TOPICAL GROUP RF3: MAGNETIC DIPOLE MOMENTS, ANTIHYDROGEN, AND QIS

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OVERVIEW

- Experiments and theory overview for:
  - Magnetic dipole moments (electron and muon)
  - Antihydrogen experiments at CERN
  - QIS
- Summary for RF3 topical group

MAGNETIC DIPOLE MOMENTS

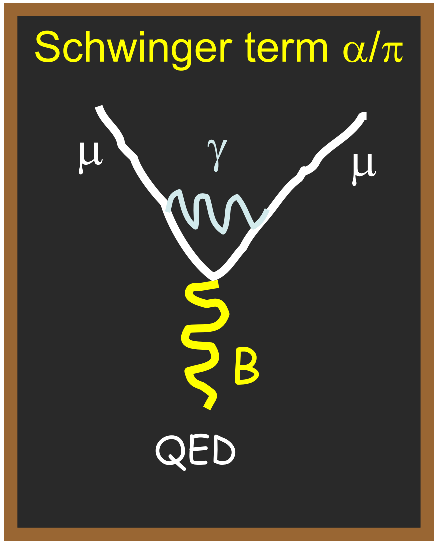
CHARGED LEPTON MAGNETIC MOMENTS

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

- Magnetic moment for spin-½ particle in Dirac theory: g ≡ 2
- Deviation from g = 2 from loop corrections
- Comparison of precise calculation and measurement offers search for BSM physics

$$a^{Expt.} = a^{SM} + a^{New\ Physics}$$

- Enhanced sensitivity $(m_\mu / m_e)^2 \approx 43{,}000$!
- Muon lives long enough (2.2 μs) !



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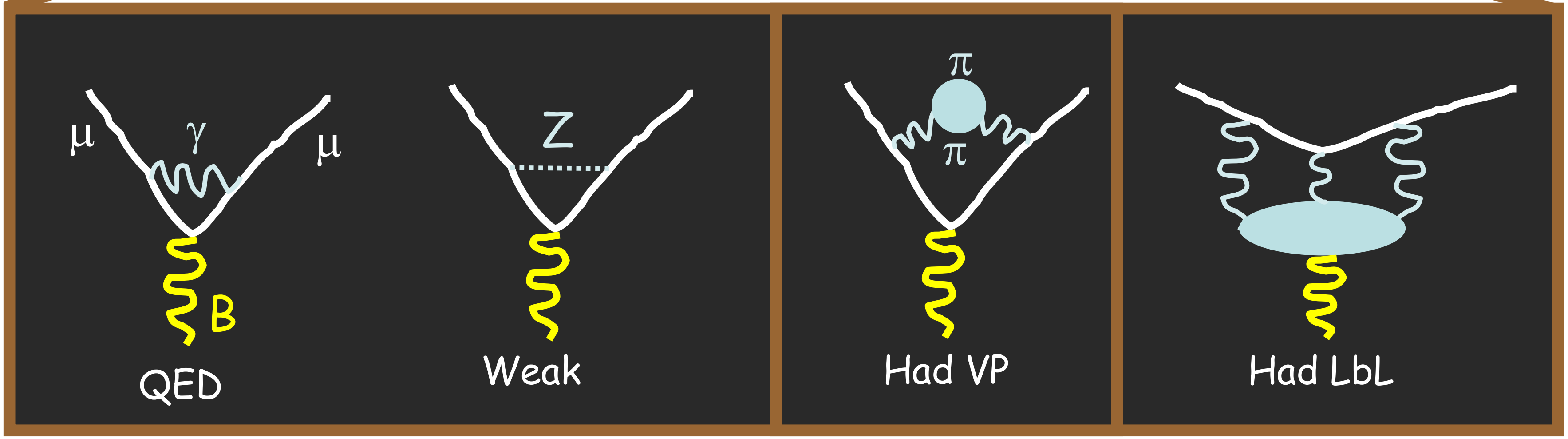
CHARGED LEPTON MAGNETIC MOMENTS

$$a_\mu^{Expt.} = a_\mu^{SM} + a_\mu^{New\ Physics}$$



Known well beyond current experimental precision

Known slightly better than current experimental precision – more improvements planned

THEORY INITIATIVE RESULT RELEASED https://arxiv.org/abs/2006.04822

arXiv.org > hep-ph > arXiv:2006.04822

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High Energy Physics – Phenomenology

[Submitted on 8 Jun 2020]

