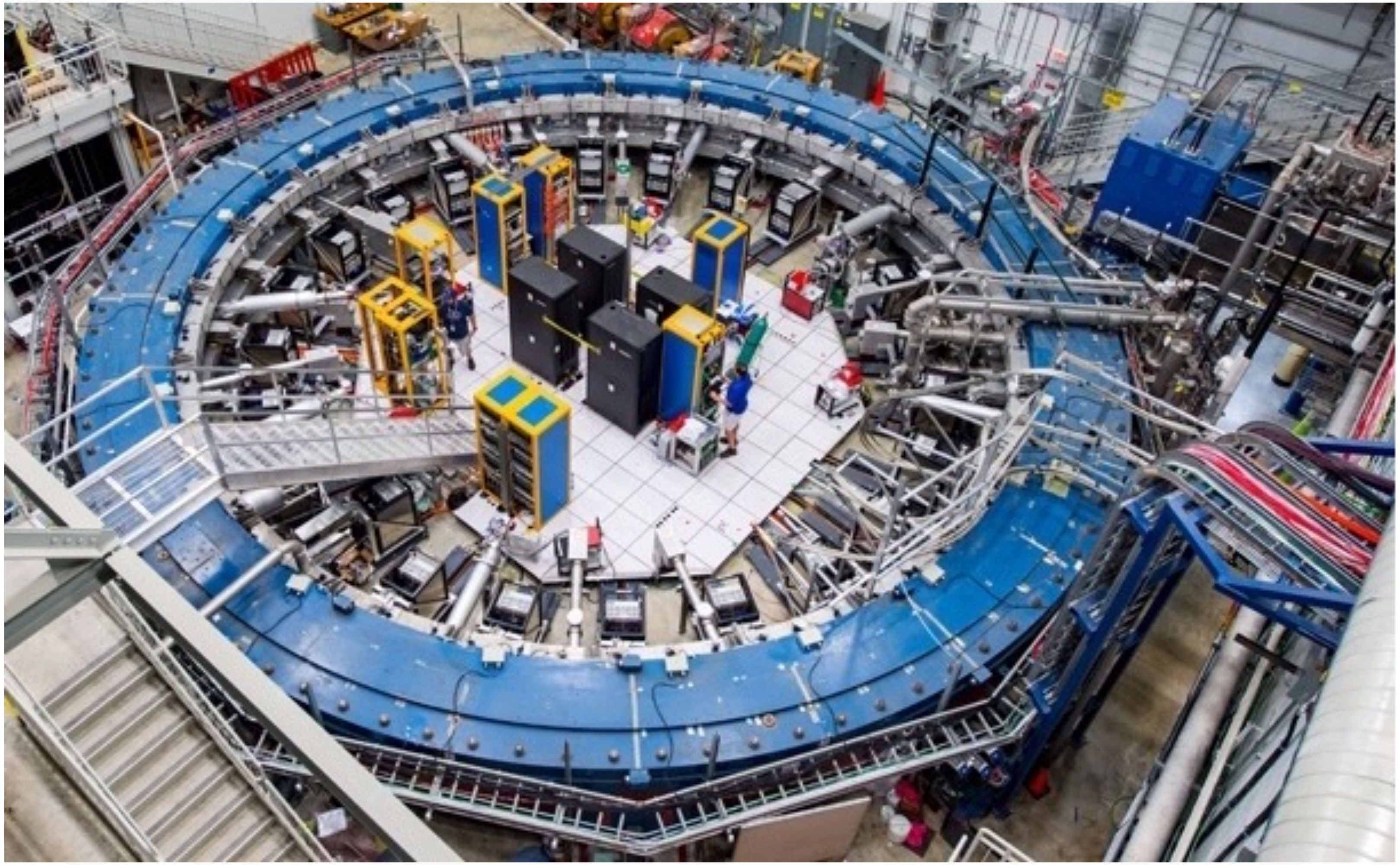
Fermilab

A New Measurement of the Muon Anomalous Magnetic Moment to 0.43 ppm

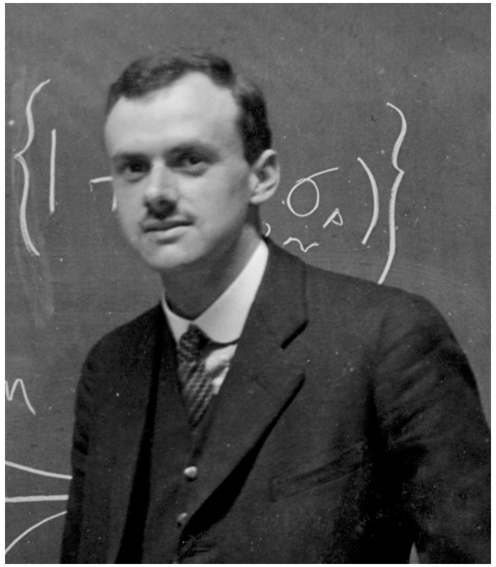


Hogan Nguyen
Fermilab

Seminar
Institute of Nuclear Physics
PAN, Krakow, Poland
October 7th, 2021

Charged particles with spin have a magnetic moment.

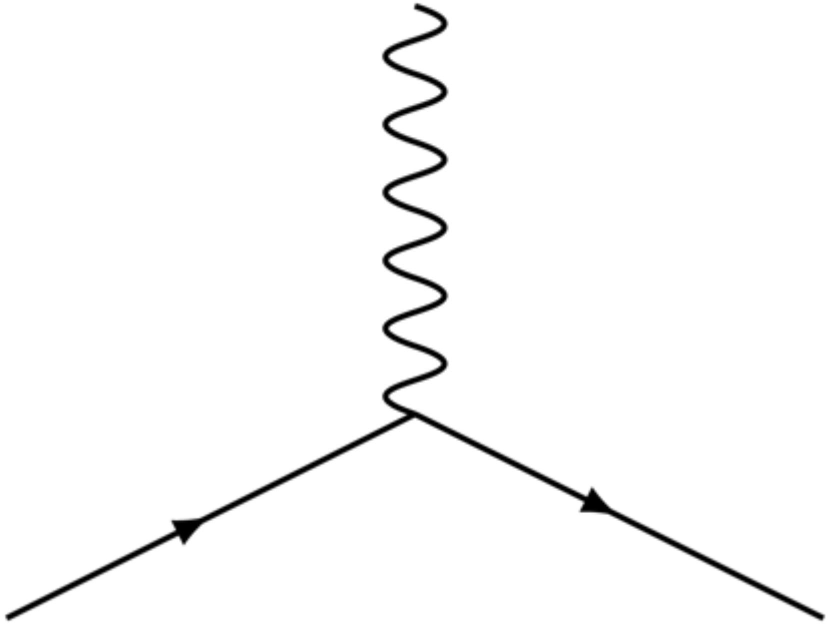
$$\boldsymbol{\mu} = g_{\mu} \frac{e}{2m_{\mu}} \boldsymbol{S}$$



g_{μ} = gyromagnetic ratio

A triumph of the Dirac Equation and Quantum Electrodynamics (QED)

Lowest Order QED Predicts $g_{\mu} = 2$

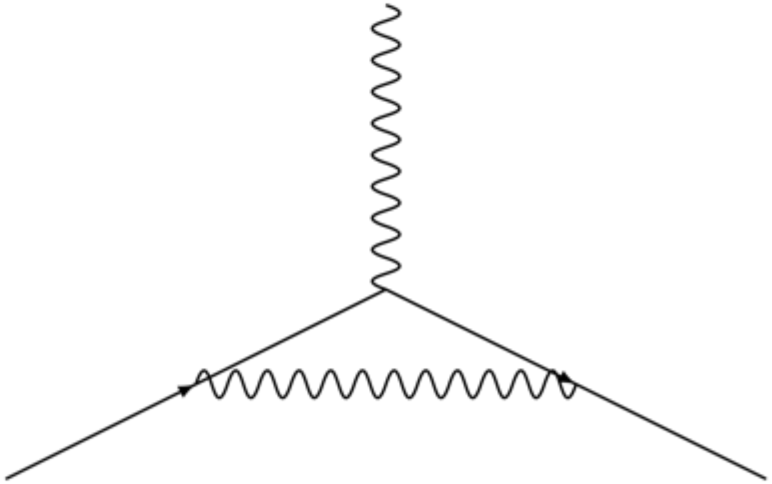


However, Quantum Corrections predicts $g_\mu \neq 2$

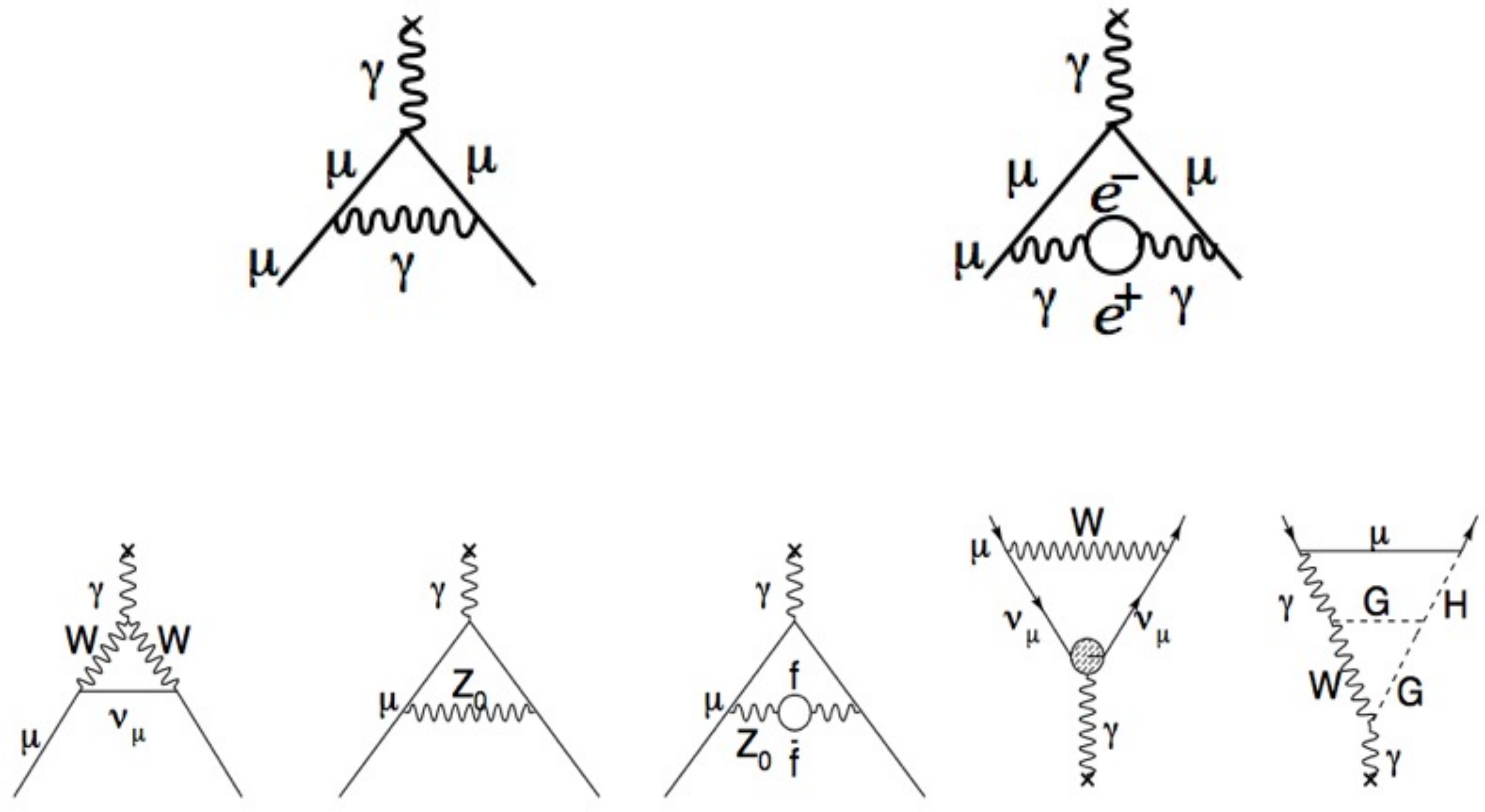
The anomalous portion is called a_μ

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

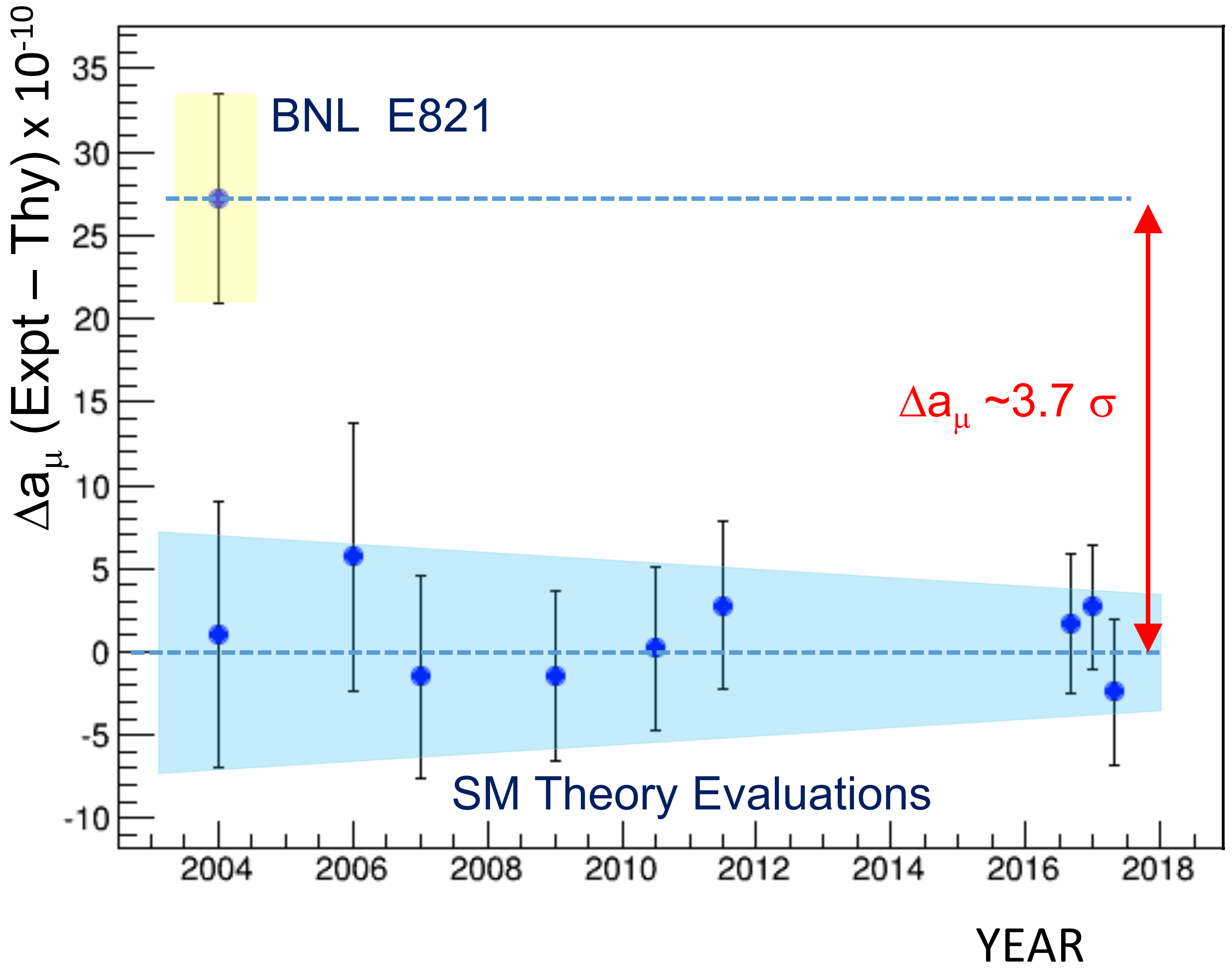
Schwinger was the first to calculate the 1-loop QED correction.



a_μ probes TeV scale physics via quantum corrections !



History of Theory and Measurements



Plot by D. Hertzog

Muon g-2

>200 collaborators
35 Institutions
7 countries

experimentalists
accelerator physicists
... and theorists

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS
- KAIST

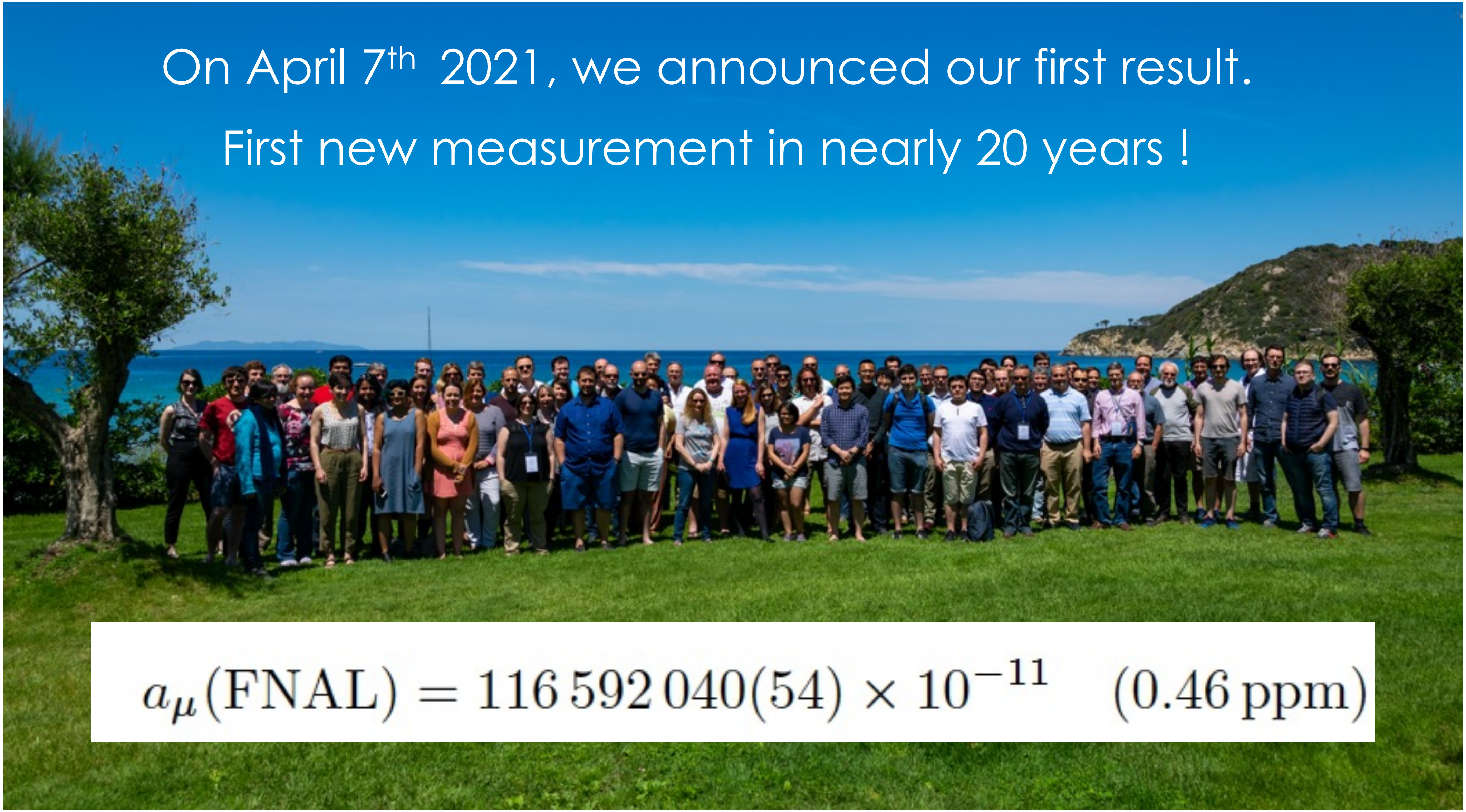
Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

g-2 Apparatus Moved From BNL to Fermilab

On April 7th 2021, we announced our first result.

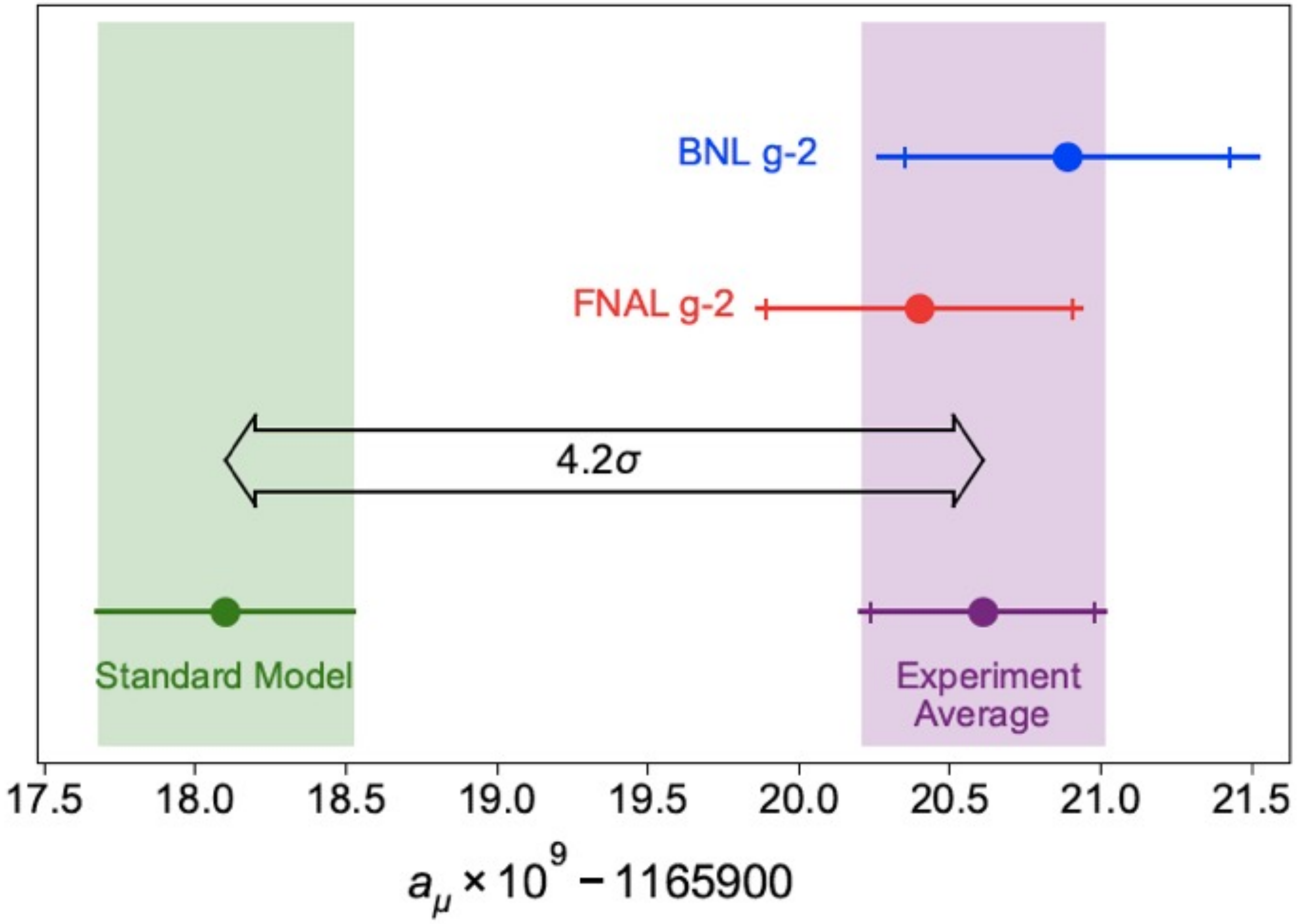
First new measurement in nearly 20 years !



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

We agree with BNL !



3.7 σ

3.3 σ

Made Quite a Splash!

On April 7, 2021

Luke Skywalker approves…

Mark Hamill @HamillHimself · Apr 7
Evidence is mounting that The Force has been with us…
ALWAYS.

> **The New York Times** @nytimes · Apr 7
> Breaking News: Evidence is mounting that a tiny subatomic particle is being influenced by forms of matter and energy that are not yet known to science but which may nevertheless affect the nature and evolution of the universe. nyti.ms/3uzXOCb

1.3K 13.2K 92.7K

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PHYSICS

Long-Awaited Muon Measurement Boosts Evidence for New Physics

Initial data from the Muon g-2 experiment have excited particle physicists searching for undiscovered subatomic particles and forces

By Daniel Garisto on April 7, 2021

NATIONAL GEOGRAPHIC LOGIN

The Muon g-2 ring … negative 450 degr… travel through a m…
PHOTOGRAPH …

SCIENCE |

New ex… particl… physic…

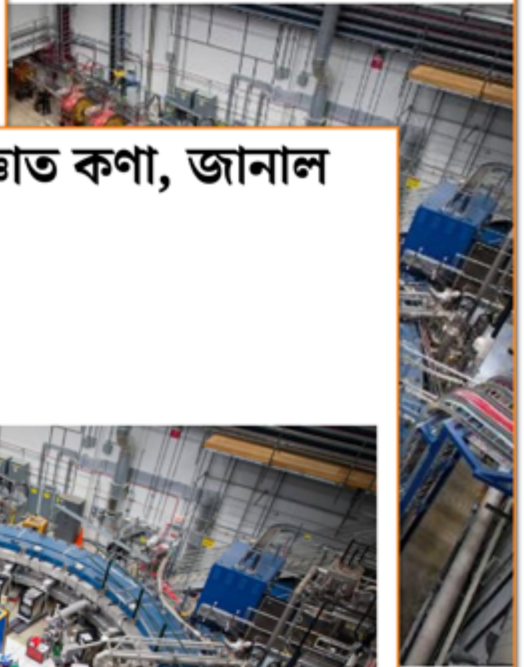
A heavier siblin… "Standard Mod…

The New York Times

OUT THERE

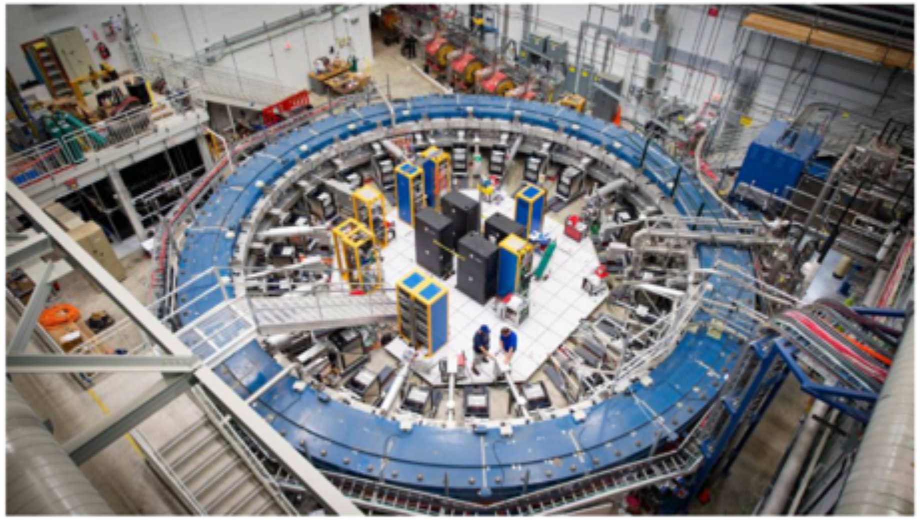
…ticle's Wobble Could …Known Laws of Physics

…ticles known as muons suggest that there …nd energy vital to the nature and evolution of …ot yet known to science.



ব্রহ্মাণ্ডে রয়েছে আরও অজ্ঞাত কণা, জানাল চেনা কণার আজব আচরণ

নিজস্ব সংবাদদাতা কলকাতা ০৯ এপ্রিল ২০২১ ১৬:৫৭



ফার্মিল্যাব-এর সেই মিউয়ন জি মাইনাস ২ রিং। যেখানে চেনা কণার অদ্ভুত আচরণ ধরা পড়েছে। ছবি সৌজন্যে- ফার্মিল্যাব।

Why all the excitement ?

BNL and FNAL agree: results are less likely to be a fluke

The Standard Model prediction is extremely solid (more later)

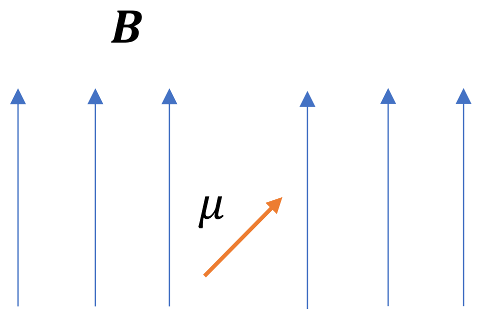
We can talk seriously about new physics

The Theory .....

