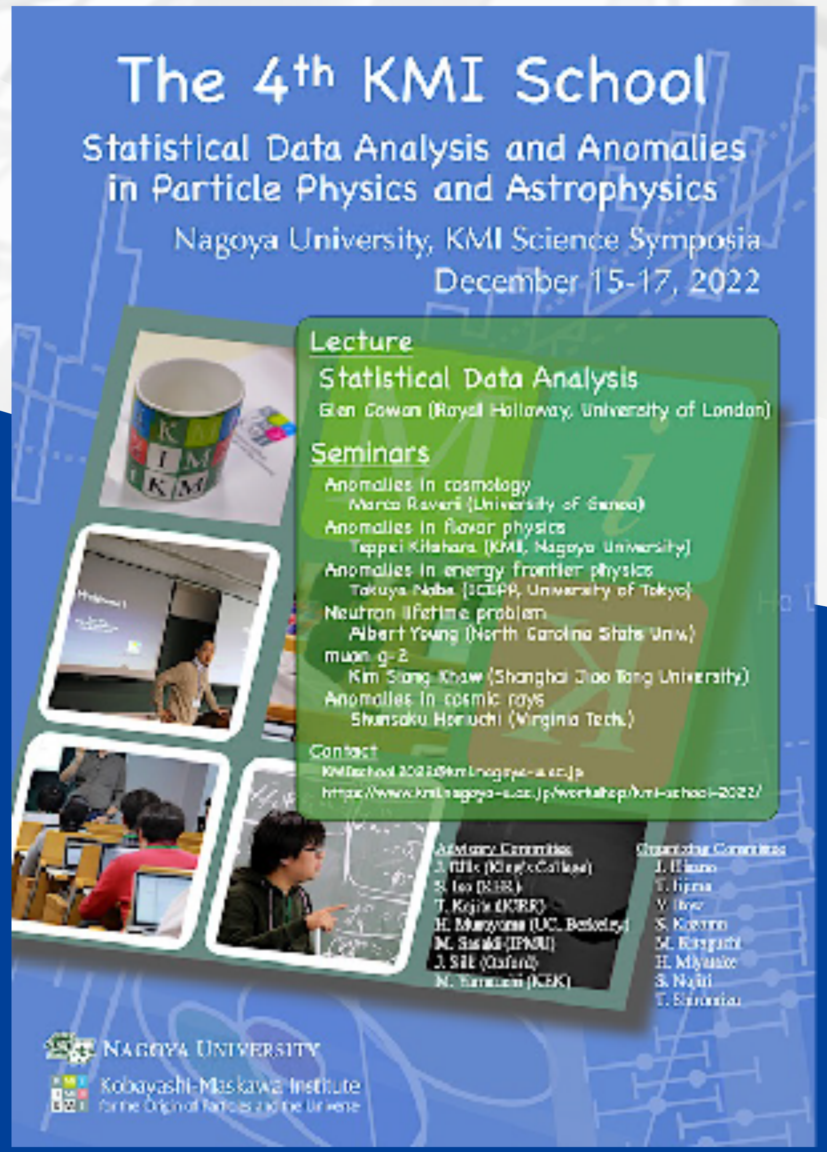
The Fermilab Muon g-2 experiment

Kim Siang Khaw

The 4th KMI School, KMI, Nagoya University

2022.12.15



The 4th KMI School

Statistical Data Analysis and Anomalies in Particle Physics and Astrophysics

Nagoya University, KMI Science Symposia

December 15-17, 2022

Lecture

Statistical Data Analysis

Glen Cowan (Royal Holloway, University of London)

Seminars

Anomalies in cosmology

Marco Raveri (University of Genoa)

Anomalies in flavor physics

Teppei Kitahara (KMI, Nagoya University)

Anomalies in energy frontier physics

Takuya Nobe (ICEPP, University of Tokyo)

Neutron lifetime problem

Albert Young (North Carolina State Univ.)

muon g-2

Kim Siang Khaw (Shanghai Jiao Tong University)

Anomalies in cosmic rays

Shunsaku Horiuchi (Virginia Tech.)

Contact

KMIschool 2022@kmi.nagoya-u.ac.jp

https://www.kmi.nagoya-u.ac.jp/workshop/kmi-school-2022/

Advisory Committee

Organizing Committee

Nagoya University

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

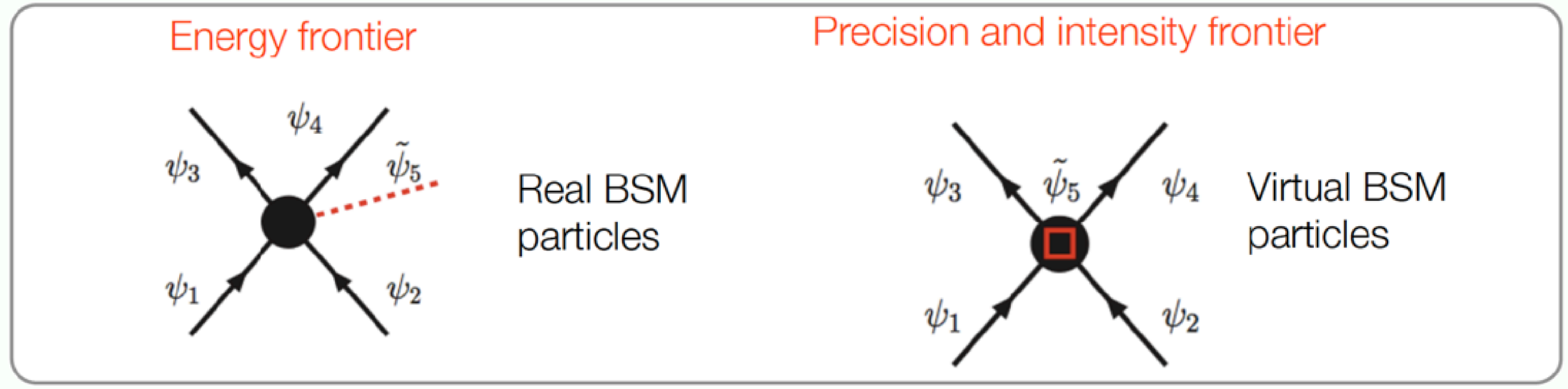
李政道研究所

TSUNG-DAO LEE INSTITUTE

Homepage: http://web.tdli.sjtu.edu.cn/kimsiang84/
Email: kimsiang84@sjtu.edu.cn
A recent review on muon g-2: Nucl. Phys. B 975 (2022) 115675

Probing BSM with muons

- Muon is a very sensitive probe for BSM physics
- The Muon Trio in Precision and Intensity Frontiers
  - *g-2, EDM, charged lepton flavor violation (cLFV)*


Energy frontier

Precision and intensity frontier

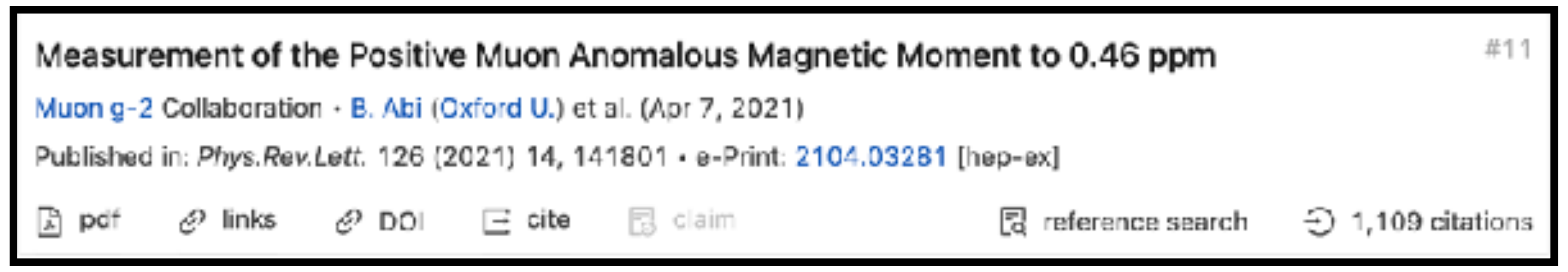
Real BSM particles

Virtual BSM particles

Unveil new physics

Probe energy scale otherwise unreachable E > 1000 TeV

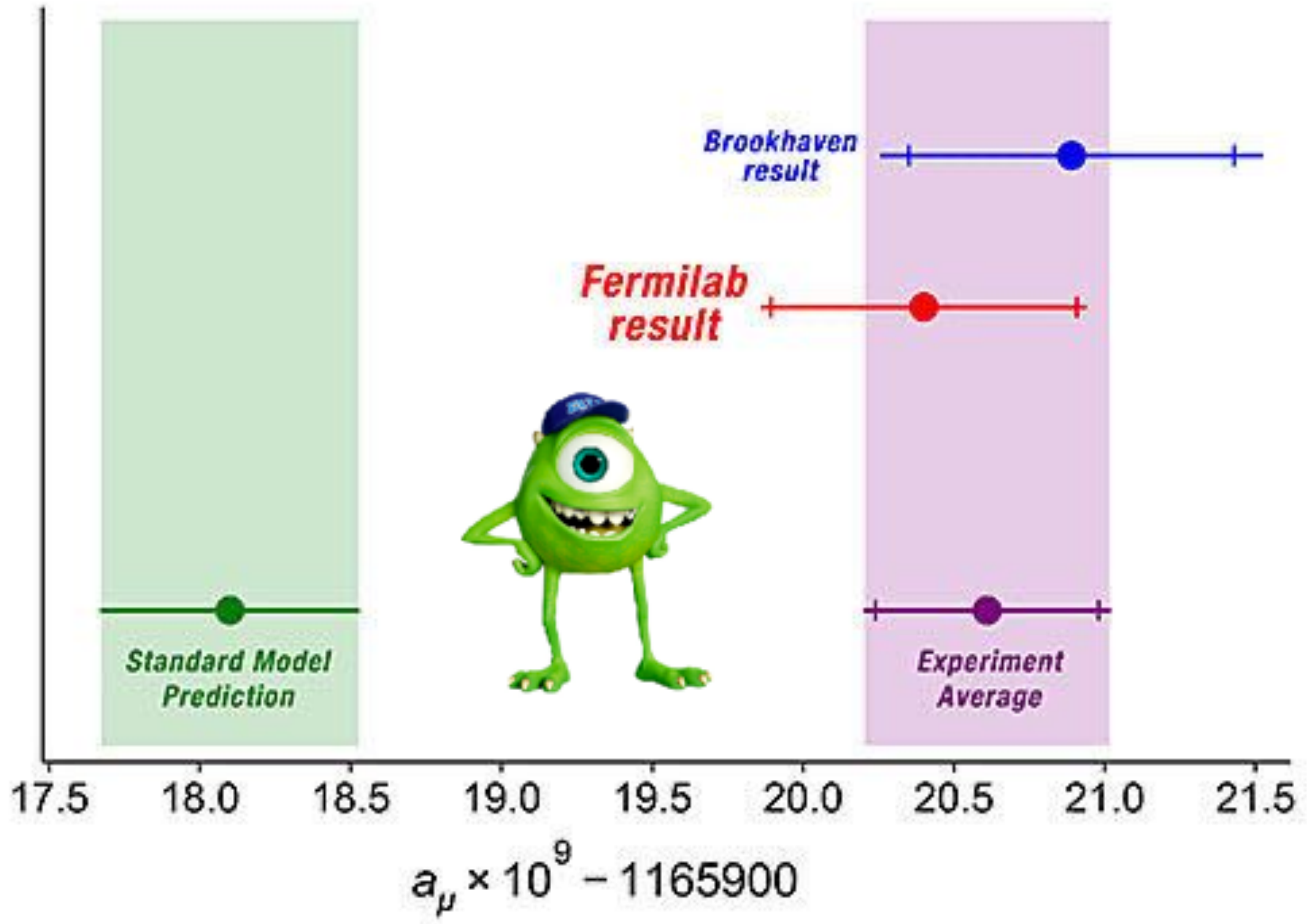
Apr 7, 2021

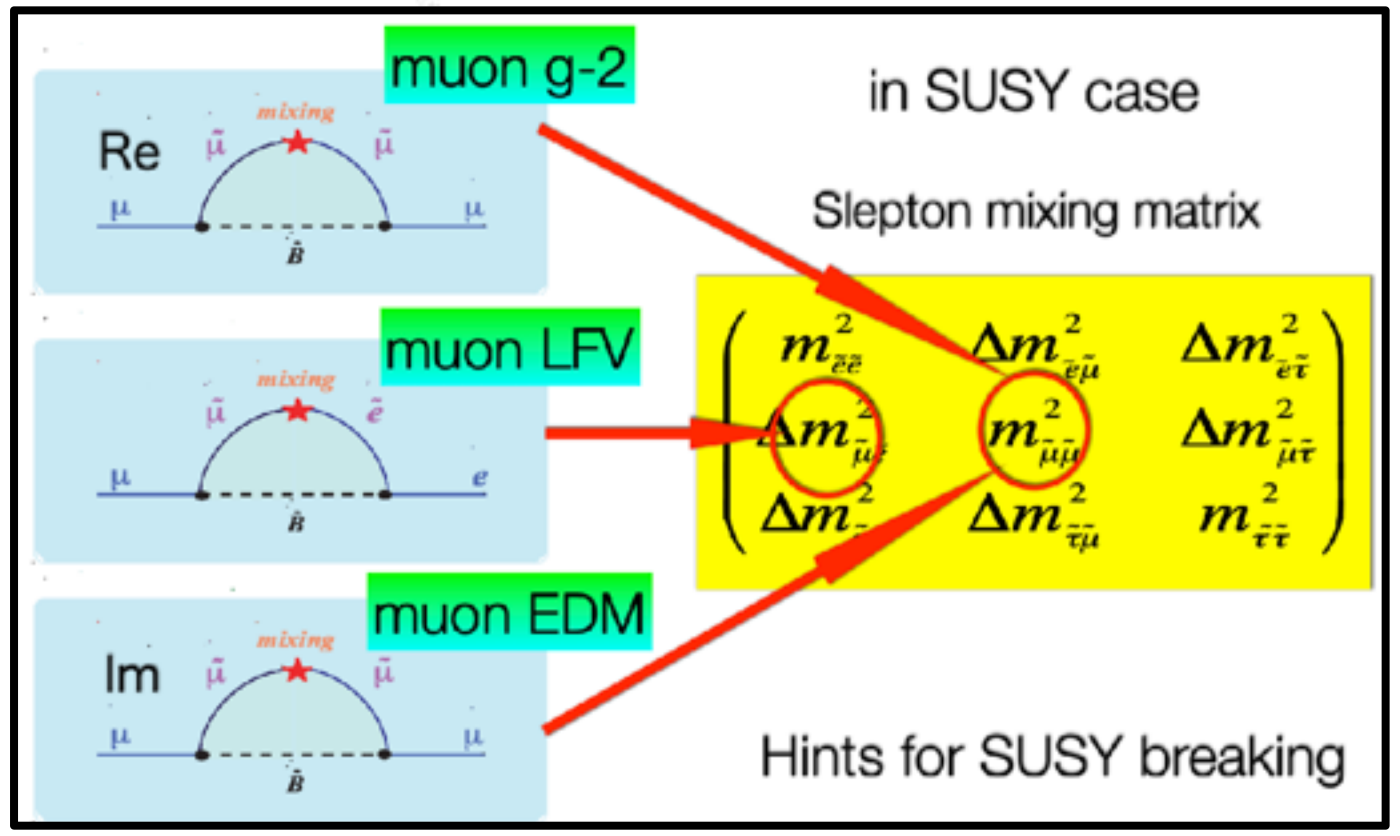


Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm #11

Muon g-2 Collaboration • B. Abi (Oxford U.) et al. (Apr 7, 2021)

Published in: *Phys.Rev.Lett.* 126 (2021) 14, 141801 • e-Print: 2104.03281 [hep-ex]





muon g-2

muon LFV

muon EDM

in SUSY case

Slepton mixing matrix

Hints for SUSY breaking

Courtesy Yoshitaka Kuno

Very active research area!

TRIUMF

TWIST, Mu studies

Fermilab

Muon g-2, Mu2e

Paul Scherrer Institut (PSI)

muEDM, MEG II, Mu3e, MUSE, CREMA, etc

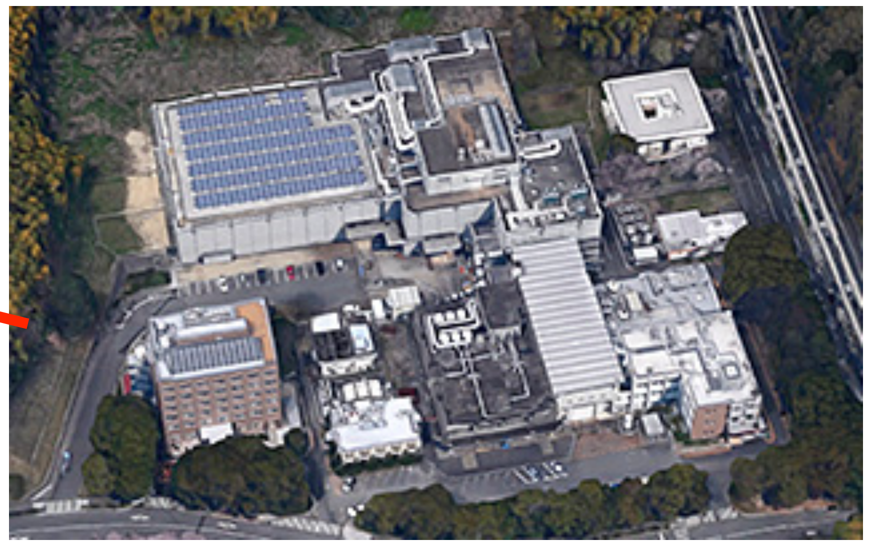
> 20 muon physics experiments!

HIAF/CiADS

Next generation muon g-2/EDM?

J-PARC

Muon g-2/EDM, COMET, DeeMe, Mu HFS/1S-2S, etc



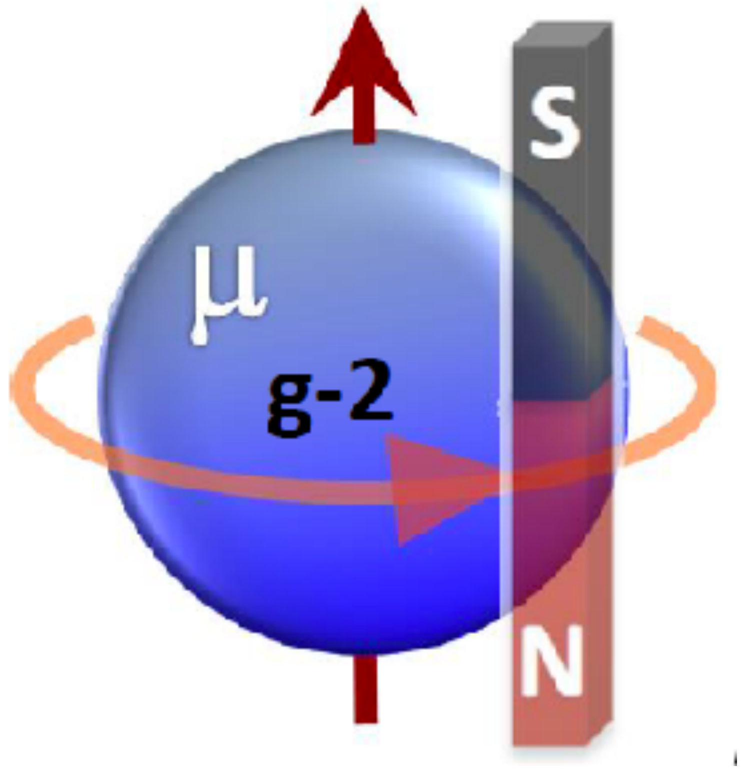
RCNP, Osaka

Muon Applications

CSNS

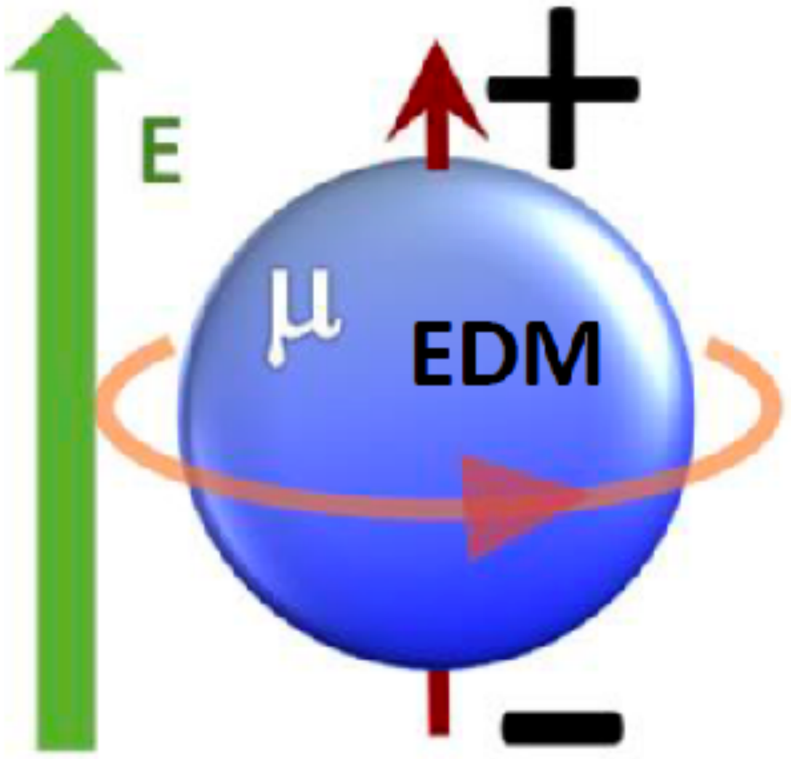
Applications, MACE

The Muon Moments: g-2 and EDM



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

- g-2 can be calculated and measured to very high precision
  - SM Theory: 370 ppb
  - Fermilab experiment: 460 ppb
- Precision test of SM calculations
  - Sensitive to 4-loop QED, QCD, and EW
- The difference between theoretical and experimental values probes BSM physics
  - Complementary to LHC searches



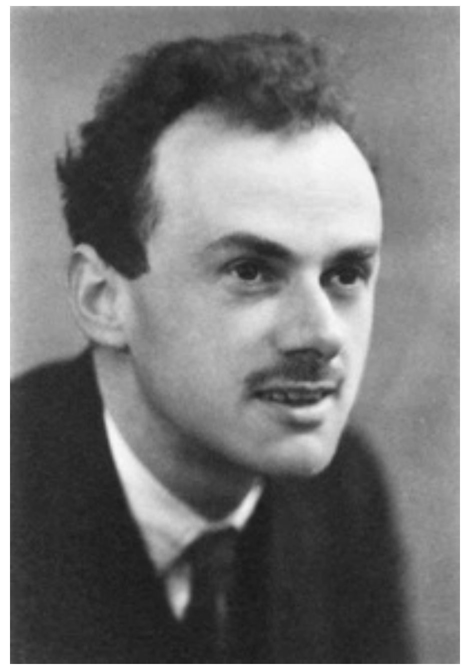
$$\vec{d} = \eta\frac{e}{2m}\vec{s}$$

- A search for new physics which is essentially “background-free”
  - The contribution from SM’s CKM matrix is too small (d ~ 10^{-42} e cm)
  - Current limit d ~ 10^{-19} e cm
- Many BSM models predict large EDMs
  - Complementary to LHC searches
- Baryon asymmetry in the universe (BAU) requires more CPV
  - EDMs are good probes of BSM CPV

History of g-2

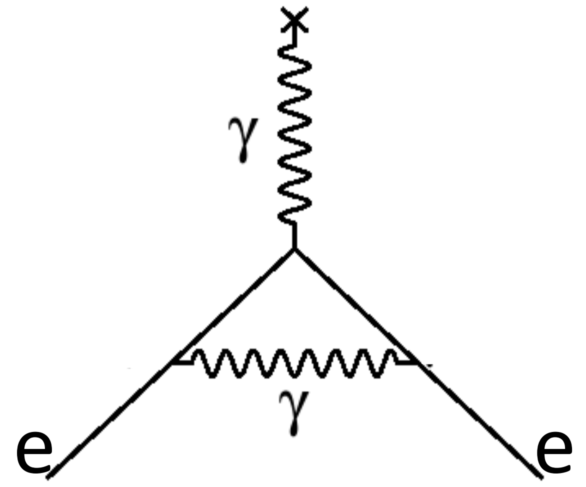
- g-factor relates spin to magnetic moment
  - Dirac's prediction (1928): $g_e = 2$

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



- Magnetic anomaly discovered in the electron (Kusch and Foley, 1948)
  - $g_e = 2.00238(6)$ by measuring atomic energy levels
- Julian Schwinger calculated g_e using quantum electrodynamics (QED)
  - QED one-loop correction gives

$$g_e \approx 2(1 + \frac{\alpha}{2\pi}) \approx 2.00232$$

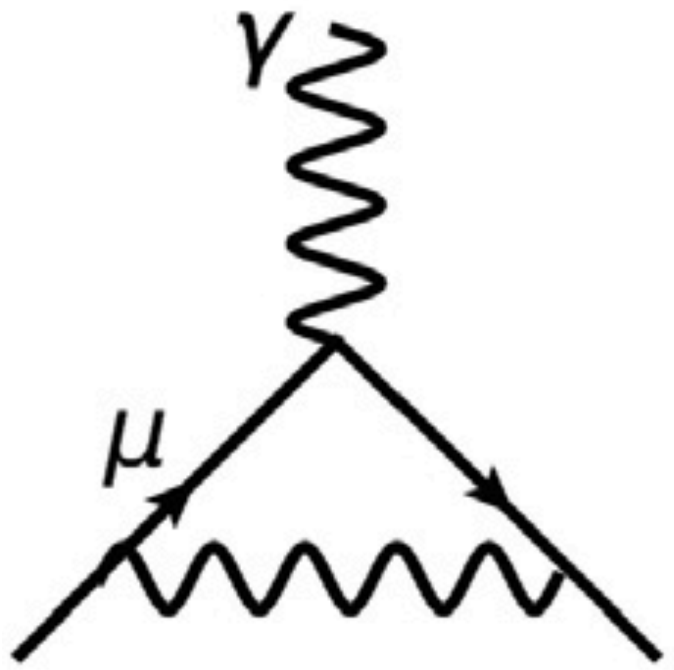


0.1% of g-factor

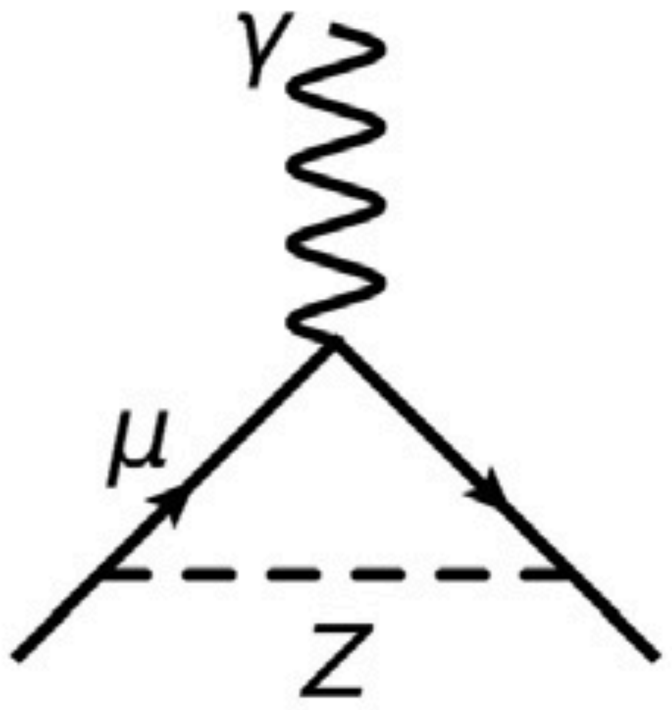
- Fractional deviation from Dirac's prediction is called magnetic anomaly

$$a = \frac{g-2}{2}$$

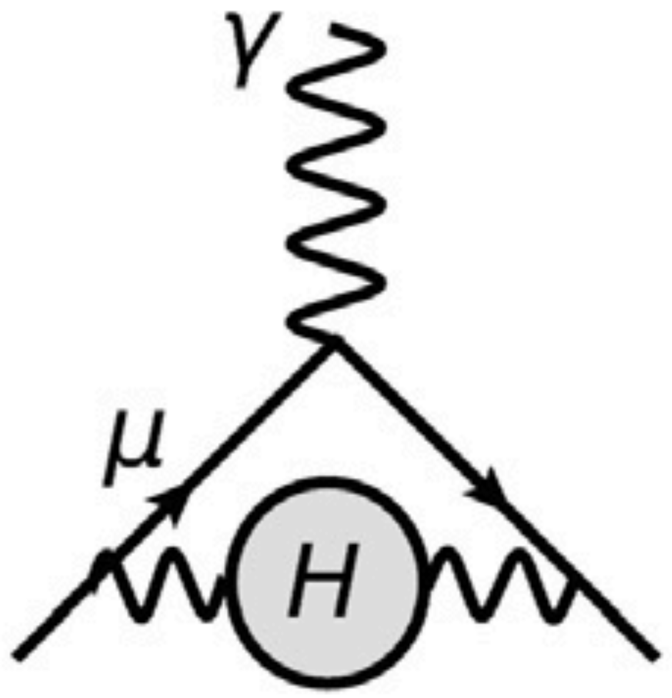
Standard Model Prediction of a_μ



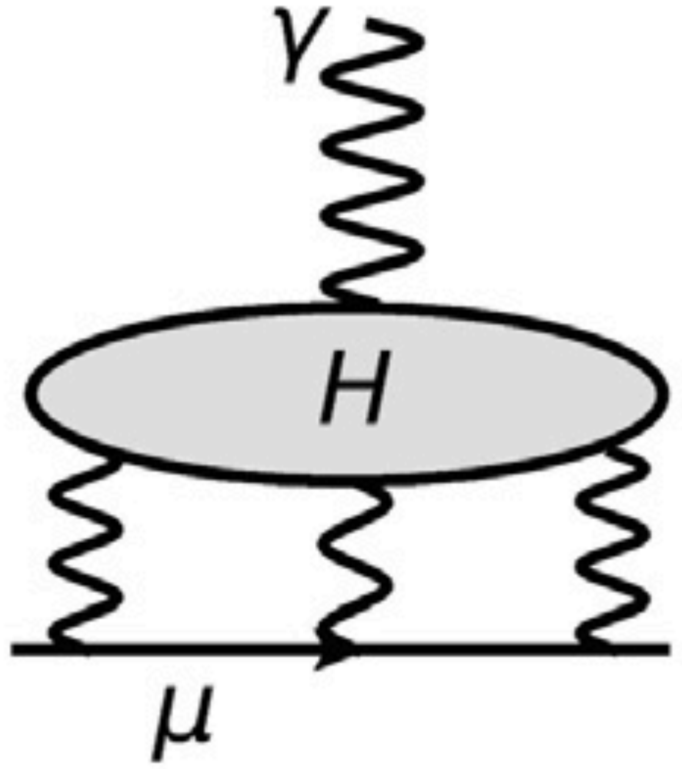
QED



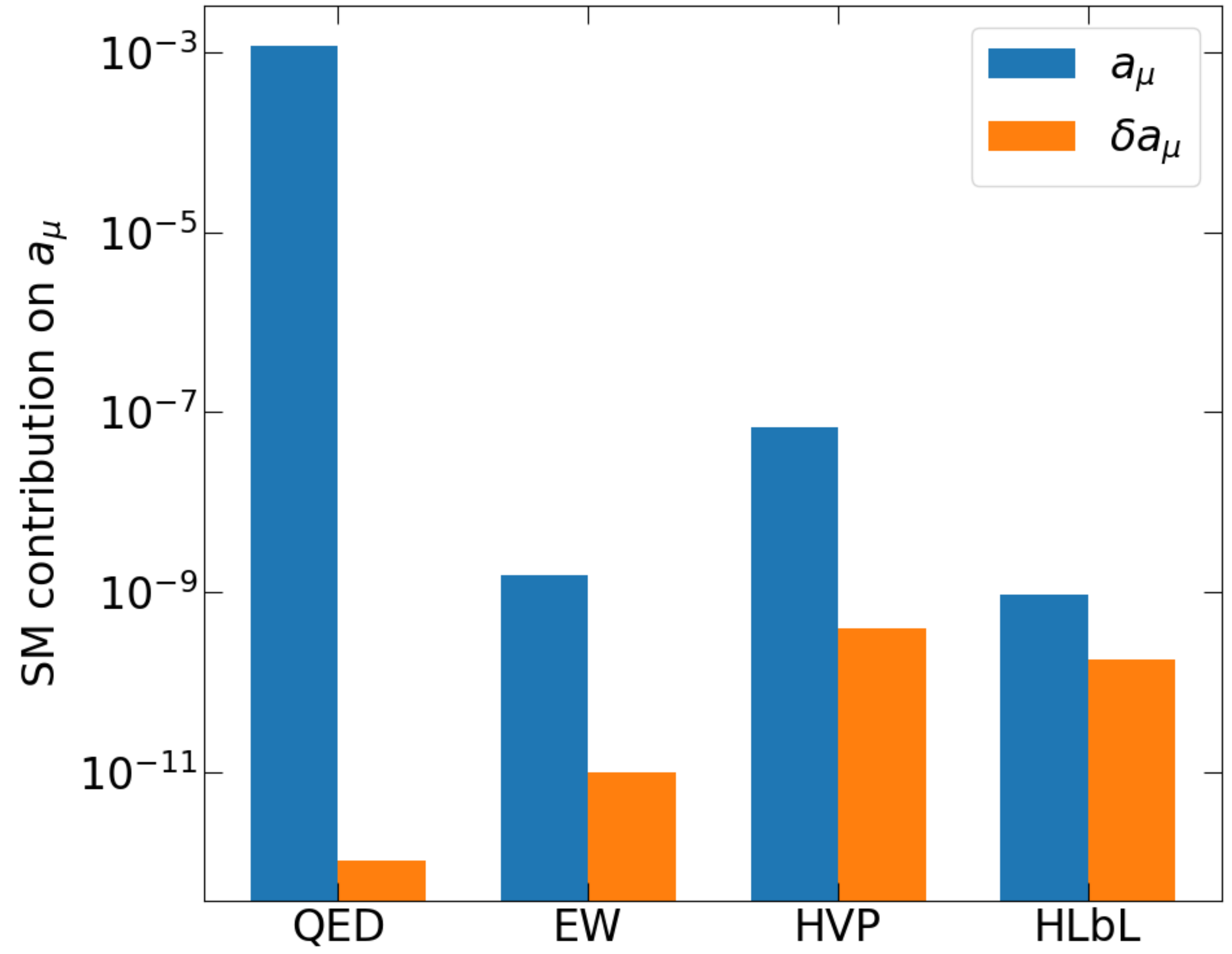
EW



HVP

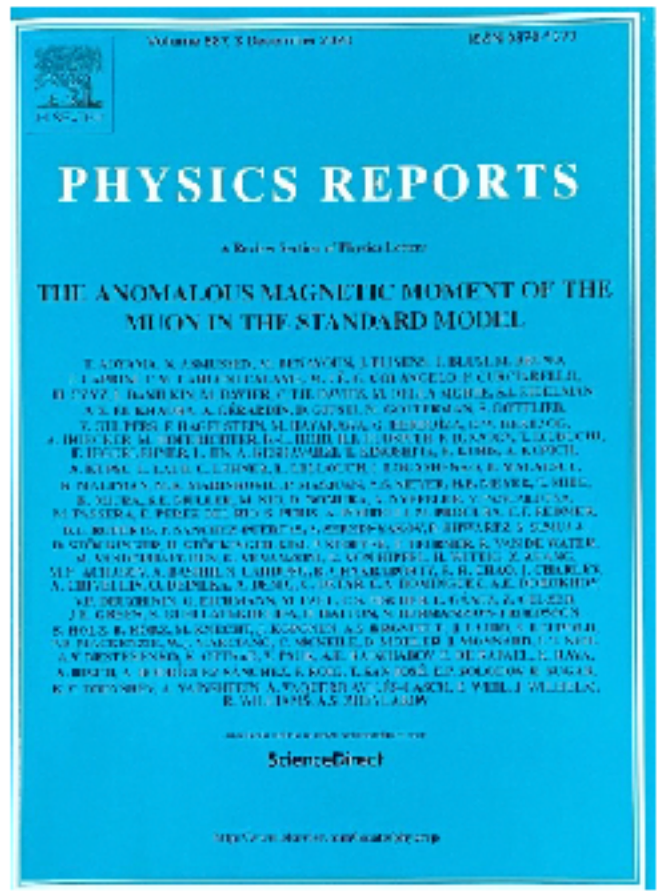


HLbL



$$a = \frac{g-2}{2}$$

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP, LO}} + a_\mu^{\text{HVP, NLO}} + a_\mu^{\text{HVP, NNLO}} + a_\mu^{\text{HLbL}} + a_\mu^{\text{HLbL, NLO}}$$
$$= 116\,591\,810(43) \times 10^{-11}$$ (370 ppb)



