Precision muon lifetime at PSI

MuLan Experiment

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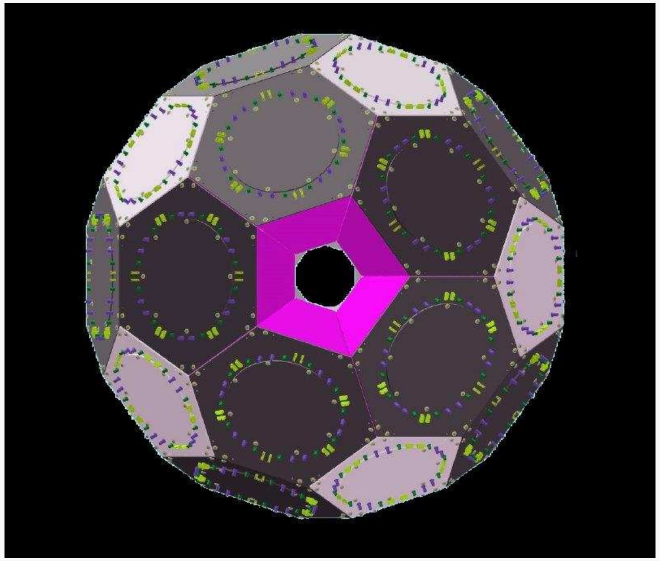

On behalf of the MuLan Collaboration

Outline

- √ Motivation
- √ Experimental Principle
- √ Detector
- √ First Results
- √ Future

Scientific Questions

What are the fundamental electroweak parameters?

$$G_F, \alpha(Z), m_Z$$

Precision μ^+ lifetime

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Precision μ^+ lifetime

$$\mu^+ \rightarrow e^+ + \tilde{\nu}_e + \nu_\mu$$

Current World average

$$\tau_{\mu^+} = 2197.03 \quad \pm 0.04\,\text{ns} \quad (18\text{ppm})$$

$$\Downarrow \qquad \Downarrow$$

$$\pm 0.002\,\text{ns} \quad (1\text{ppm})$$

Muon Lifetime

The muon lifetime τ_μ is closely related to the Fermi coupling constant GF , which sets the basic strength of the weak interaction:

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

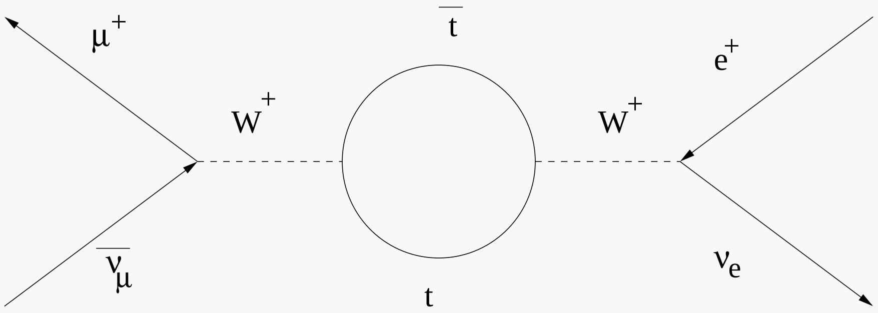
QED radiative corrections: Two-loop diagrams finished in 1999 by Stuart and van Ritbergen*; now known to < $\pm$ 0.3 ppm (previously $\pm$ 30 ppm)

Extraction of G_F is now limited by the muon lifetime a truly fundamental parameter of the standard model that should be measured as precisely as possible with today s technology.

*T. van Ritbergen and R.G. Stuart, Phys. Rev. Lett. 82, 488 (1999); and Phys. Rev. D 437, 201 (1998).

How fundamental is G_F?

How electroweak corrections are related to muon decay?



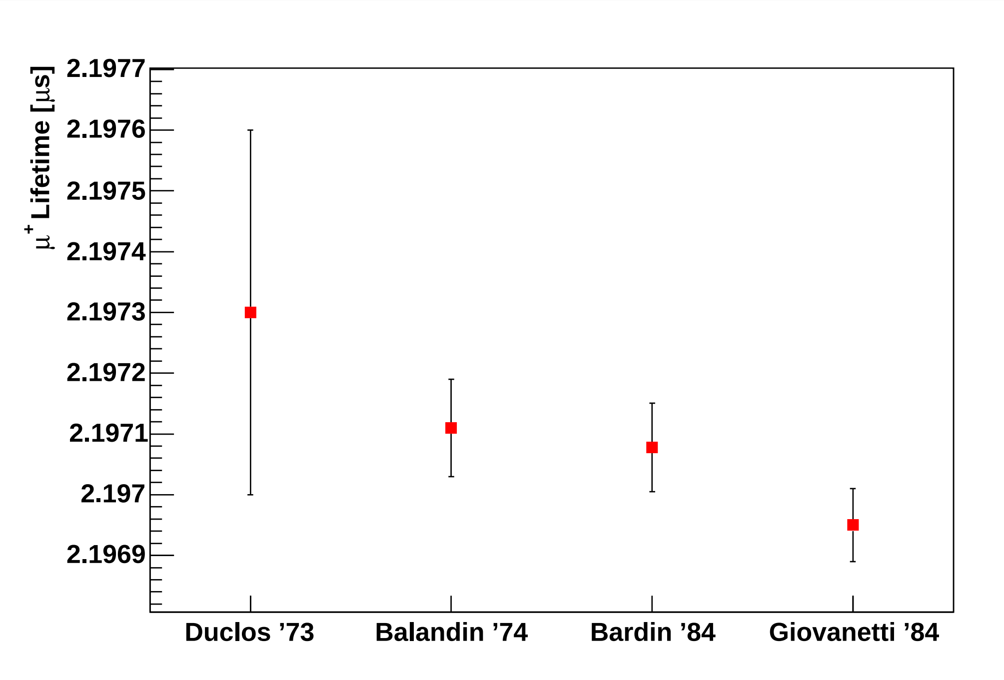
They are contained in the term Δr

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

which defines the Fermi constant in terms of the SM weak coupling constant g

- ✓ Predictive power in weak sector of SM
  - Input: G_F (17 ppm), α (4 ppb at $q^2 = 0$), M_Z (23 ppm)
  - Top quark mass prediction: $m_t = 177 \pm 20$ GeV
  - 2004 Update from D0 $m_t = 178 \pm 4.3$ GeV
- ✓ Lesson learned in M_Z
  - Predicted precision at turn on of LEP ~550 ppm
  - Final precision achieved was ~23 ppm
  - What will the next generation of accelerators bring?

Experimental status



- √ Experiments mostly statistics limited
- √ PDG: $\tau_\mu = 2.19703 \pm 0.00004$ μs (18 ppm)
- √ Our goal: 1 ppm uncertainty in τ_μ (0.5 ppm in G_F)

$$\frac{\delta G_F}{G_F} = 4\frac{m^2_{\nu_\mu}}{m^2_\mu} - \frac{5}{2}\frac{\delta m_\mu}{m_\mu} - \frac{1}{2}\frac{\delta \tau_\mu}{\tau_\mu}$$

10^{12} Statistics: more than one muon at a time

- 1 ppm measurement $\rightarrow$ at least 10^{12} stopped muons.
- Each muon (or pion) enters target individually with pre– and post–quiet periods. Watch for decay positron and record its time.
- For 10^{12} muon, one need about 4×10^{7} s . . . several years
- To be practical, we need to observe several muons at once:

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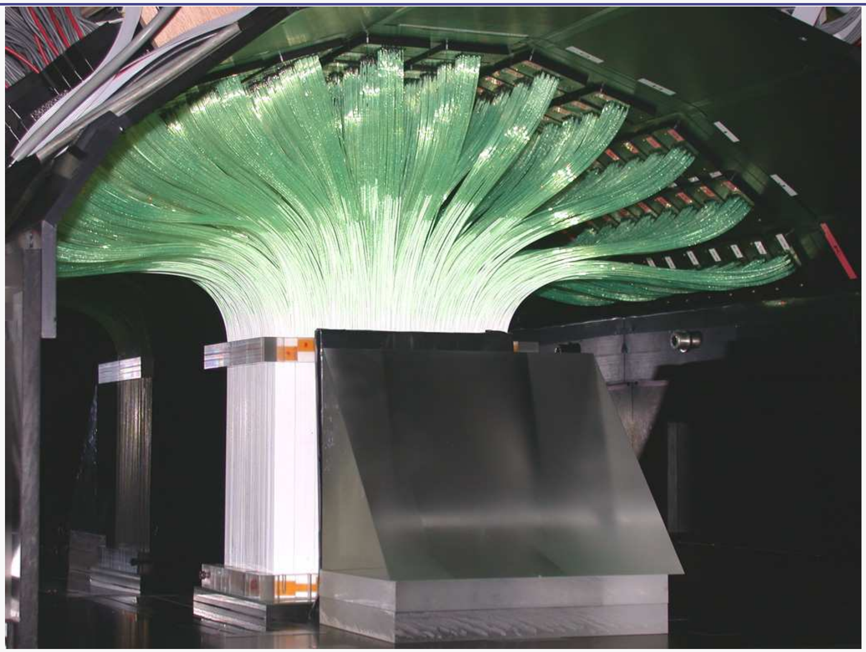
Spatial separation FAST	
	

