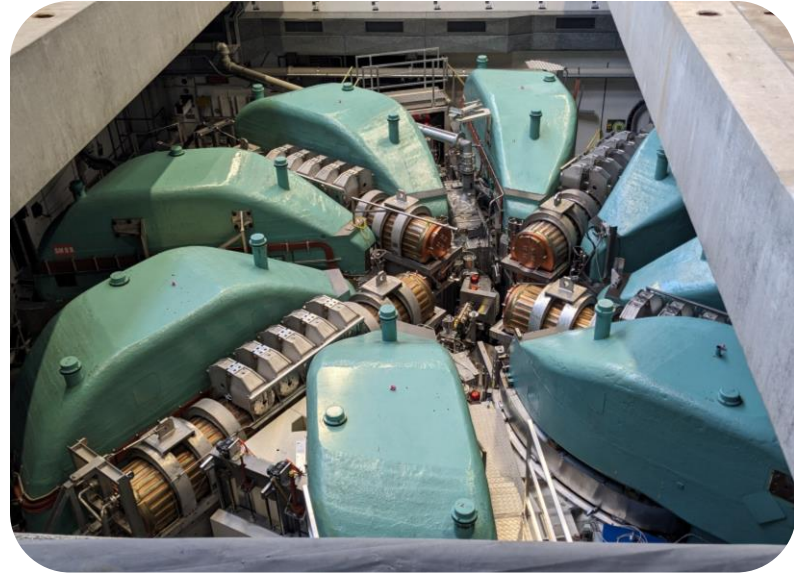
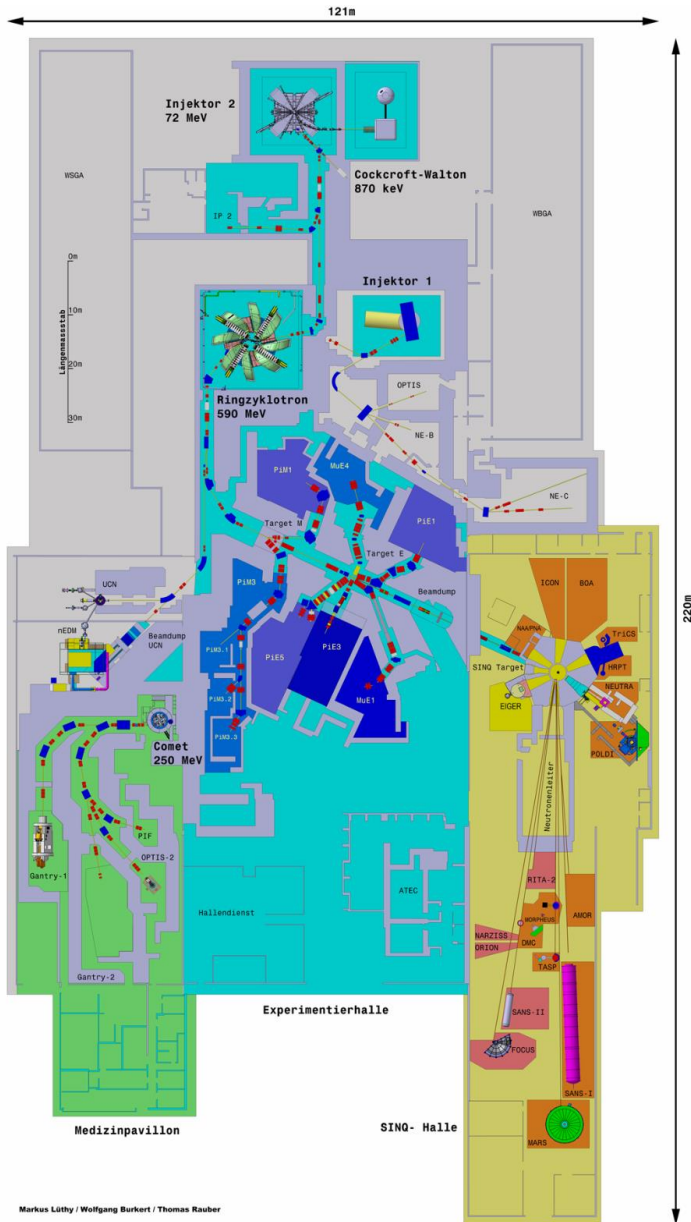


# Muon lifetime: the MuLan experiment



PRD **87**, 052003 (2013)

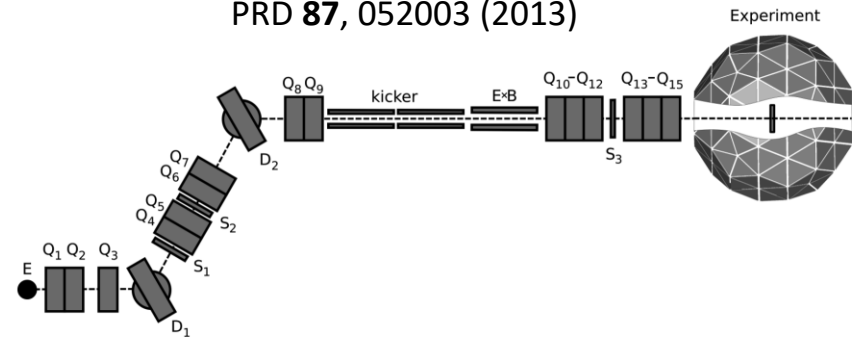


FIG. 5. Schematic view of the  $\pi E3$  beamline including the E target station, opposing vertical bending magnets (D), quadrupole focusing magnets (denoted Q), slit systems (S), electrostatic kicker,  $\vec{E} \times \vec{B}$  velocity separator, and the location of the experiment. See text for details.

# Muon lifetime: the MuLan experiment

PRD **87**, 052003 (2013)