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama, N. Asmussen, M. Benayoun, J. Bijnens, T. Blum, M. Bruno, I. Caprini, C. M. Carloni Calame, M. Cè, G. Colangelo, F. Curciarello, H. Czyż, I. Danilkin, M. Davier, C. T. H. Davies, M. Della Morte, S. I. Eidelman, A. X. El-Khadra, A. Gérardin, D. Giusti, M. Golterman, Steven Gottlieb, V. Gülpers, F. Hagelstein, M. Hayakawa, G. Herdoíza, D. W. Hertzog, A. Hoecker, M. Hoferichter, B.-L. Hoid, R. J. Hudspith, F. Ignatov, T. Izubuchi, F. Jegerlehner, L. Jin, A. Keshavarzi, T. Kinoshita, B. Kubis, A. Kupich, A. Kupść, L. Laub, C. Lehner, L. Lellouch, I. Logashenko, B. Malaescu, K. Maltman, M. K. Marinković, P. Masjuan, A. S. Meyer, H. B. Meyer, T. Mibe, K. Miura, S. E. Müller, M. Nio, D. Nomura, A. Nyffeler, V. Pascalutsa, M. Passera, E. Perez del Rio, S. Peris, A. Portelli, M. Procura, C. F. Redmer, B. L. Roberts, P. Sánchez-Puertas, S. Serednyakov, B. Shwartz, S. Simula, D. Stöckinger, H. Stöckinger-Kim, P. Stoffer, T. Teubner, R. Van de Water, M. Vanderhaeghen, G. Venanzoni, G. von Hippel, H. Wittig, Z. Zhang, M. N. Achasov, A. Bashir, N. Cardoso, B. Chakraborty, E.-H. Chao, J. Charles, A. Crivellin, O. Deineka, A. Denig, C. DeTar, C. A. Dominguez, A. E. Dorokhov, V. P. Druzhinin, G. Eichmann, M. Fael, C. S. Fischer, E. Gámiz, Z. Gelzer, J. R. Green, S. Guellati-Khelifa, D. Hatton, N. Hermansson-Truedsson et al. (32 additional authors not shown)

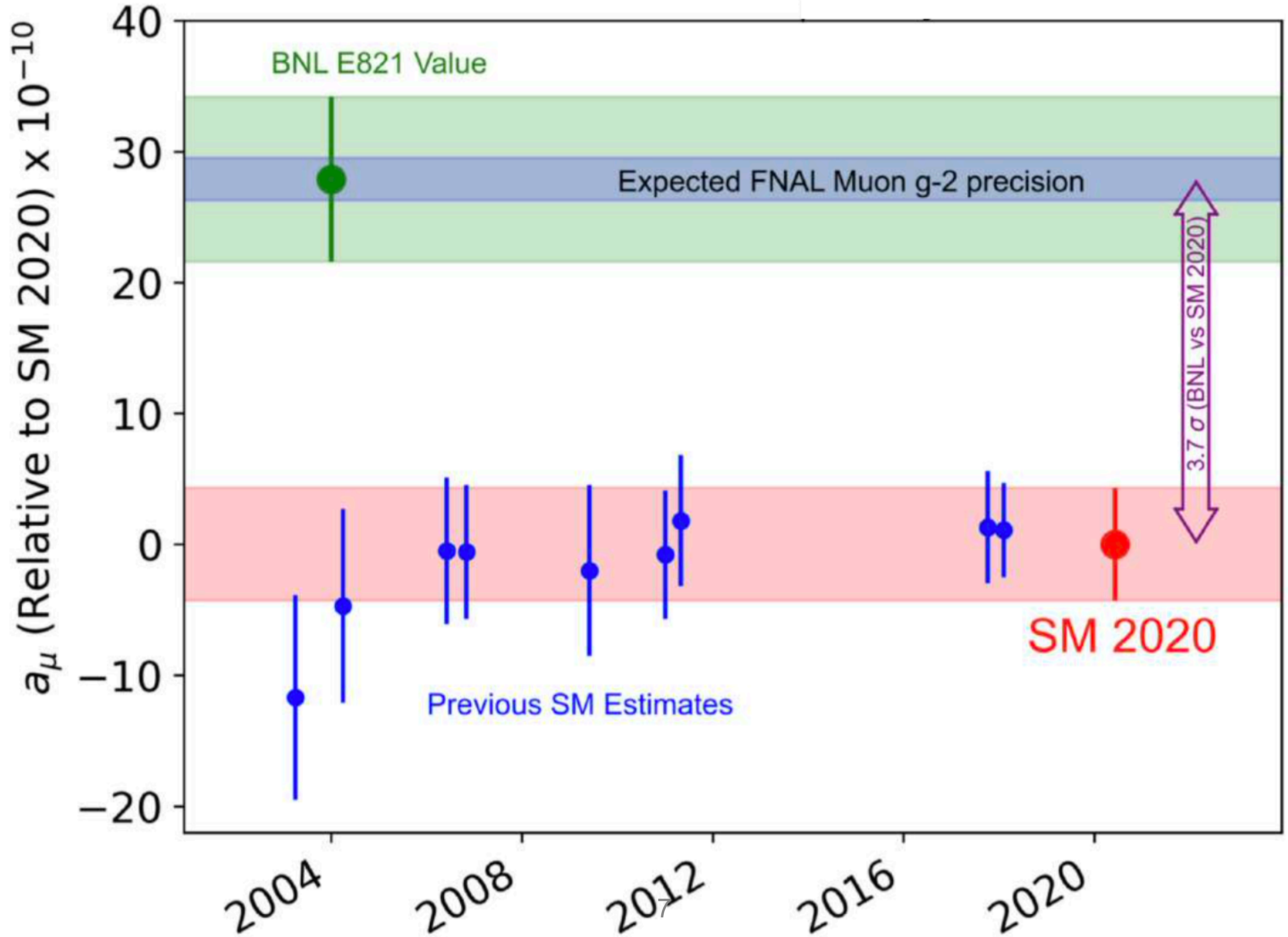
We review the present status of the Standard Model calculation of the anomalous magnetic moment of the muon. This is performed in a perturbative expansion in the fine-structure constant α and is broken down into pure QED, electroweak, and hadronic contributions. The pure QED contribution is by far the largest and has been evaluated up to and including $\mathcal{O}(\alpha^5)$ with negligible numerical uncertainty. The electroweak contribution is suppressed by $(m_\mu/M_W)^2$ and only shows up at the level of the seventh significant digit. It has been evaluated up to two loops and is known to better than one percent. Hadronic contributions are the most difficult to calculate and are responsible for almost all of the theoretical uncertainty. The leading hadronic contribution appears at $\mathcal{O}(\alpha^2)$ and is due to hadronic vacuum polarization, whereas at $\mathcal{O}(\alpha^3)$ the hadronic light-by-light scattering contribution appears. Given the low characteristic scale of this observable, these contributions have to be calculated with nonperturbative methods, in particular, dispersion relations and the lattice approach to QCD. The largest part of this review is dedicated to a detailed account of recent efforts to improve the calculation of these two contributions with either a data-driven, dispersive approach, or a first-principle, lattice-QCD approach. The final result reads $a_\mu^{SM} = 116\,591\,810(43) \times 10^{-11}$ and is smaller than the Brookhaven measurement by 3.7σ. The experimental uncertainty will soon be reduced by up to a factor four by the new experiment currently running at Fermilab, and also by the future J-PARC experiment. This and the prospects to further reduce the theoretical uncertainty in the near future-which are also discussed here-make this