To fully appreciate the implications of a_μ

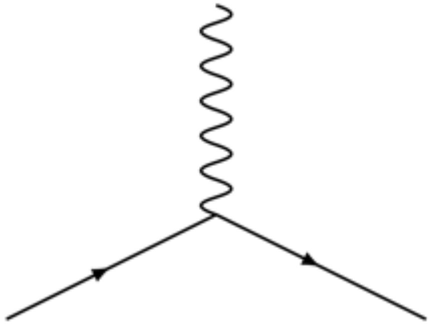
I must review (or introduce) some concepts
in Quantum Field Theory

e.g. See Peskin & Schroeder: Introduction to QFT



$$U = -\frac{e}{m}(1)\,\boldsymbol{s}\cdot\boldsymbol{B}$$

Nonrelativistic QM



$$M \sim \bar{u}_\mu[e\gamma_\alpha]u_\mu A^\alpha(q)$$

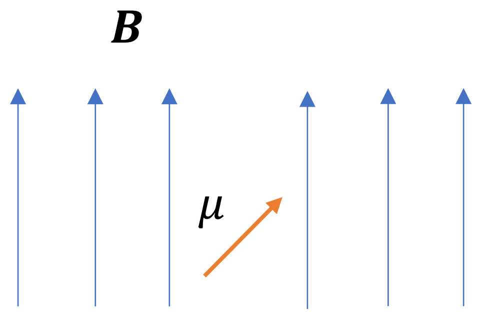
Lowest Order

Quantum Field Theory Language and Dirac Spinors

γ_α connects $u_L \to \overline{u_L}$ and $u_R \to \overline{u_R}$

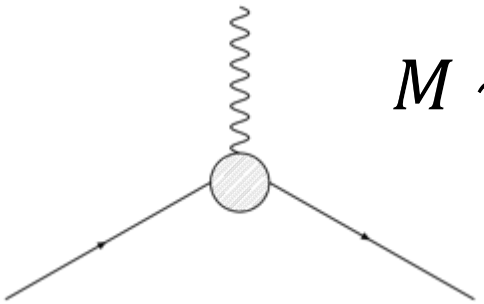
Basic property of Dirac Gamma Matrices and Spinors

"It does not flip chirality"



$$U = -\frac{e}{m}\left(1 + a_\mu\right) \boldsymbol{s} \cdot \boldsymbol{B}$$

Nonrelativistic QM



$$M \sim \bar{u}_\mu \left[e F_1(q^2)\gamma_\alpha + \frac{ie}{2m} \boldsymbol{F_2(q^2)\sigma_{\alpha\beta}} q^\beta \right] u_\mu A^\alpha(q)$$

$F_1(0) = 1$ $\quad$ $\boldsymbol{F_2(0) = a_\mu}$

Most General Form for a CP conserving interaction between a muon and EM field

(QFT Language)

$\boldsymbol{\sigma_{\alpha\beta}}$ flips Chirality

It connects $\boldsymbol{u_L \rightarrow \overline{u_R}}$ and $\boldsymbol{u_R \rightarrow \overline{u_L}}$

General Statements

Diagrams contributing to $\boldsymbol{a_\mu}$ are

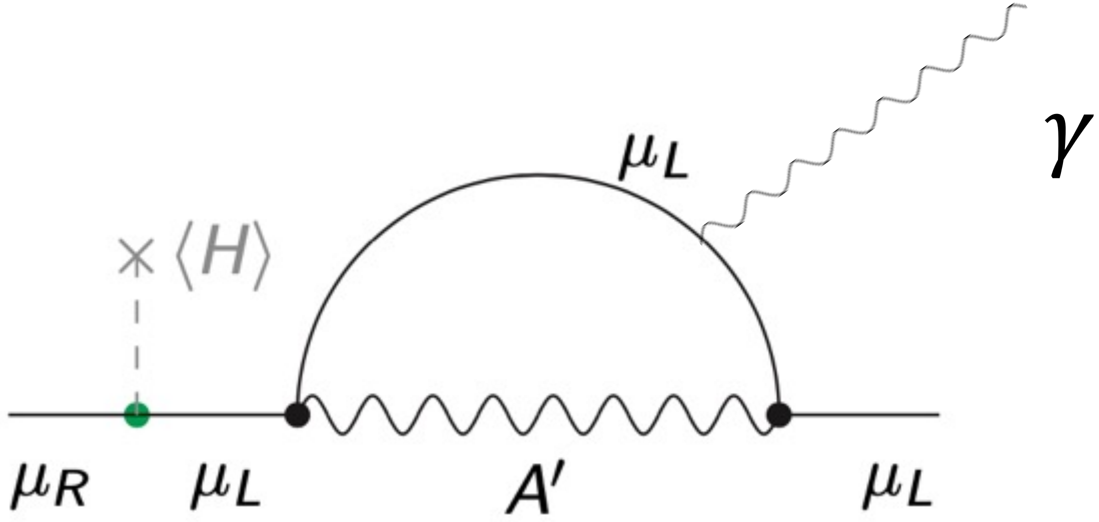
Loop-induced
CP Conserving
Flavor Conserving

and

Flips Chirality

The Higgs coupling to fermions flips chirality !

Example: Dark Photon



$$\Delta a_\mu \sim \frac{m_\mu^2}{M_{NP}^2}$$

(One power of m_μ for C-flip, another for the loop integral. Mass Scale for NP in the denominator)

General Statements

Diagrams contributing to $\boldsymbol{a_\mu}$ are

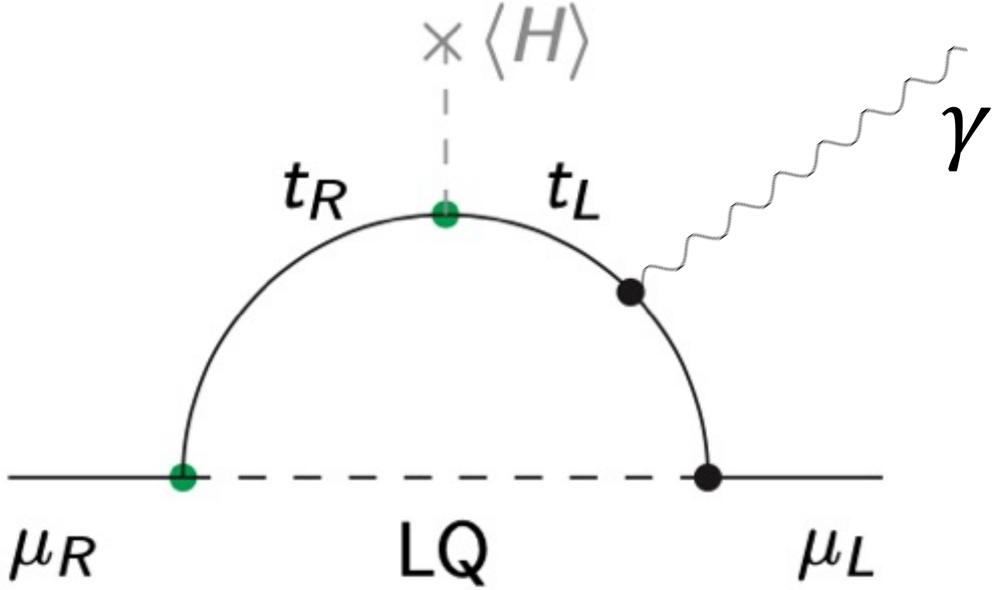
Loop-induced
CP Conserving
Flavor Conserving

and

Flips Chirality

The Higgs coupling to fermions flips chirality !

Example: Lepto Quark



$$\Delta a_\mu \sim \frac{m_\mu m_t}{M_{LQ}^2} \text{ (LQ couplings)}$$

(One power of m_μ for the loop integral.
One power of m_t for the C-flip, LQ couplings,
Mass Scale for LQ in the denominator)

The Standard Model Prediction

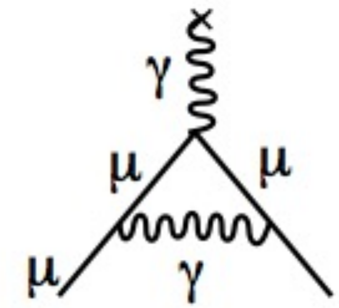
g-2 Theory Initiative to arrive at consensus SM prediction

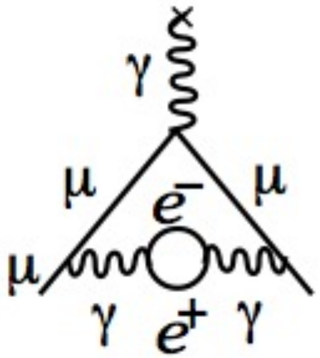
White Paper (WP) released in 2020

WP20 g-2 Theory Initiative

$$a_\mu = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{Weak}) + a_\mu(\mathrm{Hadronic})$$

QED
(known to at least 5 loops)

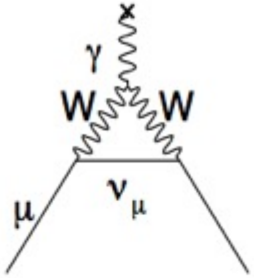


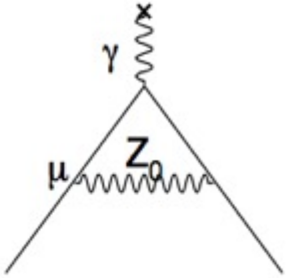


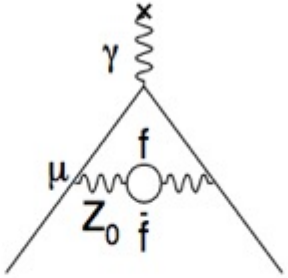
$116\,584\,718.9\,(1) \times 10^{-11}$

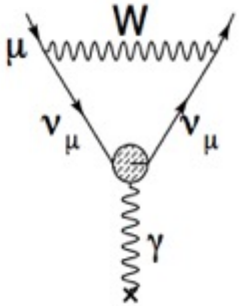
0.001 ppm

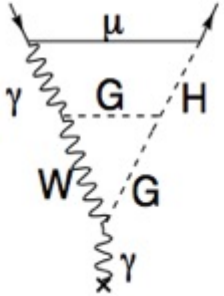
EW











$153.6\,(1.0) \times 10^{-11}$

0.01 ppm

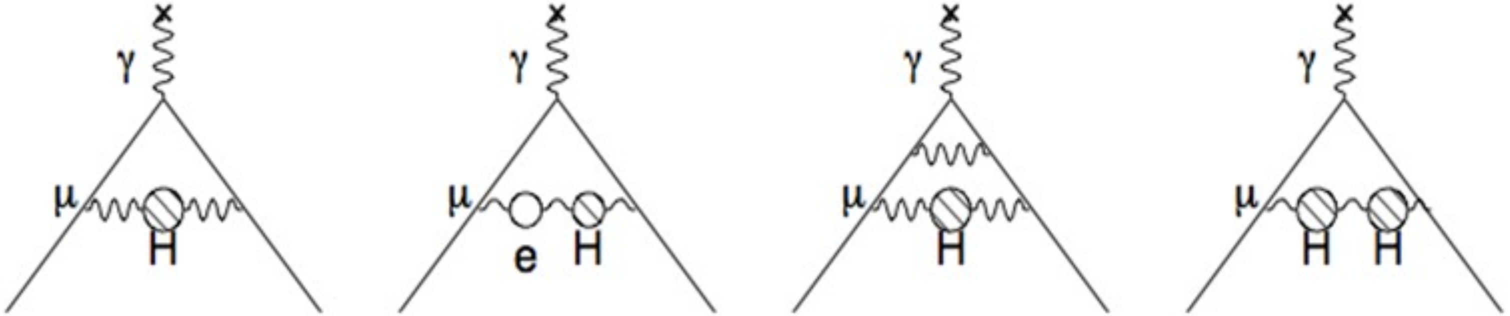
QED: Largest Size but smallest error

EW: Small contribution, but is a benchmark for sensitivity to higher mass scales

WP20 g-2 Theory Initiative

$$a_\mu = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$

Hadronic Vacuum Polarization

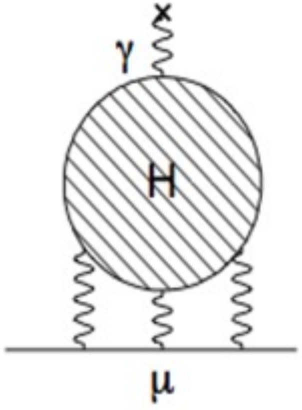


$6845\,(40) \times 10^{-11}$

[0.6%]

0.37 ppm

Hadronic Light-by-Light



$92\,(18) \times 10^{-11}$

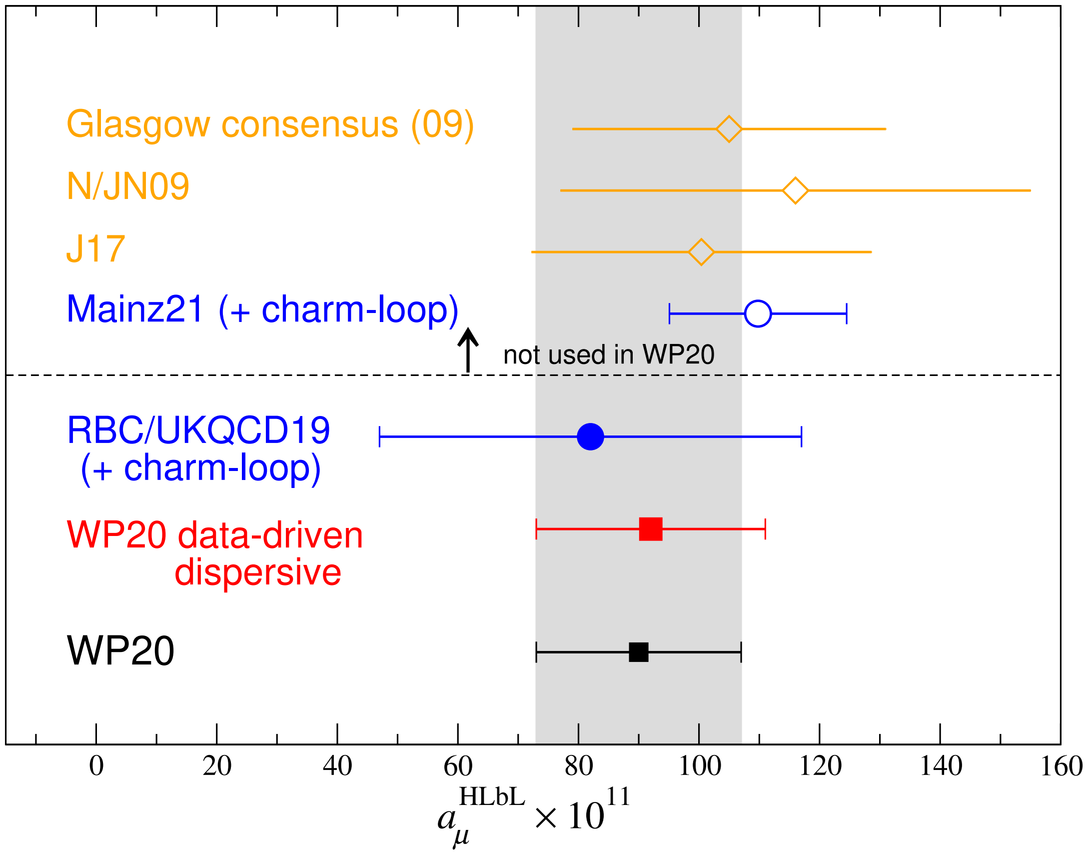
[20%]

0.15 ppm

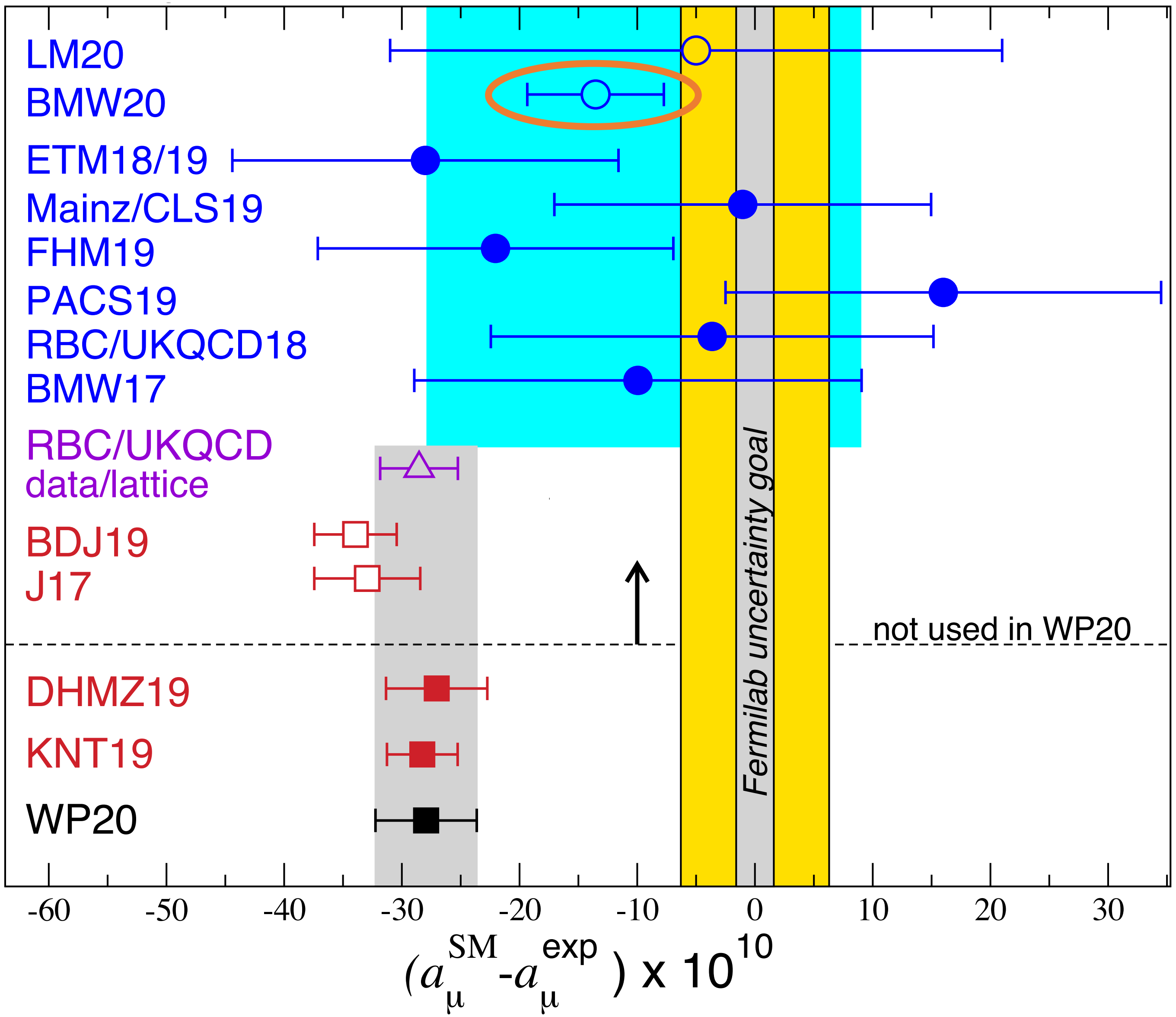
These two terms receive most of the attention.

WP20 uses primarily data-driven dispersive results

Hadronic Light-by-Light



$a_\mu^{SM} - a_\mu^{exp}$ for various HVP Estimates



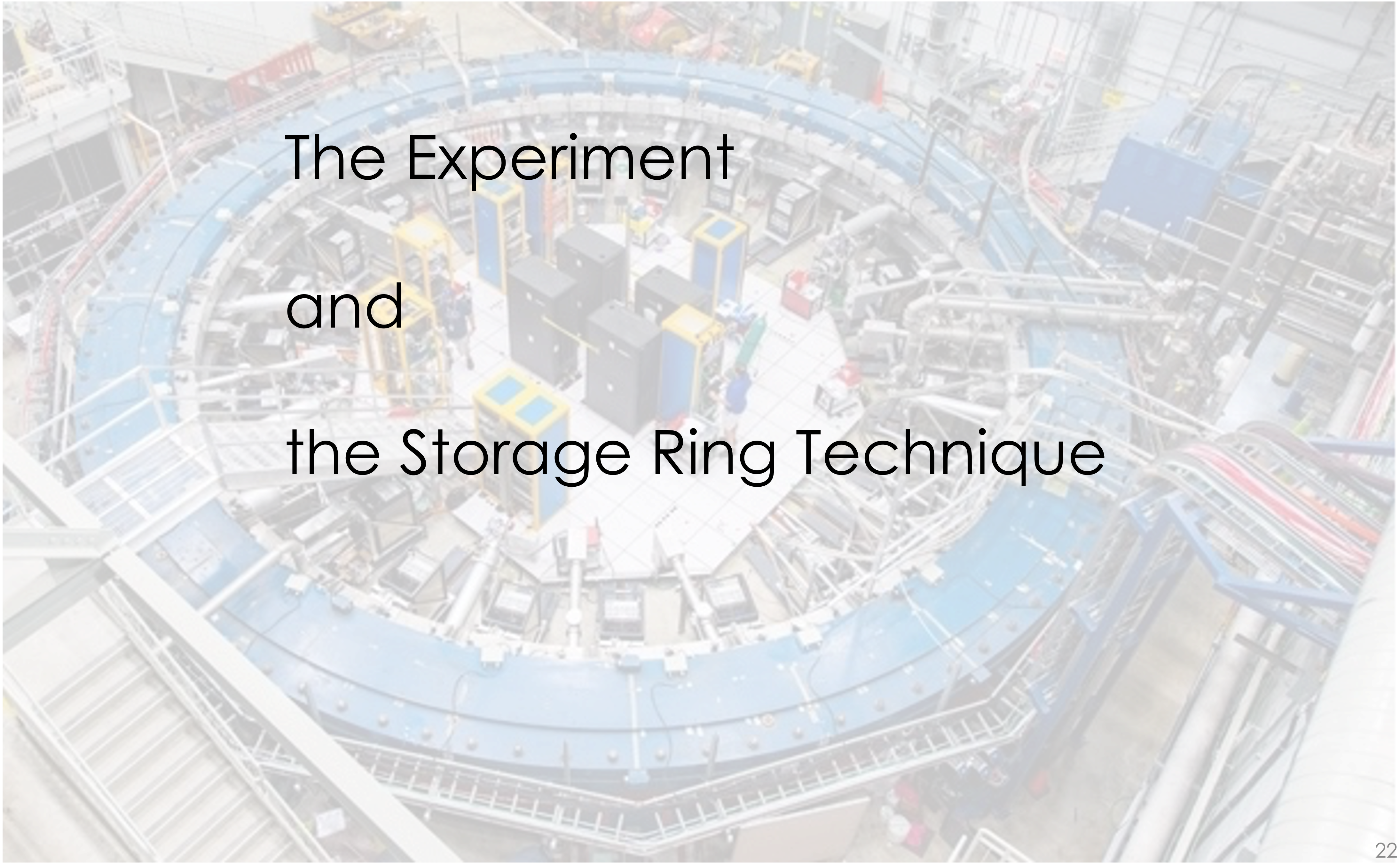
Lattice
Data-Based Dispersive
Lattice and Data
Official WP20 Value

Some Context

The BMW20 Result is the first Lattice QCD HVP result with sub % accuracy. The result is in tension with the traditional dispersive method using data. On its own, BMW20 result implies much less room for new physics.

Combining the BMW20 result is currently not straight forward. (More discussion at the end)

We will continue to use the recommended Theory Initiative value, which currently does not include BMW20



The Experiment

and

the Storage Ring Technique

Muons: A Great Tool for Experimentalists

Can be produced copiously in proton collisions and pion decays

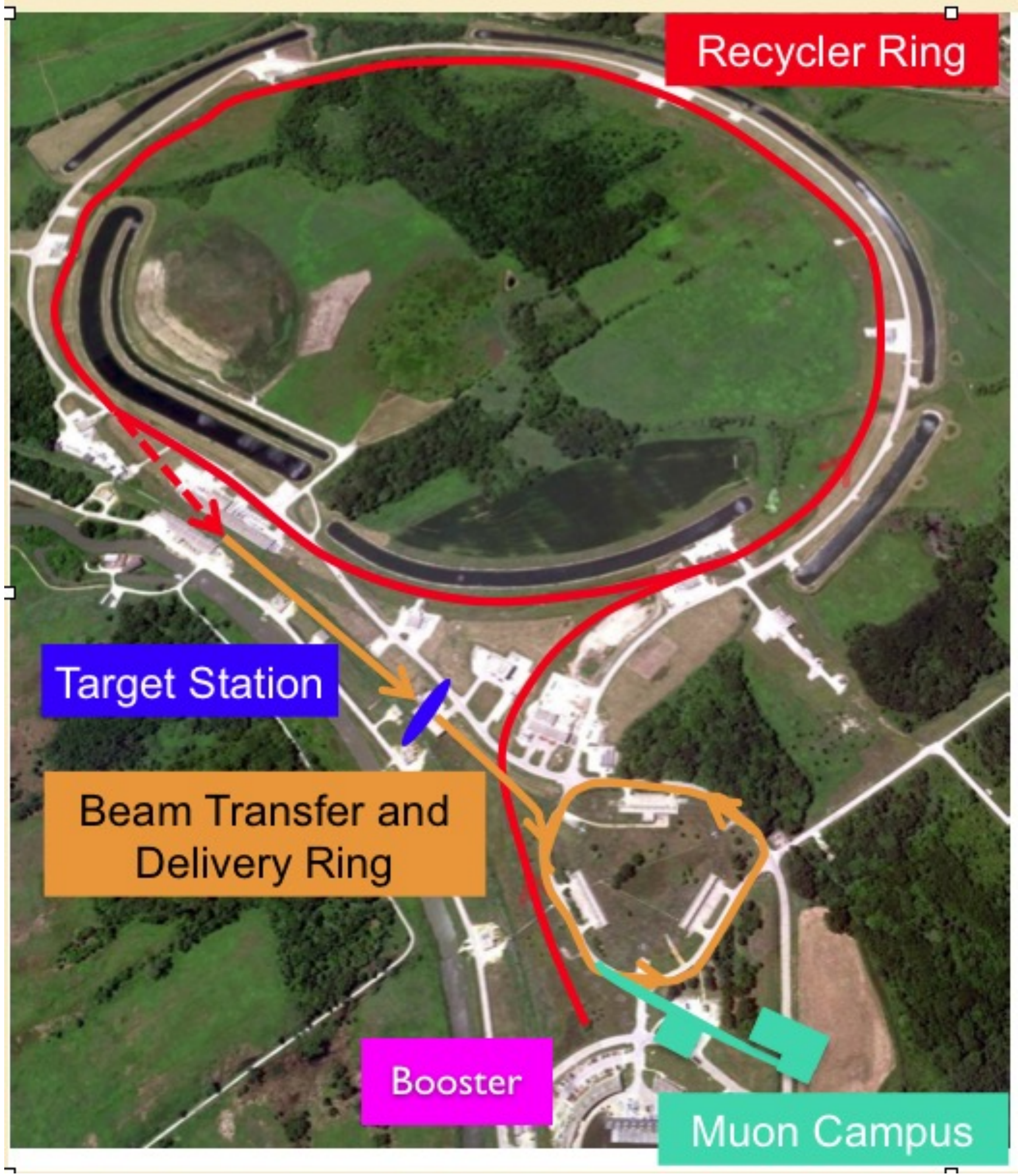
Can select momentum and polarization

Lucky Combination of lifetime, mass, and charge

Decays are very simple

Self-Analyzing Weak Decay

We use a precision magnetic field to continuously probe the muon spin for at least 10 lifetimes.



