Search for CPT and Lorentz Violation Effects in the Muon g-2 Experiment

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On Behalf of the Muon g-2 Collaboration

ICHEP (Beyond the Standard Model Session)

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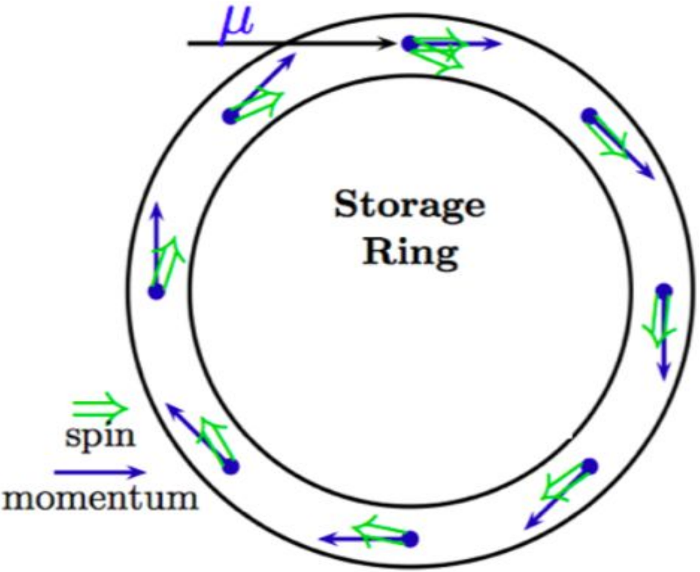
Measurement of a_μ

- Anomalous precession frequency: $\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu c}$ (Ideally)

- Magnetic field: $2\hbar\boldsymbol{\omega_p} = 2\boldsymbol{\mu_p}|\mathbf{B}|$



Measured experimentally

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

3 ppb

22 ppb

0.3 ppt [1]

[1] 2017 **CODATA Values**

Standard Model Extension(SME) and CPTLV for Muon :

- For the muon, SME lagrangian:

$$\mathcal{L}' = -a_\kappa \overline{\psi}\gamma^\kappa\psi - b_\kappa \overline{\psi}\gamma_5\gamma^\kappa\psi - \frac{1}{2}H_{\kappa\lambda}\overline{\psi}\sigma^{\kappa\lambda}\psi + \frac{1}{2}ic_{\kappa\lambda}\overline{\psi}\gamma^\kappa \overleftrightarrow{D}^\lambda\psi + \frac{1}{2}id_{\kappa\lambda}\overline{\psi}\gamma_5\gamma^\kappa \overleftrightarrow{D}^\lambda\psi$$

  - All terms violate Lorentz invariance
  - a_κ, b_κ Coefficients are CPT-odd, all others are CPT-even

$b_\kappa \longrightarrow$ **Can be determined by Muon g-2 experiment**

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CPTLV Signals with Muon g-2 experiment

CPTLV Signatures

Sidereal Oscillation in $\mathcal{R}(=\omega_a/\omega_p)$

- Spectral analysis on a run-by-run basis
- Multi-parameter fit (“run ~ 1 hour” of data collection)

$$b_{\perp}^{\mu^{\pm}} = \frac{\overset{\wedge}{\omega}{}_a^{\mu^{\pm}}}{2|sin\chi|}$$

