

# BU Ratio Method – 60H Unblinding

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2/25/19

# Disclaimer

- Almost all plots are from fits to the 5033A dataset (or 5033D)
- Only the single ratio fit plot is from the gold data, which I'll identify later
- This is condensed version of my report (with parts still to be written or updated) – DocDB 16270

# High Level Summary

- Lead Analysts: Nick Kinnaird, James Mott
- Positron reconstruction: Recon West
- Software Release: v9\_17\_00
- Dataset: gm2pro\_daq\_full\_run1\_60h\_5036A\_goldList
- Gain correction method: Default
- Pileup correction method: Asymmetric shadow window, doublets only
- Lost muon extraction: Triple coincidence, excluded from fit

# High Level Summary

- CBO model: Exponential envelope, frequency from tracking analysis
- VW model: Exponential envelope, constant frequency, excluded from fit
- Fit Range: 30 – 650  $\mu$ s
- $R = -20.35 \text{ ppm (blinded)} \pm \sim 1.327 \text{ ppm (stat.)} \pm \sim 0.095 \text{ ppm (syst.)}$
- $\chi^2/\text{NDF} = 4204 / 4150$
- P value = 0.2768

# Fit Function

$$R(t) = \frac{2f(t) - f_+(t) - f_-(t)}{2f(t) + f_+(t) + f_-(t)}$$

$$f_{\pm}(t) = f(t \pm T_a/2)$$

$$f(t) = N_{cbo}(t) \cdot N_{2cbo}(t) \cdot (1 + A \cdot A_{cbo}(t) \cdot \cos(\omega_a t + \phi))$$

$$N_{cbo}(t) = 1 + A_{cbo-N} \cdot e^{-t/\tau_{cbo}} \cdot \cos(\omega_{cbo}(t) \cdot t + \phi_{cbo-N})$$

$$\textcolor{red}{N_{2cbo}(t) = 1 + A_{2cbo-N} \cdot e^{-t/\tau_{cbo}} \cdot \cos(2 \cdot \omega_{cbo}(t) \cdot t + \phi_{2cbo-N})}$$

$$\textcolor{red}{A_{cbo}(t) = 1 + A_{cbo-A} \cdot e^{-t/\tau_{cbo}} \cdot \cos(\omega_{cbo}(t) \cdot t + \phi_{cbo-A})}$$

$$\omega_a = 2\pi \cdot 0.2291 \text{ MHz} \cdot (1 + R \times 10^{-6})$$

These gave stable fit parameters for 5033A but not the gold data set – still need to play around some.

# Analysis Procedures

# Histogramming

- Apply artificial dead time (ADT) of 6 ns
- Randomize times with  $\pm 149.15$  ns
- Apply energy threshold of 1700 MeV
- Split data into 4 histograms with weighting as:

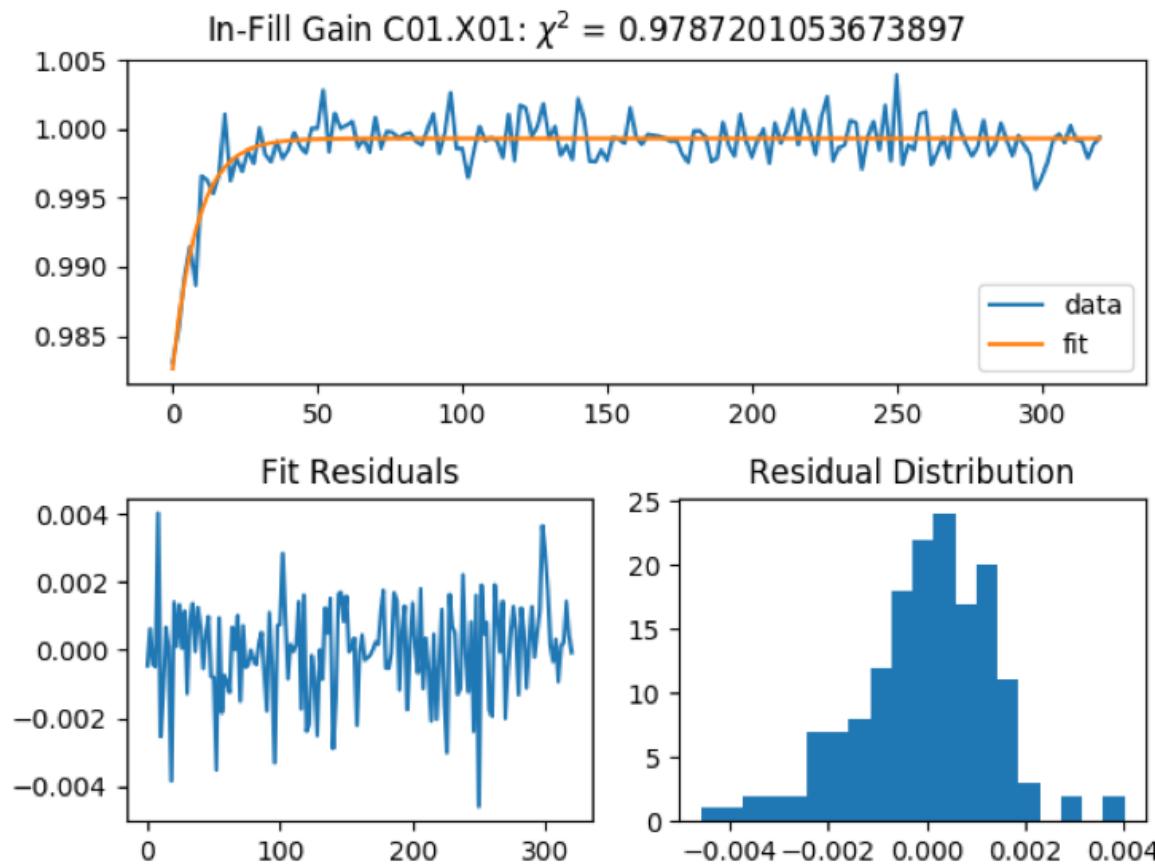
$$u_+(t) : u_-(t) : v_1(t) : v_2(t) = e^{T/2\tau} : e^{-T/2\tau} : 1 : 1$$

- With times in the first two histograms shifted down and up half a g-2 period respectively
- Form the ratio histogram and fit

$$U(t) = u_+(t) + u_-(t)$$
$$V(t) = v_1(t) + v_2(t)$$
$$R(t) = \frac{V(t) - U(t)}{V(t) + U(t)}$$

# Gain Correction

- Default from calibration team



# Pileup Correction

- For each fill and each calorimeter create a vector of time – energy pairs from the clusters
- For each cluster look in a time window (SDT) a gap time away (SGT) for a shadow hit
- Construct pileup doublets if a shadow hit is found:

$$E_{doublet} = C \cdot (E_1 + E_2) \quad \text{C set to 1 by default}$$

$$t_{doublet} = \frac{t_1 \cdot E_1 + (t_2 - SGT) \cdot E_2}{E_1 + E_2}$$

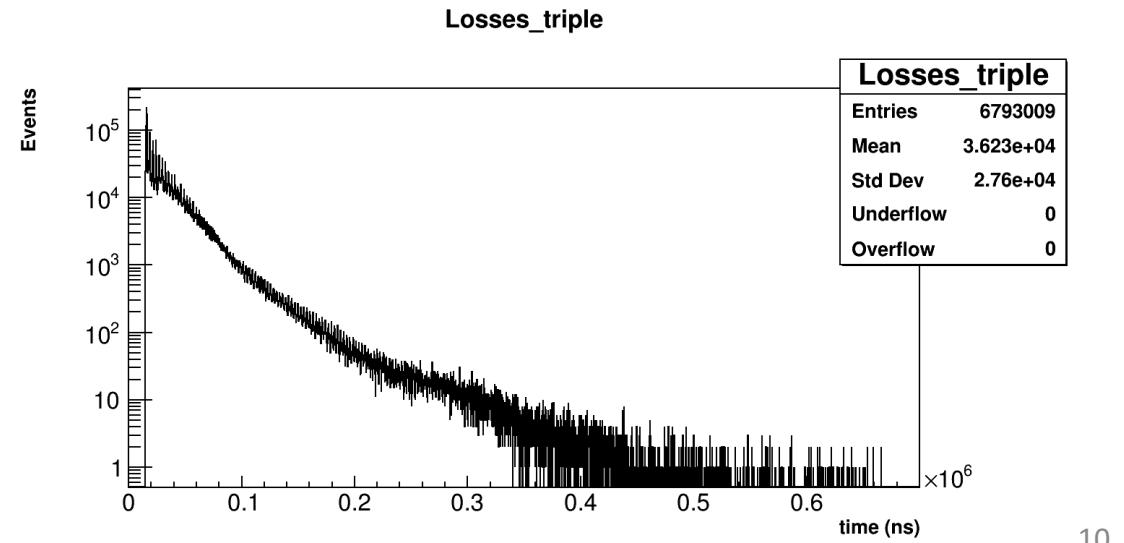
- Construct pileup spectra:  $P = D - S$  (doublets minus singlets)
- Subtract pileup spectra off calorimeter spectra

# Lost Muon Extraction

- Triple coincidence of clusters in 3 consecutive calorimeters are made with an energy cut of  $10 \text{ MeV} < E < 250 \text{ MeV}$  and  $5 \text{ ns} < dt < 8.5 \text{ ns}$

$$\Lambda(t) = 1 - \kappa_{loss} \int_0^t L(t') e^{(t'/\gamma\tau_\mu)} dt'$$

- Not included in ratio fit



# CBO

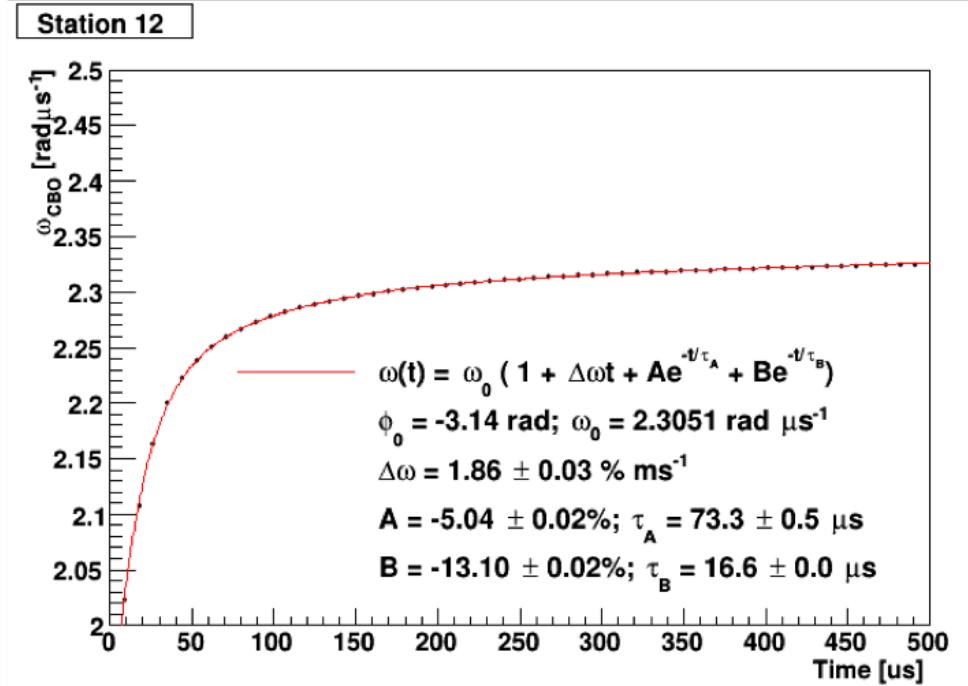
- Frequency from tracking analysis:
- Function pieces as:
- Not all cbo terms included in calorimeter sum fit, all included in individual calo fits

$$N_{cbo}(t) = 1 + A_{cbo-N} \cdot e^{-t/\tau_{cbo}} \cdot \cos(\omega_{cbo}(t) \cdot t + \phi_{cbo-N}),$$

$$N_{2cbo}(t) = 1 + A_{2cbo-N} \cdot e^{-t/\tau_{cbo}} \cdot \cos(2 \cdot \omega_{cbo}(t) \cdot t + \phi_{2cbo-N}),$$

$$A_{cbo}(t) = 1 + A_{cbo-A} \cdot e^{-t/\tau_{cbo}} \cdot \cos(\omega_{cbo}(t) \cdot t + \phi_{cbo-A}),$$

$$\phi_{cbo}(t) = 1 + A_{cbo-\phi} \cdot e^{-t/\tau_{cbo}} \cdot \cos(\omega_{cbo}(t) \cdot t + \phi_{cbo-\phi})$$

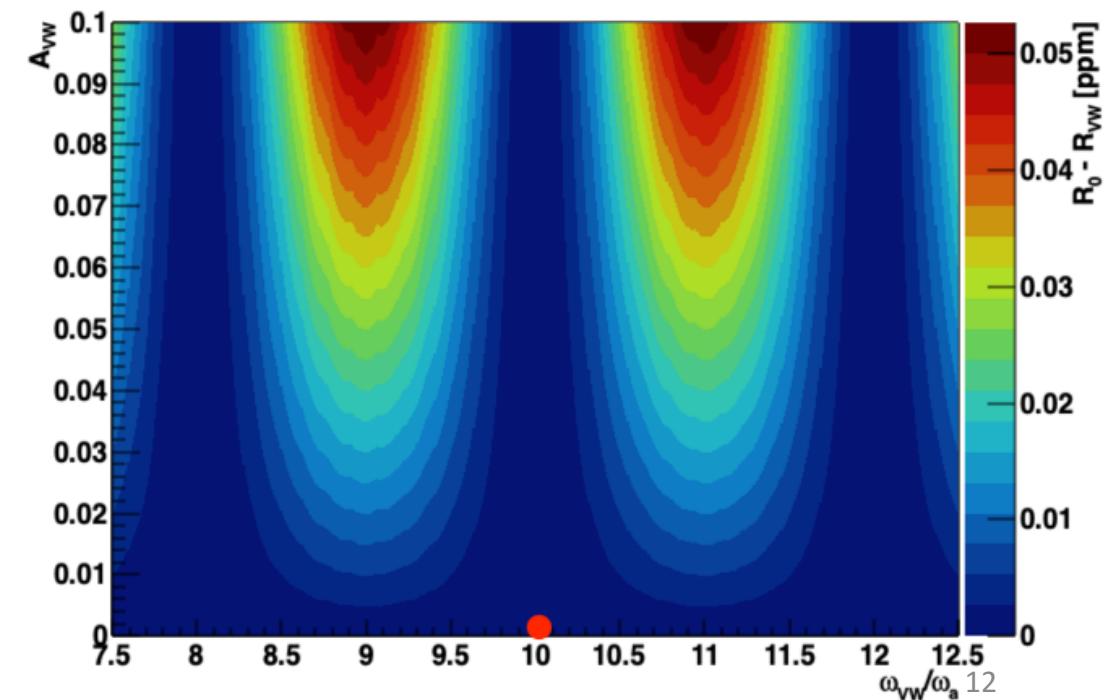


# VW

- Form as:

$$V(t) = 1 + A_{VW} e^{-t/\tau_{VW}} \cos(\omega_{VW} t + \phi_{VW})$$

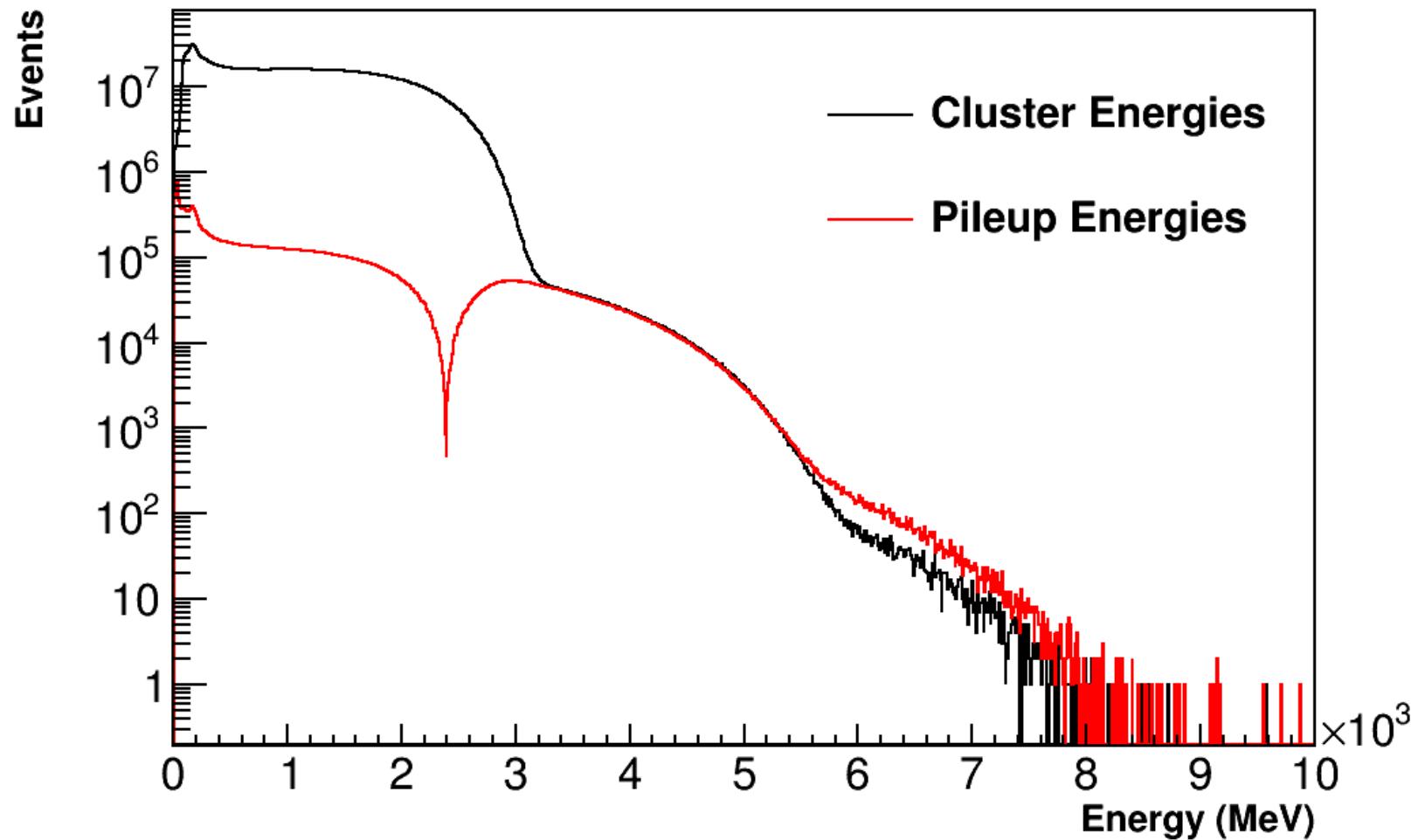
- Not included in ratio fit, since it divides out due to the VW frequency being very near an even multiple of the g-2 frequency

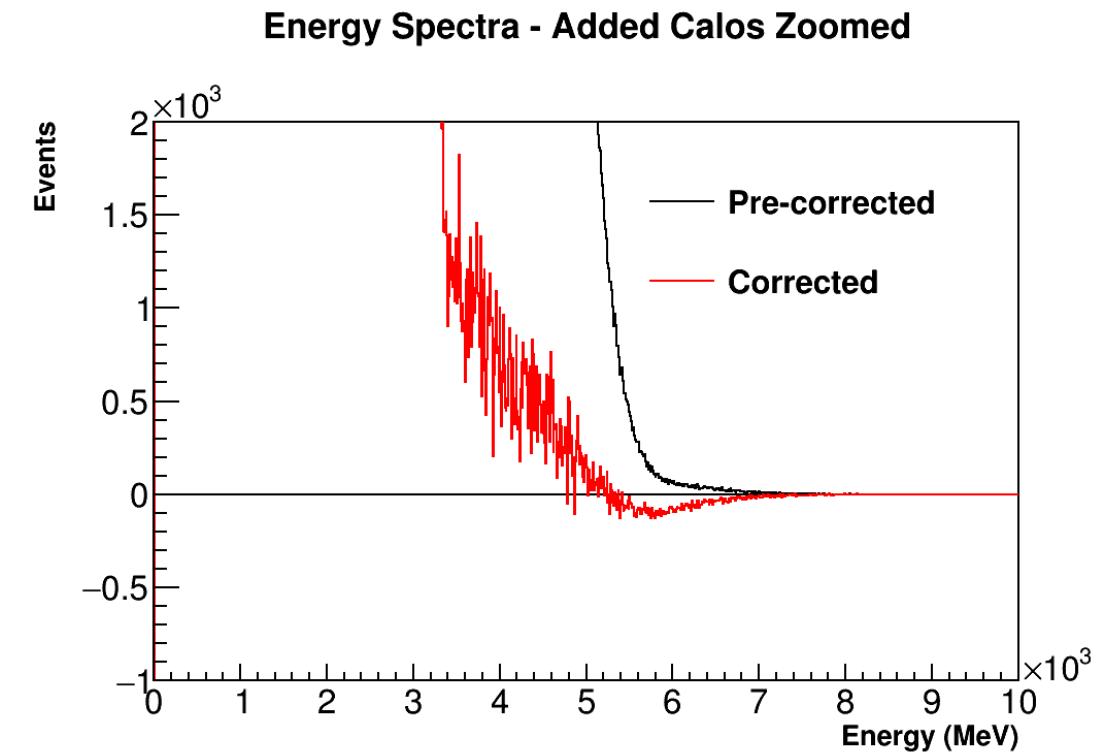
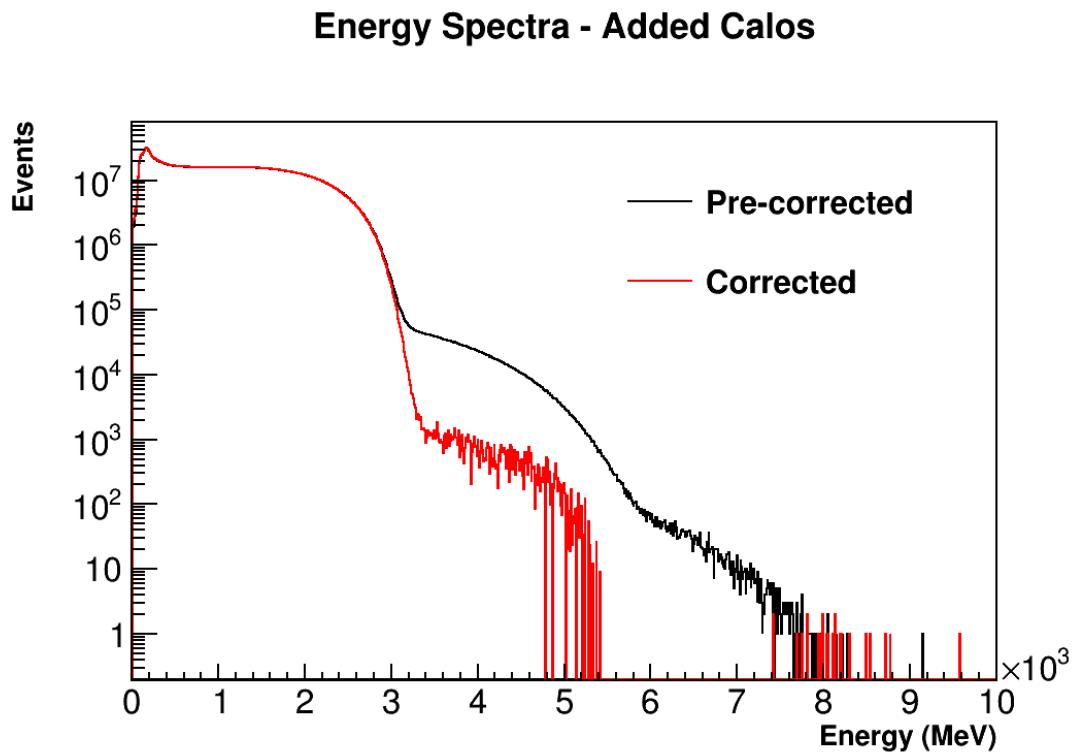


