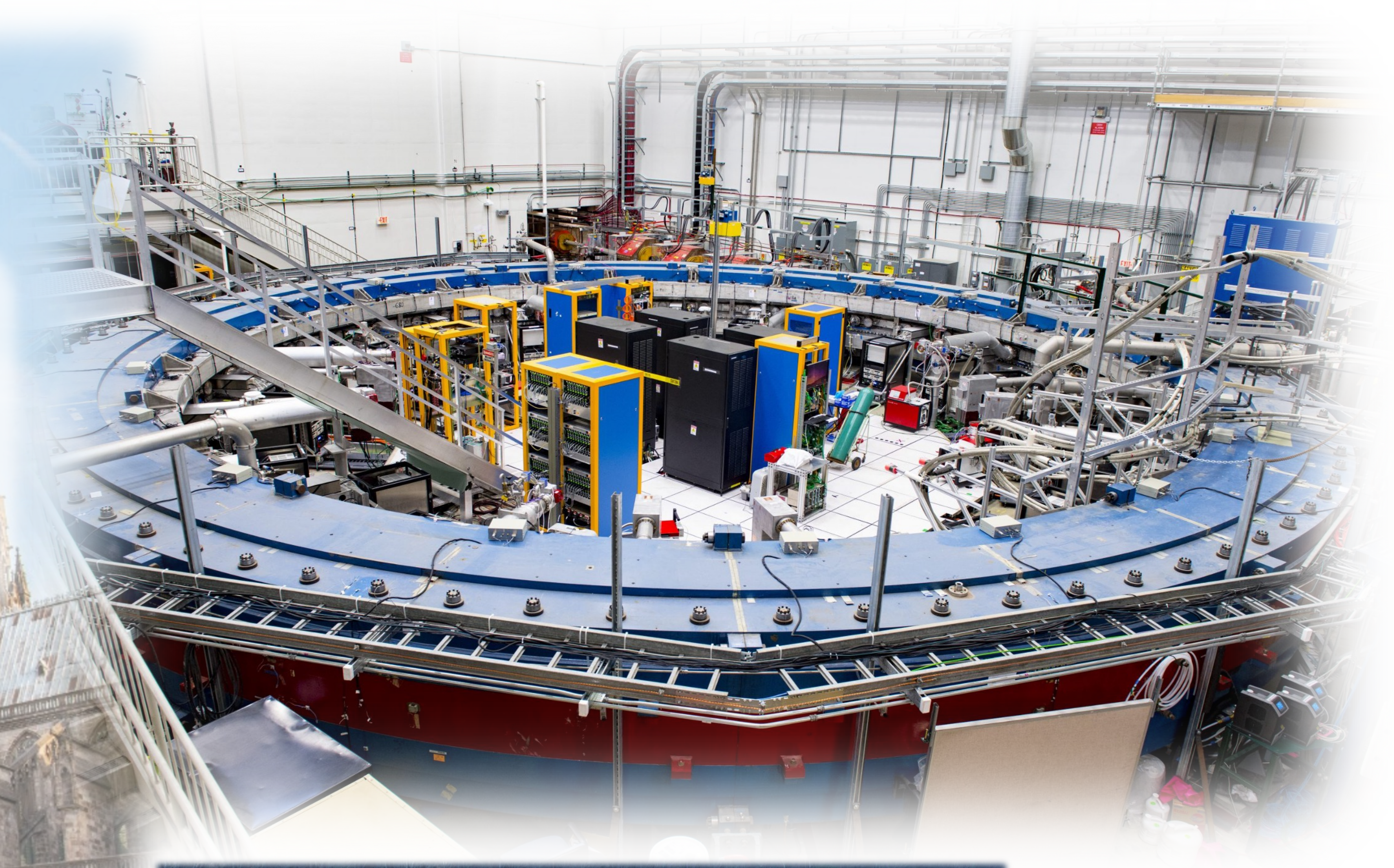
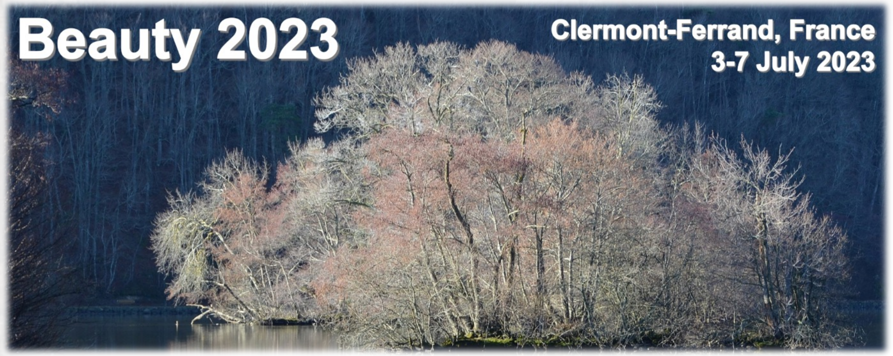
Muon *g-2* experiment at Fermilab and muons at large

E. Bottalico

Beauty 2023

6 July 2023





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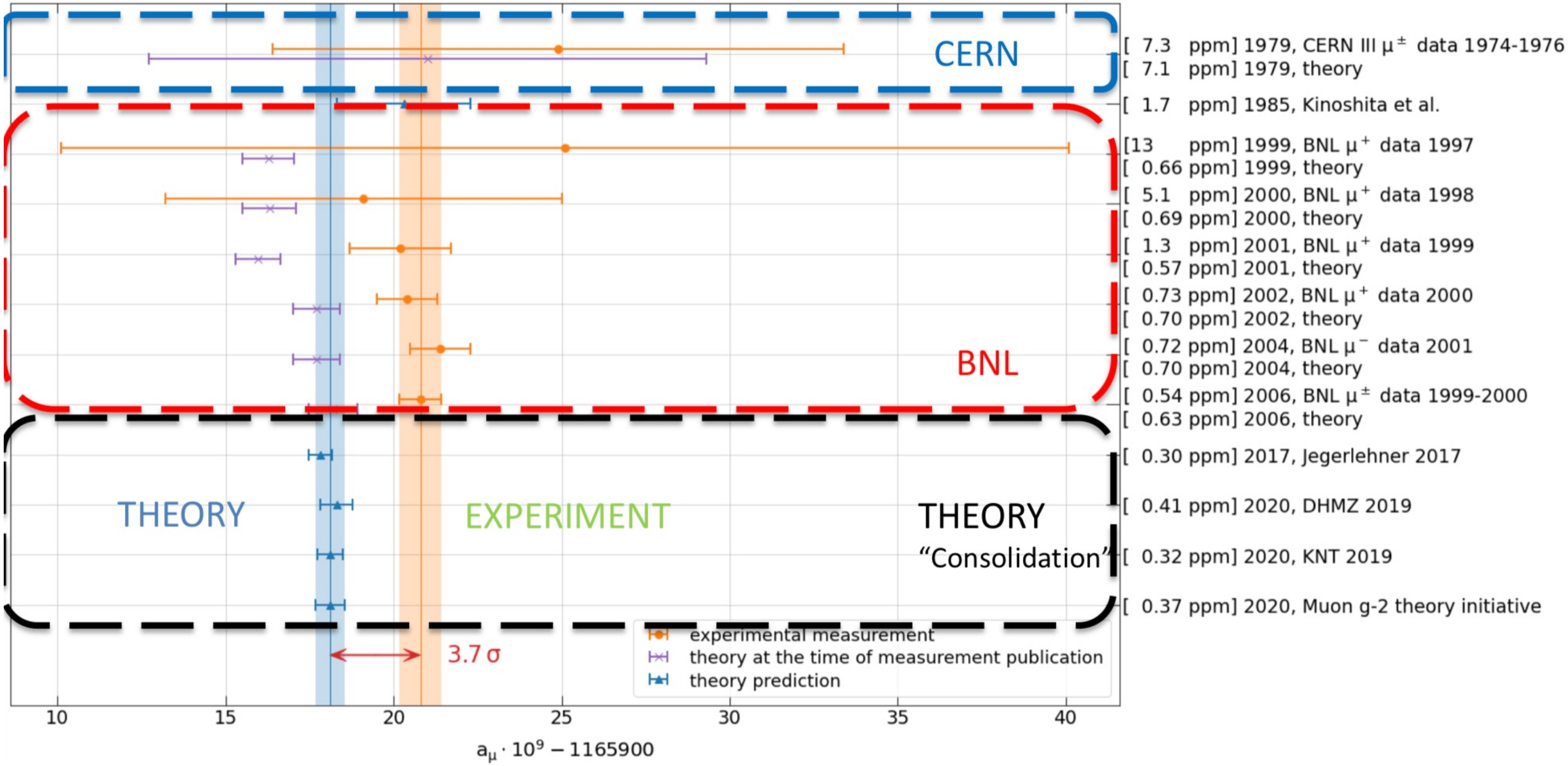
The history of Muon g-2

The history of the Muon g-2 experiments finds its roots in the series of experiment at CERN



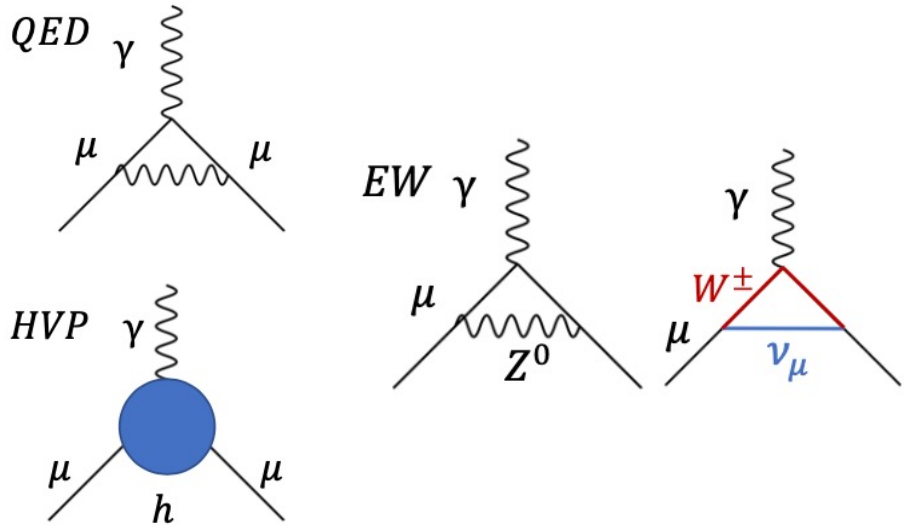
What is the Muon g-2?

The intrinsic magnetic moment of a particle with spin is:

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

The g-factor (gyromagnetic) defines the coupling between the spin and the magnetic field:

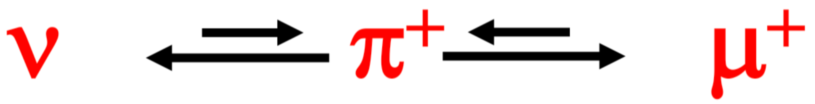
- g = 1 classic theory;
- g = 2 Dirac quantum theory;
- g = 2.00233… quantum field theory.



How such precision is possible?

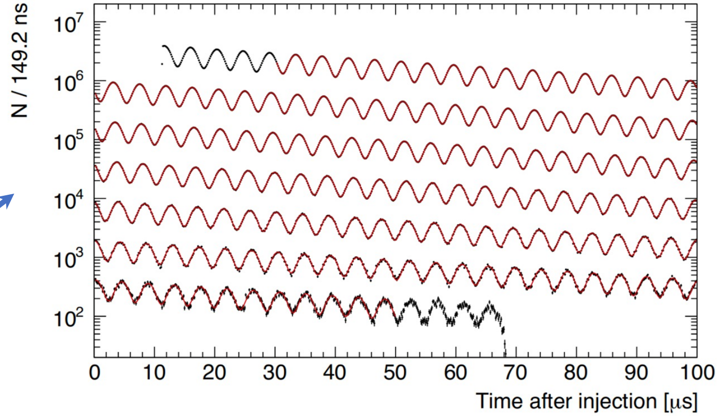
- 4 nature gifts allow to reach this very high precision:

1. ***Muons strongly polarized (95%):***
   - It is possible thanks to the weak pion decay



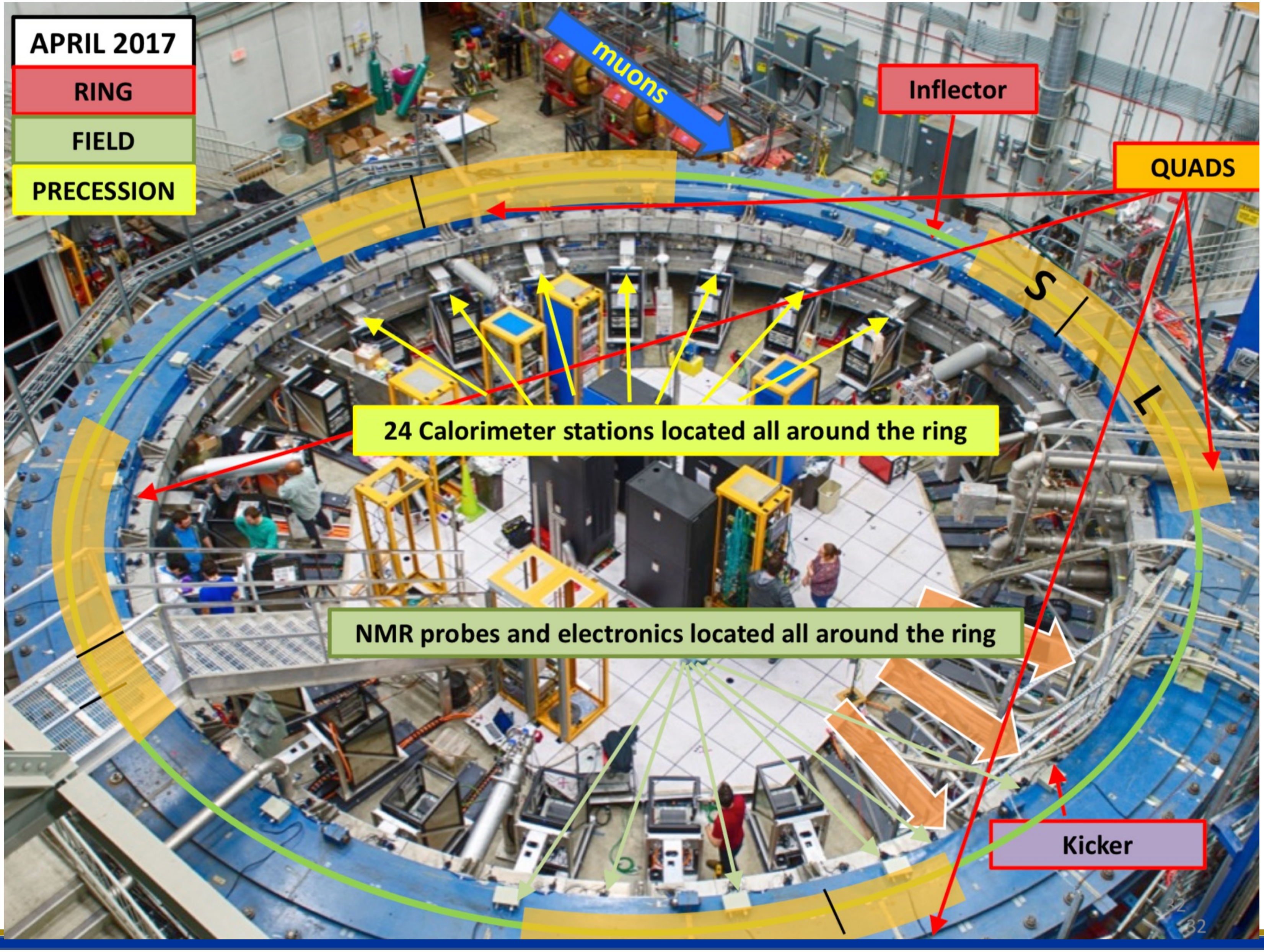
2. ***Precession frequency proportional to (g-2)***
   - $\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_c = \left(\frac{g-2}{2}\right) \cdot \frac{e\vec{B}}{m}$

3. ***Magic momentum $P_\mu = 3.094$ Gev/c:*** $\gamma = \sqrt{1 + \frac{1}{a_\mu}} \sim 29.3$
   - $\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\left(\vec{\beta} \times \vec{E}\right)\right]$



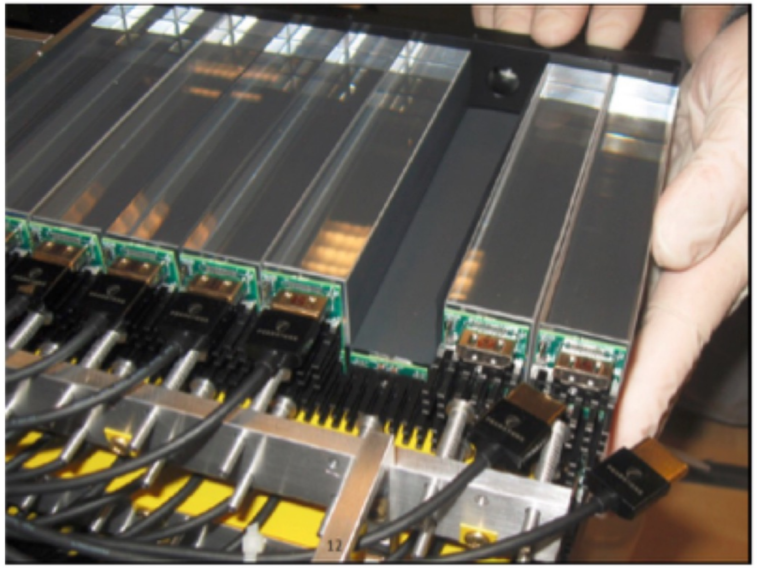
4. ***Positron emitted preferably in direction of the muon spin***

