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

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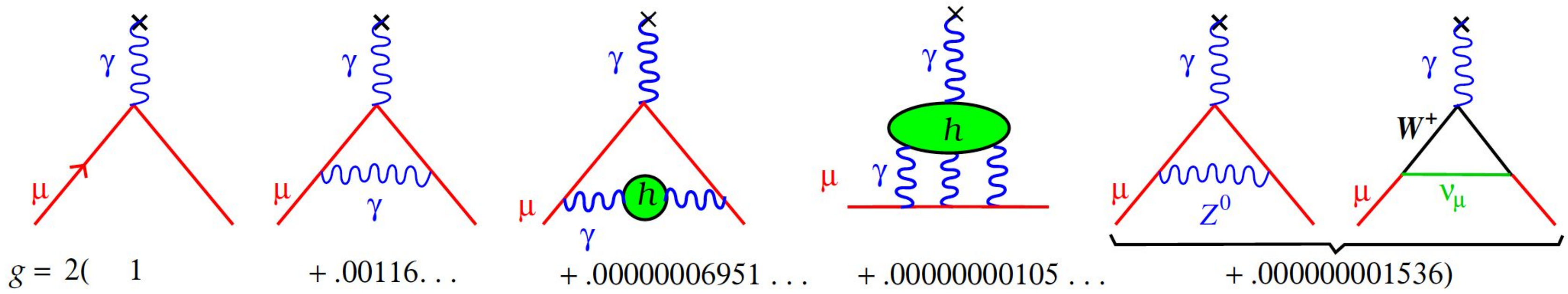
ANL

Outline

- Probe New Physics with Muons
- Muon g-2 Experiment: in a nutshell
- CPT LIV Tests with g-2 data
- Operations, Maintenance and Upgrades of the EQS
- Summary

a_μ predictable using SM

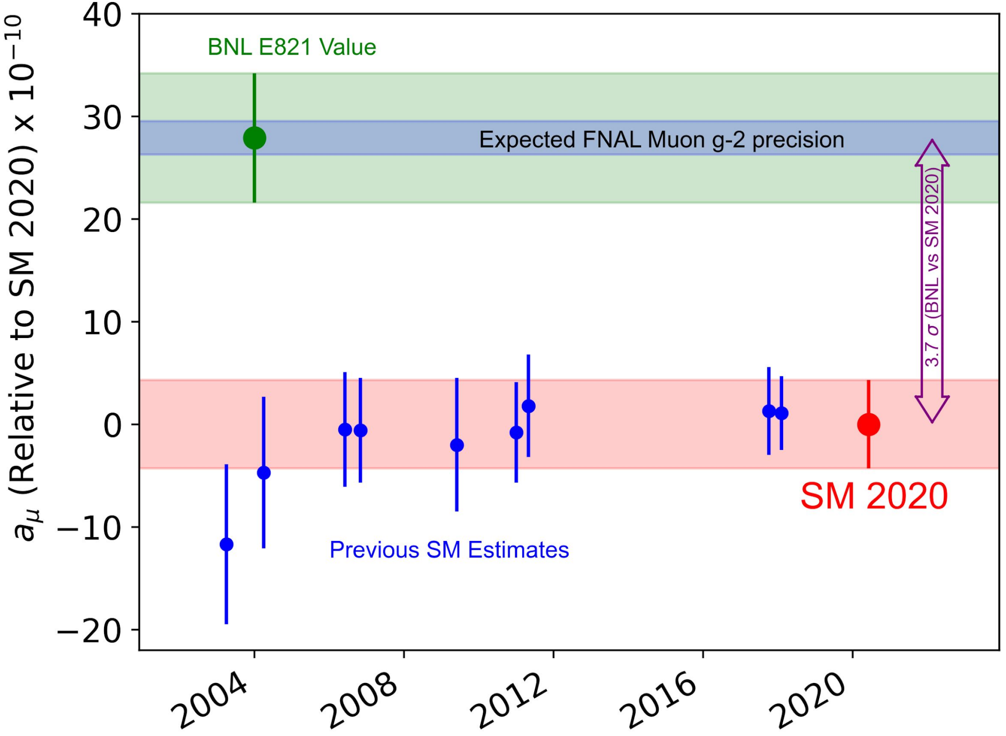


QED	Hadronic VP	Hadronic LbL	Electroweak
$\sim 1 \times 10^{-3}$	$\sim 7 \times 10^{-8}$	$\sim 9 \times 10^{-10}$	$\sim 15 \times 10^{-10}$

full re-evaluation of SM value released by Muon g-2 Theory initiative (https://muon-gm2-theory.illinois.edu/)

$$a_\mu = \frac{g_\mu - 2}{2}, \; \vec{\mu} = (1 + a_\mu)\frac{e}{m}\vec{s}$$

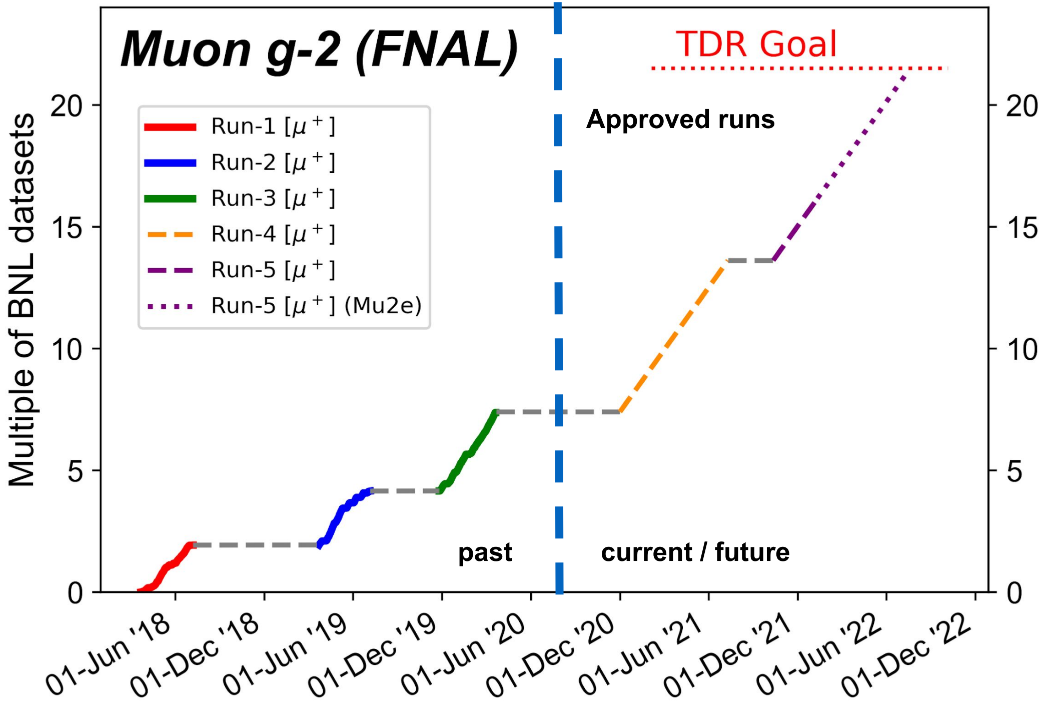
a_μ measured to 540 ppb at BNL



$$a_\mu^{exp} - a_\mu^{SM} = (27.9 \pm 7.6) \times 10^{-10}$$

- ~ 3.7σ discrepancy b/w BNL measurement & SM prediction
- 540 ppb(BNL) → 140 ppb (**FNAL goal**)
- SM uncertainty dominated by hadronic contributions

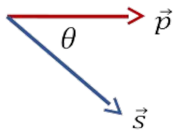
The experiment has completed 3 data runs



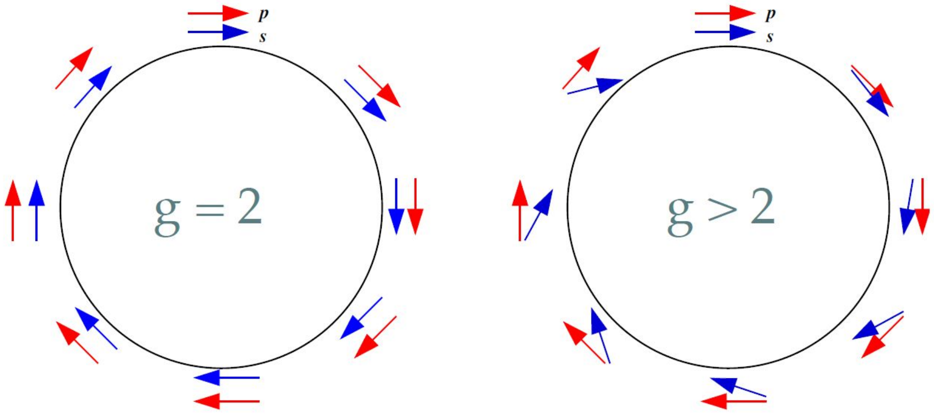
- ~8X BNL statistics as of Run 3
- ~18.5X BNL - goal to achieve the projected precision
- 1st publication soon!
- This talk will focus on **Run 2** (2019)

Measurement of a_μ

- Anomalous precession frequency: $\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu c}$ (Ideally)
- Magnetic field: $2\hbar\omega_{p'} = 2\mu_{p'}|B|$



$$\omega_a = \dot{\theta}$$



Measured experimentally

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_{p'}} \frac{\mu_{p'}}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

10.5 ppb Hydrogen Maser

22 ppb Muonium

0.26 ppt [1] Electron g-2/QCD

[1] CODATA

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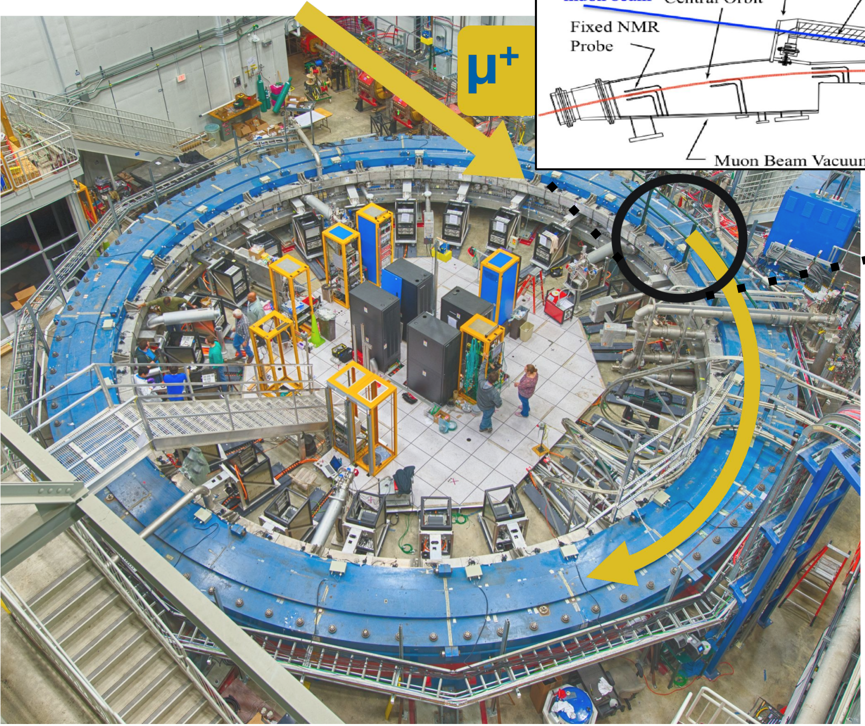
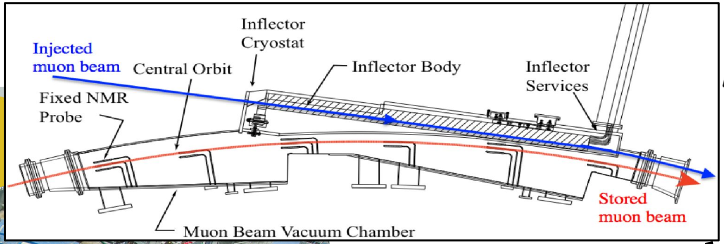
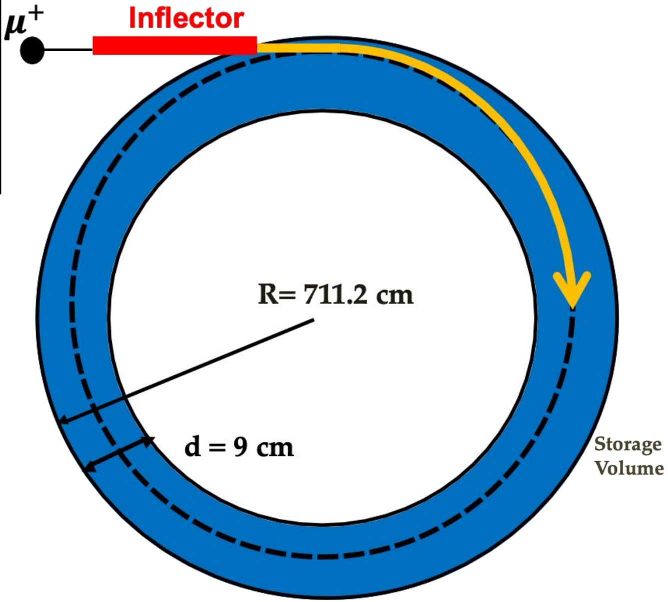
Muon Beam Injection