- 4+ year long international collaborative effort
- Website: https://muon-gm2-theory.illinois.edu/white-paper/

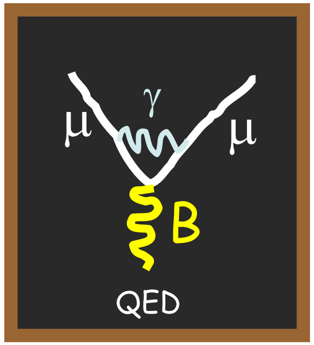
Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
HVP LO (e^+e^-)	6931(40)
HVP NLO (e^+e^-)	–98.3(7)
HVP NNLO (e^+e^-)	12.4(1)
HVP LO (lattice, $udsc$)	7116(184)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, uds)	79(35)
HLbL (phenomenology + lattice)	90(17)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Difference: $\Delta a_\mu := a_\mu^{exp} - a_\mu^{SM}$	279(76)

THEORY INITIATIVE RESULT RELEASED https://arxiv.org/abs/2006.04822

- Updated theory result currently yields a 3.7σ discrepancy
- Would yield 6σ with 140ppb precision from experiment

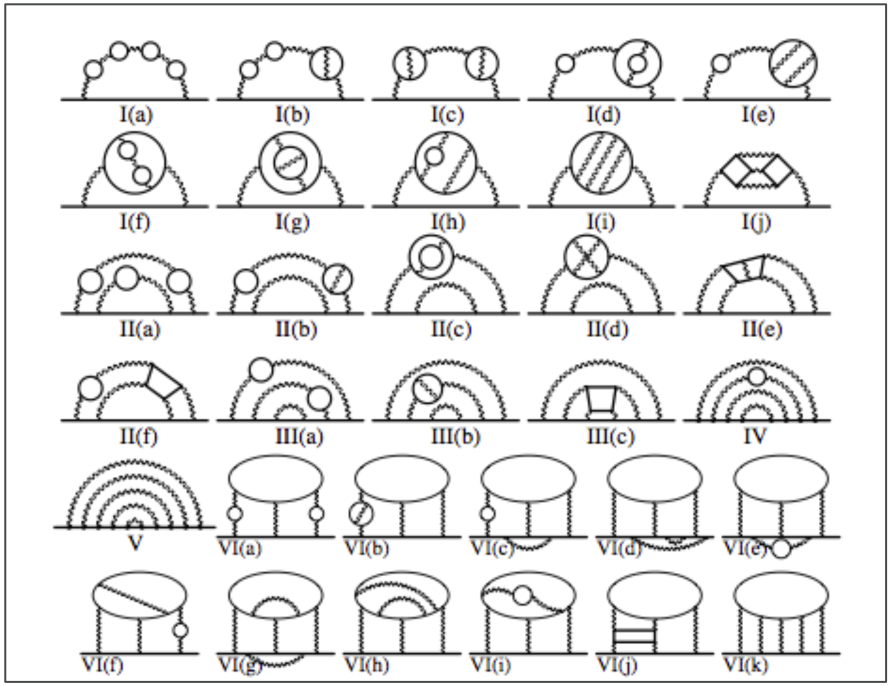


QED CONTRIBUTIONS WELL UNDER CONTROL BUT REQUIRE FINE STRUCTURE CONSTANT α



$$a_\mu^{\rm QED} = A_1 + A_2(m_\mu/m_e) + A_2(m_\mu/m_\tau) + A_3(m_\mu/m_e, m_\mu/m_\tau)$$

