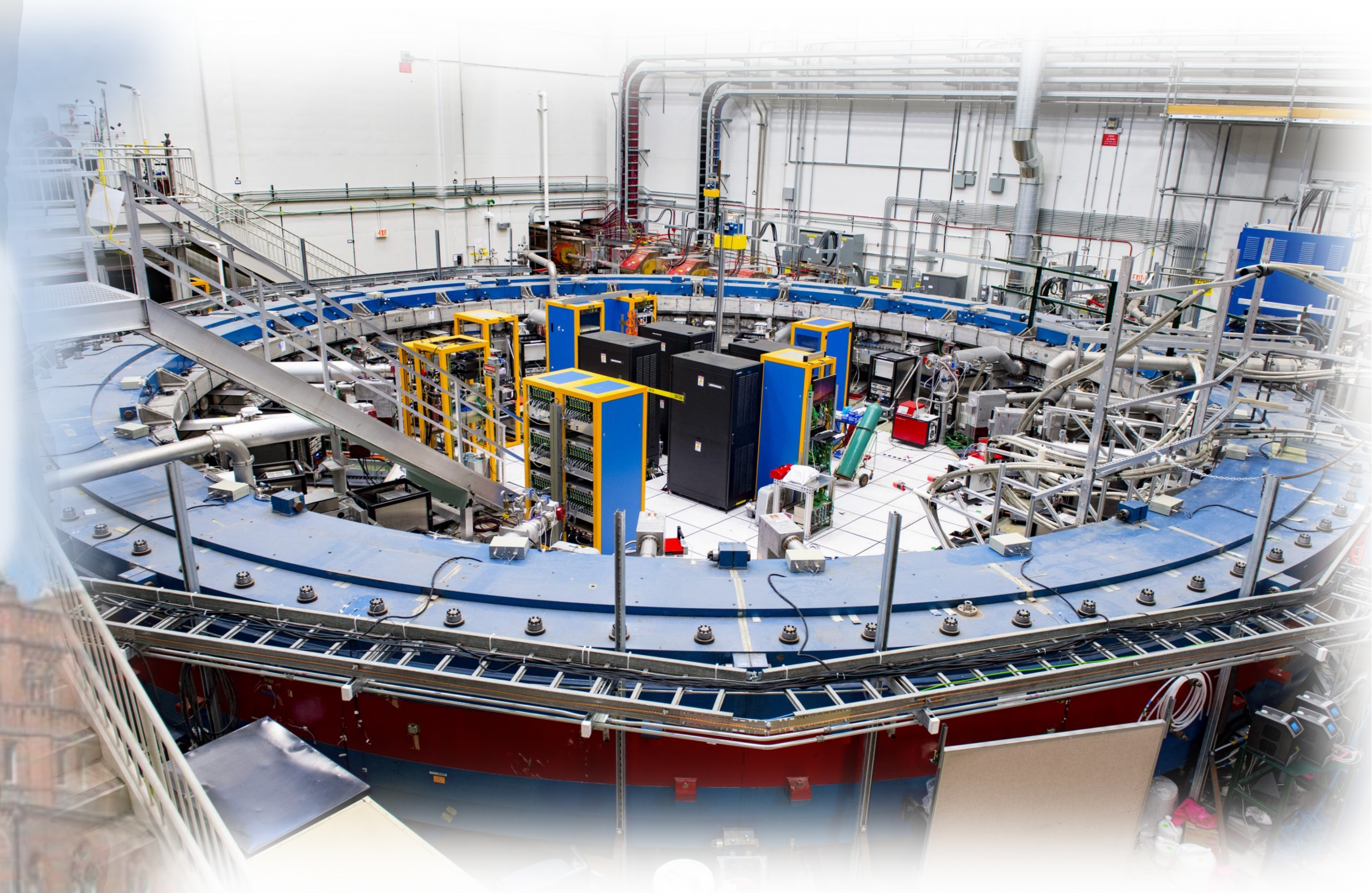
Beam Dynamics in *g*-2 experiment at Fermilab