# Analysis Results

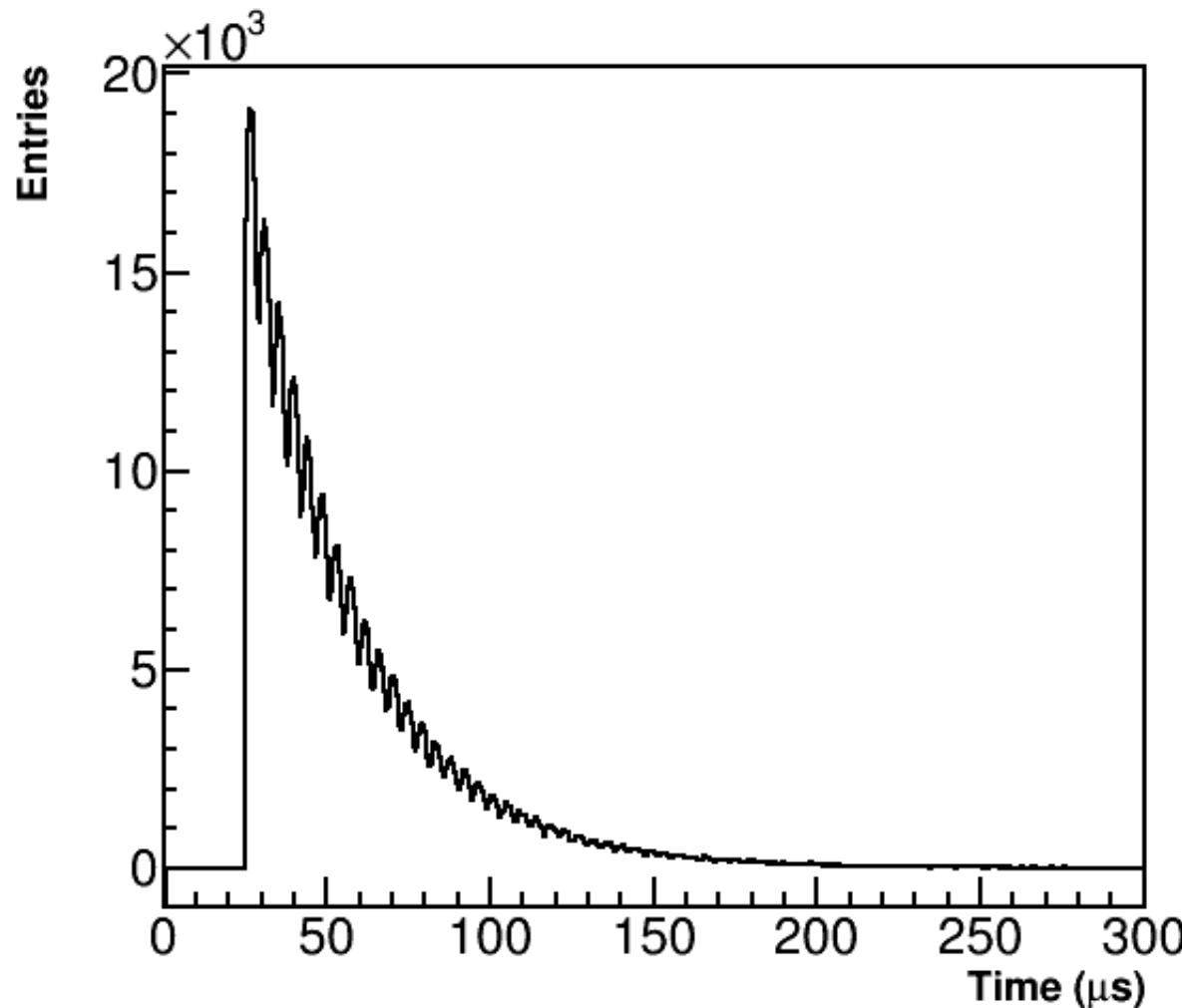
# Pileup Correction

**Cluster Energies vs Pileup Energies**

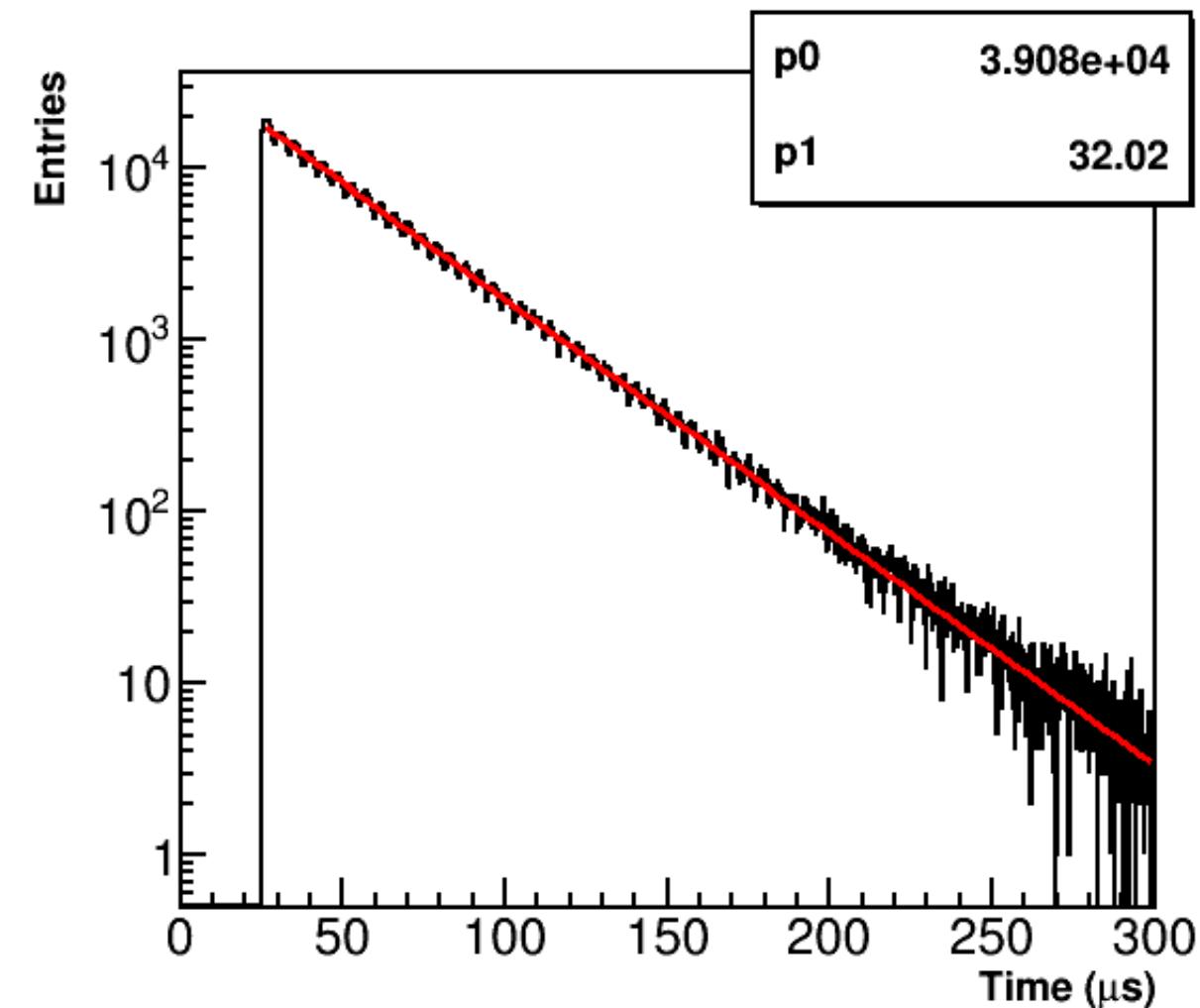




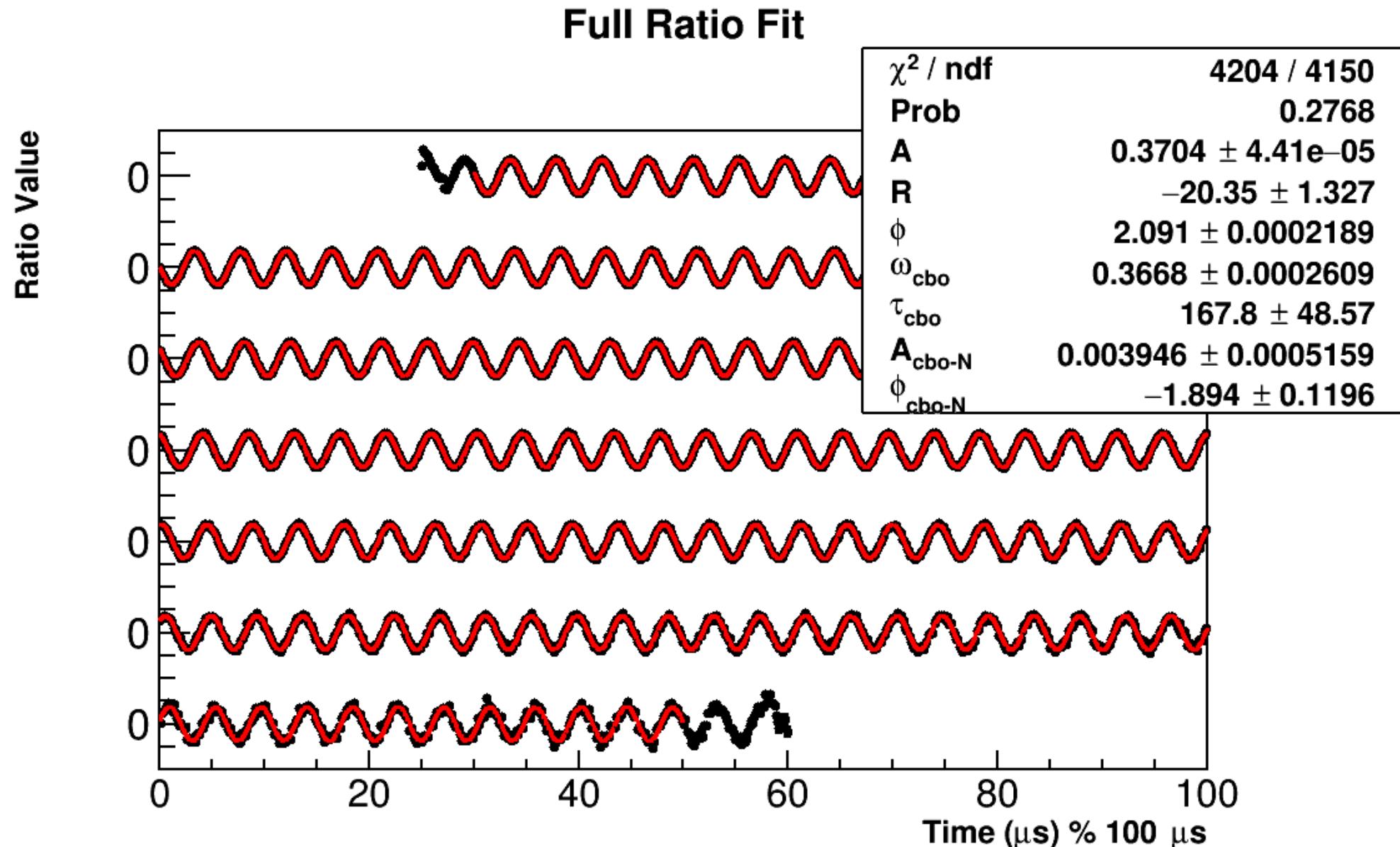
Pileup Time Spectrum (Above Threshold)



Pileup Time Spectrum (Above Threshold)