PHYSICS REPORTS

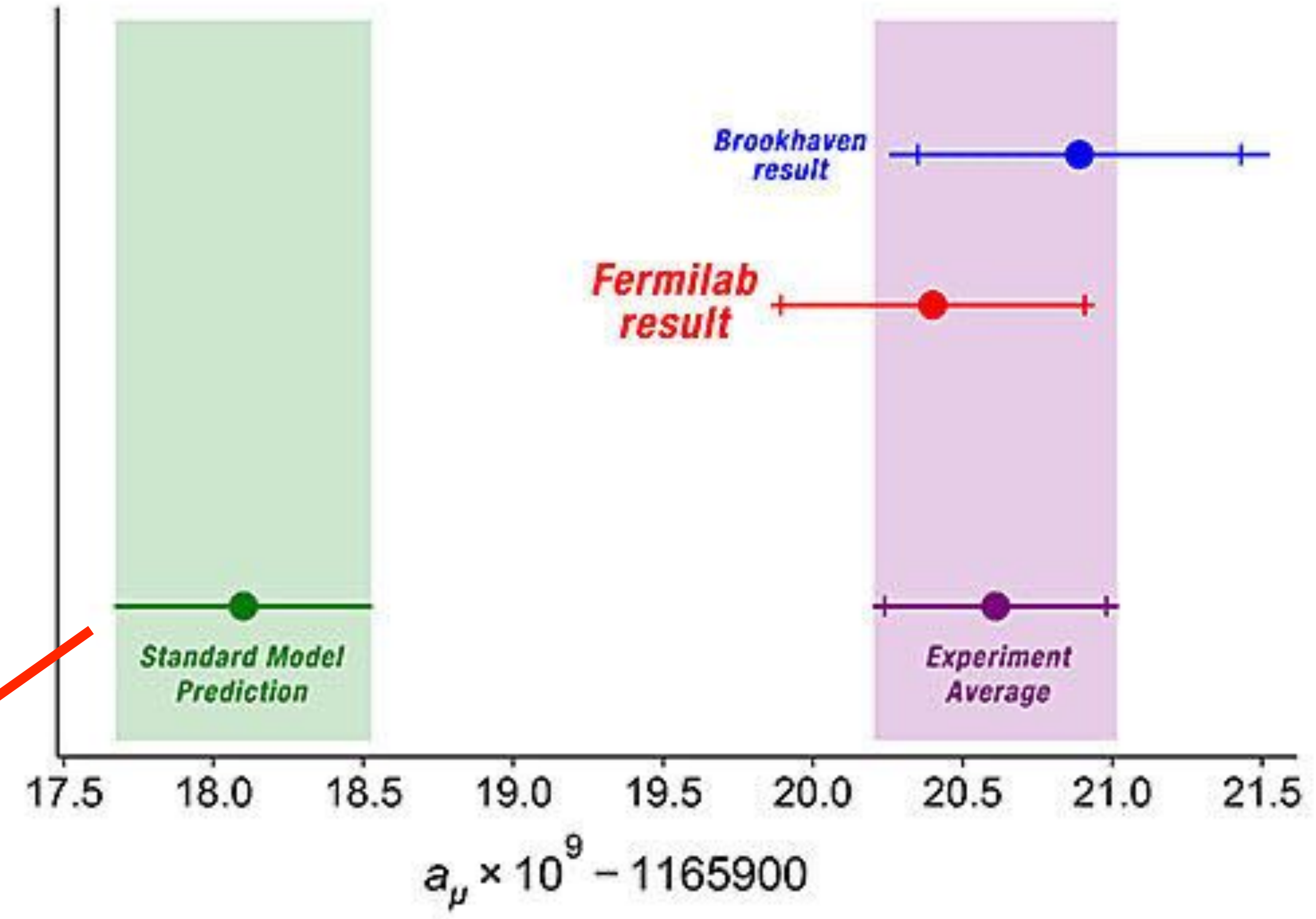
THE ANOMALOUS MAGNETIC MOMENT OF THE MUON IN THE STANDARD MODEL

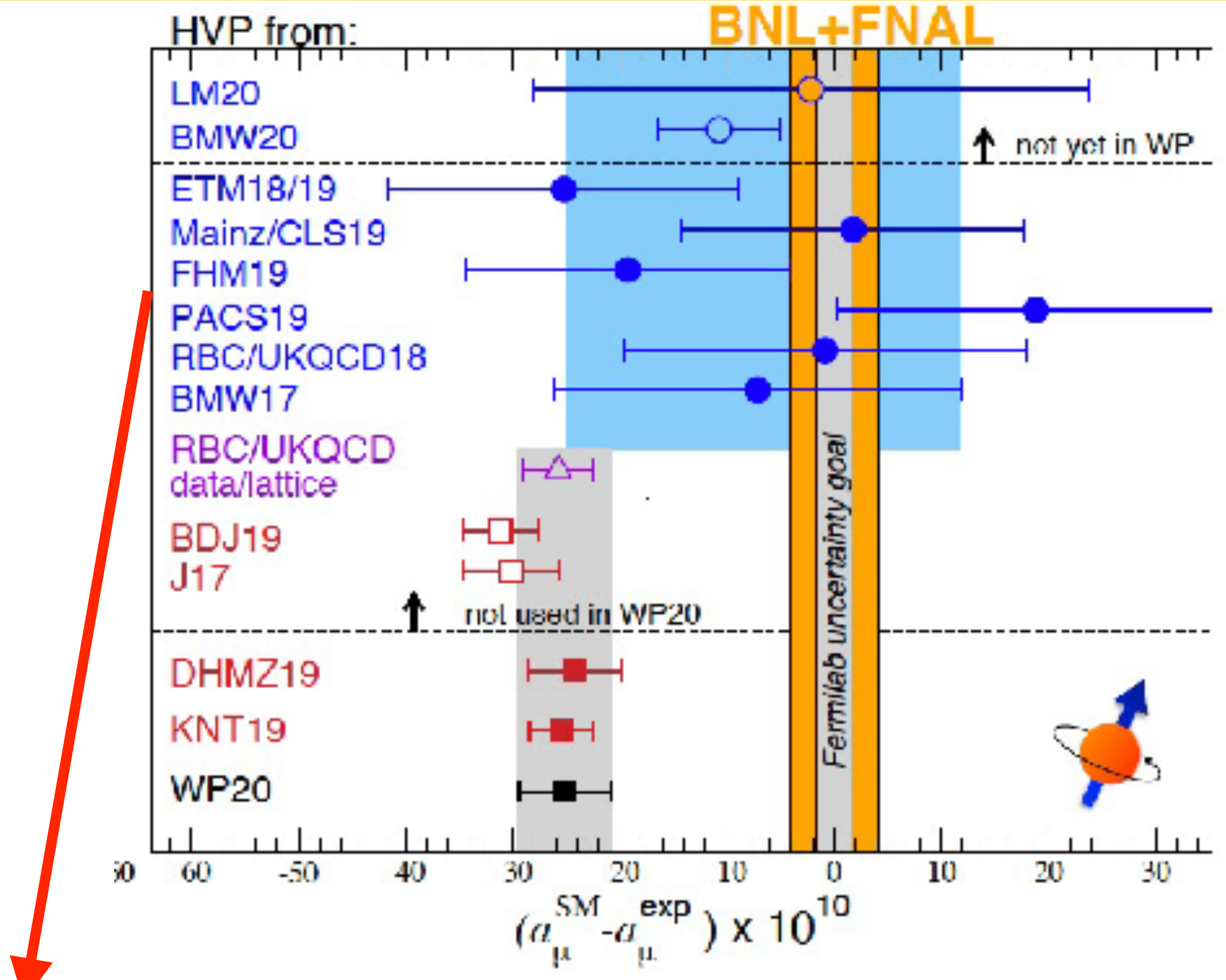
Theory Initiative White Paper: T. Aoyama et al. Phys. Rept. **887** (2020)

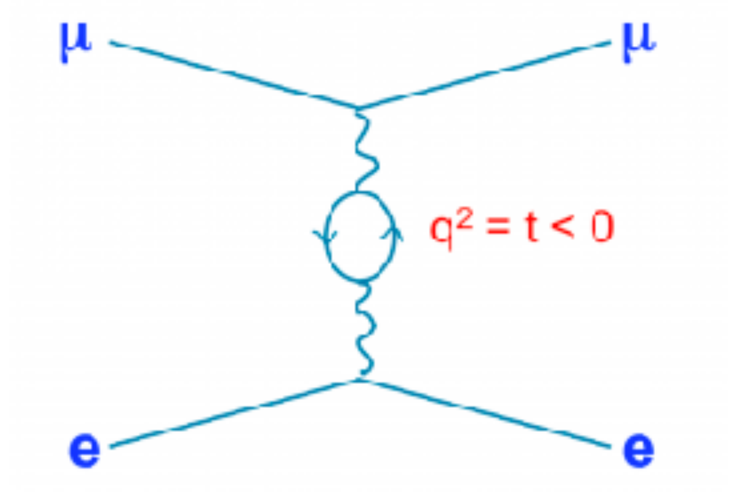
More on HVP contributions

Theory initiative: estimate of ~2025 to sort all this out

New results from CMD-3, BaBar, BES-III and Belle-II expected!

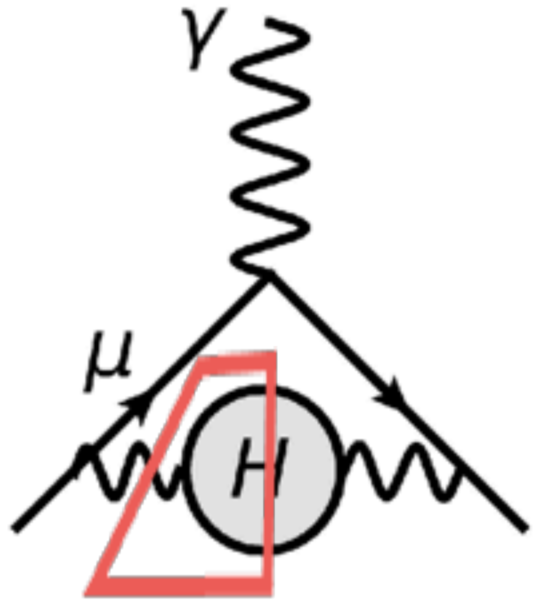


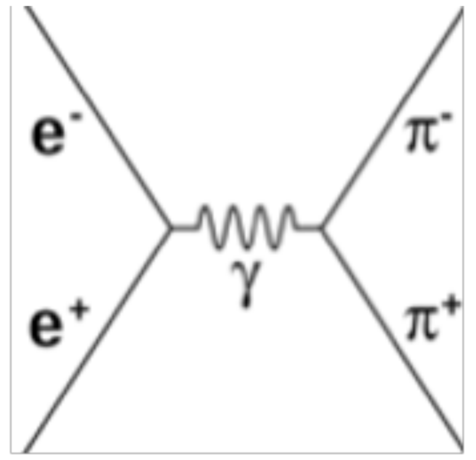




Very important cross check!
First run: 2022-2024

1) Dispersion relation + low energy e⁺e⁻ -> hadrons

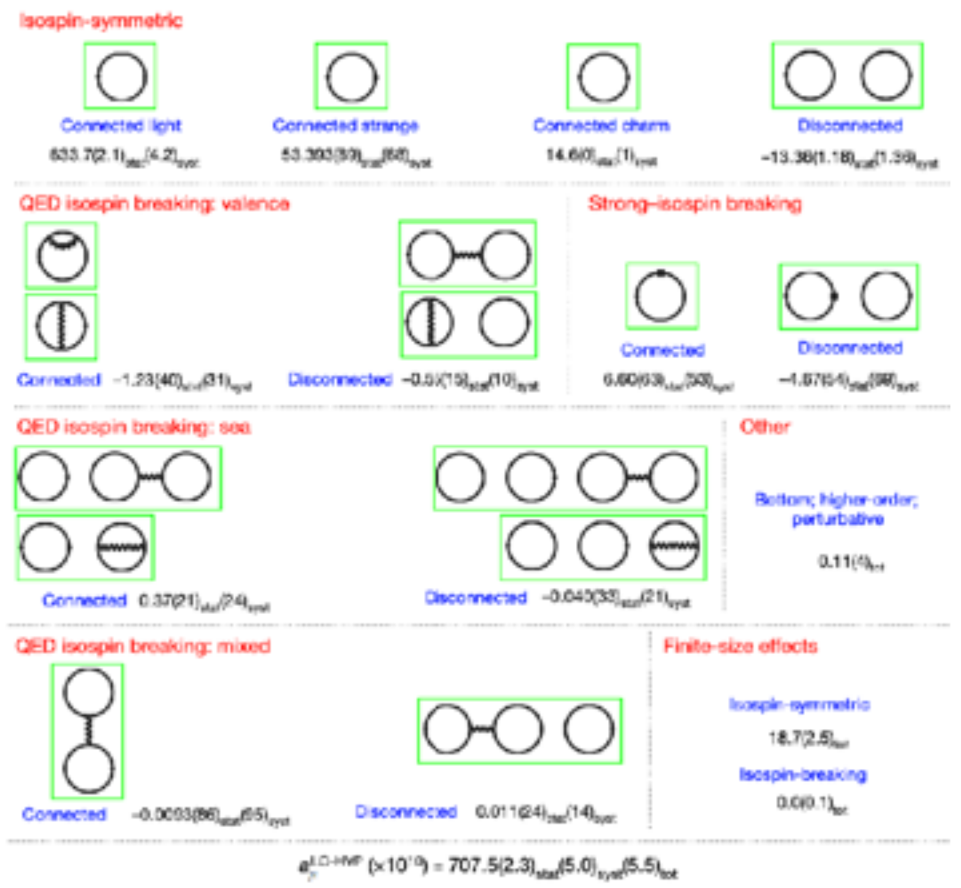




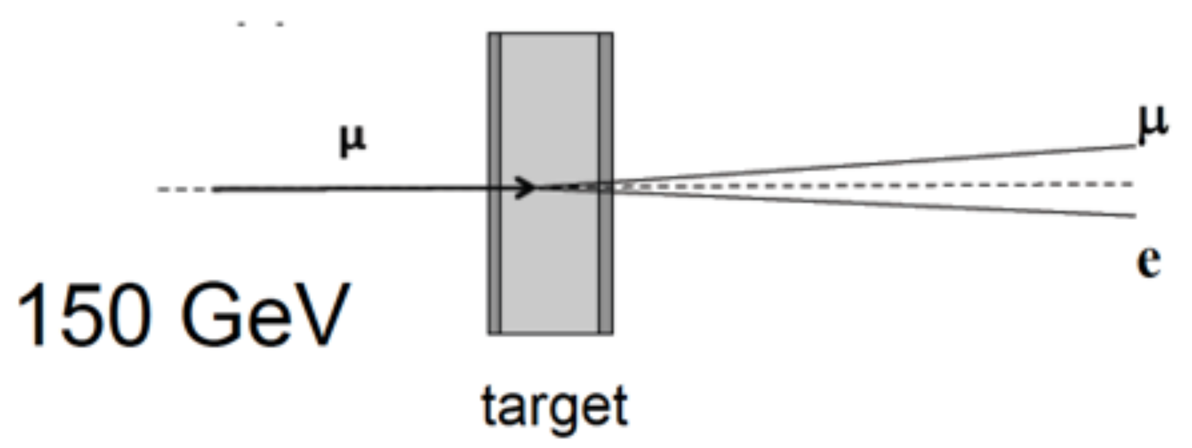
e⁺e⁻ to hadrons

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

2) Lattice QCD + supercomputers



3) Dispersion relation + muon scattering on electrons



Phys. Lett. B 746 (2015), 325

$$a_\mu^{HLO} = \frac{\alpha}{\pi} \int_0^1 dx\, (1-x) \cdot \Delta\alpha_{had}\left(-\frac{x^2 m_\mu^2}{1-x}\right)$$

The “first” muon g-2 experiment

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

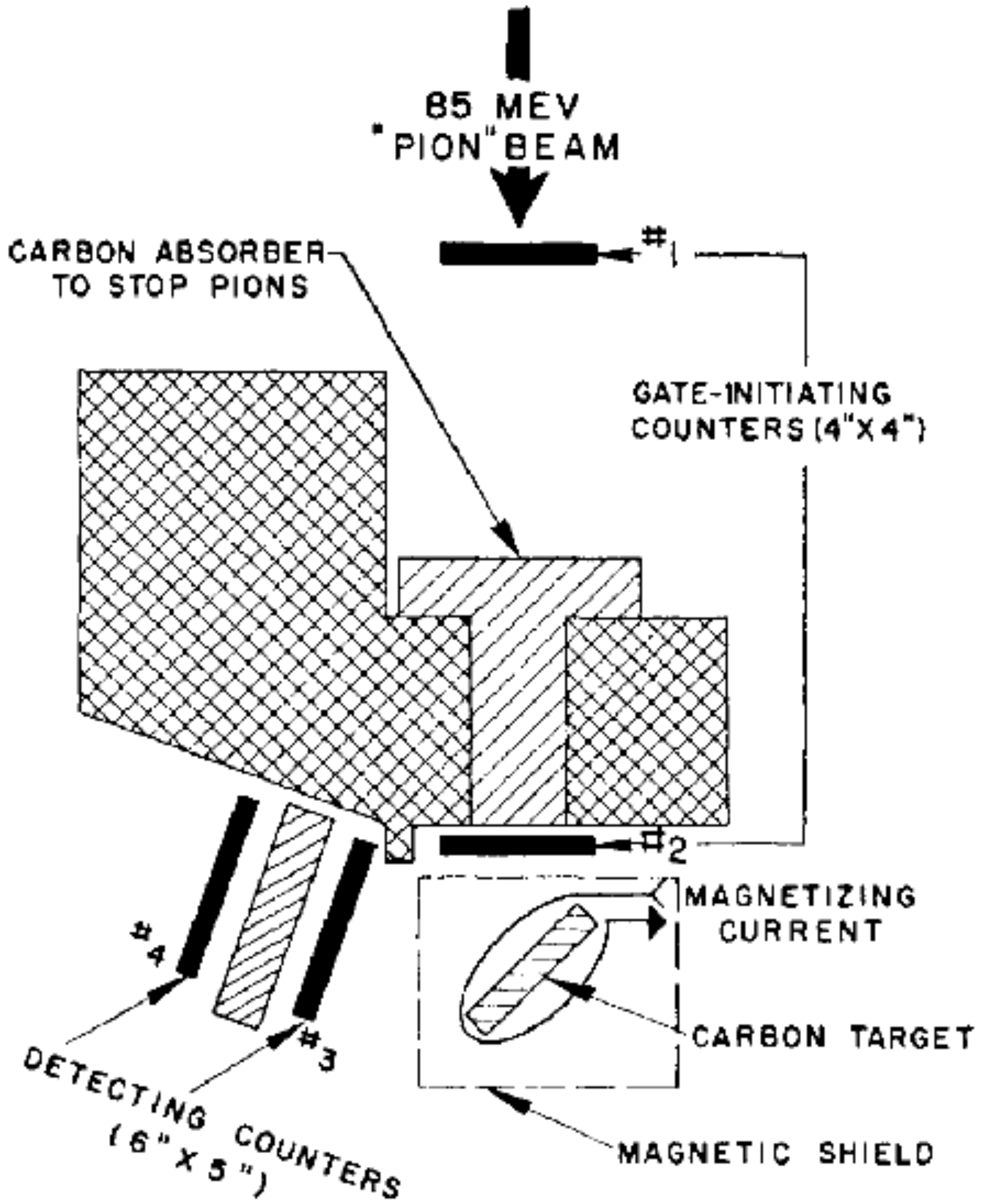
Richard L. Garwin,† Leon M. Lederman, and Marcel Weinrich
Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York

(Received January 15, 1957)

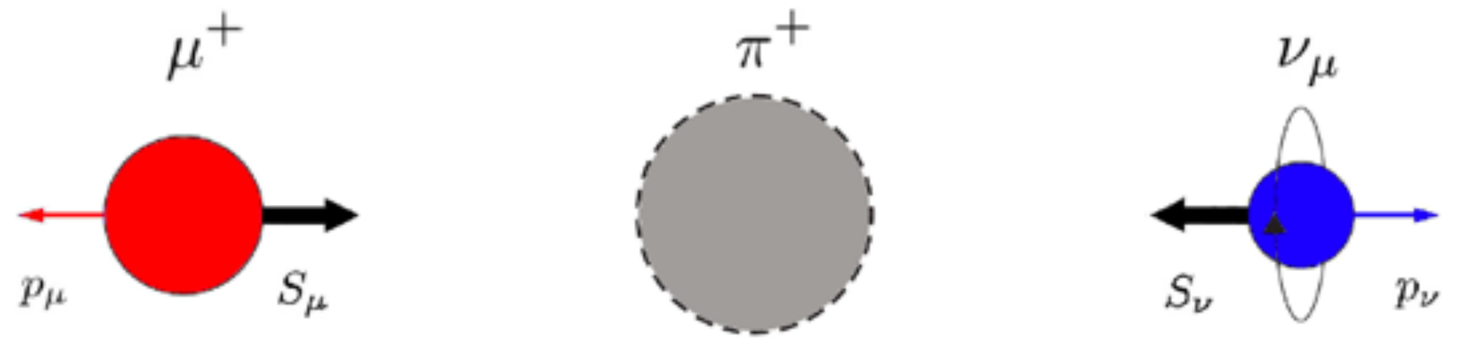
Lee and Yang[1–3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the “weak” interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+ \rightarrow \mu^+ + \nu, \quad (1)$$

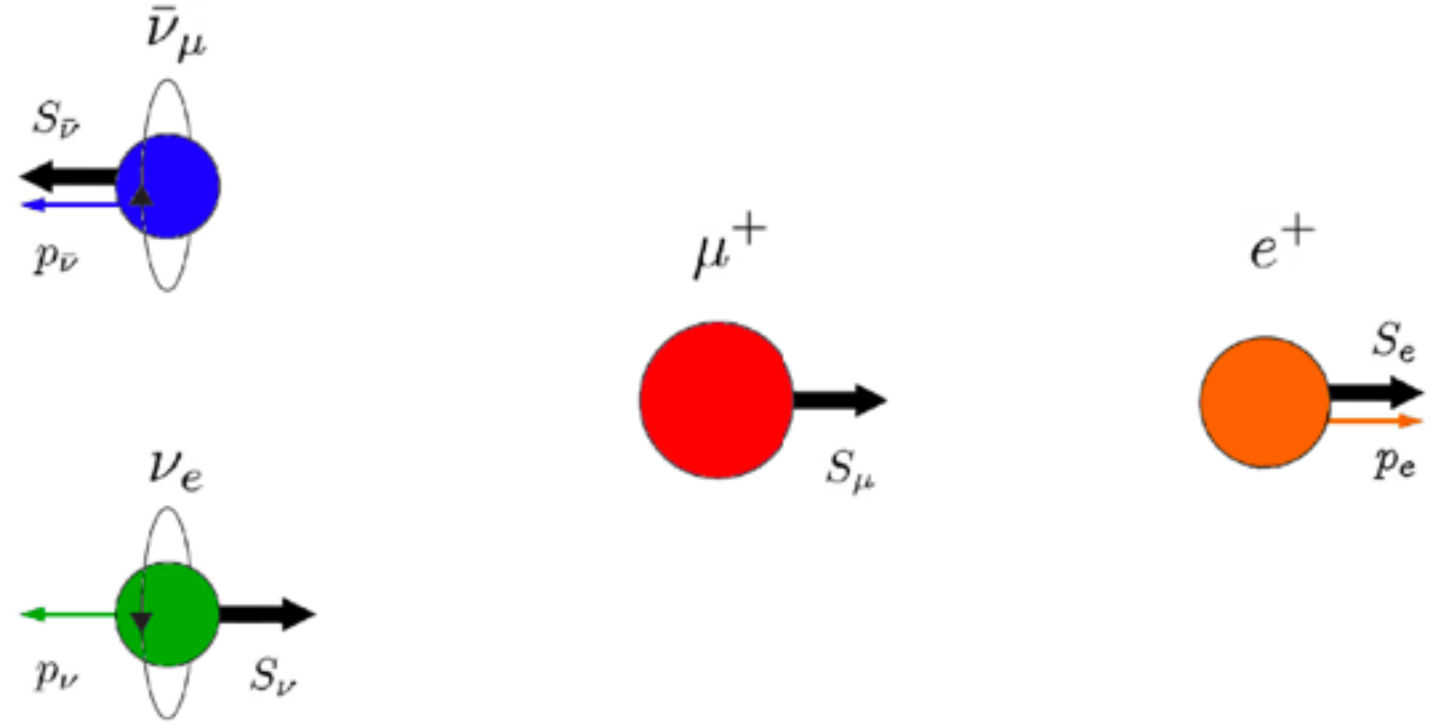
$$\mu^+ \rightarrow e^+ + 2\nu. \quad (2)$$



Pion decay



Muon decay



- The result was g = 2.0 ± 0.1 for the muon
- Subsequent experiments indicated that g > 2

