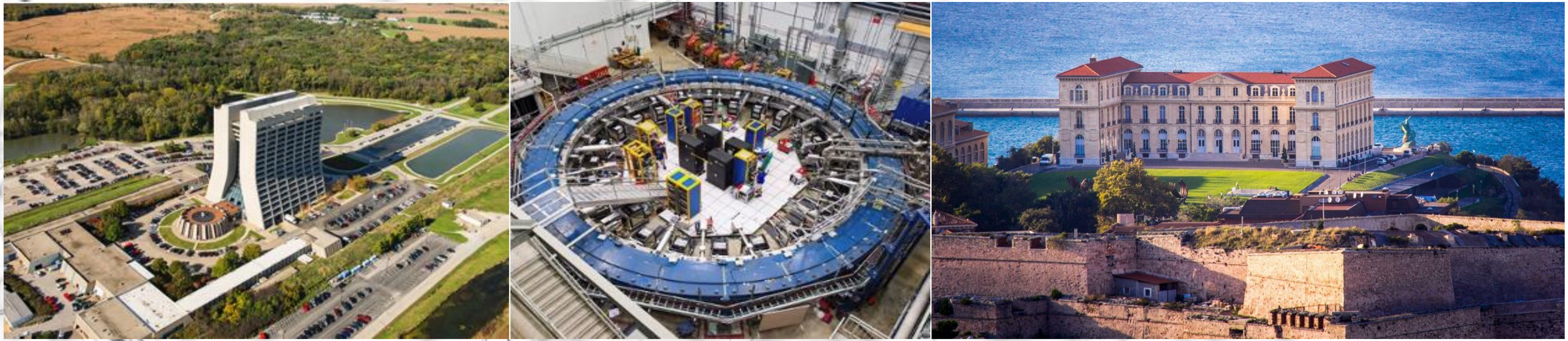


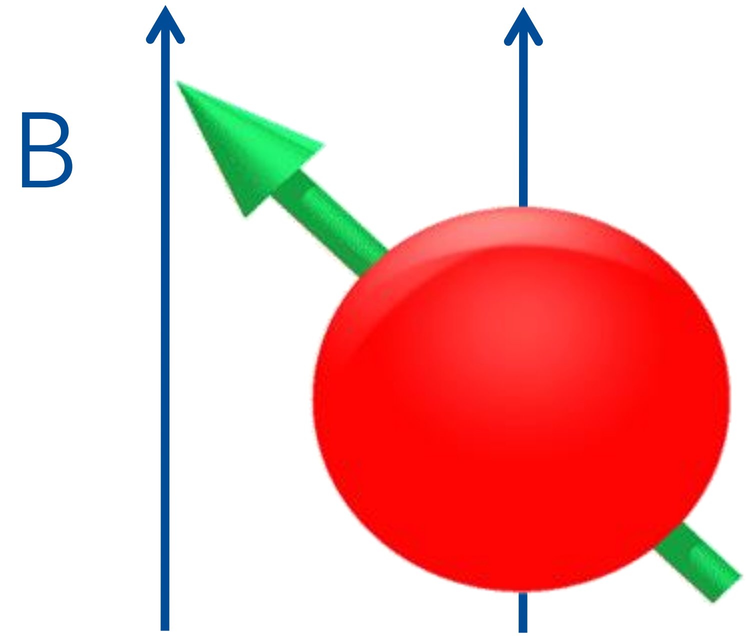
MEASURING THE ANOMALOUS PRECESSION FREQUENCY AT THE FERMILAB MUON G-2 EXPERIMENT

ESTIFA'A ZAID ON BEHALF OF THE FNAL MUON G-2 COLLABORATION, UNIVERSITY OF LIVERPOOL

EPS 2025, MARSEILLE

MUONS IN A MAGNETIC FIELD

Covered in more detail in S.Charity EPS Plenary talk



Muons have spin or intrinsic angular momentum

A muon in a magnetic field will precess about the field like a spinning top → magnetic moment

Rate of precession is proportional to magnetic field strength

g determines spin precession frequency in a magnetic field

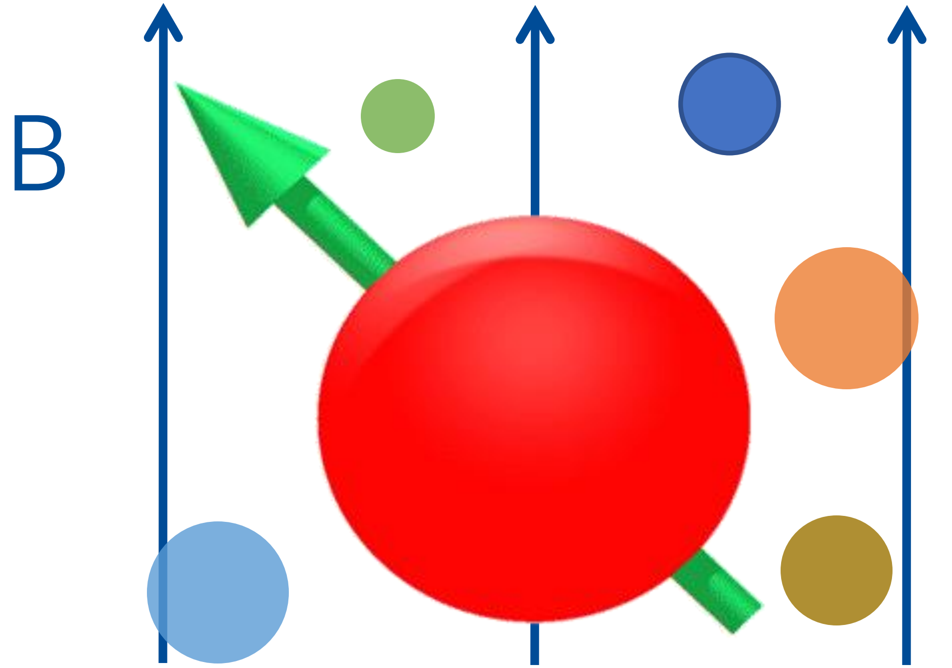
Torque in a B-field

$$\vec{\mu} \times \vec{B}$$

Magnetic Moment

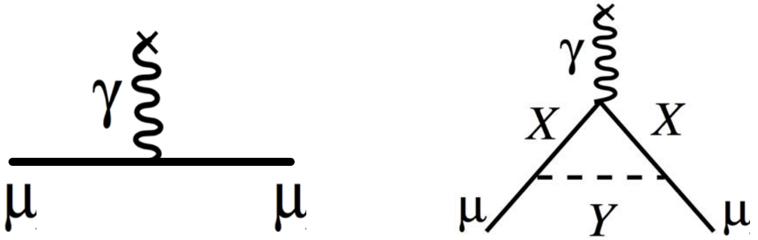
$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

MUONS IN A MAGNETIC FIELD



For a pure Dirac spin-1/2 charged fermion, ***g*** is exactly 2

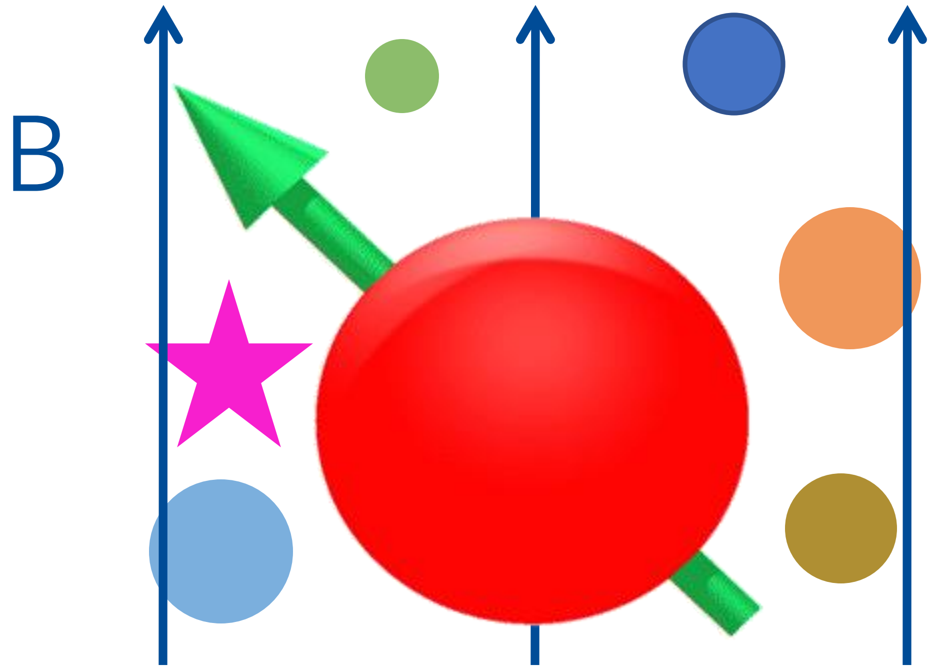
Muons are never alone: virtual particles can pop in and out of existence for a very short time and affect the muon's interaction with the magnetic field



$g = 2$ $g > 2$

Interactions between the muon and virtual particles alter the value of ***g***

WHAT IF A NEW PARTICLE IS PRESENT ?



All of the interesting physics is in the loop terms so we define:

$$\boxed{a_\mu = \frac{g-2}{2}}$$

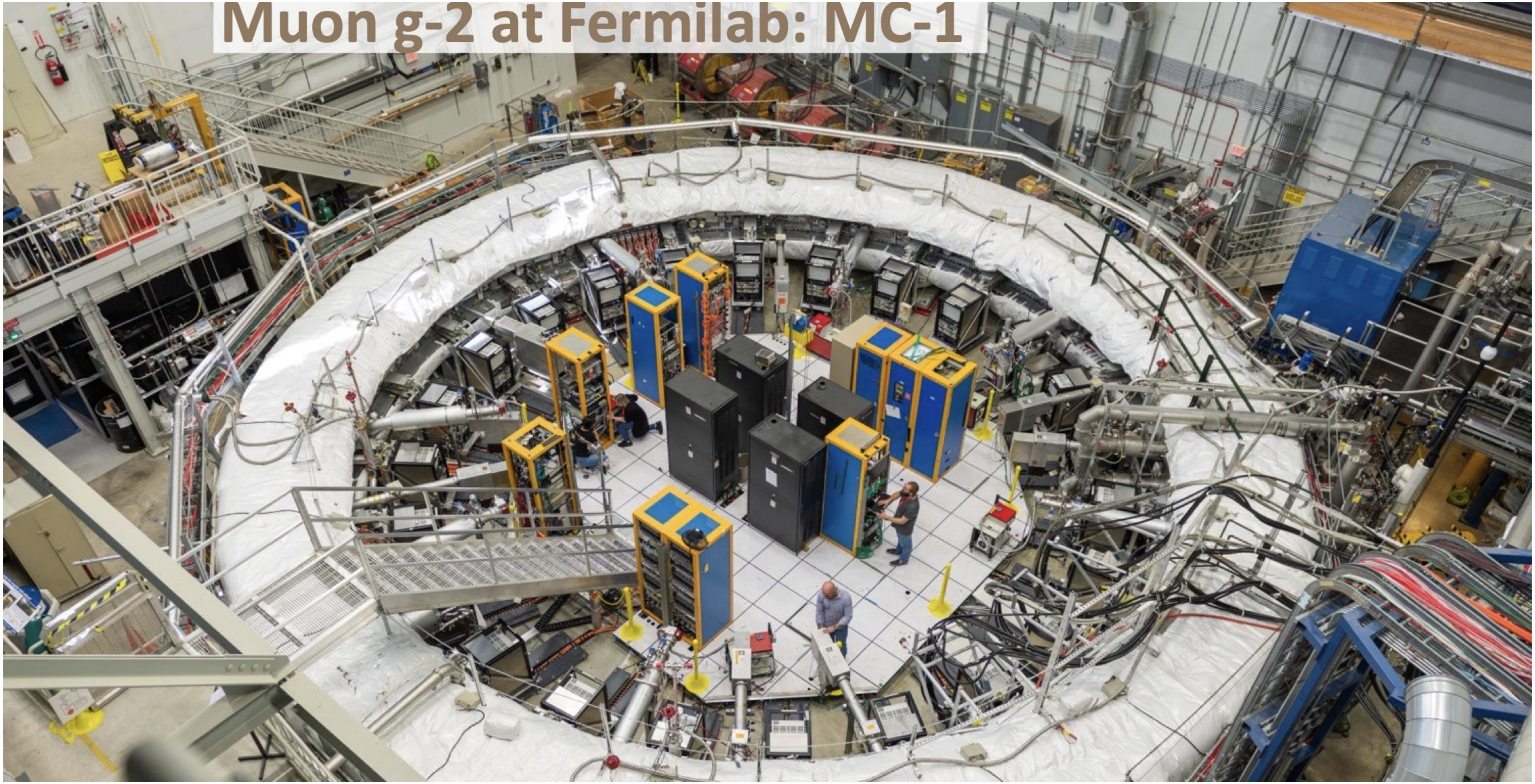
If a new particle exists ..

g would differ from the value predicted by the SM

This would be a sign of physics beyond the SM!