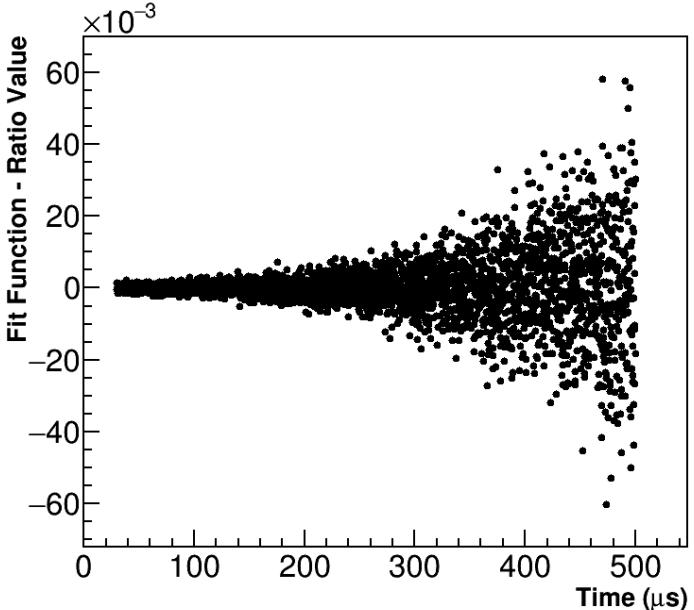


# Fit – Gold Data

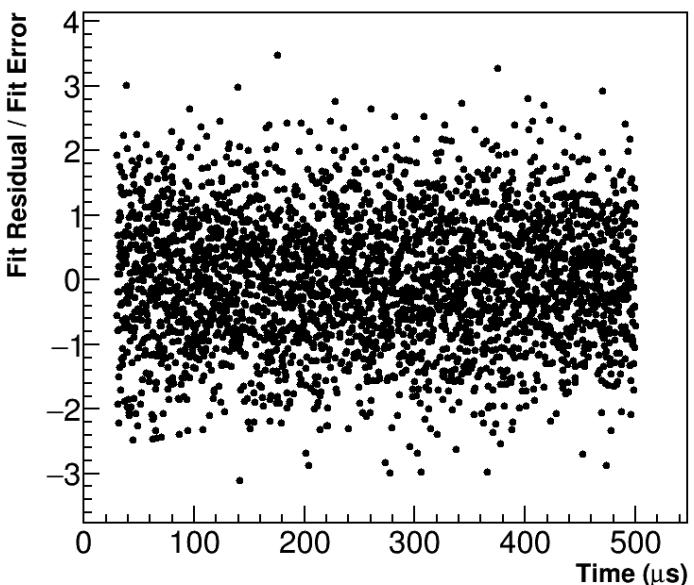


Missing 190/1,498,587 Fills

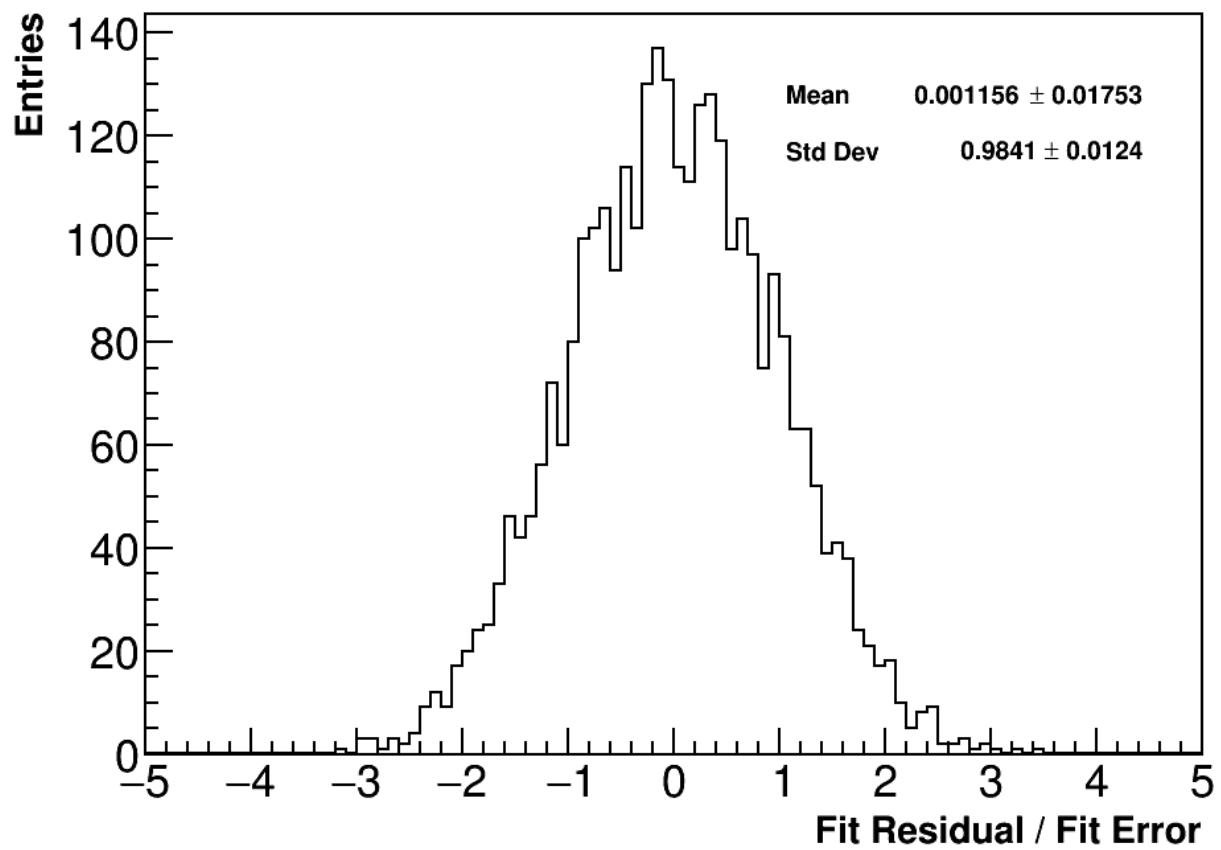
**Fit**



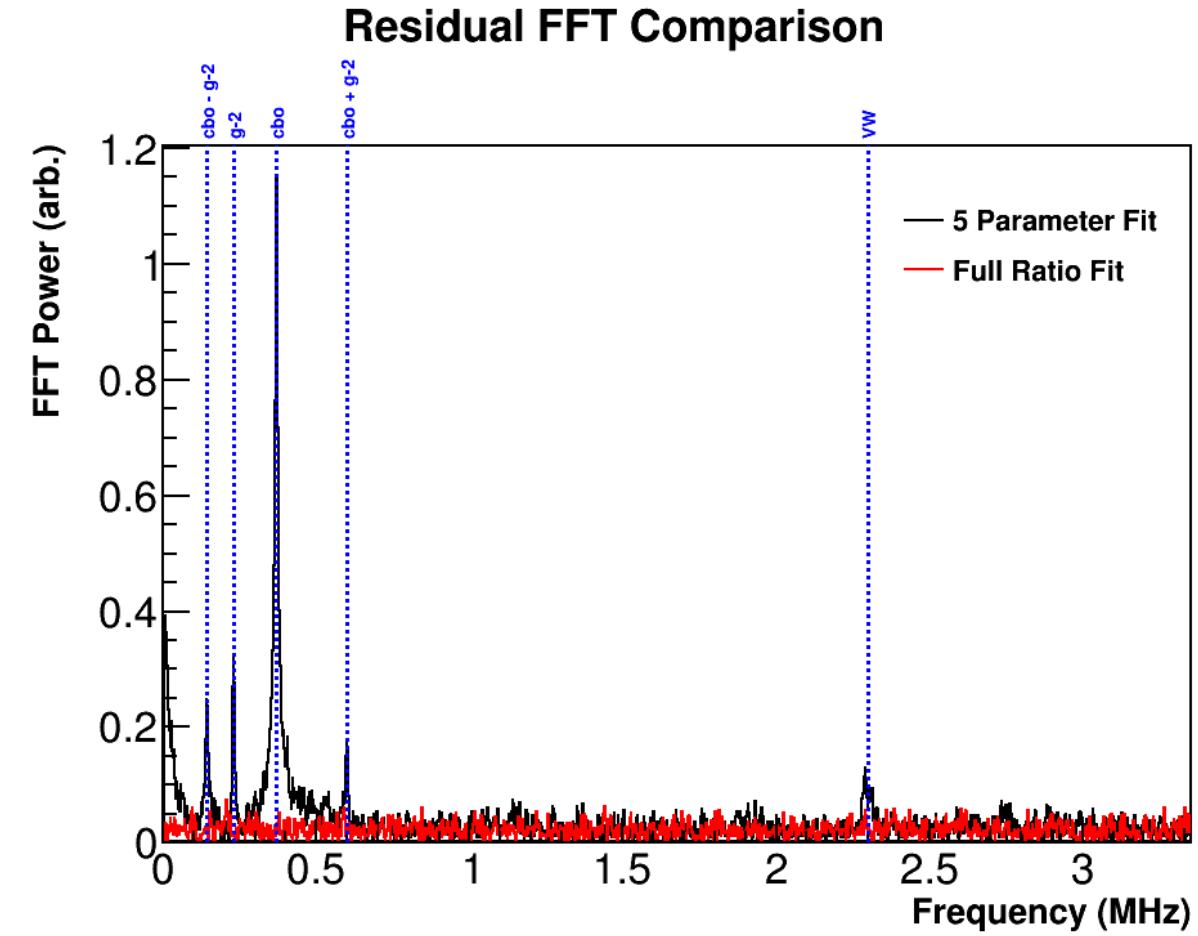
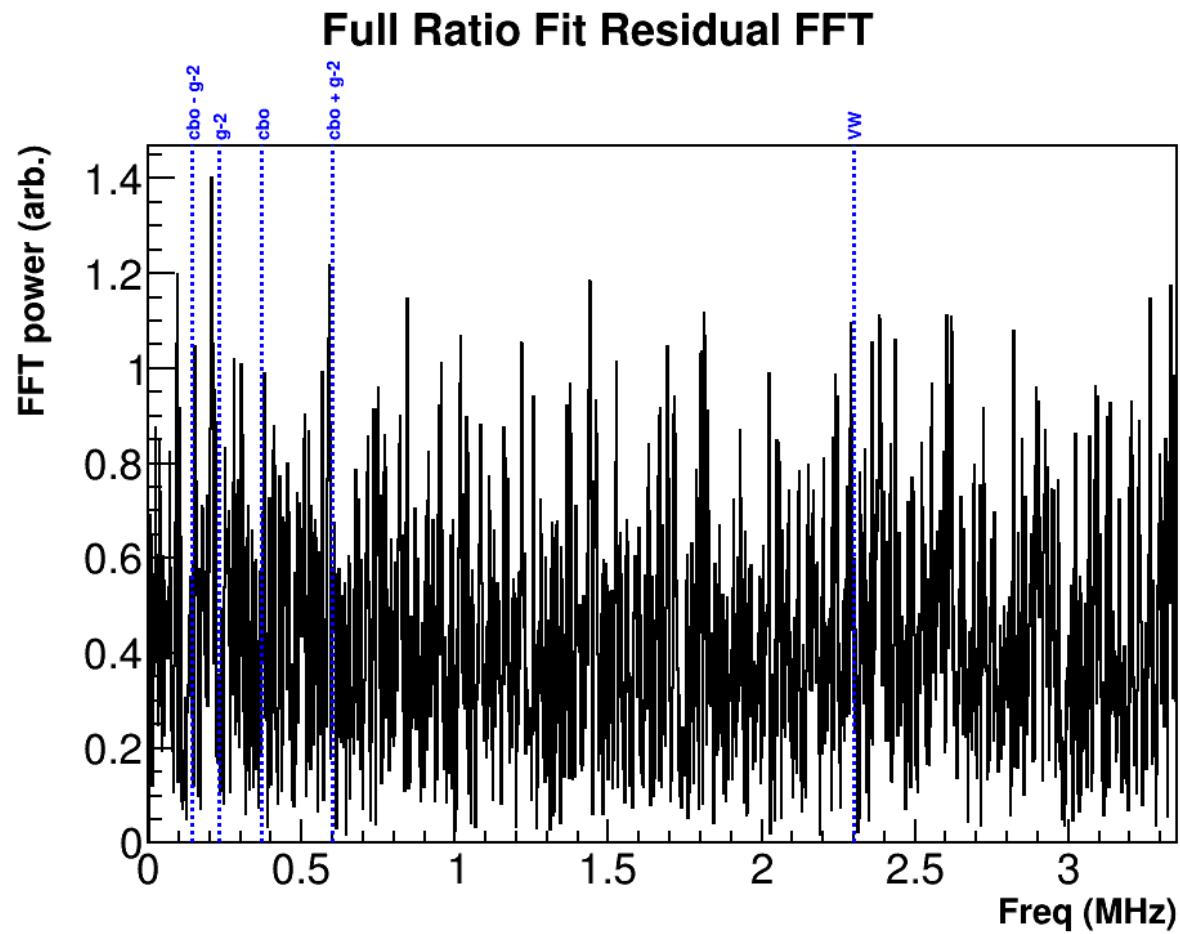
**Full Ratio Fit Pull**



**Full Ratio Fit Projected Pull**

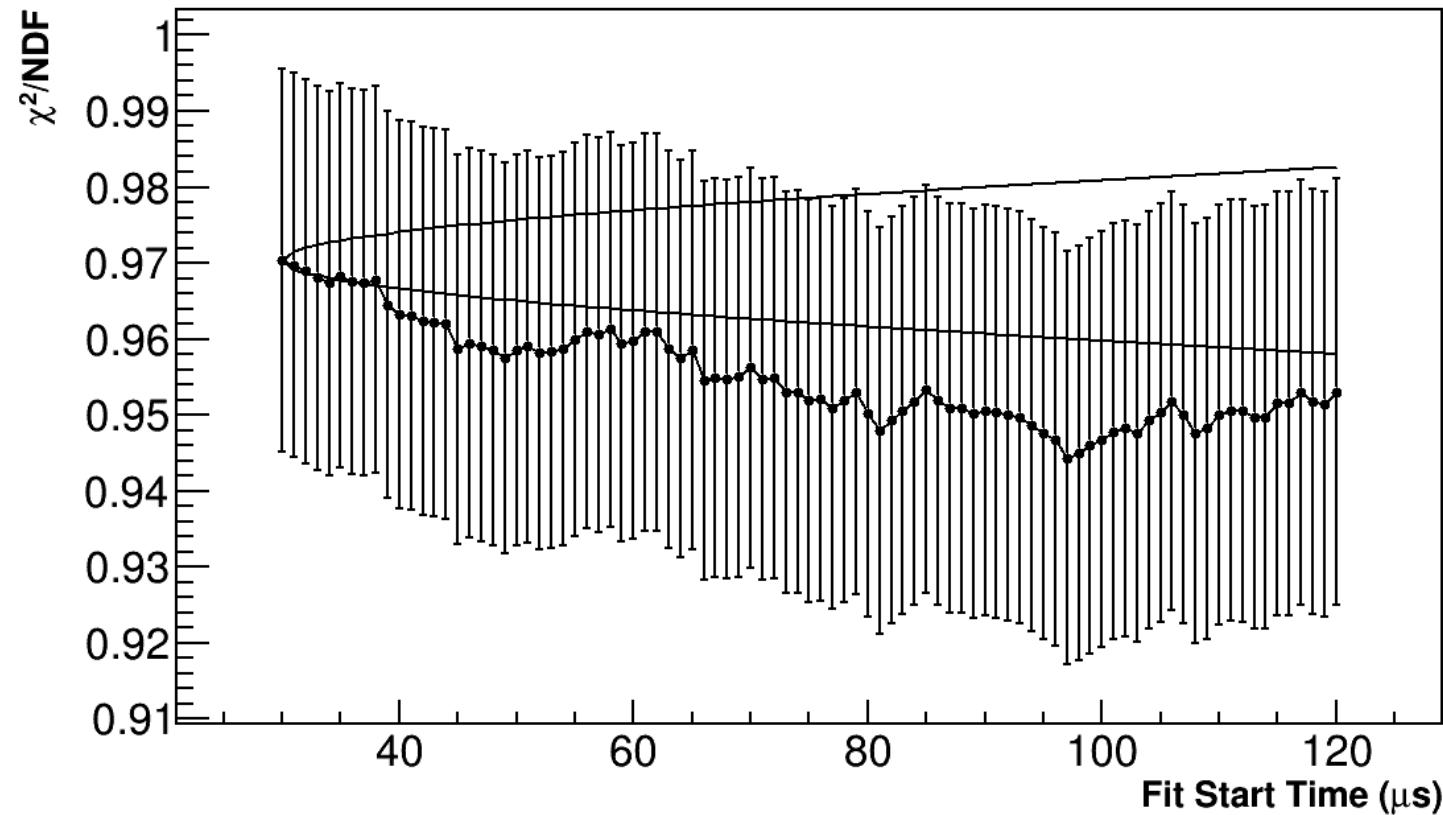


# Fit Residual FFT



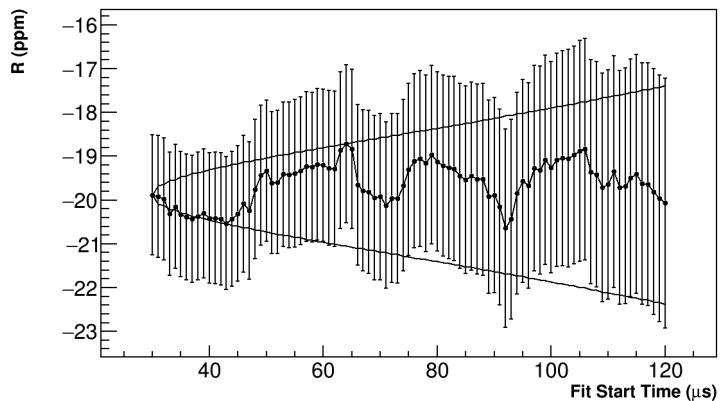
# Fit Start Time Scan

**Full Ratio Fit  $\chi^2/\text{NDF}$  Vs Fit Start Time**

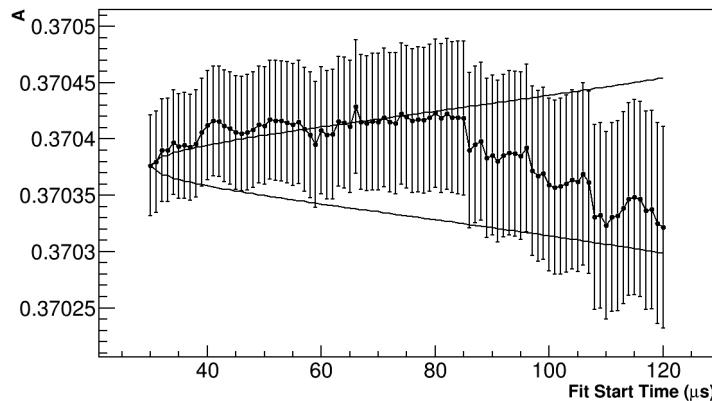


# Fit Start Time Scan

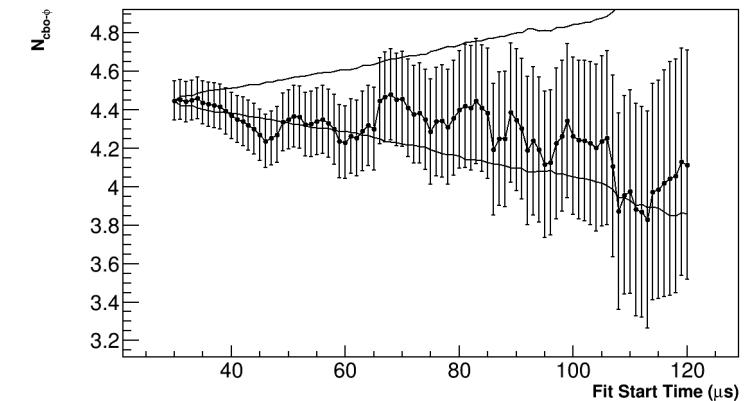
Full Ratio Fit R Vs Fit Start Time



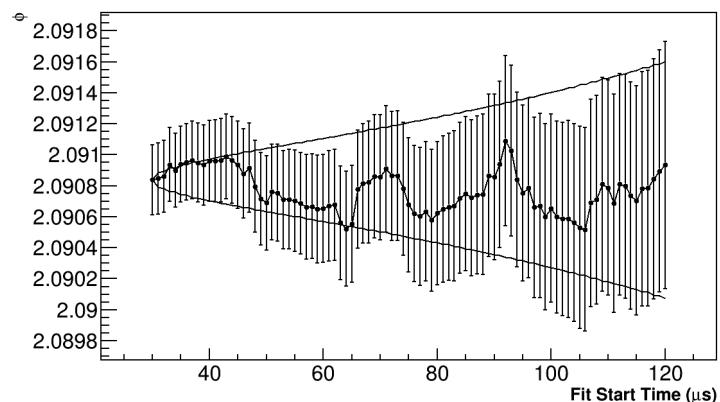
Full Ratio Fit A Vs Fit Start Time



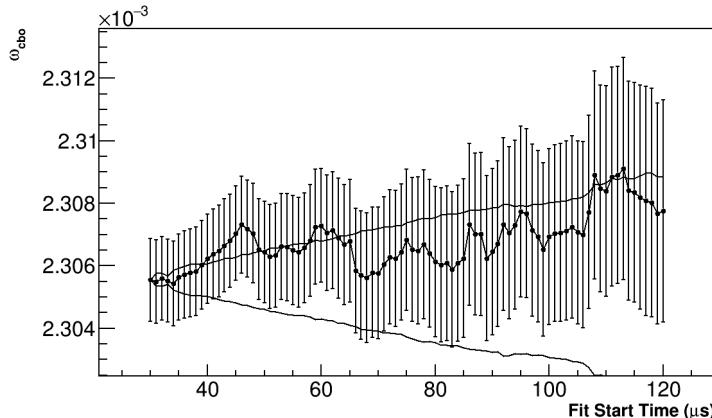
Full Ratio Fit  $N_{cbo-\phi}$  Vs Fit Start Time



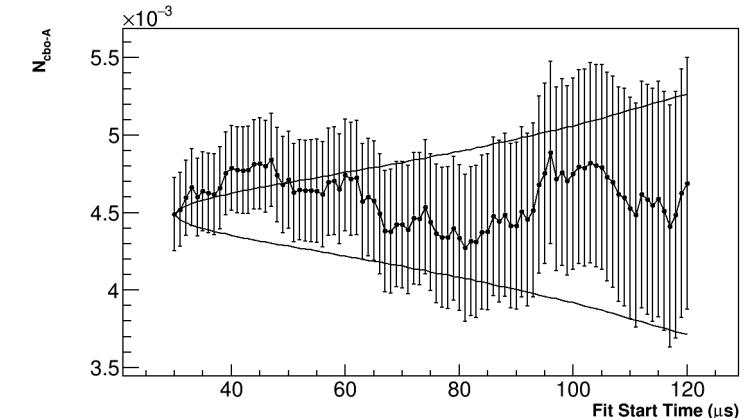
Full Ratio Fit  $\phi$  Vs Fit Start Time



