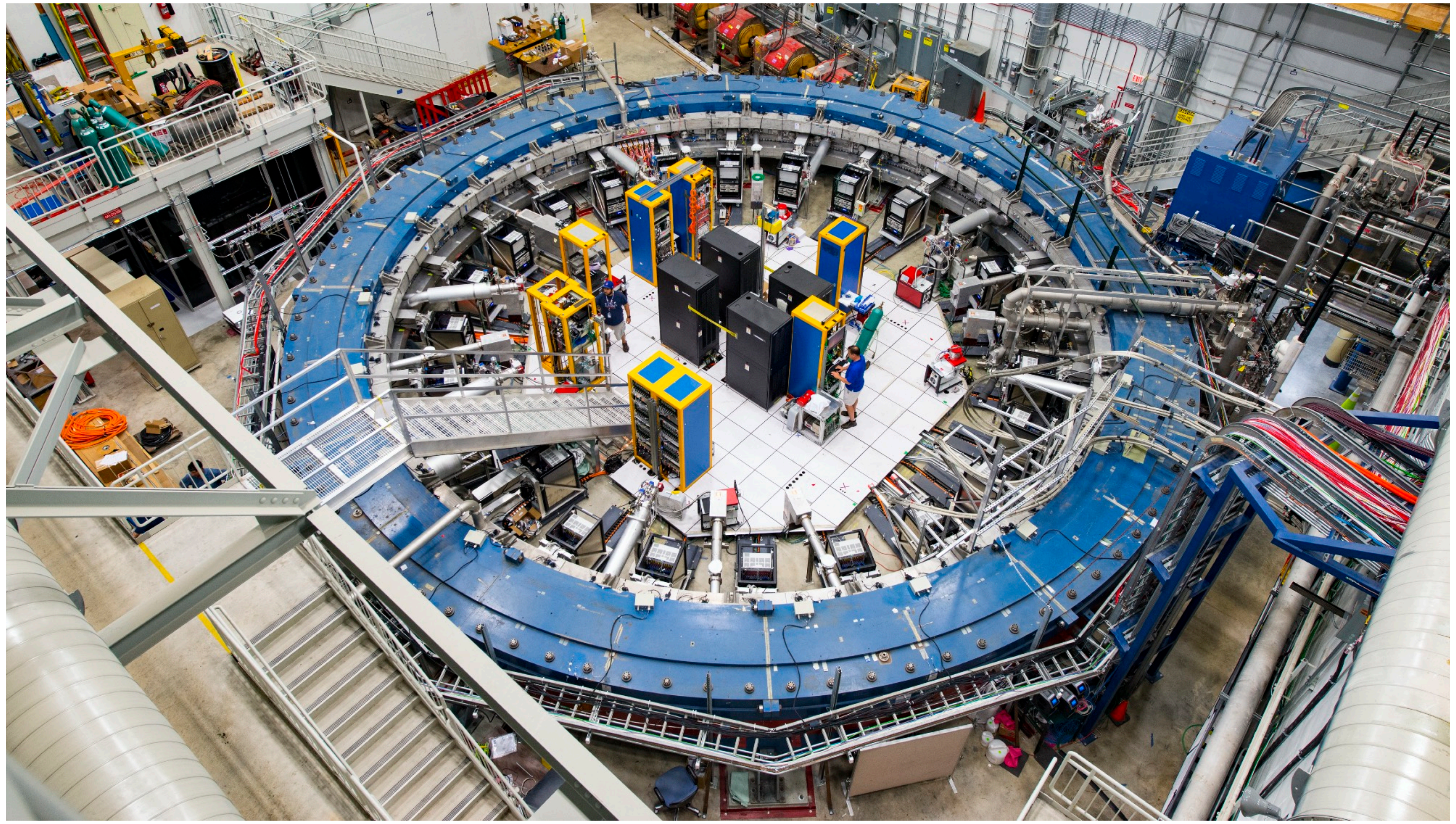


Measuring the muon anomalous magnetic moment with the g-2 experiment at Fermilab

Saskia Charity, Fermi National Accelerator Laboratory

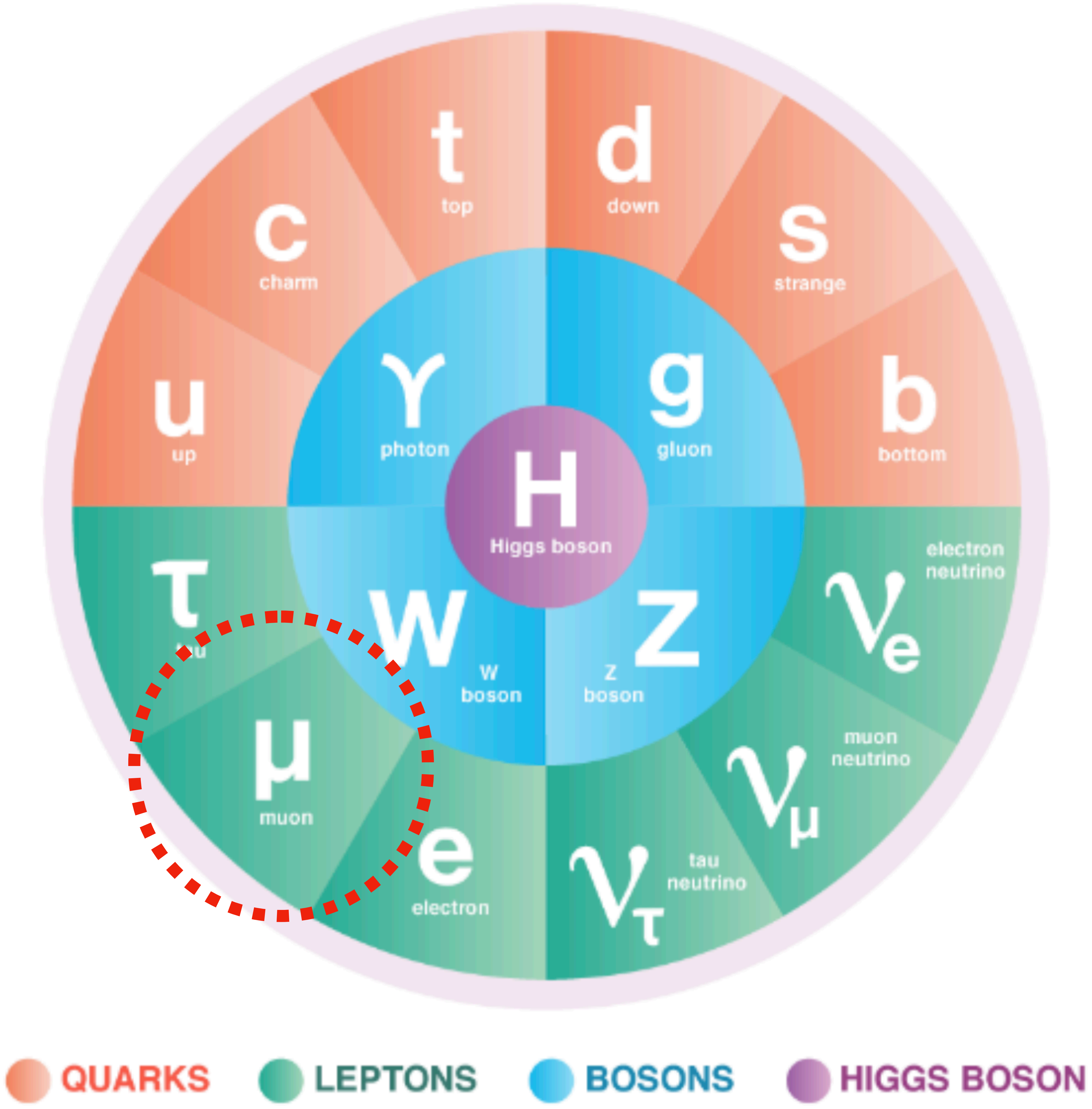
Tollestrup Award Talk, 54th Fermilab Users Meeting

04 August 2021

What are muons?

muons are **leptons** (like electrons)

they have **spin** (intrinsic angular momentum)



they are **unstable** (lifetime = 2.2 μs)

$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

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

mass = 207 x mass of electron

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The muon magnetic moment

Muons have an intrinsic **magnetic moment**, caused by their spin (intrinsic angular momentum)

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

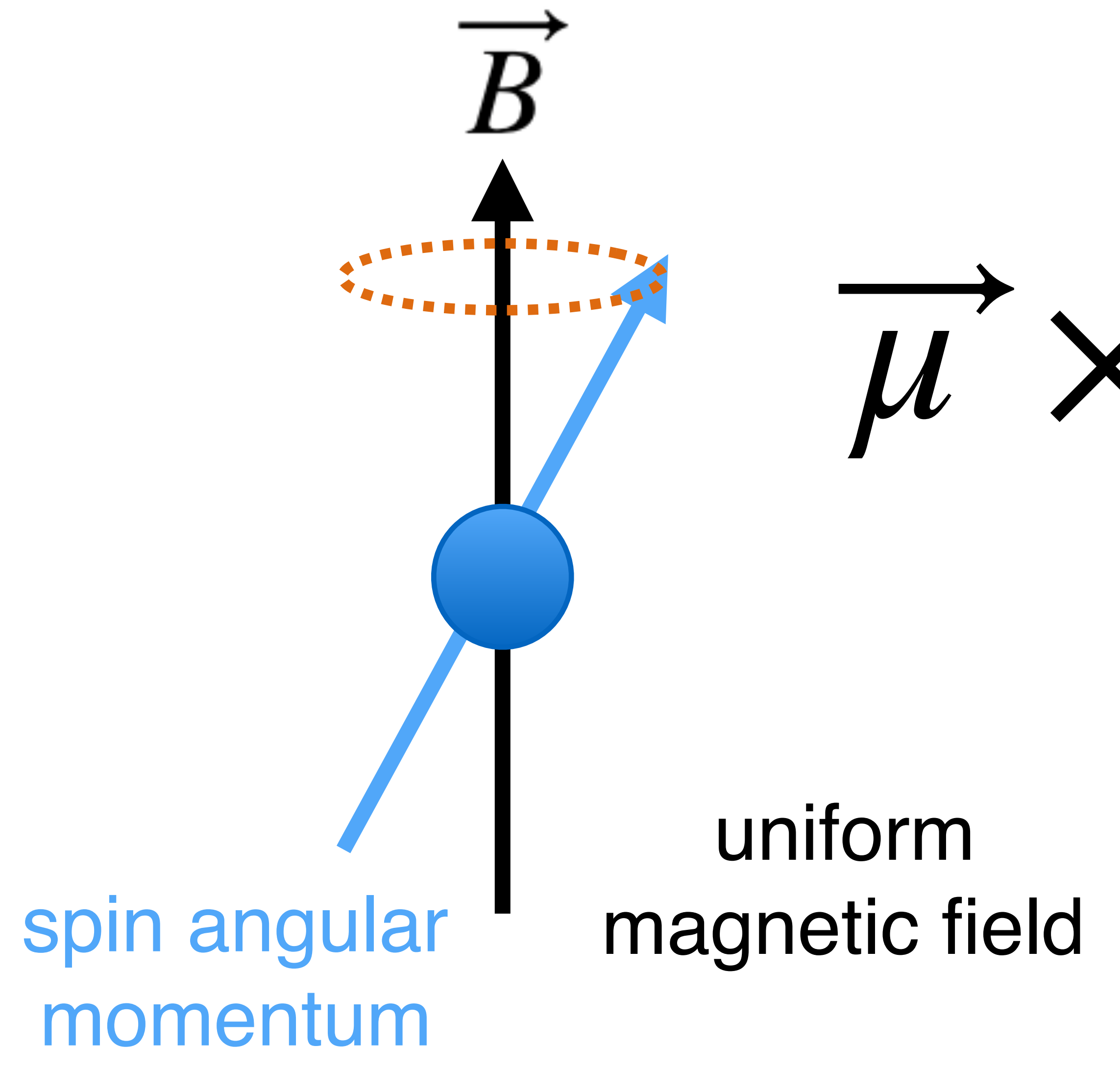
g = gyromagnetic ratio
μ = magnetic moment
s = spin
m = mass

Dirac: g = 2 for leptons

Define "anomalous" magnetic moment: how different is g from 2?