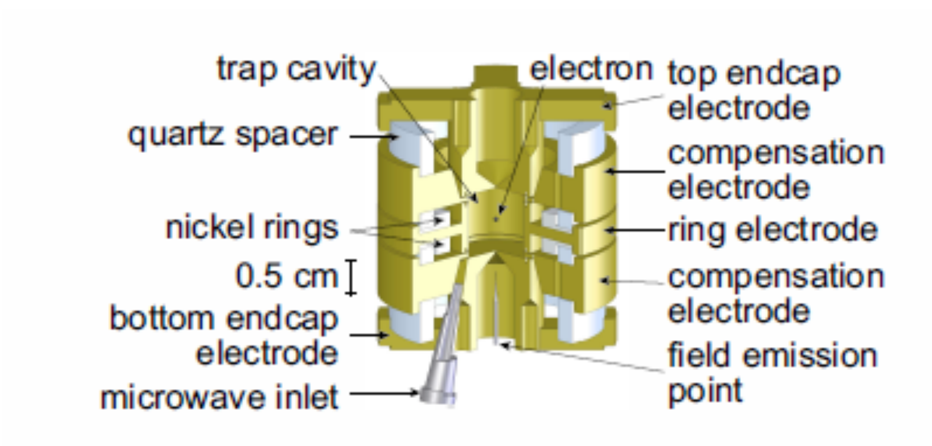
$$A_i = \left(\frac{\alpha}{\pi}\right)A_i^{(2)} + \left(\frac{\alpha}{\pi}\right)^2 A_i^{(4)} + \left(\frac{\alpha}{\pi}\right)^3 A_i^{(6)} + \cdots, \qquad \text{for } i = 1, 2, 3$$



T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, Phys. Rev. Lett. 109, 111808 (2012)

ELECTRON g-2 USED TO BE BEST MEASUREMENT FOR α

- One-electron quantum cyclotron gives measurement of $g_e/2$ with precision of 0.28 ppt
- For a long time this was the best measurement of the fine structure constant α with a precision of 0.37 ppb



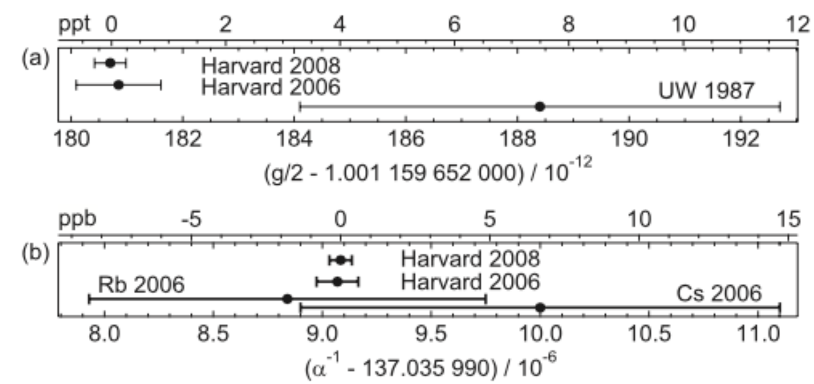


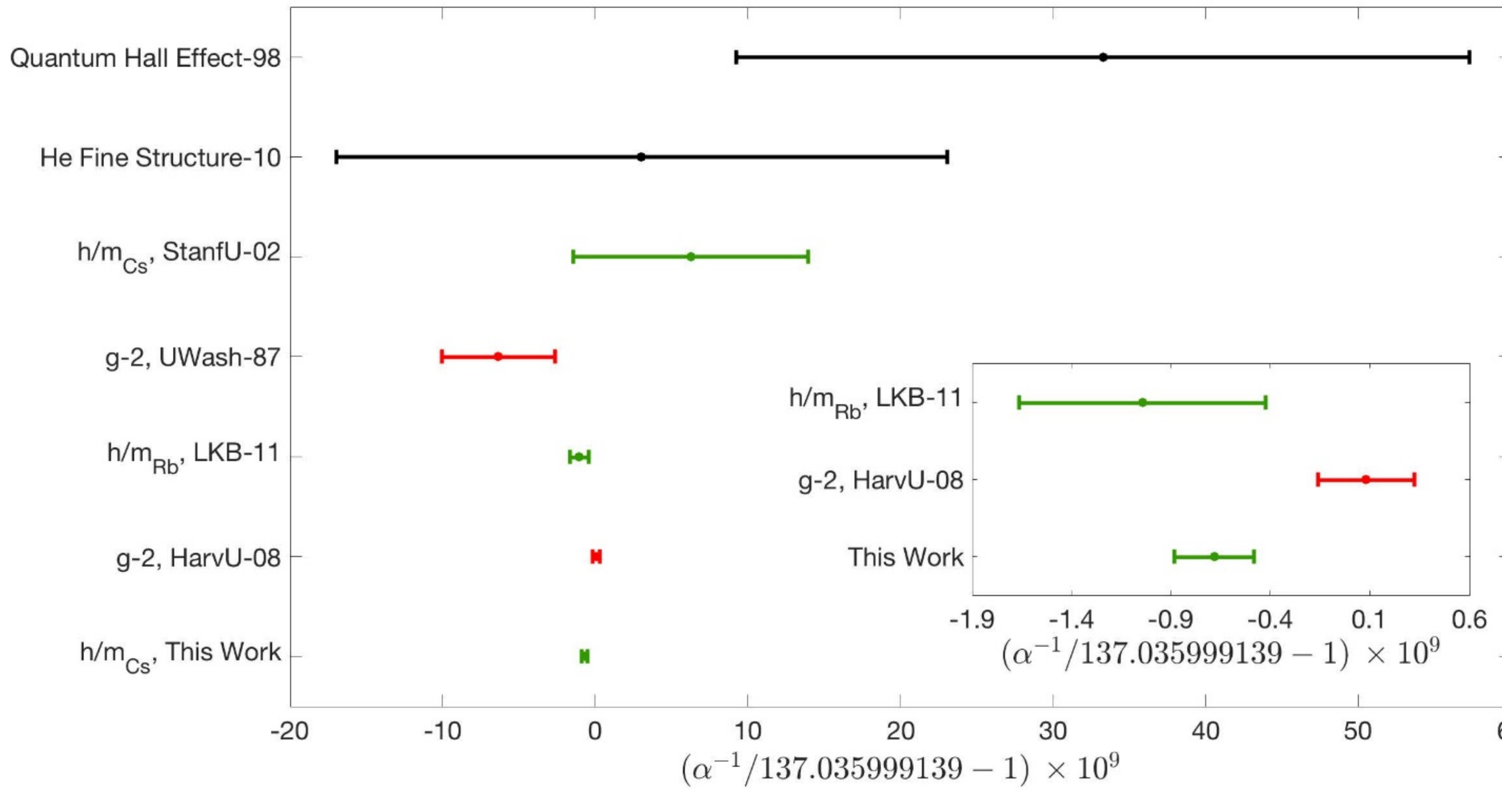
FIG. 1. Most accurate measurements of the electron $g/2$ (a), and most accurate determinations of α (b).

