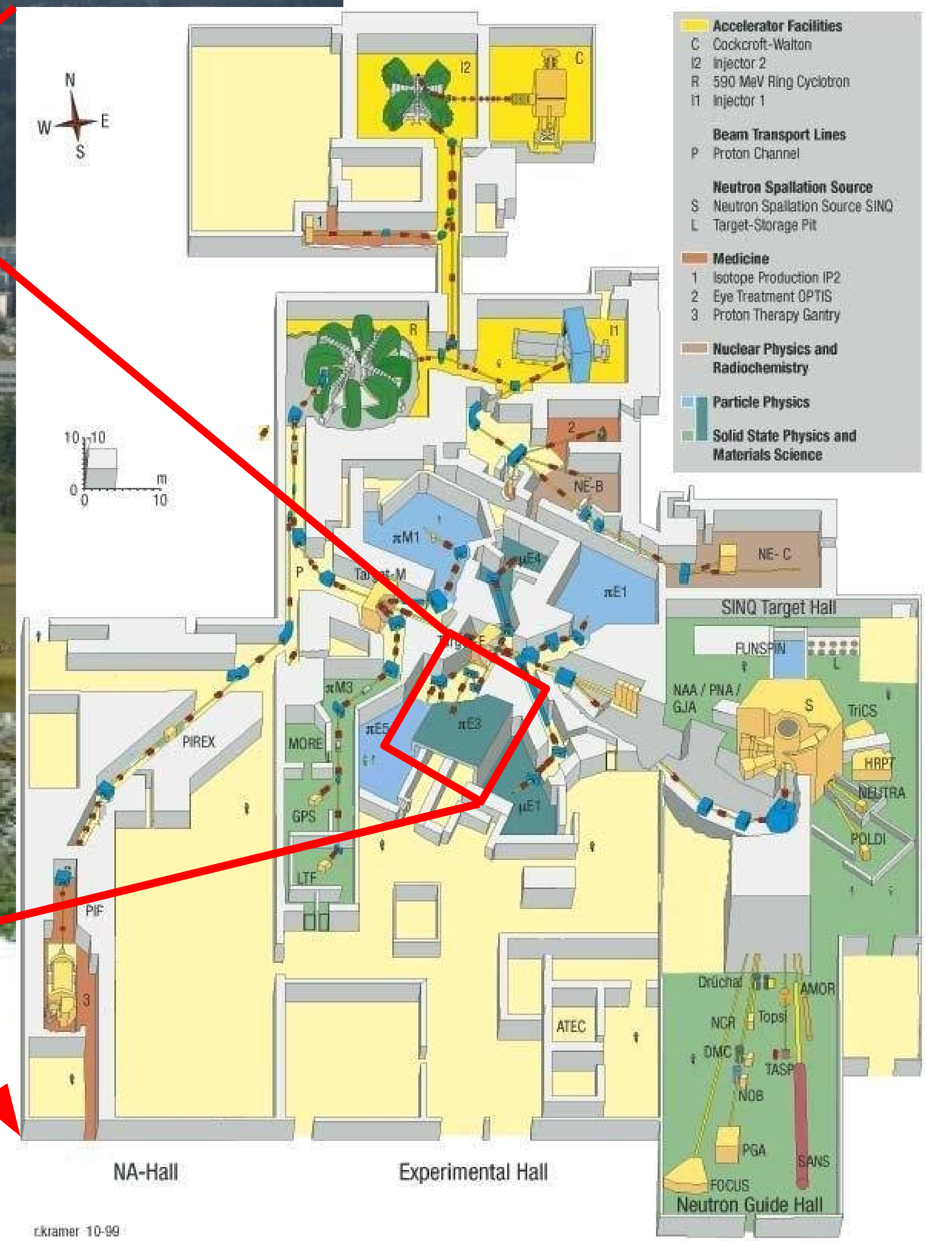




πE3 Beamline,
Paul Scherrer Institut,
Villigen, Switzerland

Finding muons isn't such a problem





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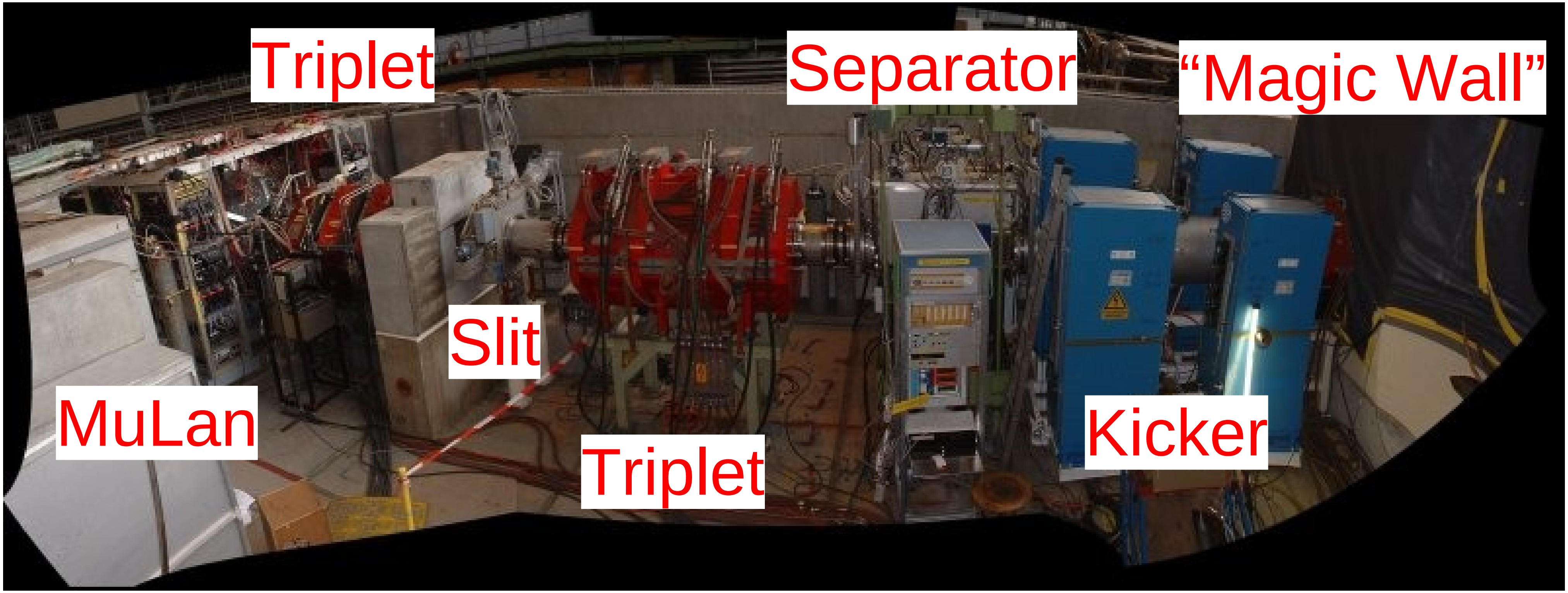
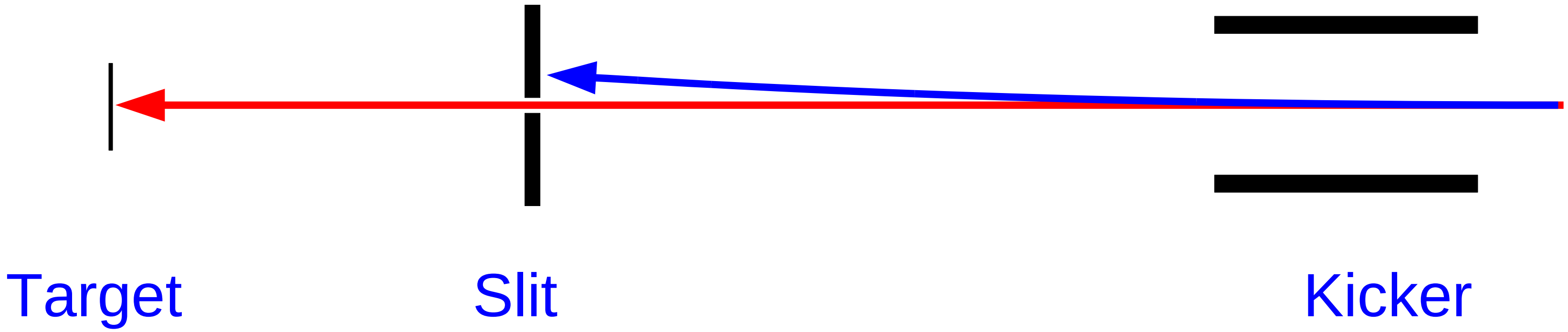
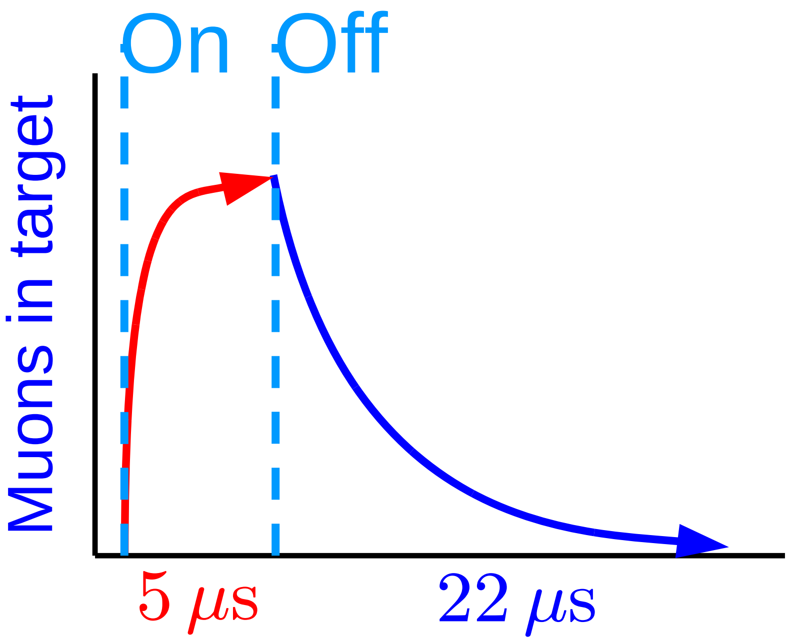
Villigen, Switzerland