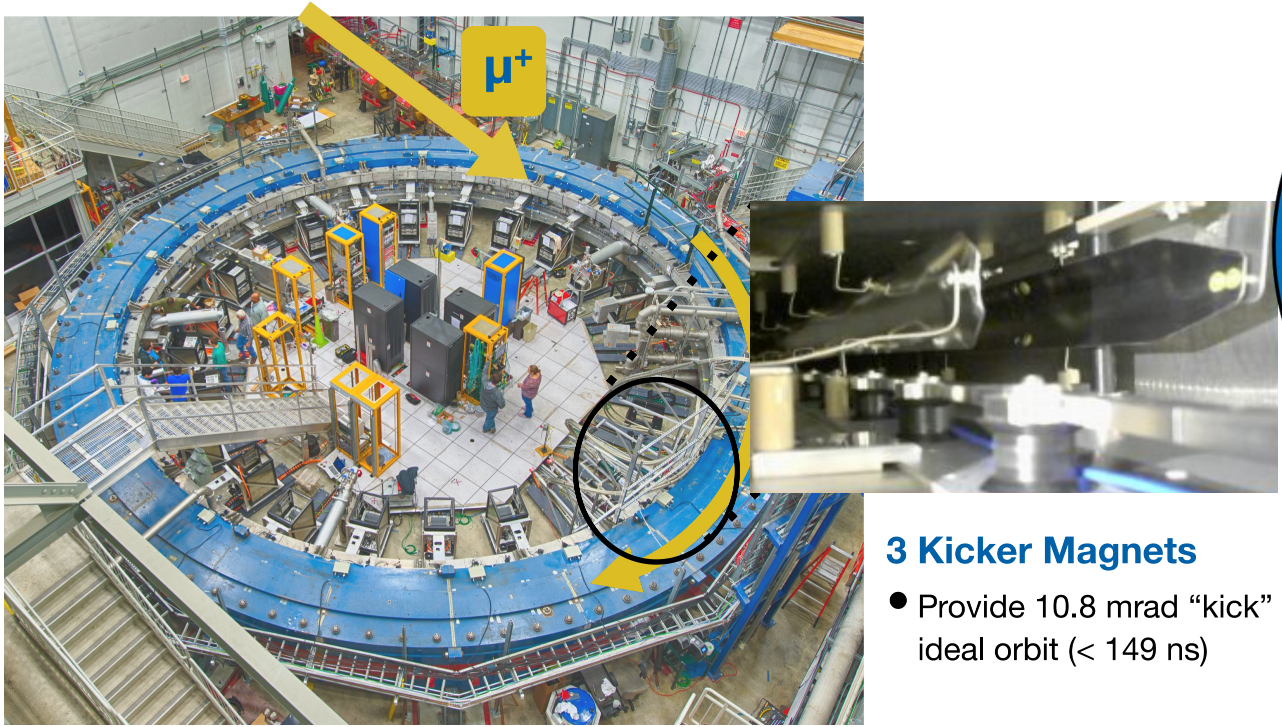


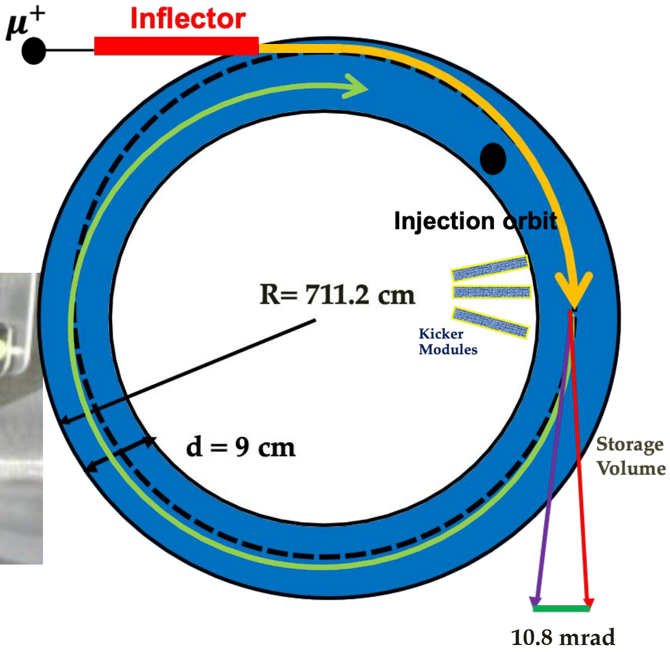


Inflector Magnet

- Provides field free region to deliver beam to edge of storage region
- Stops strong deflection of the beam
- Incident beam center 77mm off from storage region center

Storing the Muons





3 Kicker Magnets

- Provide 10.8 mrad "kick" to direct muons into ideal orbit (< 149 ns)

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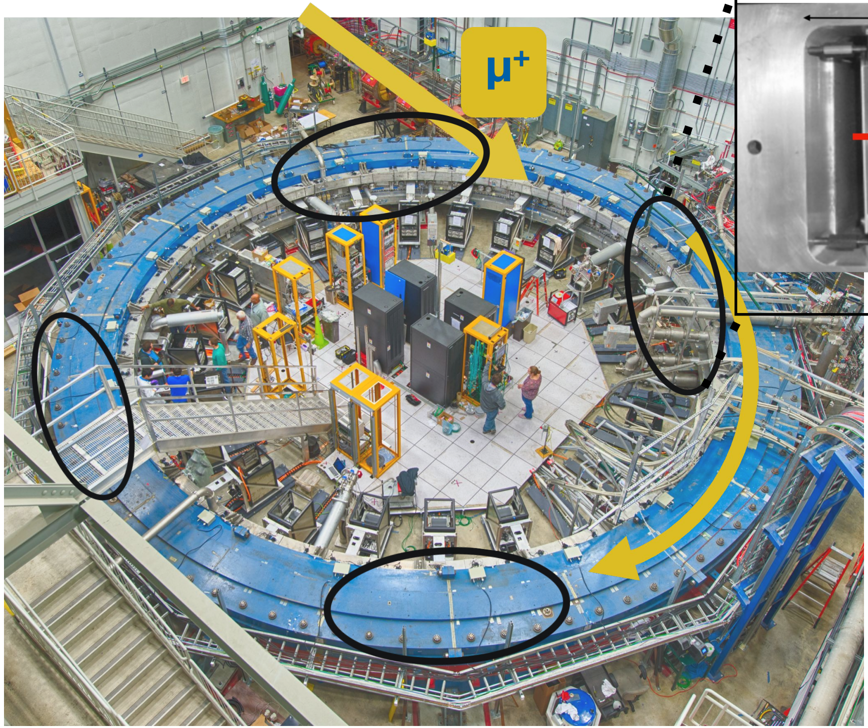
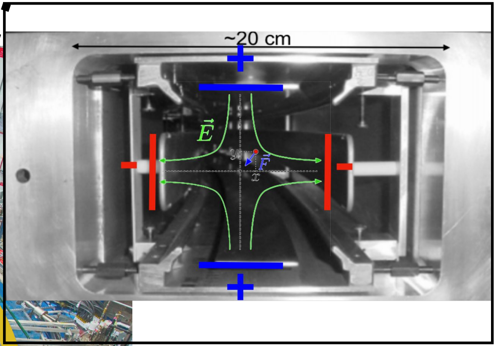
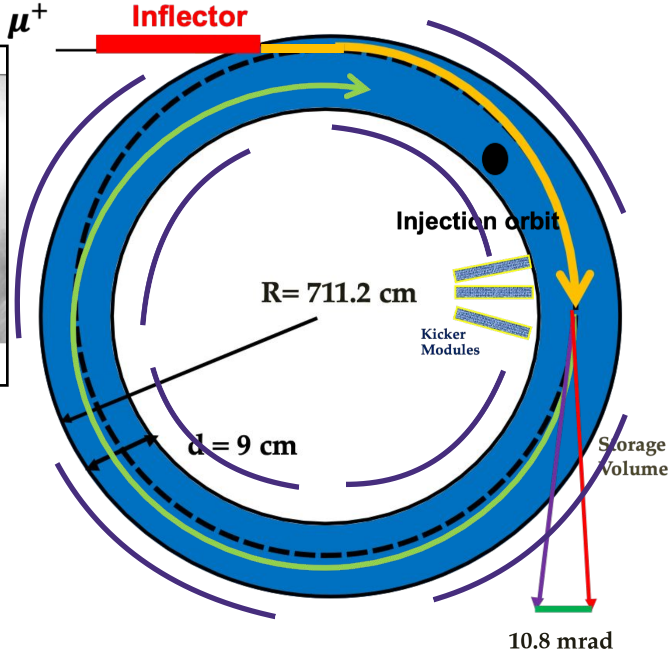
Focusing the Muon Beam







Electrostatic Quadrupoles

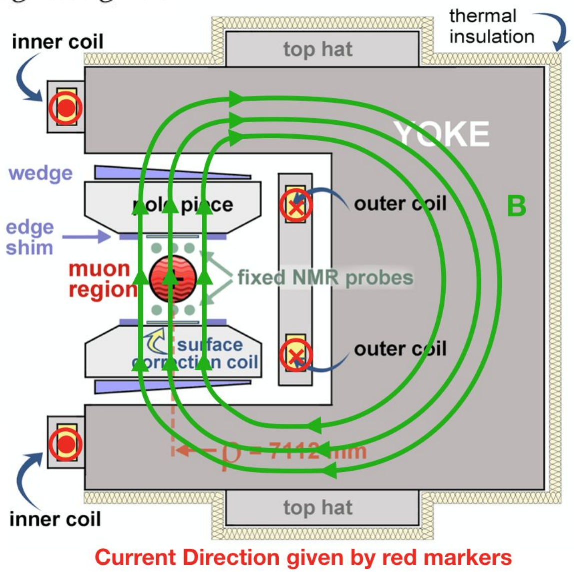
- Focuses muon beam vertically

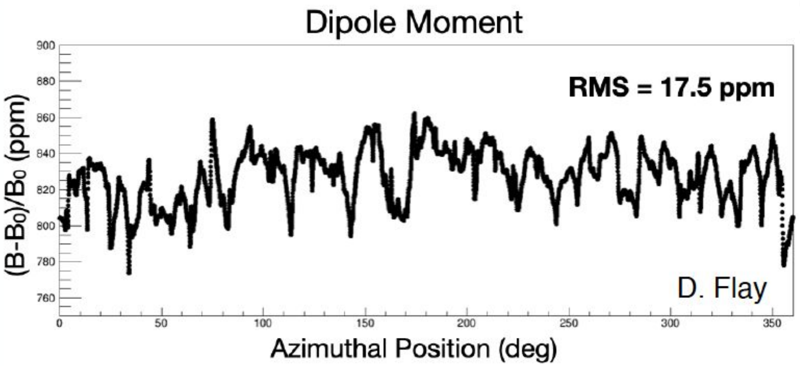
Muon Beam Storage and Focusing

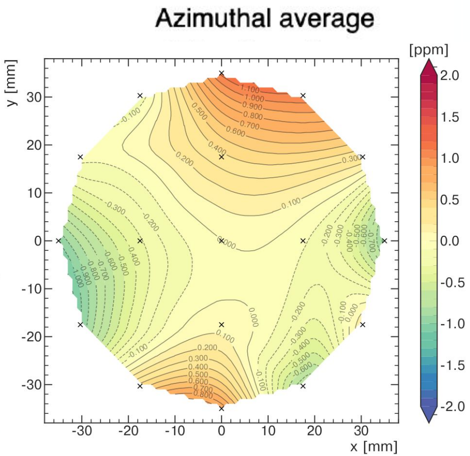
$$a_\mu = \frac{\omega_a}{\tilde{\omega}_{p'}} \frac{\mu_{p'}}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Storage Ring Magnetic Field :