Hanneke et al. PRL 100 (2008) 120801

NEW ^{133}CS MEASUREMENT OF α [0.2 PPB]

- Matter-wave interferometer with laser pulses to direct and combine matter waves along their different trajectories
- Experiment measures h/m_{At}
- Rydberg R_∞ known to 0.6ppt
- Atom-to-electron mass ratio m_{At}/m_e known to <0.1ppb for many atoms
- 2.5σ tension with electron g-2

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{At}}{m_e}\frac{h}{m_{At}}$$

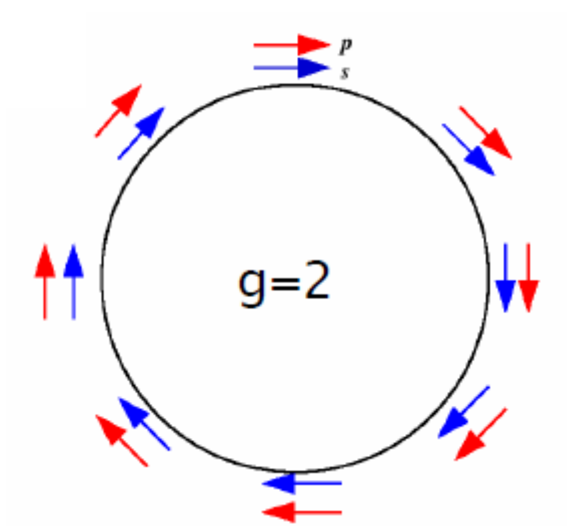


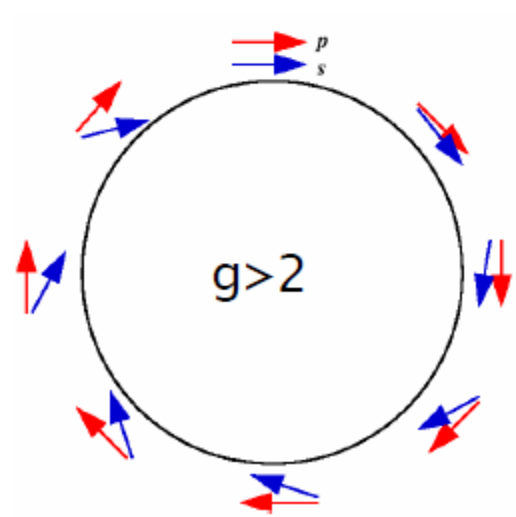
MUONS IN A STORAGE RING (NO E FIELD YET)

- Cyclotron frequency: $$\omega_c = \frac{e}{m\,\gamma} B$$
- Spin precession frequency: $$\omega_S = \frac{e}{m\,\gamma} B\,(1 + \gamma\; a_\mu)$$

Larmor + Thomas precession

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_c = \frac{e}{m}\left(a_\mu\,\vec{B}\,\right)$$





MUONS IN B AND E FIELD

- In presence of additional E-field (neglecting β·B and EDM terms):

$$\vec{\omega}_a = \frac{e}{m}\left(a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right)$$