$$\Delta\omega_a \equiv < \omega_a^{\mu^+} > - < \omega_a^{\mu^-} >$$

Currently only μ^+ data for Fermilab Muon g-2 experiment

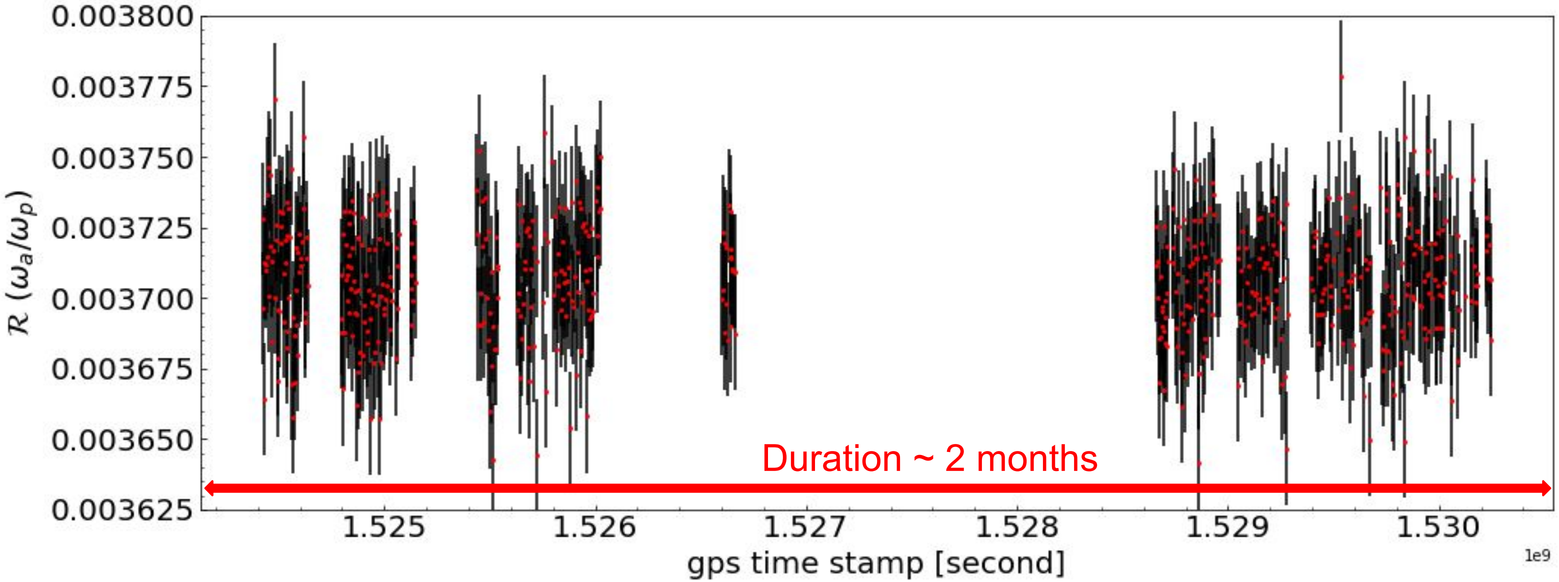
$$\Delta\omega_a = \frac{4b_Z}{\gamma}cos\chi$$

CPTLV Test : (Simulation Studies)

Simulated Data :

All plots shown here are simulated data based on the average $\mathcal{R}$ = 0.0037072083 ($\delta\mathcal{R}$ = 20 ppm) [2001, BNL results]

Ingredient : $\mathcal{R}(=\omega_a/\omega_p)$ on a run-by-run basis along with the GPS timestamps



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Lomb-Scargle(LS) Test:

- Spectral analysis technique for unequally spaced data
- Normalized Periodogram $P_N(\omega)$

- Scan frequencies, calculate Spectral Power at each ω:

$$P_N(\omega) \equiv \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_j (h_j - \bar{h}) \cos\omega(t_j - \tau)\right]^2}{\sum_j \cos^2\omega(t_j - \tau)} + \frac{\left[\sum_j (h_j - \bar{h}) \sin\omega(t_j - \tau)\right]^2}{\sum_j \sin^2\omega(t_j - \tau)}\right\}$$

$$\bar{h} = \sum_i w_i h_i \qquad \sigma^2 = \sum_i w_i (h_i - \bar{h})^2 \qquad \tan(2\omega\tau) = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}$$

$$w_i = \frac{(\frac{1}{y_{err}})^2}{\sum_i (\frac{1}{y_{err}})^2}$$

LS - frequency where the peak appears (if any)

Multi parameter fit (MPF) :

- A 4-parameter fit, with T_0 const. at sidereal time (86164.09 seconds)