Full Ratio Fit  $\omega_{cbo}$  Vs Fit Start Time

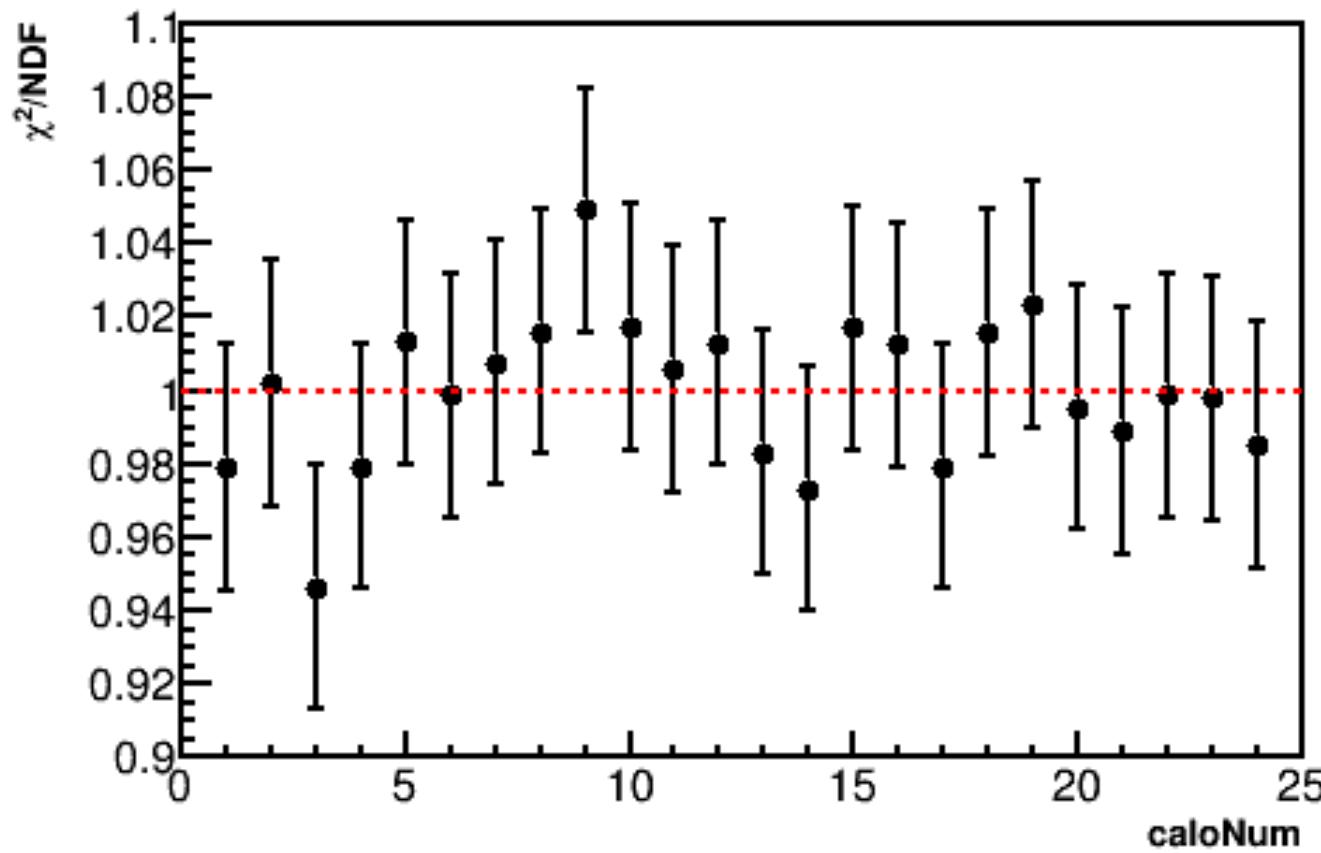


Full Ratio Fit  $N_{cbo-A}$  Vs Fit Start Time



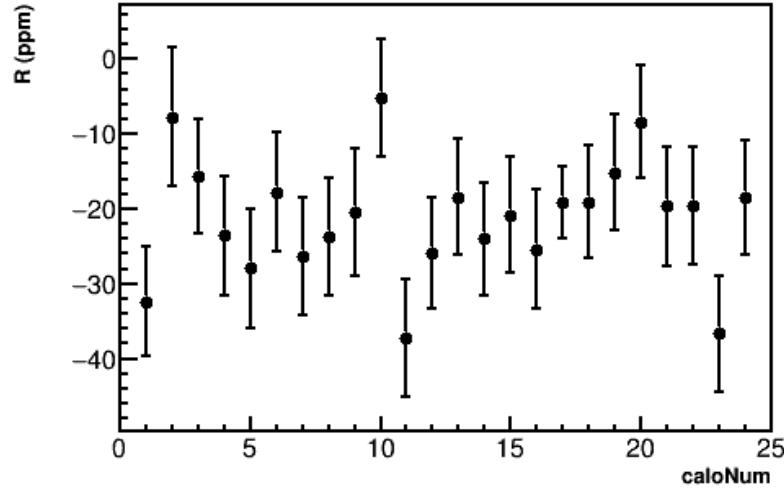
# Per Calo Fits

Full Ratio Fit  $\chi^2/\text{NDF}$  Vs Calo Num

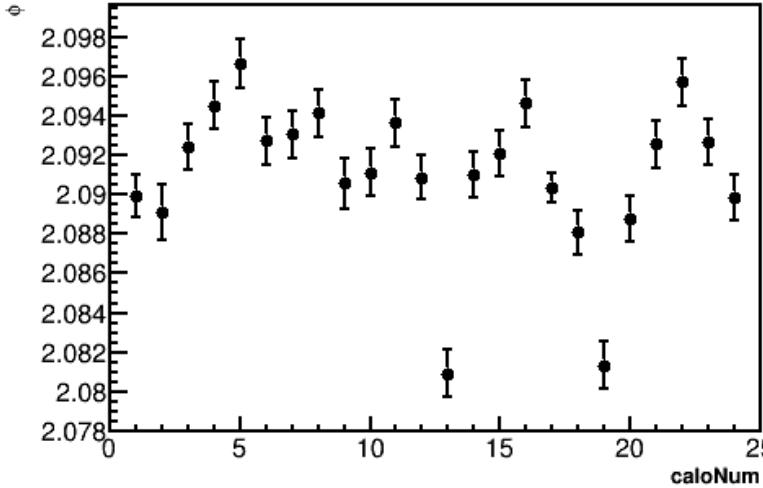


# Per Calo Fits

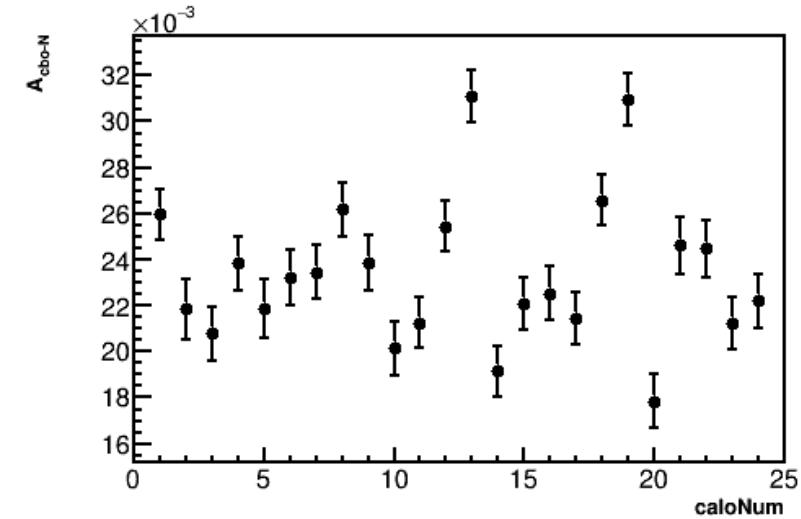
Full Ratio Fit R Vs Calo Num



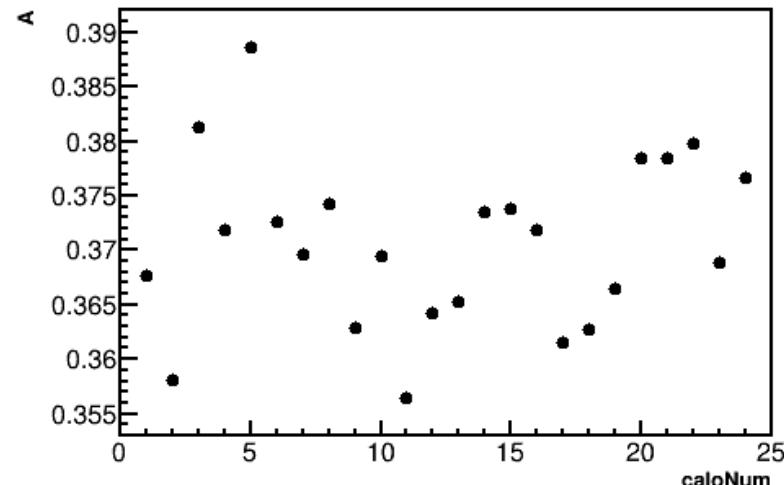
Full Ratio Fit  $\phi$  Vs Calo Num



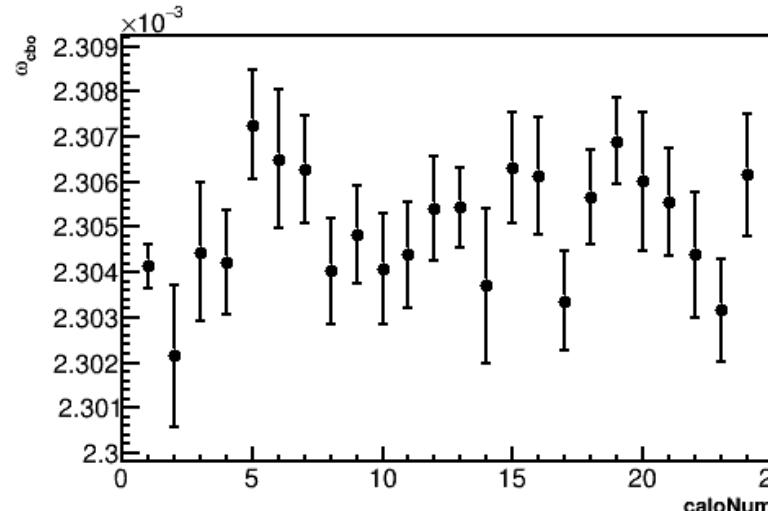
Full Ratio Fit  $A_{cbo-N}$  Vs Calo Num



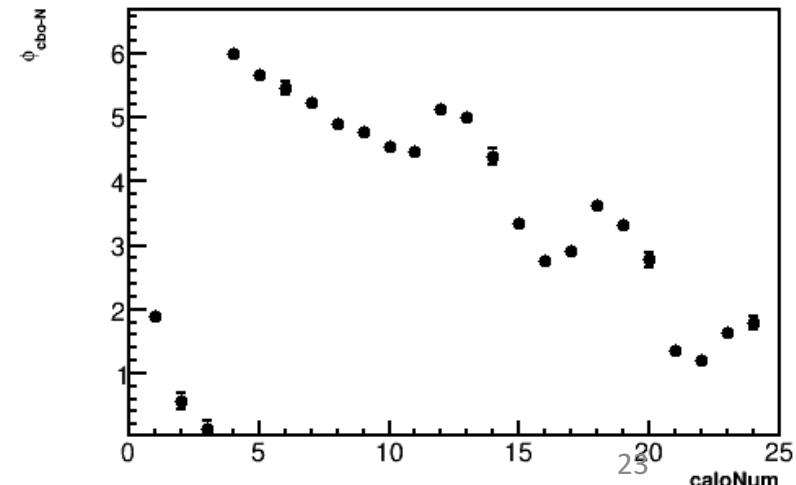
Full Ratio Fit A Vs Calo Num



Full Ratio Fit  $\omega_{cbo}$  Vs Calo Num

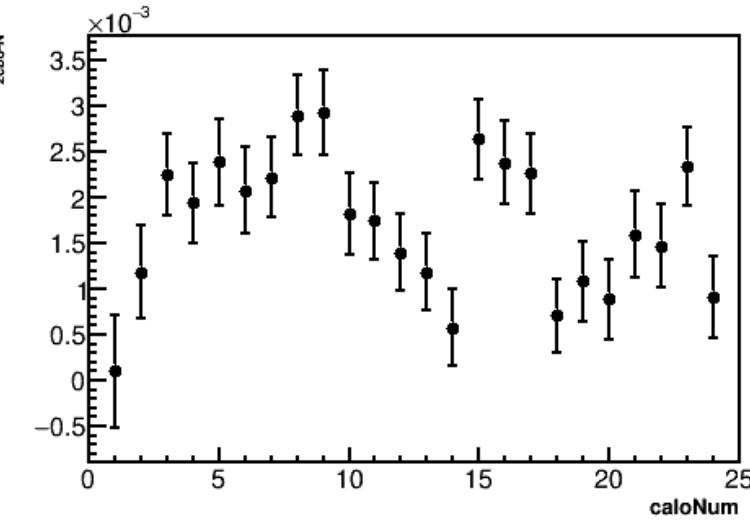


Full Ratio Fit  $\phi_{cbo-N}$  Vs Calo Num

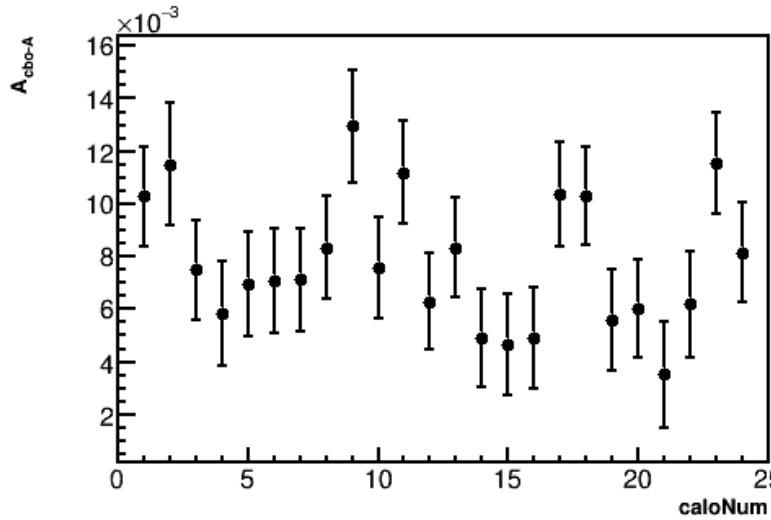


# Per Calo Fits

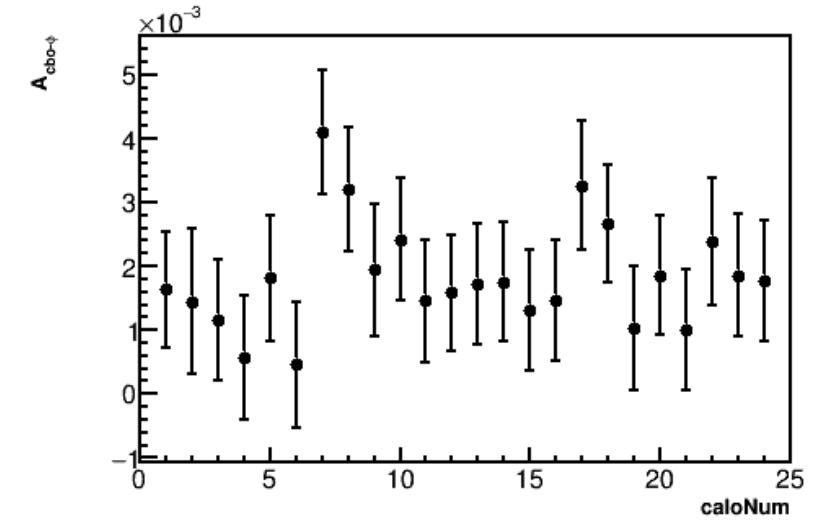
Full Ratio Fit  $A_{2\text{cbo-N}}$  Vs Calo Num



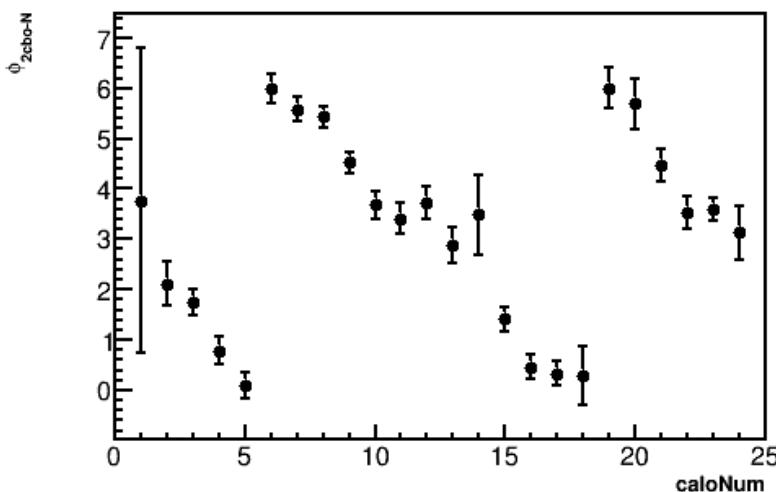
Full Ratio Fit  $A_{\text{cbo-A}}$  Vs Calo Num



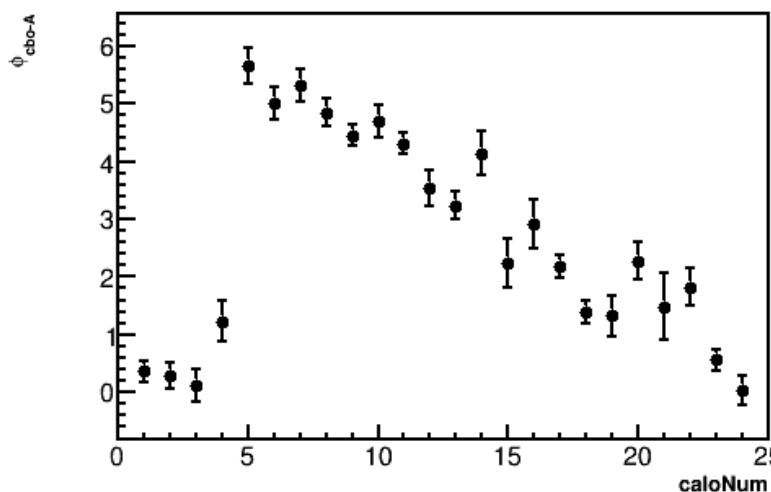
Full Ratio Fit  $A_{\text{cbo-}\phi}$  Vs Calo Num



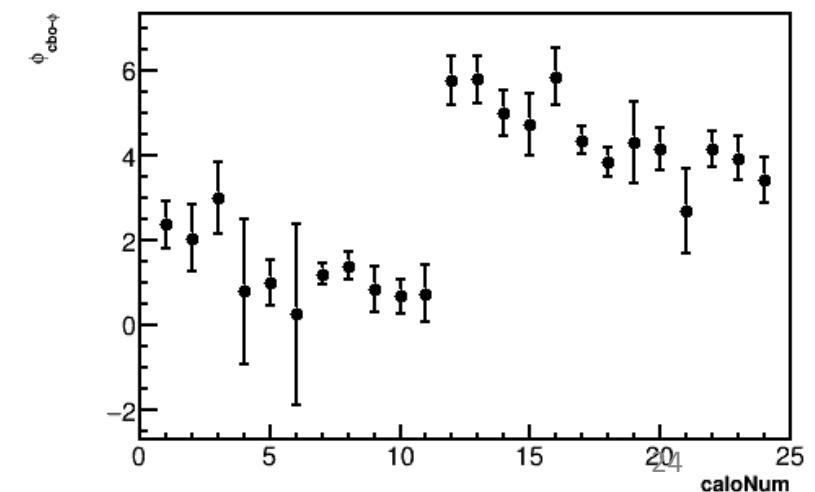
Full Ratio Fit  $\phi_{2\text{cbo-N}}$  Vs Calo Num



Full Ratio Fit  $\phi_{\text{cbo-A}}$  Vs Calo Num



Full Ratio Fit  $\phi_{\text{cbo-}\phi}$  Vs Calo Num



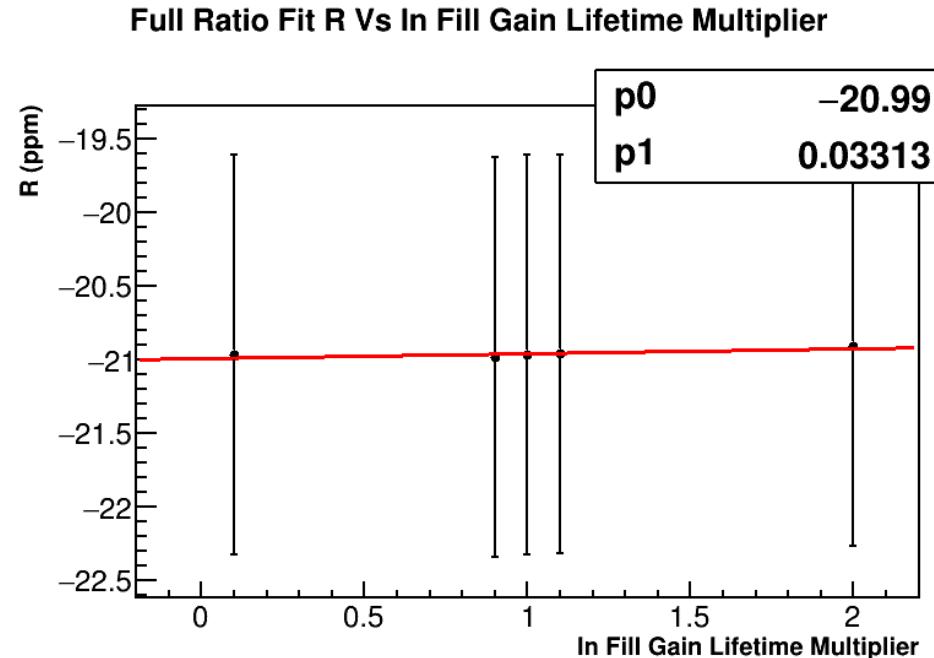
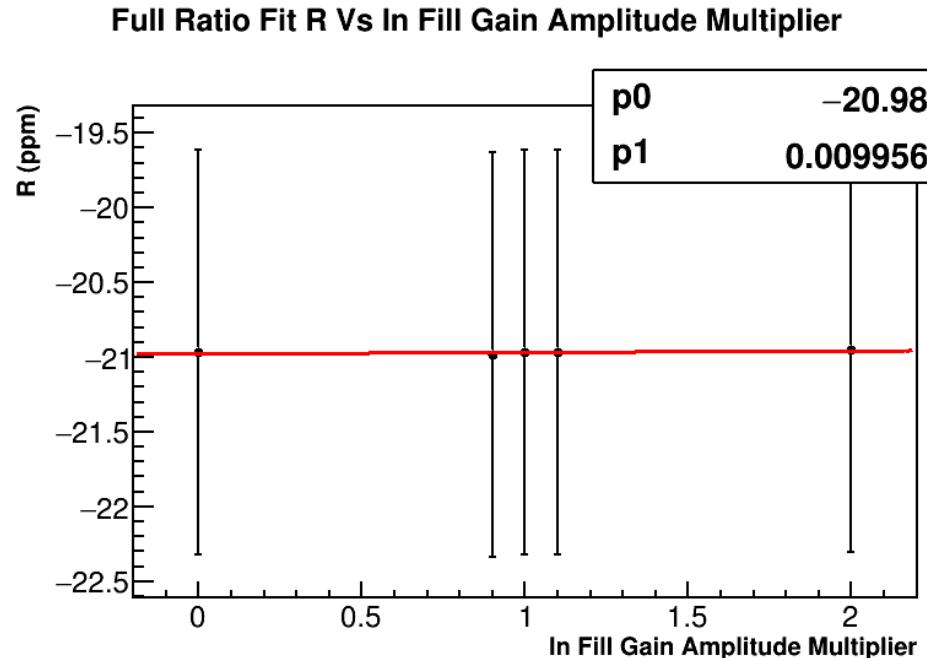
# Systematic Evaluations

- Everything here evaluated on 5033A dataset

# In-Fill Gain

$$E = E_0(1 - A \cdot e^{-t/\tau})$$

- Stored crystal in fill gain amplitude and lifetime parameters
- Undid the correction at the histogram phase and reapplied new correction factors (in multiples of the original factors)



# In-Fill Gain

- Systematic error calculated in the usual way, slope times uncertainty

$$\delta R_A = \delta \alpha_A \times \frac{dR}{d\alpha_A}$$

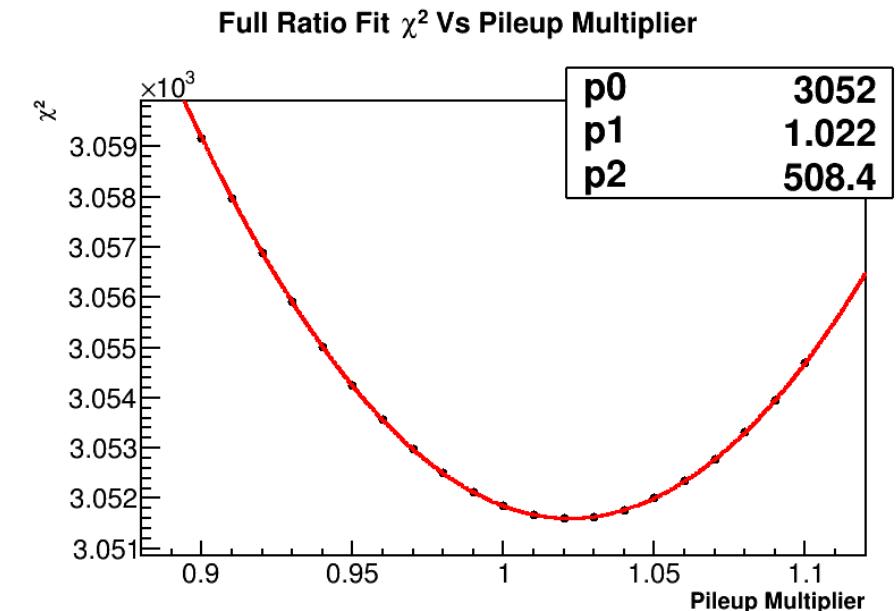
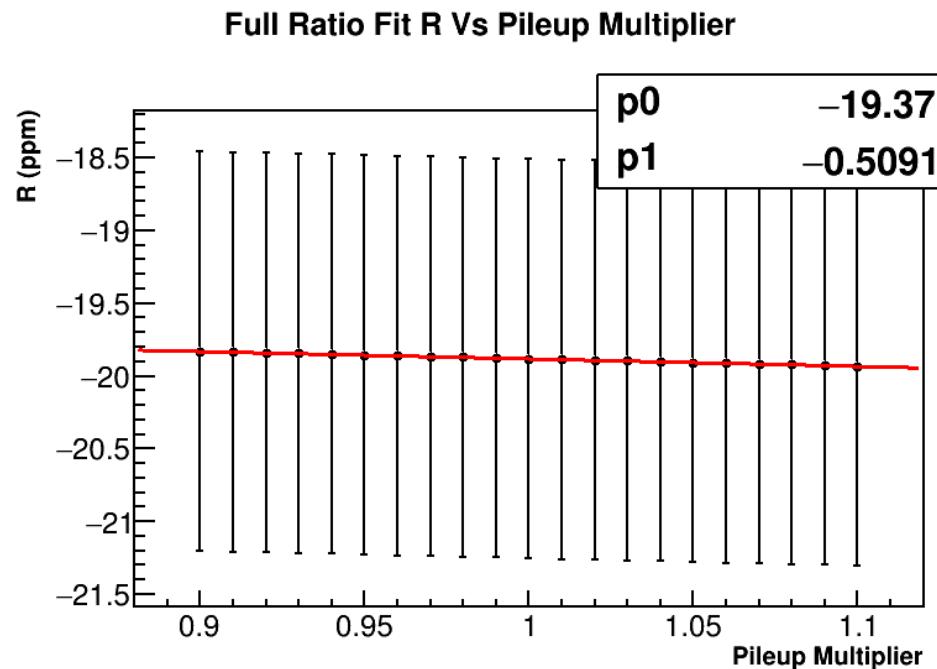
$$\delta R_\tau = \delta \alpha_\tau \times \frac{dR}{d\alpha_\tau}$$