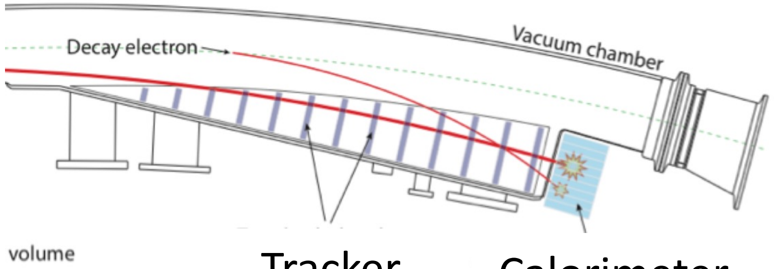
g-2 short recap: The Ring

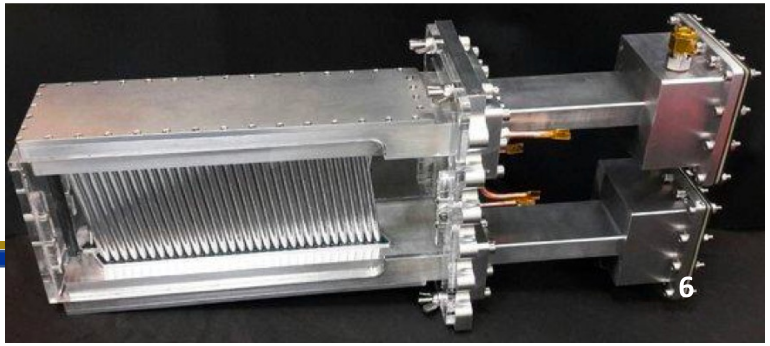


Detectors

- **24 electromagnetic calorimeters:**
  - 54 PbF2 crystals read by 54 SIPMs.
  - Crystal length 14 cm, 15 X_0.
  - Cherenkov light faster then showers (signal width ∼nanoseconds).
  - Laser calibration system, allows the energy and time calibration of the calorimeters
- **Two straw tubes trackers.**
  - 32 planes of drift tubes filled with a 50:50 mixture of Ar/Ethane.





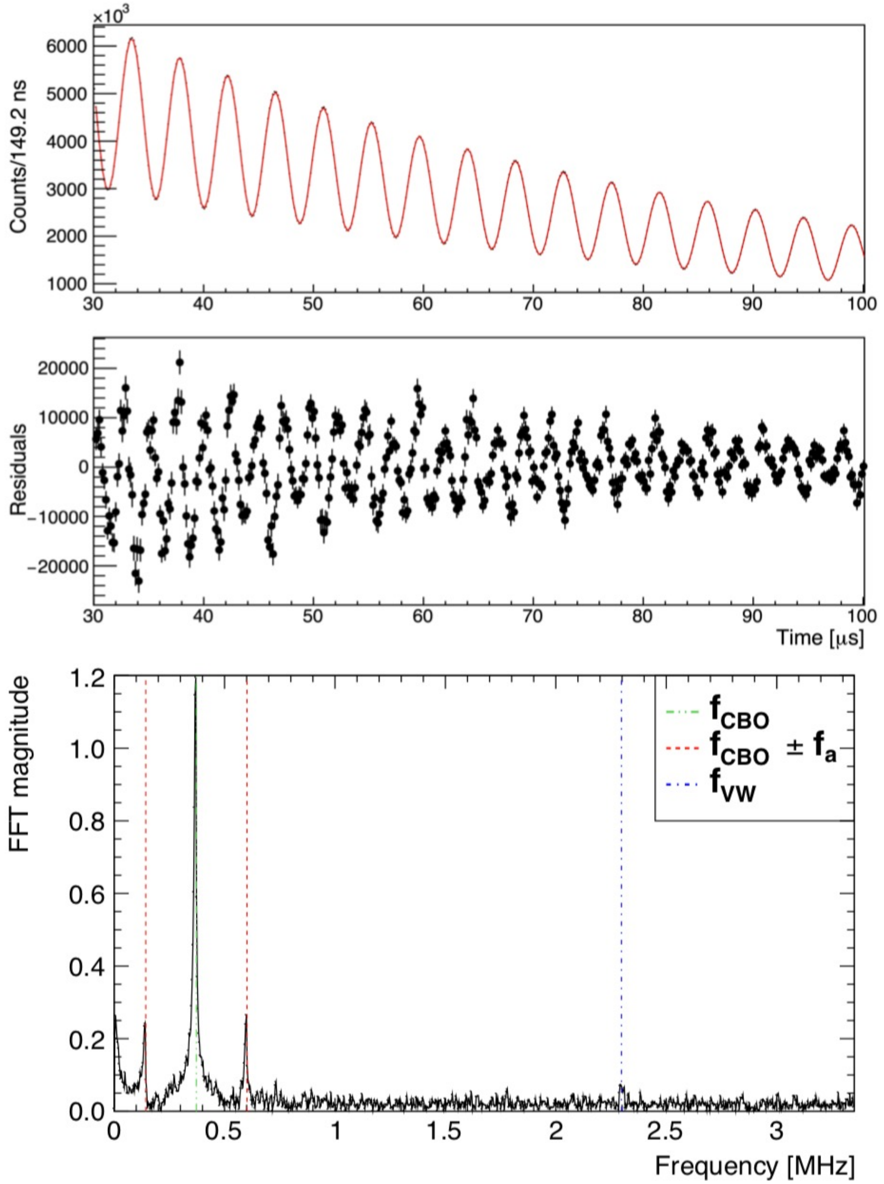


ω_a measurement

- The simplest function which describes the number of emitted positron from muon decay is:

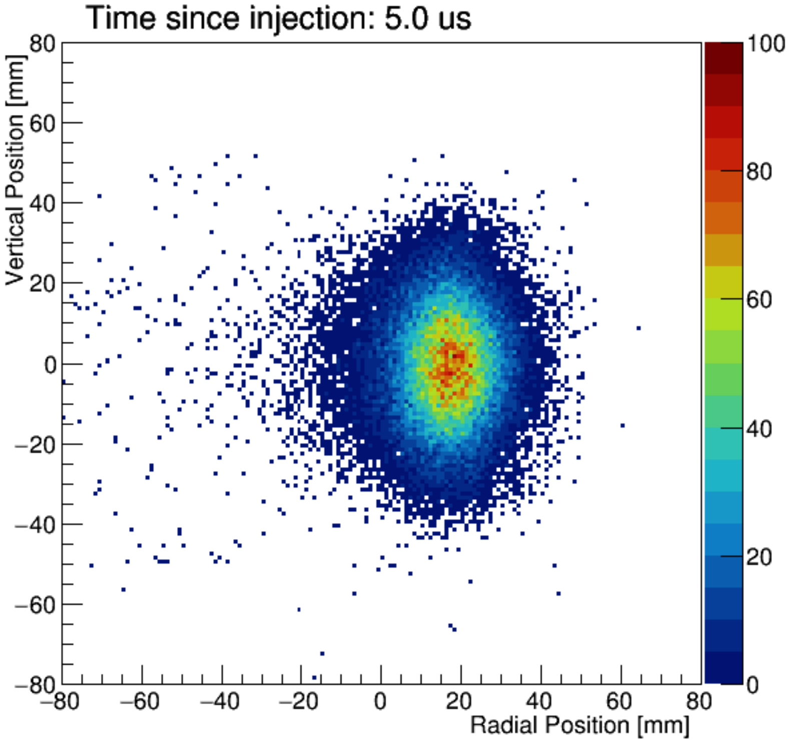
$$N(t) = N_0 \cdot e^{-\frac{t}{\tau}} \cdot (1 + A \cdot \cos(\omega_a \cdot t + \varphi))$$

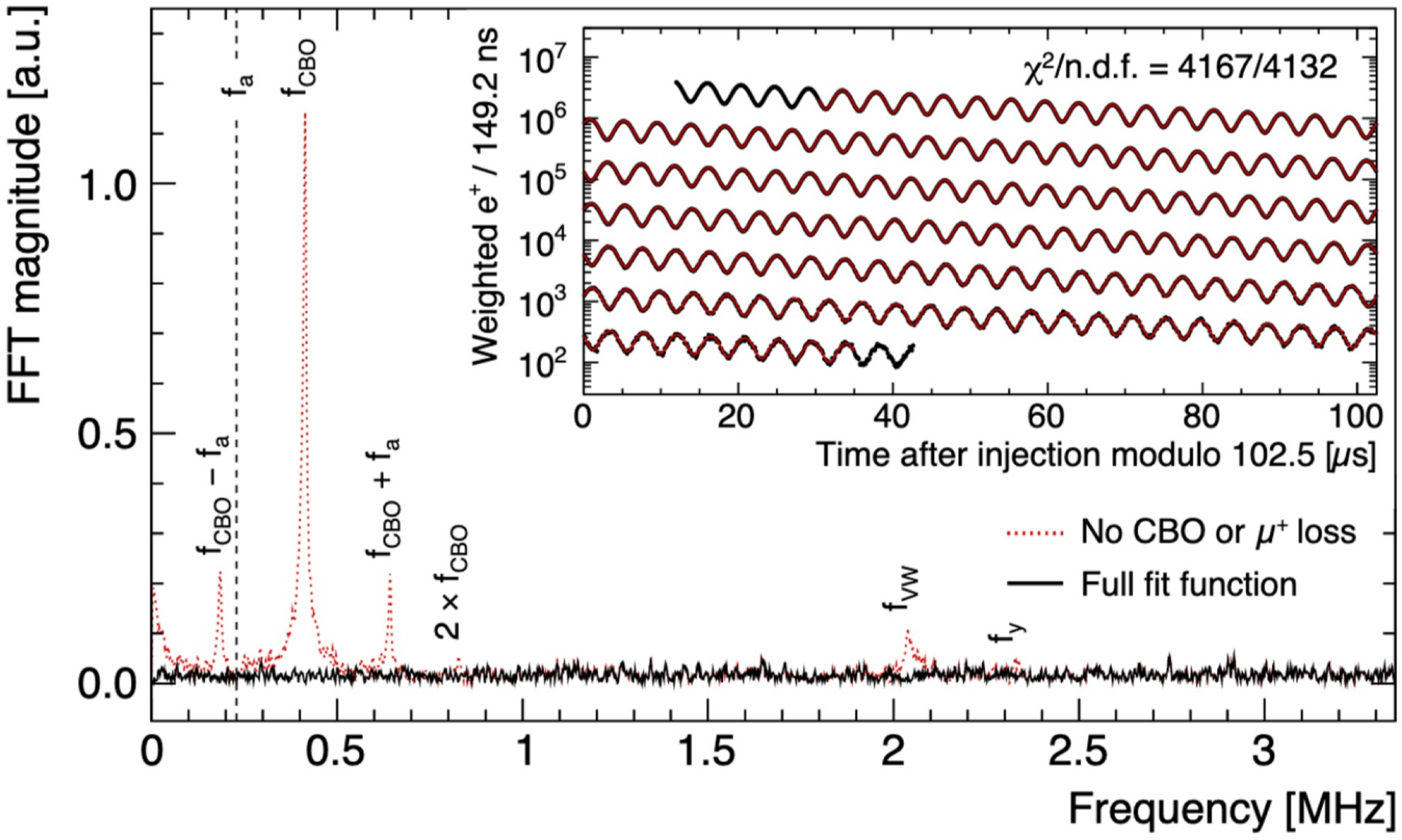
- From the Fast Fourier Transform (FFT) of the fit's residual many frequency peaks arise due to beam dynamics effect didn't account from the previous function



ω_a measurement

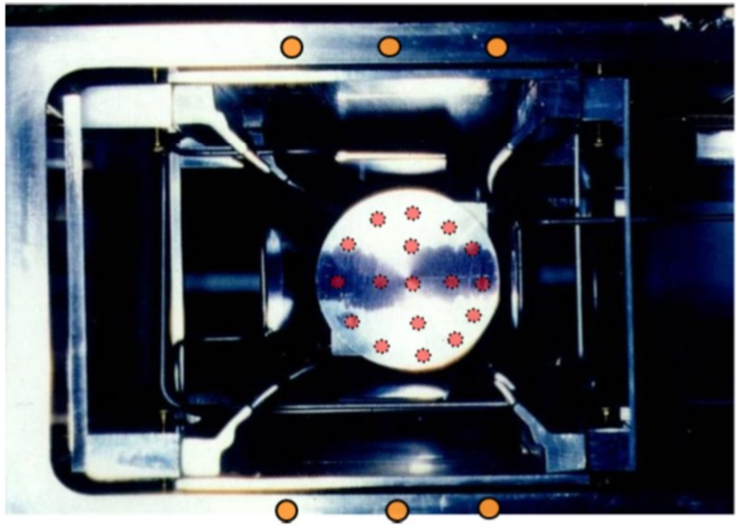
- Taking into account for the beam motion, the fit function gets more complicated up to contain **22 parameters**.



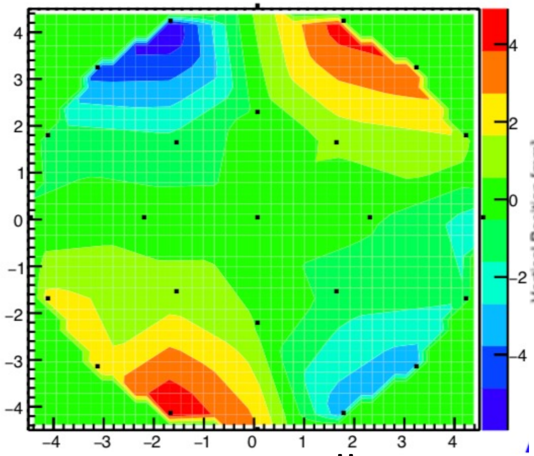


$\tilde{\omega}'_p$ Measurement

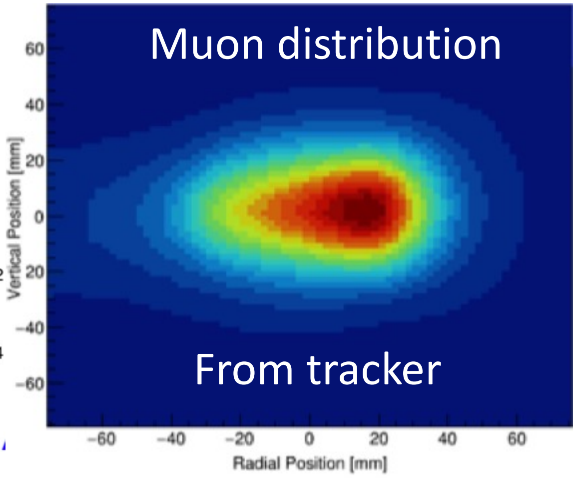
- The magnetic field is measured by:
  - **378 fixed probes** around the ring;
  - **17 NMR probes** moved around the ring via a trolley.
  - The tracker measures the muon distribution around the ring.
  - The magnetic field map is **weighted with the muon distribution** to obtain the effective field experienced by muons.



Field map



From trolley



a_μ Extraction

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

Beam dynamics corrections

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

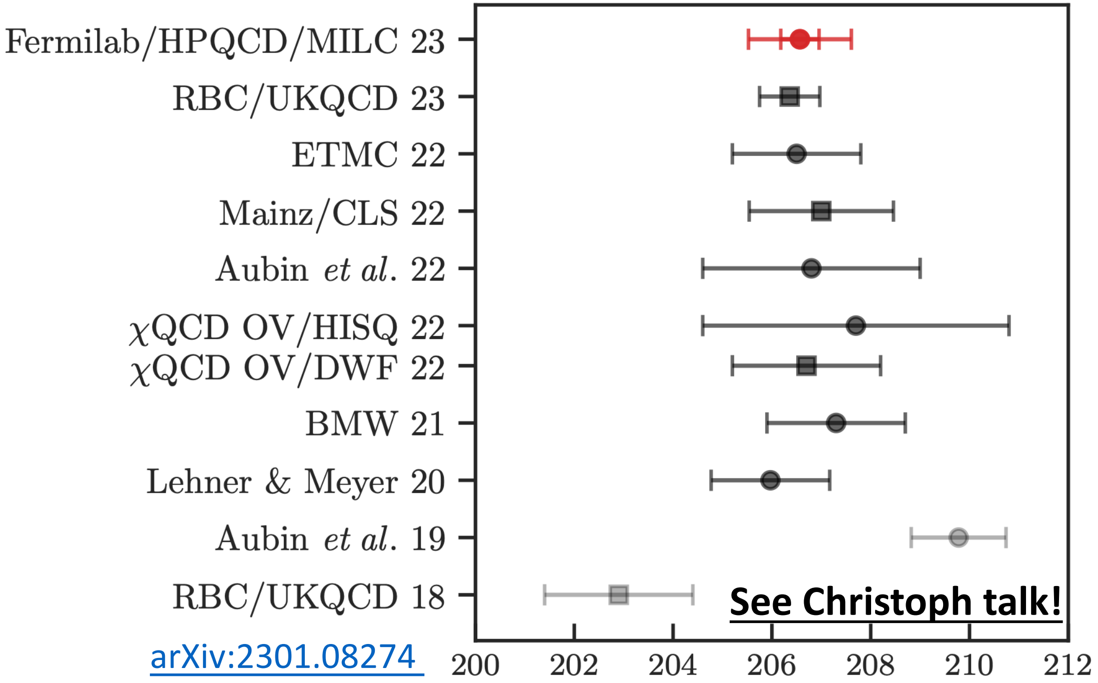
Transient field corrections

These corrections have been obtained during Run1 analysis.