Clean Source of Intense and >90% Polarized 3.1 GeV Muons

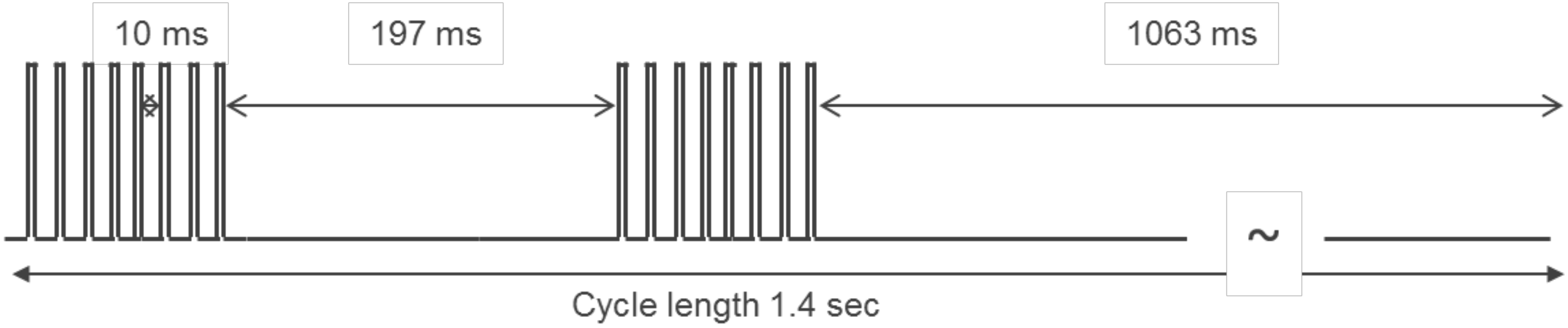
Tight FODO spacing (w.r.t. BNL)

Long Decay Line

Kicker for Proton removal

24

Beam Time Structure

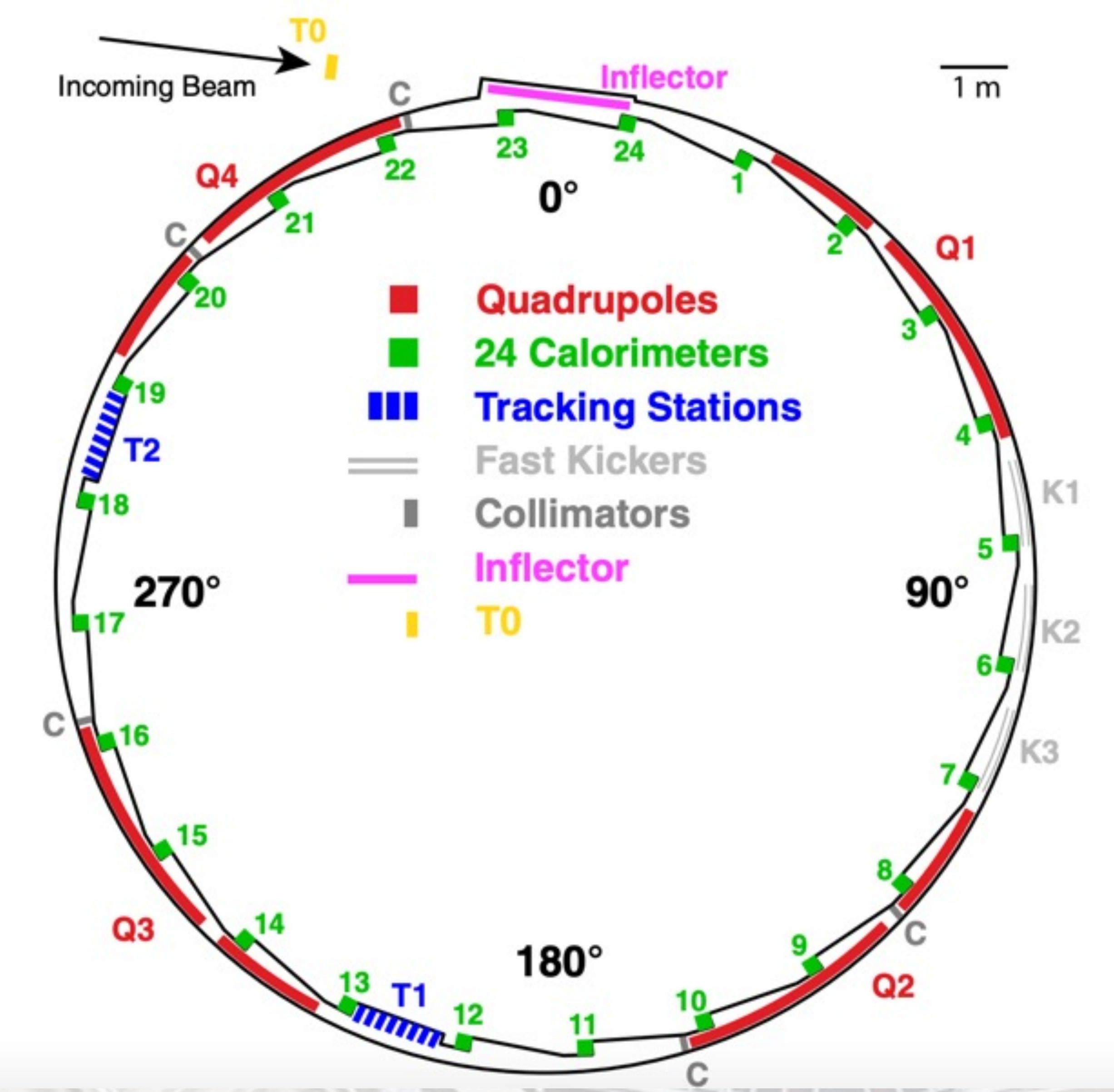


16 fills every 1.4 seconds

~ 10,000 muons per fill

~ 700 μsec fill duration (~ 10 muon lifetimes)

Ring Anatomy

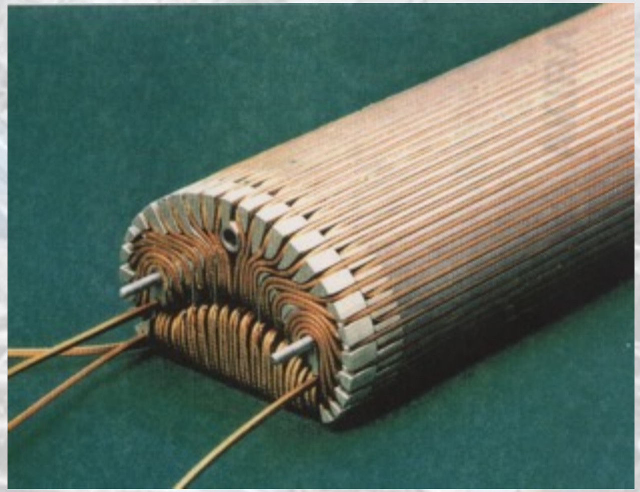


1.45 Tesla Magnet

14.2 meter Diameter Ring

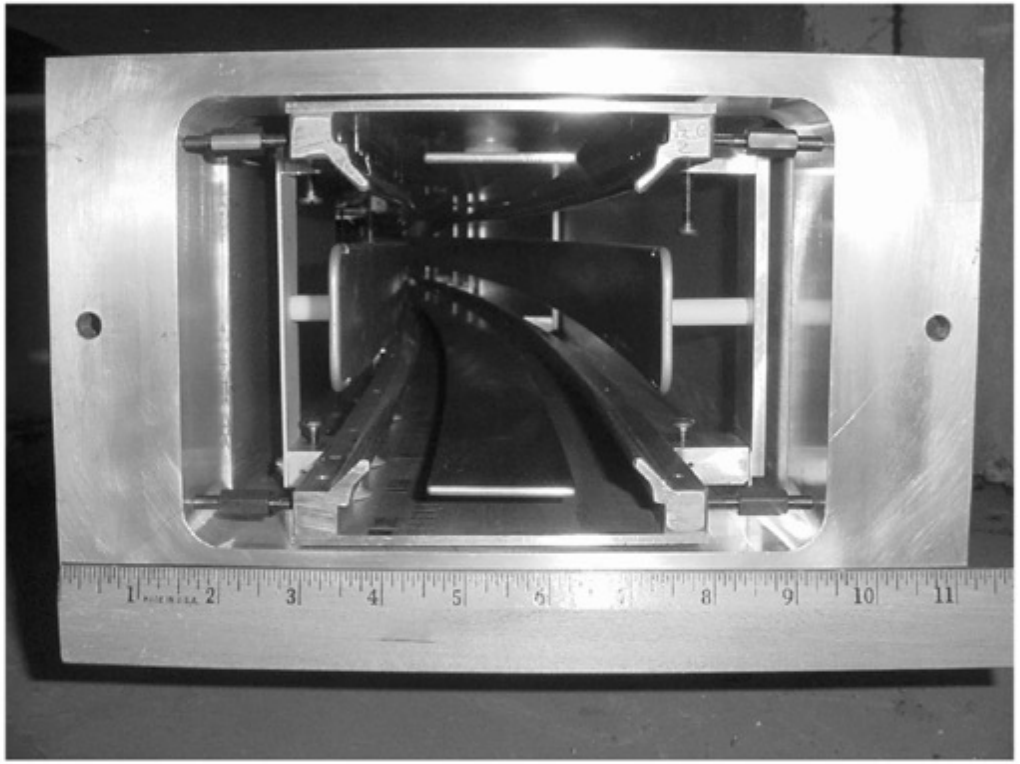
~5 cm diameter beam
in an evacuated volume

Superconducting Inflector



Beam Storage Components

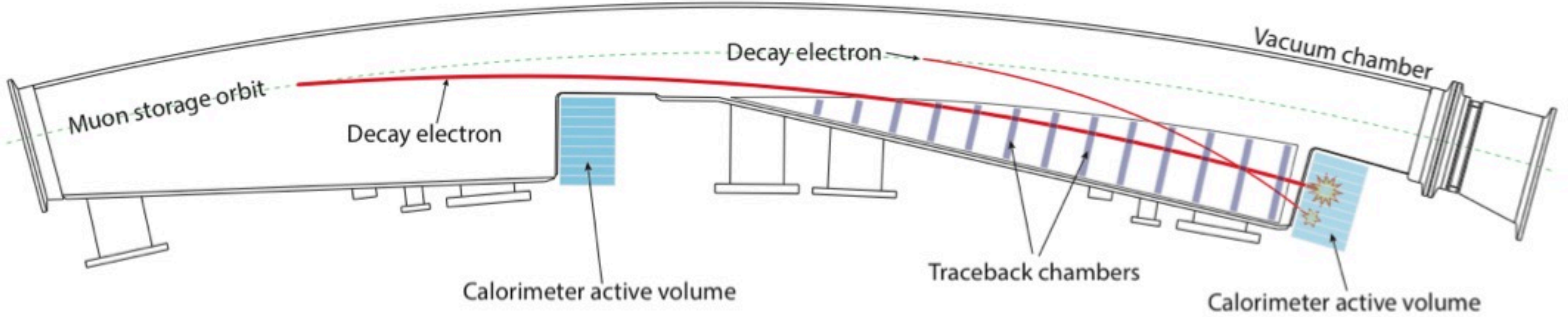
8 Quads for vertical focusing
(43% Coverage)



10 mrad Magnetic Kicker

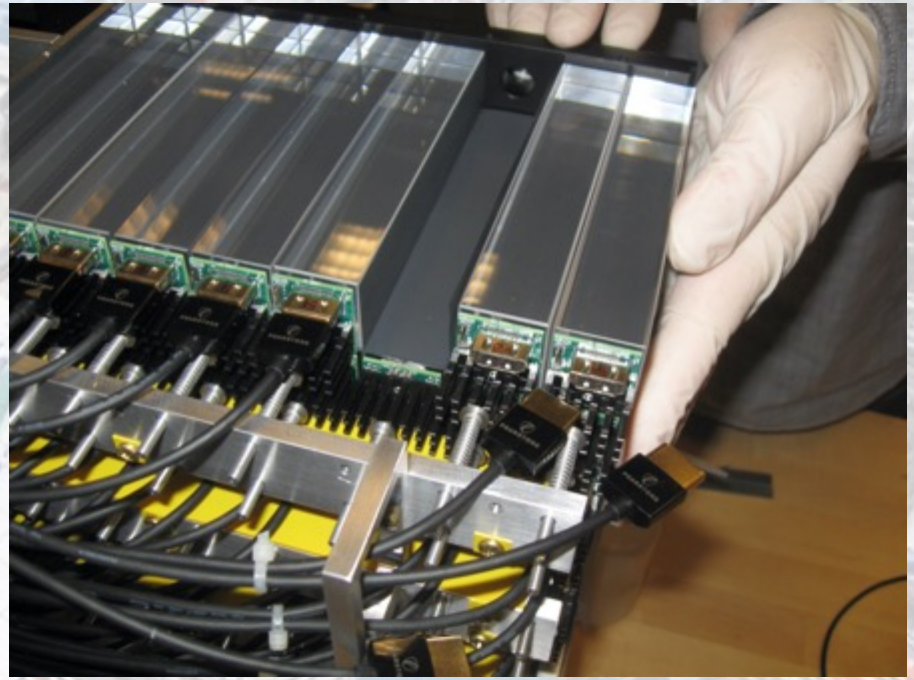
Positron Detectors

1/12 of the ring



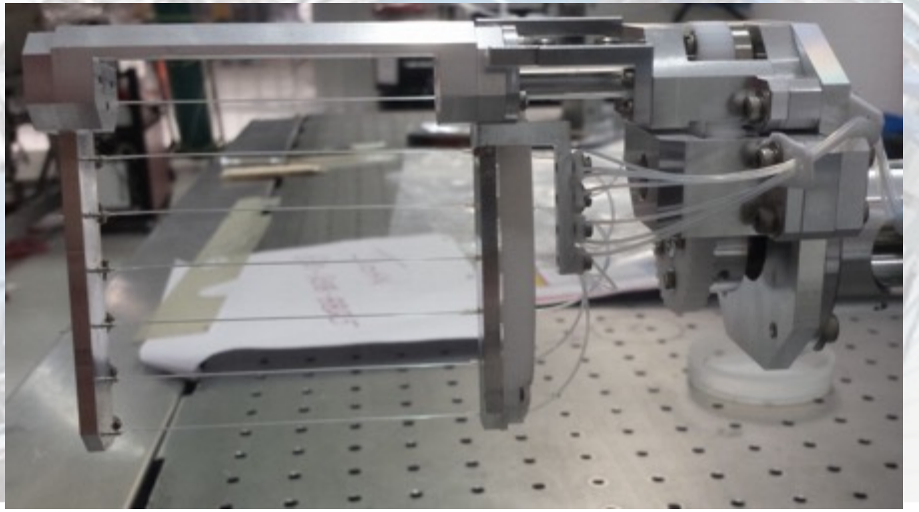
Particle Detectors

24 stations of PbFl2 Xtals



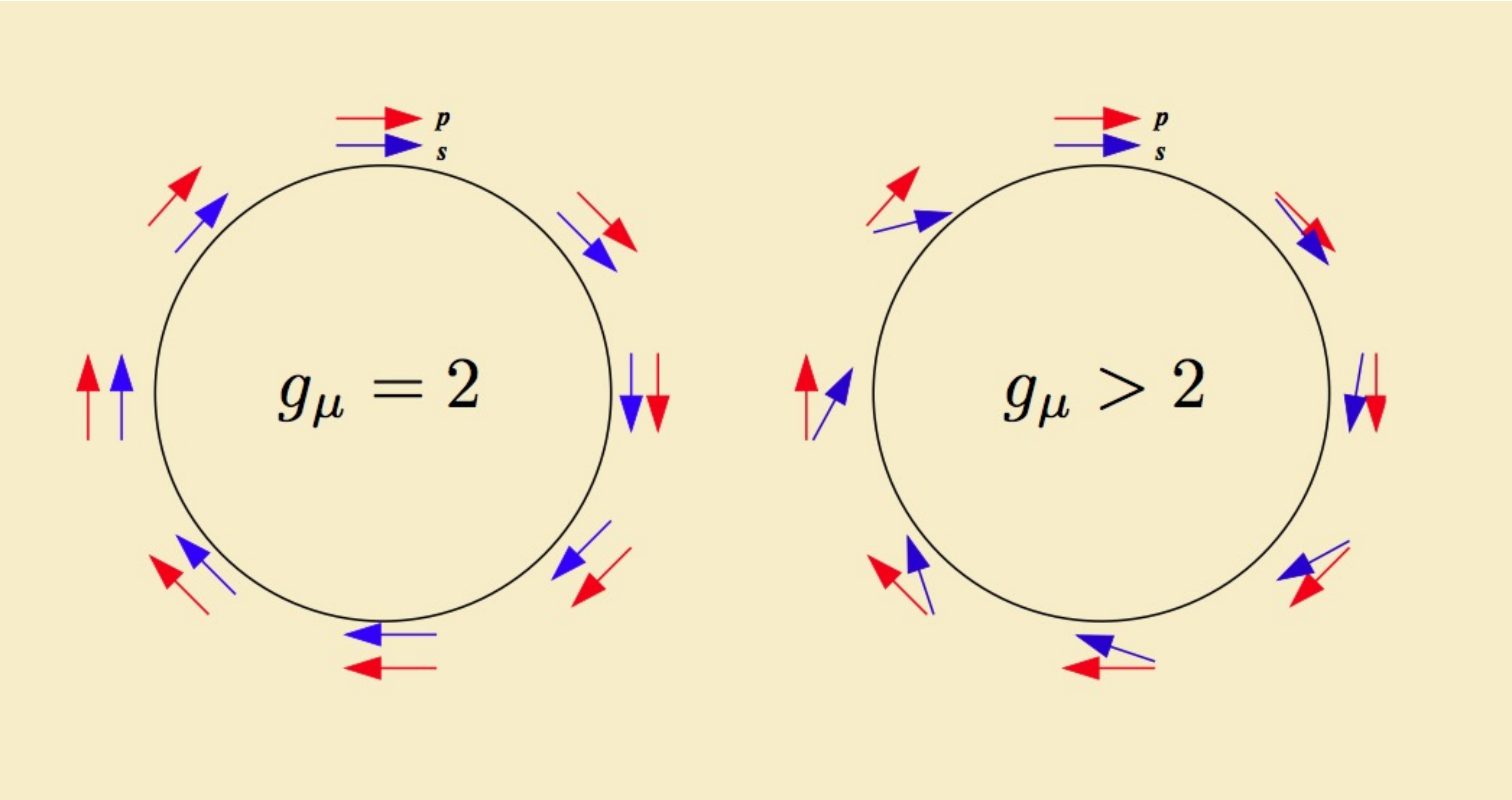
2 in-vacuum non-destructive positron tracking stations

destructive fiber beam profile monitors
and beam-entrance detectors



Spin and Momentum Precession in a Storage Ring

Amazing Property shown by the Bargmann-Michel-Telegdi Equation (1954)



The difference frequency is

$$\omega_s - \omega_c \equiv \omega_a$$

Rate of change of longitudinal polarization

True for any momentum (i.e. Any Ring Size)
Can be done on a table top !

Spin and Momentum Precession in a Storage Ring

for an ideal planar circular orbit in a pure B field,
there is an *amazing simplification:*

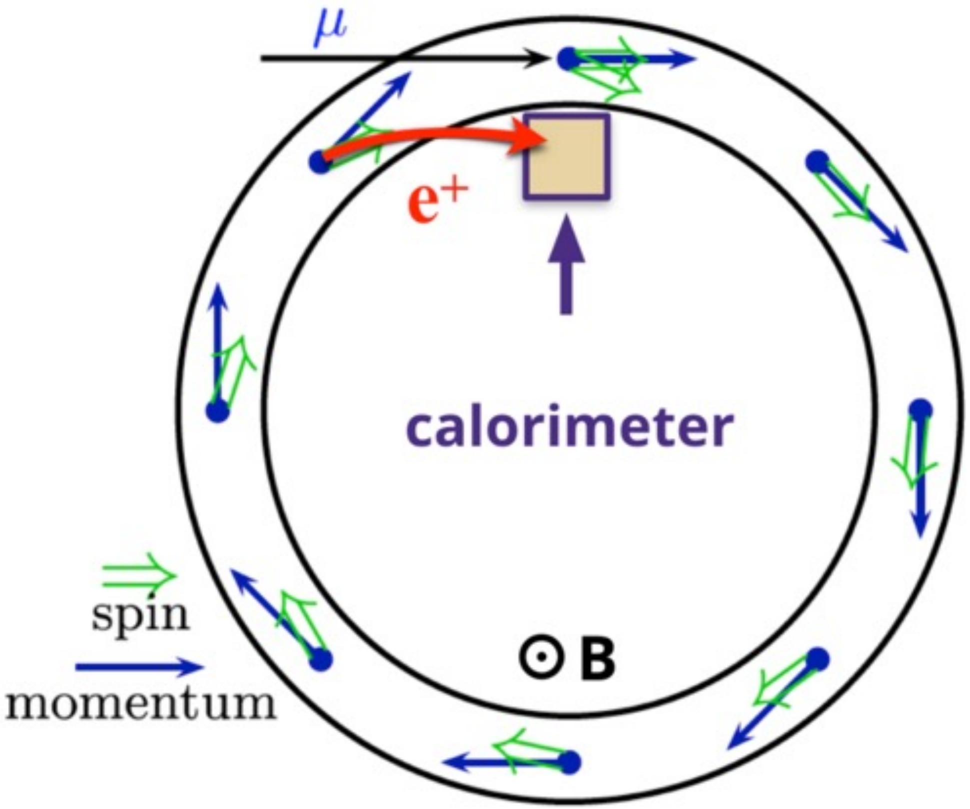
$$\boldsymbol{\omega_s} - \boldsymbol{\omega_c} = \boldsymbol{\omega_a} = -\frac{q}{m_\mu}\left(a_\mu \boldsymbol{B}\right)$$

"All" we have to do is measure $\boldsymbol{\omega_a}$ and $\boldsymbol{B}$

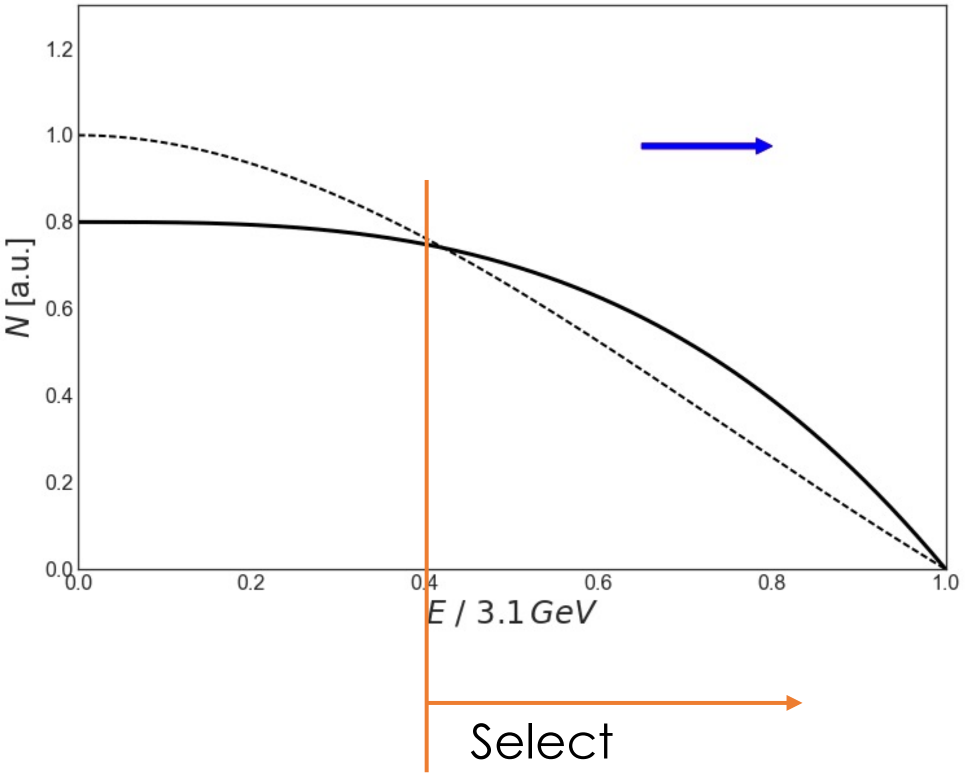
Measure the magnetic field B

Measure ω_a (the rate of change of longitudinal polarization)
and correct for the non-ideal case

Measuring Muon Longitudinal Polarization



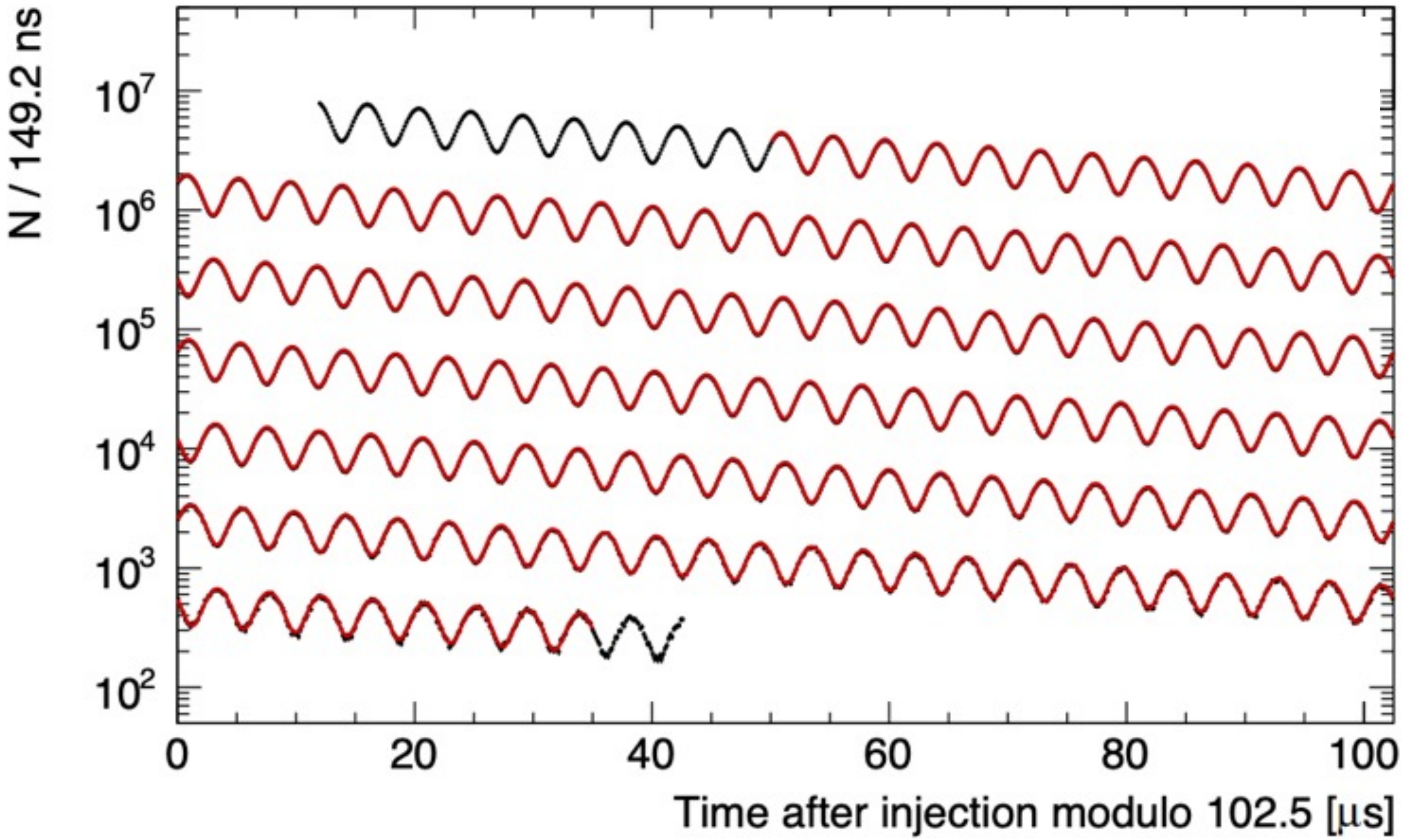
Tagging high energy positrons



Main Analysis Plot

Number of Positrons Above 1.7 GeV versus Time in Fill

The frequency is ω_a



Actually: Spin and Momentum Precession in Electric and Magnetic Field are very complicated

$$\frac{d\boldsymbol{\beta}}{dt} = \frac{e}{\gamma m}\left(\boldsymbol{E} + \boldsymbol{\beta}\; x\; \boldsymbol{B} - \boldsymbol{\beta}(\boldsymbol{\beta}\cdot\boldsymbol{E})\right)$$

$$\frac{d}{dt}(\widehat{\boldsymbol{\beta}}\cdot\boldsymbol{s}) = -\frac{e}{mc}\boldsymbol{s}_{\perp}\cdot\left[\, a_{\mu}\widehat{\boldsymbol{\beta}}\;\boldsymbol{x}\;\boldsymbol{B} + \left(\frac{g\beta}{2} - \frac{1}{\beta}\right)\boldsymbol{E}\,\right]$$

Our Experimental Observable

Use “Magic” Momentum Muons (3.1 GeV/c)