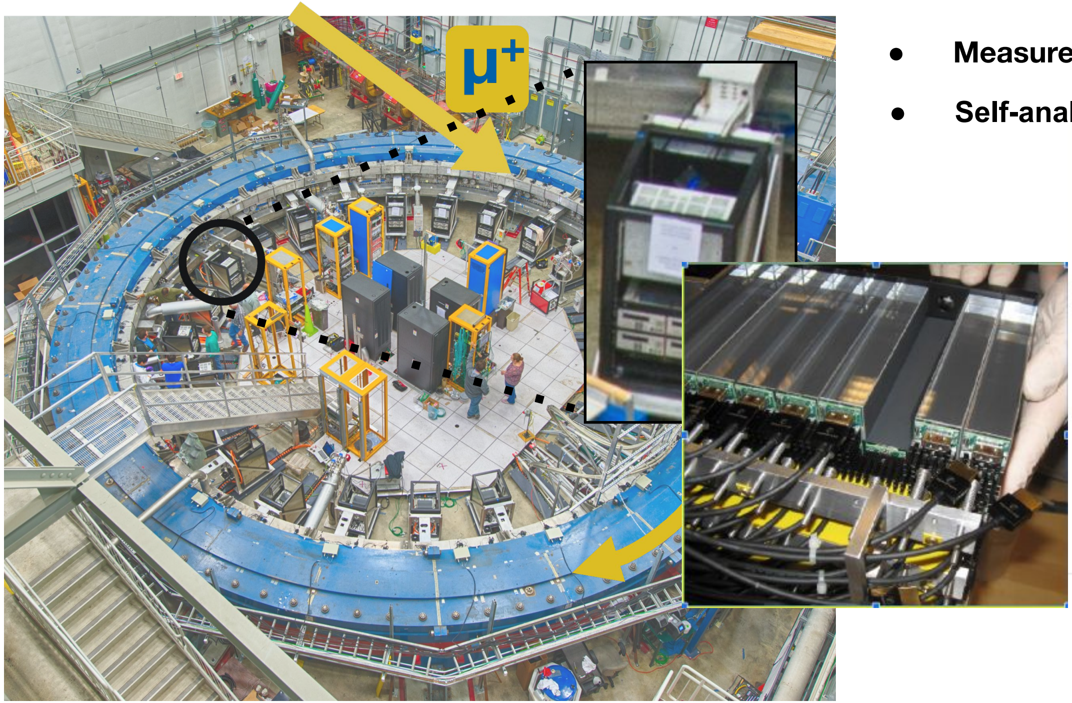
- Needed for physics measurement (determine at all times)
- Provides radial confinement
- Pulsed NMR of protons: $2\hbar\omega_{p'} = 2\mu_{p'}|B|$



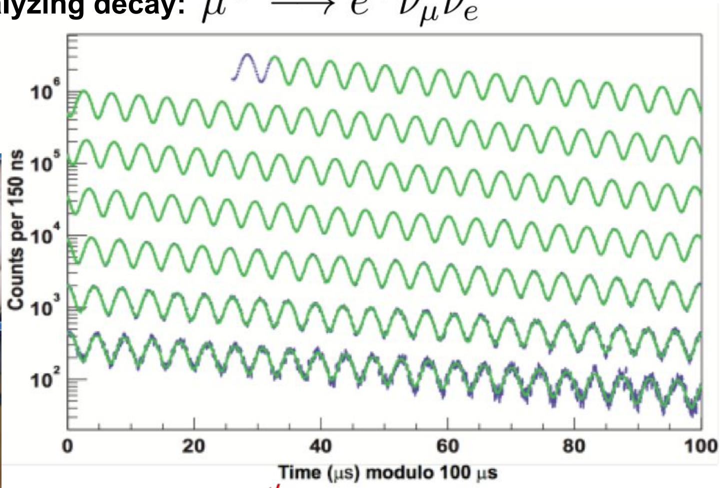




Muon Spin Precession (ω_a) in g-2 Ring



- **24 Calorimeters with 54 Cherenkov PbF_2 crystals with very fast SiPMs stationed around the ring**
- **Measure arrival time & energy of the decay e^+**
- **Self-analyzing decay:** $\mu^+ \longrightarrow e^+ \bar{\nu}_\mu \nu_e$



$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A\cos(\omega_a t + \phi)]$$

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_{p'}} \frac{\mu_{p'}}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Significant Detector Effects

Two (or more) decay positrons hit a calorimeter too close in space and time

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The overlapping pulses are treated as a single pulse of higher energy(pileup events)

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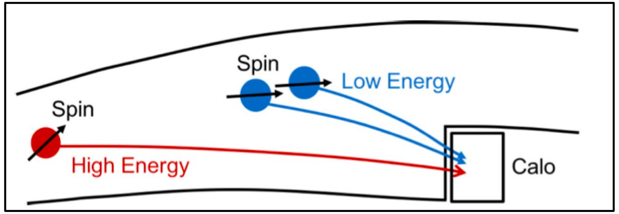
Pileup events distort the time (carries a different g-2 phase) and energy spectra

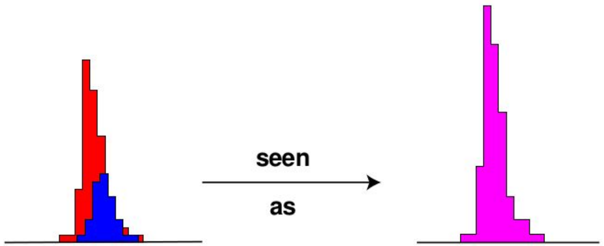


- Pileup events have different phase than the non-pileup events
- Construct pileup double spectrum if a shadow pulse is found :

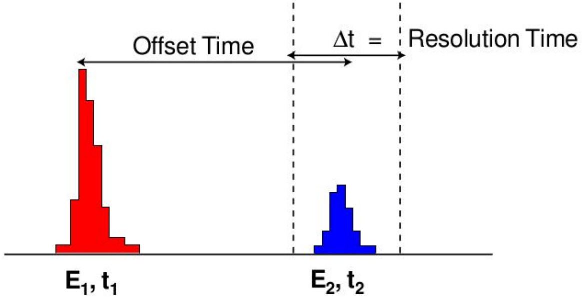
$$E_D = C(E_1, E_2) \times (E_1 + E_2)$$

$$T_D = \frac{t_1 + t_2}{2}$$

- **Pileup spectrum = doublets - singlets**



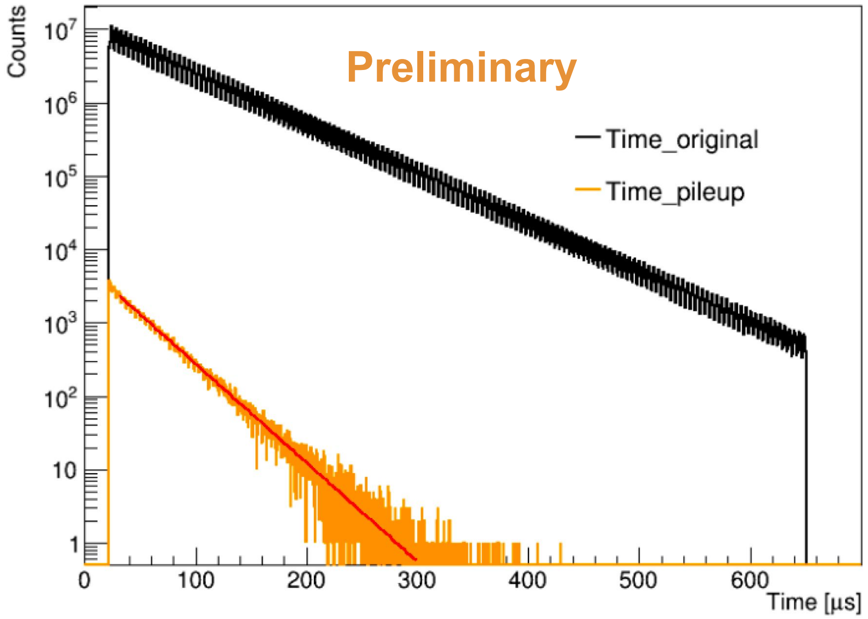
Pileup: Overlapping pulses cannot be resolved

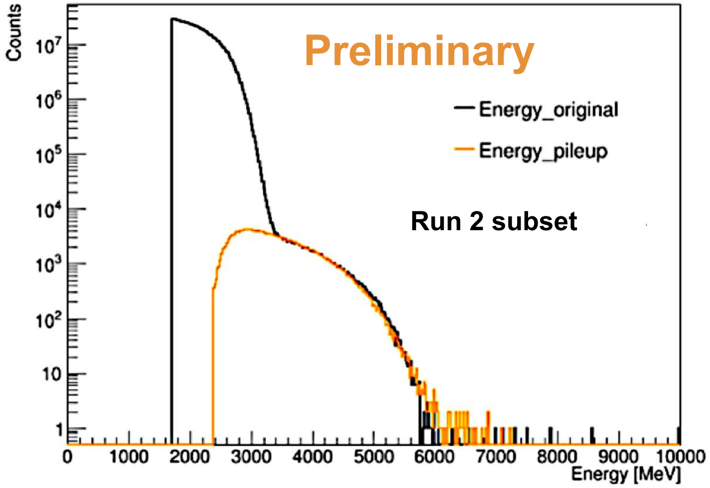


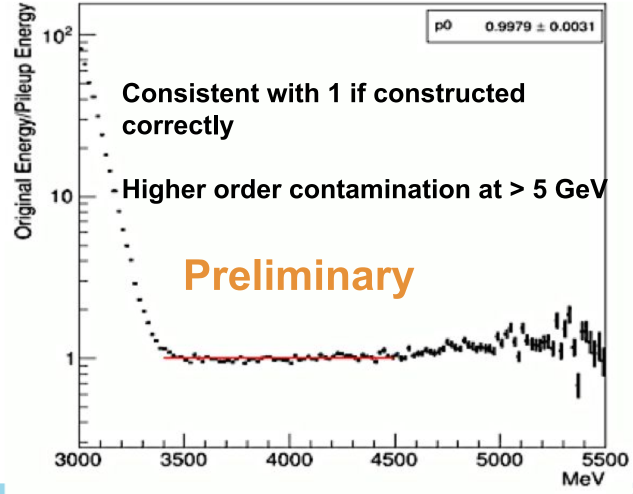
Pileup Construction: Shadow Method

Probability of having overlapping pulses is the same as pulses being separated by a small time offset

Pileup Events







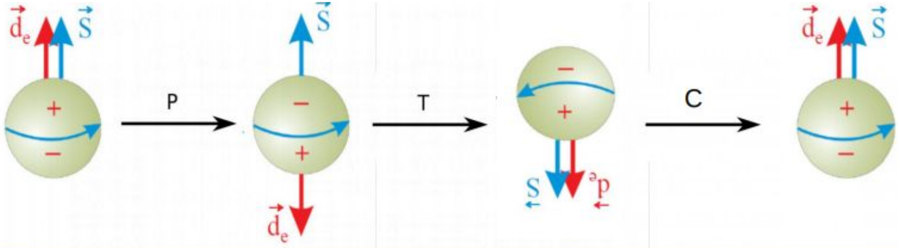
Method of correction : subtract pileup events from corresponding hit spectrum, before fitting to extract precession frequency

Muon g-2 Responsibilities :

- Studied the beam distribution and beam dynamics
  - Provided input for beam tuning (2018)
- Served as the Ring operation Co-coordinator for the Electrostatic Quadrupole Systems (2018/2019)
  - Serving as on-call expert since 2019
  - Responsible for maintenance and upgrades of the EQS
- Systematic Studies on ω_a: Pileup estimation
  - Developed Pileup construction algorithm (2018/2019)
- Developed framework for a fitting method to extract ω_a - foundation for CPT LV analysis
- Developed CPT LV analysis framework - 3 different techniques included in the package

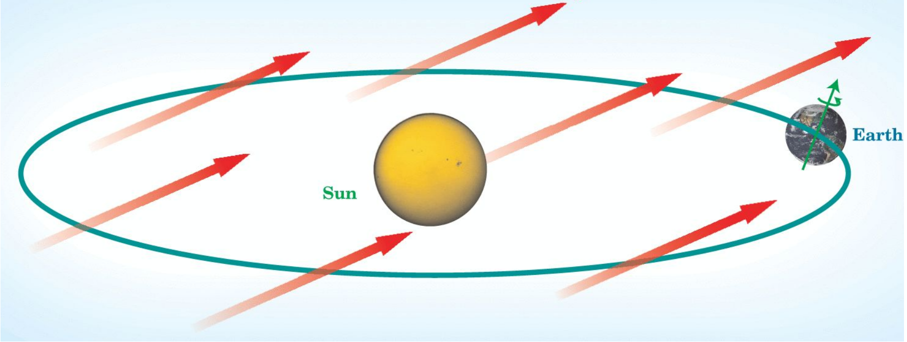
CPT and Lorentz Symmetry:

- Transformations
  - Lorentz : rotations about and boosts along 3 spatial directions
  - CPT :
    - C: Charge (particle→antiparticle)
    - P: Parity (Spatial inversion: mirror + upside down)
    - T: Time (flip direction of time flow)



- Minimal SM: Lorentz/CPT invariant
- SM: low-energy limit of a more fundamental theory
- Standard Model Extension (SME):
  - Allows for CPT and LV, quantitatively described by coefficients, experimentally determined/constrained

CPT and Lorentz Violation (LV)



Existence of a preferred direction, Uniform constant vector

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Lorentz Violation

In a Lab on the Earth's surface, measurements change as the Earth rotates, as the orientation changes relative to b, leading to a cyclic variation in the measurement over a sidereal day.