To achieve this, we need very precise SM calculations and a very precise experimental measurement

Muon g-2 at Fermilab: MC-1



KEY PRINCIPLES OF MEASURING G-2

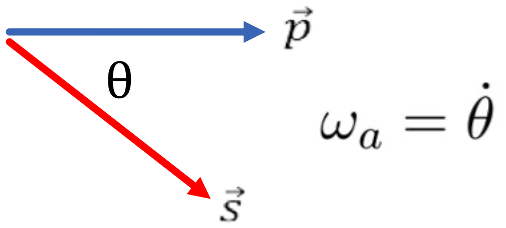
$$\omega_a = \omega_s - \omega_c = a_\mu \frac{e}{m_\mu c} B$$

To get this

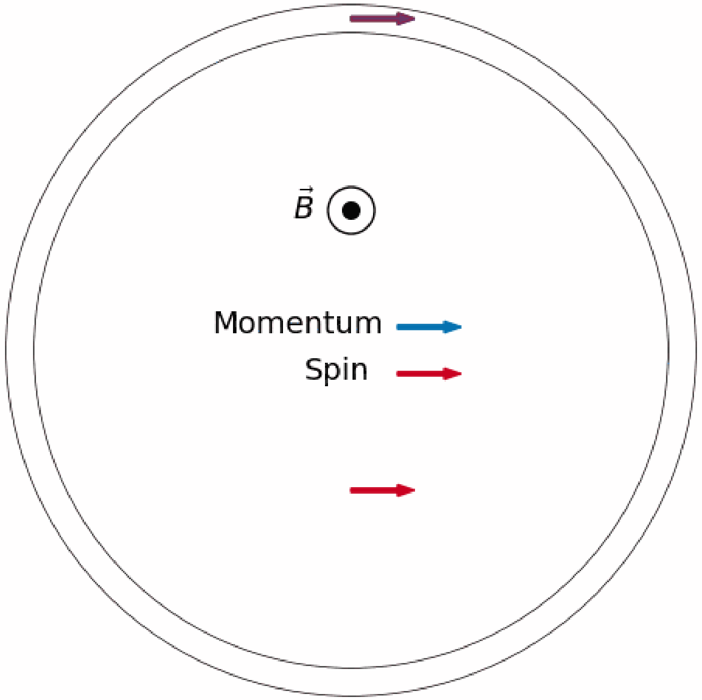
Measure these

Spin rotates ahead of momentum as muon orbits the ring.

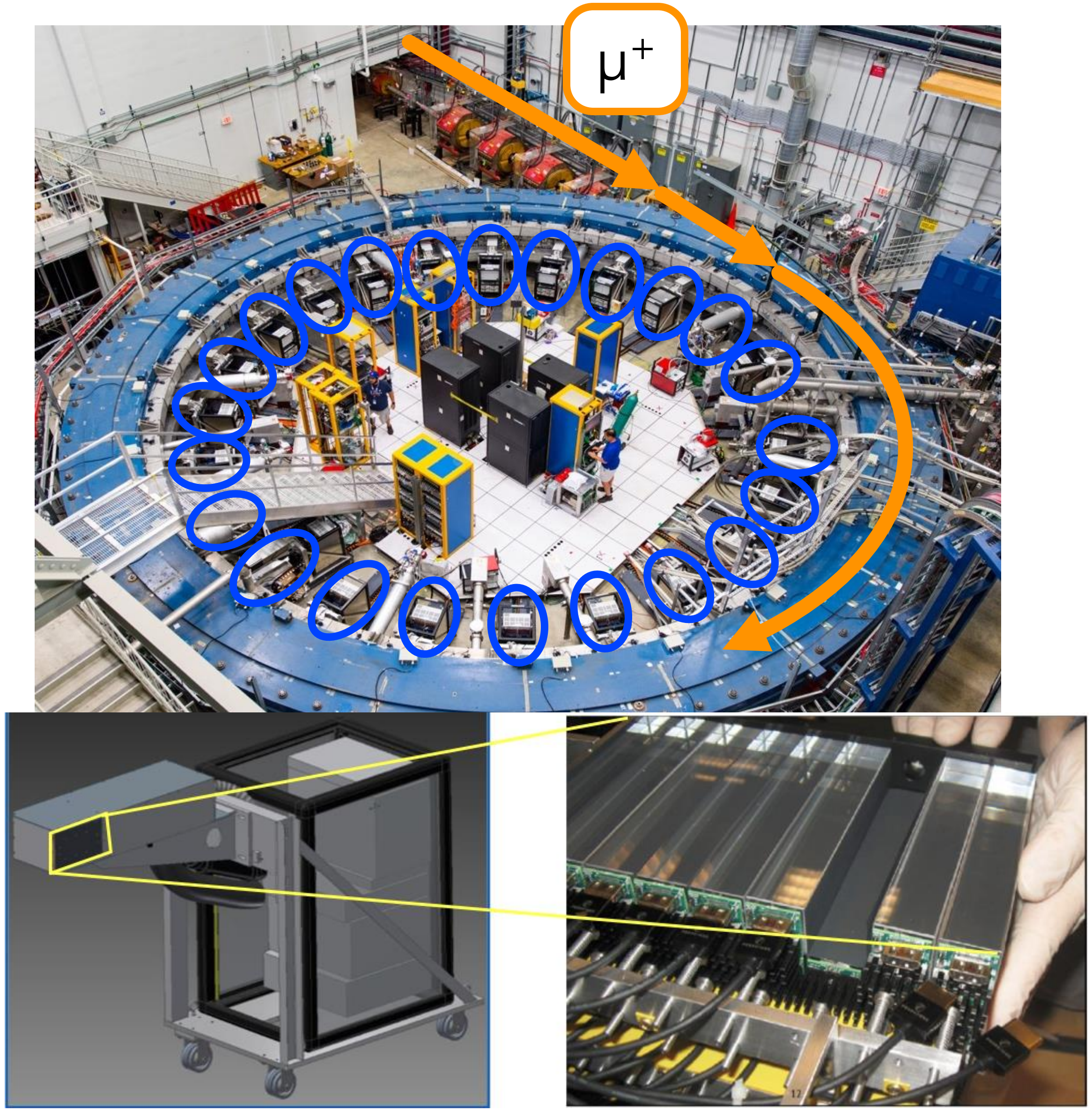
At a given point in the ring spin rotates radially in and out with a frequency of ω_a



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



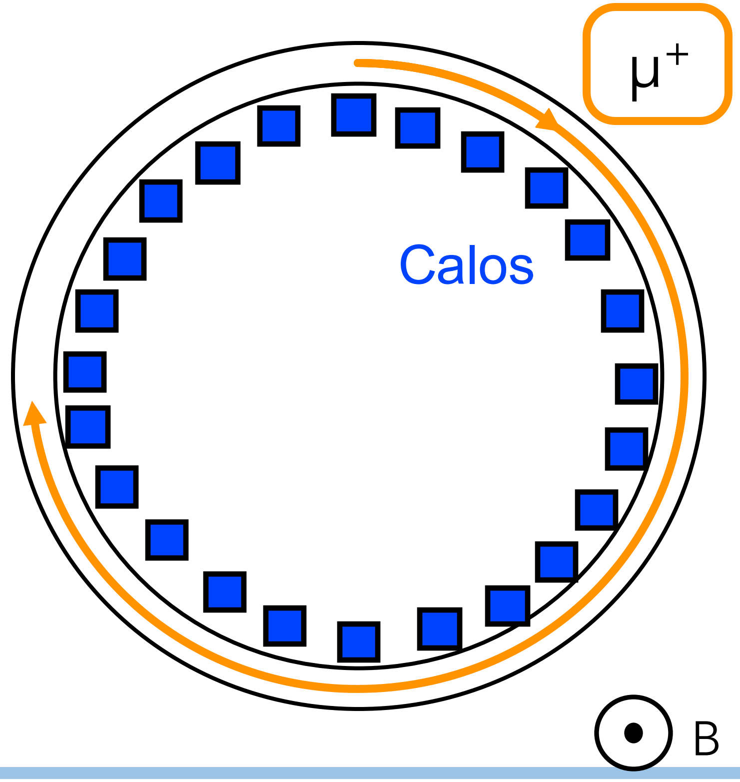
CALORIMETERS



There are 24 electromagnetic calorimeters around the ring. They measure time and decay energy of the e^+

9x6 arrays of PbF_2 crystals

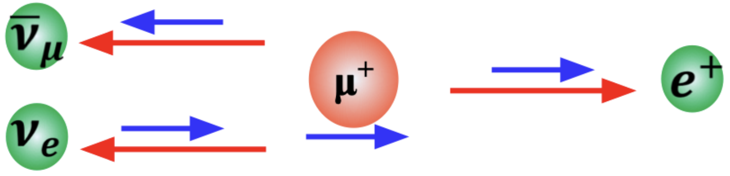
Fast SiPM readout

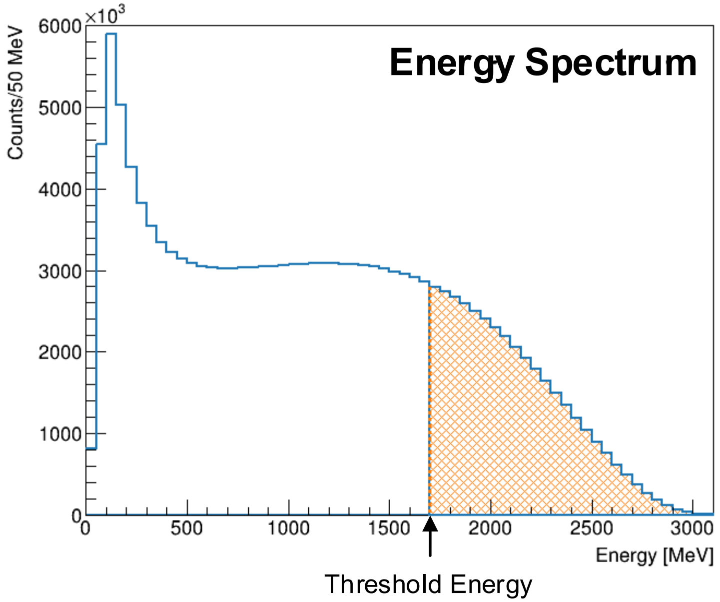


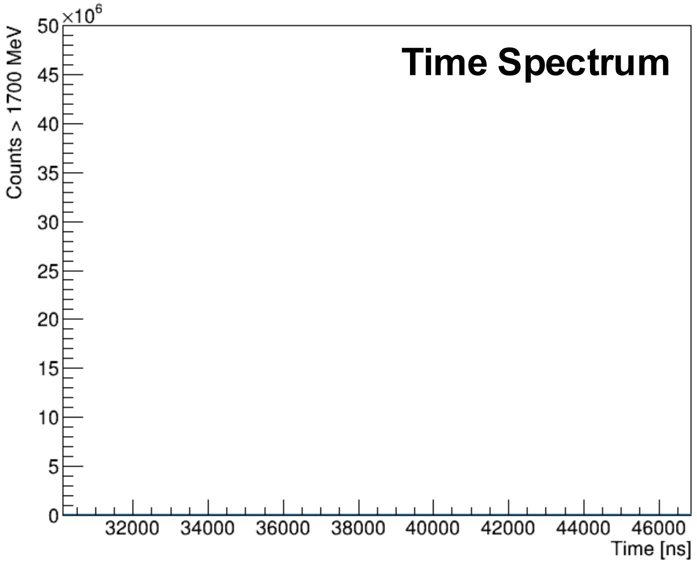
MEASURING ω_a

Due to parity violation, polarised muon decays are self-analysing, as the μ^+ spin points towards and away from the calorimeters the number of high energy e^+ oscillates as they are preferentially emitted in the direction of muon spin.