- Taking the uncertainty as 10%, I get a systematic error (added in quadrature) of **3.5 ppb**
- Need to estimate the uncertainty in a better way, and want to take more points and recalculate this

# Gain

- For the SDTP, want to calculate R w/ and w/o it to calculate the systematic error – I think it's going to be very small
- Need to do this at the reconstruction level

# Pileup Amplitude



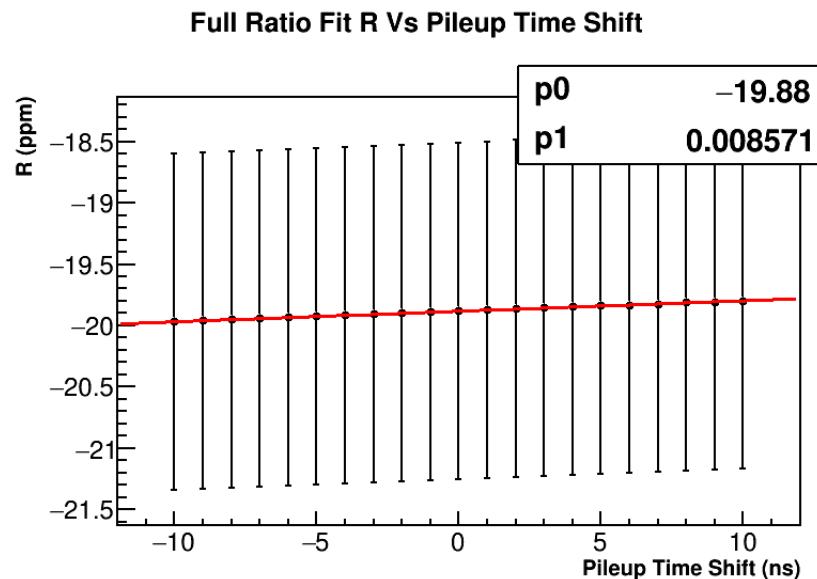
$$\delta\alpha_{pm} = \sqrt{1/508.4}$$

$$\delta R_{pm} = \delta\alpha_{pm} \times \frac{dR}{d\alpha_{pm}}$$

Systematic error: **22.6 ppb**

# Pileup Phase

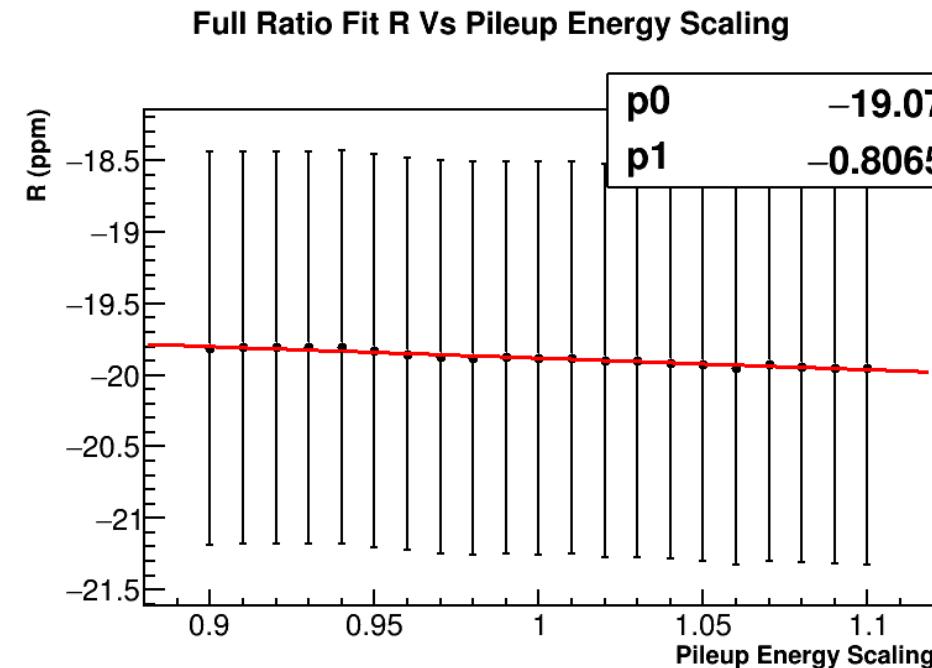
- Time shift pulses before filling pileup histograms and refit



$$\delta R_{pp} = \delta \alpha_{pp} \times \frac{dR}{d\alpha_{pp}}$$

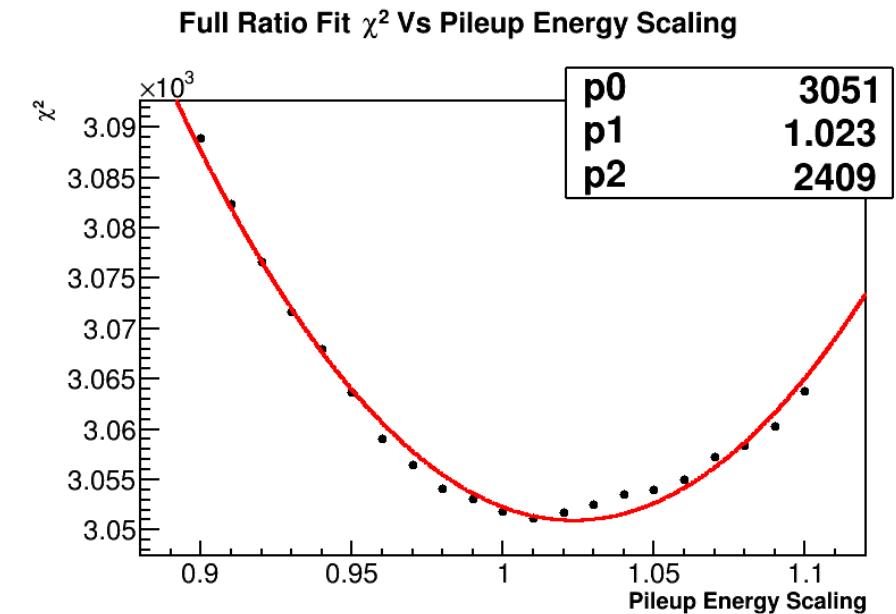
- Take the uncertainty on the pileup time conservatively at 3 ns
- Systematic error: **25.7 ppb**

# Pileup Phase



$$\delta R_{pe} = \delta \alpha_{pe} \times \frac{dR}{d\alpha_{pe}}$$

$$E_{doublet} = C \cdot (E_1 + E_2)$$



$$\delta \alpha_{pm} = \sqrt{1/2409}$$

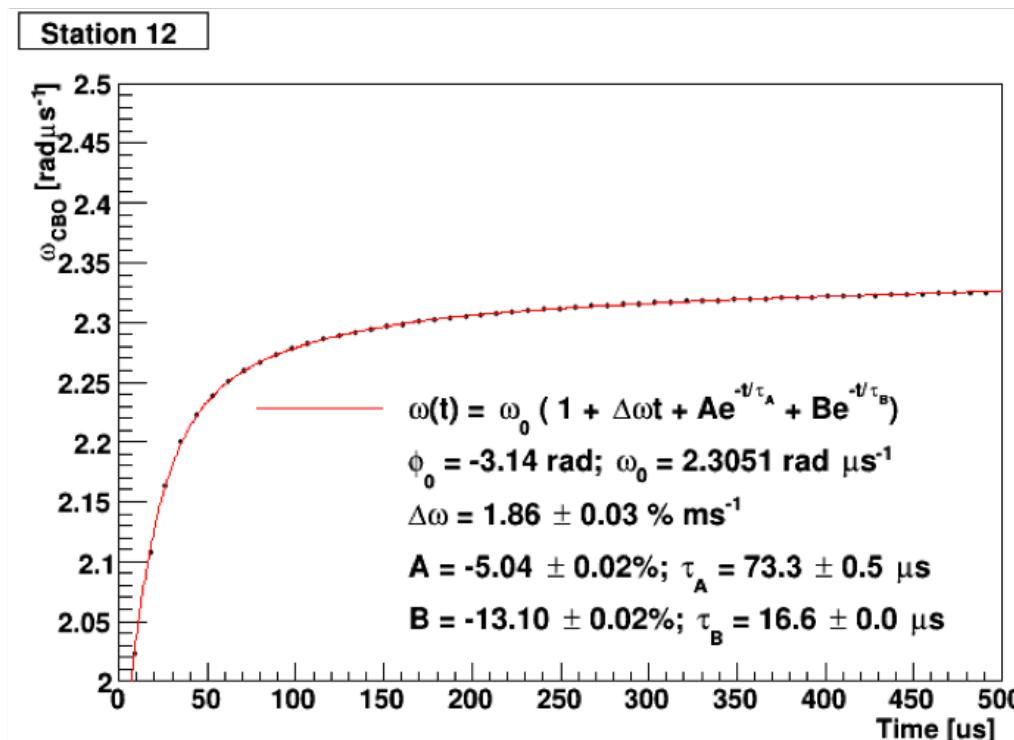
Systematic error: 16.1 ppb

# Total Pileup Systematic Error

- **37.8 ppb** added in quadrature

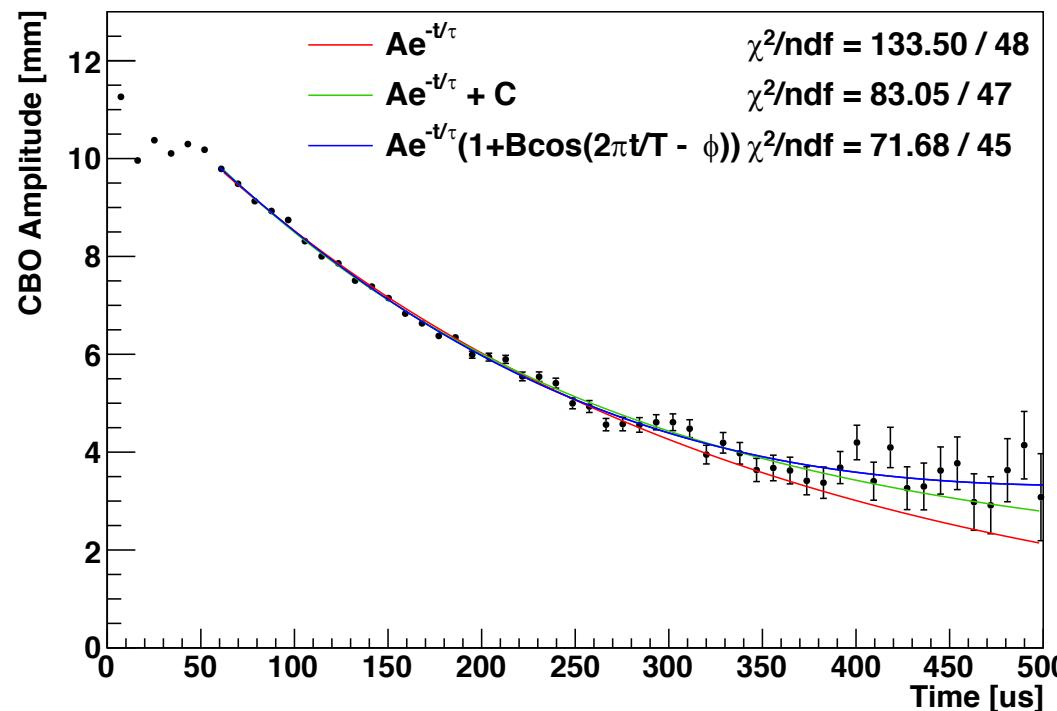
# CBO Frequency

- Varied parameters in frequency function by  $\pm 2\sigma$
- Systematic error conservatively estimated at **30 ppb**



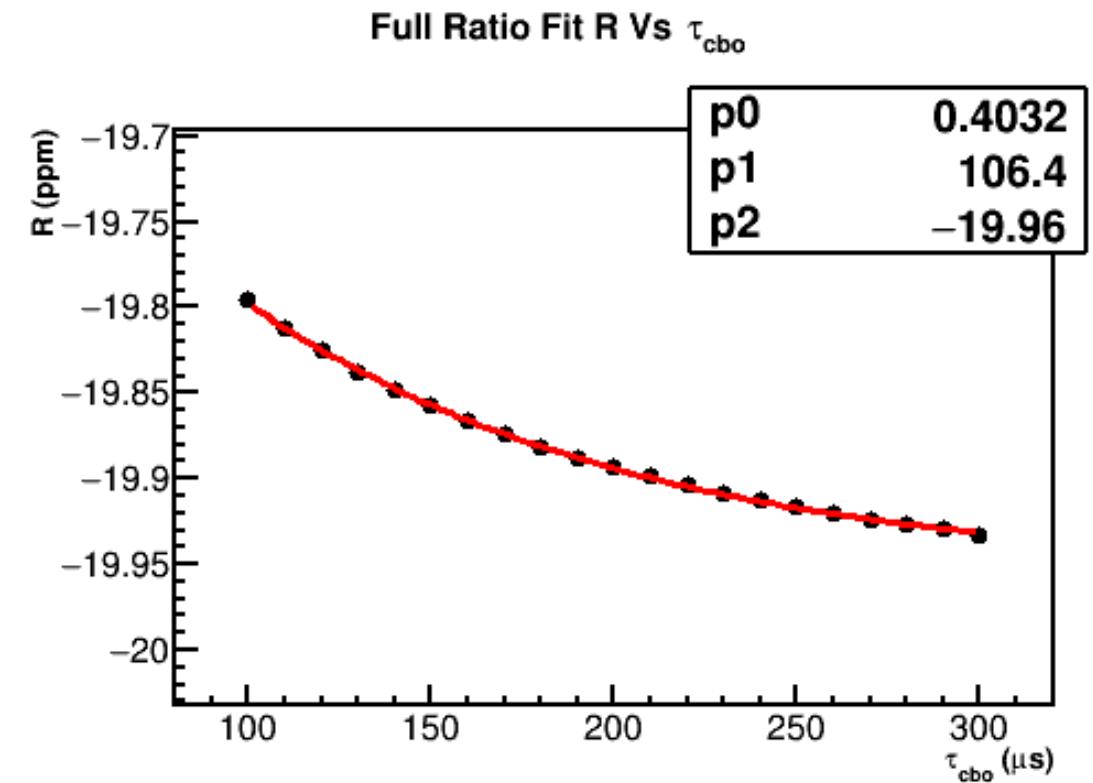
# CBO Shape

- Fit with various shapes determined in tracking analysis
- Largest change on R taken as the systematic error at **21.1 ppb**



# CBO Lifetime

- The lifetime was originally fixed in the ratio fit, and is now going to be left free – but I calculated a systematic error for it which I'll include here
- Scanned over the lifetime parameter
- R vs lifetime fit to a parabola, and the change in R for the fixed lifetime  $\pm$  the lifetime error from a T method fit taken as the systematic error at **12.1 ppb**



# Total CBO Systematic Error

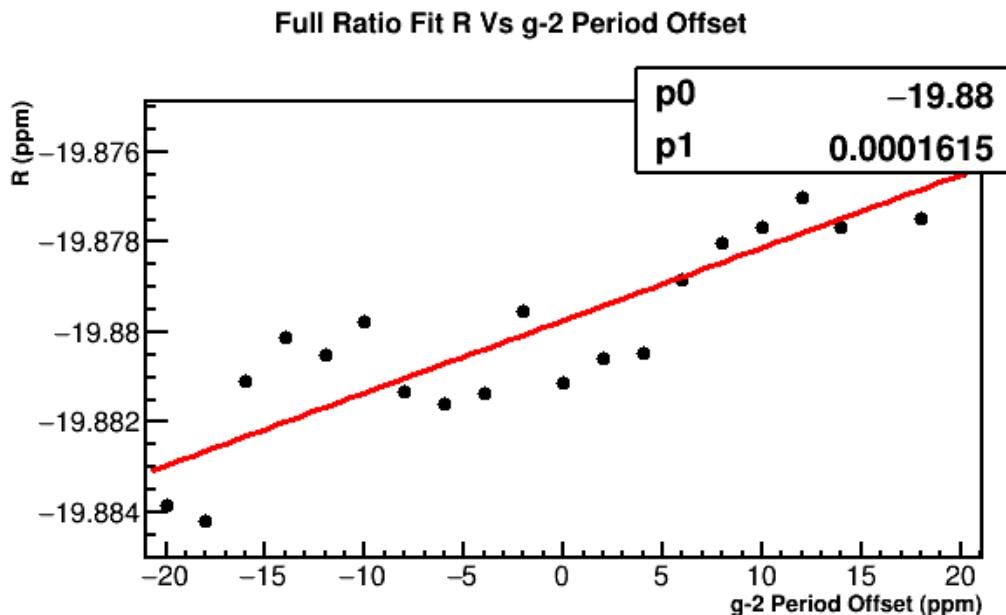
- **38.6 ppb** added in quadrature
- Still want to calculate a systematic error from excluding certain CBO pieces (like the phi cbo term)

# Lost muons and VW

- Lost muon function: Fit w/ and w/o lost muon function and parameter determined from T method fit: **36.1 ppb**
- Need to calculate other lost muon systematic error parts
- VW function: Fit w/ and w/o VW function and parameters determined from T method fit: **< 1 ppb**

# g-2 period

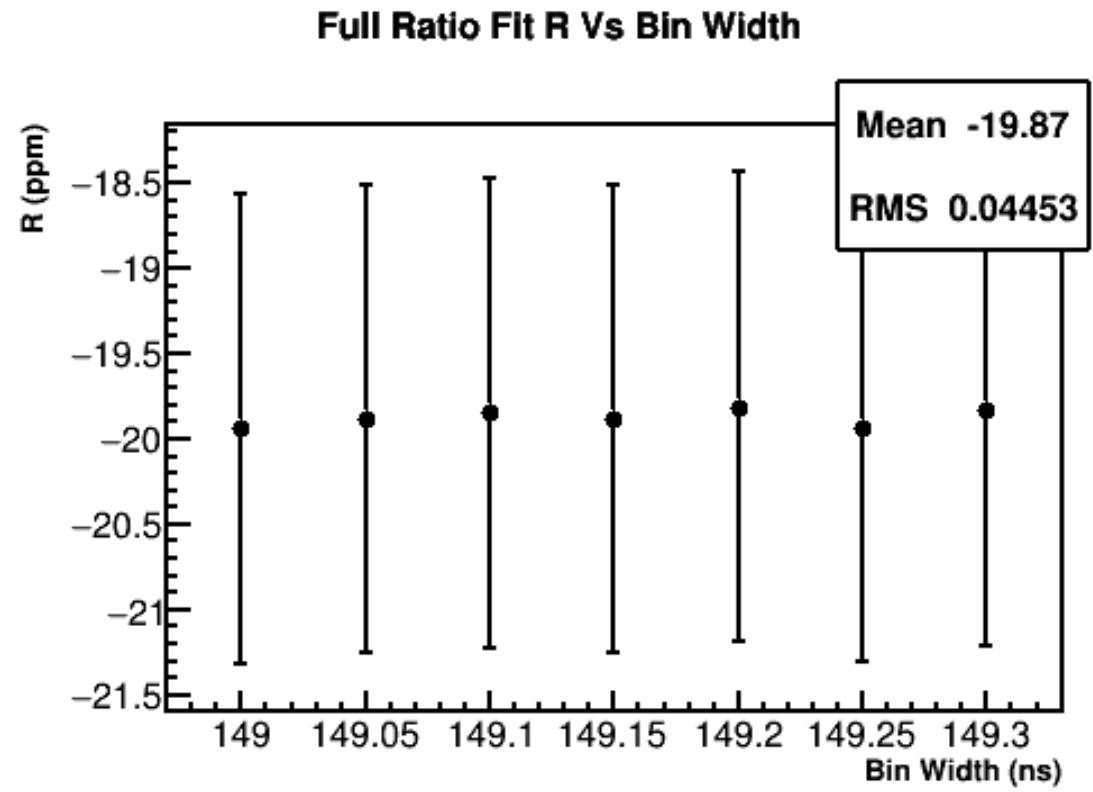
- g-2 period used in making the ratio histogram:
- Uncertainty taken at 10 ppm, systematic error calculated at **1.6 ppb**



$$\delta R_{period} = \delta \alpha_{period} \times \frac{dR}{d\alpha_{period}}$$

# Bin Width

- Performed histogramming and fitting stages with various bin widths
- Took the RMS spread in fitted R values as the systematic error at **44.5 ppb**
- Want to redo this one with more points and a range defined more appropriately

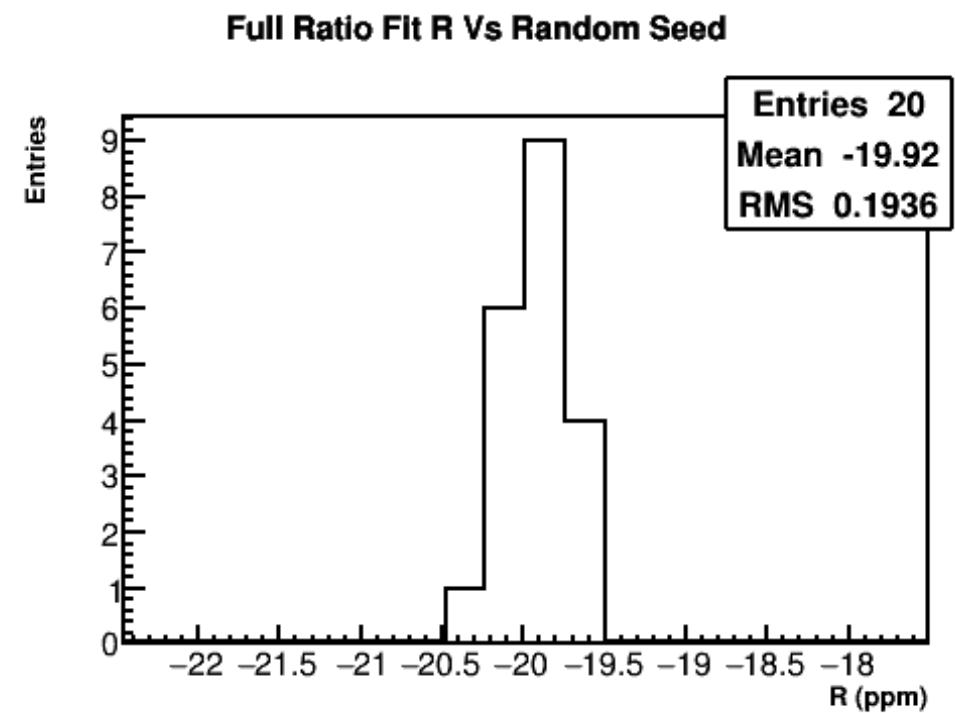


# Randomization

- Performed fitting with 20 different random seeds
- The systematic error is calculated as (where N is the number of random seeds):

$$\delta R_{rand} = \sigma(R) / \sqrt{N - 1}$$

- Systematic error calculated at **44.4 ppb**
- Want to redo this with more seeds



(This done on 5033A, so mean doesn't correspond to the final R answer yet.)

