Testing the Standard Model with Most Accurate Muon g-2 Measurement

René Reimann for the Muon g-2 collaboration

Oct 8th, 2024

BLV2024, Karlsruhe

2024

PRISMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Outline

- **Why is Muon g-2 a good test of the SM?**
- How to measure the Muon g-2?
- Improvements in Run-2/3 results
- Outlook & Conclusions

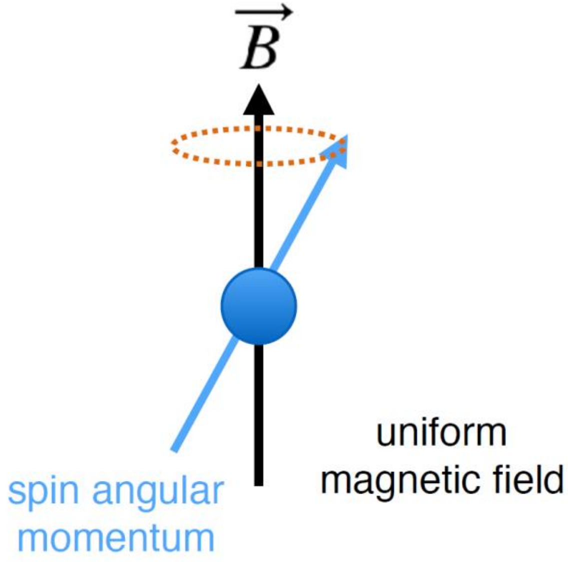
Muon magnetic moment

$$\vec{\mu}_\mu = -g_\mu \frac{e}{2m_\mu} \vec{S}$$

magnetic moment

proportionality constant

spin



Potential energy

$$U = -\vec{\mu} \cdot \vec{B}$$

Torque → precession

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

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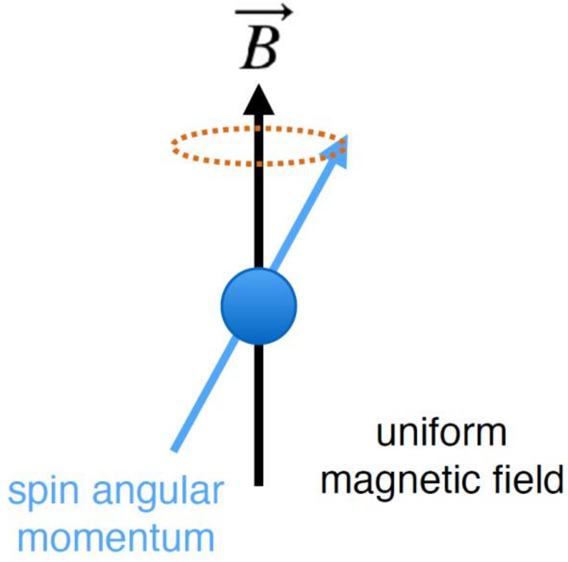

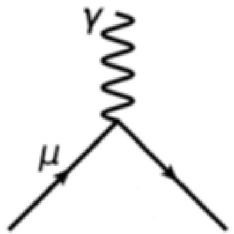

Dirac
(bare lepton)
g=2

1928

PRL 126, 141801 (2021)

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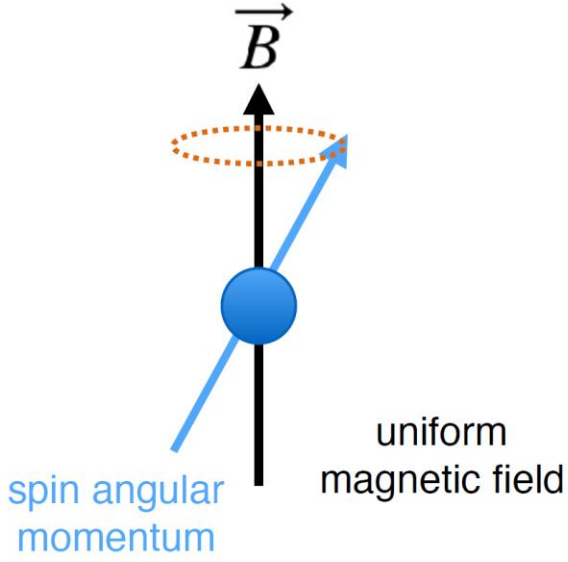

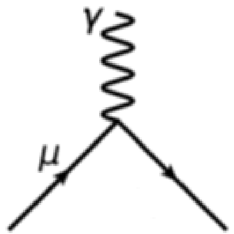

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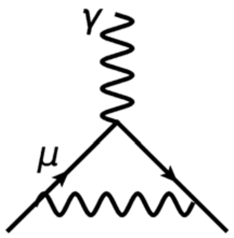

Schwinger

α/2π

1947

PRL 126, 141801 (2021)

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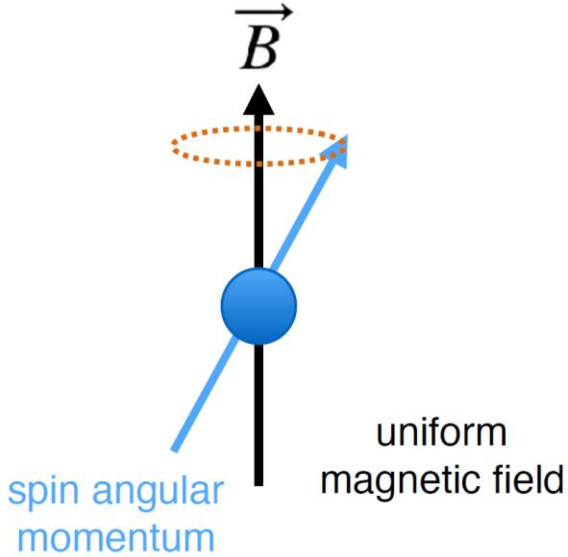

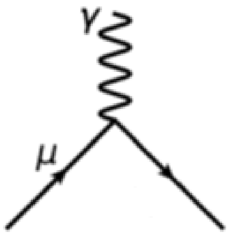

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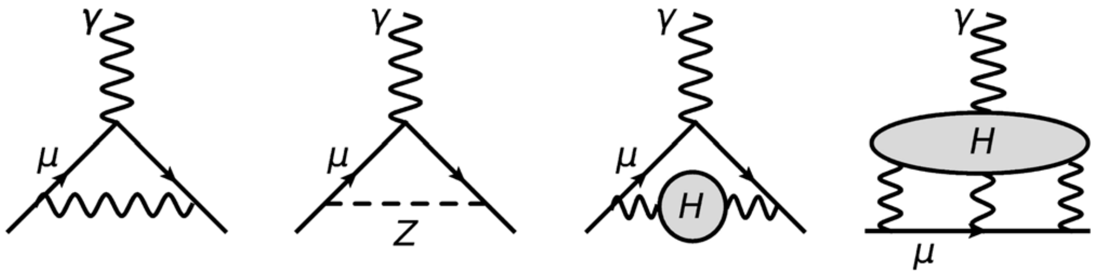

anomalous magnetic moment

today

PRL 126, 141801 (2021)

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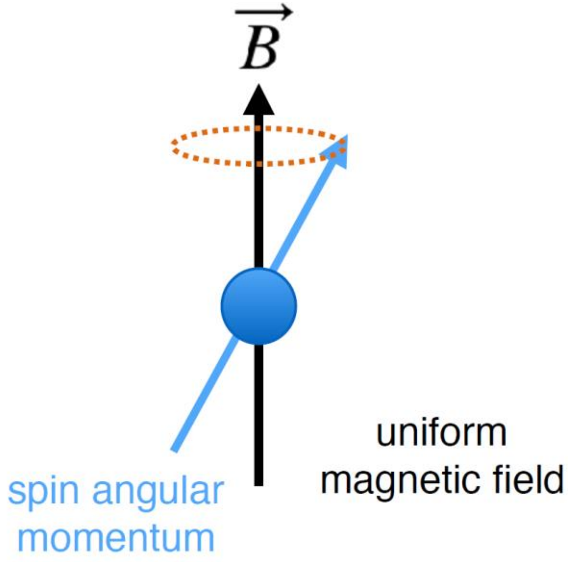

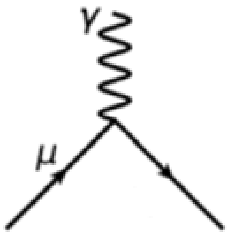

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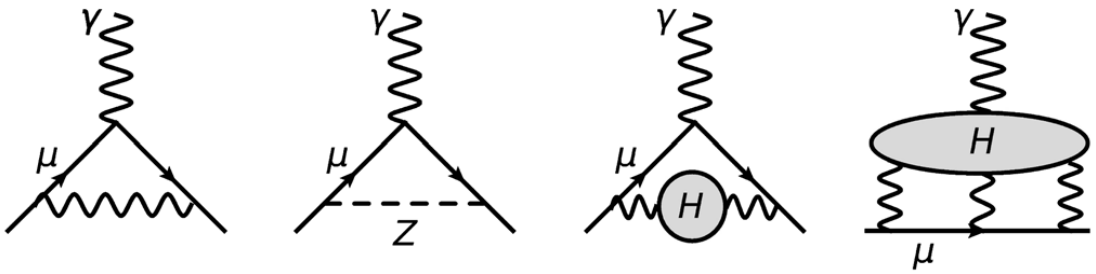

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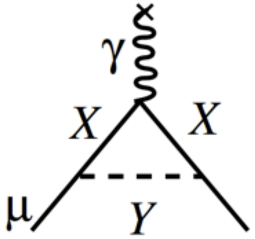
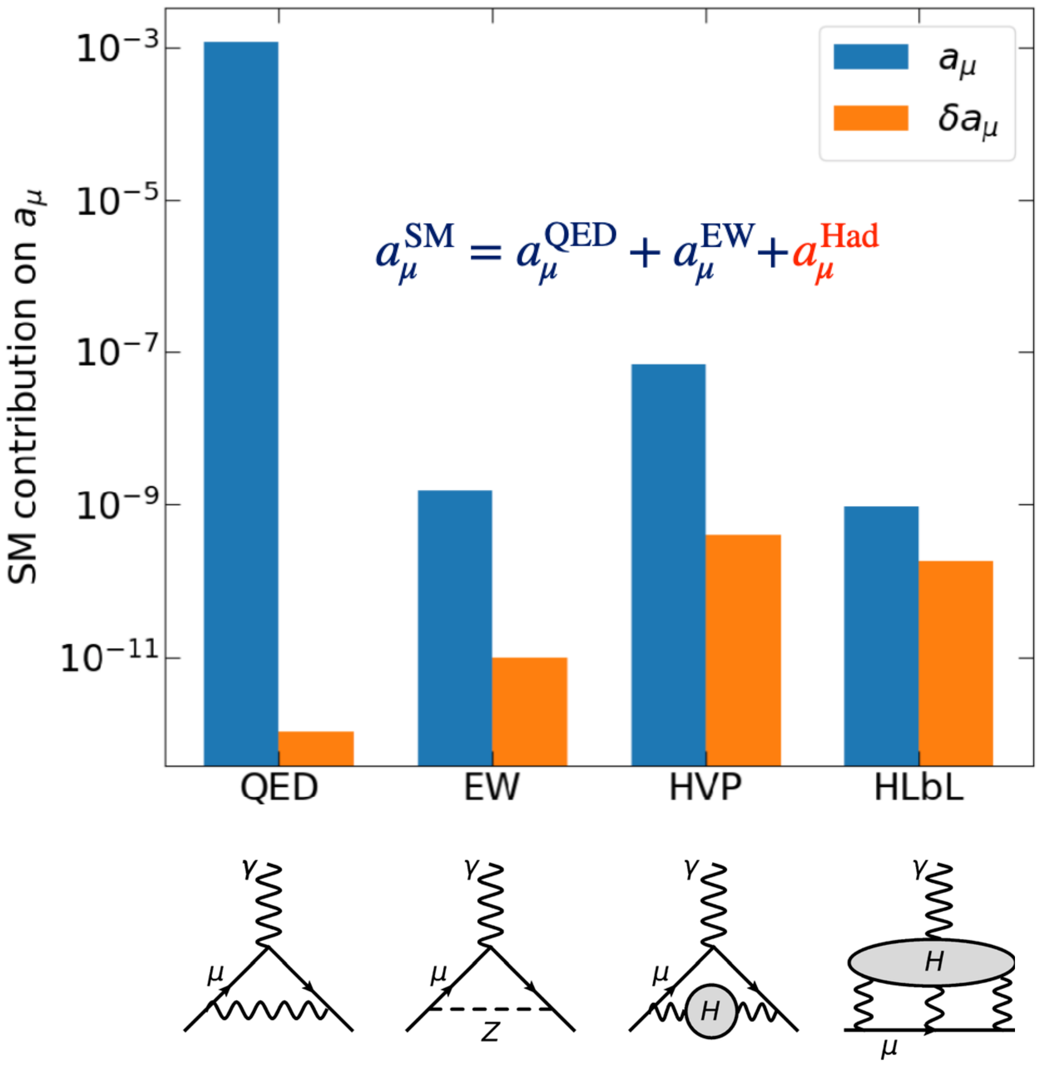


BSM physics

PRL 126, 141801 (2021)

Standard Model Calculation



- QED: perturbative approach ($\alpha_{QED} \ll 1$)
  known to 5-loop level

- EW: perturbative approach ($\alpha_{EW} \ll 1$)
  known to 2-loop level

- Hadronic Vacuum Polarization (HVP)
  no perturbative approach ($\alpha_{QCD} \sim 1$)
  dispersive approach (data-driven)
  lattice approach (first principle)

- Hadronic Light-by-light (HLbL)
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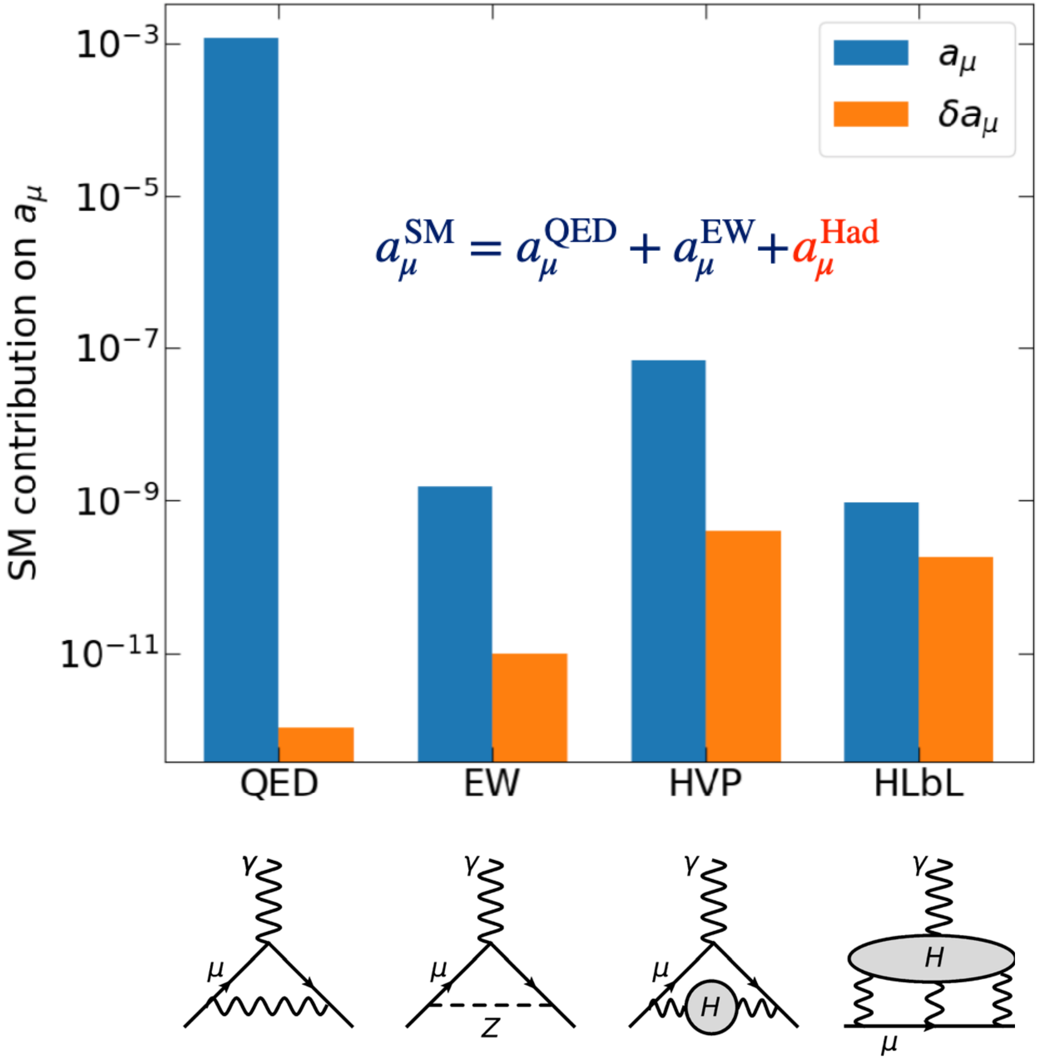
Standard Model Calculation



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  tension
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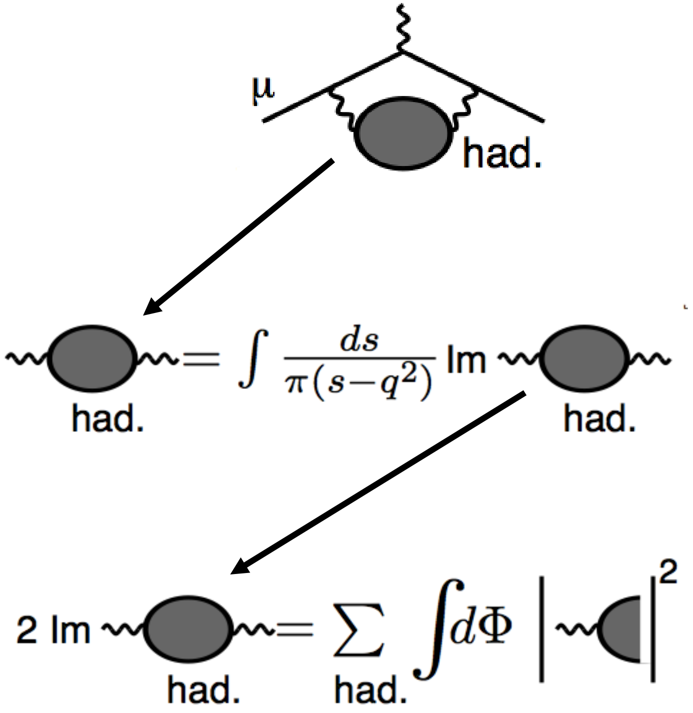
  dispersive approach (data-driven)
  lattice approach (first principle)
  agreement

Dispersive Approach

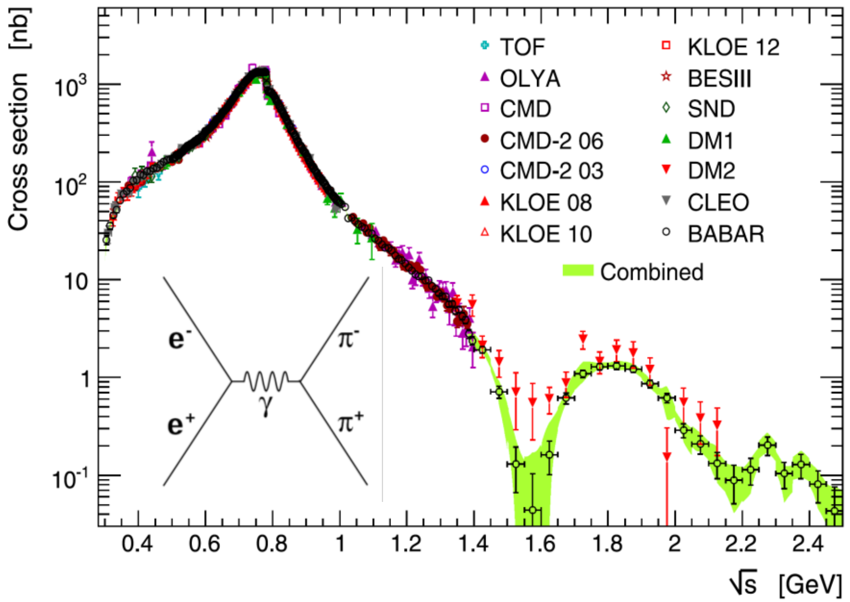


$a_\mu^{\text{had,LO}}$

Dispersion Relation
follows from causality

Optical Theorem
follows from unitarity
of scattering matrix

Cross section data used in TI 2020 a_μ^{HVP} prediction



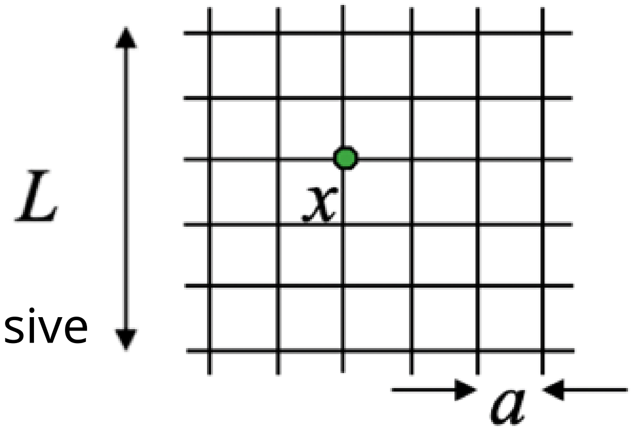
Davier et. al, Eur. Phys. J. C. 80 (2020)

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

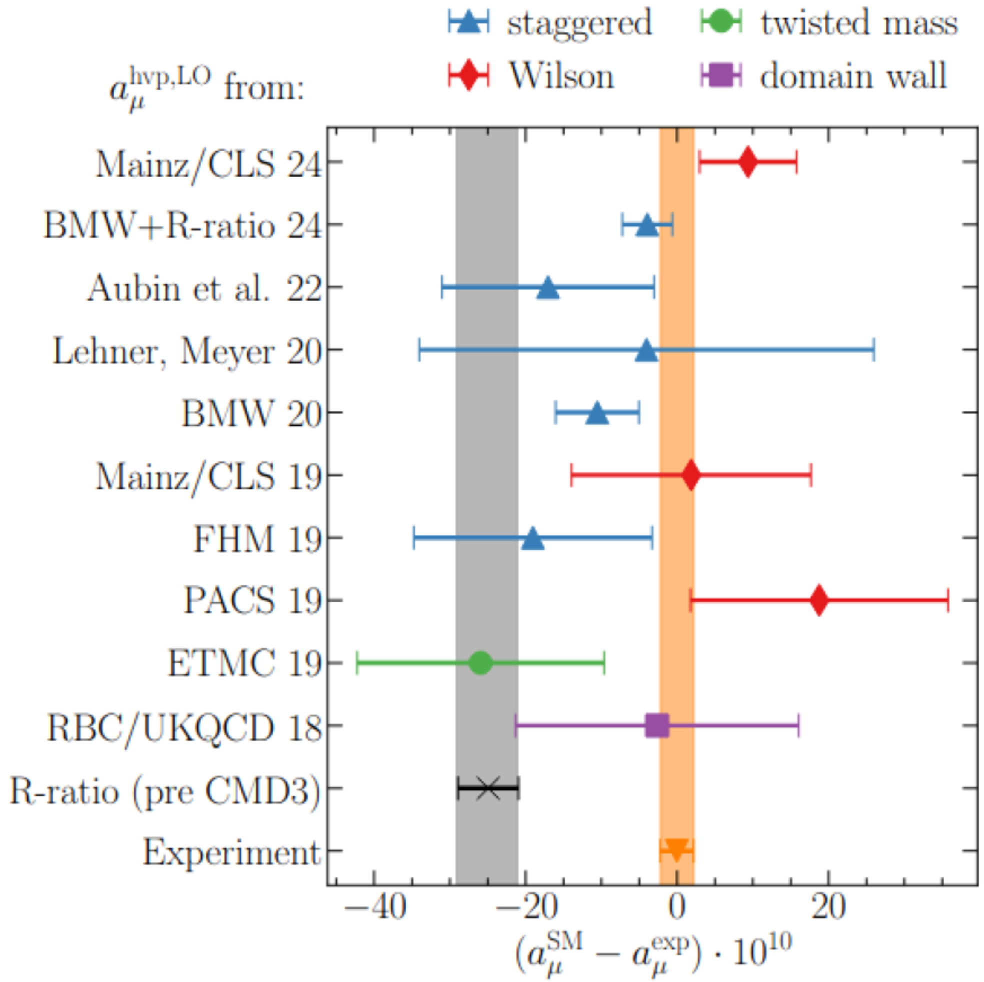
- calculated from total hadronic cross-section $\sigma_{\text{had}}(s)$
- 1/s weight → low energies most important
- $\pi^+ \pi^-$ contribute 73% to LO