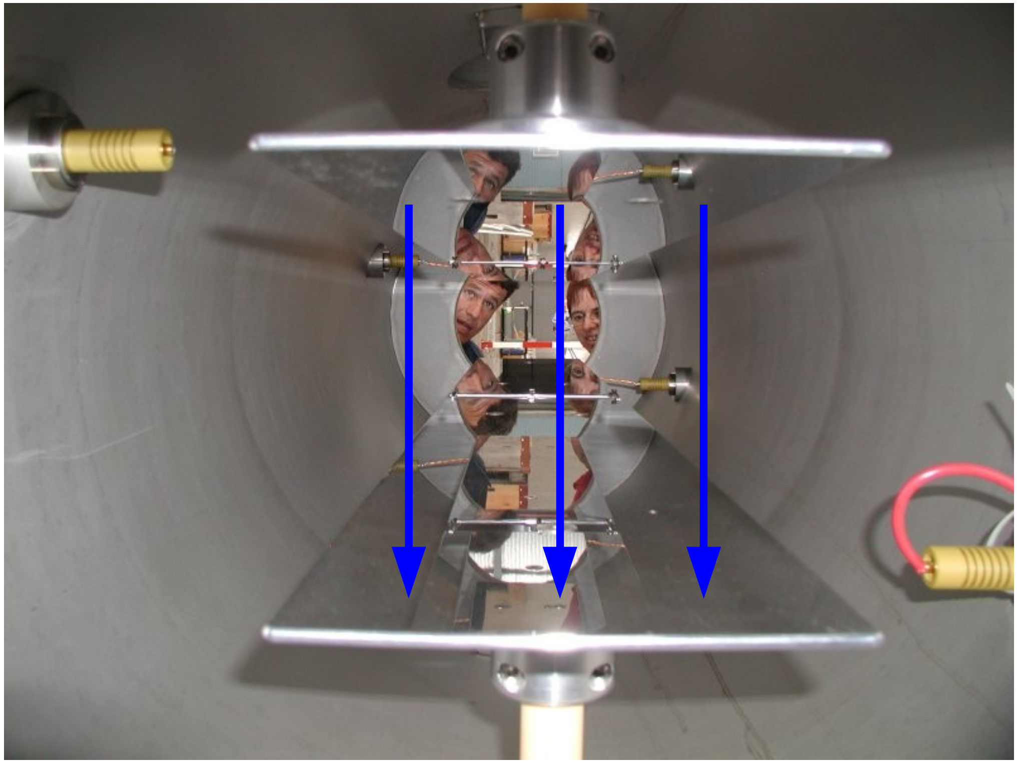
Filling the bucket



Time structuring the beam



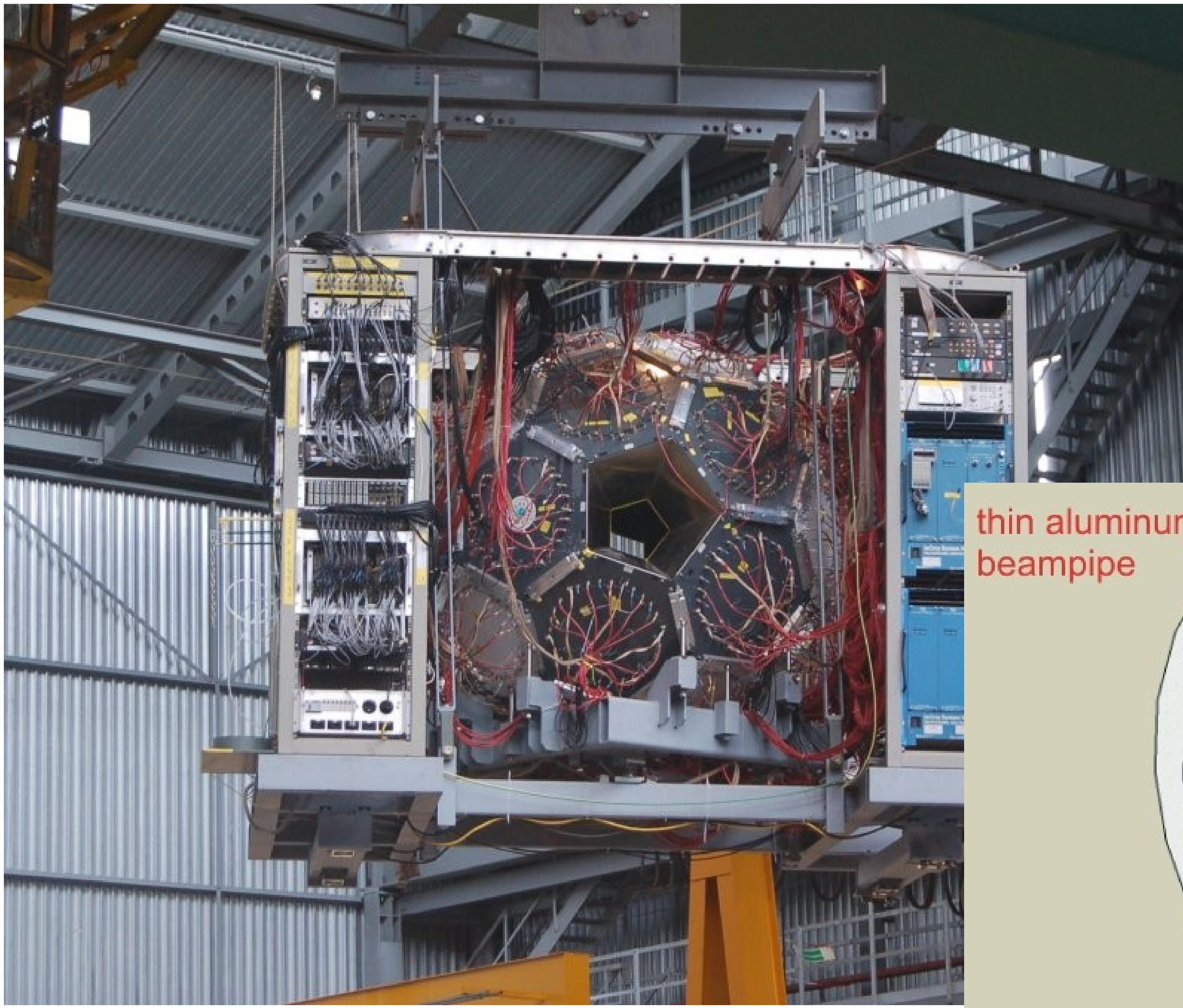




$$N_{\mathrm{in}}(t) = R_\mu \tau \left(1 - e^{-t/\tau}\right)$$

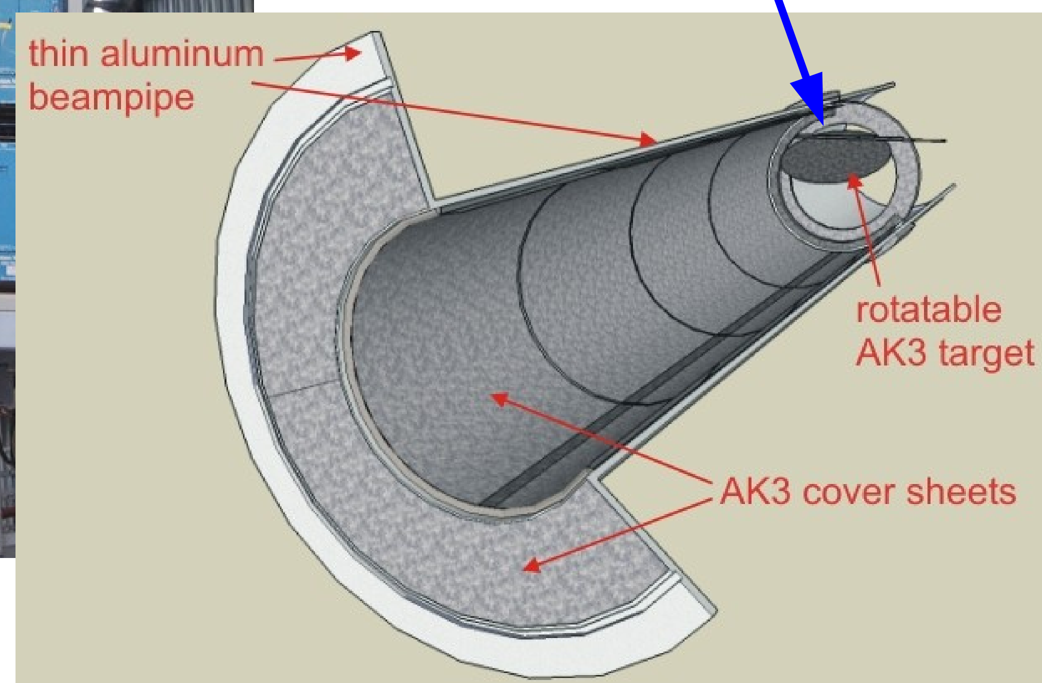
$$N_{\mathrm{out}}(t) = N_{\mathrm{in}}(t_c) e^{-t/\tau}$$

Where exactly is the bucket?

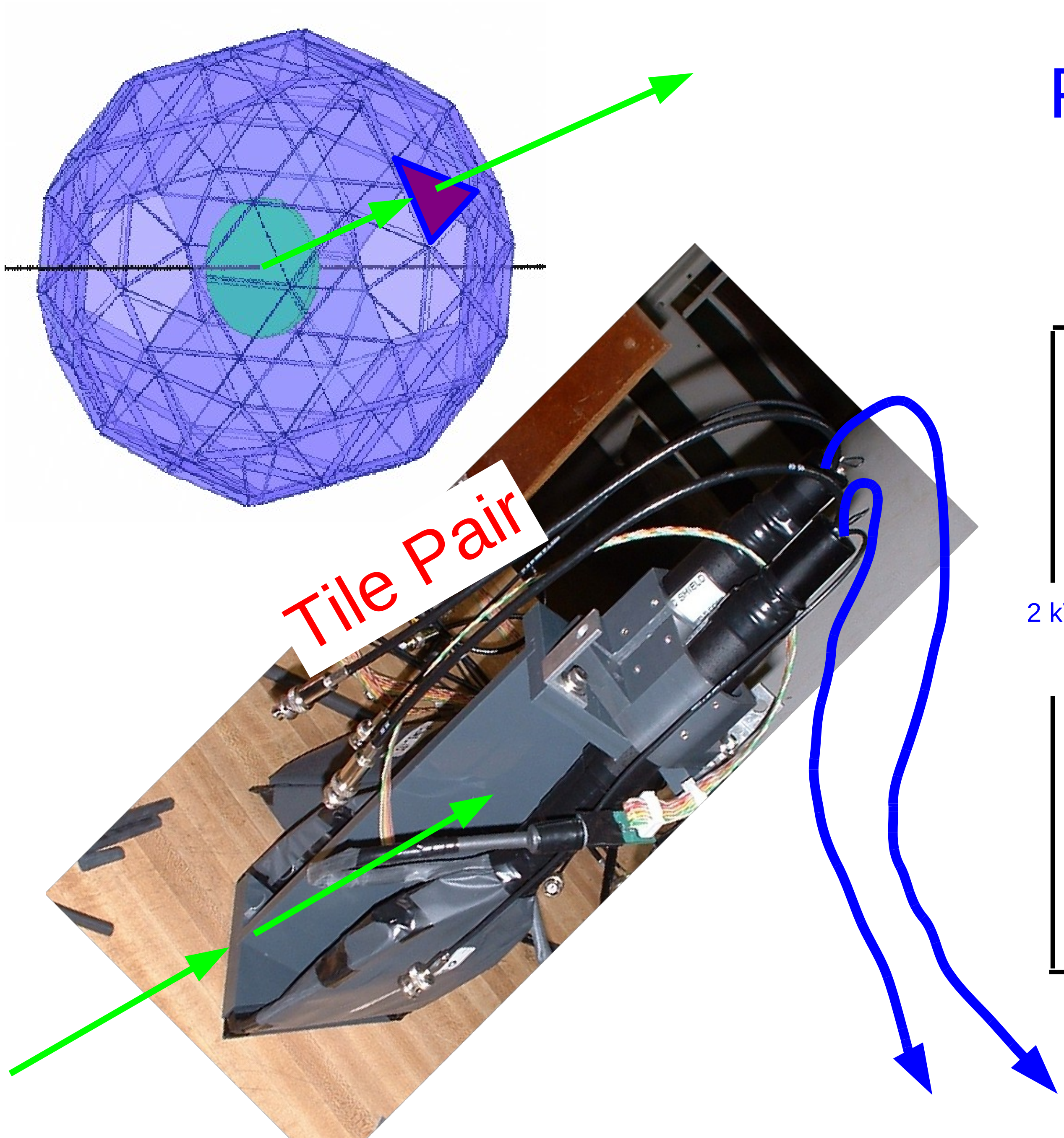


Rob Carey: “The world's largest research grade soccer ball”

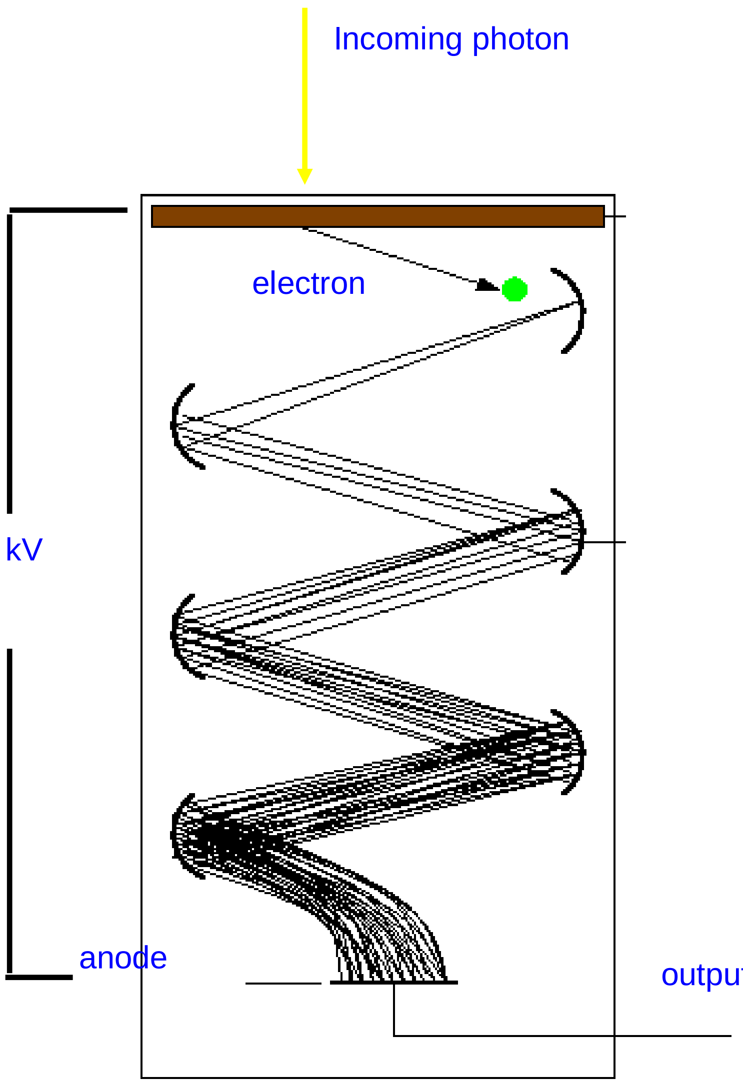
Right there!