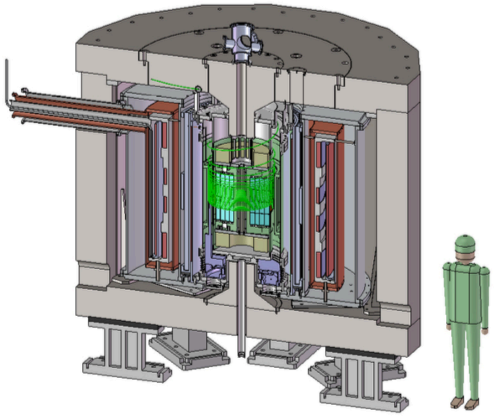
Magic momentum (γ = 29.3, p=3.094 GeV/c)
E field for vertical focusing
CERN-III, BNL E821, Fermilab E989

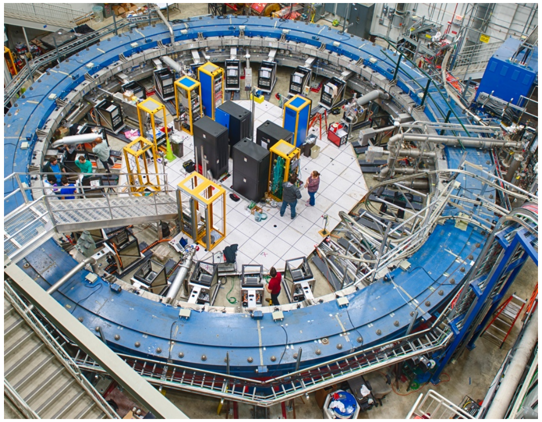
No E field: E = 0
Weak magnetic focusing
J-PARC E34

$$\omega_a = e/m\ a_\mu\ B$$

- Measuring the anomalous moment a_μ requires both
  1. the spin precession frequency ω_a
  2. the magnetic field **B**

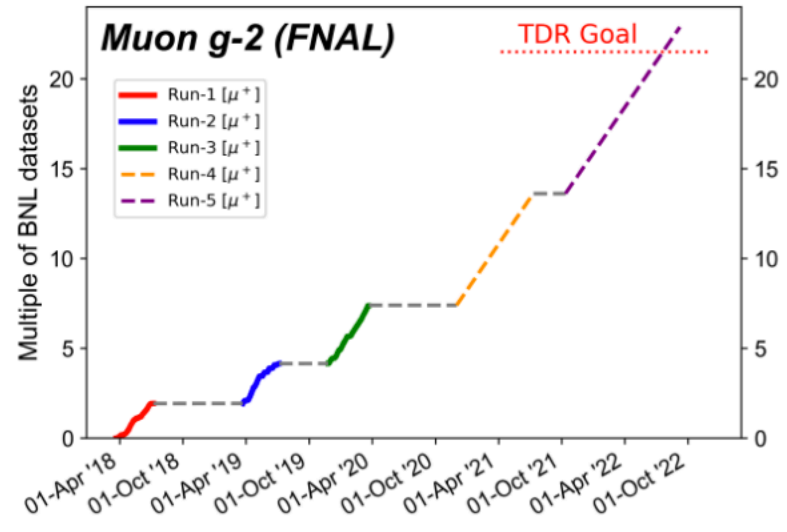
NEW g-2 EXPERIMENTS AIM AT ~140 PPB





	E34 @ JPARC	E989 @ Fermilab
Beam	High-rate, ultra-cold muon beam (p = 300 MeV/c)	High-rate, magic-momentum muons (p = 3.094 GeV/C)
Polarization	P_{max} = 50%	$P \approx$ 97%
Magnet	MRI-like solenoid ($r_{storage}$ = 33cm)	Storage ring (7m radius)
B-field	3 Tesla	1.45 Tesla
B-field gradients	Small gradients for focusing	Try to eliminate
E-field	None	Electrostatic quadrupole
Electron detector	Silicon vanes for tracking	Lead-fluoride calorimeter
B-field measurement	Continuous wave NMR	Pulsed NMR
Current sensitivity goal	~400 ppb (possibly 100 ppb)	140 ppb

MUON g-2 EXPERIMENTS STATUS AND OUTLOOK



- Fermilab Muon g-2 E989 experiment:
  - Ongoing experiment, Runs 1-3 completed
  - First result (~BNL precision) this year
  - Run 4 and 5 will proceed
  - Prospects beyond that:
    - μ^- run (also good for CPT/LV tests)
    - More dedicated muon EDM
- J-PARC E34 g-2/EDM experiment:
  - A lot of ongoing R&D, not fully funded yet
  - Data taking maybe in a few years
  - One limitation is the muonium source (interest for other measurements)
- Muon g-2 theory:
  - Theory initiative will continue
  - Progress especially with LatticeQCD expected
  - Could bring us to 10σ with improved Muon g-2 experimental precision