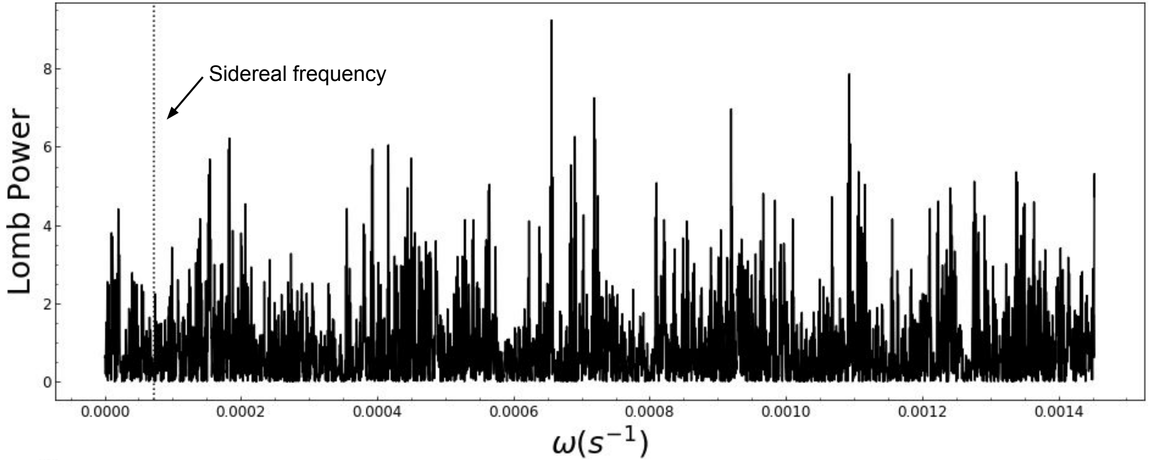
- get the signal ampl. directly from the fit as compared to LS
- C_0 - time average of R - (a const. in time)

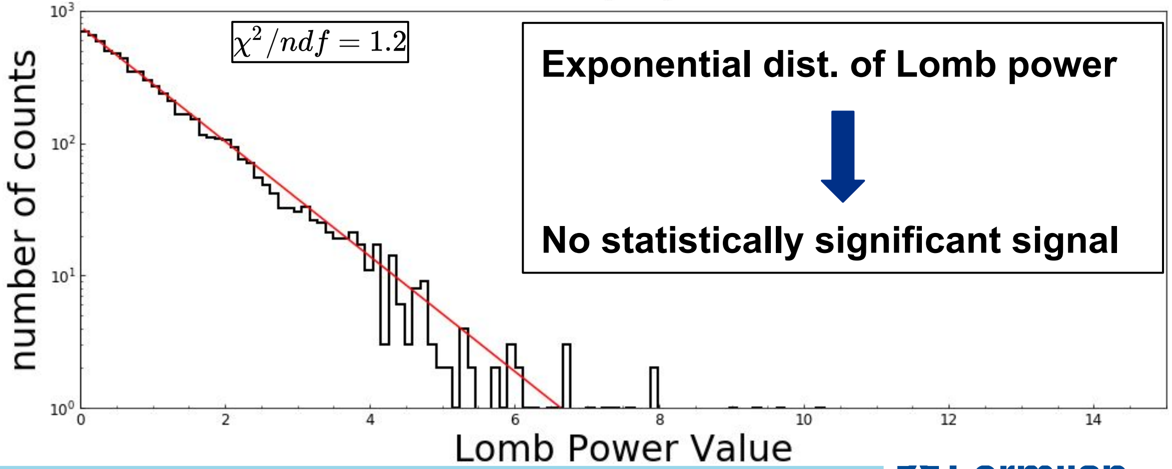
$$\mathcal{R}(t) = C_0 + A_0 cos(\frac{2\pi t}{T_0} + \phi_0)$$

MPF - Amplitude of the signal (if any) directly

Lomb-Scargle Test :

- **Scan frequencies, calculate Spectral Power $P_N(\omega)$ at each ω**
- $P_N(\omega)$ **is a measure of the statistical significance, or likelihood, of a signal at a given frequency**
- **Higher $P_N(\omega) \rightarrow$ more significant periodic signal at ω**