E. Bottalico

HEP Annual Meeting

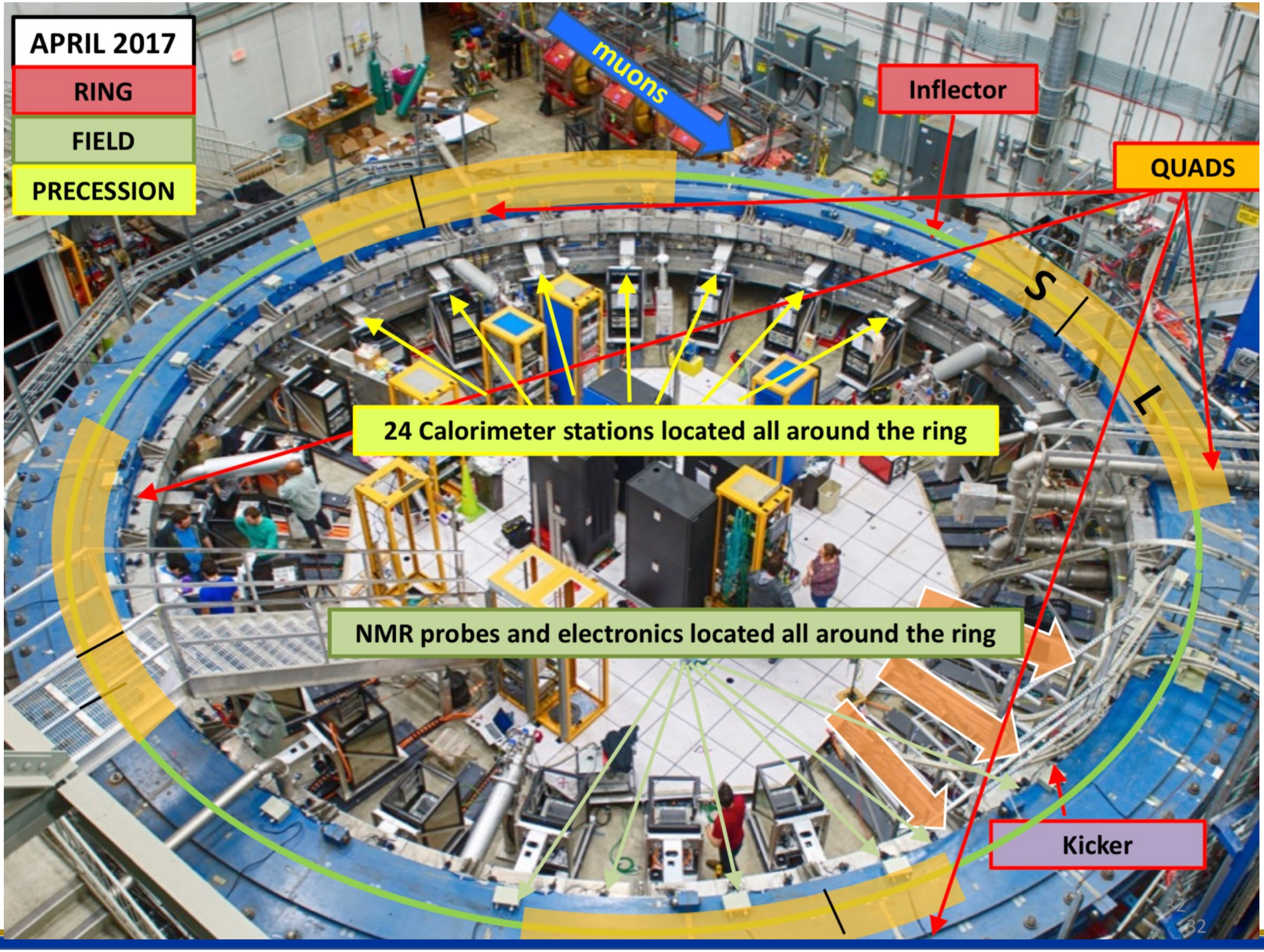
19 May 2023

μ g-2

UNIVERSITY OF LIVERPOOL

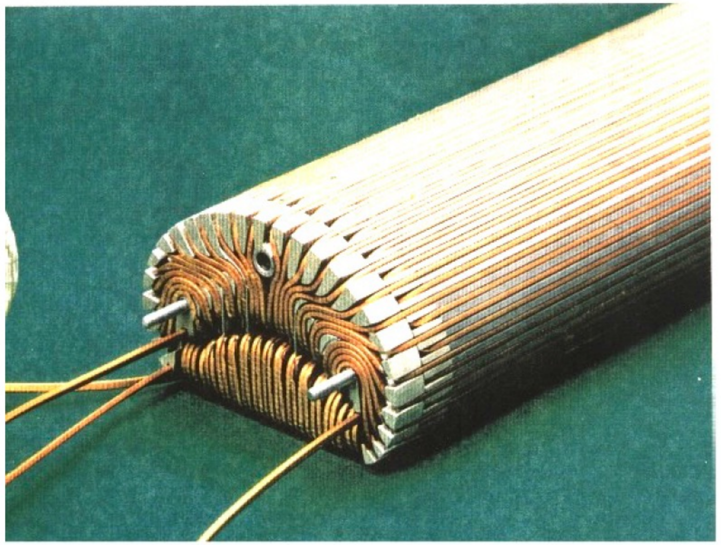
LEVERHULME TRUST

g-2 short recap: The Ring

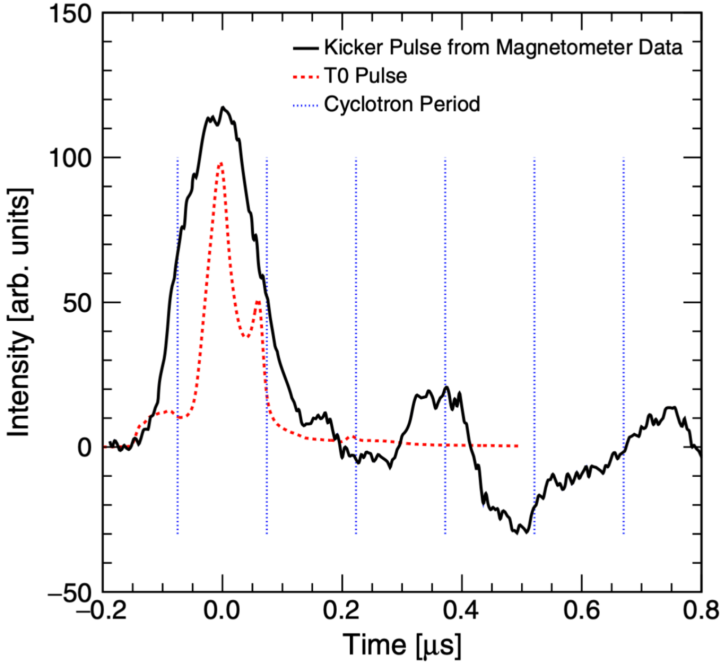


Kickers and Inflector

- The **inflector** cancels the storage ring field such that the muons are not deflected by the main **1.45 T** field.
- Superconducting, operational current ~2.6 kA.

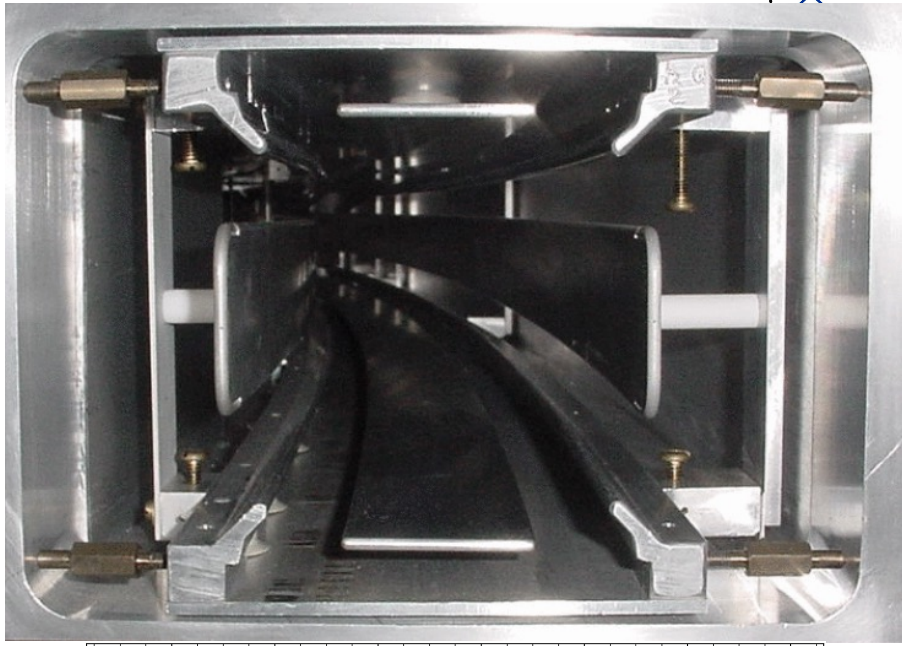


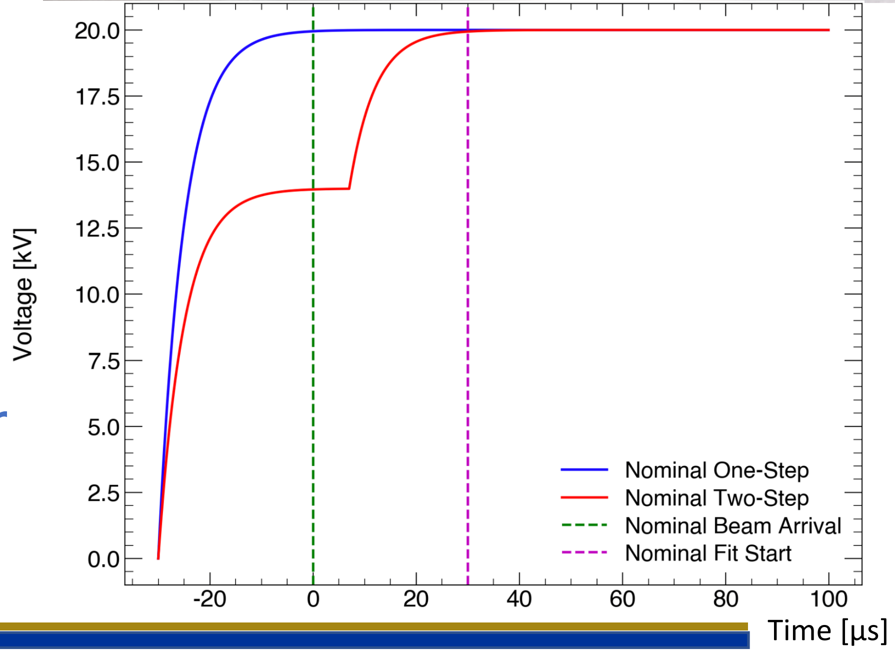
- **3 Kickers** are necessary to inject magic momentum muons along the magic radius (7.11 m) with a required kick at order of 10 mrad.
- 4 kA current in 200 ns pulse.
- Design kick strength has been reached in Run-3 (~160 kV).