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$







We count the rate of high energy decay positrons.

Then we fit the time spectrum to the oscillation frequency to extract ω_a.

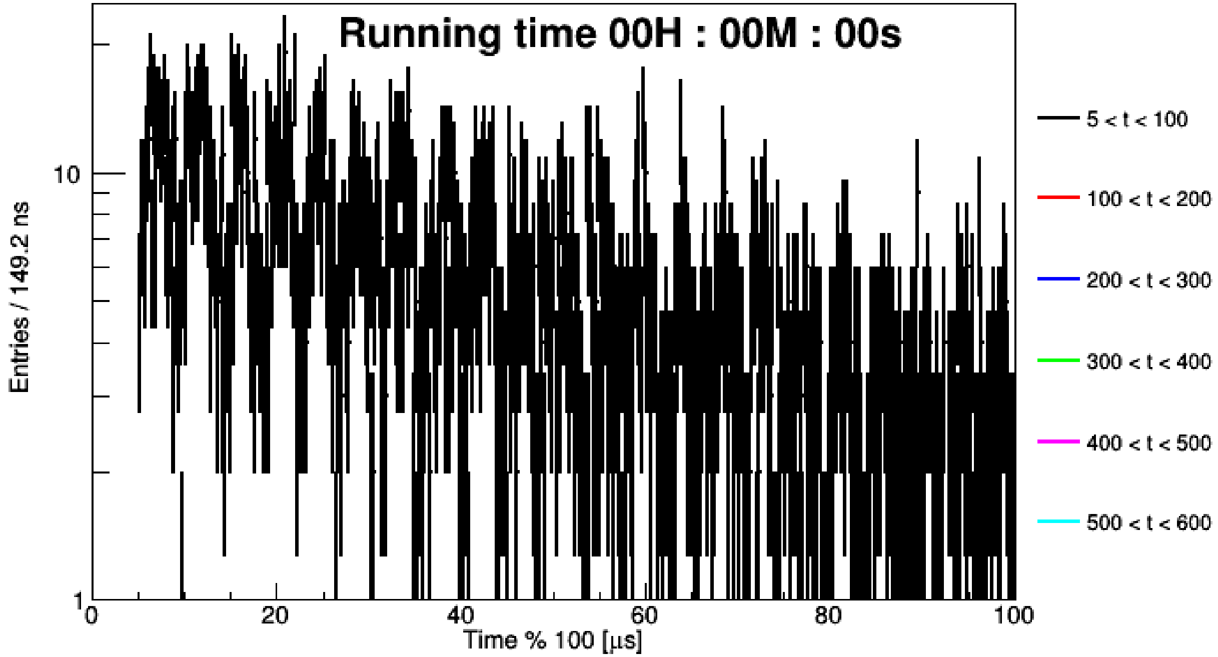
MEASURING ω_a

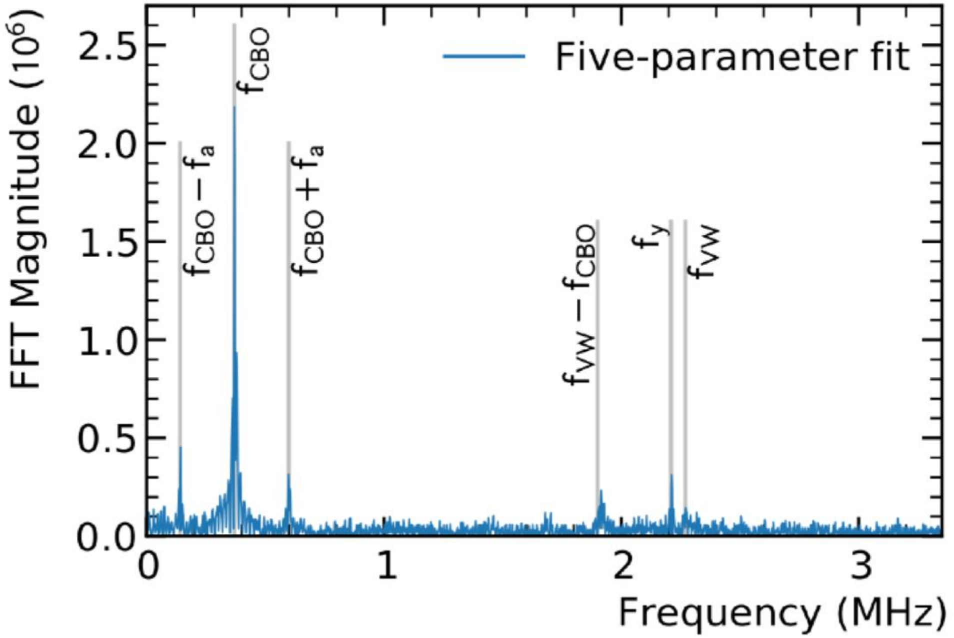
We count the rate of high energy decay positrons. Number of decay positrons vs time is proportional to anomalous precession frequency

Then we fit the time spectrum to the oscillation frequency to extract ω_a.

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

5-parameter fit function





MEASURING MUON G-2

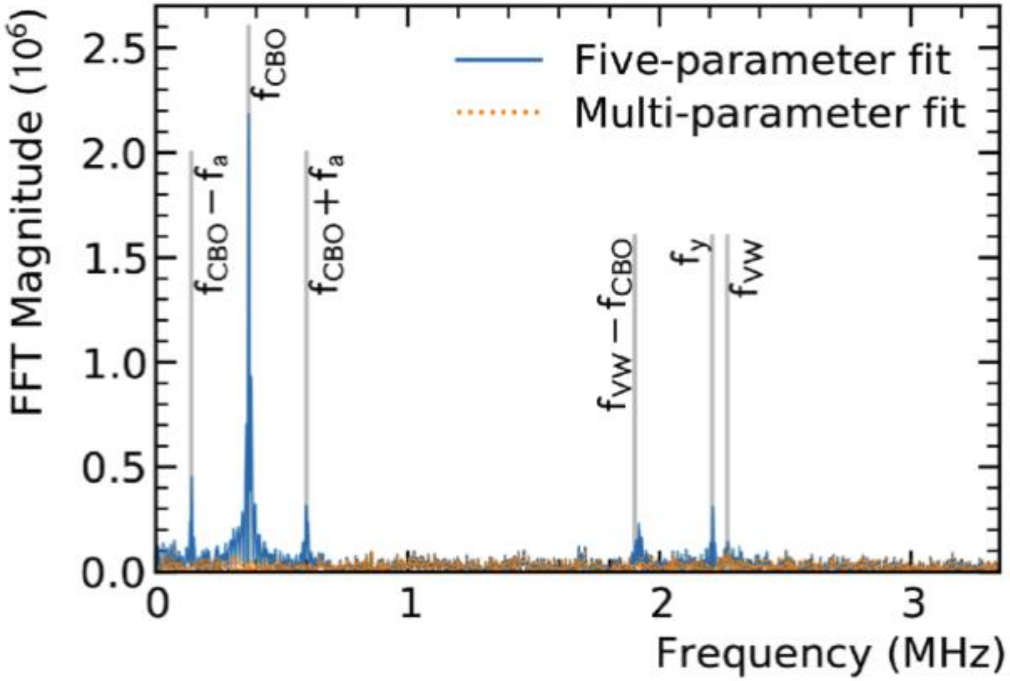
Simplest model captures exponential decay and g-2 oscillation

We must account for beam oscillations, muon losses and detector effects which shift ω_a by a few ppm

Each beam dynamic effect contributes to an additional frequency component to the wiggle plot.

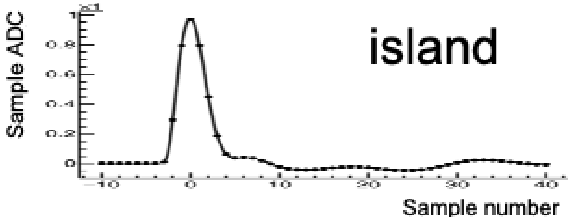
$$
\begin{aligned}
N(t) = Ne^{-t/\tau_\mu}\,&[1 + A\cdot\cos(\omega_a t - \phi + \phi_{BO}(t))]\cdot \\
&\cdot\left(1 + A_{CBO}\cos(\omega_{CBO}t - \phi_{CBO})e^{-\frac{t}{\tau_{CBO}}}\right)\cdot \\
&\cdot\left(1 + A_{VW}\cos(\omega_{VW}t - \phi_{VW})e^{-\frac{t}{\tau_{VW}}}\right)\cdot \\
&\cdot\left(1 + A_{2CBO}\cos(\omega_{2CBO}t - \phi_{2CBO})e^{-\frac{t}{\tau_{2CBO}}}\right)\cdot \\
&\cdot\left(1 + A_{y}\cos(\omega_{y}t - \phi_{y})e^{-\frac{t}{\tau_{y}}}\right)\cdot \\
&\cdot\left(1 - k_{LM}\int_0^t L(t')e^{t'/\tau_\mu}dt'\right)\cdot \\
&\cdot\left(1 + [A_+\cos(\omega_+(t)t - \phi_+) + A_-\cos(\omega_-(t)t - \phi_-)]\,e^{-\frac{t}{\tau_{CBOVW}}}\right)
\end{aligned}
$$

From 5 parameters to over 30!

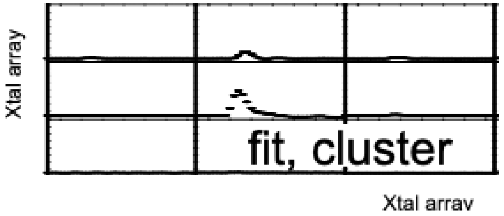


ω_a ANALYSIS STEPS

Data Acquisition → Raw SiPM data → Positron hitting a crystal is an event. We assign hit times and amplitudes

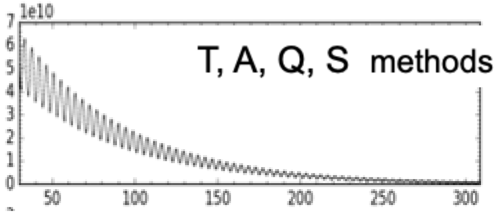


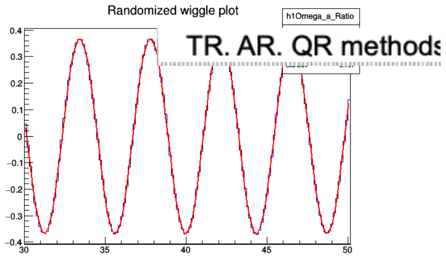
Reconstruction → Crystal hits → Clustering Algorithm groups crystal hits together to form an event from each cluster. Energy of the event is the sum of the crystals



Corrections Pile up subtraction + Gain Corrections + Residual Slow term

Histograms → 2-D time vs energy histograms → Wiggle plots are constructed from histograms using different methods. Methods depend on how positron events are weighted as a function of energy.



