Anomalous Precession Frequency Analysis at Fermilab Muon g-2 Experiment

DPF-PHENO 2024

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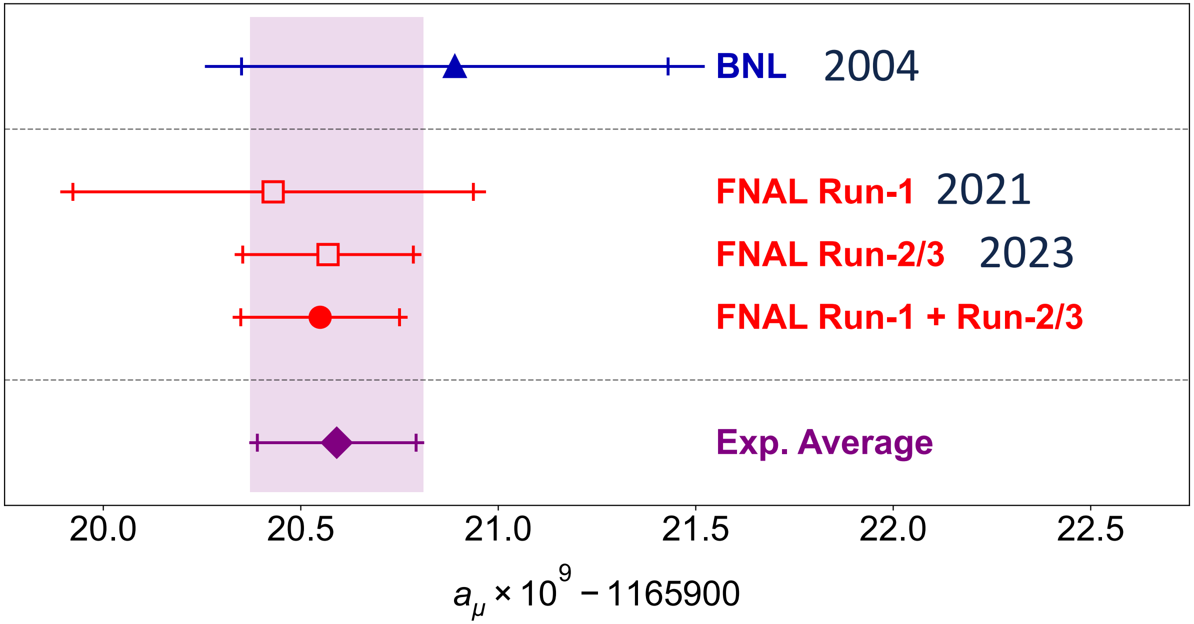
Murong Cheng

On behalf of the Muon g-2 collaboration

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

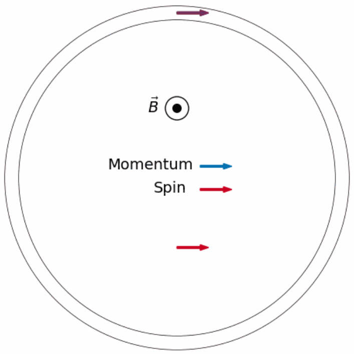
Muon g-2 Measurement Result



aμ(FNAL; Run-2/3) = 0.00 116 592 057(25) [215 ppb]
aμ(FNAL) = 0.00 116 592 055(24) [203 ppb]
aμ(Exp) = 0.00 116 592 059(22) [190 ppb]

- Run-2/3 result is consistent with Run-1 and BNL
- Uncertainty reduced by more than x2 compared to Run-1

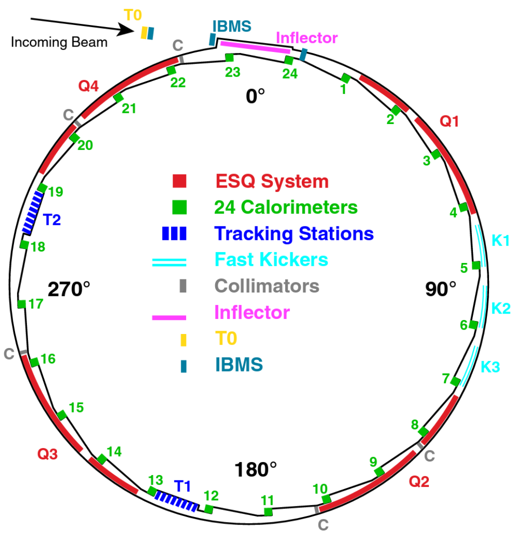
Muon g-2 Experiment at Fermilab



To measure the magnetic anomaly: $\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m}$

Spin frequency: $\omega_s = -\frac{e}{\gamma m} B\,(1 + \gamma a_\mu)$ Cyclotron frequency: $\omega_c = -\frac{e}{\gamma m} B$

Highly polarized muon from $\pi^+ \rightarrow \mu^+ + \nu_\mu$



Inflector: creates an almost field-free region in the storage ring avoid muon deflected by magnetic field

Kicker: kick the muon beam to the central orbit by producing another magnetic field

Electrostatic quadrupole system: vertically focus muon beam

Tracker: measure beam oscillation

Calorimeter: measure time and energy of decayed positrons

Measuring a_μ

$$B = \frac{\omega'_p}{2\mu_p}$$

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

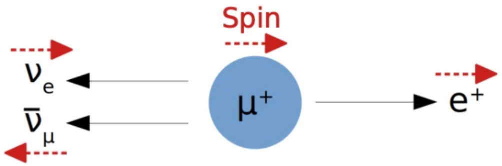
Real world equation:

Corrections from Beam Dynamics

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \times \frac{1+C_e+C_p+C_{pa}+C_{dd}+C_{ml}}{1+B_k+B_q}$$

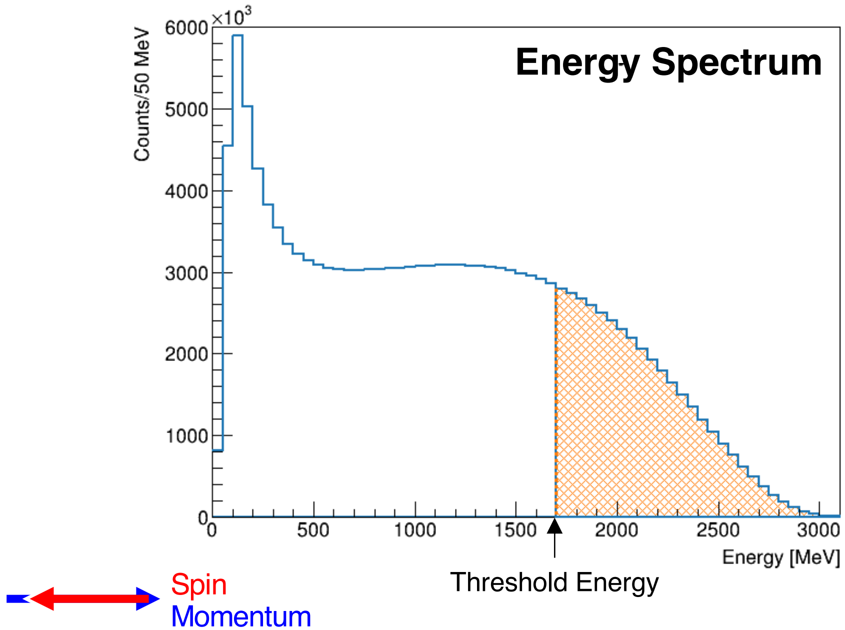
Corrections from Magnetic Field Transient