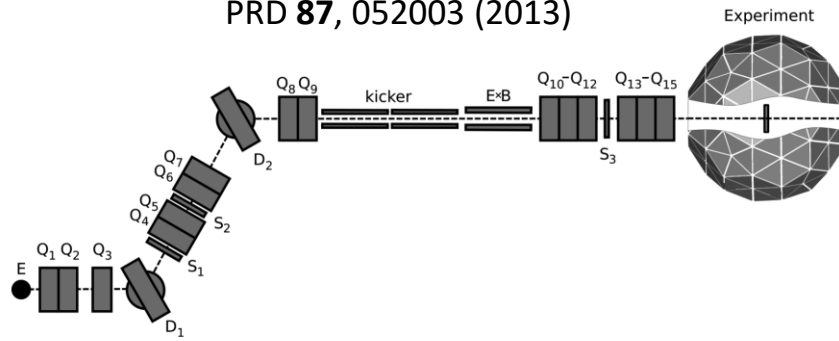
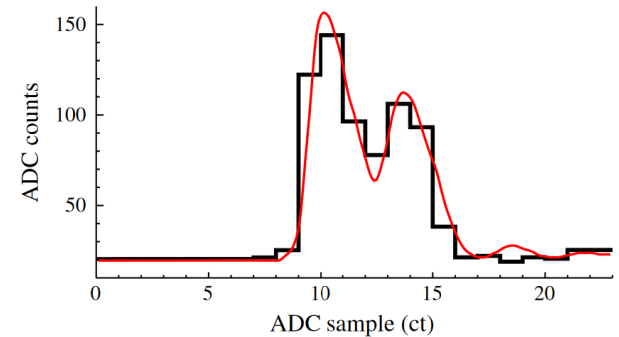
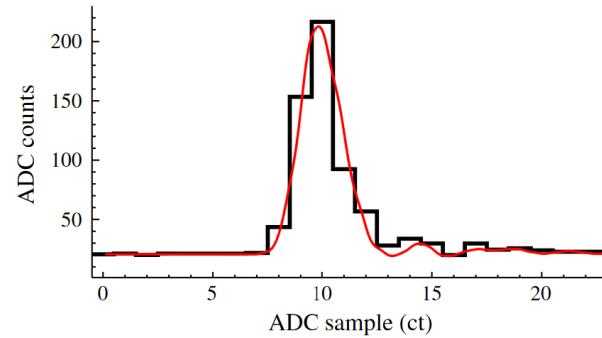
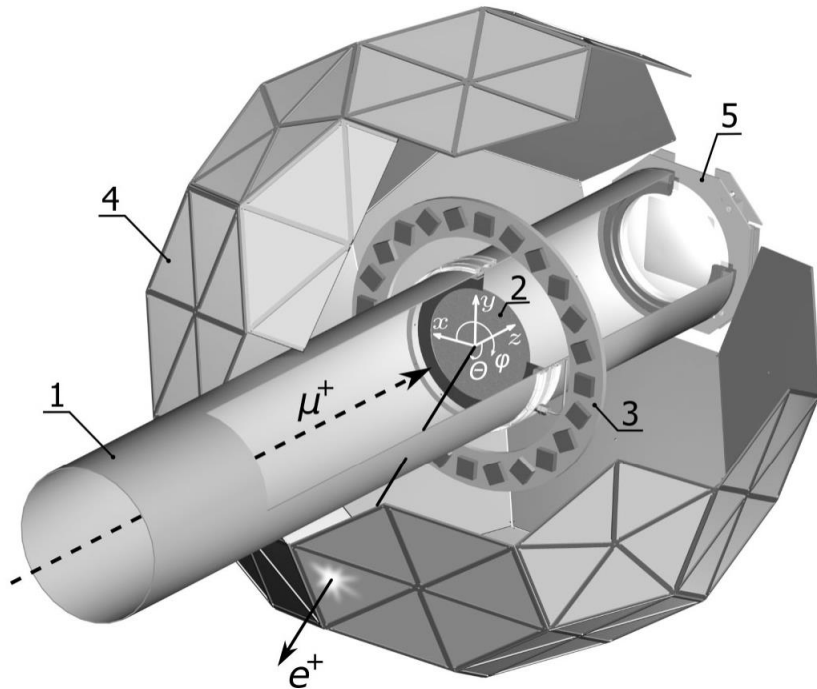
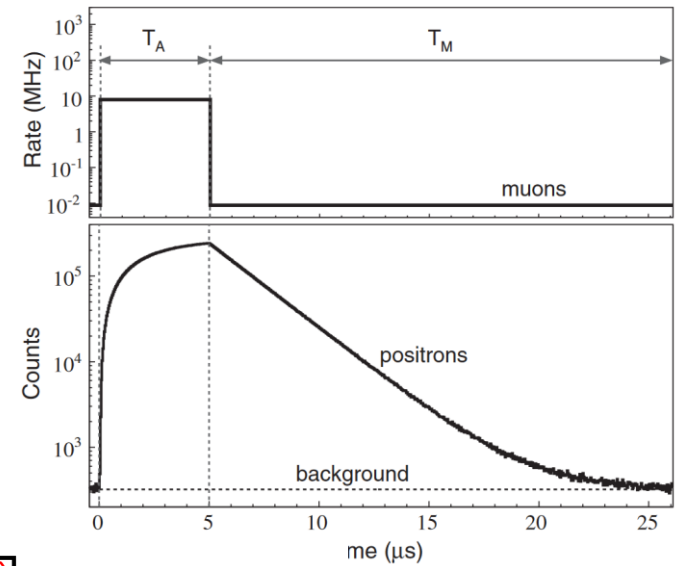


FIG. 5. Schematic view of the  $\pi$ E3 beamline including the E target station, opposing vertical bending magnets (D), quadrupole focusing magnets (denoted Q), slit systems (S), electrostatic kicker,  $\vec{E} \times \vec{B}$  velocity separator, and the location of the experiment. See text for details.



# Muon lifetime: the MuLan experiment

PRD **87**, 052003 (2013)

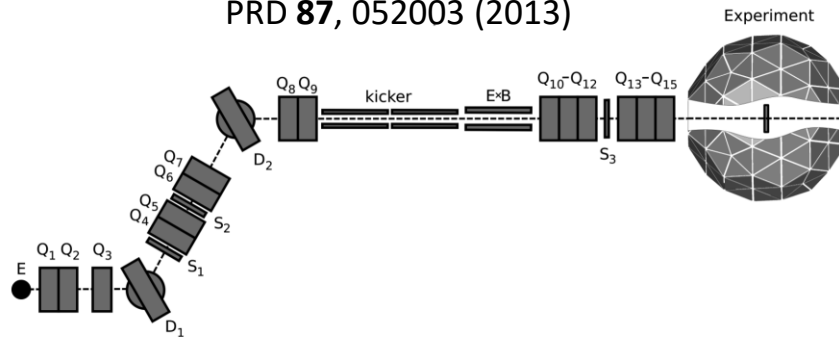
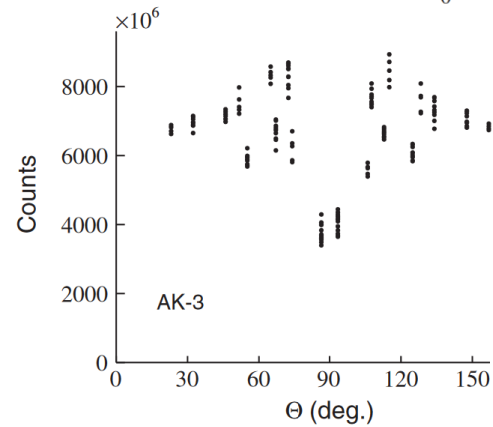
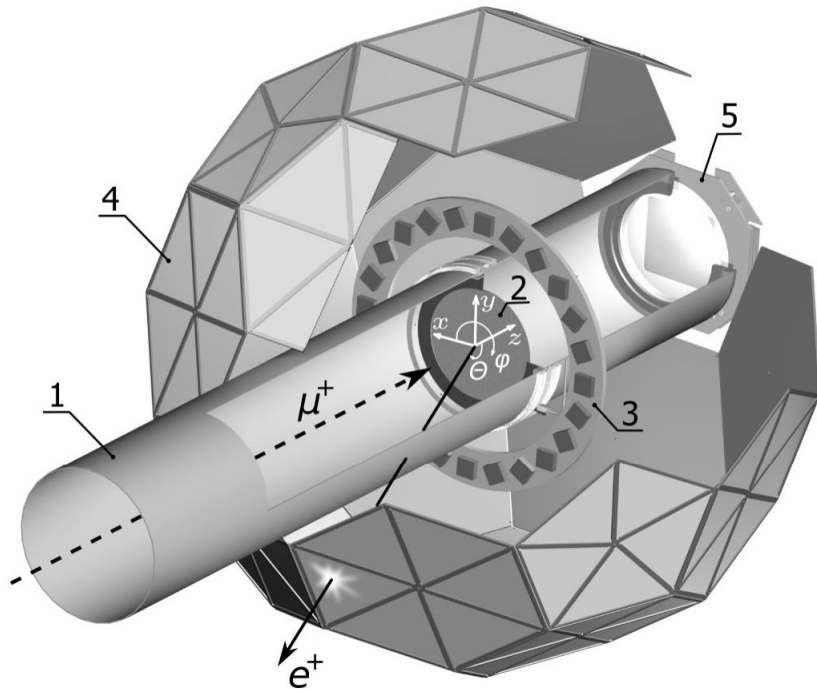
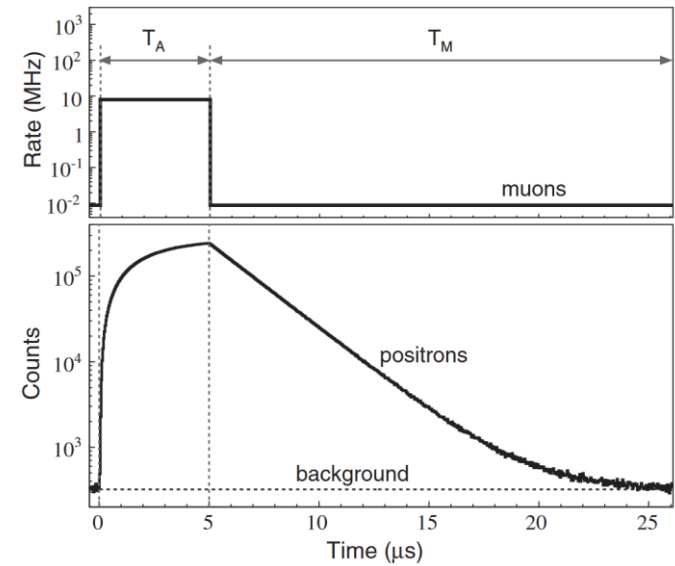
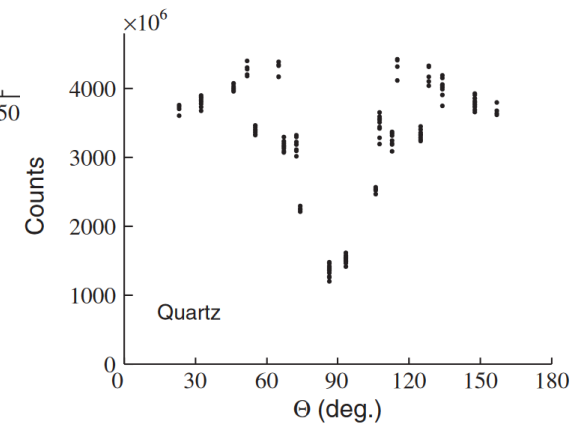