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

Magnetic moment interacts with **external magnetic fields**



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

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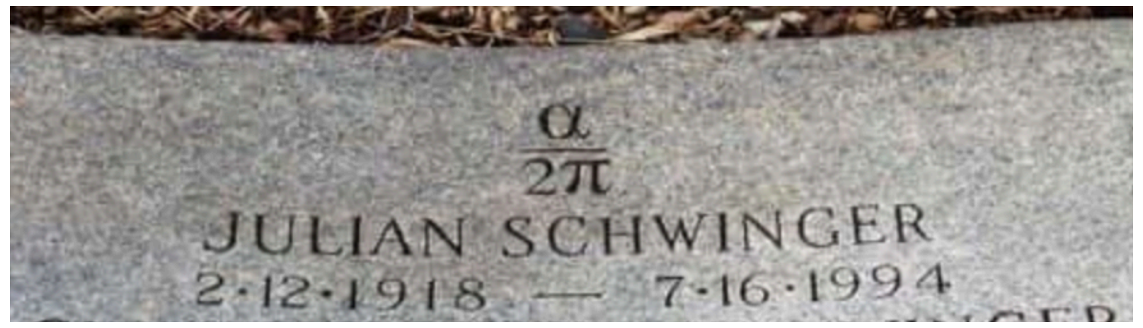
The muon magnetic moment

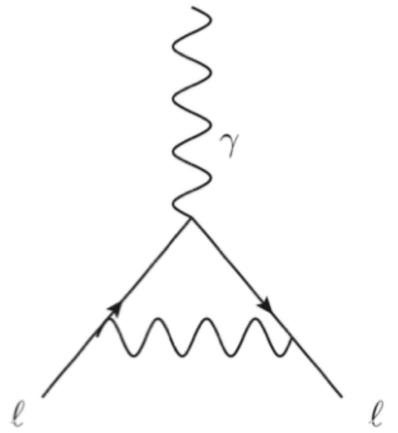
$$a_\mu = \frac{g-2}{2} \qquad \vec{\mu} = g\frac{q}{2m}\vec{s}$$

g = gyromagnetic ratio
μ = magnetic moment
s = spin
m = mass

Schwinger: lepton g is > 2



leptons have loop interaction with a virtual photon

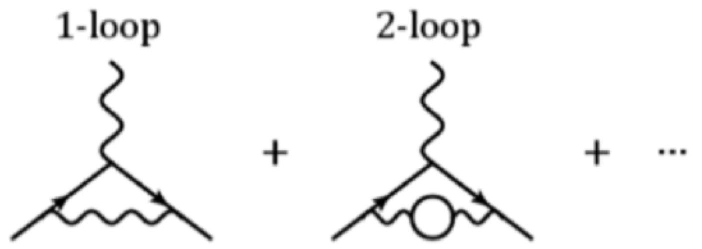


Quantum-mechanical correction that increases the value of *a*

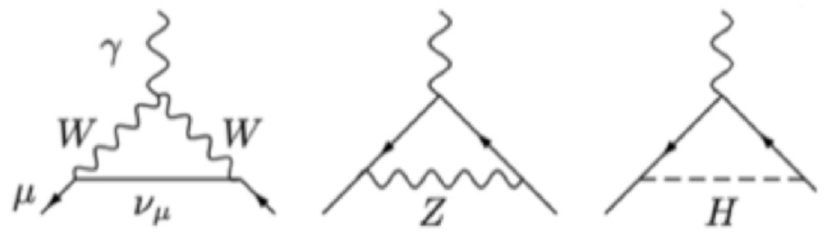
$$a_l = \frac{\alpha}{2\pi}$$

It's now well known that g > 2 : muons undergo virtual interactions with all particles in the SM…

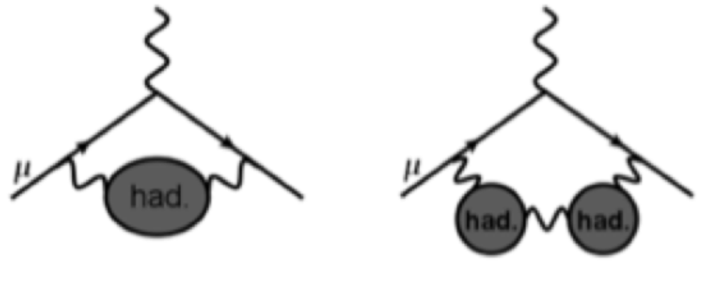
QED



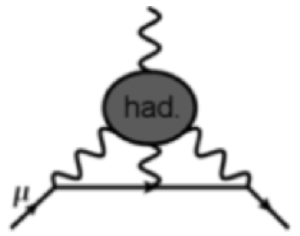
EW



HVP

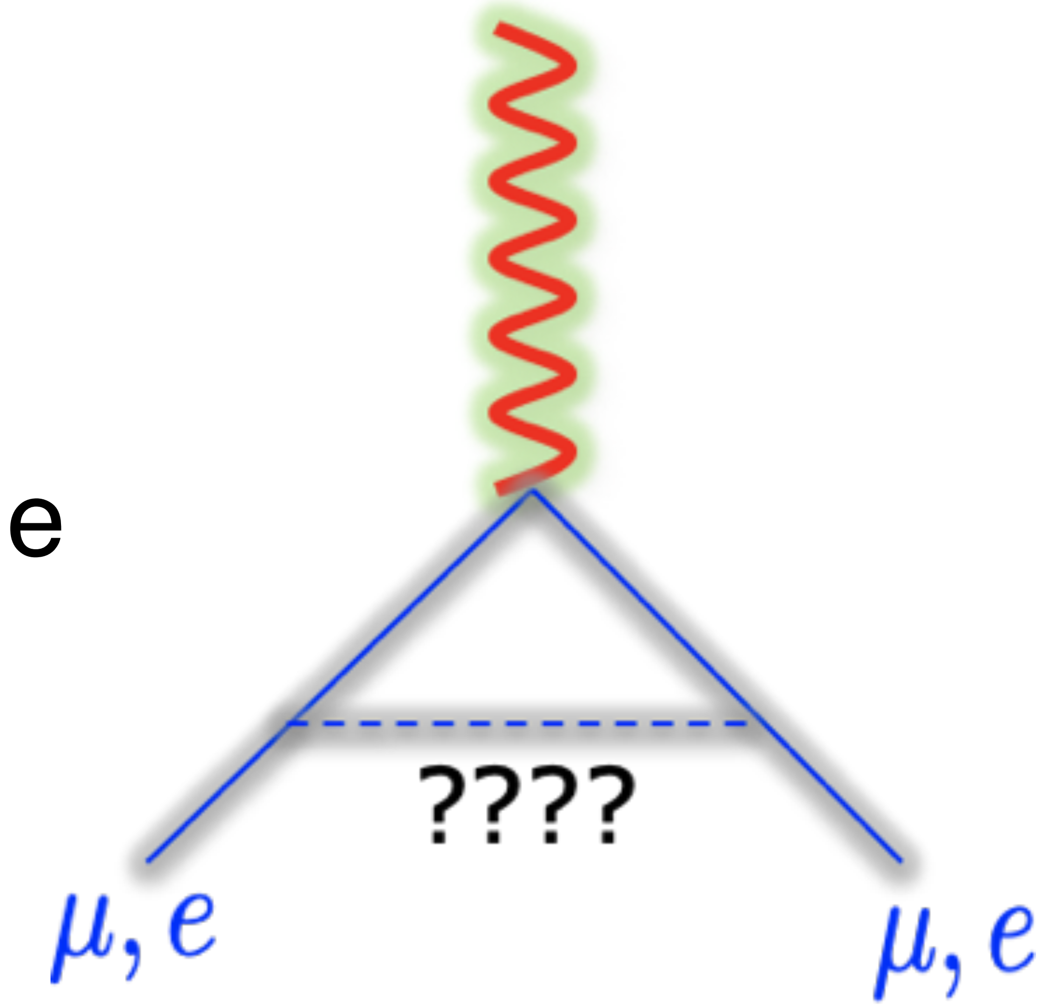


HLbL



> 12,000 diagrams!

… and maybe some interactions beyond the SM?