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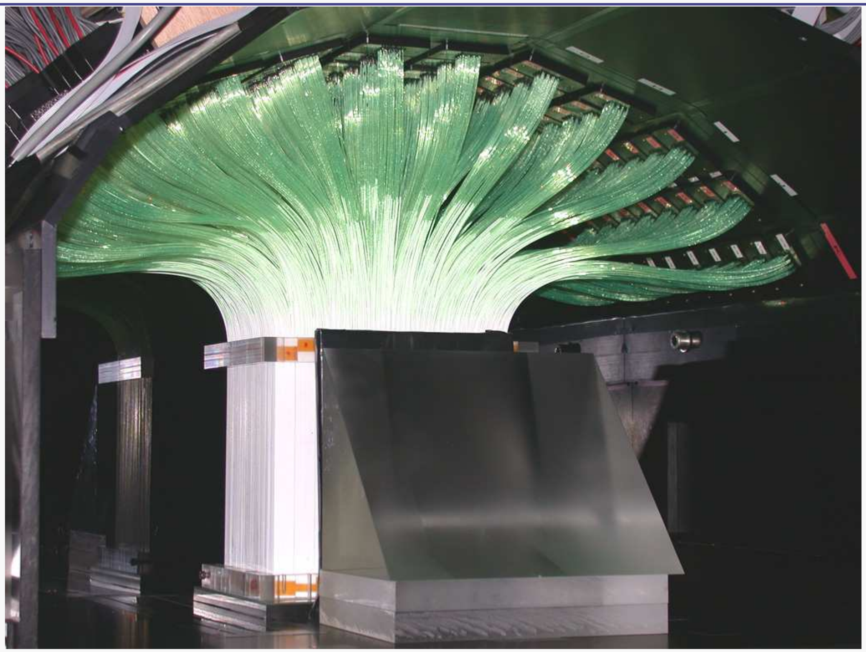
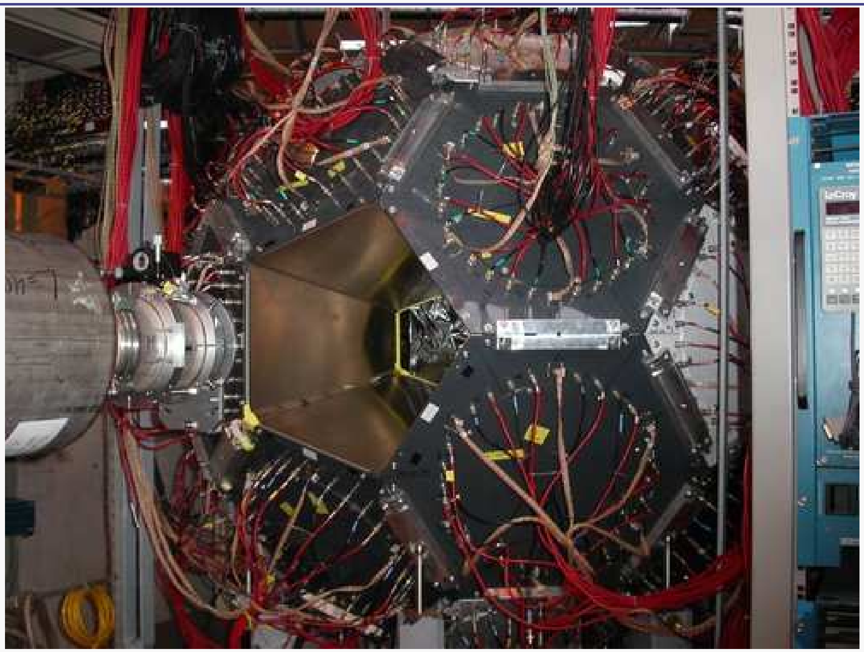
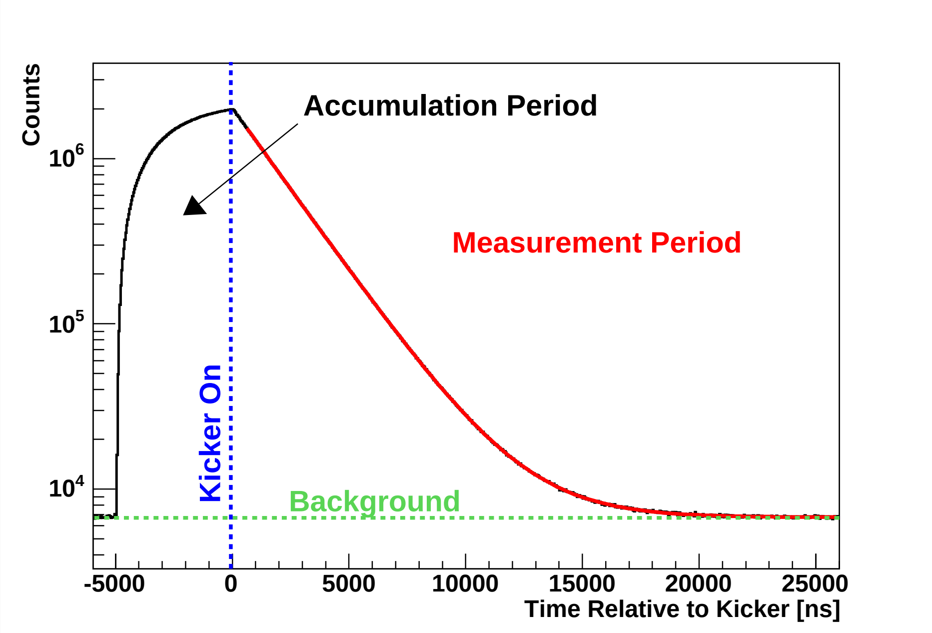
Spatial separation FAST	Bunched muons MuLan
	

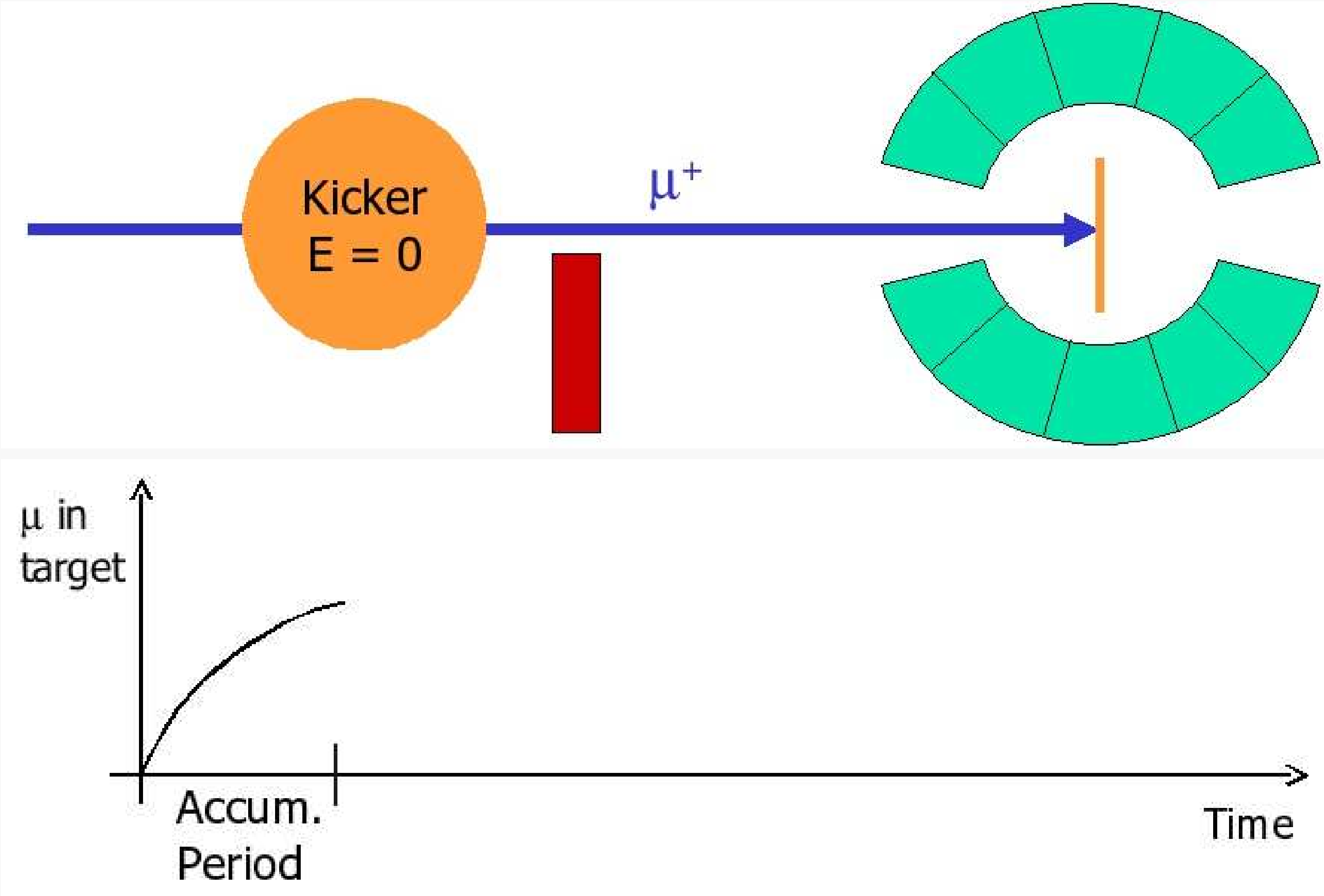
Muon Lifetime Techniques

- Burst of N muons arrives during accumulation period T_{acc}
  - Observe muon decays during measuring period of length T_{meas}
  - No other muons arrive during this time
  - Get another burst
- Ideally:
  - A small $N \Longrightarrow$ Reduces pileup
  - $T_{acc} + T_{meas} \sim 32\mu$s $\Longrightarrow$ Cycles fast