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## Asymmetries



# Muon lifetime: the MuLan experiment

PRD **87**, 052003 (2013)

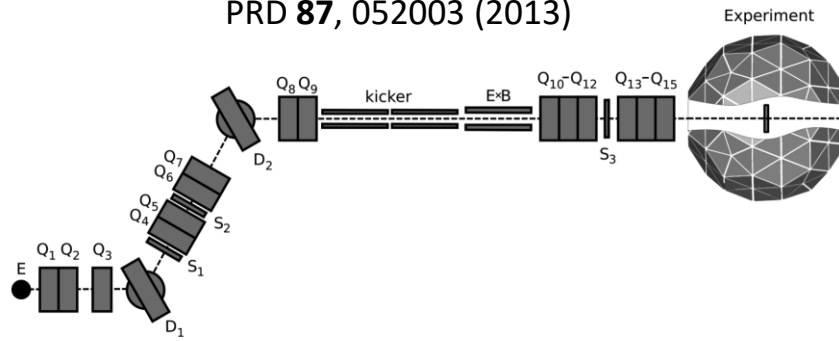
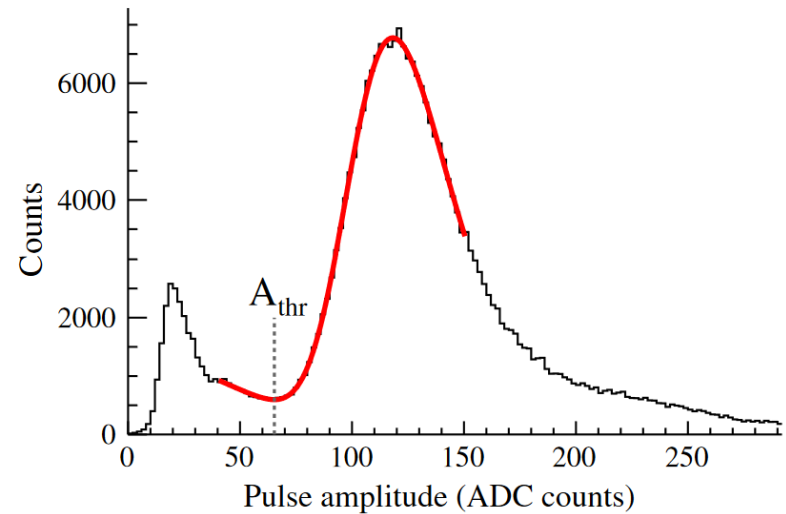
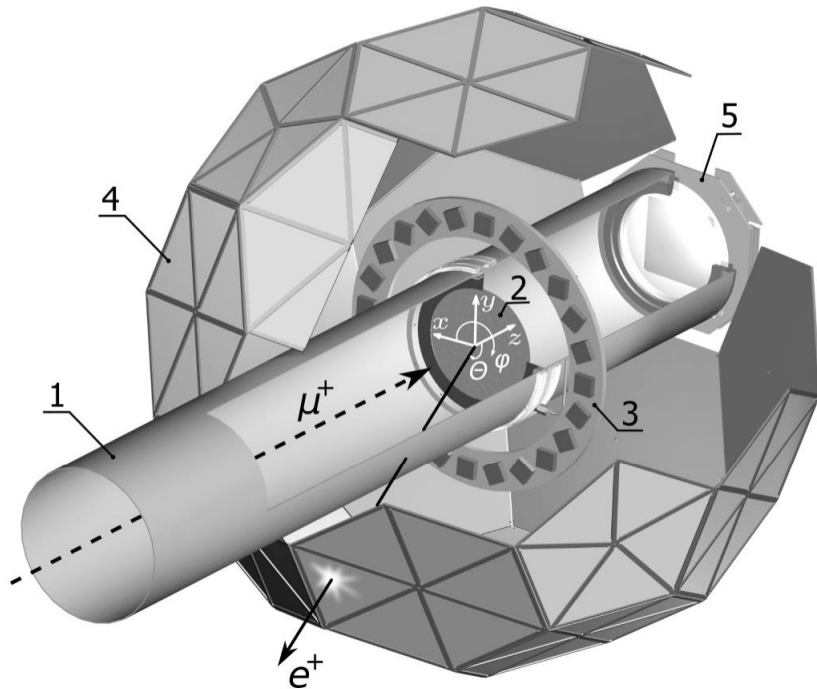
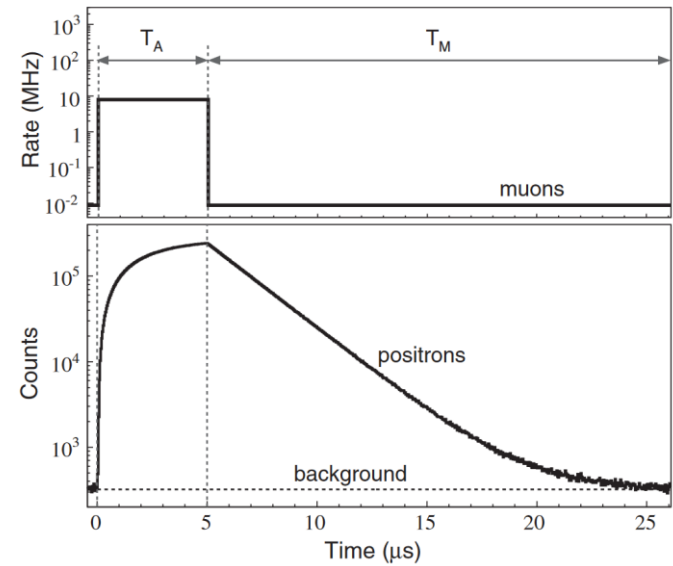


FIG. 5. Schematic view of the  $\pi$ E3 beamline including the E target station, opposing vertical bending magnets (D), quadrupole focusing magnets (denoted Q), slit systems (S), electrostatic kicker,  $\vec{E} \times \vec{B}$  velocity separator, and the location of the experiment. See text for details.