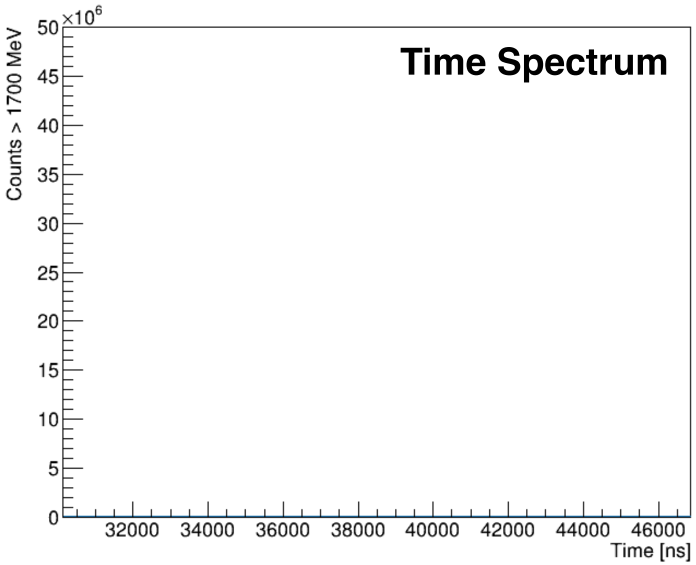
To measure ω_a



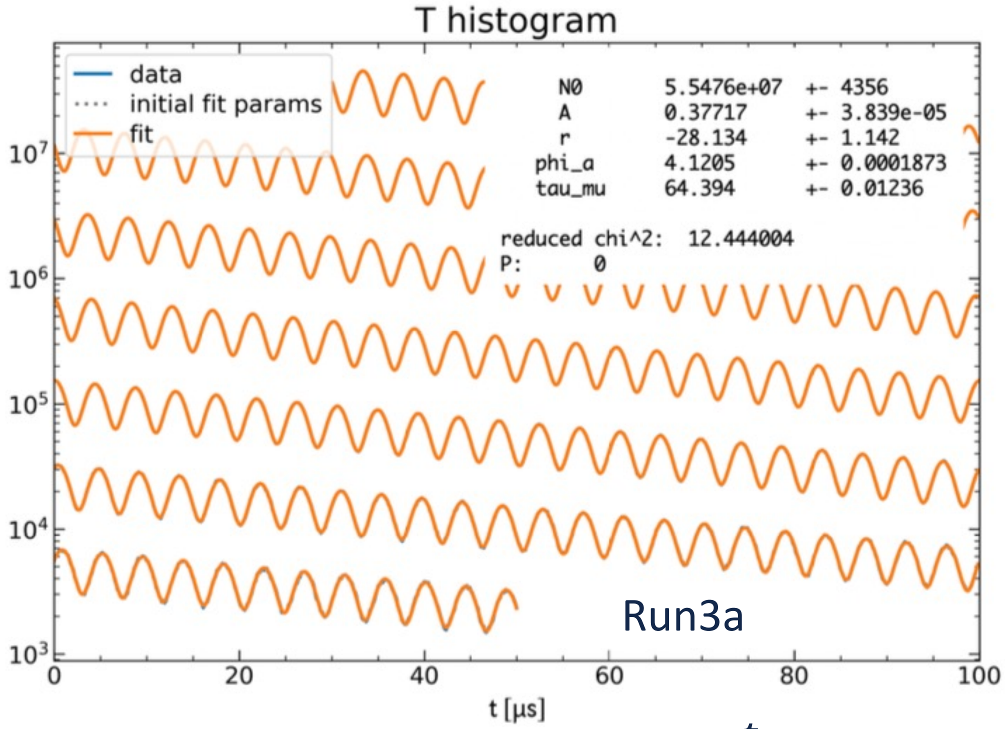
Muon decay

- Parity violation
- Positron tends to be emitted along the changing spin direction
- As the muon spin points towards & away from calorimeters, the number of high energy positrons oscillates





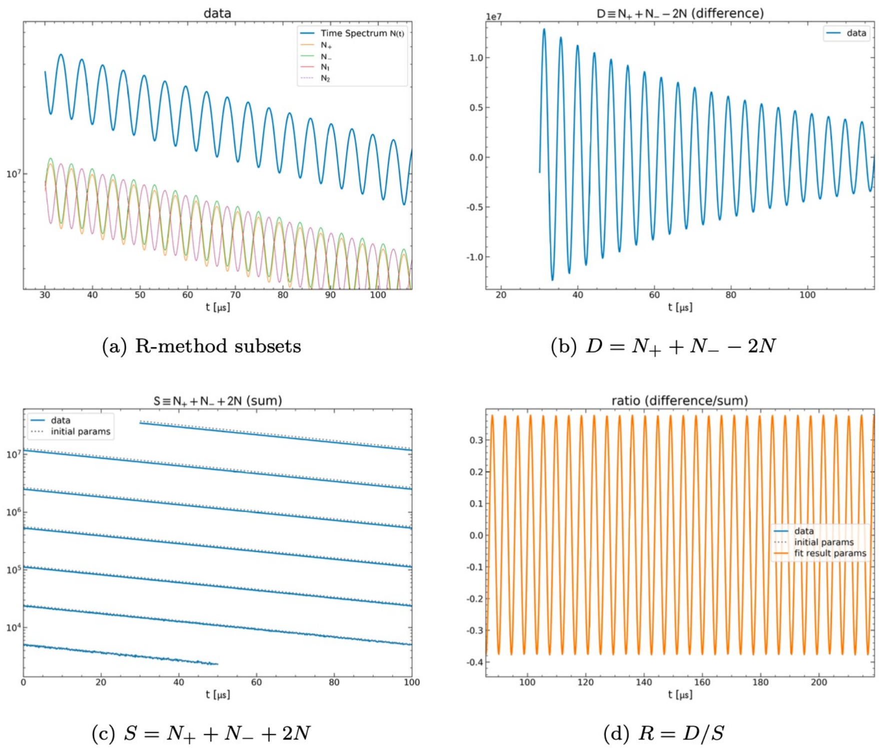
ω_a analysis



$$N(t) = N_0 \cdot e^{-\frac{t}{\tau}} \cdot [1 + A\cos(\omega_a - \phi_a)]$$

- Threshold method:
  - Highest energy positrons contain highest signals
  - Apply an energy threshold cut
  - Fit all positrons with energies above the threshold