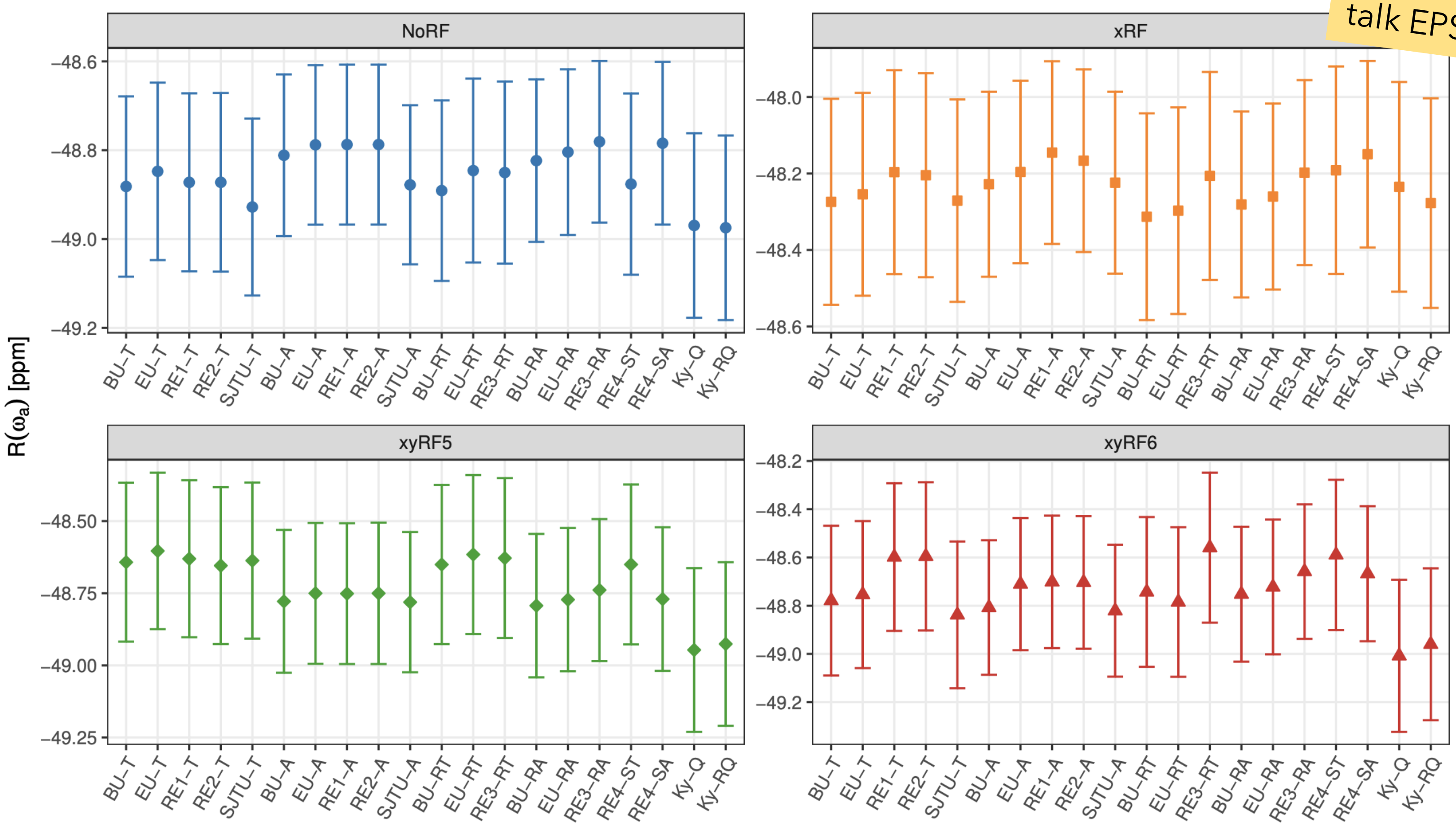


Fitting → Wiggle plot → Multi parameter fit to obtain ω_a. Fits include terms to account for Beam oscillations, lost muons and detector effects

POWER IN DIVERSITY OF APPROACHES

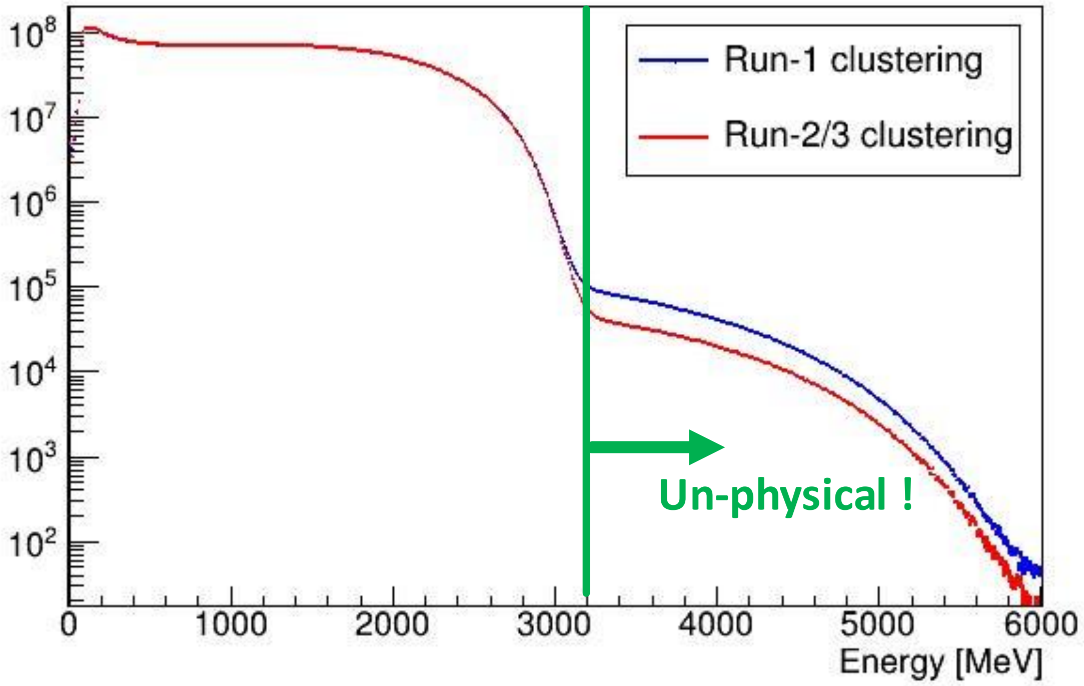
Run 4/5/6 analysis had 5 groups, 8 Methods, 20 unblinded ω_a analyses

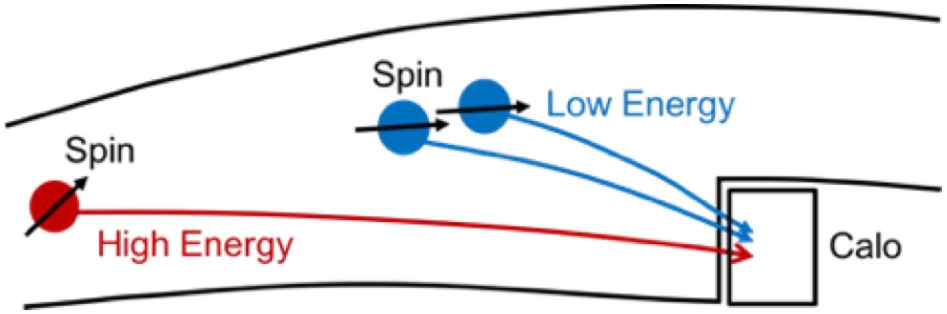
Combination covered in A.Lusiani talk EPS25 T07



PILEUP SUBTRACTION

Pileup occurs when two or more positrons are **misidentified** as a single positron due to arriving too close in time / space





Pileup methods attempt to identify which events are pile up based on time separation of the cluster traces.

BUILDING WIGGLE PLOTS

T-Method

- All positron events are integrated in energy above a fixed threshold, with equal weights (p(E) = 1).
- Greater threshold: wider ω_a oscillations
- Lower threshold: more positrons
- Compromise: ~ 1.7 GeV

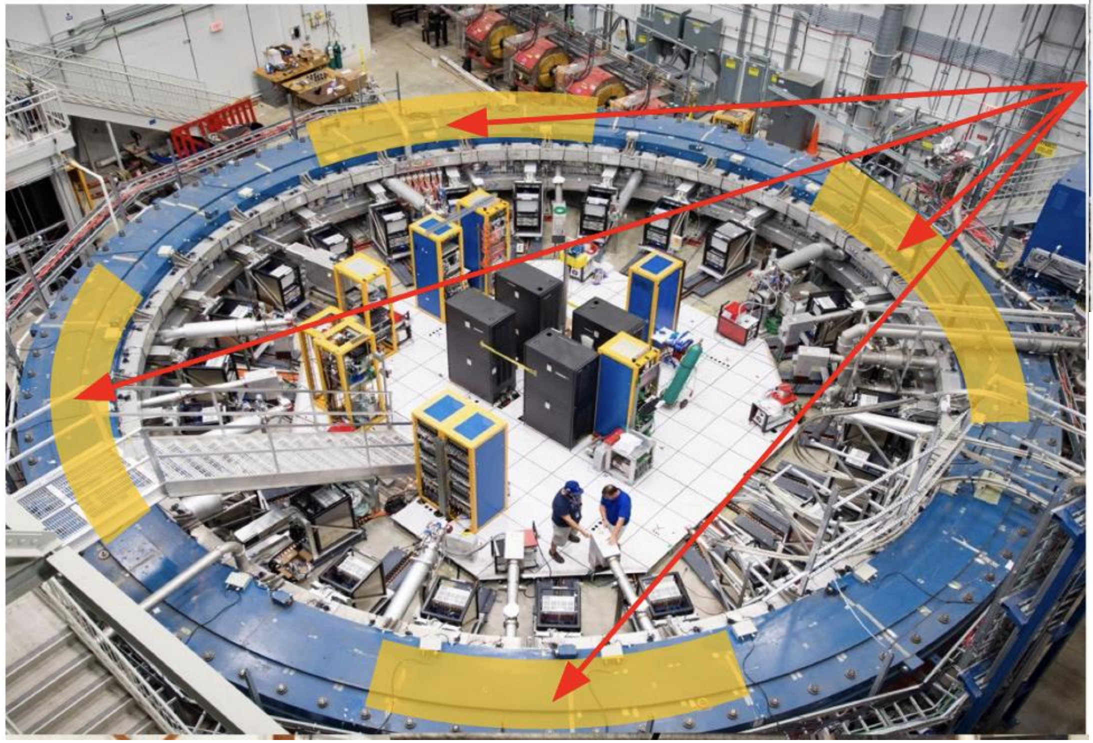
A-Method

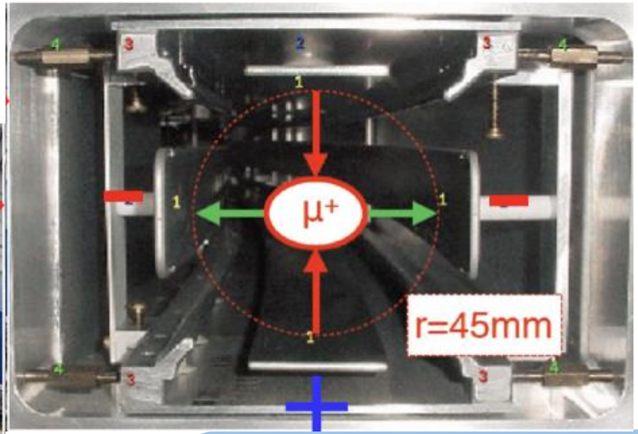
- Each positron event is weighted with the asymmetry function A(E) as a function of the positron energy.
- All positron events are integrated in energy above a fixed threshold
- Lower uncertainty than T-Method

R-Method

- Randomly splits positron events into 4 separate groups. Shifts some of them in time and combines them
- T-Method / A-method then employed.
- Cancels out the exponential term in the 5-parameter function and reduces sensitivity to slow term effects

QUADRUPOLES





The muon beam is contained horizontally by the B field

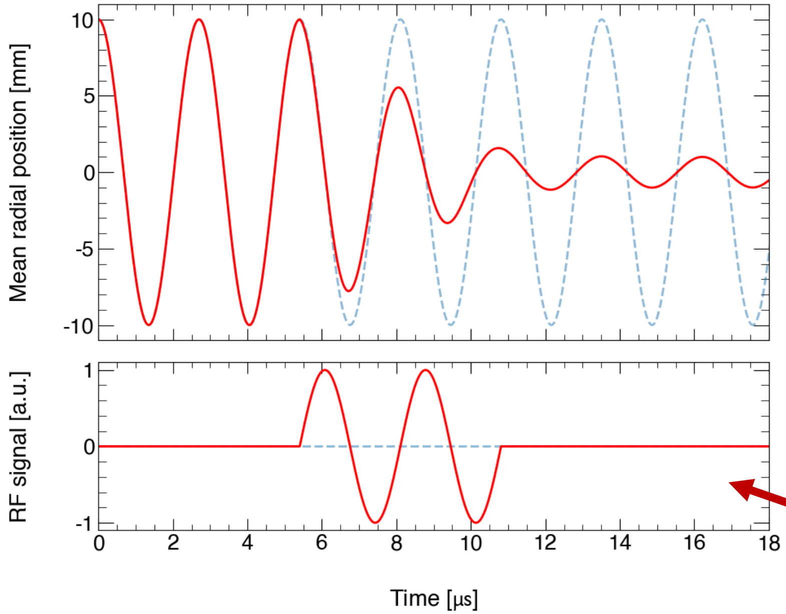
But the beam also moves vertically, to contain it 4 electrostatic quadrupoles are used.