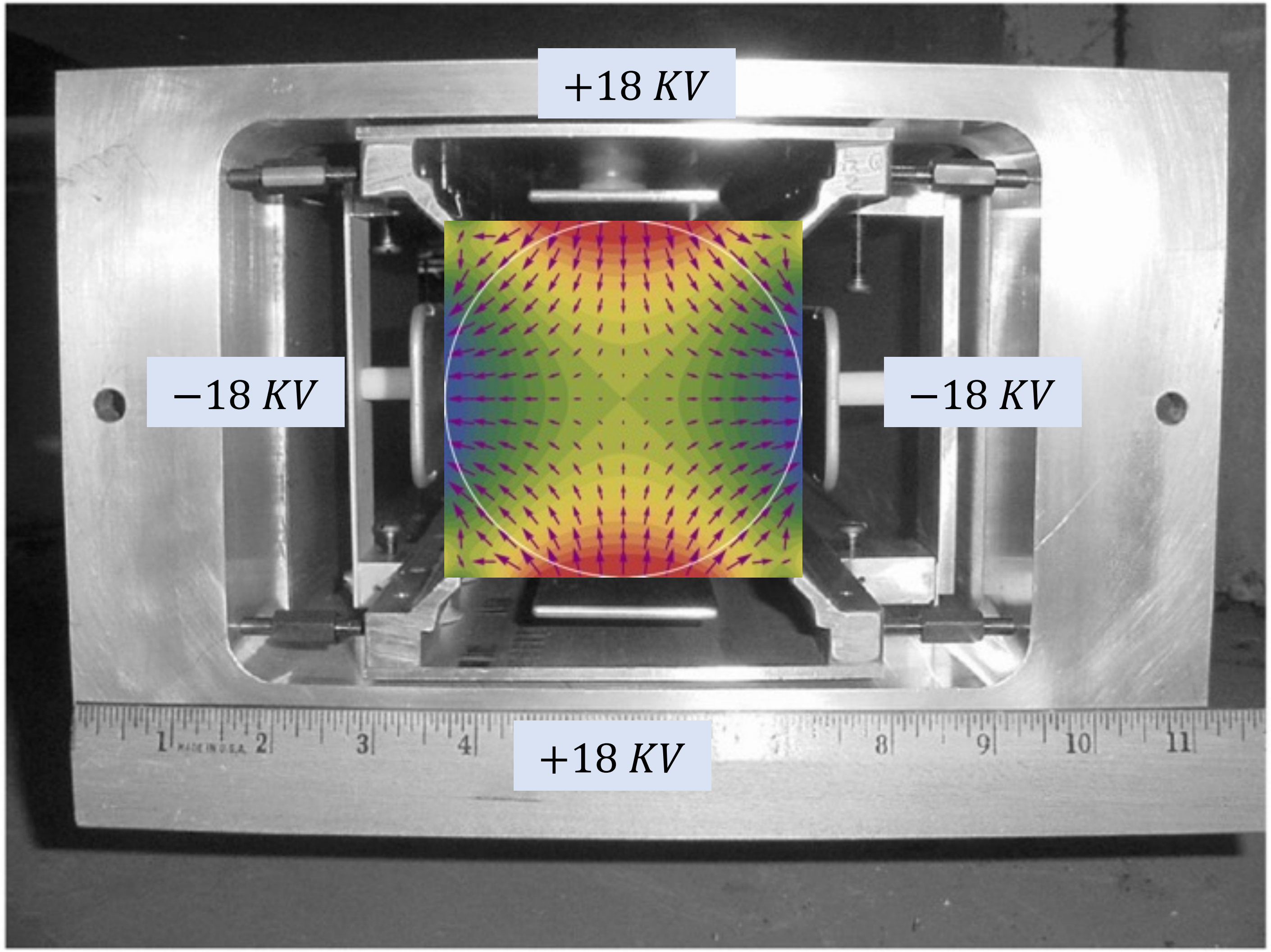
Electric Field Perturbation

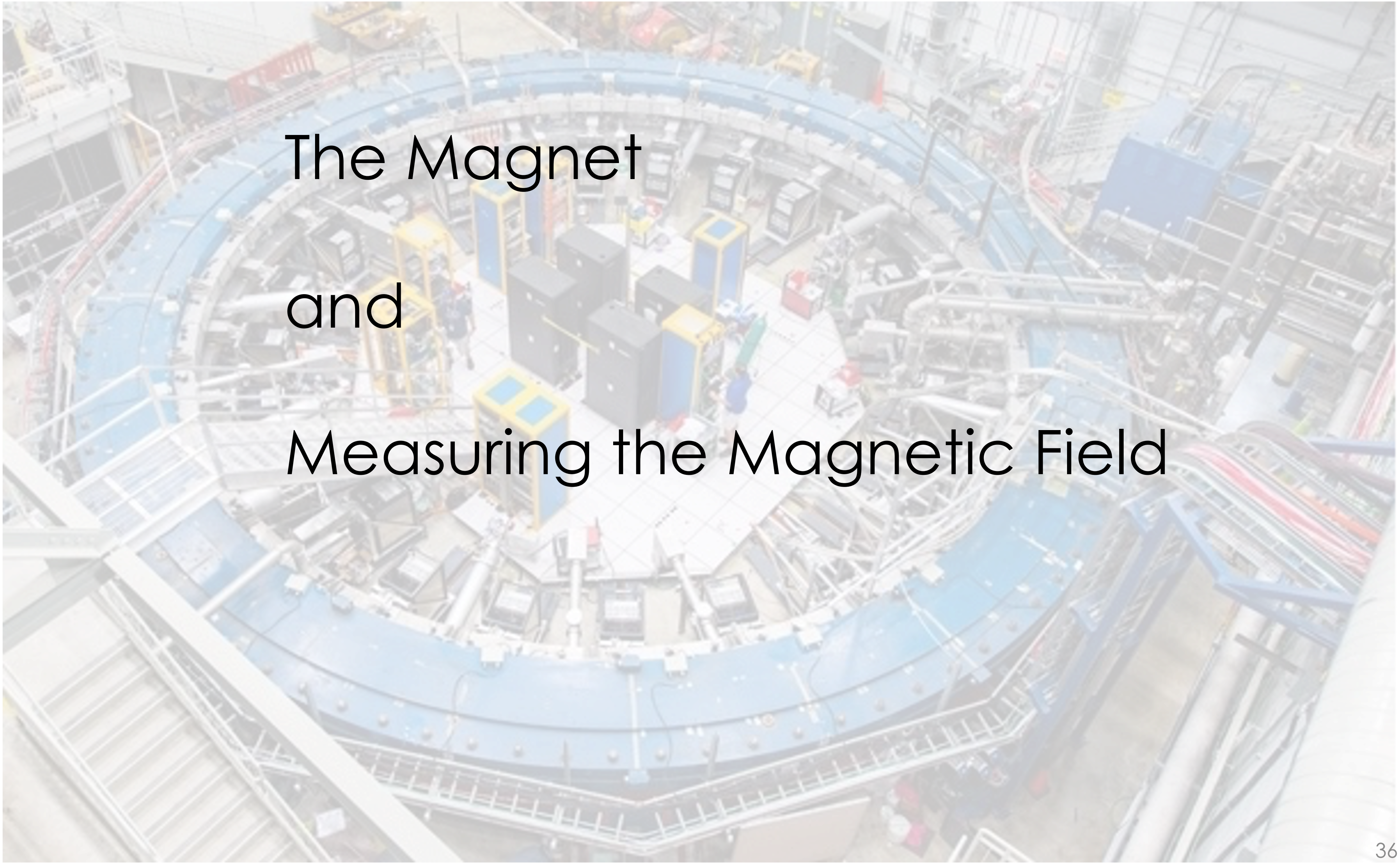
The Magic Momentum Technique

Can use Electrostatic Quadrupoles
with only a
small penalty

Vertical Focusing

Horizontal Defocusing



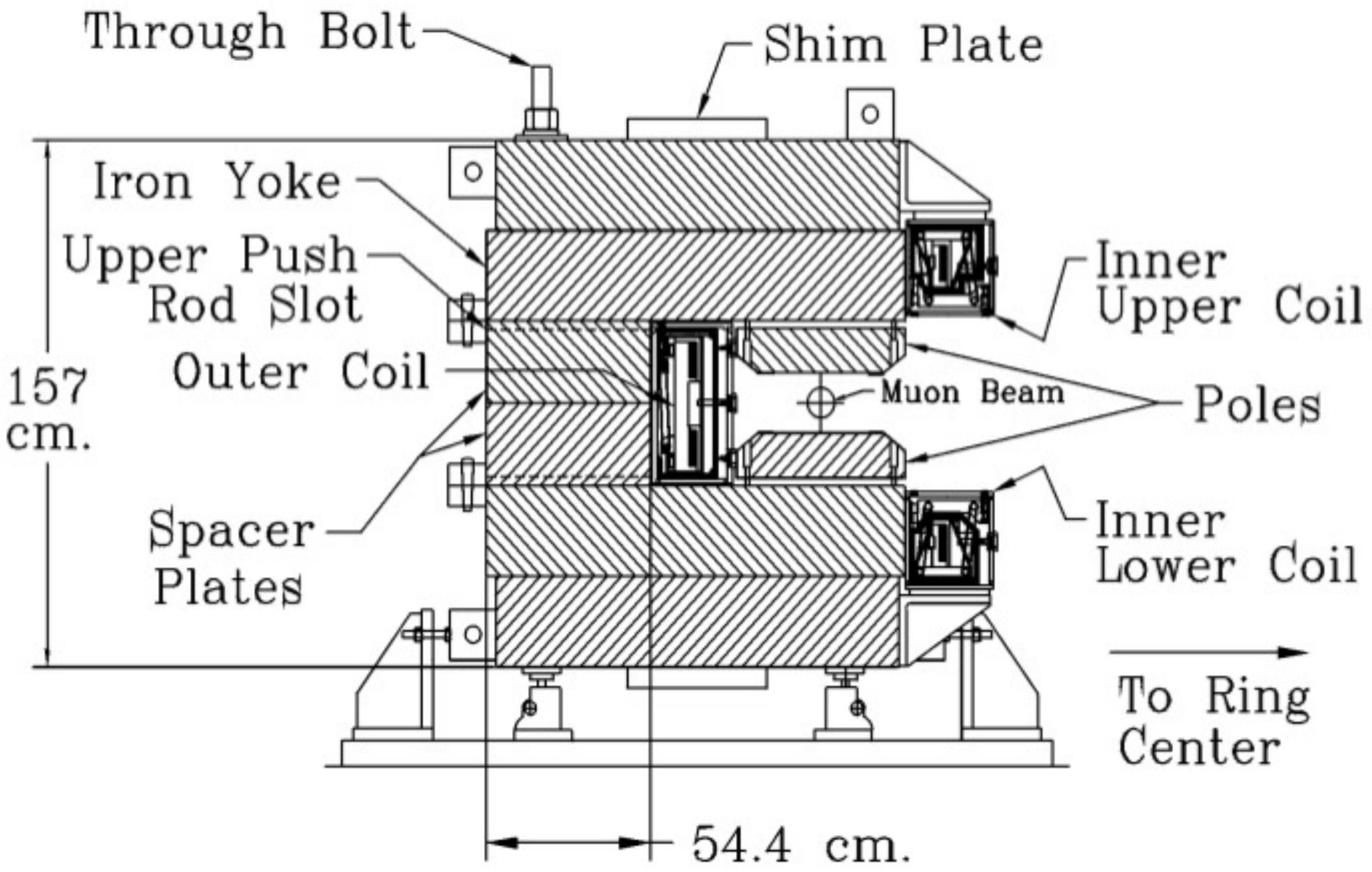


The Magnet

and

Measuring the Magnetic Field

Gordon Danby's (BNL) Ingenious Magnet Design

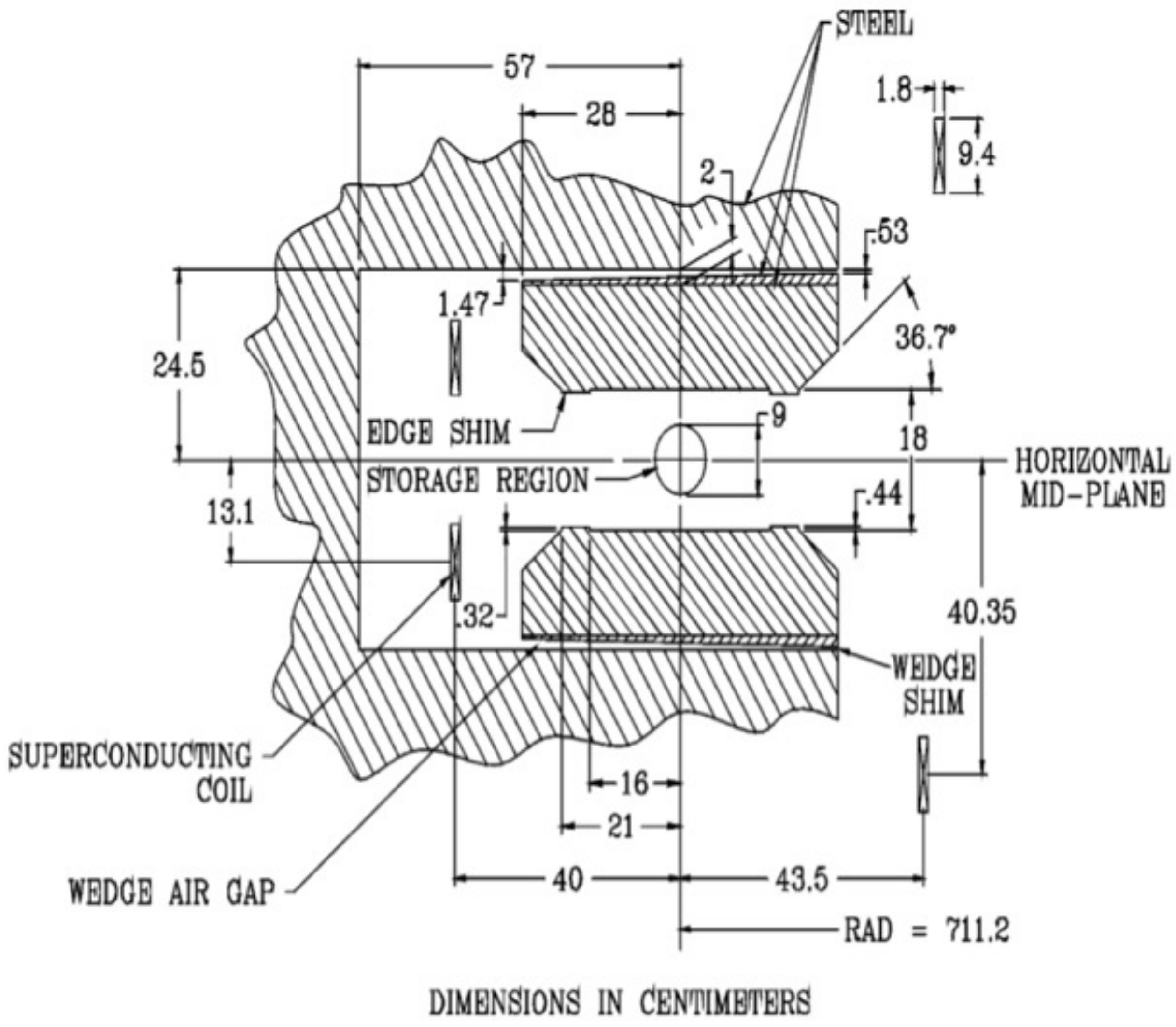


Super Conducting Technology allowed for low heat load

6 Mega Joules of stored EM Energy

Built by BNL in the mid 1990's

A 600T Precision Swiss Watch



~10000 Adjustment Knobs

Dipole
1 Magnet Current
24 Outer Shim Plates
~8500 Thin shim foils

Quadrupole
864 Wedge Shims

Sextupole
144 Edge Shims

Radial Field
~20 Trim Coils

Measuring the Field with Proton NMR

$$a_\mu = \frac{\omega_a}{B}\frac{m_\mu}{e}$$

For protons at rest in the magnetic field, their spin also precesses:

$$\omega_p = \frac{g_p e}{2m_p} B$$

(Larmor Frequency)

Measure the proton Larmor Frequency and extract B using external constants $\frac{g_p e}{2m_p}$

Measuring the Field with Proton NMR

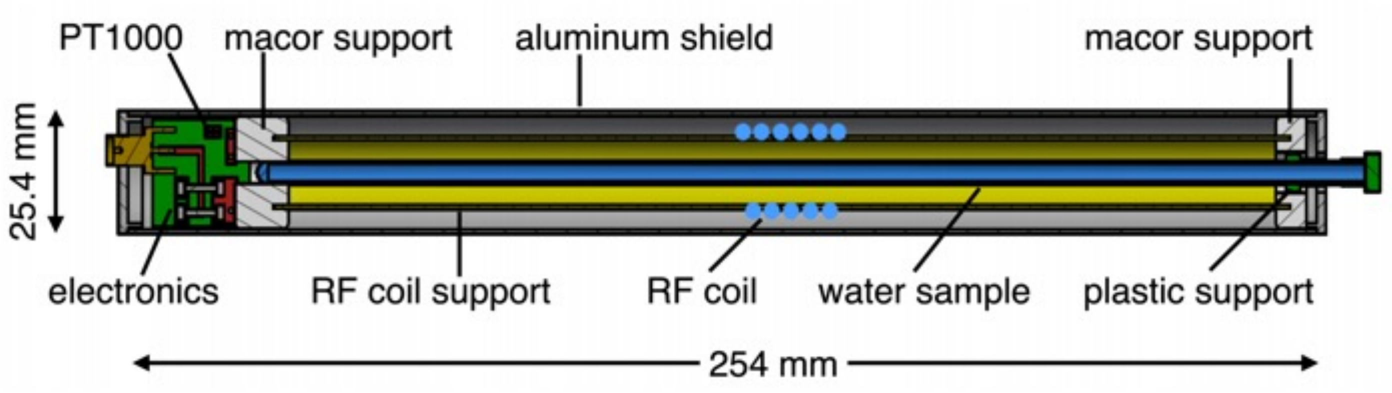
$$a_\mu = \frac{\omega_a}{B}\frac{m_\mu}{e} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)}\frac{\mu'_p(T_r)}{\mu_e(T_r)}\frac{\mu_e(H)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

Actually, we take external constants from:

H-maser, Muonium HFS, and Penning Trap experiments, and QED Theory.

Known to ~ 24 ppb

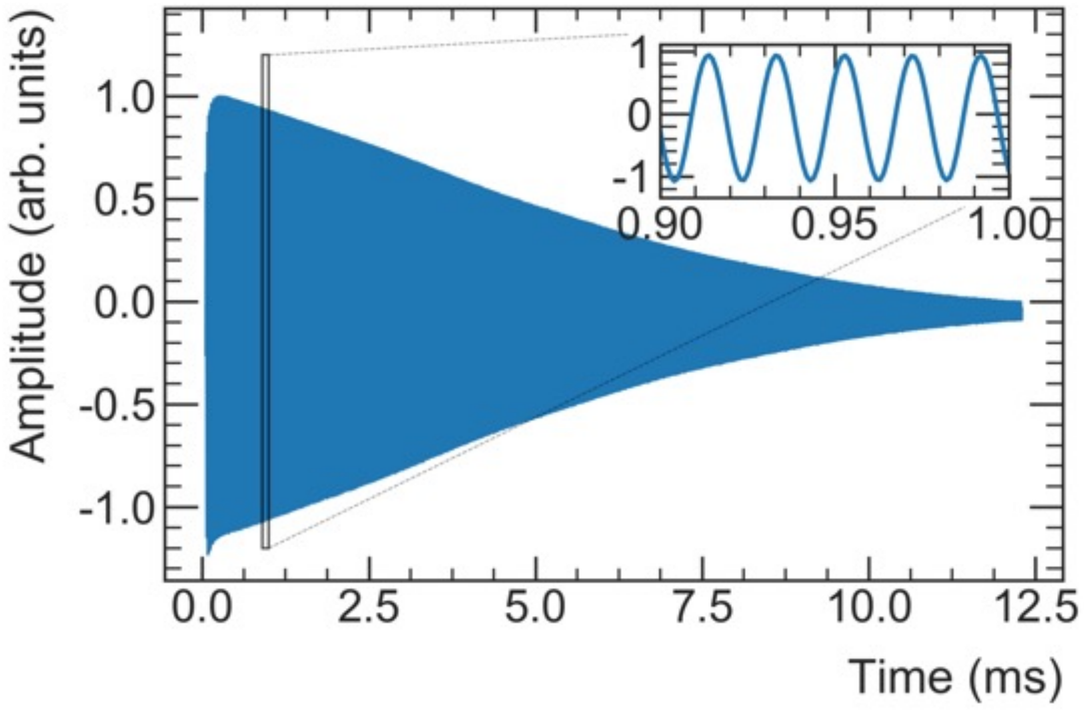
Pulsed NMR



O(1 msec) Bandwidth
O(10 Hz) Sampling Rate

Easily achieve ppb precision in a high field

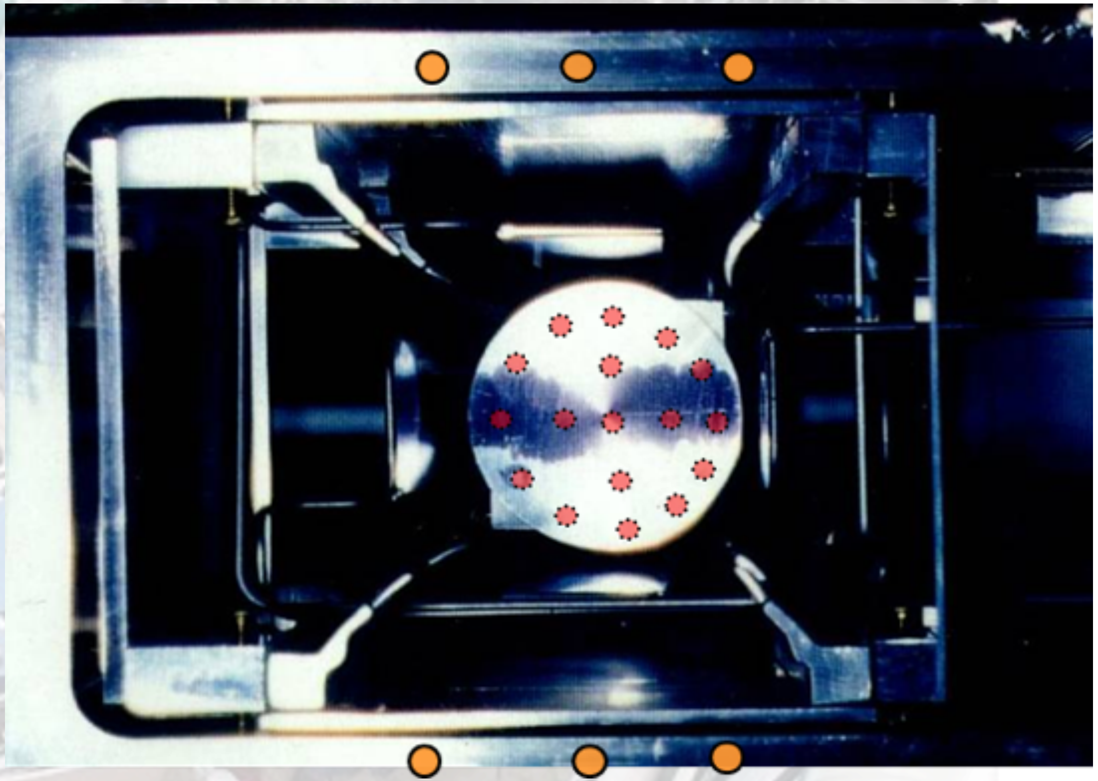
Typical "Proton Precession" Signal in Water



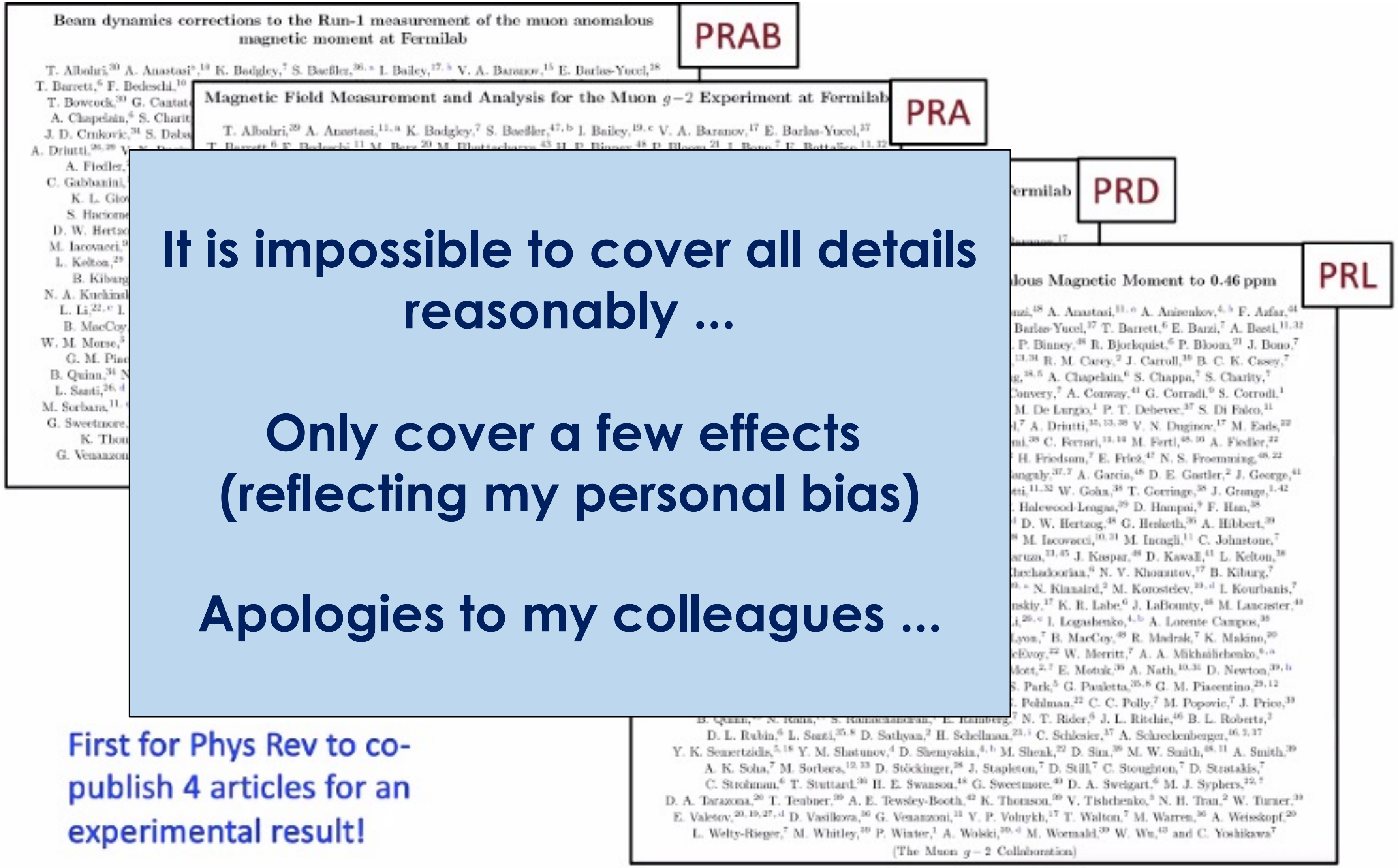
NMR Probes

"Fixed" NMR probes
(monitors B during muon storage)

"Trolley" measures 2D profile
(must turn OFF beam)



4 publications representing 3 Years of Analysis

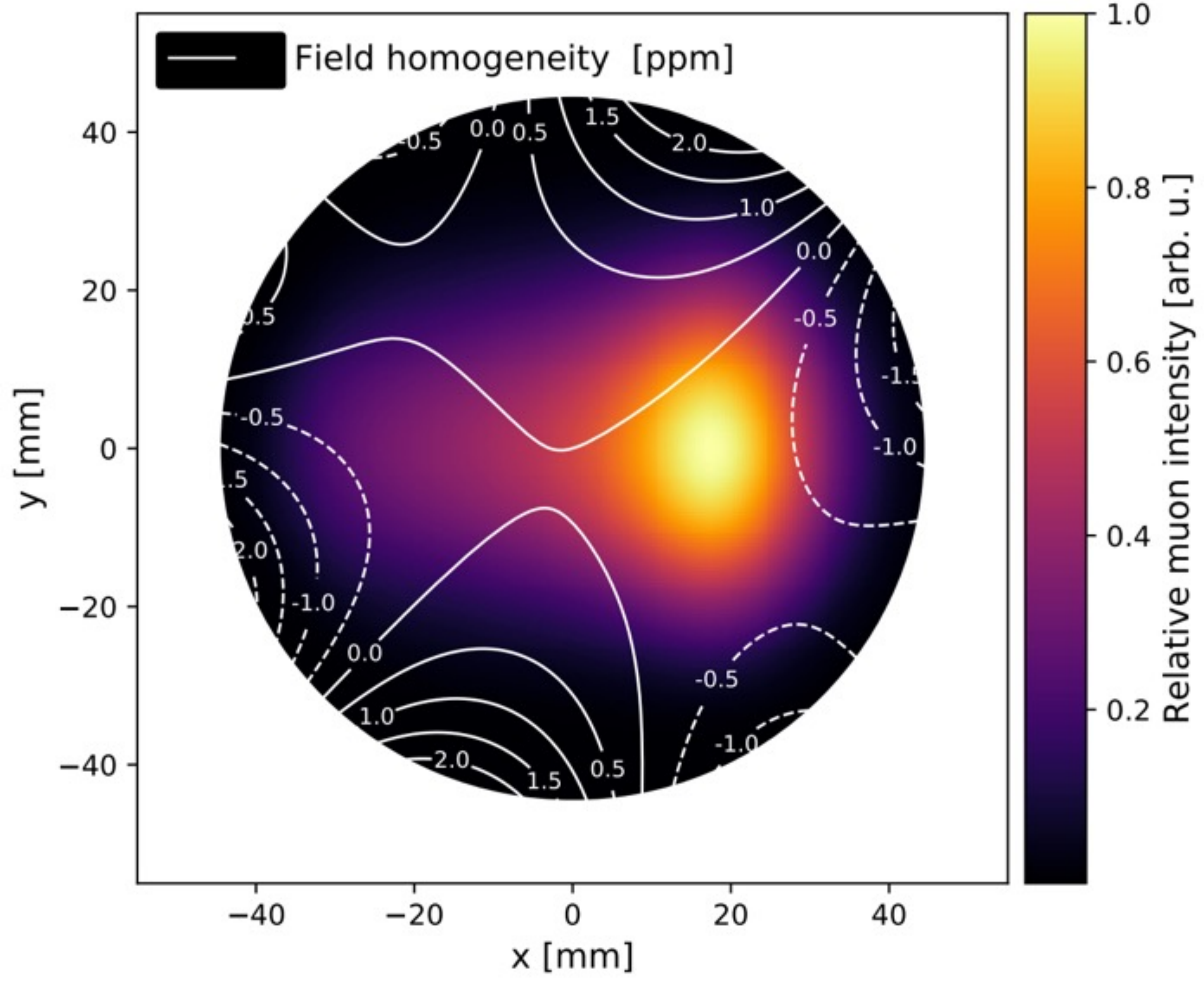


It is impossible to cover all details reasonably ...

Only cover a few effects (reflecting my personal bias)

Apologies to my colleagues ...

First for Phys Rev to co-publish 4 articles for an experimental result!