C_{pa}, B_k, B_q corrections included in systematic error in E821.

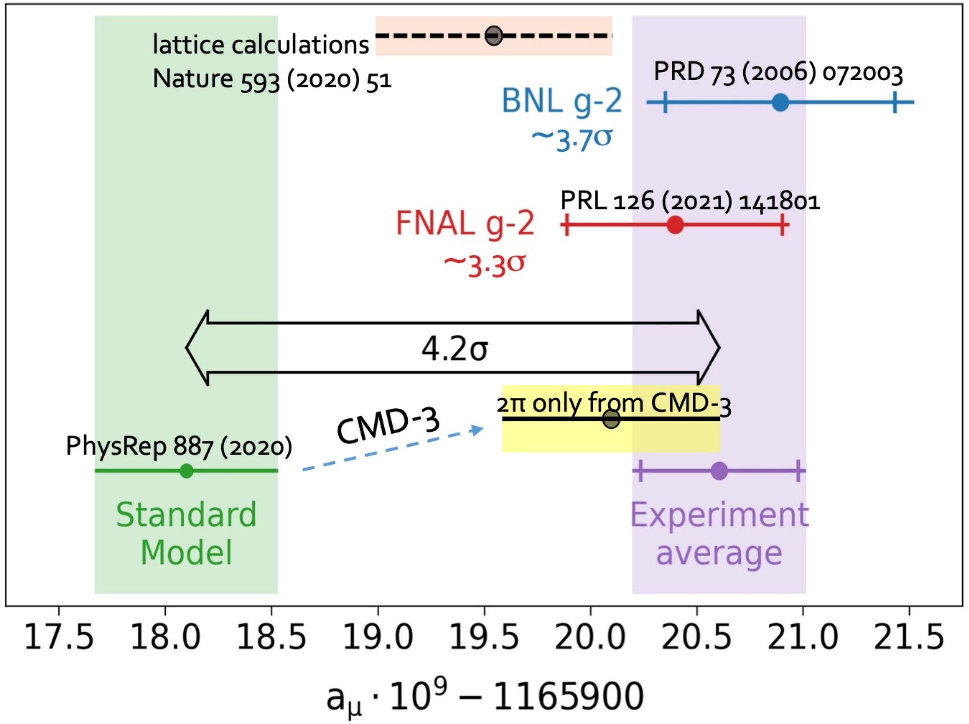
Run-1 result

- On **7th April 2021** the Run-1 result has been revealed showing 4.2σ from SM estimate.
- In **2021** the **BMW group** published a lattice calculation of a_μ^{HVP}, with a comparable error w.r.t WP2021 result, reducing the discrepancy with g-2 experiment up to **1.5σ**.
- In **2023 CMD-3** presented a result that is in agreement with BMW calculation and experimental results.



arXiv:2301.08274

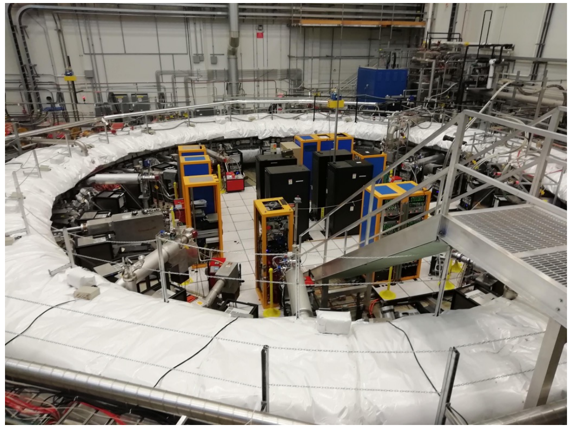
F. Ignatov – Recent $e^+e^- \to \pi^+\pi^-$ measurement with the CMD-3 detector

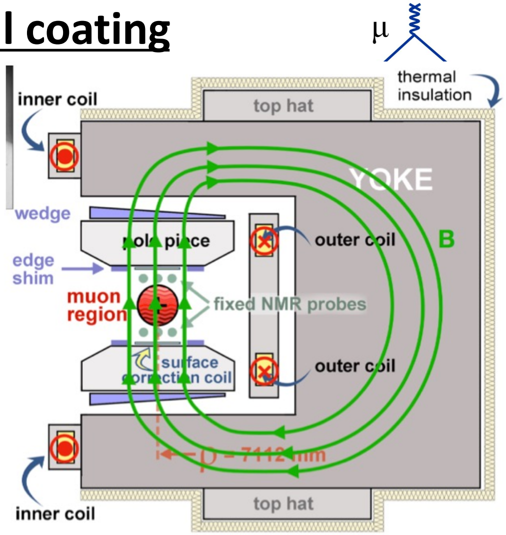


Run2/3 analysis

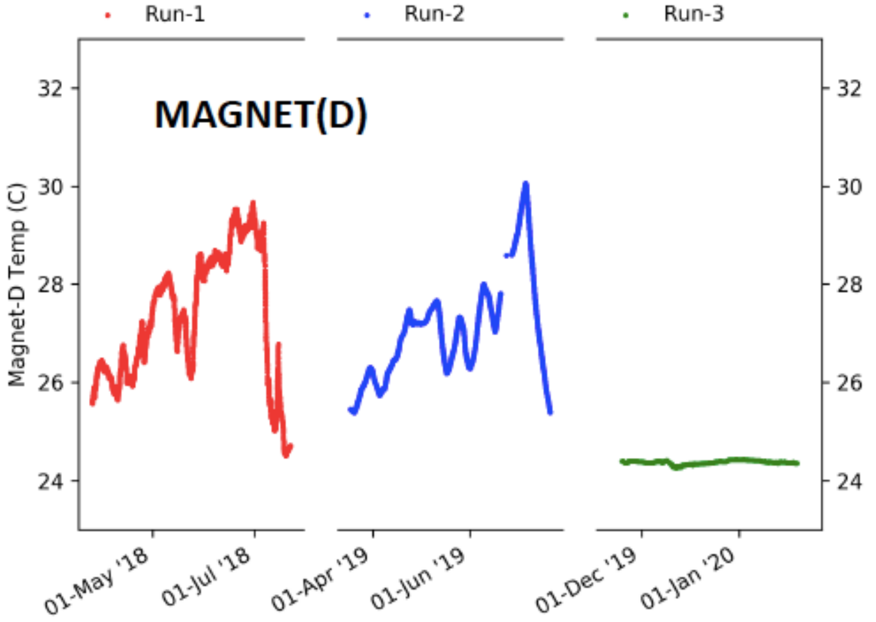
- During Run2 and Run3 (late 18 - early 20) different upgrades have been done:
  - **Fixing damaged resistors** (Run2);
  - Main magnet Thermal coating (Run2);
  - Conditioning system for the experimental hall (Run3);
  - **Improving of the kickers voltage** (second part of Run3 – Run3b).
- Run2/3 analysis is ongoing, the expected **statistical uncertainty** is ~200ppb, with a syst. unc. O(100ppb), halving the Run1 uncertainty.

Thermal coating





Conditioning system



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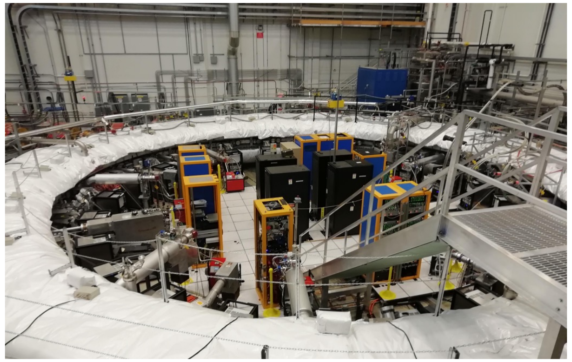
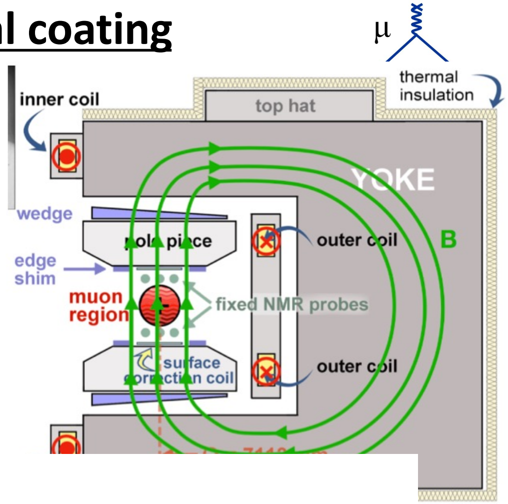
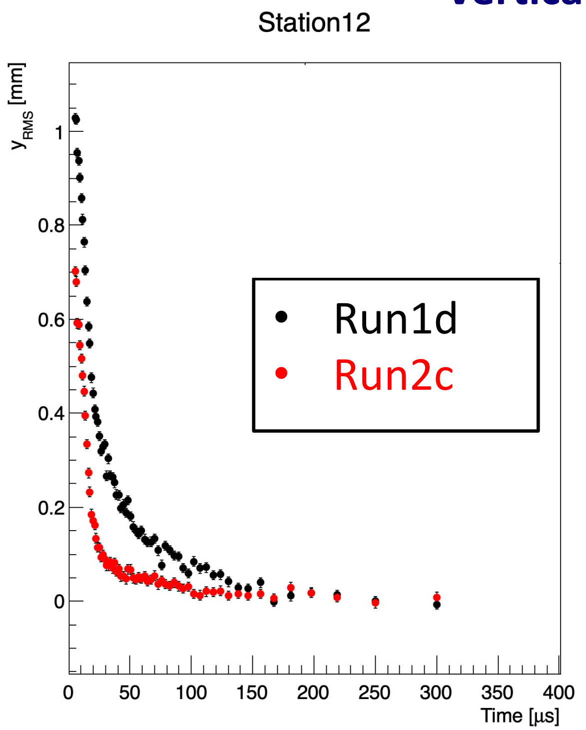
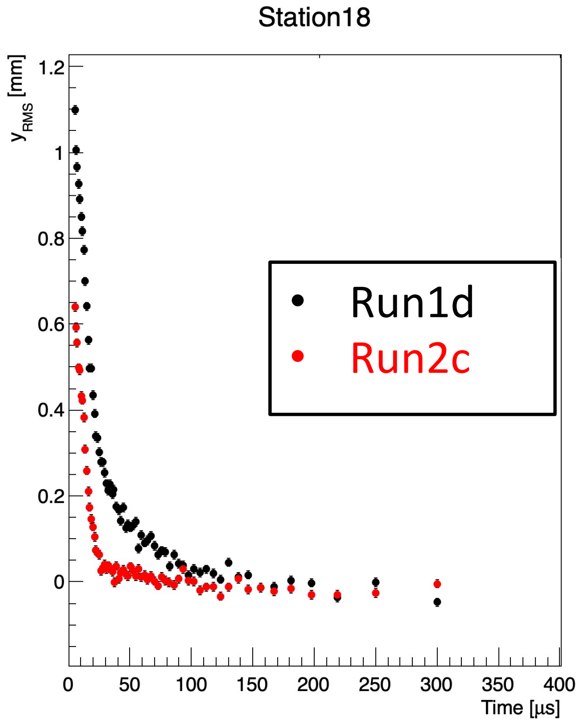


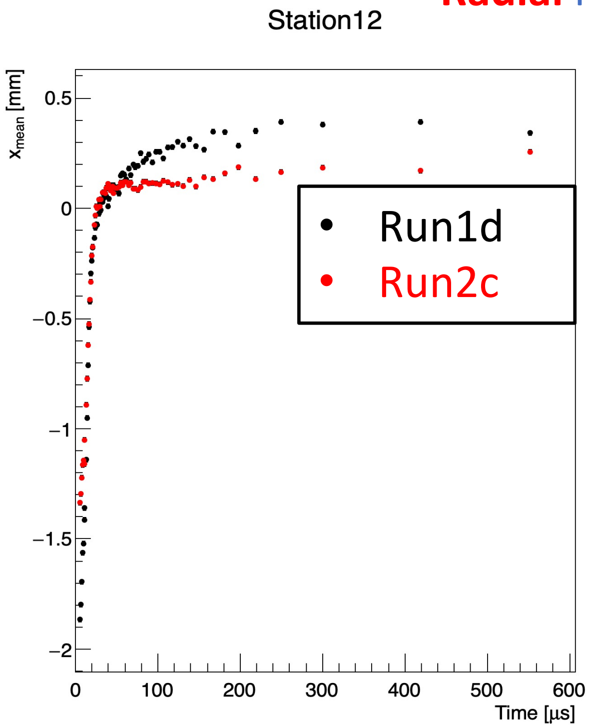


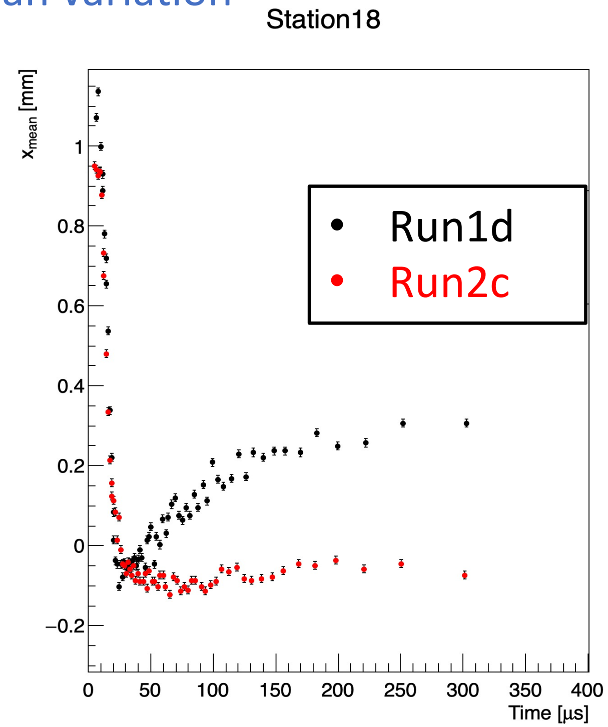
Vertical width variation





Radial mean variation





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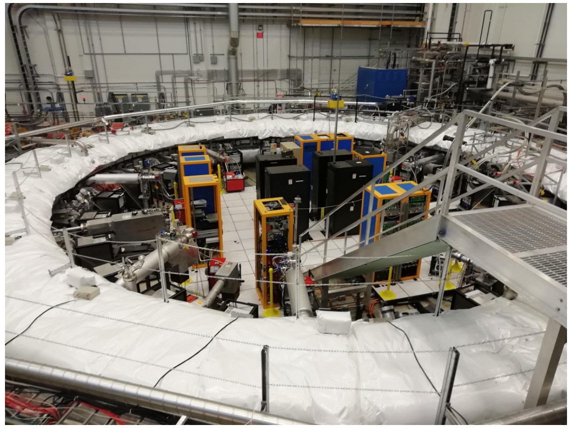
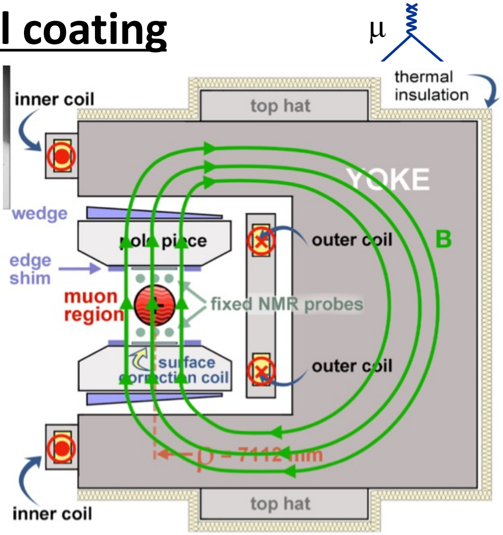
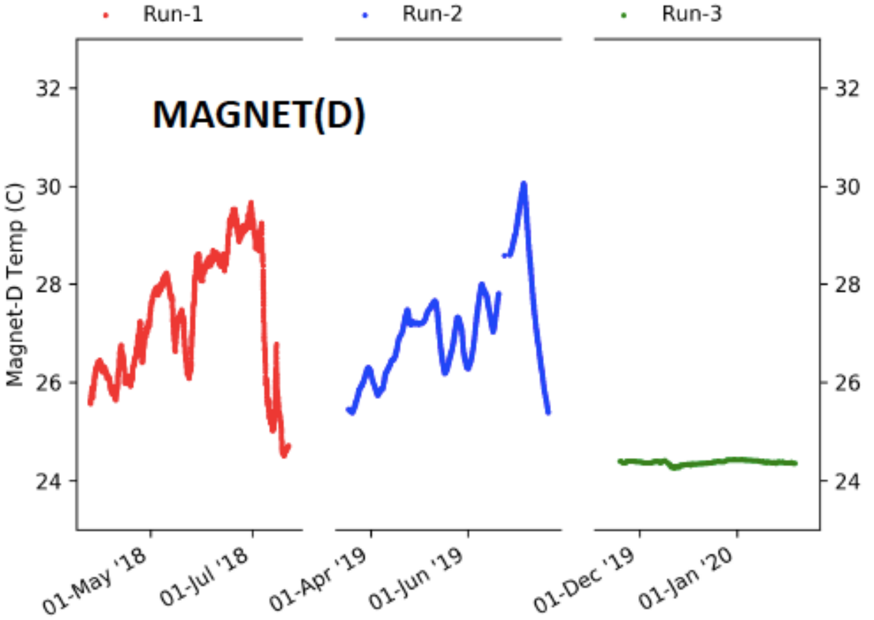