# Muon lifetime: the MuLan experiment

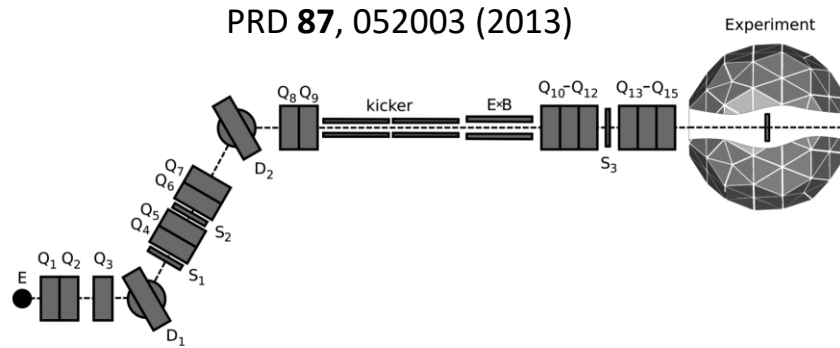
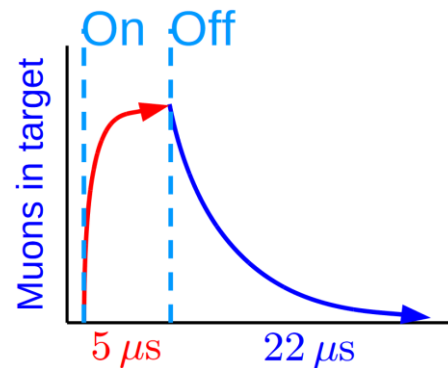
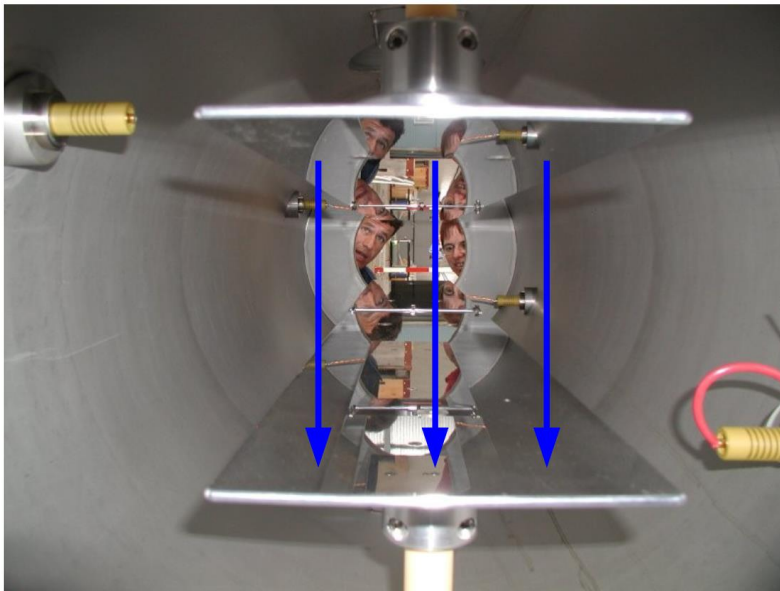
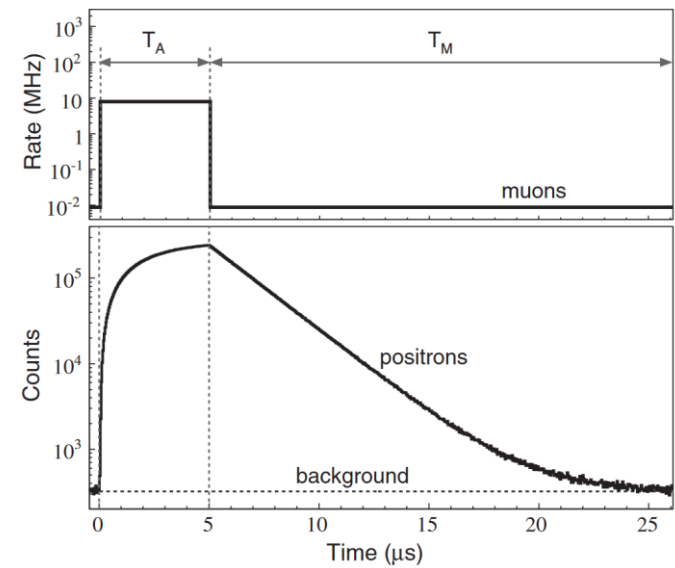
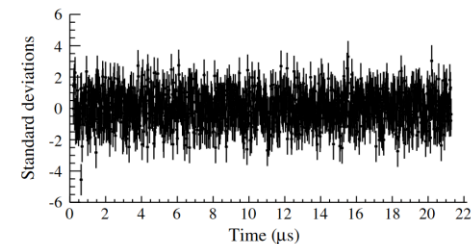
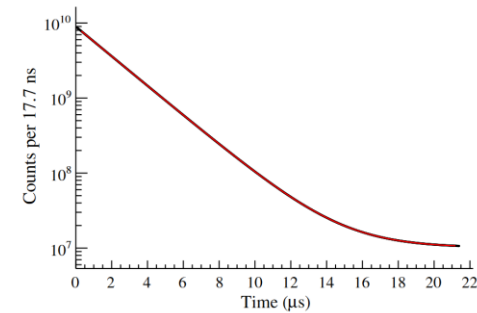


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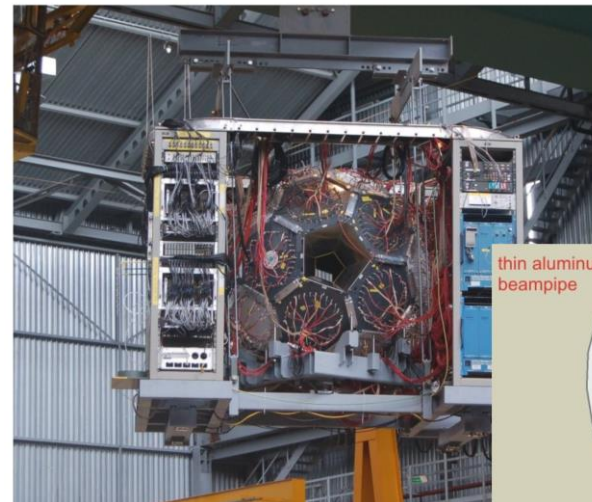
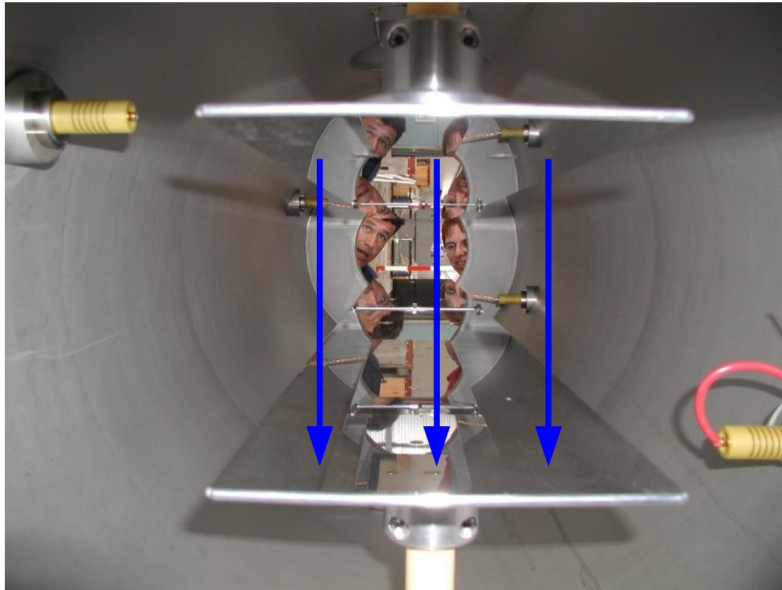
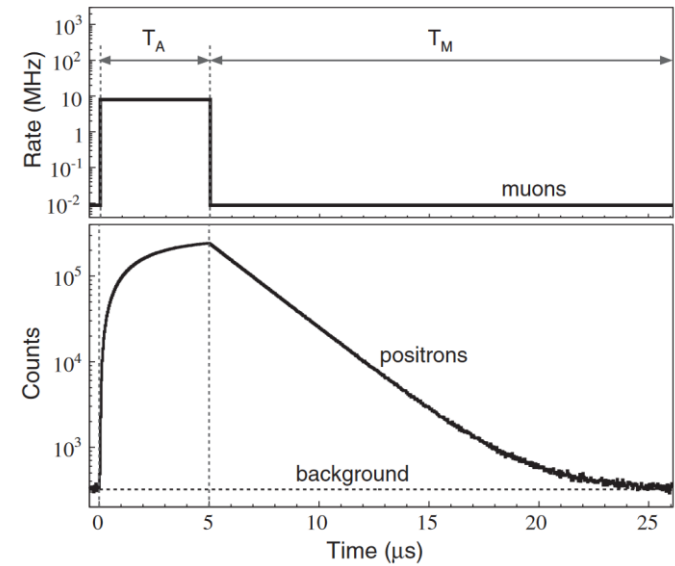
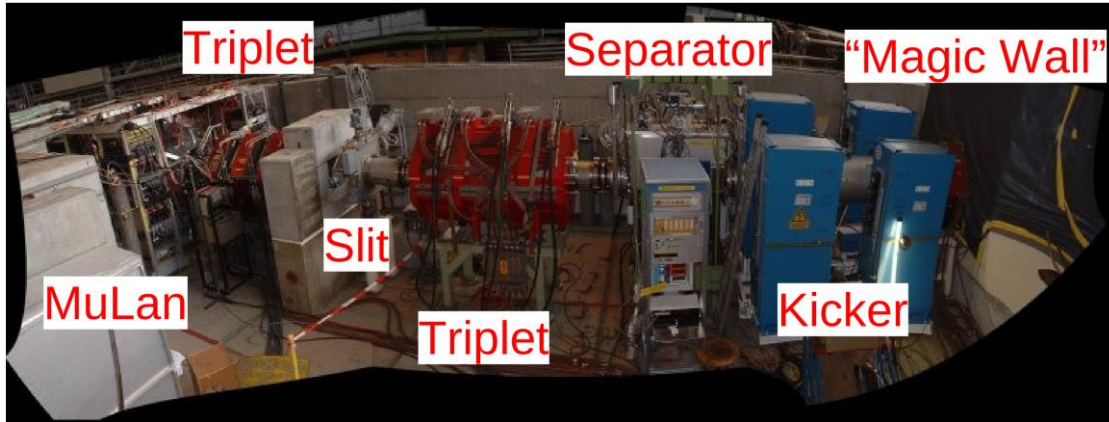