ω_a analysis

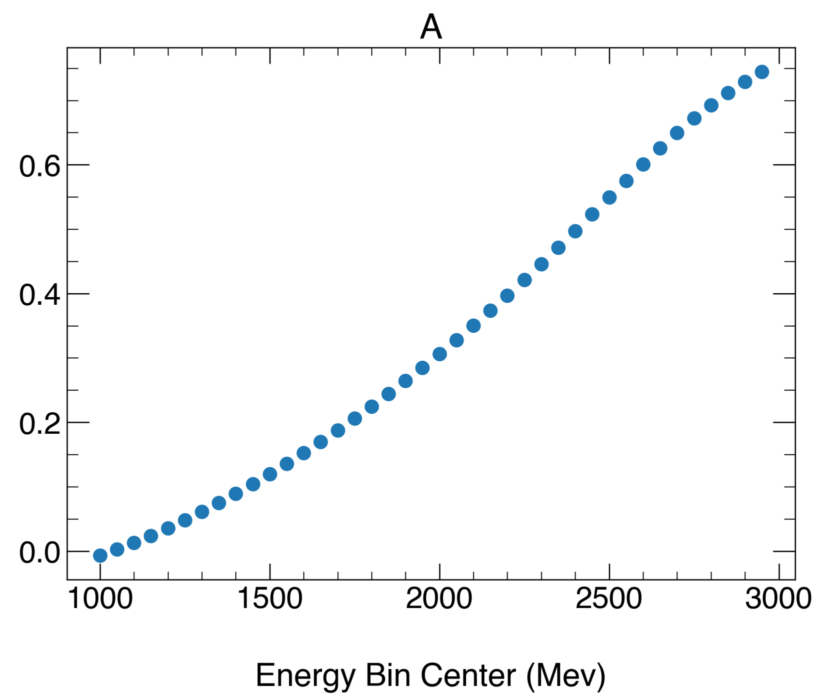


(a) R-method subsets

(b) $D = N_+ + N_- - 2N$

(c) $S = N_+ + N_- + 2N$

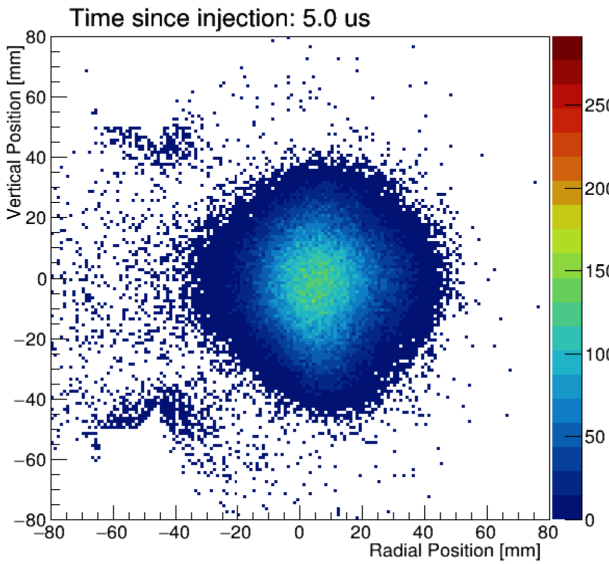
(d) $R = D/S$

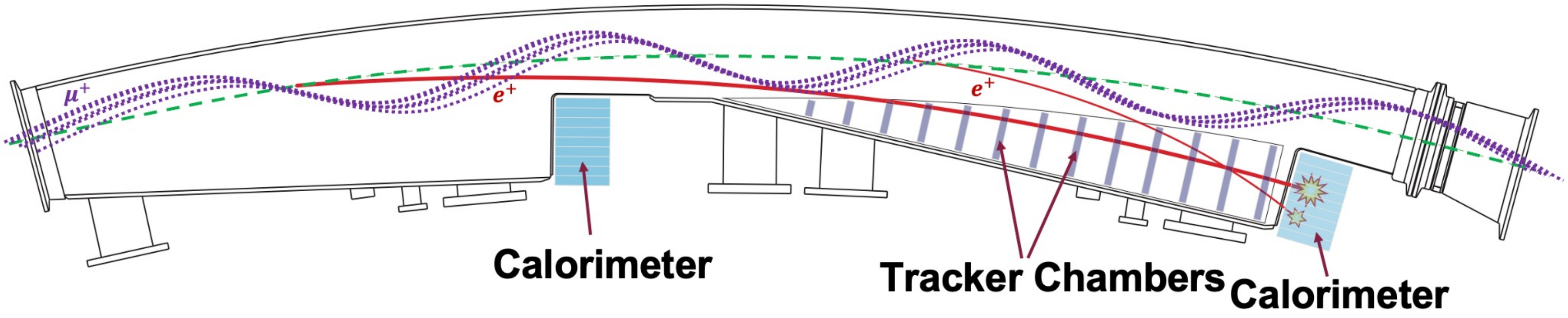


- **R**atio method:
  - Enhance the g-2 oscillation in the numerator and remove it in the denominator.
- **A**symmetry-weighted method:
  - Energy-weighted version of Threshold method

Coherent Betatron Oscillation (CBO)

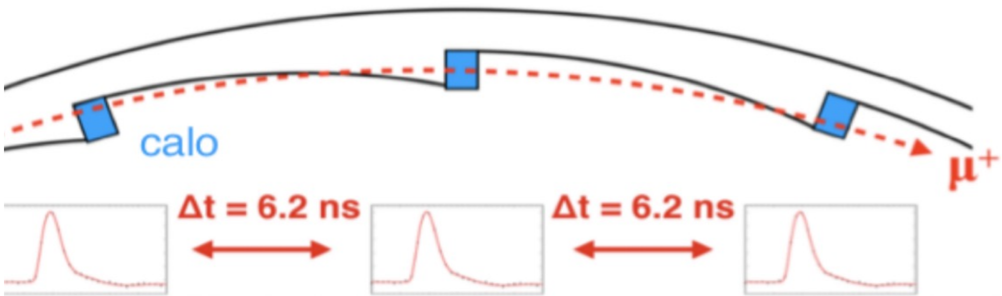
- Muons fail to stay in the perfect circular orbit, oscillate in radial direction
- $\omega_{CBO} = \omega_c - \omega_x$ cyclotron frequency – horizontal beam oscillation frequency
- $N_{CBO}(t) = 1 + A_{CBO} \cdot e^{-t/\tau_{CBO}} \cdot \cos(\omega_{CBO} t + \phi_{CBO})$





Muon loss

- Some muons are lost from the storage ring before they decay during the measurement window
- When passing through consecutive calorimeters, it has a characteristic energy of around 170 MeV and a characteristic time of flight of around 6.15 ns.