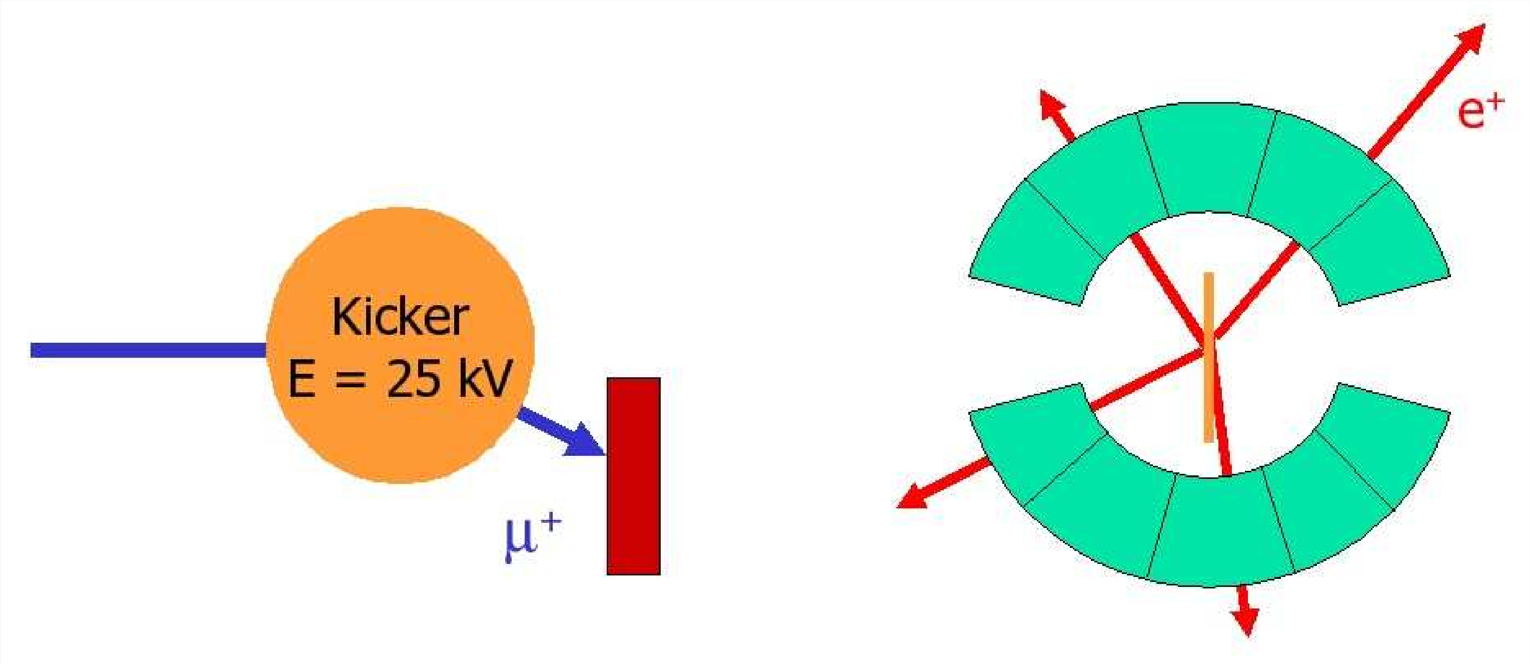
Pulsed Muon Beam

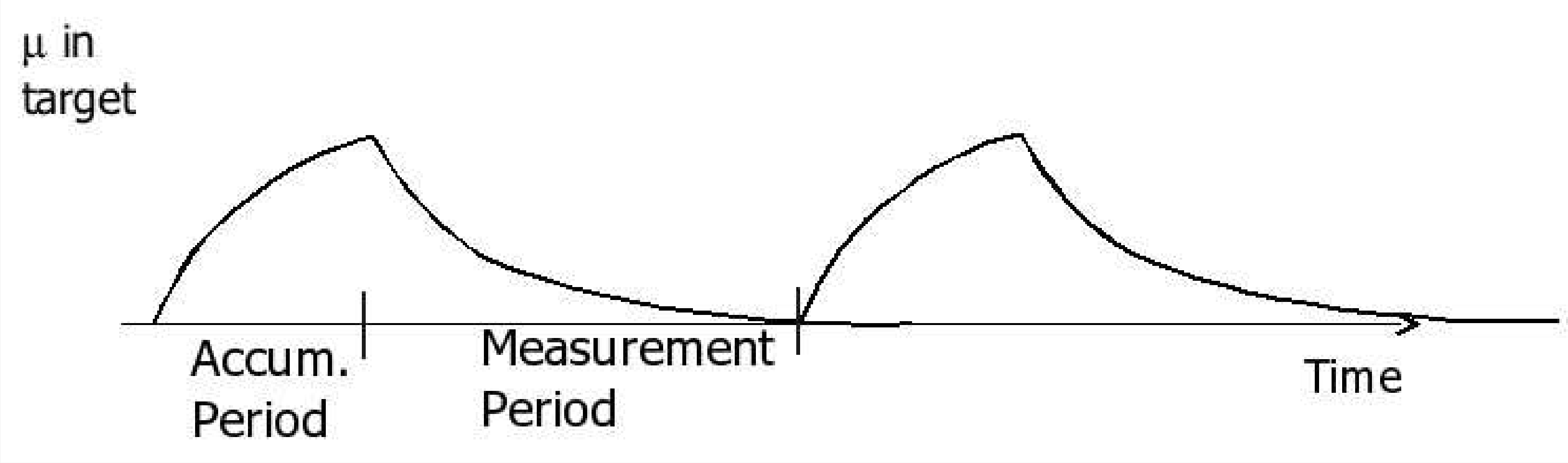
√ Collect handful of muons in a few μs **Accumulation Period**