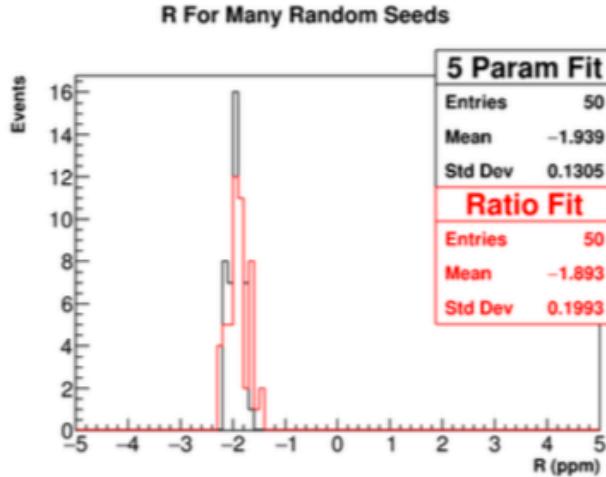
# Systematic error table

Summary of Systematic Errors	
Systematic Error	60 H
Gain (incomplete)	3.5
Pileup	37.8
Lost Muons (incomplete)	36.1
CBO	38.6
VW	< 1
Bin Width	44.5
Randomization	44.4
Other (incomplete)	1.6
Total	90.5

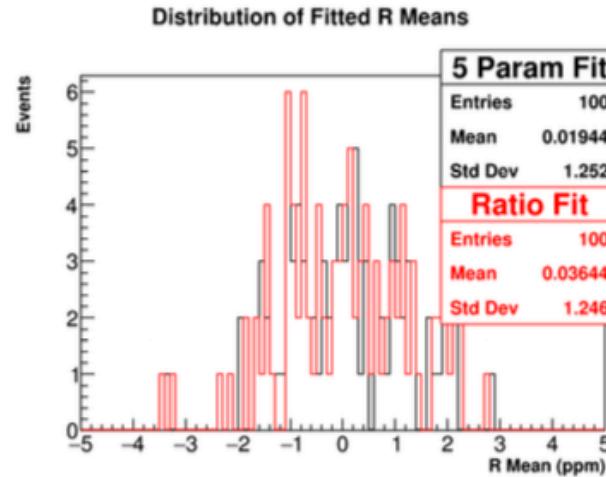
Still some systematic errors to estimate/finish

# T Method MC Comparison

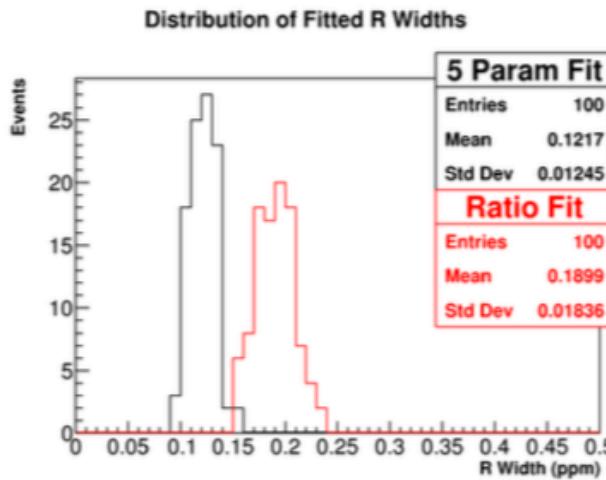
- Performed 100 pseudo-experiments in MC
- Each pseudo-experiment consisted of a set of “positron” hits with stats comparable to the 60H dataset
- Each set of hits was time randomized with 50 random seeds
- 5 parameter fits and 3 parameter ratio fits were performed on all sets of hits



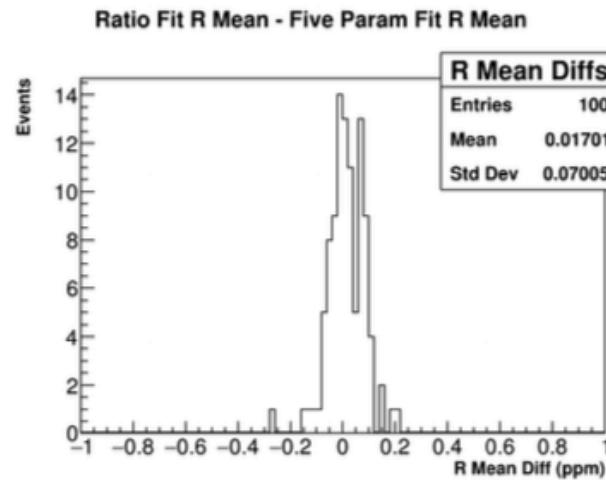
(a) Fitted R distributions for a single pseudo-experiment for 5 parameter and 3 parameter ratio fits, for 50 different random seeds.



(b) The distribution of means of the fitted R distributions, for 100 separate pseudo-experiments.



(c) The distribution of widths of the fitted R distributions, for 100 separate pseudo-experiments.



(d) The distribution of differences in fitted R means between 5 parameter fits and 3 parameter ratio fits per pseudo-experiment for 100 pseudo-experiments.

The width of the bottom right plot tells me the expected spread in average fitted R values for 50 different random seeds between a 5 parameter fit and a 3 parameter ratio fit— a difference of 70 ppb is consistent to  $1\sigma$

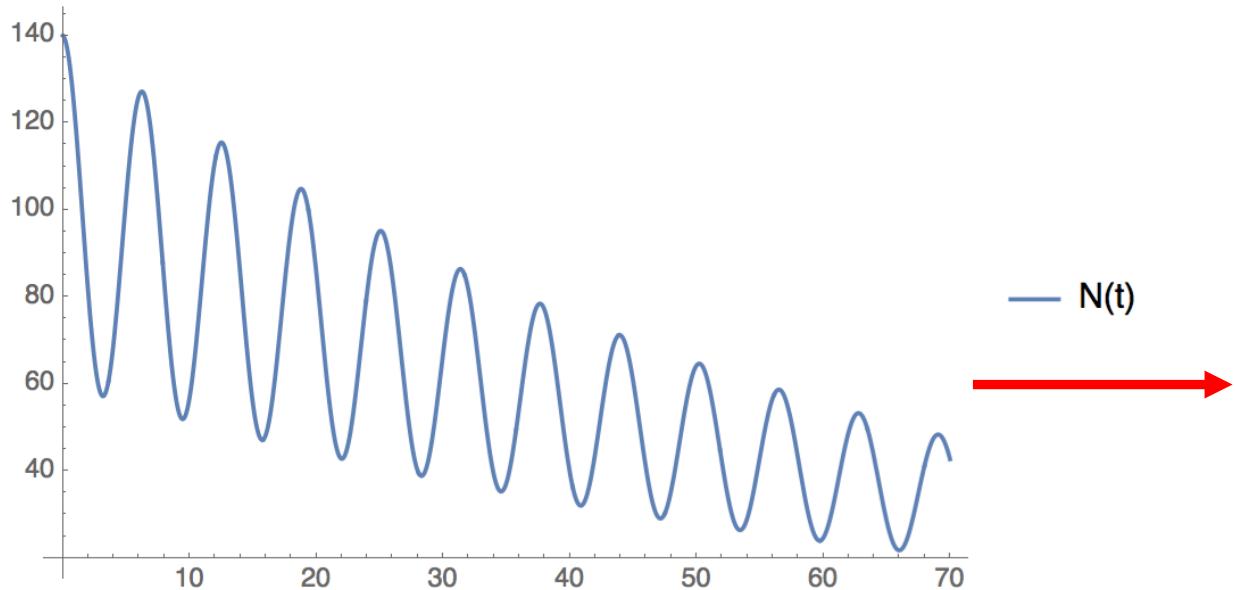
# Summary

- $R = -20.35 \text{ ppm (blinded)} \pm \sim 1.327 \text{ ppm (stat.)} \pm \sim 0.095 \text{ ppm (syst.)}$
- $\chi^2/\text{NDF} = 4204 / 4150$
- P value = 0.2768
- Need to make slight tuning adjustments on Gold dataset (and include missing file), then reproduce all fits, plots, and systematic studies for my report

# Backup

# How the ratio method works

$$N_5(t) = N_0 e^{-t/\tau} (1 + A \cos(\omega_a t + \phi))$$



$$\begin{aligned}u_+(t) &= N_5(t + T/2)/4 \\u_-(t) &= N_5(t - T/2)/4 \\v_1(t) &= v_2(t) = N_5(t)/4\end{aligned}$$

Randomly split positron time spectra into 4 sets, two with time spectra shifted up and down by half a g-2 period, and two unchanged. (Equal weighting corresponding to  $\frac{1}{4}$  factors.)

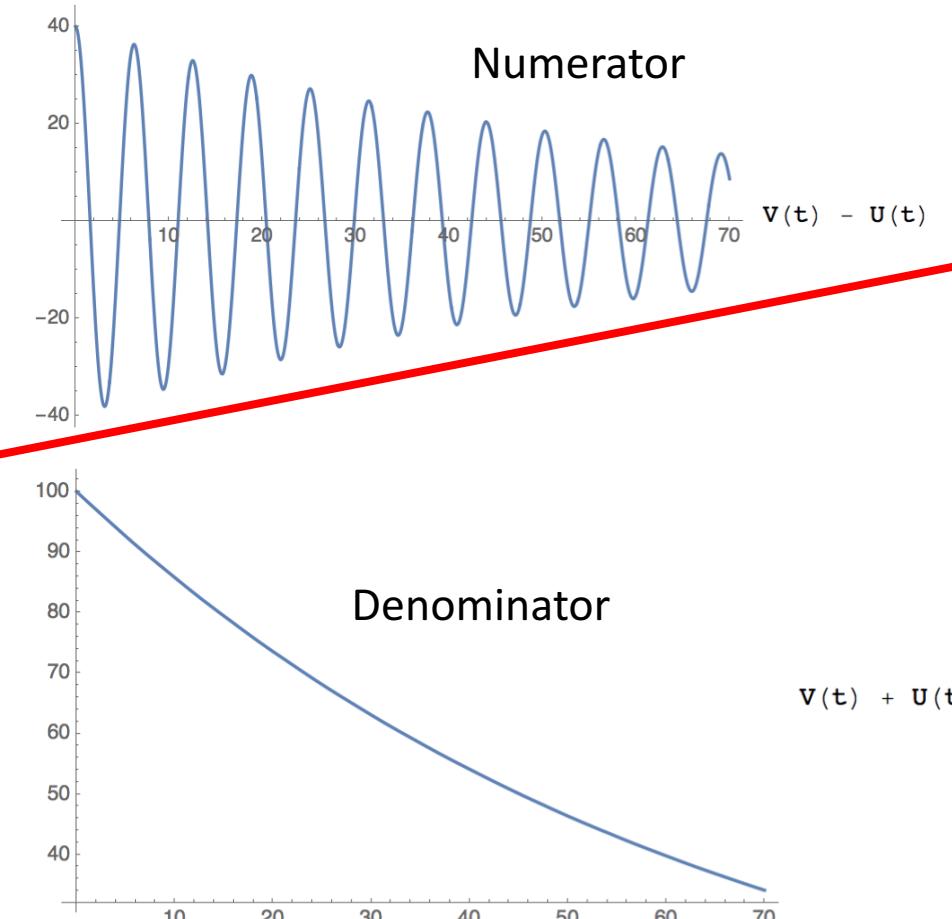
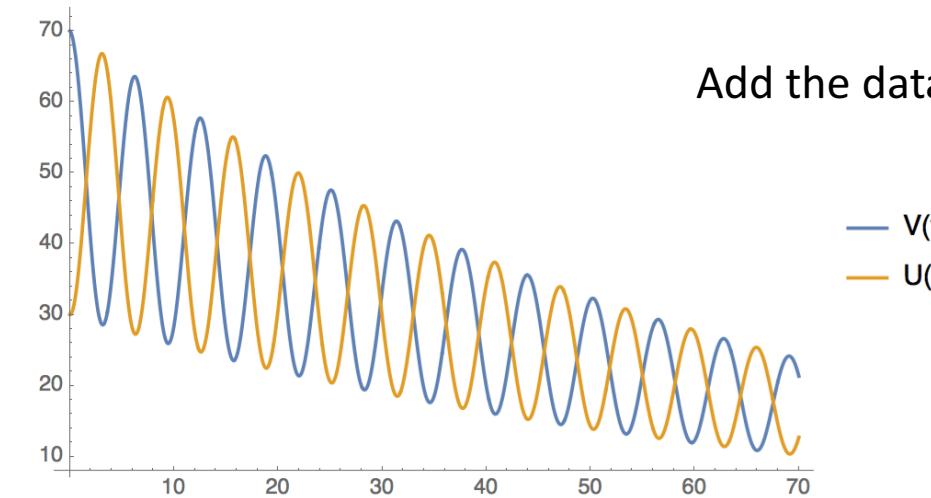
$$N_5(t \pm T/2) = N_0 e^{-t/\tau} e^{\mp T/2\tau} (1 + A \cos(\omega_a t \pm \omega_a \frac{T}{2} + \phi)) \quad T \approx \frac{2\pi}{\omega_a}$$

Add the datasets separately:

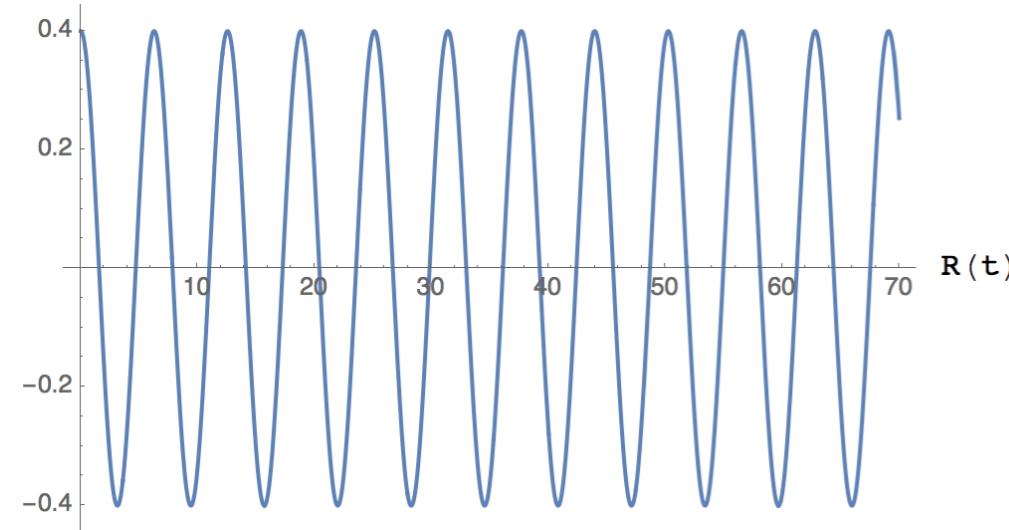
$$U(t) = u_+(t) + u_-(t)$$

$$V(t) = v_1(t) + v_2(t)$$

$$R(t) = \frac{V(t) - U(t)}{V(t) + U(t)}$$



=



$$R(t) = A \cos(\omega_a t + \phi) - \frac{1}{16} \left( \frac{T}{\gamma \tau} \right)^2 + (h.o.)$$

Exponential gets divided out – fit is now down to 3 parameters.  
Less sensitivity to slow effects which divide out.

# Better weighting procedure

(for the # of counts in the histograms, not the weighting of the counts themselves)

$$u_+(t) : u_-(t) : v_1(t) : v_2(t) = 1 : 1 : 1 : 1$$



$$u_+(t) : u_-(t) : v_1(t) : v_2(t) = e^{T/2\tau} : e^{-T/2\tau} : 1 : 1$$

Exponential factors now cancel out and the ratio equals the simple form exactly (in the absence of further fit parameters like CBO and the limit that T is exactly the g-2 period.)

$$\approx \pi$$

$$N_5(t \pm T/2) = N_0 e^{-t/\tau} e^{\mp T/2\tau} \left(1 + A \cos(\omega_a t \pm \omega_a \frac{T}{2} + \phi)\right)$$

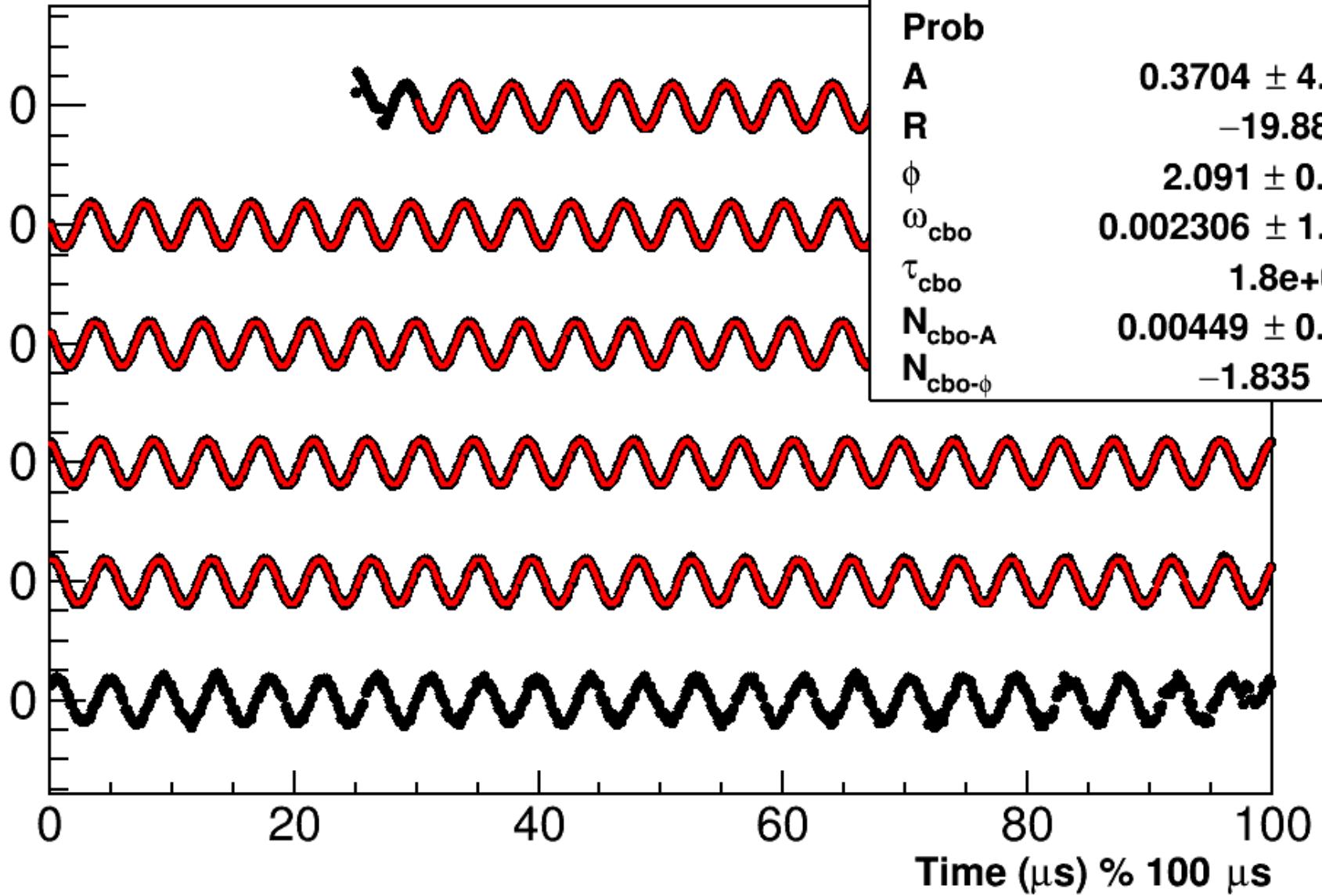
$$R(t) = A \cos(\omega_a t + \phi) - \frac{1}{16} \left(\frac{T}{\gamma\tau}\right)^2 + (h.o.) \longrightarrow R(t) = A \cos(\omega_a t + \phi)$$

This weighting accounts for the muon decay during half a g-2 period.