Combining CBO and ML, got 9-par fit function:

Muon loss

$$N(t)_{9-par} = N_0 \cdot e^{-\frac{t}{\tau_\mu}}[1 + A\cos(\omega_a + \phi_0)] \cdot \Lambda(t) \cdot N_{CBO}(t)$$

ω_a analysis - Fit function

$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A \cdot A_{cbo}(t)\cos(\omega_a t) - (\phi_0 + \phi_{cbo}(t))]$$
$$\cdot \Lambda(t) \cdot N_{cbo}(t) \cdot N_{2cbo}(t) \cdot N_{VW}(t) \cdot N_y(t) \cdot N_n(t)$$

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

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

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

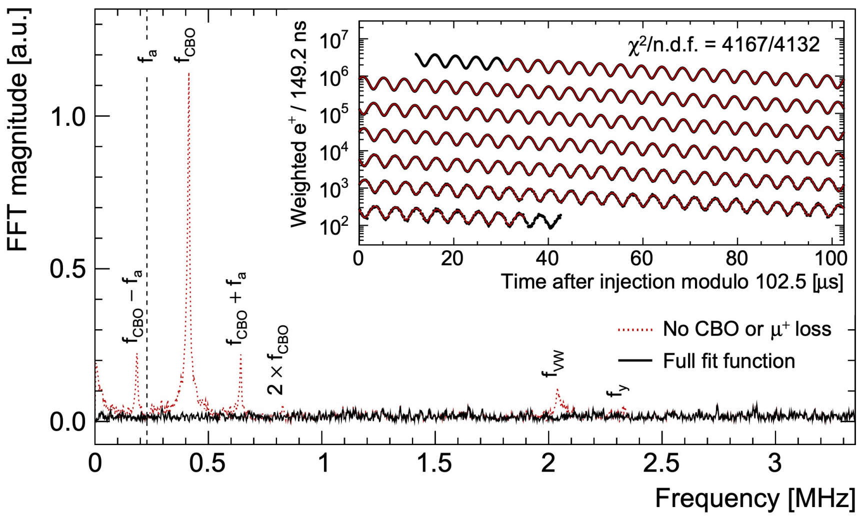
$$N_{2cbo}(t) = 1 + A_{2cbo-N}(e^{-2t/\tau_{cbo}} + C_{cbo})\cos(2\omega_{cbo}(t)t - \phi_{2cbo-N})$$

$$\omega_{cbo}(t)t = \omega_{cbo}t + A_d e^{-t/\tau_d}$$

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

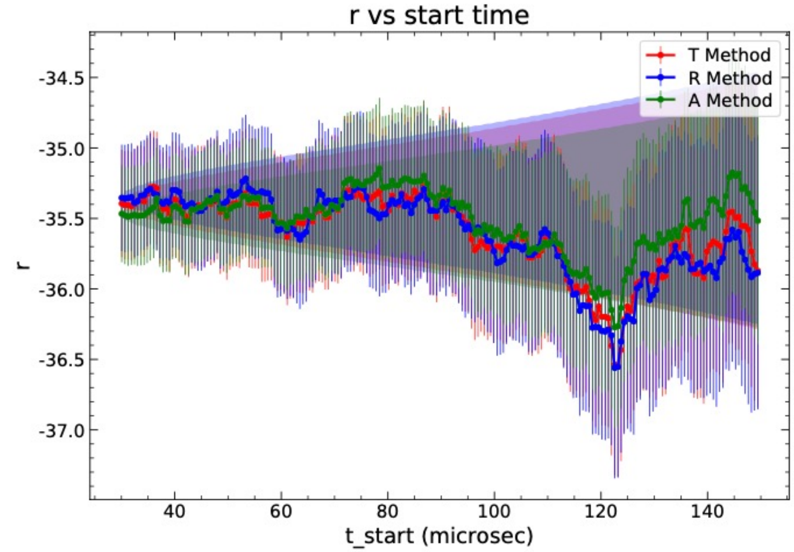
$$N_y(t) = 1 + A_y e^{-t/\tau_y}\cos(\omega_y t - \phi_y)$$