Credit: Thomas Teubner

Lattice QCD Approach



- First principle calculation to predict a_μ
- Numerical integration on finite space-time lattice → very computing intensive



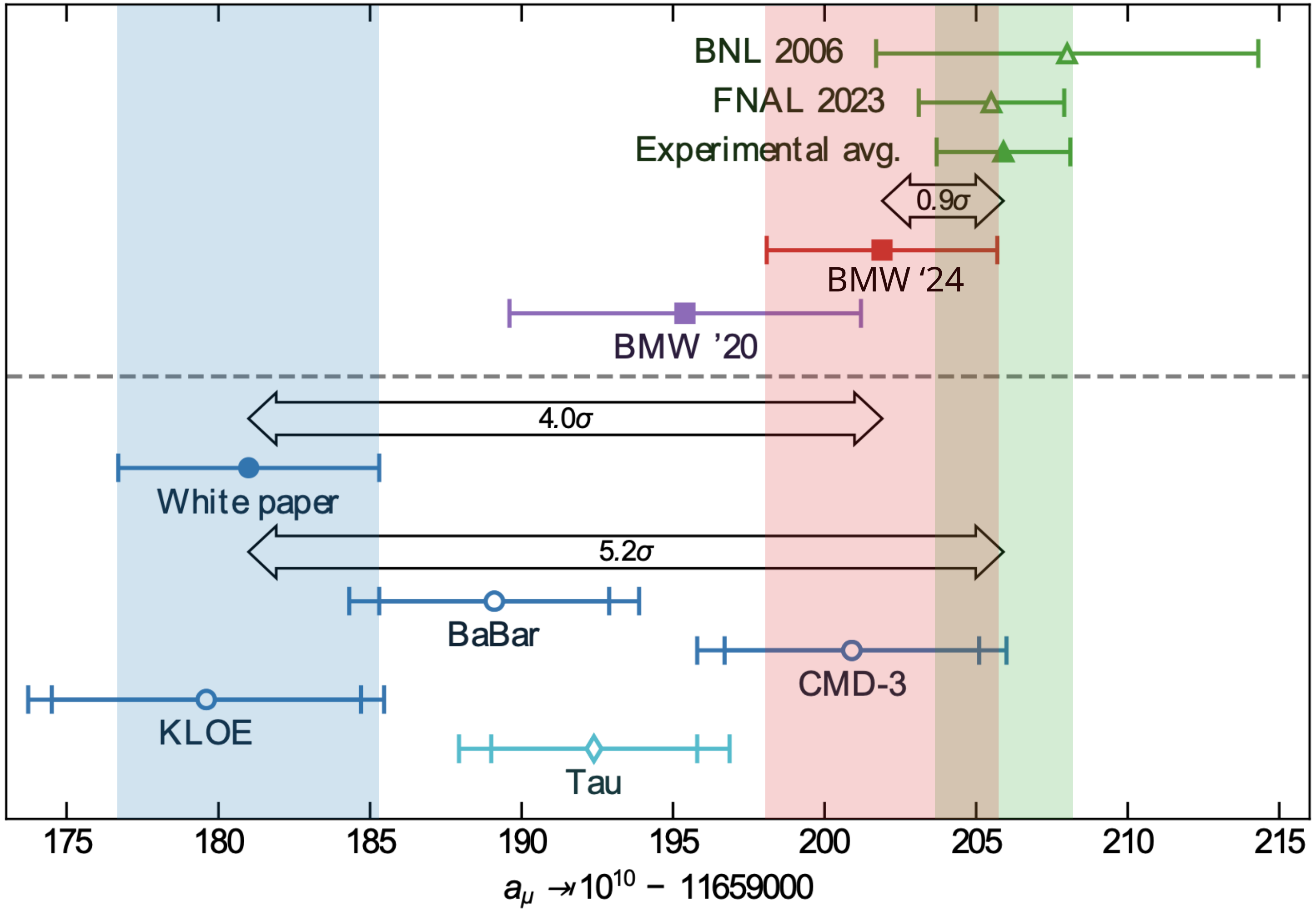
Preliminary: Consistency between different groups

First prediction with <1% uncertainty by BMW

Lattice results not included in TI white paper due to low precision

The Muon g-2 Puzzle

M. Hoferichter, Workshop of TI, Sep 2024 @KEK



Muon g-2 Puzzle

tension between theory (white paper) and experiment

New muon g-2 Puzzle

Inconsistency between

- lattice and data-driven approach
- different e^+e^- experiments

Experiment

→ improve statistics & systematics of measurement

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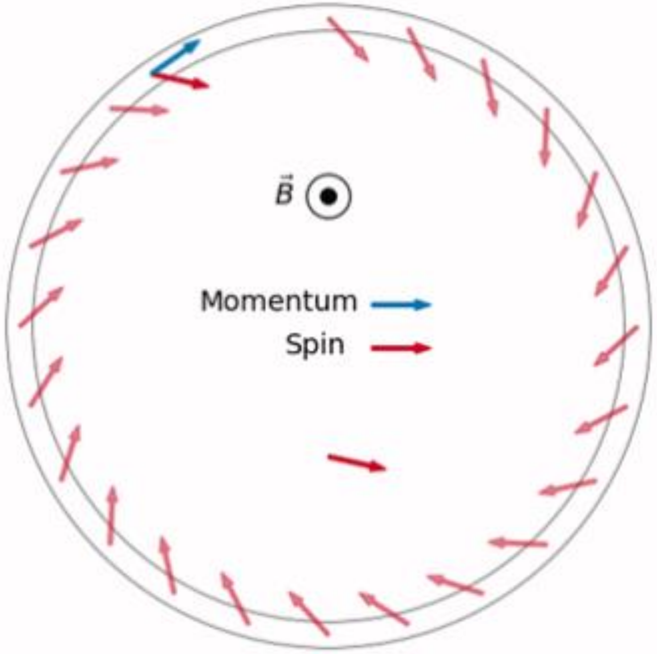
Muon in homogeneous magnetic field

Cyclotron Motion

centrifugal force = Lorentz force

$$\vec{\omega}_C = -\frac{e}{m\gamma}\vec{B}$$



Spin Precession

magnetic moment and field couple

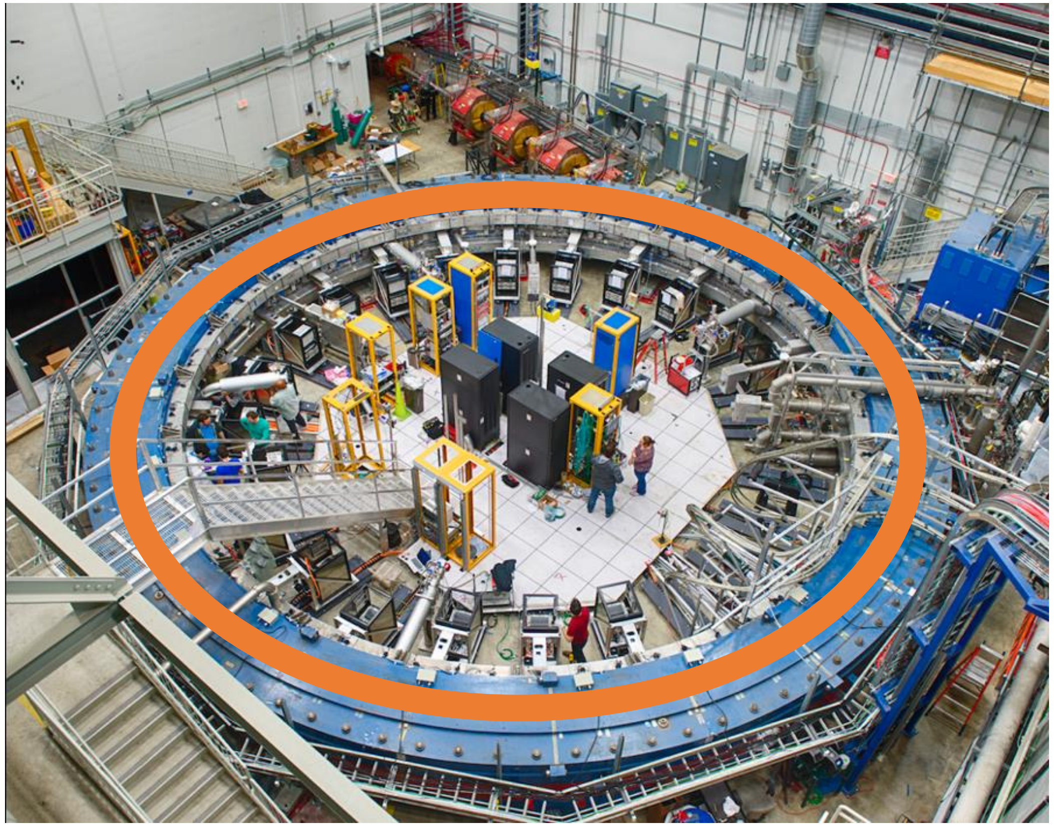
$$\vec{\omega}_S = -g\frac{e}{2m}\vec{B} - (1-\gamma)\frac{e}{\gamma m}\vec{B}$$

$$\underbrace{\omega_s - \omega_c}_{\omega_a} = g_\mu \frac{e}{2m_\mu}B - \frac{e}{m}B = \underbrace{\frac{g_\mu - 2}{2}}_{a_\mu}\frac{e}{m_\mu}B$$

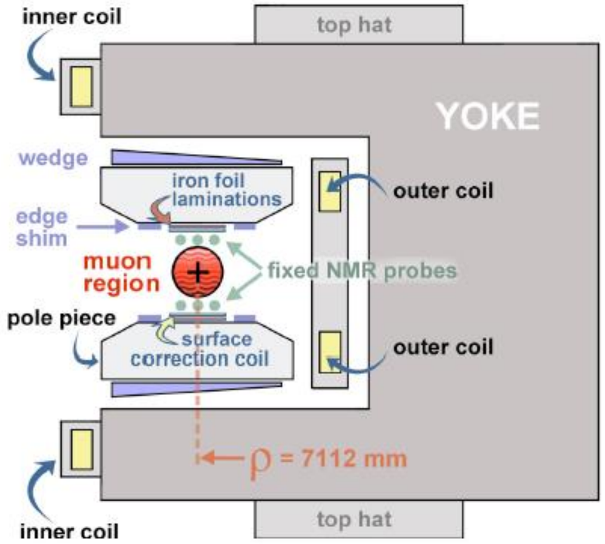
anomalous spin-precession frequency

anomalous magnetic moment

The Muon g-2 experiment at FNAL



- 1.45 T vertical magnetic field



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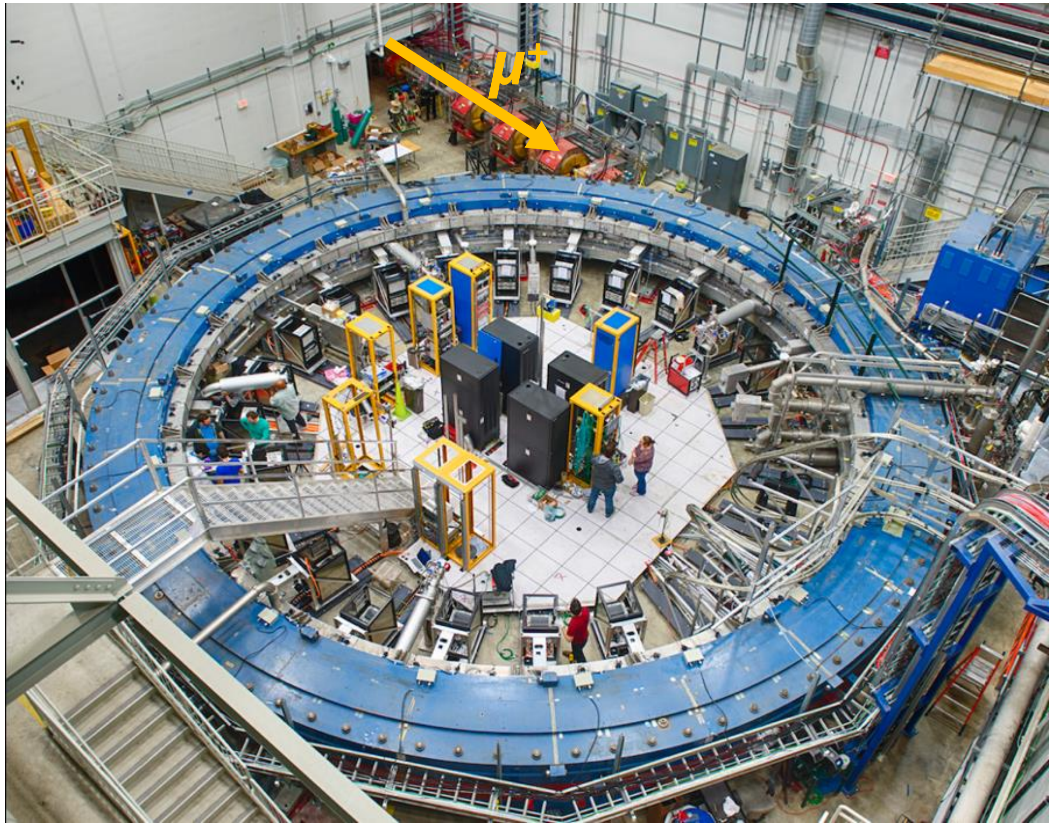

- 1.45 T vertical magnetic field
- highly polarized μ⁺ provided by FNAL muon campus at

$$p_\mu^{magic} = 3.094 \frac{GeV}{c} \pm 0.5\%$$

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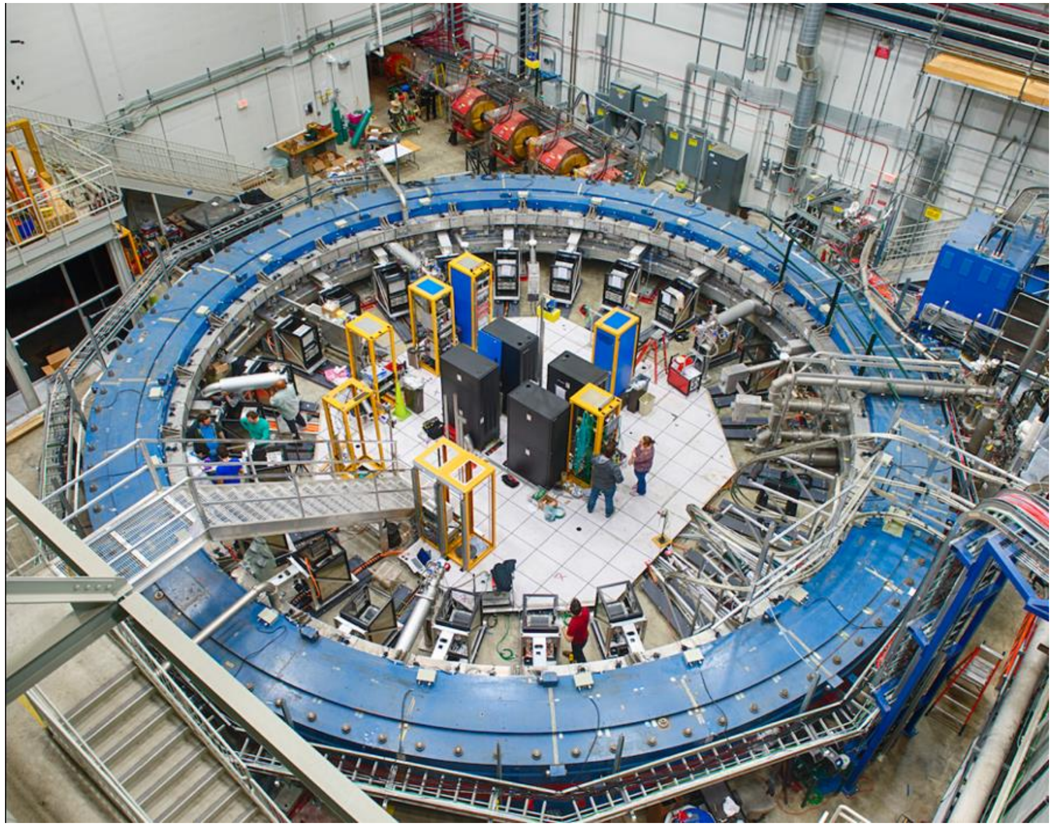

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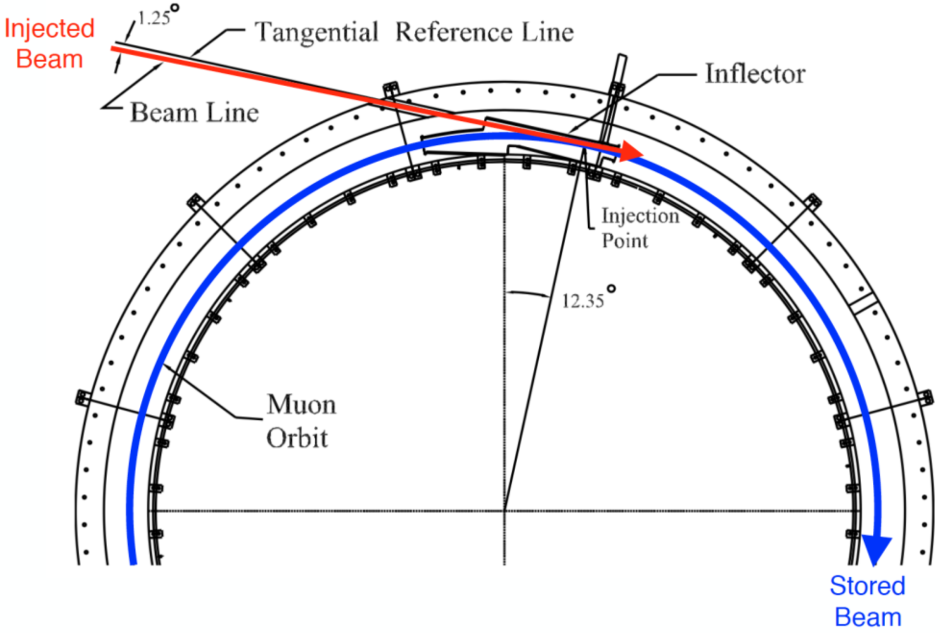
- Superconducting inflector magnet in back of iron yoke



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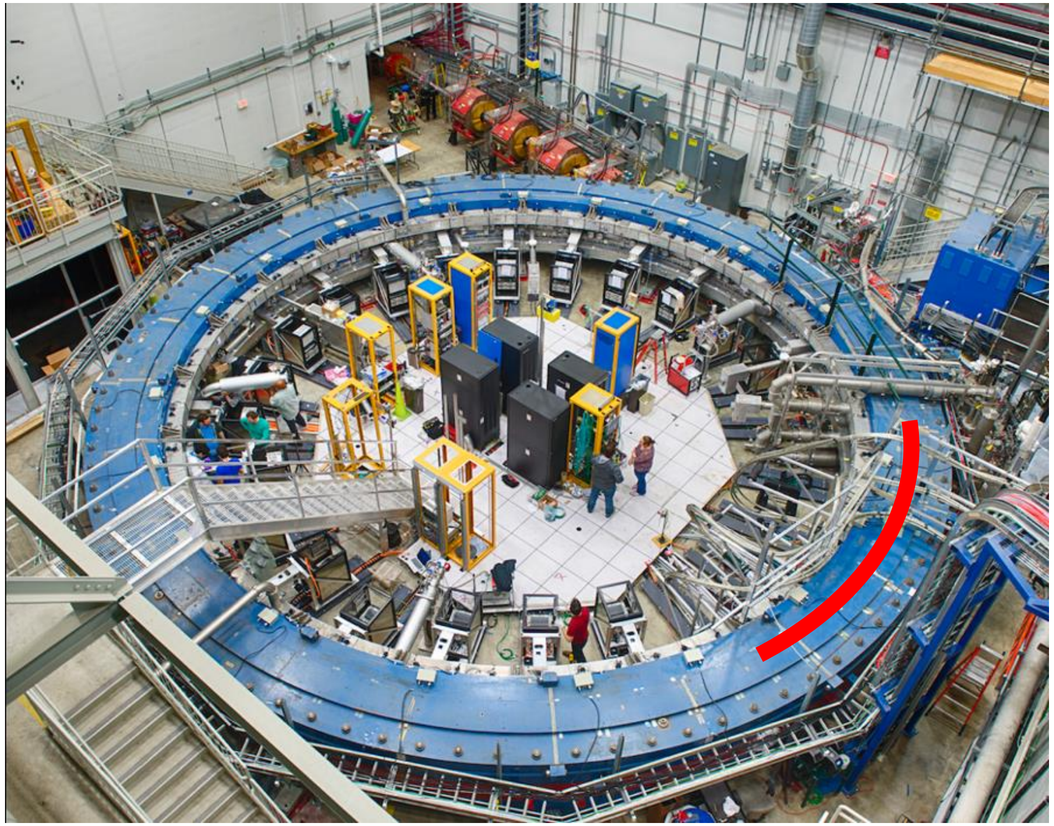