The 4 sections cover 43% of the ring circumference.

MAIN IMPROVEMENTS

COHERENT BETATRON OSCILLATION TASK FORCE

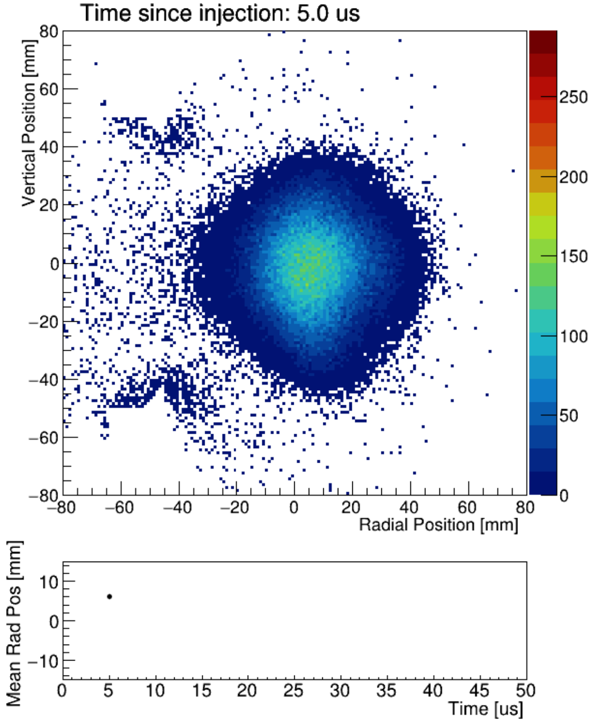
RF has reduced CBO greatly



Split data into 4 datasets

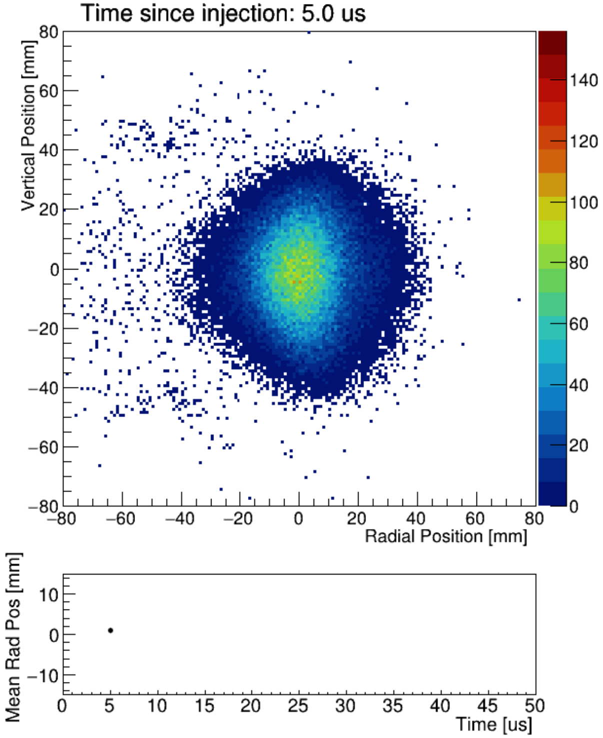
noRF, xRF, xyRF5, xyRF6

No Additional RF on ESQ



Additional RF on ESQ

Significant reduction in oscillation amplitude



RF acts like a forced harmonic oscillator (for 6 µs)

If tuned correctly to the CBO frequency:

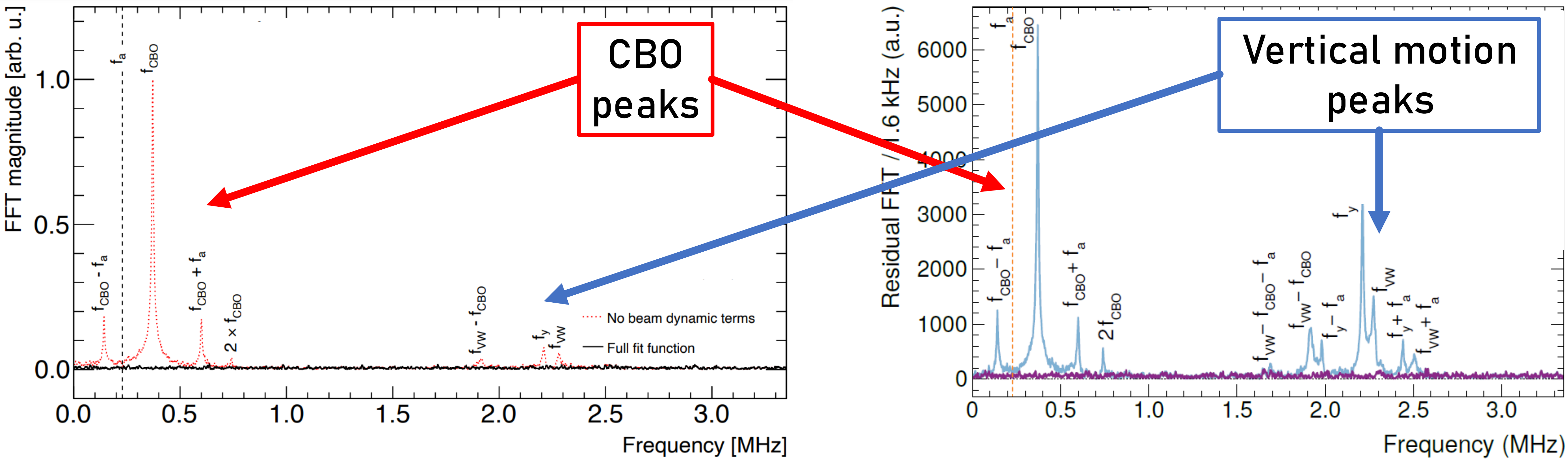
- Phase-shifts different muon distributions
- Reduces the oscillation of the mean of the particle ensemble (reduces the coherence)

MAIN IMPROVEMENTS
BEAM OSCILLATIONS

Higher statistics has provided access to frequency components

New models, new methods and extensive studies.

Run 2/3 **Run 4/5/6**



CBO peaks

Vertical motion peaks

MAIN IMPROVEMENTS

RESIDUAL SLOW TERM TASK FORCE

Identified an **Intensity-Dependent Gain Sag**

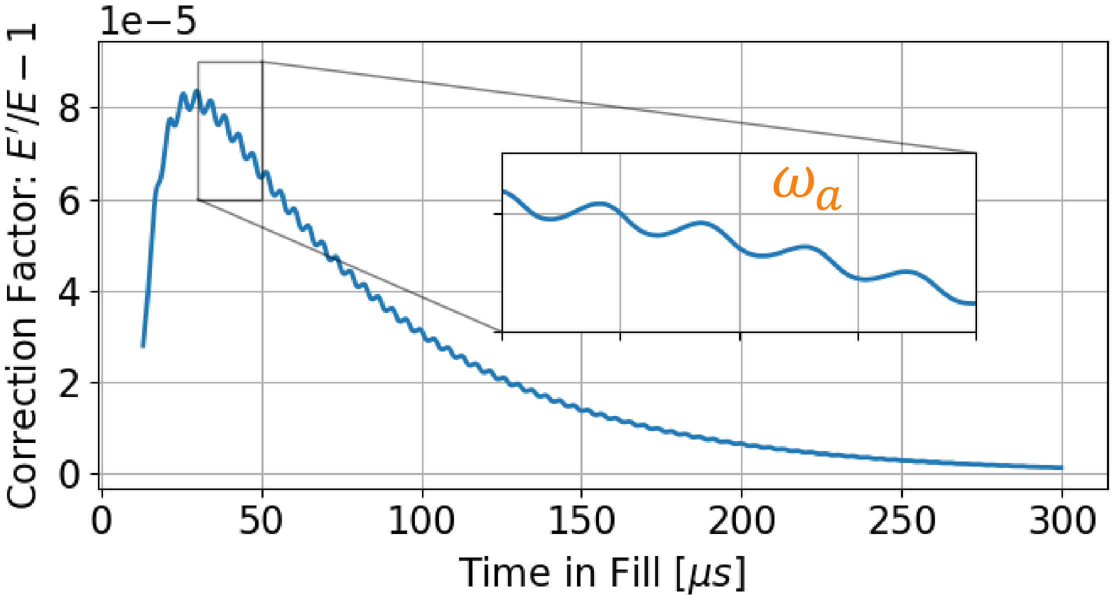
- with a magnitude below our stability design goal (10^{-4})

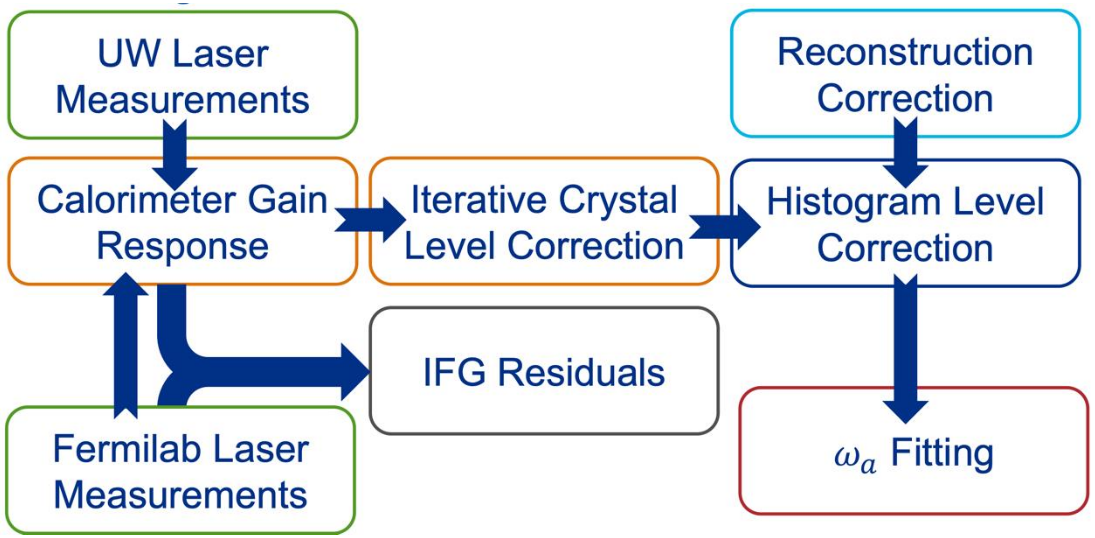
New! Sensitive also below 10^{-4} if

- Rate & Energy dependent
- Time constant $\sim 1/\omega_a$
- Correction shows ω_a-behavior but **out of phase**
- Time-dependent phase-change
- Fitted ω_a sensitive to such effects