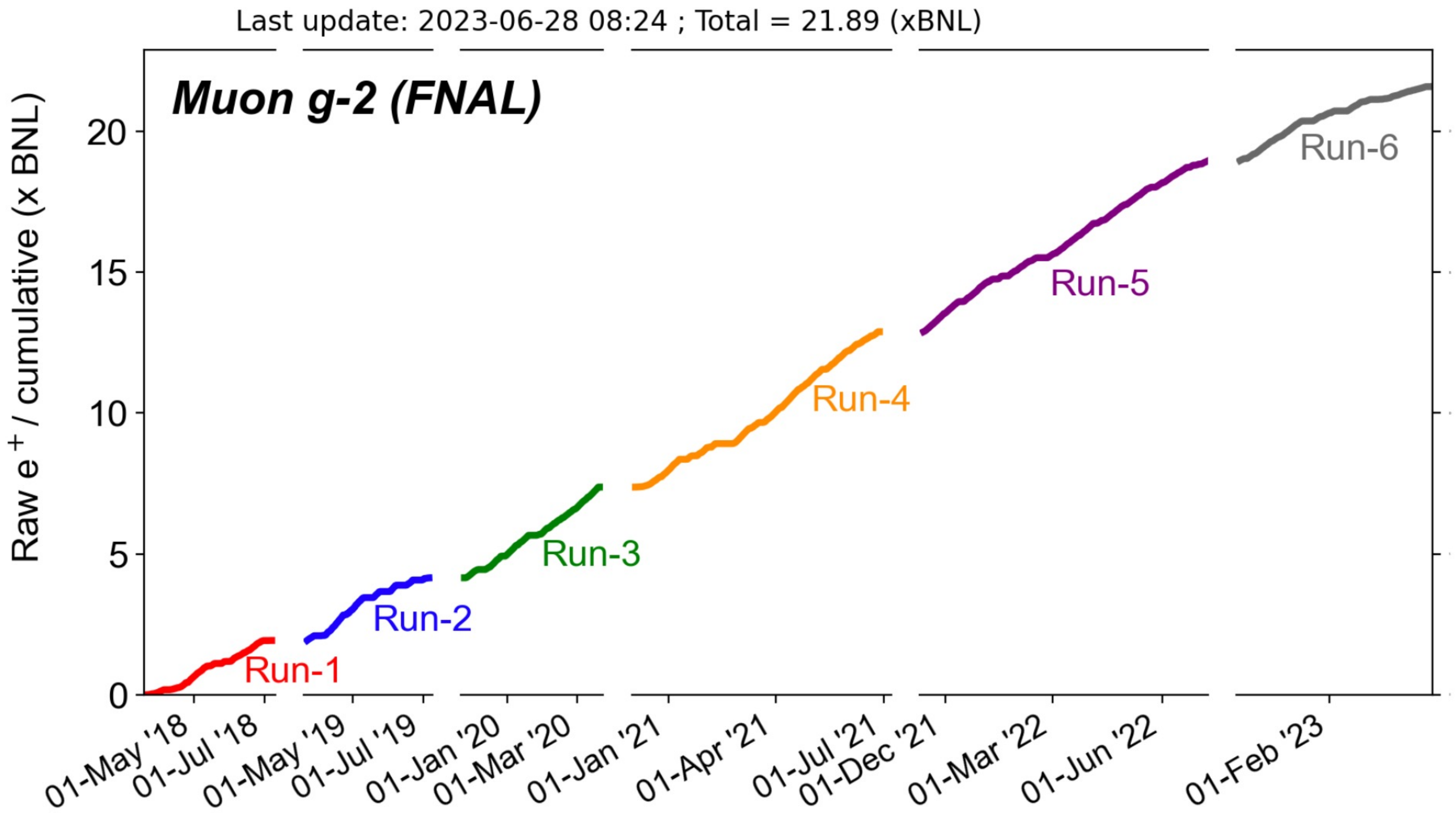


Conditioning system



Muon *g*-2 Outlook

- Run 6 is currently ongoing, it will finish on 8th July 2023.
- We reached the TDR goal of 21 BNL on 27th February 2023.
- Run-2/3 publication soon. **(I can't say more 🤐)**
- Run-4/5/6 result is expected in **2025/2026**.



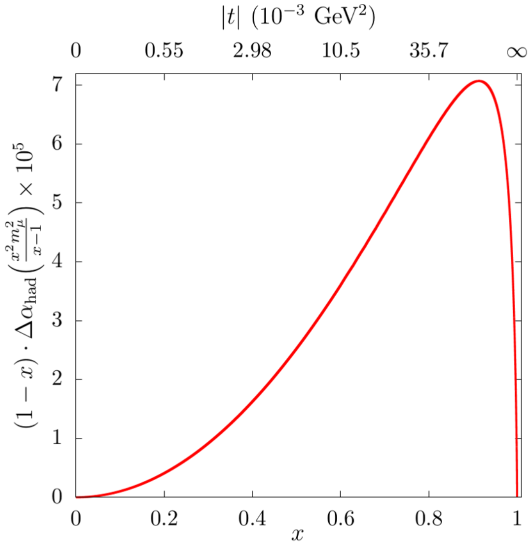
Muons at large

MUonE Experiment at CERN

[Letter of Intent: The MUonE Project, SPSC-I-252]

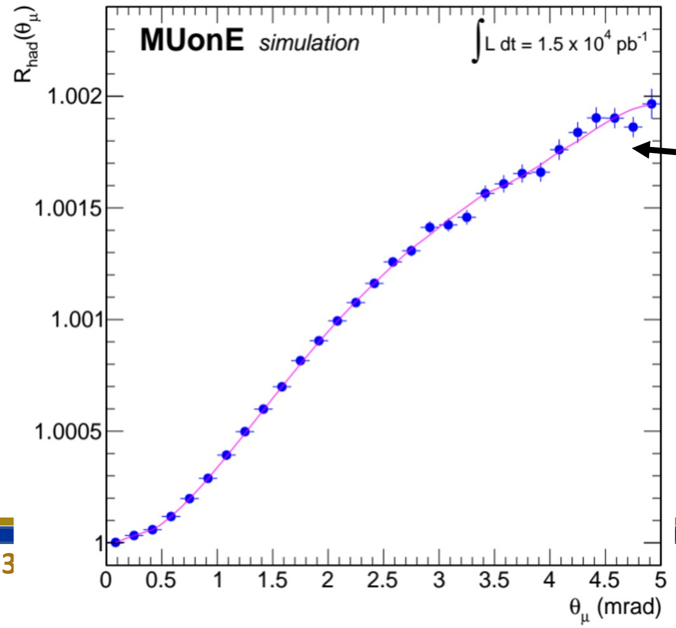
Extraction of $\Delta\alpha_{had}$ from the shape of the $\mu e \rightarrow \mu e$ differential cross section:

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$



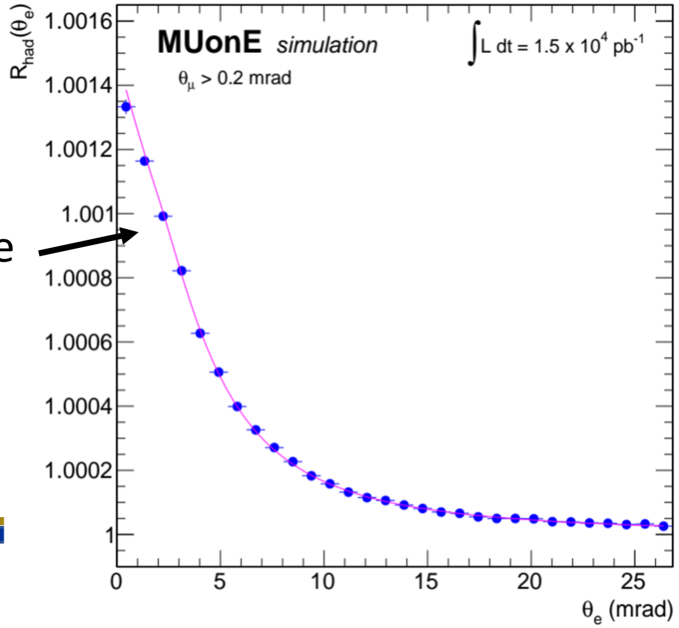
$$R_{\rm had} = \frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$

From theoretical calculation @NNLO — To be measured

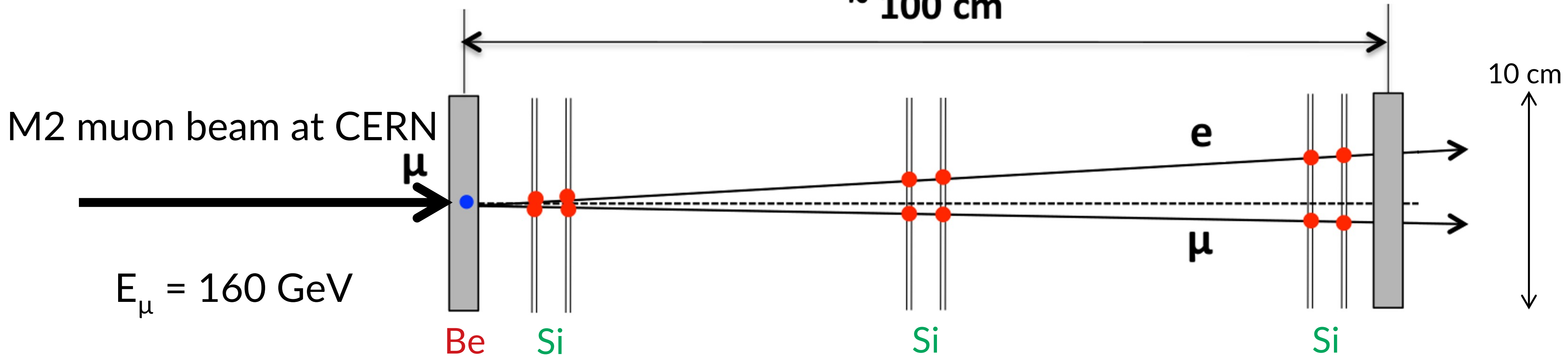


Region of interest:

- Muon at large angle
- Electron at small angle

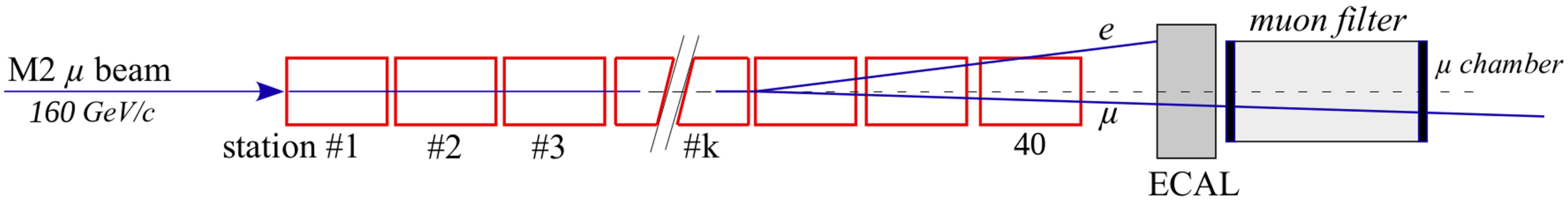


MUonE Experiment at CERN



Beryllium target 1.5 cm thickness

Tracking system: 3 pairs of silicon strip detectors

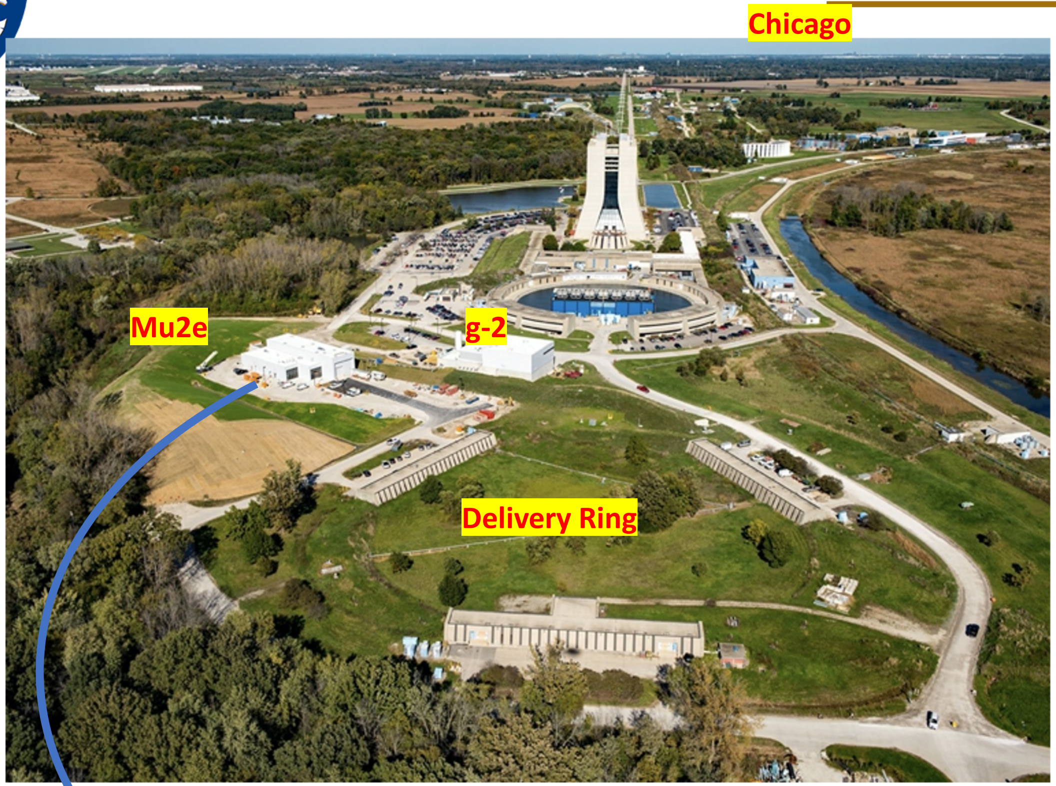


- 40 stations (target + tracking).
- 3 years of data taking.
- Goal 0.3% statistical error and comparable systematic.

MUonE Experiment at CERN

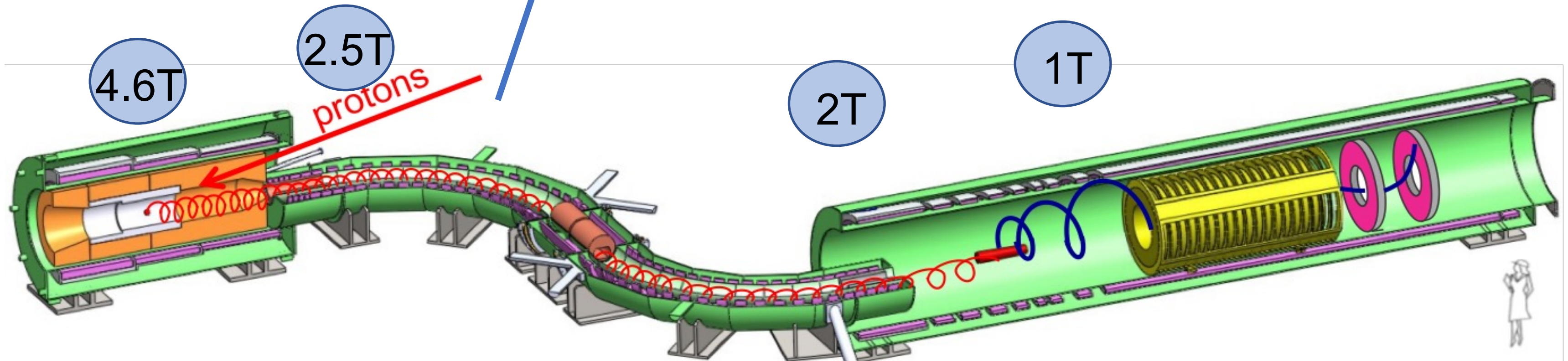
- **Current schedule:**
  - 3 weeks Test Run in Aug/Sept 2023:
    - Proof of concept of the experimental proposal using 2 tracking stations + calorimeter.
  - Towards the full experiment: 10 stations before LS3 (2025):
    - Four months data taking: ~2% (stat) measurement of a_{μ}^{HLO}
    - Full apparatus (40 stations) after LS3 (2029).