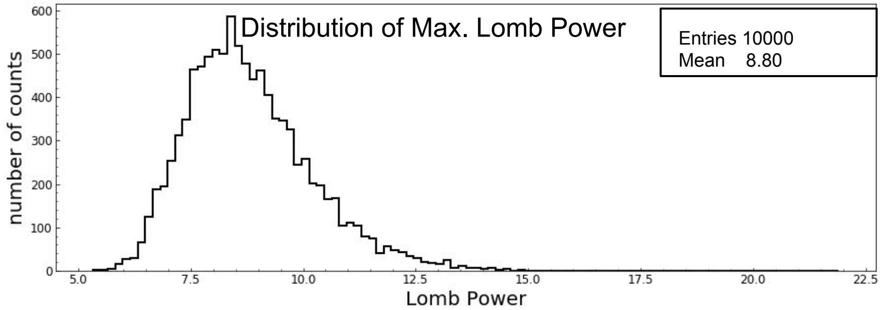


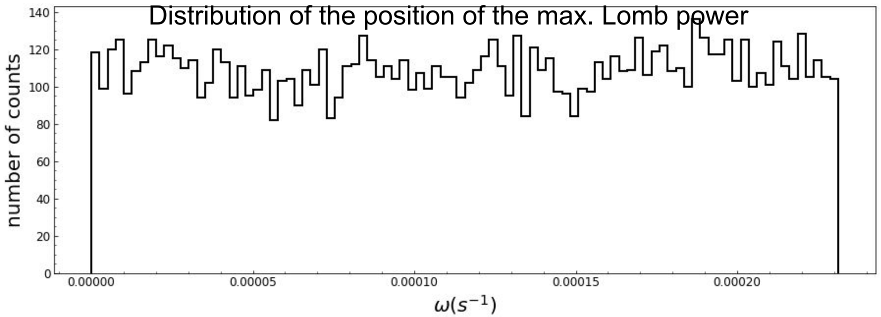
Exponential dist. of Lomb power

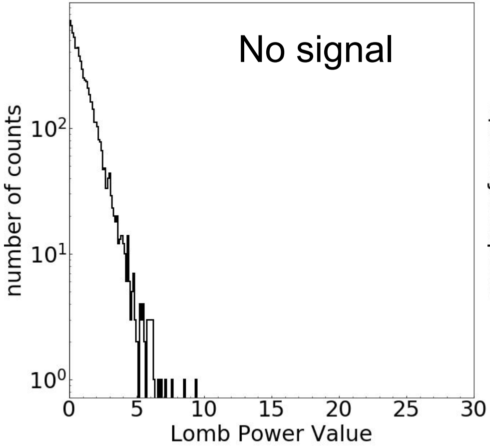
No statistically significant signal

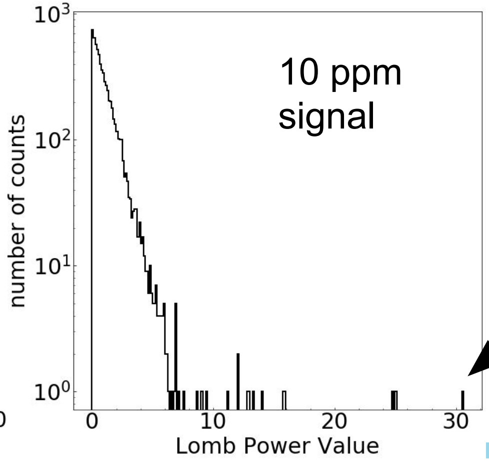
Spectral Analysis for Uneven Simulated Data

- 10,000 simulated data groups (No artificial signal added)
  - Max. Lomb power distribution, mean ~ 8
  - Max.Lomb power distributed equally over the Freq. range