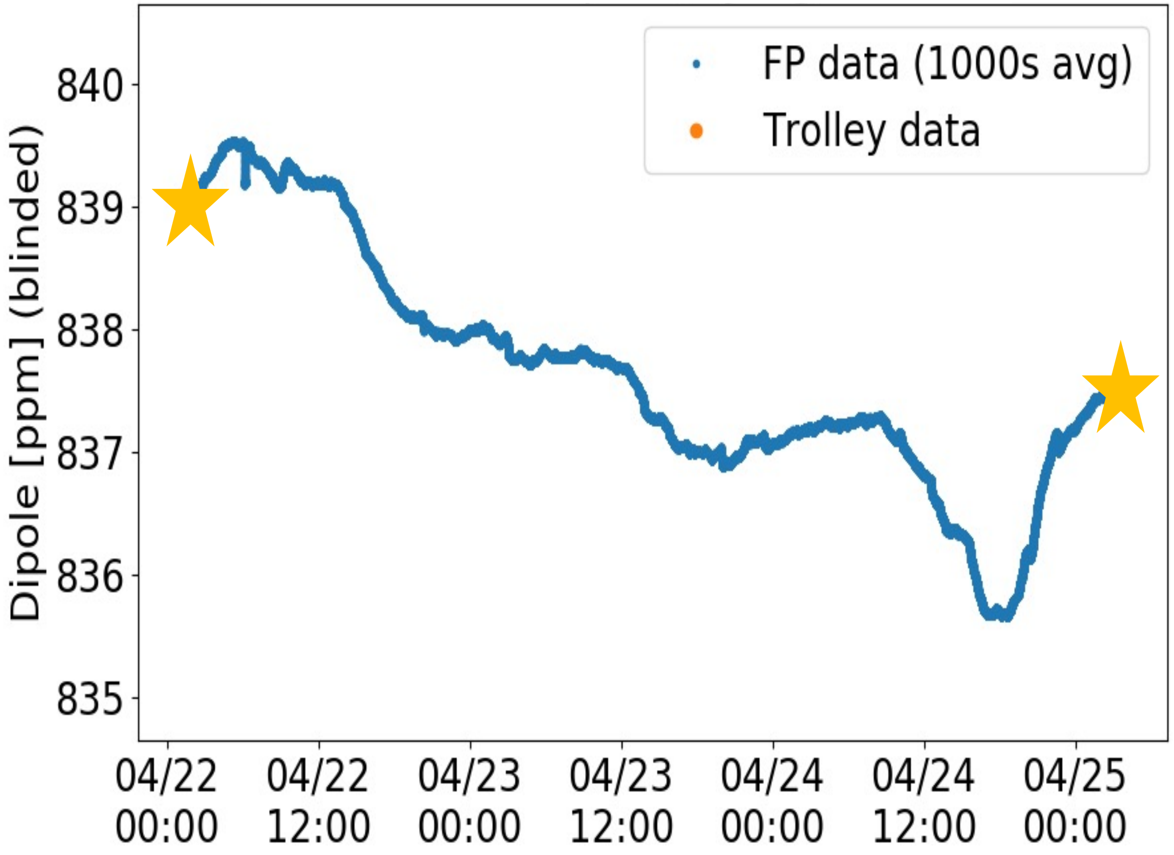
Main Worries

What is the Field in between trolley runs ? *magnet stability*

How do we know ω_p is correct ? *Absolute Calibration Procedure*

Magnetic Transients caused by pulsed kicker and quads

Typical Magnet Stability

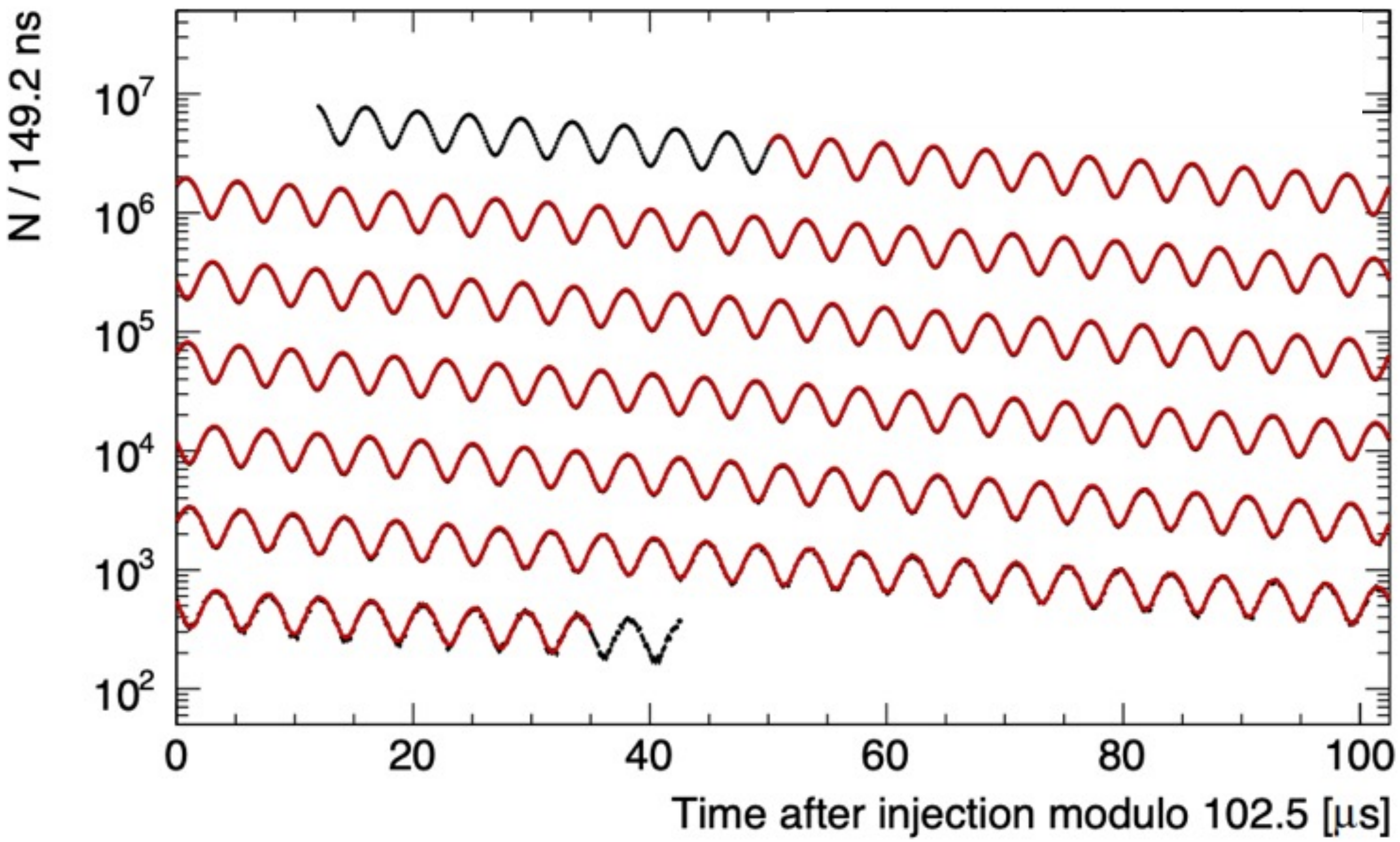


Order Few ppm drift over 3 days

Related to hall temperature stability

(No longer a problem)

Main Worries: Early-to-late Effects



Detector Gain Stability

Pileup Background to e^+

Phase Population changes

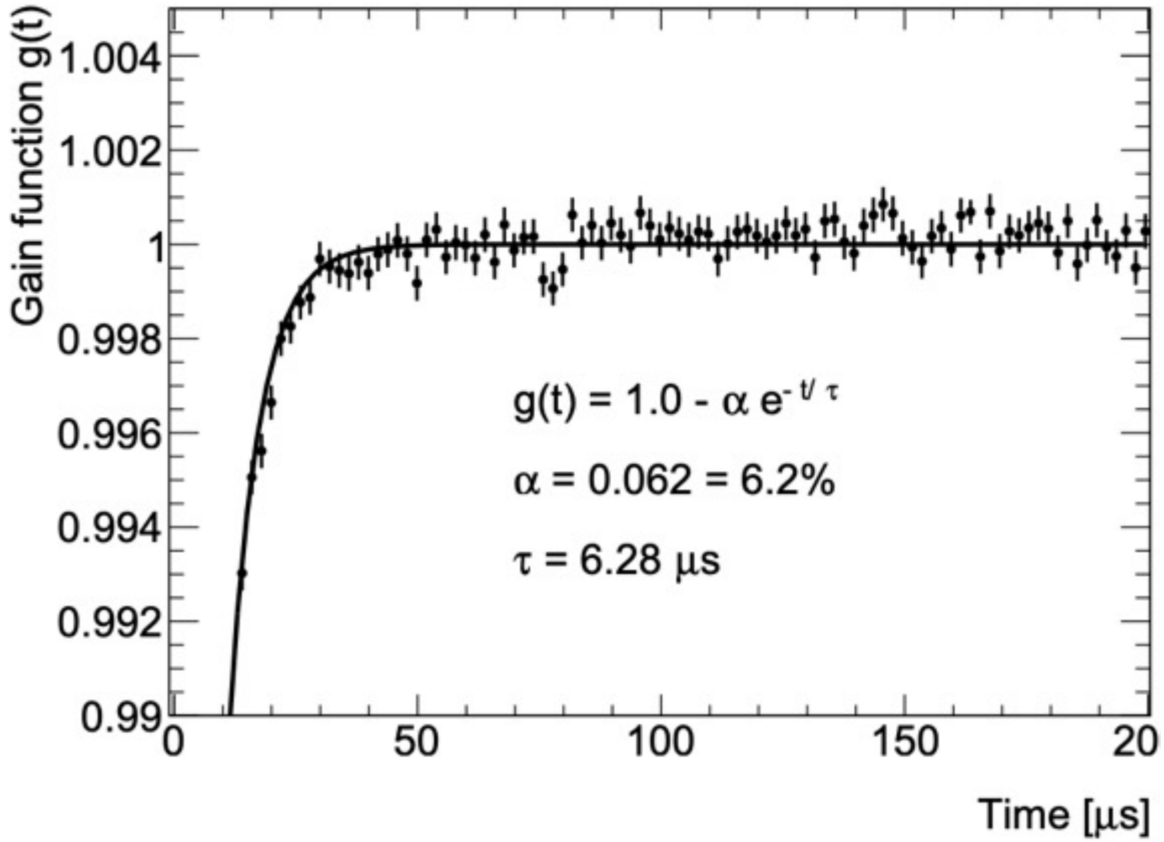
Beam Motion (since it couples to detector acceptance)

Really an ensemble

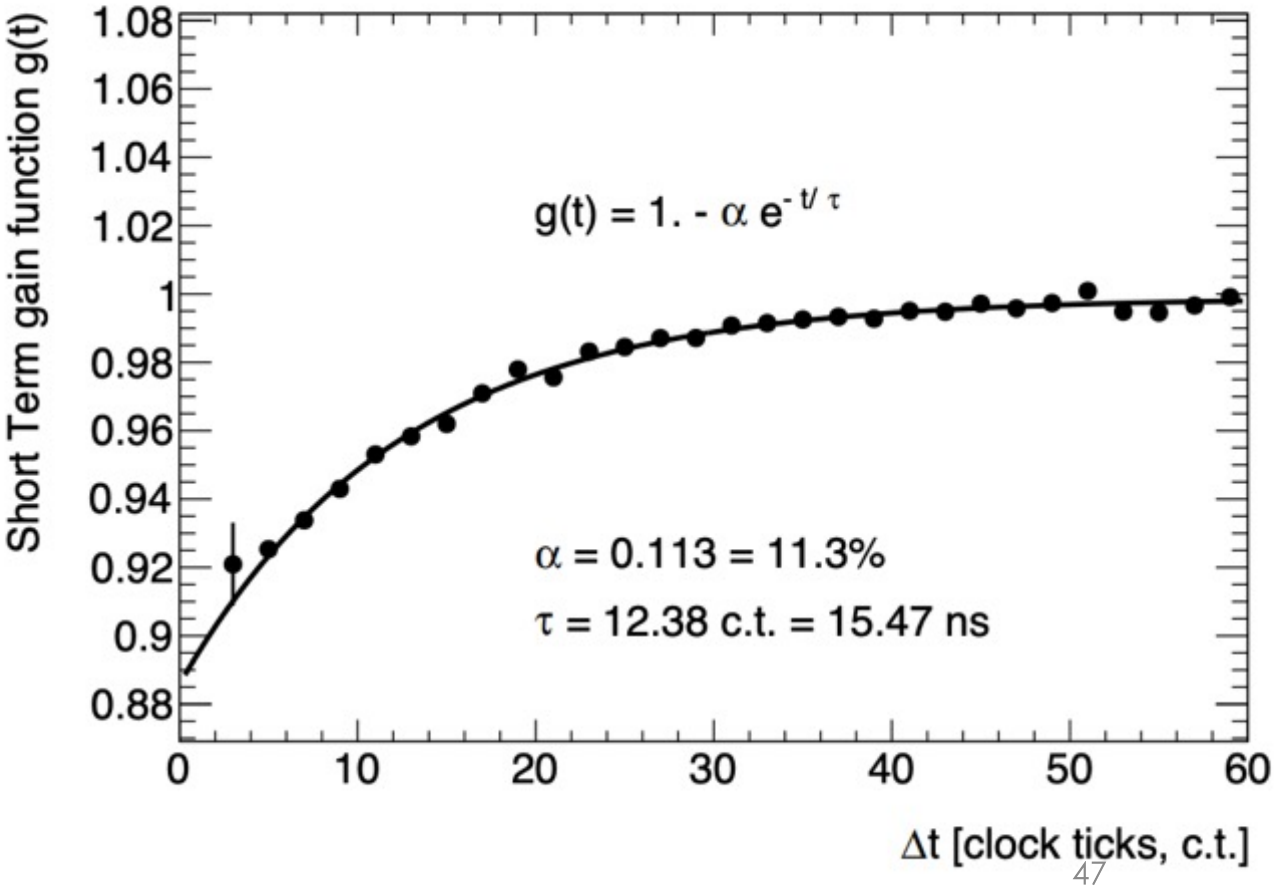
$$N(t) = N_0 e^{-t/\gamma\tau_\mu}\left(1 + A(E_{\mathrm{th}})\cos(\omega_a t + \phi_0)\right).$$

Gain Stability: Mapped with Laser System

Gain Drop from initial beam flash at injection



Gain Drop from consecutive hits



Master Formula

Hardware Blinded Clock

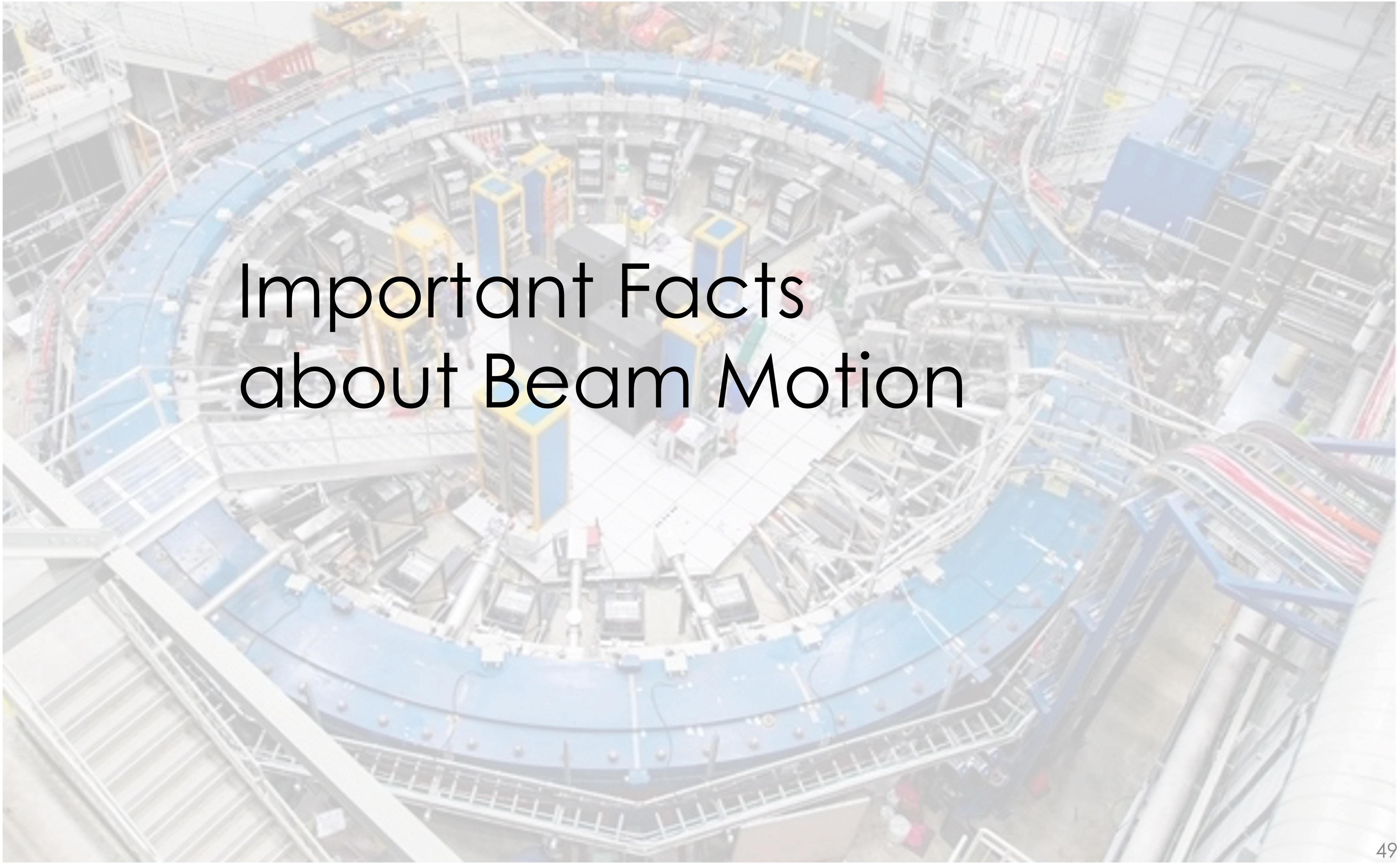
Beam Dynamics Corrections

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Absolute Field Calibration

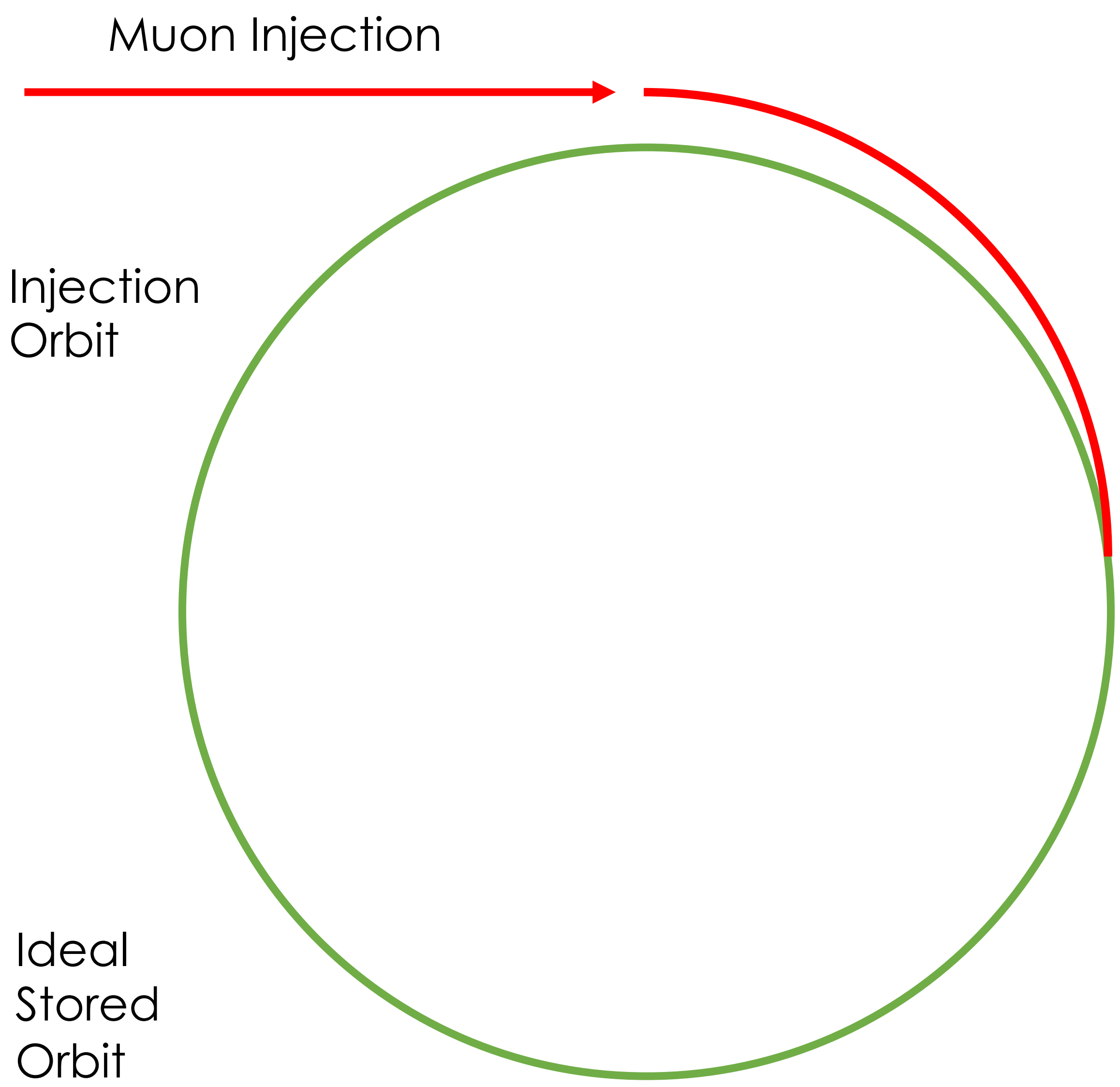
Spatial Convolution with muon beam

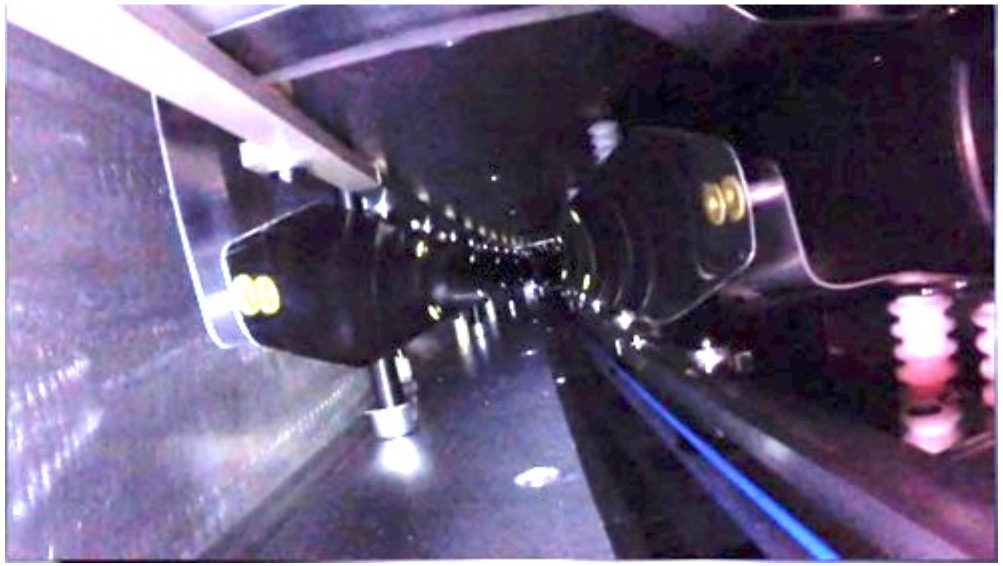
Magnetic Transient Corrections



Important Facts about Beam Motion

Ideal Injection and Kick

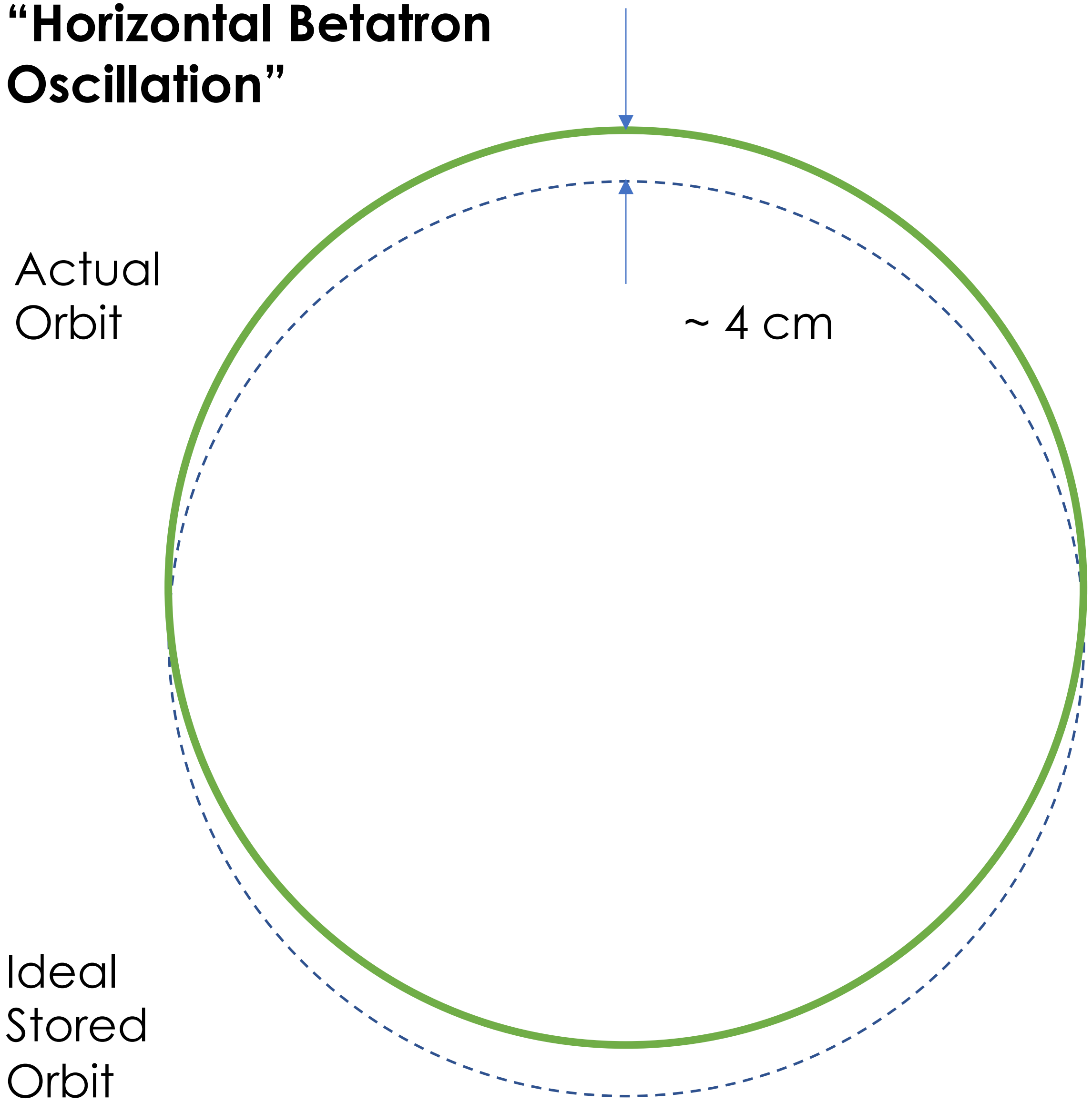


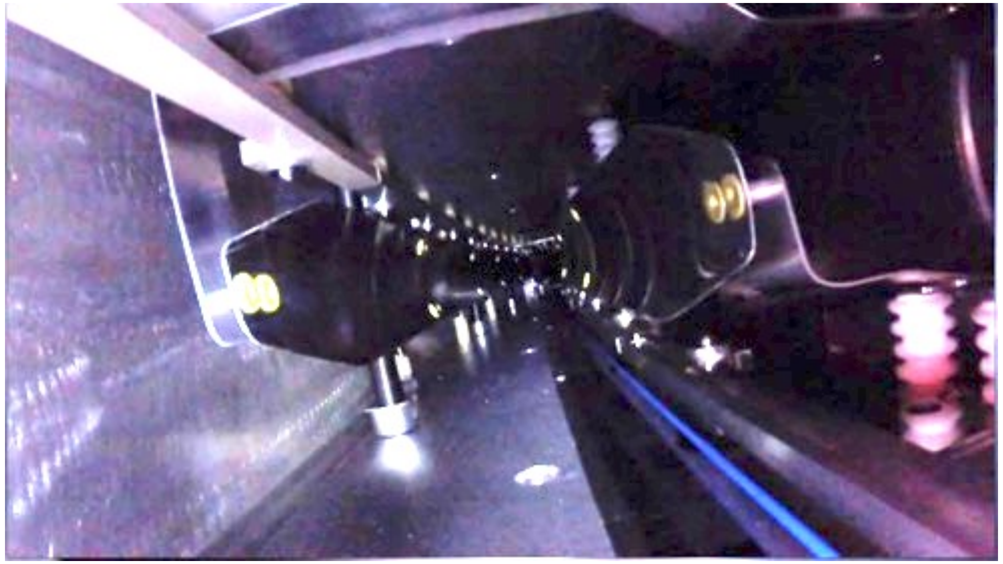


~200 Gauss Kick
~ 5000 Amps
~ 200 nsec pulse

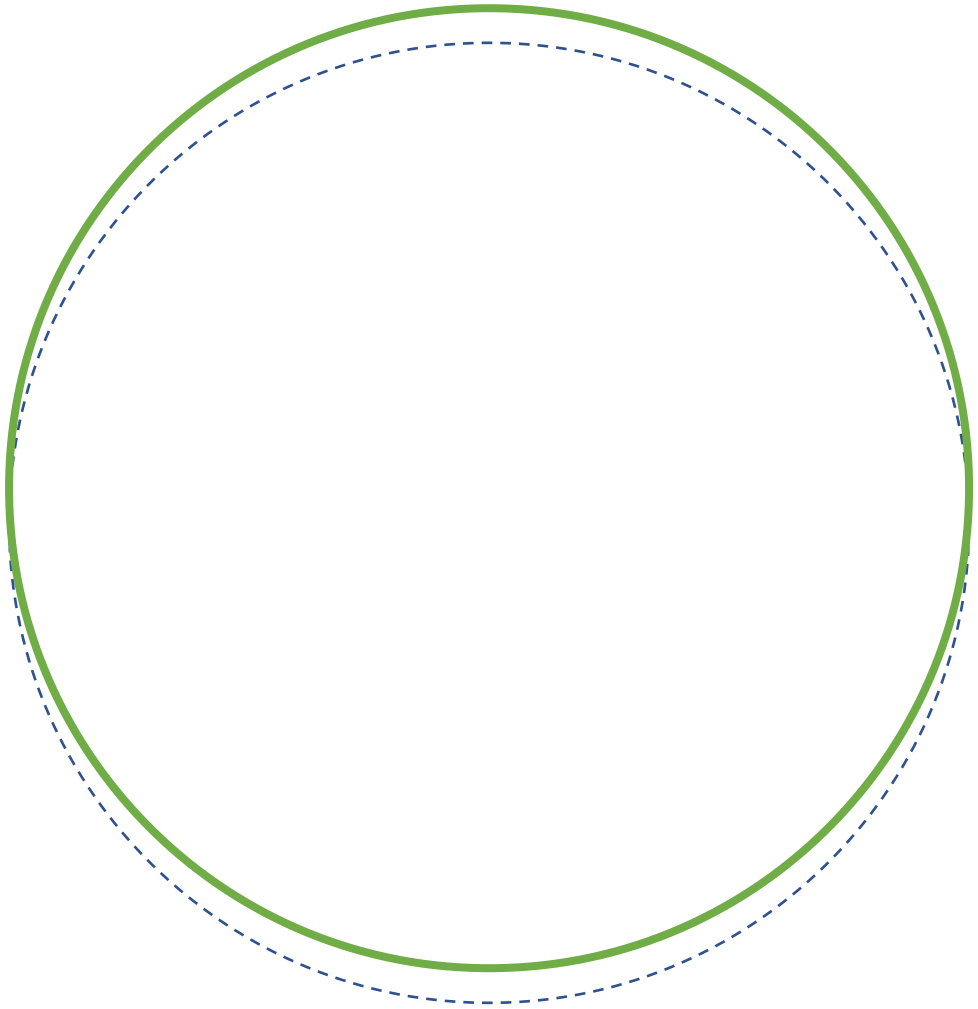
Kick not strong enough

“Horizontal Betatron Oscillation”