Evolution of the g-2 precision

FNAL goal: 4 x improvement

Storage Ring

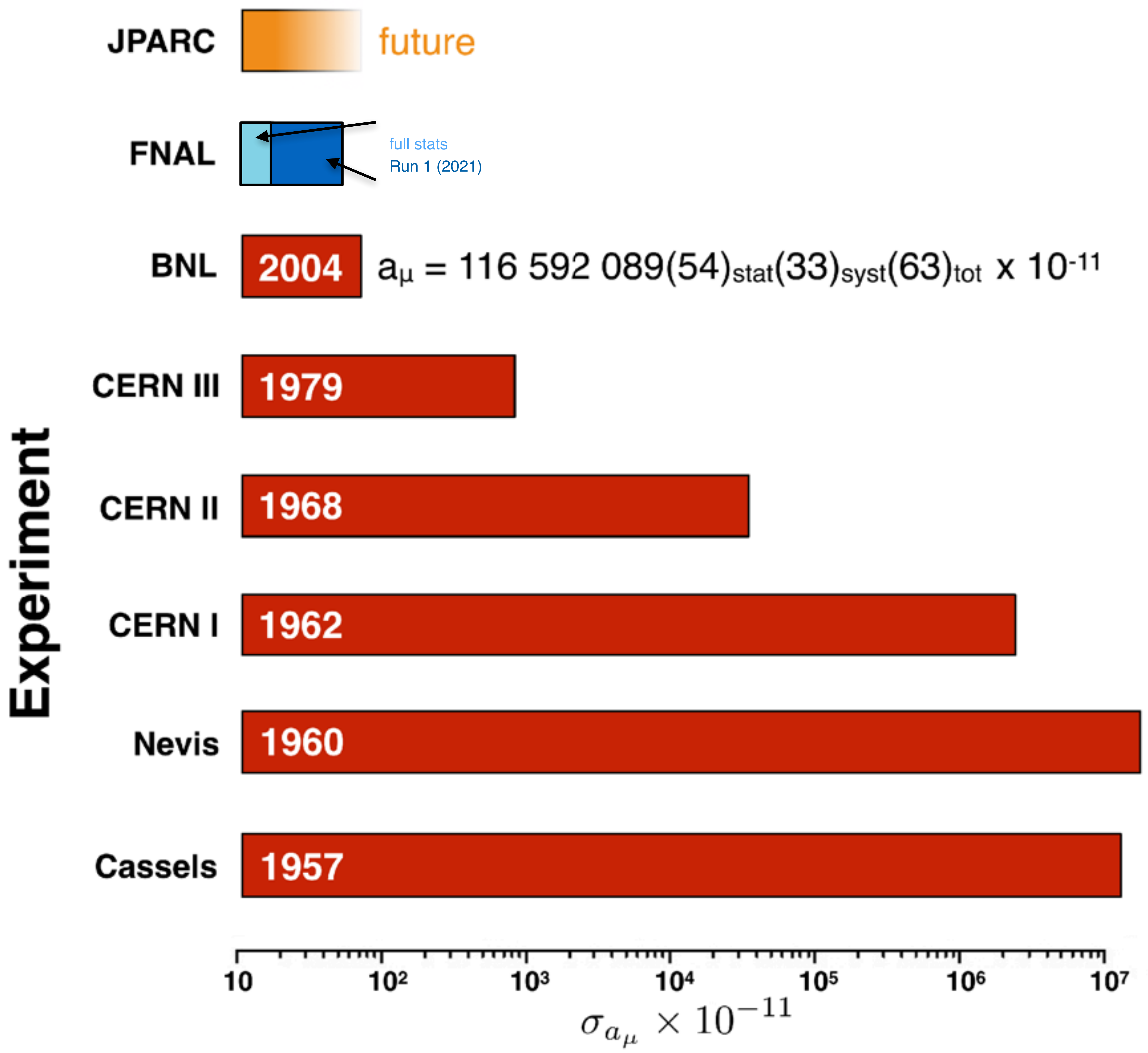
Dilated lifetime

measurement of a_μ, more precise

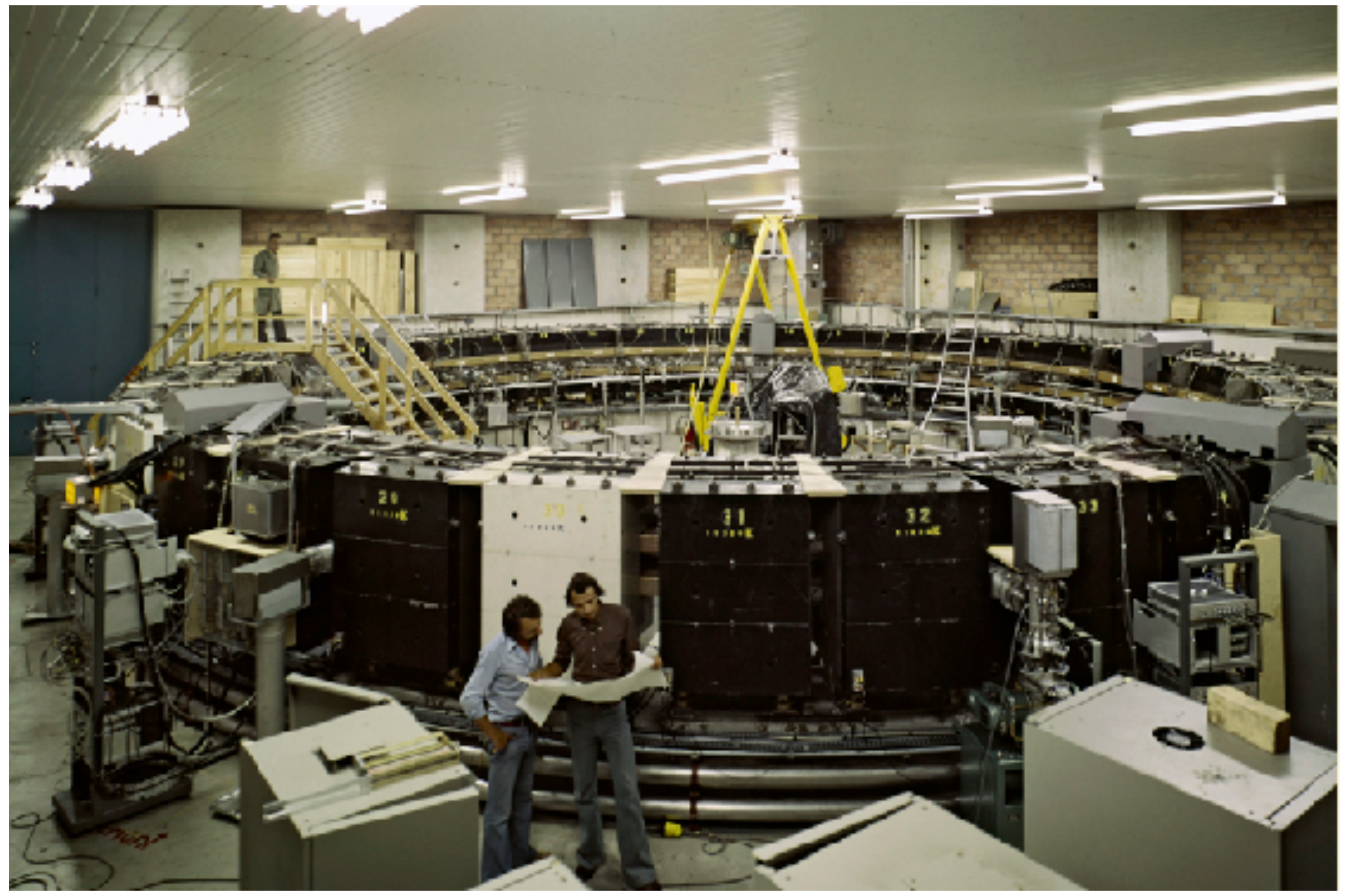
Stopped Muons

Stop muons in a magnetic field

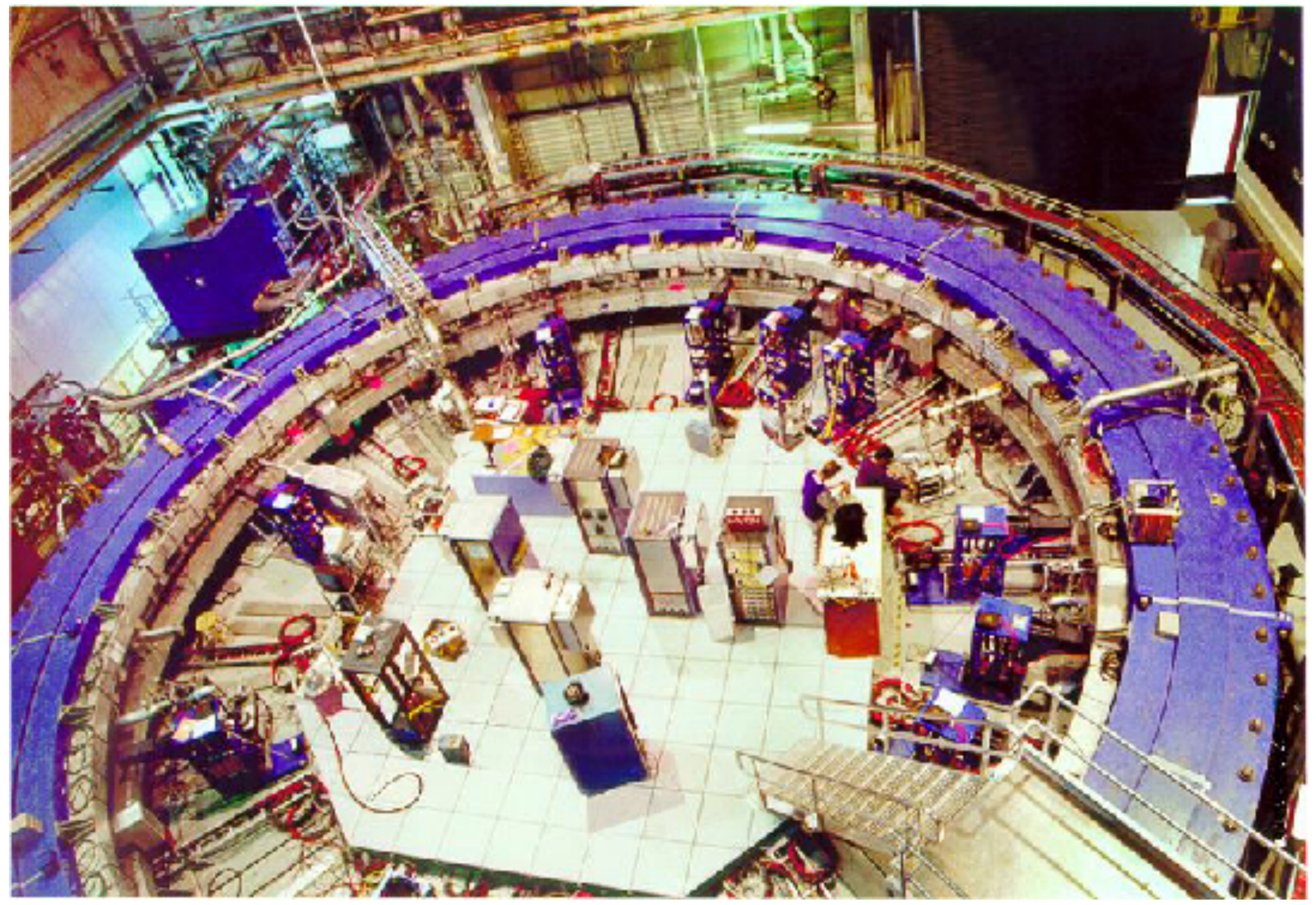
measurement of g_μ directly



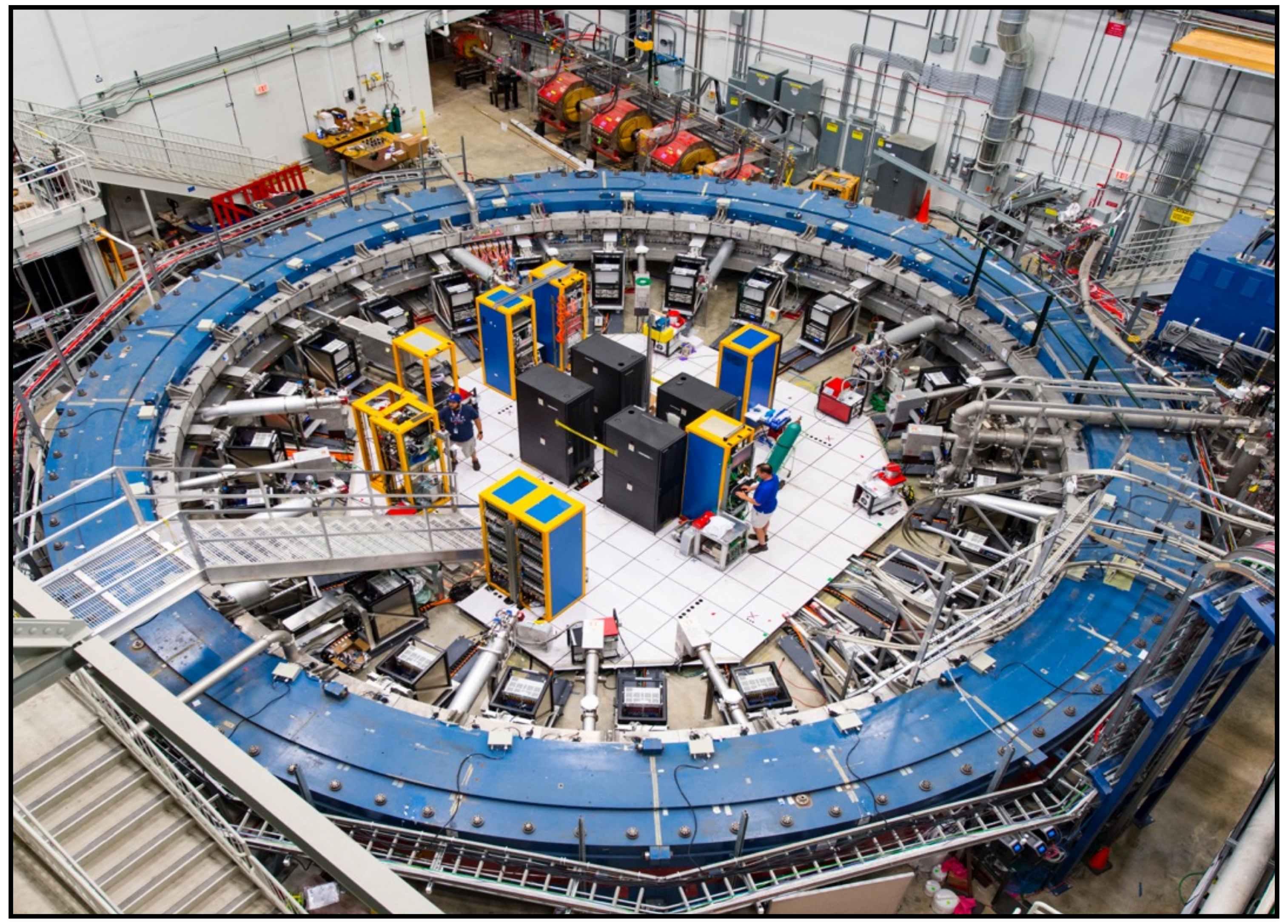
Four generations of storage rings



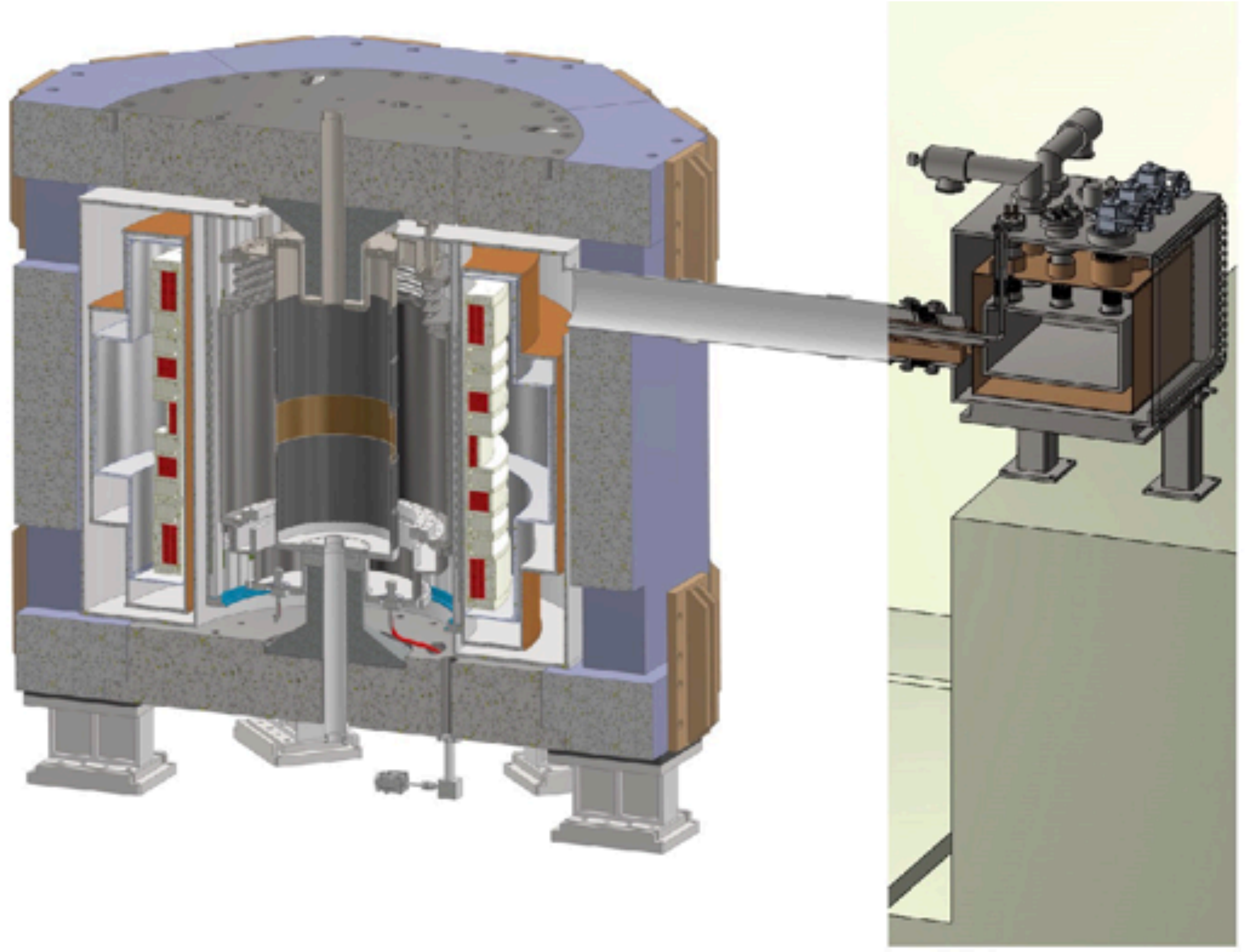
CERN
1960-1970s
7.3 ppm
(completed)



BNL
1990-2000s
0.54 ppm
(completed)



Fermilab
2009-2023
0.14 ppm
(in progress)



J-PARC
2009-2030s
0.45 ppm
(under construction)

Muon g-2 Collaboration

(>200 collaborators, 35 institutes, 7 countries)

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

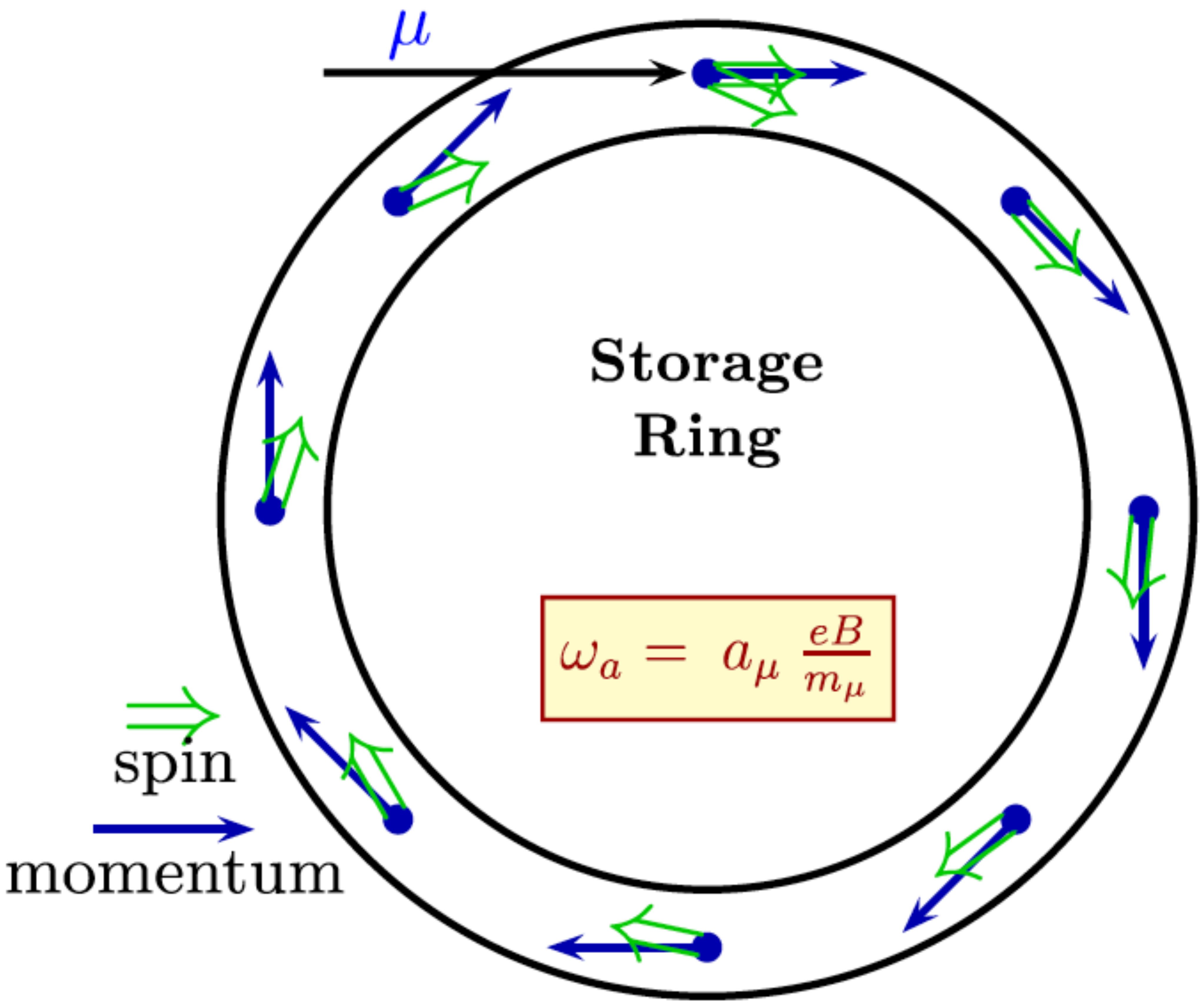
Lancaster/Cockcroft
Liverpool
Manchester
University College London

Kim Siang Khaw
SJTU/TDLI

We include: Particle-, Nuclear-, Atomic-, Optical-, Accelerator-, and Theoretical Physicists
And we combine our effort to measure a single value, g-2, to 140 ppb (BNL - 540 ppb)!

Muon g-2 collaboration meeting at Elba, Summer 2019

Principle of g-2 measurement



Larmor **Thomas**

$$\omega_s = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$

Cyclotron

$$\omega_c = \frac{eB}{\gamma m}$$

Anomalous precession frequency

$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$

measure difference in frequency precisely

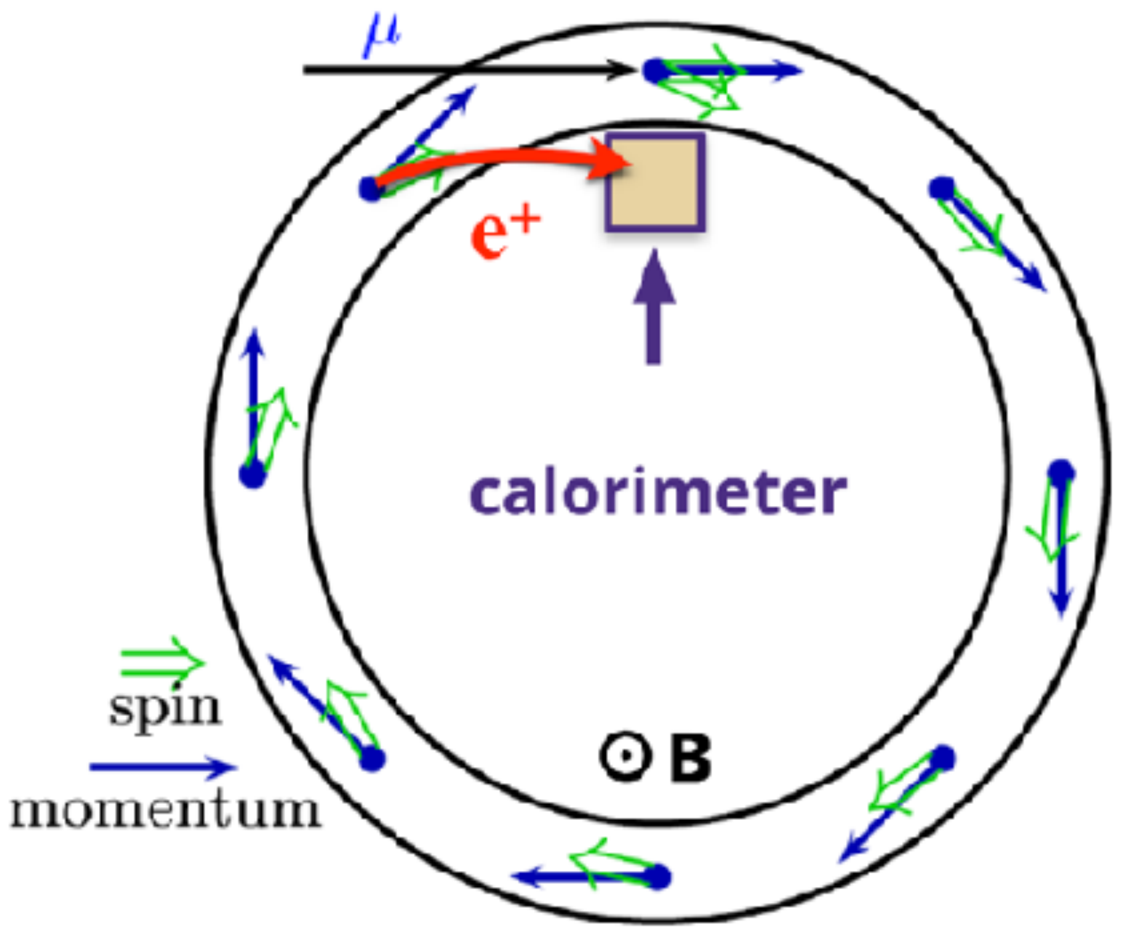
$$\omega_a = a_\mu \frac{eB}{m}$$

homogenous field and precise field measurement

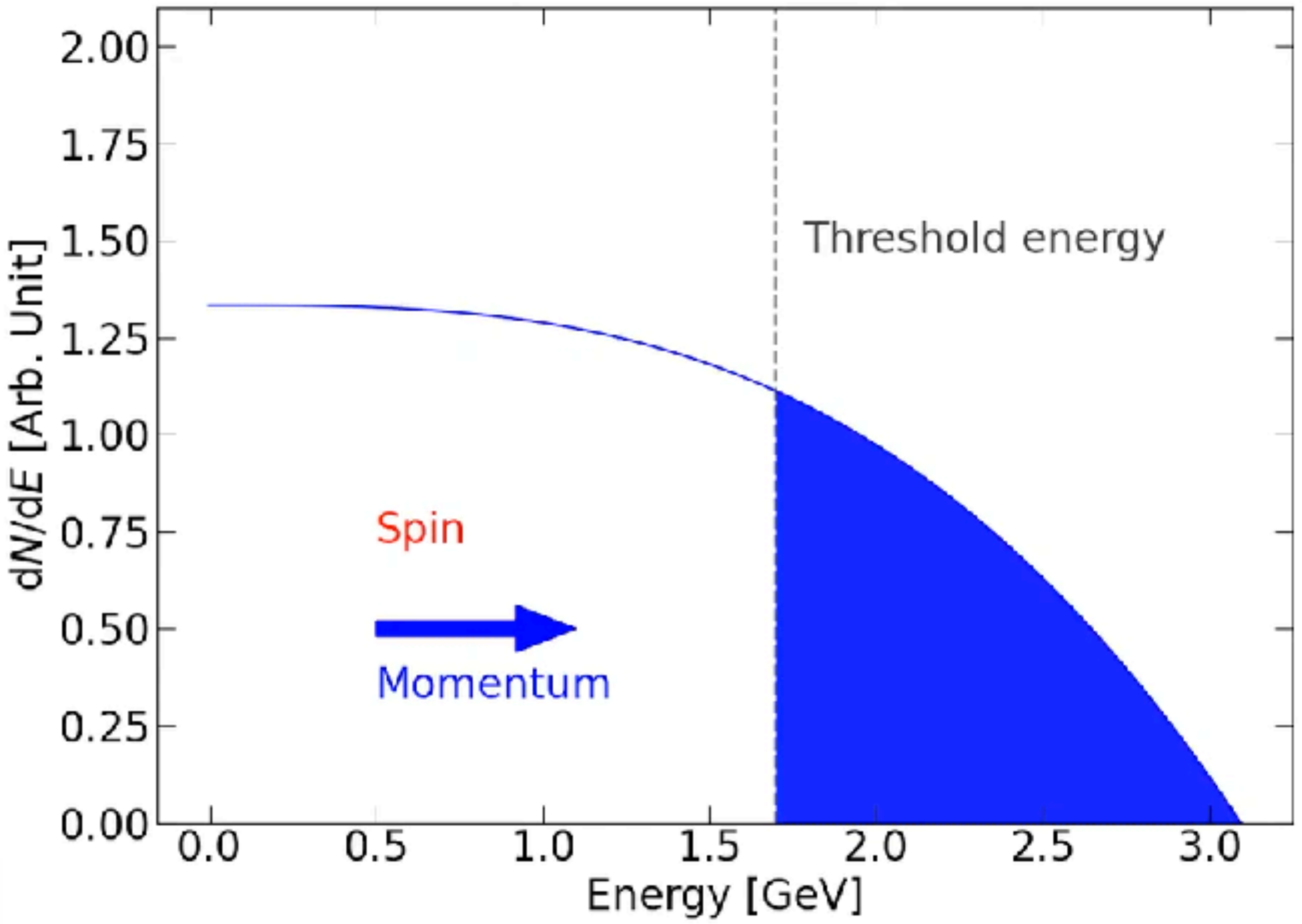
Precession frequency measurement

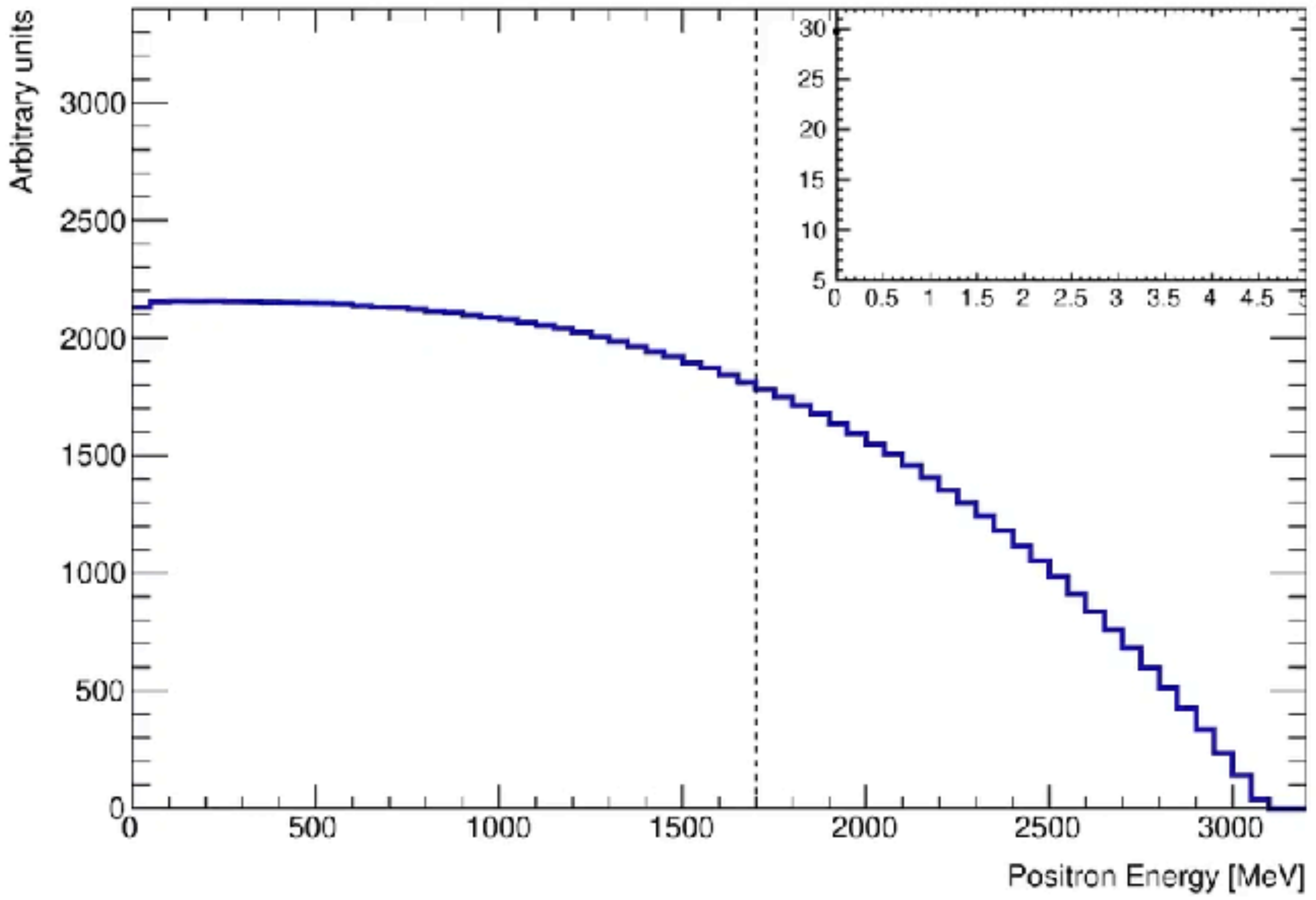
$$\boxed{\omega_a = a_\mu \frac{eB}{m}}$$