Long tail → Significant Signal Peak

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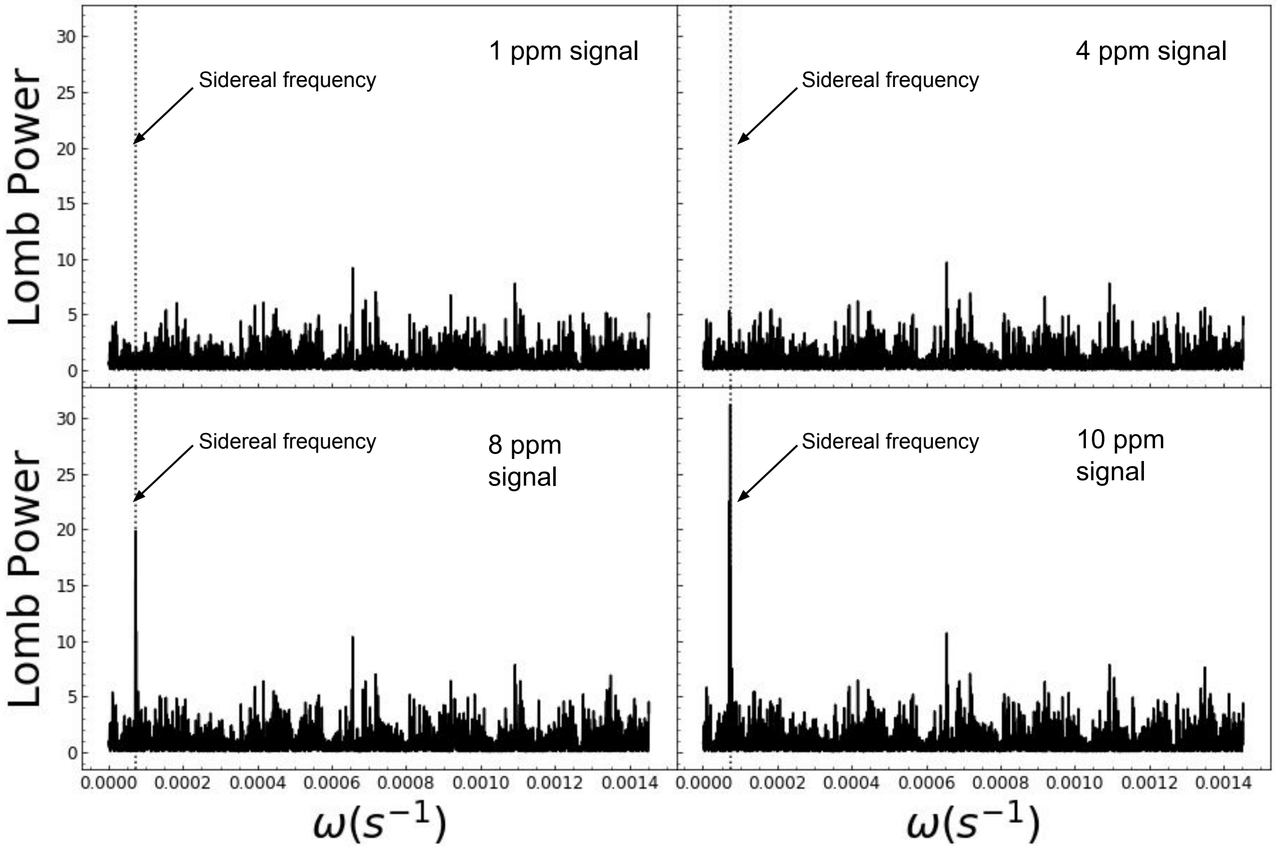
Sensitivity vs Amplitude :

- **Random $\mathcal{R}(t)$ generated**
  - **$<\mathcal{R}>$ = 0.0037072083, $\delta\mathcal{R}$ = 20 ppm**
- **Add artificial signal at ω_s to simulated data**
  - Signal with amplitude > 5 ppm required for significant detection
- **~ 20 ppm uncertainty on data**