Quadrupoles

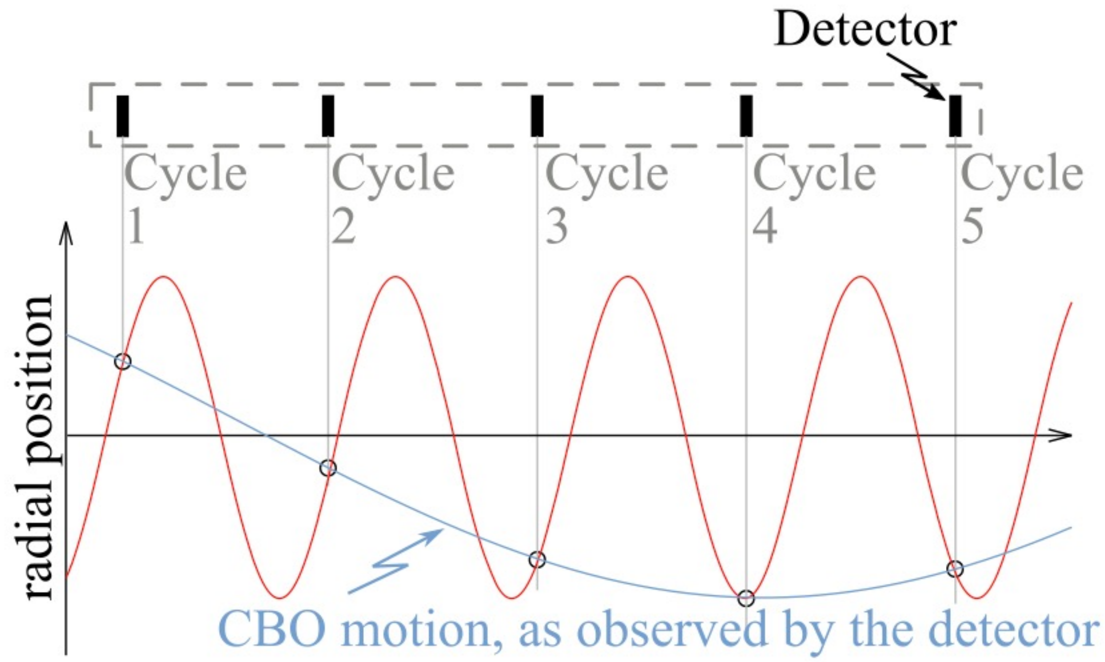
- The Electrostatic Quadrupoles (ESQ) system allows to strongly focus the beam vertically, four ESQ stations are symmetrically placed around the ring.
- The plates are raised from ground to operating voltage prior to each *fill* with RC charging time constants of **$\sim 5\ \mu s$**.
- This procedure, known as **scraping**, initially displaces the beam vertically and horizontally with respect to the central closed orbit.





ω_a measurement – CBO oscillation

- Given the restoring force by radial magnetic field, the beam oscillates radially (vertically too) as the betatron frequency: $\omega_{BO} = \omega_c\sqrt{1-n}$, where $\boldsymbol{n}$ is the field-index.
- The beam is measured by detectors, calorimeters and trackers.
- The $\omega_{BO} < \omega_C$, so calorimeters see a different phase at each turn, measuring an oscillation called **Coherent Betatron Oscillation** (**CBO**), given by $\omega_{CBO} = \omega_C - \omega_{BO}$



$$2\pi f_{CBO} = \omega_C - \omega_{BO} = \omega_C(1-\sqrt{1-n})$$

$$\omega_{CBO} = 2.34\, rad/\mu s$$

Where $T_C \sim 0.149\, ns$ and $n \sim 0.108$

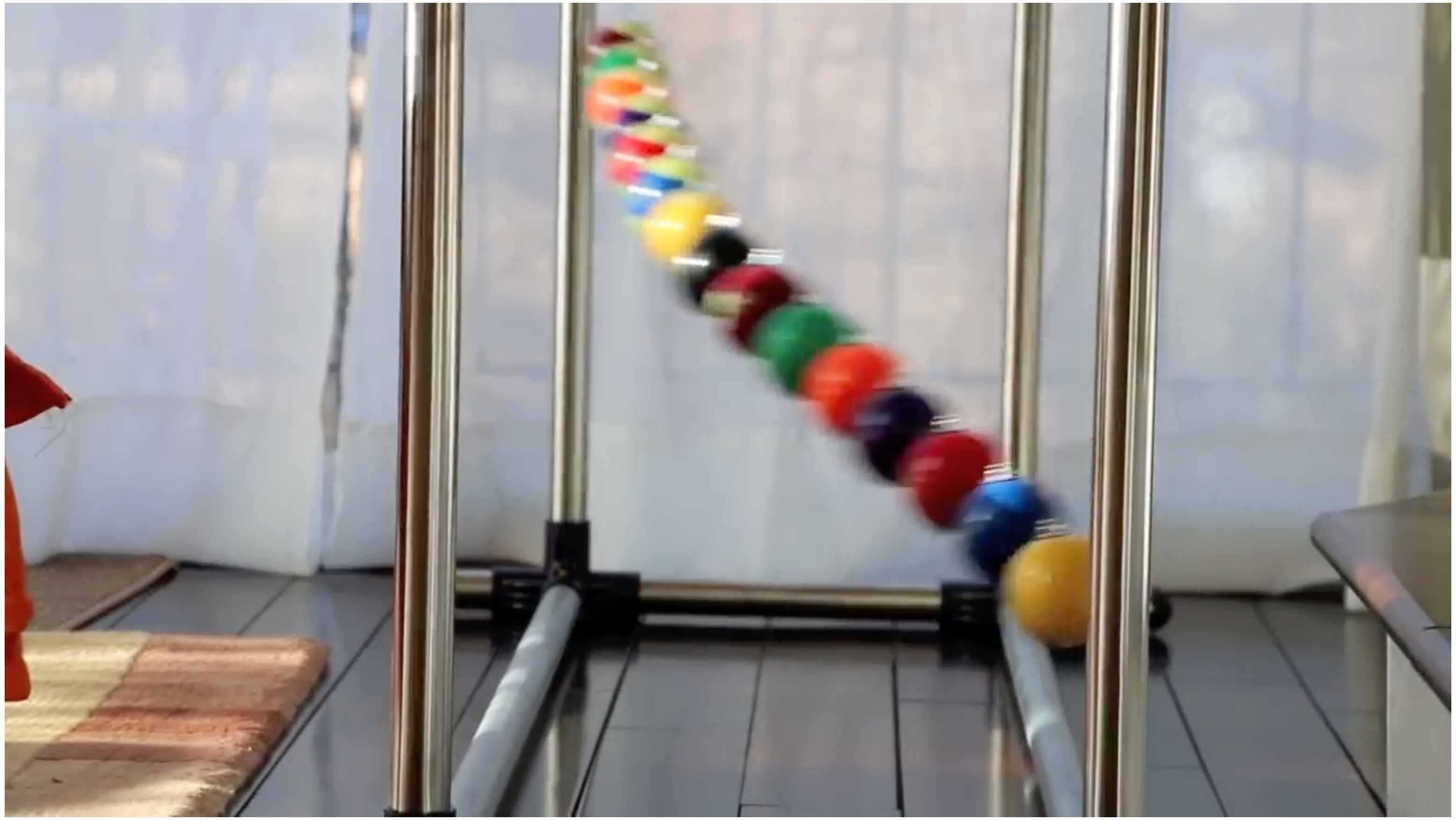
How does the beam move?