Watching the bucket empty

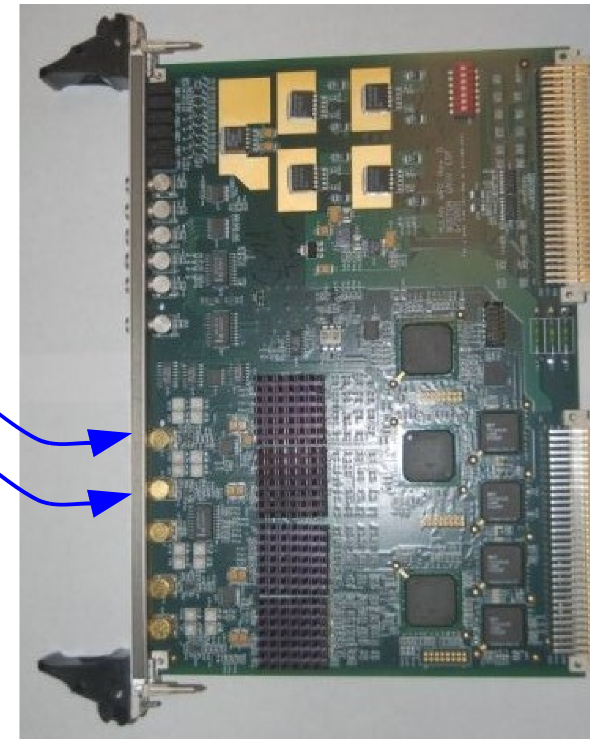


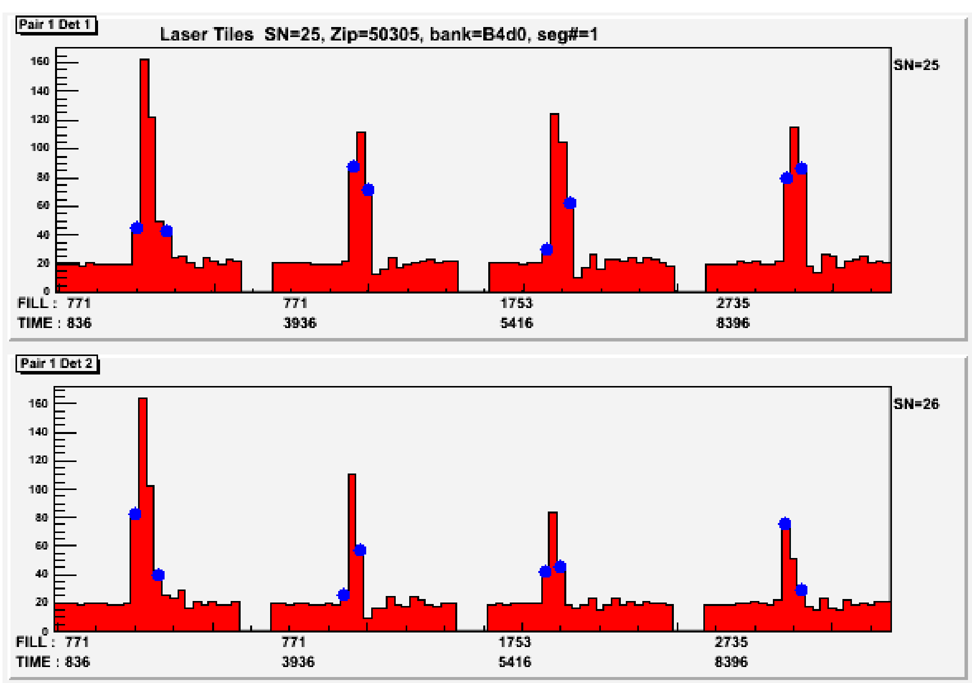
Photomultiplier tube



Watching the bucket empty

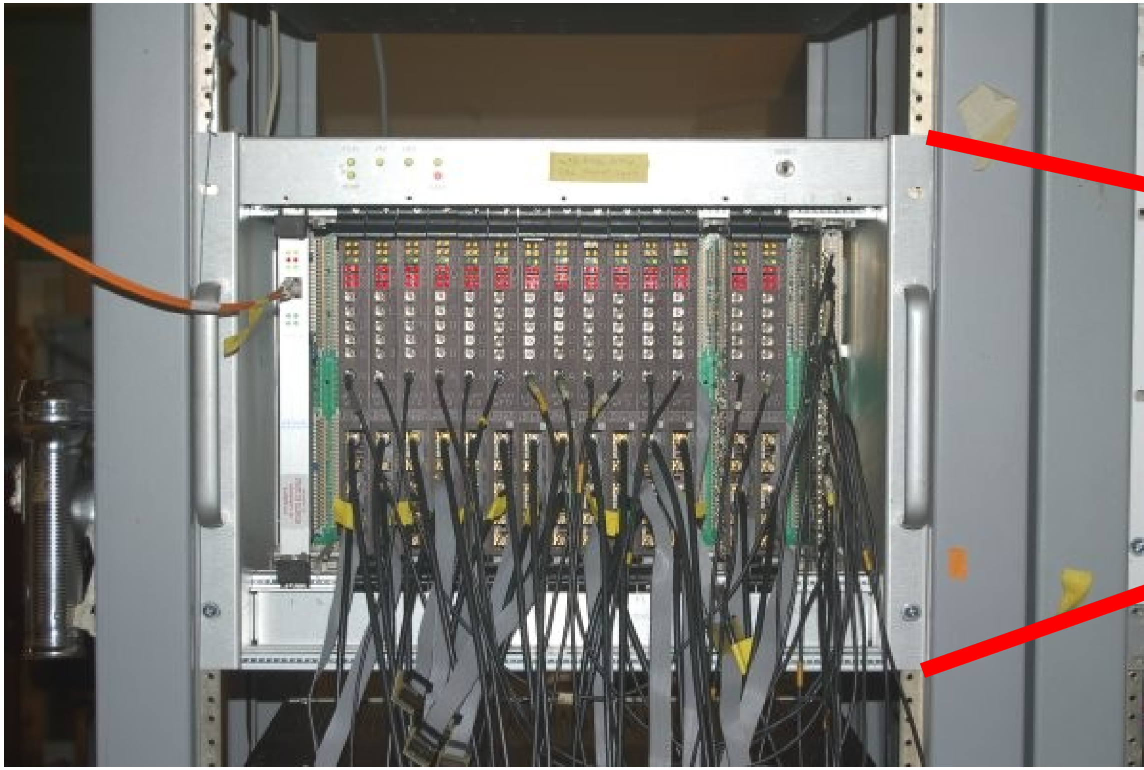
The PMTs feed the WFDs

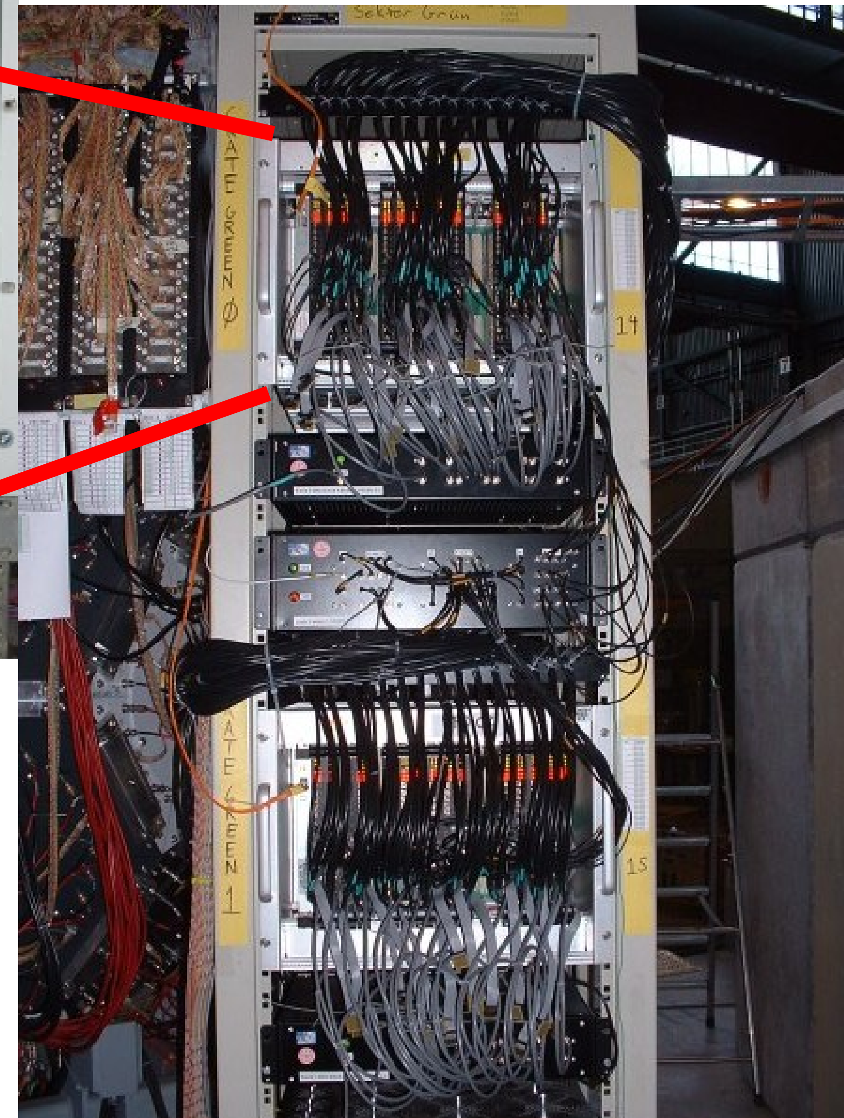




This gives about 40 MB/s of data that has to be stored!

Where does all that data go?

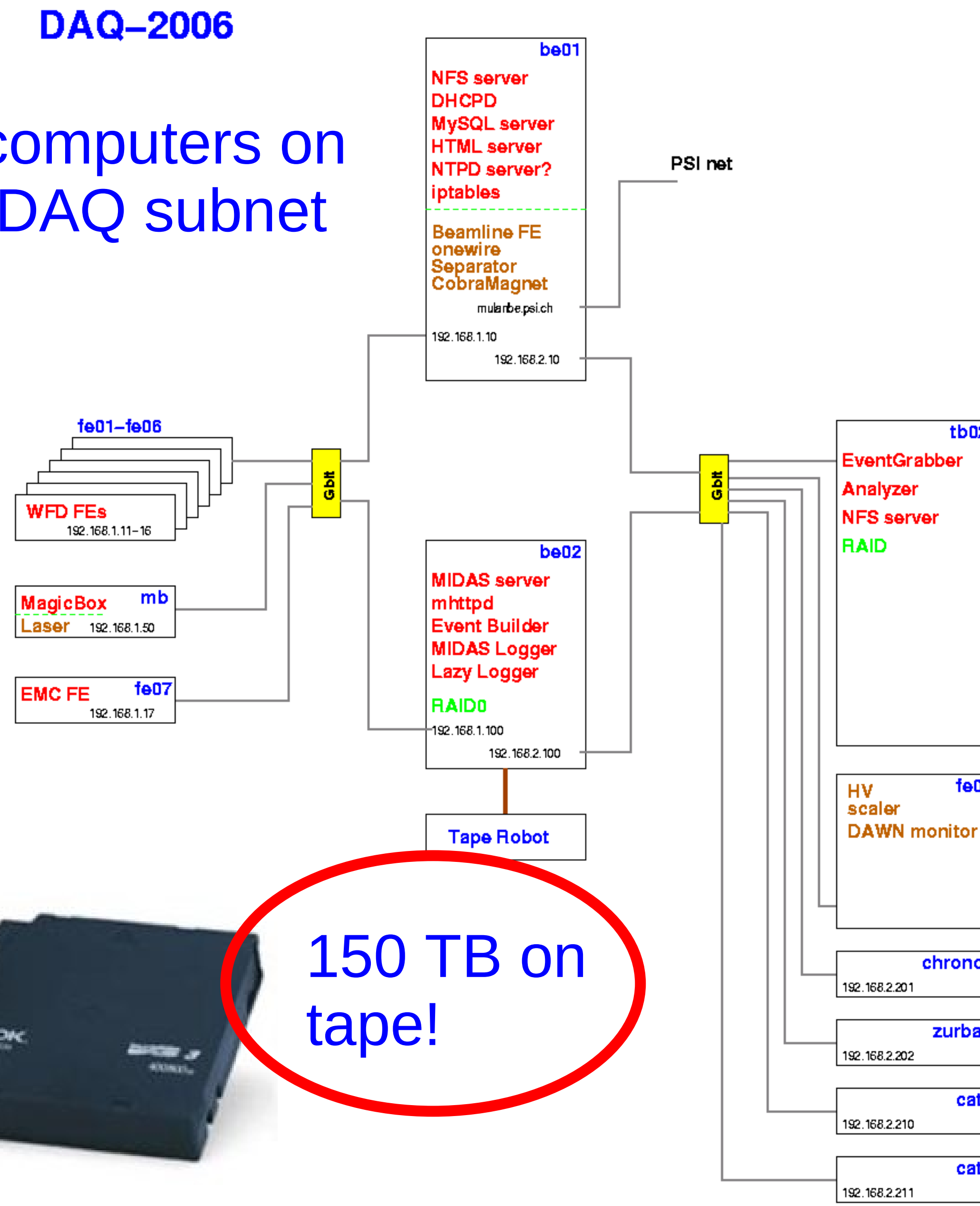




There's about 5 km of coaxial cable carrying HV and analog data to 85 WFDs spread over 6 crates in three racks.

Computers and tapes galore!

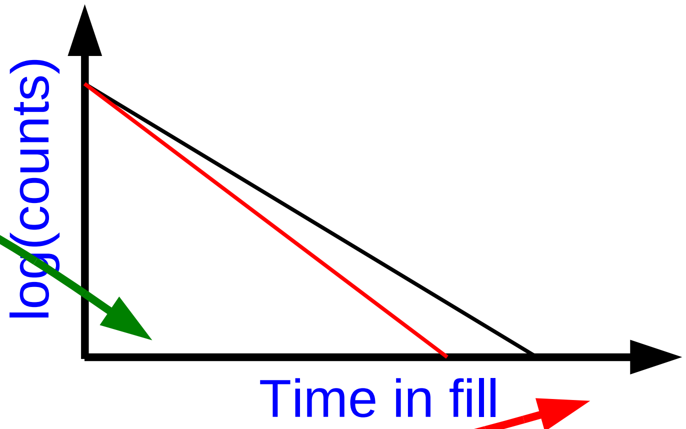
16 computers on the DAQ subnet



150 TB on tape!

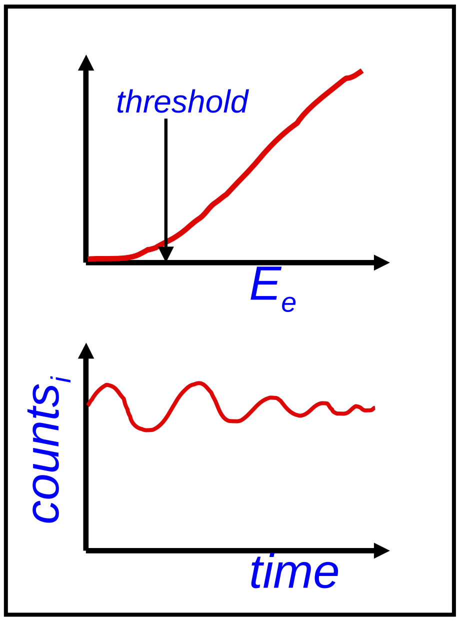
Tishchenko, *et.al.* Nucl.Instrum.Meth.A592:114-122,2008.

Time-dependent systematics are the core concern for a 10^{12} data set

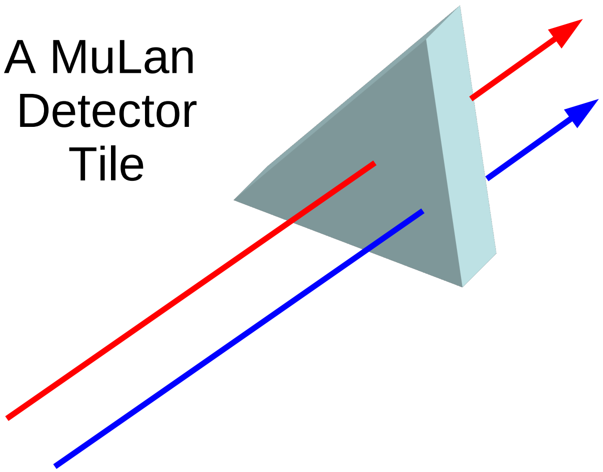


Early-to-late changes, for instance:

- Instrumental issues
  - PMT gains
  - Discriminator threshold walk
  - Kicker voltage sag
  - Pileup
- Physics issues
  - Spin polarization
  - Non-flat background sources

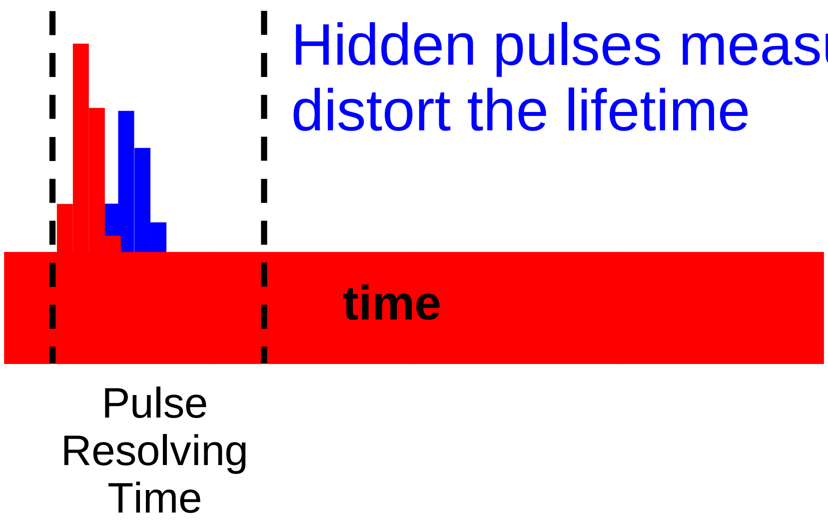


What's pileup?