$$N_{in}(t) = R_{\mu}\tau \left(1 - e^{-t/\tau}\right)$$

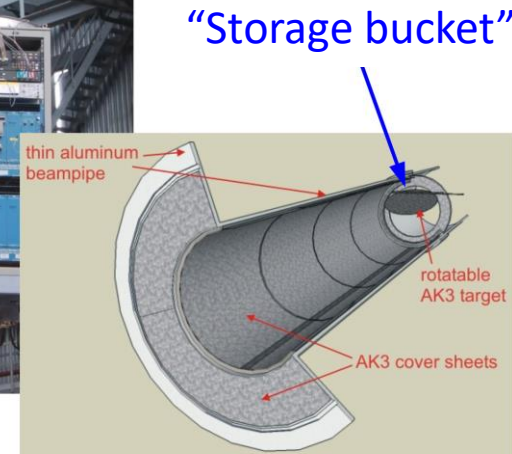
$$N_{out}(t) = N_{in}(t_c)e^{-t/\tau}$$



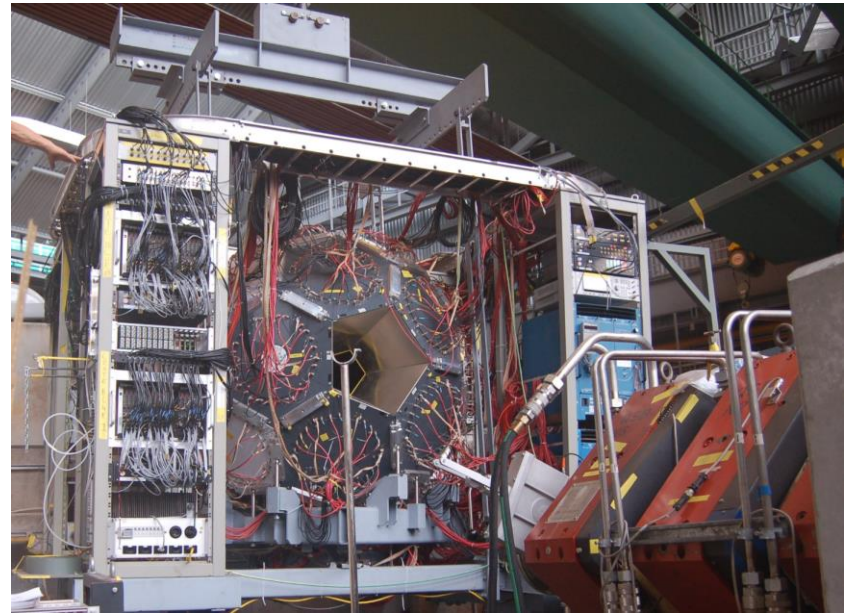
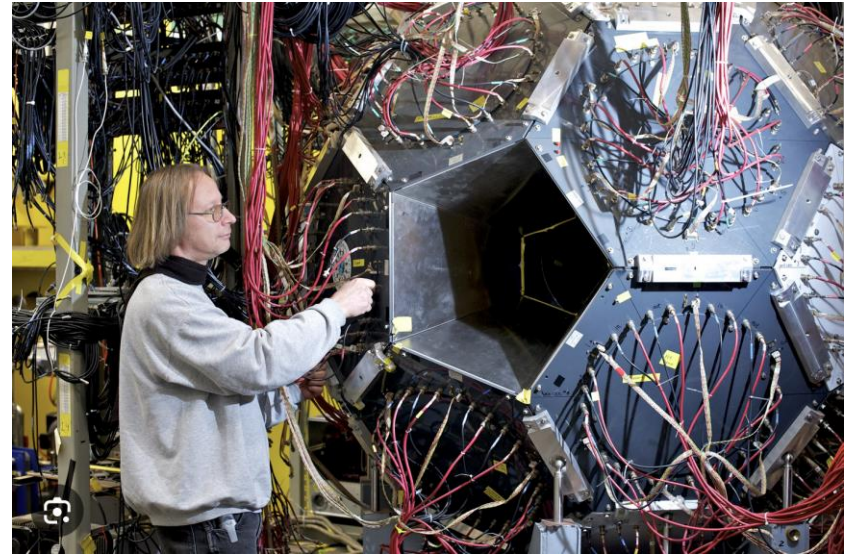
# Muon lifetime: the MuLan experiment



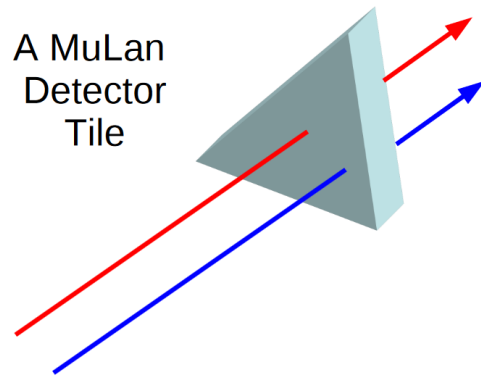
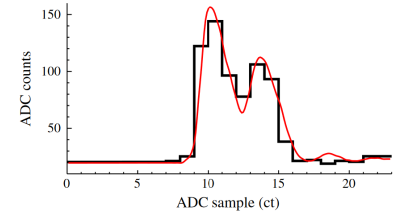
Rob Carey: "The world's largest research grade soccer ball"



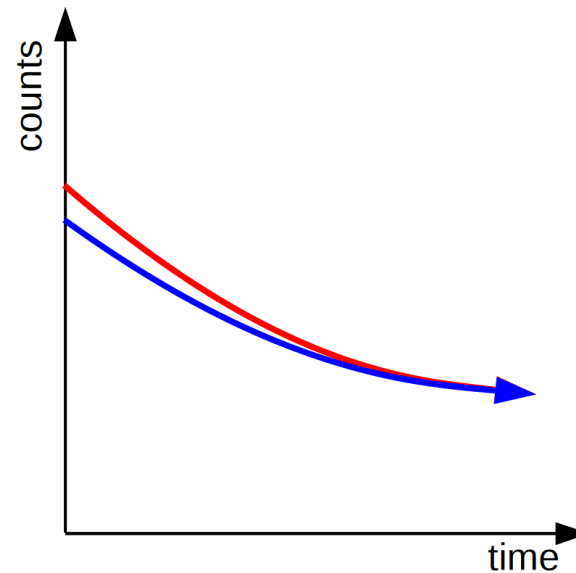
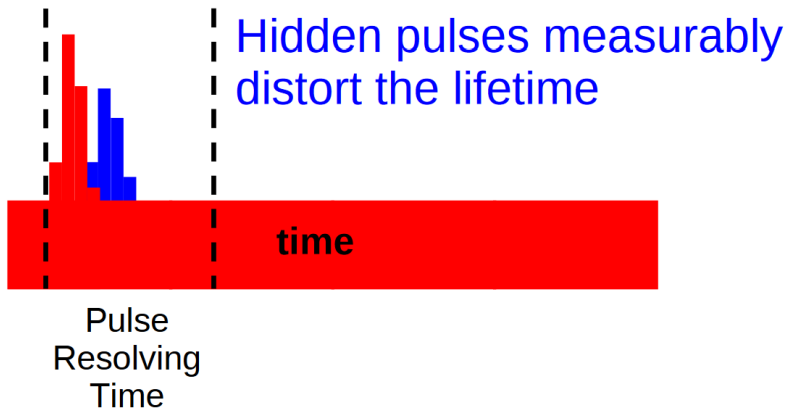
# Muon lifetime: the MuLan experiment