Run-4/5/6: New! Identified physical explanation

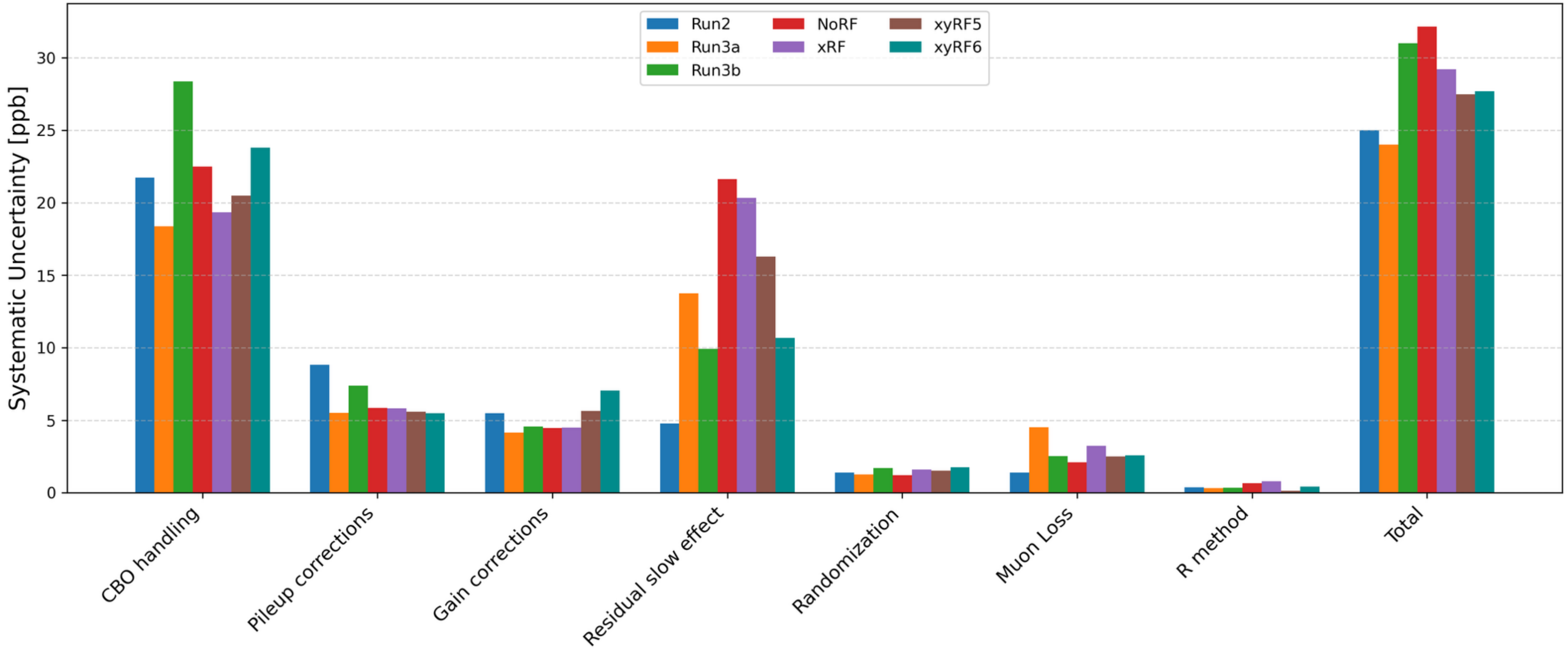
Detector effect due to preceding positron hits (rate dependent):
20-40 ppb effect, ~25ppb uncertainty

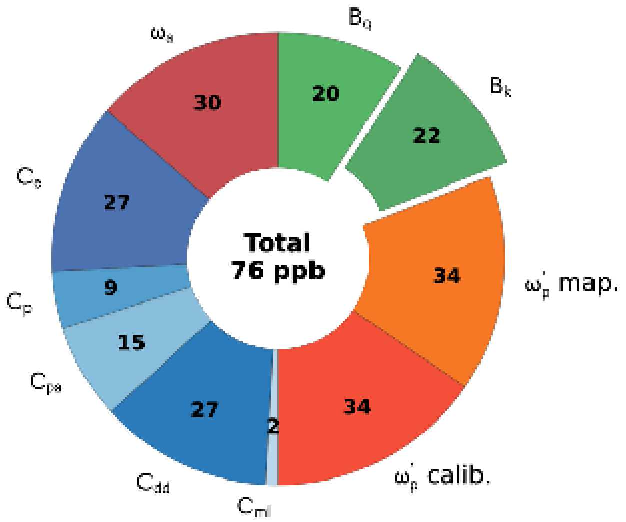




SYSTEMATIC UNCERTAINTIES

CBO and slow term are still the largest sources of systematic uncertainty in ω_a





MEASURING MUON G-2 - CORRECTIONS

$\hbar\omega_p = 2\mu_p|\vec{B}|$

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}}\,\frac{\mu'_p(T_r)}{\mu_B}\,\frac{m_\mu}{m_e}$$

Unc. 4 ppb Unc. 22 ppb

$$\Big\downarrow$$

$$\frac{\overbrace{f_{clock}}^{\text{Clock blinding frequency}}\,\overbrace{\omega_a^m}^{\text{Anomalous precession frequency}}\left(1+\overbrace{C_e+C_p+C_{pa}+C_{dd}+C_{ml}}^{\text{Beam dynamics corrections}}\right)}{\underbrace{f_{calib}}_{\text{Absolute calibration frequency}}\langle\underbrace{\omega'_p(T_r)}_{\text{Magnetic field map}}\times\underbrace{M}_{\text{Muon beam distribution}}\rangle\left(1+\underbrace{B_k+B_q}_{\text{Transient magnetic field corrections}}\right)}$$

There are seven effects which need to be corrected for.

1. **Electric field correction (C_e)**
2. **Pitch correction (C_p**
3. **Muon loss correction (C_{ml}**
4. **Phase acceptance correction (C_{pa})**
5. **Differential decay correction (C_{dd})**
6. **Quad Transient (B_q)**
7. **Kicker Transient (B_k)**

Covered in E.Bottalico Talk EPS25 T07

MUON G-2 AT FERMILAB

New Run-4/5/6 result released by FNAL muon g-2 experiment in June 25.

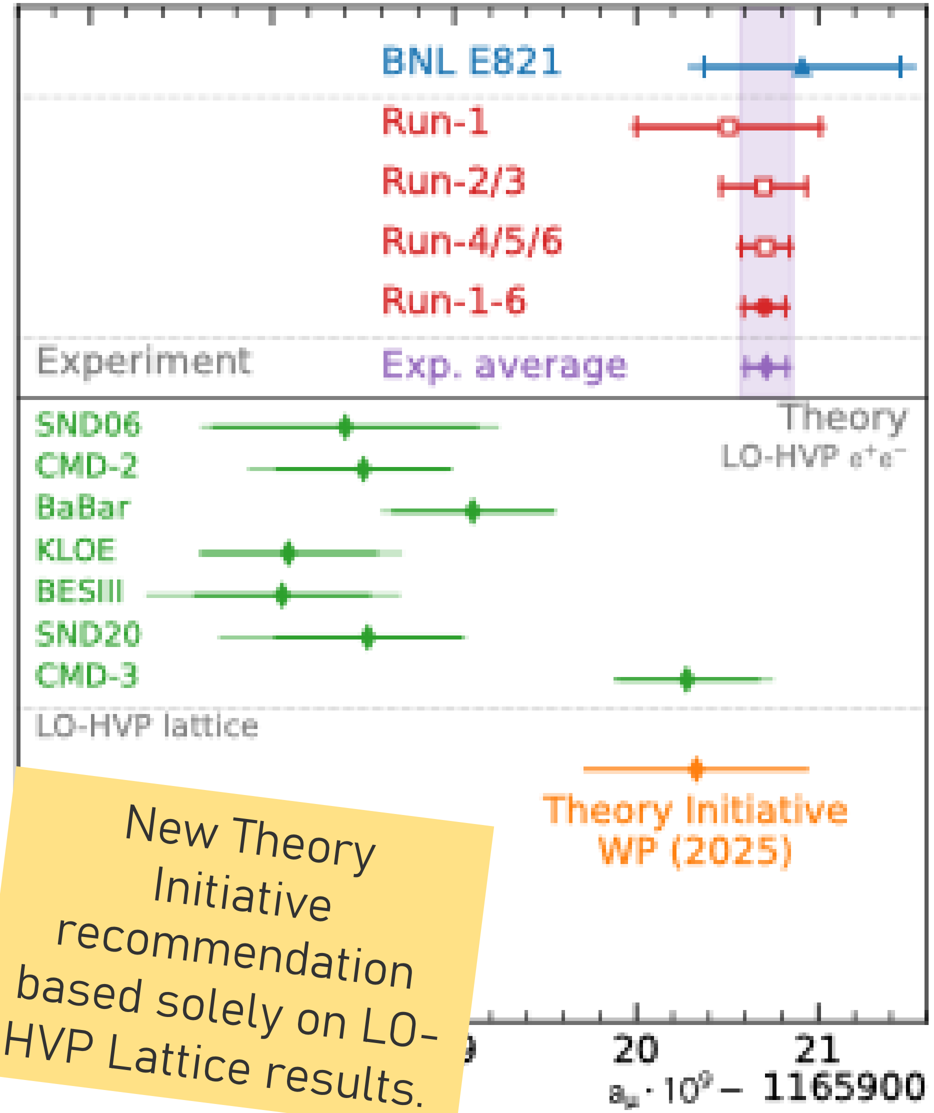
$$a_\mu(\textbf{Run 1–6}) = \mathbf{0.001165920705(148)}$$

Most precise determination of a_μ for many years to come

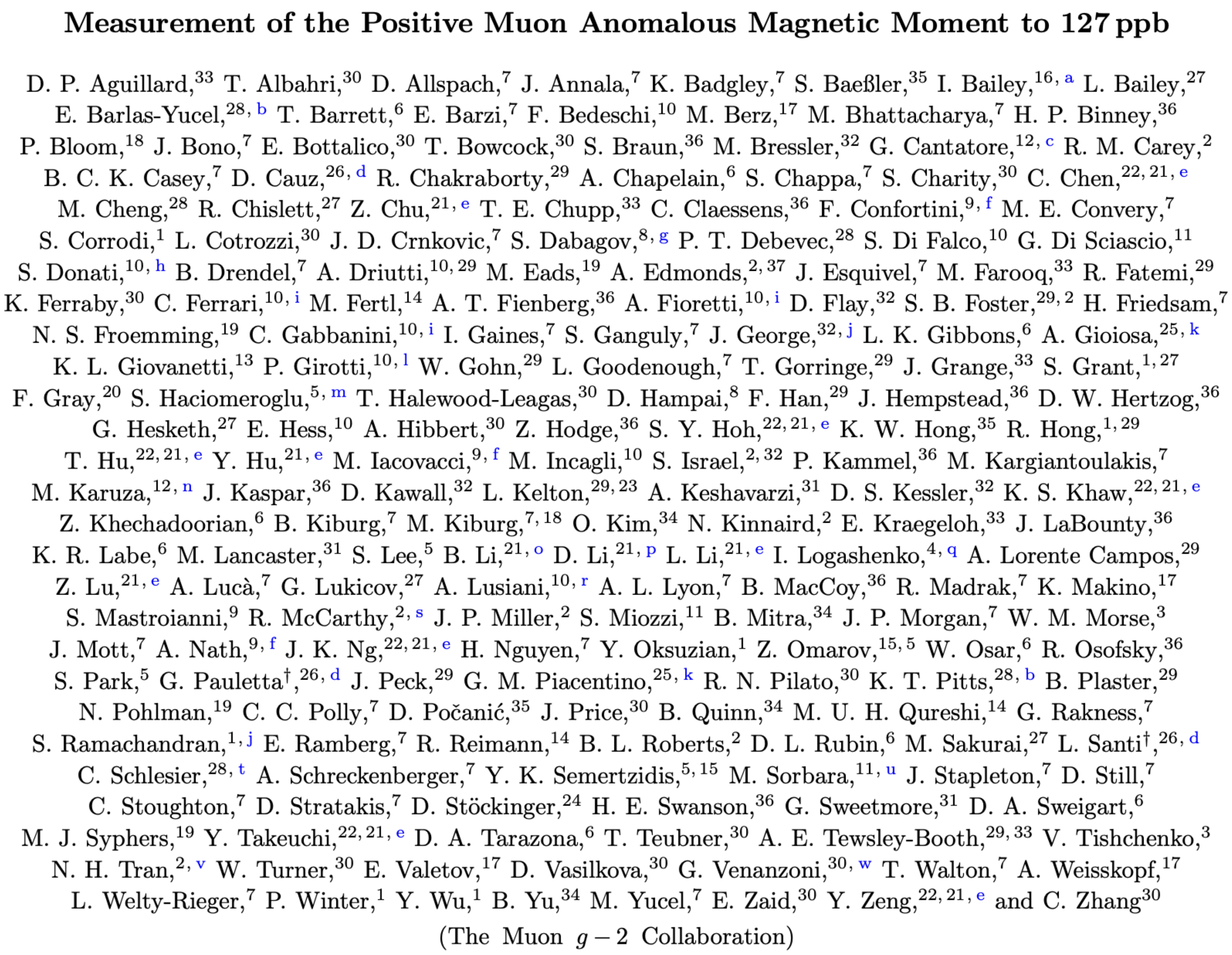
127 ppb measurement tests all Standard Model contributions

Result in excellent agreement with previous measurements.