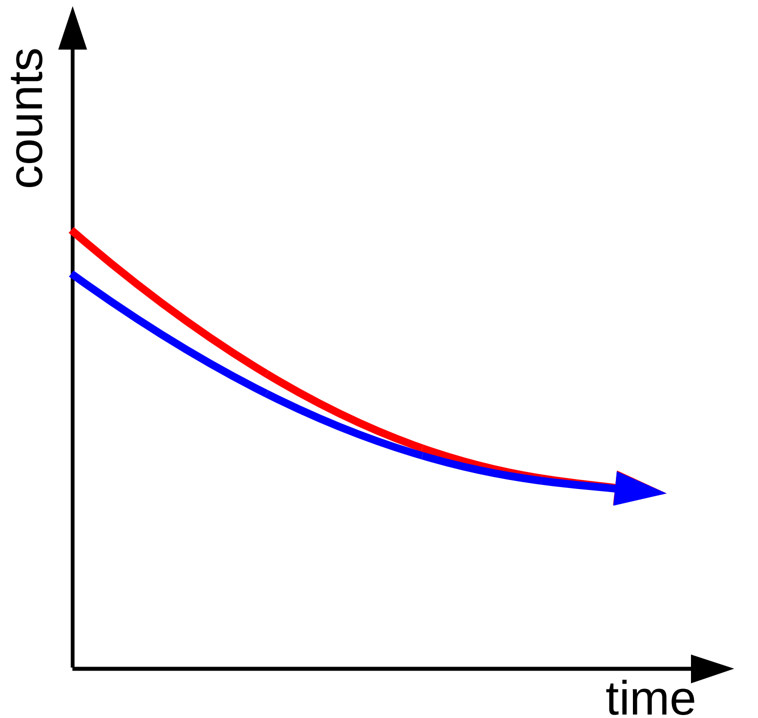


$$P_{\text{pileup}} \propto \int_0^{t_r} P(t)P(t+t')\mathrm{d}t'$$

$$\propto e^{-2t/\tau}$$

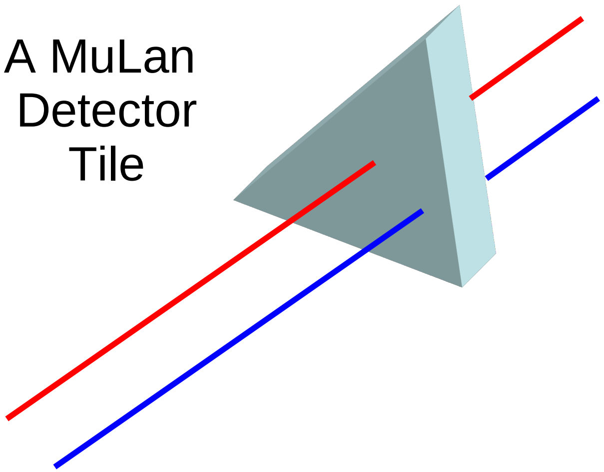


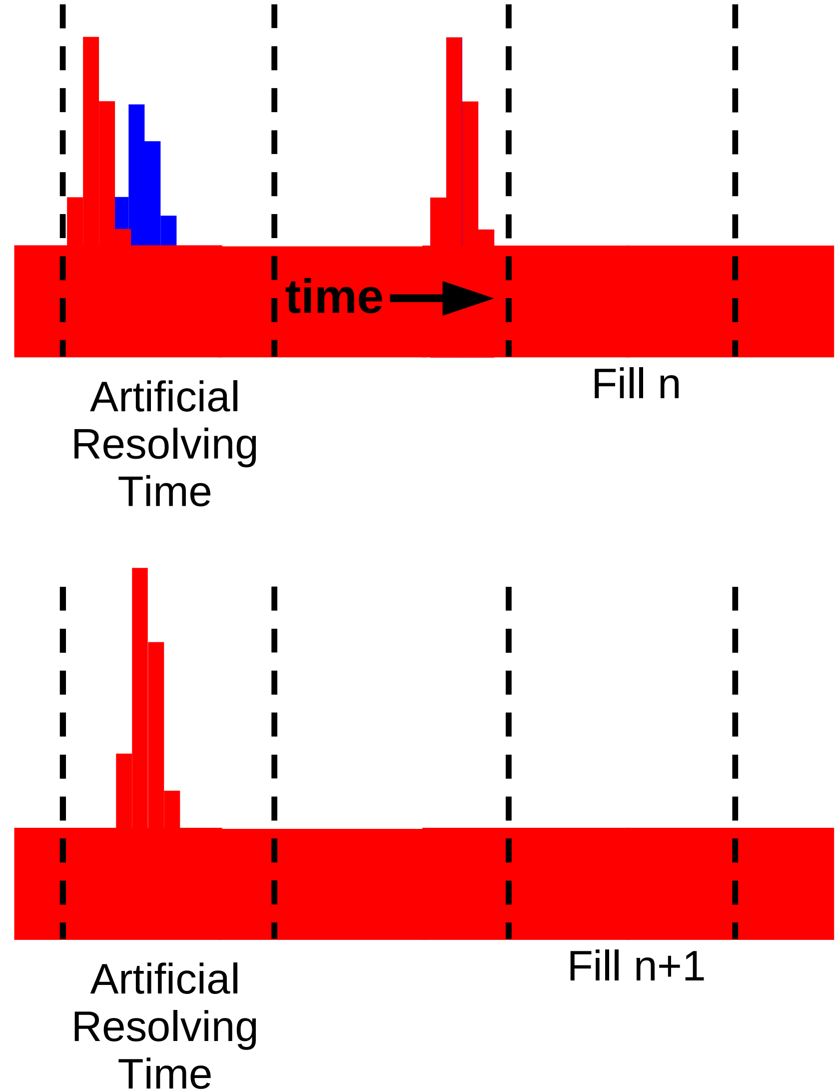
Hidden pulses measurably distort the lifetime

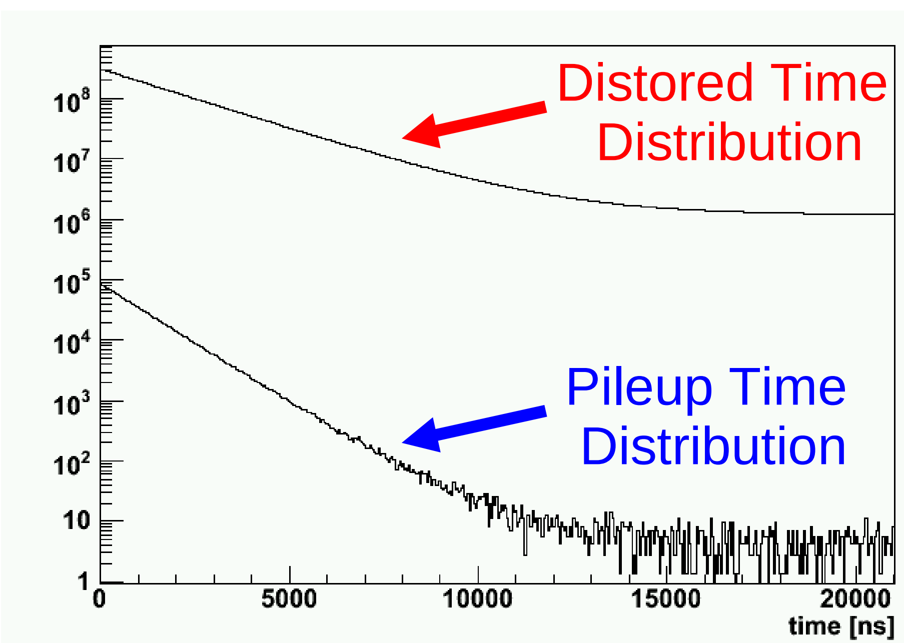


We could fit for this, at a significant cost in statistical error ... but we can actually use the data itself to construct a correction function!

Here's how it's done

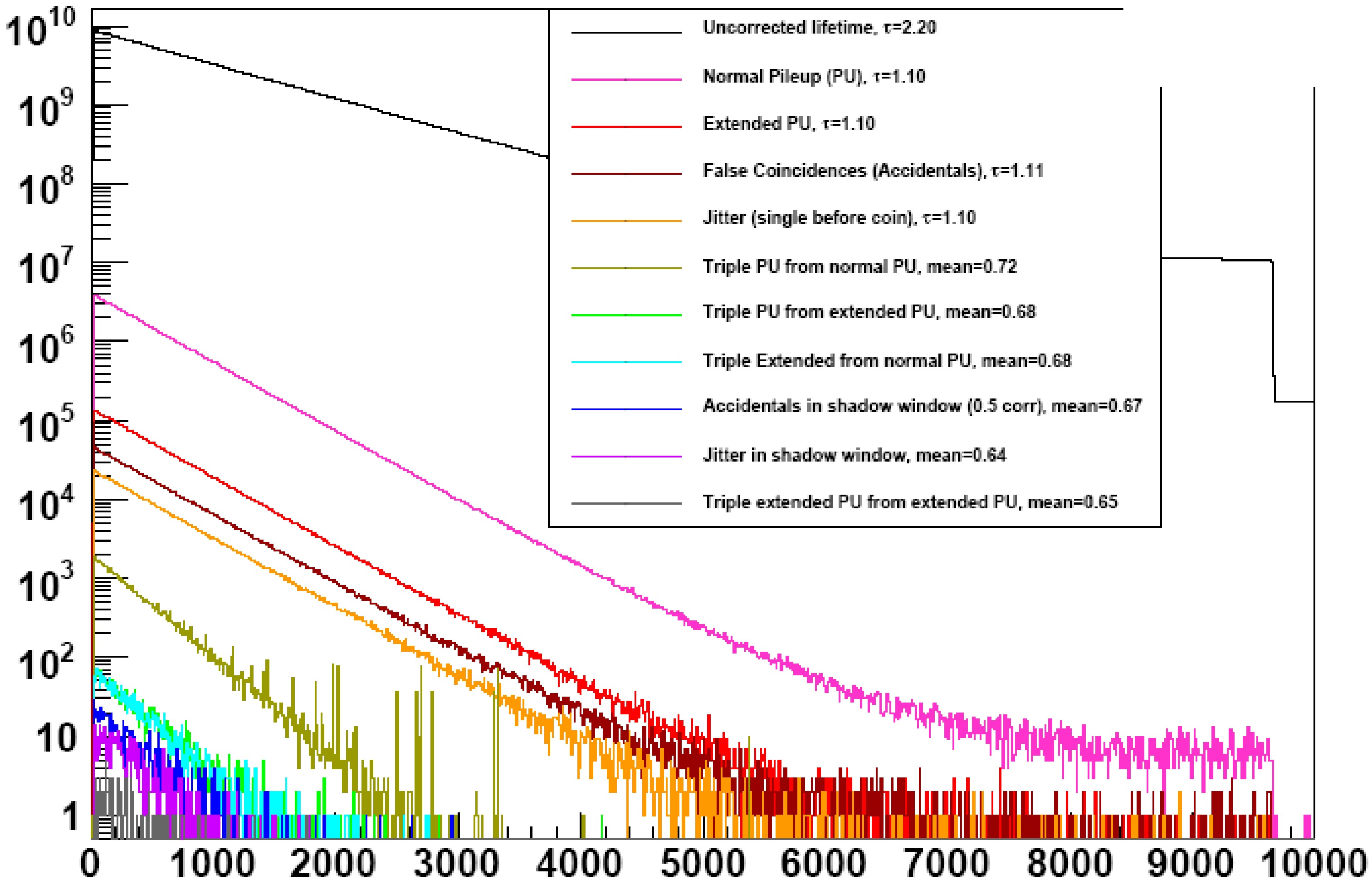






Adding the pileup distribution to the normal distribution (statisically) corrects for what's killed by the imposed deadtime!

In practice, there are many different pileup correction terms

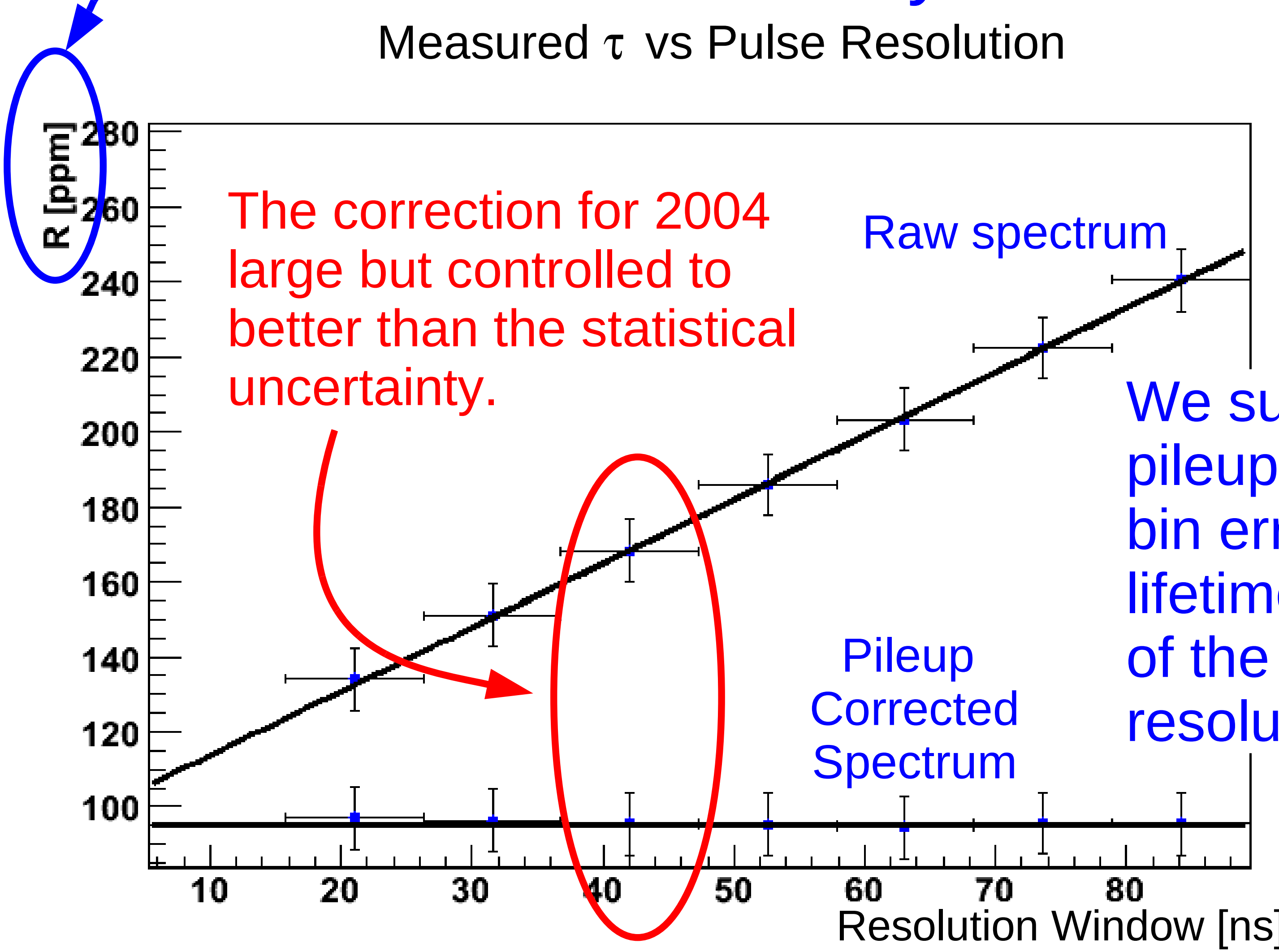


Left uncorrected, these terms shift the lifetime fit by hundreds of ppm at large resolving times.