# How the pileup correction is done



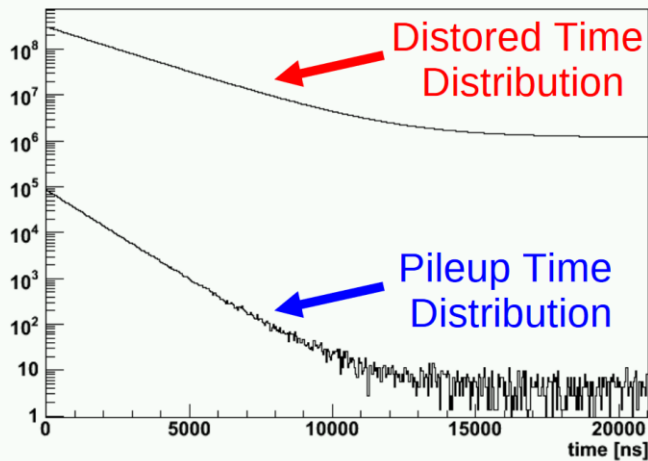
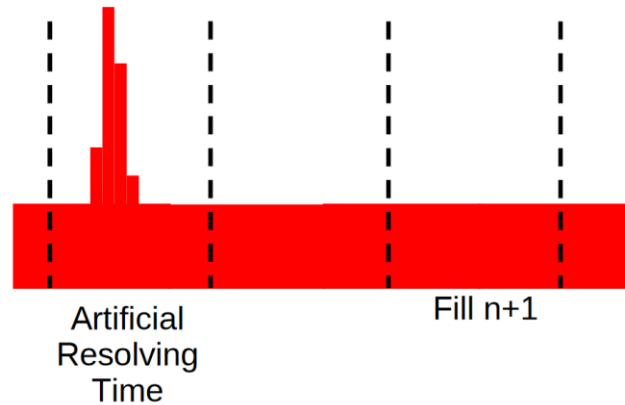
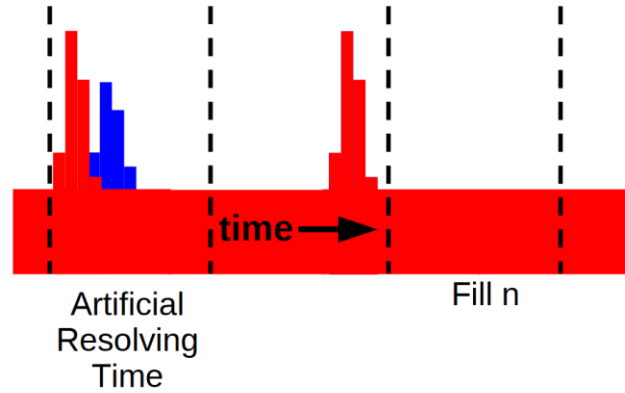
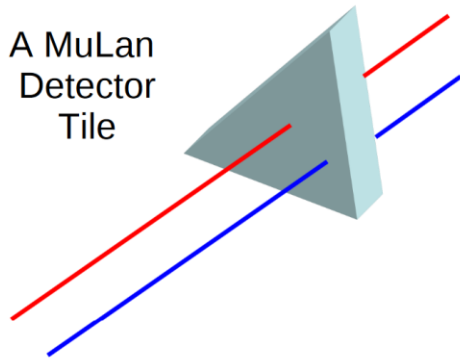
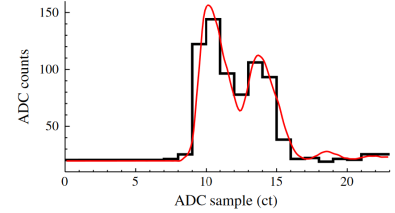
$$P_{\text{pileup}} \propto \int_0^{t_r} P(t)P(t + t')dt'$$
$$\propto e^{-2t/\tau}$$



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!

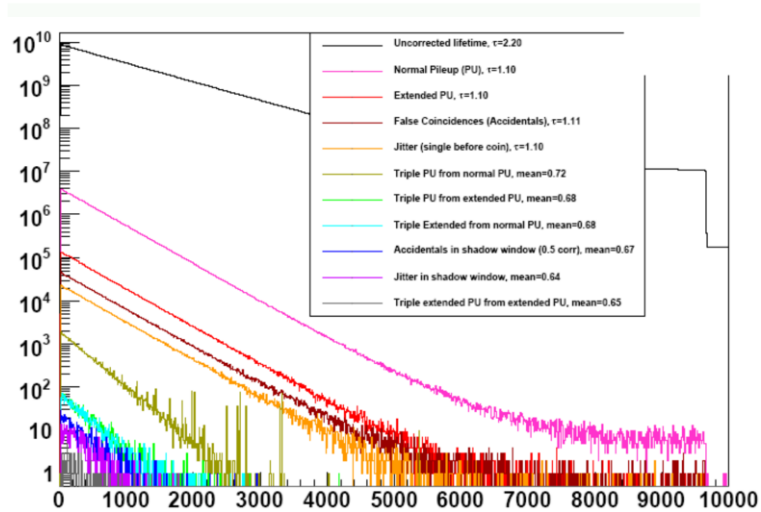
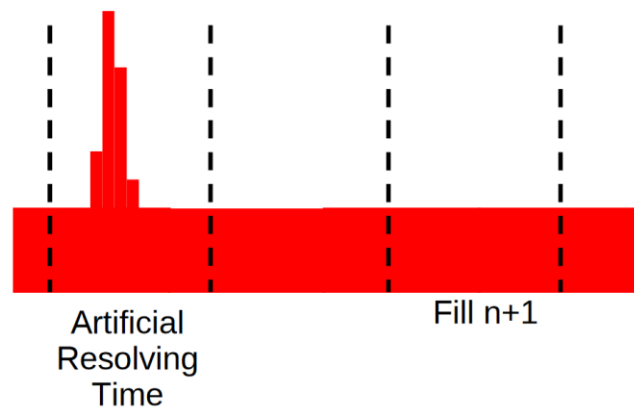
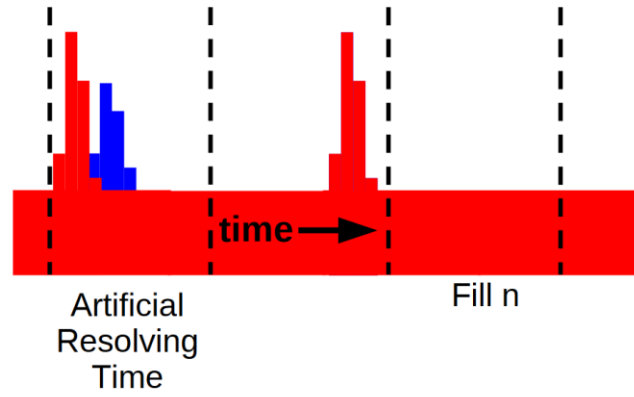
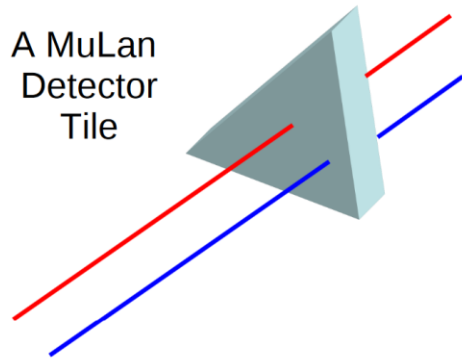
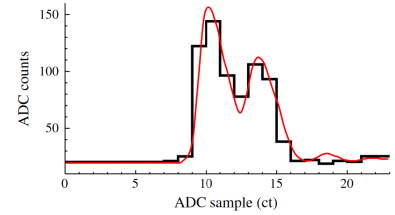