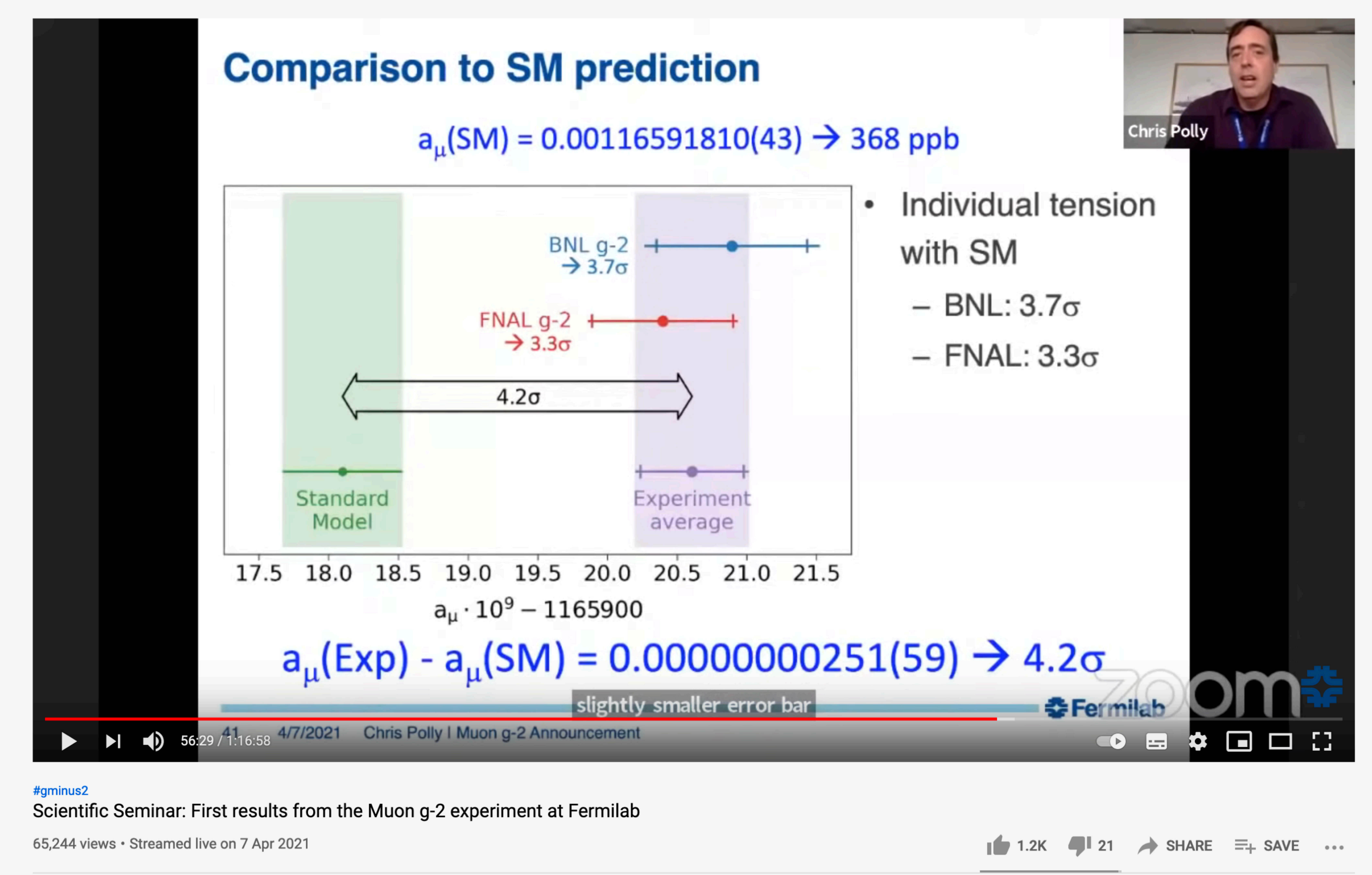


The muon magnetic moment

$$a_\mu = \frac{g-2}{2} \qquad \vec{\mu} = g\frac{q}{2m}\vec{s}$$

g = gyromagnetic ratio
μ = magnetic moment
s = spin
m = mass

Schwing



nical correction
he value of *a*

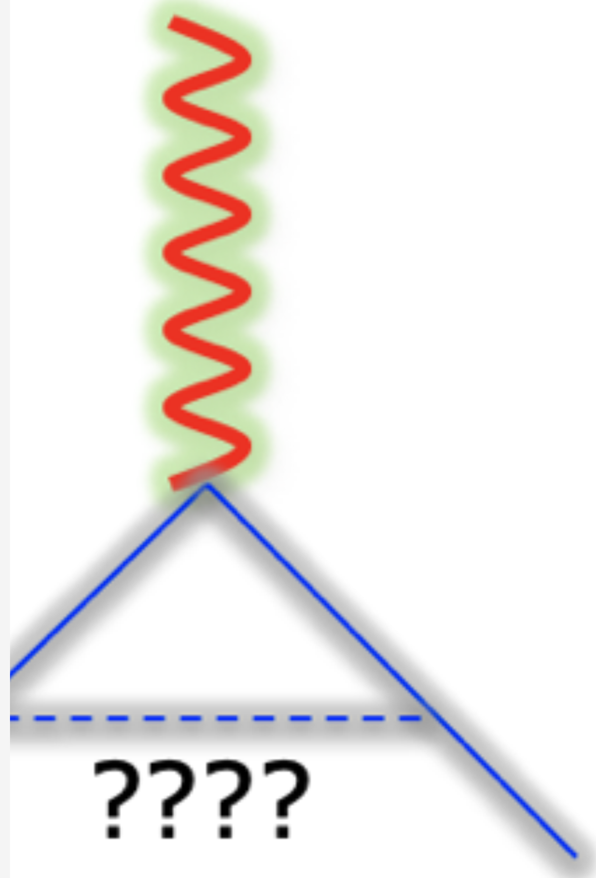
$$\frac{\alpha}{2\pi}$$

It's now well
virtual interac

QED

+

HLbL



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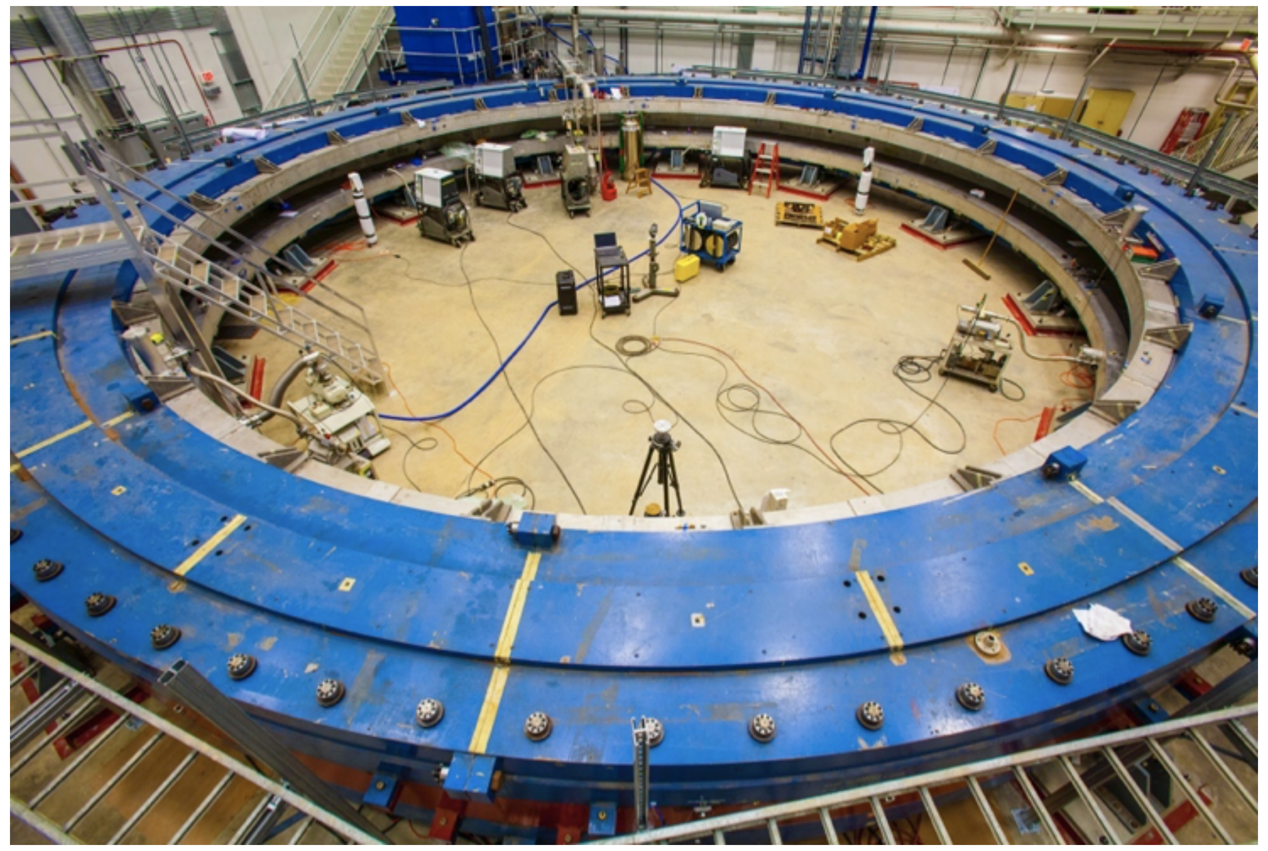
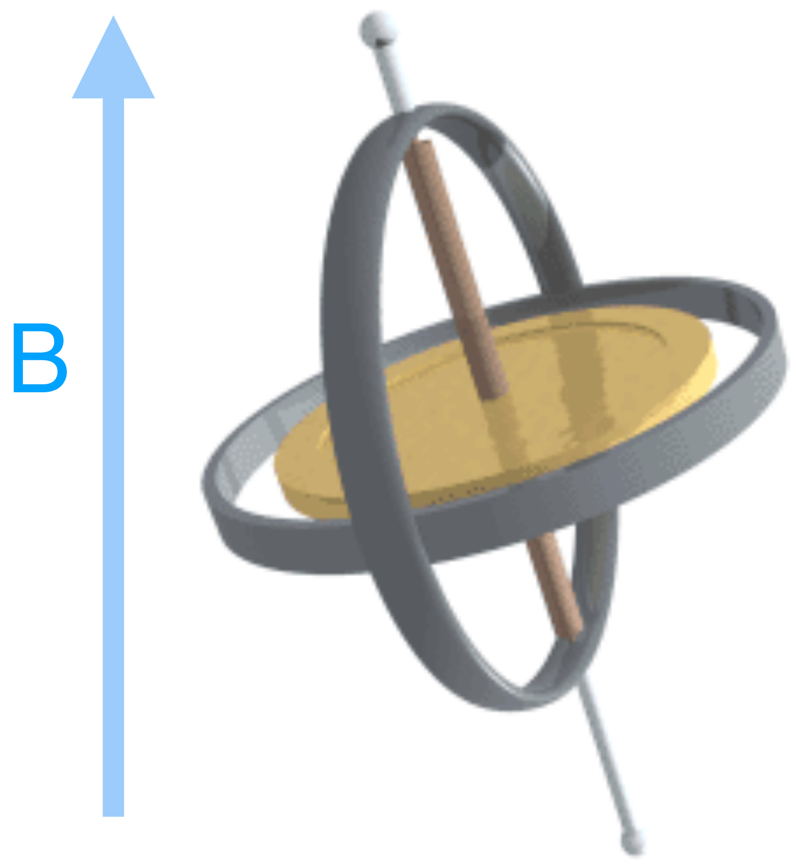
How do we measure a_μ?

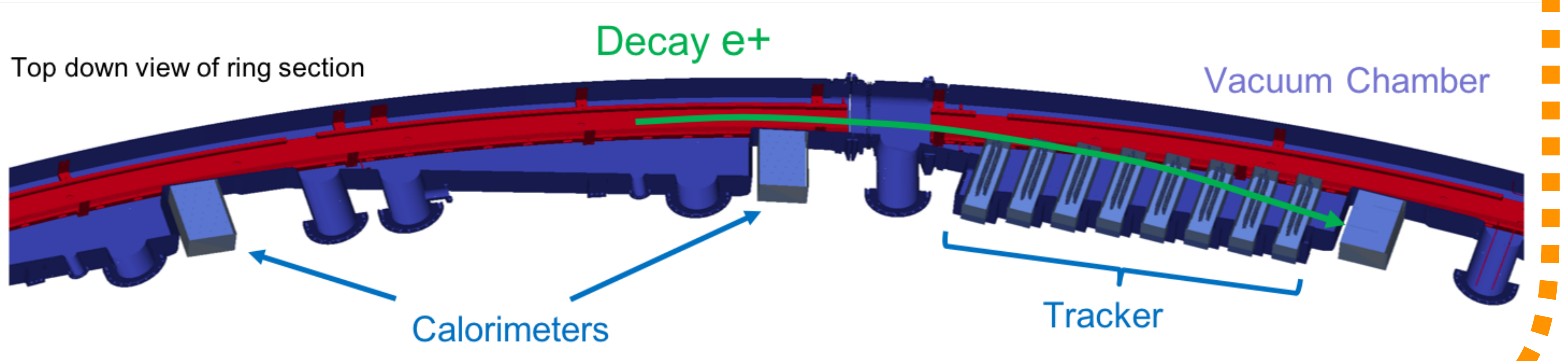
A beam of muons is injected into the **storage ring** magnet



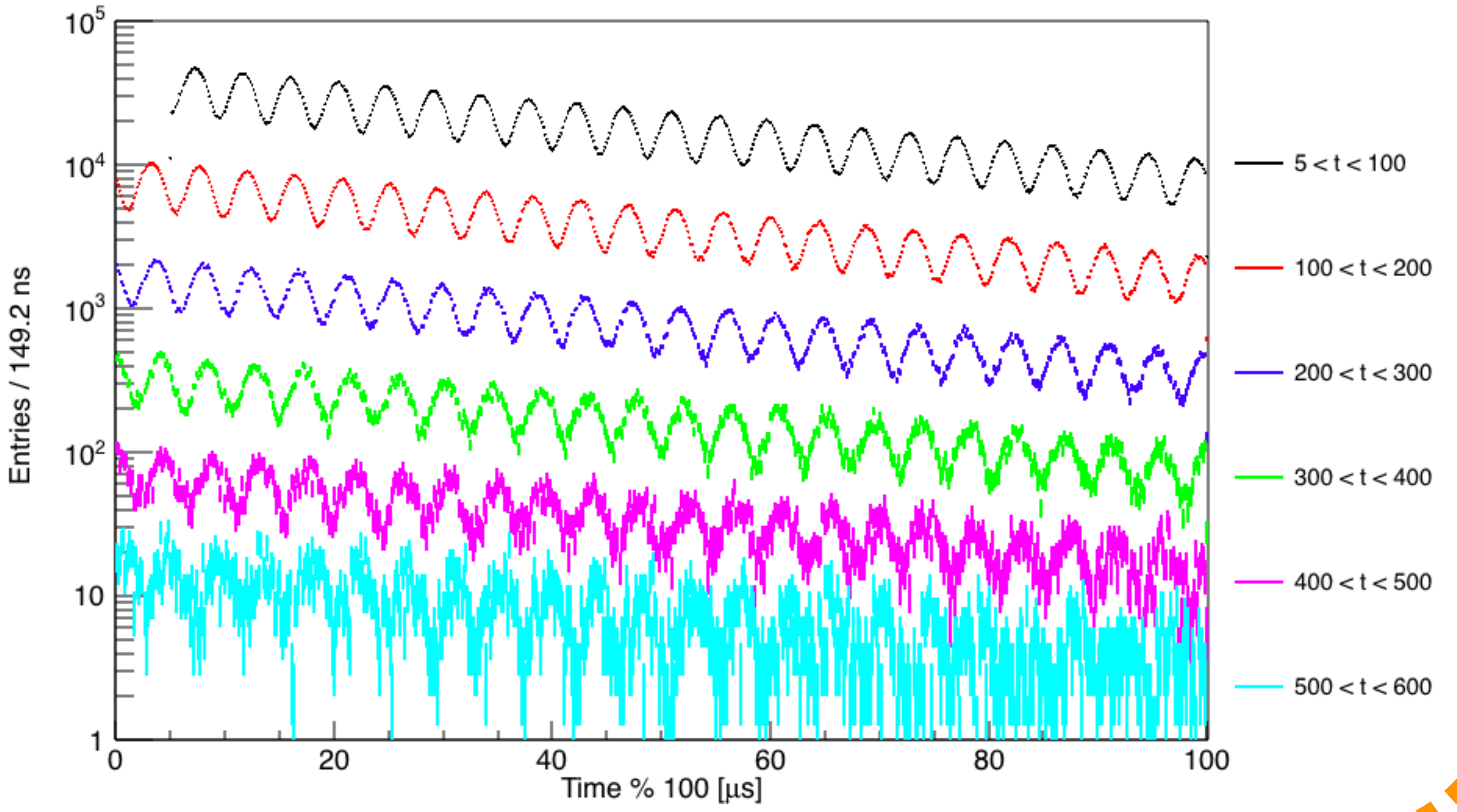
Muons orbit around the magnet and **precess**