- How really does the beam move inside the ring?

?

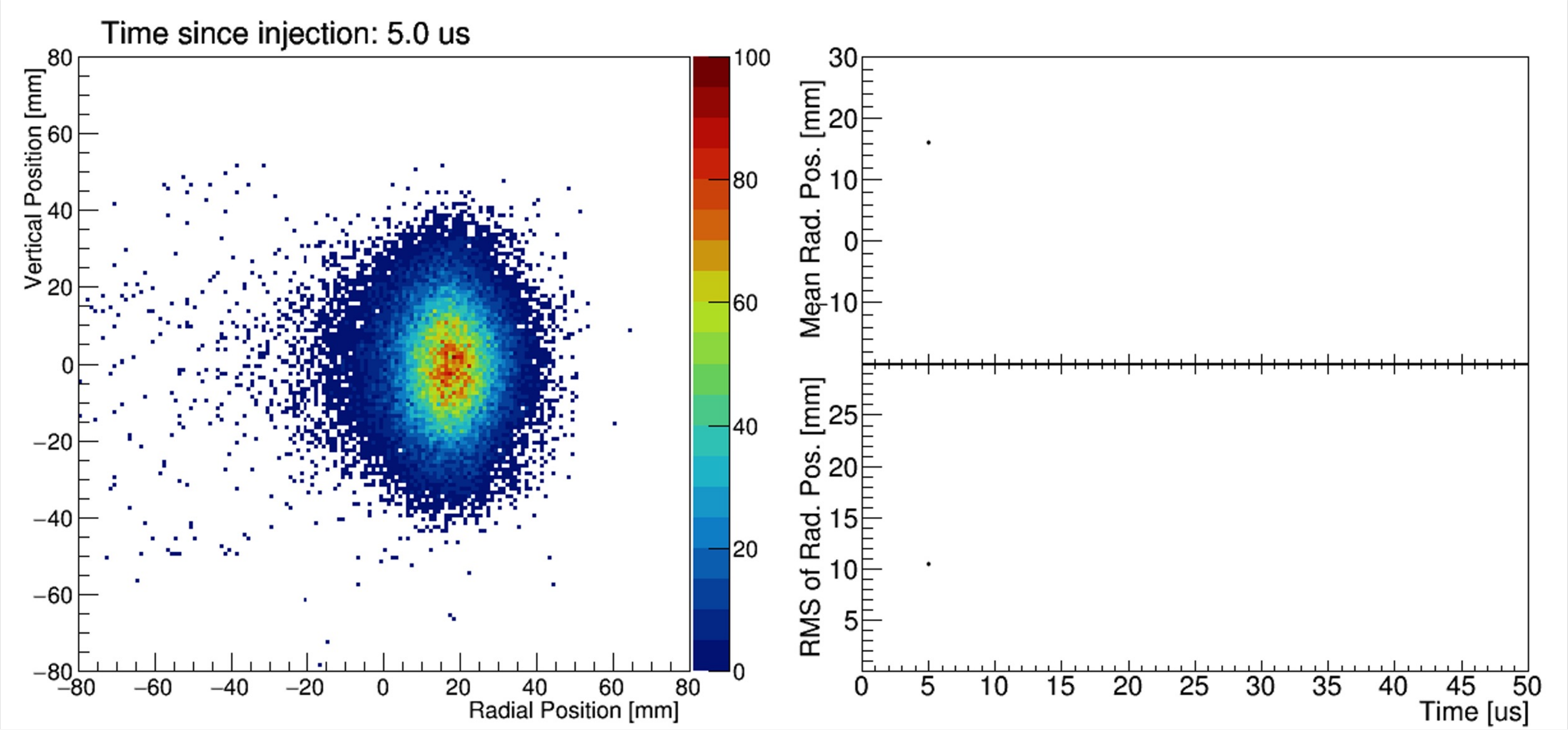
How does the beam move?

- Like this!



The beam motion inside the ring

- What we observe by detectors is the spatial projection and many fill average of the previous representation.
- Here what the tracker detectors see:



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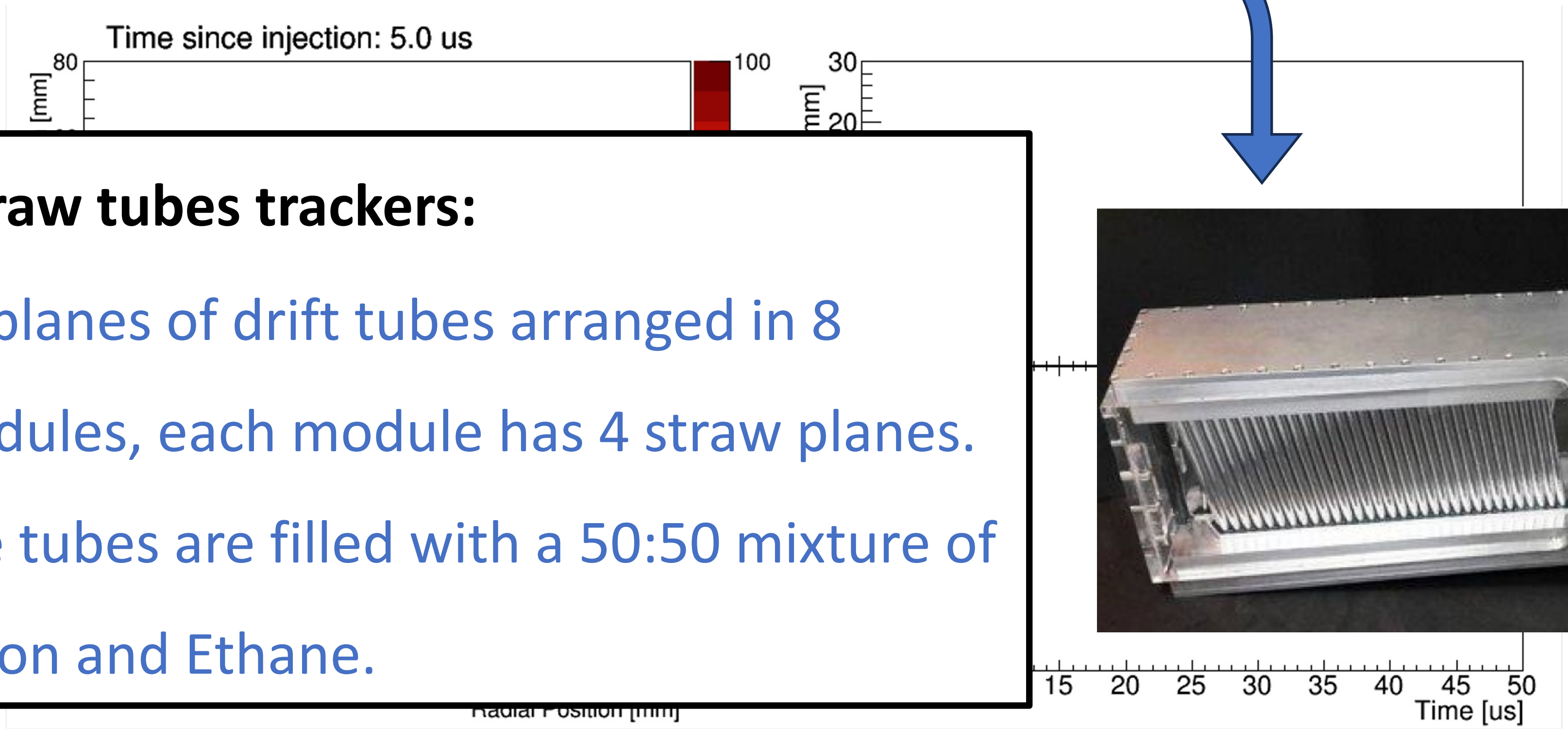
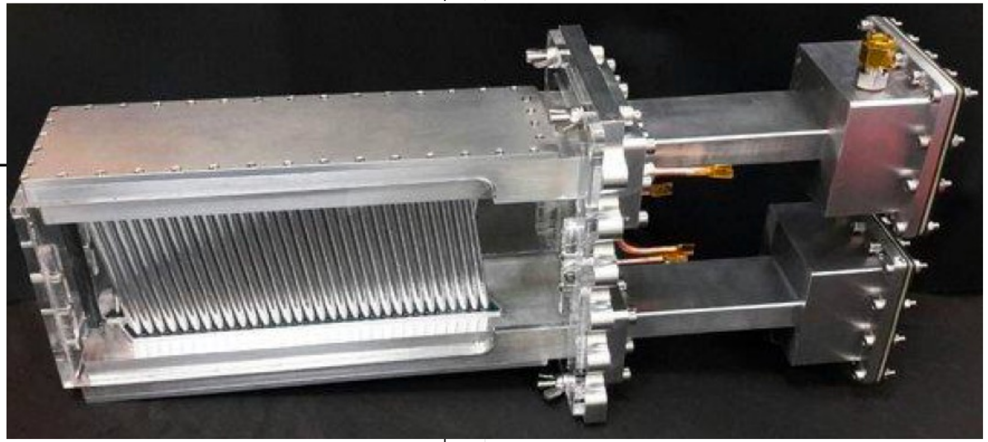


- **Two straw tubes trackers:**
  - 32 planes of drift tubes arranged in 8 modules, each module has 4 straw planes.
  - The tubes are filled with a 50:50 mixture of Argon and Ethane.

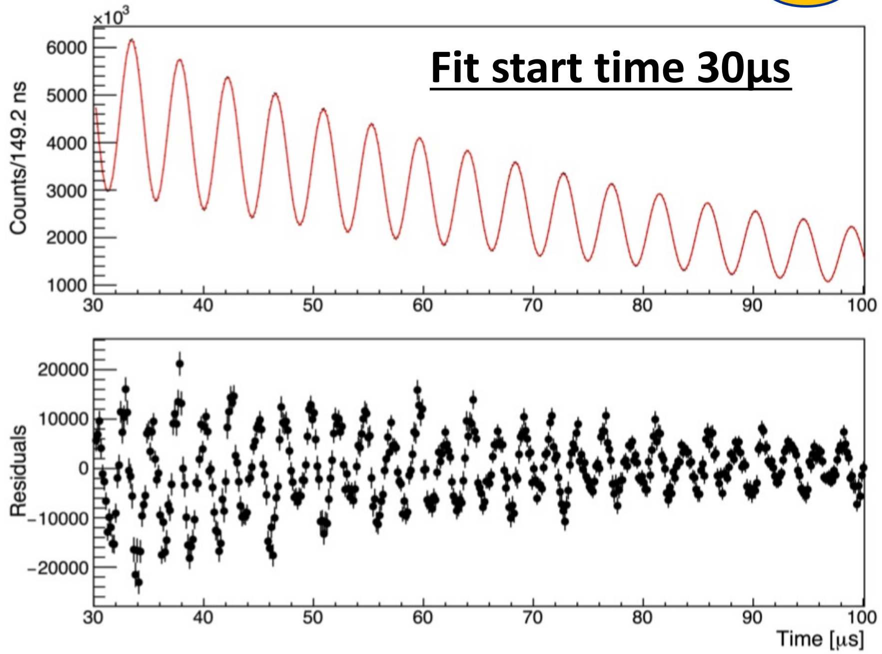


ω_a measurement

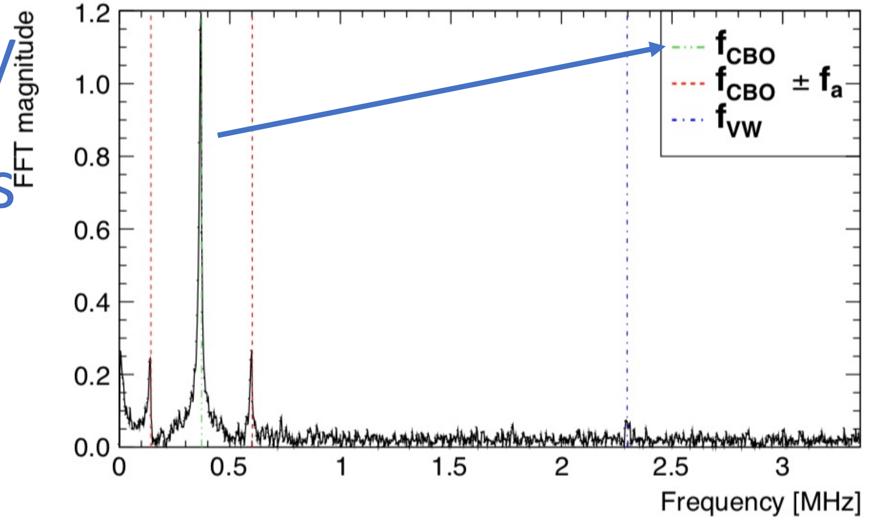
See Cedric next talk!