# How the pileup correction is done



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

# How the pileup correction is done

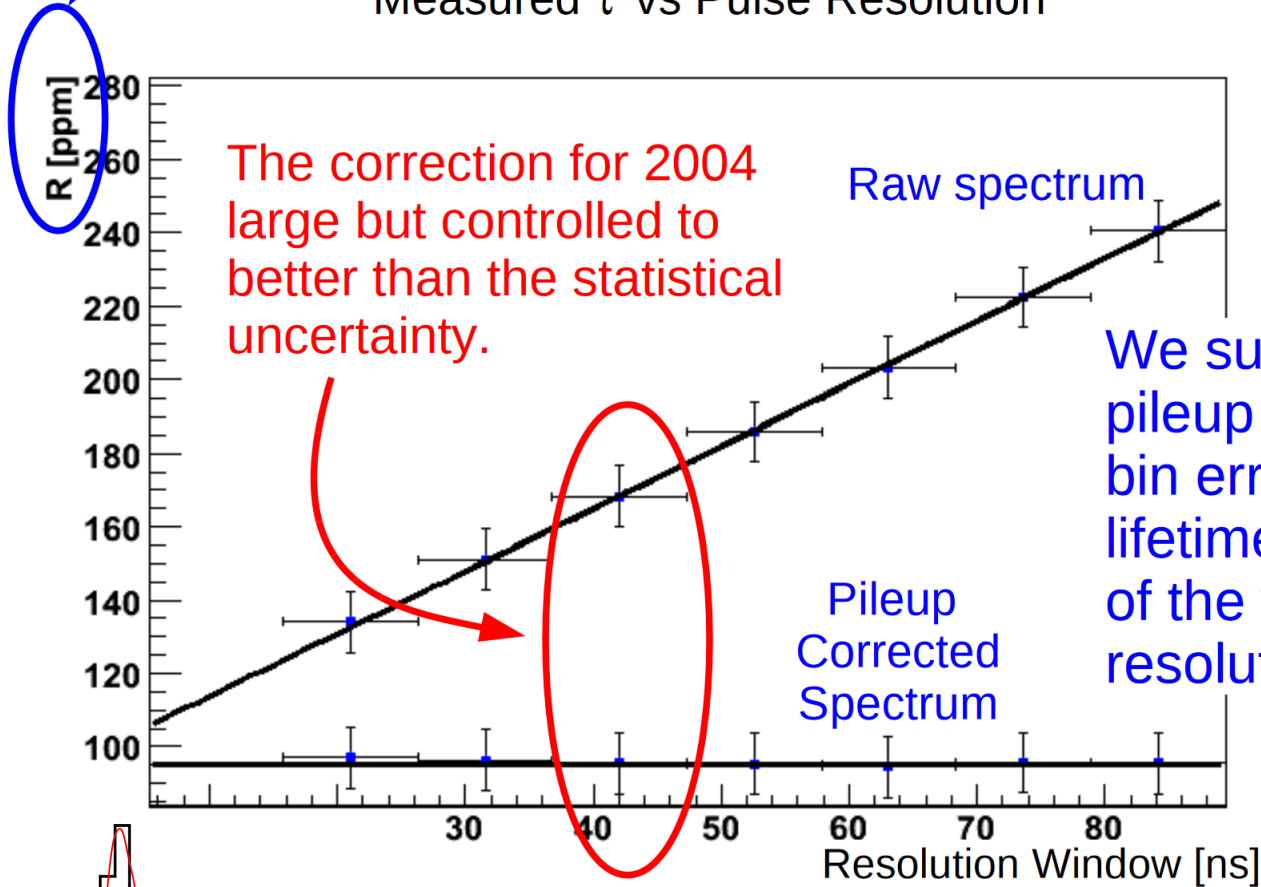
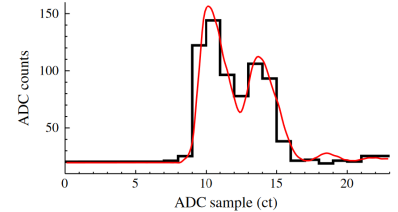


Adding the pileup distribution to the normal distribution (statistically) corrects for what's killed by the imposed deadtime!

# How the pileup correction is done

**Blind analysis!**

Measured  $\tau$  vs Pulse Resolution

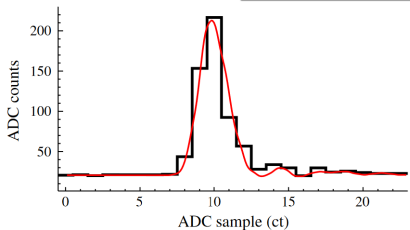


The correction for 2004 large but controlled to better than the statistical uncertainty.

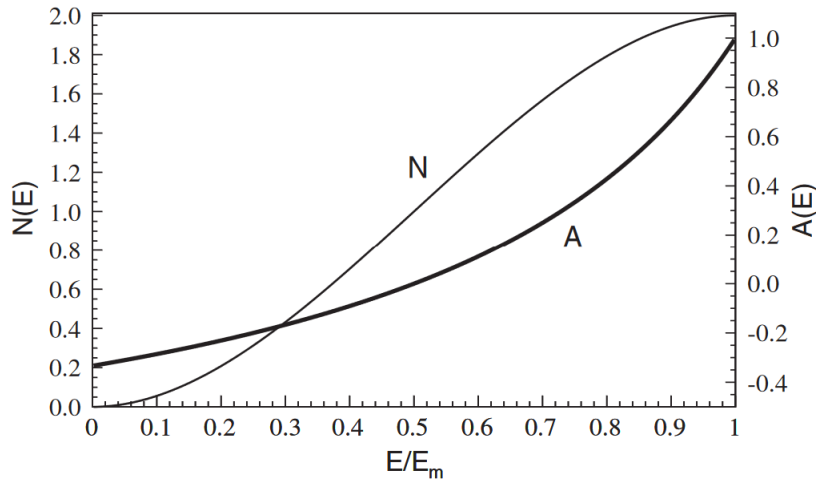
Raw spectrum

Pileup Corrected Spectrum

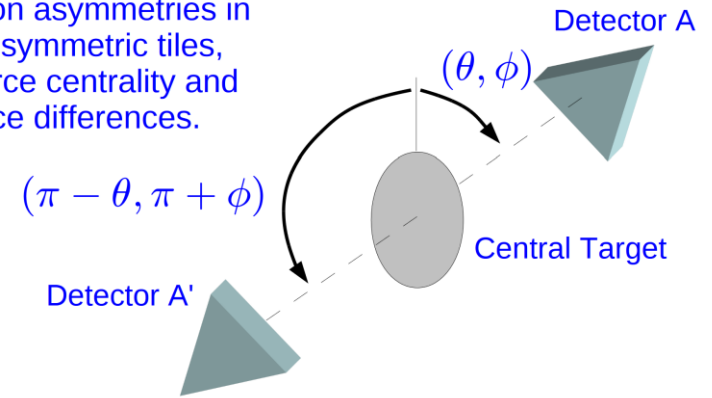
We sum the normal and pileup spectra (and correct bin errors!); the corrected lifetime fit is independent of the width of the time resolution window.



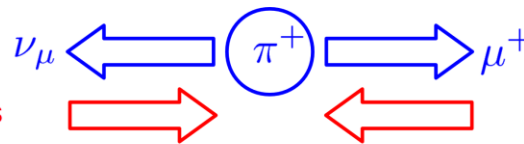
# Asymmetries and polarization



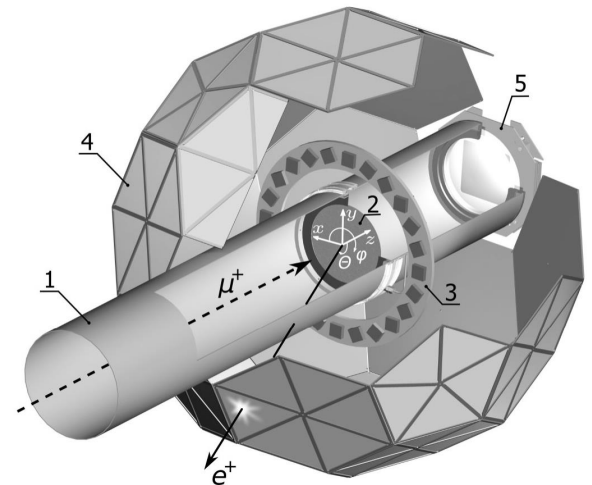
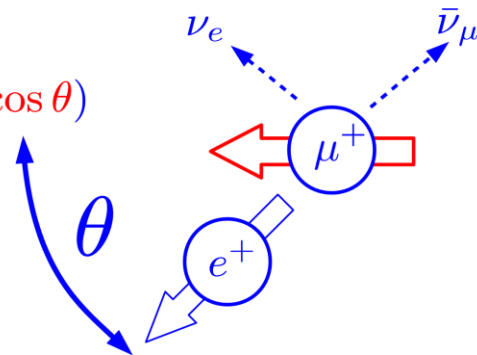
Point symmetry of the detector cancels polarization asymmetries in sum over symmetric tiles, up to source centrality and acceptance differences.