Mu2e at Fermilab



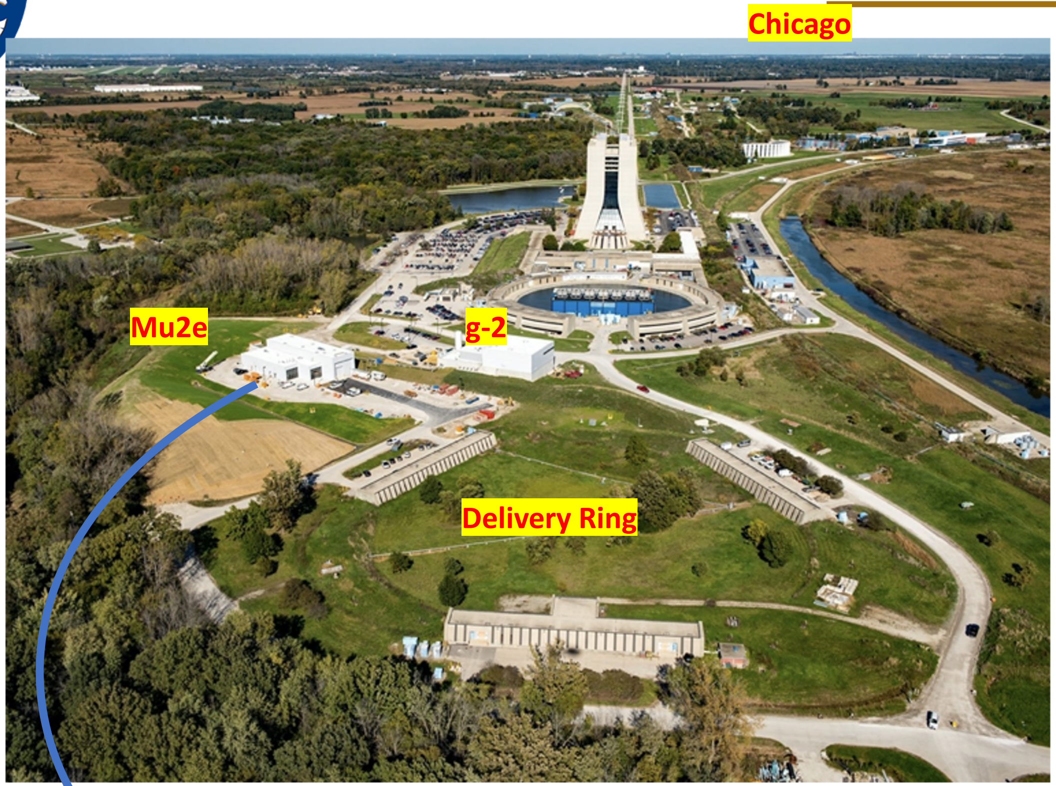
Transport Solenoid (TS)

- Selects low momentum, negative muons
- Antiproton absorber in the mid-section



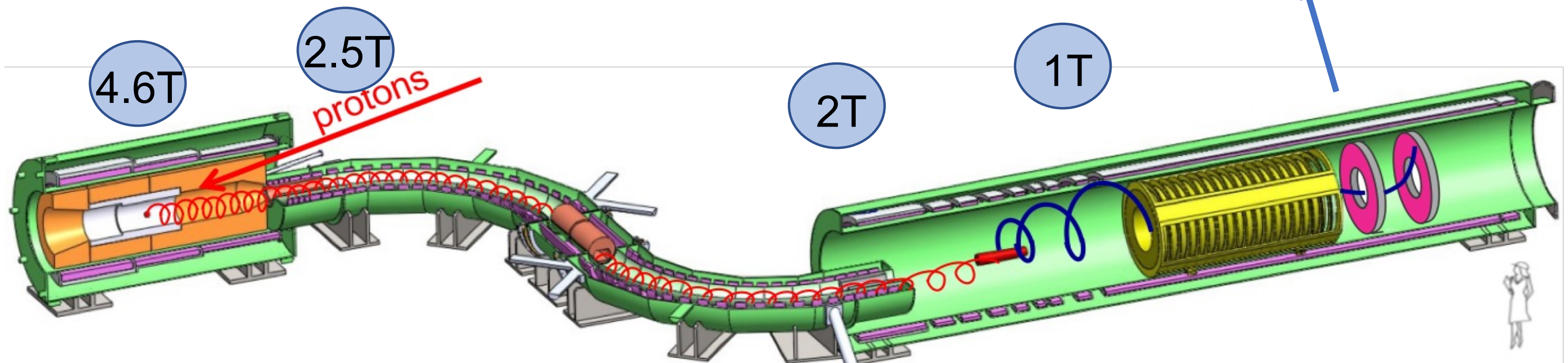
The Mu2e experiment and the INFN contribution – Fermilab 2021 Summer Student School at LNF

Mu2e at Fermilab



Target and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field "reflects" downstream conversion electrons emitted upstream (isotropic process)



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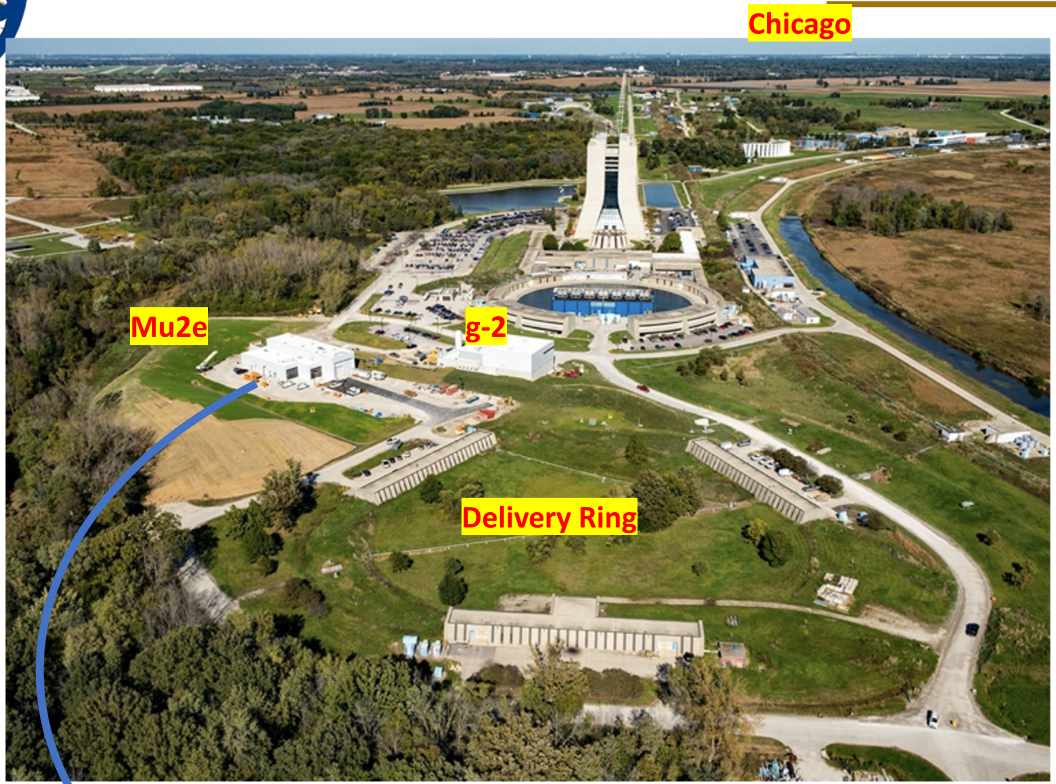
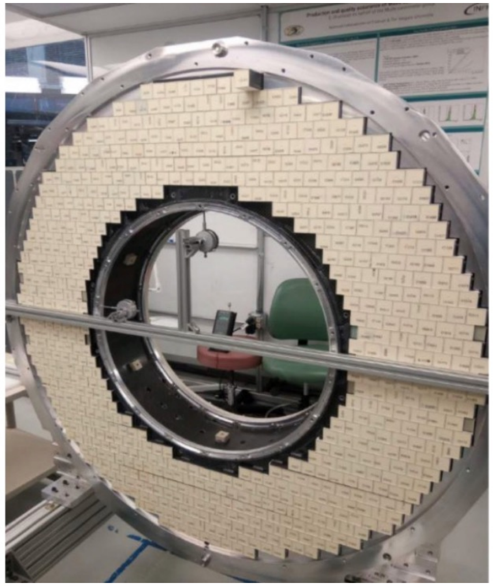
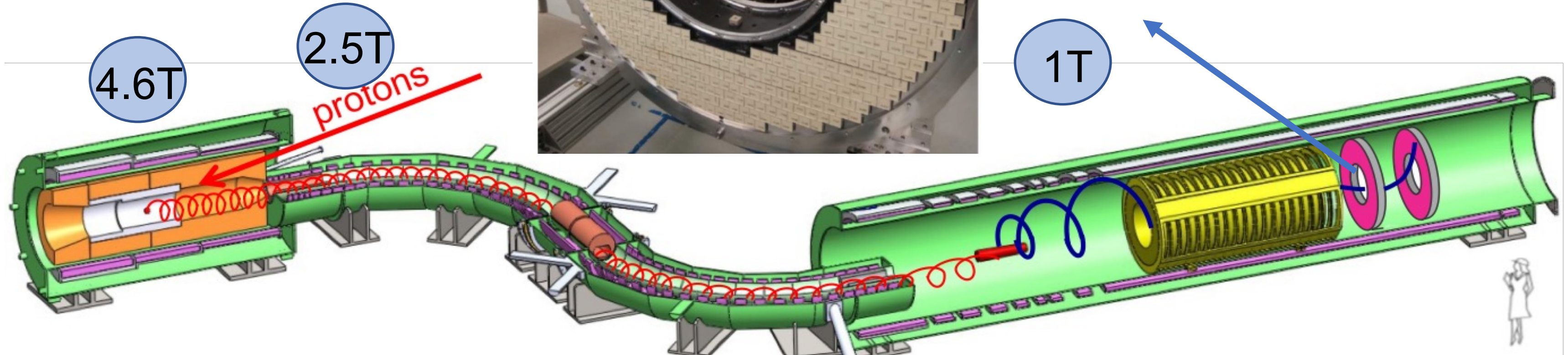
Mu2e at Fermilab



Calorimeters:

- ~1300 CsI crystals, each with 2 SiPM readouts





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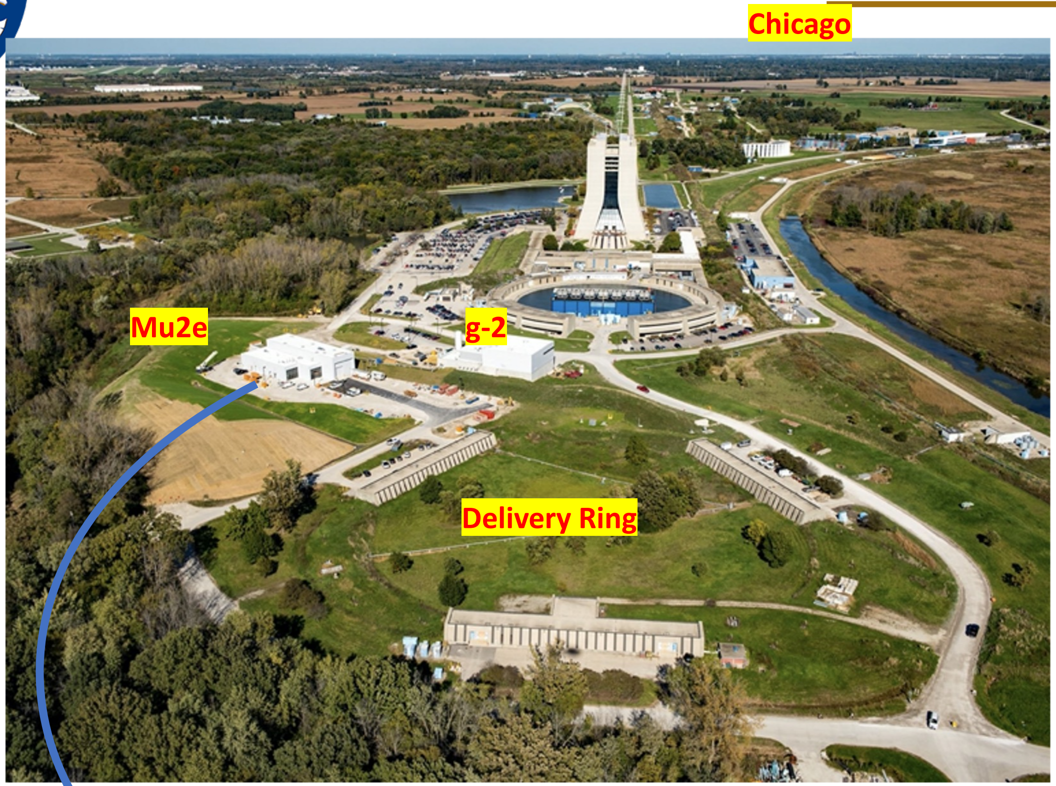
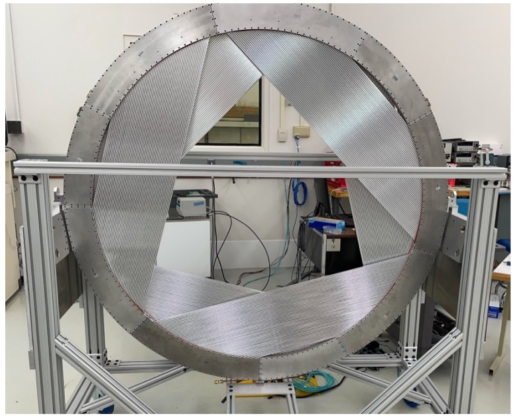
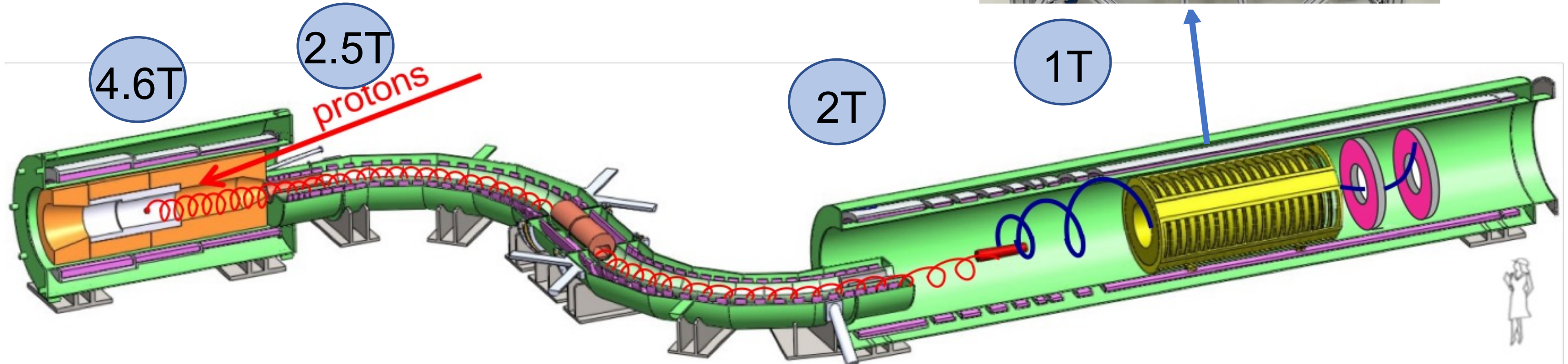
Mu2e at Fermilab



Tracker:

- >20k straw tubes filled with Ar/CO2 mixture
- 36 planes, 6 panels per plane





The Mu2e experiment and the INFN contribution – Fermilab 2021 Summer Student School at LNF

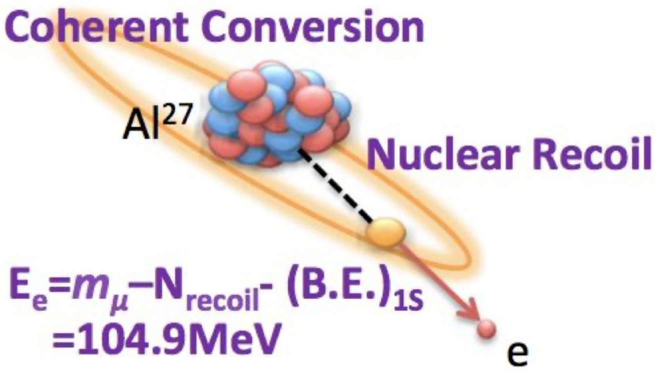
Mu2e – Experimental Concept

- Searching for the neutrinoless conversion of $\mu \rightarrow e$ in the presence of a nucleus:

$$\mu^- + N \rightarrow e^- + N$$

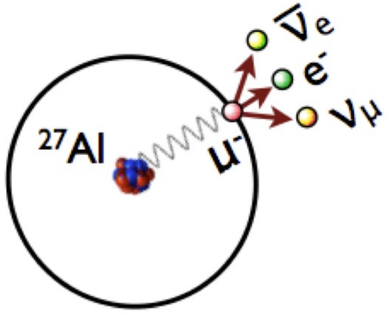
$$R_{\mu\rightarrow e} = \frac{\Gamma\left(\mu^- + N(Z,A) \rightarrow e^+ + N(Z,A)\right)}{\Gamma\left(\mu^- + N(Z,A) \rightarrow \nu_\mu + N(Z-1,A)\right)} < 6\times10^{-17}(90\%\ CL)$$

- **Practically forbidden in SM** $\left(\sim 10^{54}\right)$
- The experiment workflow:
  - Muons are stopped in an aluminium target.
  - When stopped muons convert to electrons, the nucleus recoils and the electron is emitted at a specific energy.
  - **Signal**, $E_e = 104.9$ MeV is unambiguous sign of new physics.
  - Main intrinsic background is **Decay In Orbit** (DIO) events.