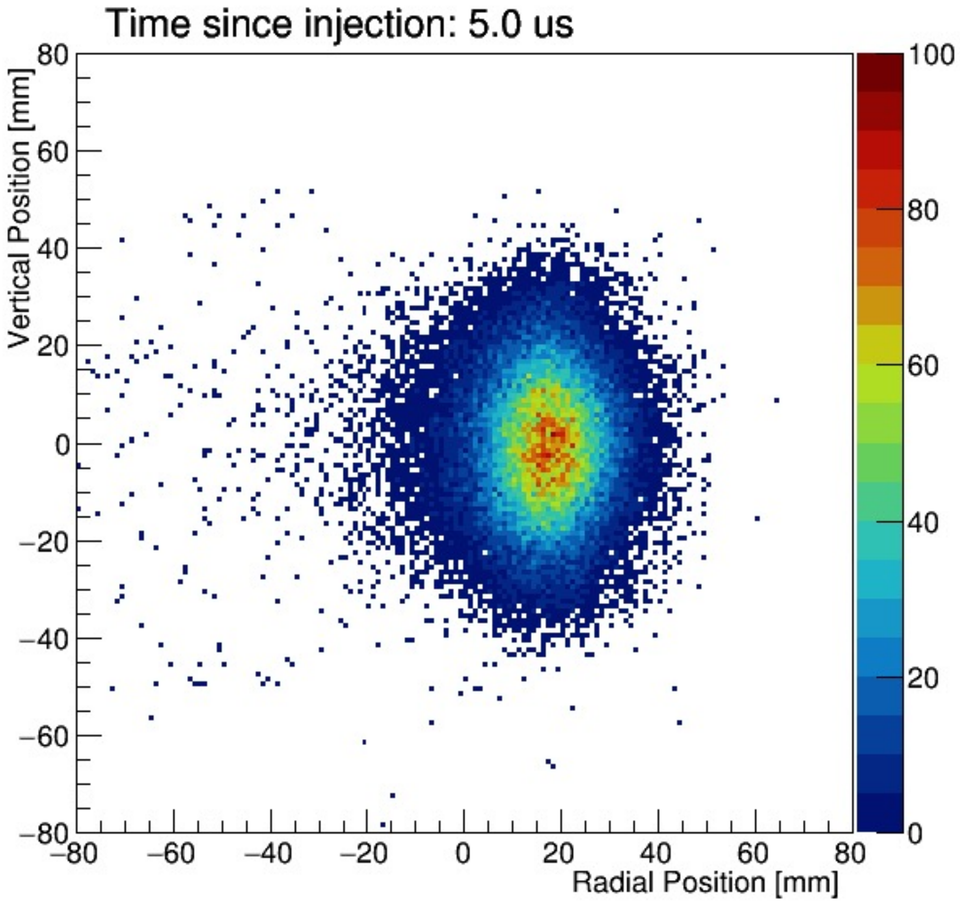
~200 Gauss Kick



Quads decreases Horizontal Betatron tune

$$\nu_x < 1$$

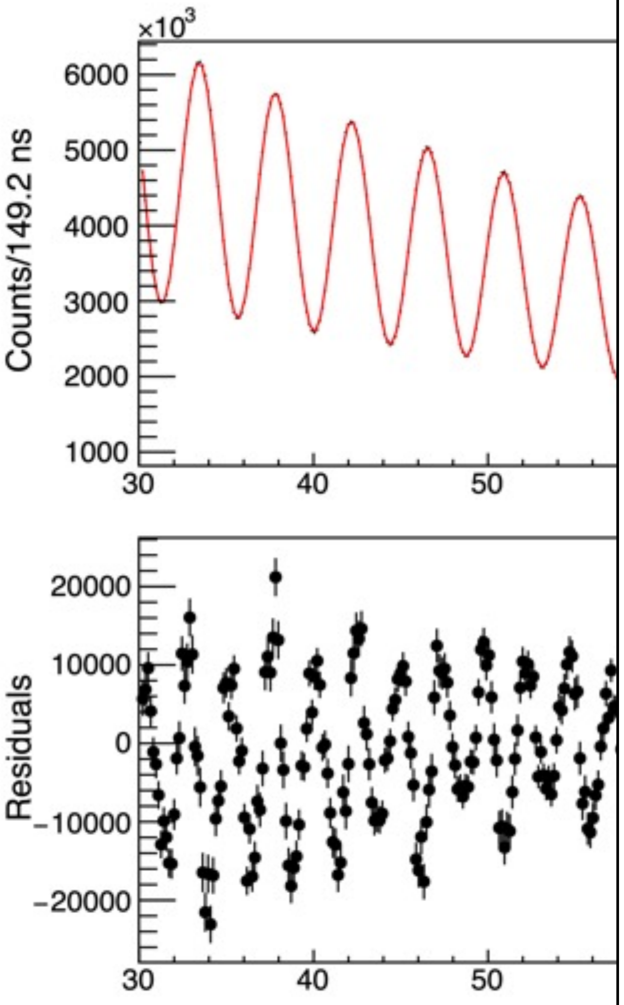
Horizontal Coherent Betatron Motion (due to $\nu_x < 1$)

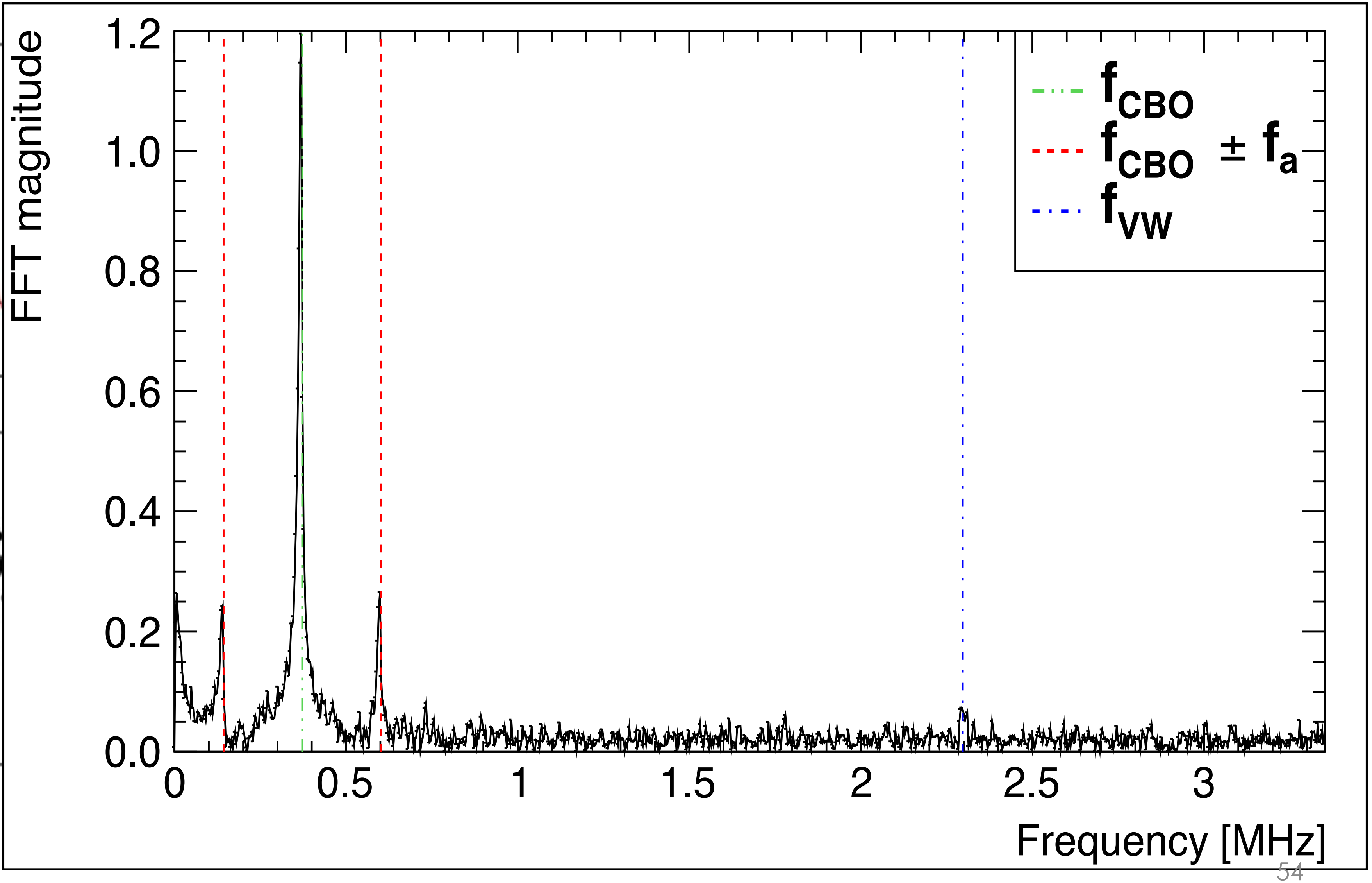


View seen by a the trackers

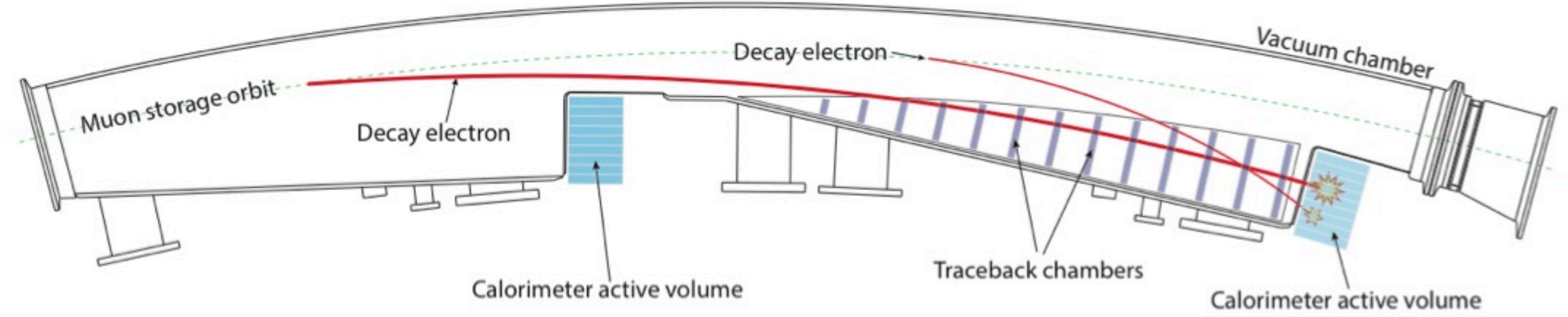
(similar effect in vertical direction)

5 parameter fit residuals poor due to Beam motion



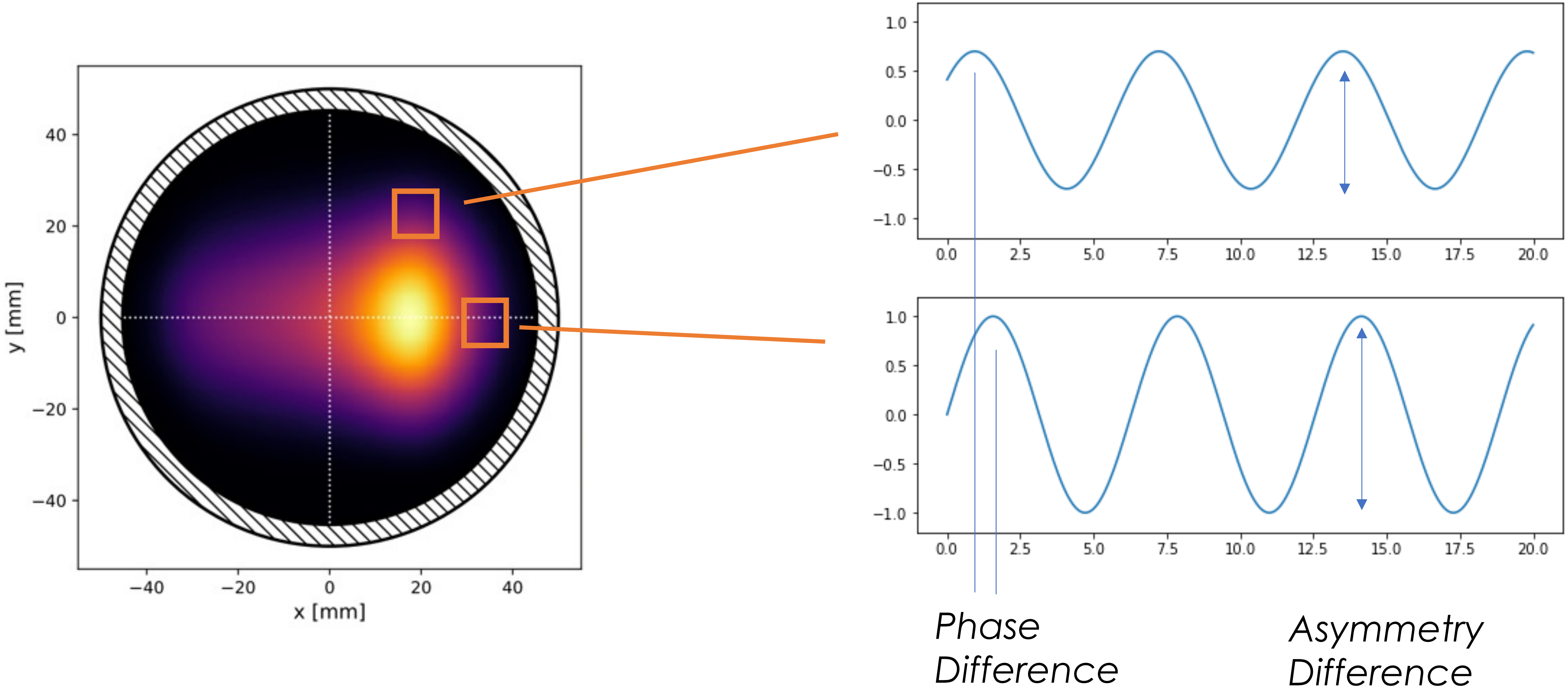


Finite Calorimeter Acceptance



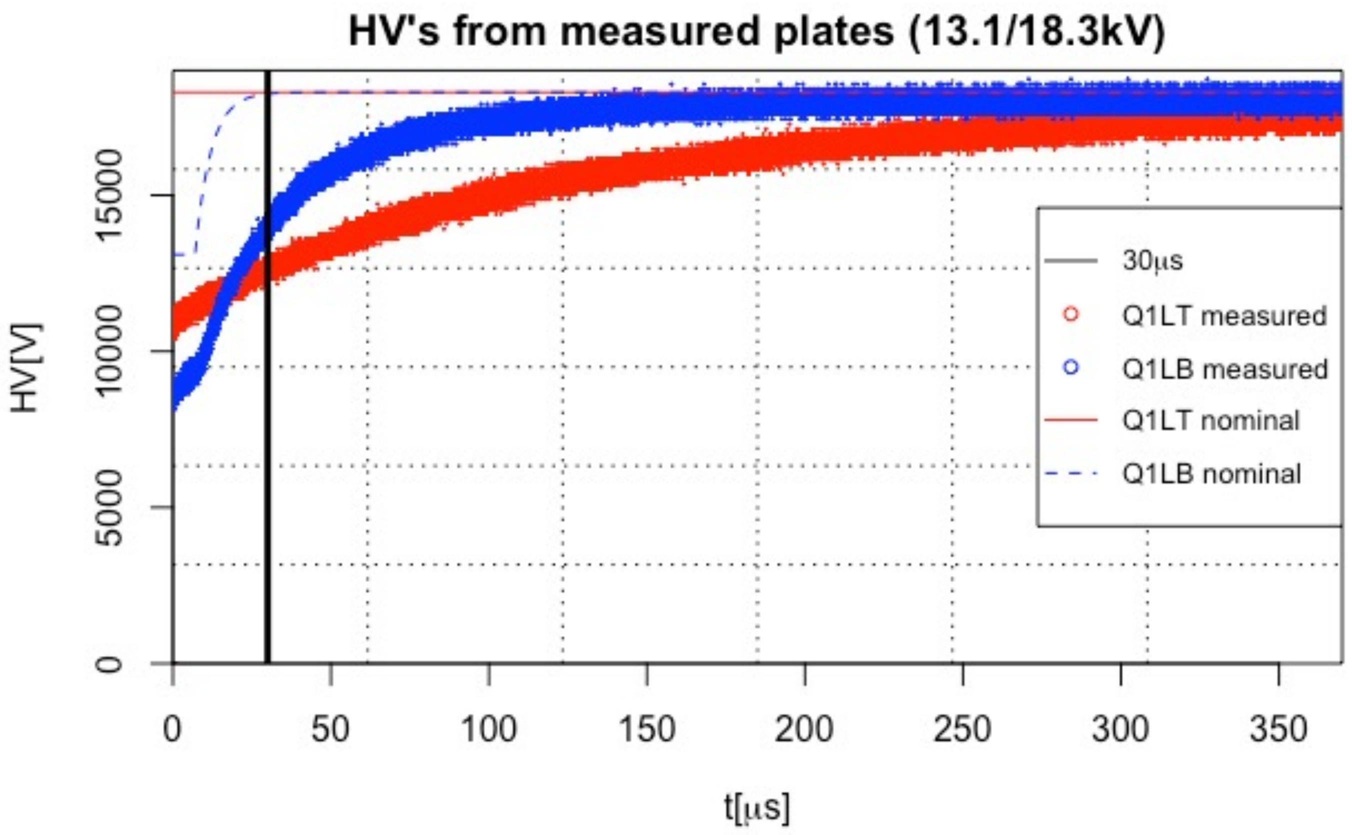
Since calorimeter size is finite,
we are sensitive to decay vertex position

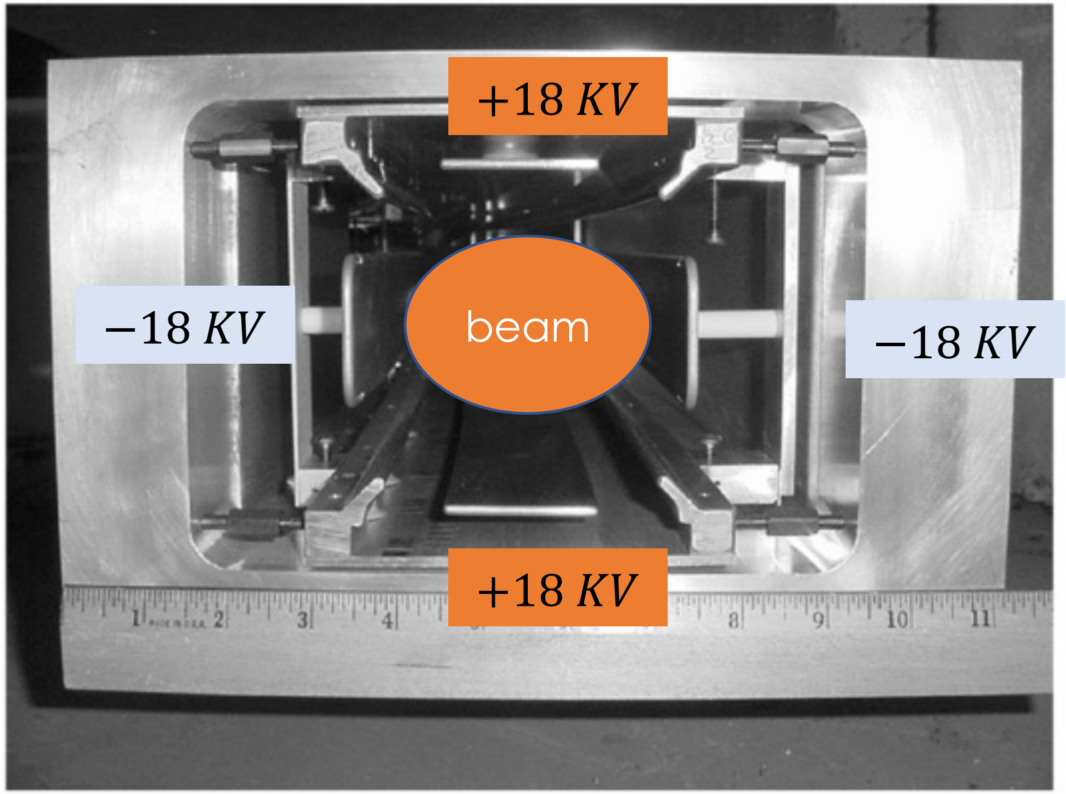
"Wiggle" Phase and Asymmetry has a 2D dependence



The ω_a plot is the ensemble average. ***The beam profile must be well-understood during measurement period***.

2 damaged Quad Resistors caused Beam Instability in Fill





Two (out of 32) Quad Electrode Voltages rose too slowly

“Phase Acceptance” Correction took 1 year to pin down.

Run 1 Datasets

Dataset	Quad field index	Kicker [kV]	Number of Positrons
1a	0.108	130	0.9B
1b	0.120	137	1.3B
1c	0.120	132	2.0B
1d	0.108	125	4.0B

Total statistics =8.2B e^+ ~ 1.2x BNL

Run 1 collected in spring 2018.

4 datasets based on the quadrupole and kicker voltages

22 Parameter Fit

$$N_0\, e^{-\frac{t}{\gamma\tau}}\,(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{2\mathrm{CBO}}(t) \cdot J(t)$$

$$A_{\mathrm{BO}}(t) = 1 + A_A \cos(\omega_{\mathrm{CBO}}(t) + \phi_A)e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$\phi_{\mathrm{BO}}(t) = 1 + A_\phi \cos(\omega_{\mathrm{CBO}}(t) + \phi_\phi)e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{CBO}}(t) = 1 + A_{\mathrm{CBO}} \cos(\omega_{\mathrm{CBO}}(t) + \phi_{\mathrm{CBO}})e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{2\mathrm{CBO}}(t) = 1 + A_{2\mathrm{CBO}} \cos(2\omega_{\mathrm{CBO}}(t) + \phi_{2\mathrm{CBO}})e^{-\frac{t}{2\tau_{\mathrm{CBO}}}}$$

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

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

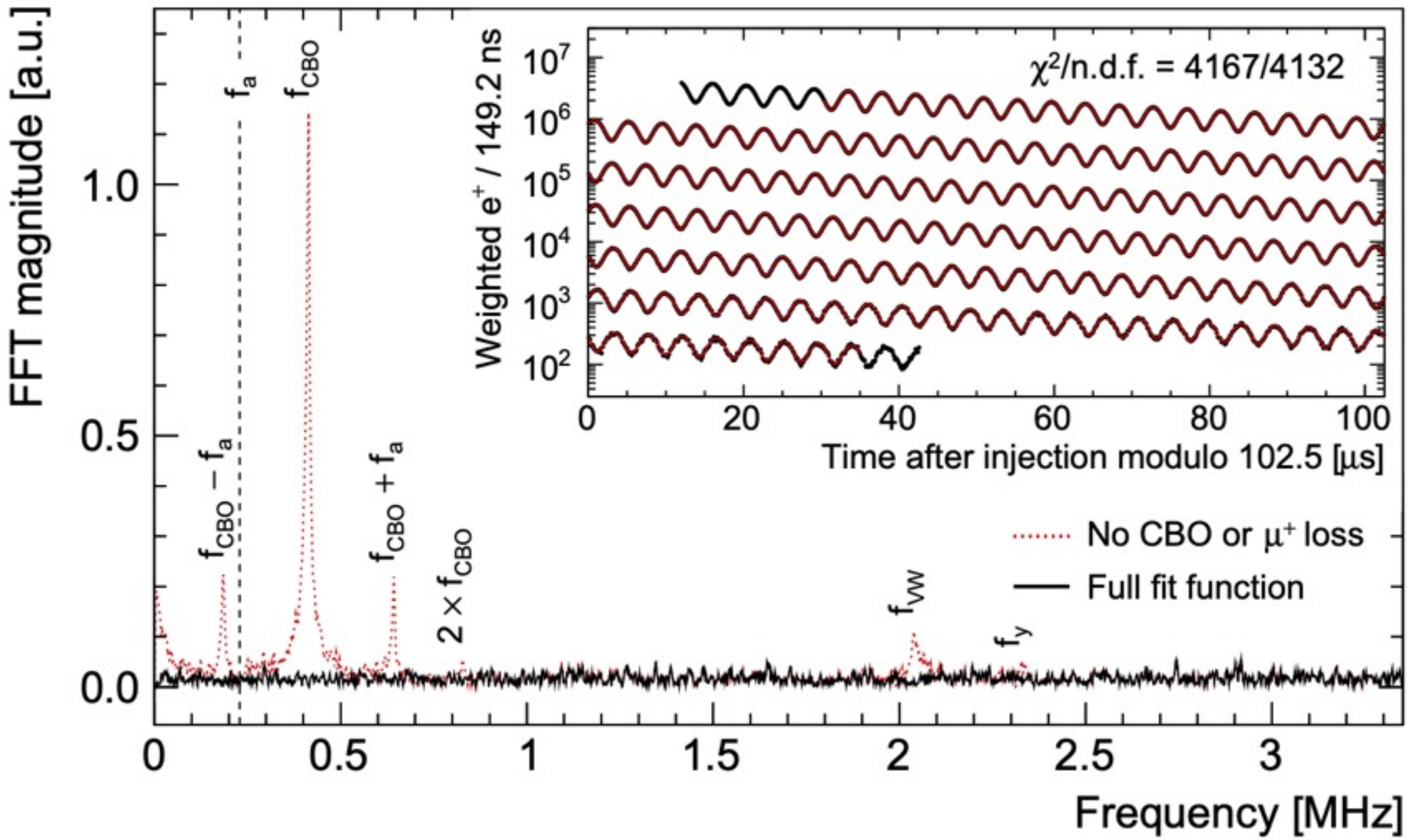
$$J(t) = 1 - k_{LM}\int_{t_0}^{t} \Lambda(t)dt$$

$$\omega_{\mathrm{CBO}}(t) = \omega_0 t + Ae^{-\frac{t}{\tau_A}} + Be^{-\frac{t}{\tau_B}}$$

$$\omega_y(t) = F\omega_{\mathrm{CBO}(t)}\sqrt{2\omega_c/F\omega_{\mathrm{CBO}}(t) - 1}$$

$$\omega_{\mathrm{VW}}(t) = \omega_c - 2\omega_y(t)$$

Final Result from a 22 parameter fit (dataset 1d)



Uncertainties

Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a (statistical)	–	434
ω_a (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{calib}\langle\omega'_p(x,y,\phi) \times M(x,y,\phi)\rangle$	–	56
B_q	-17	92
B_k	-27	37
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total	–	462