$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$



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



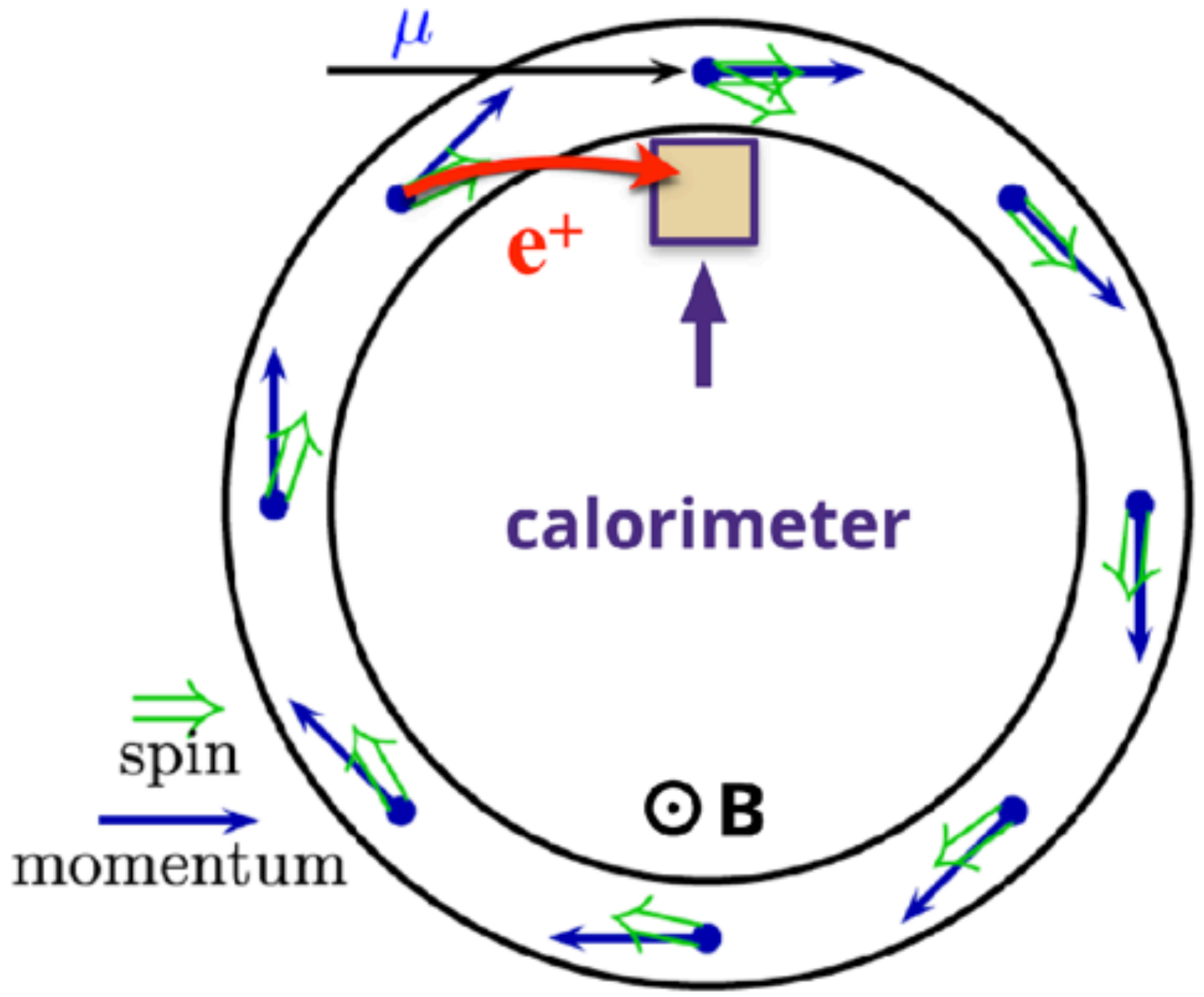


Magnetic field measurement

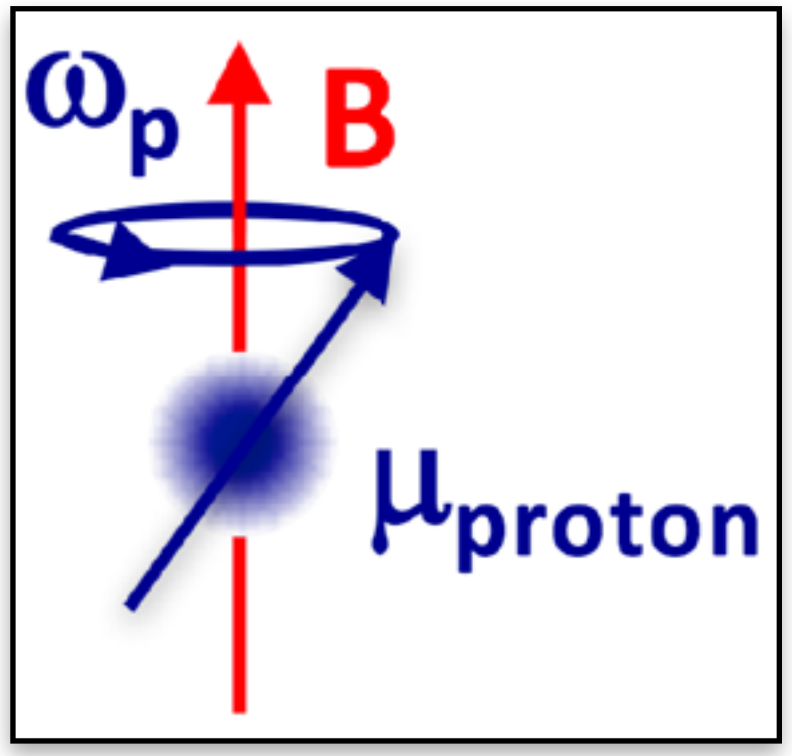
$$\omega_a = a_\mu \frac{e\boxed{B}}{m}$$

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

$$\mu_e = g_e \frac{e\hbar}{4m_e}$$



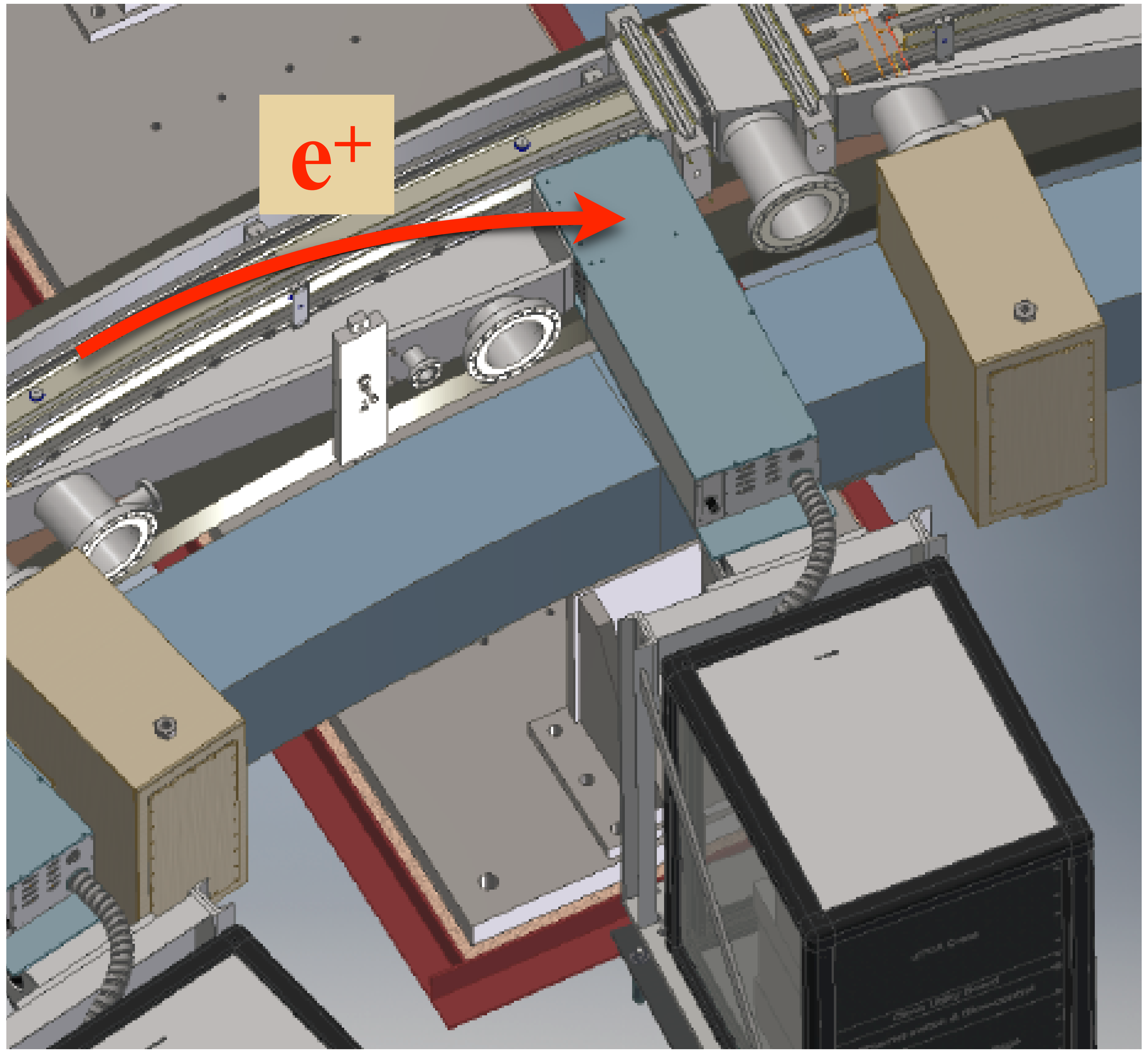
pNMR probes around the storage ring



We measure these two

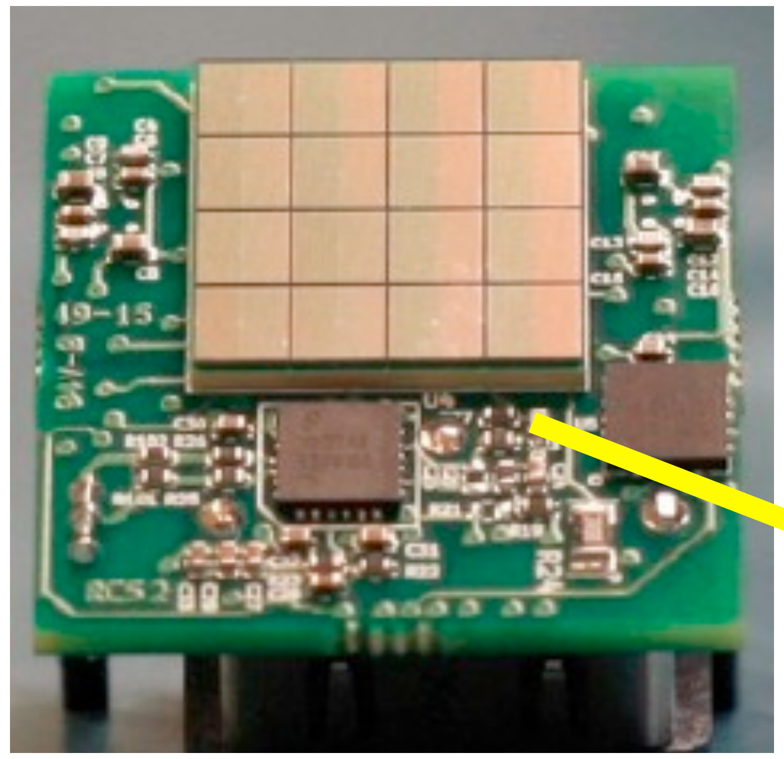
$$a_\mu^{\text{Exp}} = \underset{0.3\text{ ppt}}{\frac{g_e}{2}}\boxed{\frac{\omega_a}{\tilde{\omega}_p}}\underset{22\text{ ppb}}{\frac{m_\mu}{m_e}}\underset{3\text{ ppb}}{\frac{\mu_p}{\mu_e}}$$

Calorimeters measure positron time and energy

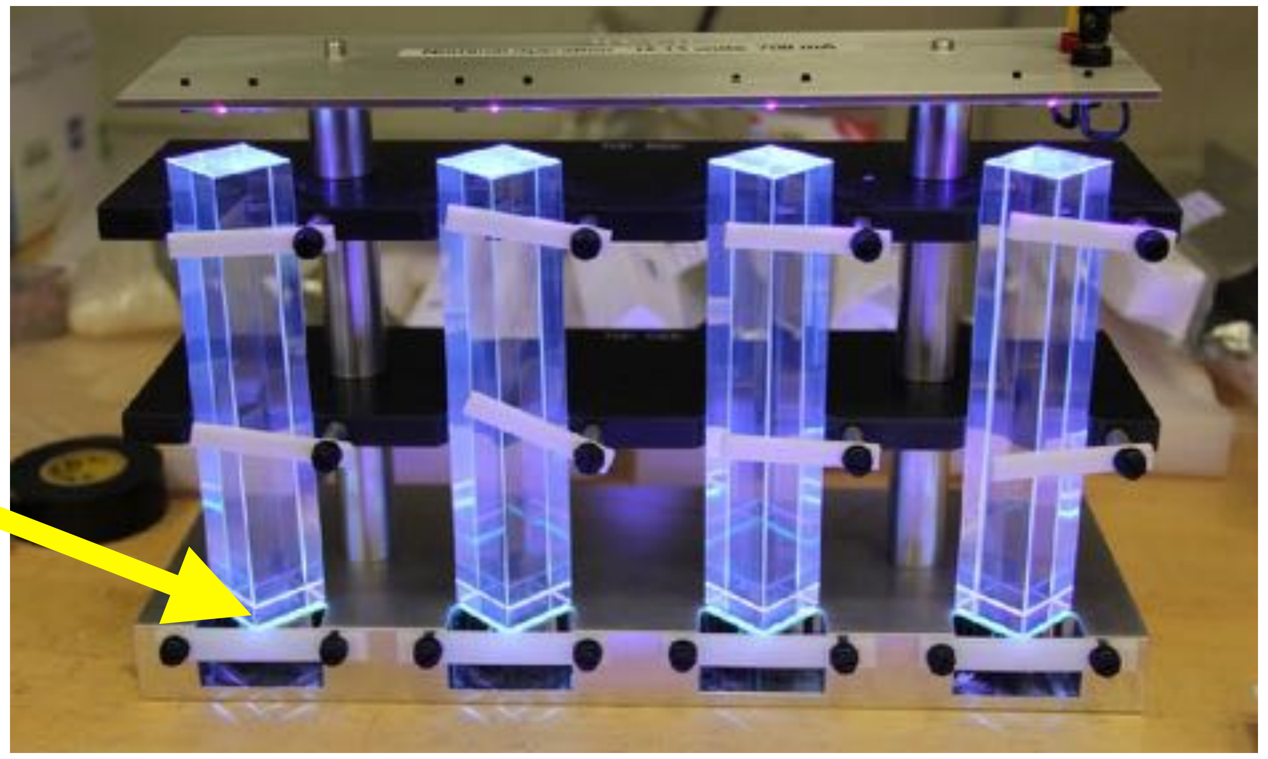


Decay positron curving in and striking a calorimeter

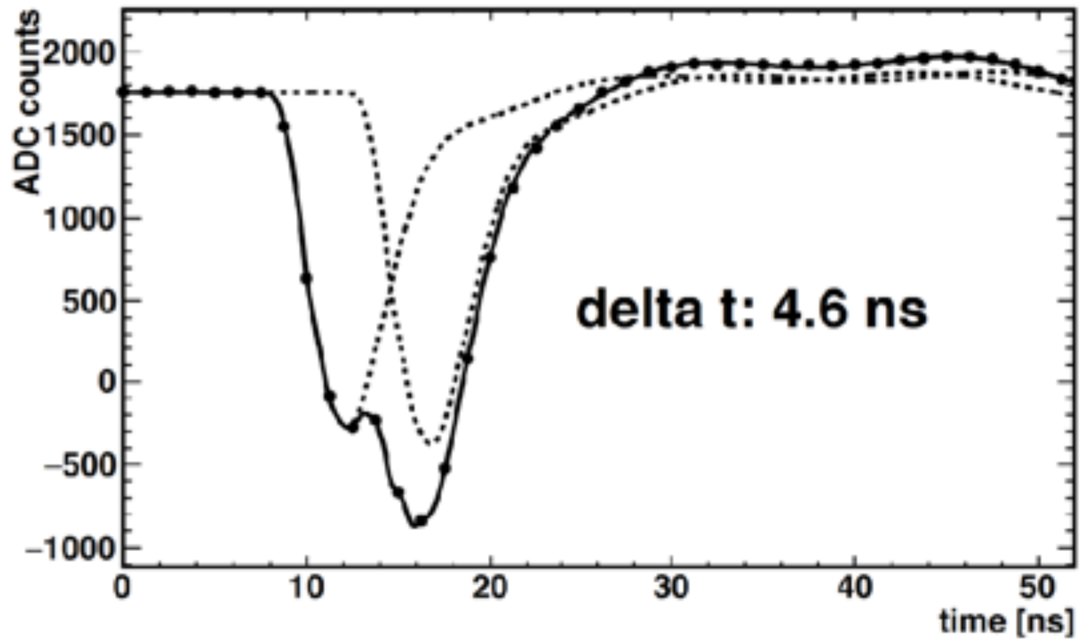
SiPM



PbF_2

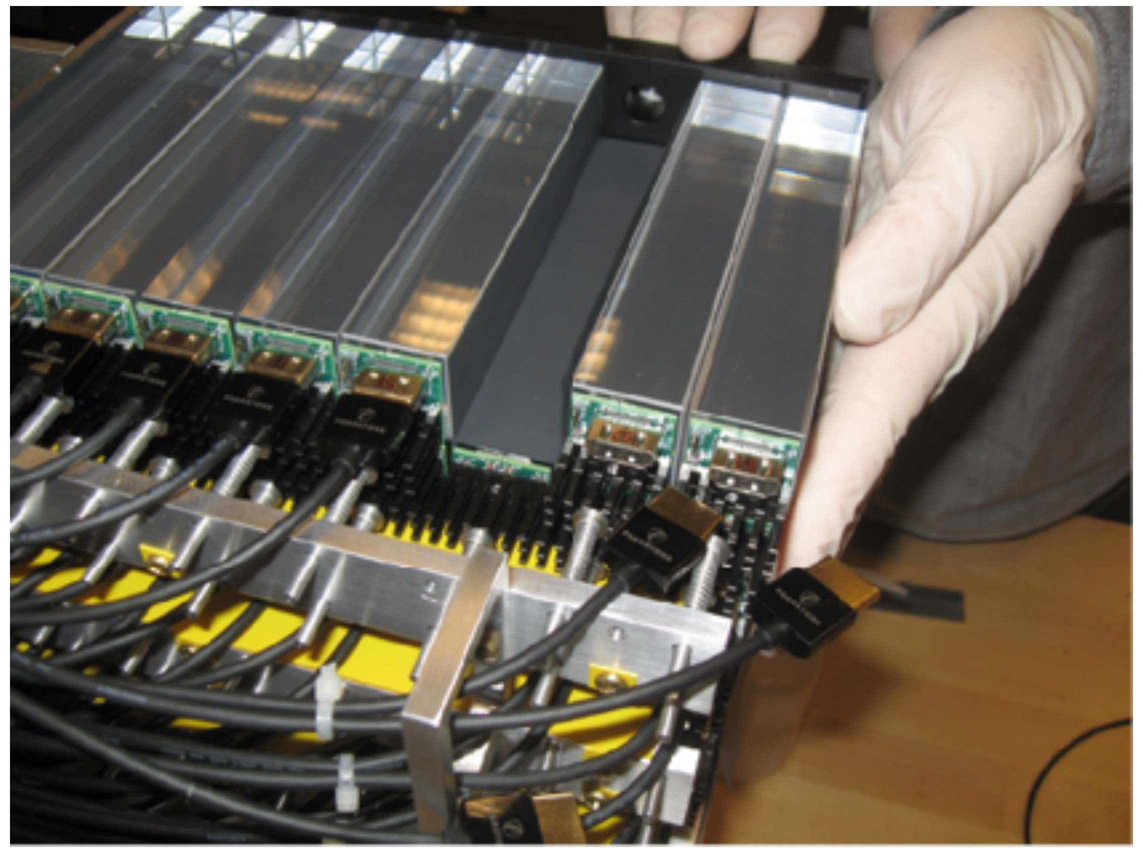


pileup separation



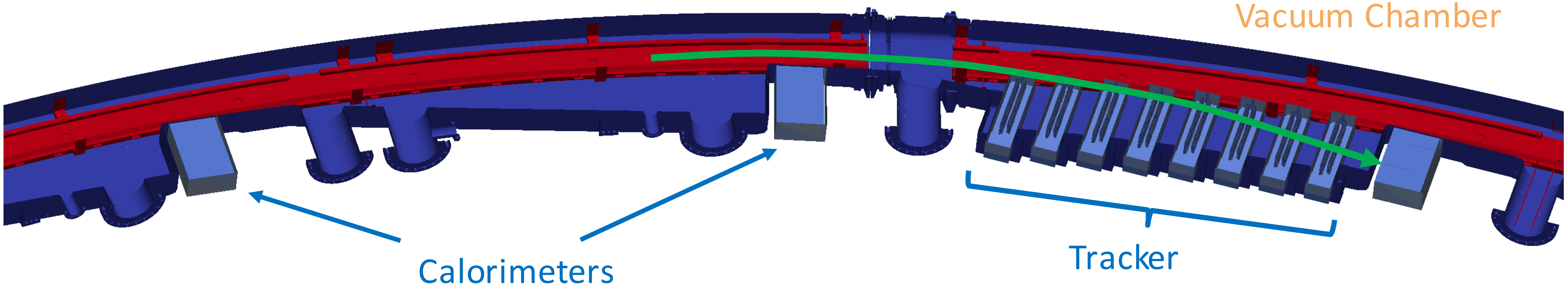
PMT-like signal, B-field operation, 100% separation > 2.5 ns