- The simplest function which describes the number of emitted positron from muon decay (so called "**wiggle plot**") is:

$$N(t) = N_0 \cdot e^{-\frac{t}{\tau_\mu}} \cdot (1 + A \cdot \cos(\omega_a \cdot t + \varphi))$$



- From the **FFT** of the fit's residual shows many frequency peaks due to **beam dynamics** effects that are not modeled by the previous function.



a_μ Extraction

For the measurement of a_μ the measured ω_a and ω_p need to be corrected by:

Cedric next talk!

Beam dynamics corrections

$$R'_\mu \approx \frac{f_{clock}\,\omega_a^m(1 + C_e + C_p + C_{ml} + \boldsymbol{C_{pa}})}{f_{calib} < \omega'_p(x,y,\phi)\times M(x,y,\phi) > (1 + B_k + B_q)}$$

Saskia previous talk

Transient field corrections

These corrections have been obtained during Run1 analysis.

$\boldsymbol{C_{pa}}$, B_k, B_q corrections were not present in E821.

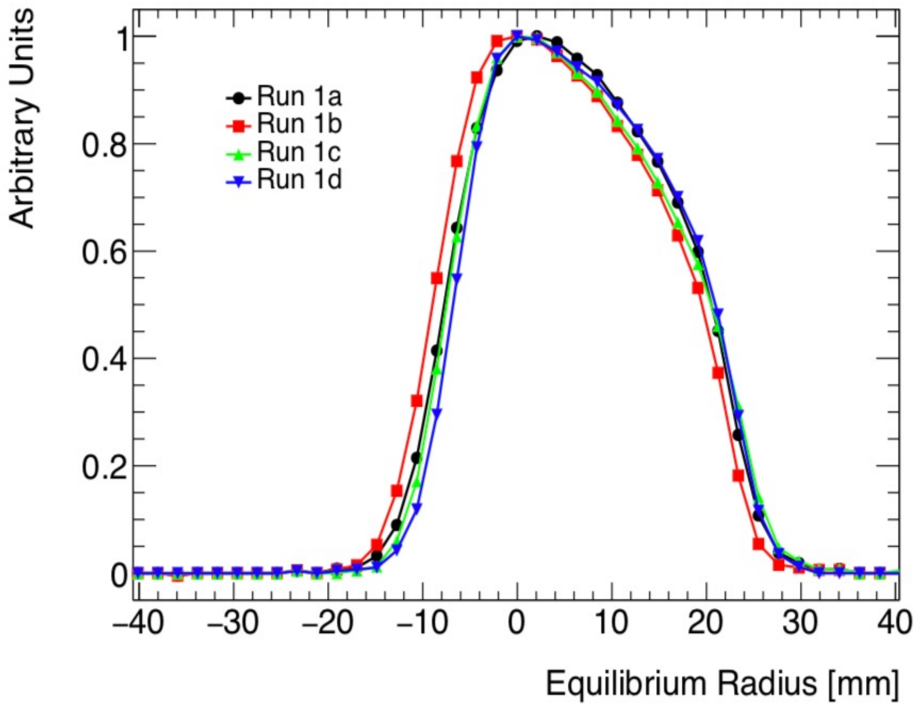
Beam dynamics correction to ω_a: C_e

Considering the extended expression of the spin precession frequency in a magnetic field:

$$\overrightarrow{\omega_a} = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta}\times\vec{E}) - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta}\right]$$

This term introduces a bias on ω_a that needs to be corrected by Electric Field correction:

$C_e = 2n(1-n)\beta^2 \frac{<x_e^2>}{R_0^2}$ is proportional to the equilibrium radius distribution x_e.



$$C_e \sim 489\ ppb$$

a_μ systematic sources

Many systematics come from effects that **change** the **phase** of the detected positrons **over time** and introduce a bias on ω_a:

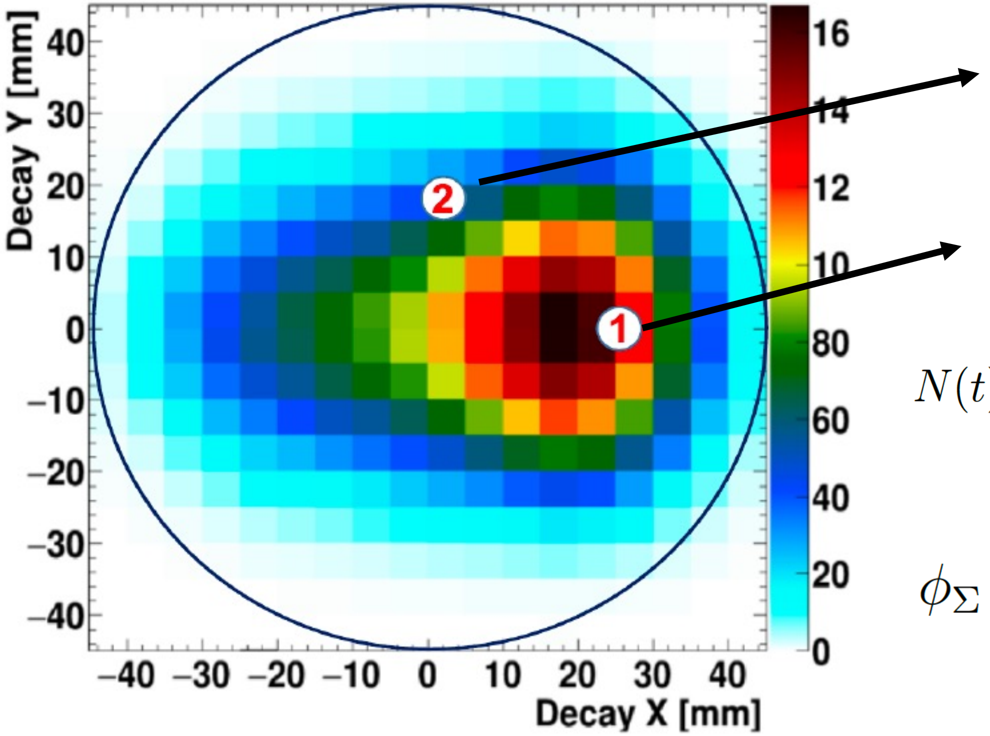
$$\cos(\omega_a t + \phi(t)) = \cos(\omega_a t + \phi_0 + \phi' t + \ldots)$$
$$= \cos((\omega_a + \phi')t + \phi_0 + \ldots)$$

In general, anything that changes from **early-to-late** within each muon fill can be a cause of systematic error, as:

- Beam distortion
- Muon losses
- Varying lifetime
- Rate dependent reconstruction

Beam dynamics correction to $\boldsymbol{\omega_a}$: C_{pa}

- The measured *g-2* phase of the muon is decay vertex position dependent.
- It is obtained as weighted average of the phases measured by each (x,y) pair position.