To reach the required precision, $\sim 10^{18}$ stopped muons are needed.

From Tomo Miyashita Talk (Fermilab User Meeting-2018)



Decay In Orbit

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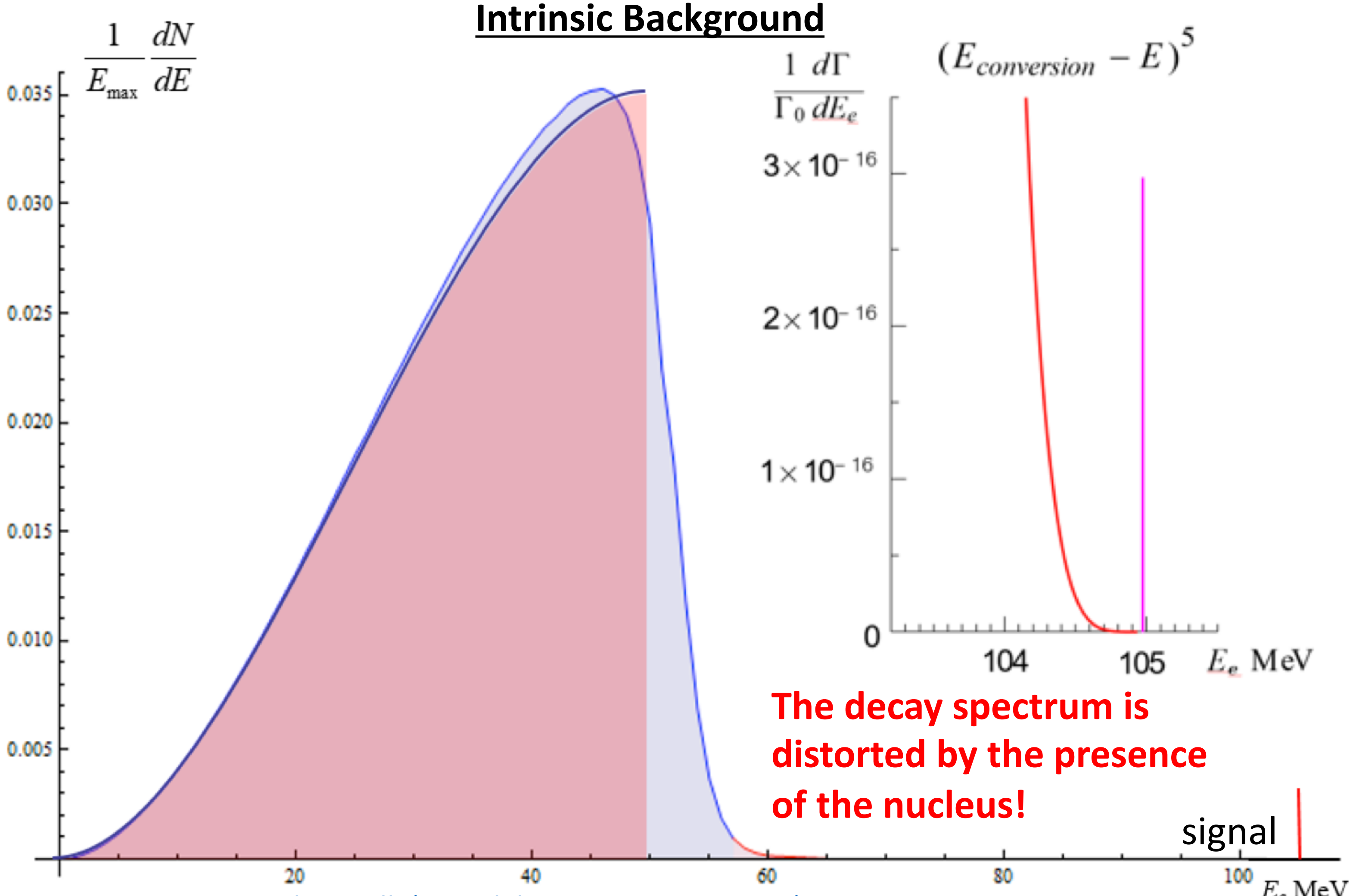
Intrinsic Background



The decay spectrum is distorted by the presence of the nucleus!

[From Tomo Miyashita Talk (Fermilab User Meeting-2018)]

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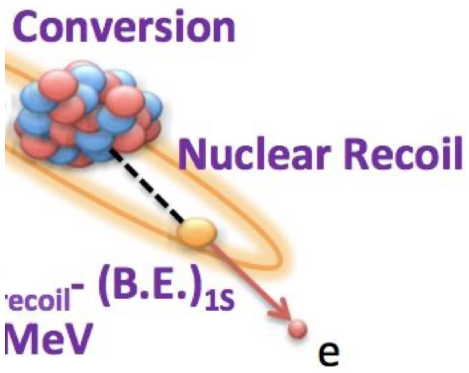
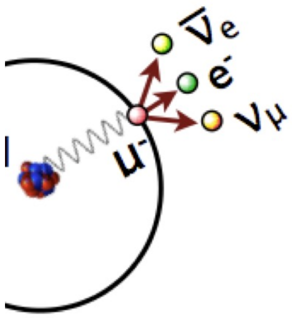




Decay In Orbit

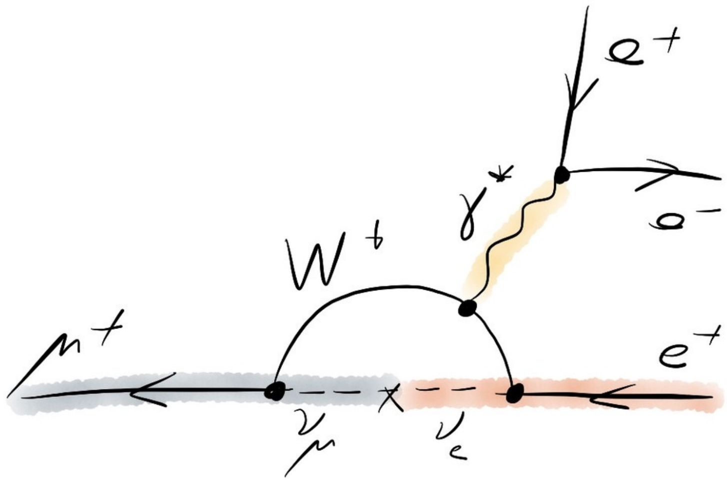
Mu2e

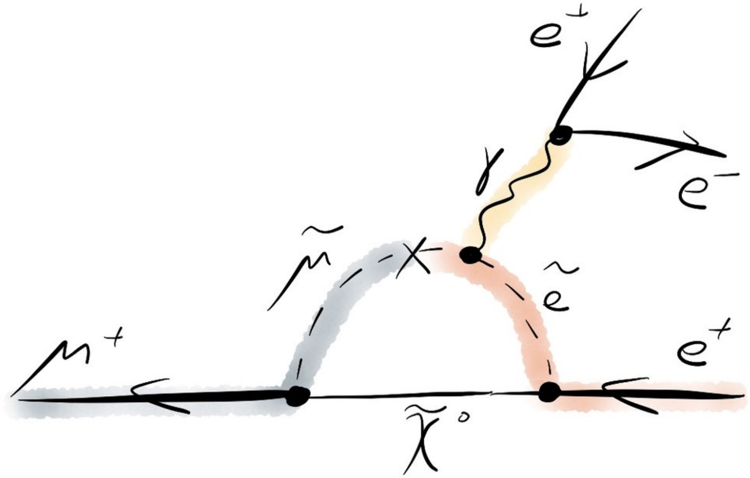
- **Current schedule:**
  - Complete the project by the end of 2025
  - Commission and take data in 2026
  - Publish first results in 2027
  - Increase statistics by x10 after 2years long shutdown

From Mu2e: getting on mass shell – New Frontiers in Lepton Flavor (Pisa-2023)

Mu3e at PSI

From Mu3e - Andrea Loreti (Particle Physics Annual Meeting Liverpool)



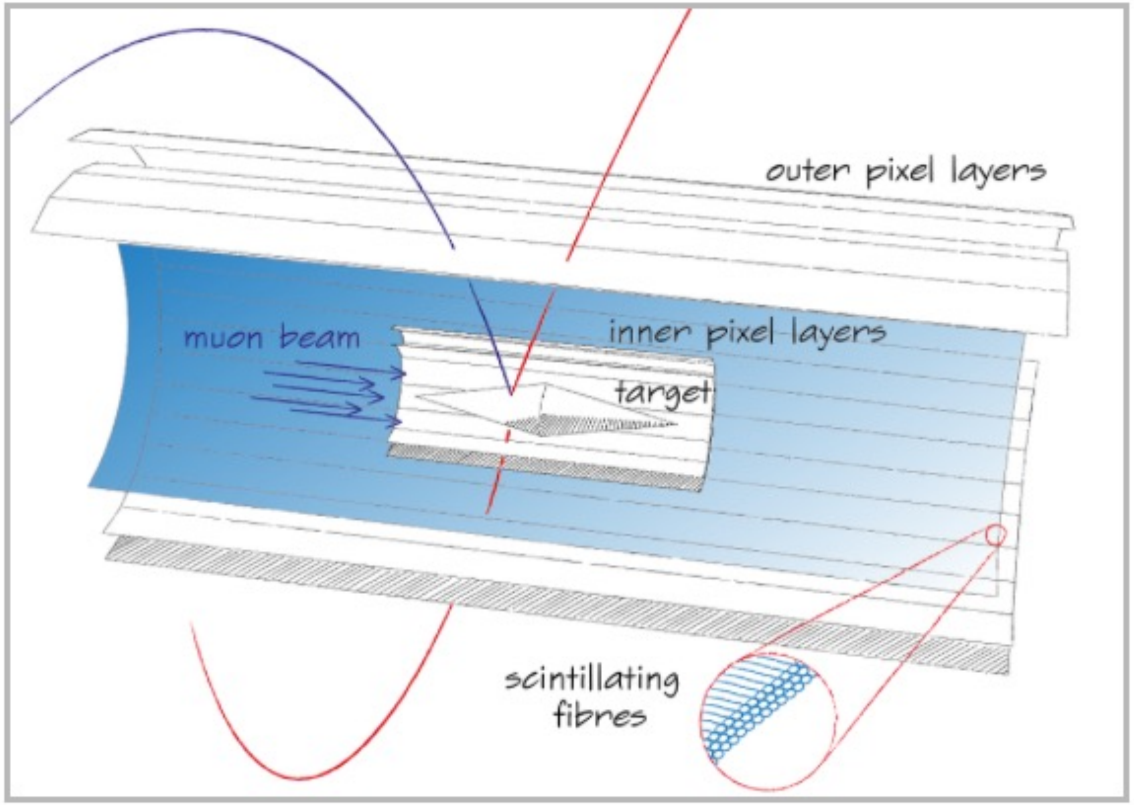


- $BR(\mu^+ \to e^+ + \gamma) \sim O\left(\frac{m_\nu}{m_W}\right)^4 \sim \mathbf{10^{-54}}$
- Neutrino oscillations at weak interaction scales ($\mathbf{10^{-15}}$m) are practically zero
- There are theories Beyond the Standard Model (BSM) that predict lower values for CLFV processes like Mu3e. Any observation of CLFV would mean new physics BSM.
- **Mu3e goals:**
  - **BR**$(\mu^+ \to e^+e^+e^-) <$ $\mathbf{2\times10^{-15}}$ $(10^8 \mu/s$ phase I)
  - **BR**$(\mu^+ \to e^+e^+e^-) <$ $\mathbf{10^{-16}}$ $(10^9 \mu/s$ phase II)

Mu3e at PSI

Detector:

- **Ultra-light silicon pixel tracker** for vertexing.
- **Two timing detectors**: scintillating fibres (250ps) and scintillating tiles (100ps) for charge reconstruction and background discrimination



Requirements:

- High rate capability (>10^9 muon/s)
- Good vertex resolution (< 200 μm)
- Good time resolution (< 100 ps)
- Excellent momentum resolution (< 0.5 MeV/c)

Mu3e at PSI

The **time line** for the Mu3e experiment is currently the following:

- 2014-2022 Detector development
- 2023/24 Detector construction, installation and commissioning at PSI
- 2025+ Data taking at up to a few 10^9muons/s (Phase I)
- 2027+ Construction of a new muon beam line at PSI
- 2028++ Data taking at up to $2 \cdot 10^9$ muon/s (Phase II)

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

F. Jegerlehner

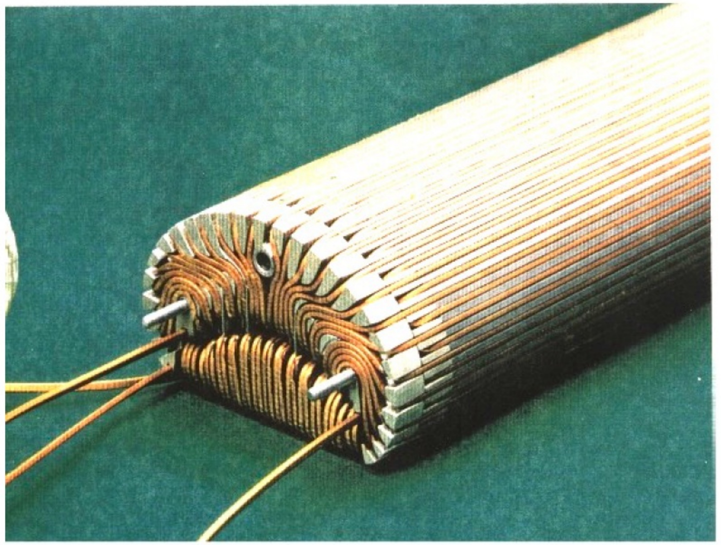
Thank you!!!

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

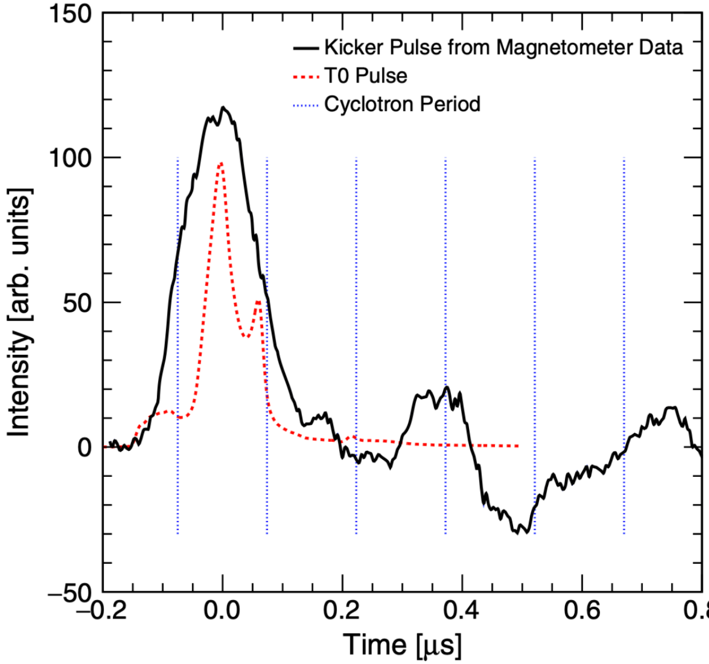
BACK-UP

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.