SME and CPTLV in Muon g-2:

- 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_κ ⟶ **Can be determined by Muon g-2 experiment**

CPTLV Signals with Muon g-2 experiment at Fermilab

CPT LV Signatures

Current

Sidereal Oscillation in $\mathcal{R}(=\omega_a/\tilde{\omega}_{p'})$

(T = 23h 56 min.)

Measured experimentally

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_{p'}} \frac{\mu_{p'}}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

- **Spectral analysis**
- **Multi-parameter fit**

$$b_\perp^{\mu^\pm} = \frac{\hat{\omega}_a^{\mu^\pm}}{2|sin\chi|} < 1.4 \times 10^{-24}\text{GeV}$$

(BNL limit)

Future

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

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

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

Lomb-Scargle(LS) Test:

- **Spectral analysis technique for unequally spaced data**
- **Normalized Periodogram $P_N(\omega)$**
- **Scan frequencies, calculate Spectral Power at each ω:**

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

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

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

Frequency range : $[0, 5F_C]$

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)**

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

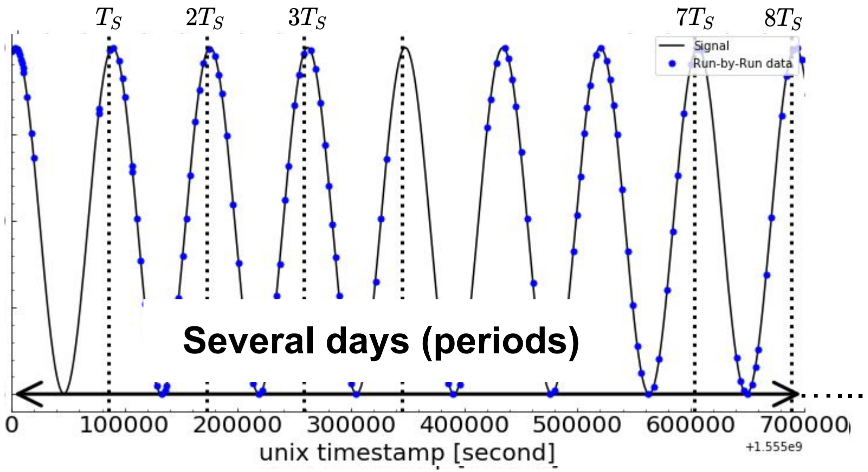
MPF - Amplitude of the signal (if any) directly

Analysis flow :

Run 2 data

Run by Run

- run ~ 1 hour of data collection
- Extract ω_a for each run



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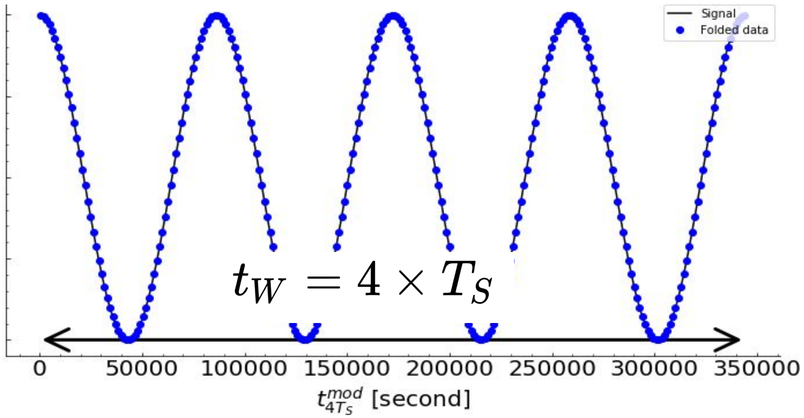
- time of an event modulo a time window t_w
- Equal sized time bins



Apply Lomb Scargle test and MPF

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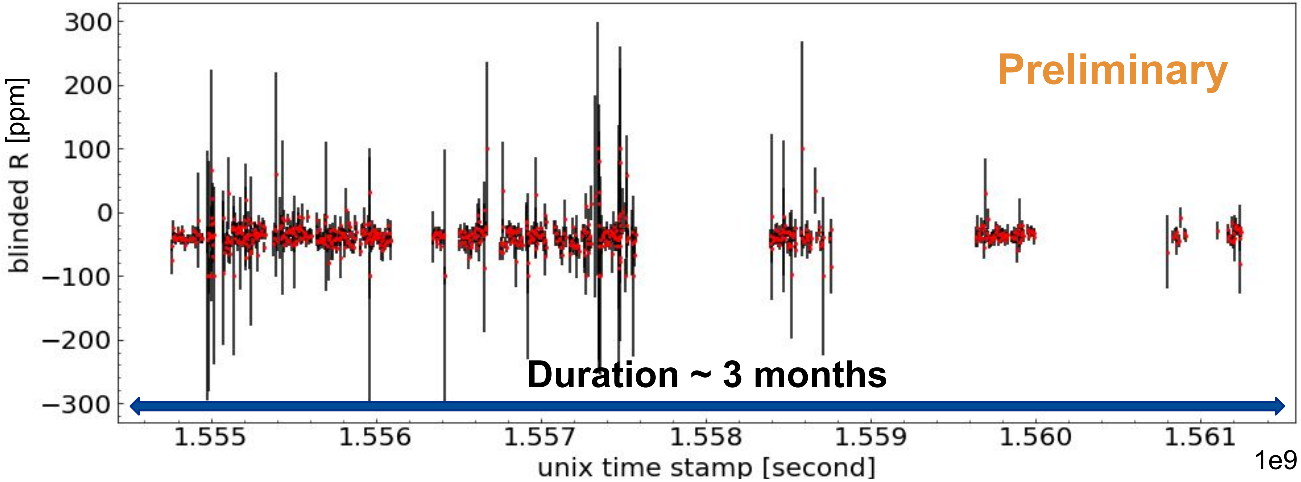
Run by run analysis :

Ingredient :

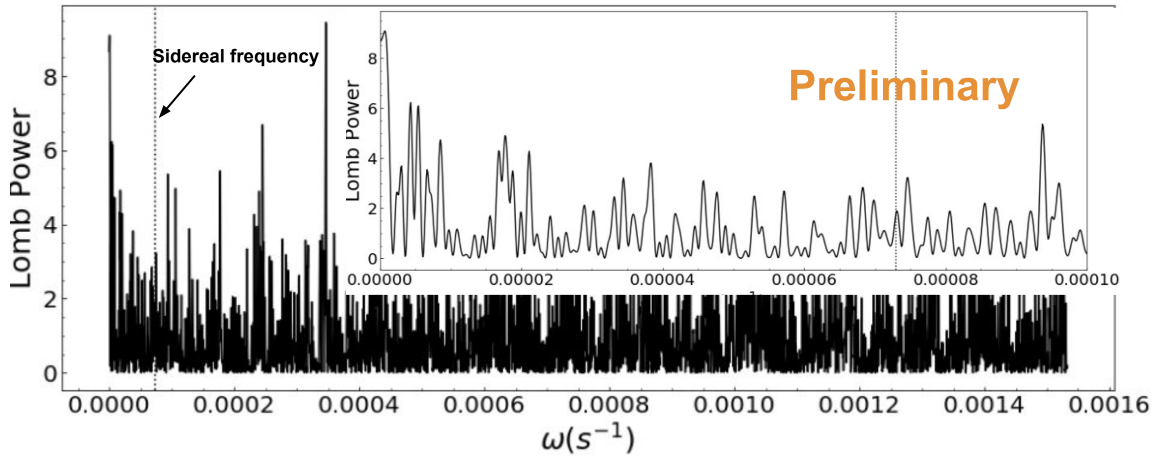


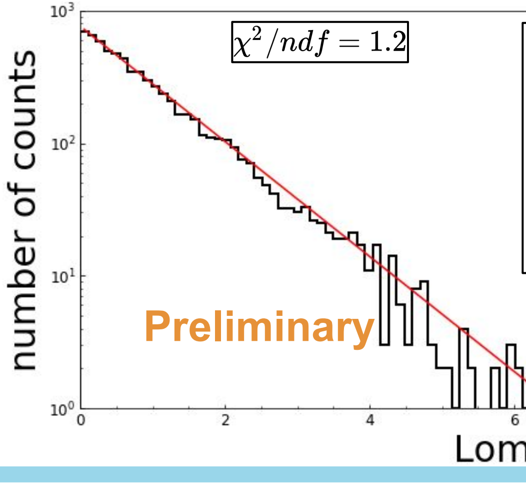
A subset of Run 2 data

data point uncertainty δR~ 10 ppm

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

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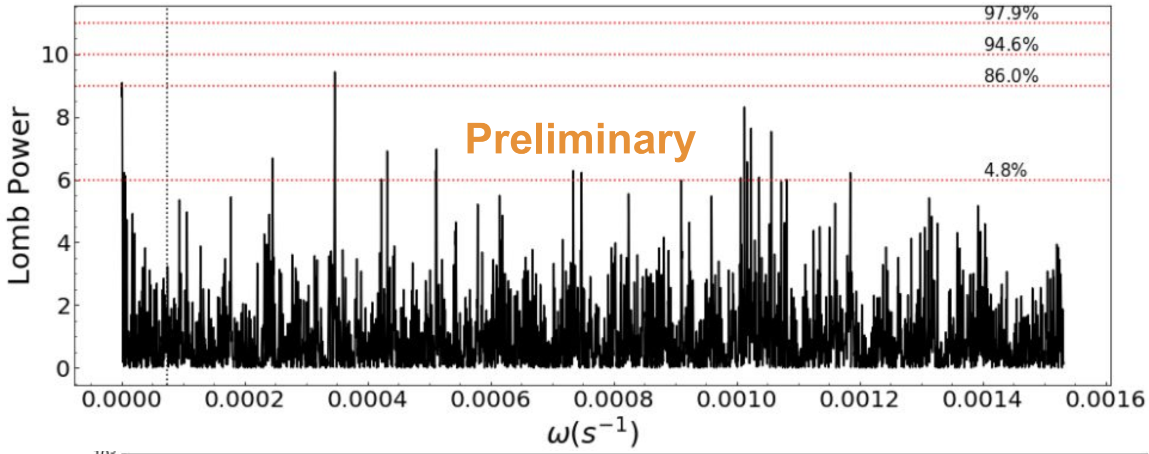
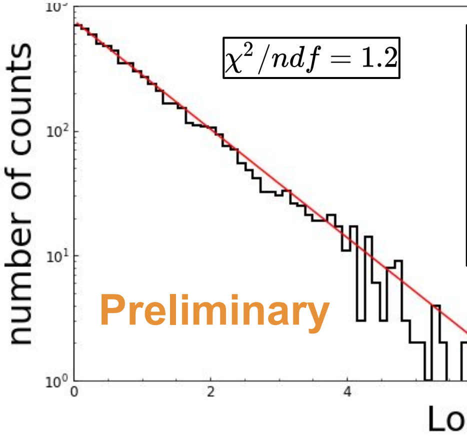
Quantify the significance of the peak:

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





Exponential dist. of Lomb power

No statistically significant signal

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

$P_N(\omega_s) =$ **1.7 (No signal)**

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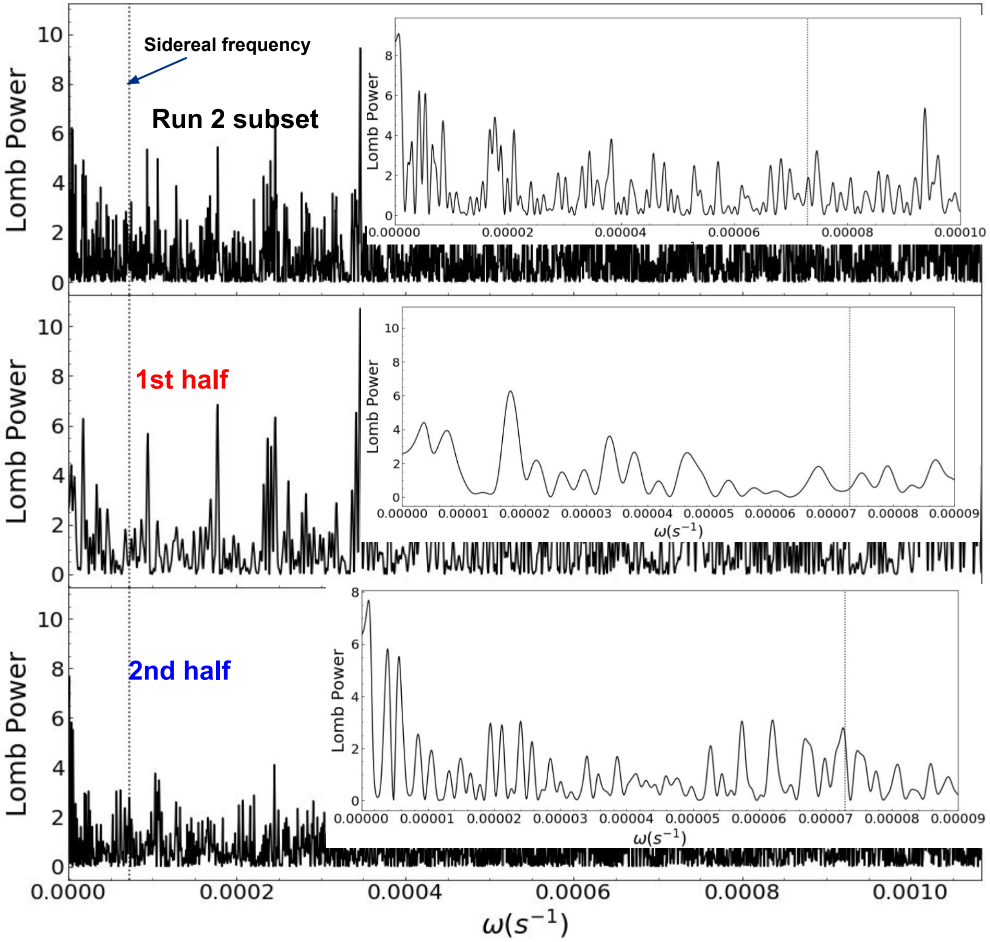
More tests