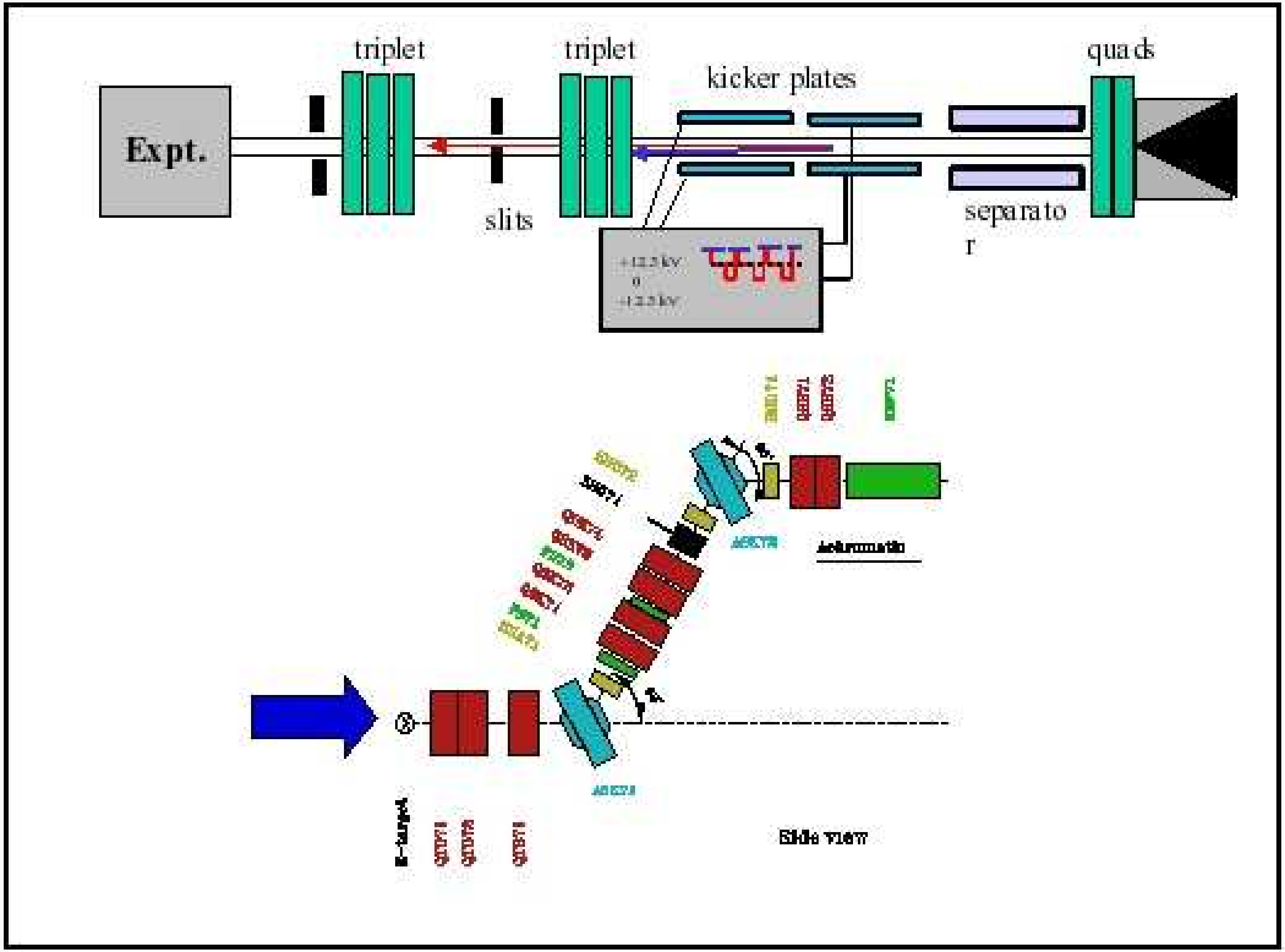
Pulsed Muon Beam

√ Turn off beam and watch them decay   Measurement Period





πE3 Beamline



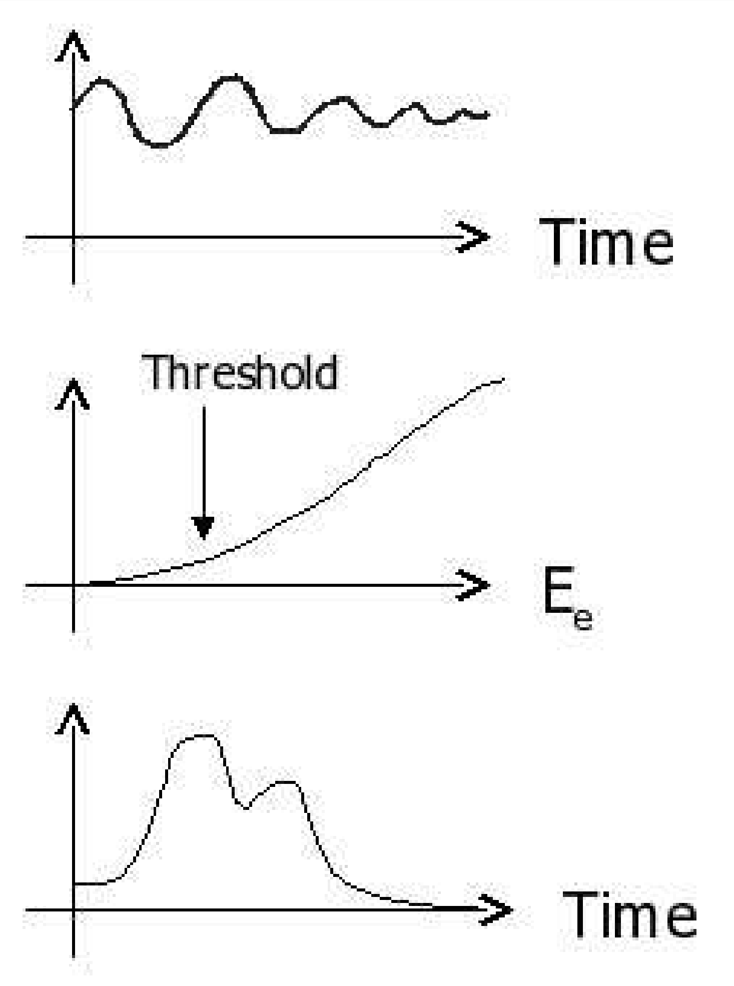
Beam Rate > 12 MHz; Spot at target, few cm^2

Fast Kicker

- √ TRIUMF-built kicker
  - ◇ ∼45 ns rise/fall time,
  - ◇ ± 12.5 kV,
  - ◇ two 75 cm plates
- √ Extinction factor
  - ◇ is quite subtle (seems momentum dependent)
  - ◇ 1000 for simulated kicker,
  - ◇ > 400 with static field on real kicker
- √ Some bad news too . . .

What can go wrong?

- √ Rotation of average spin:
  Target choice
- √ Gain and threshold changes:
  Stable electronics and PMTs
- √ Pileup:
  Segmented detector
  and fast electronics



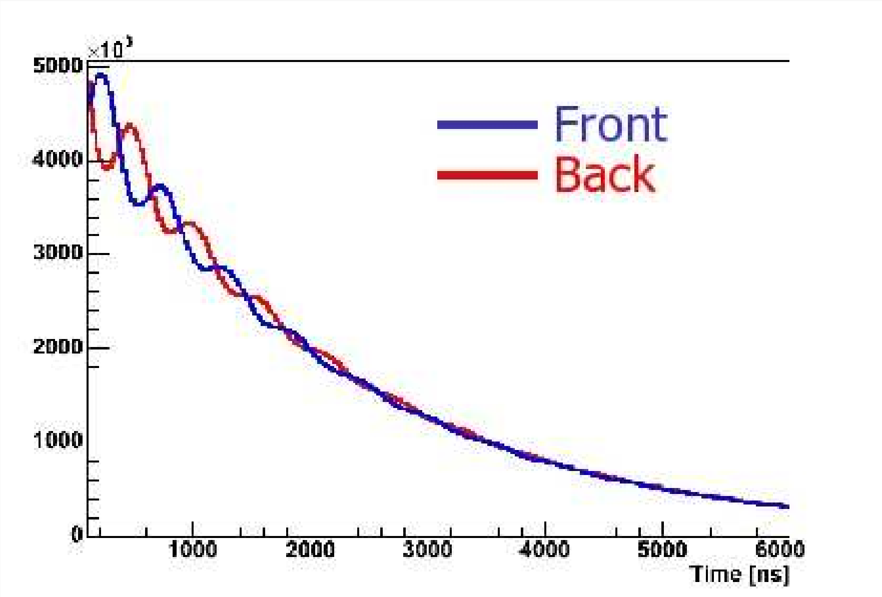
Impact of muon spin rotation (μSR)

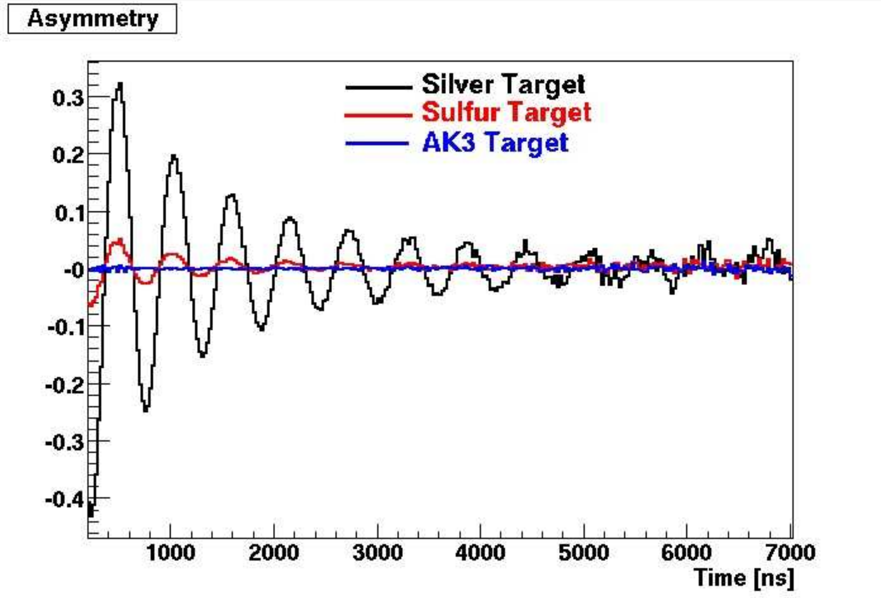
muon beam is polarized $\Longrightarrow$ muon precesses in magnetic field

Decay e^+s are preferentially emitted in the direction of the μ^+ spin.

Residual polarization effects will produce direction-dependent distortions in the μ^+ lifetime histograms.