$$N_2(t) = N_{02}e^{-t/\tau}\left[1 + A_2\cos(\omega_a t + \phi_2)\right]$$

$$N_1(t) = N_{01}e^{-t/\tau}\left[1 + A_1\cos(\omega_a t + \phi_1)\right]$$

$$N(t) = N_1(t) + N_2(t) = N_\Sigma e^{-t/\tau}\left[1 + A_\Sigma\cos(\omega_a t + \phi_\Sigma)\right]$$

$$\phi_\Sigma = \arctan\frac{N_{01}A_1\sin(\phi_1) + N_{02}A_2\sin(\phi_2)}{N_{01}A_1\cos(\phi_1) + N_{02}A_2\cos(\phi_2)}$$

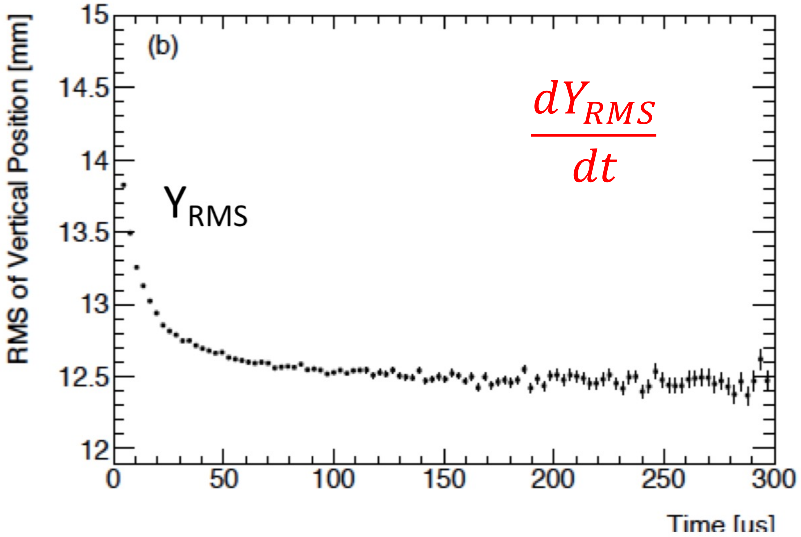
Beam dynamics correction to ω_a: C_{pa}

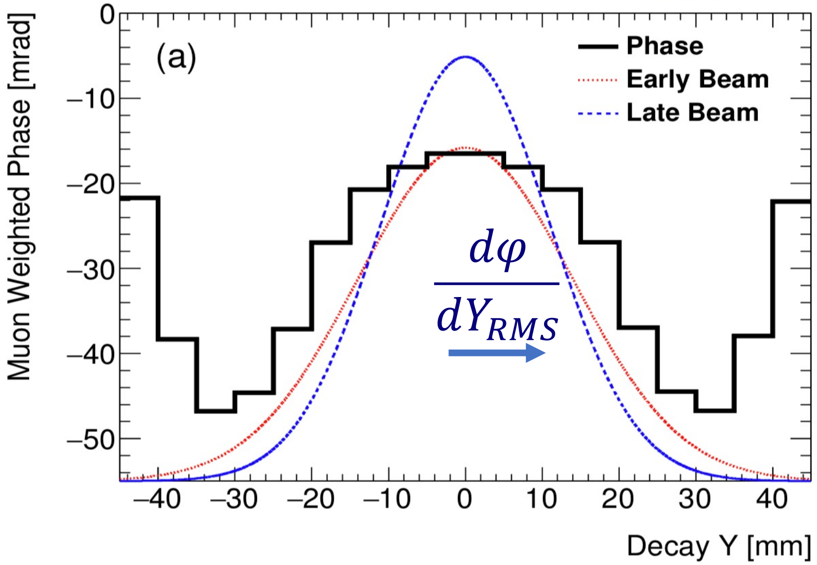
C_{pa}: it is a Phase Acceptance effect. It is due to:

1. Beam variation during the *fill;*
2. Phase measured as function of the decay position.

1) 2)

$$\Delta\omega_a = \frac{d\varphi}{dt} = \frac{dY_{RMS}}{dt} \cdot \frac{d\varphi}{dY_{RMS}}$$





The effect was large in Run1 due to *broken resistors*

$$C_{pa} \sim 180\, ppb$$

We expect a reduction in Run2/3 (~50ppb/ ~20ppb)

Beam dynamics correction to ω_a

- These are the results for the BD corrections from Run-1, the **phase acceptance** (C_{pa}) correction was one of the topic I addressed during my PhD.
- Now analysis is ongoing to finalize the Run-2/3 beam dynamics corrections, stay tuned!

	Correction Factor [ppb]	Uncertainty [ppb]
ω_a (stat.)	–	434
ω_a (syst.)	–	56
f_b/f_0	–	2
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{calib} \langle \omega'_p(x,y,\phi) \cdot M(x,y,\phi) \rangle$	–	56
B_q	−17	92
B_k	−27	37
$\mu'_p(34.7^\circ C)/\mu_e$ [PCK77]	–	10
m_μ/m_e [LAMPF-99; CD-2018]	–	22
$g_e/2$ [HFG08]	–	0
Total Systematic	–	157
Total Fundamental Factors	–	25
Total	544	461

“The closer you look the more there is to see”

F. Jegerlehner

Thank you!!!

- For any question or just to have a chat – elia@liverpool.ac.uk

BACK-UP

ω_a measurement

See Cedric next talk!

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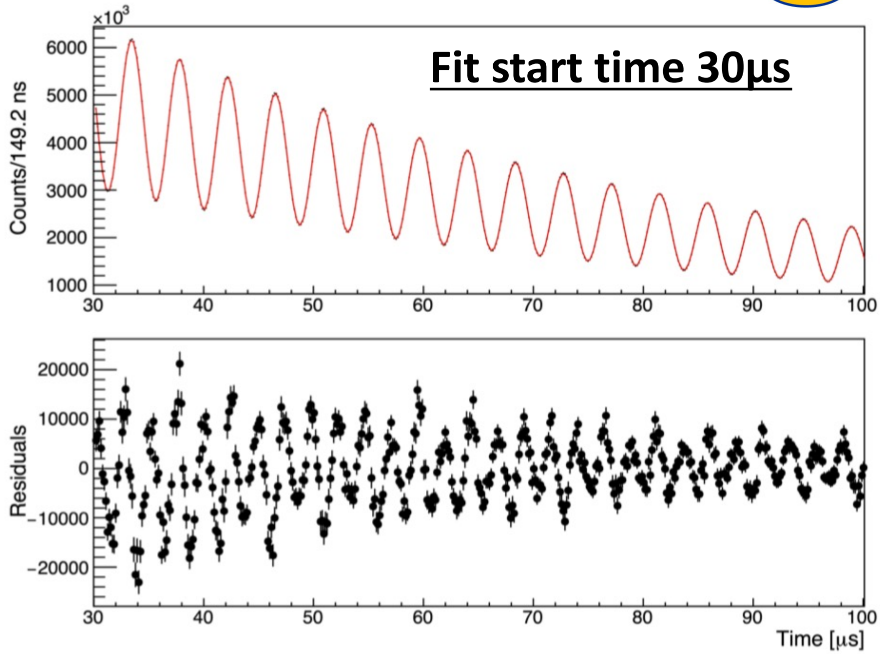