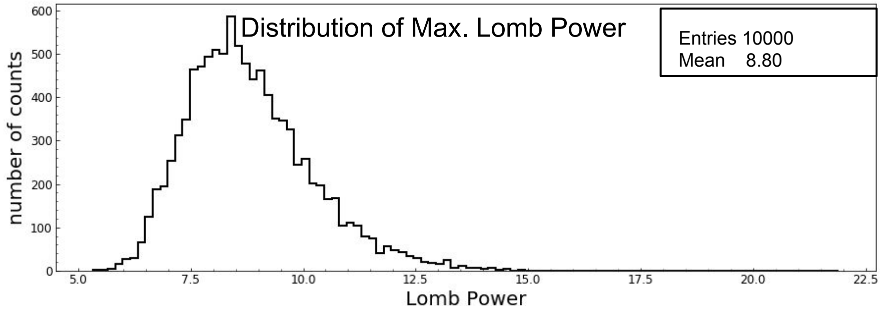


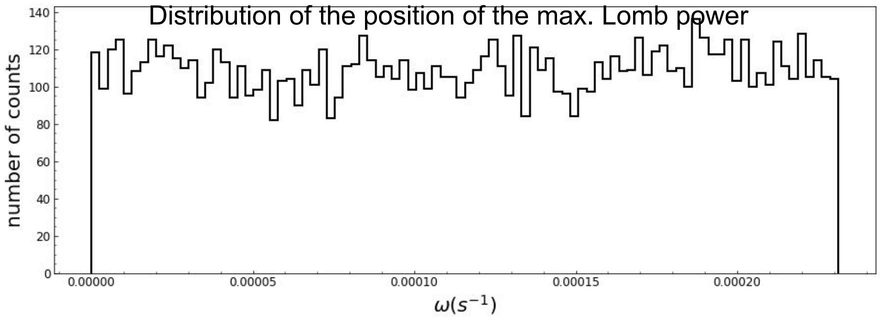
- Run 2 subset - small peak (Power = 1.7)
- Further tests confirm that comes from the noise

Spectral Analysis for Uneven Simulated Data

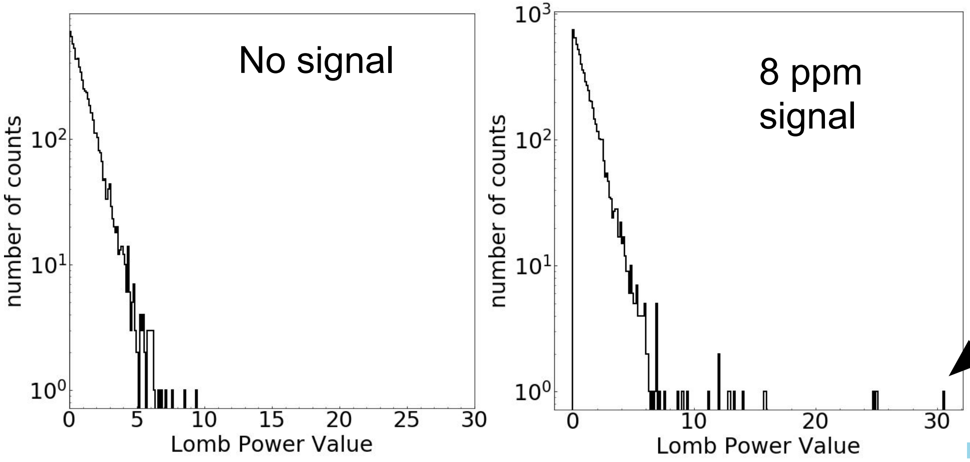
- **simulated data generated - real data time-stamp**
  - random no. generated based on real data inputs
  - δR from real data

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





Lomb Power distribution for one simulated data group

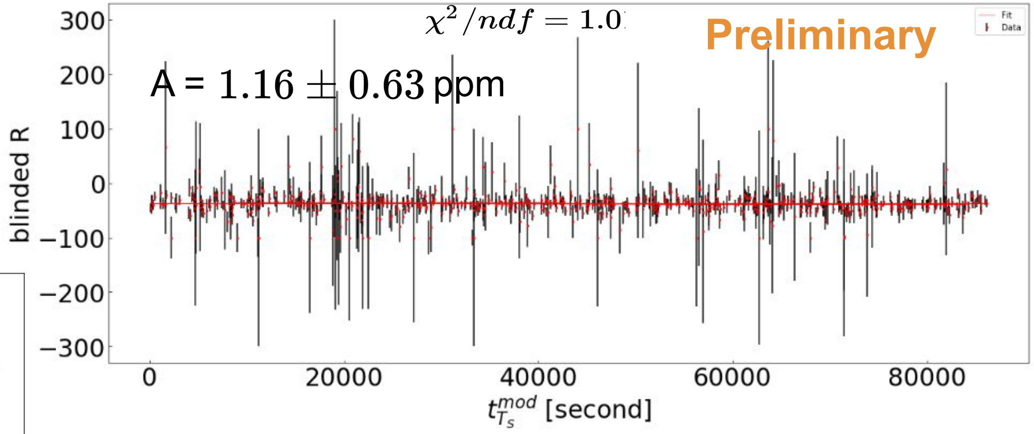


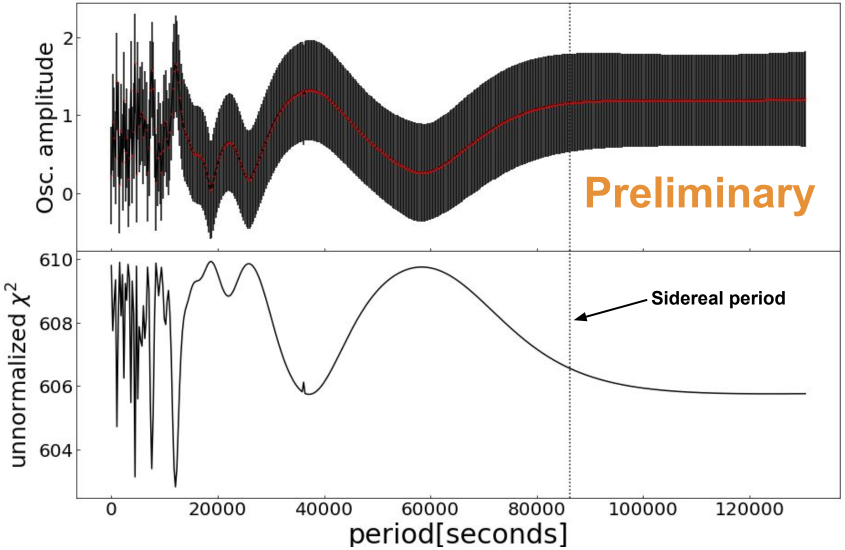
Long tail → Significant Signal Peak

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**

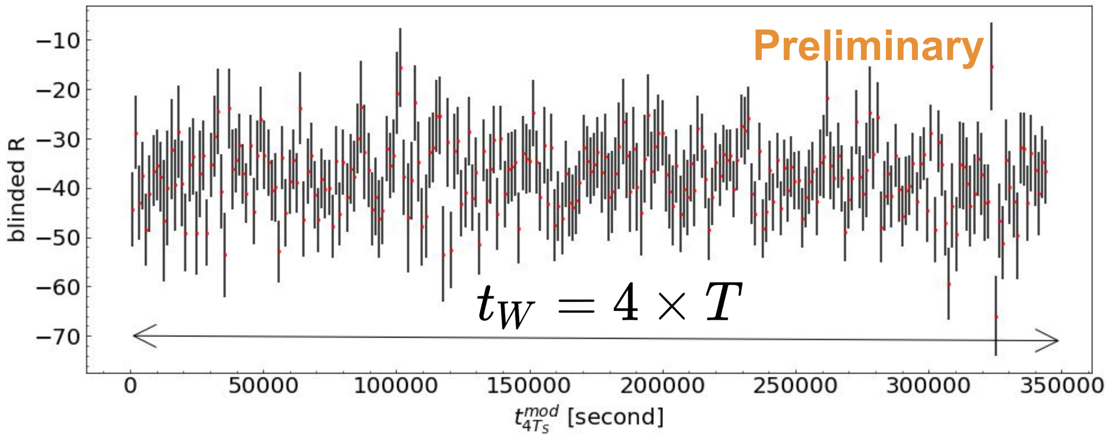




Oscillation period scan :

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

Folded data analysis :



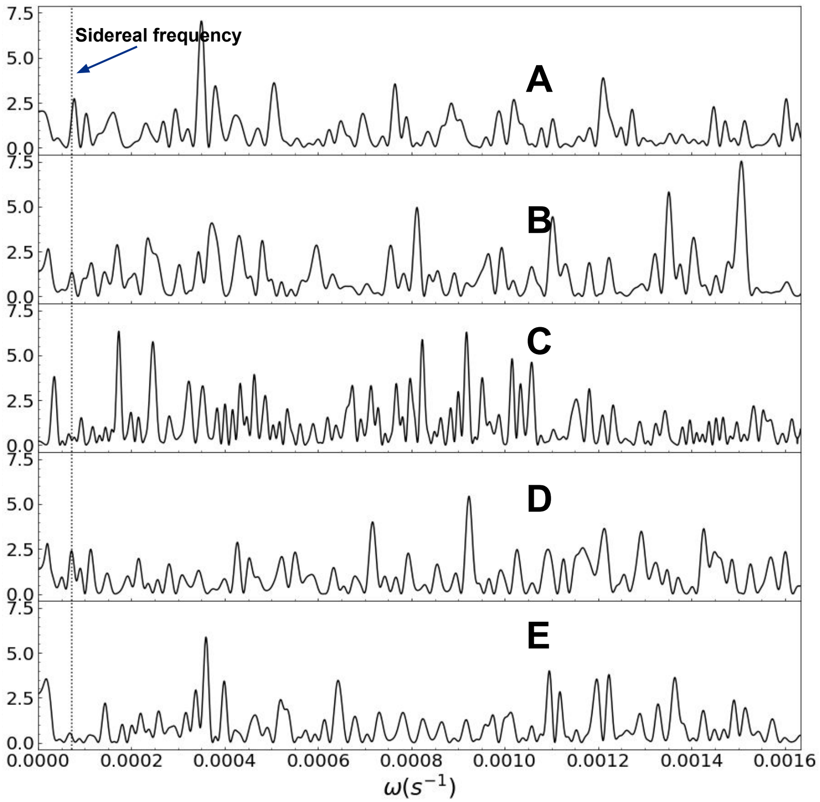
- **Pros :**
  - **cancel other freqs as well as improving the stats**
- **Cons:**
  - **loss of time str. of the whole experimental period**

- **Windows - C, D, E chosen randomly**
  - **if we introduced sidereal osc. by binning data A, B**

Window Name(W)	Window Size[seconds]	Bin Width [seconds]
A	W $= 4 \times T_S$	1346.31
B	W $= 4 \times T_D$	1350.0
C	W $= 4 \times 123594$	1931.16
D	W $= 4 \times 89903$	1404.73
E	W $= 4 \times 92801$	1450.02

LS and MPF on Folded data :

Lomb Scargle test



Multi parameter fit

Window size (W)	fix $T = T_S$	fix $T = 24$h
A ($W = 4 \times T_S$)	$\chi^2 = 0.95$ $A = -1.26 \pm 0.63$ $\phi = 1.34$	$\chi^2 = 0.95$ $A = -1.24 \pm 0.63$ $\phi = 1.37$
B ($W = 4 \times T_D$)	$\chi^2 = 1.15$ $A = 1.03 \pm 0.63$ $\phi = 0.47$	$\chi^2 = 1.15$ $A = 1.03 \pm 0.63$ $\phi = 0.50$
C ($W = 4 \times 123594s$)	$\chi^2 = 1.15$ $A = 0.46 \pm 0.61$ $\phi = 2.46$	$\chi^2 = 1.15$ $A = 0.46 \pm 0.61$ $\phi = 2.56$
D $W = 4 \times 89903$	$\chi^2 = 0.95$ $A = -1.34 \pm 0.62$ $\phi = 0.46$	$\chi^2 = 0.95$ $A = -1.34 \pm 0.62$ $\phi = 0.46$
E $W = 4 \times 92801$	$\chi^2 = 0.86$ $A = 0.52 \pm 0.63$ $\phi = 0.32$	$\chi^2 = 0.86$ $A = 0.53 \pm 0.63$ $\phi = 1.15$