Muons decay to electrons which are recorded by detectors



Muon precession frequency = frequency of number of electrons in detectors vs time



Muon precession frequency

$$a_\mu \propto \omega_a$$

Anomalous magnetic moment

But that's not the end of the story…

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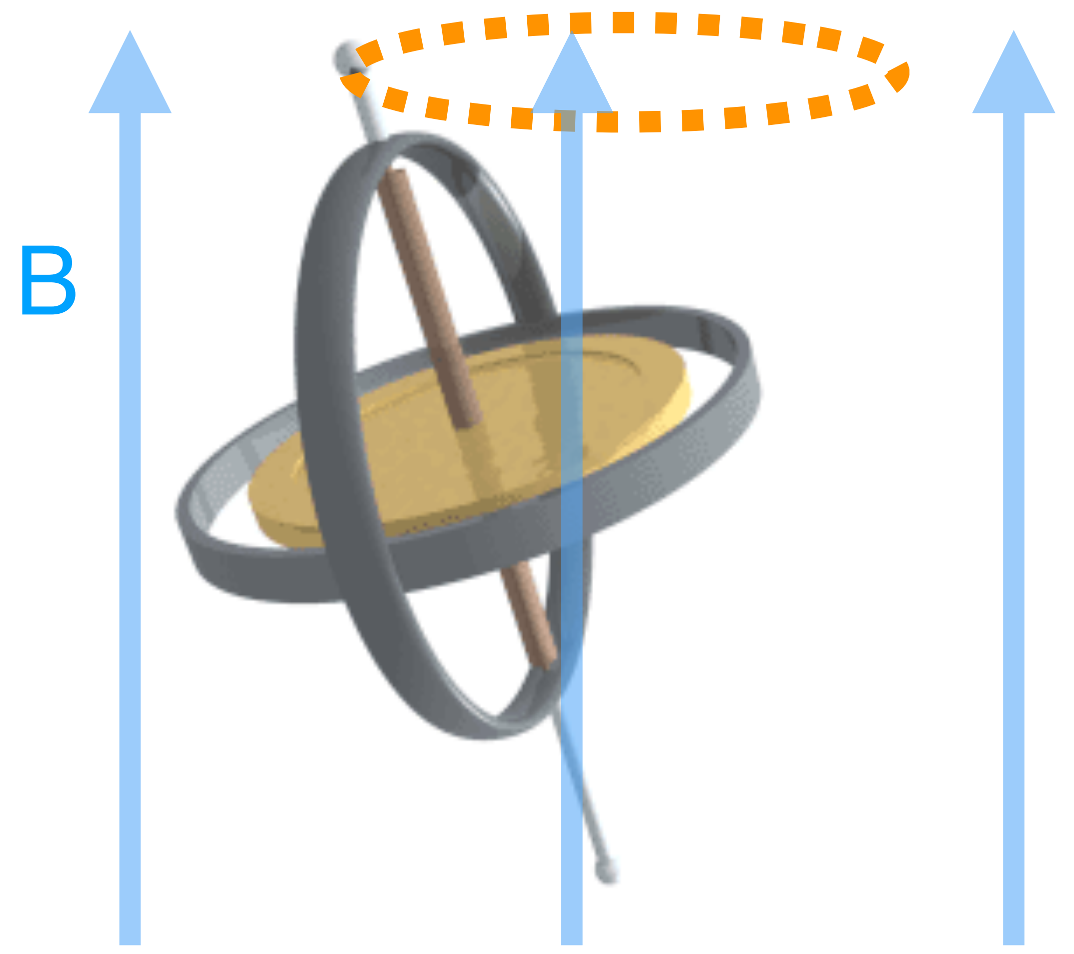
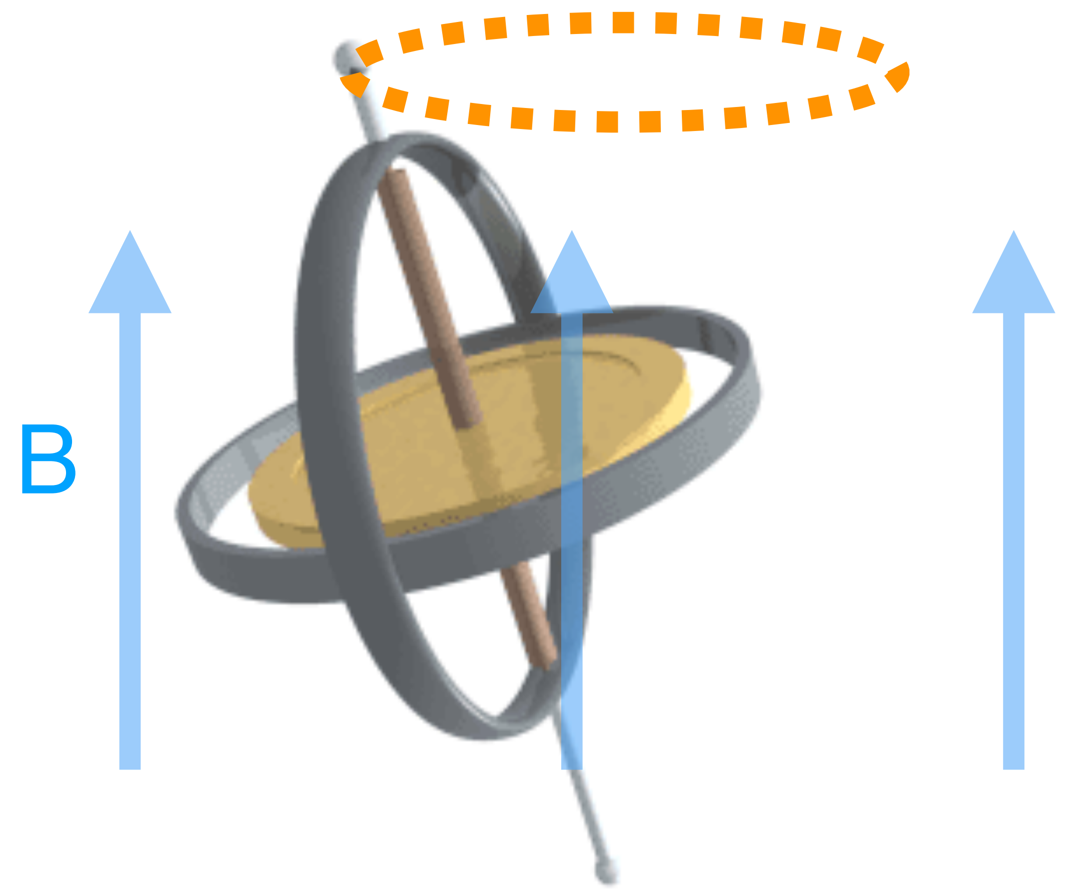
Precession frequency and magnetic field

If the magnetic field changes, so does the precession frequency



Precession frequency and magnetic field

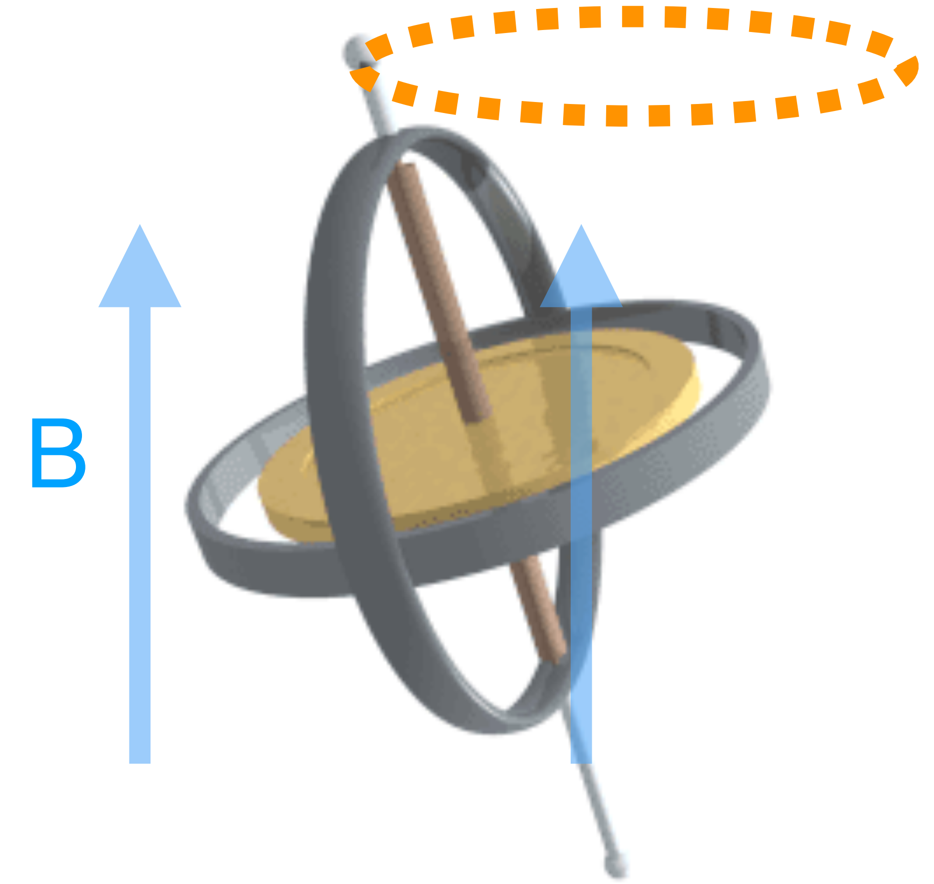
If the magnetic field changes, so does the precession frequency



Any change in the magnetic field will affect the value of a_μ that we measure

Precession frequency and magnetic field

If the magnetic field changes, so does the precession frequency



Any change in the magnetic field will affect the value of a_μ that we measure

We need to measure the **ratio** between the muon precession frequency and the **magnetic field**

$$a_\mu \propto \frac{\omega_a}{B}$$

We use proton NMR to measure B, which means we actually measure the **proton precession frequency**:

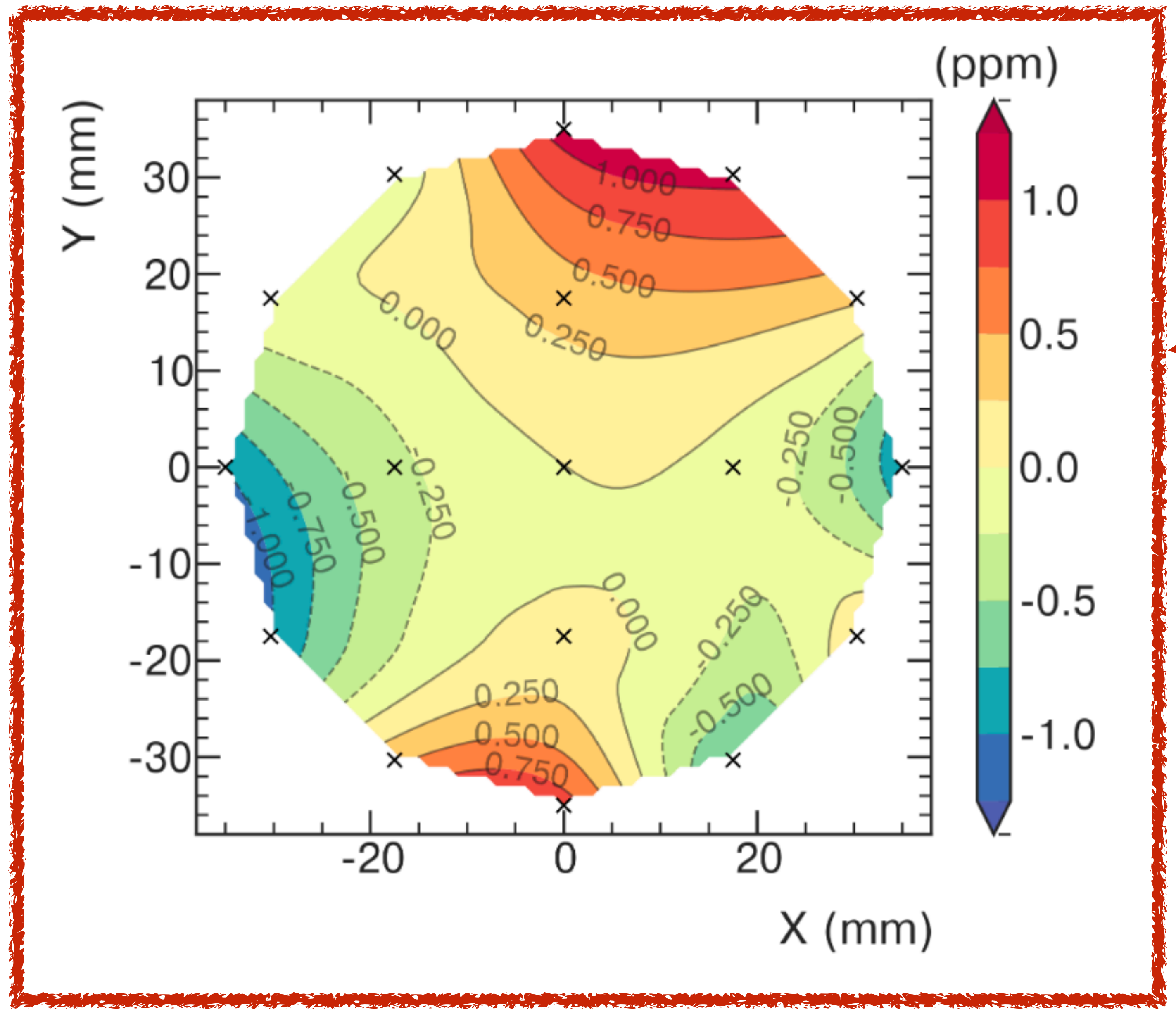
$$\hbar\omega_p{}' = 2\mu_p B$$

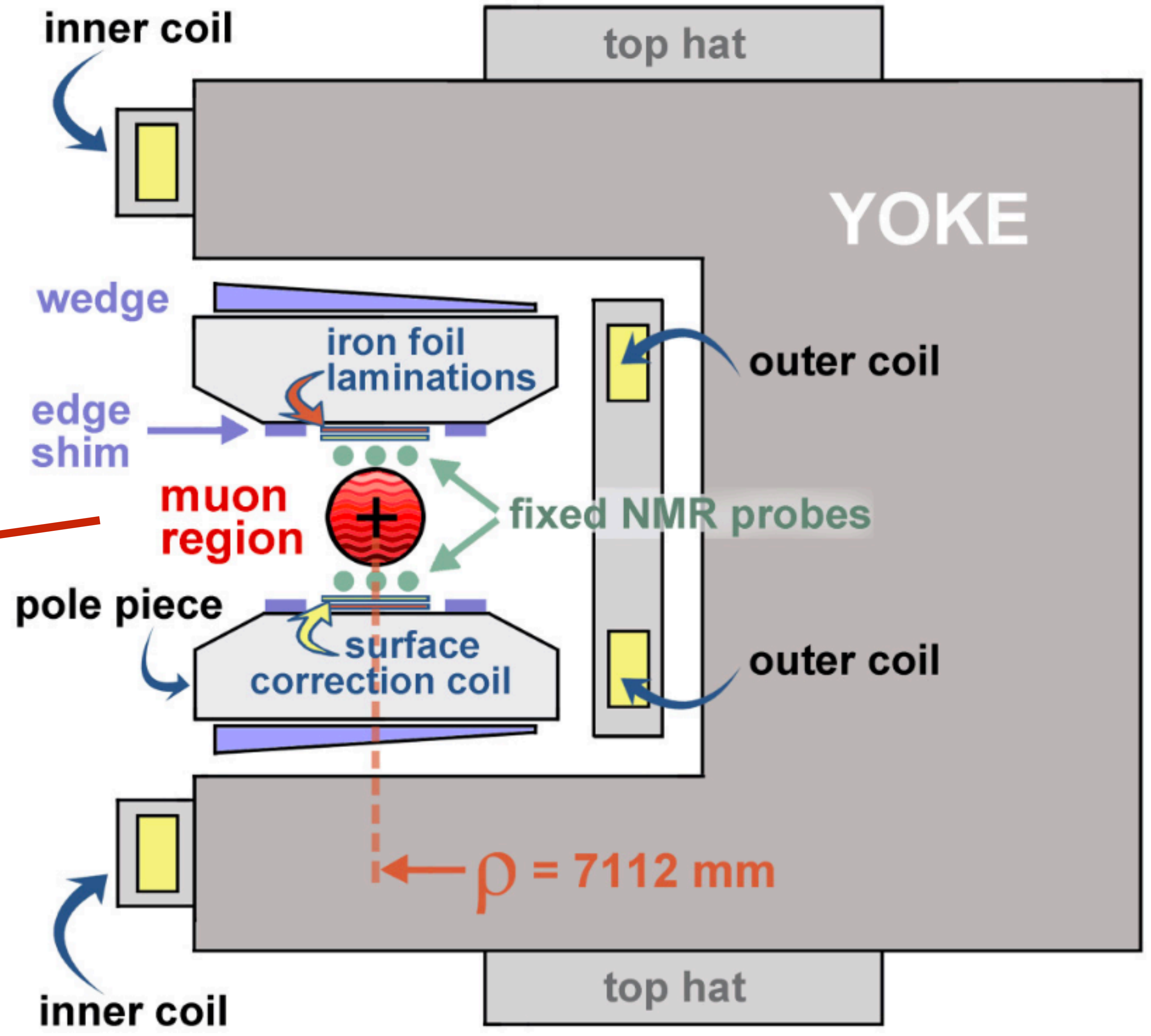
Finally, we need to relate the proton precession frequency to the muon beam distribution — **the "muon-weighted" field**

$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p{}'}$$

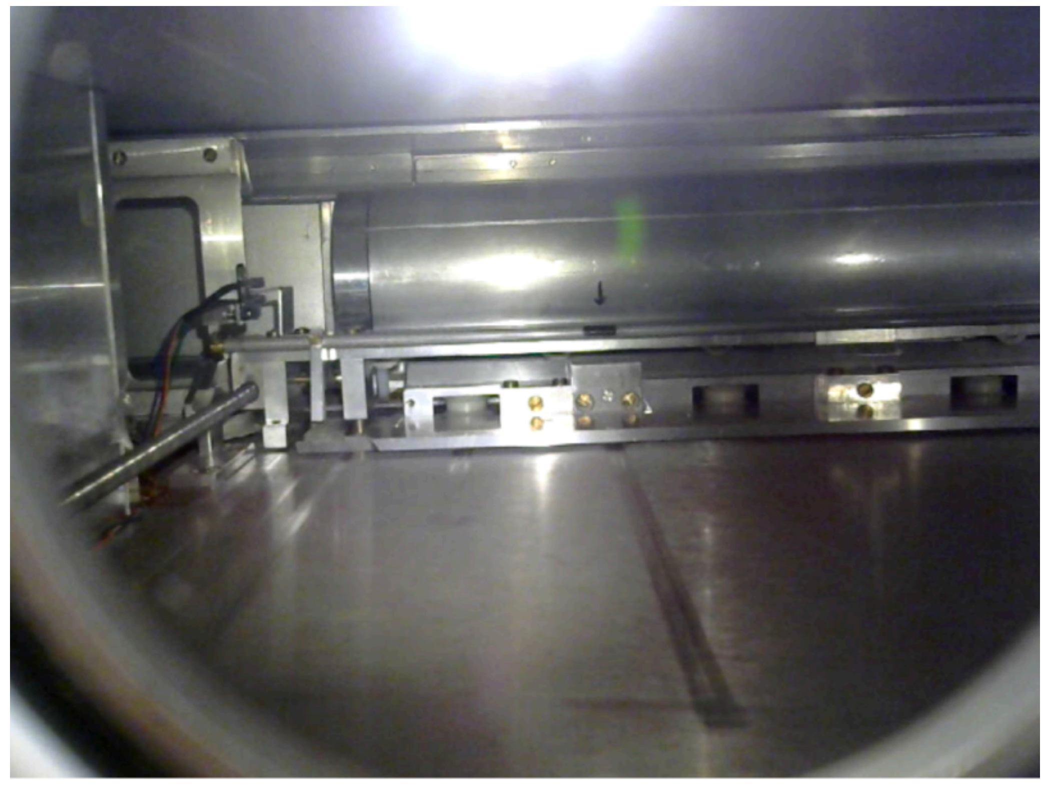
How do we measure the magnetic field?

Field inside the storage ring has **gradients** - not perfectly uniform over the whole muon storage region