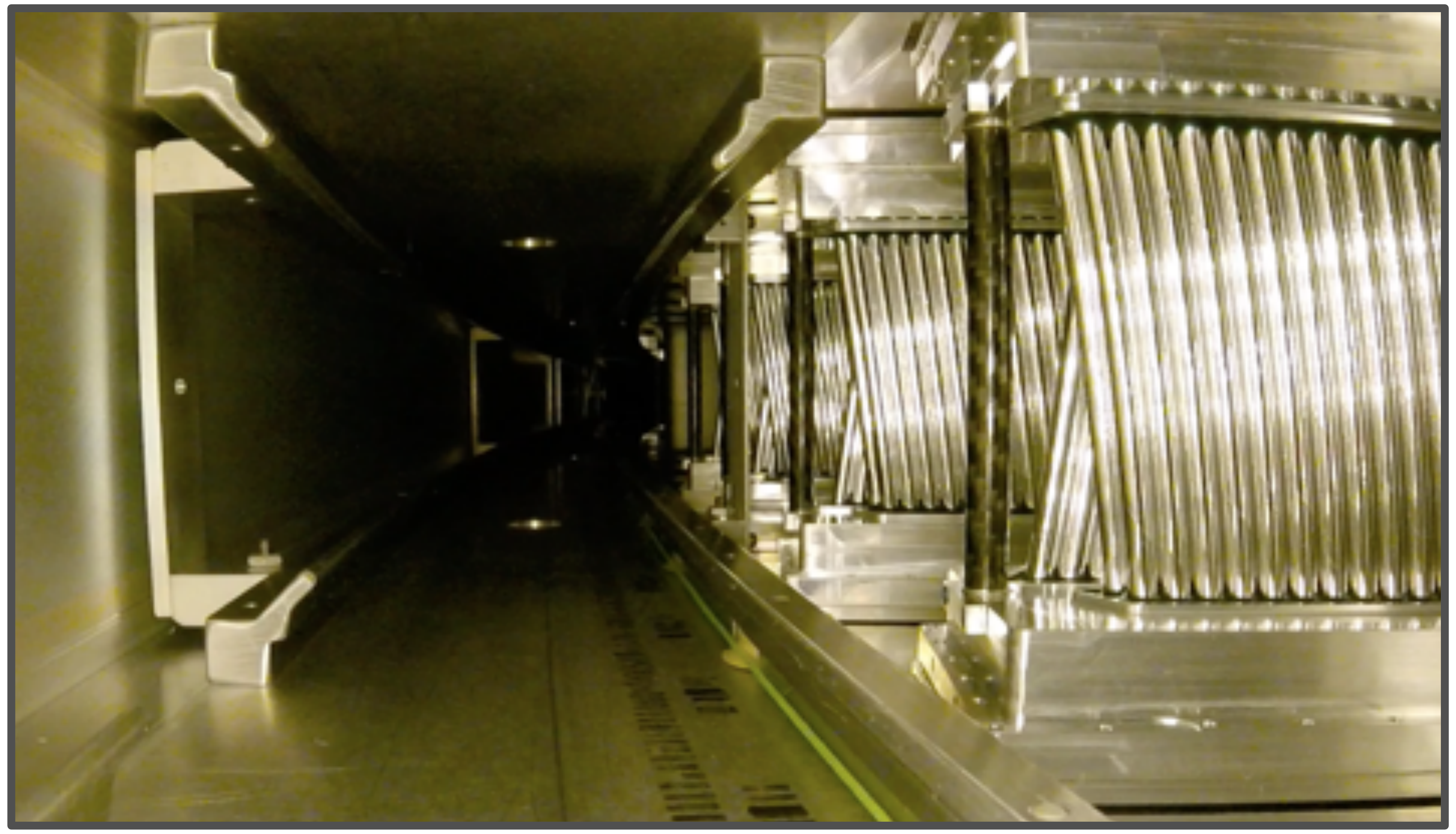
Opened up calorimeter

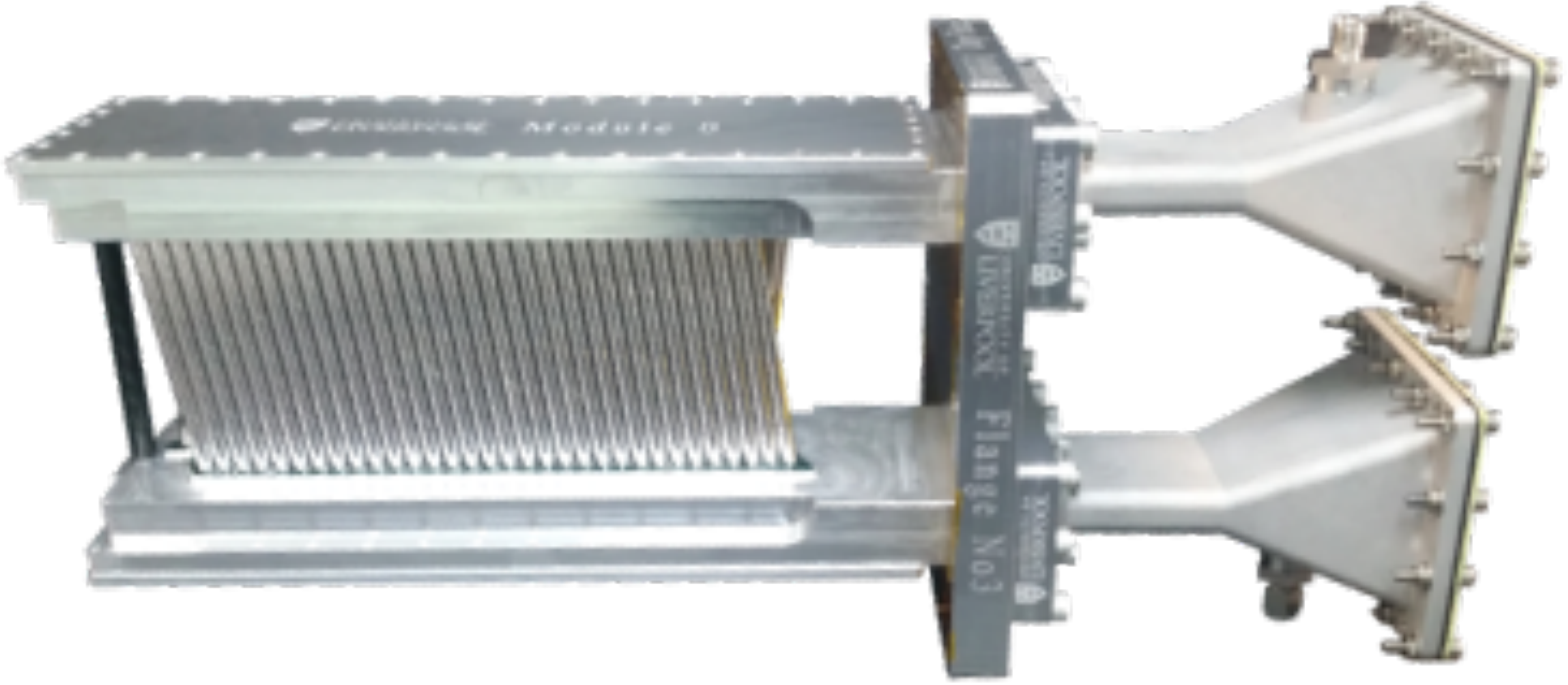


Stacking crystals

Trackers extrapolate e^+ to muon decay position

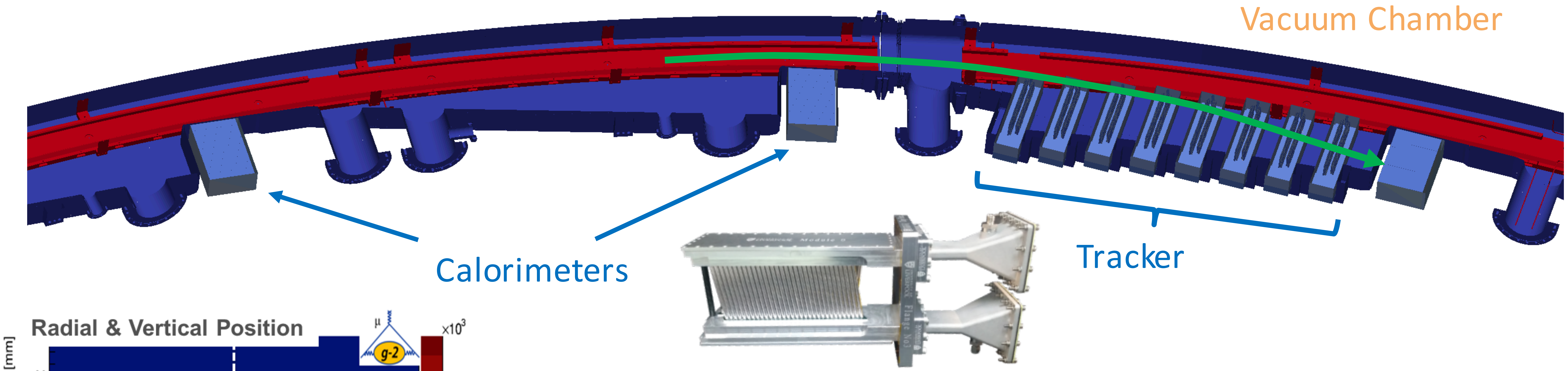


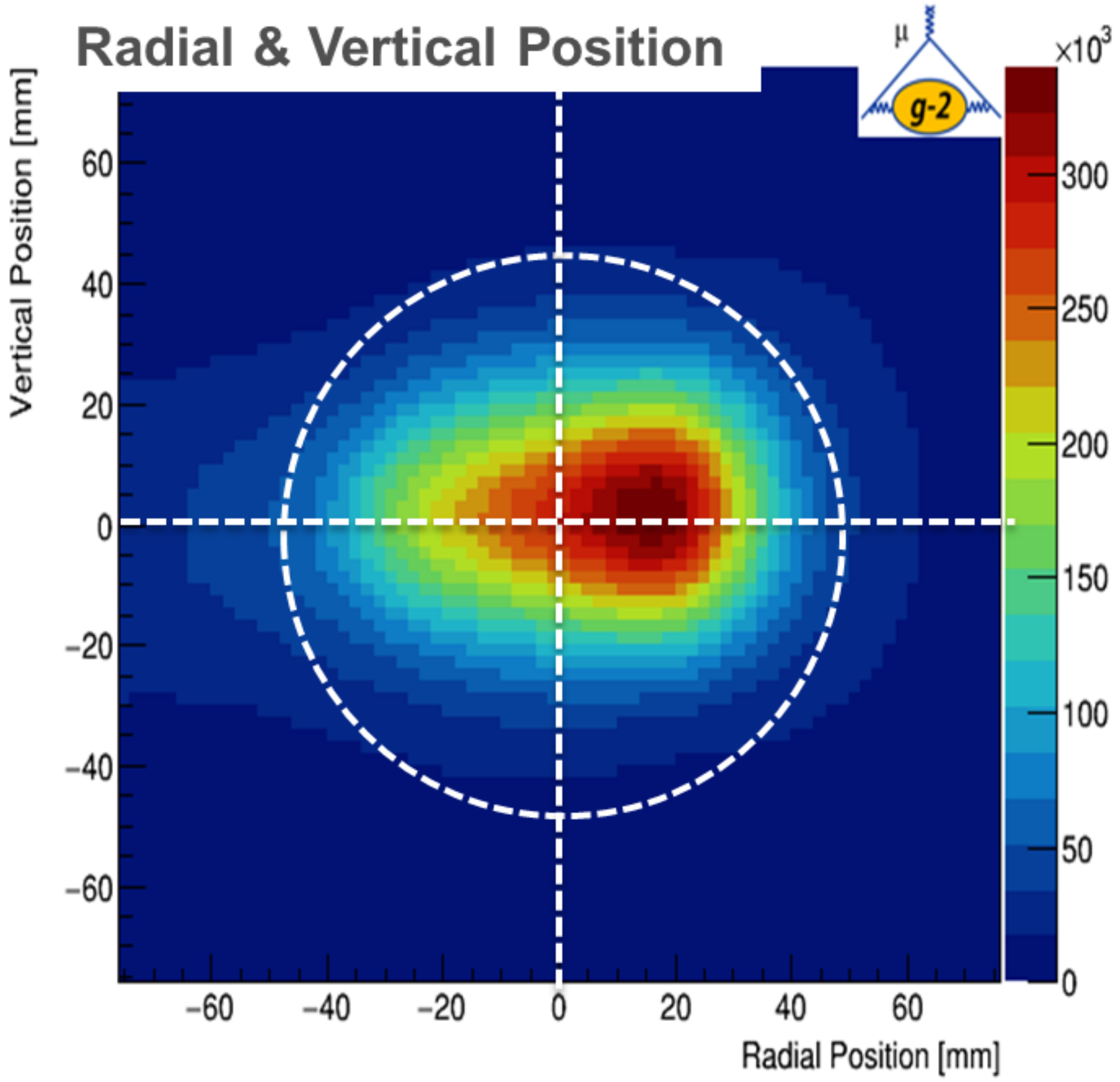


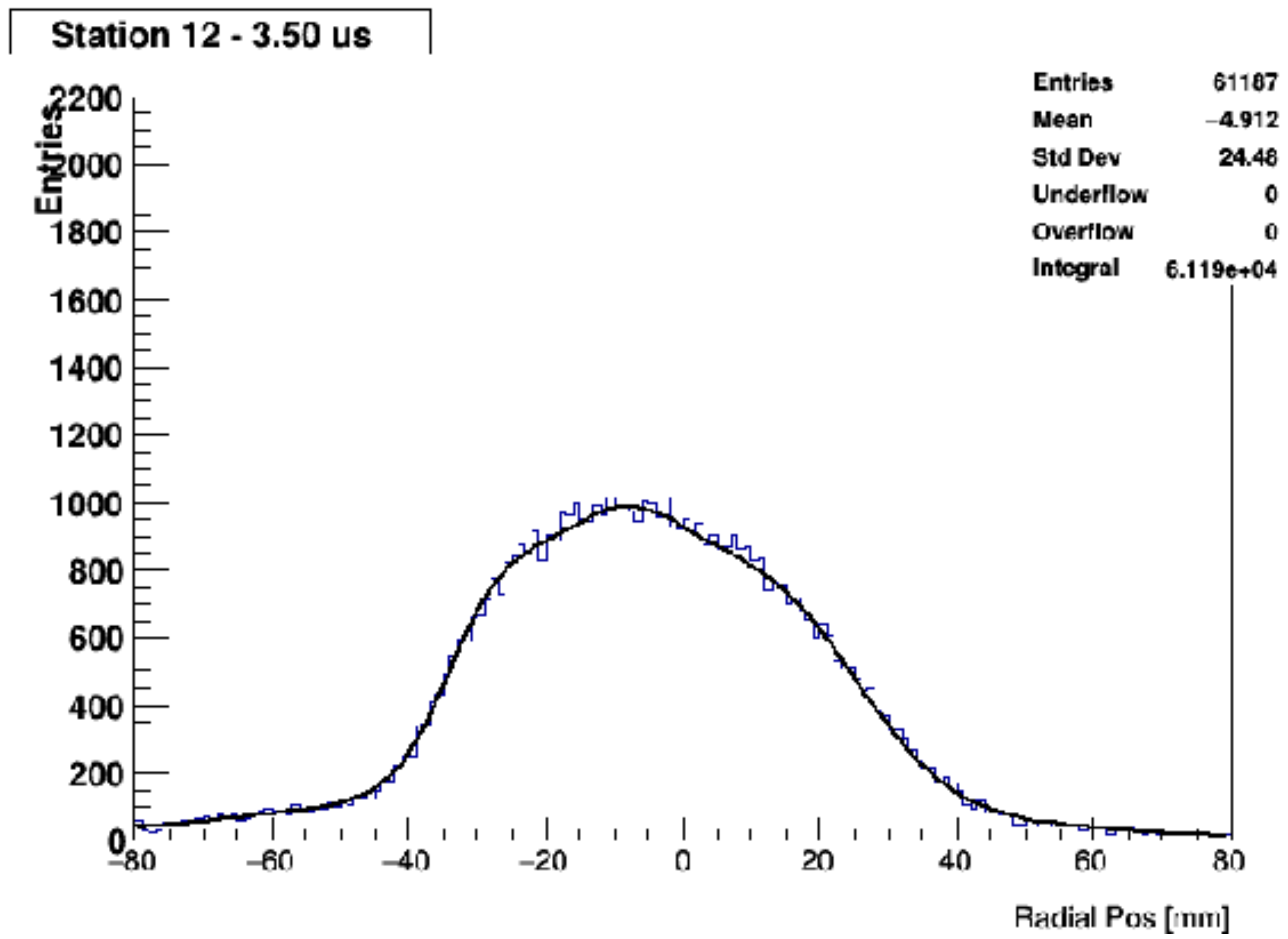


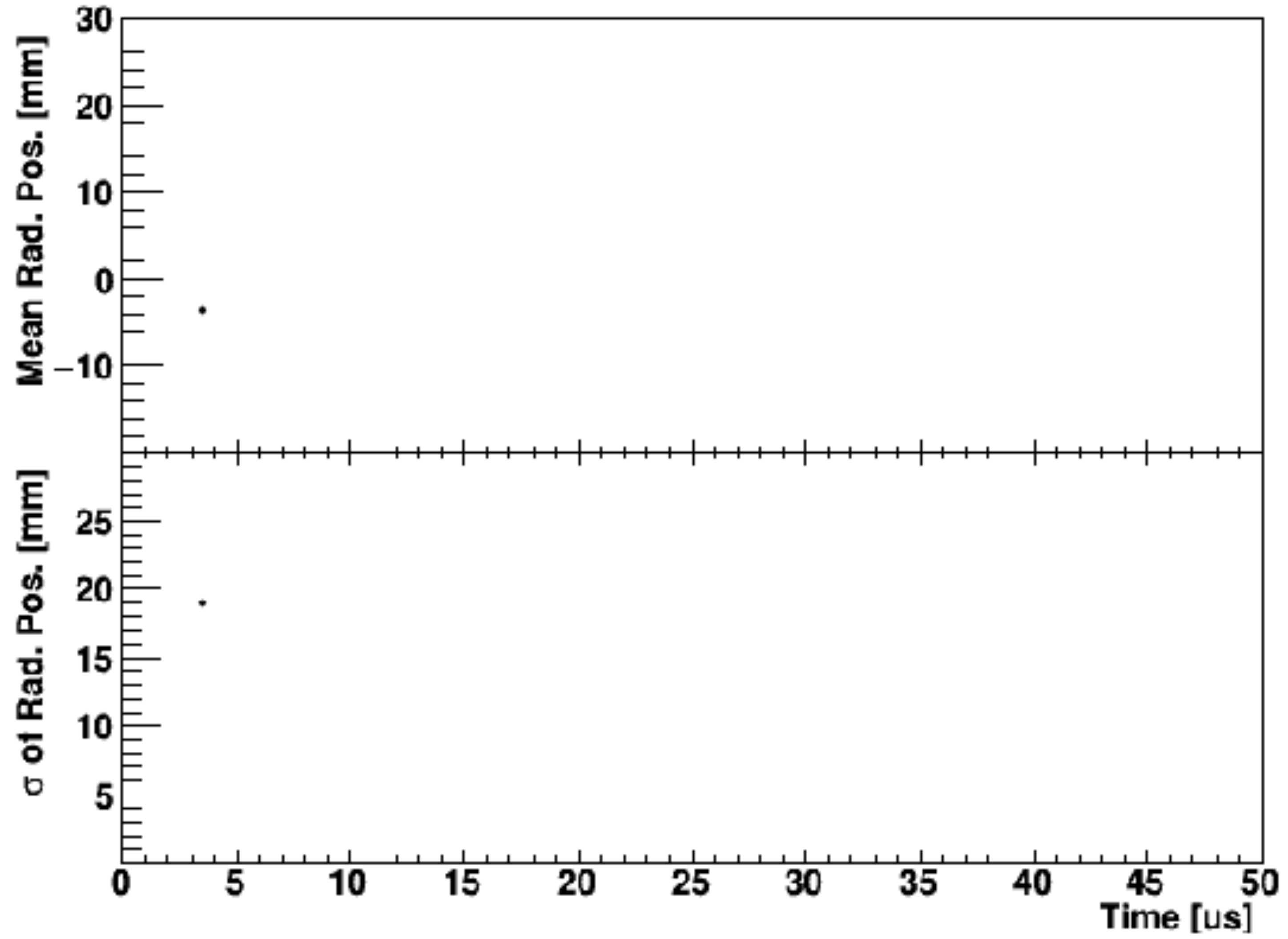
The SWISS KNIFE for g-2 experiment

Trackers extrapolate e^+ to muon decay position



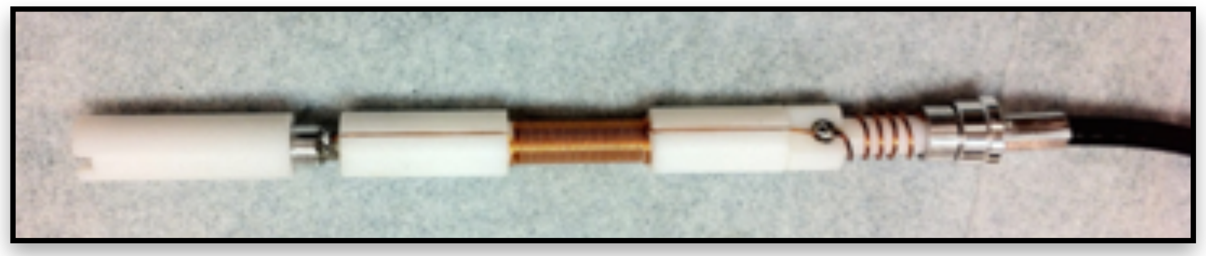






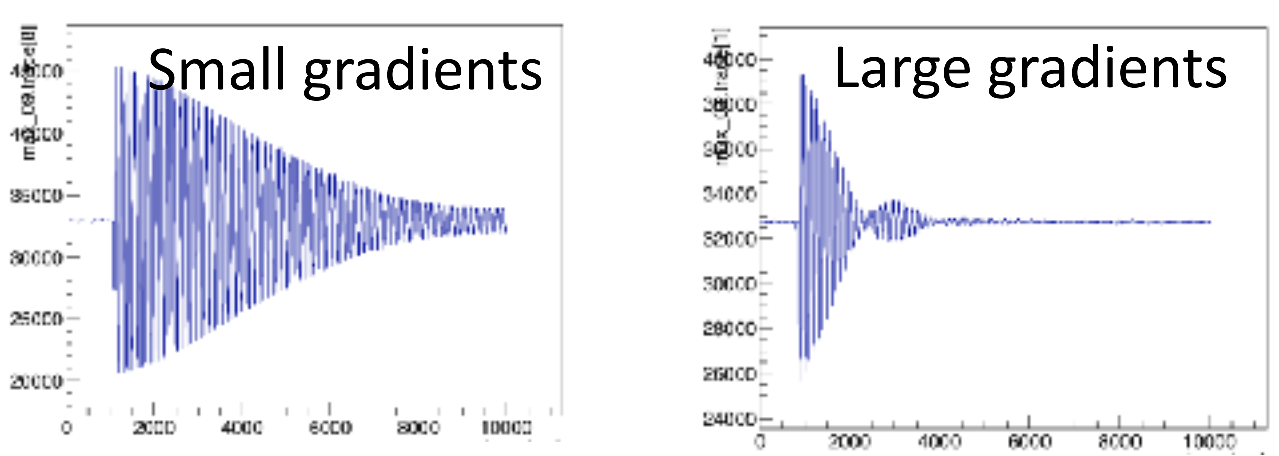
NMR probes measure magnetic fields

A 25-element **pNMR Trolley** was used to map the field during rough shimming adjustments (see video)

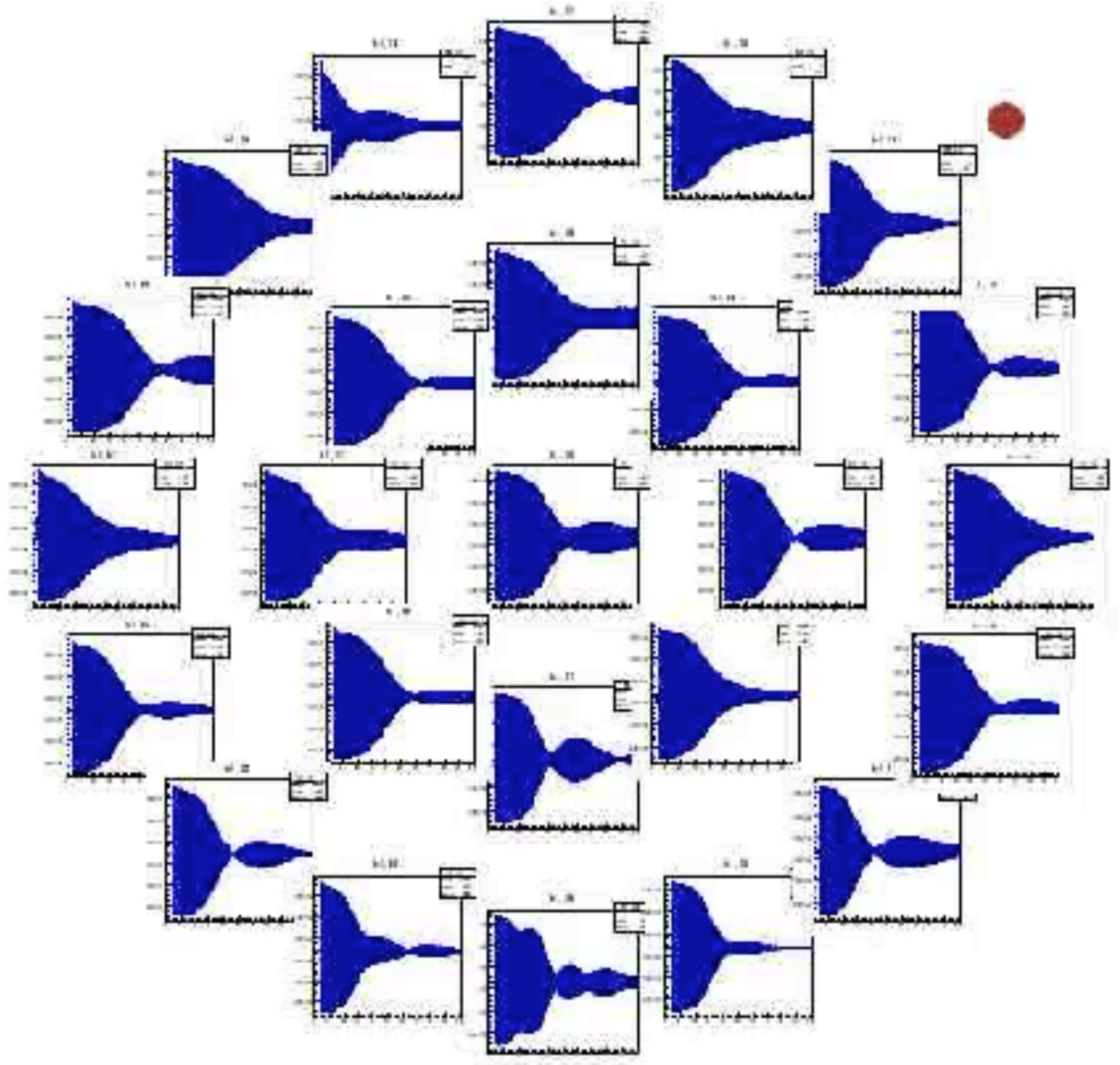


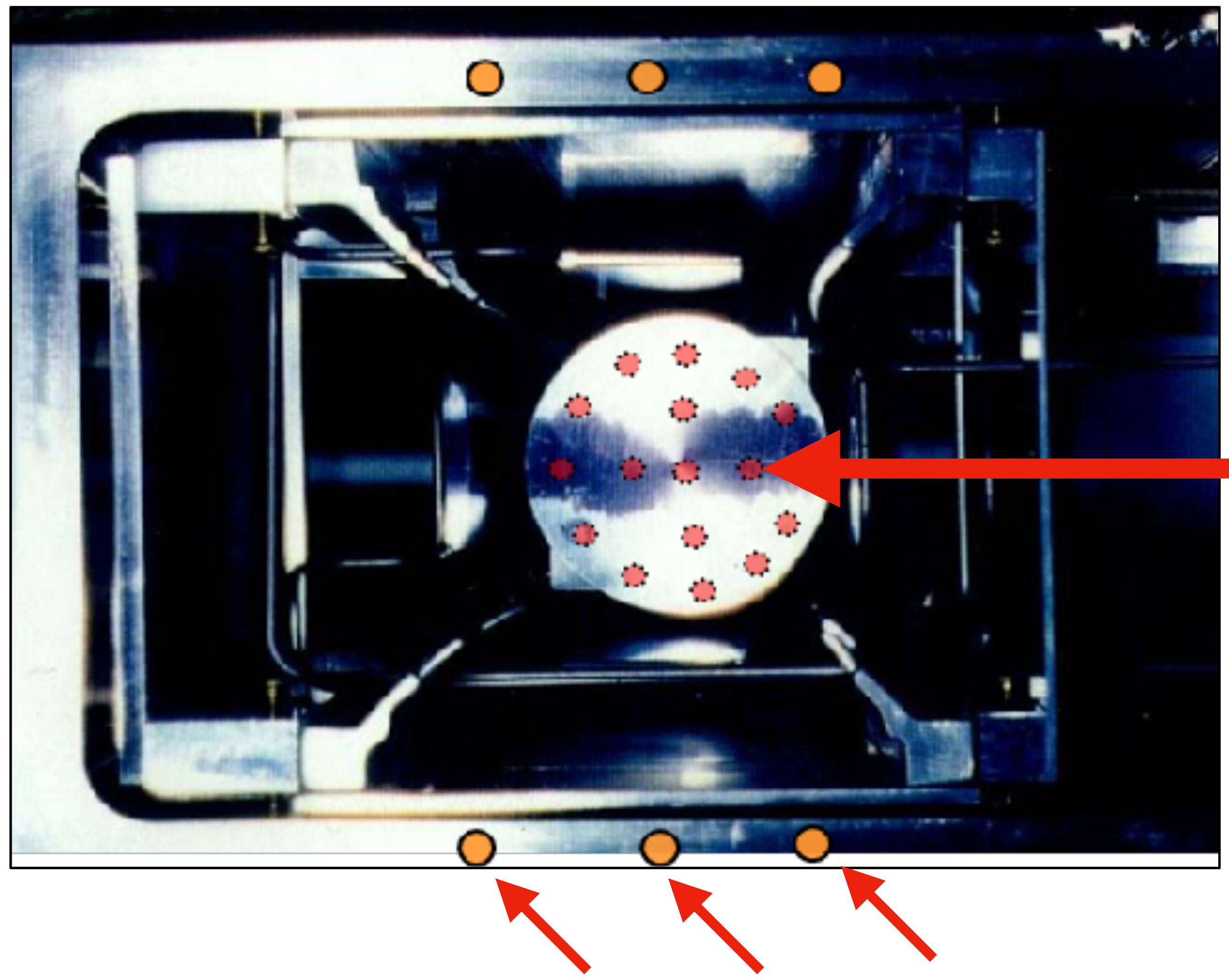
A 17-element **pNMR Trolley** maps the field IN VACUUM during running periods

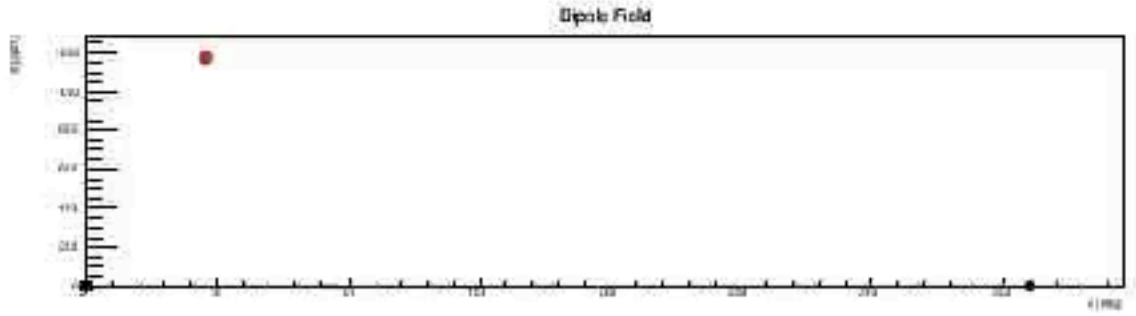
(FID) Waveforms with ~10 ppb resolution



Shimming Trolley Probe Matrix

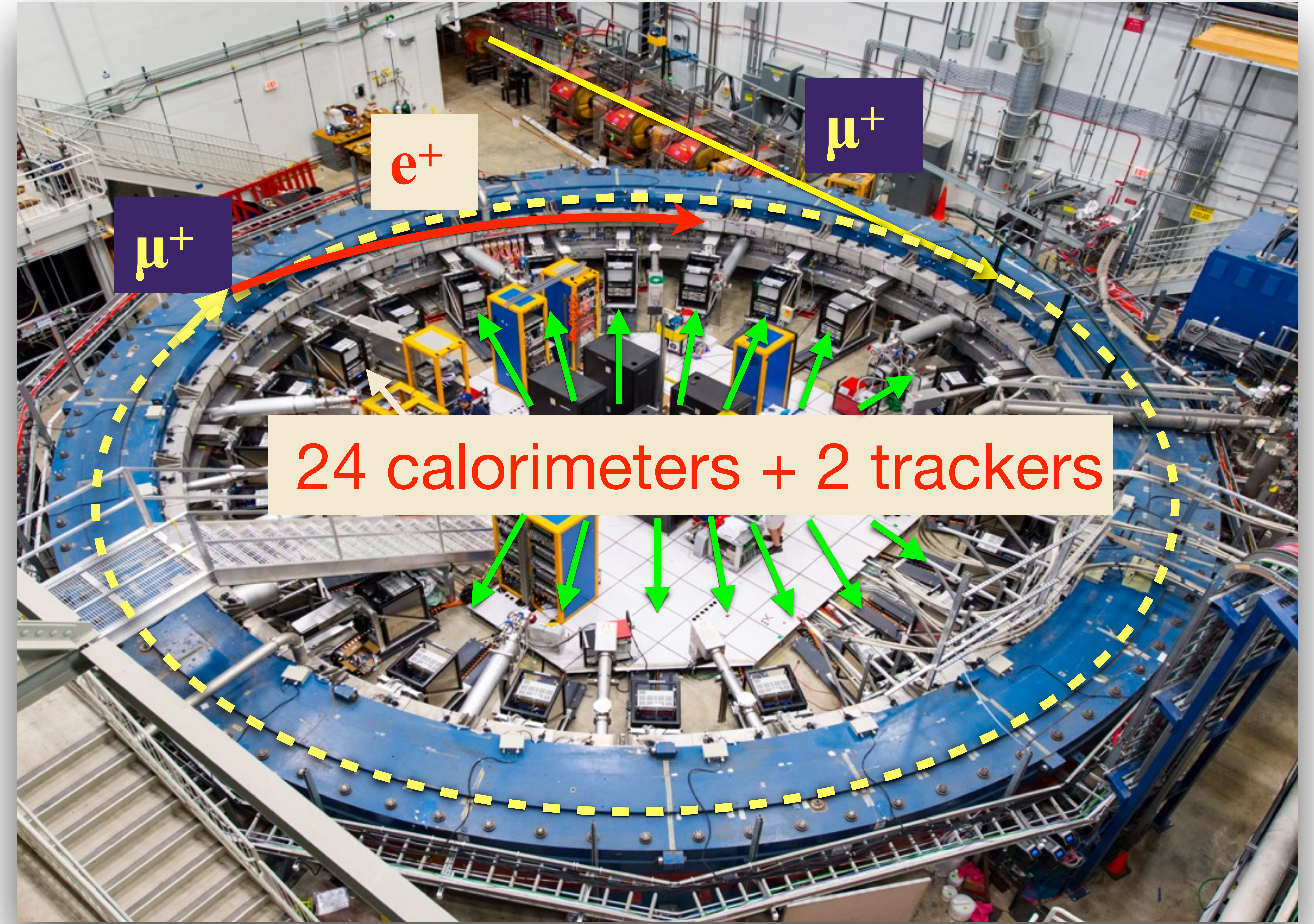


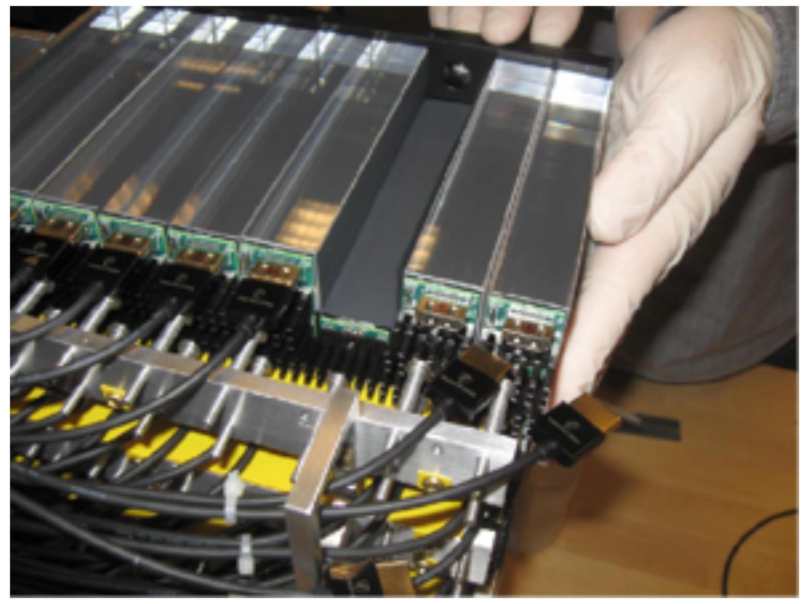




378 **Fixed Probes** above and below the vacuum chamber measure the field continuously throughout the experiment

A grand view of the g-2 ring





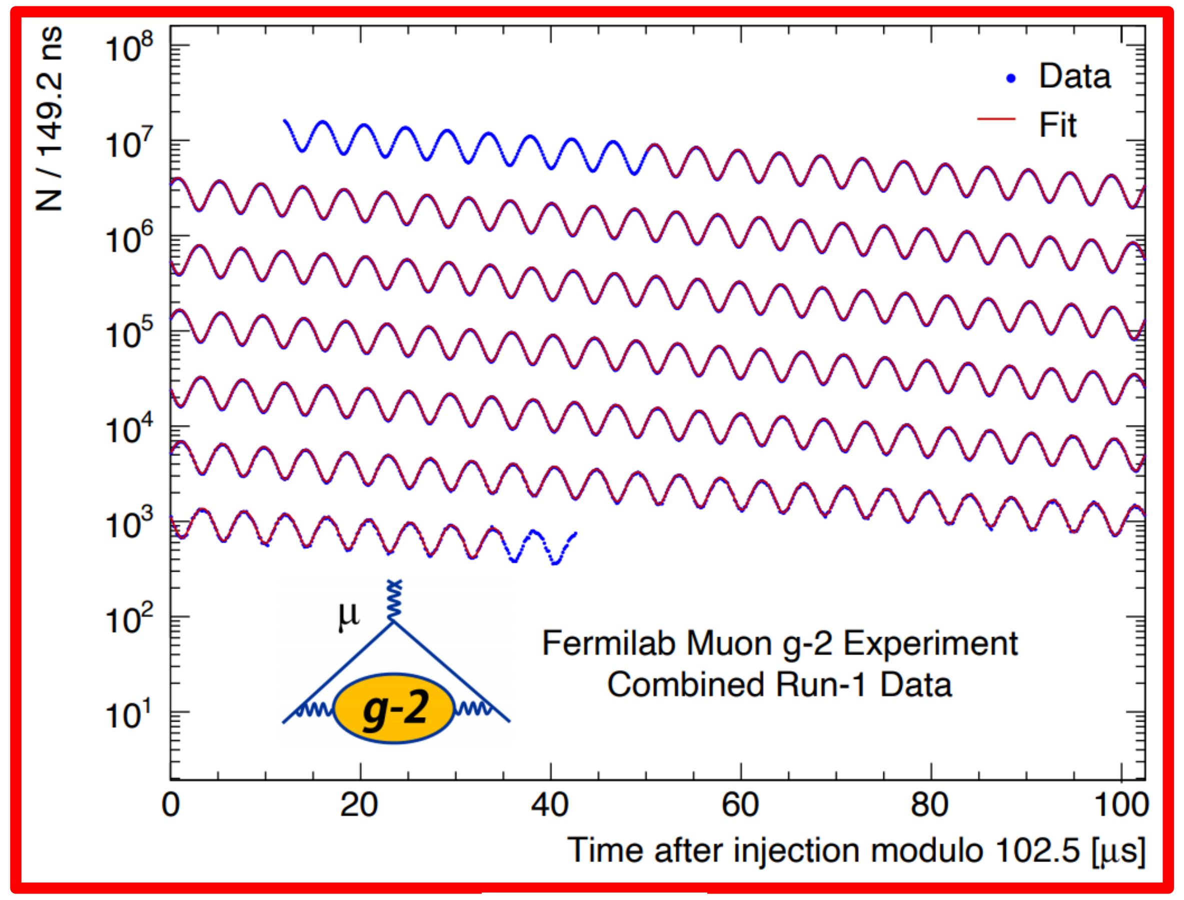
1. Inject muon beam into the storage ring and store them
2. Monitor the magnetic field with fixed and trolley probes
3. Detect positrons with calorimeters and trackers

Additional corrections

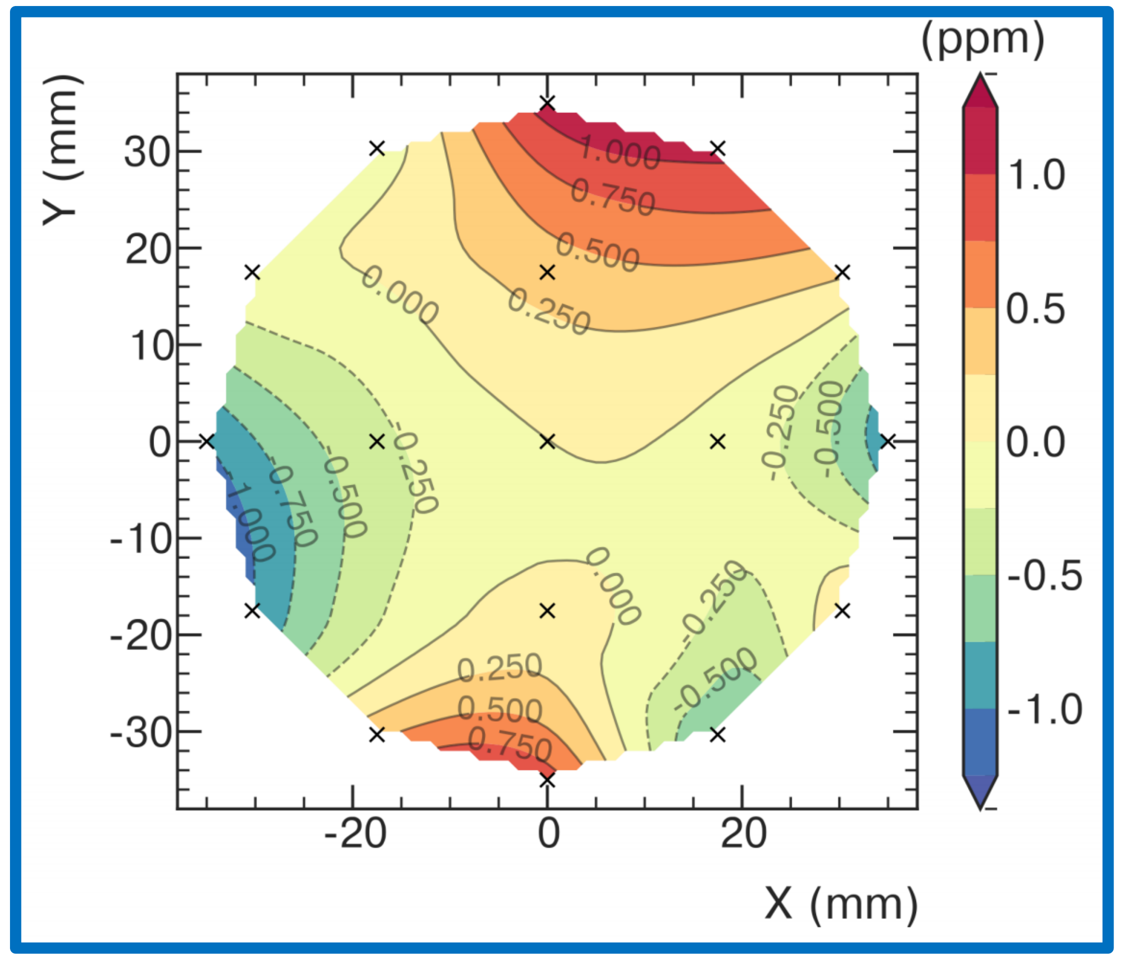
$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}}\,\underset{\text{11 ppb}}{\frac{\mu'_p(T_r)}{\mu_e(H)}}\,\underset{\text{0 ppb}}{\frac{\mu_e(H)}{\mu_e}}\,\underset{\text{22 ppb}}{\frac{m_\mu}{m_e}}\,\underset{\text{0.3 ppt}}{\frac{g_e}{2}}$$