434 ppb statistical

$\oplus$

157 ppb systematic

Multiple Independent Analyses

6 extractions of ω_a emphasizing different systematics

2 independent reconstructions

3 e^+ pileup algorithms

3 spin/momentum simulations

2 FEA of quad field

2 Momentum distribution extraction methods

2 B-field tracking algorithms

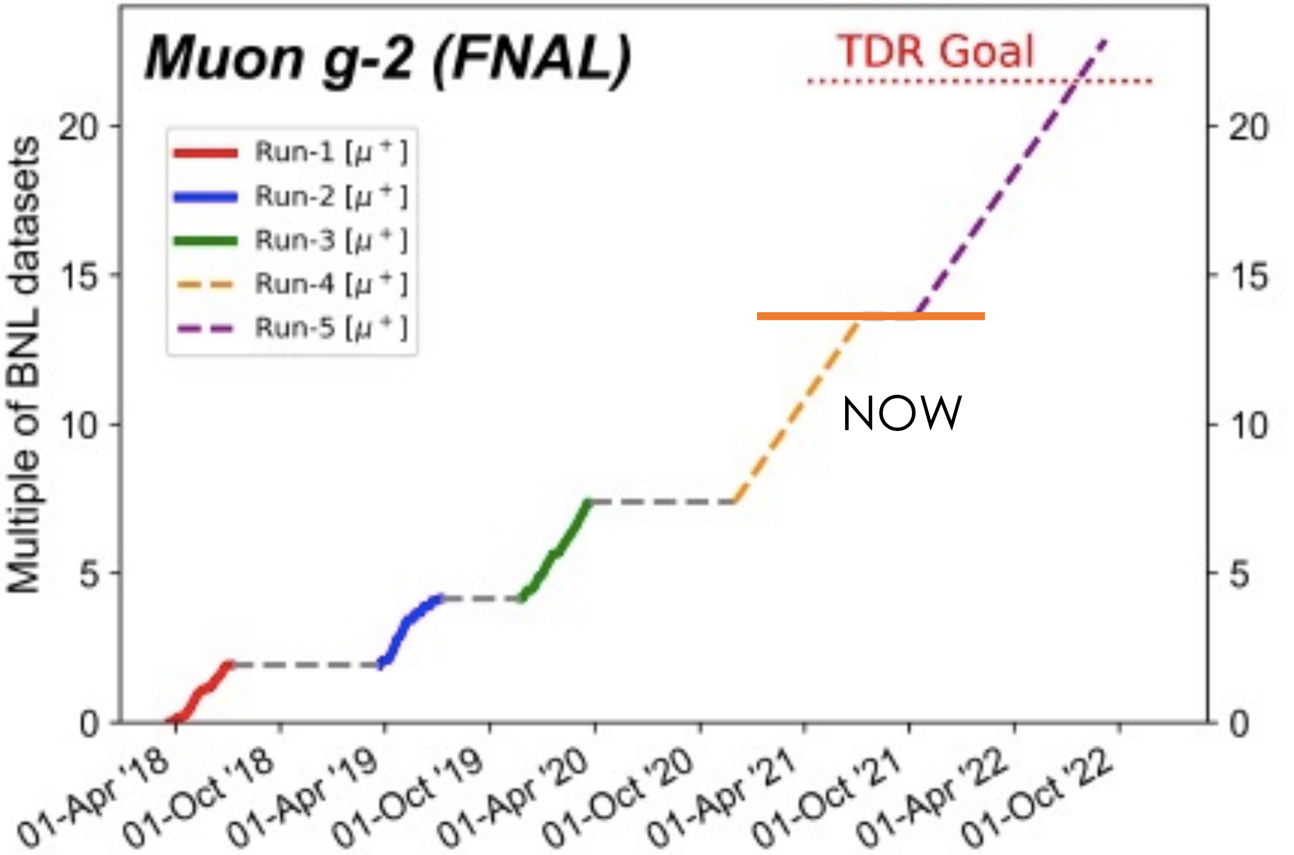
2 proton precession waveform fitters

2 absolute field calibrations

2 kicker transient measurements

The Future

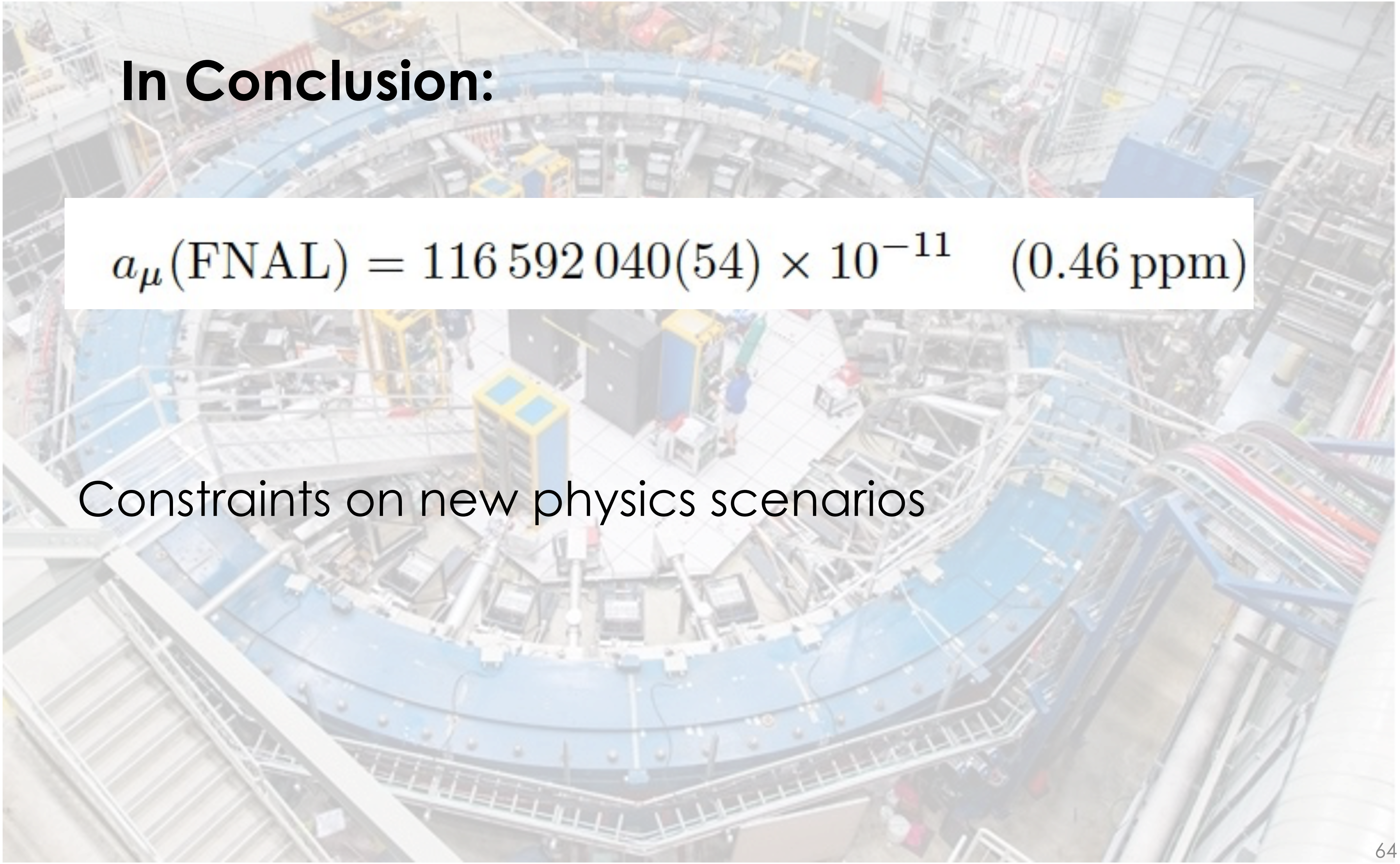
- RUN1 is only 6% of the final dataset ... with 4 configurations.
- Recently surpassed 10 BNL data sets.
- Runs 2, 3 has ~1 data-taking configuration with higher kick setting
- Run 4 (now) has the best kicker setting (met TDR) !



In Conclusion:

$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\text{ppm})$$

Constraints on new physics scenarios



Implications for New Physics Landscape

Figure of Merit: $a_{\mu\,2020} - a_{\mu\,SM} \sim 1.7\, a_{\mu\,Weak}$

Wide variety of models with 1, 2, or 3 field extensions.

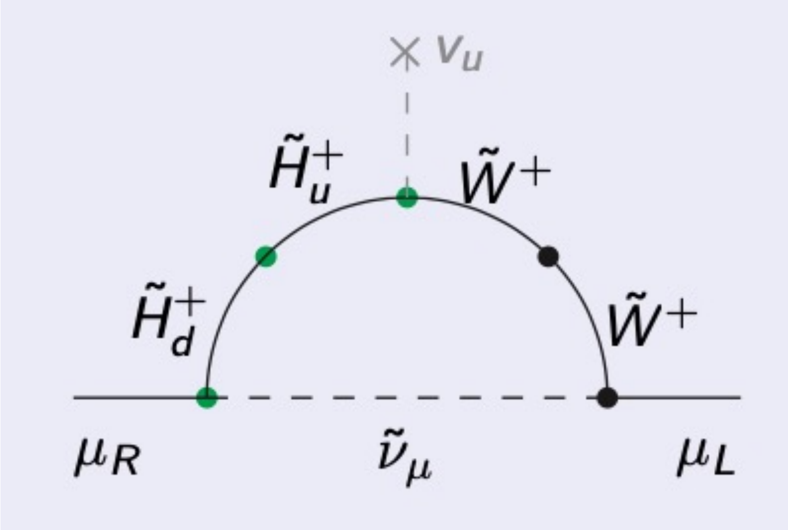
Few survive the combined constraints from the LHC and DM searches, and a_μ. They predict too small a_μ.

Notable models that are still viable: 2 Higgs Doublet, Scalar Lepto-Quark, general MSSM models.

See https://arxiv.org/pdf/2104.03691.pdf. Athron, et. al.

Ideas for Resolving: $a_{\mu\ 2020} - a_{\mu\ SM}$

Higgs → $\mu^+\mu^-$ measurement at the LHC or future lepton colliders would be very interesting since chirality flipping enhancements is related to the mass mechanism.



Higgsino, Winos, and neutralino correction to the muon mass

Open Questions with the SM prediction

BMW lattice calculation is in tension with traditional data-driven Dispersive technique.

The dispersive technique has been studied for decades. Uncertainties are agreed to be experimental.

(Is there new physics in this difference ?)

There are other ideas: MuonE

We await the next word from the theory community.

Dispersive Technique

Dispersion Relation
+ Analyticity
+ Optical Theorem
+ Data from
e^+e^- and $\tau \to hadrons$

$$a_\mu^{\text{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\text{th}}}^{\infty} ds\, \frac{1}{s}\hat{K}(s)\sigma_{\text{had}}(s)$$

BMW20

First sub% ab-initio
Lattice QCD calculation

"One piece of a_μ" does not agree with other lattice calculations.

"Other pieces" to be compared

Implies larger discrepancy
of hadronic cross section at low E

Other New Approaches

MUonE Proposal (CERN)

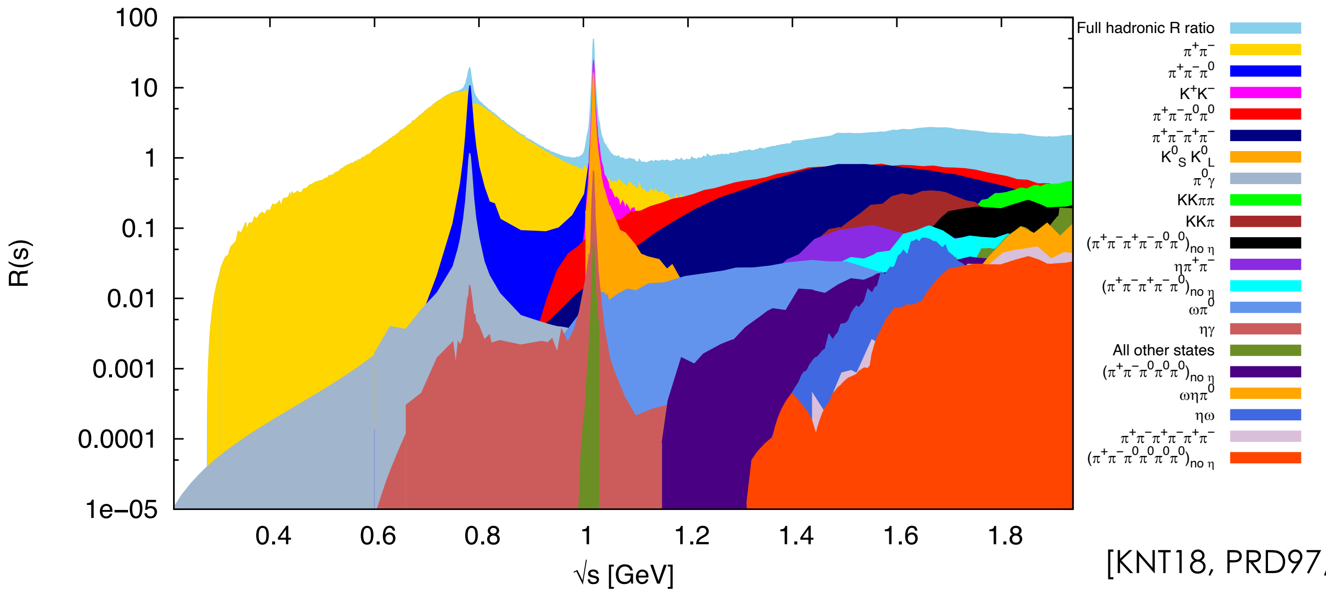
$\mu^+e^- \to \mu^+e^-$ elastic scattering of 150 GeV muons in the Feynman x range = 0 - 0.93

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

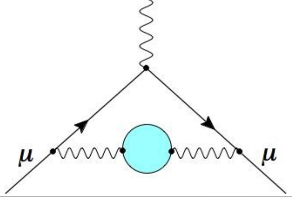
$\Delta\alpha_{had}(t(x))$ from
$\mu^+e^- \to \mu^+e^-$ elastic scattering

$$t(x) = \frac{x m_\mu^2}{x-1} < 0$$

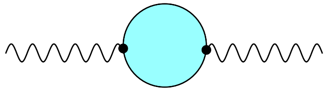
x =Feynman x



[KNT18, PRD97, 114025]



Hadronic vacuum polarization

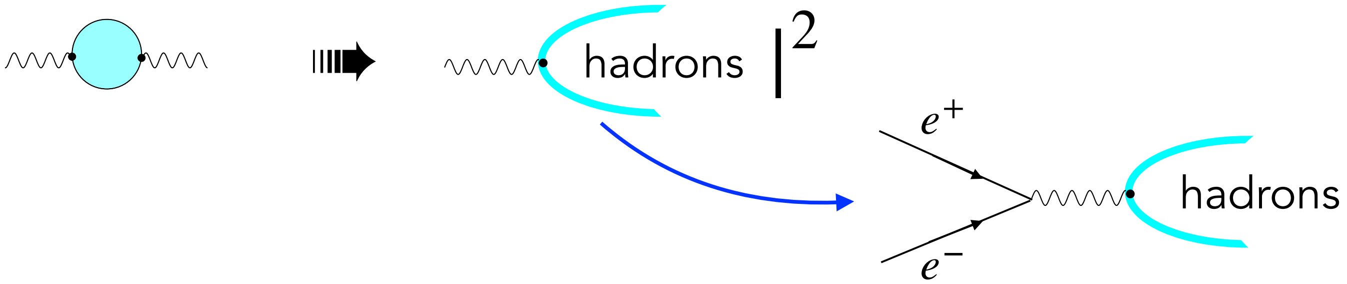


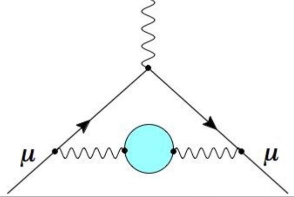
$\hat{\Pi}(q^2)$

Leading order HVP correction:

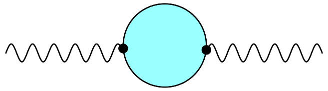
$$a_\mu^{\rm HVP,LO} = \left(\frac{\alpha}{\pi}\right)^2 \int dq^2 \omega(q^2)\, \hat{\Pi}(q^2)$$

- Can rewrite the integral in terms of the hadronic e^+e^- cross section:





Hadronic vacuum polarization



$\hat{\Pi}(q^2)$

Leading order HVP correction:

$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int dq^2 \omega(q^2)\, \hat{\Pi}(q^2)$$

- Calculate $a_\mu^{\mathrm{HVP,LO}}$ in Lattice QCD

  Compute correlation function: $C(t) = \frac{1}{3} \sum_{i,x} \langle j_i(x,t) j_i(0,0) \rangle$

  Obtain $a_\mu^{\mathrm{HVP,LO}}$ from an integral over Euclidean time:

$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, \tilde{w}(t)\, C(t)$$

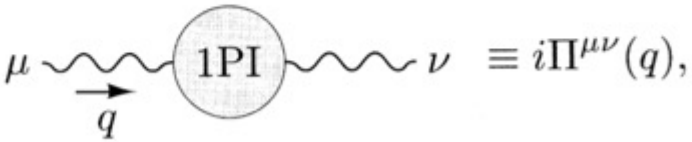
Dziękuję Ci

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

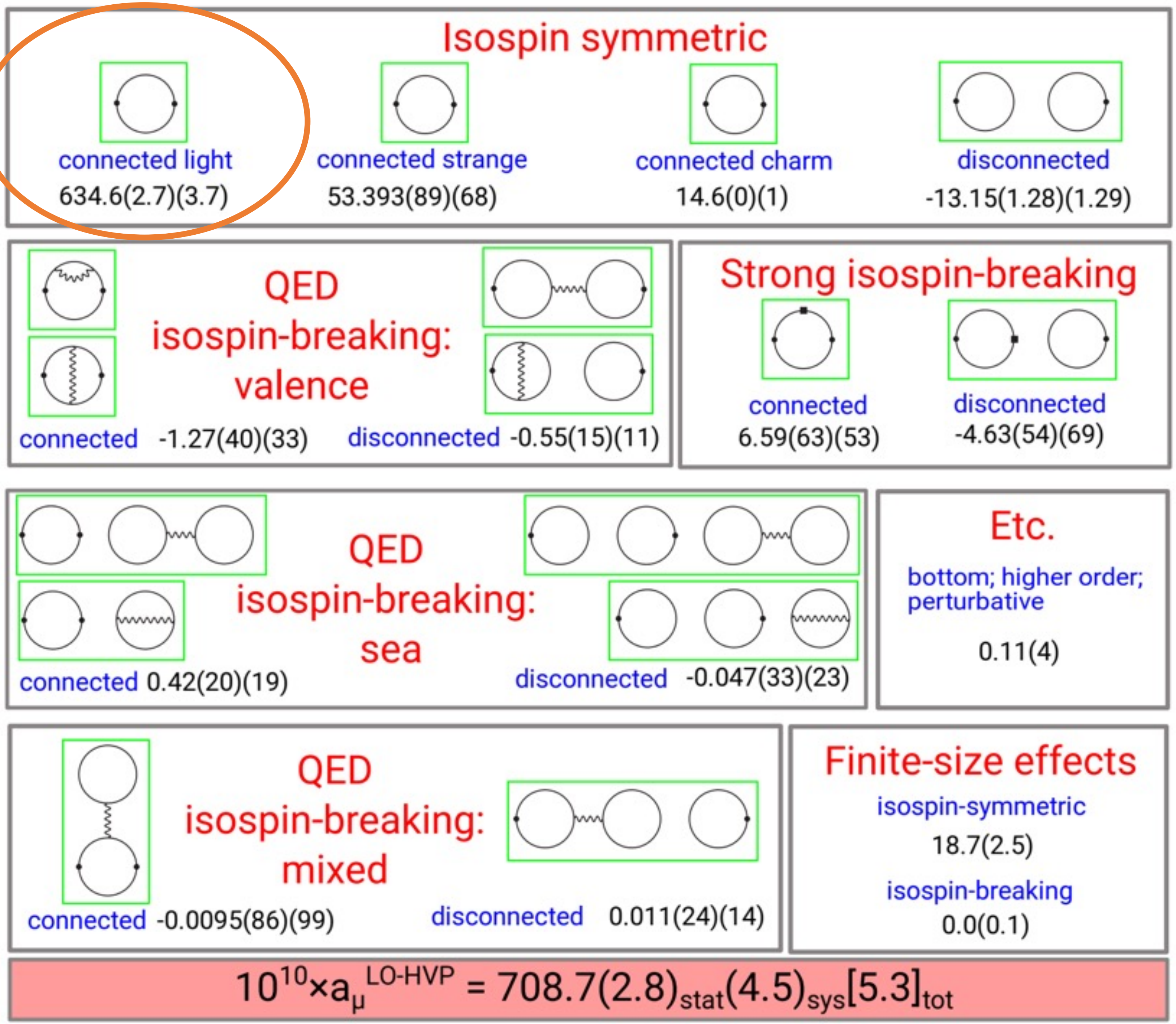
Back up

From BMW20 (archive version)

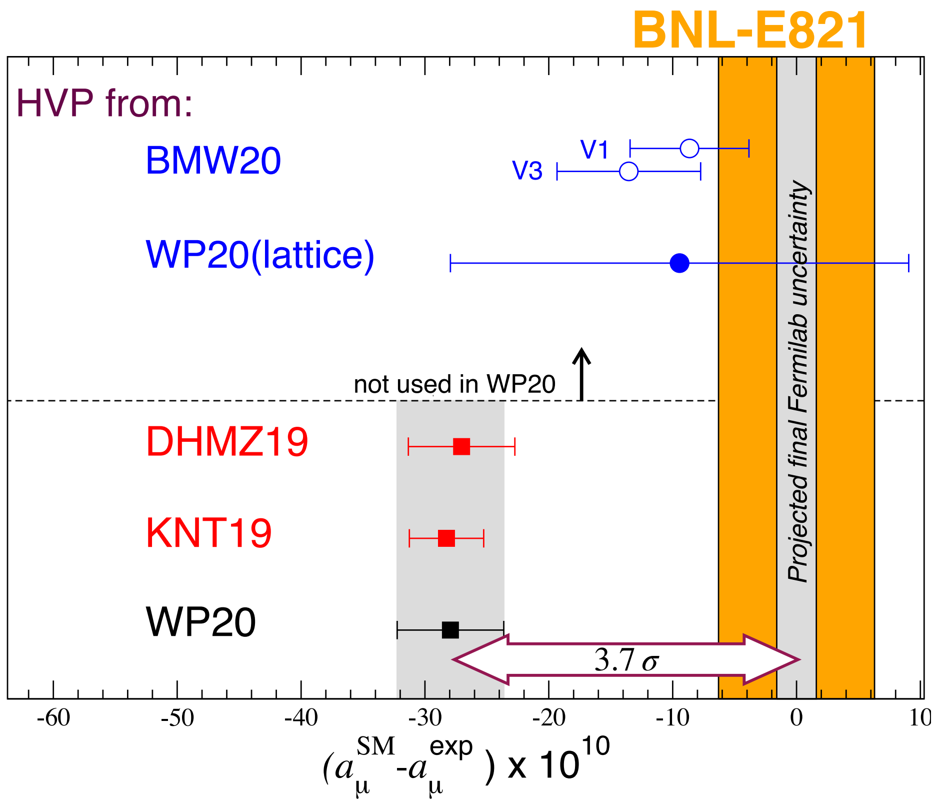
"1 particle Irreducible diagrams"



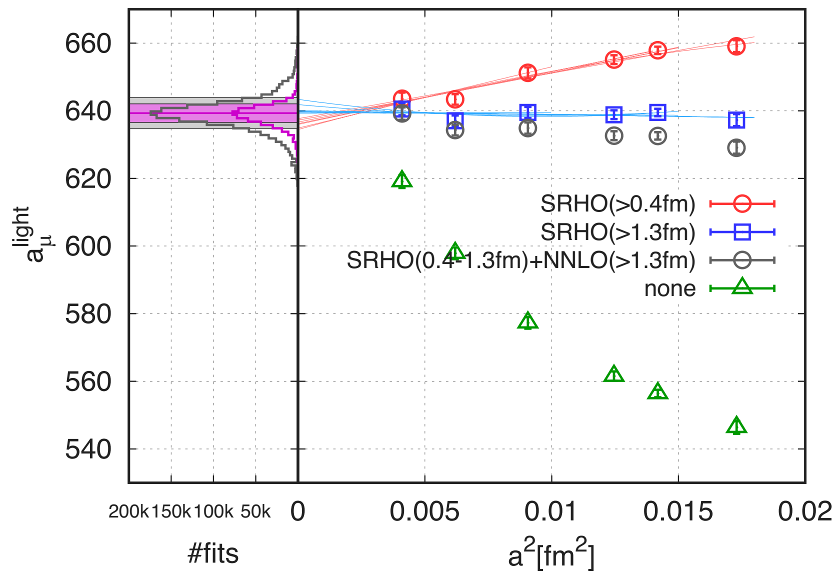
See e.g. Peskin/Schroeder Chapter 7

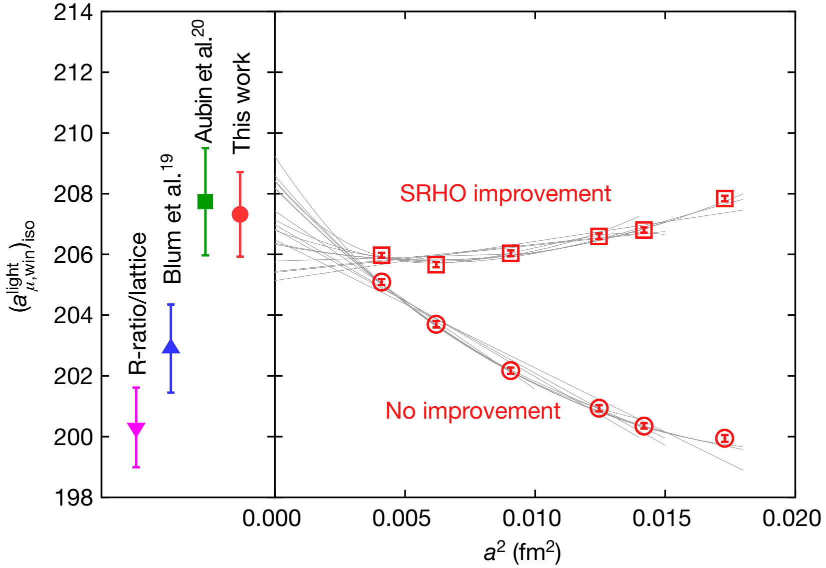


Lattice HVP: Tension betw. BMW & data-driven. Syste



BMW20 [Borsanyi et al, arXiv:2002.12347, 2021 Nature]





BMW20: large systematics from **continuum limit**

- upper right panel: limit and uncertainty estimation
- lower right panel: limit for central window compared to other lattice and data-driven results

Lattice HVP: Cross checks, window method (I)

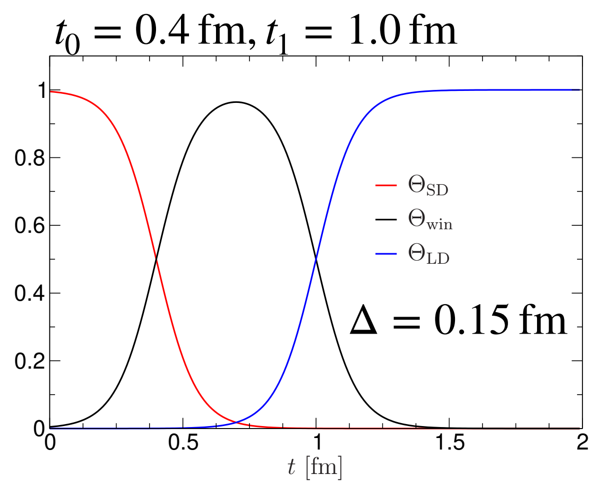
$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, \tilde{w}(t)\, C(t)$$

- Use windows in Euclidean time to consider the different time regions separately.

Short Distance (SD) $t : 0 \to t_0$

Intermediate (W) $t : t_0 \to t_1$

Long Distance (LD) $t : t_1 \to \infty$



- Compute each window separately (in continuum, infinite volume limits,…) and combine

$$a_\mu = a_\mu^{\mathrm{SD}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{LD}}$$

Lattice HVP: Cross checks, window method (II)

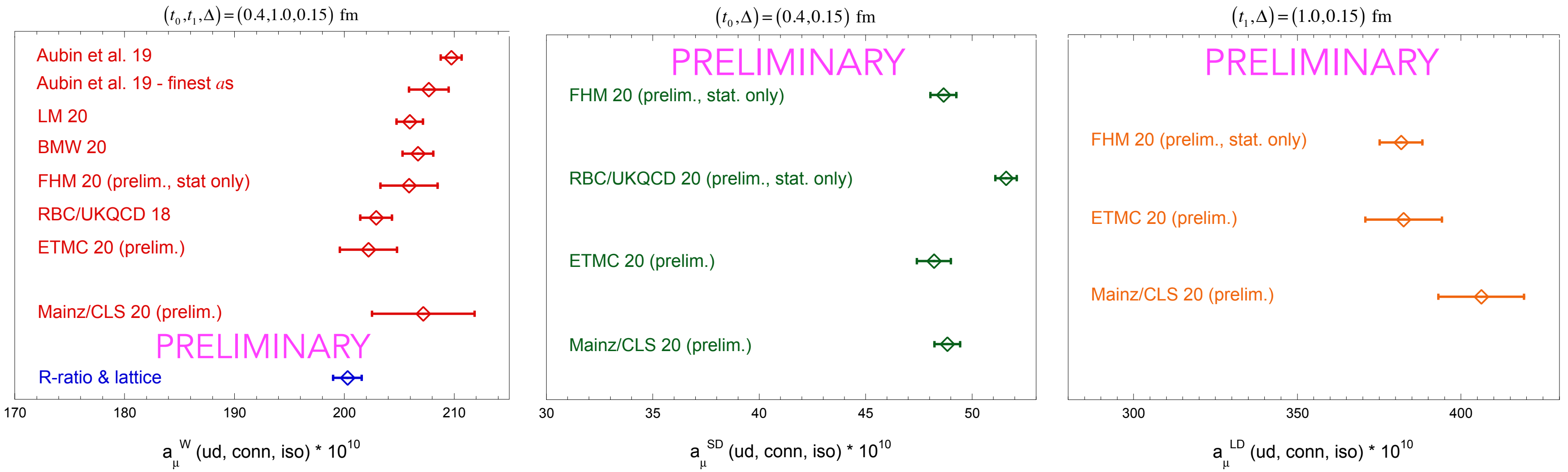
H. Wittig @ Lattice HVP workshop

$$t_0 = 0.4\,\text{fm}, t_1 = 1.0\,\text{fm}$$
$$\Delta = 0.15\,\text{fm}$$

$$a_\mu = a_\mu^{\text{SD}} + a_\mu^{\text{W}} + a_\mu^{\text{LD}}$$

“Window” quantities

(Plots from Davide Giusti)



- Straightforward reference quantities
- Can be applied to individual contributions (light, strange, charm, disconnected,…)
- **Large discrepancies** between different results, also with data-driven: **BMW vs KNT: 3.7σ**
- Individual results **must sum up**, and different groups & discretisations **must agree** (universality)

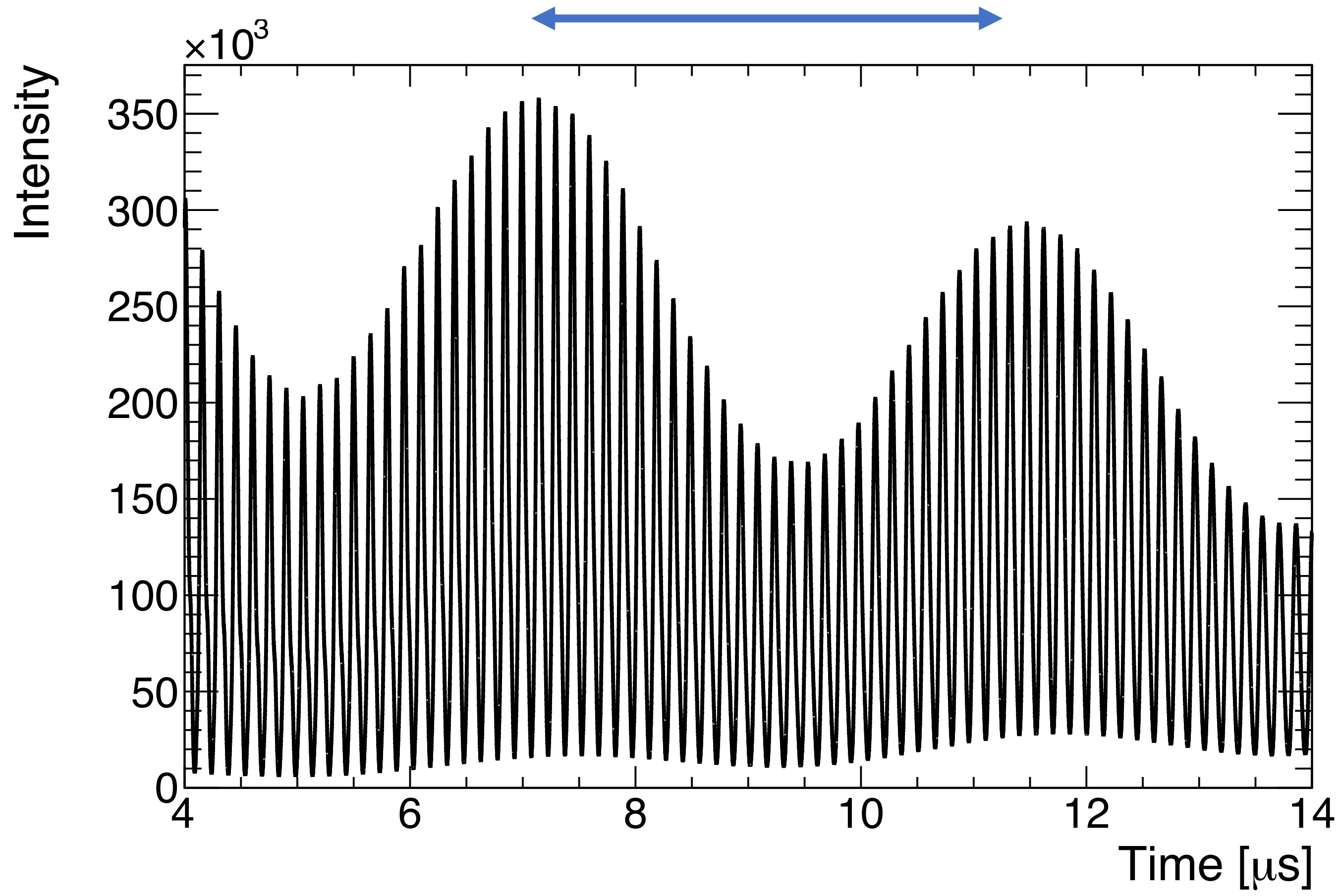
Comparisons

We essentially used the BNL magic momentum storage ring technique. But newer technology allowed us to scrutinize further and discovered new effects. We dedicated more time for special runs.