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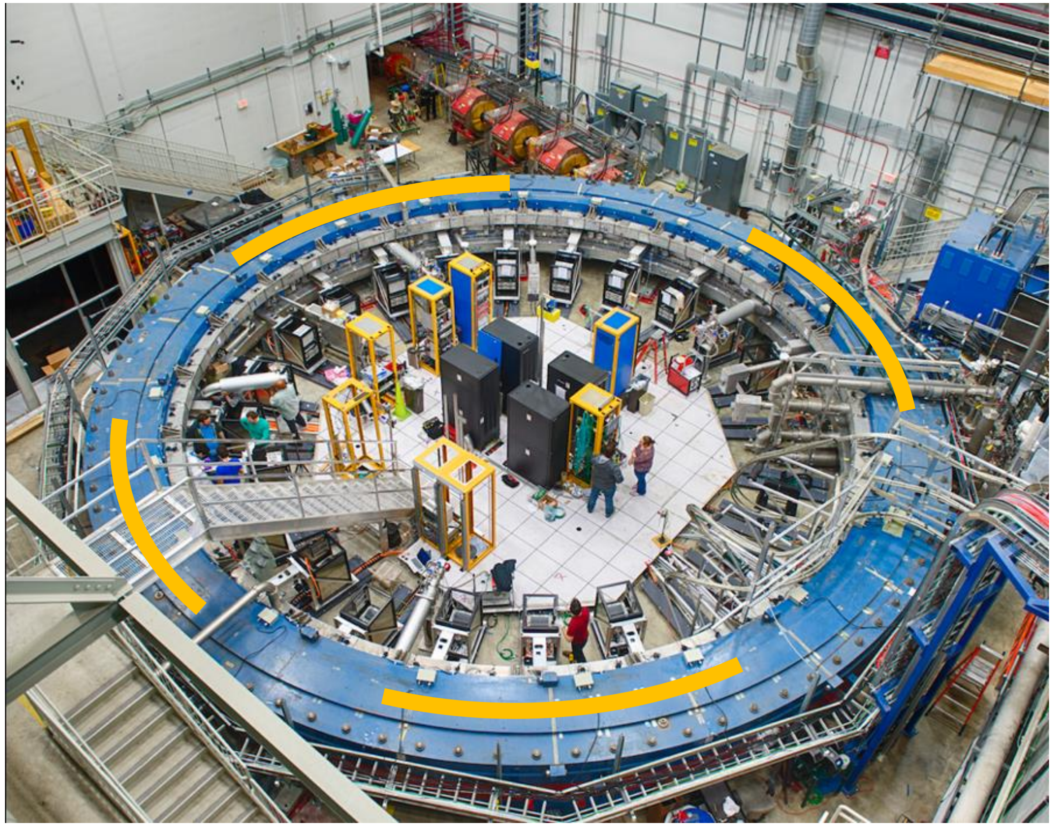

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- Four electro-static quadrupoles covering 43% of ring to focus beam

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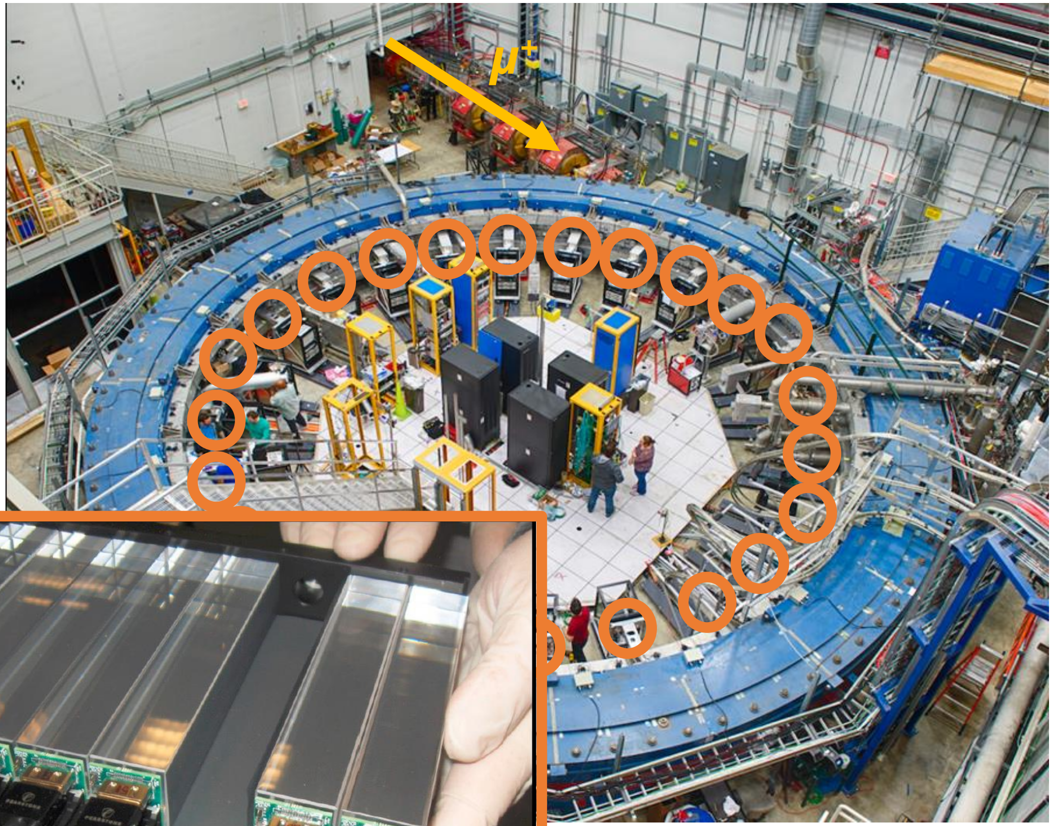
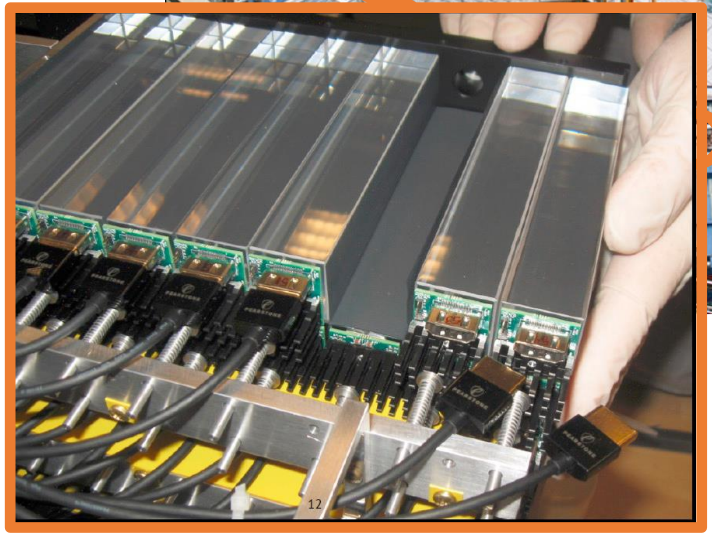
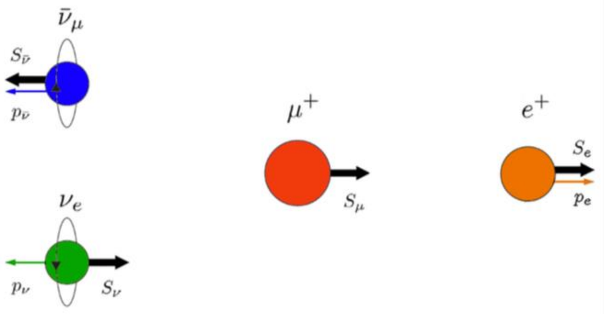
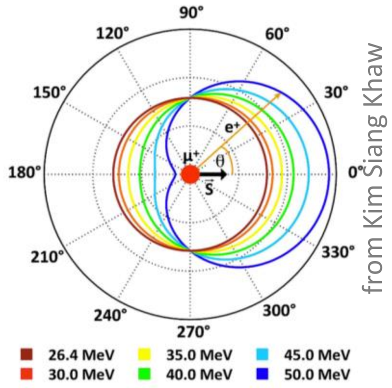
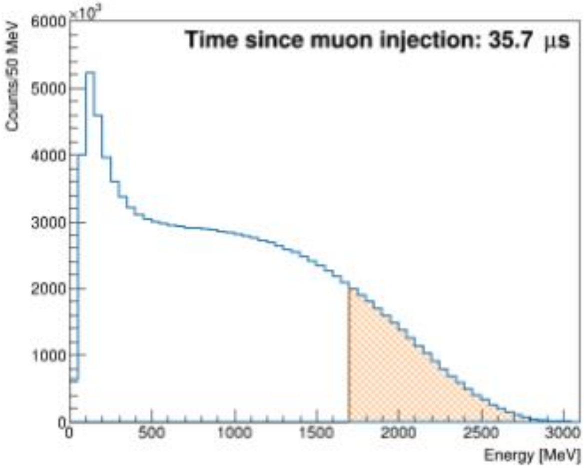


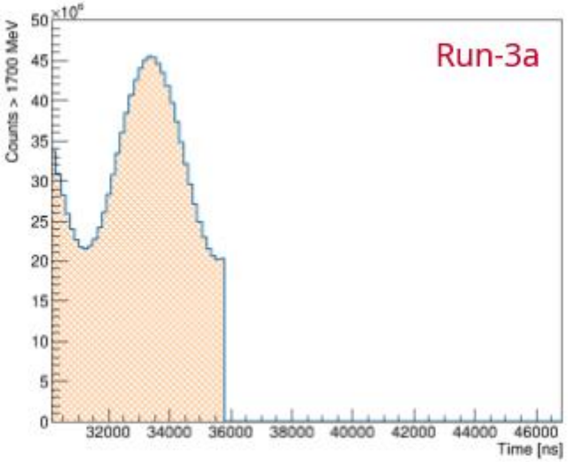


- 24 PbF2 crystals calorimeters
- Detect in spiraling positrons from muon decay









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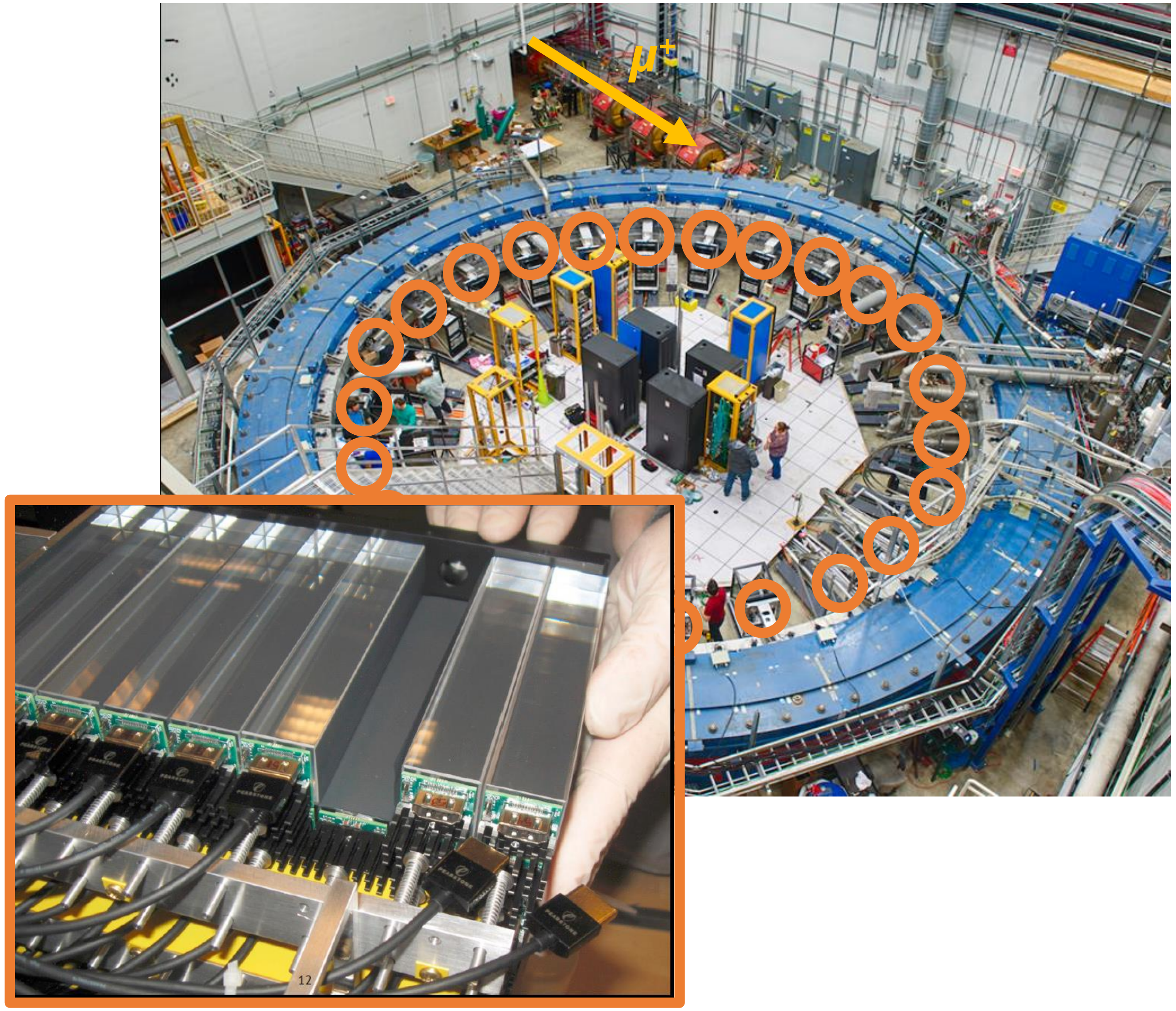

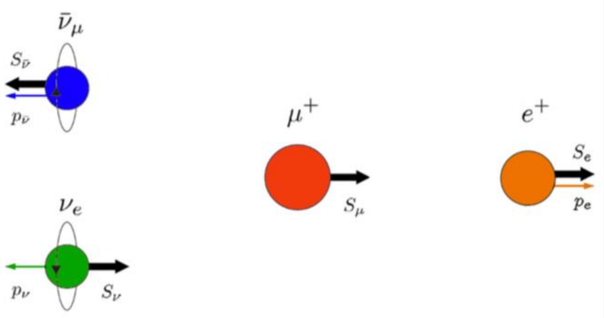

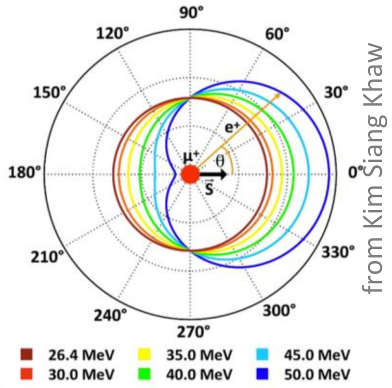

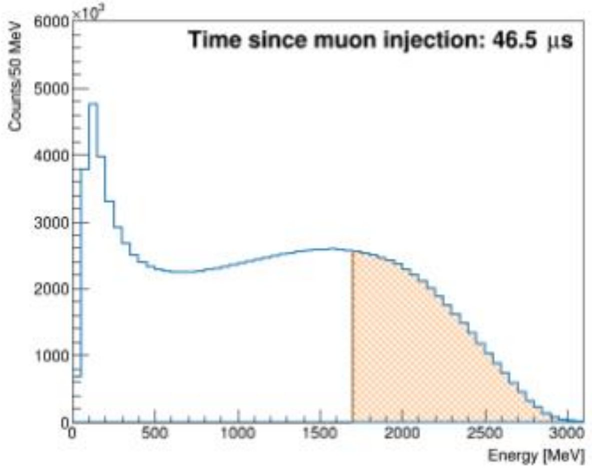

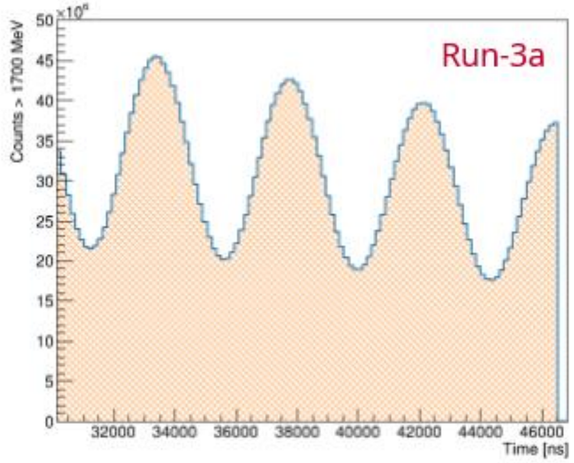

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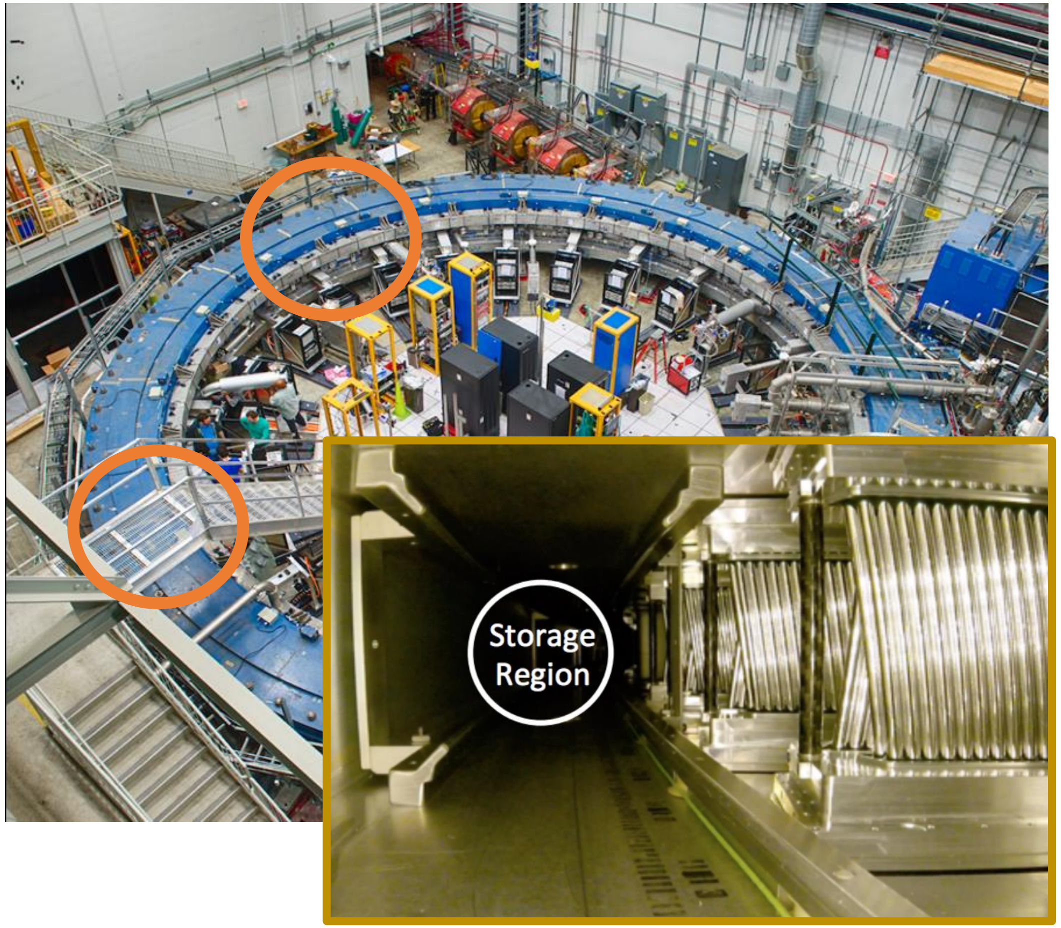
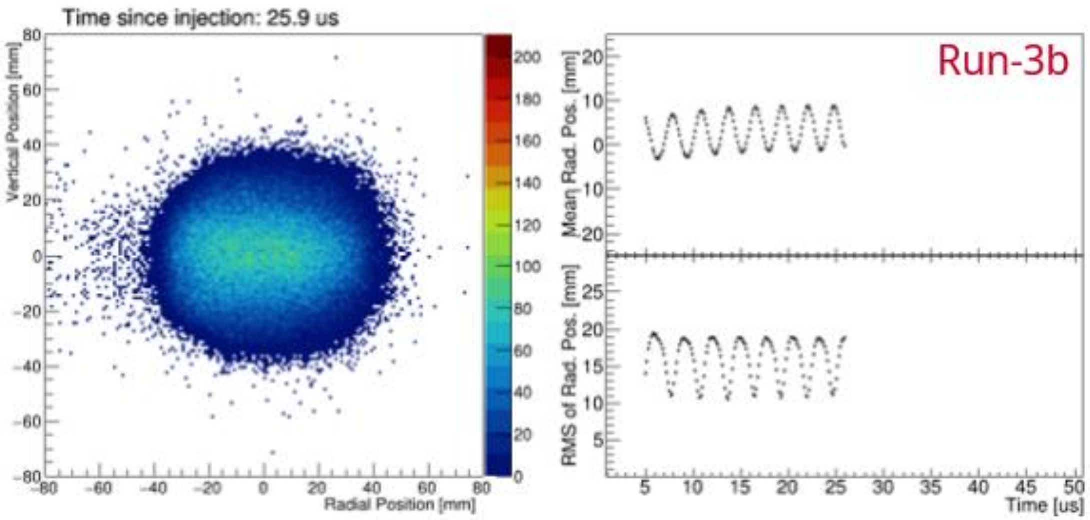


- Two tracking stations based on gas-filled straw tubes
- Determine e+ trajectory to decay position and extrapolate to find muon beam distribution!