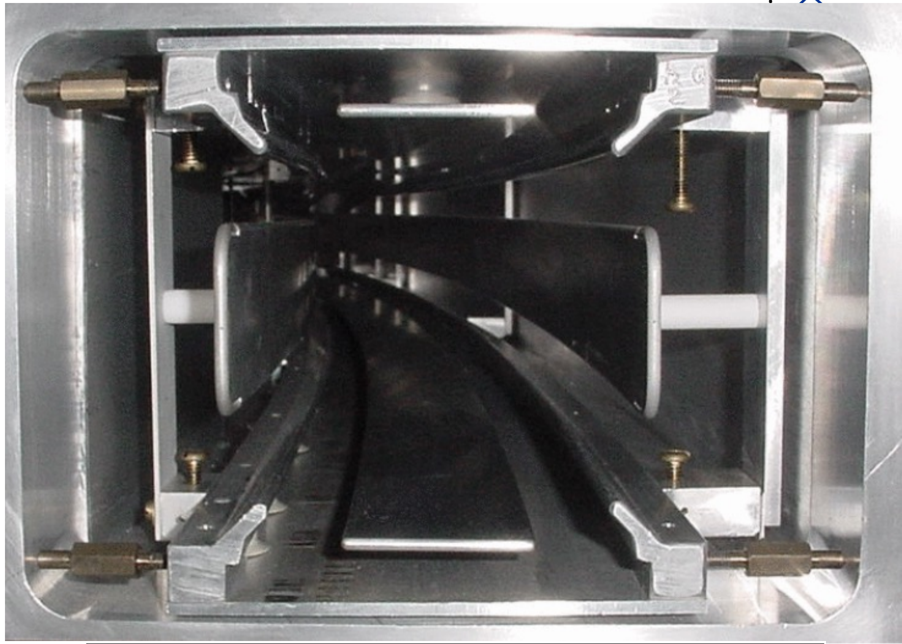


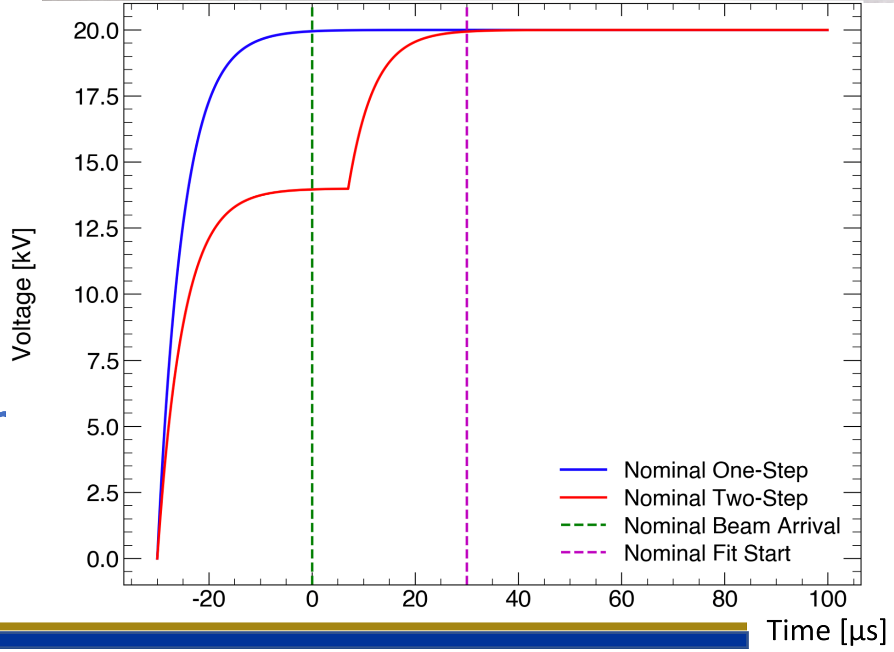
- **3 Kickers** are necessary to inject magic momentum muons along the magic radius (7.11 m) with a required kick at order of 10 mrad.
- 4 kA current in 200 ns pulse.
- Design kick strength has been reached in Run-3 (∼160 kV).



Quadrupoles

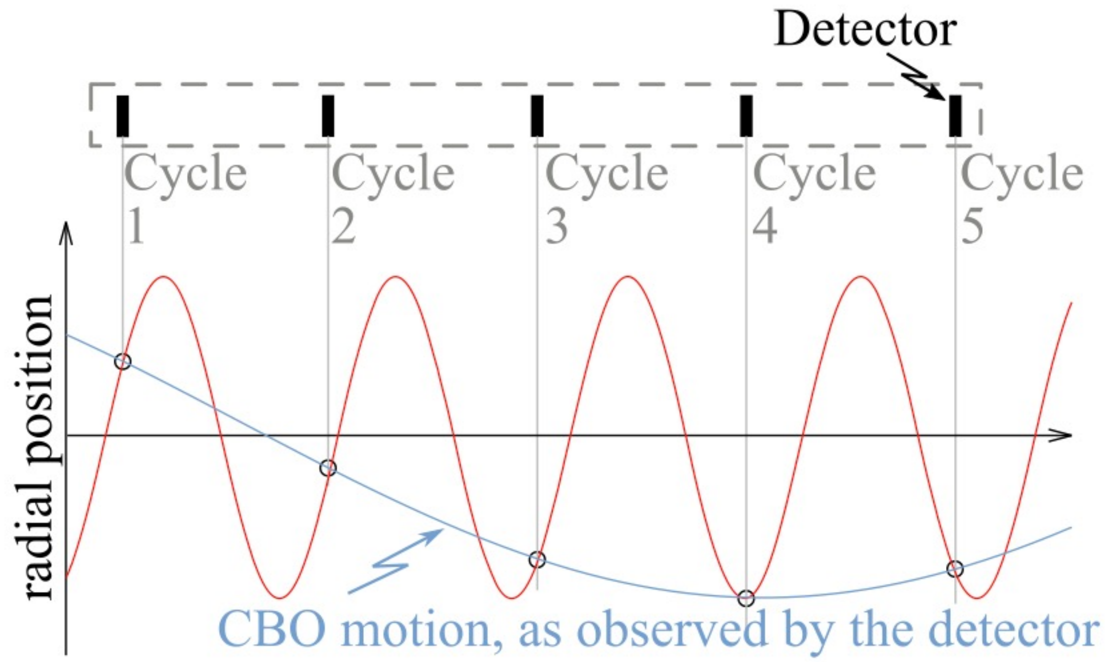
- The Electrostatic Quadrupoles (ESQ) system allows to strongly focus the beam vertically, four ESQ stations are symmetrically placed around the ring.
- The plates are raised from ground to operating voltage prior to each *fill* with RC charging time constants of **$\sim 5\ \mu s$**.
- This procedure, 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 $\omega_{CBO} = \omega_C - \omega_{BO}$



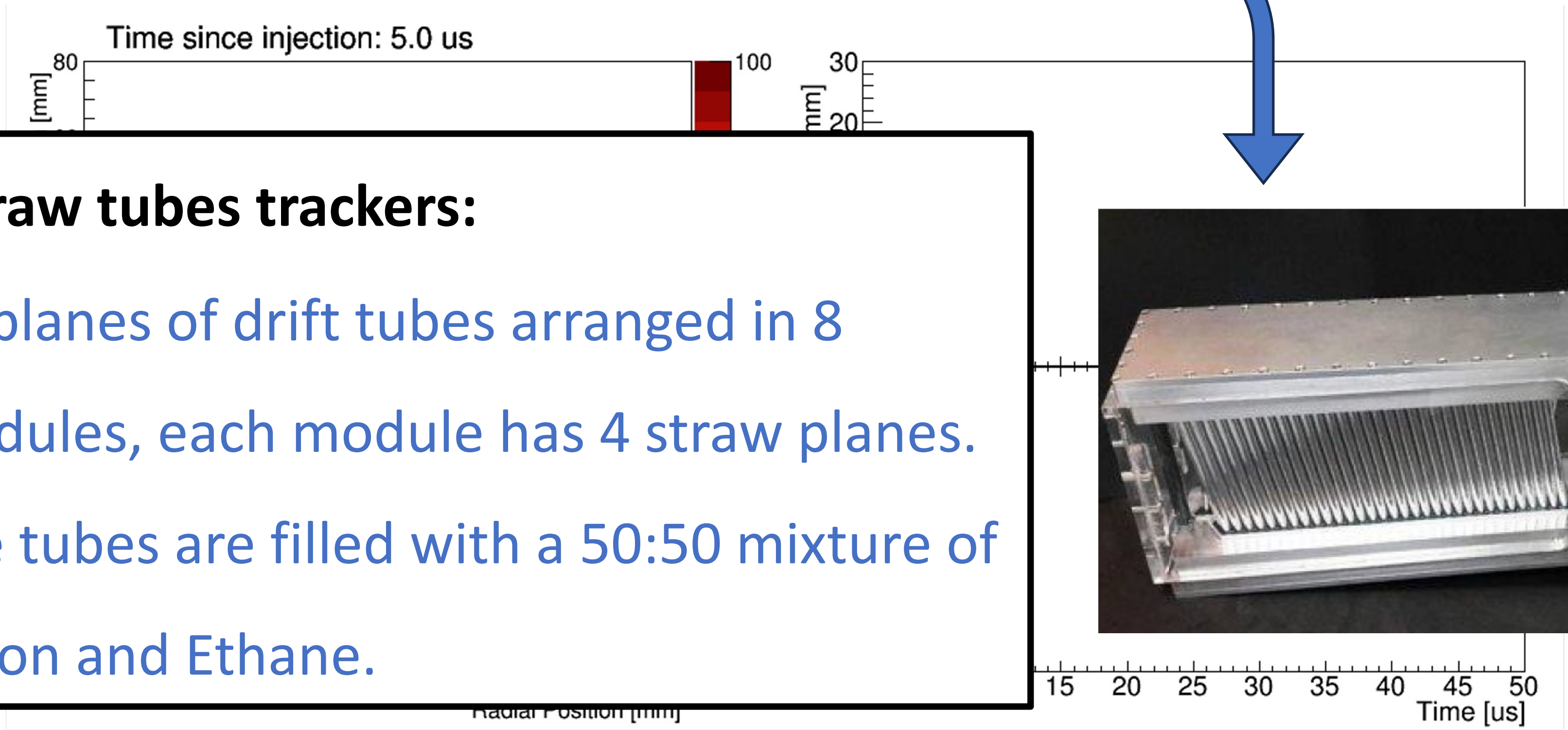
$$2\pi f_{CBO} = \omega_C - \omega_{BO} = \omega_C(1-\sqrt{1-n})$$

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

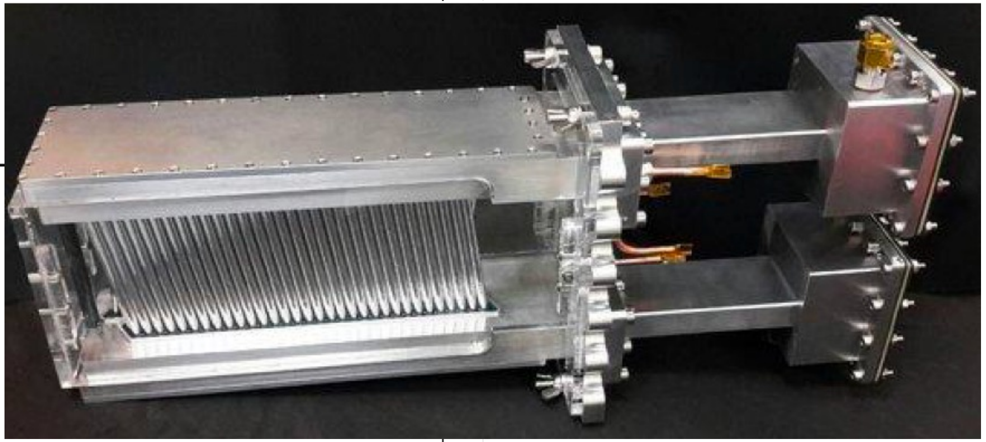
Where $T_C \sim 0.149\, ns$ and $n \sim 0.108$

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:



- **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.

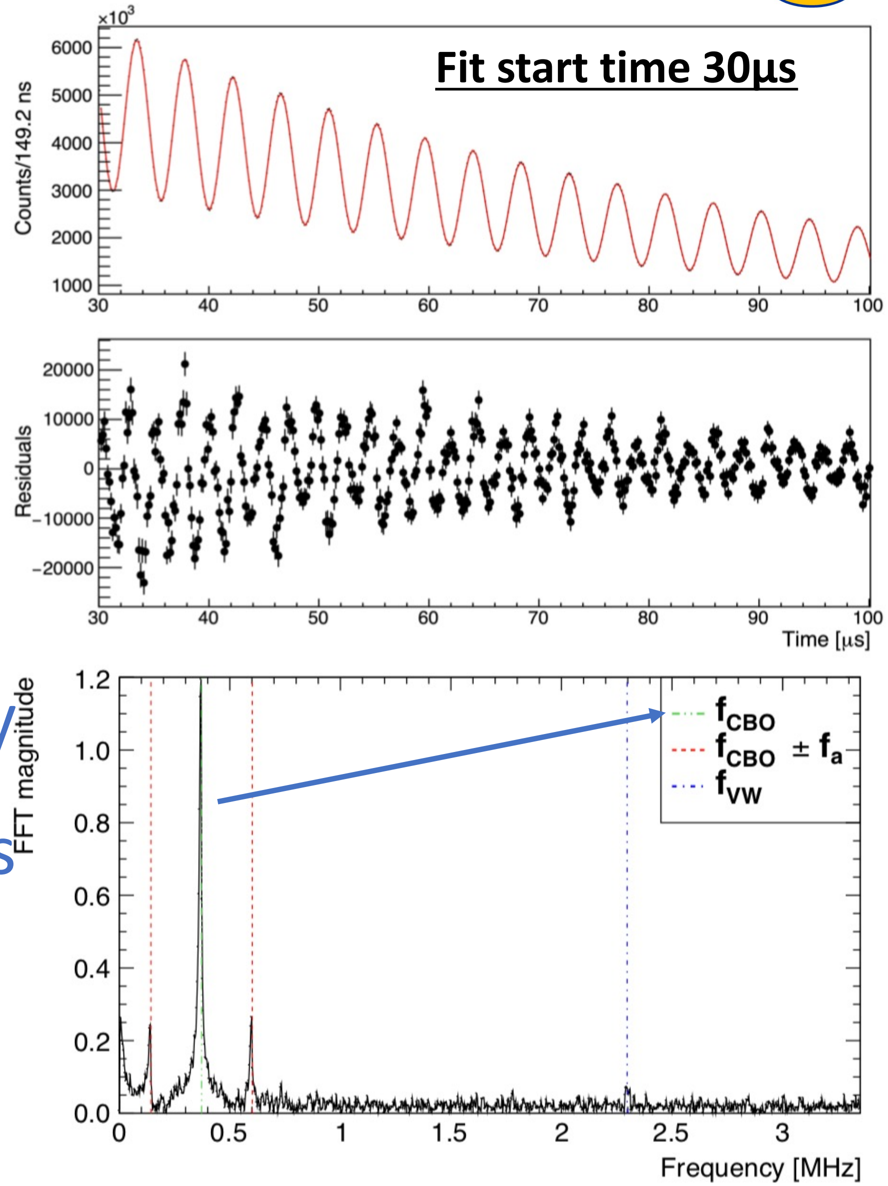


ω_a measurement

- 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.



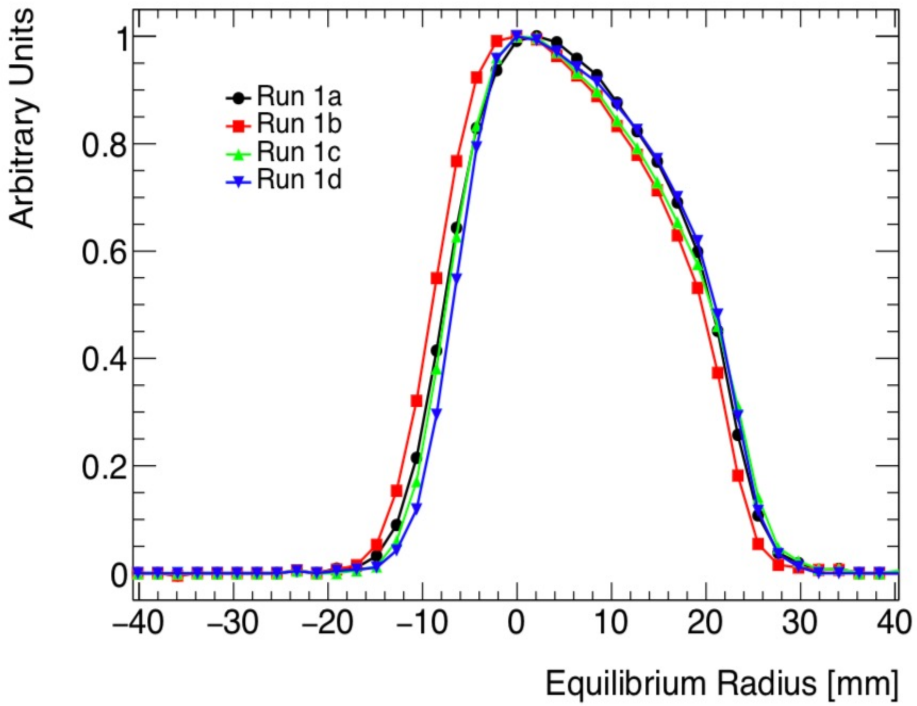
Beam dynamics correction to $\boldsymbol{\omega_a}$: C_e

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:

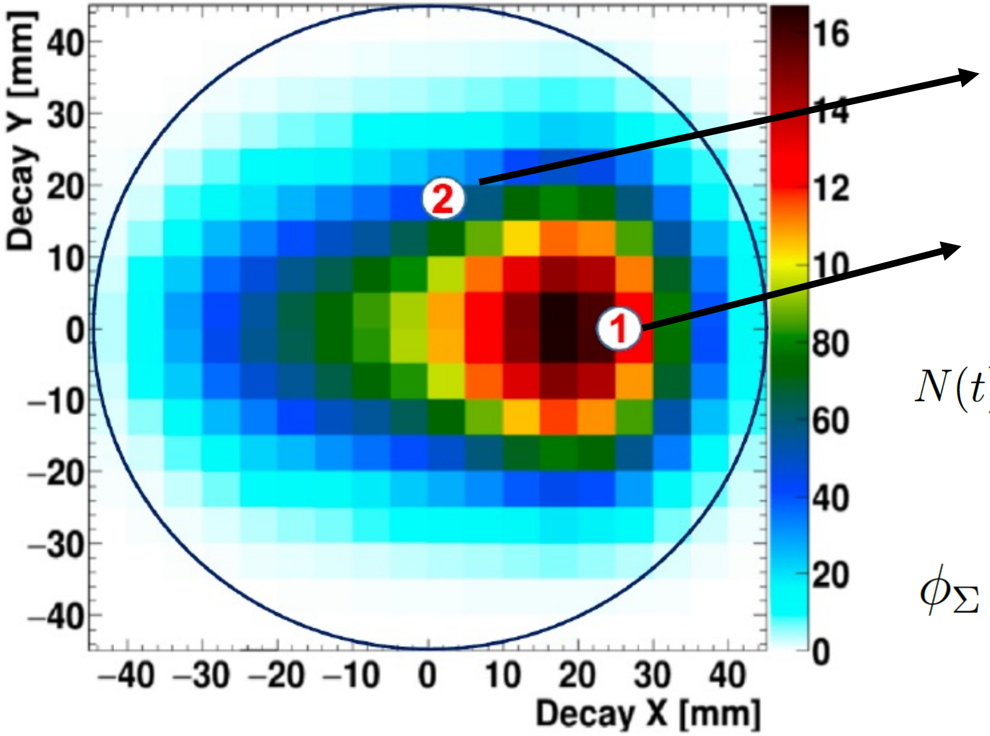
$$cos(\omega_a t + \phi(t)) = cos(\omega_a t + \phi_0 + \phi' t + ...)$$
$$= cos((\omega_a + \phi')t + \phi_0 + ...)$$

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.