Jparc g-2 uses a low energy storage ring technique (no quads, no kickers, no inflector). But there are trade offs with rate and material and beam emittance.

Determining Momentum Distribution by Observing Beam Debunching

Slow Modulation is from a_μ



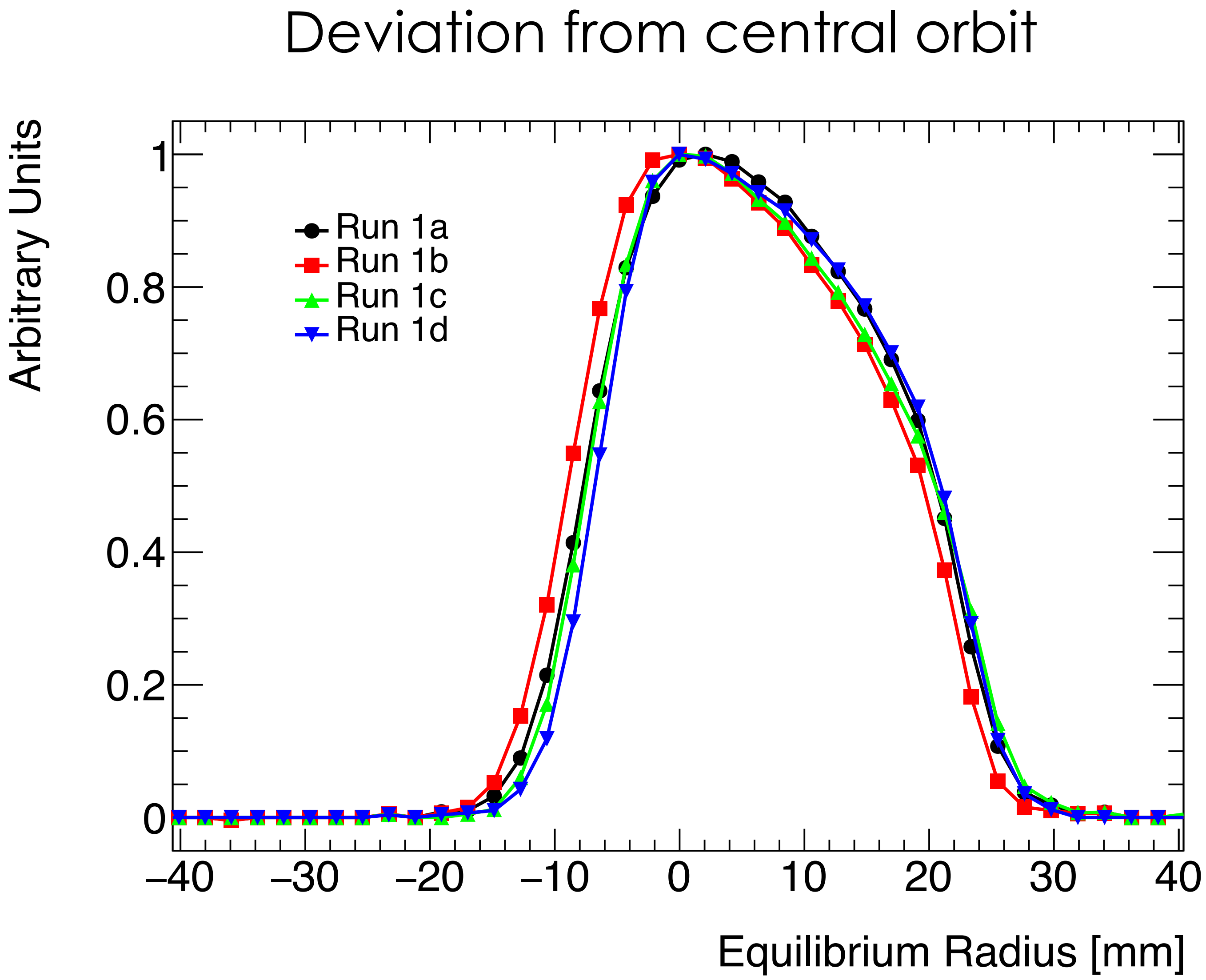
Lower momentum muons have *shorter* cyclotron period

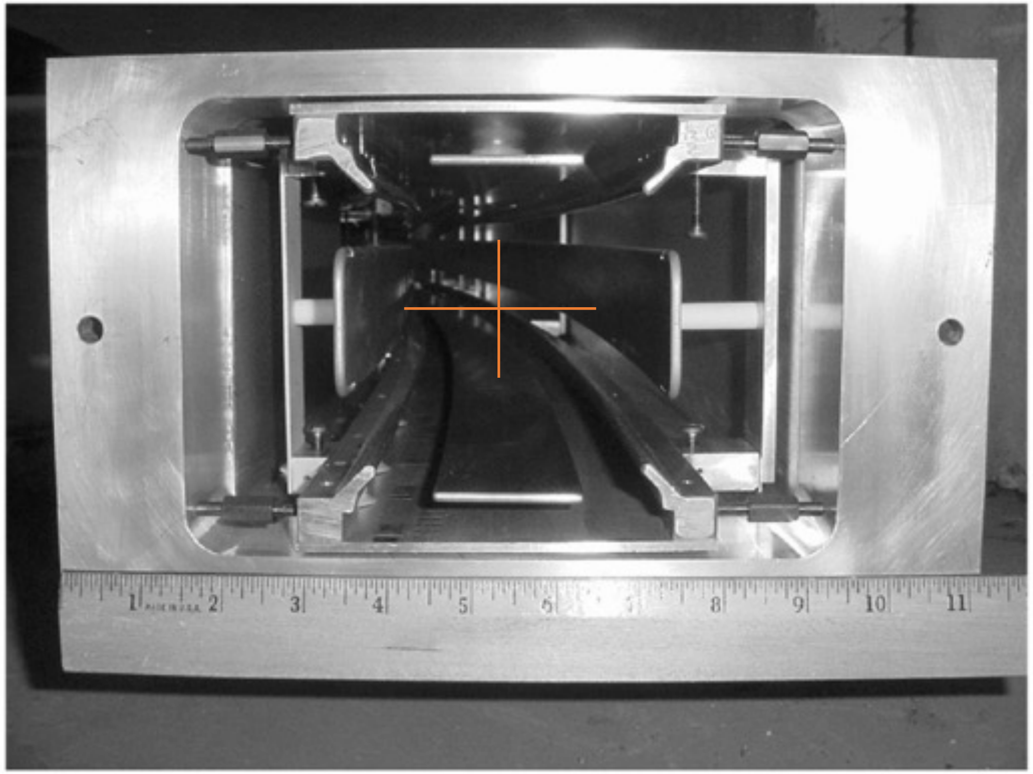
Higher momentum muons have *longer* cyclotron period

We can extract the rotation period distribution.

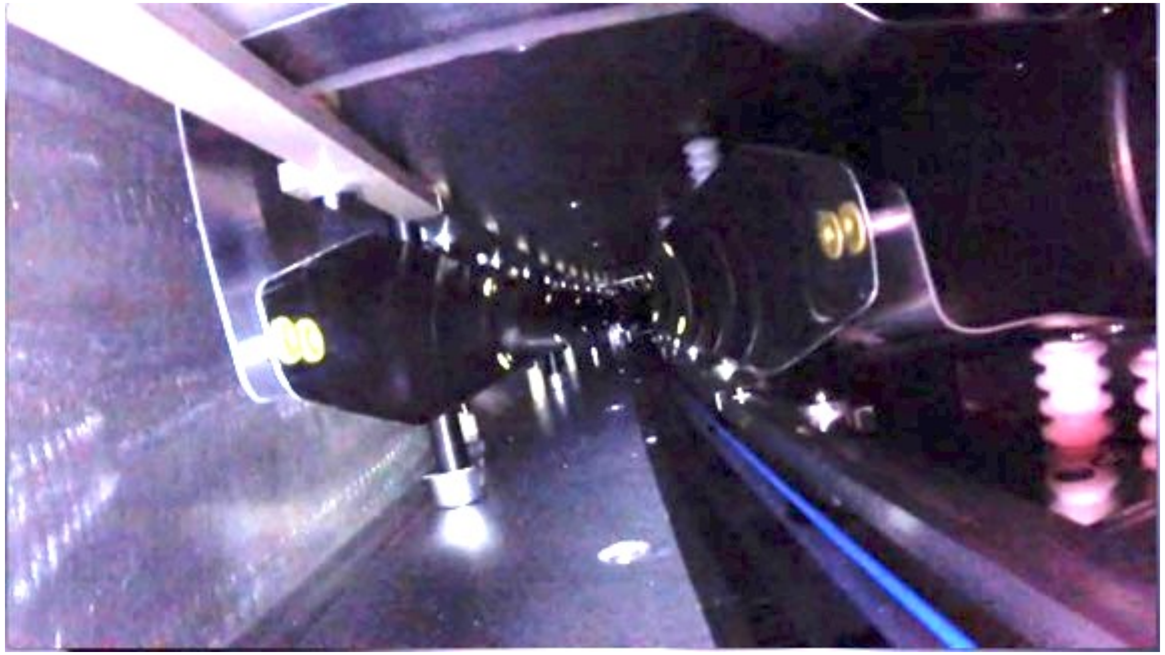
Fast Modulation is from the ~ ***150 nsec cyclotron period***

Determining Momentum Distribution by Observing Beam Debunching





B-field Transients from Kickers and Quads



Large Currents Required to Kick the Muons

Reaction Eddy Currents and Impedance mismatch currents

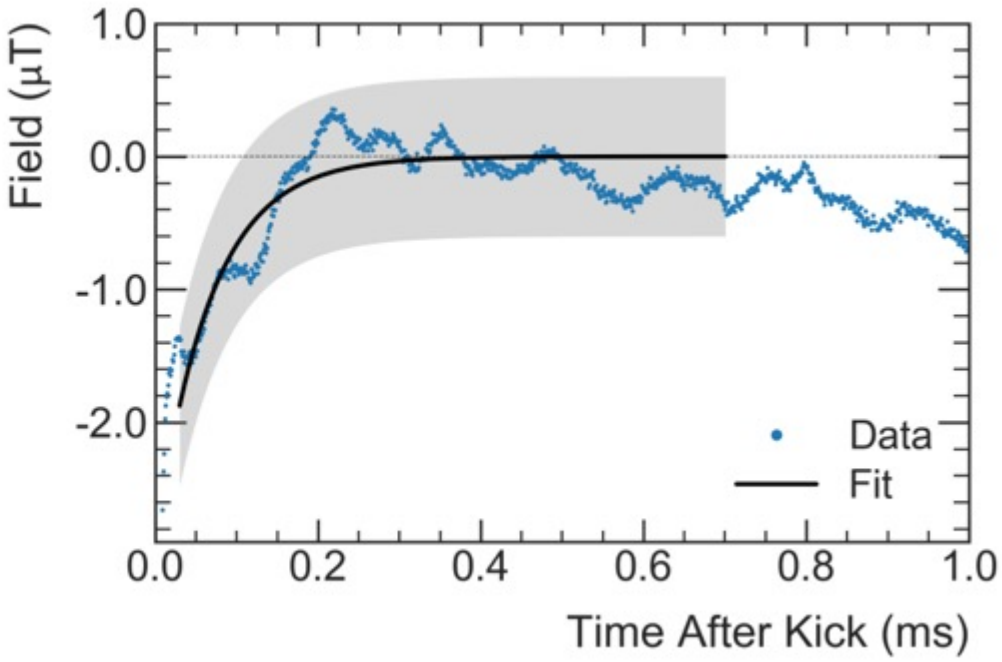
Mechanical Motion due to Lorentz Forces

Mechanical Motion due brief impulse of Electrostatic forces.

Vibration of metals in a magnetic field

Faraday Magnetometer

Kicker Transient Measurements

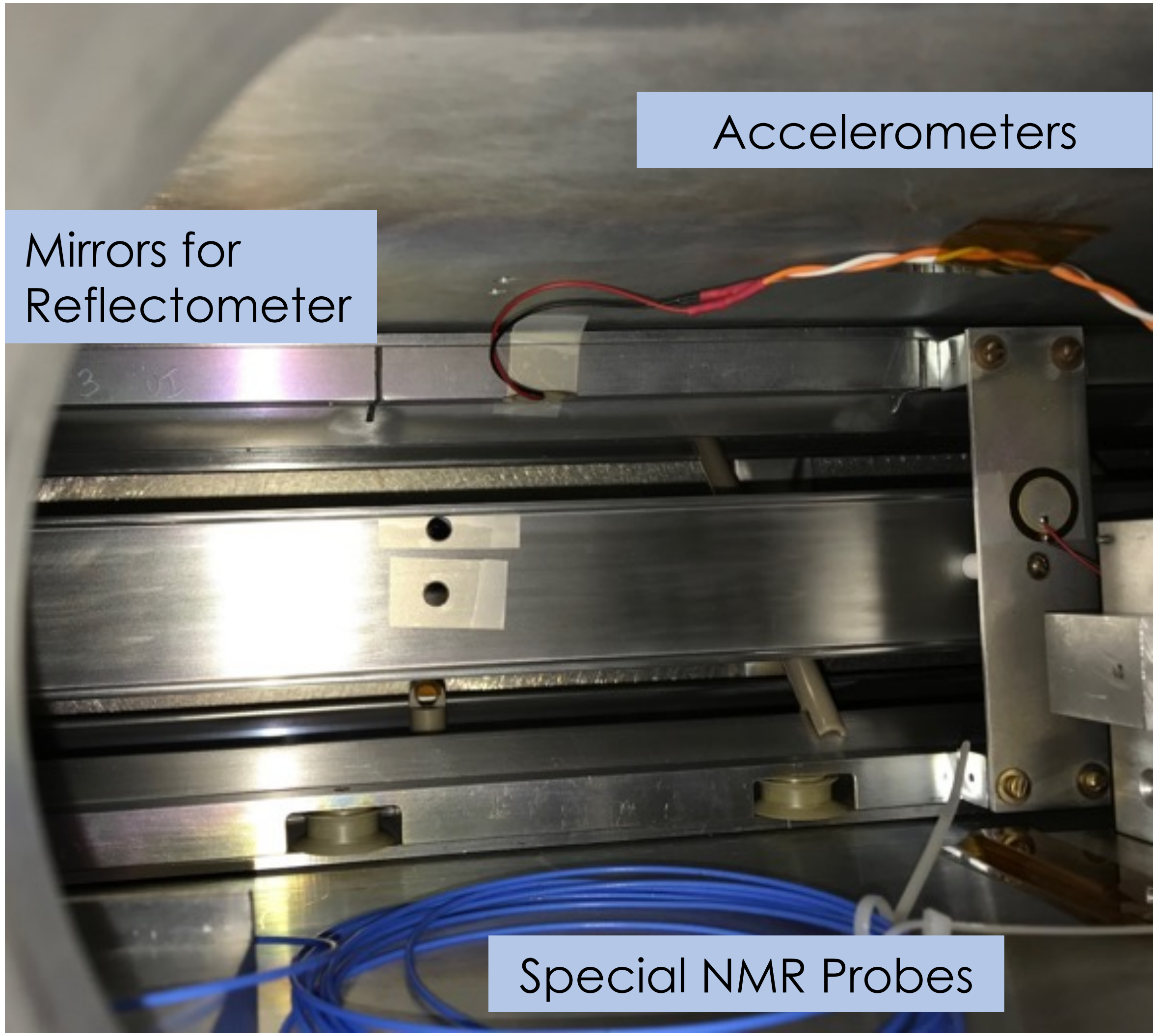


Extremely difficult measurement requiring several groups over 3 years during beam-off period to accomplish.

B-field Transients from Quads

This was a surprise and a worry

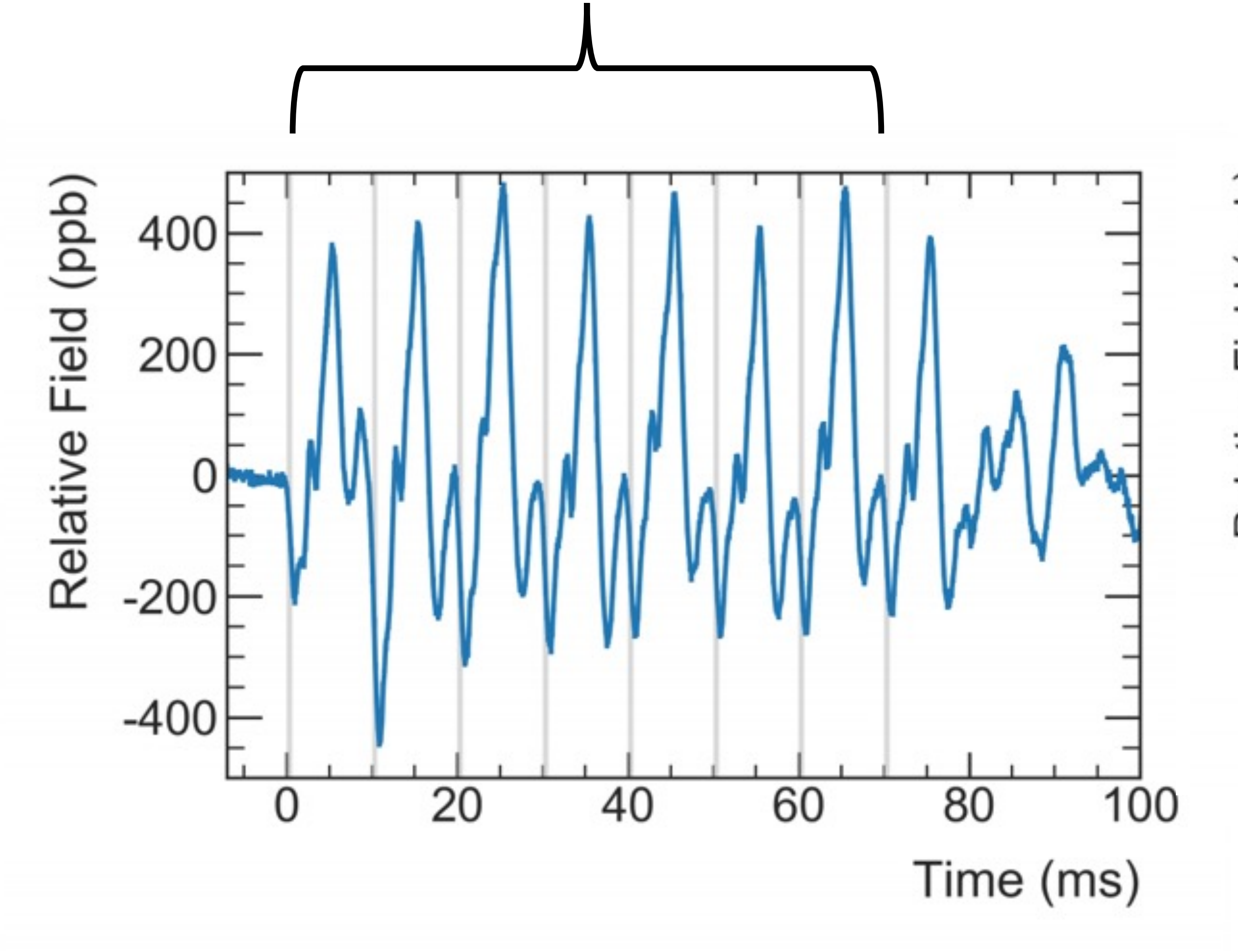
Corresponded to mechanical vibrations of the Quad plates caused by electrostatic impulses



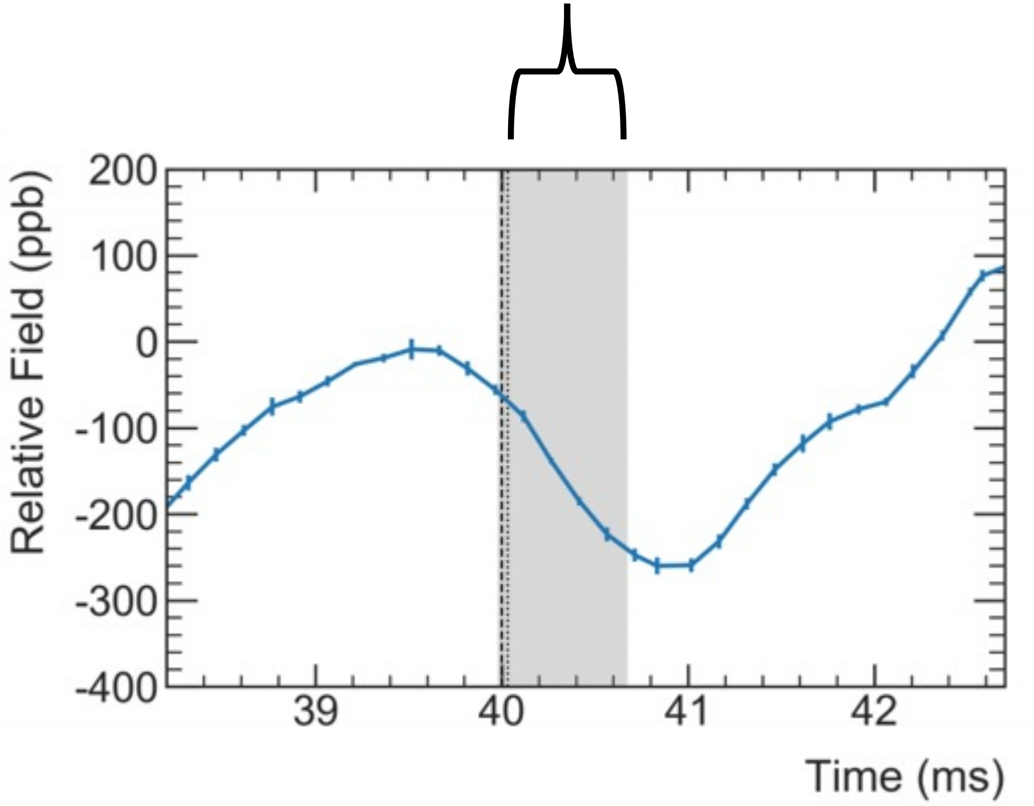
Required 1 year of study using specialty NMR probes and mechanical measurements

B-field Transients from the Quad System

Train of 8 Pulses of the Quad system



Transient during Muon Fill



Small Correction with large error

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Chirality Connection

$\bar{\mu}\gamma^{\alpha}\mu = \bar{\mu}_L\,\gamma^{\alpha}\,\mu_L + \bar{\mu}_R\,\gamma^{\alpha}\,\mu_R$

g = 2 part connects same chirality states

$\bar{\mu}\sigma^{\alpha\beta}\mu = \bar{\mu}_L\,\sigma^{\alpha\beta}\,\mu_R + \bar{\mu}_R\,\sigma^{\alpha\beta}\,\mu_L$

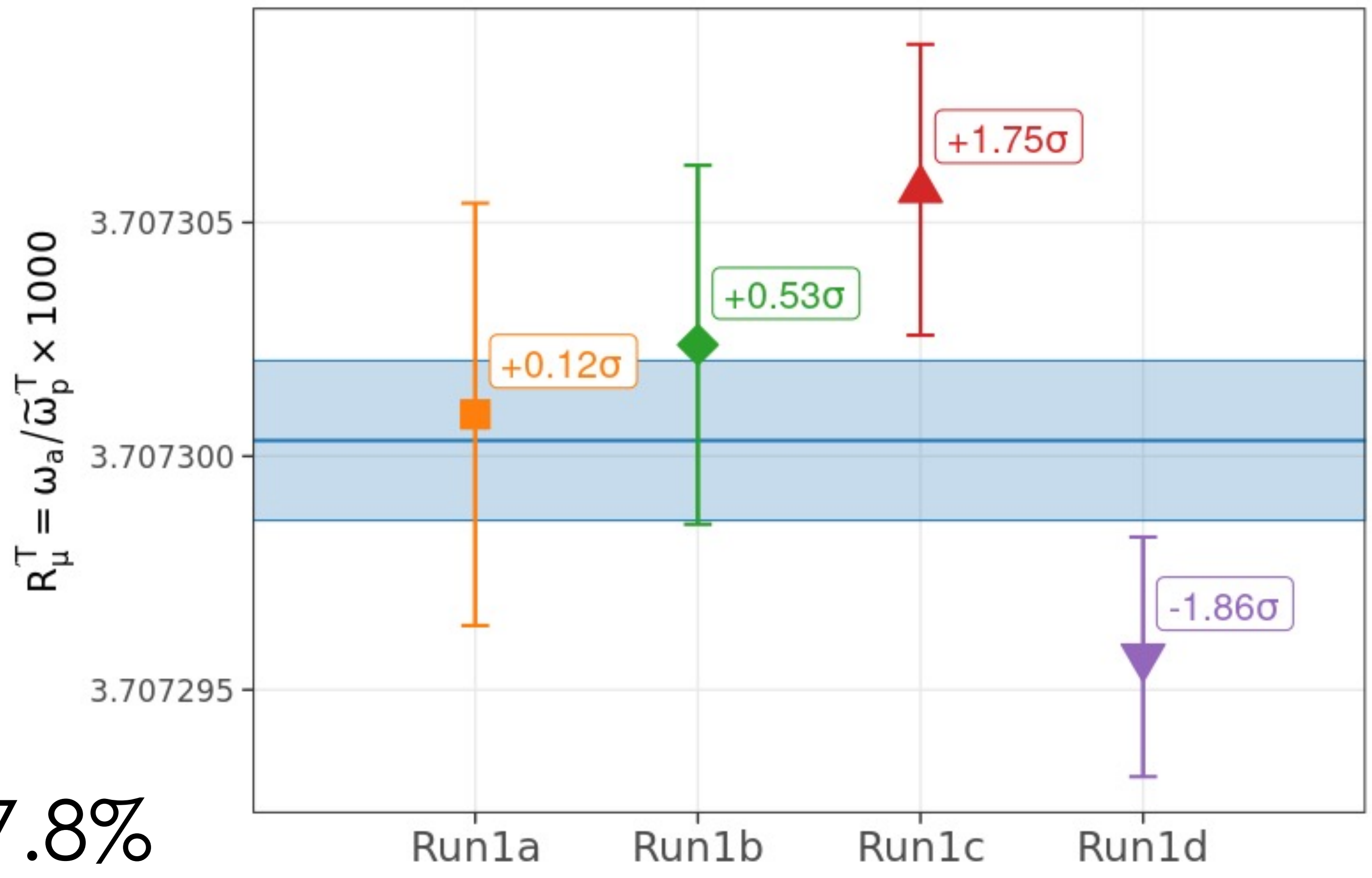
a_μ part connects opposite chirality states

$\bar{\mu}\,m\,\mu = \bar{\mu}_L\,m\,\mu_R \;+\; \bar{\mu}_R\,m\,\mu_L$

$mass$ terms connects opposite chirality states

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Blinded Results from 4 data periods



$\chi^2/\text{ndf}=6.8/3$ $P(\chi^2)=7.8\%$

Fit Stability