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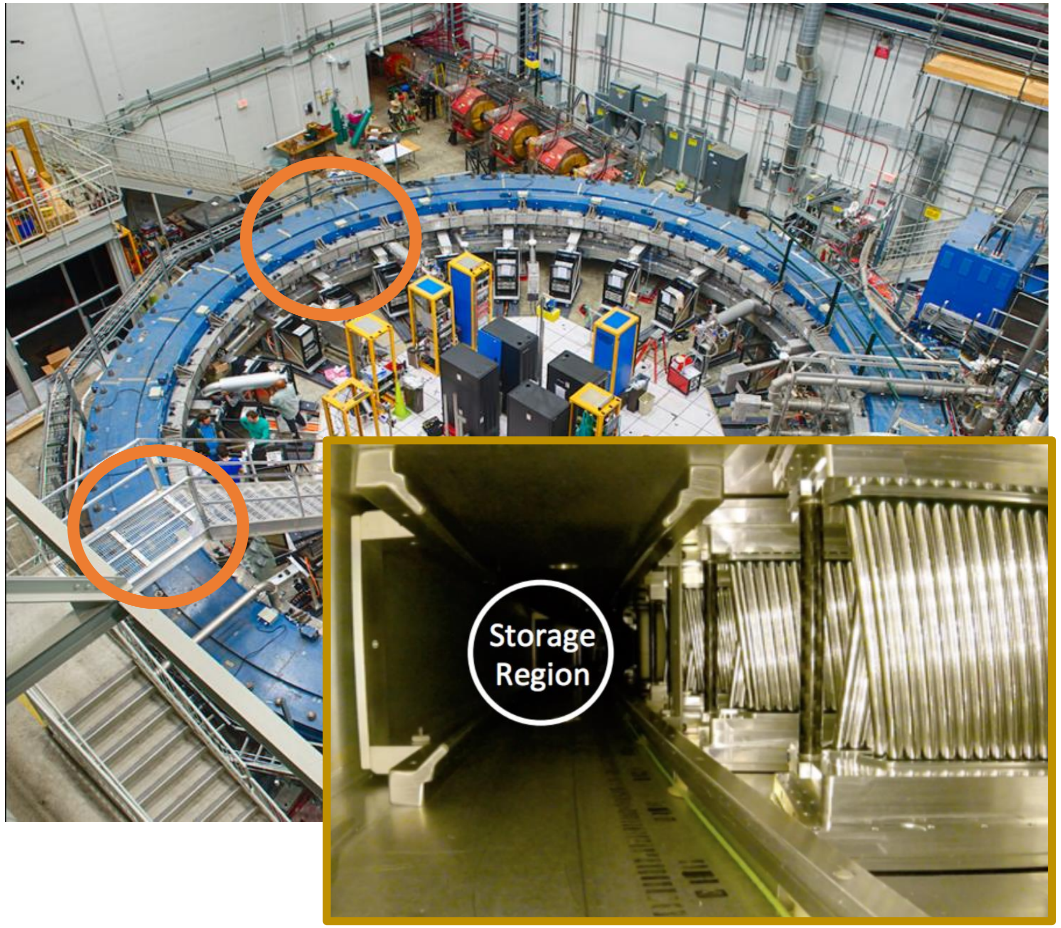

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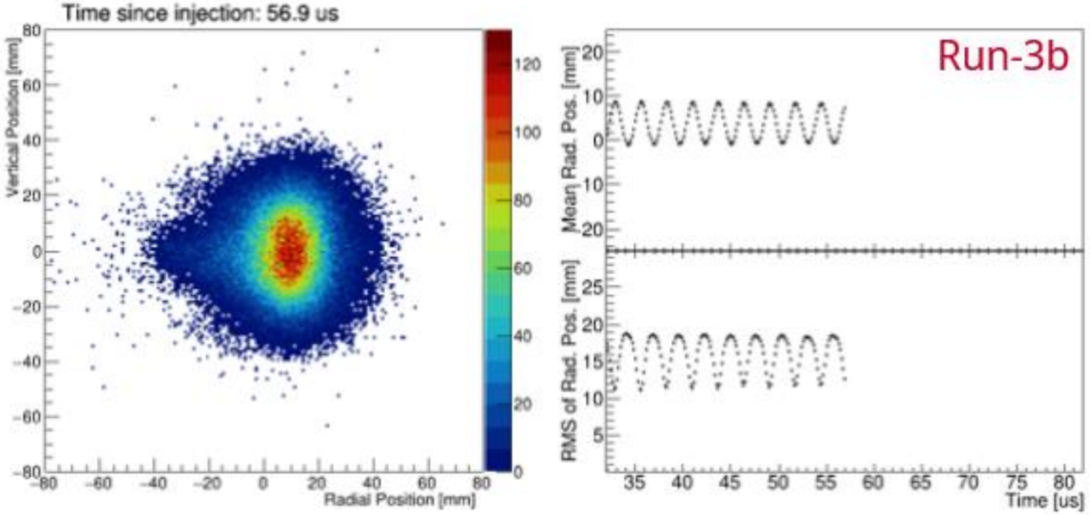

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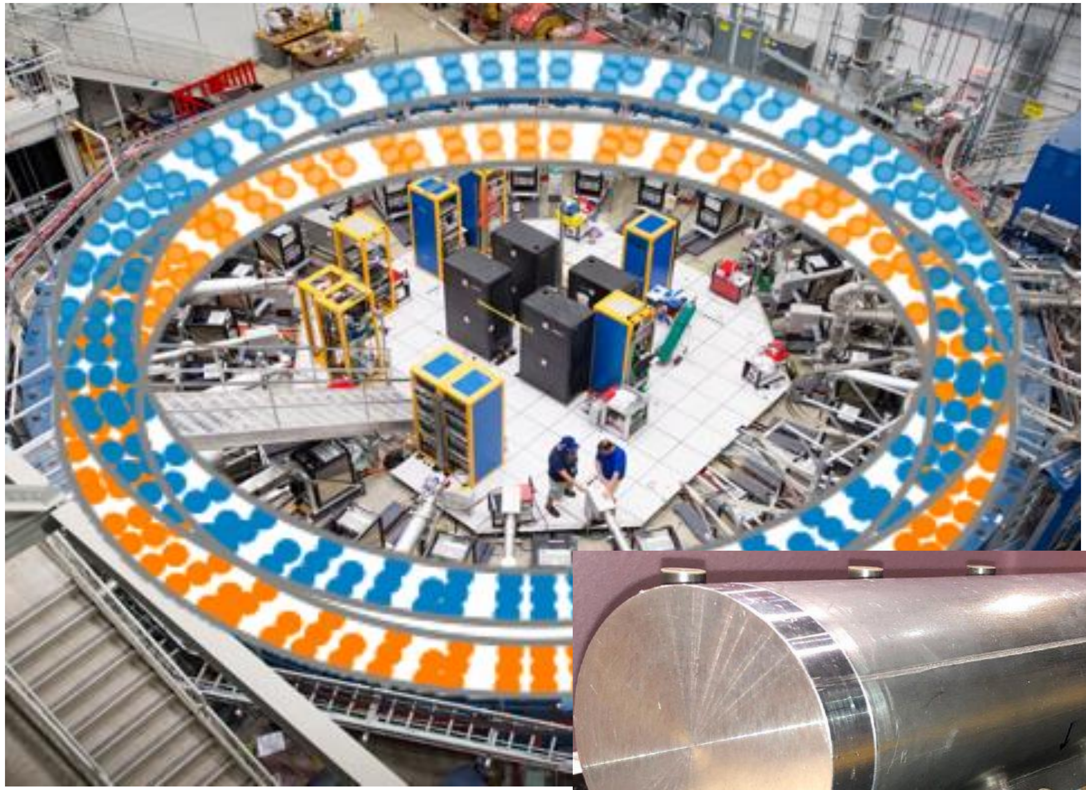
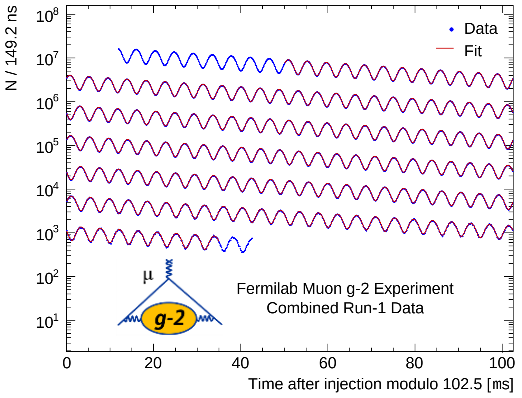


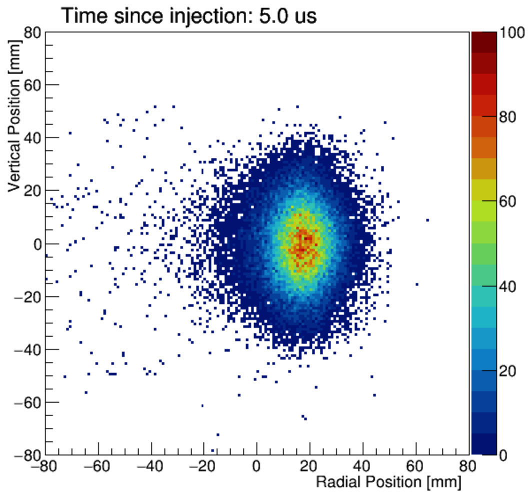
- 378 NMR probes in vacuum chamber walls to track magnetic field drift 24/7
- Movable device with 17 NMR probes measures spatial field distribution in muon storage region
- Externally calibrated absolute water NMR probe

Extracting a_μ



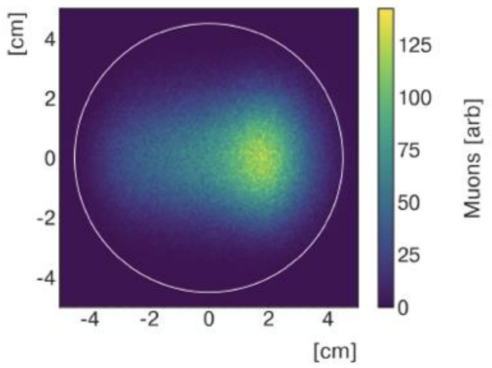
Anomalous spin precession frequency

Muon beam dynamics corrections



Clock blinding

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\mathrm{clock}}\,\omega_a^{\mathrm{meas}}(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{\mathrm{calib}}\langle M(x,y,\phi)\,\omega'_p(x,y,\phi)\rangle(1 + B_k + B_q)}$$

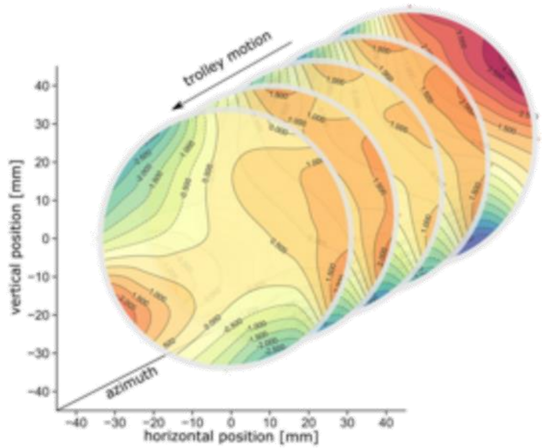


Spatial muon distribution

Magnetic field calibration

Spatial distribution of magnetic field

Transient magnetic fields



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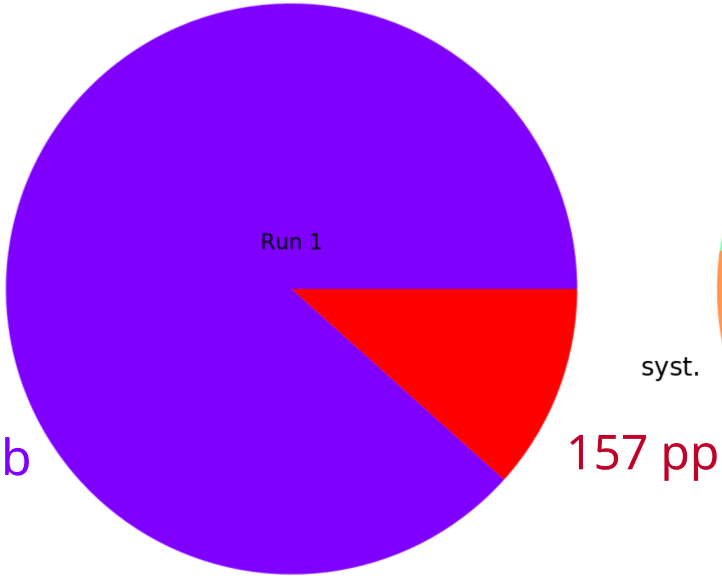
Uncertainties Run1 vs Run2

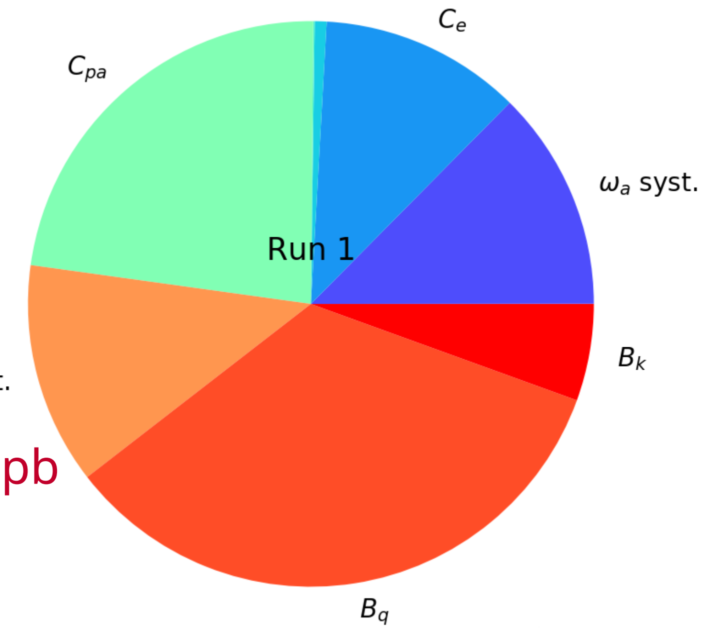
Run-1

Total uncertainty: 462 ppb

434 ppb



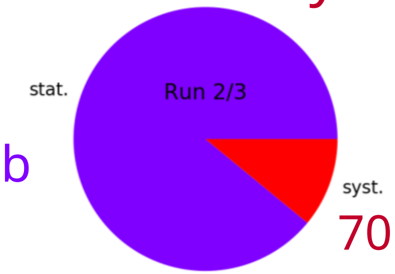
157 ppb



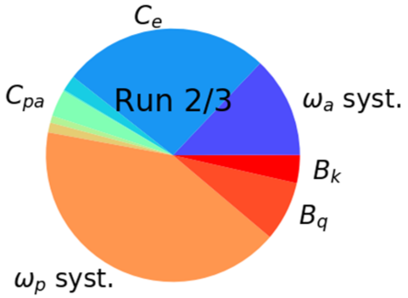
Run-2/3

Total uncertainty: 215 ppb

201 ppb



70 ppb



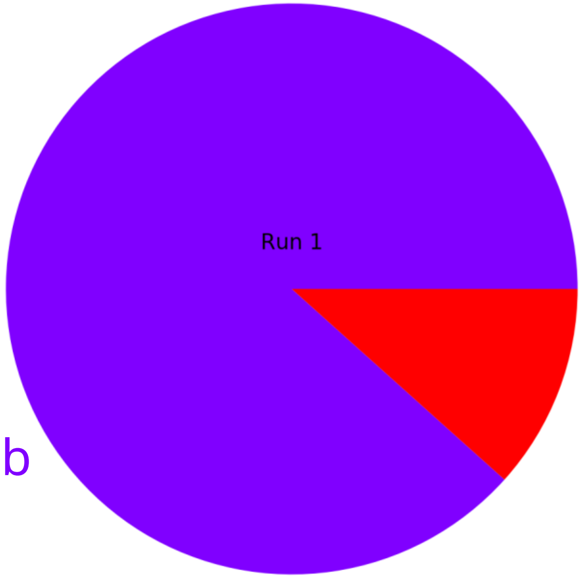
- Uncertainty reduced by factore >2
- Statistic and systematic uncertainty reduced by similar amount
- Systematic uncertainty below TRD goal
- Still statistics dominated

Radius: uncertainty
Area: variance

Improvements: Statistics

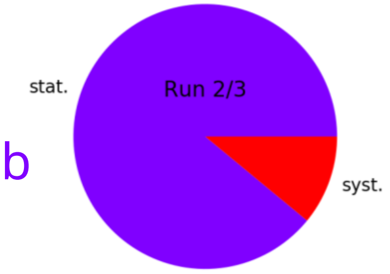
Run-1

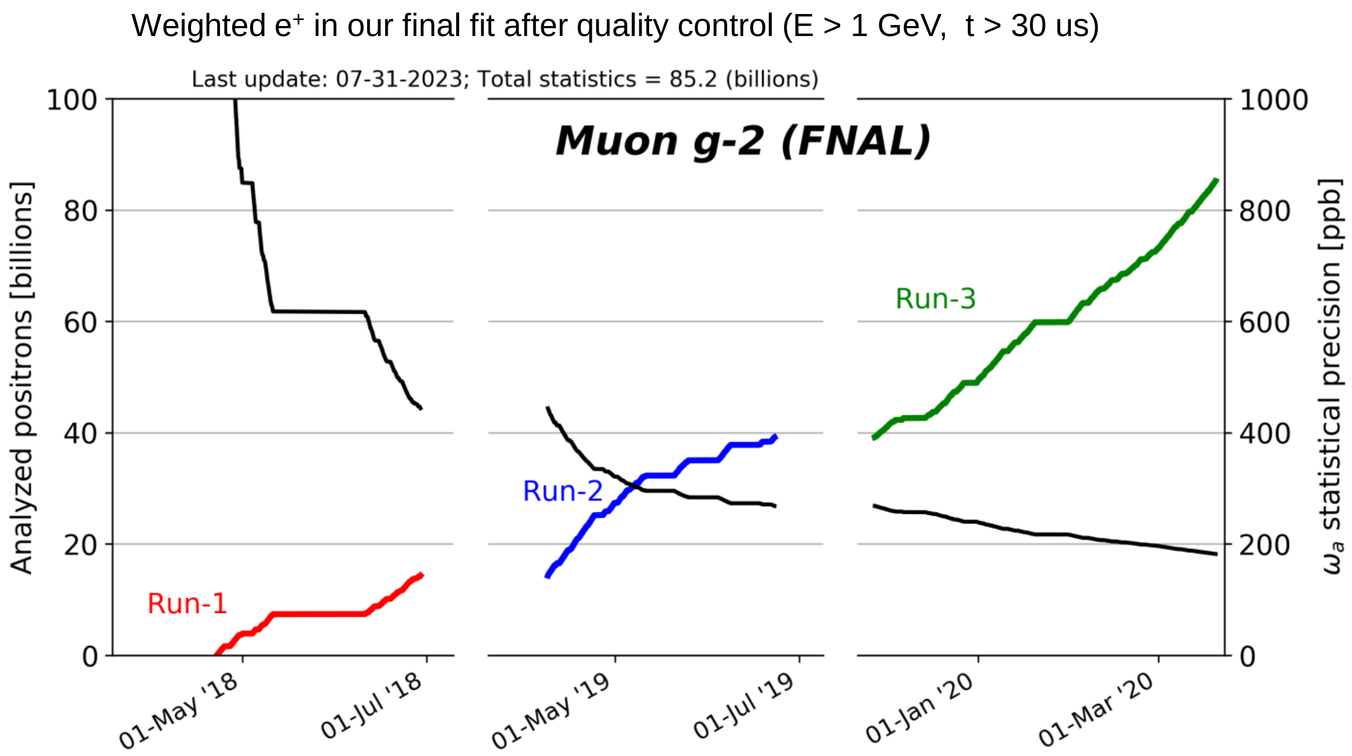
434 ppb



Run-2/3

201 ppb

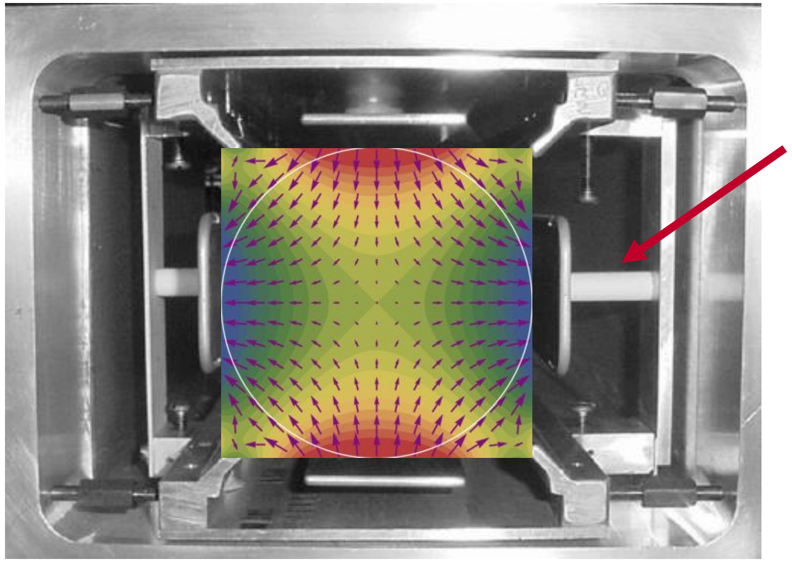


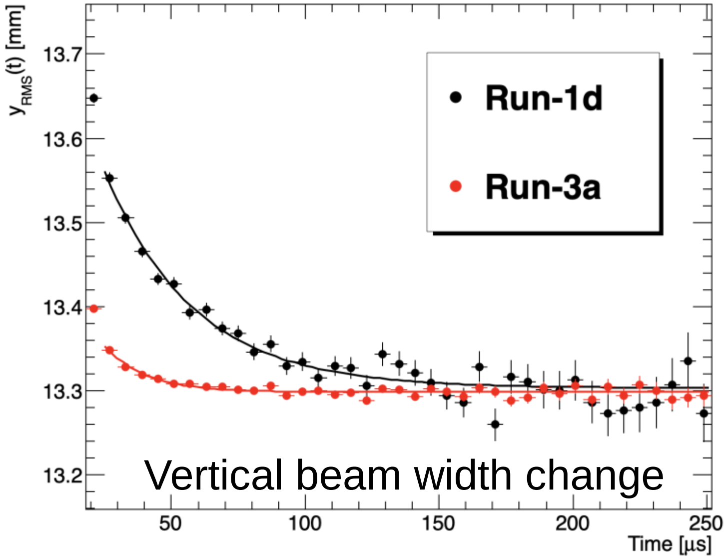


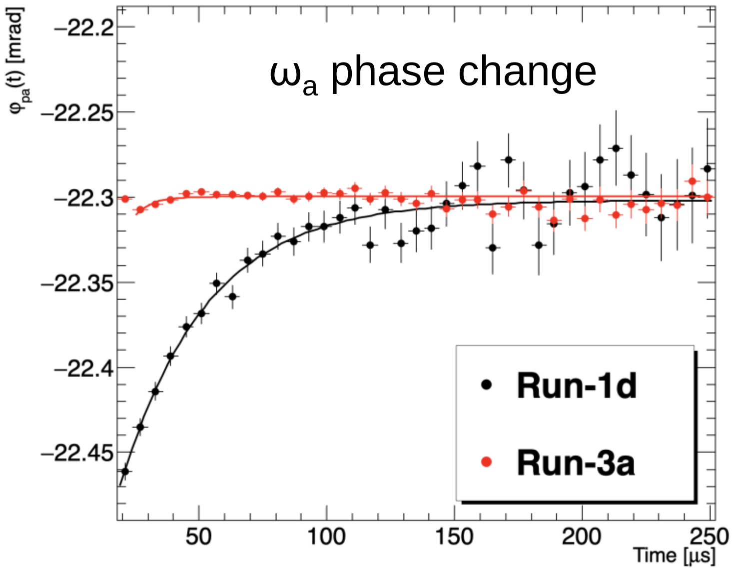
Radius: uncertainty
Area: variance

Improvements: Running Conditions

- Electro-static quadrupoles keep muon beam stable
- 2 out of 32 resistors damaged in quad plates → unstable beam storage
- Redesigned and replaced before Run-2

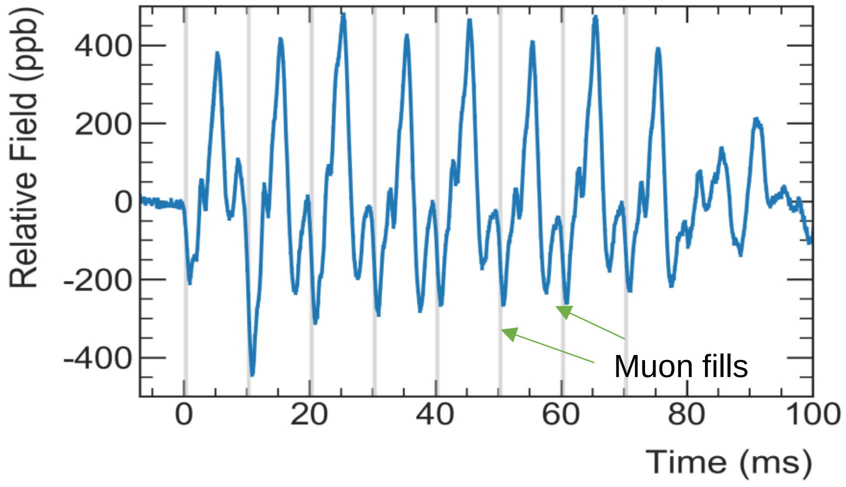


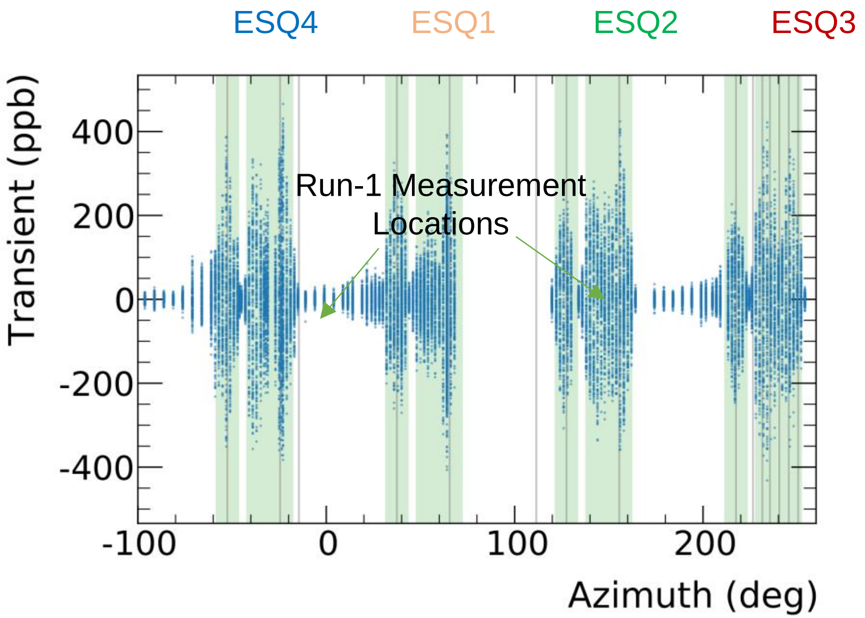




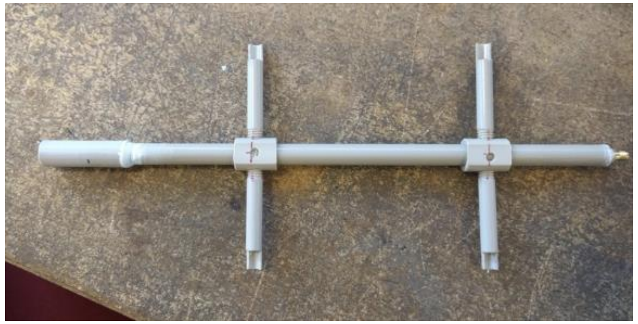
- Reduces phase acceptance uncertainties 75 ppb → 13 ppb
- Beam oscillation frequencies become also more stable

Improvements: Systematic Studies



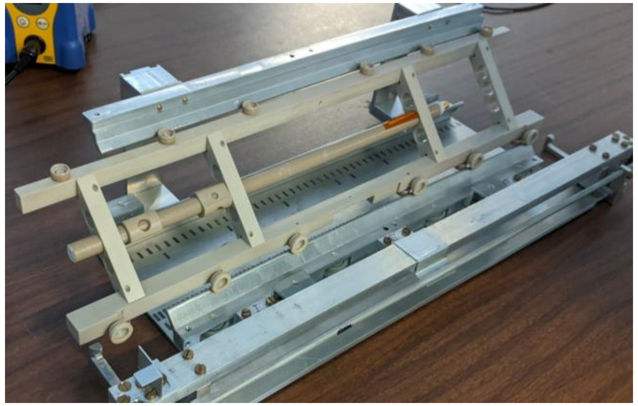


Pulsing electrostatic quadrupoles for beam confinement leads to magnetic field transient.