Pointlike symmetric geometry; fit $F + B$, monitor with $F - B$



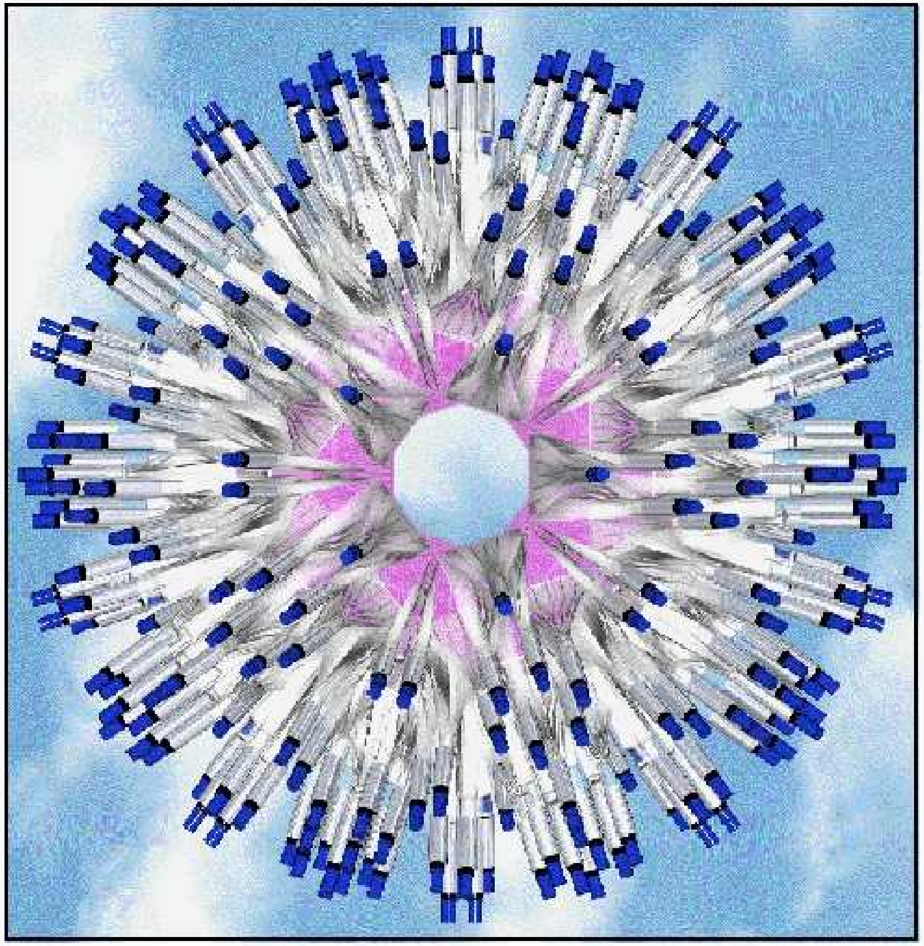


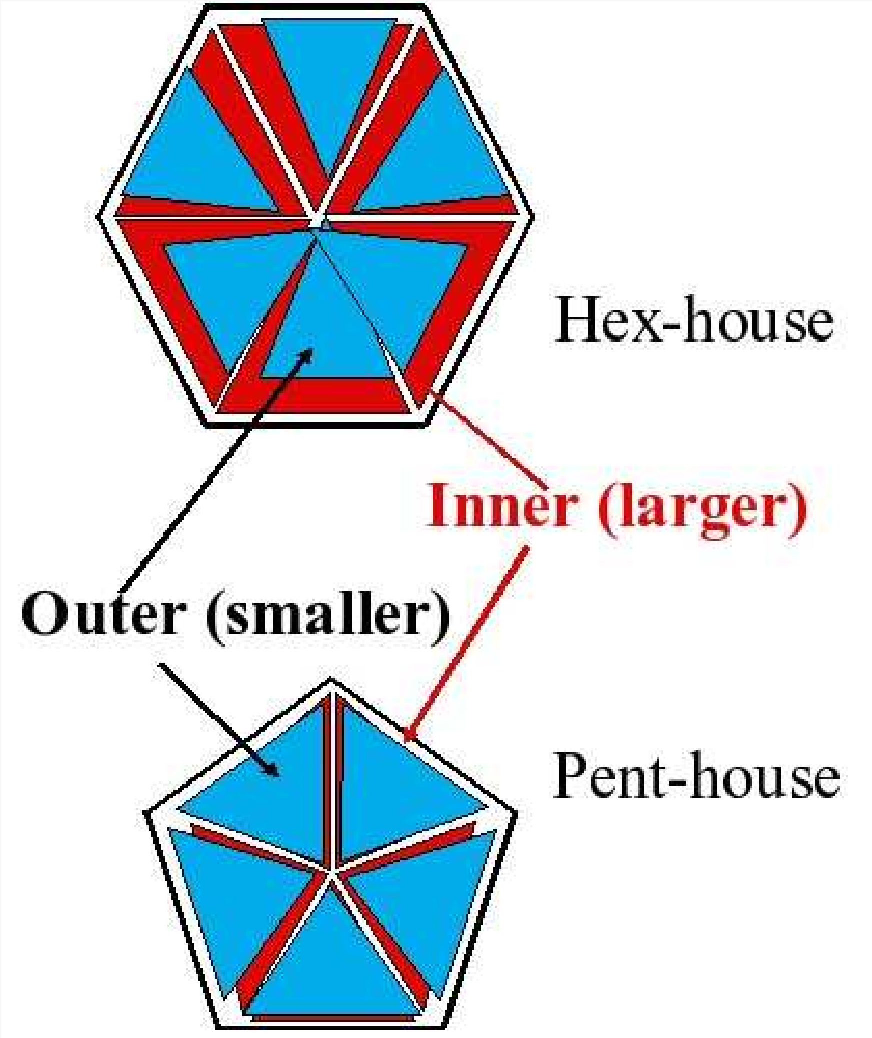
Arnokrome-3 (AK3) (30% chromium, 10% cobalt, 60% iron)

Internal Field $\approx$ 1 T.

No observable precession frequency up to 320 MHz or $< B >= 2.4$ T.

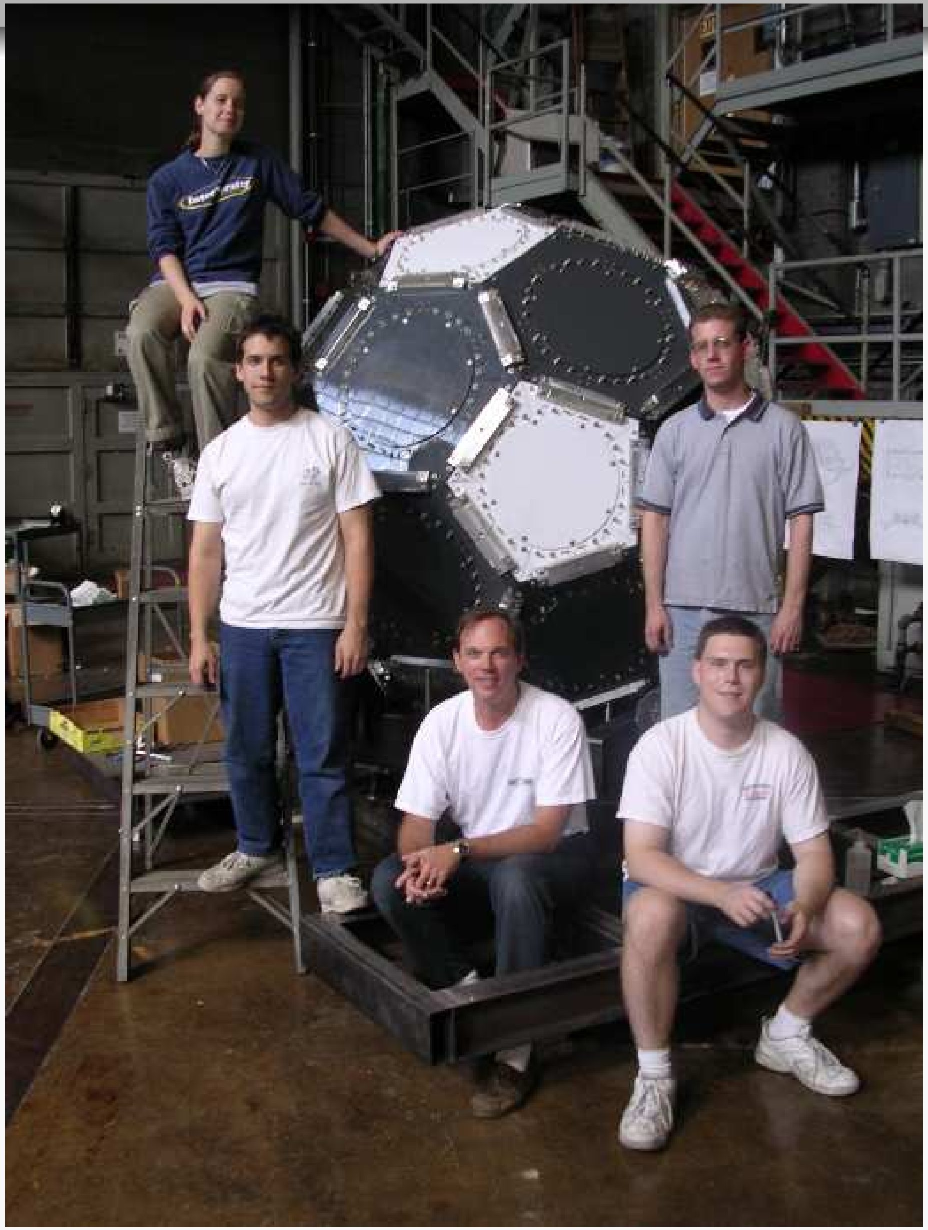
Scintillators: 32–sided, soccer–ball geometry