How well does this method correct pileup?

Blind analysis!

2004

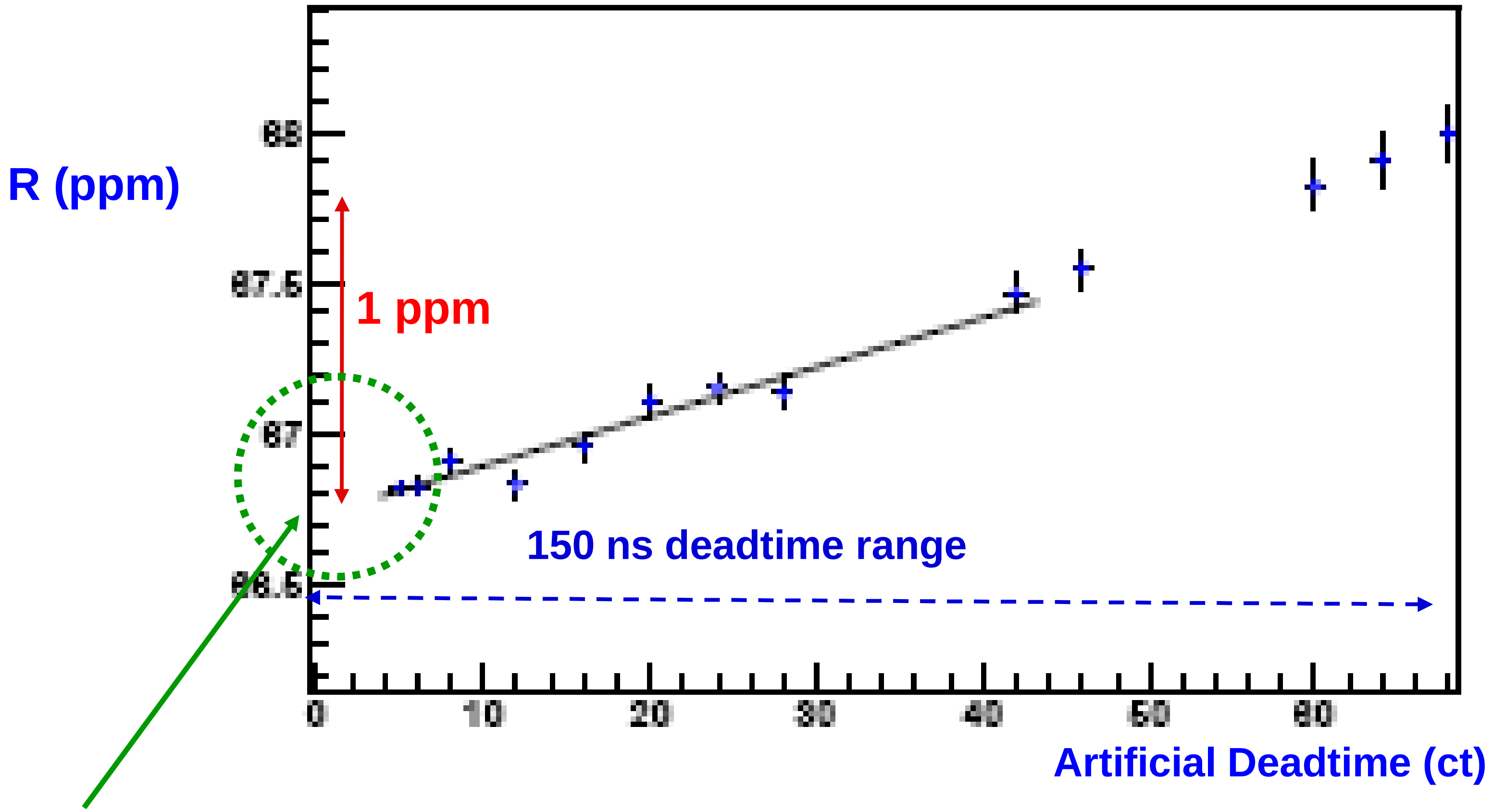


We sum the normal and pileup spectra (and correct bin errors!); the corrected lifetime fit is independent of the width of the time resolution window.

(±) ppm

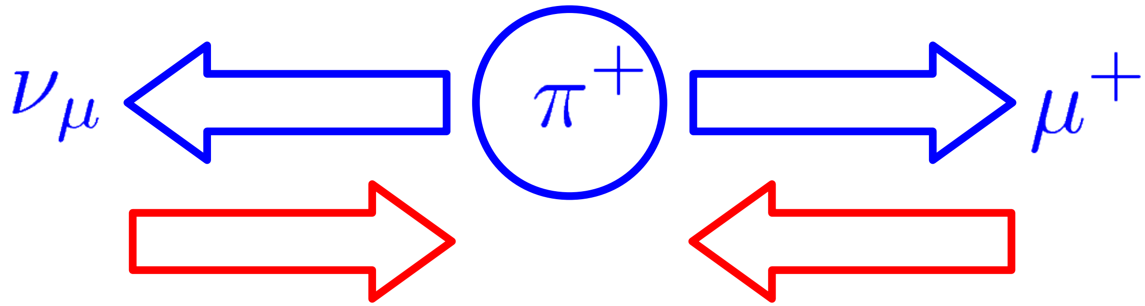
How well does this method correct pileup?

2006/2007



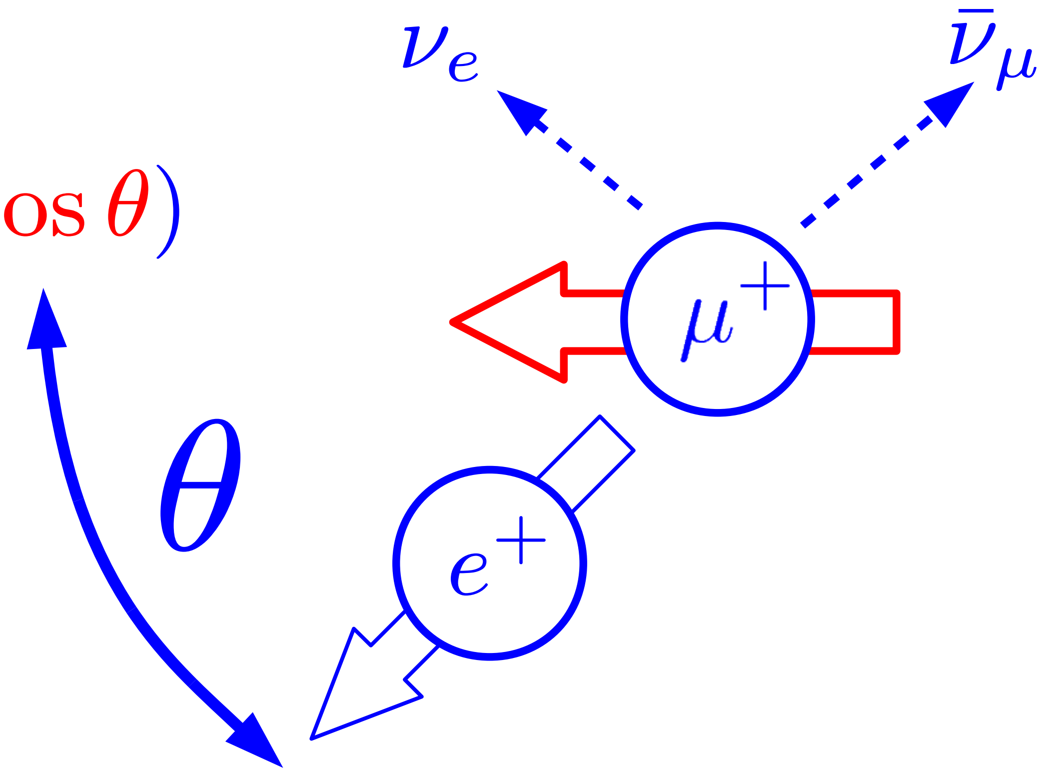
Extrapolation to 0 deadtime should be correct answer and our indications are that this extrapolation is right, but we continue to investigate the source of this shallow slope.

Muon beams are naturally polarized, and the Michel electron is not produced isotropically!



Parity violation in weak decays *requires* left-handed neutrinos

$$\frac{\mathrm{d}^2\Gamma_\mu^\pm}{\mathrm{d}y\mathrm{d}\theta} = n(y)\left(1 \mp a(y)\cos\theta\right)$$



Add in spin precession in magnetic fields and material based spin exchange interactions, and things can get complicated very quickly!

Longitudinal component

Muon Lifetime

$$f(t) = N\Big[1 + \frac{1}{3}\vec{P}_1 \cdot \hat{r}_D e^{-t/T_1} + \frac{1}{3}P_2 \sin(\omega t + \phi) e^{-t/T_2}\Big] e^{-t/\tau_\mu} + B$$

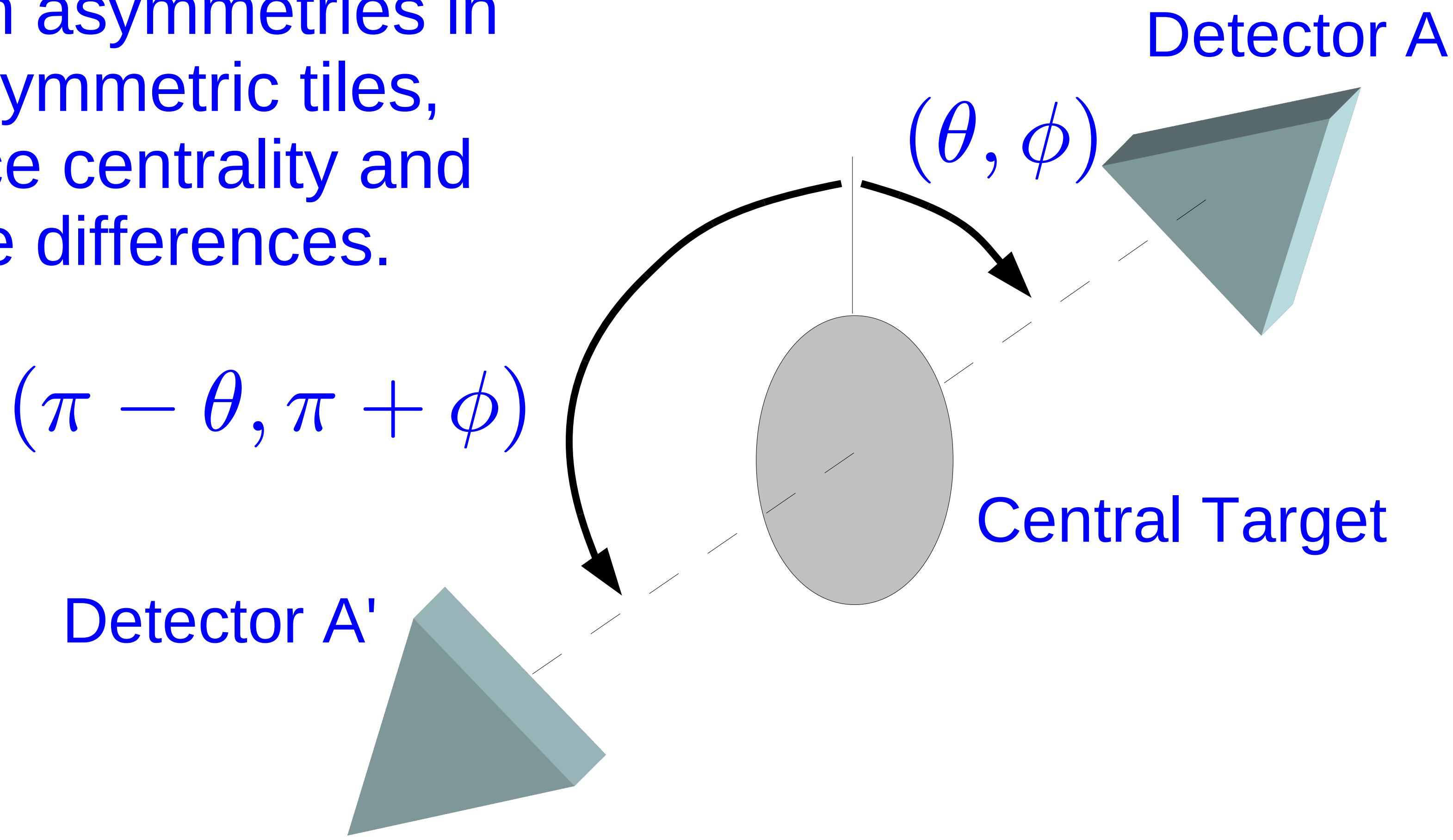
Transverse component

Flat background

Any mismeasured polarization terms can have a large impact on the lifetime measurement