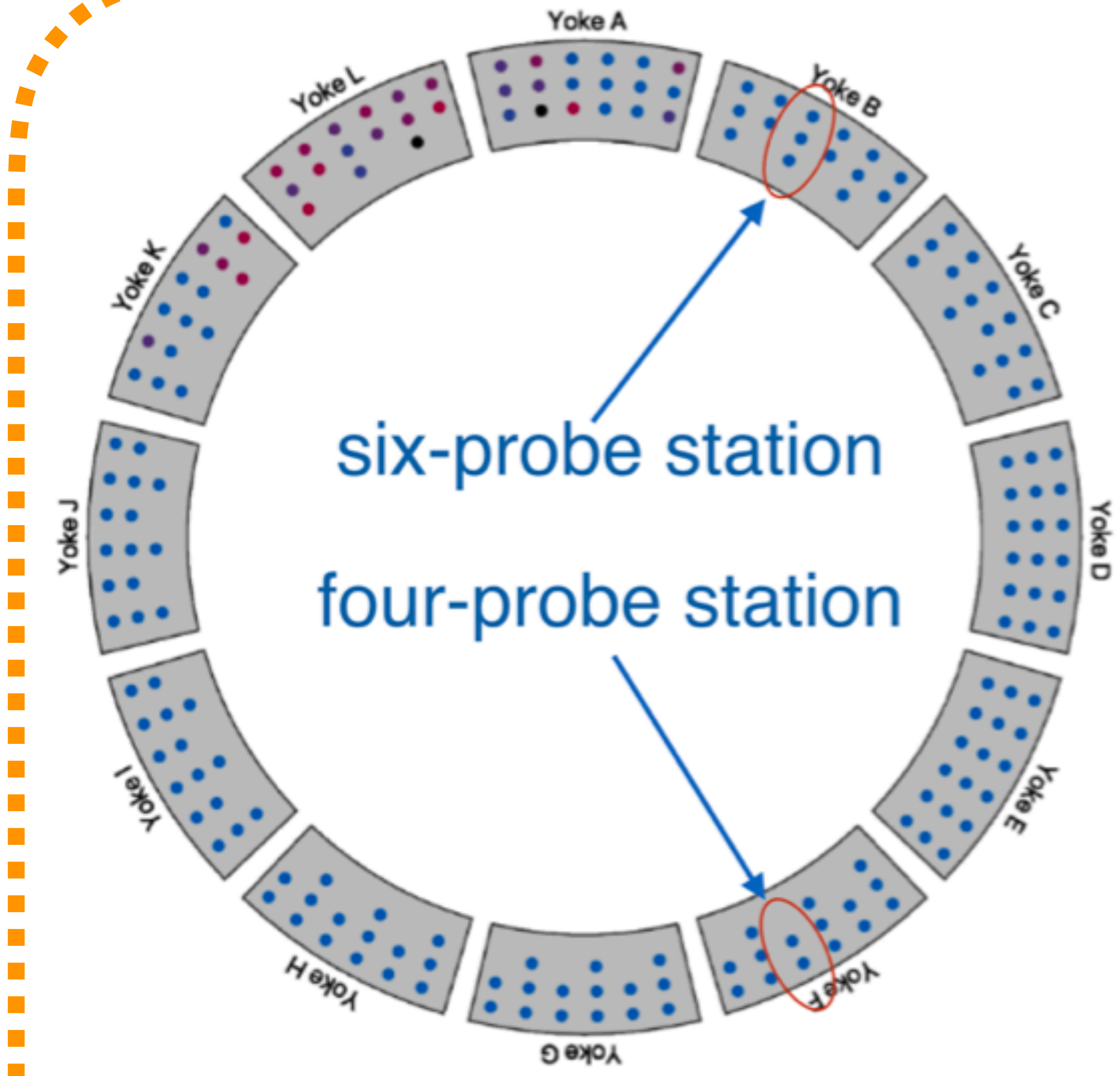


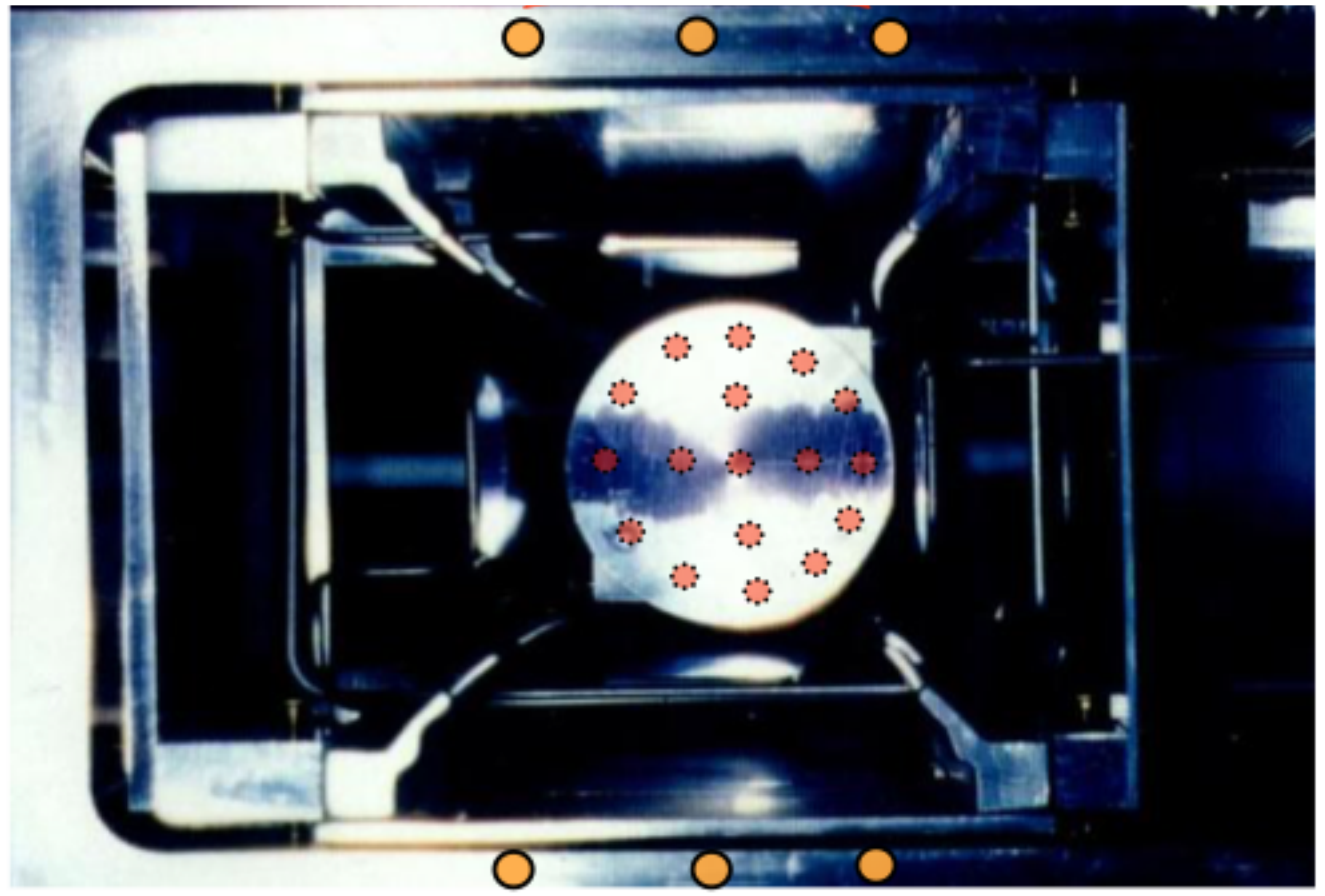
Gradients in muon region measured every ~3 days by a trolley with 17 NMR probes



More trolley details in: S. Corrodi *et al* 2020 *JINST* **15** P11008

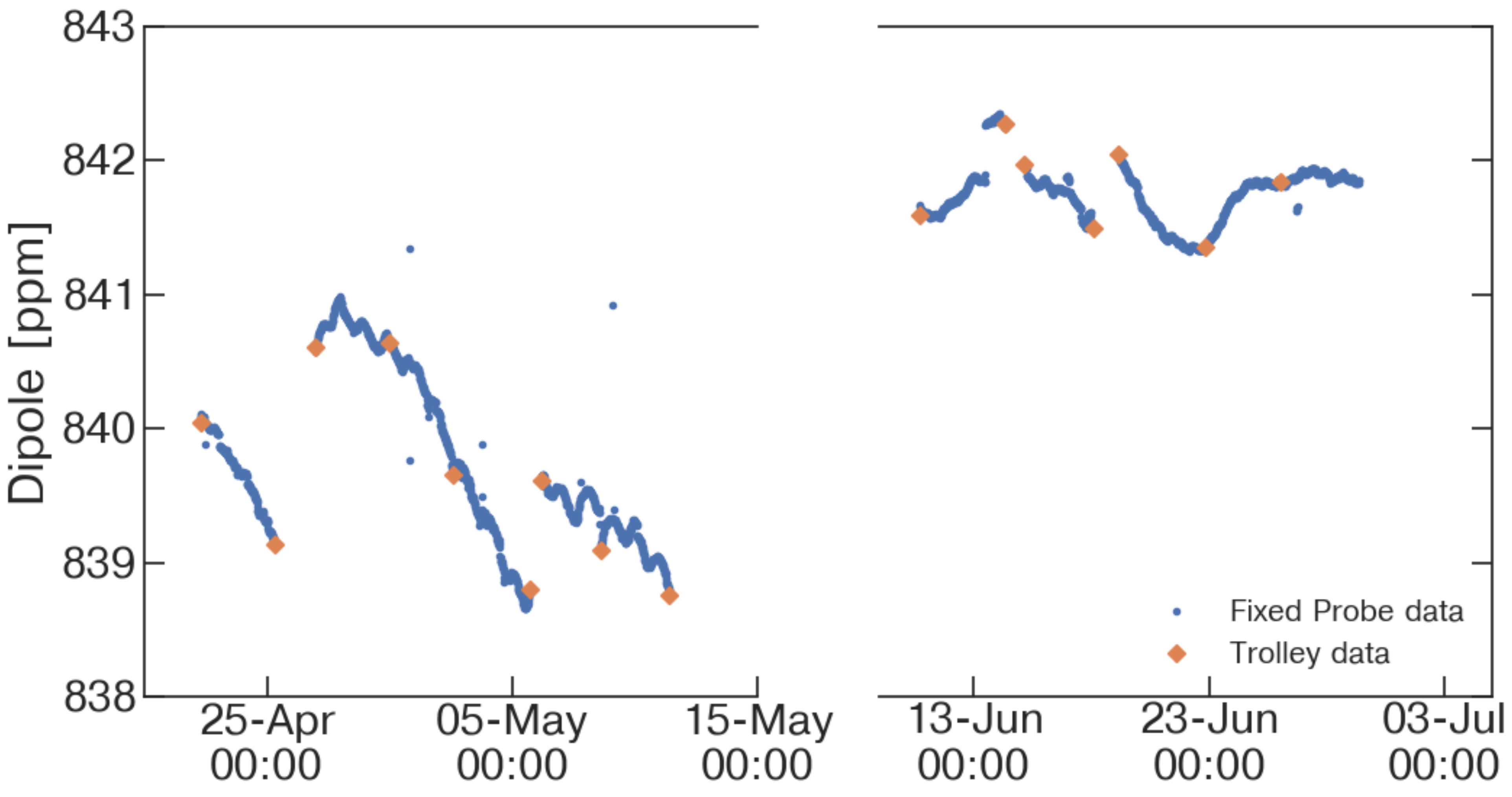
How do we measure the magnetic field?





Field gradients are not the same all the time — but we can't use the trolley to measure when we're receiving beam

Instead, we monitor changes over time with 378 "fixed" NMR probes



Relate trolley measurements to fixed probe measurements to obtain the field during the times the muons were present