5033A Fit

# Full Ratio Fit

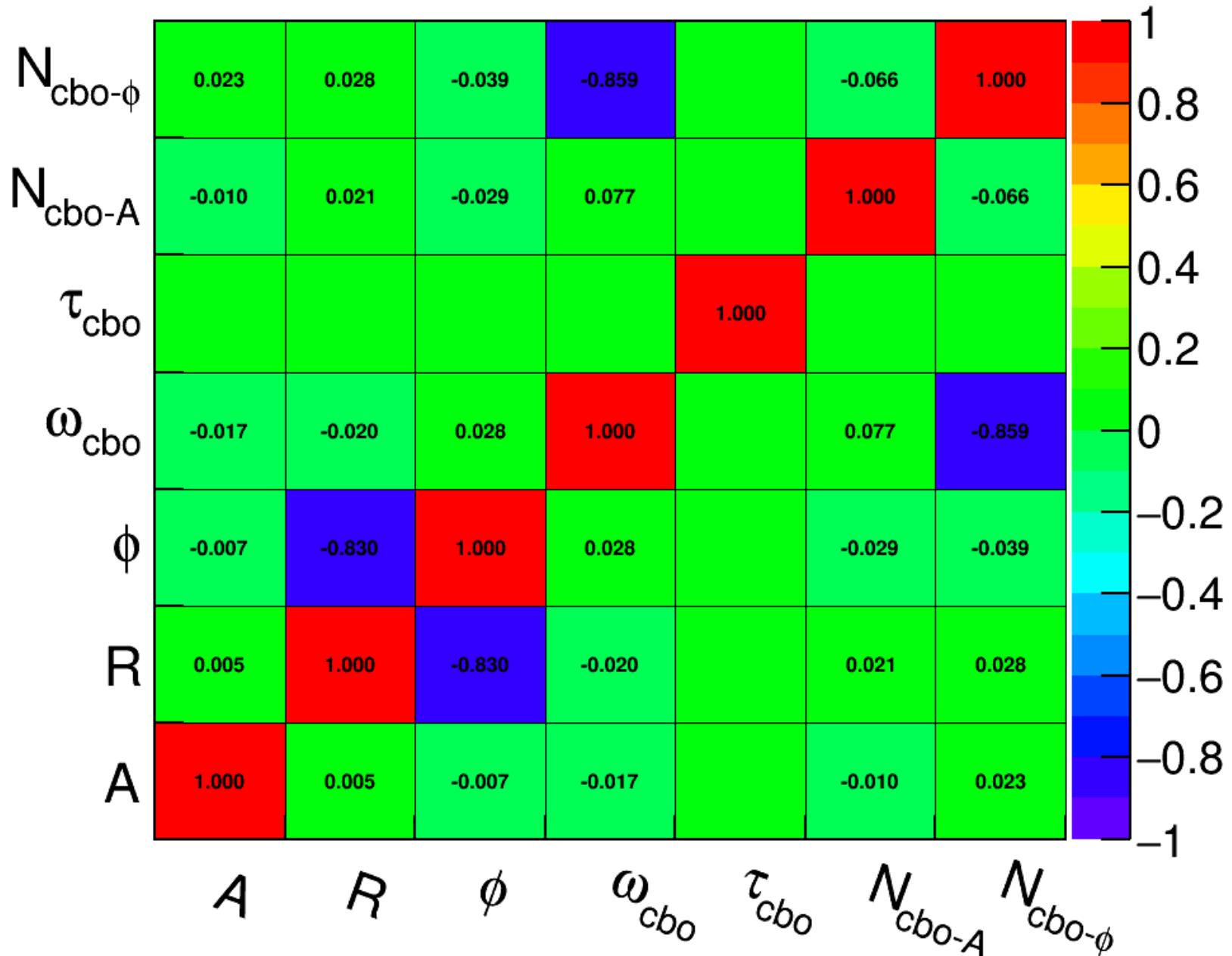
Ratio Value



$\chi^2 / \text{ndf}$	3052 / 3145
Prob	0.8806
A	$0.3704 \pm 4.493\text{e-}05$
R	$-19.88 \pm 1.373$
$\phi$	$2.091 \pm 0.0002249$
$\omega_{\text{cbo}}$	$0.002306 \pm 1.325\text{e-}06$
$\tau_{\text{cbo}}$	$1.8\text{e+}05 \pm 0$
$N_{\text{cbo-A}}$	$0.00449 \pm 0.0002365$
$N_{\text{cbo-}\phi}$	$-1.835 \pm 0.1017$

# Correlation matrix

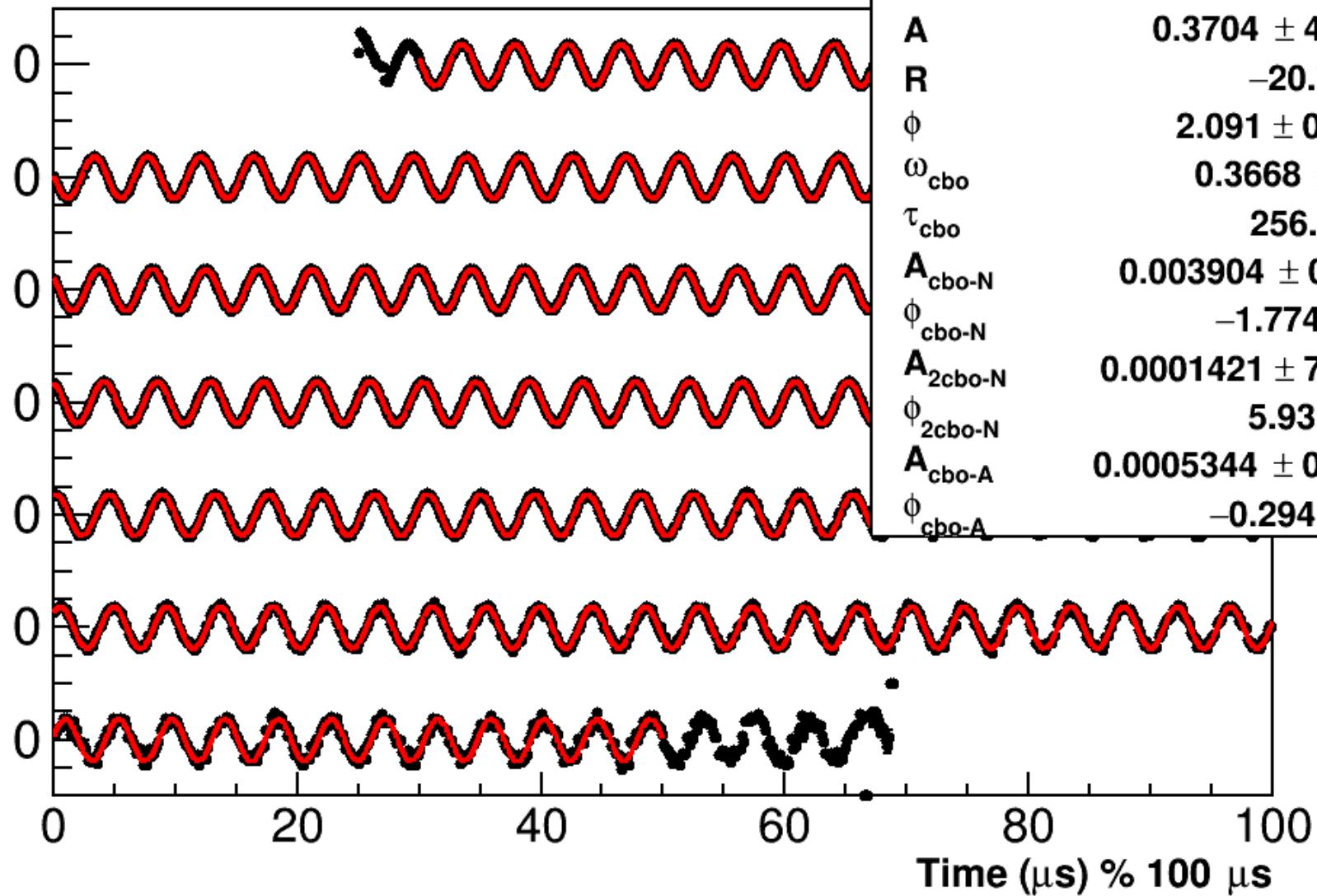
5033A



# Fit - 5033D (partial)

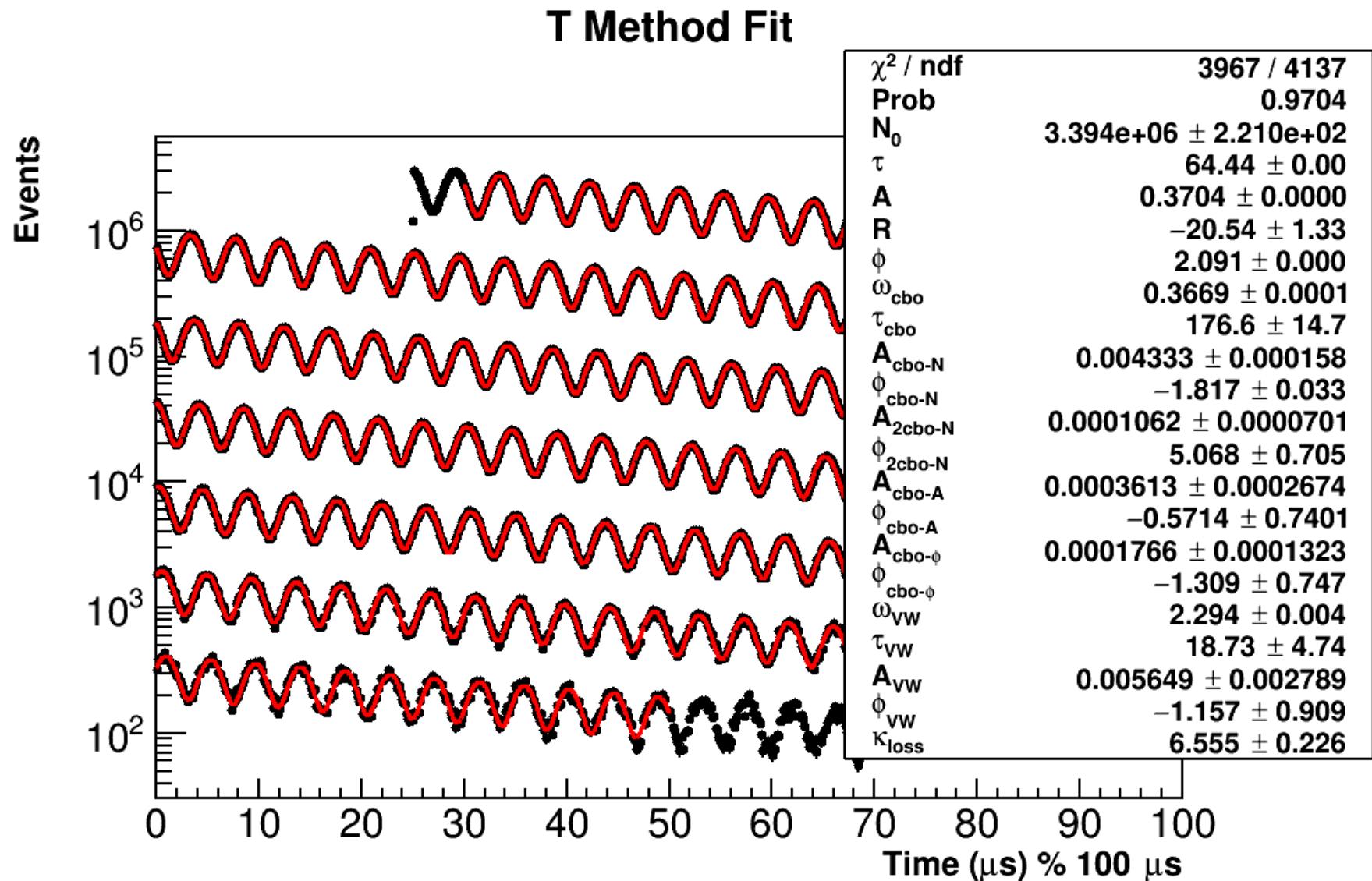
## Full Ratio Fit

Ratio Value



$\chi^2 / \text{ndf}$	4122 / 4146
Prob	0.601
A	$0.3704 \pm 4.448\text{e-}05$
R	$-20.7 \pm 1.338$
$\phi$	$2.091 \pm 0.0002208$
$\omega_{\text{cbo}}$	$0.3668 \pm 0.00021$
$\tau_{\text{cbo}}$	$256.9 \pm 75.85$
$A_{\text{cbo-N}}$	$0.003904 \pm 0.0003951$
$\phi_{\text{cbo-N}}$	$-1.774 \pm 0.1061$
$A_{2\text{cbo-N}}$	$0.0001421 \pm 7.861\text{e-}05$
$\phi_{2\text{cbo-N}}$	$5.93 \pm 0.5929$
$A_{\text{cbo-A}}$	$0.0005344 \pm 0.0003502$
$\phi_{\text{cbo-A}}$	$-0.294 \pm 0.6704$

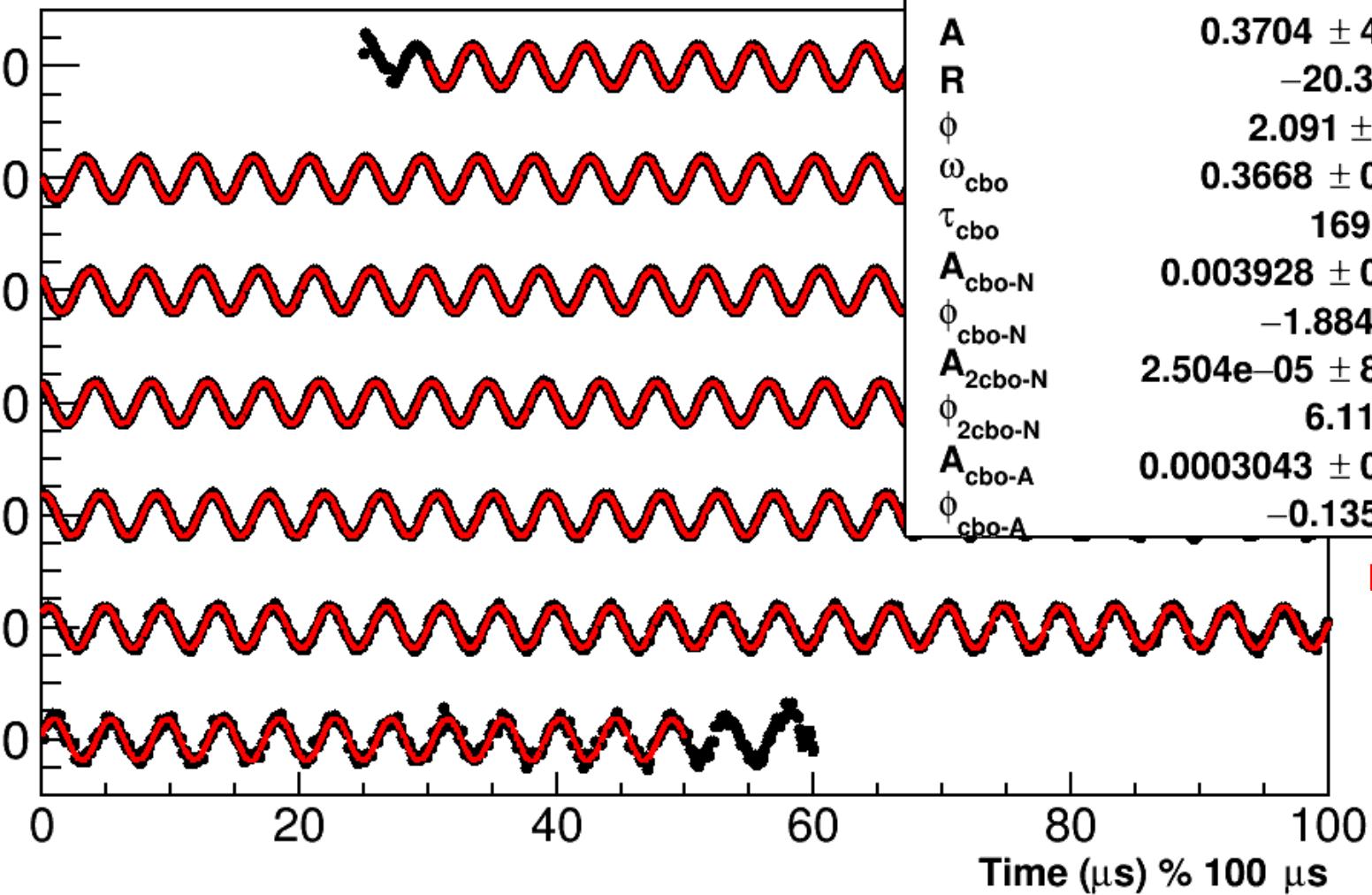
# 5033D (partial) T Method Fit



# Gold Fit (one missing file)

## Full Ratio Fit

Ratio Value

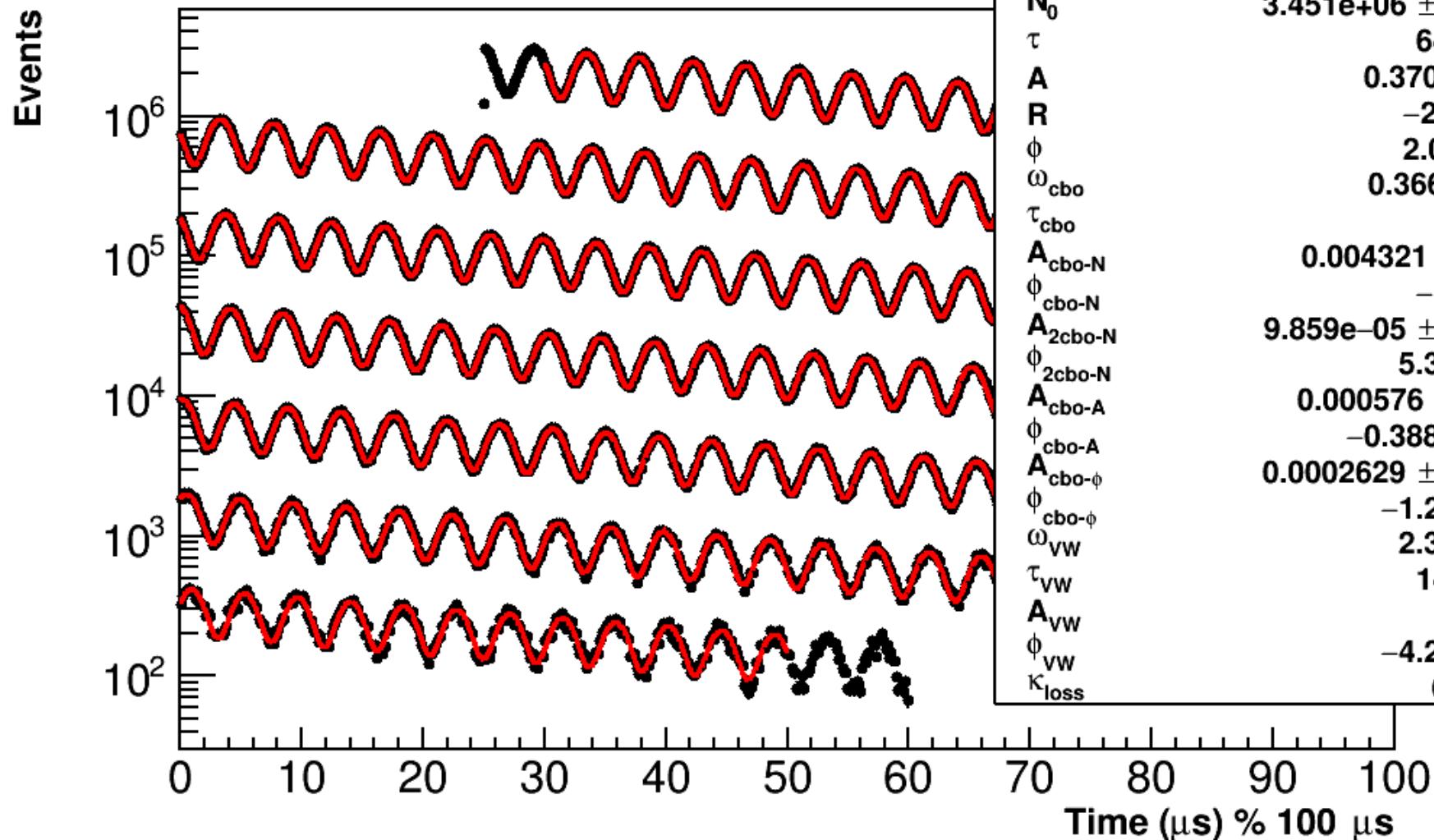


$\chi^2 / \text{ndf}$	4203 / 4146
Prob	0.2646
A	$0.3704 \pm 4.413\text{e-}05$
R	$-20.37 \pm 1.327$
$\phi$	$2.091 \pm 0.000219$
$\omega_{\text{cbo}}$	$0.3668 \pm 0.0002613$
$\tau_{\text{cbo}}$	$169.1 \pm 48.95$
$A_{\text{cbo-N}}$	$0.003928 \pm 0.0005137$
$\phi_{\text{cbo-N}}$	$-1.884 \pm 0.1204$
$A_{2\text{cbo-N}}$	$2.504\text{e-}05 \pm 8.885\text{e-}05$
$\phi_{2\text{cbo-N}}$	$6.113 \pm 3.539$
$A_{\text{cbo-A}}$	$0.0003043 \pm 0.0003973$
$\phi_{\text{cbo-A}}$	$-0.1351 \pm 1.325$