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

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

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

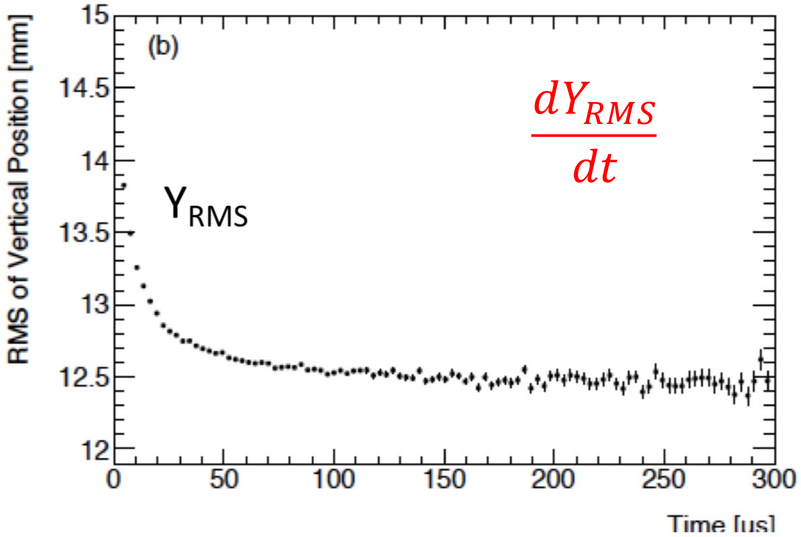
$$\phi_\Sigma = \arctan\frac{N_{01}A_1\sin(\phi_1) + N_{02}A_2\sin(\phi_2)}{N_{01}A_1\cos(\phi_1) + N_{02}A_2\cos(\phi_2)}$$

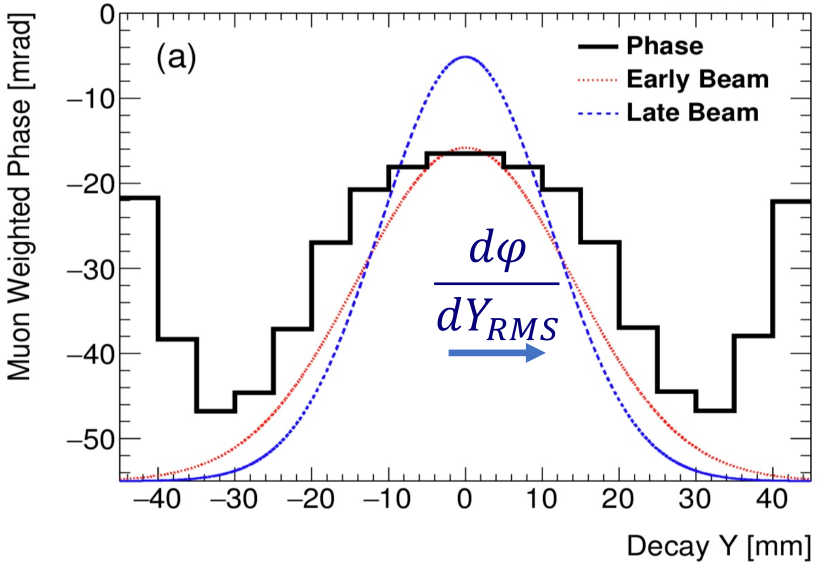
Beam dynamics correction to ω_a: C_{pa}

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.

$$\Delta\omega_a = \frac{d\varphi}{dt} = \underbrace{\frac{dY_{RMS}}{dt}}_{1)} \cdot \underbrace{\frac{d\varphi}{dY_{RMS}}}_{2)}$$





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

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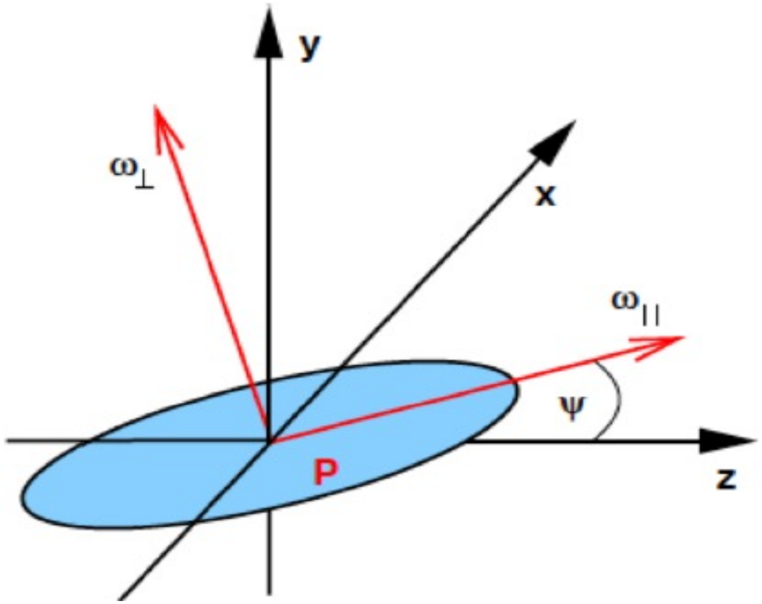
$$C_p \sim 200\, ppb$$



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

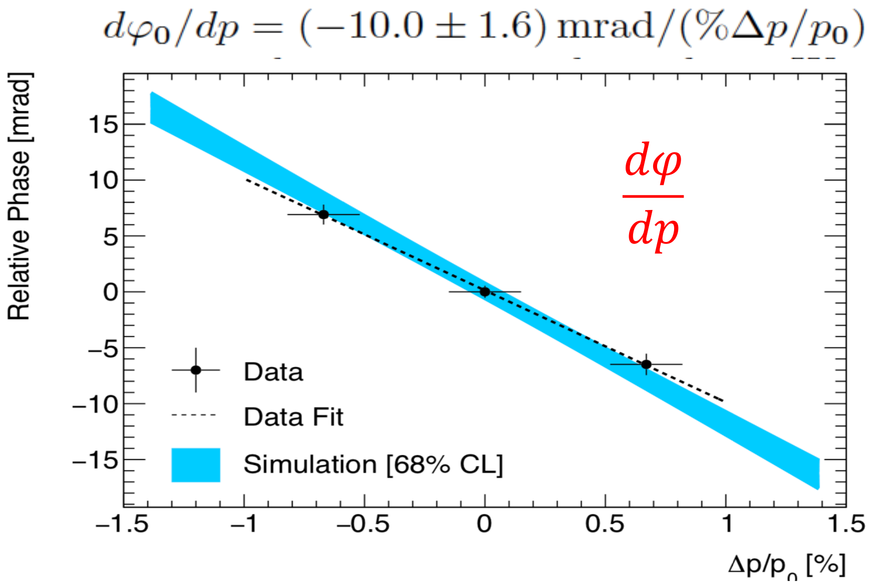
Beam dynamics correction to $\boldsymbol{\omega_a}$: C_{lm}

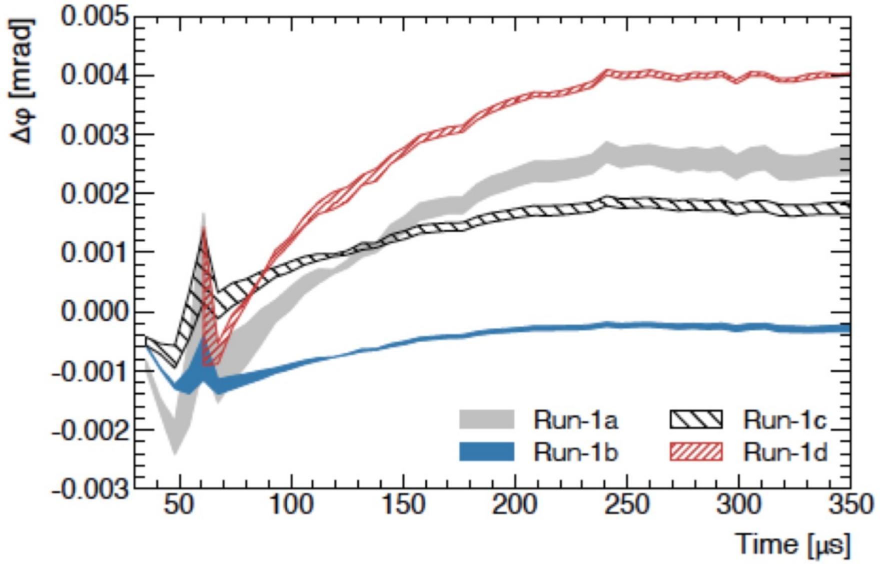
$\boldsymbol{C_{lm}}$: describes the motion introduced on ω_a phase due to the loss of muon during the *fill*. It's explained by:

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

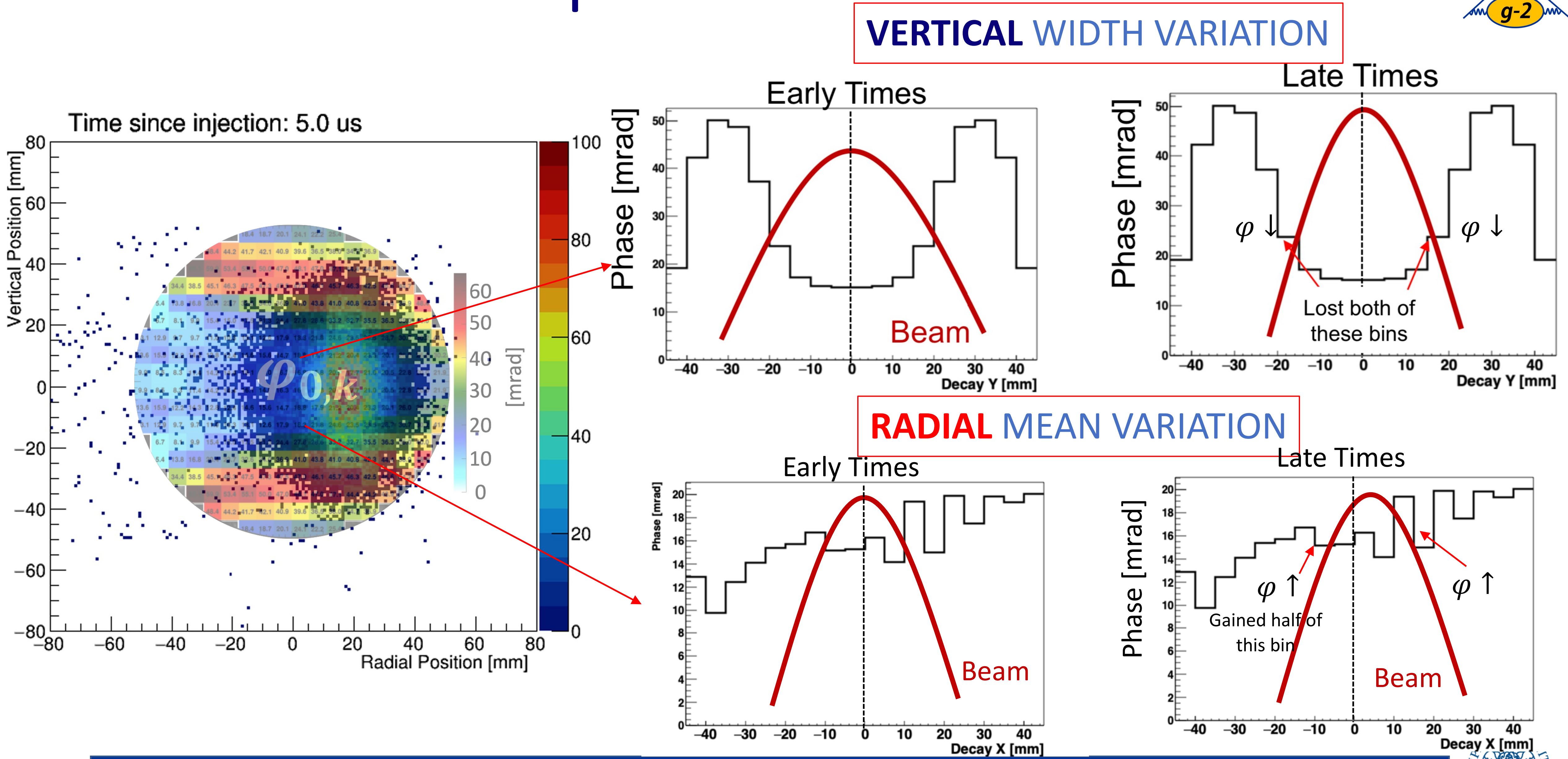
$$\Delta\omega_a = \frac{d\varphi}{dt} = \underbrace{\frac{d\varphi}{dp}}_{1)} \cdot \underbrace{\frac{dp}{dt}}_{2)}$$

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





Phase acceptance: Beam Motion Effects



Mu2e at Fermilab

- Searching for the neutrinoless conversion of $\mu \to e$ in the presence of a nucleus: $\boldsymbol{\mu^- + N \to e^- + N}$
- Practically forbidden in SM (~10^{-54})

$$R_{\mu\to e} = \frac{\Gamma(\mu^- + N(Z,A) \to e^+ + N(Z,A))}{\Gamma\left(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A)\right)} < 6\times10^{-17}(90\%\ CL)$$

- **Signal**, $E_e = 104.9$ MeV is unambiguous sign of new physics

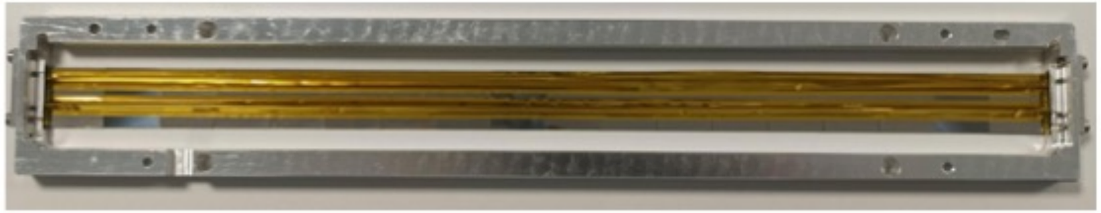
Liverpool contribution: **Stopping Target Monitor (STM)**

- **Measure number of stopped muons (denominator) to 10%**
- Muon stopped in Al target cause 3 characteristic γ emissions:
  - 347 keV from 2p→1s (prompt)
  - 1809 keV from nuclear capture (864 ns)
  - 844 keV from decay of metastable $^{26}Mg^*$ capture product, 9.5 min
- **High-purity Germanium (HPGe) detector (Liverpool) : high resolution (1-2 keV) for determination of closely spaced transitions**
- LaBr detector : high rate capability
- HPGe tested at Liverpool and in test beam @ ELBE
- Currently being installed at FNAL

g-2 omega_p measurement and Mu2e - Saskia Charity (Particle Physics Annual Meeting Liverpool)

Mu3e Liverpool Group

- The Liverpool group is responsible for the construction of the **outer layers** of the pixel detector, together with Oxford, assembling the outer modules of the pixel detector.
- The group is also working on software and analysis studies to characterise the track and vertex reconstruction efficiency.
- FOR MORE INFO:
  - https://www.physi.uni-heidelberg.de/Forschung/he/mu3e/
  - https://www.psi.ch/en/mu3e/



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