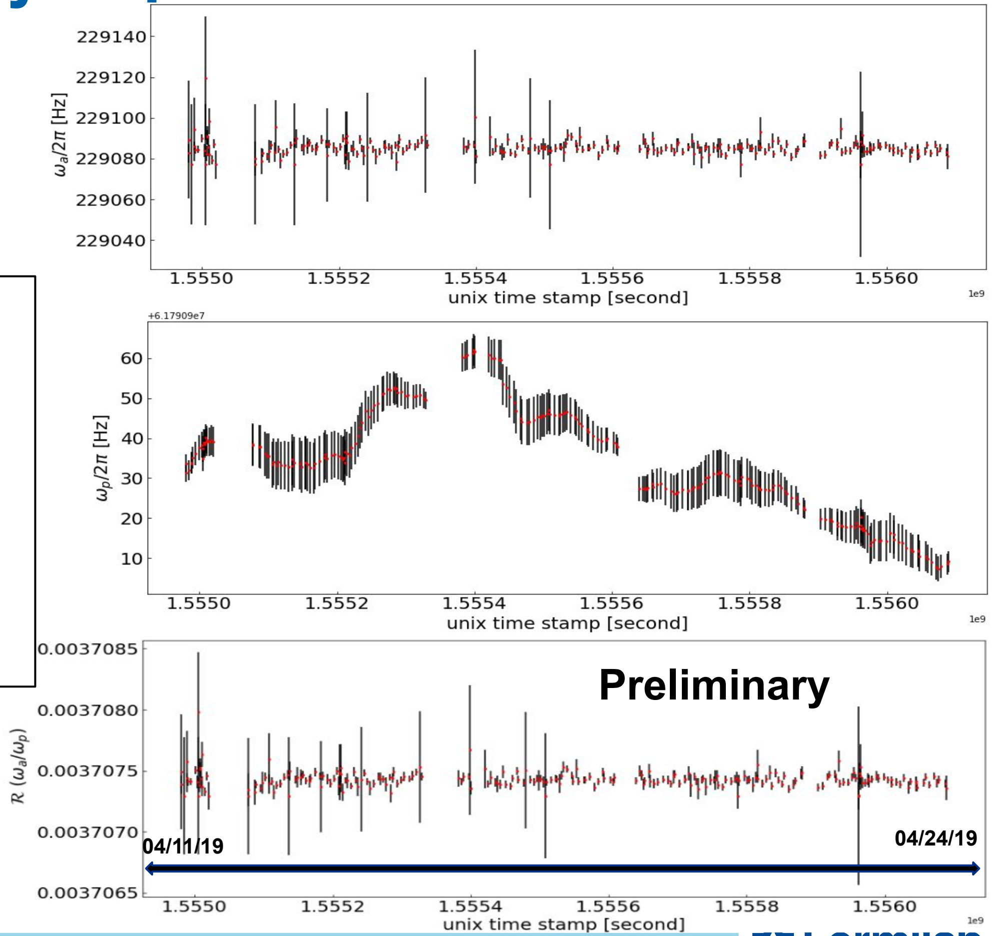
$\downarrow$

> 5 ppm detectable Oscillation amplitude



Preliminary Run2 subset analysis plots :

- ω_a , ω_p measurements both blinded
- Calculate $\mathcal{R}(= \omega_a / \omega_p)$: Run-by-Run basis (Run ~ 1 hour of data collection)
- Approaches to search for oscillation
  - Multi parameter fit
  - Lomb-Scargle test



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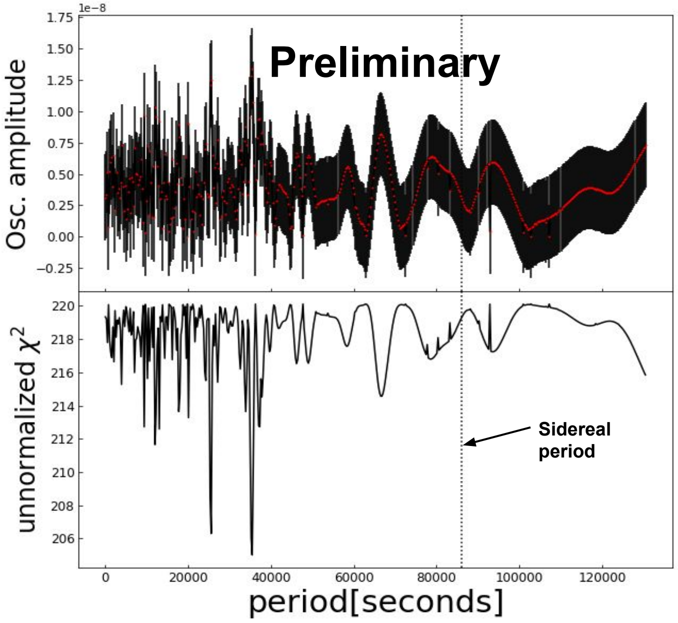
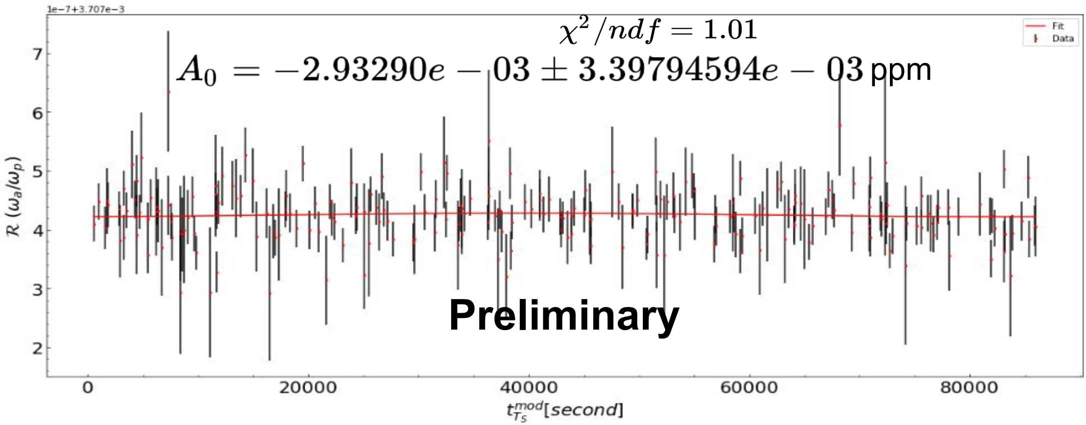
Multi parameter fit : $$\mathcal{R}(t) = C_0 + A_0 cos(\frac{2\pi t}{T_0} + \phi_0)$$