ANTIHYDROGEN EXPERIMENTS

OVERVIEW

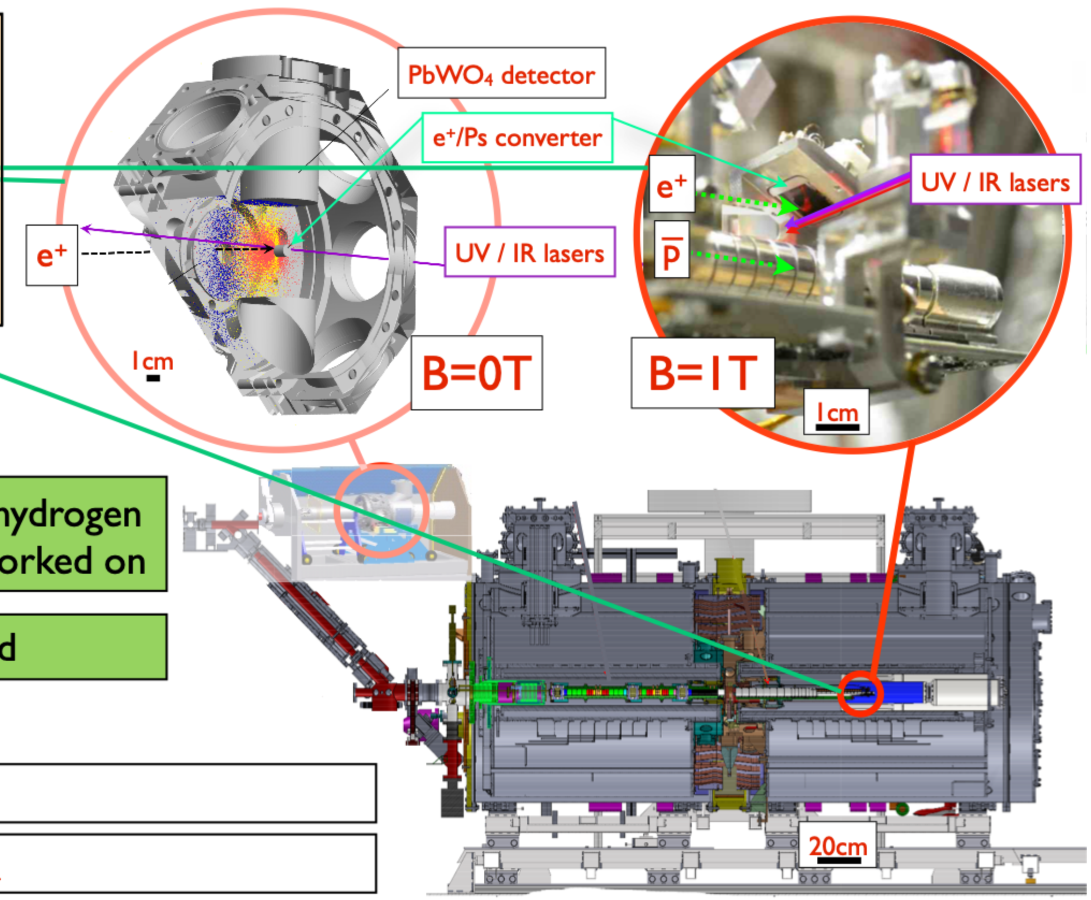
- Experiments with anti-protons at CERN aim to study:
  - Hyperfine structure of antihydrogen (ASACUSA, ALPHA) and antiprotonic helium (ASACUSA) with spectroscopy
  - Basic properties of the anti-proton (BASE)
  - Gravitational effects on antimatter (GBAR, AEgIS, ALPHA-g)
- These experiments offer:
  - Tests of fundamental symmetries such as CPT
  - Searches for physics beyond the Standard Model
- The community does currently have small US involvement, which could be an opportunity for the future
- Experimental details were provided from collaborators of those experiments

AE$\bar{g}$IS: pulsed production of $\overline{H}$, Ps, ... for: tests of WEP, fundamental symmetries, interactions

2018: $Ps^* + \bar{p} \rightarrow \overline{H}^* + e^-$

pulsed production ($\sigma_t^{form} \sim 100$ ns) of antihydrogen achieved; rate increase by $O(10^3)$ being worked on

pulsed beam of 2^3S metastable Ps achieved

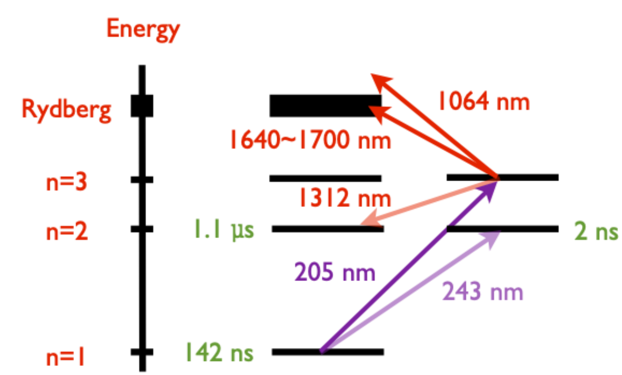


ongoing work on / towards :

- $\overline{H}$ pulsed beam formation
- Gravity measurement with $\overline{H}$ pulsed beam
- enhanced 2^3S production,
  formation of "intense" metastable Ps beam for inertial sensing
  laser-cooling of o-Ps
- laser-cooling of anionic molecule C_2^- (sympathetic cooling of $\bar{p}$)