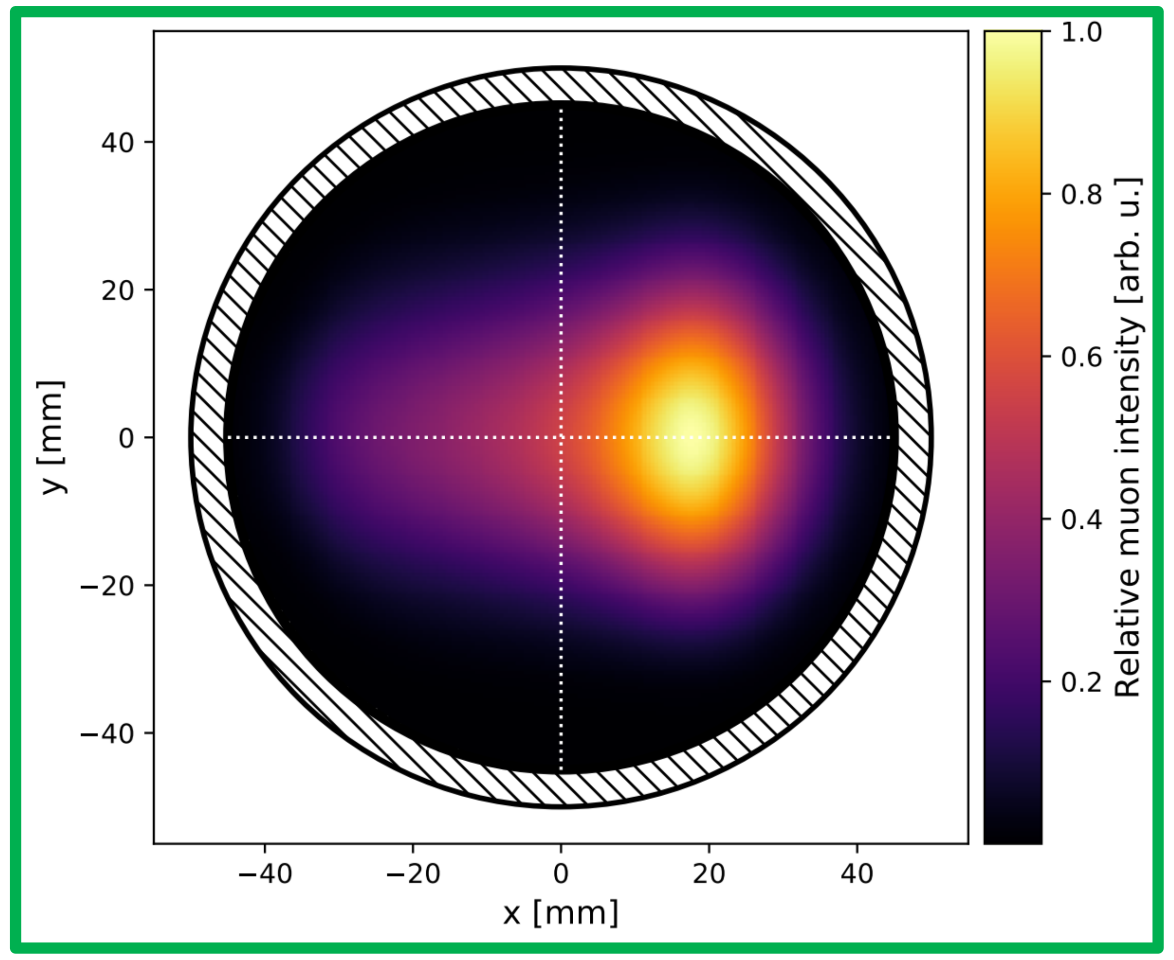
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{\overset{\text{Unblinding conversion factor}}{f_{\text{clock}}}\ \overset{\text{Measured } g-2 \text{ frequency}}{\omega_a^m}\left(1+\overbrace{C_e+C_p+C_{ml}+C_{pa}}^{\text{Corrections from the beam dynamics systematic effects}}\right)}{\underset{\text{NMR probe calibration factor}}{f_{\text{calib}}}\ \underbrace{\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle}_{\text{Magnetic field weighted over the muon distribution and azimuthally averaged}}\left(1+\underbrace{B_k+B_q}_{\text{Corrections from the transient magnetic field}}\right)}$$

Visualizing the measurements

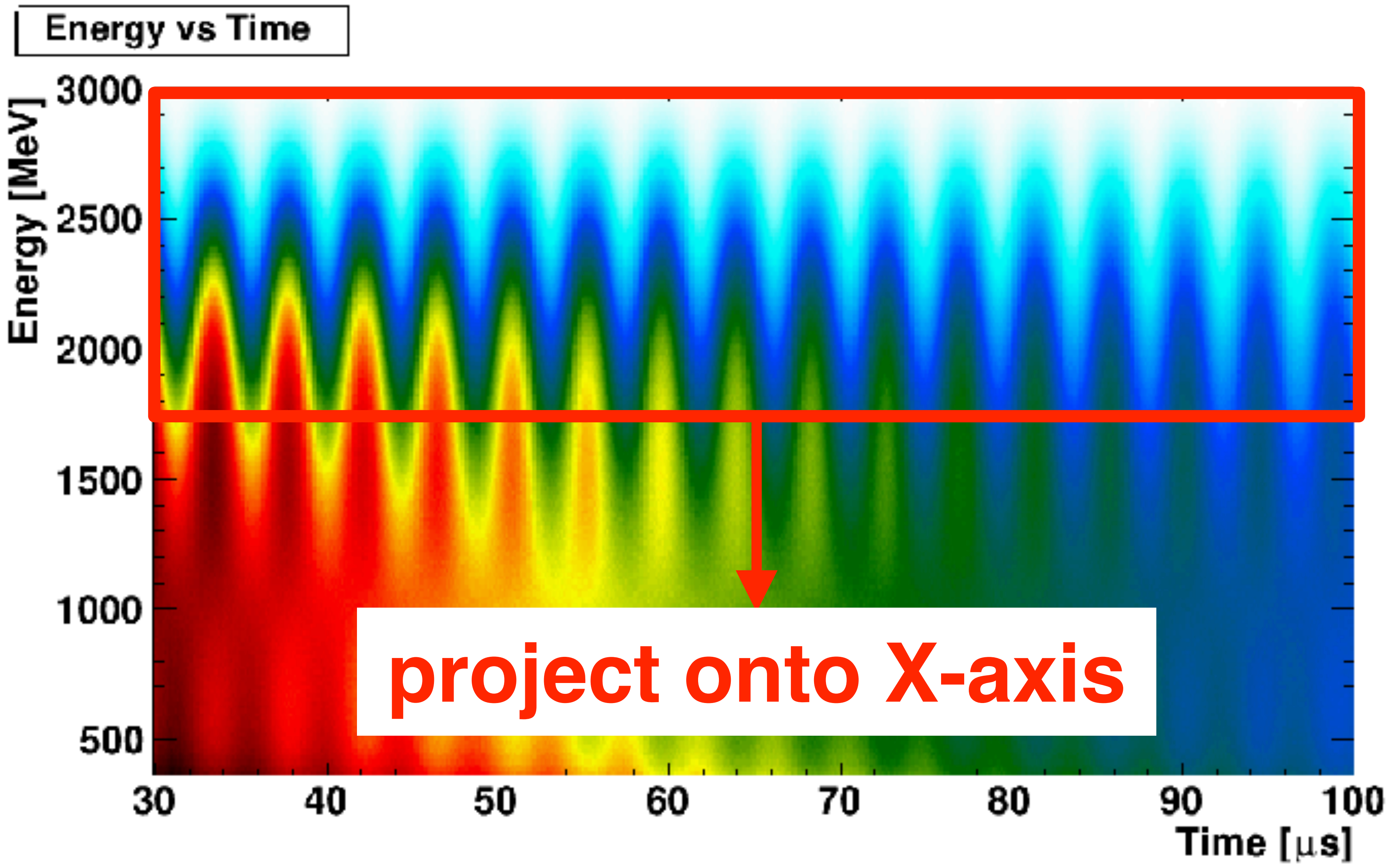


$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\;\omega_a^m\;(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\text{calib}}\;\langle\;\omega_p(x,y,\phi)\times M(x,y,\phi)\;\rangle(1+B_k+B_q)}$$





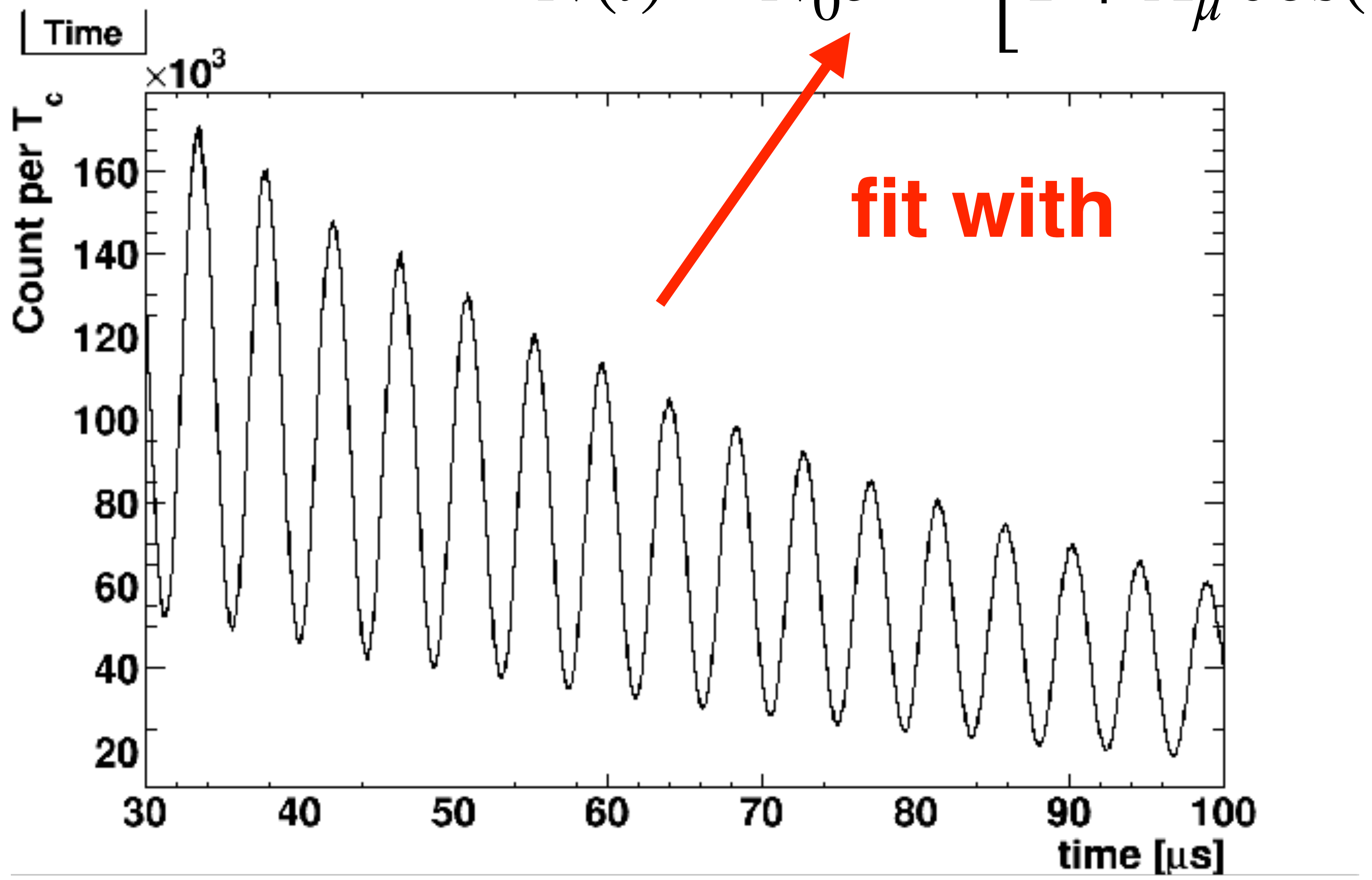
Systematics in ω_a ?

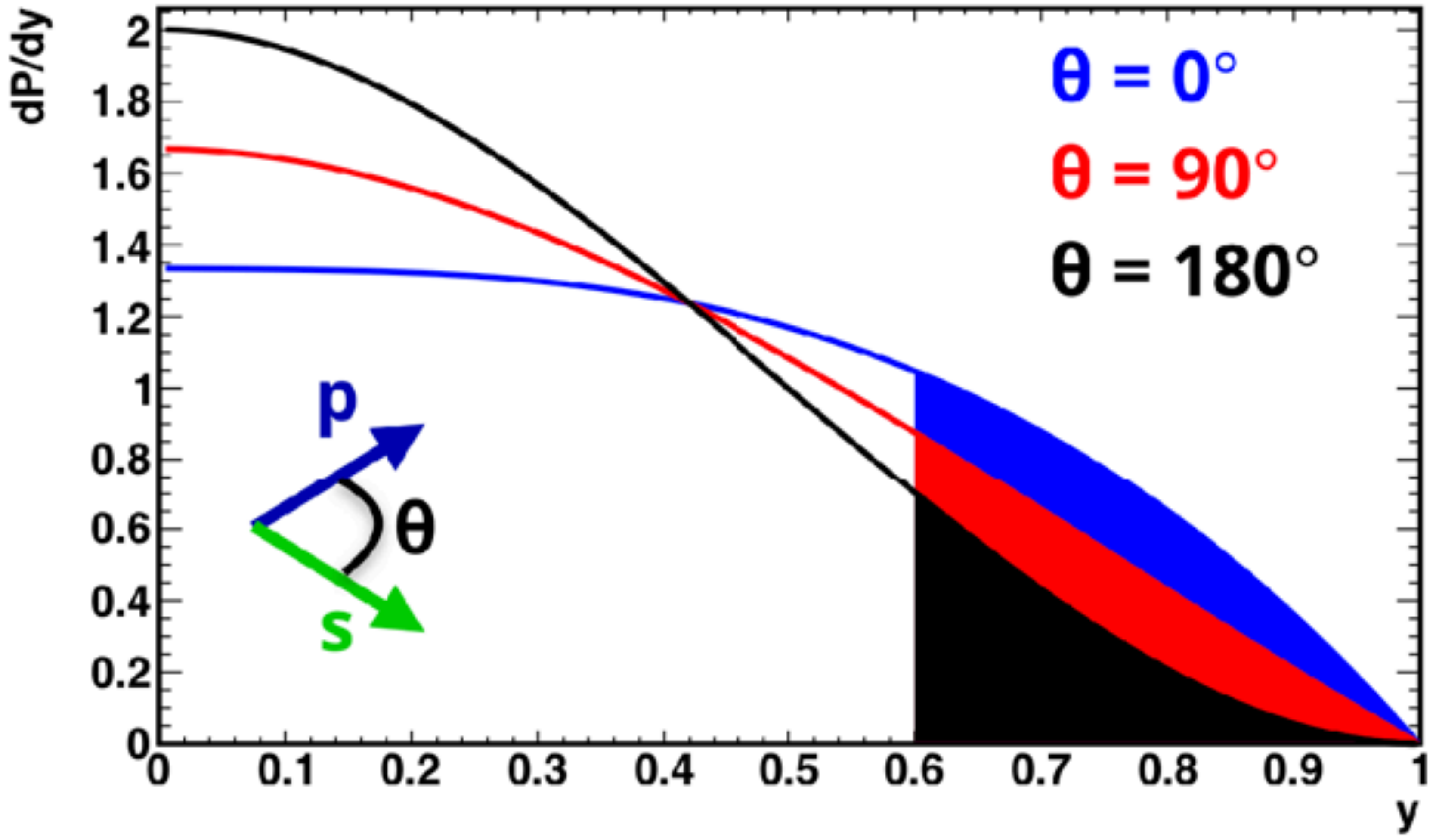


project onto X-axis

$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega t + \phi)\right]$$

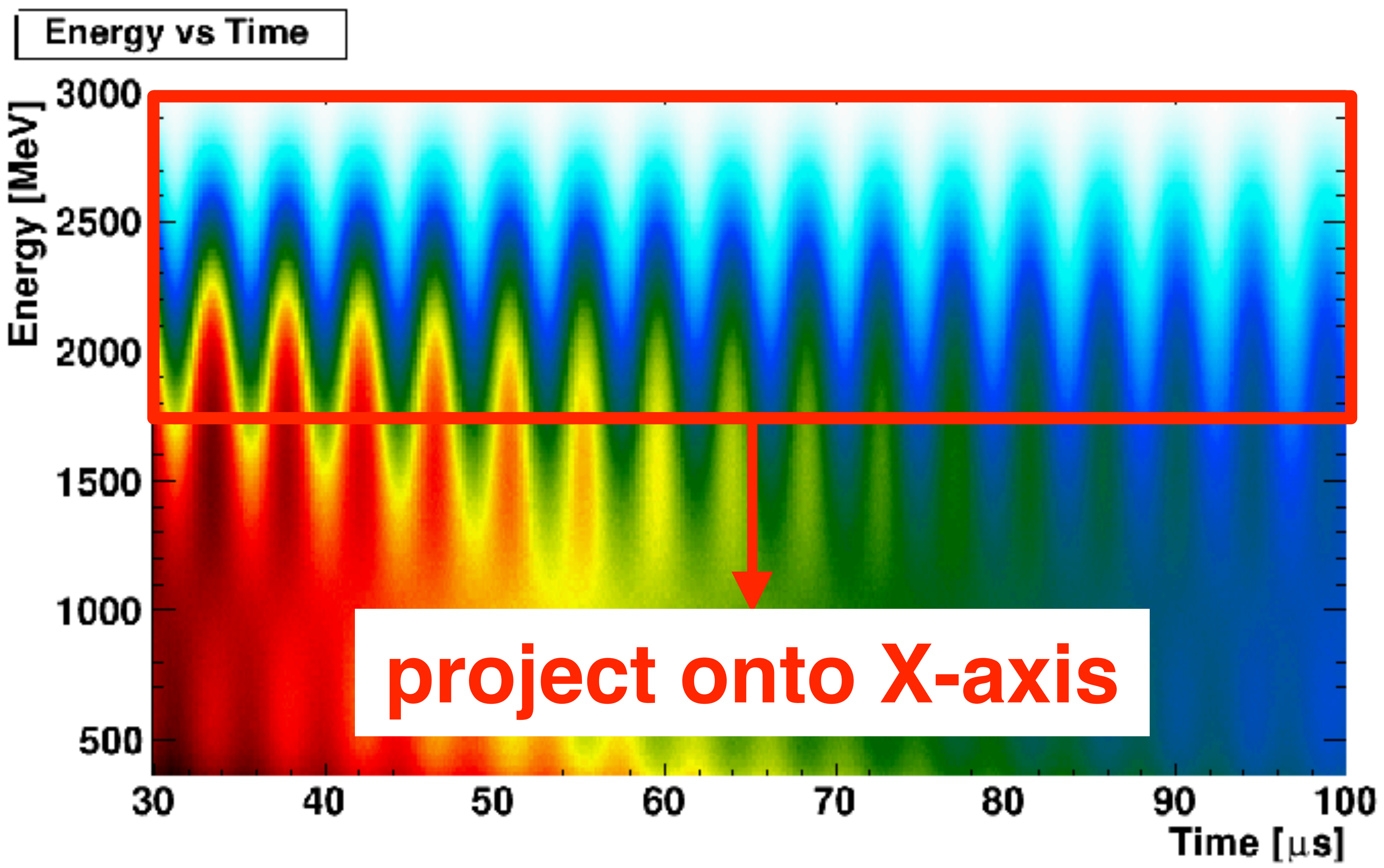
fit with

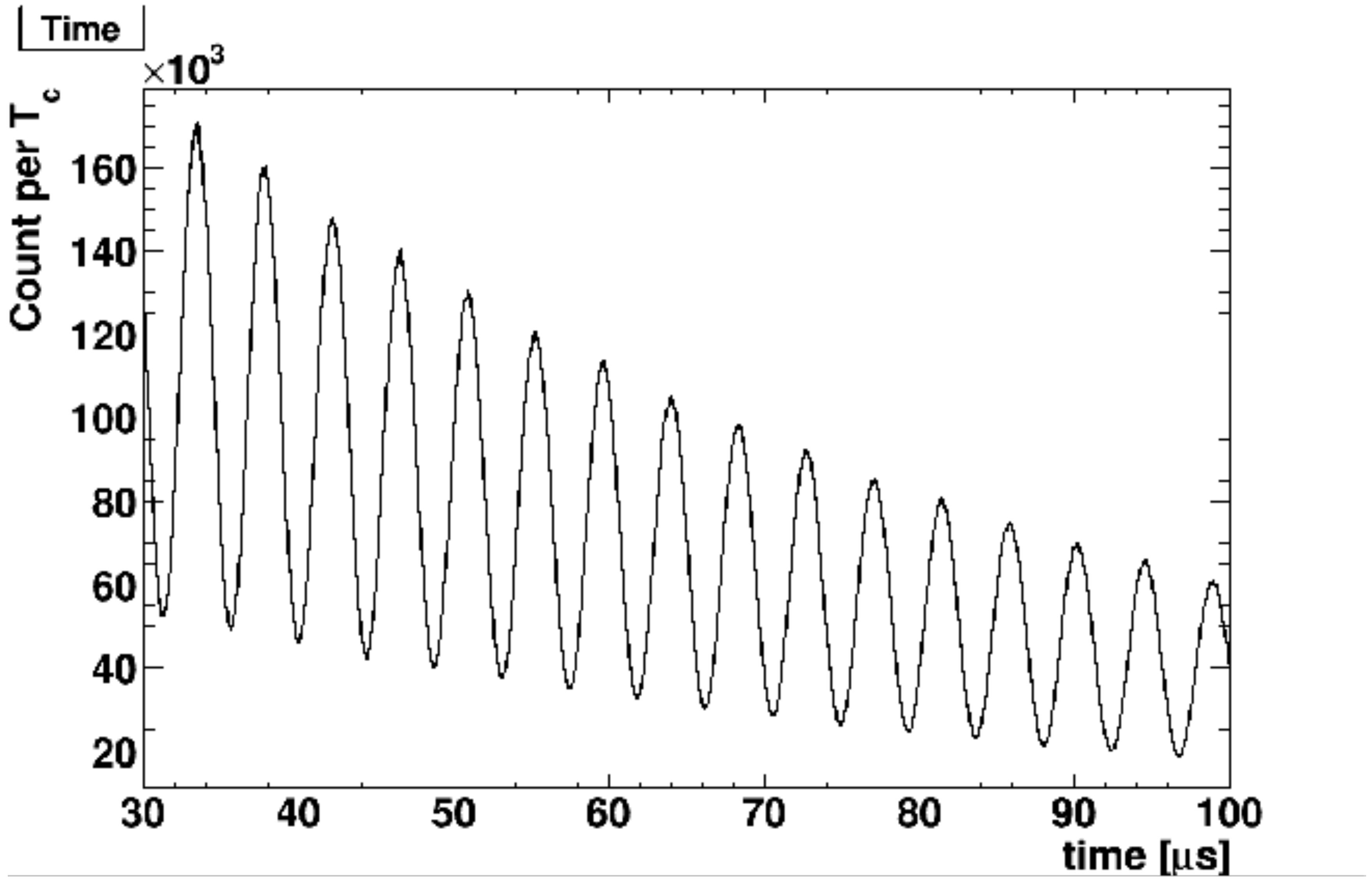




Is that all? NO!

Systematics in ω_a ?





$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega t + \phi)\right]$$

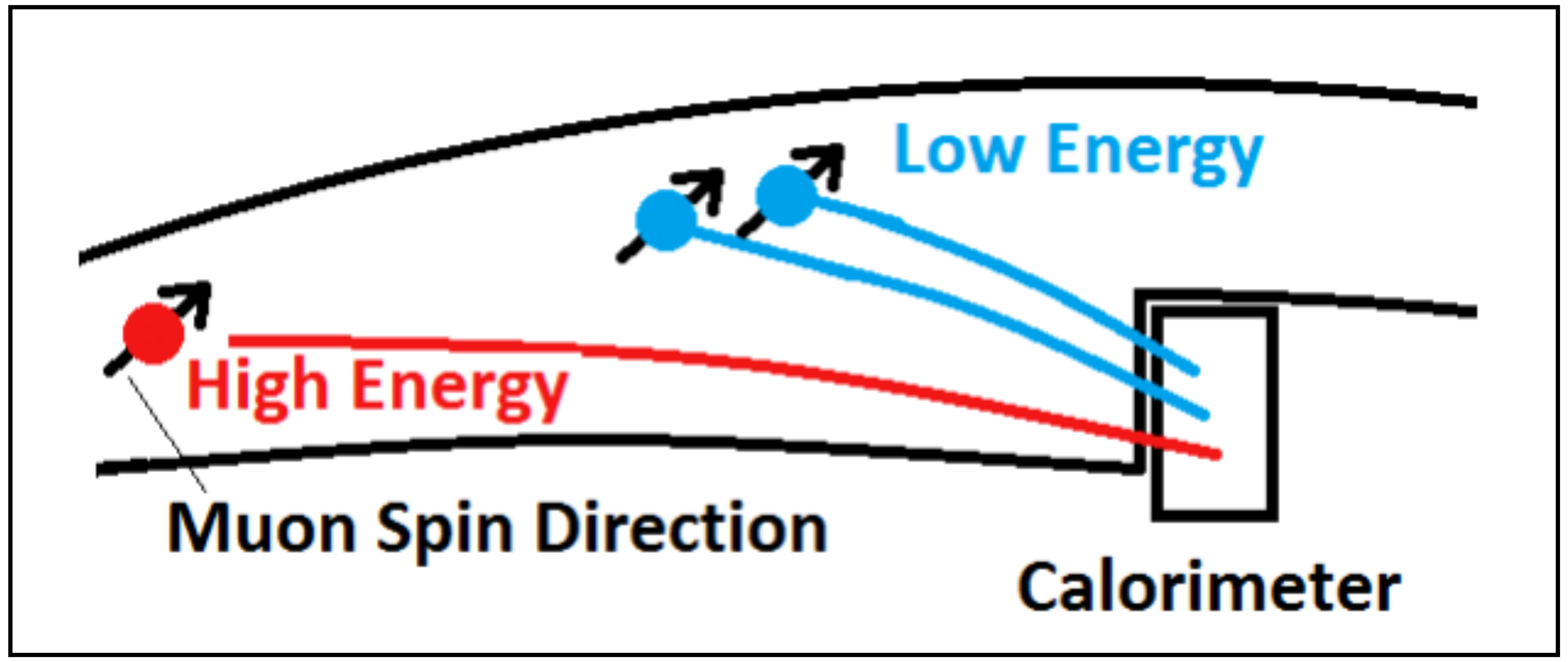
If the phase is time dependent (“early-to-late” effect)

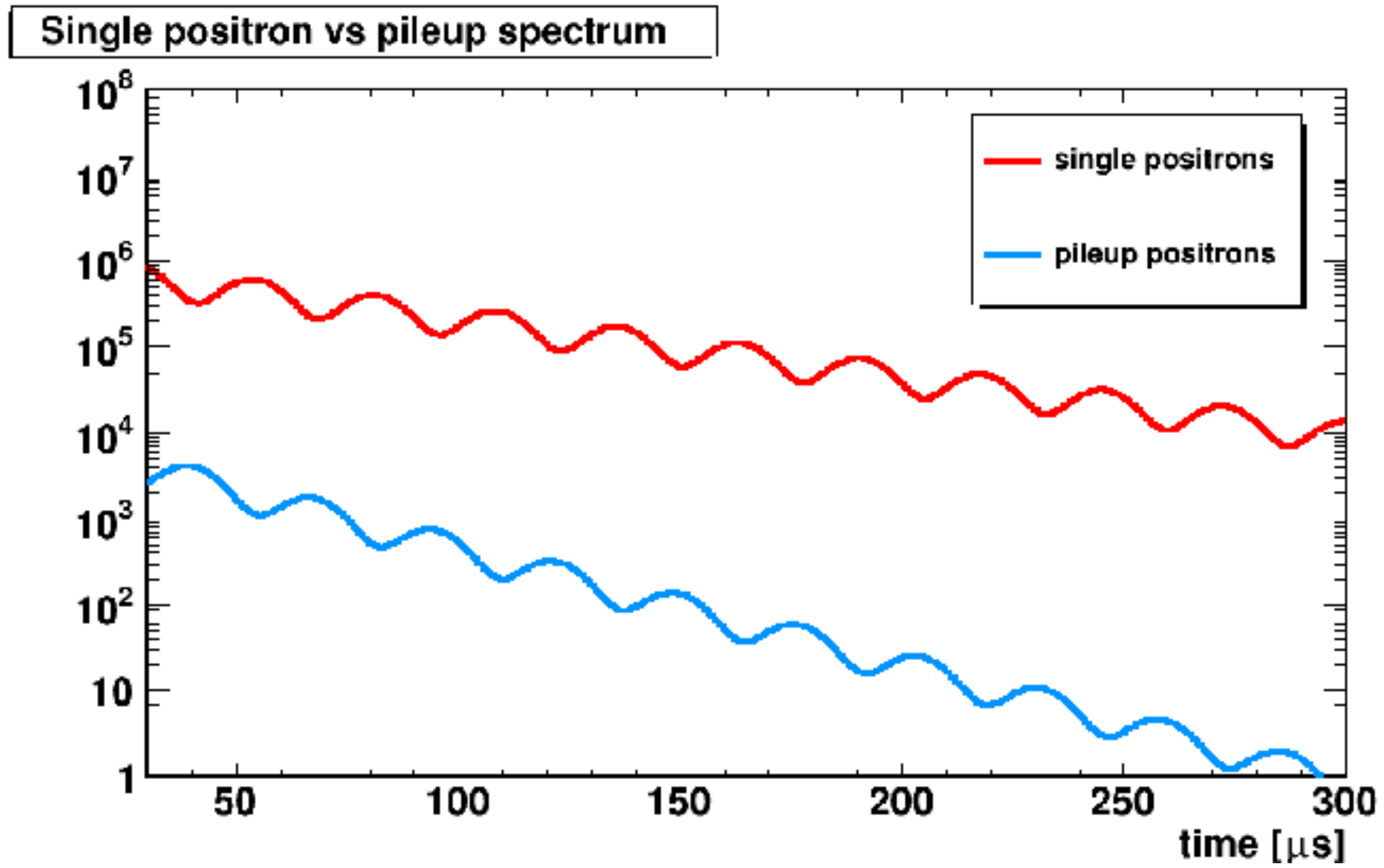
$$\begin{aligned}\omega t + \phi &= \omega t + \phi(t)\\ &= \omega t + \phi_0 + \phi' t\\ &= (\omega + \phi')t + \phi_0\end{aligned}$$

Frequency is shifted!