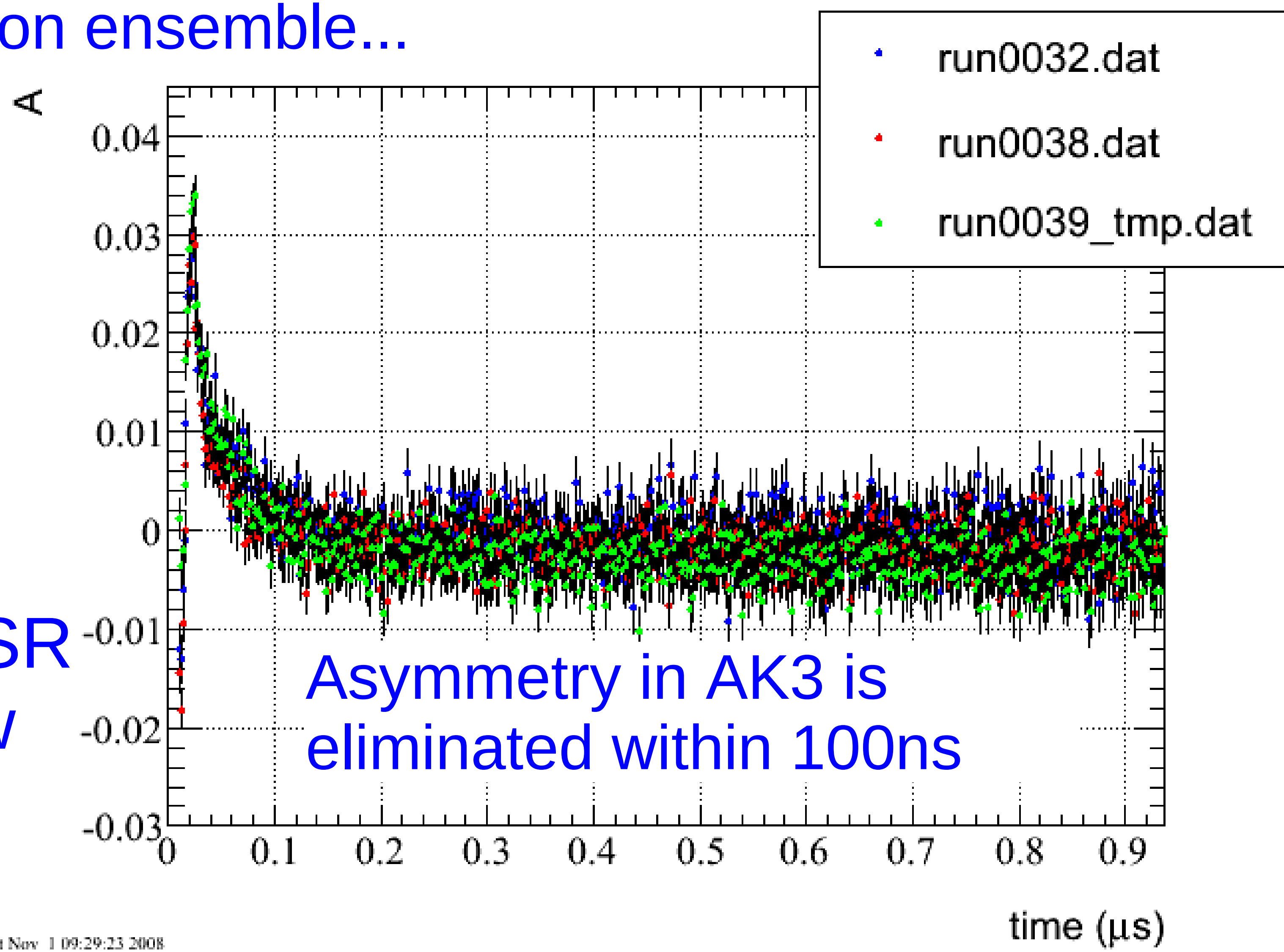
Since we start with nearly 100% polarized beam, how do we control polarization issues?

Point symmetry of the detector cancels polarization asymmetries in sum over symmetric tiles, up to source centrality and acceptance differences.



In 2006, we chose a target with high internal magnetic field (Arnokrome III) to minimize the residual polarization

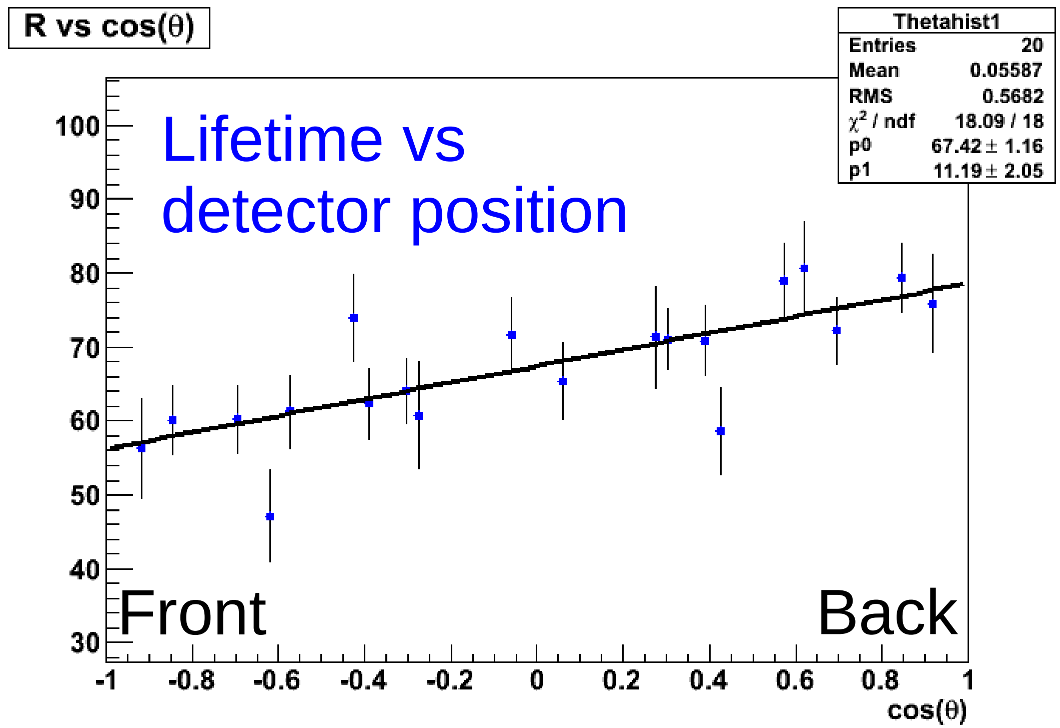
The high internal field should rapidly dephase the incoming muon ensemble...

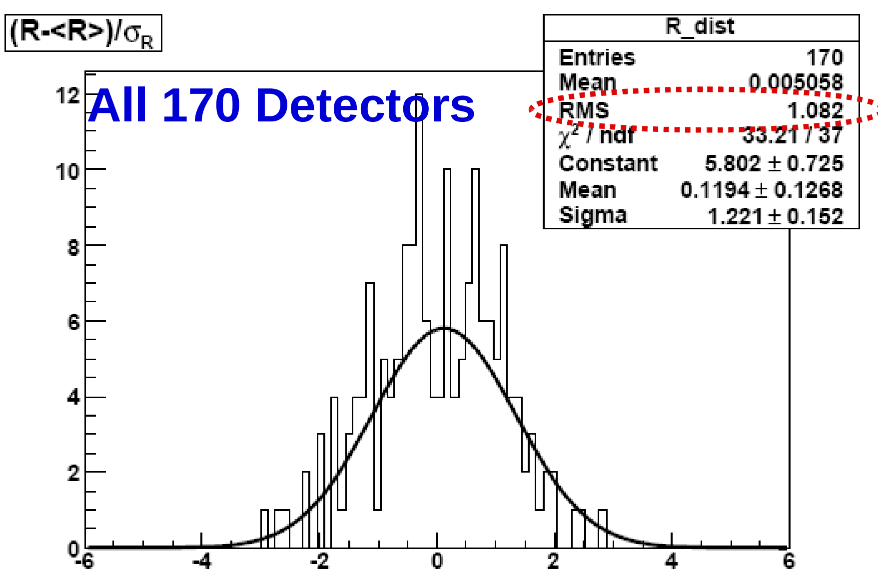


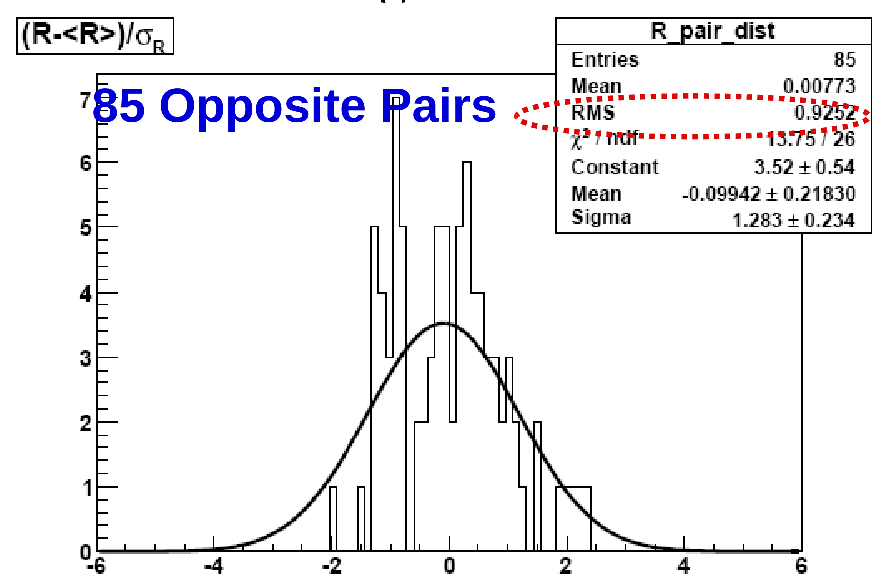
Asymmetry in AK3 is eliminated within 100ns

... and dedicated μSR studies show exactly that.

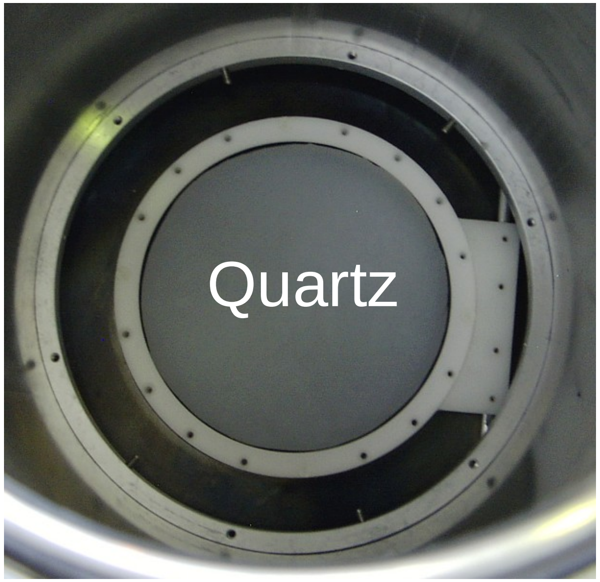
There's a small longitudinal remnant, but it cancels in the pointwise sums