$\frac{\omega_a}{\tilde{\omega}'_p}$	Stat. Uncertainty (ppb)	Syst. Uncertainty (ppb)	Total Uncertainty (ppb)
Run-1	434	159*	462
Run-2/3	201	78*	216
Run-4/5/6	114	76	137
Run-1-6	**98**	**78**	**125**



New Theory Initiative recommendation based solely on LO-HVP Lattice results.



Measurement of the Positive Muon Anomalous Magnetic Moment to 127 ppb

D. P. Aguillard,[33] T. Albahri,[30] D. Allspach,[7] J. Annala,[7] K. Badgley,[7] S. Baeßler,[35] I. Bailey,[16,a] L. Bailey,[27]
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P. Bloom,[18] J. Bono,[7] E. Bottalico,[30] T. Bowcock,[30] S. Braun,[36] M. Bressler,[32] G. Cantatore,[12,c] R. M. Carey,[2]
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K. Ferraby,[30] C. Ferrari,[10,i] M. Fertl,[14] A. T. Fienberg,[36] A. Fioretti,[10,i] D. Flay,[32] S. B. Foster,[29,2] H. Friedsam,[7]
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K. L. Giovanetti,[13] P. Girotti,[10,l] W. Gohn,[29] L. Goodenough,[7] T. Gorringe,[29] J. Grange,[33] S. Grant,[1,27]
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C. Schlesier,[28,t] A. Schreckenberger,[7] Y. K. Semertzidis,[5,15] M. Sorbara,[11,u] J. Stapleton,[7] D. Still,[7]
C. Stoughton,[7] D. Stratakis,[7] D. Stöckinger,[24] H. E. Swanson,[36] G. Sweetmore,[31] D. A. Sweigart,[6]
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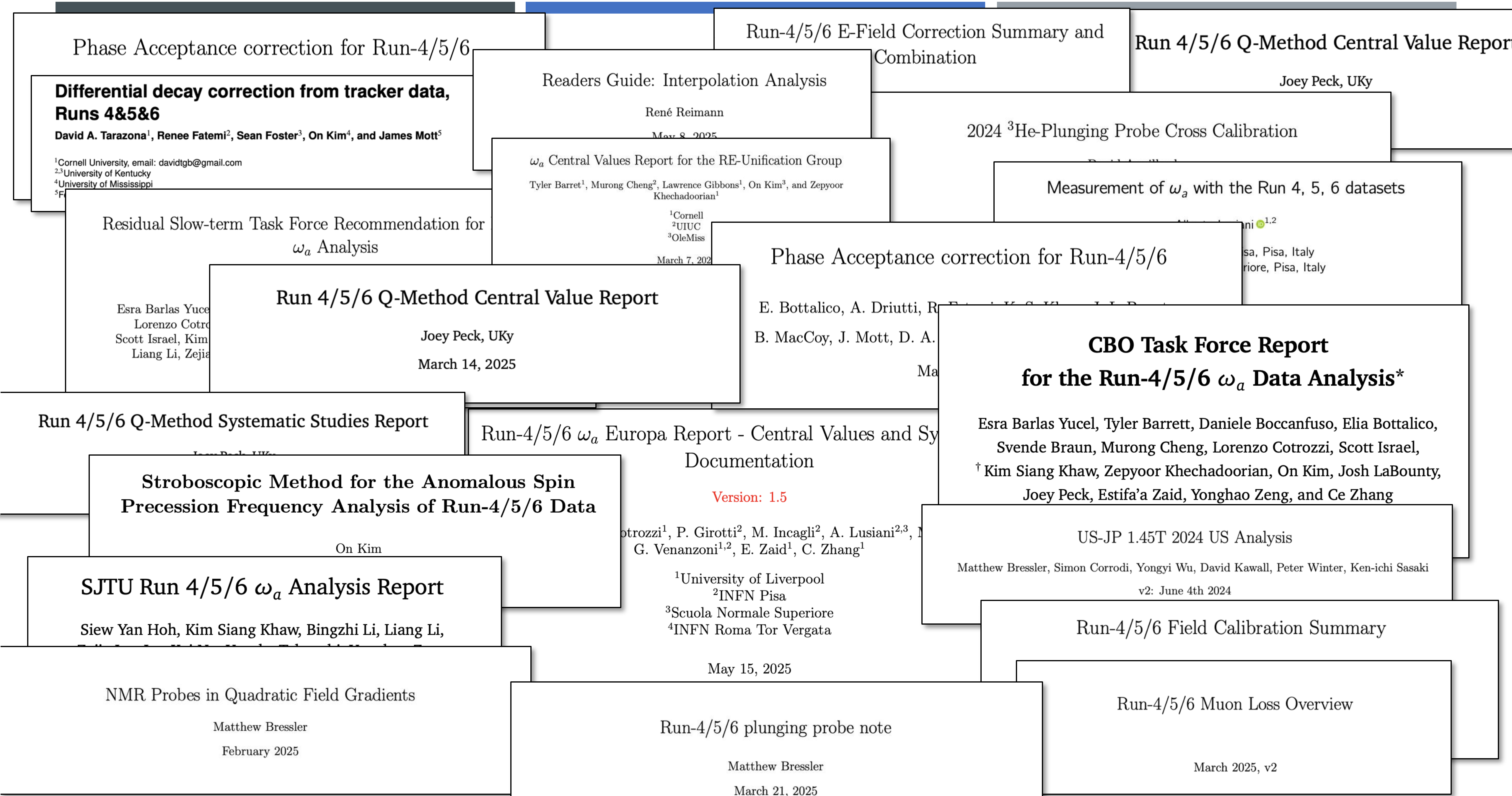
N. H. Tran,[2,v] W. Turner,[30] E. Valetov,[17] D. Vasilkova,[30] G. Venanzoni,[30,w] T. Walton,[7] A. Weisskopf,[17]
L. Welty-Rieger,[7] P. Winter,[1] Y. Wu,[1] B. Yu,[34] M. Yucel,[7] E. Zaid,[30] Y. Zeng,[22,21,e] and C. Zhang[30]
(The Muon $g-2$ Collaboration)

THANK YOU VERY MUCH

On behalf of the Muon g-2 Collaboration



Phase Acceptance correction for Run-4/5/6

Differential decay correction from tracker data, Runs 4&5&6

David A. Tarazona[1], Renee Fatemi[2], Sean Foster[3], On Kim[4], and James Mott[5]

[1]Cornell University, email: davidtgb@gmail.com
[2,3]University of Kentucky
[4]University of Mississippi
[5]F

Run-4/5/6 E-Field Correction Summary and
Combination

Run 4/5/6 Q-Method Central Value Repor

Joey Peck, UKy

Readers Guide: Interpolation Analysis

René Reimann

2024 ^{3}He-Plunging Probe Cross Calibration

ω_a Central Values Report for the RE-Unification Group

Tyler Barret[1], Murong Cheng[2], Lawrence Gibbons[1], On Kim[3], and Zepyoor Khechadoorian[1]

[1]Cornell
[2]UIUC
[3]OleMiss

March 7, 202

Measurement of ω_a with the Run 4, 5, 6 datasets

ni [1,2]

sa, Pisa, Italy
riore, Pisa, Italy

Residual Slow-term Task Force Recommendation for
ω_a Analysis

Esra Barlas Yuce
Lorenzo Cotr
Scott Israel, Kim
Liang Li, Zejia

Phase Acceptance correction for Run-4/5/6

E. Bottalico, A. Driutti, R
B. MacCoy, J. Mott, D. A.

Ma

Run 4/5/6 Q-Method Central Value Report

Joey Peck, UKy

March 14, 2025

CBO Task Force Report
for the Run-4/5/6 ω_a Data Analysis*

Esra Barlas Yucel, Tyler Barrett, Daniele Boccanfuso, Elia Bottalico,
Svende Braun, Murong Cheng, Lorenzo Cotrozzi, Scott Israel,
† Kim Siang Khaw, Zepyoor Khechadoorian, On Kim, Josh LaBounty,
Joey Peck, Estifa'a Zaid, Yonghao Zeng, and Ce Zhang

Run 4/5/6 Q-Method Systematic Studies Report

Run-4/5/6 ω_a Europa Report - Central Values and Sy
Documentation

Version: 1.5

otrozzi[1], P. Girotti[2], M. Incagli[2], A. Lusiani[2,3],
G. Venanzoni[1,2], E. Zaid[1], C. Zhang[1]

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[3]Scuola Normale Superiore
[4]INFN Roma Tor Vergata

May 15, 2025

Stroboscopic Method for the Anomalous Spin Precession Frequency Analysis of Run-4/5/6 Data

On Kim

US-JP 1.45T 2024 US Analysis

Matthew Bressler, Simon Corrodi, Yongyi Wu, David Kawall, Peter Winter, Ken-ichi Sasaki