$$N_n(t) = 1 + A_n e^{-t/\tau_n}\cos(\omega_n t - \phi_n)$$

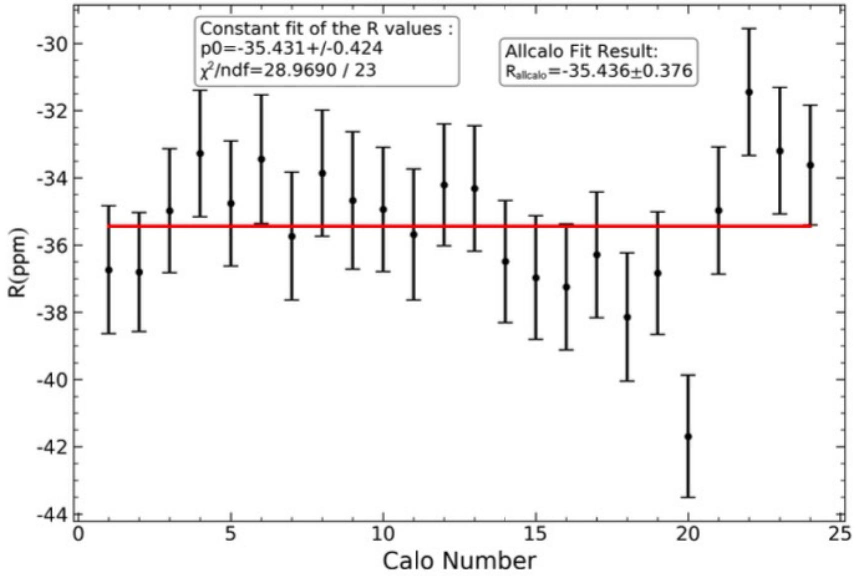


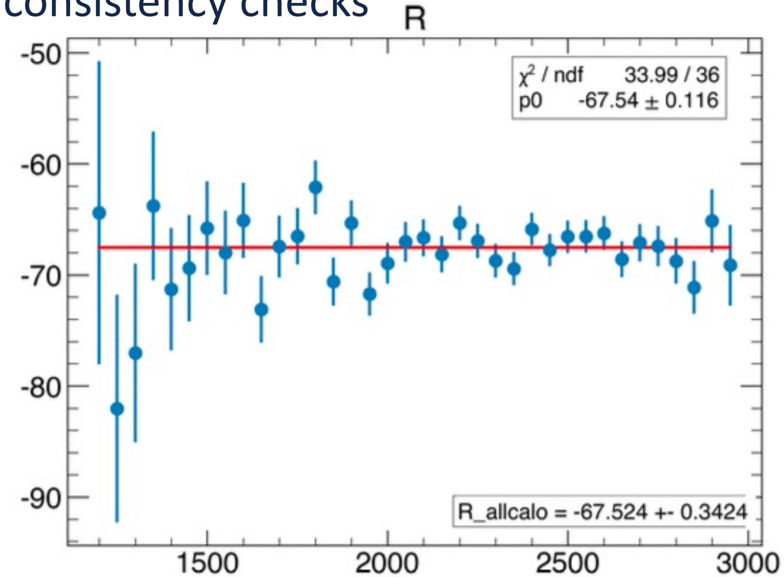
Consistency checks

- Fit start time scans
- Positron energy binned scans
- Per calorimeters scans



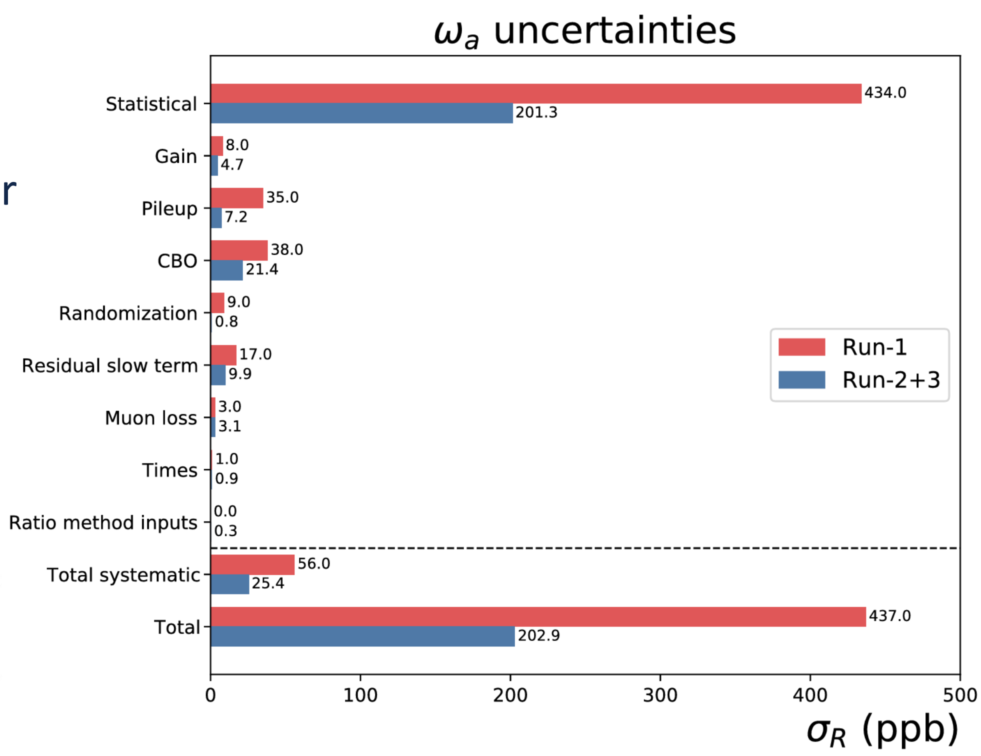
Run-2 R value (blinded ω_a) consistency checks

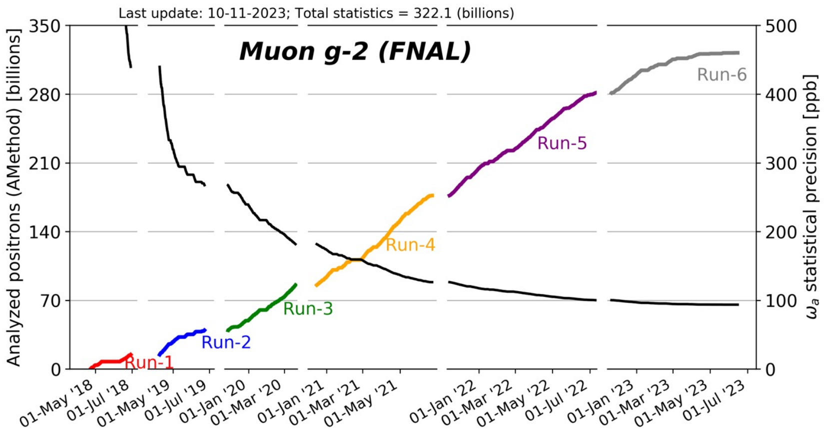




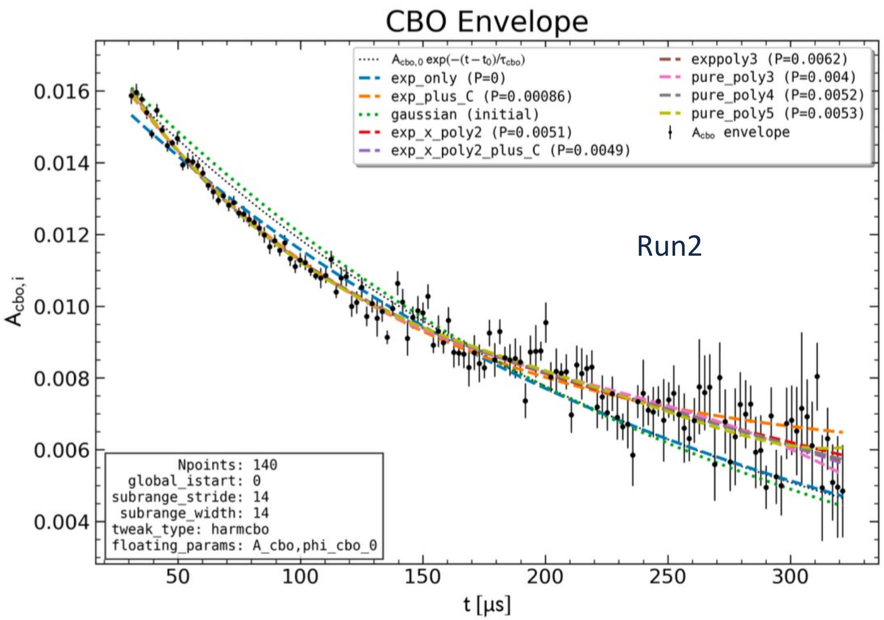
Statistical and systematic uncertainties

- Comparing to Run-1, Run-2/3 statistical and systematic uncertainties are both reduced by factor of 2.2
- Statistical uncertainty dominates the error
- Run-4/5/6 aims to lead to another factor of 2 improvement in statistical precision and reduce the systematic uncertainties