ω_a Systematics

- **Detector Effect**
  - Positron pileup
  - Gain instability
- **Beam Dynamics**
  - Horizontal betatron motion
  - Vertical betatron motion
  - Beam de-bunching
- **Spin Dynamics**
  - Spin-momentum correlation + muon losses



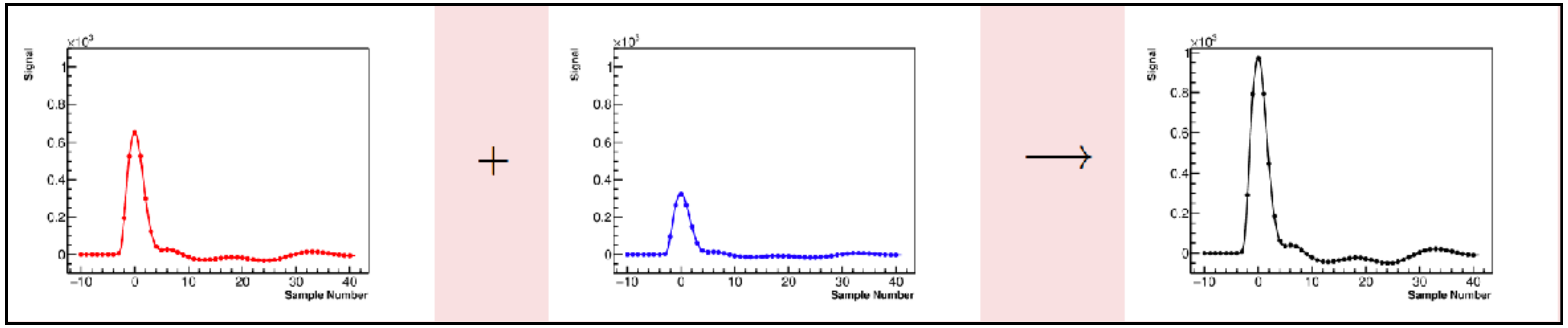


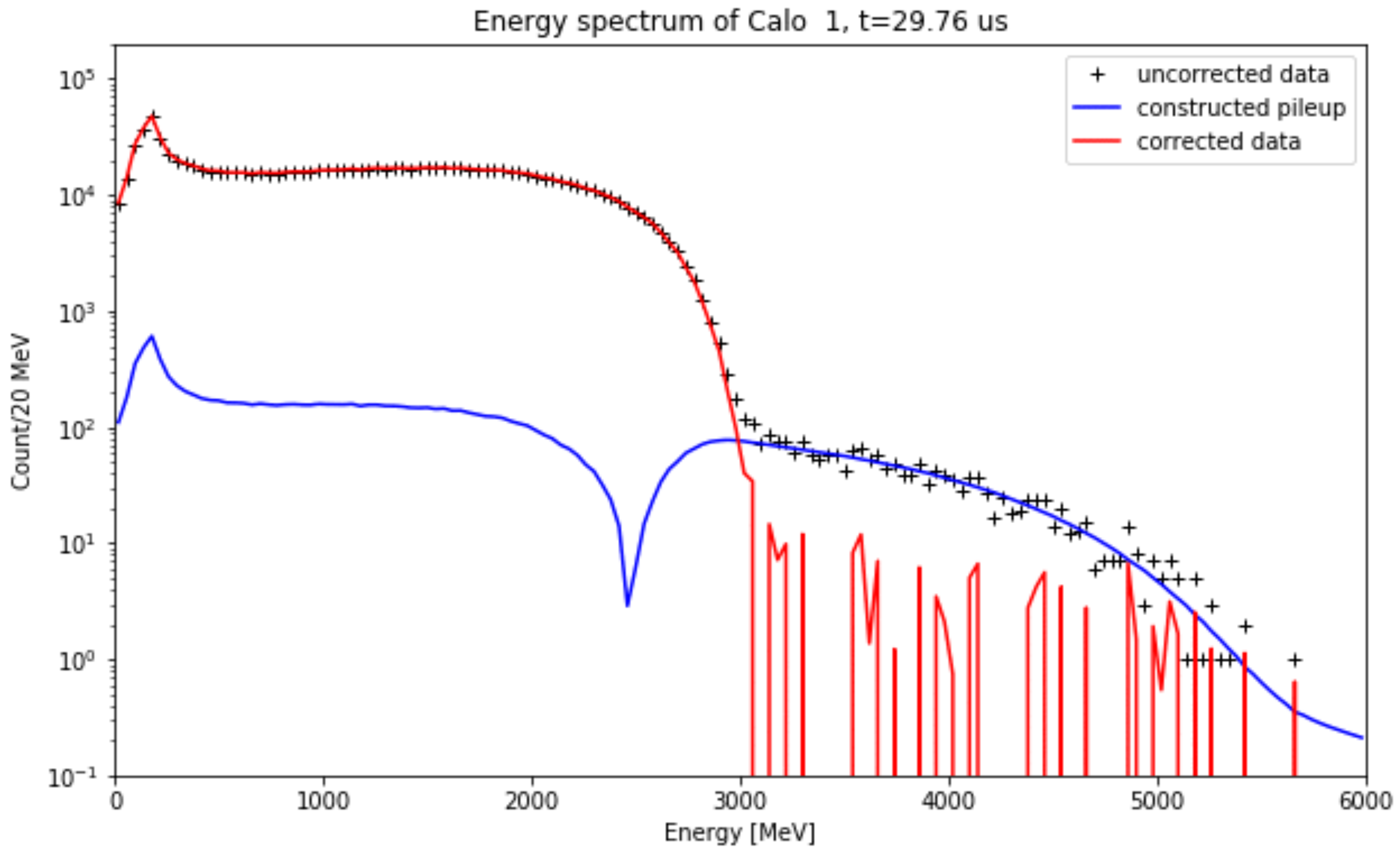
$$A_1 \cos(\omega t + \phi_1) + A_2 \cos(\omega t + \phi_2) = A_3 \cos(\omega t + \phi_3)$$

ω_a Systematics

- **Detector Effect**
  - Positron pileup
  - Gain instability
- **Beam Dynamics**
  - Horizontal betatron motion
  - Vertical betatron motion
  - Beam de-bunching
- **Spin Dynamics**
  - Spin-momentum correlation + muon losses

Artificially constructing pileup spectrum and removing it from the raw data

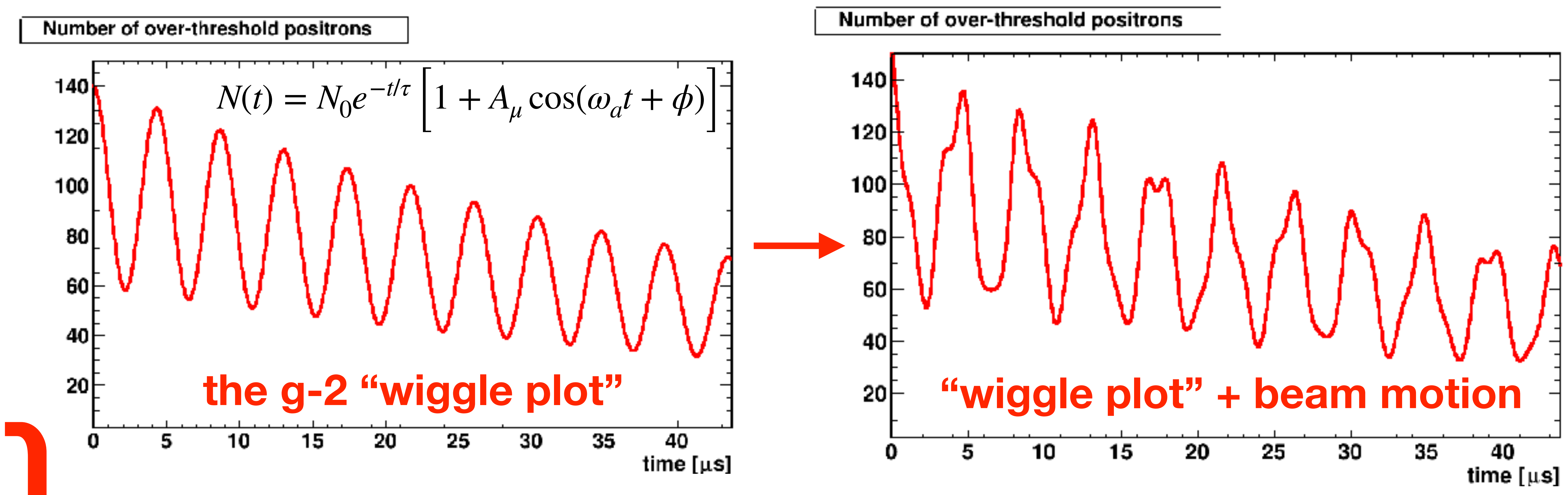




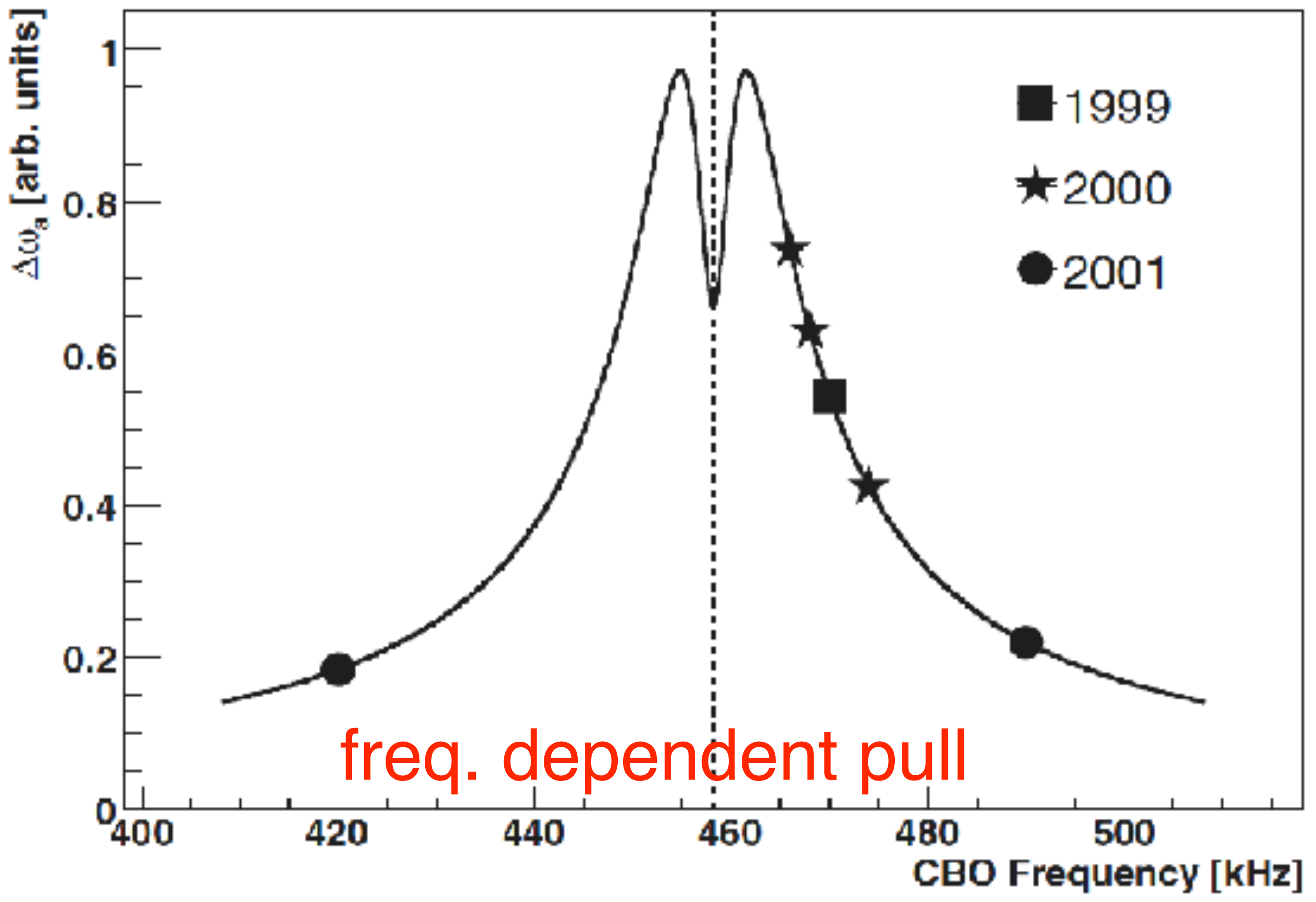
ωa Systematics

- **Detector Effect**
  - Positron pileup
  - Gain instability
- **Beam Dynamics**
  - Horizontal betatron motion
  - Vertical betatron motion
  - Beam de-bunching
- **Spin Dynamics**
  - Spin-momentum correlation + muon losses

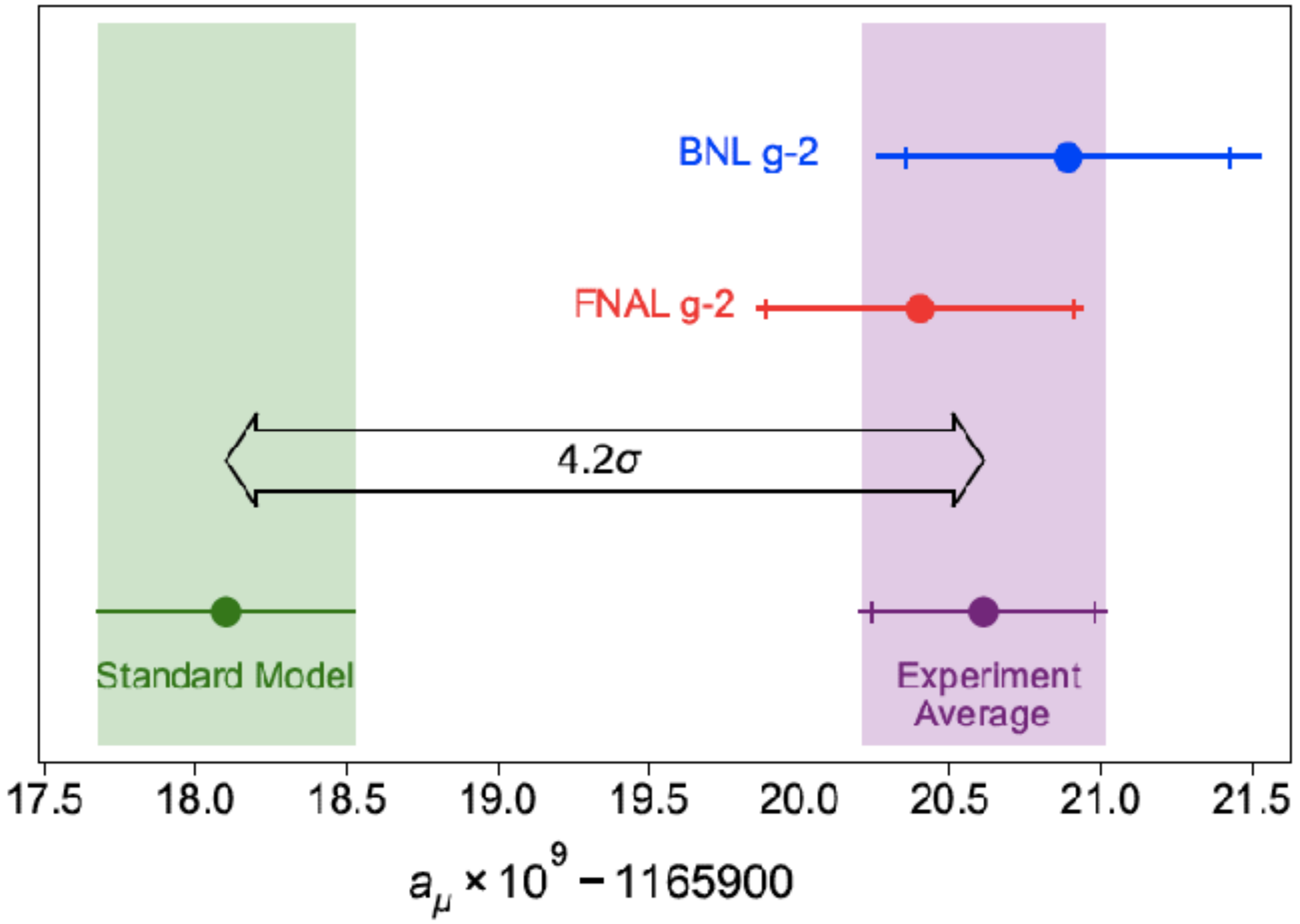
Detector acceptance effect


$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$

$$\boxed{C(t) = 1 - e^{-t/\tau_{\rm cbo}} A_1 \cos(\omega_{\rm cbo} t + \phi_1)}$$



Run-1 result (Apr 2021)



Quantity	Correction (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

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

The result, physicists say, suggests that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

"This is our Mars rover landing moment," said Chris Polly, a physicist at the Fermi National Accelerator Laboratory, or Fermilab, in Batavia, Ill., who has been working toward this finding for most of his career.

The particle under scrutiny is the muon, which is akin to an electron but far heavier, and is an integral element of the cosmos. Dr. Polly and his colleagues — an international team of 200 physicists from seven countries — found that muons did not behave as predicted when shot through an intense magnetic field at Fermilab.

The aberrant behavior poses a firm challenge to the bedrock theory of physics known as the Standard Model, a suite of equations that enumerates the fundamental particles in the universe (17, at last count) and how they interact.

"This is strong evidence that the muon is sensitive to something that is not in our best theory," said Renee Fatemi, a physicist at the University of Kentucky.

The results, the first from an experiment called Muon g-2, agreed with similar experiments at the Brookhaven National Laboratory in 2001 that have teased physicists ever since.

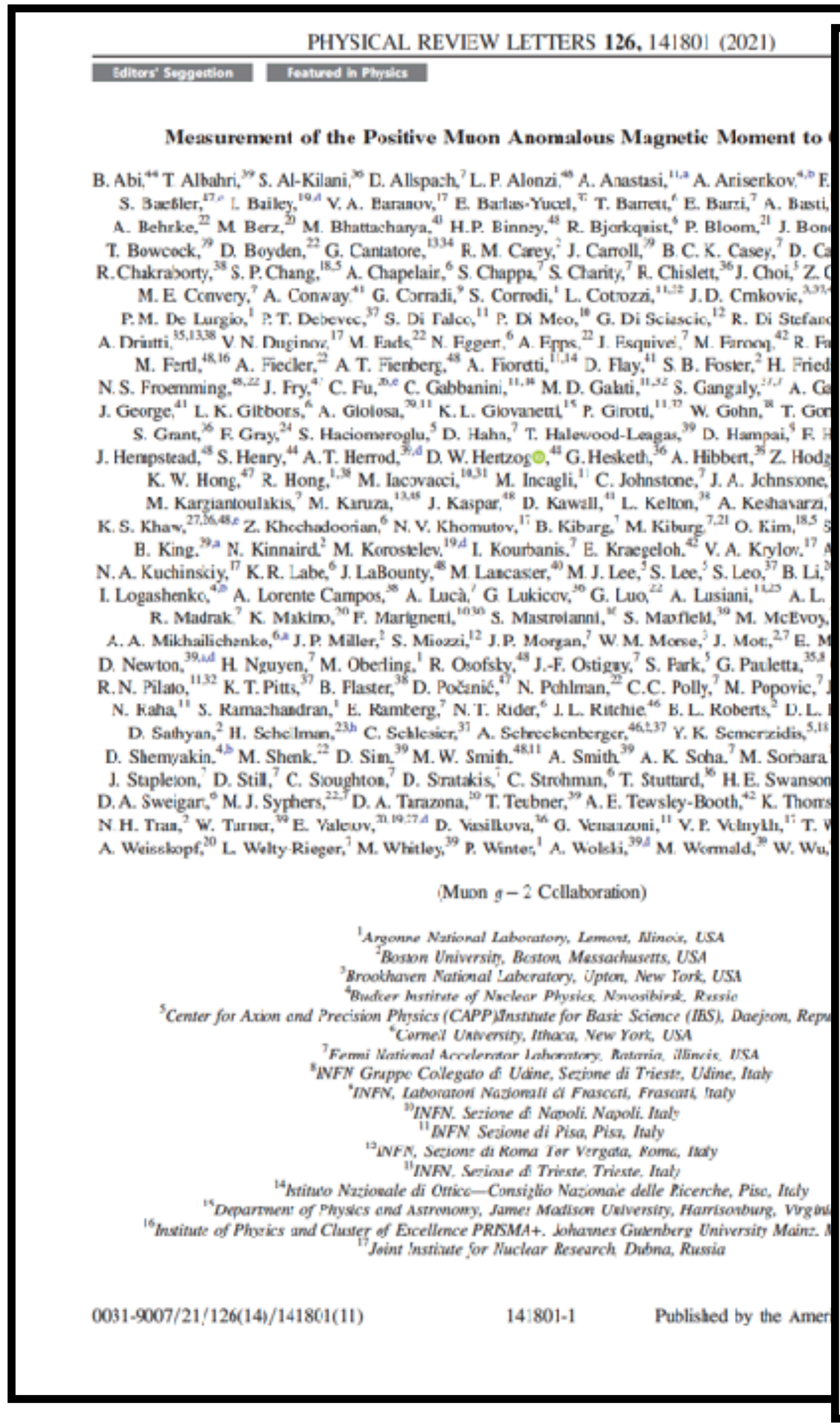
At a virtual seminar and news conference on Wednesday, Dr. Polly pointed to a graph displaying white space where the Fermilab findings deviated from the theoretical prediction. "We can say with fairly high confidence, there

Continued on Page A18

REIDAR HAHN/FERMILAB, VIA ASSOCIATED PRESS

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

Four papers in the Physical Review Series


PHYSICAL REVIEW LETTERS 126, 141801 (2021)

Editors' Suggestion | Featured in Physics

Measurement of the Positive Muon Anomalous Magnetic Moment to

(Muon $g-2$ Collaboration)

0031-9007/21/126(14)/141801(11) 141801-1 Published by the Amer

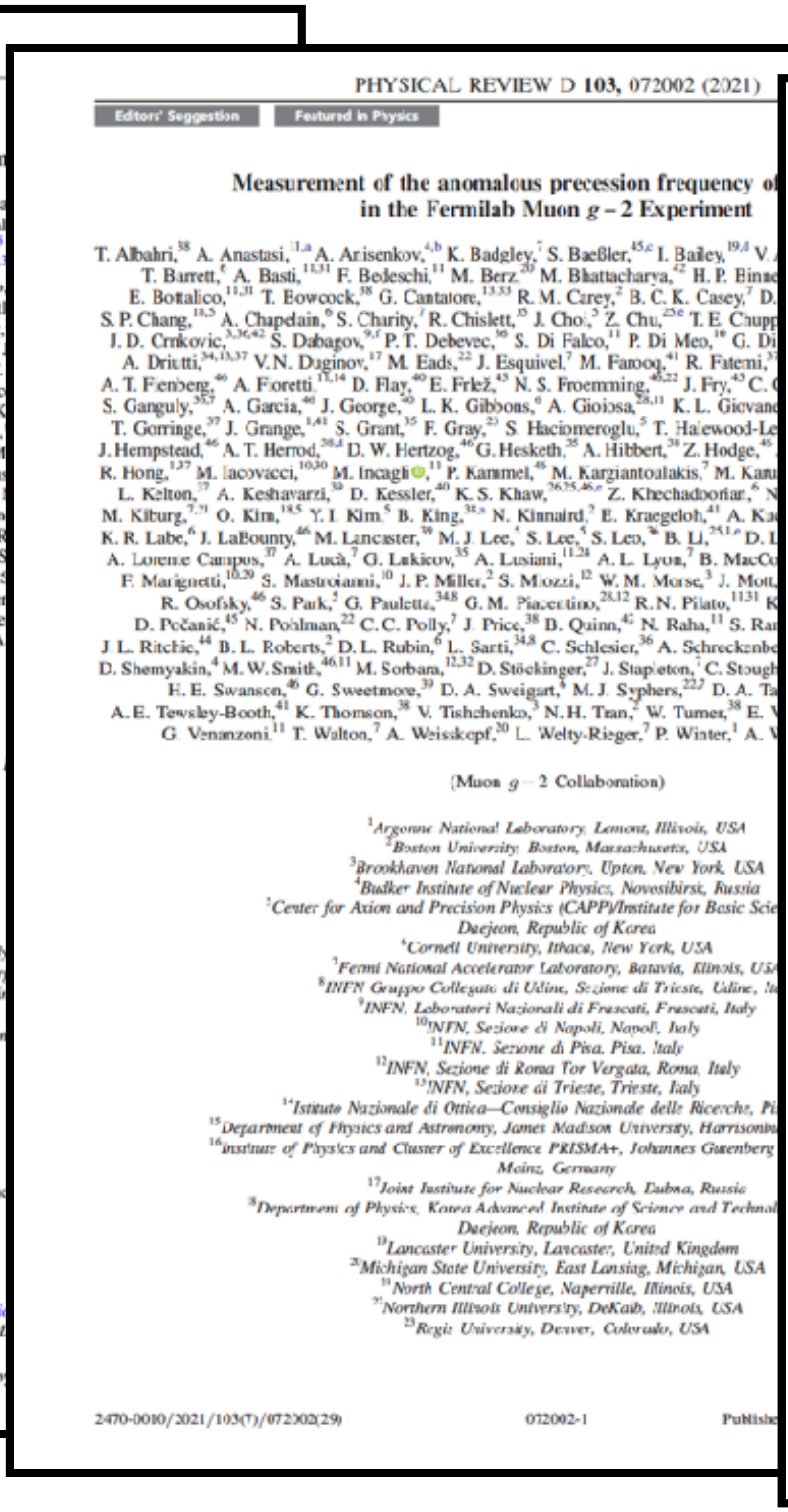

PHYSICAL REVIEW A 103, 042208 (2021)

Featured in Physics

Magnetic-field measurement and analysis for the Muon $g-2$ Experim

(The Muon $g-2$ Collaboration)

2469-9926/2021/103(4)/042208(35) 042208-1 Published b

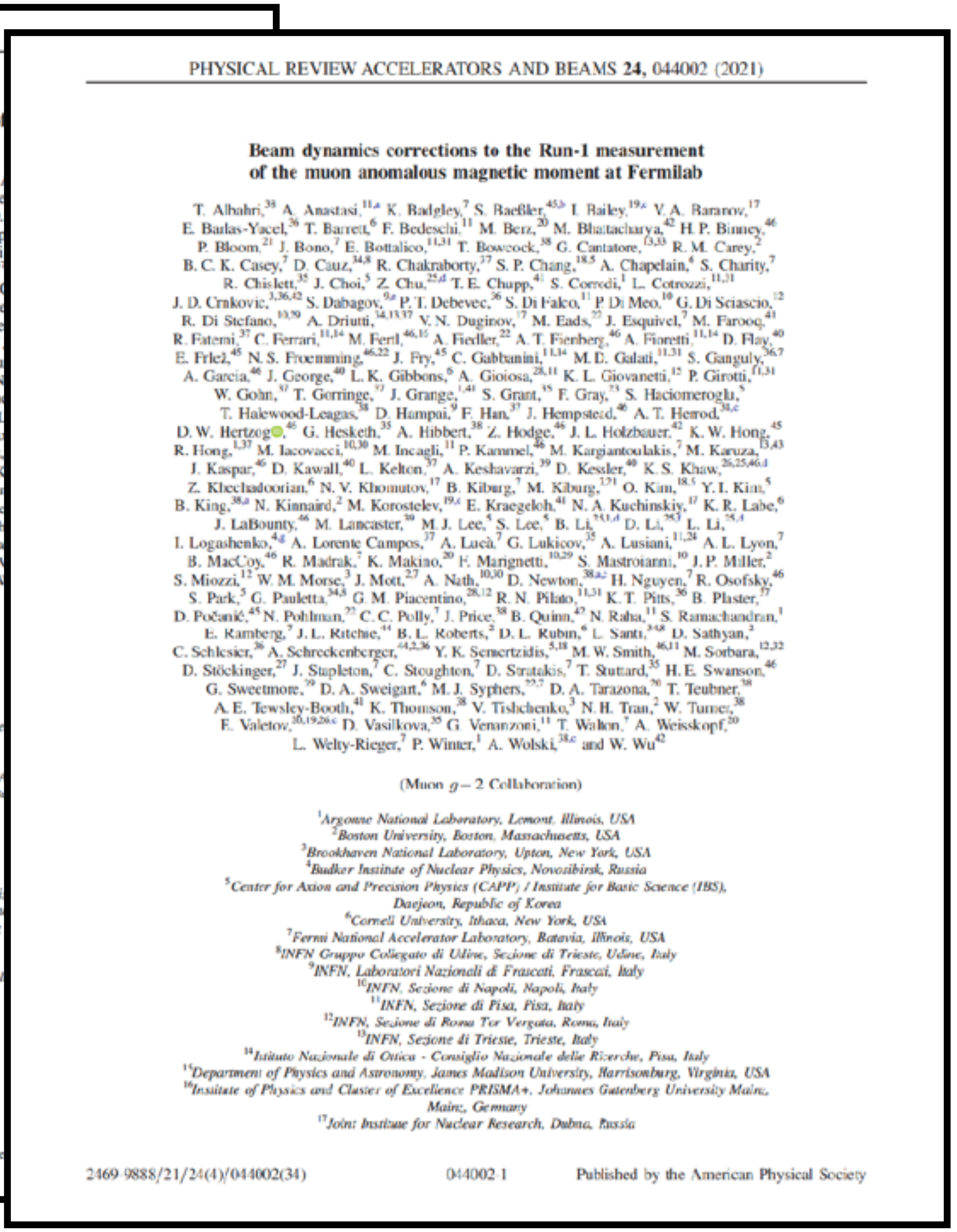

PHYSICAL REVIEW D 103, 072002 (2021)

Editors' Suggestion | Featured in Physics

Measurement of the anomalous precession frequency of the Fermilab Muon $g-2$ Experiment

(Muon $g-2$ Collaboration)

2470-0010/2021/103(7)/072002(29) 072002-1 Publishe


PHYSICAL REVIEW ACCELERATORS AND BEAMS 24, 044002 (2021)

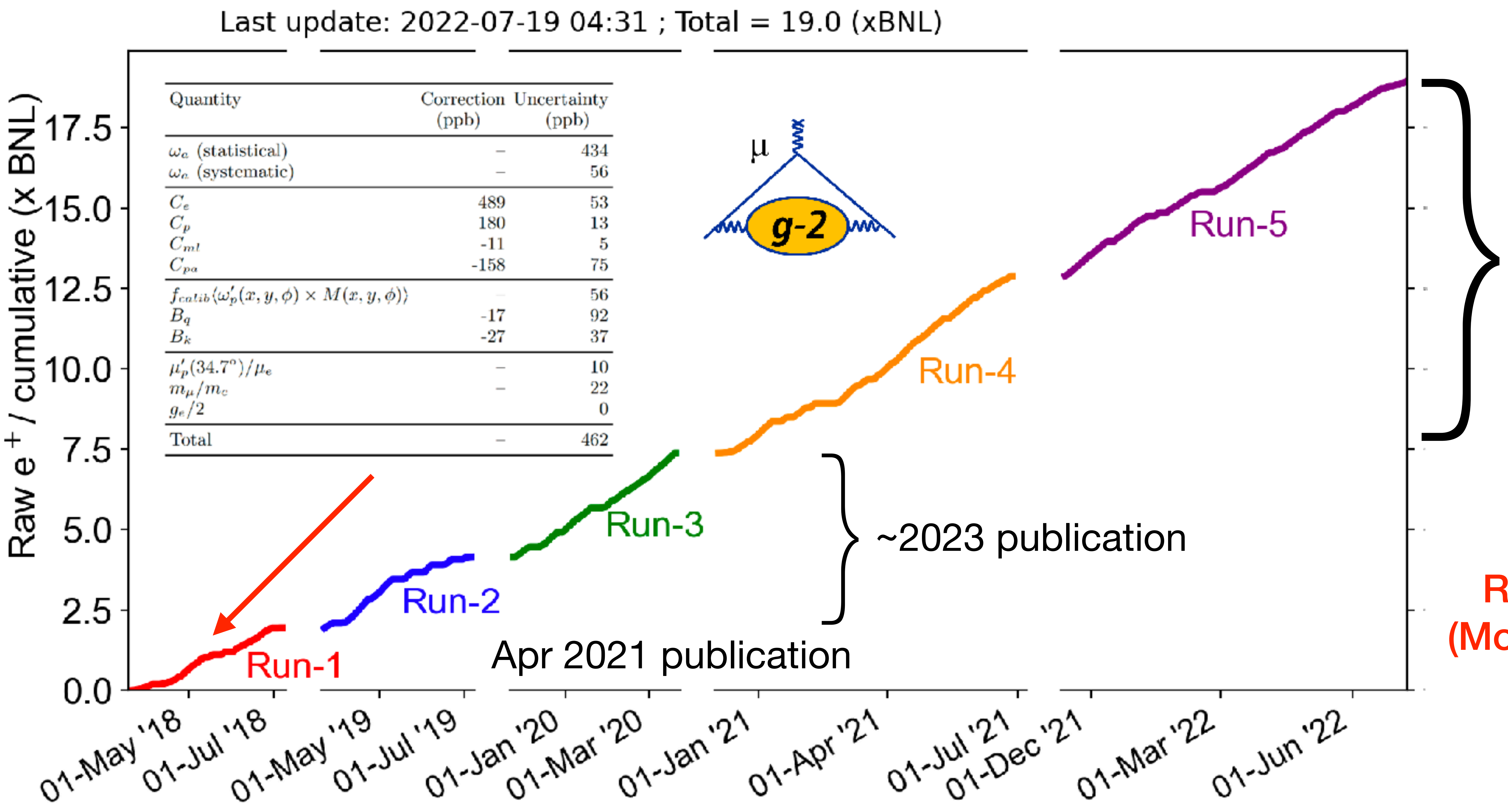
Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

(Muon $g-2$ Collaboration)

2469-9888/21/24(4)/044002(34) 044002-1 Published by the American Physical Society

For more details, please refer to our papers (only 100+ pages!)