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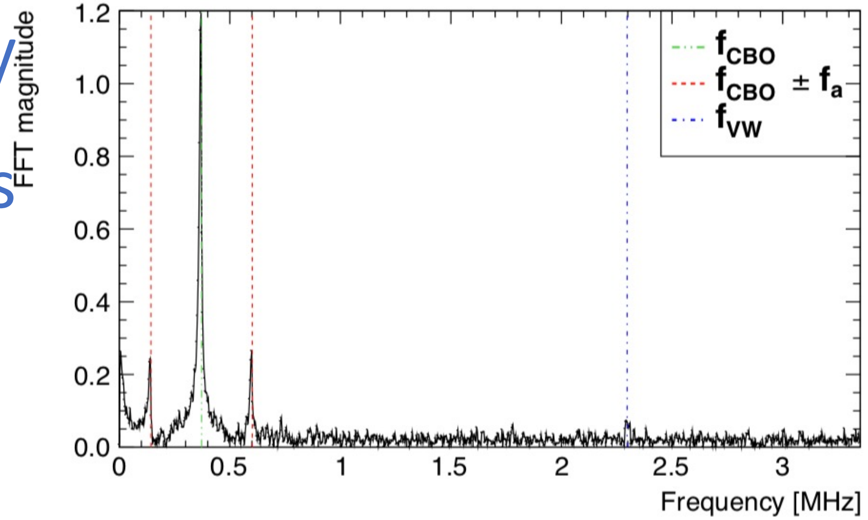

Beam dynamics correction to $\boldsymbol{\omega_a}$: C_p

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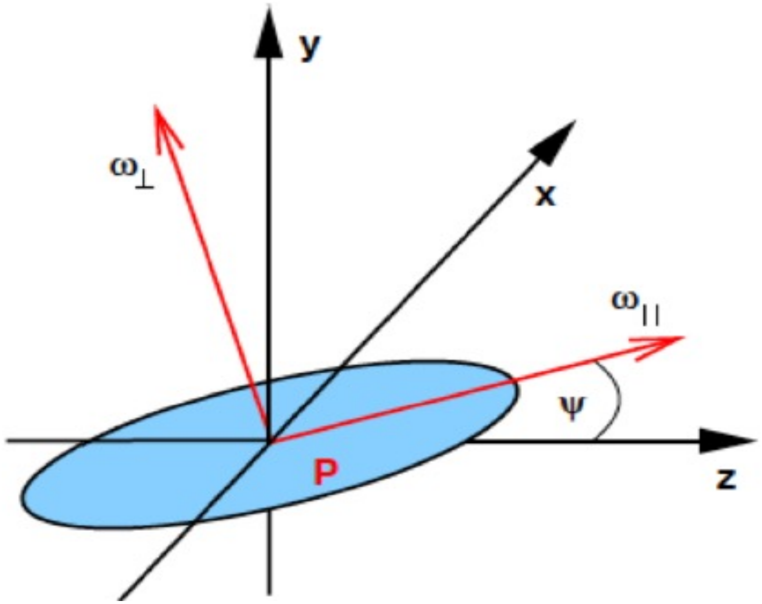
$C_p \sim 200\, ppb$



$\boldsymbol{C_p}$: the pitch correction $C_p = n < A_y^2 > /4R_0^2$ depends on amplitude vertical oscillation (A_y).

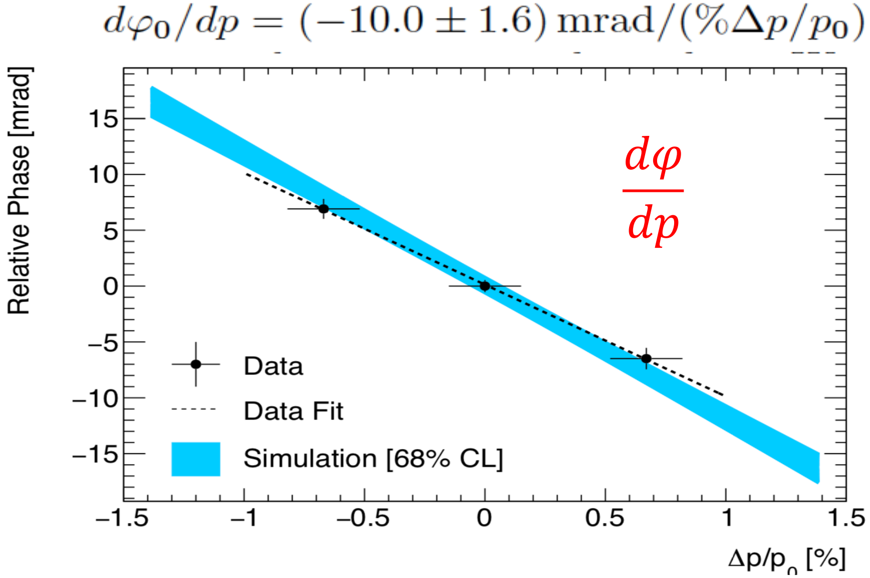
Beam dynamics correction to ω_a: C_{lm}

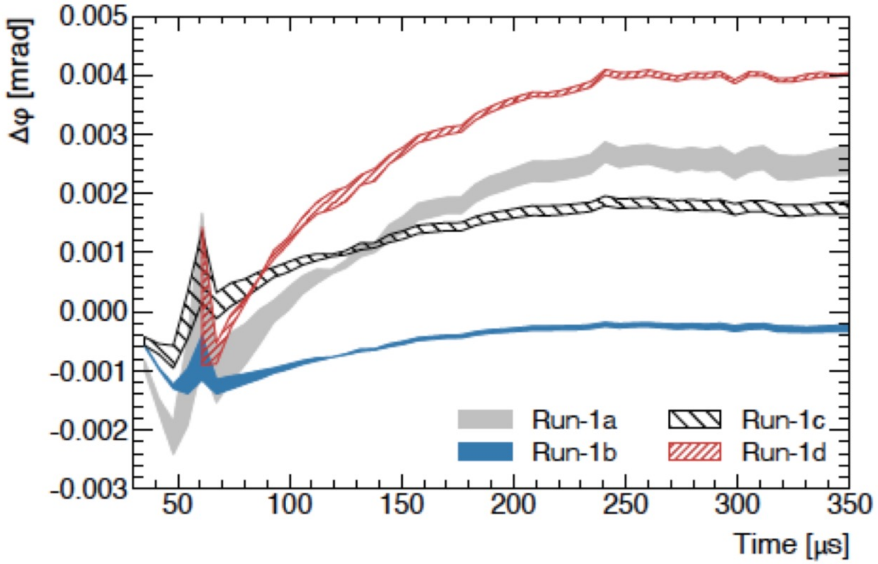
C_{lm}: describes the motion introduced on ω_a phase due to the loss of muon during the *fill*. It's explained by:

1. Muons with different momentum have different phase;
2. The number of loss muon change as function of momentum.

$$\Delta\omega_a = \frac{d\varphi}{dt} = \underset{1)}{\frac{d\varphi}{dp}} \cdot \underset{2)}{\frac{dp}{dt}}$$

$$C_{lm} < 20\ ppb$$





Phase acceptance: Beam Motion Effects