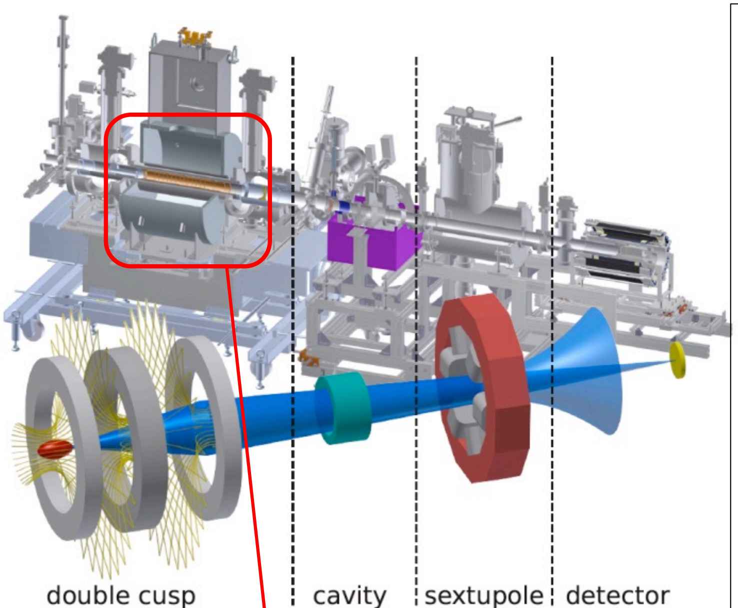
possible future systems:

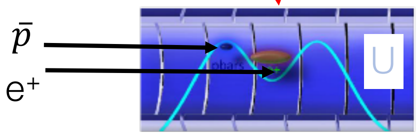
- pulsed formation of $\bar{p}p$, antiprotonic atoms, antiprotonic molecules



ASACUSA – ANTIHYDROGEN

In-beam hyperfine spectroscopy of antihydrogen





$\bar{H}$ formation in Nested Penning trap

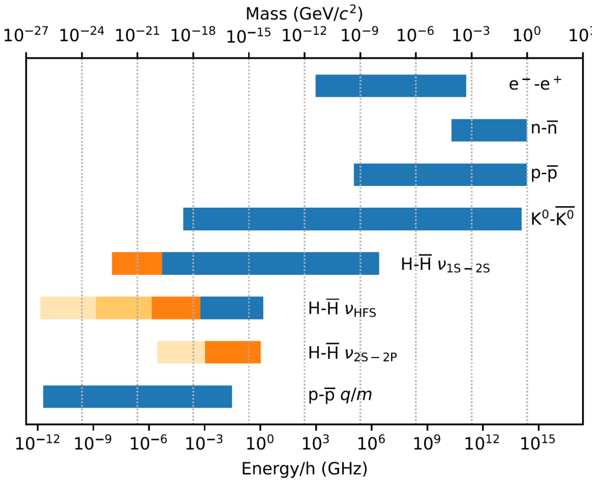
Status

- 2010 $\bar{H}$ formed
- 2014 $\bar{H}$ beam observed
- 2016 H spectroscopy in same apparatus to 2.7 ppb
- 2017 $\bar{H}$ beam quantum state distribution

Goal

- 1 ppm by Rabi spectroscopy
- x10–30 by Ramsey spectroscopy

Comparison of CPT tests



Blue – measured
Orange – next phases
Light yellow – value for hydrogen

*E. Widmann et al., Hyperfine Interact (2019) 240: 5. doi:*10.1007/s10751-018-1536-9

Slide from Eberhard Widmann

QIS EXPERIMENTS

OVERVIEW

- This topical group should also cover:
  - QIS: quantum coherence at e^+e^- machines as a tool to study fundamental parameters
  - QIS: quantum mechanics tests at e^+e^- and hadronic machines
- We reached out to a few people in this field and other Snowmass conveners that have QIS topics.
- Not yet any feedback or interest from the community
- If you or someone you know is interested in activities in these areas, please let us know or submit an LOI

TOPICAL GROUP CLOSING REMARKS

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OVERALL SUMMARY

- Tests of fundamental symmetries (P, CP, CPT,...) offer a vibrant program for the next decade:
  - EDMs will be a strong part of the next decades research program, especially with new prospects of storage ring EDMs
  - Magnetic dipole moments (electron, muon) remain also have research timelines that span the next decade; the first Muon g-2 result might help to clarify the path forward
  - Parity violation program (at JLab) will continue for many years
  - Antihydrogen experiments will continue to make progress at their two main focus areas (precision spectroscopy, antigravity)

TOPICAL GROUP WORKSHOPS AND COMMUNICATION

- Workshops planned / in consideration
  - **Dipole Moment workshop** in **September**
  - A workshop covering the other main topics (P-violation experiments, antihydrogen) might depend on community feedback / interest / LOIs
  - **Workshop** to discuss use of the **Muon g-2 storage ring and that muon campus building** in the future will be held ~**March 2021:**

- Please sign up for our communication channels:
  - Email list: **SNOWMASS-RPF-03-FUNDAMENTL-SMALL@FNAL.GOV**
  - Slack channel: **#rpf-03-fundamental-small**

- Please submit LOIs and contributed papers.

- Remember this is a commYOUnity event!

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