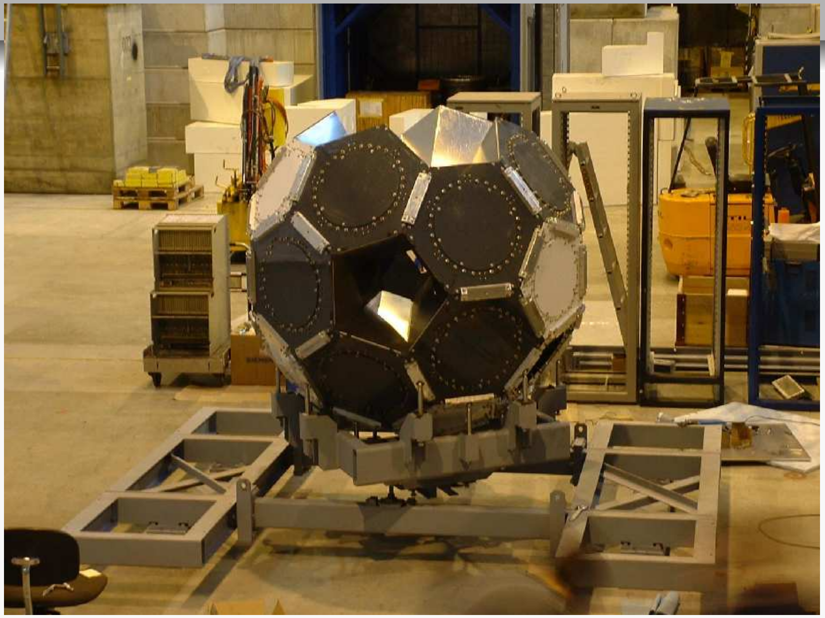




The complete detector has 30 active “houses”, with 170 tile pairs

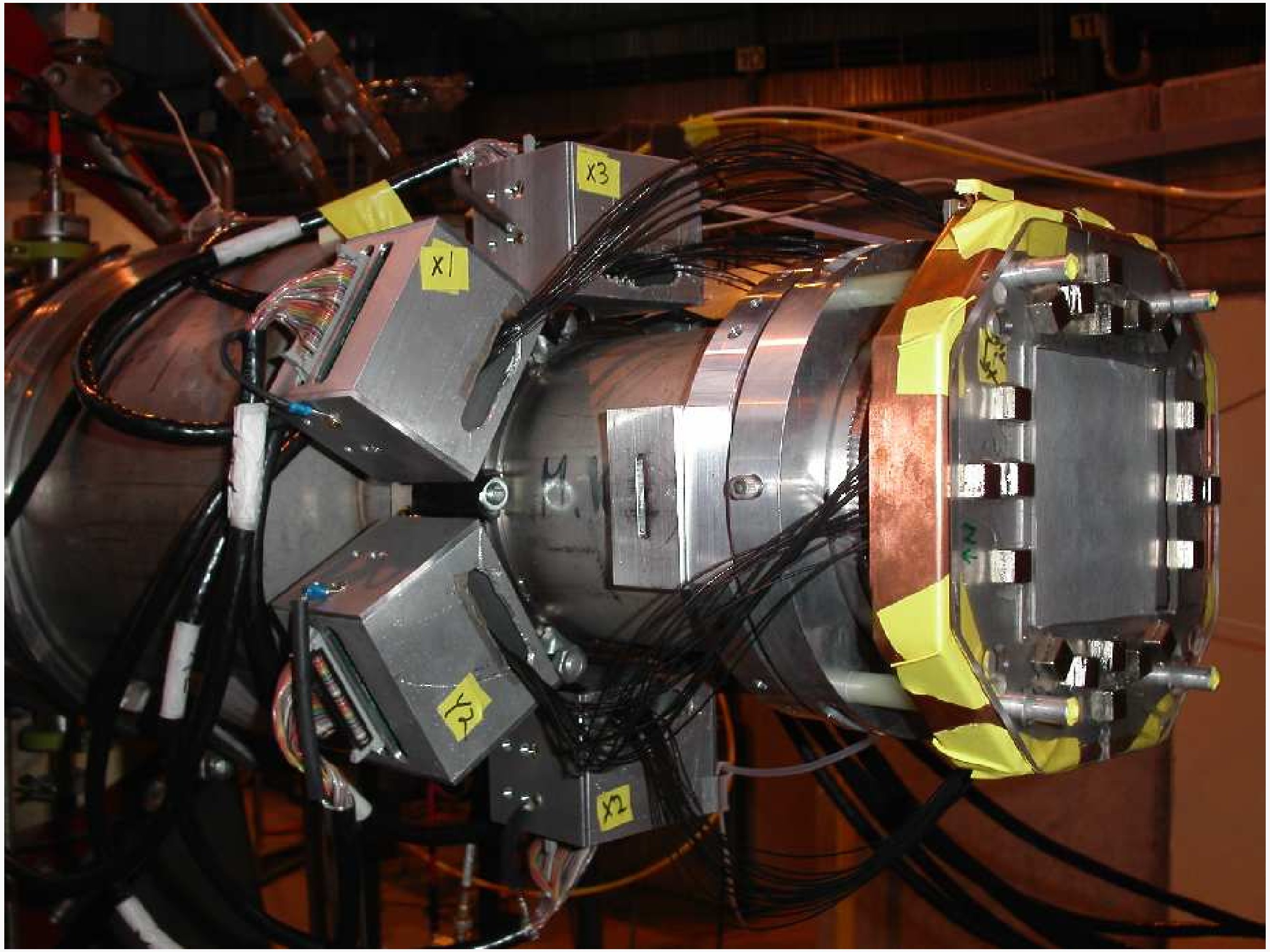
The Crew





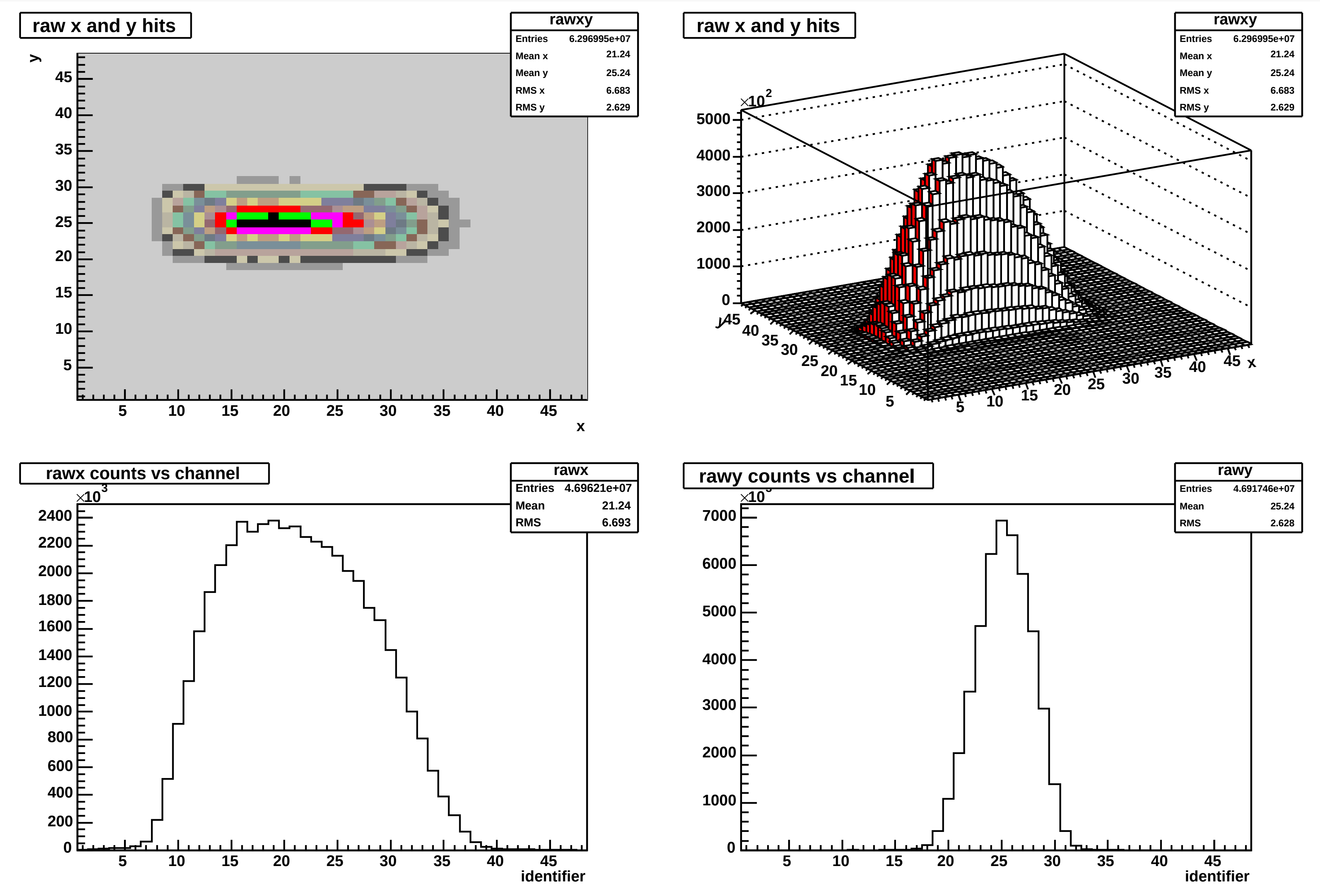
“Sneaky Muons”