Run 1

- Limited measurement points
- Large uncertainty: 92 ppb



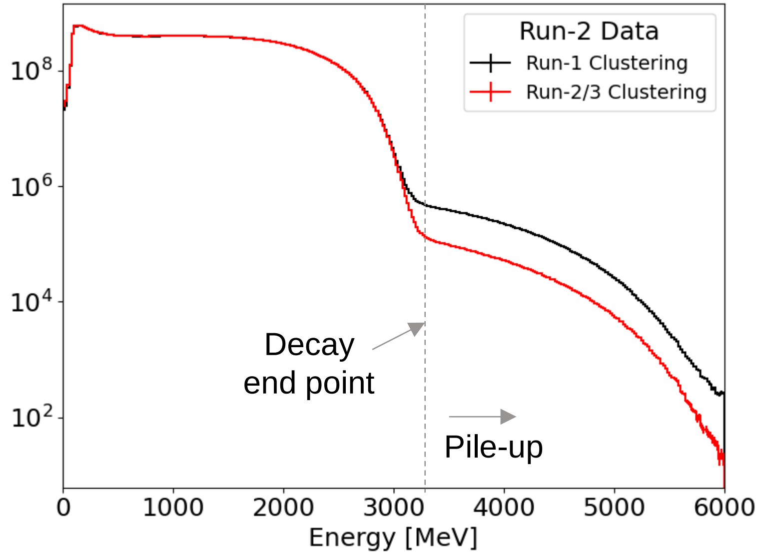
Run 2/3

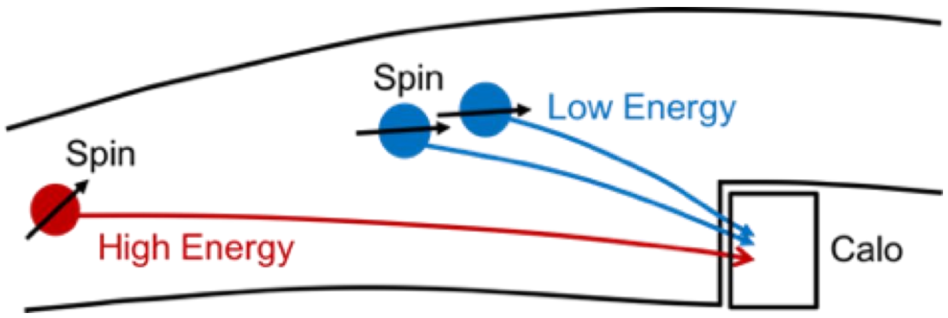
- Probe movable on trolley rails
- Detailed measurement campaign over > 1 month
- Uncertainty reduced to 20 ppb

Improvements: Analysis

Pile-up correction

- 2 e+ **arriving at same time** can be mistaken for 1
- Rate dependent → can **bias ω_a**
- Reduced uncertainty by:
  - Improved **reconstruction**
  - Improved **correction algorithm**



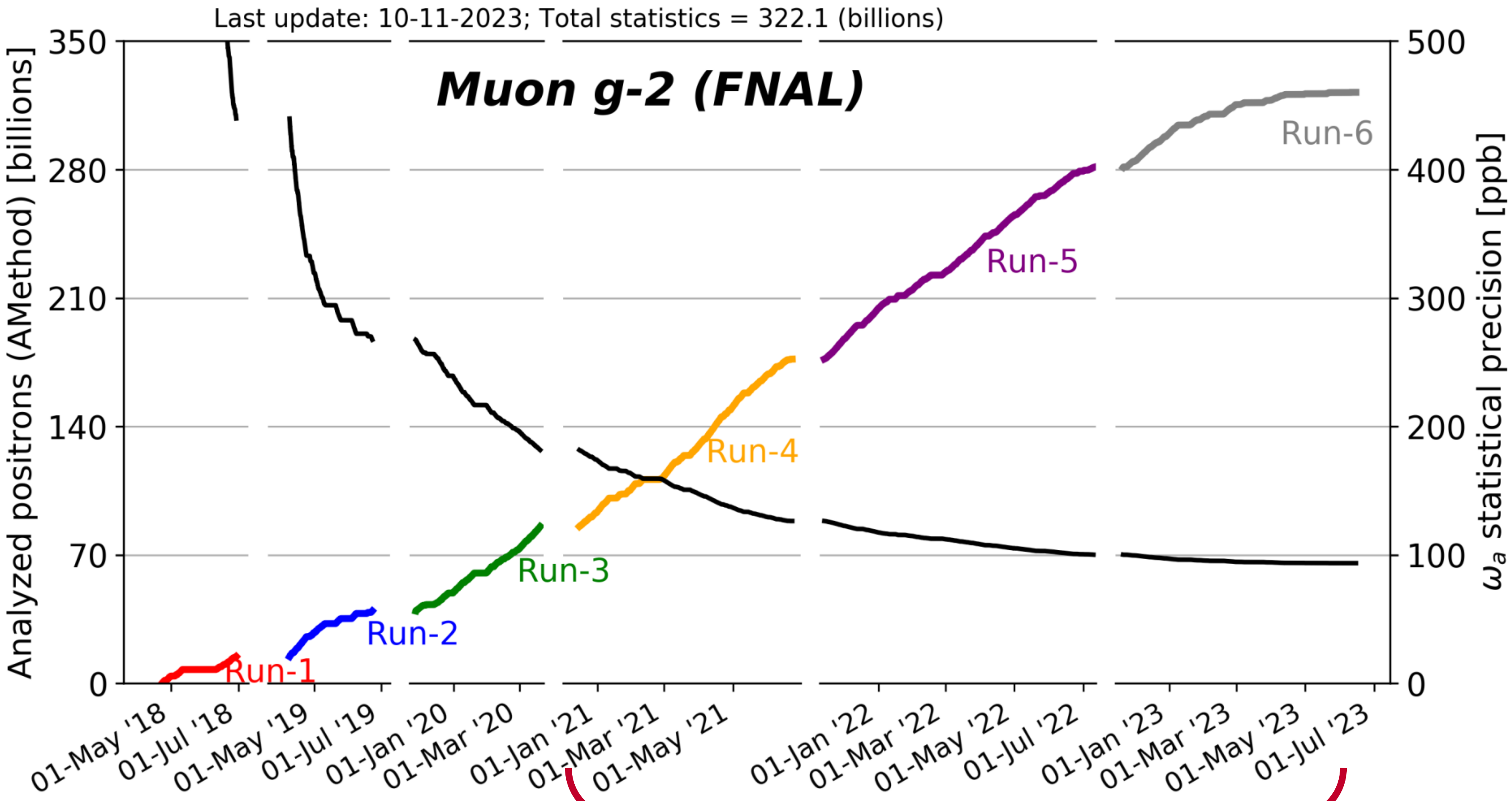


Phase of high-energy muon
≠
Phase of two low-energy muons

Outline

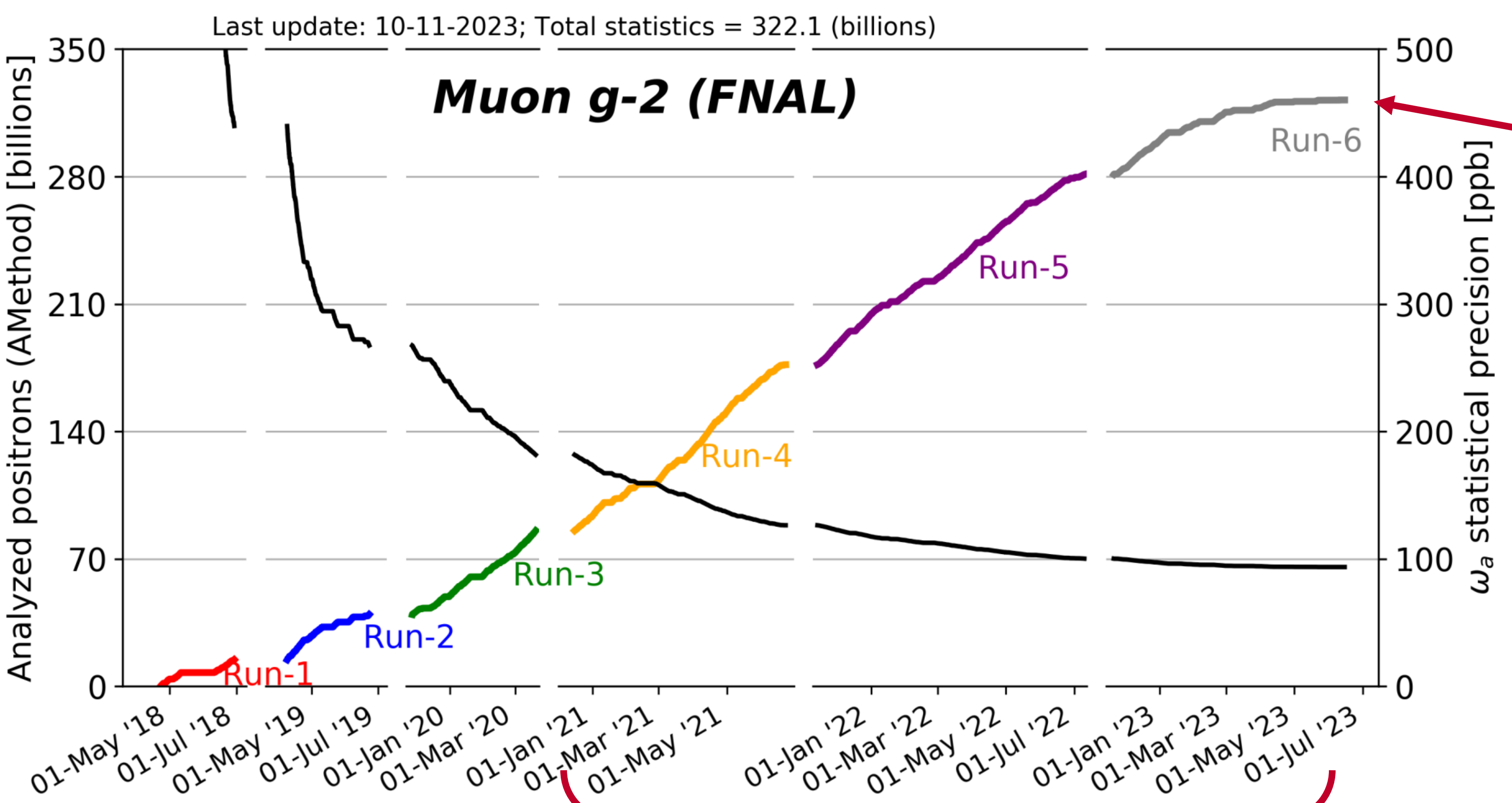
- Why is Muon g-2 a good test of the SM?
- How to measure the Muon g-2?
- Improvements in Run-2/3 results
- **Outlook & Conclusions**

Outlook



Much more statistics
Another factor of about 2 in statistic uncertainty

Outlook

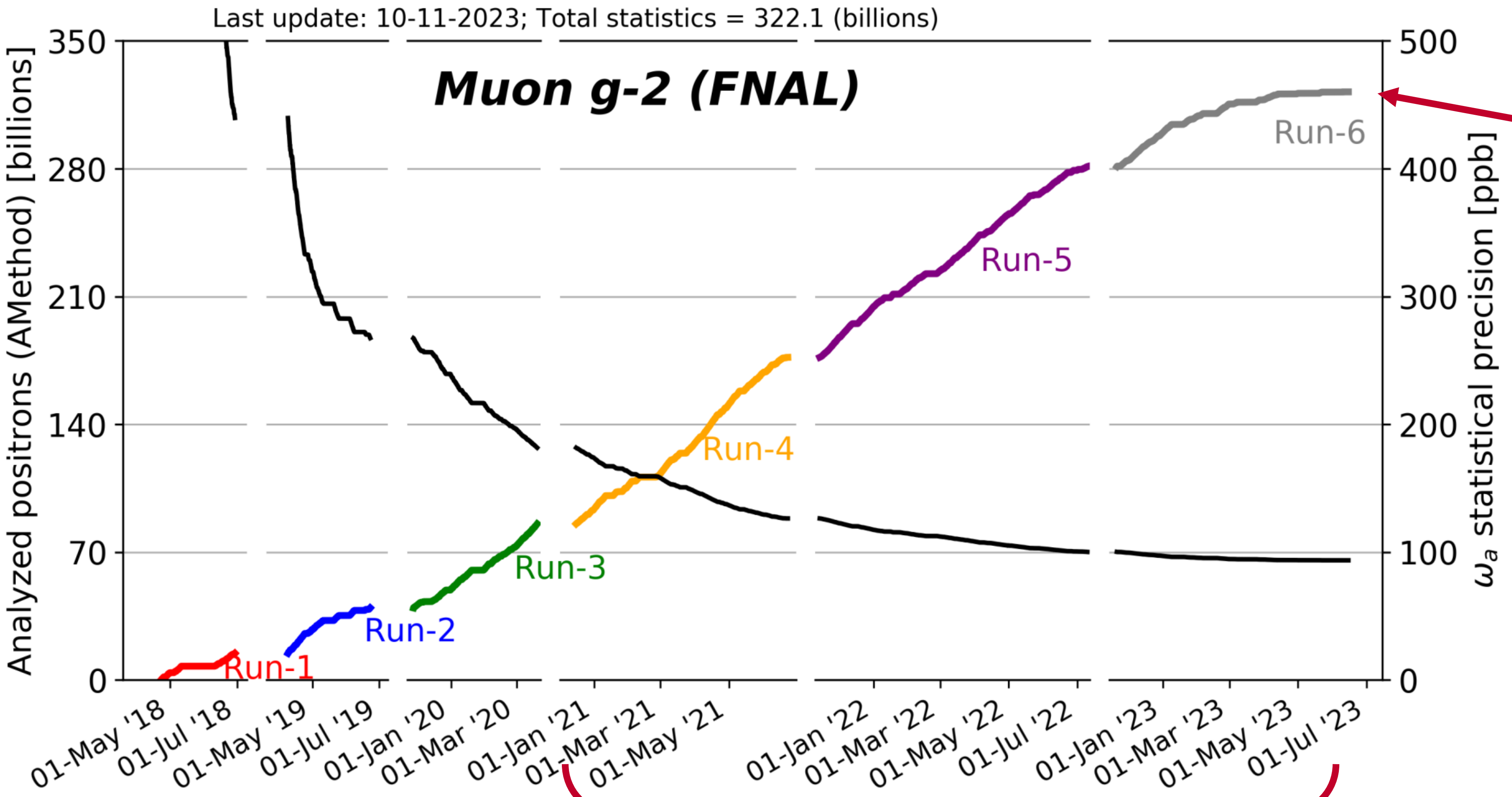


Exceeded TRD goal of 21 BNL statistcs

Last part of run 6 dedicated to systematic studies

Much more statistics
Another factor of about 2 in statistic uncertainty

Outlook



Exceeded TRD goal of 21 BNL statistcs

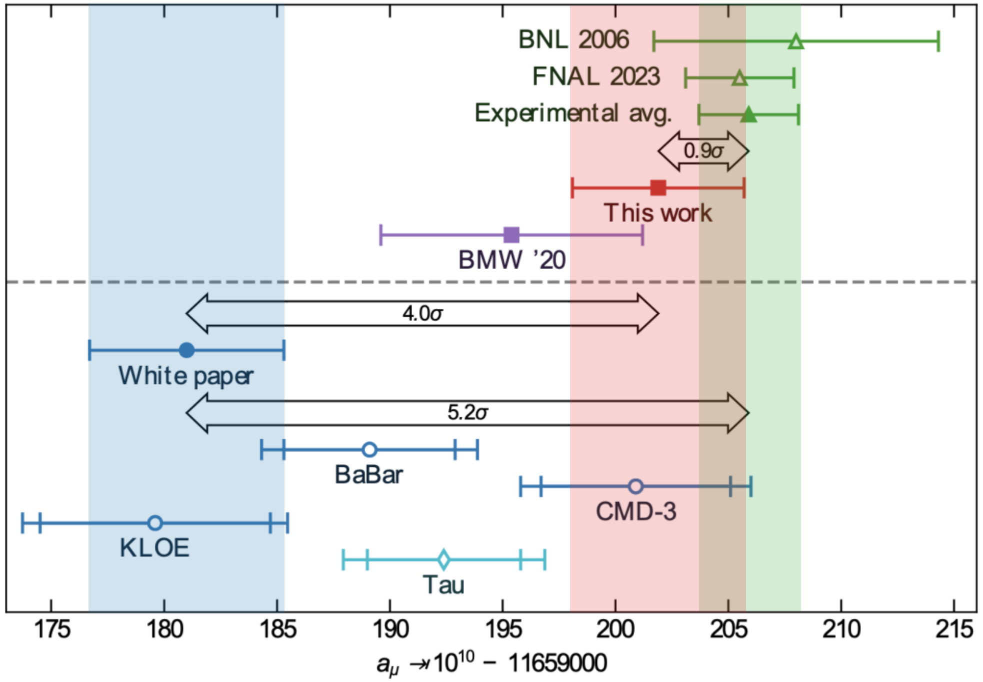
Last part of run 6 dedicated to systematic studies

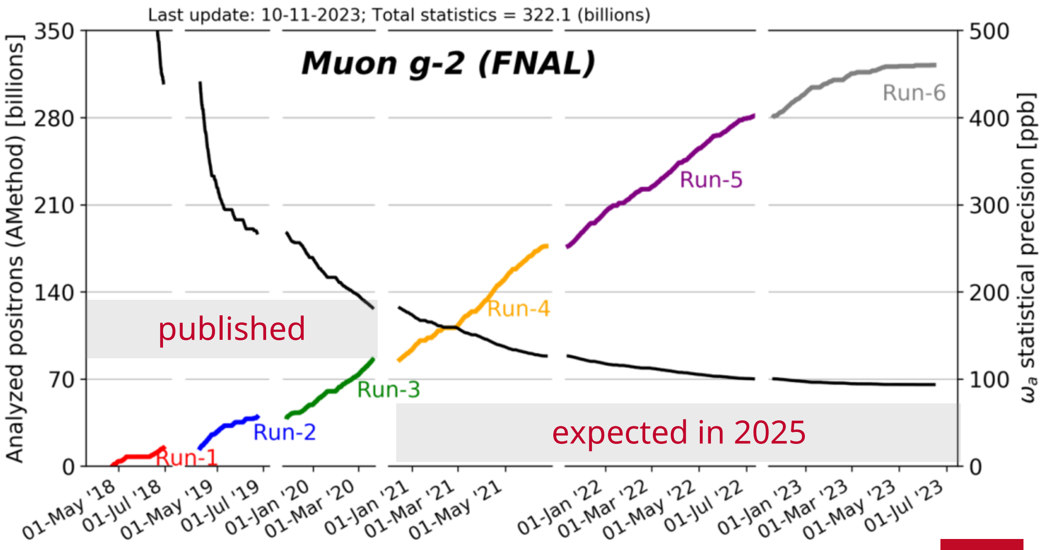
Further systematic studies w/o beam concluded end Jan 2024

Much more statistics
Another factor of about 2 in statistic uncertainty

Conclusions

- High precision measurements of Muon g-2 stringent test on SM theory
- First time a three-way comparison of a_μ is possible
  - Dispersive-approach lattice approach, experiment
  - Very interesting
- Run-2/3 data consistent with Run-1 and BNL
- Improvement by factor >2 in statistical and systematic uncertainty
- Surpassed TRD goals in statistics and systematics
- Another reduction by factor of 2 in statistical uncertainty from Run-4/5/6
- Experimental result will be long standing reference for theory developments





Thank you for your attention

Summer Collaboration meeting at University of Liverpool July 24-28, 2023

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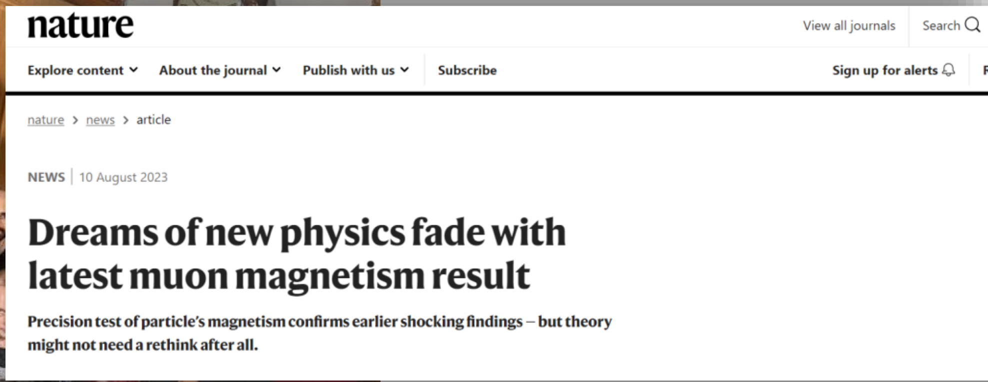
Science

Scientists at Fermilab close in on fifth force of nature

10 August



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NEWS | 10 August 2023

Dreams of new physics fade with latest muon magnetism result

Precision test of particle's magnetism confirms earlier shocking findings – but theory might not need a rethink after all.