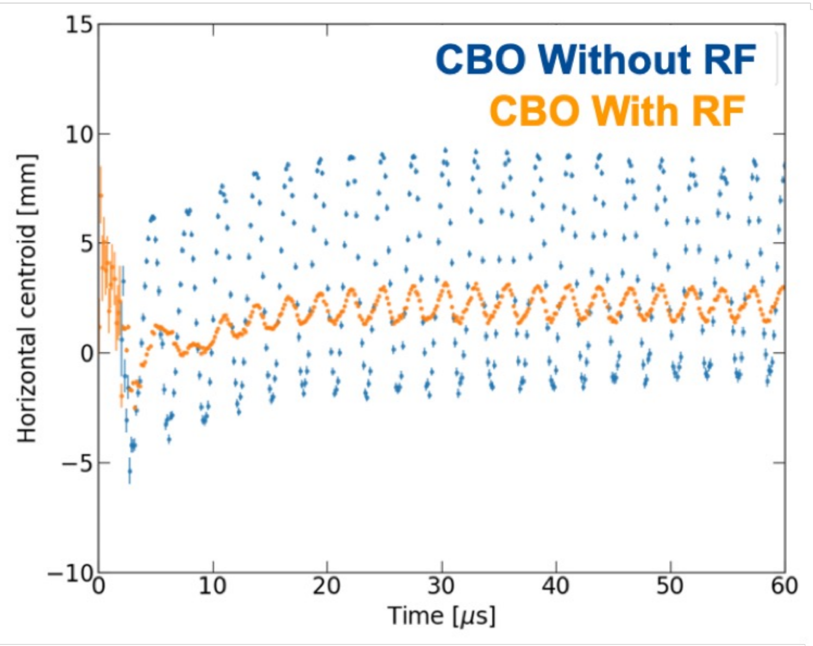
CBO decoherence envelope study

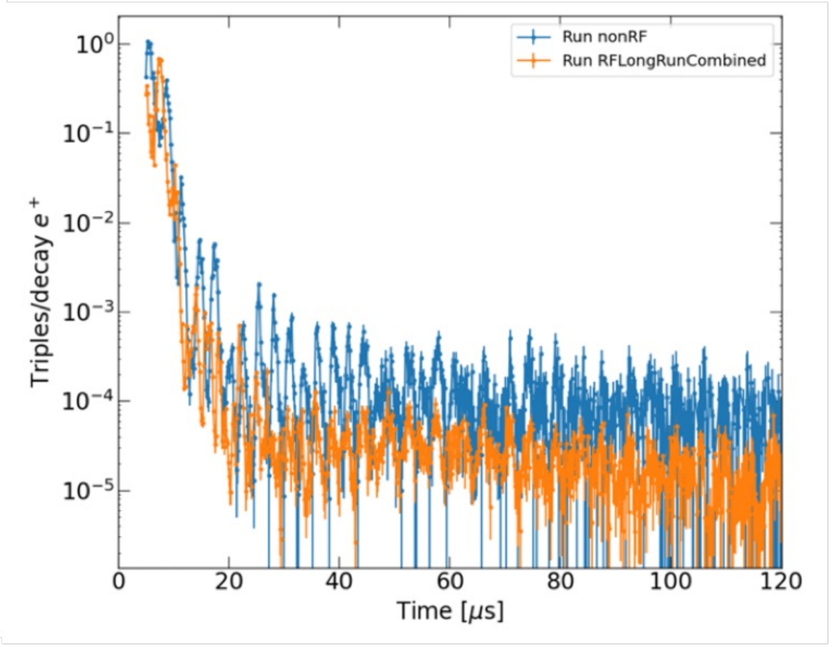


- Perform sliding window fit and show how different models describe the CBO envelope
- Run-2/3: Estimate the R value shift to be used as uncertainty on the CBO decoherence envelope

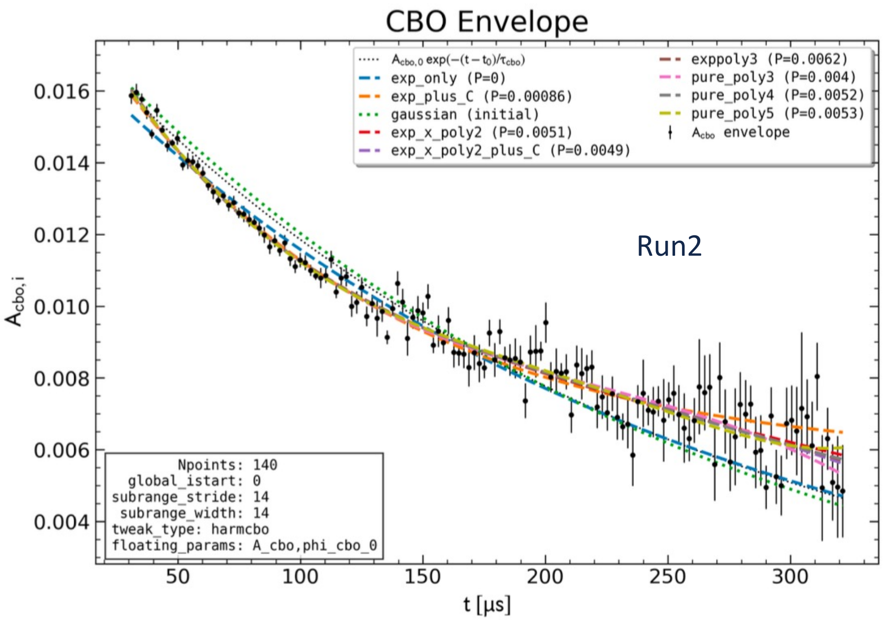
Radio Frequency (RF) system

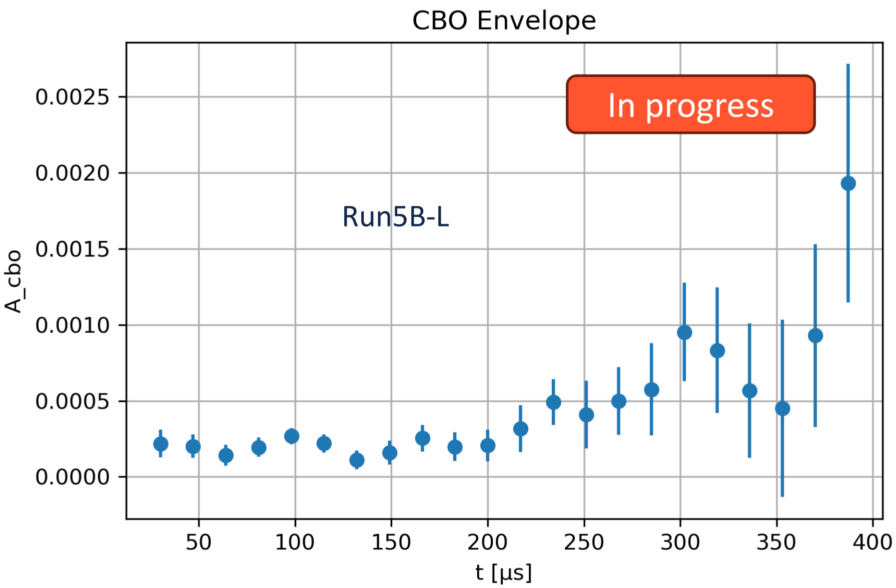
- Starting from Run-5, the RF system is employed
  - A harmonically varying horizontal dipole electric field is applied to the beam out of phase with the CBO.
  - Reduce CBO amplitude by factor of 5.
  - Also reduce muon loss by factor of 4.





CBO decoherence envelope study





- Perform sliding window fit and show how different models describe the CBO envelope
- Run-2/3: Estimate the R shift to be used as uncertainty on the CBO decoherence envelope
- CBO amplitude is much reduced in Run-5/6, the similar studies are being performed. Beam dynamics changed due to the RF system, so different CBO envelopes are under investigation.

Thanks for listening! Questions?

Acknowledgements

- Department of Energy (USA),
- National Science Foundation (USA),
- Istituto Nazionale di Fisica Nucleare (Italy),
- Science and Technology Facilities Council (UK),
- Royal Society (UK),
- Leverhulme Trust (UK),
- European Union's Horizon 2020,
- Strong 2020 (EU),
- German Research Foundation (DFG),
- National Natural Science Foundation of China,
- MSIP, NRF and IBS-R017-D1 (Republic of Korea)