During beam-off period sneaky muons lead to time dependent background



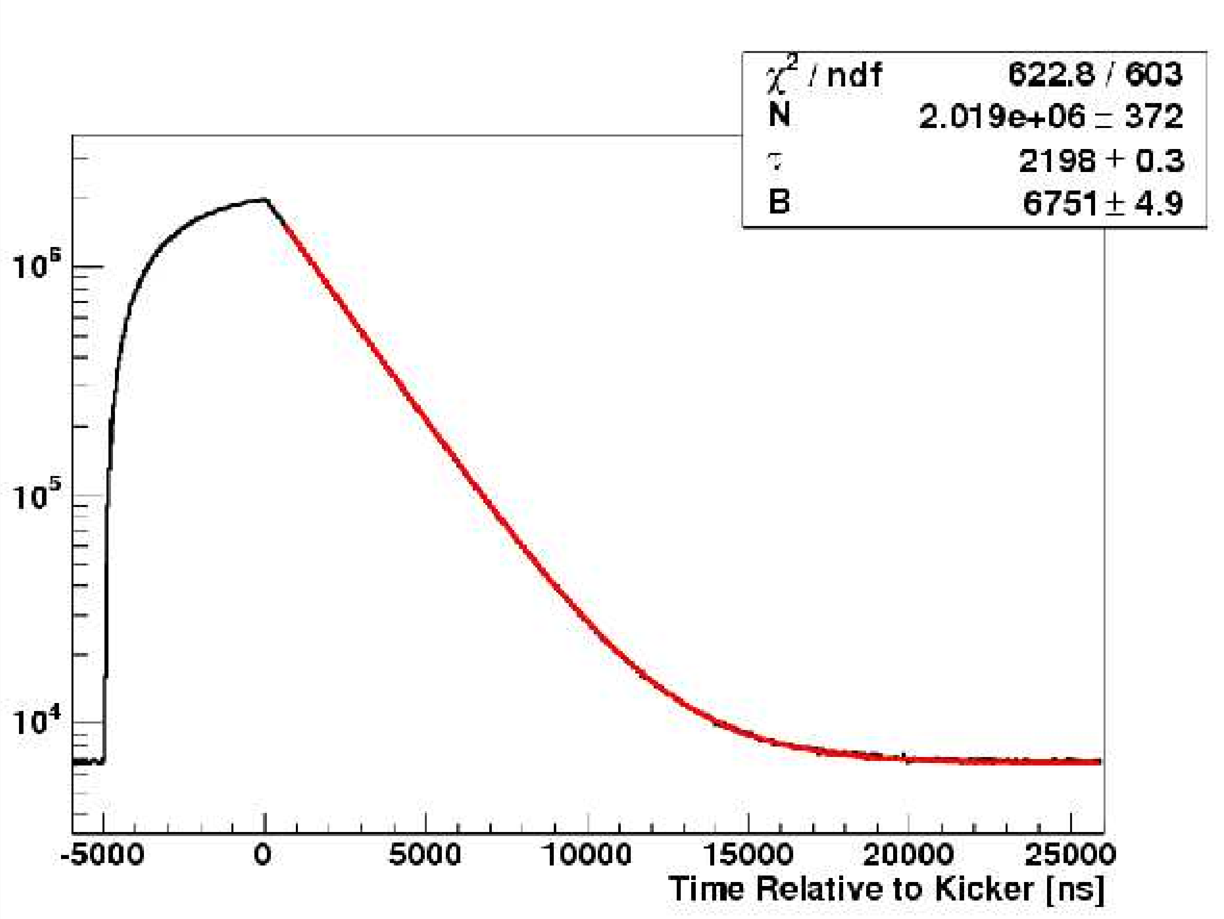
high rate (MHz), thin, fast (30 ns FWHM) wire chamber
Efficiency $>$95%, stable within 5%
Active Area 94×100 mm

Beam Profile



First physics fits

(the clock timescale is only approx in ns . . . and they don't know the offset)



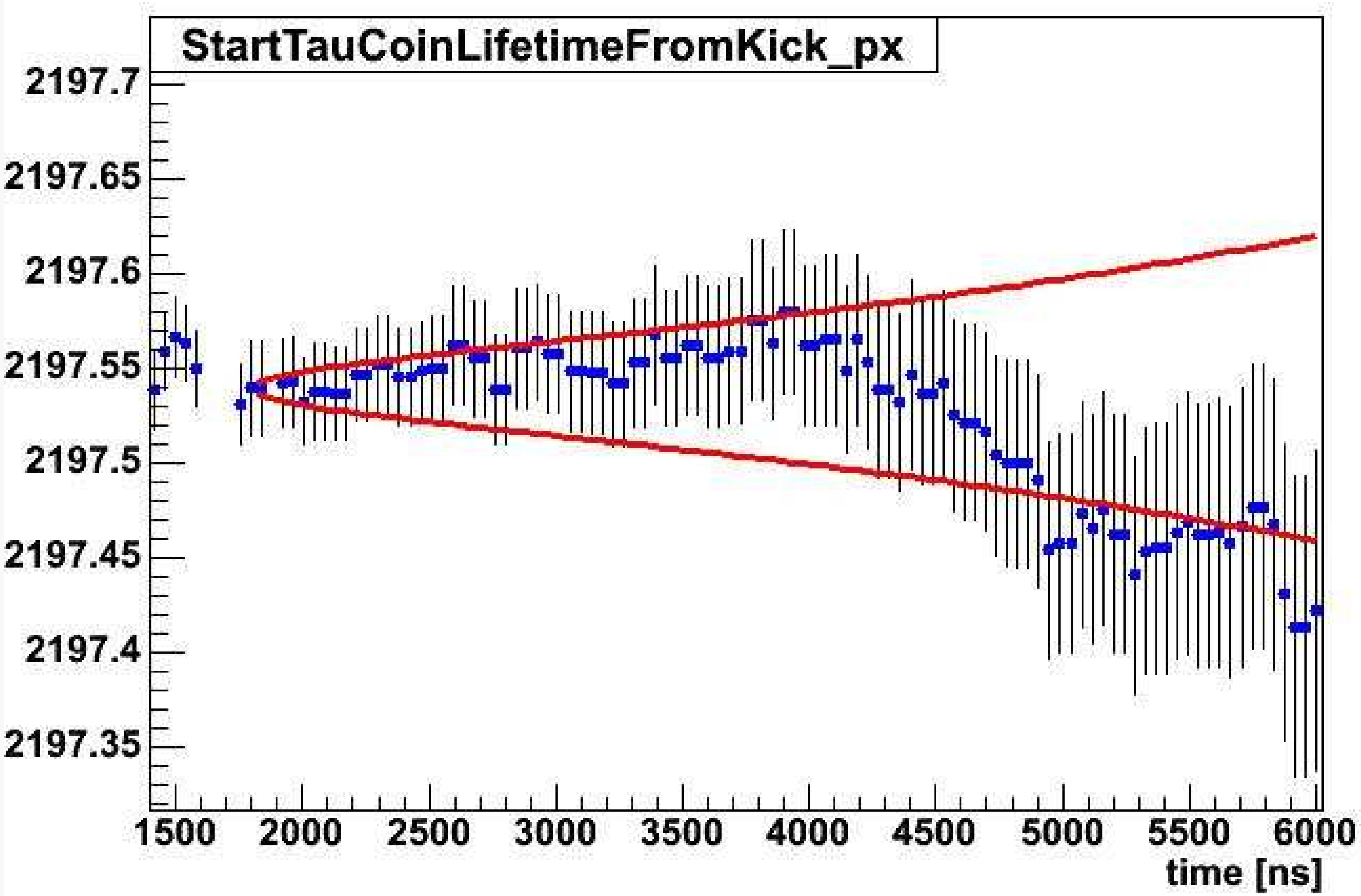
All kicked data summed up without too much screening

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

Better than 10 ppm and good, stable fits (so far)

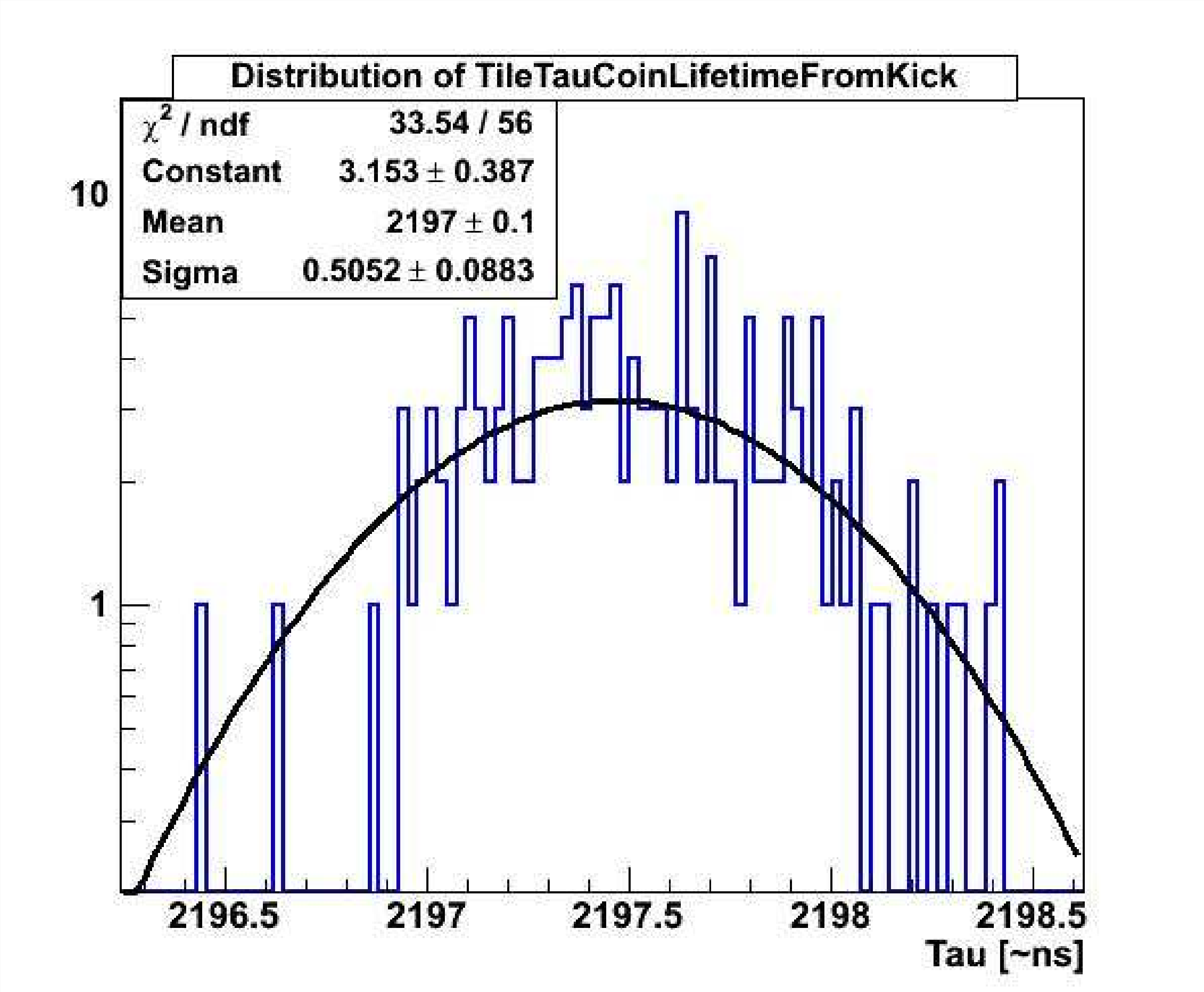
Fit Stability

Stability of fit parameters versus fit start time is a good barometer of fit quality