Backup

Beyond Standard Model Physics

- Extra contribution to anomalous magnetic moment
- Naïve scaling

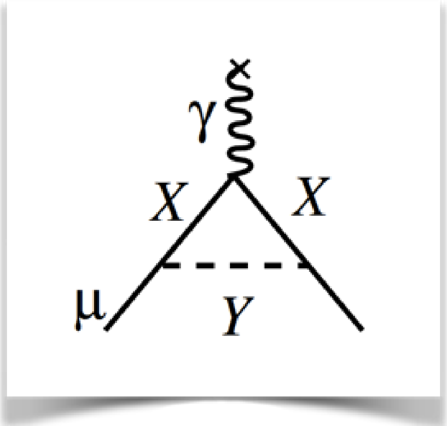
$$a_\mu = a_{\text{QED}} + a_{\text{weak}} + a_{\text{hadron}} + a_{\text{BSM}}$$

$$\Delta a_l^{\text{BSM}} \propto \frac{g_{\text{BSM}}}{16\pi^2} \frac{(\text{lepton mass})^2}{(\text{new particle mass})^2}$$

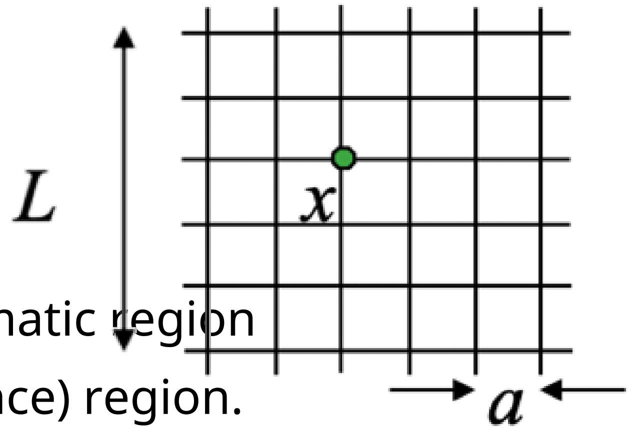
- Comparison with electron g-2

$$\left(\frac{m_\mu}{m_e}\right)^2 = \left(\frac{105\,\text{MeV}}{0.5\,\text{MeV}}\right)^2 \approx 43000$$

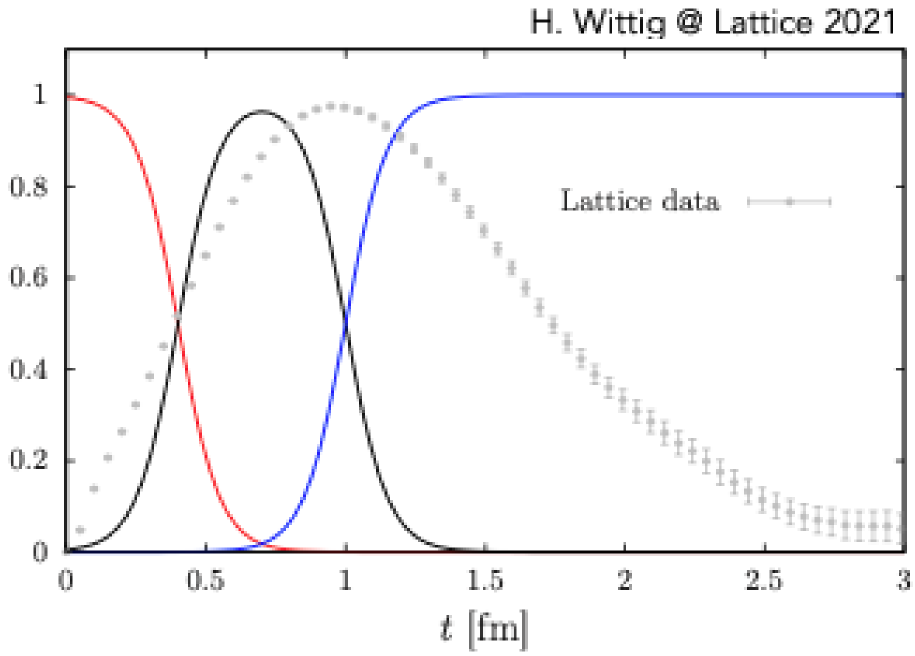
- Muon g-2 is ~43000 more sensitive to new physics compared to electron g-2



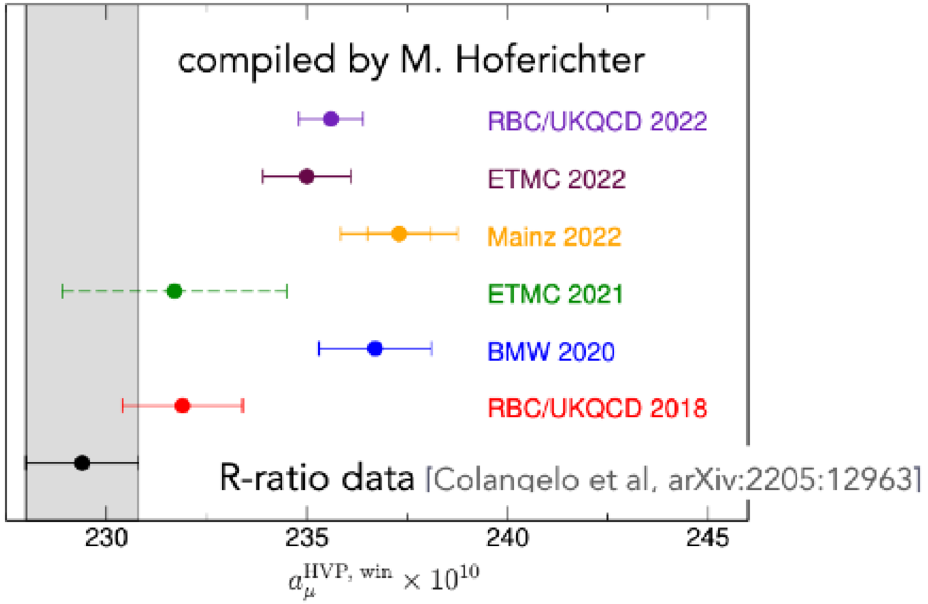
Lattice approach



- First principal calculation by discretizing Euclidian space-time
- BMW is presently the only sub 1% (HVP) lattice calculation in the full kinematic region
- Cross-checks performed by other groups but only **in limited** (30%) (distance) region.

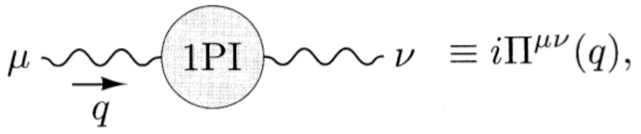


A. El-Khadra, P5 town hall, 21-24 Mar 2023



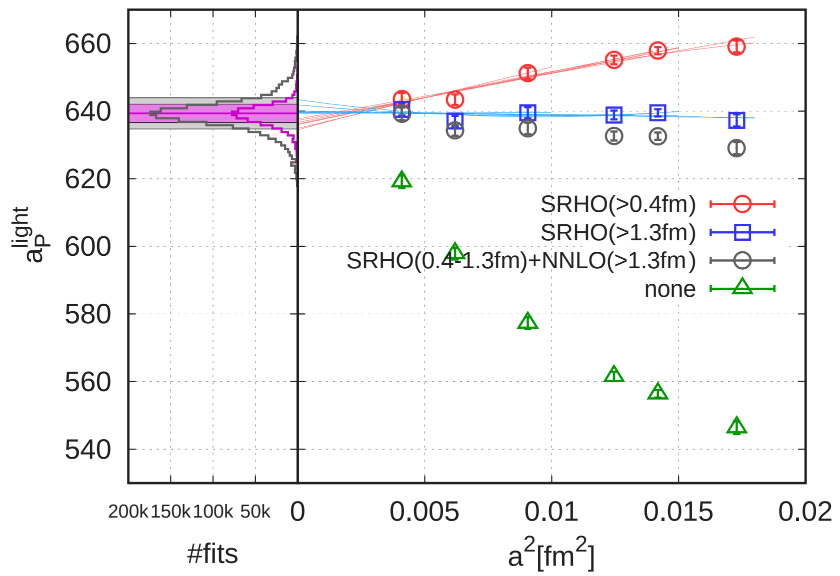
JG|U

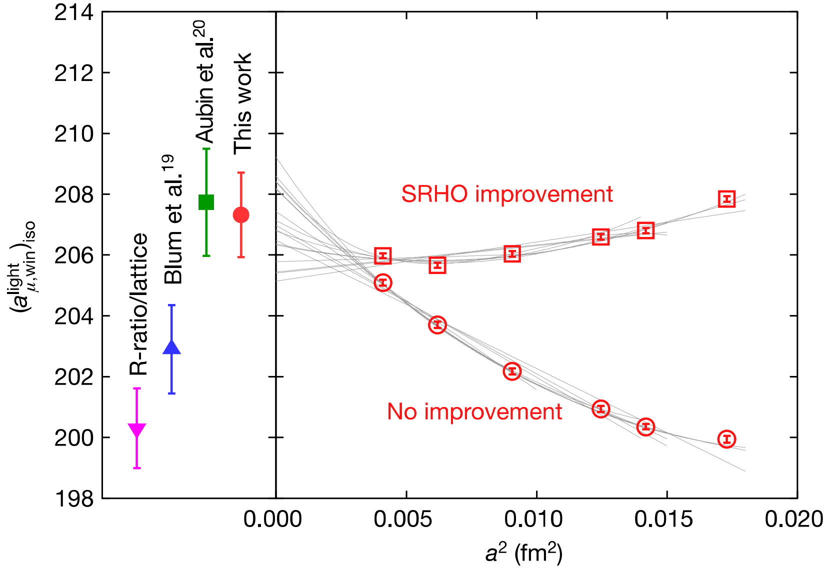
Lattice approach

- BMW20: First sub% calculation of HVP contribution on lattice
- Calculation of “1 particle Irreducible diagrams”
- Large s  nit

➢ upper right panel: limit and uncertainty estimation

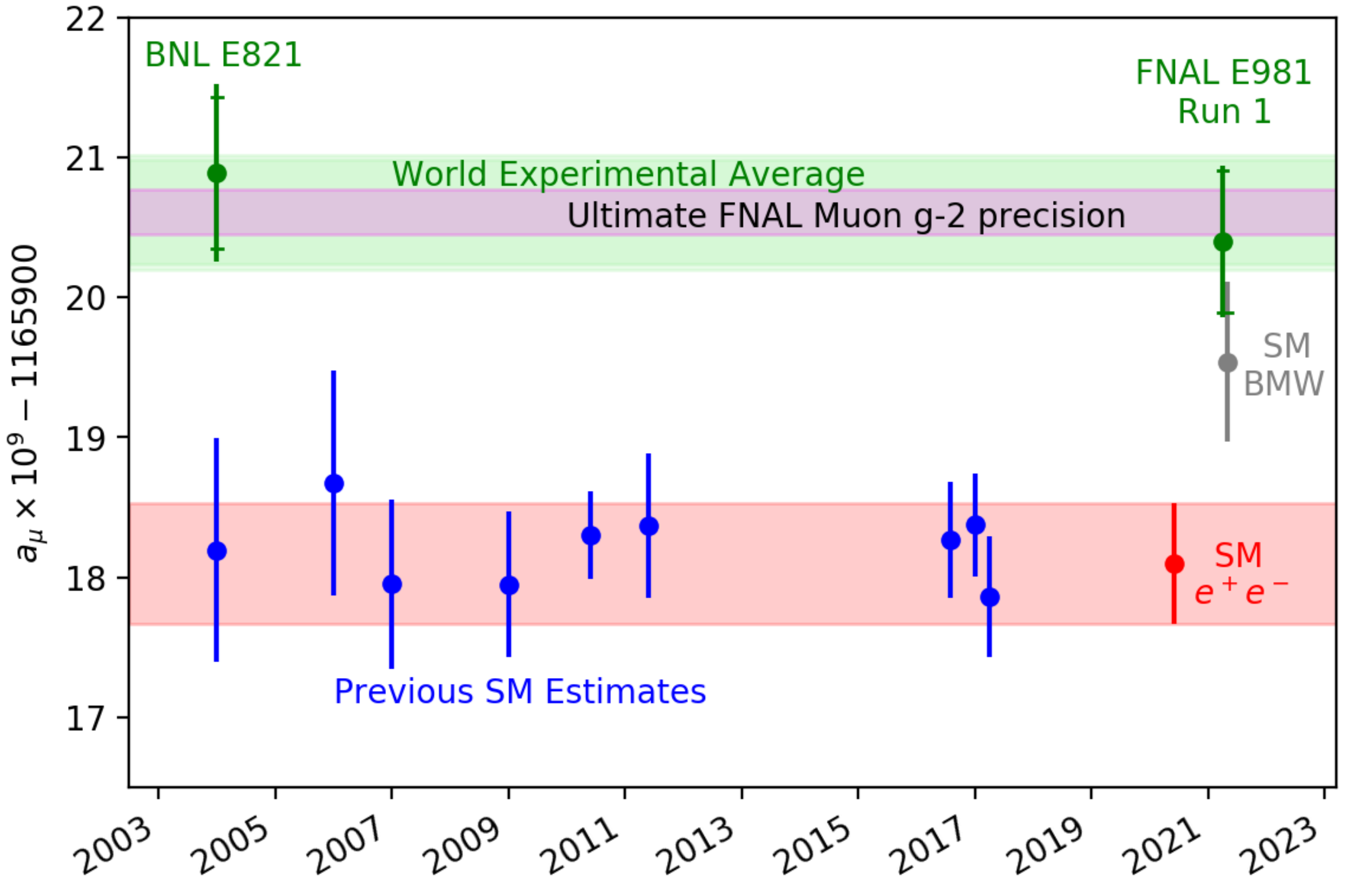
➢ lower right panel: limit for central window compared to other lattice and data-driven results





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

The Muon g-2 Puzzle



- Long standing discrepancy between theory calculation and experimental result

- Uncertainty in theory calculation dominated by calculation of hadronic vacuum polarization

Extracting a_μ

Anchor *B*, *e* and m_μ to other high-precision measurements and calculations

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

$$\tilde{B} = \frac{\hbar\tilde{\omega}'_p}{2\mu'_p}$$

Measure magnetic field with NMR
→ proton spin-precession

10.5 ppb uncertainty — Metrologia 13, 179 (1977)

exact — Rev. Mod. Phys. 88, 035009 (2016)

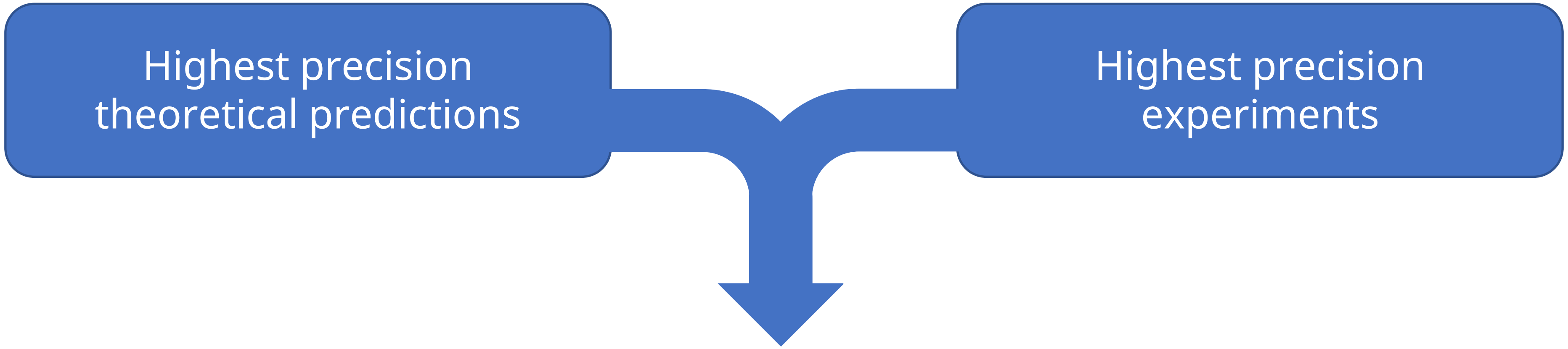
22 ppb uncertainty — Phys. Rev. Lett. 82, 11 (1999)

0.13 ppt uncertainty — Phys. Rev. Lett. 130, 071801 (2023) / CODATA

25 ppb total external uncertainty

Why is Muon g-2 a good test of the SM?

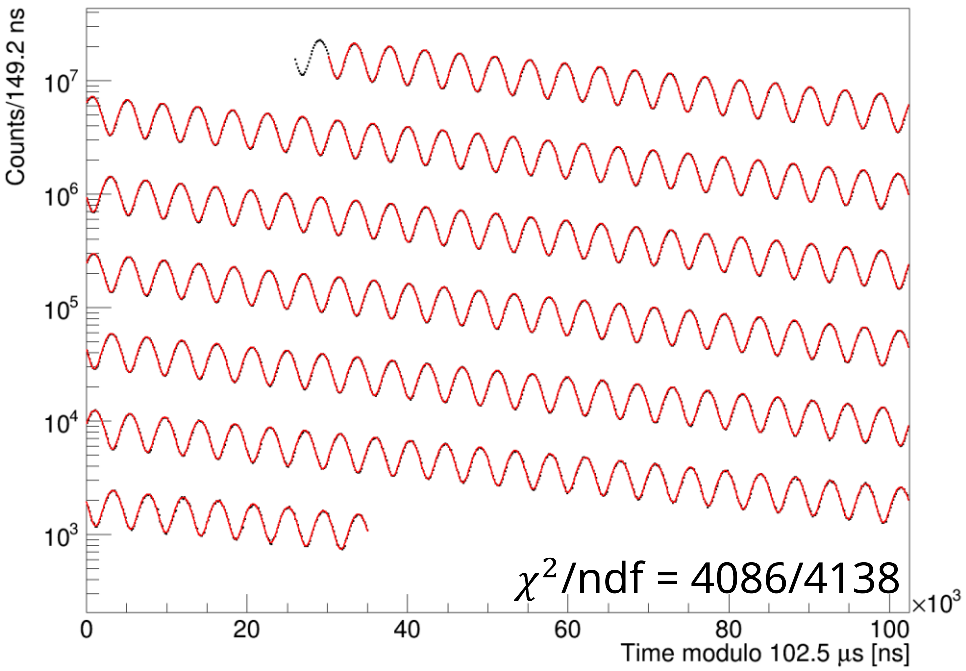
From a theoretician's point of view, the muon is a very clean system
in which highest precision predictions are achievable!

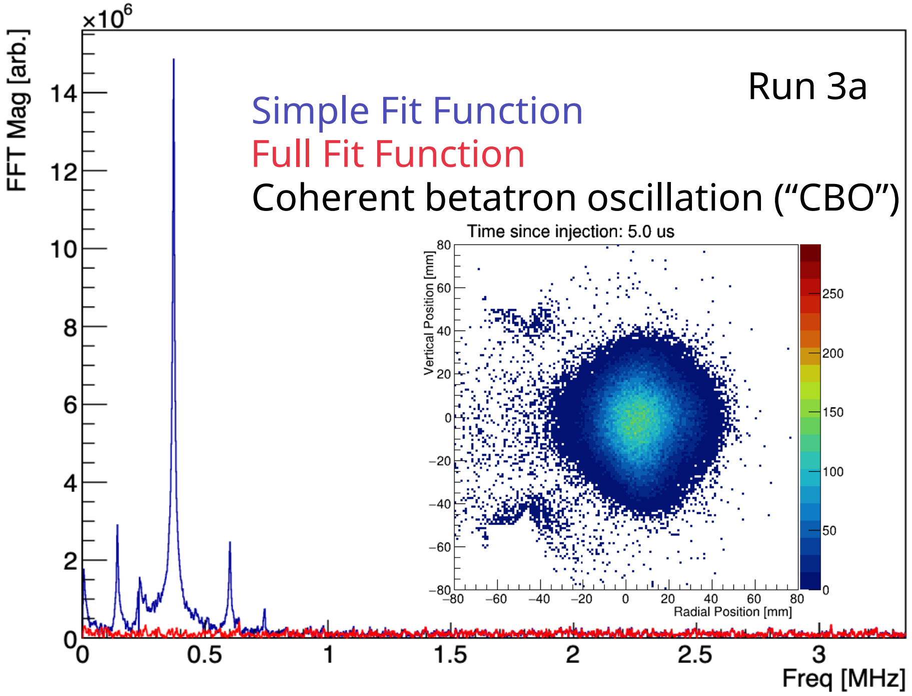


"They allow for high-precision tests!"