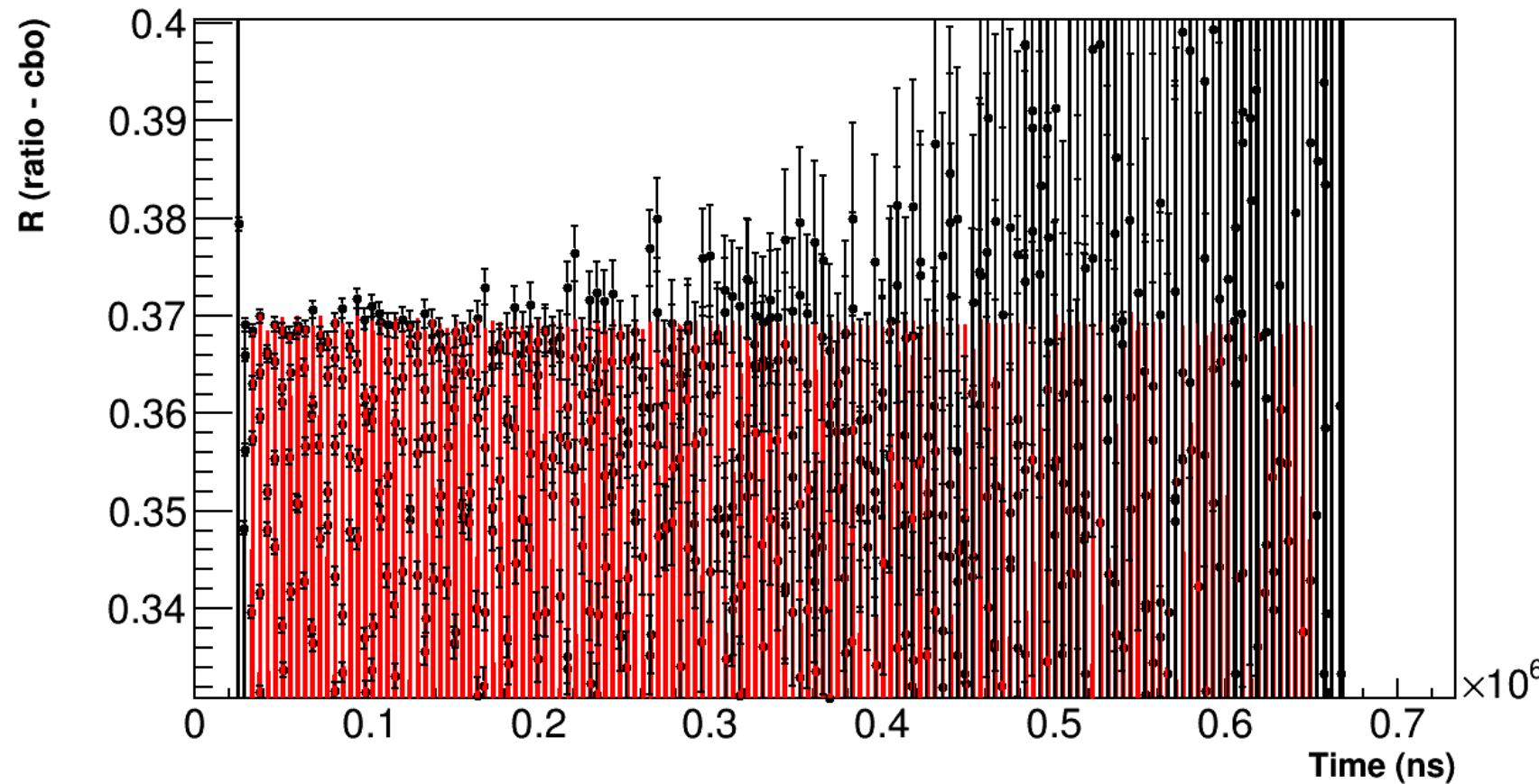
Extra cbo terms included

# Gold Fit (one missing file)

## T Method Fit

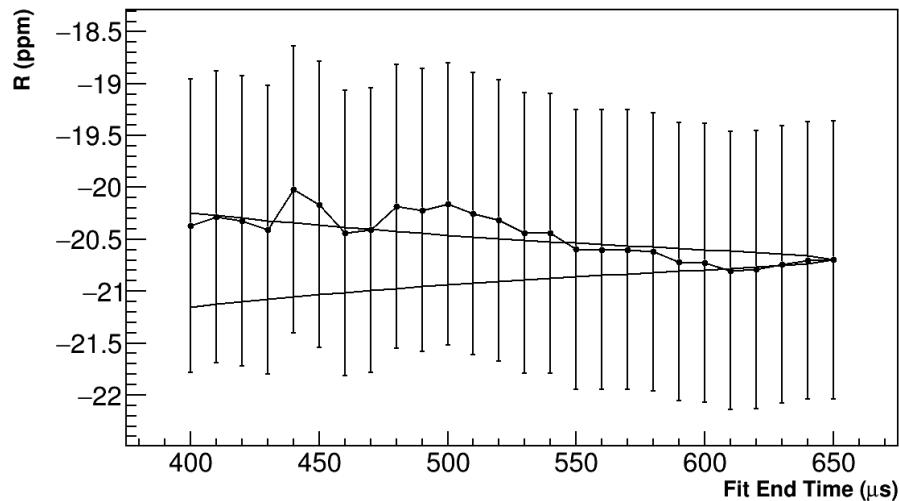


## Fit end scans

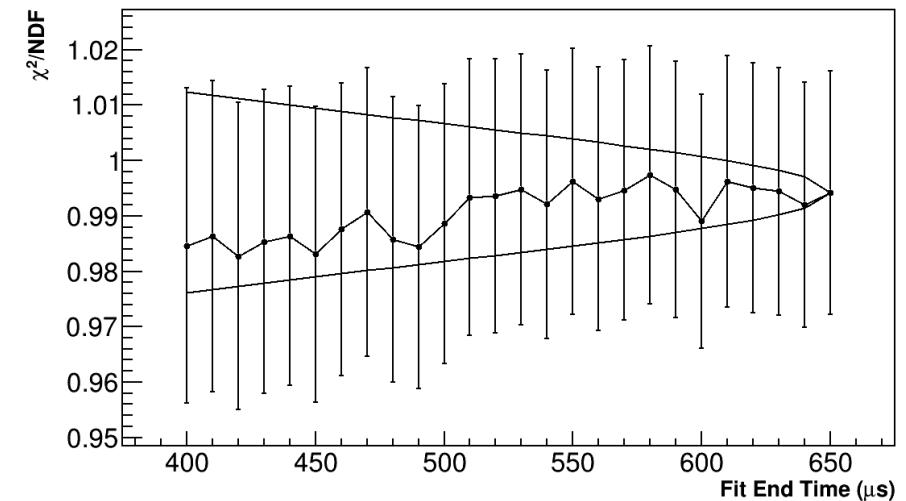


# Fit end scans

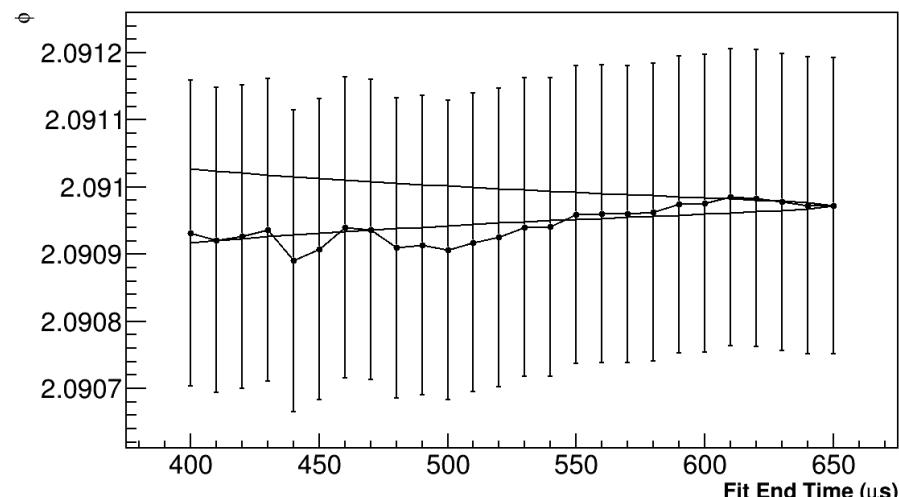
Full Ratio Fit R Vs Fit End Time



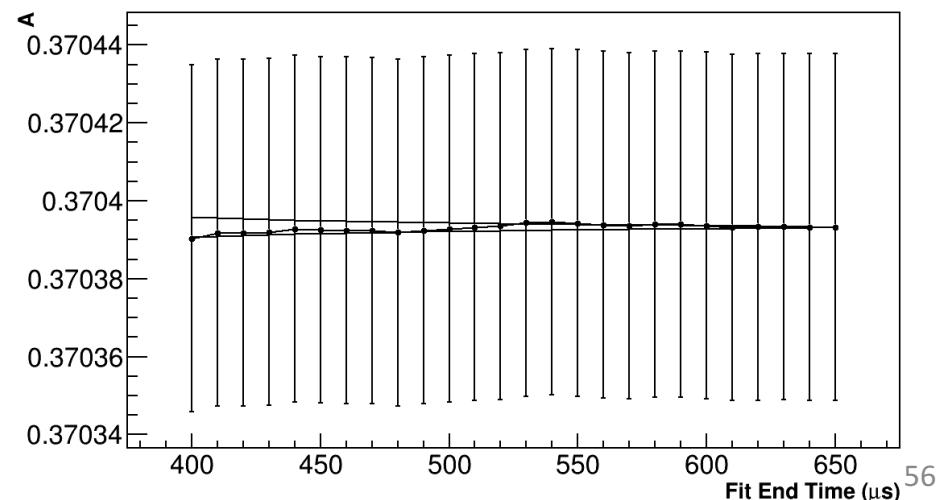
Full Ratio Fit  $\chi^2/NDF$  Vs Fit End Time



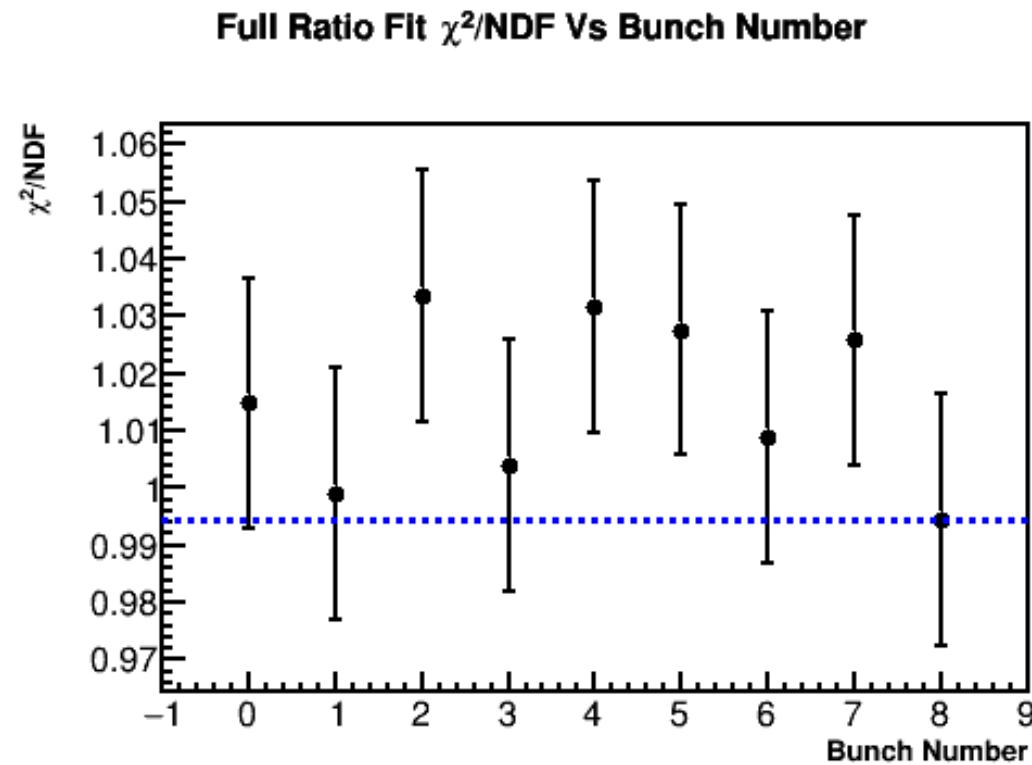
Full Ratio Fit  $\phi$  Vs Fit End Time



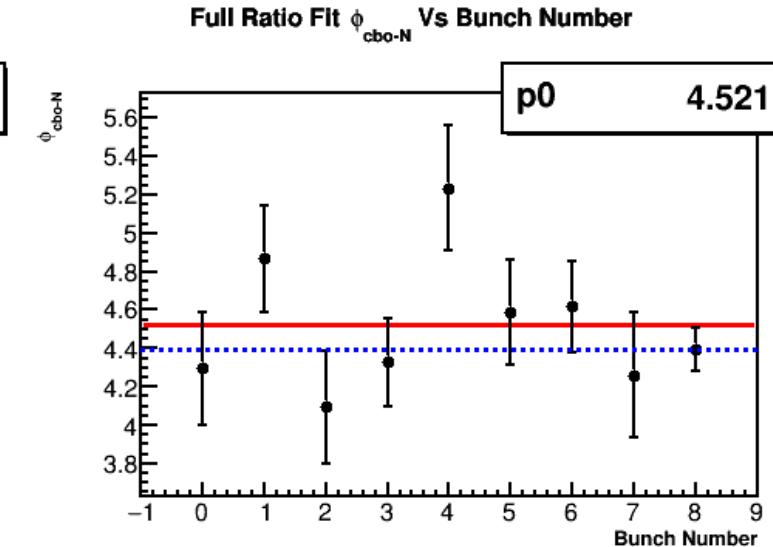
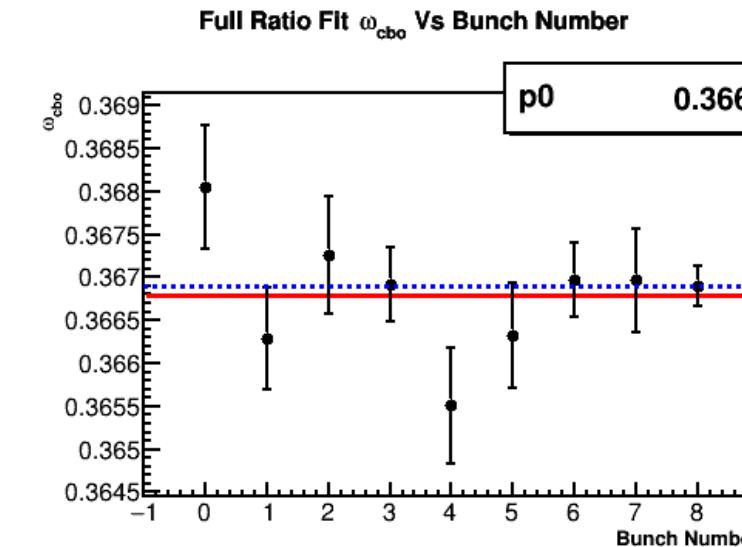
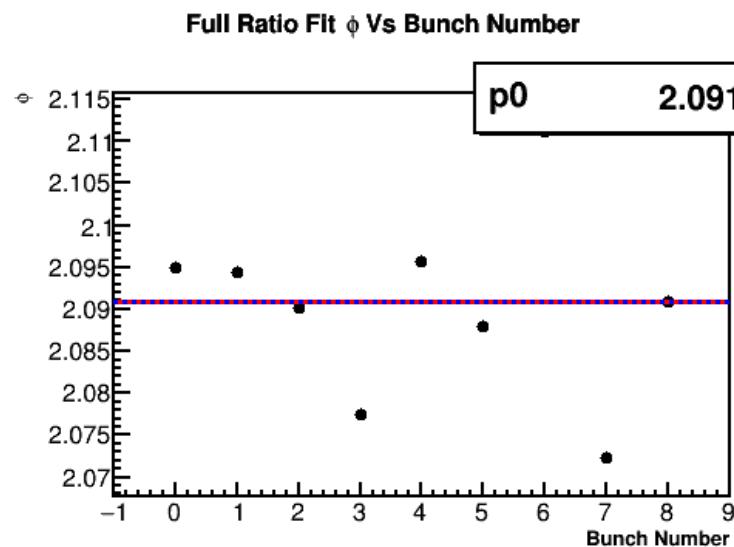
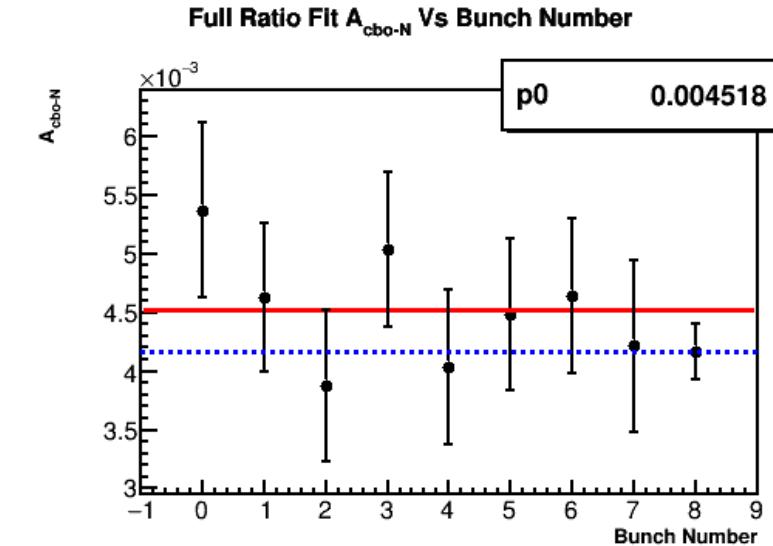
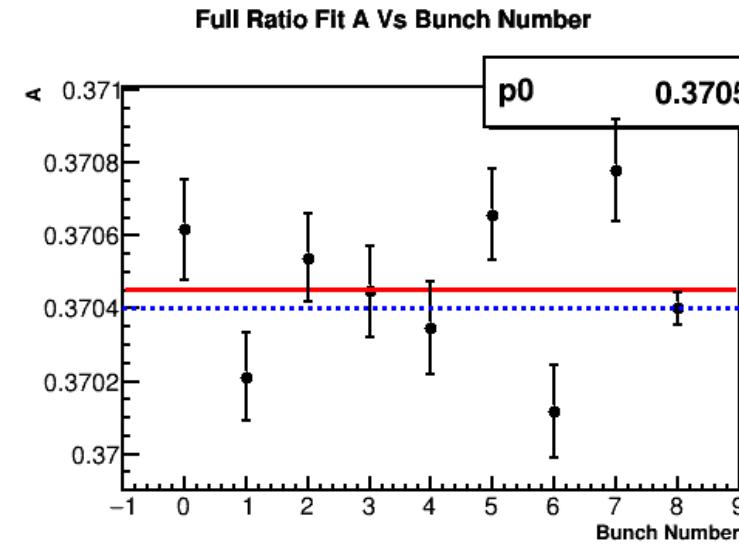
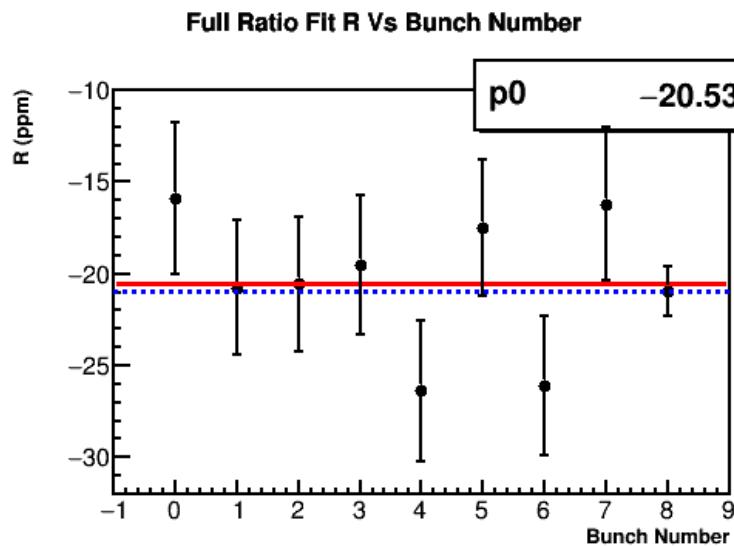
Full Ratio Fit A Vs Fit End Time



# Fit Results Vs Bunch Number



Bunch 8 is all bunches added together, the dotted blue line is set to the value at bunch 8.



Bunch 8 is all bunches added together, red line is a fit to bunches 0 - 7, the dotted blue line is set to the value at bunch 8.