Parity violation in weak decays requires left-handed neutrinos



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



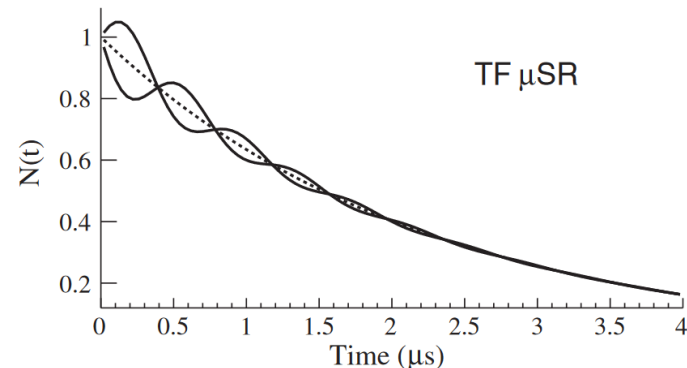
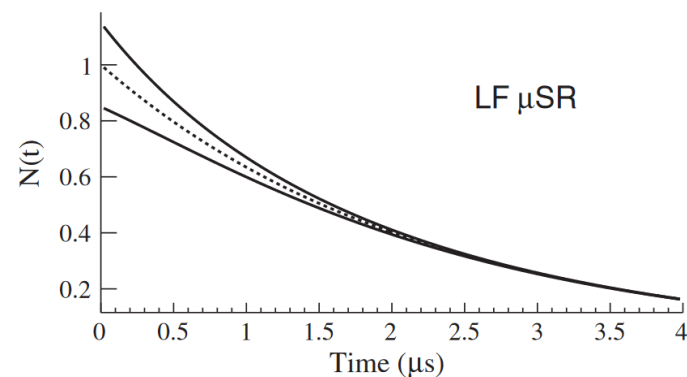
# Asymmetries and polarization

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

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

Longitudinal component  $\downarrow$   
 Muon Lifetime  $\downarrow$   
 Transverse component  $\nearrow$   
 Flat background  $\nearrow$

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

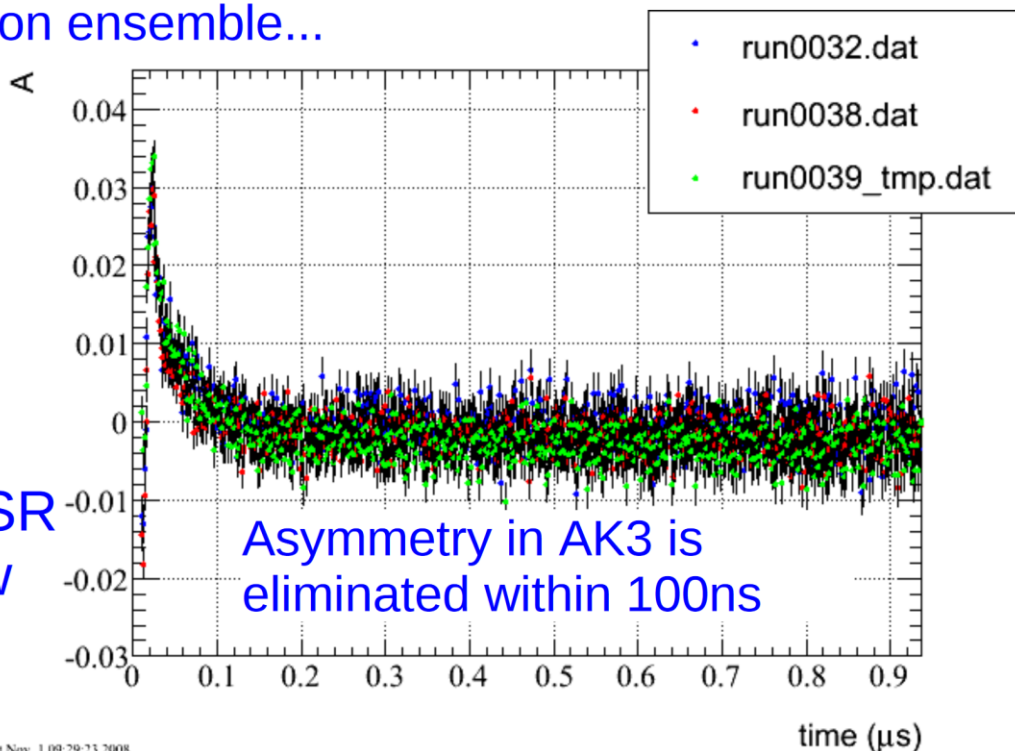
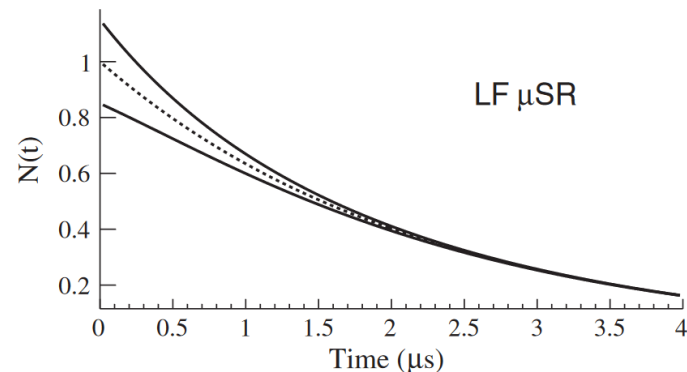


# Asymmetries and polarization

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...

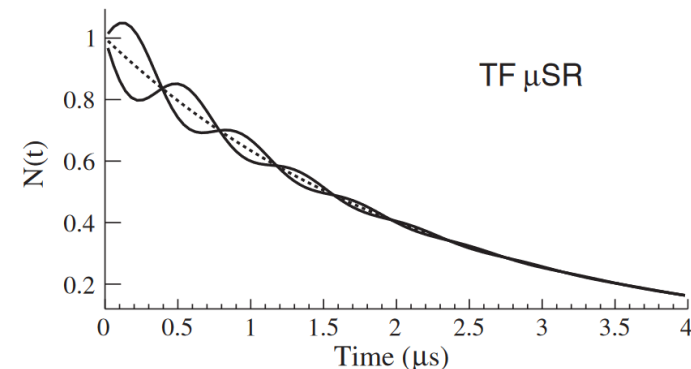
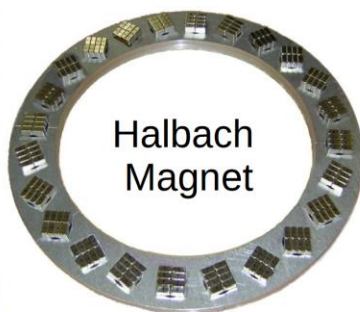
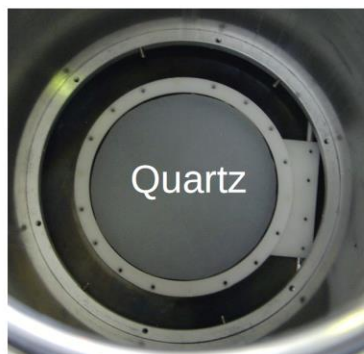
... and dedicated  $\mu$ SR studies show exactly that.



Sat Nov 1 09:29:23 2008

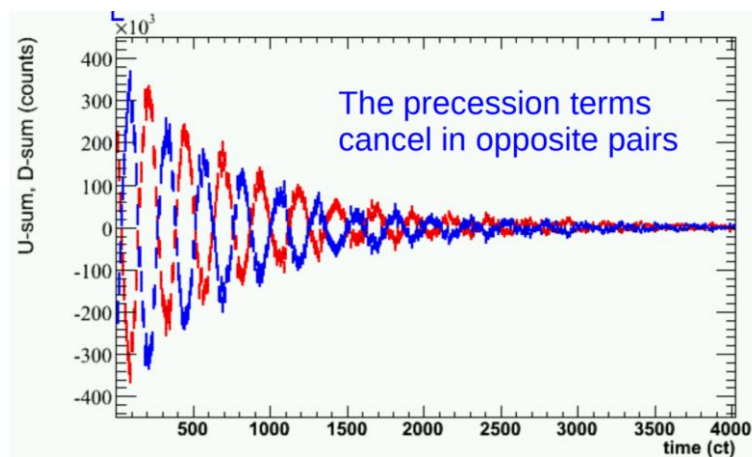
# Asymmetries and polarization

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



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

- 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!



# Muon lifetime: the MuLan experiment

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

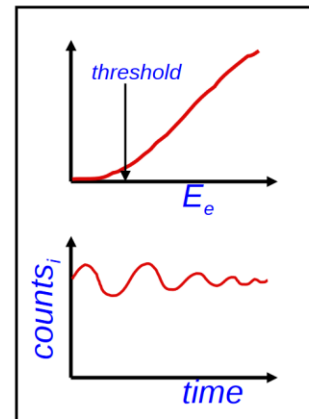
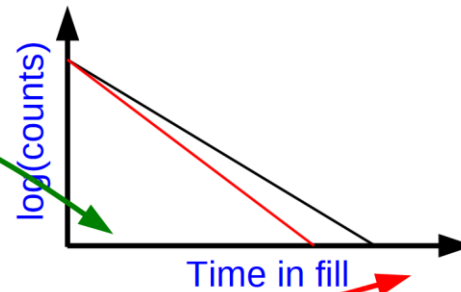
Kicker voltage sag

Pileup

Physics issues

Spin polarization

Non-flat background sources





# Muon lifetime: the MuLan experiment