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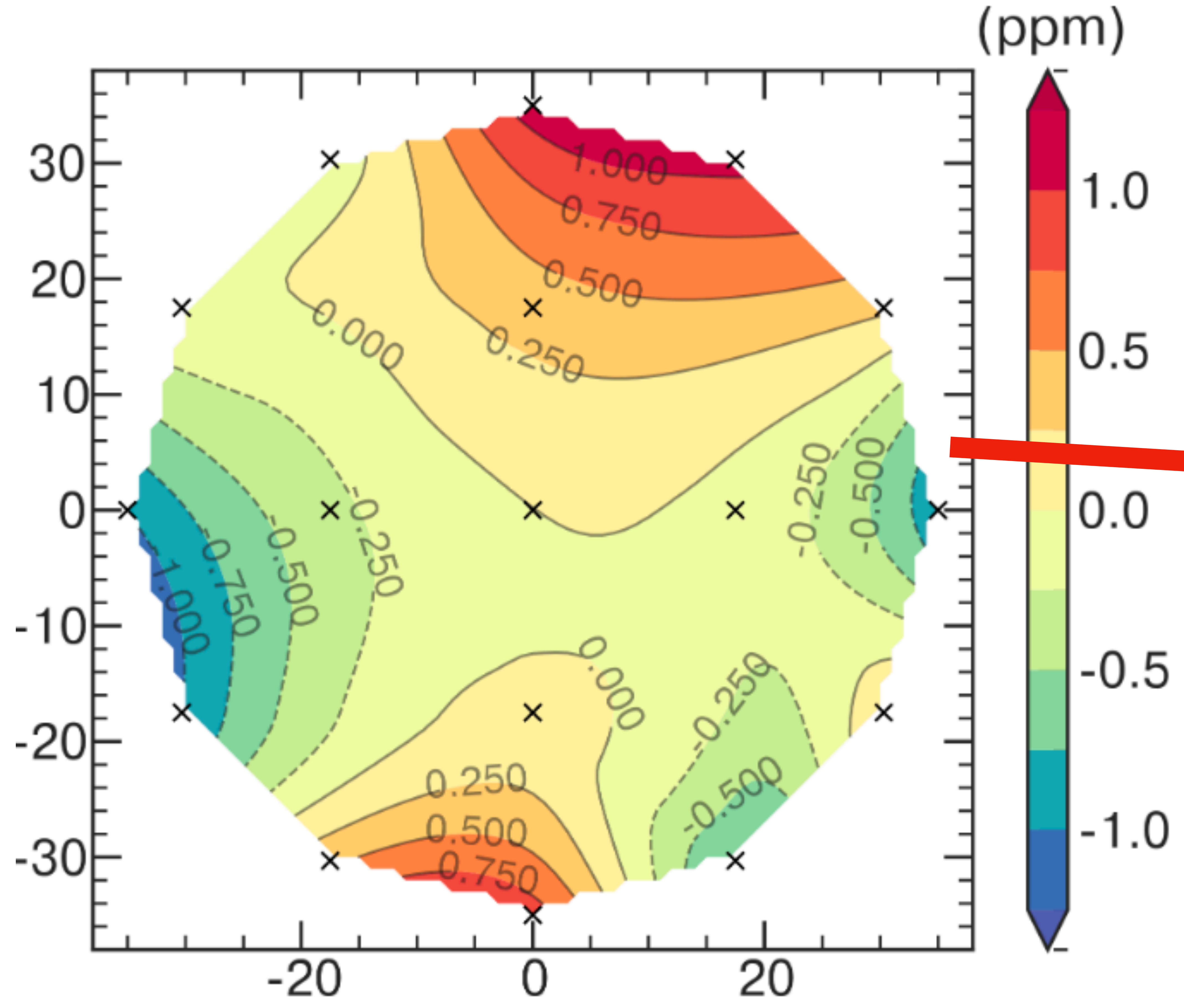
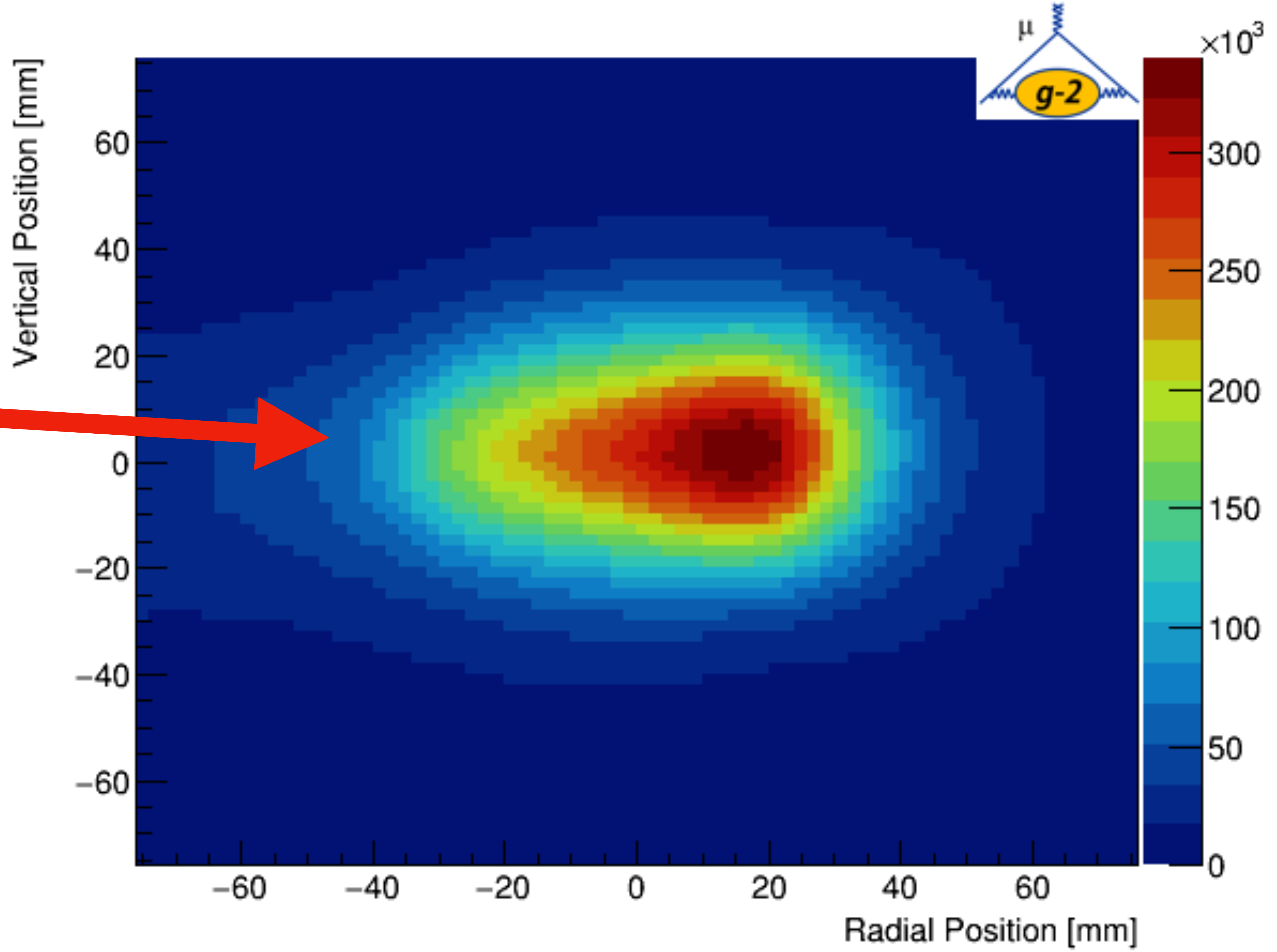
The muon-weighted field



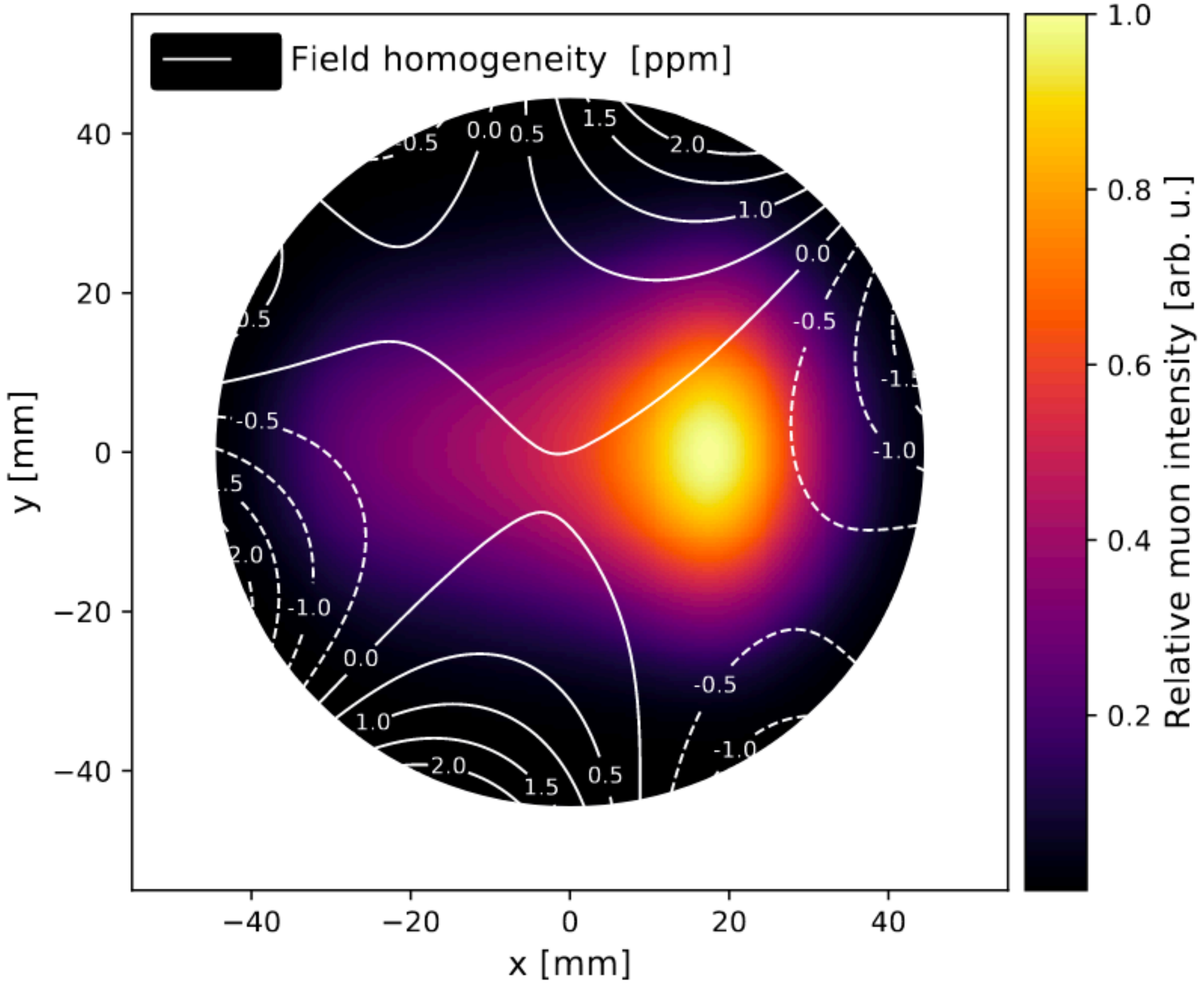


The muon beam does not sample all parts of the ring equally - some parts of the field are used more than others

The muon-weighted field

We need to mathematically combine the average muon beam distribution with the measured magnetic field map

- Measure the magnetic field all around the ring, at all times when muons are present
- Accurately measure the beam distribution using tracking detectors
- Try to keep the beam in the middle of the ring, where the field gradients are smaller