With, $T_0 = T_S$

χ^2/ndf **: Doesn't change for a constant fit**





Oscillation period scan :

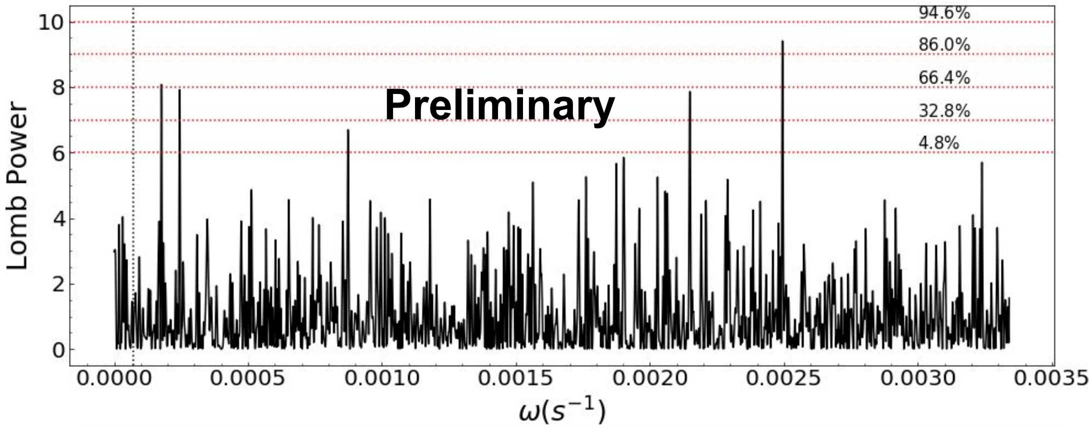
- **Step through different values of T_0 keeping other parameters free**
- T_S **is not a** χ^2 **minima**
- **No significant oscillation at any scanned frequency**

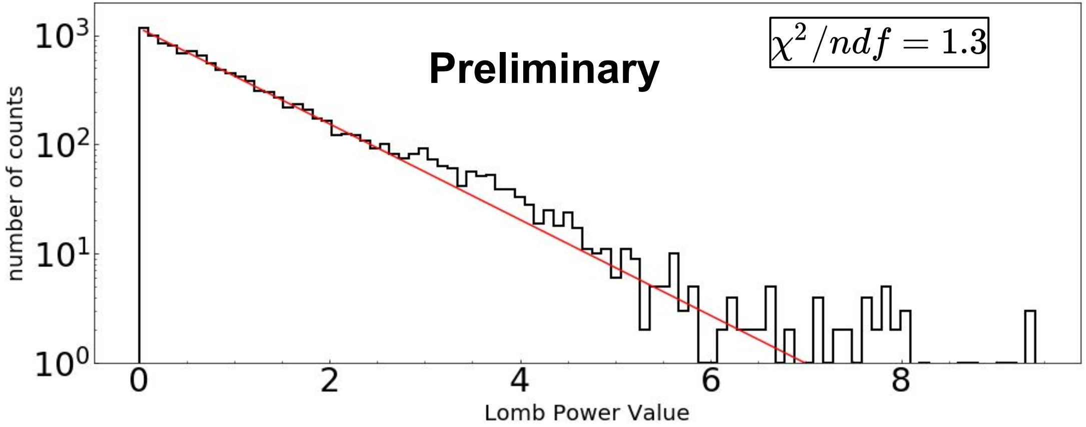
Lomb-Scargle Test :

Lomb Power, P_N	C.L.(%)
6	4.8
7	32.8
8	66.4
9	86.0
10	94.6
11	97.9

C.L. of P_N - Prob.(P < P_N)

$P_N(\omega_s) = 0.83$ **(No significant signal in the subset of the data)**





Summary :

- Simulation studies show that sensitivity scales with uncertainty of $\mathcal{R}(=\omega_a/\omega_p)$
    - Fermilab Muon g-2 experiment (E989) aims X4 improvement of limits on CPT/LV parameters
- A small subset of Run 2 data : Nothing significant at the sidereal frequency
    - Stay tuned for the full Run2 analysis!
- First search for annual variation in $\mathcal{R}(=\omega_a/\omega_p)$ will be made using E989 data

Thanks to the organizers for the virtual ICHEP meeting!