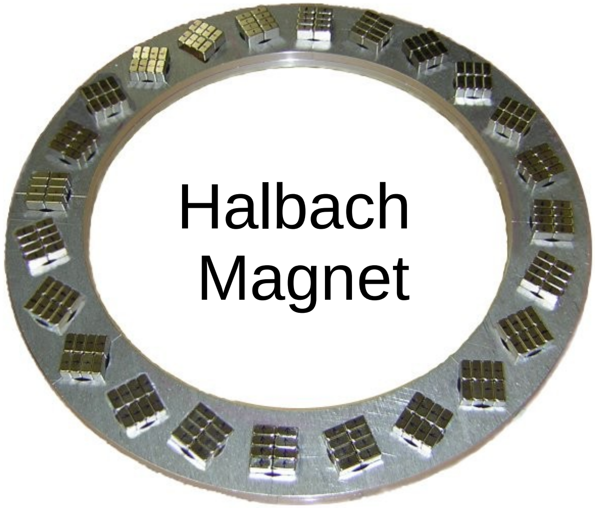


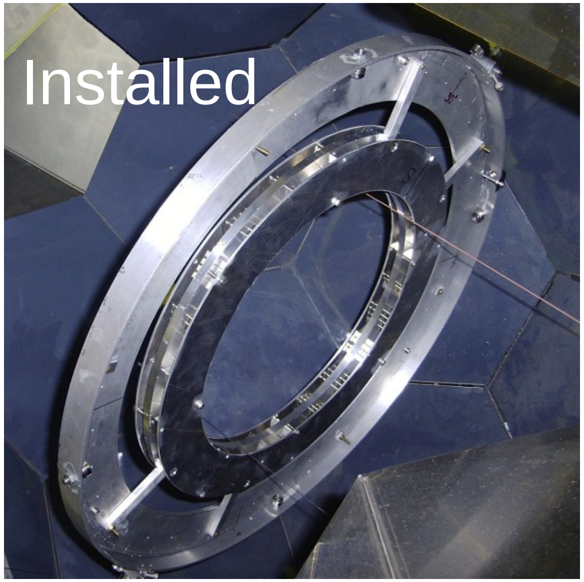




For 2007, we chose a muonium forming target with an externally applied field



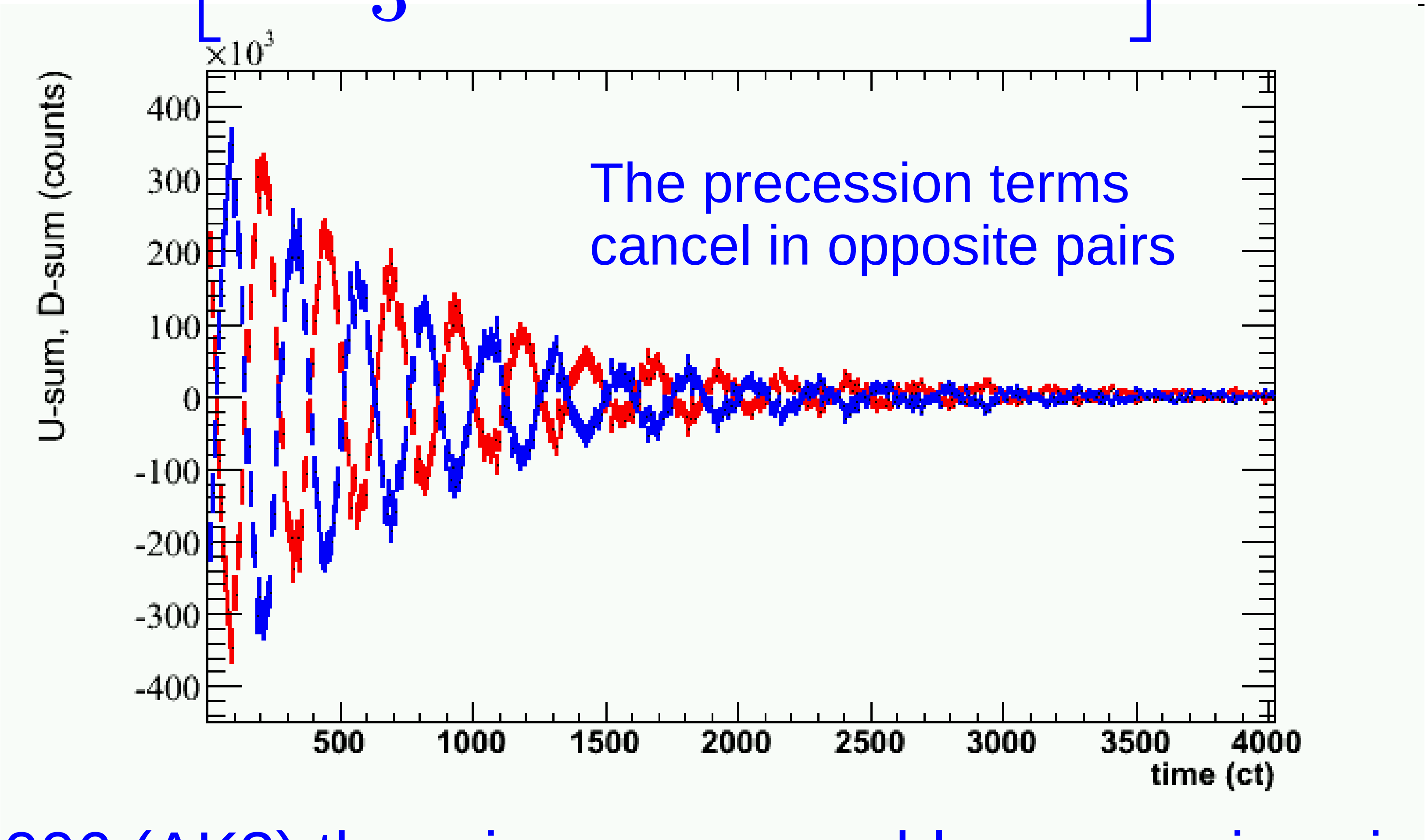




- 90% Muonium formation
  - Test of free vs bound lifetime (theory says they're the same)
  - High magnetic moment gives high precession frequency (100x free muons)
- 10% “free muons”
  - We must fit for their precession!

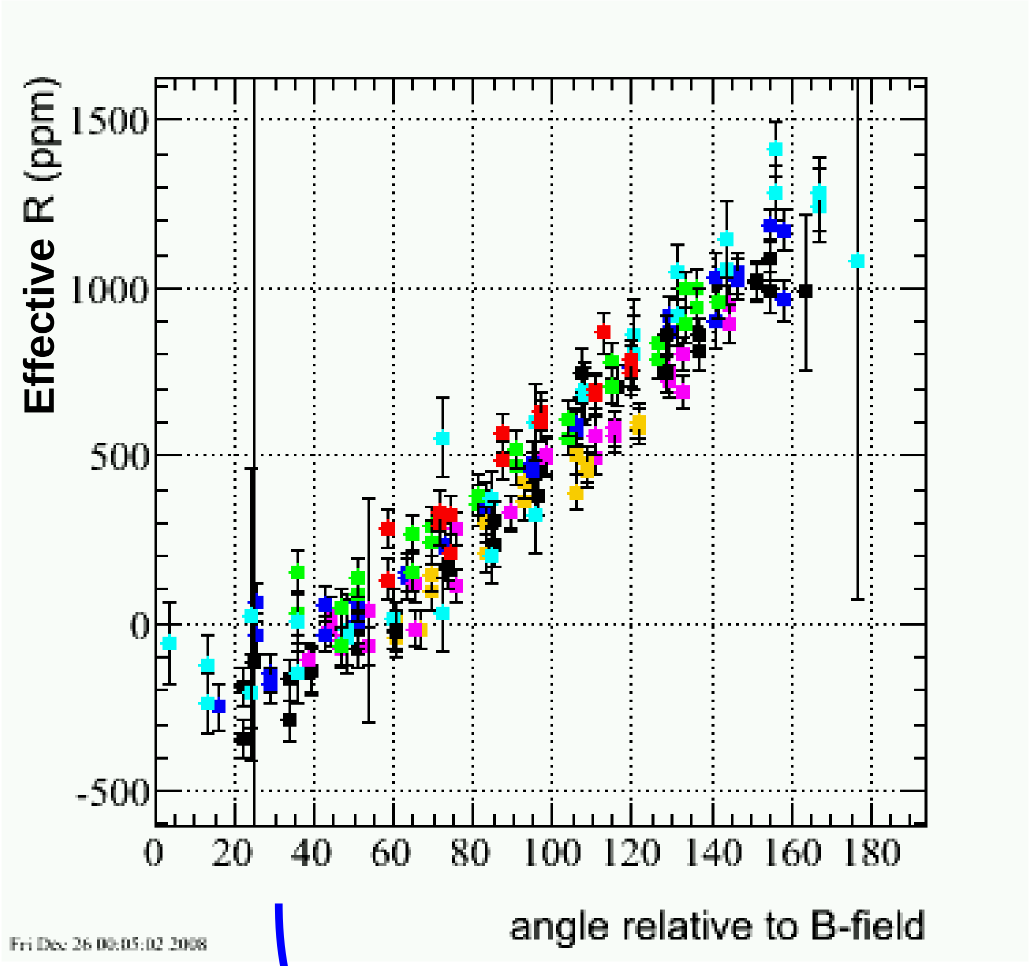
For 2007, we add the precession term directly to the individual detector's fit functions...

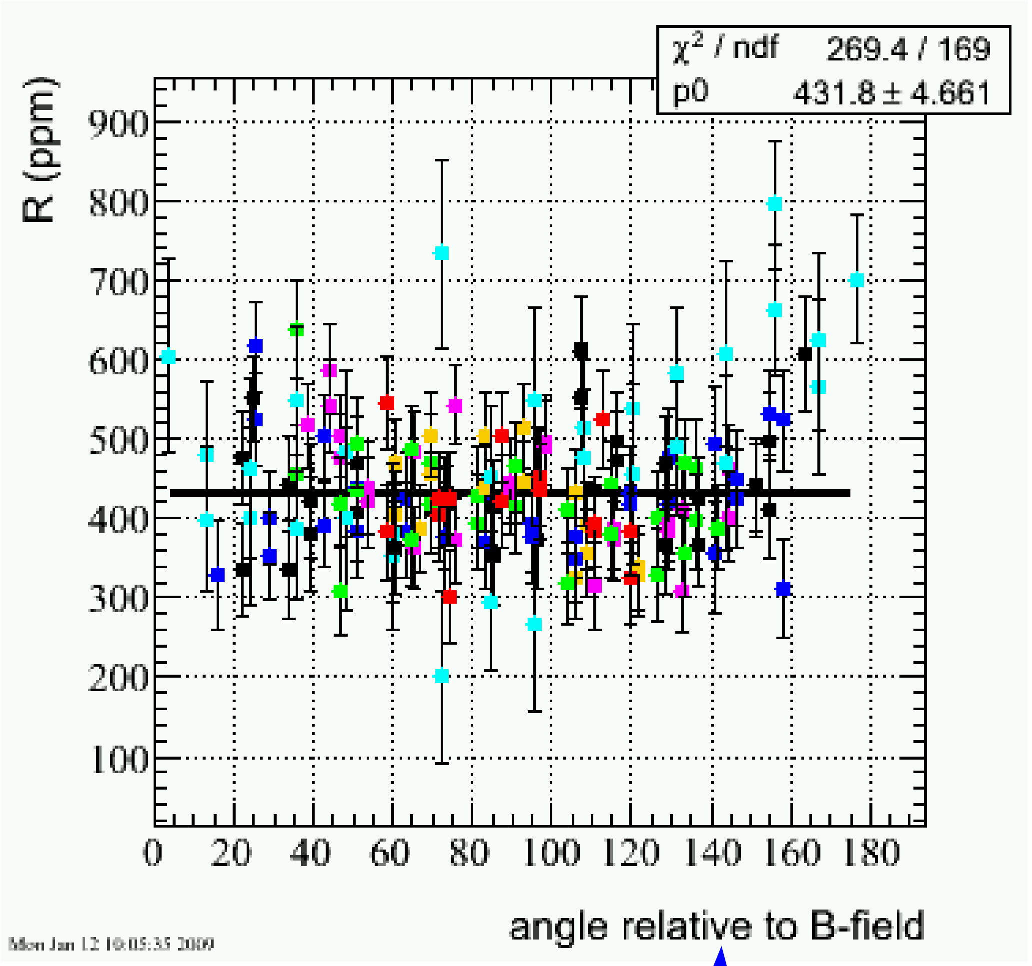
$$F(t) = N\left[1 + \frac{1}{3}P_2 \sin(\omega t + \phi)e^{-t/T_2}\right]e^{-t/\tau_{\text{eff}}} + B$$



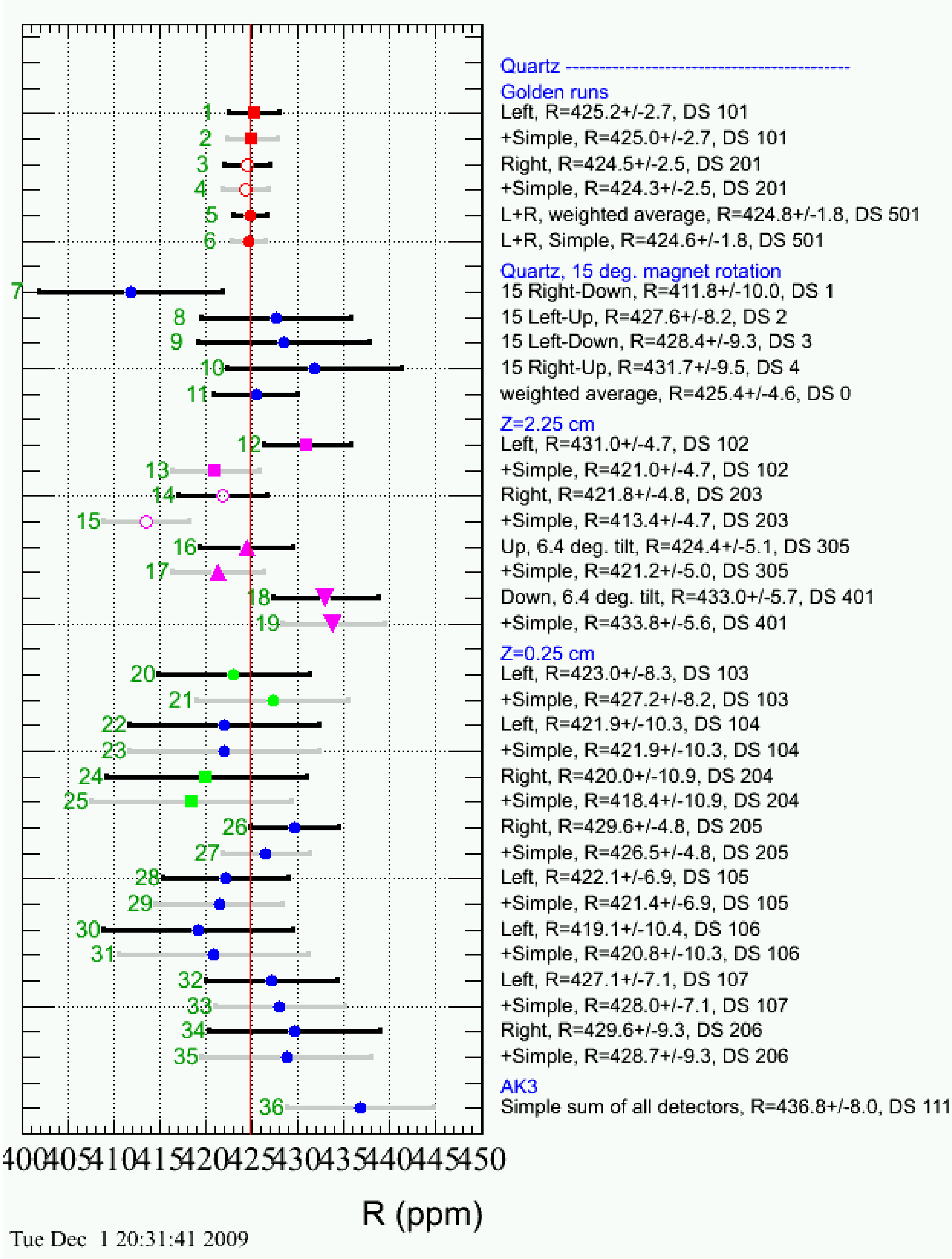
In 2006 (AK3) there is no measurable precession signal, so there's nothing to fit!

...while the effects of the residual longitudinal polarization is measured in the ensemble of all detector fits.