- **Power spectra peaks depend on data binning**
- **Osc. Amp inconsistent among different windows**
- **Peak at TS pop in and out**
  - **Statistical variation**
  - **No significant Signal**

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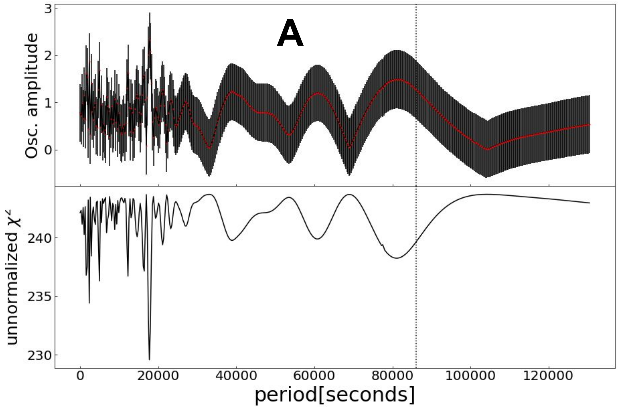
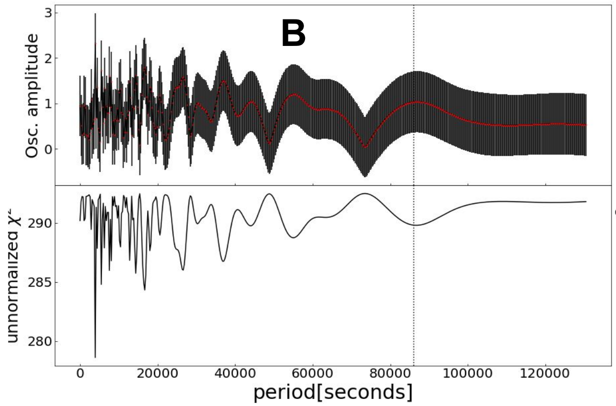
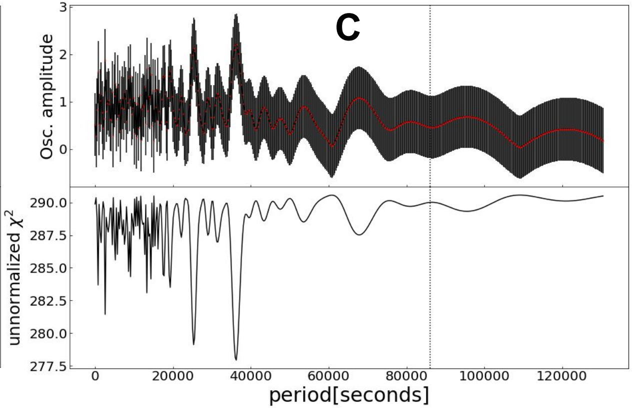
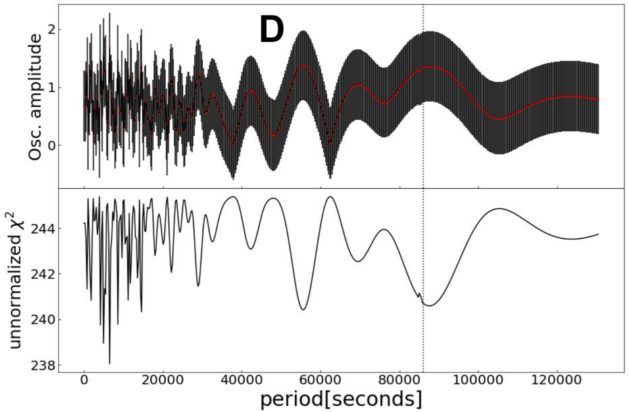
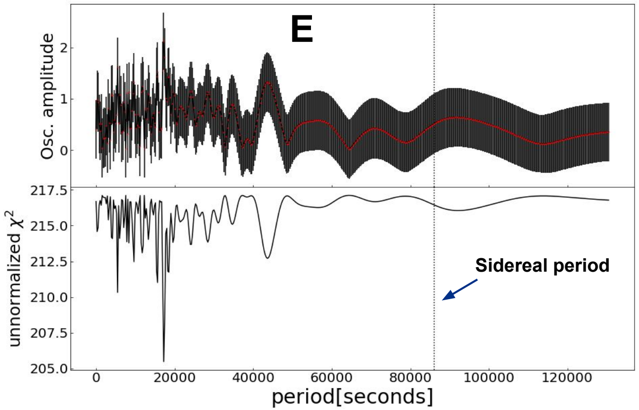
MPF for different bin widths :









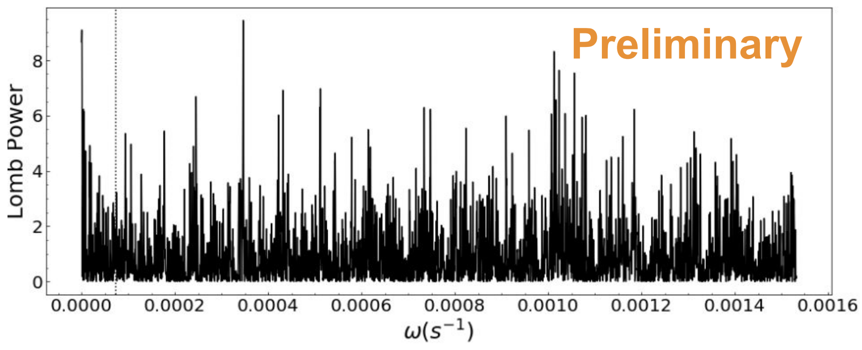


- T_S minimum for only data group B (24 hours)
- A, C, D, E - T_S is not a minima

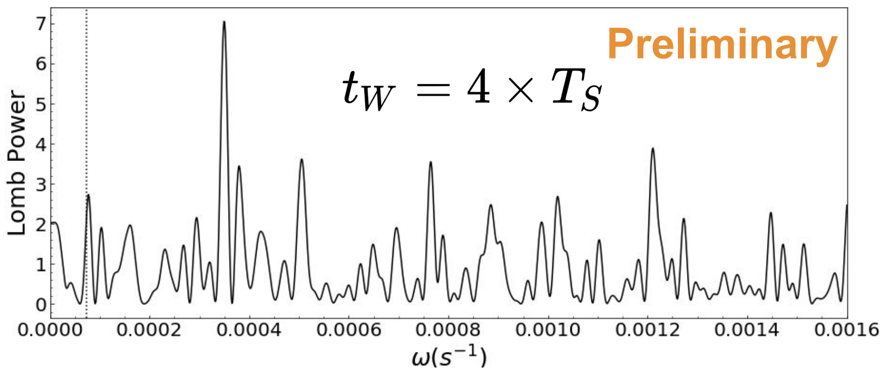
No significant signal in the data

Summary : Run by Run and Folded data

Run by run data



Folded data



- MPF : A = 1.16 ± 0.63 ppm
- No significant osc. - LS, MPF

- MPF : A = 1.26 ± 0.65 ppm
- No significant osc. - LS, MPF

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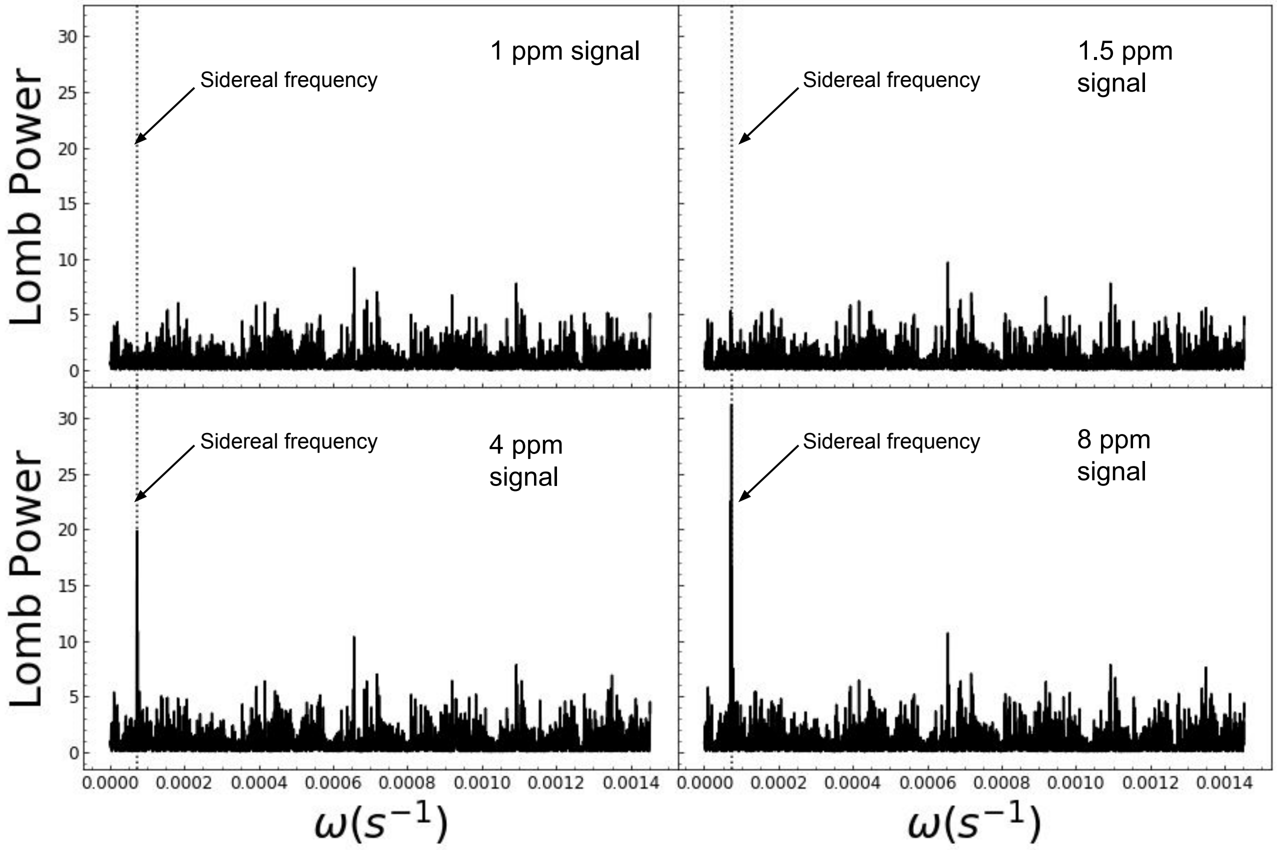
Sensitivity studies on simulated data for Run 2 time-stamp of events

Sensitivity vs Amplitude :

- **simulated data generated - real data time-stamp**
  - random no. generated based on real data inputs
  - δR from real data
- **Add artificial signal at ω_s to simulated data**
  - Signal with amplitude > 2 ppm required for significant detection
- **~ 10 ppm uncertainty on data**

↓

> 2 ppm detectable Oscillation amplitude



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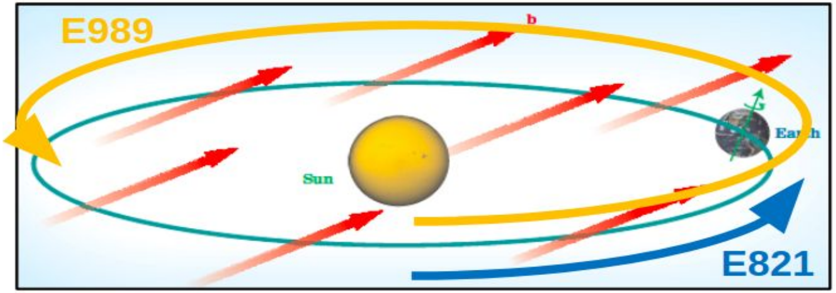
Summary

- Run 1 publication very soon!
- 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
- First search for annual variation in $\mathcal{R}(=\omega_a/\omega_p)$ will be made using E989 data