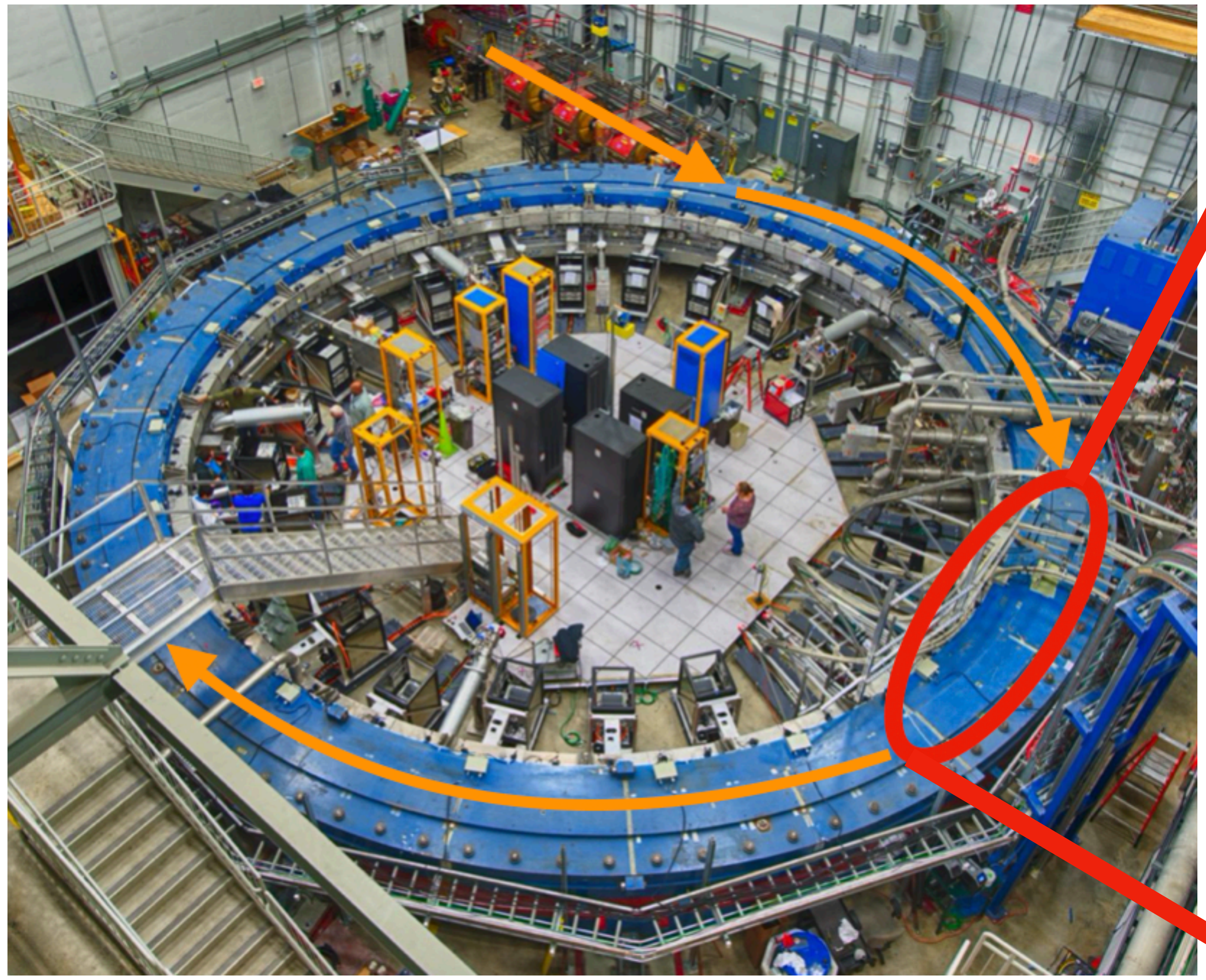


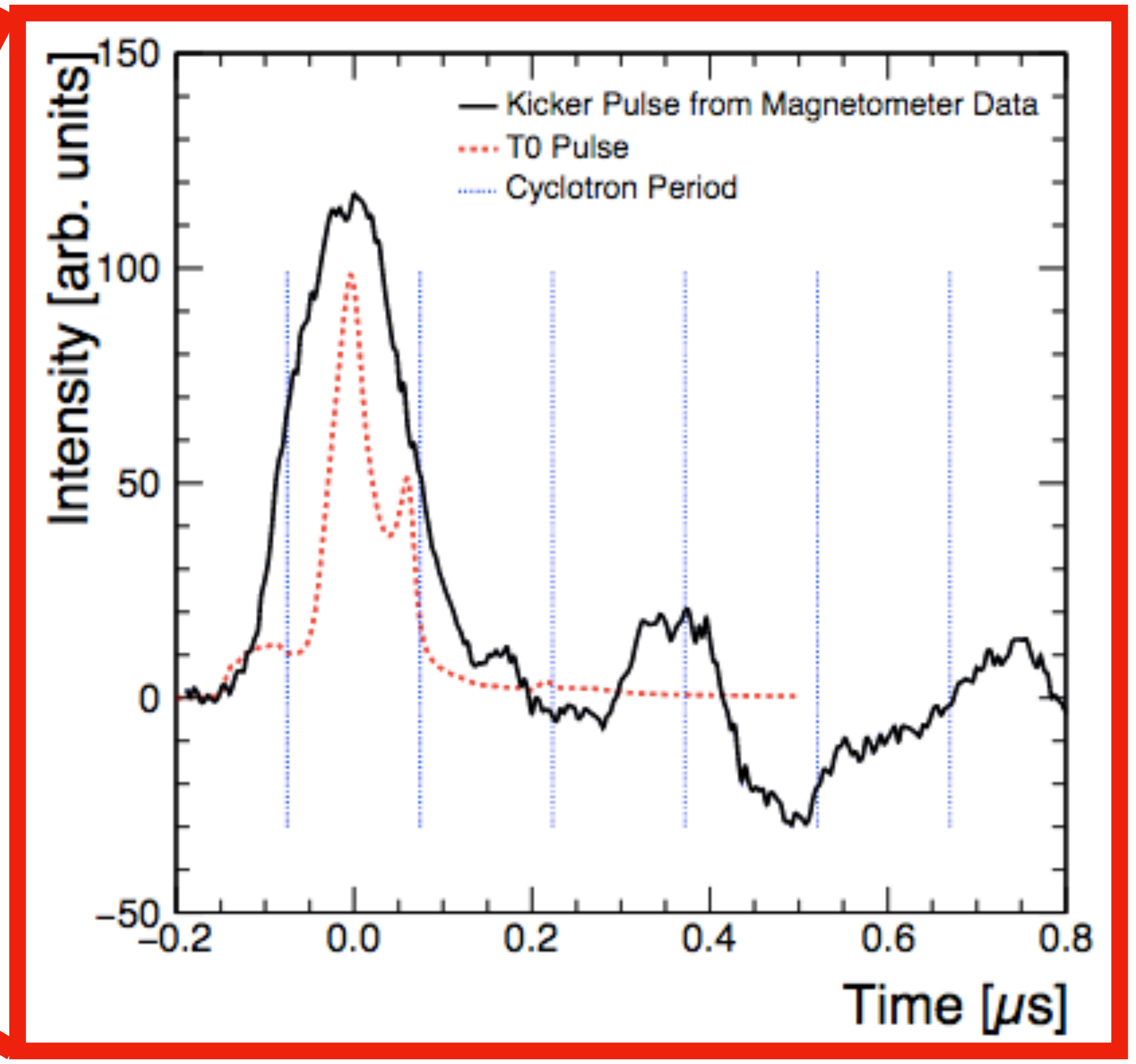
We need to do all this very precisely: experimental uncertainty budget is 50% ω_a and 50% ω_p

$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}_p{}'}$$

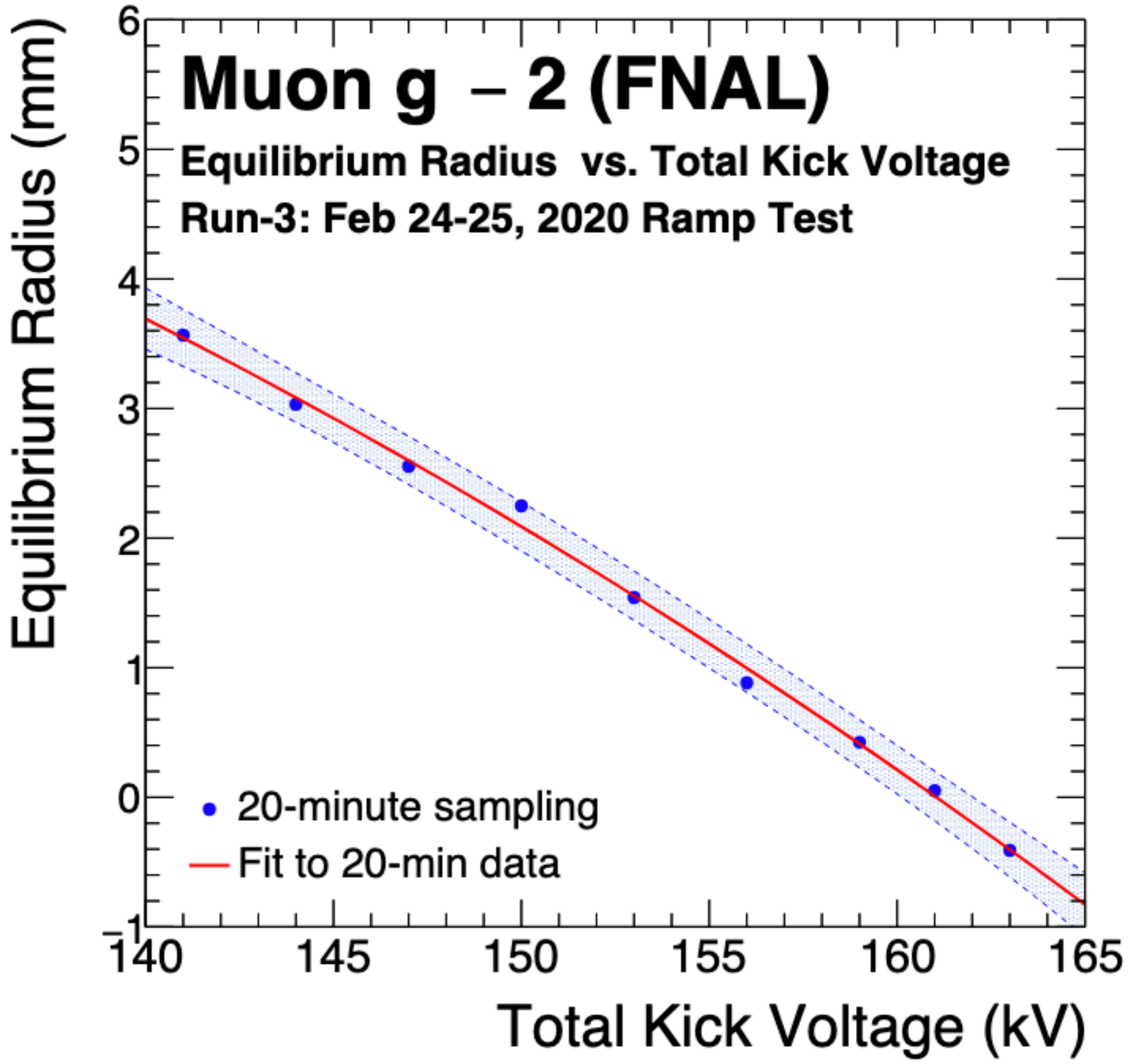
Centering the muon beam: the fast muon kicker

Muon beam injected at slightly wrong angle - need to “kick” the muons onto the correct orbit to get them to stay in the ring





Central beam radius directly proportional to kicker voltage



More kicker details in: A.P. Schreckenberger *et al* NIM A 1011 (2021) 165597

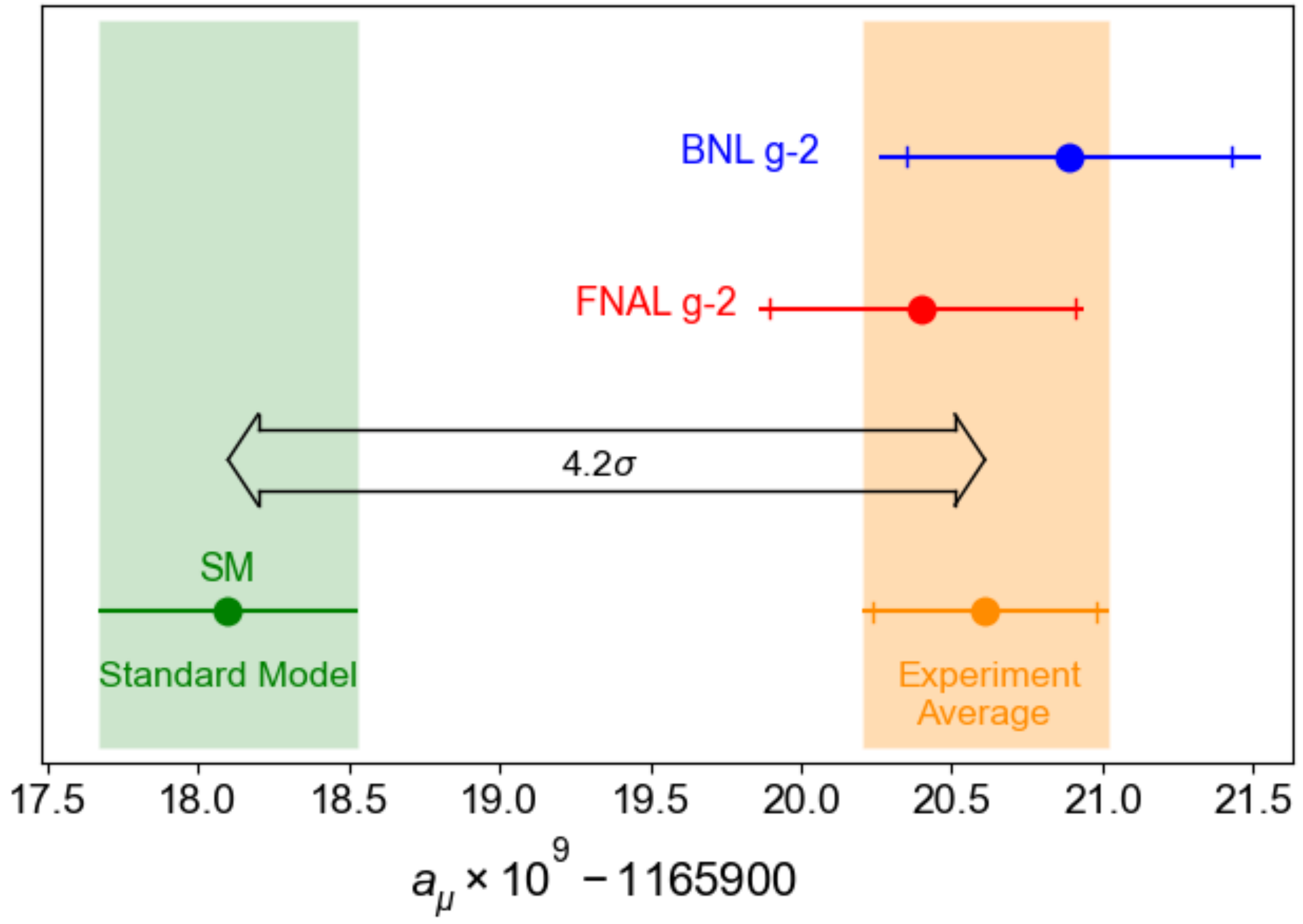
“New Horizons” for Muon Physics

Measured discrepancy with currently accepted SM prediction is 4.2σ (when combined with previous measurement at BNL)

This result was from < 10% of our total dataset - already have much more data recorded that is being analyzed now

Will the gap widen to 5σ? If it does, what is the reason? Will the SM value stay the same?

Either way, muon physics is pushing the boundaries of our understanding of the SM - and perhaps muons will point us to finding new physics!



Many other interesting muon experiments at labs around the world (including Fermilab)

+ more to come…

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Thank you to a fantastic collaboration!!!