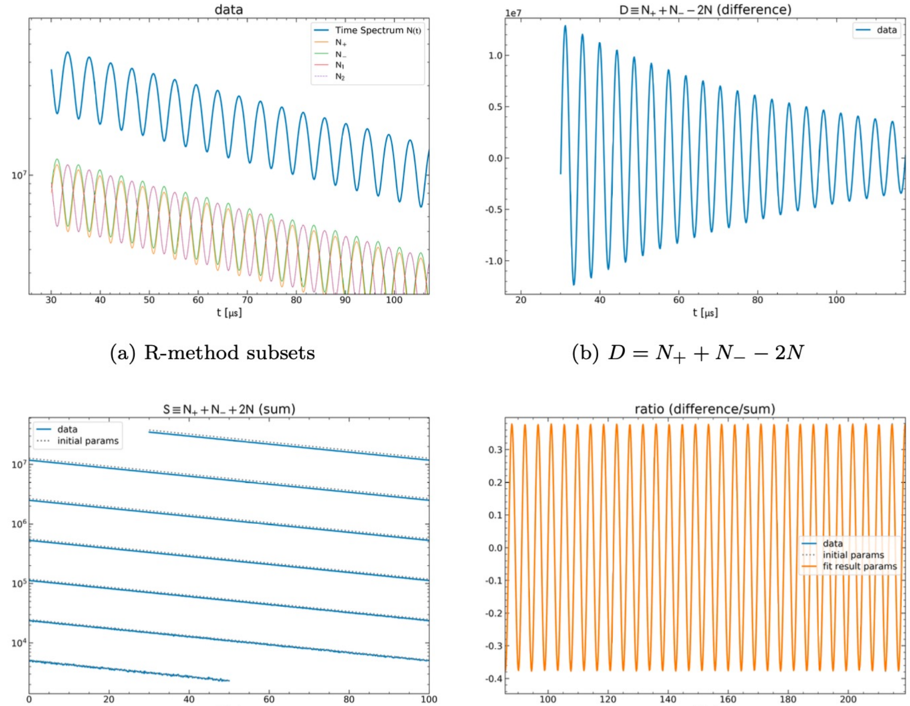
Back-up

ω_a analysis – R-method

- **R**atio method:
  - Decayed positron counts randomly divided into 4 histograms
  - Enhance the g-2 oscillation in the numerator and remove it in the denominator.

$$R(t) = \frac{N_+\left(t+\frac{T_a}{2}\right)+N_-\left(t-\frac{T_a}{2}\right)-2N(t)}{N_+\left(t+\frac{T_a}{2}\right)+N_-\left(t-\frac{T_a}{2}\right)+2N(t)}$$

  - The ratio divides out the slow effects



(a) R-method subsets

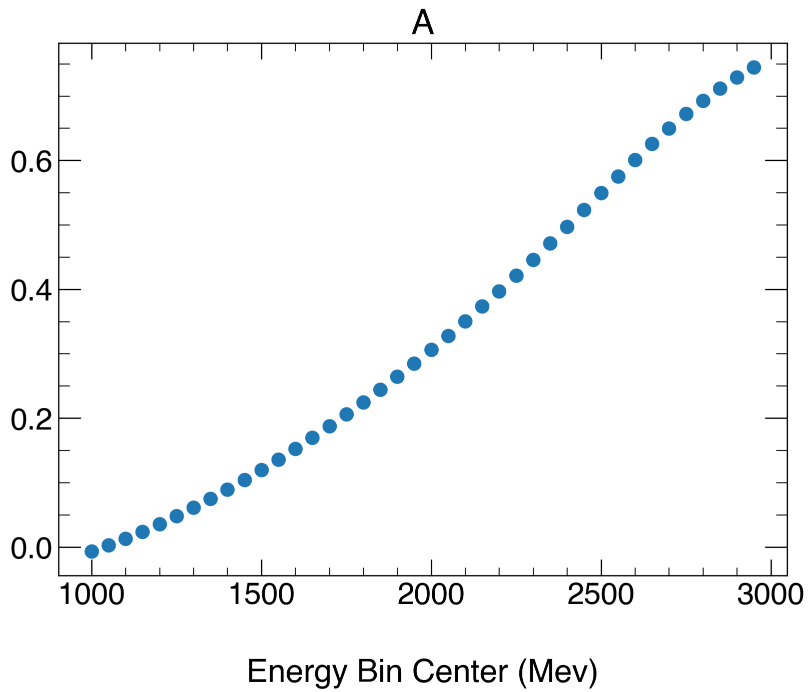
(b) $D = N_+ + N_- - 2N$

(c) $S = N_+ + N_- + 2N$

(d) $R = D/S$

ω_a analysis – A-method

- **A**symmetry-weighted method:
  - Energy-weighted version of Threshold method
  - T-method w(E) = 1, E > 1750 MeV
  - A-method w(E) = A(E), 1050 MeV < E < 3050 MeV
  - Reduce the statistical uncertainty



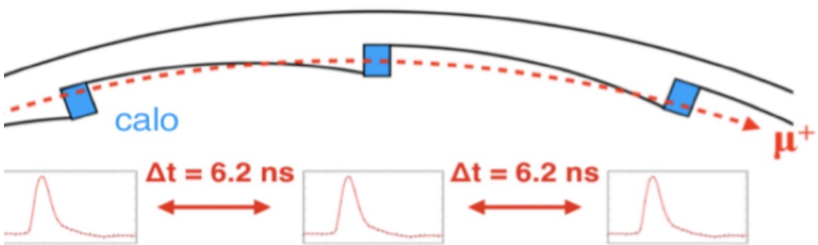
- **A**symmetry-weighted **R**atio method:
  - Energy-weighted version of Ratio method

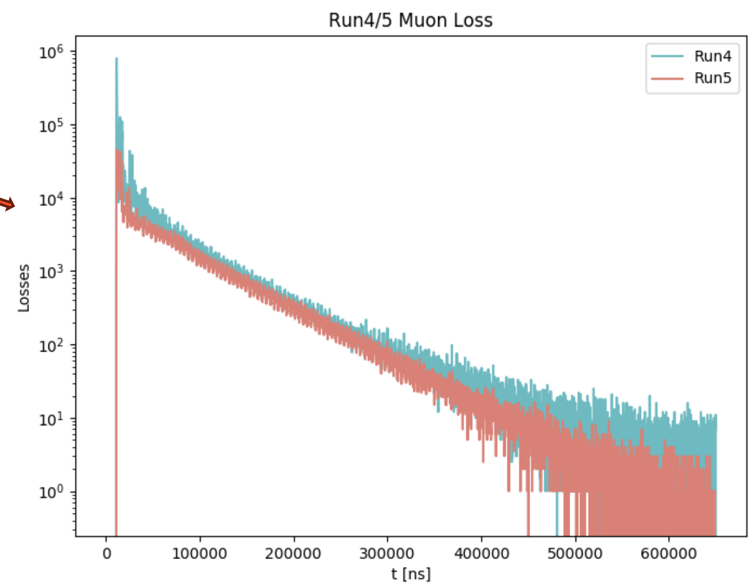
Muon loss

- Some muons are lost from the storage ring before they decay during the measurement window
- When passing through consecutive calorimeters, it has a characteristic energy of around 170 MeV and a characteristic time of flight of around 6.15 ns.