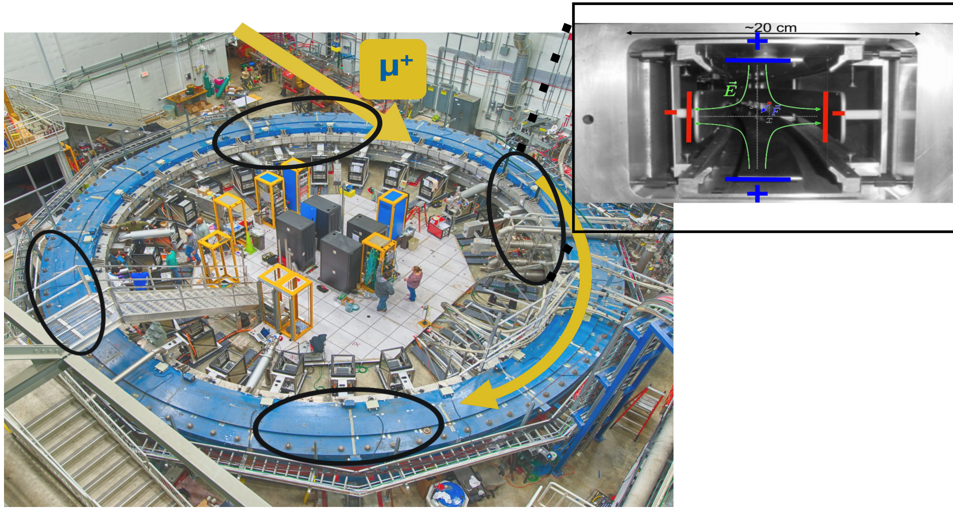


g-2 Operational Responsibilities

Operations, Maintenance and Upgrades of EQS

Operational Issues during Run 1 : Performance < 100 %

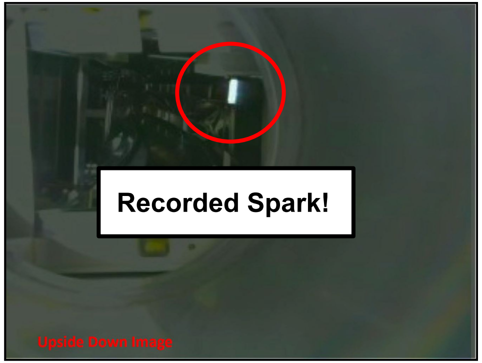
- **Voltage breakdowns (sparks)**
    - Sparks - common concern in any HV system
    - Quadrupole 1 in the way of beam injection
    - Distance b/w two high voltage (HV) leads and/or b/w high voltage lead and ground potential out of spec
    - Space limitation in order to fit within vacuum chamber, can not perturb field uniformity
- **Hardware deficiencies :** vibrations of long HV leads
- **Damaged resistors :** causing beam motion

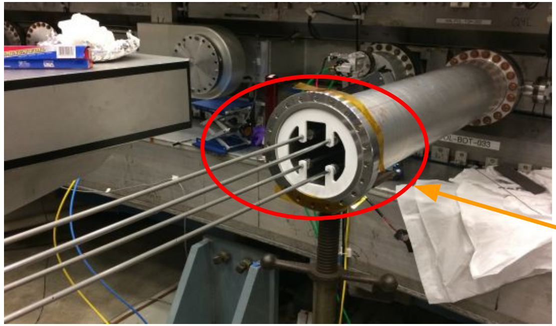


Operations, Maintenance and Upgrades of EQS

Mitigation:

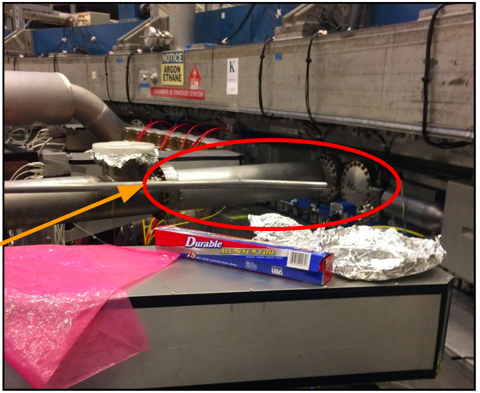
- More support to HV leads to resolve vibration issues
- Used mirrors and cameras to capture sparks
- Out of spec distance b/w high voltage leads fixed by fabricating small alignment tools, adding small (3 - 6 degree) bends to vacuum leads to match up with bend angle of quad extension
- Added more support to HV leads to resolve vibration issues
- Added new element into design - more mechanical stability





Additional support into the middle extension flange

3 degree bend into extension leads to reduce forces



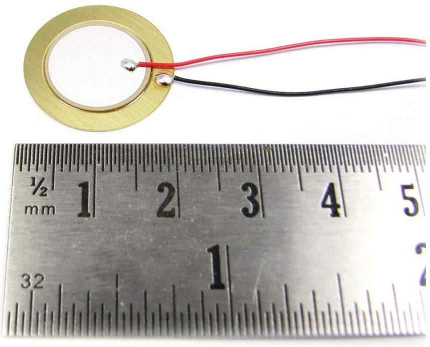
Operations, Maintenance and Upgrades of EQS : Puzzles

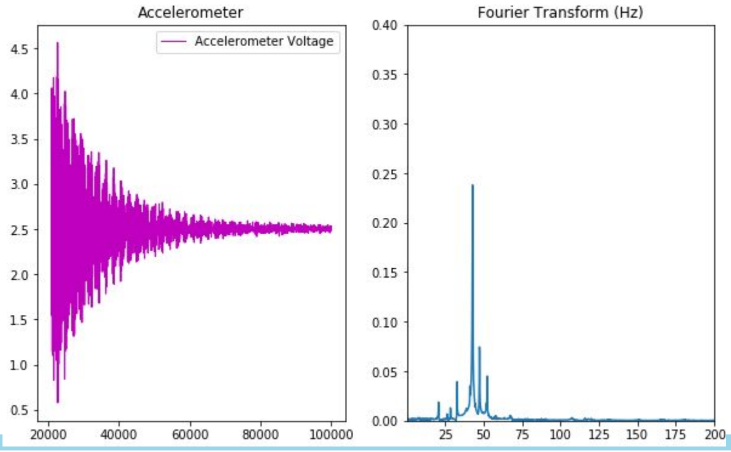
Puzzles to be solved :

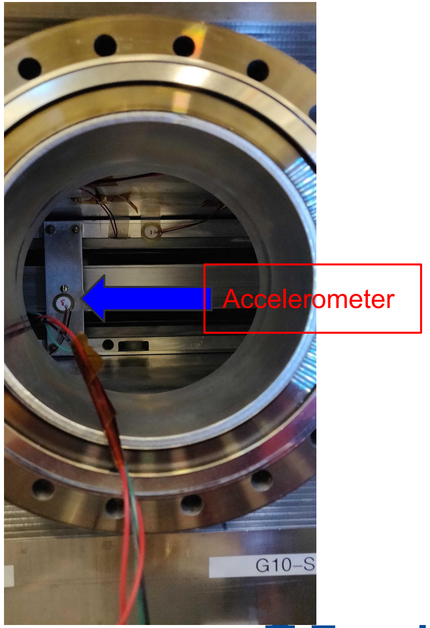
- **Time dependence of the magnetic field in the regions covered by the EQS**
  - **Models : EQS plate vibrations?**
    - Piezoelectric accelerometer
    - Laser reflection measurements

Piezoelectric accelerometers :

mechanical vibration measurement - in vacuum







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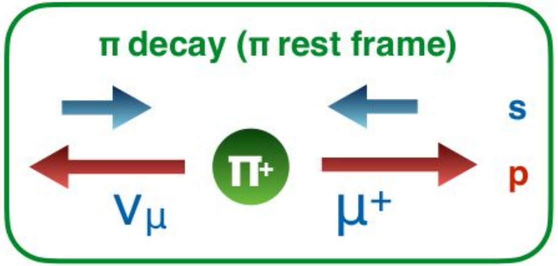
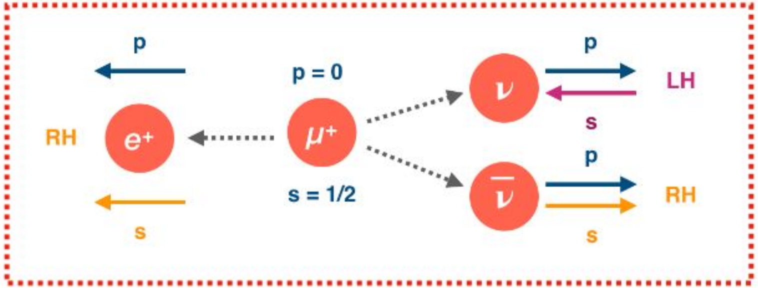
Thank you!

Backup

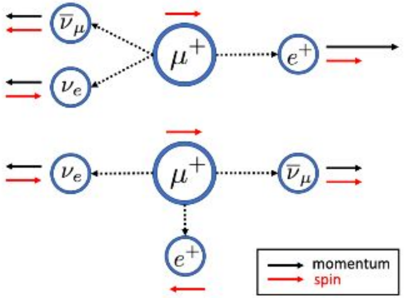
Only LH Muons must be produced→ 95% polarized beam



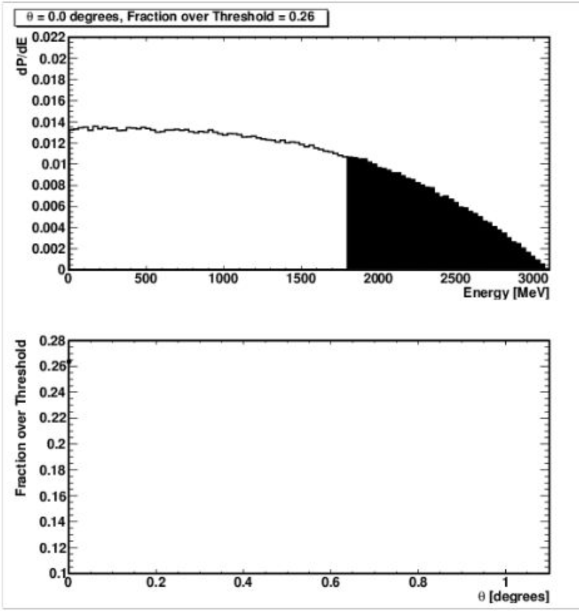
The e+ 'carries' the spin of its parent muon
We can infer the spin direction of muons by measuring the emitted positrons…



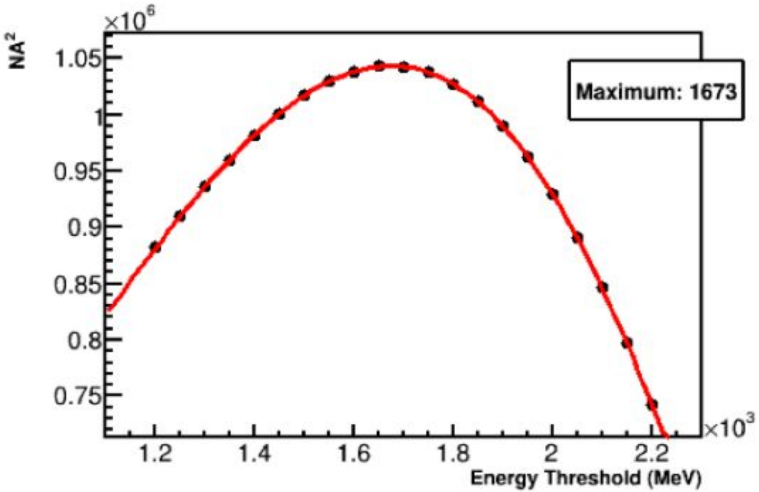
- Two important features of muon decay allows us to measure ω_a directly
- Higher energy positrons are emitted preferentially in the direction of muon spin → Highest energy positrons have the strongest correlation b/w their momentum and spin direction



Muon decay in the rest frame for maximum (top) and minimum (bottom) energy decay positrons