v2: June 4th 2024

SJTU Run 4/5/6 ω_a Analysis Report

Siew Yan Hoh, Kim Siang Khaw, Bingzhi Li, Liang Li,

Run-4/5/6 Field Calibration Summary

NMR Probes in Quadratic Field Gradients

Matthew Bressler

February 2025

Run-4/5/6 plunging probe note

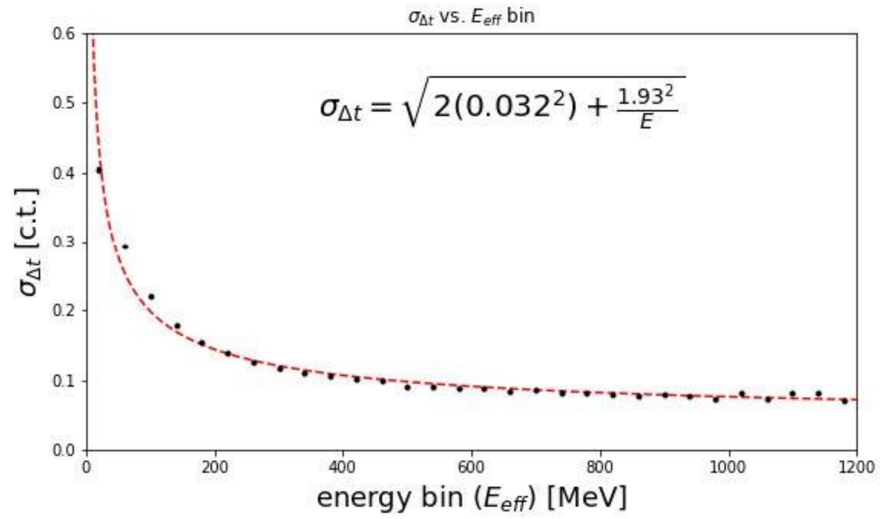
Matthew Bressler

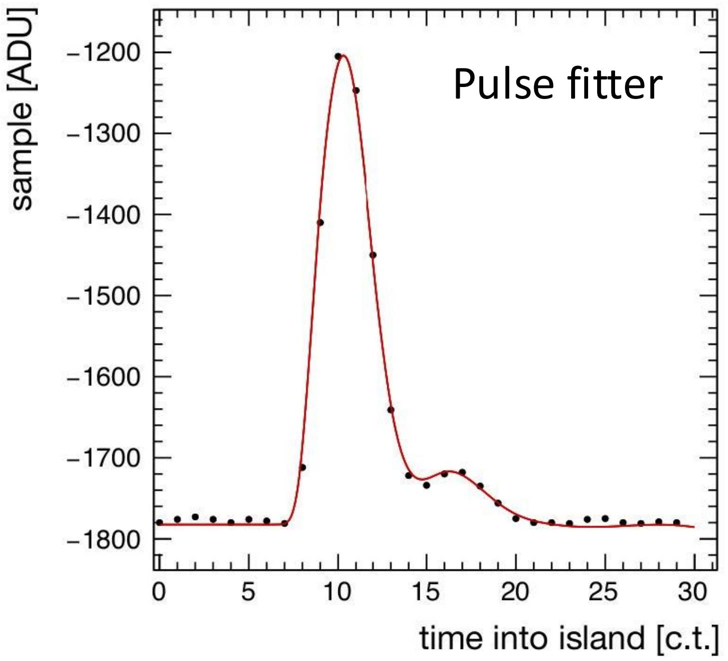
March 21, 2025

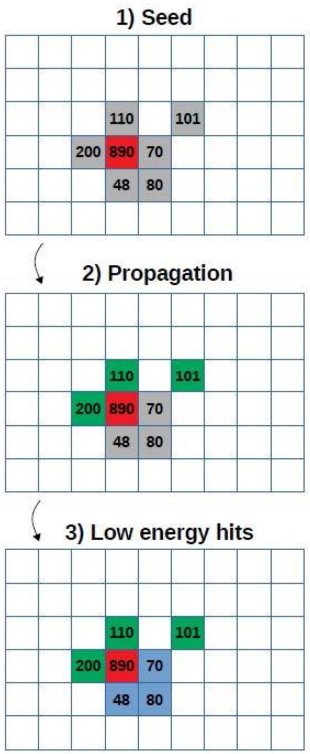
Run-4/5/6 Muon Loss Overview

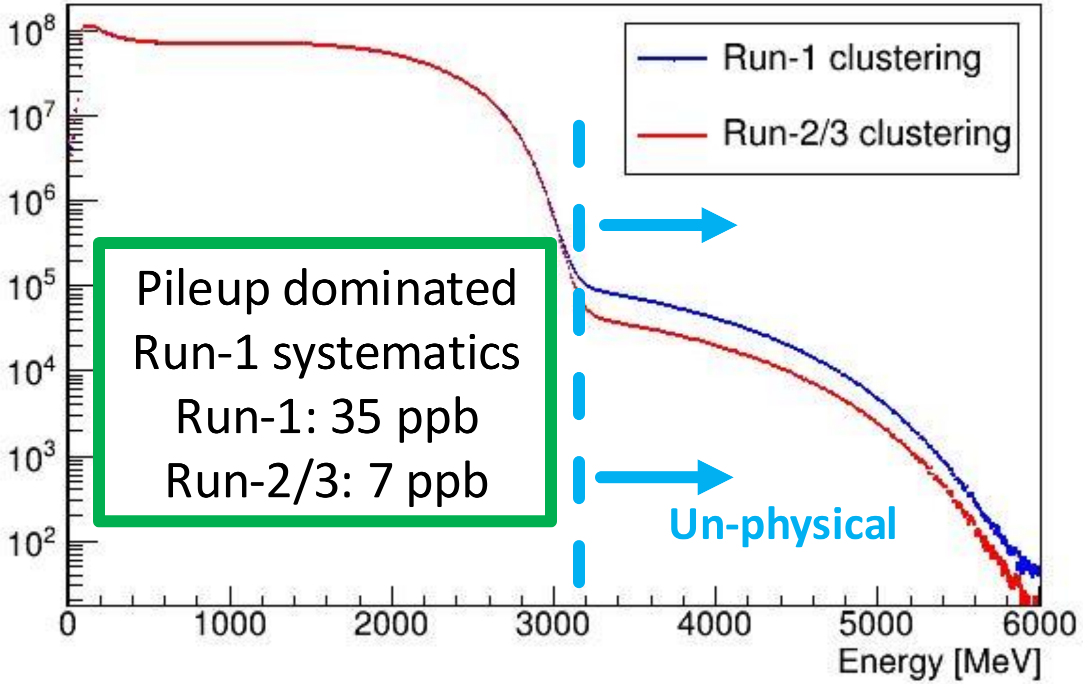
March 2025, v2

- Pulse fitter identifies traces on crystals
- Clustering algorithms reconstruct total time and energy of positron hit
- Better algorithms reduced pileup after Run-1









Pileup dominated
Run-1 systematics
Run-1: 35 ppb
Run-2/3: 7 ppb

Un-physical

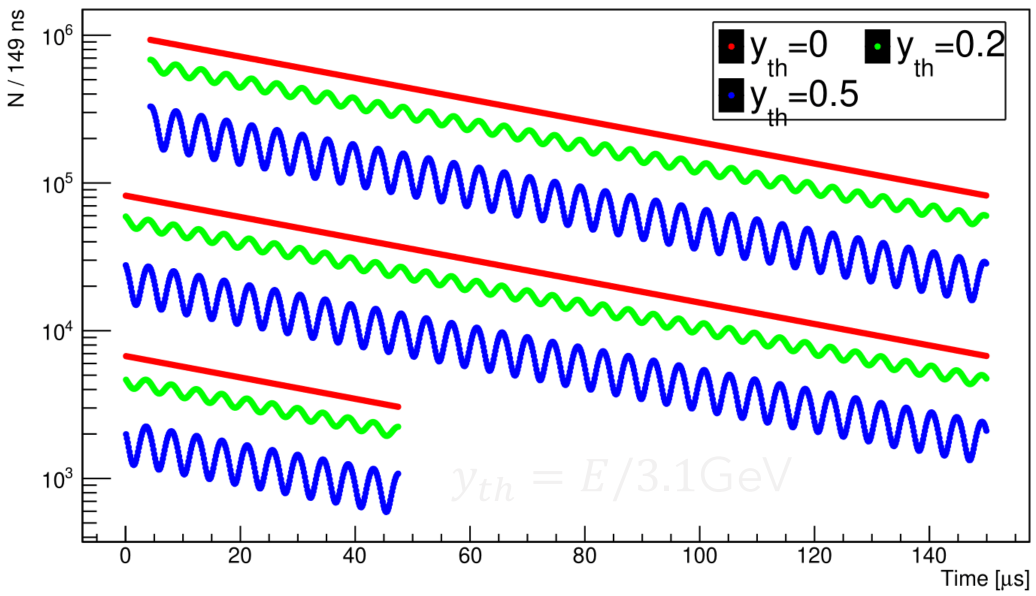
T-Method:

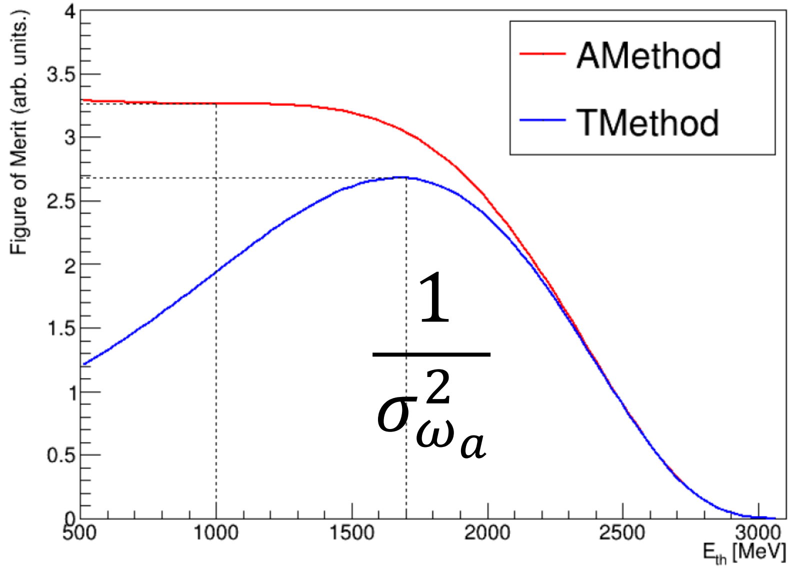
- Greater threshold: wider ω_a oscillations
- Lower threshold: more positrons
- Compromise: ~ 1.7 GeV

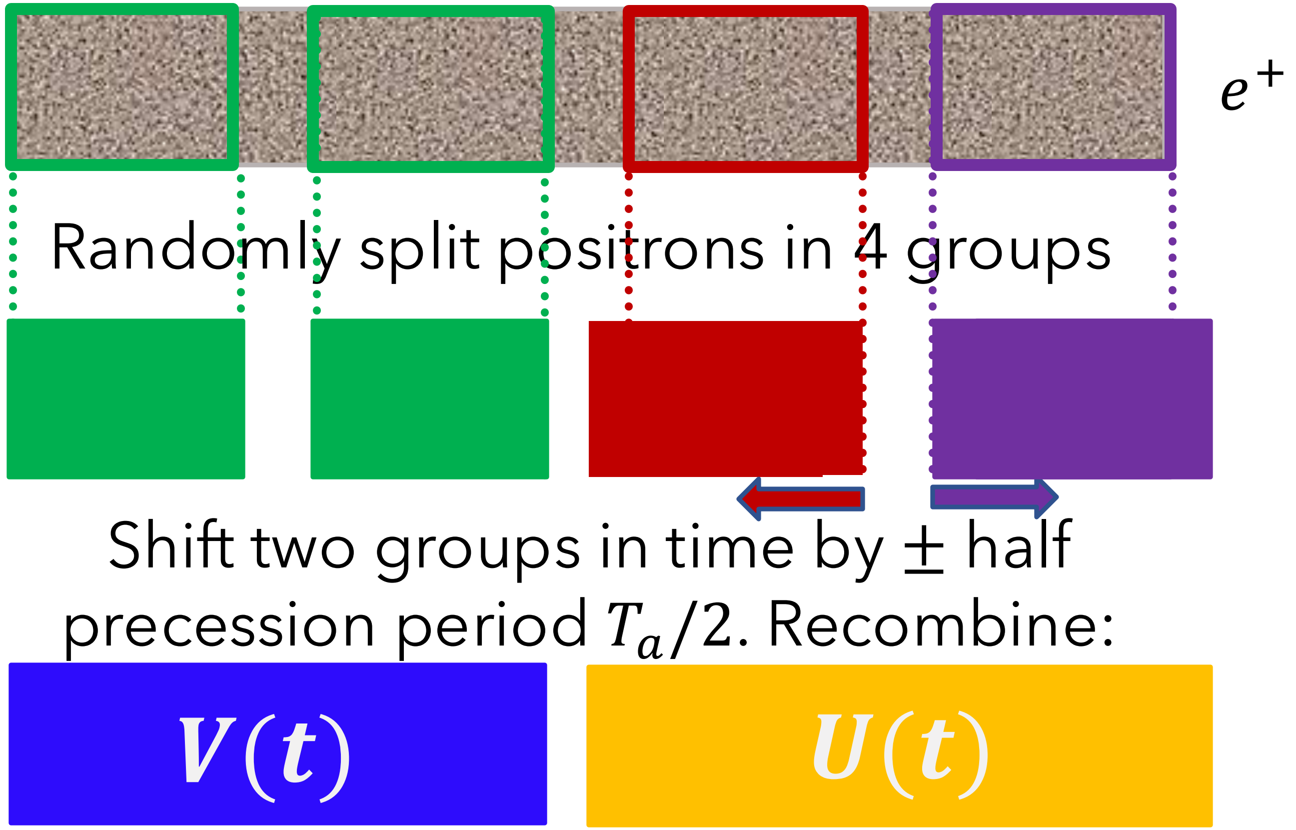
A-Method:

- Extract asymmetry (oscillation amplitude) as function of positron energy → $\mathrm{A(E)}$
- Weight each positron event with $\mathrm{A(E)}$
- σ_{ω_a}(A-Method)$\sim 90\%\ \sigma_{\omega_a}$(T-Method)

Wiggle plots for different energy thresholds







e^+

Randomly split positrons in 4 groups

Shift two groups in time by ± half precession period $T_a/2$. Recombine:

$V(t)$

$U(t)$

$$R(t) = [V(t) - U(t)]/[V(t) + U(t)]$$

It gets rid of muon lifetime and normalization N_0 in fit function. Any «slow» effect is highly reduced! There exists also a «Ratio A-Method»