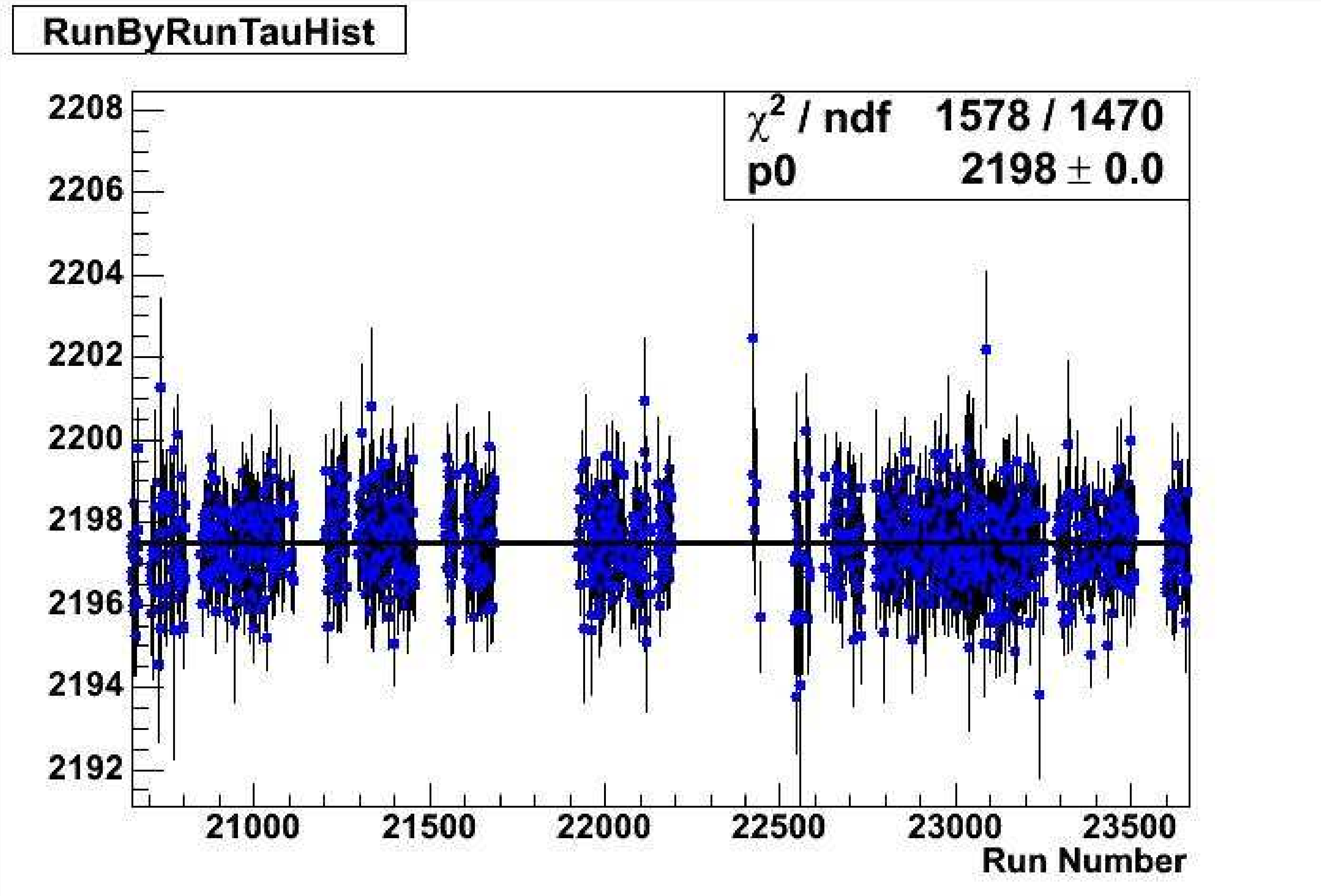
Fit Stability

Also important, behavior of different detectors . . .



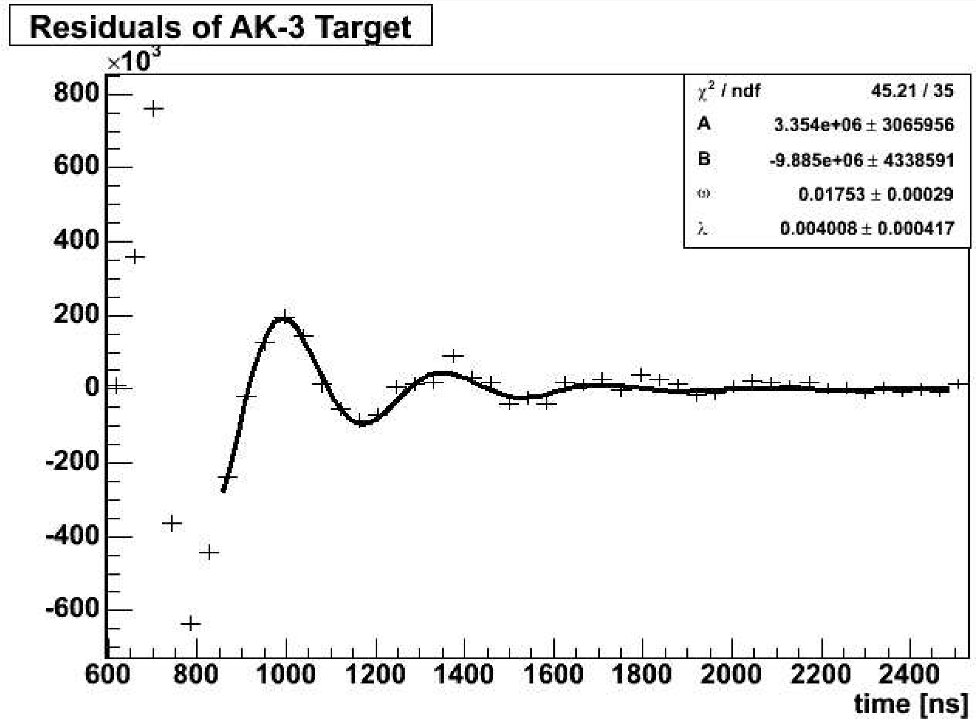
Fit Stability

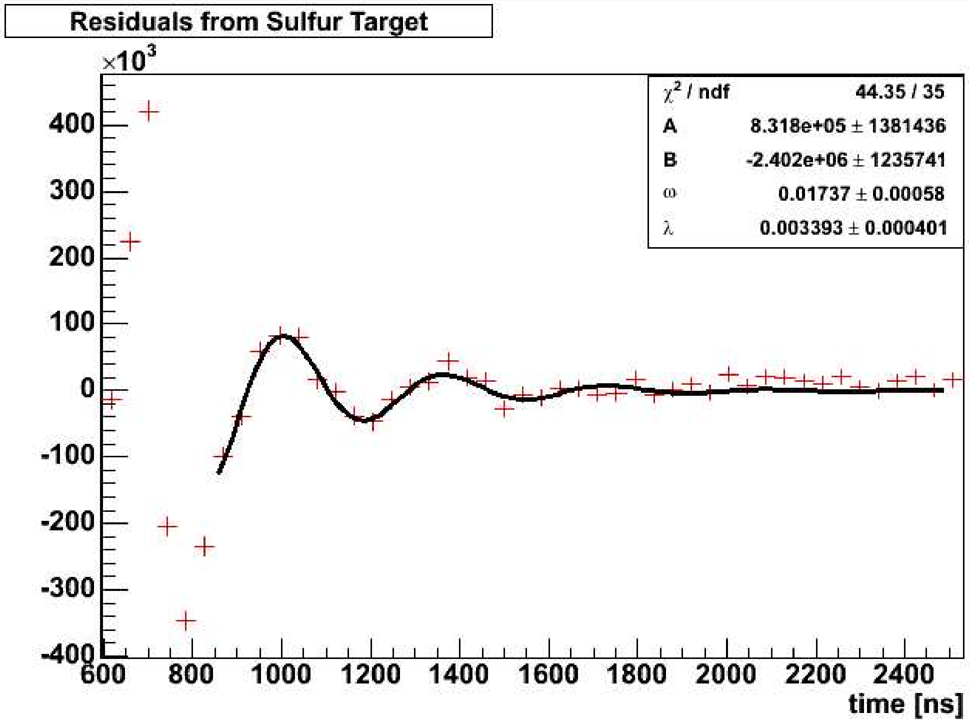
. . . and by run number, but . . .



Fit Stability

. . . These fits started about 1.8 μs after kicker off because of a nasty ripple in the data, probably from the kicker, but we are not sure yet . . . we will figure it out





Conclusion on data:

We are hoping for a 5–10 ppm result by the end of the summer

MuLan Future plans

- June 2005:
  - Beam Tuning to improve Rate and Extinction Factor
- Fall 2005:
  - First run with waveform digitizer
  - New run with improved kicker
  - First Production run with waveform digitizers
- 2006:
  - Major production run with waveform digitizers
  - Full proposed $O(10^{12})$ statistics