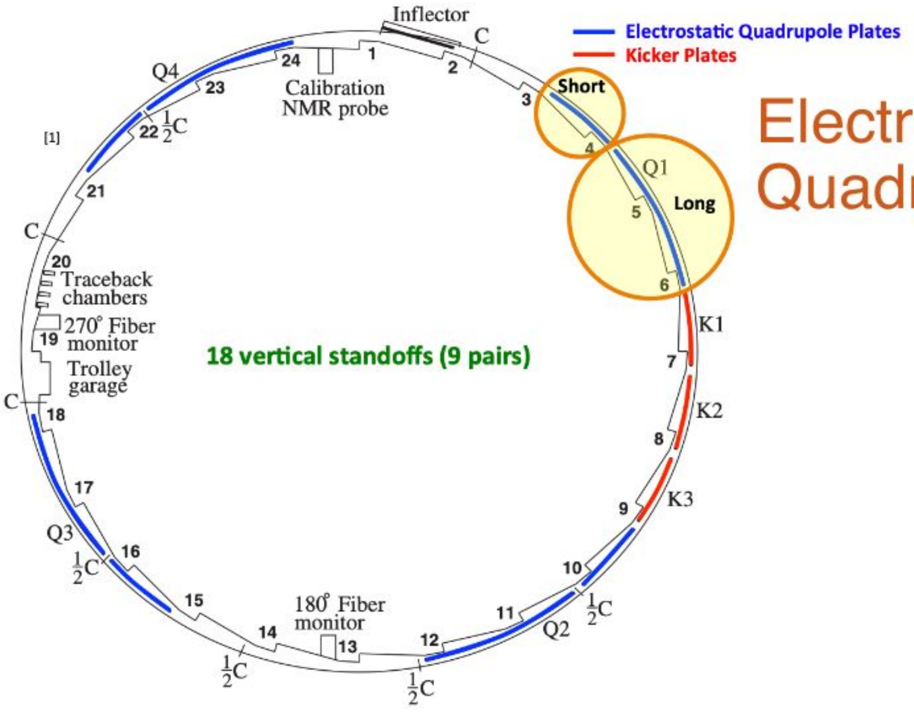


The optimal energy threshold can be determined from the NA2 quantity = FOM

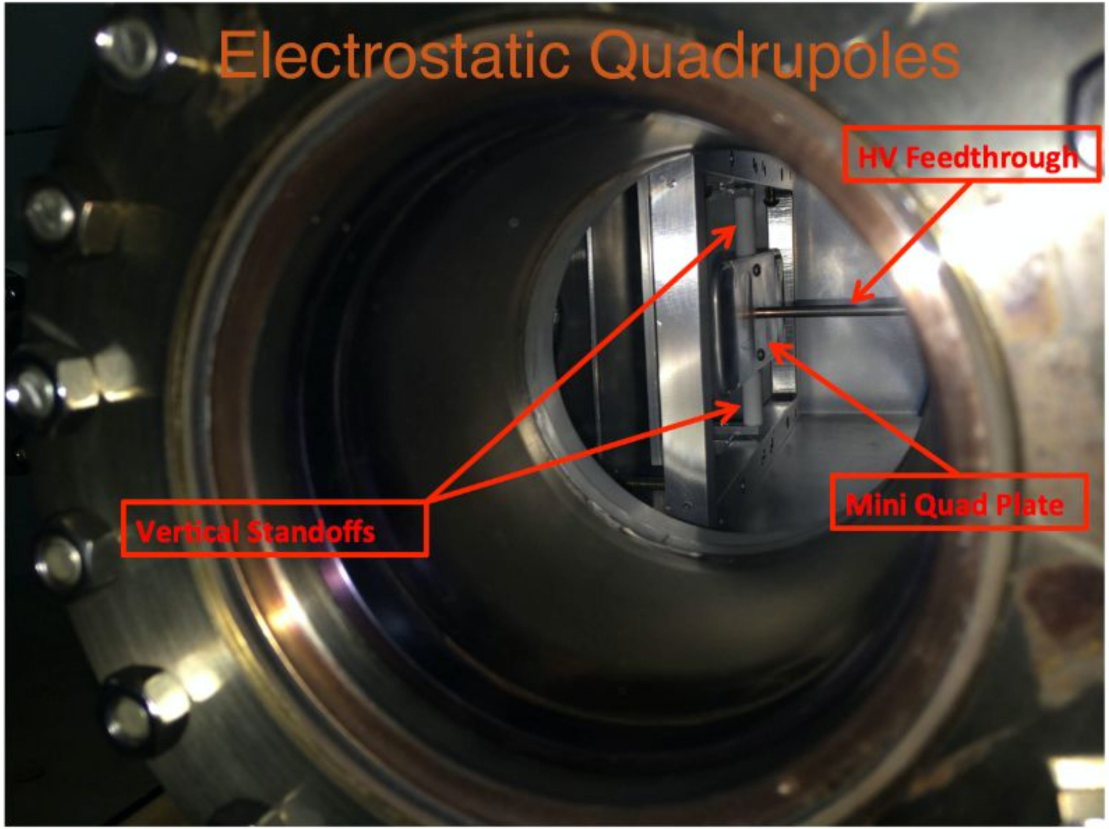


- N is the number distribution of decay positrons
- A is the so called 'asymmetry,' encoding the energy-dependent correlation between the muon spin and the decay positron direction

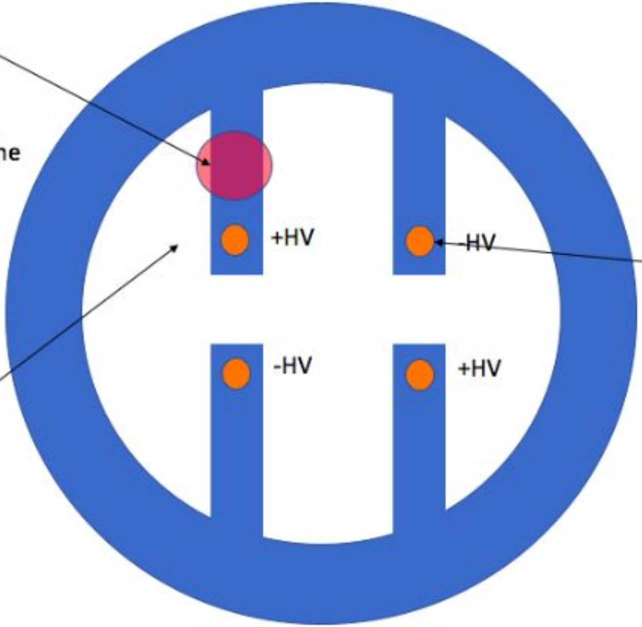
Electrostatic Quadrupoles



[1] G. W. Bennett *et al*. [Muon g-2 Collaboration], Phys. Rev. D 73, 072003 (2006) [hep-ex/0602035].


Electrostatic Quadrupoles
HV Feedthrough
Mini Quad Plate
Vertical Standoffs

During a spark, some ExB electrons drift and hit the Macor at this location. The Surface conductivity of The Macor is very low, so the charge stays put for a long time.



Aluminum Tubes carry HV and are supported by the Macor

Therefore, the electric field is very HIGH at this location, since we have negative charges near The +HV tubes.

It is likely to spark again. This is why we believe we have to lower the voltage.

Analysis framework

Fermilab's art framework and C++

Energy & time of events (MeV, ns)

Energy and time and spatial cuts applied for ω_a data

art module written in C++ (for the grid)

Run-by-Run, Folded event information in histograms & unix-timestamps

art module written in C++ (run locally on 1-D histograms)

Systematic uncertainties included
Final ω_a for CPT LV tests

Extract ω_a

Python

ω_a time-series (hdf5 format)

Lomb-Scargle test, Multi-parameter fit, FFT

C.L. calc (analytical)

Monte Carlo simulation to estimate C.L.

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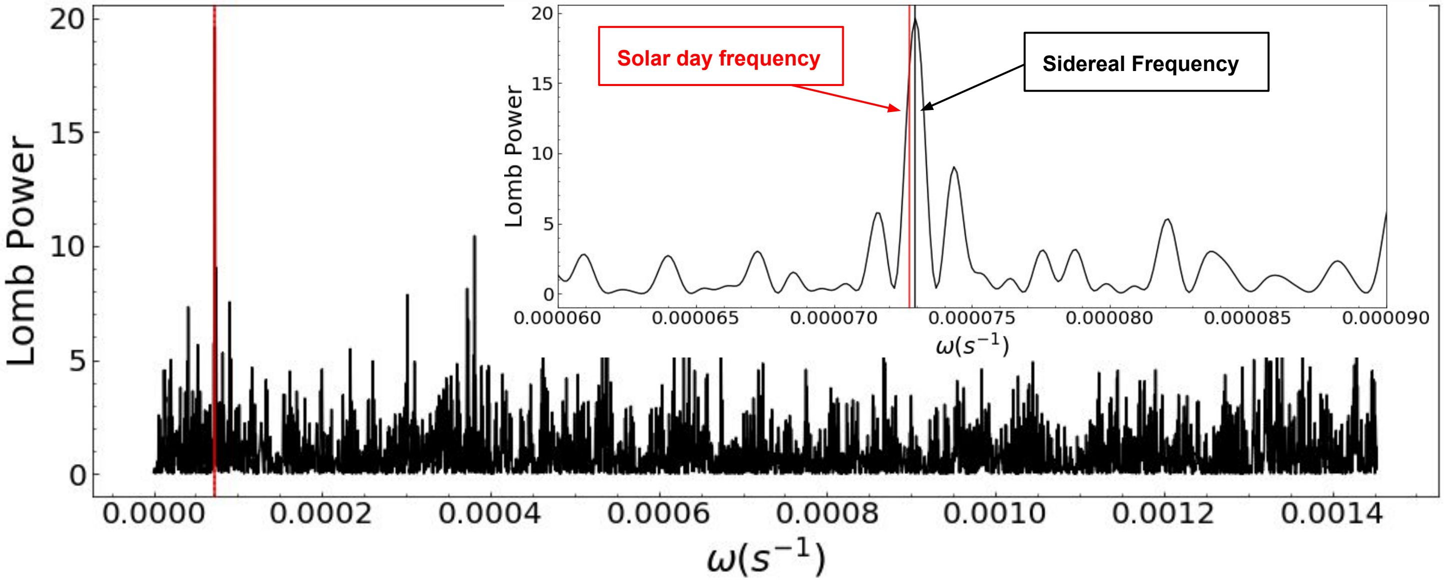
Benchmarking the analysis :

4 ppm artificial signal added to the pseudo data at sidereal frequency



Concerns:

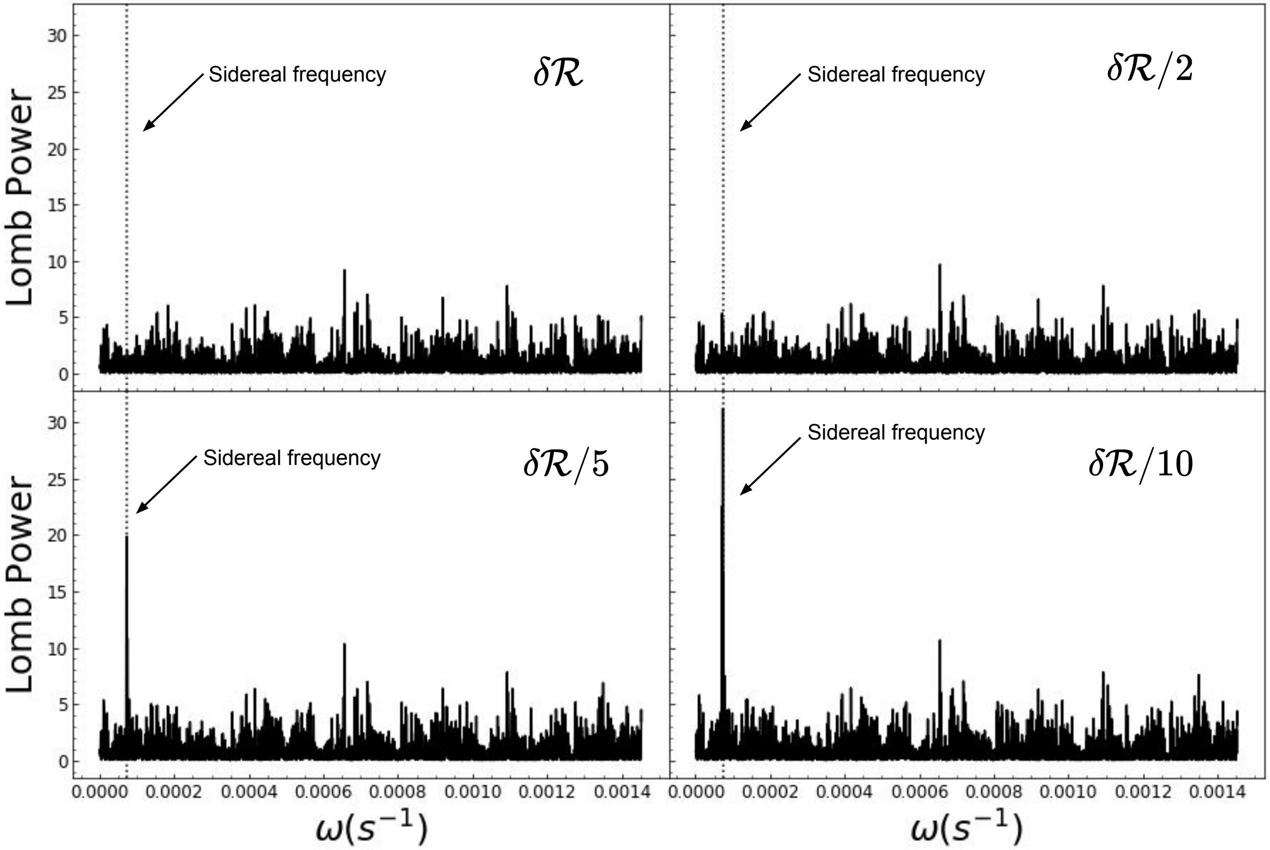
- **Spectral leakage problem to nearer bins**
- **Solar day frequency (24 hr.) falls within the frequency resolution**

→ **Finite size of the interval over which the data are sampled (~ 3.5 months)**

study the peak width and peak position for large samples

Sensitivity vs. Uncertainty:

- **Random $\mathcal{R}(t)$ generated**
- **Add 1 ppm signal at the sidereal frequency**
- **Uncertainty of each datapoint set to $\delta\mathcal{R}$ = 10 ppm, $\delta\mathcal{R}/2$, $\delta\mathcal{R}/5$, $\delta\mathcal{R}/10$**
- **1 ppm signal detectable with ~ 4 ppm uncertainty on the datapoint**



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