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

detection efficiency of lost muons





Combining CBO and ML, got 9-par fit function:

$$N(t)_{9-par} = N_0 \cdot e^{-\frac{t}{\tau_\mu}} [1 + A\cos(\omega_a + \phi_0)] \cdot \Lambda(t) \cdot N_{CBO}(t)$$

Muon loss correction

Cut criteria	Description
Coincidence level = 1.	Exclude the singlets.
Time < 15 μs.	Exclude the first 15 μs after the injection.
The number of hits in crystals ≥ 3.	Exclude non-MIP-like events.
The maximum crystal energy / cluster energy < 0.8.	Exclude non-MIP-like events.
$\Delta t_{12,23} < 5$ ns or $\Delta t_{12,23} > 7.5$ ns	Coincidence time interval cuts.
$\Delta t_{13} > 14.4$ ns	Deuteron subtraction cut.
Energy < 100 MeV or Energy > 250 MeV	MIP energy cuts.

True rate of muon loss

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\frac{N}{\tau} - \frac{L(t)}{\epsilon}$$

Proportionality constant, ε, characterizes the above method's efficiency of detecting the lost muons

$$N(t) = N(t_0) \cdot e^{-(t-t_0)/\tau} \cdot \left[1 - \frac{1}{N(t_0)\epsilon} \int_{t_0}^{t} L(t') \cdot e^{(t'-t_0)/\tau}\, \mathrm{d}t'\right]$$

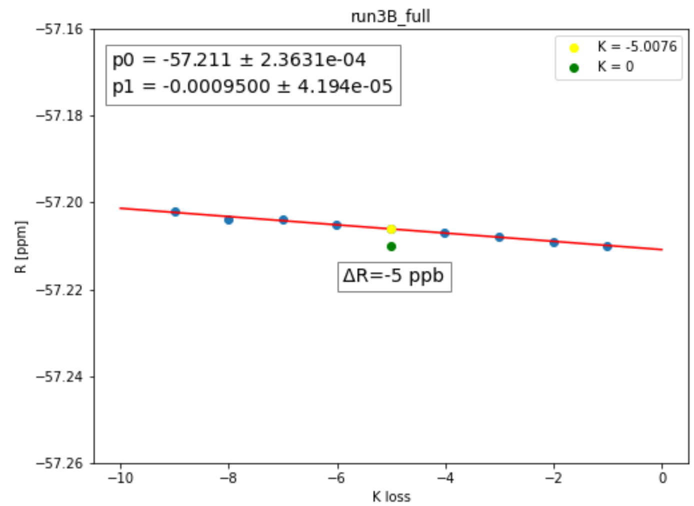
Kloss

depends only on the initial number of stored muons and the detection efficiency of lost muons

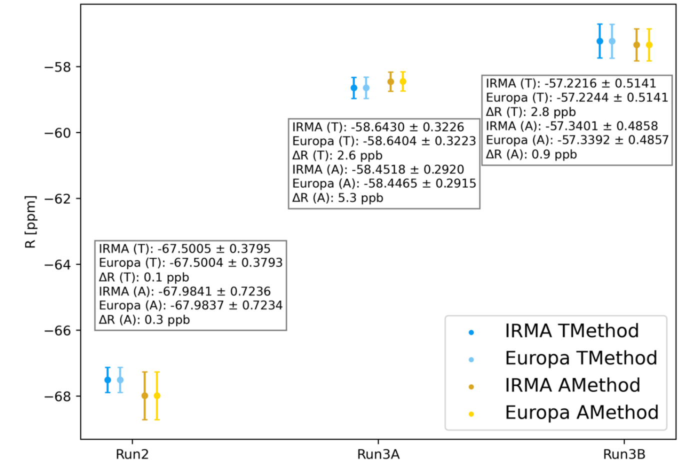
Muon loss systematic study

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

- Fixed κ_{loss}
  - R-method fit: τ_μ and κ_{loss} fixed to the values extracted from the T-method fit. This introduces uncertainty on the R-value for the R-method ω_a analysis.
  - Extract the R sensitivity for various κ_{loss} values and then multiply this sensitivity with the uncertainty on κ_{loss} from T-method fit results.



- Different muon loss models
  - Use the different Run-2/3 muon loss spectra from the Europa group, which have quadruple and quintuple coincidences besides triples.
  - Nominal fits were performed by using both IRMA and Europa's muon loss spectra

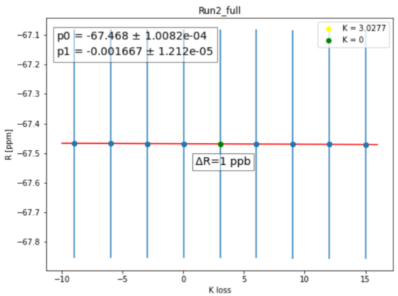


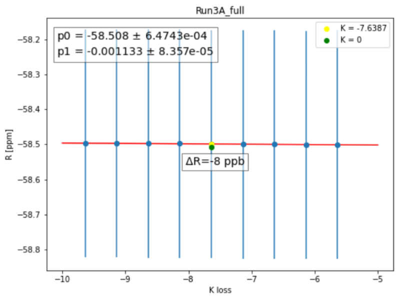
1-)Fixed Kloss Systematic

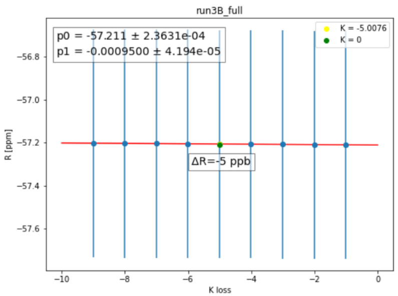
- Fix Kloss in R method (from T method)
- Scan over different Kloss value

Systematic Error due to fixed Kloss (seed 0)

	dR/dK	σ_k	δR [ppb]
Run2	-1.667	0.318	0.530
Run3A	-1.113	1.785	1.987
Run3B	-0.950	1.744	1.657







The sensitivity of R to the fixed Kloss value for Run2, Run3A, Run3B. (Seed 0)

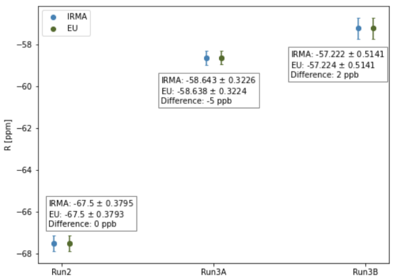
Run2: Best-fit value of Kloss from T method is 3.0277, the corresponding R method fit result R is -67.469 ppm.
Turn off Kloss value, R is -67.468 ppm.
Difference is 1 ppb.

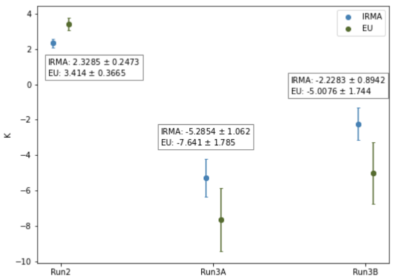
Run3A: Best-fit value of Kloss from T method is -7.6387, the corresponding R method fit result R is -58.499 ppm.
Turn off Kloss value, R is -58.507 ppm.
Difference is -8 ppb.

Run3B: Best-fit value of Kloss from T method is -5.0076, the corresponding R method fit result R is -57.206 ppm.
Turn off Kloss value, R is -57.21 ppm.
Difference is -5 ppb.

2-)Different Models Systematic

- Kloss values are different by using two muon loss models
- R values are the same in Run2 dataset
- Small differences of R values in Run3A and Run3B





Results are from T method fit