Fitting the "wiggle" plot

$$f(t) \propto \langle N \rangle_{\text{thresh}} e^{-\frac{t}{\gamma\tau}} \left[1 + \langle A \rangle_{\text{thres}} \cos\left(\omega_a t - \langle \phi \rangle_{\text{thres}}\right)\right]$$

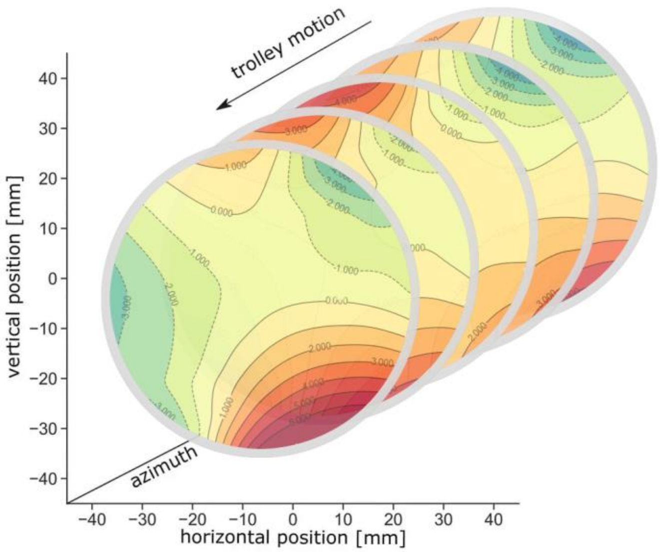




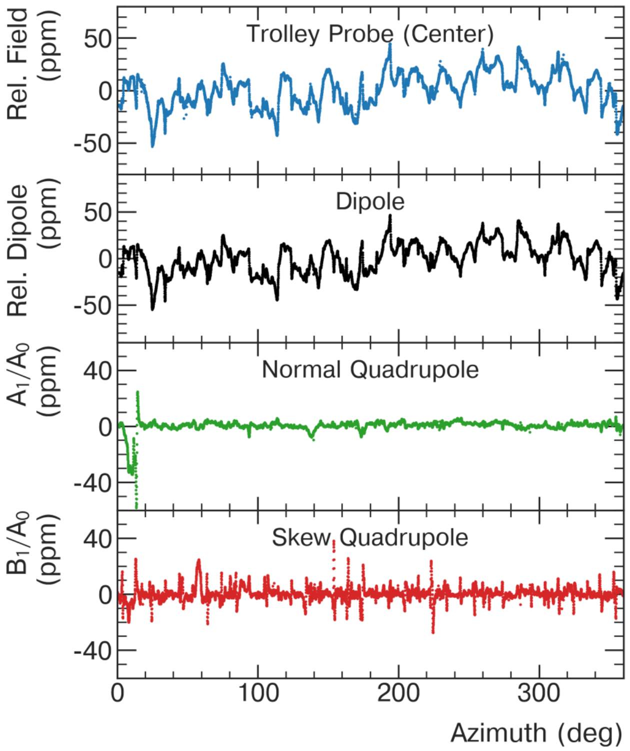
Any time dependent phase shift will bias the frequency

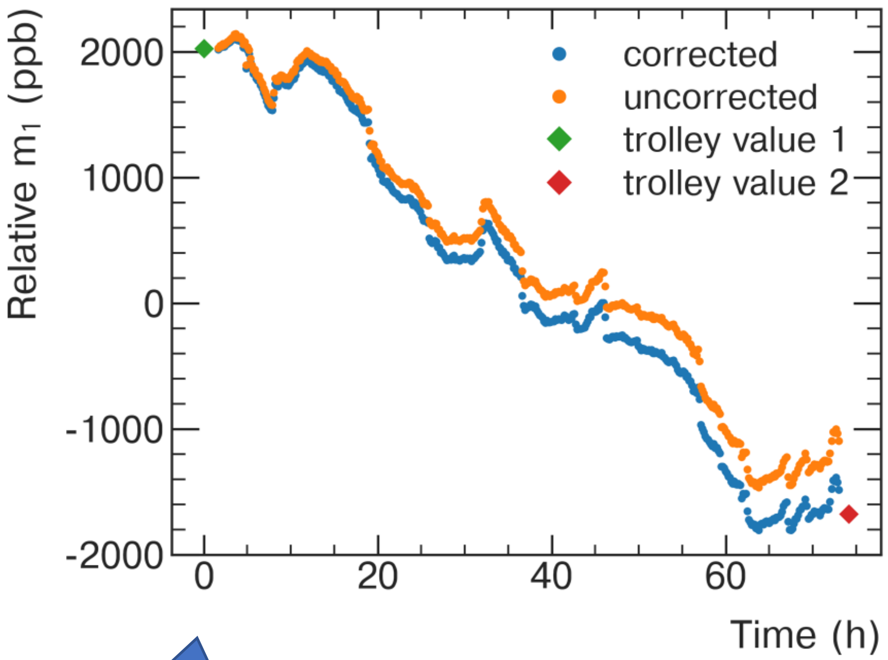
19 different analysis from 7 independent groups
Account for complex beam dynamics ~27 free parameters in fit

Magnetic field tracking



Spatial distribution described
by multipole expansion



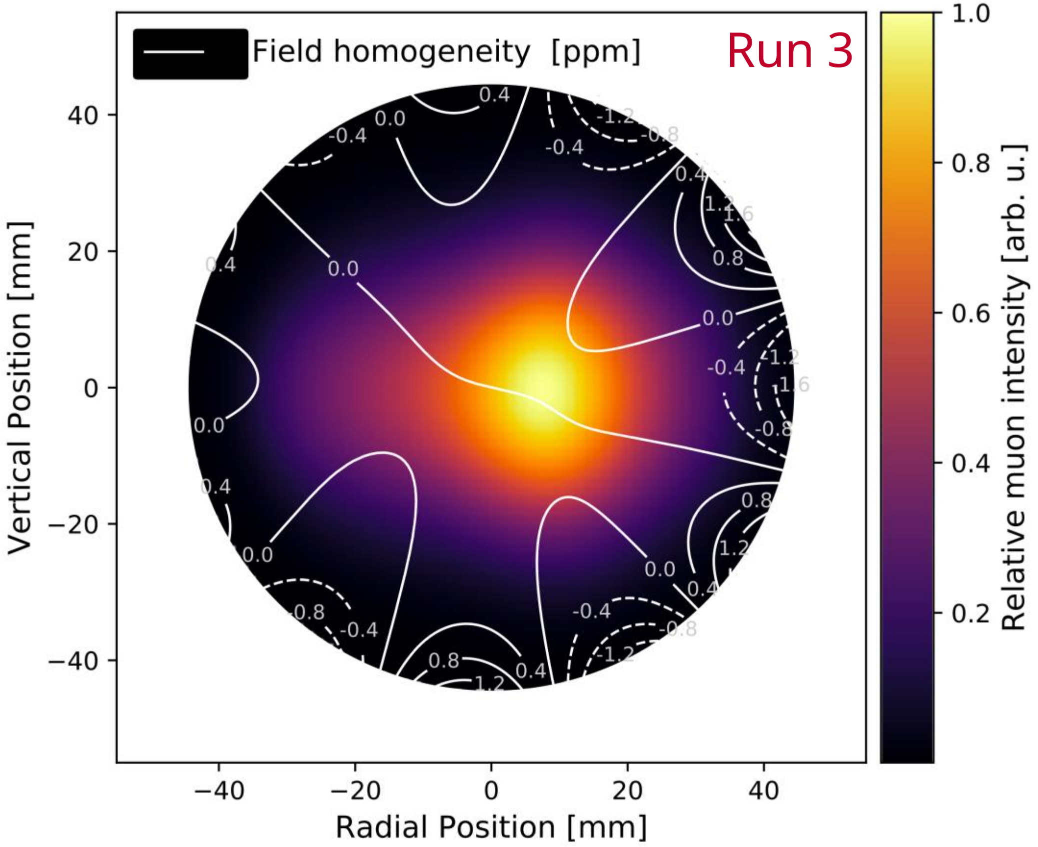


time interpolation
using fixed probe data

Muon weighted magnetic field

- We need the field seen by the muons
- Tracking magnetic field multipole moments
- Muon distribution given by tracker data and beam dynamics simulation

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\,\omega_a^{\text{meas}}\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\,\langle M(x,y,\phi)\,\omega'_p(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

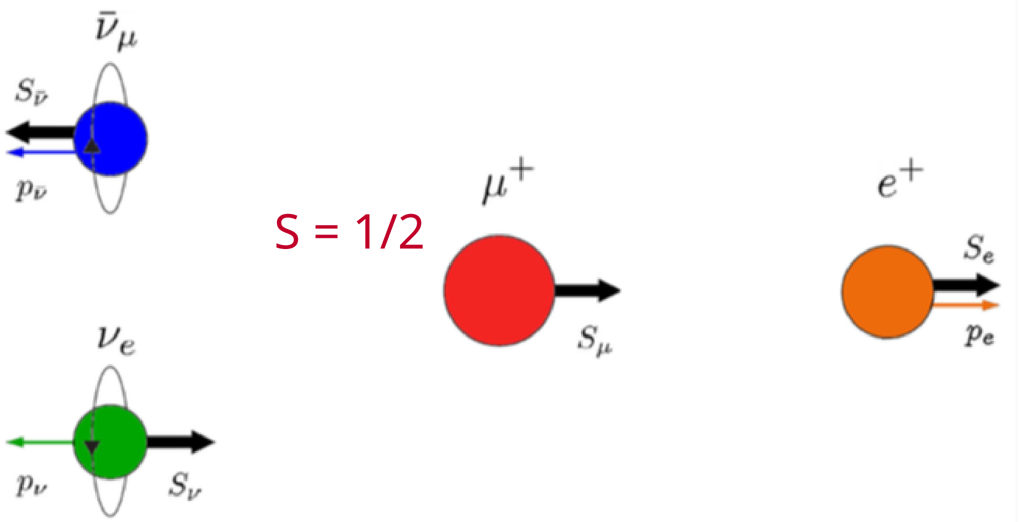


Spin projection detection

S = 1/2
right-handed

S = 1/2
left-handed

S = 1/2



S = 1/2
right-handed

Muon decay described by weak force → parity violation

Maximum positron energy ≅ 52.8 MeV

Positron emitted preferably in direction of muon spin!

Figure credit: K.S. Khaw, PhD thesis, ETHZ, 2015

Relativistic muon in magnetic & electric fields

$$\vec{\omega}_{\mathrm{a}} = \vec{\omega}_{\mathrm{s}} - \vec{\omega}_{\mathrm{c}} = \frac{e}{m}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

non-relativistic limit

electron motion
non-perpendicular
to magnetic field

cyclotron motion assumed motion
perpendicular to magnetic field

pitch of electron

relativistically generated
motional magnetic field

proportional to electric field

$a_\mu^{SM} = 116591810(43) \times 10^{-11}$

disappears for γ≈ 29.3

magic momentum

p_μ=3.094 GeV/c

Muon decay in rest frame

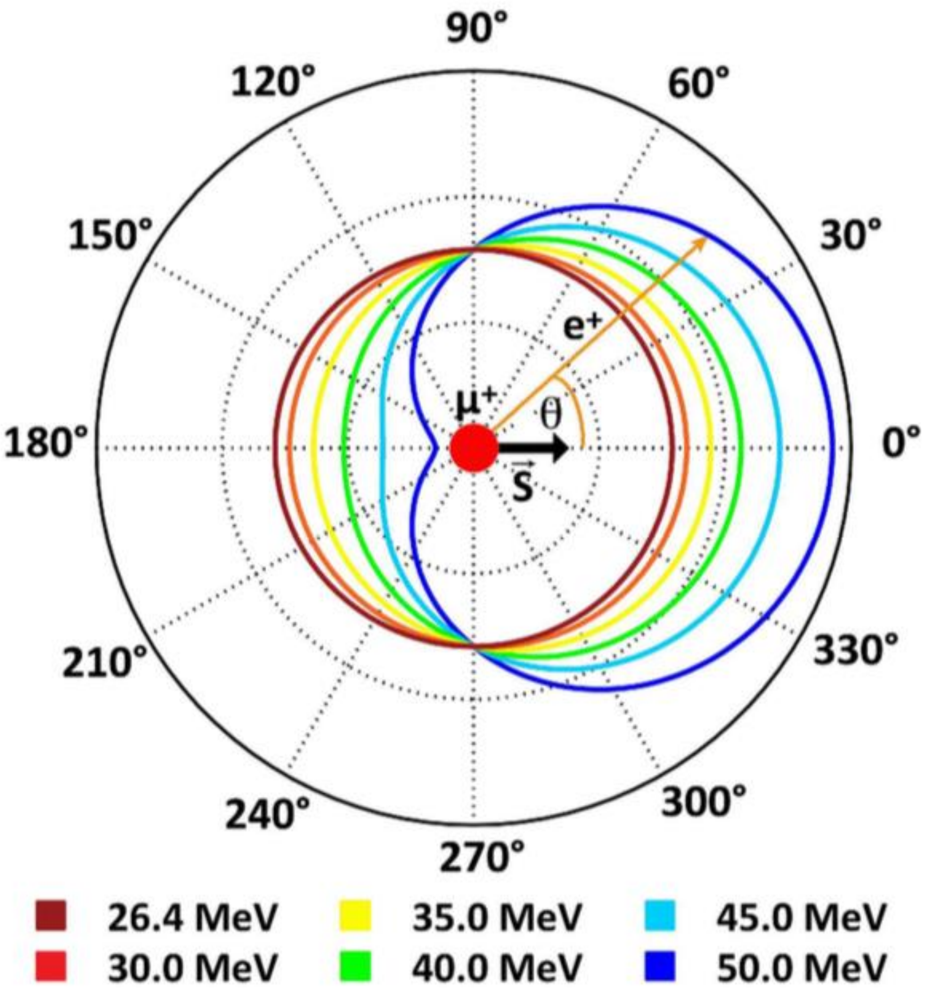


Figure credit: K.S. Khaw, PhD thesis, ETHZ, 2015

Angular differential decay distribution is energy dependent

$$N_{\mathrm{e}}\left(\theta, E_{\mathrm{e}}\right) \propto 1 - A\left(E_{\mathrm{e}}\right)\cos\theta$$

$$A\left(E_{\mathrm{e}}\right) = \frac{E_{\mathrm{e}}^{\max} - 2E_{\mathrm{e}}}{3E_{\mathrm{e}}^{\max} - 2E_{\mathrm{e}}}$$

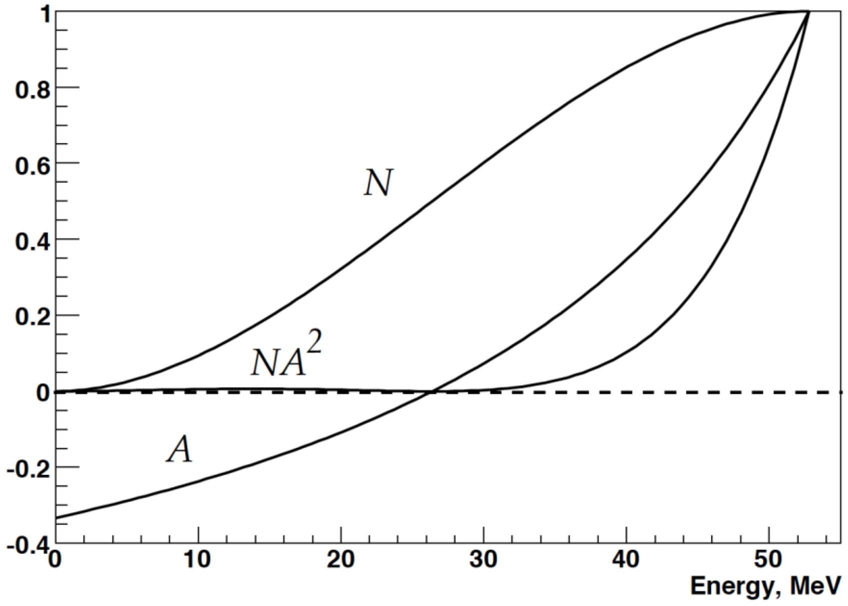


Figure: L. Roberts and W. Marciano, Lepton Dipole Moments

Magnetic field tracking

Trolley system

17 NMR probes

pulled through ring every ~3 days

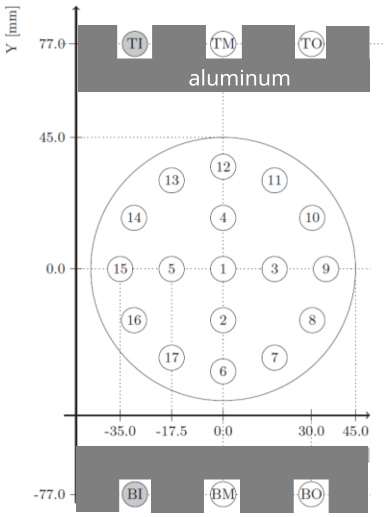
measures spatial field dist. in storage region

Fixed probe system

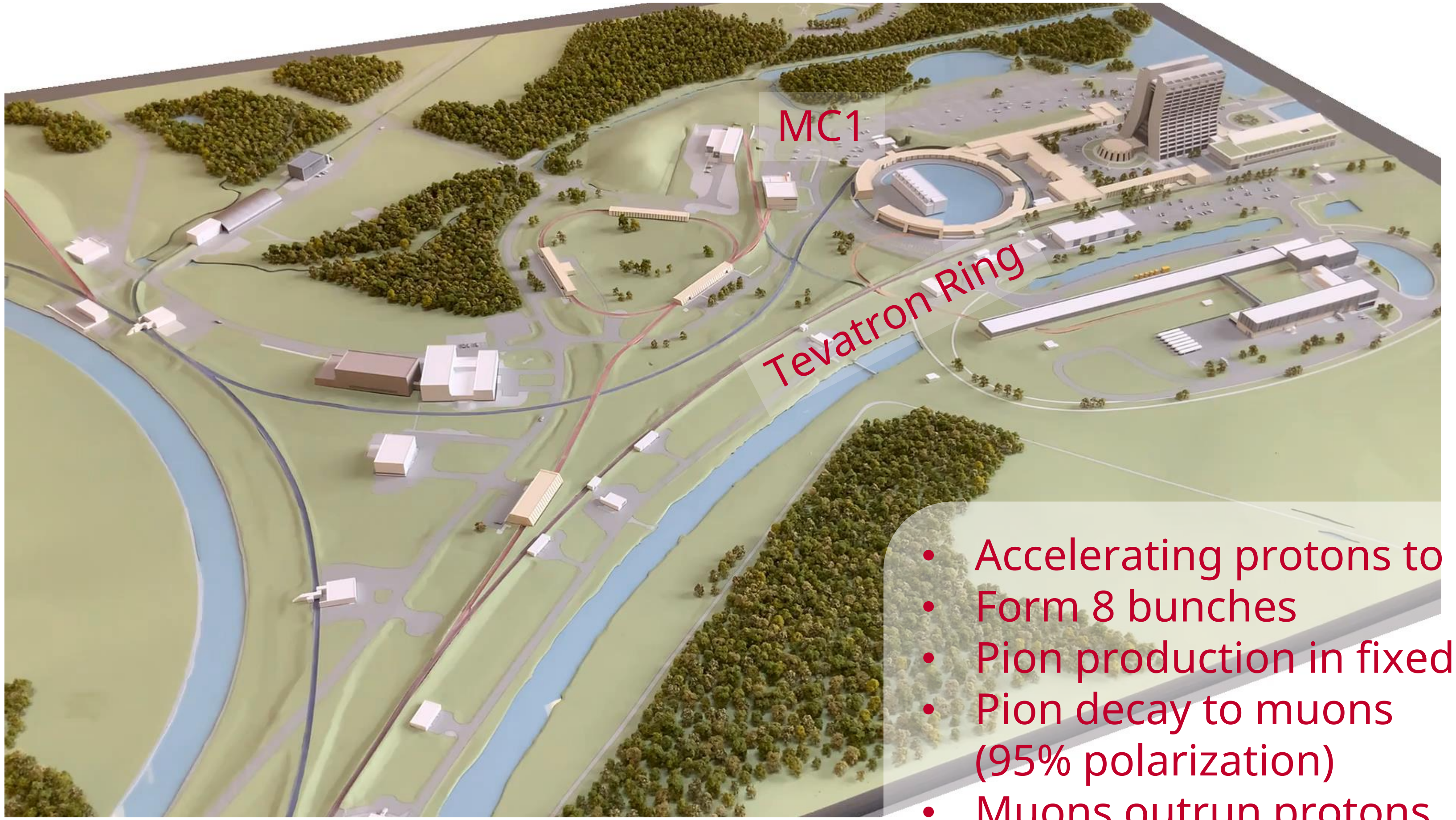
72 azimuthal location (stations)

tracks field drift 24/7

measures field differences (drift)



Muon Campus at Fermilab

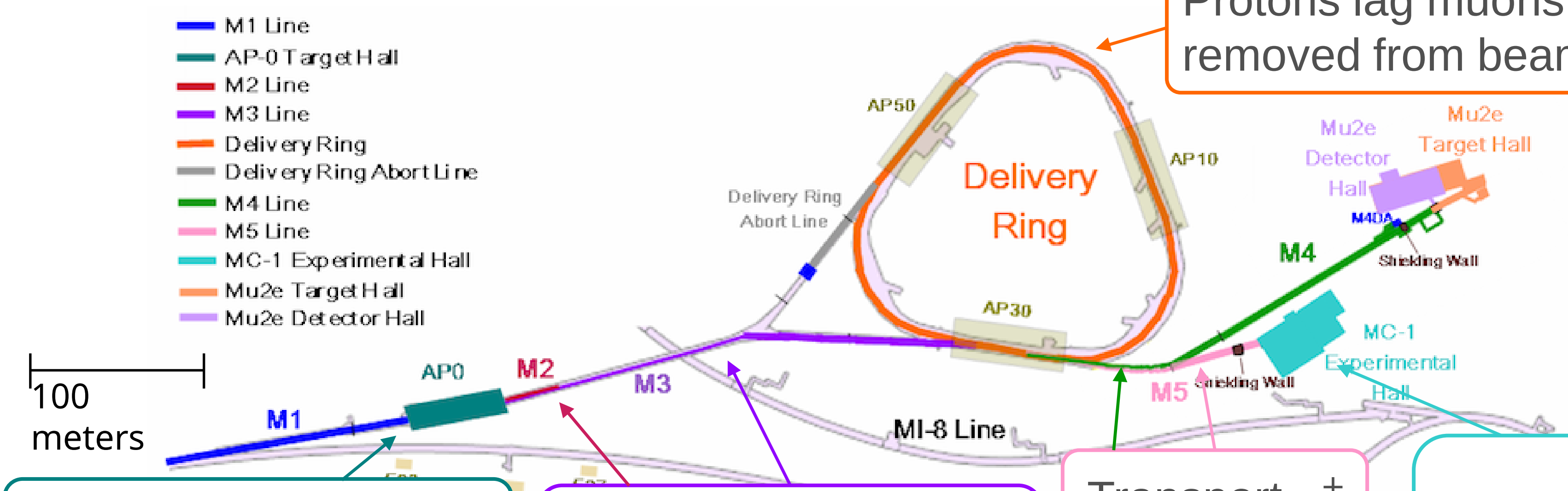


- Accelerating protons to 8 GeV
- Form 8 bunches
- Pion production in fixed target
- Pion decay to muons (95% polarization)
- Muons outrun protons
- Muon g-2 experimental hall

M. Fertl
R. Reimann

Producing the muon beam

~2.5 km beamline consisting of magnetic lenses and steering elements



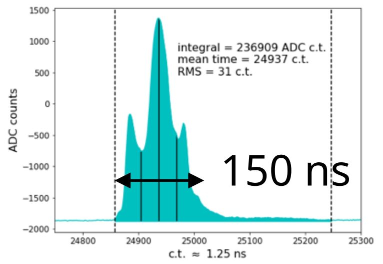
Protons lag muons, removed from beam

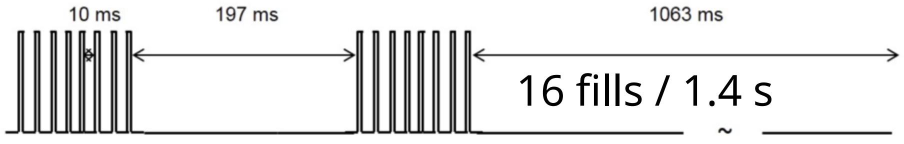
8 GeV protons strike target, produce pions