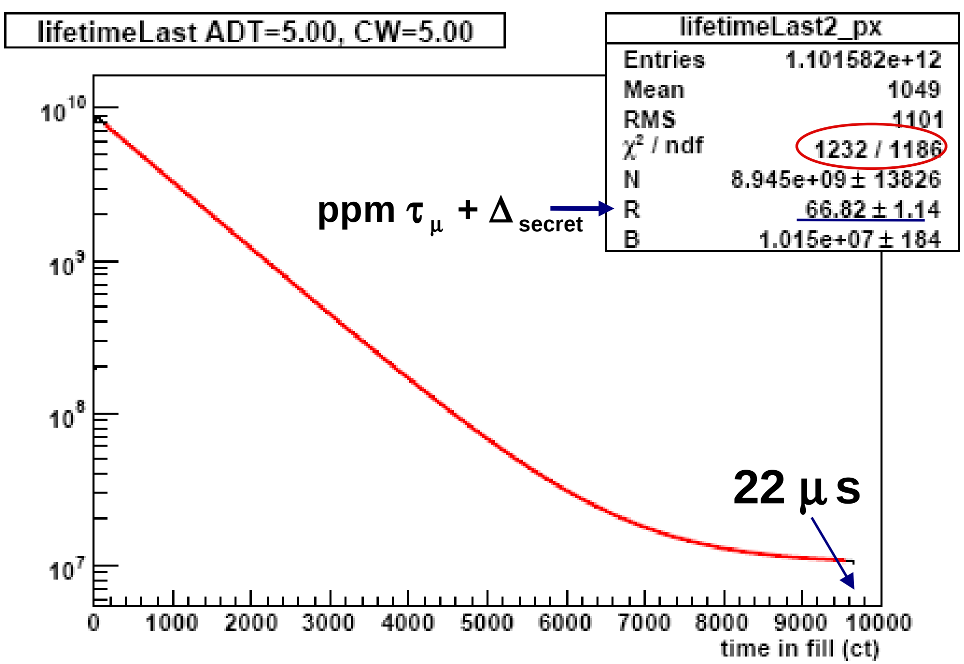


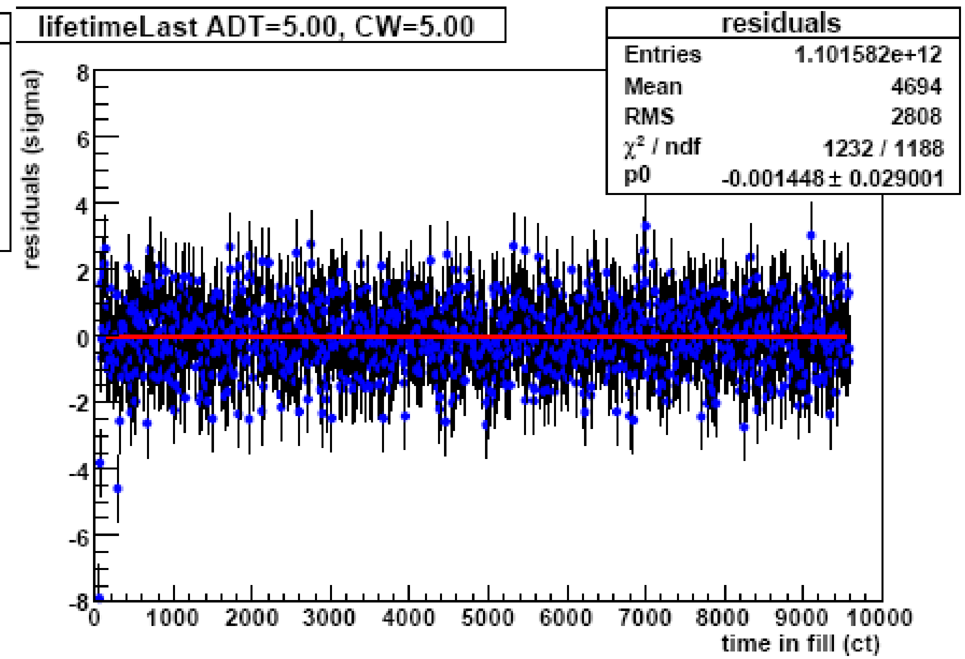
$$\Lambda_\mu = \Lambda_{\rm eff} - \frac{1}{3}\Lambda_1 \vec{P}_1 \cdot \hat{r}_D$$

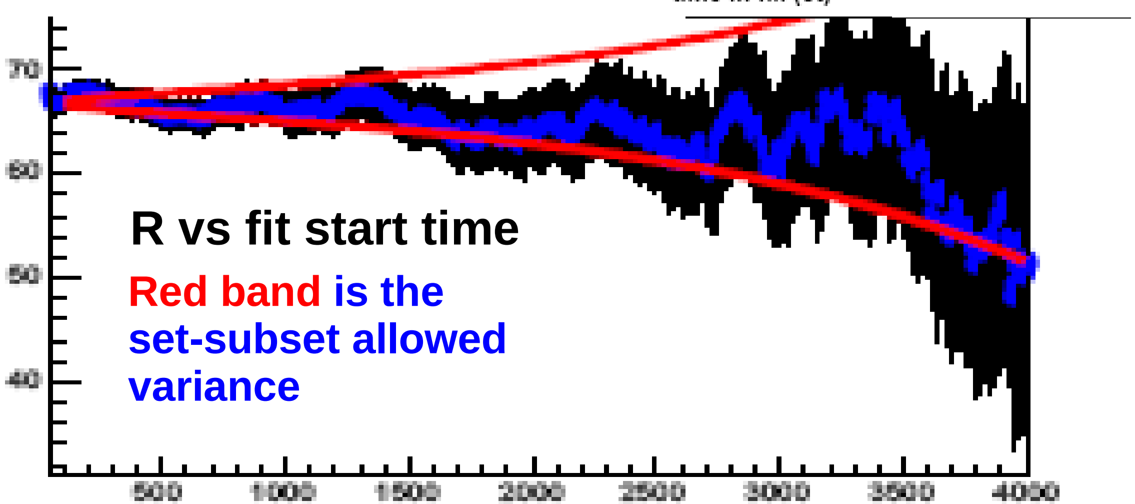


Consistency of this procedure has been tested against many run conditions, including some truly extreme examples with very large residual longitudinal effects

Fits to all 2006/2007 pileup corrected data passes many consistency tests, including structureless residuals and fit start time scans







The 2006 and 2007 datasets agree at the sub-ppm level!

Our 2004 result was strongly statistics limited

Statistics: 1.8×10^{10} muons (9.6 ppm)

Source	Size (ppm)
Extinction stability	3.5
Dead time correction	2.0
TDC response	1.0
Gain stability	1.8
Errant muon stops	2.0
Duplicate words (+1 ppm shift)	1.0
Queuing loss	0.7
Multiple hit timing shifts	0.8
Total	5.2

$$\tau_\mu = 2.197013(21)(11)\,\mu\text{s} \qquad (11\,\text{ppm})$$

$$G_F = 1.166371(6) \times 10^{-5}\,\text{GeV}^{-2} \qquad (5\,\text{ppm})$$

Our final results will improve on our 2004 results by an order of magnitude

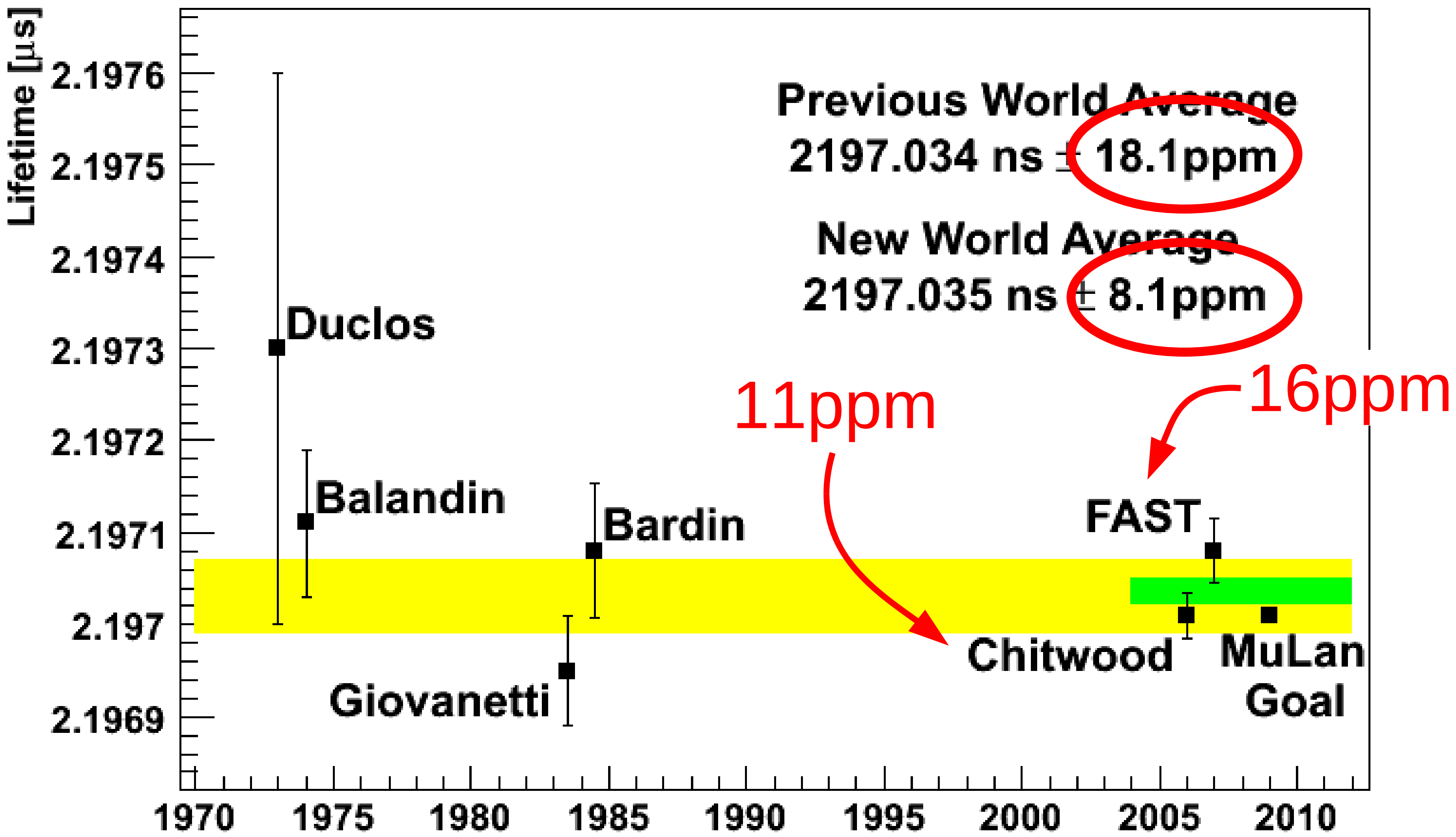
Effect	2006	2007	Comment
Kicker extinction	0.2	0.07	Final
Errant muon stops	~0	~0	In progress; small
Gain stability vs time-in-fill	0.04	0.04	Based on MPV[1] of data vs time
Gain stability vs time-after-pulse[2]	<0.2	<0.2	MPVs in next fill & laser studies
Timing stability vs time-in-fill	0.014	0.014	Final; laser studies
Timing stability vs time-after-pulse	~0	~0	Final; laser studies
Electronic pedestal fluctuation[3]	~0.2	~0.2	In progress; upper limit
Pileup correction	~0.3	~0.3	In progress; studies to be done
Residual polarization	~0	~0.2	Incomplete cancellation (quartz)
Total Systematic (DRAFT !)	**~0.4**	**~0.4**	**Highly correlated for 2006/2007**
Total Statistical	**1.14**	**1.7**	

Preliminary

[1]Most probable value of energy deposition
[2]Time-after-pulse is to the “next” pulse following a hit
[3]Coherent effect, measured in lab tests and easily inserted into fit function

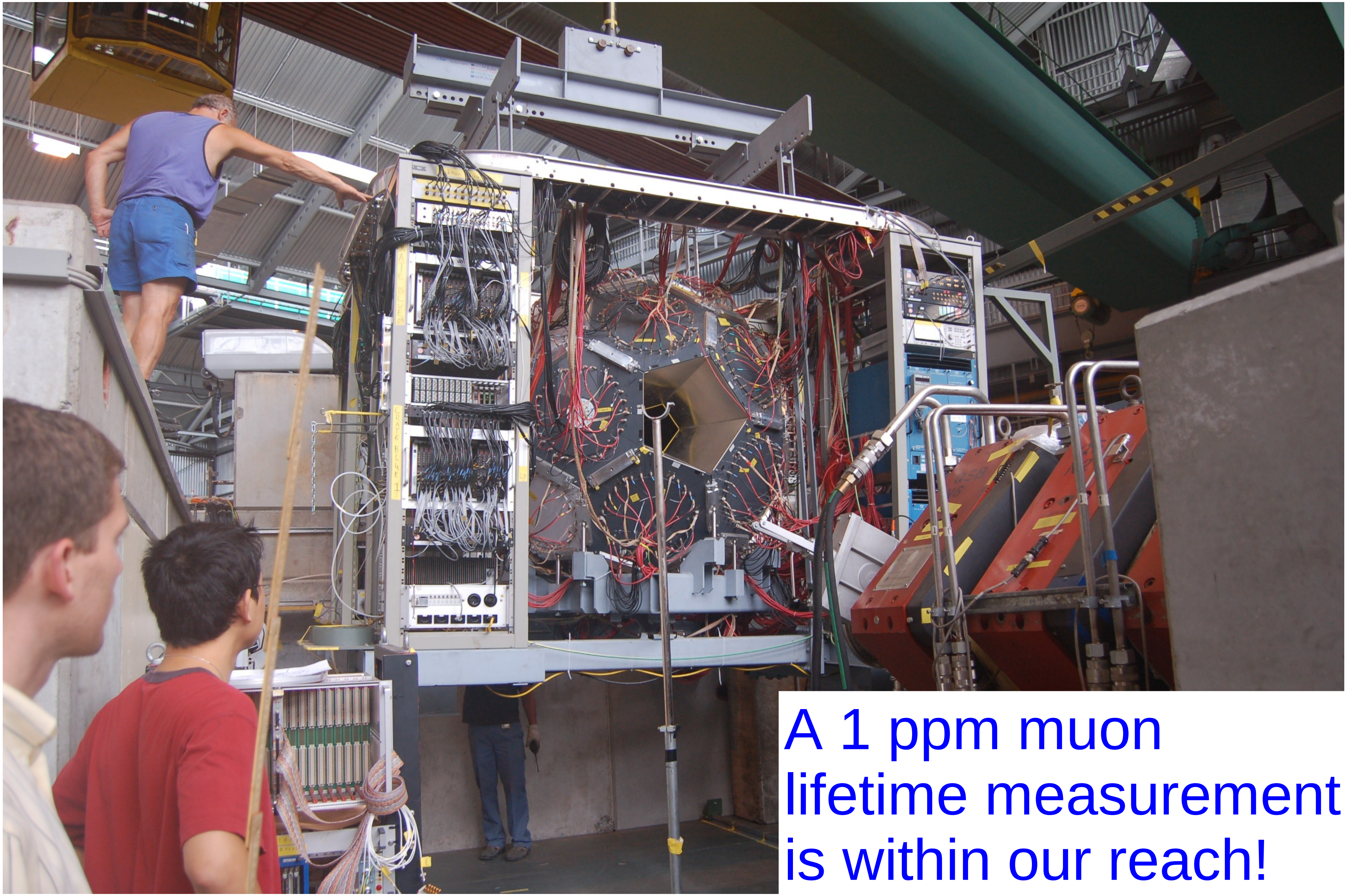
Combined (roughly): 0.95 ppm (statistical) & ~0.5 ppm (systematic)

The current world average lifetime is driven by two measurements, but will (very, very shortly!) be eclipsed by our final result



Chitwood, *et.al.* Phys. Rev. Lett. 99, 032001 (2007)
FAST Collaboration, Phys.Lett.B663:172-180,2008

Toward 1ppm ...



A 1 ppm muon lifetime measurement is within our reach!