Pions decay to muons, collect ~3.1 GeV μ^+ → polarized μ^+ beam

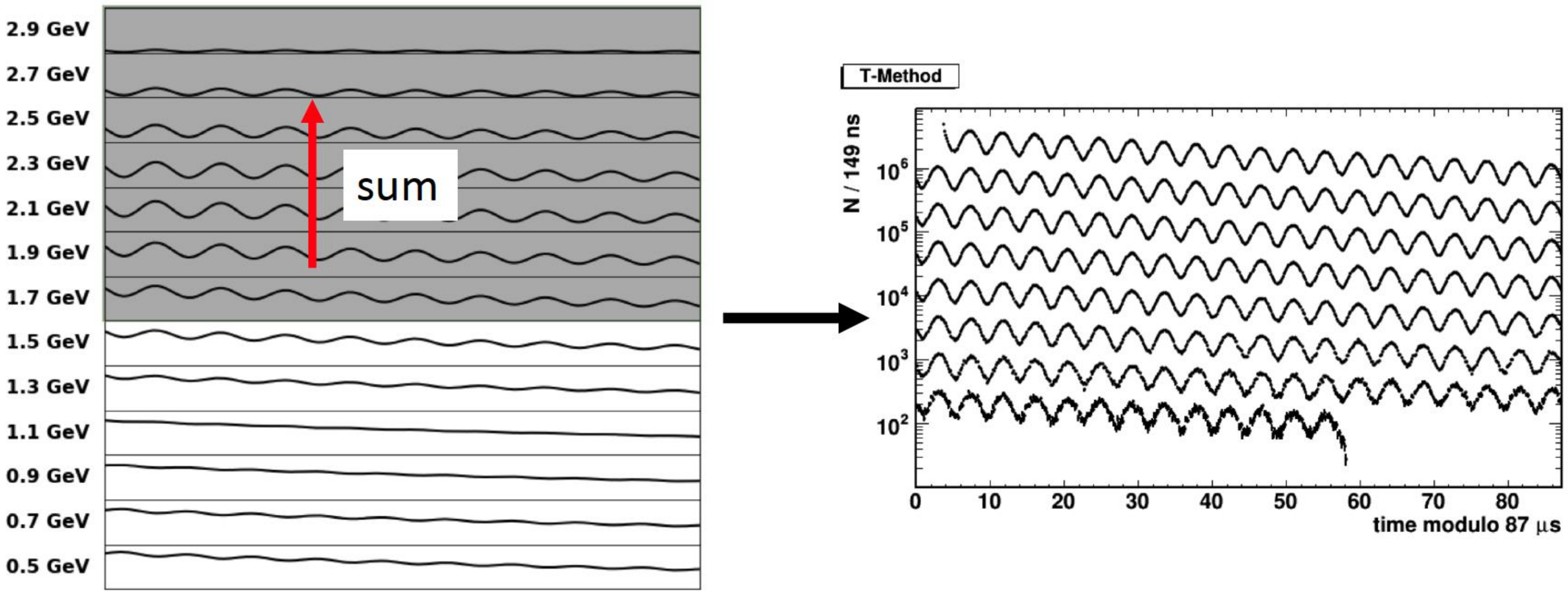
Transport μ^+ to g-2

Inject pulsed μ^+ beam into g-2 storage ring





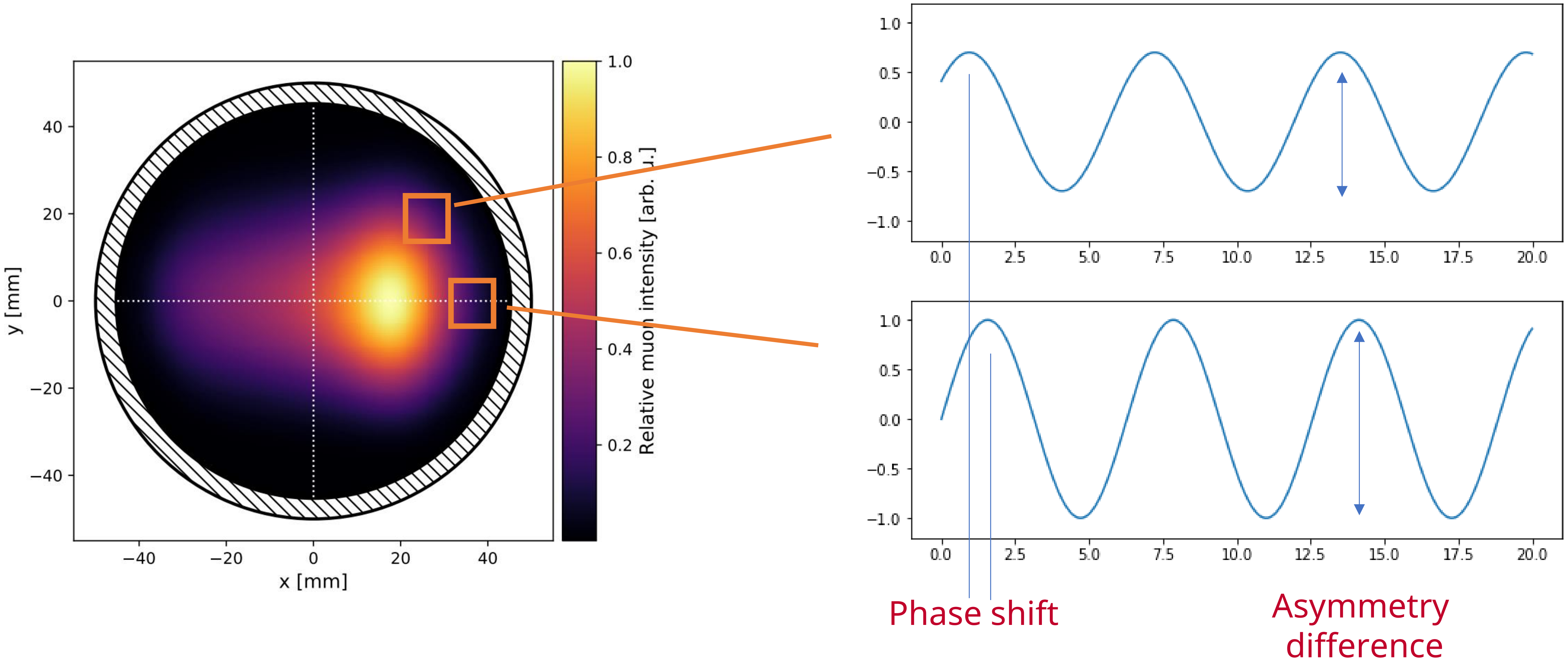
The “wiggle” plot



$$N(t) = N_0(E)\, e^{-\frac{t}{\gamma\tau}} \left[1 + A(E)\cos\left(\omega_\mathrm{a} t - \phi(E)\right)\right]$$

Exponential decay from muon lifetime modulated with $\omega_a = a_\mu \frac{e}{m_\mu} B$

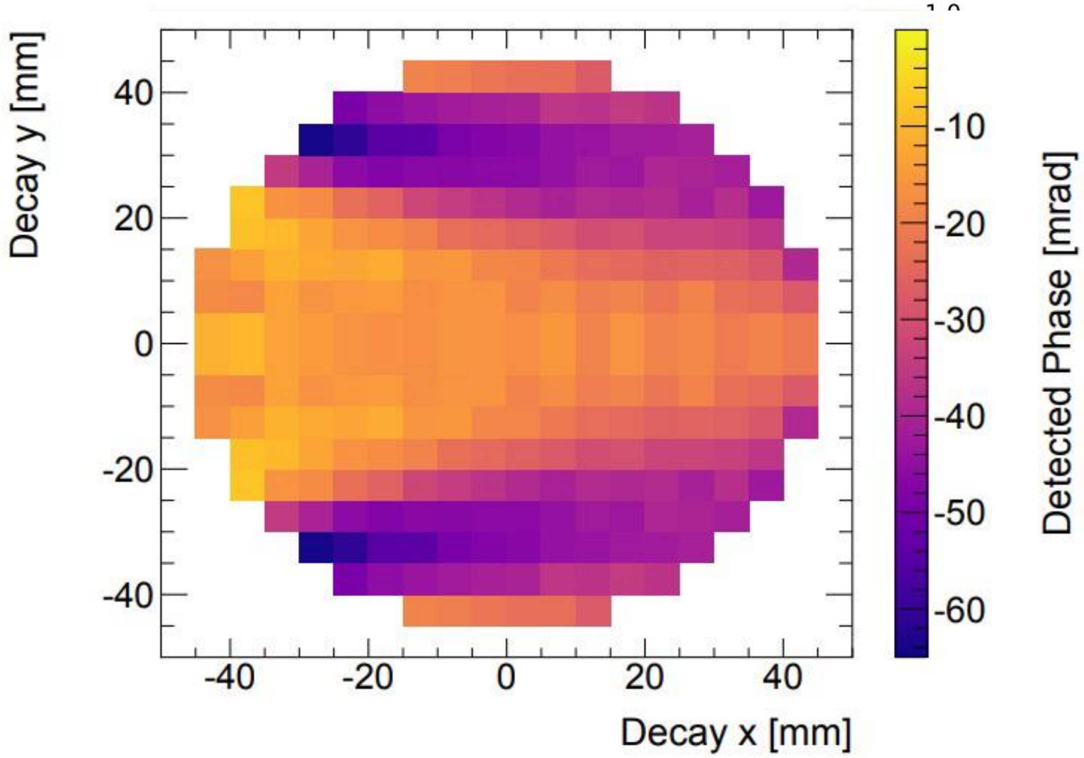
Phase acceptance

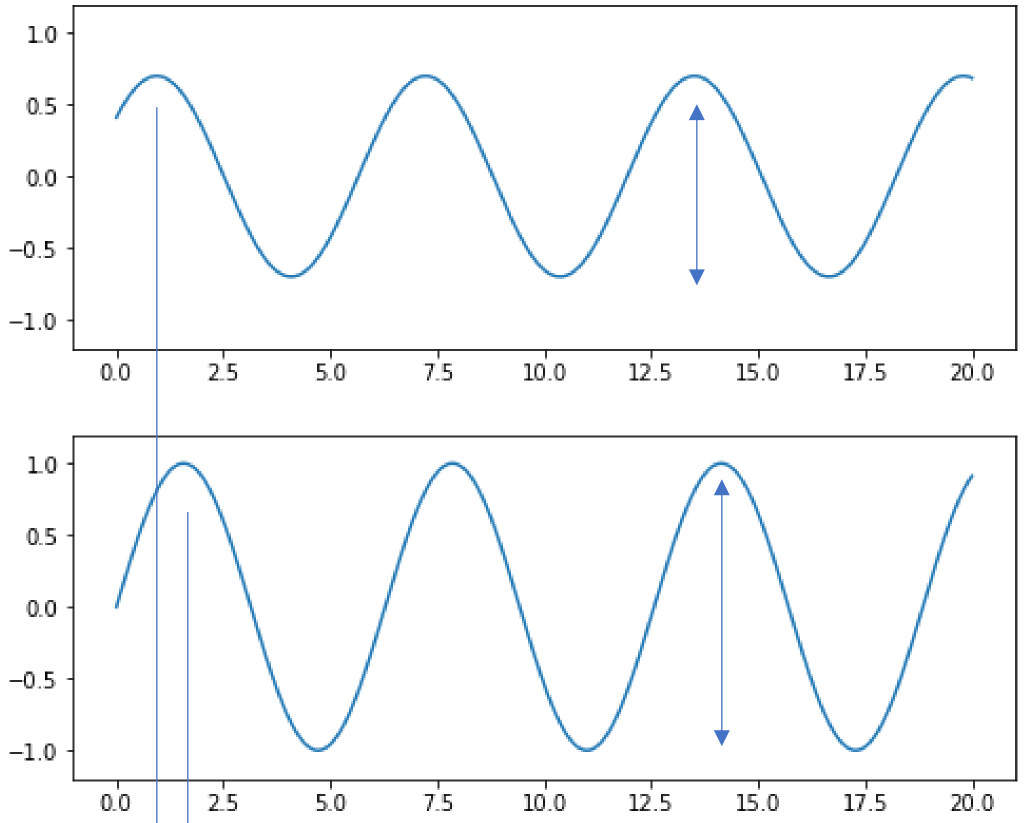


Depends on energy and time

Beam profile must be well-understood during measurement period

Phase acceptance





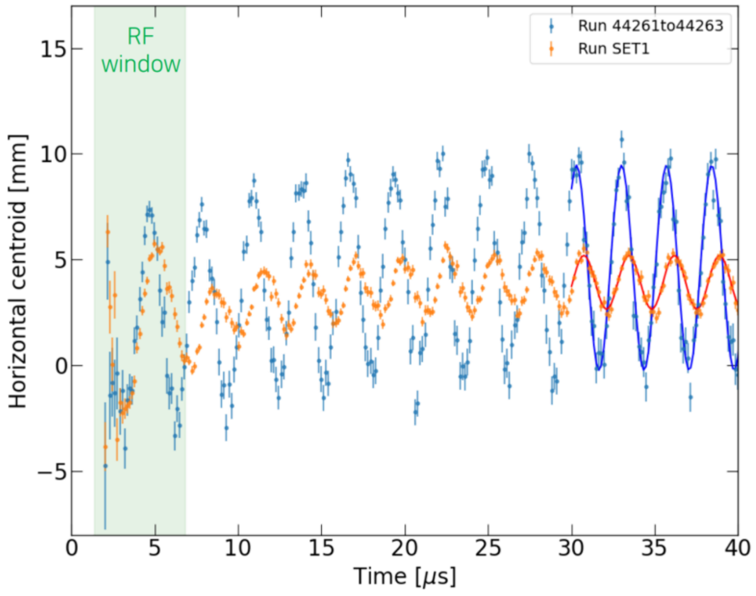
Phase shift

Asymmetry difference

Depends on energy and time
Beam profile must be well-understood during measurement period

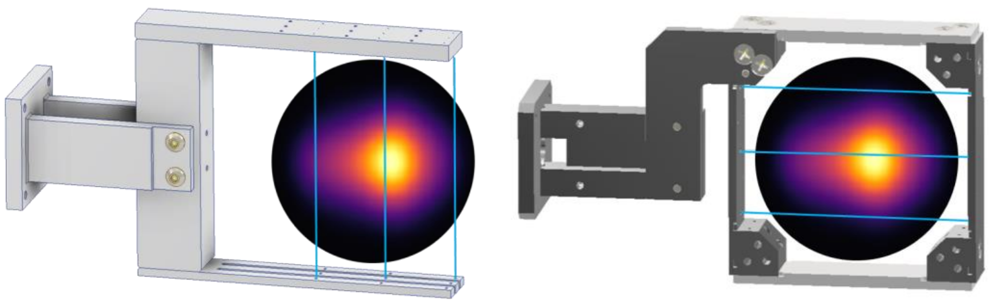
Further improvements

Improved Running Conditions



Quadrupole RF system (Run-5/6)
reduced horizontal beam oscillations

Systematic Measurements & Studies

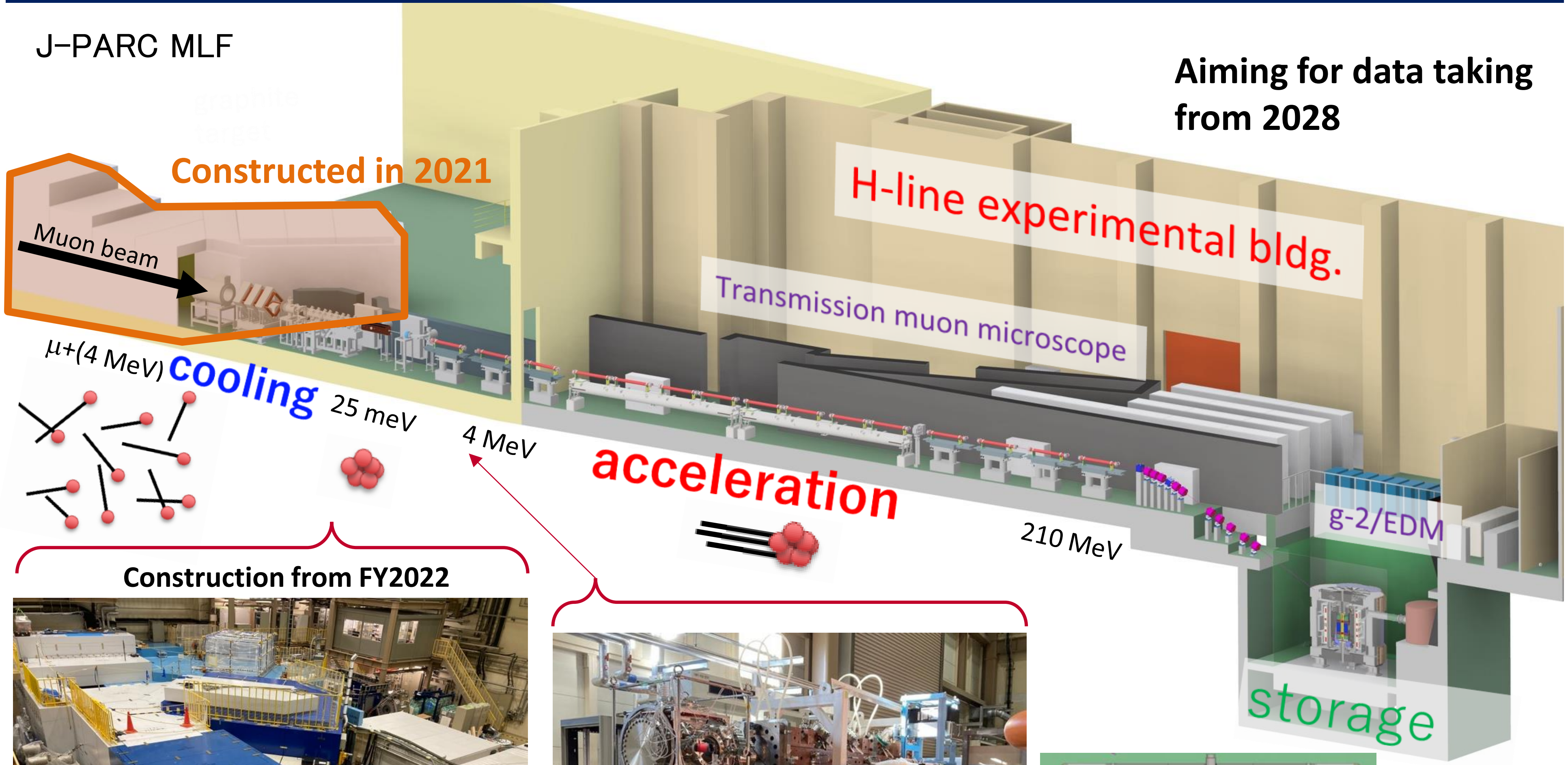


New detectors (scintillating fibers)
for direct beam measurements (Run-6)

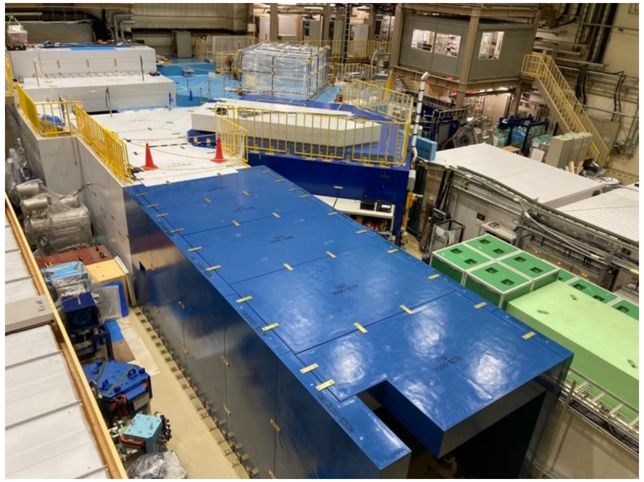
Better understanding and modeling
of beam dynamics

J-PARC muon g-2/EDM experiment

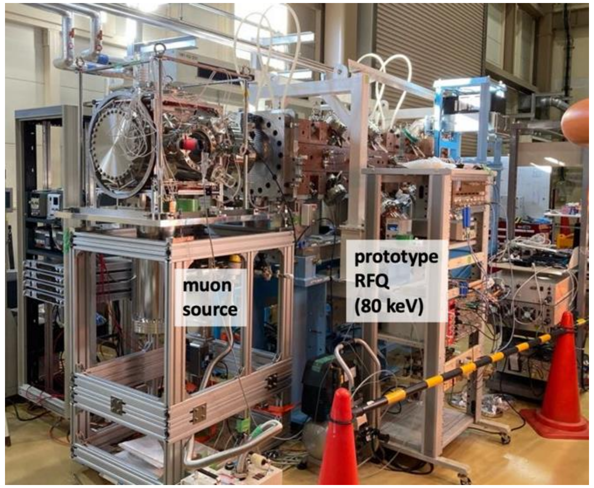
Aiming for data taking from 2028



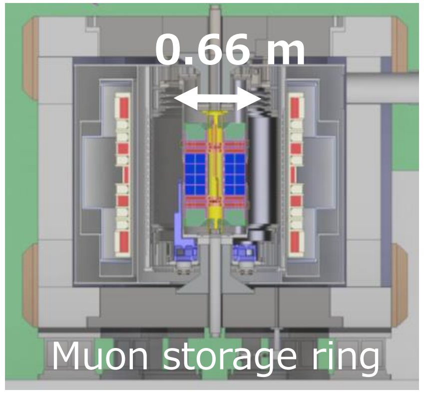
Construction from FY2022



Shields, area control (2022)

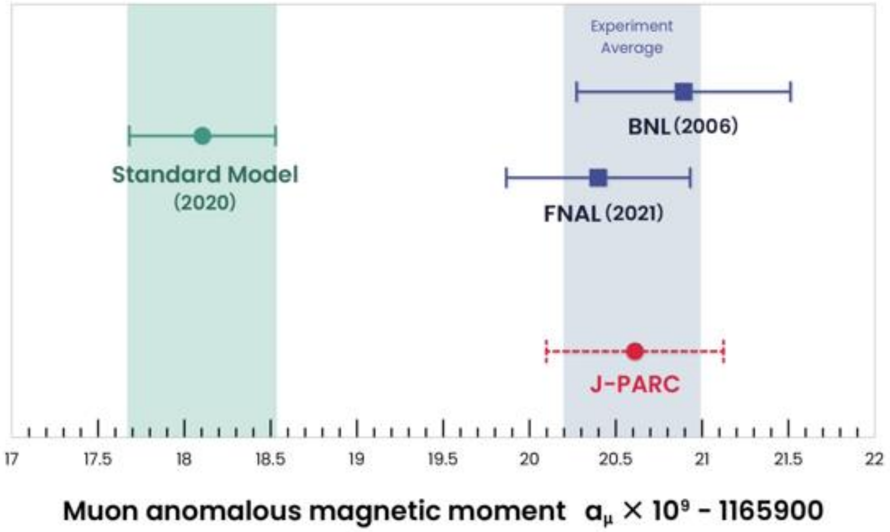


RF Acc. Test at S2 area (May 2023)



J-PARC Experiment

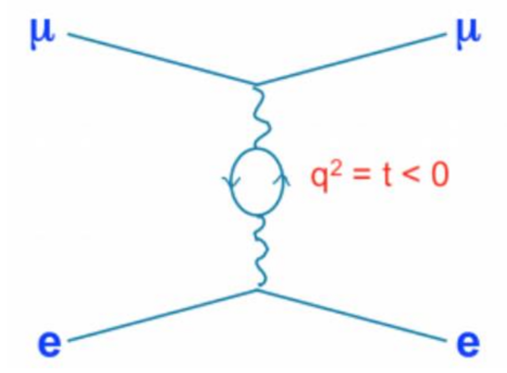
- Complementary technique
  - μ beam accelerated from rest
  - no E fields
  - smaller magnet
- Aiming for a result comparable to Run-1 result towards the end of the decade



- Under construction aiming for data taking from 2028.
- Succeeded to deliver a surface muon beam to H-line.
- Constructed the experimental area for muon cooling and the first stage of the acceleration.
- Currently taking data to demonstrate the muon cooling by using the laser ionization of muonium, followed by RF acceleration tests.

New method to measure $a_\mu^{HVP,LO}$

Muon-electron scattering μe → μe



Spacelike

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2$$

Effective Born cross-section

VP effects in leading photon t-channel incorporated in the running of α

$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha(t)}$$

$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had}$$

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

Leading-order hadronic contribution can be directly inferred by measuring the shape of the μe → μe cross-section

S. Charity

181 collaboration members worldwide

US Universities
- Boston
- Cornell
- UIUC
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central College
- Regis
- Virginia
- Washington

US National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

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