Current status



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m_μ/m_e	–	22
$g_e/2$	–	0
Total	–	462

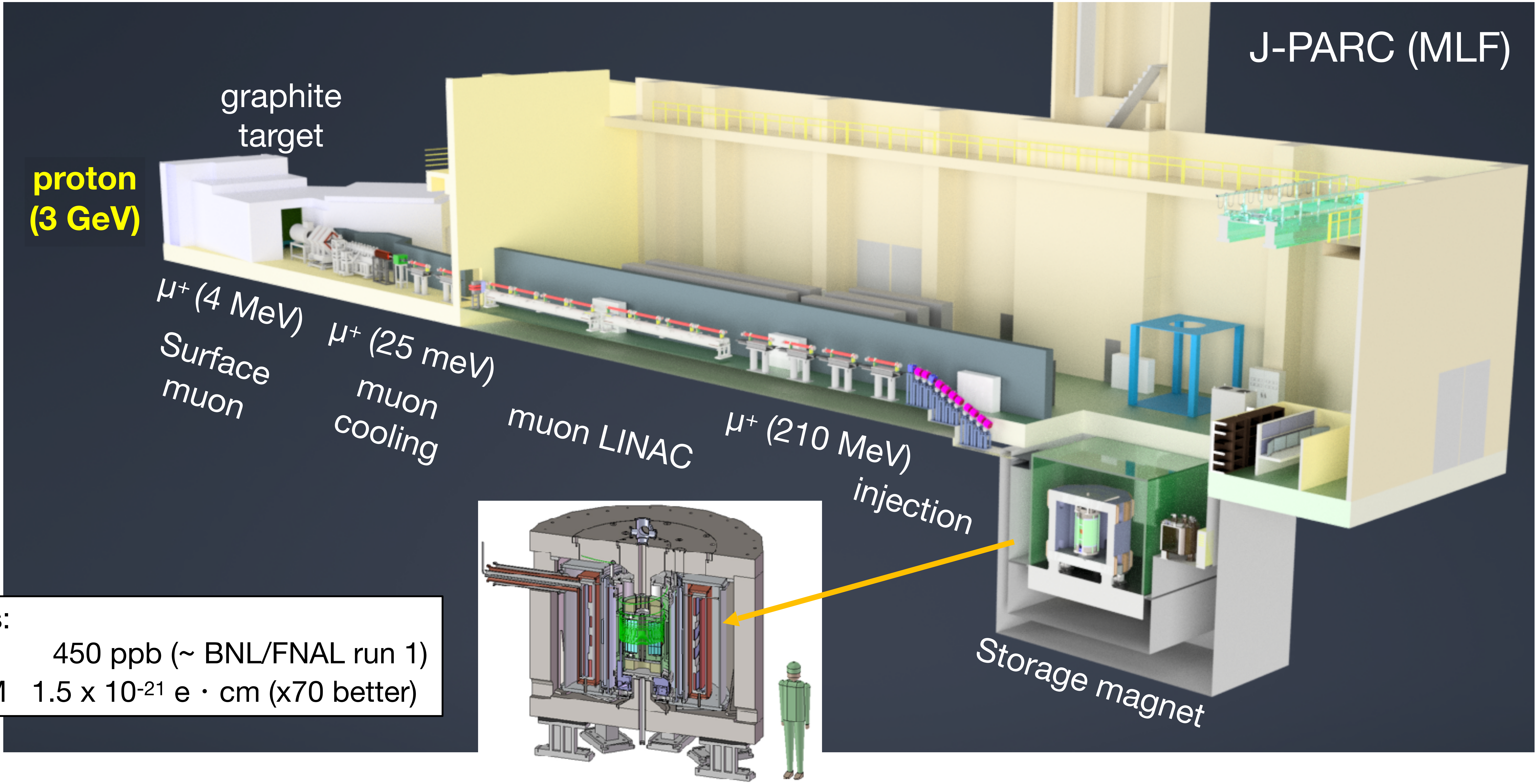
Apr 2021 publication

~2023 publication

~2024/2025 publication

Run-6 has started this Fall
(More stats + systematic runs)

J-PARC Muon g-2/EDM



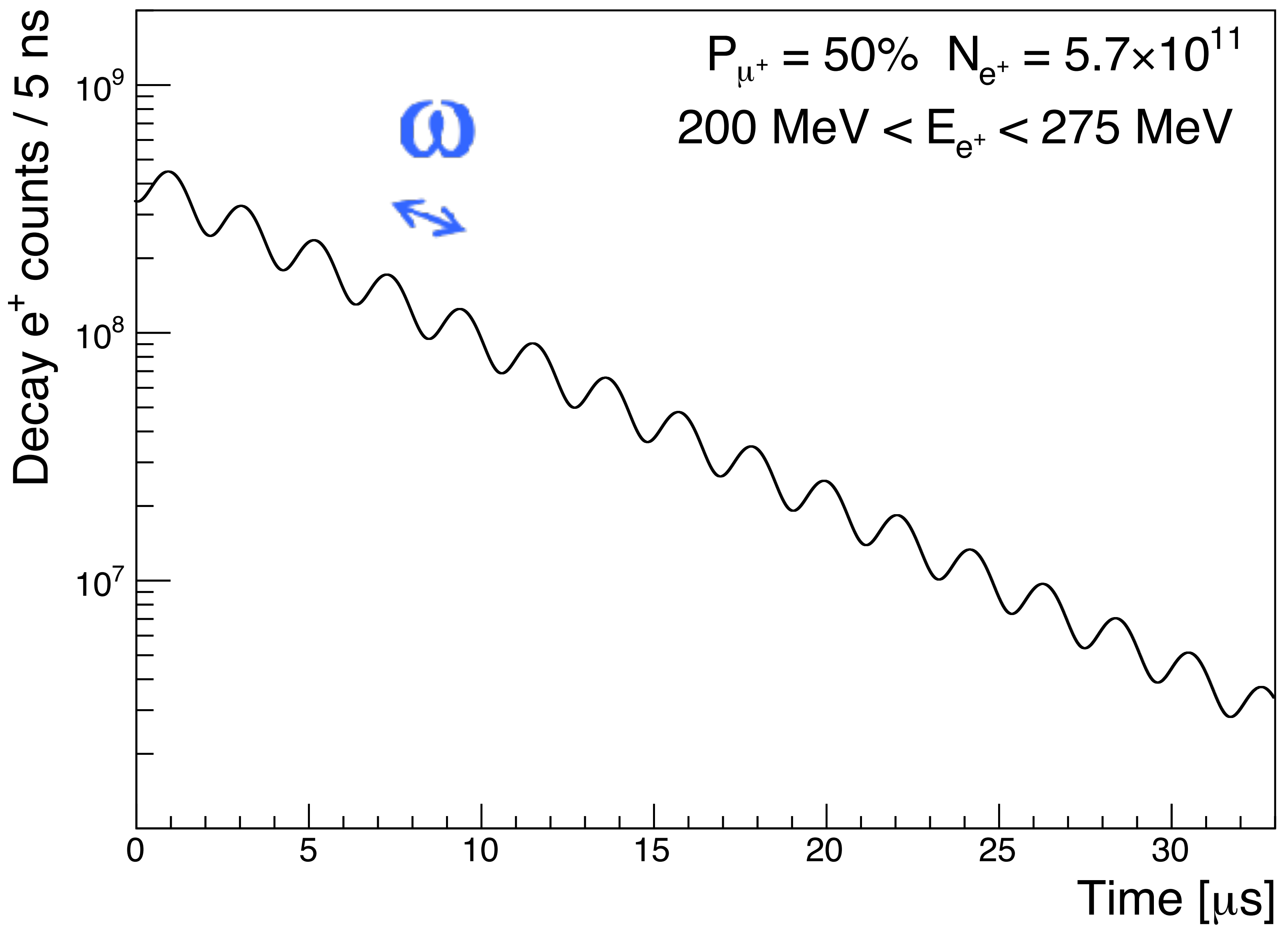
Goals:

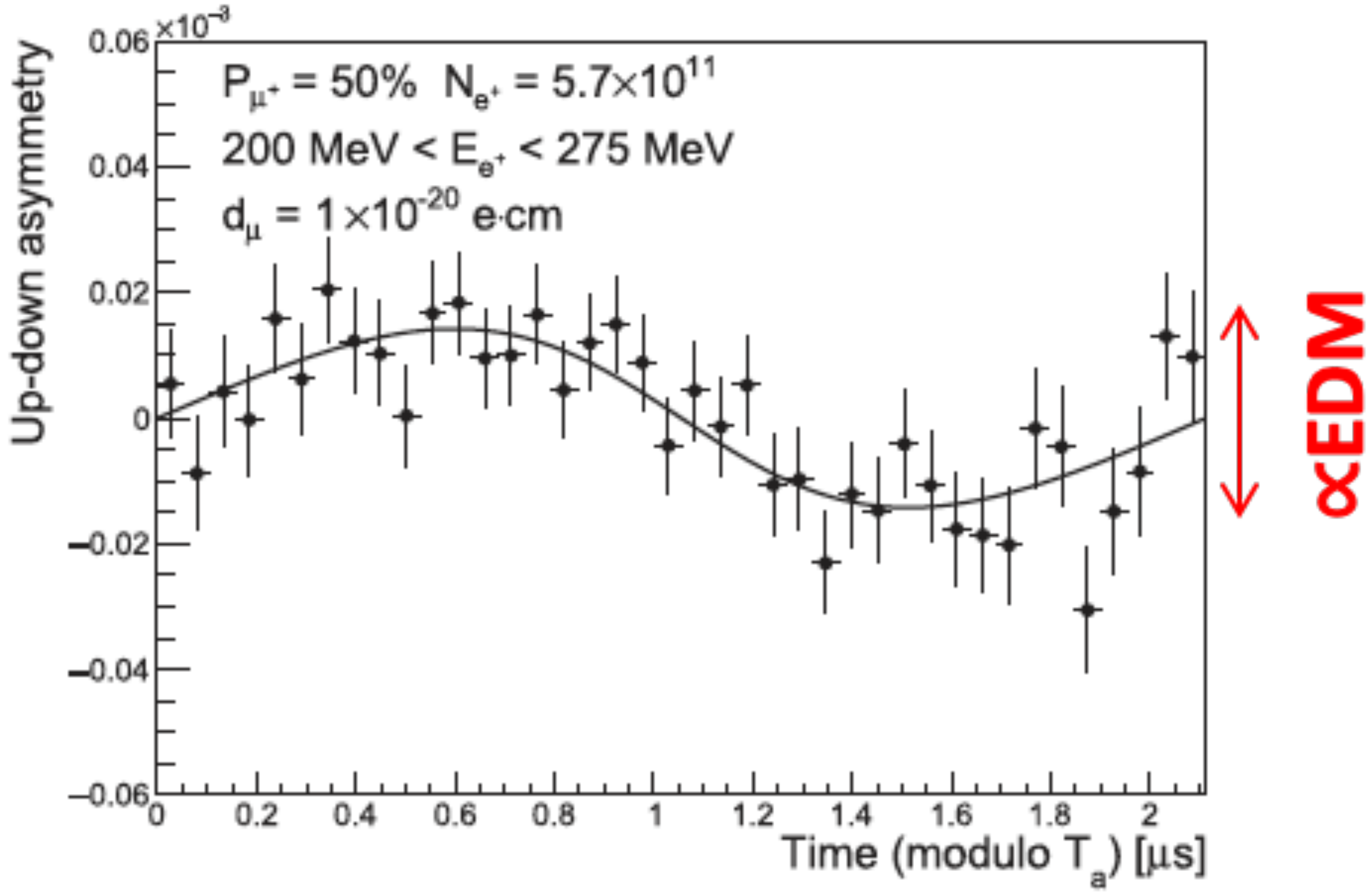
g-2	450 ppb (~ BNL/FNAL run 1)
EDM	1.5 x 10^{-21} e・cm (x70 better)

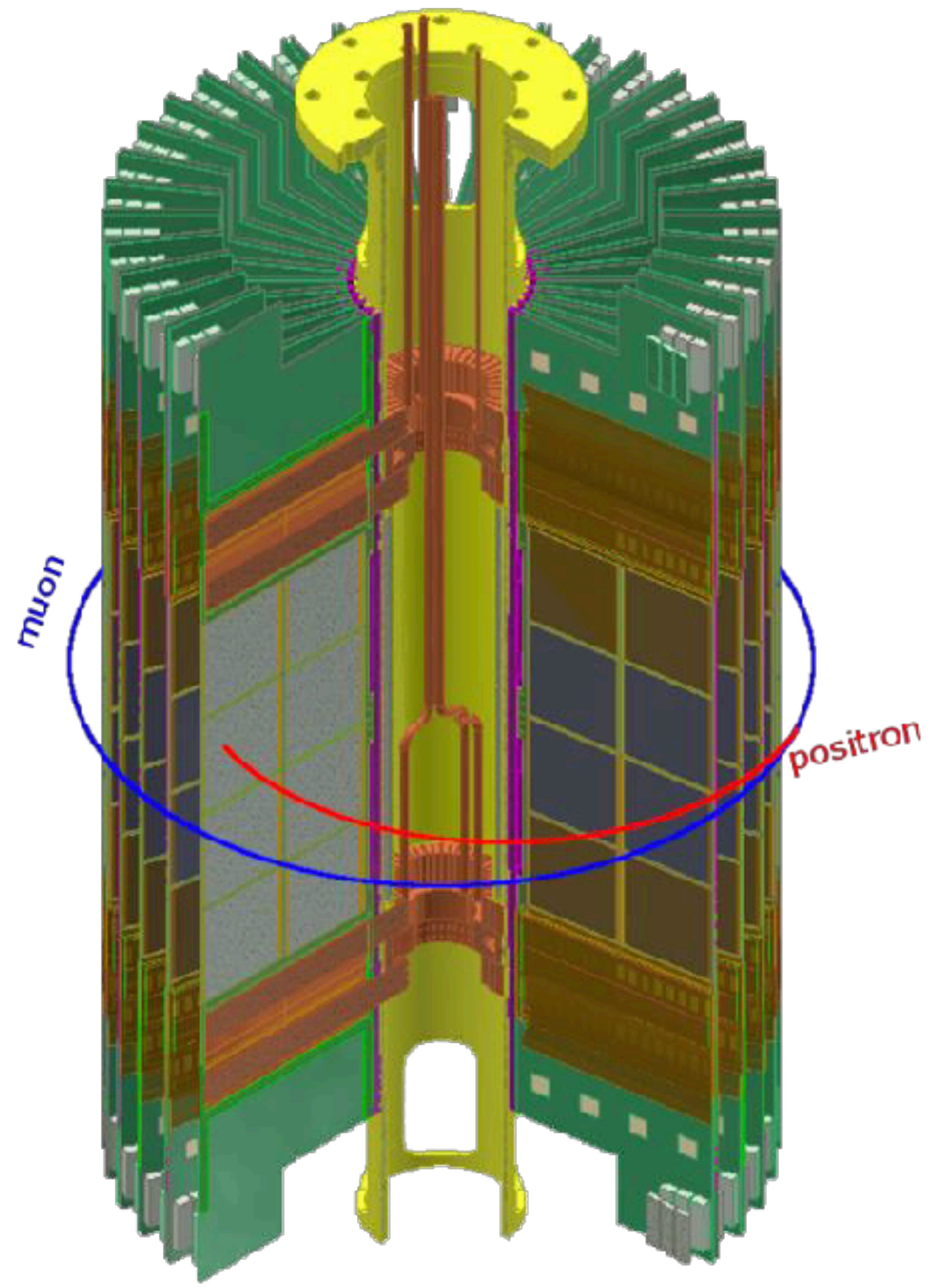
Muon g-2 and EDM

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

p = 300 MeV/c muon
No electrostatic quadrupole







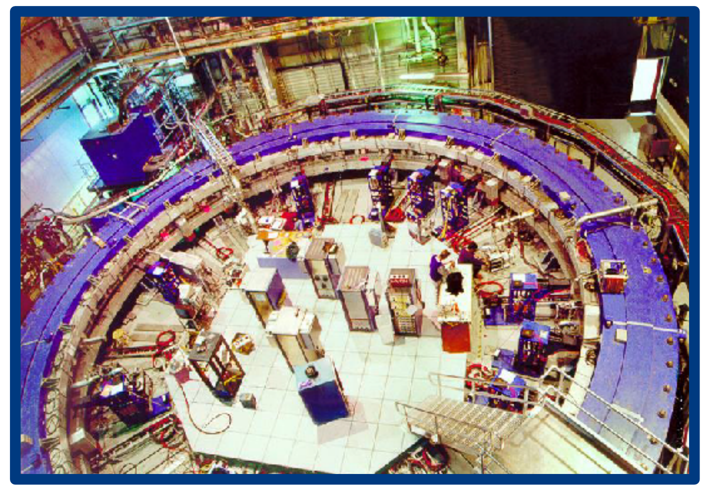
Tracker-only measurement

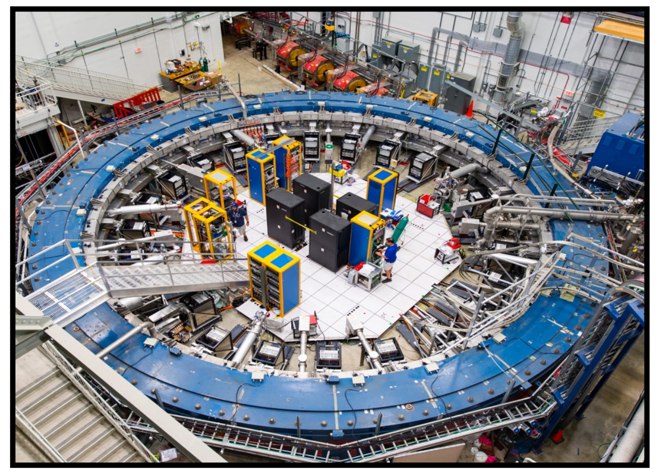
Uncertainties on a_μ [ppb]	450 (stat.) < 70 (syst.)
Uncertainties on EDM [10^{-21} e·cm]	1.5 (stat.) 0.36 (syst.)

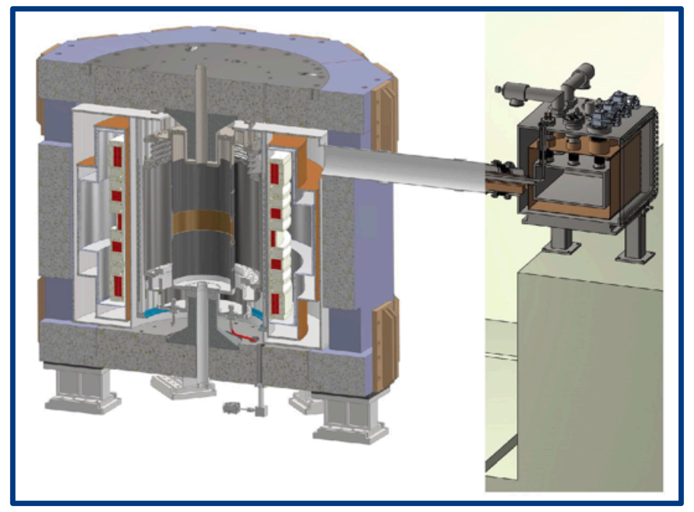
Detector misalignment

Systematics from axial E-field and radial B-field can be neglected

Fermilab vs J-PARC

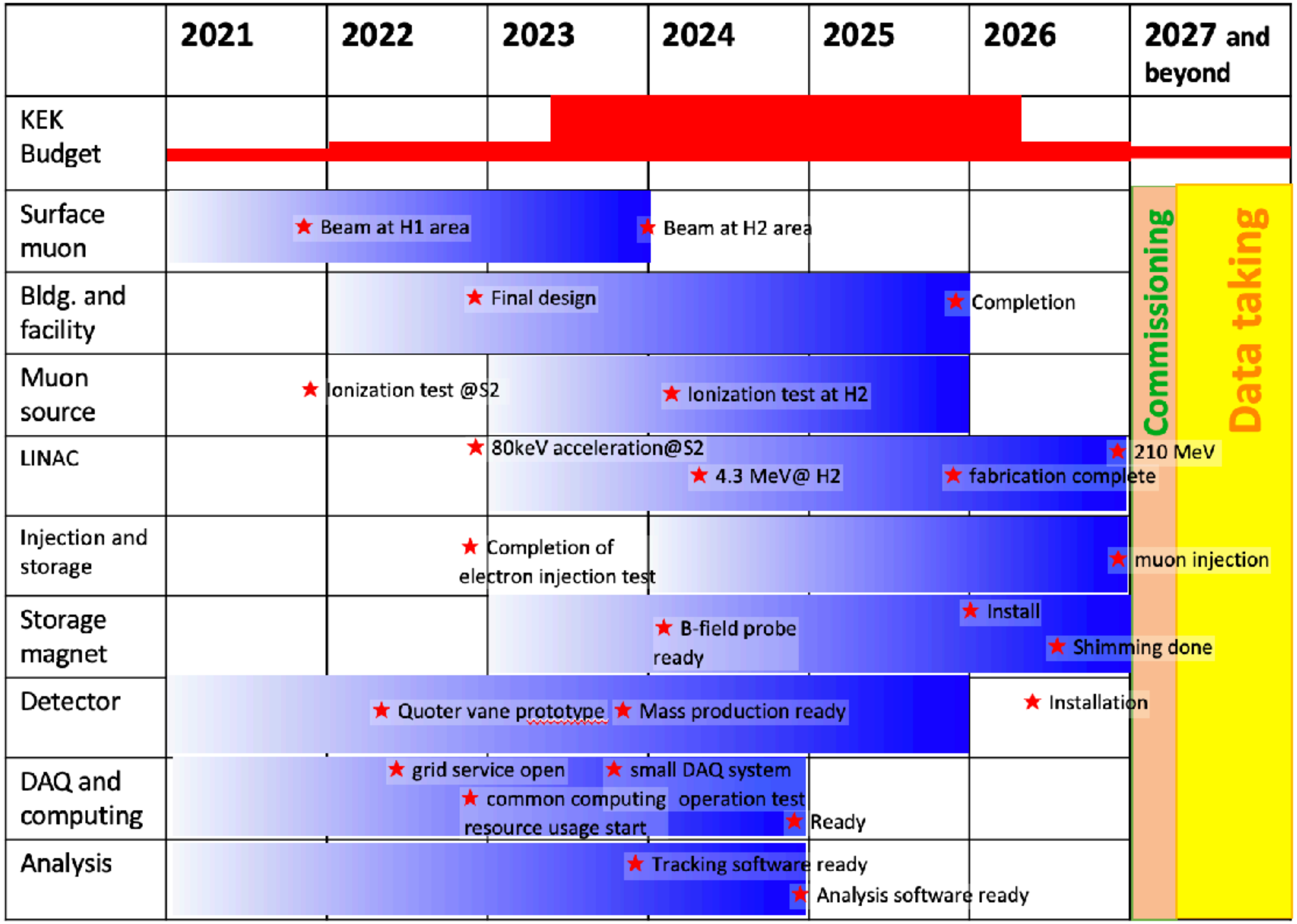




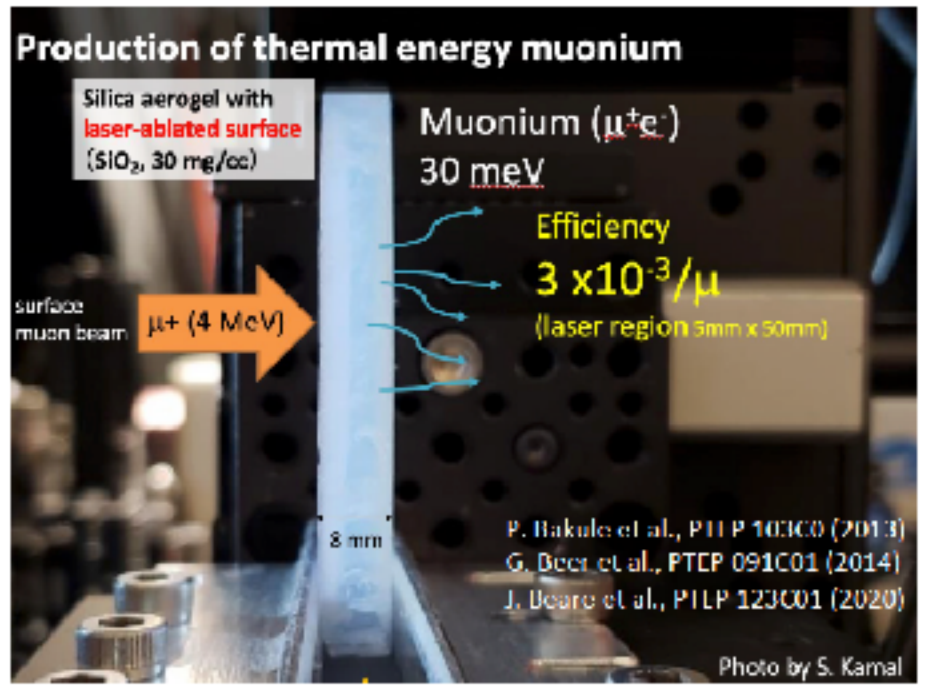


	BNL-E821	Fermilab-E989	J-PARC-E34
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	$0.2 \times 10^{-19}\ e \cdot \mathrm{cm}$	–	$1.5 \times 10^{-21}\ e \cdot \mathrm{cm}$
(syst.)	$0.9 \times 10^{-19}\ e \cdot \mathrm{cm}$	–	$0.36 \times 10^{-21}\ e \cdot \mathrm{cm}$

Schedule and milestones

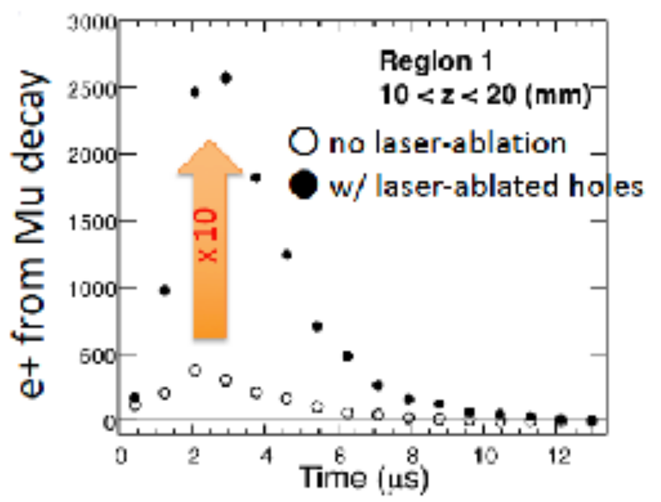


	2021	2022	2023	2024	2025	2026	2027 and beyond
KEK Budget							
Surface muon	★ Beam at H1 area			★ Beam at H2 area			Commissioning Data taking
Bldg. and facility		★ Final design			★ Completion		
Muon source	★ Ionization test @S2			★ Ionization test at H2			
LINAC		★ 80keV acceleration@S2		★ 4.3 MeV@ H2	★ fabrication complete	★ 210 MeV	
Injection and storage		★ Completion of electron injection test				★ muon injection	
Storage magnet				★ B-field probe ready		★ Install ★ Shimming done	
Detector		★ Quoter vane prototype	★ Mass production ready			★ Installation	
DAQ and computing		★ grid service open ★ common computing resource usage start	★ small DAQ system operation test	★ Ready			
Analysis			★ Tracking software ready	★ Analysis software ready			


Production of thermal energy muonium

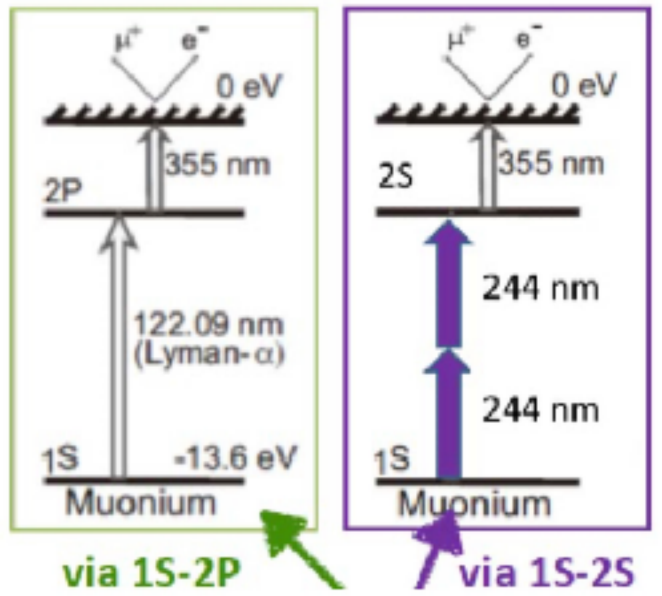
P. Bakule et al., PTEP 103C01 (2013)
G. Beer et al., PTEP 091C01 (2014)
J. Beare et al., PTEP 123C01 (2020)
Photo by S. Kamal

Muonium yield measured at TRIUMF

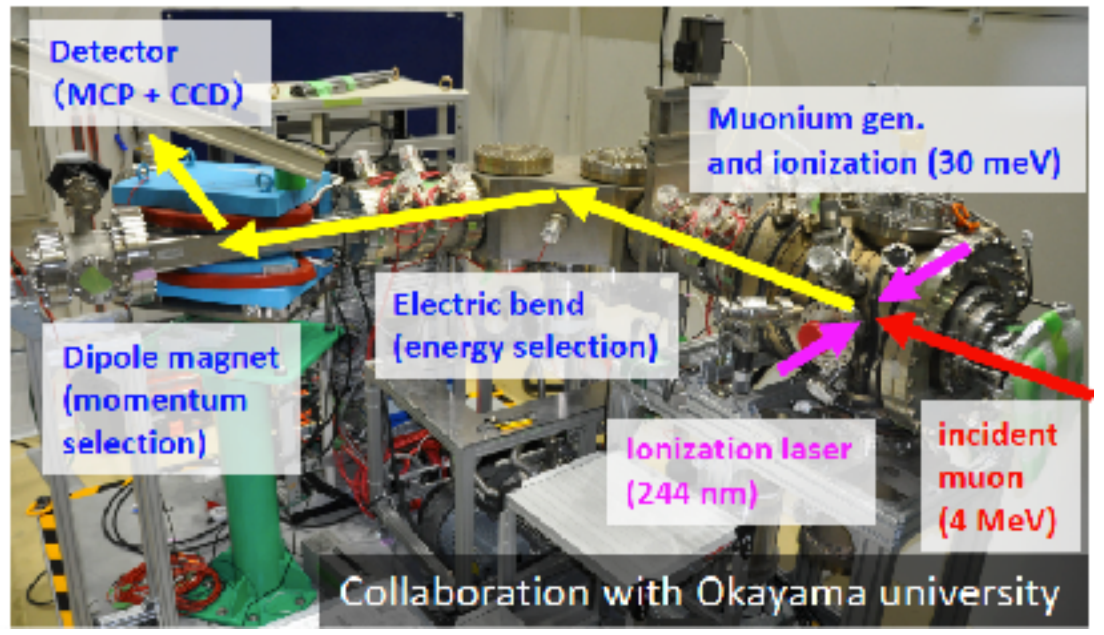


Sufficient efficiency to achieve Δa_μ~450ppb

Schemes of ionization



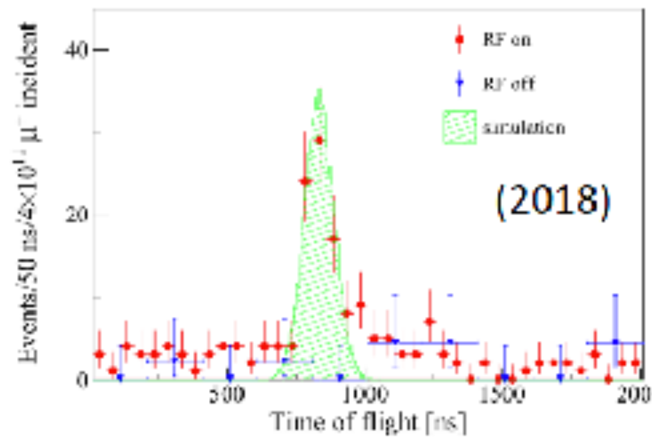
Our version of "Steven Chu's" experiment at J-PARC



Collaboration with Okayama university


Phys. Rev. AB, 19, 040101 (2016)
Phys. Rev. AB, 21, 050101 (2018)
Phys. Rev. AB, 23, 022804 (2020)
Phys. Rev. AB, 24, 033403 (2021)

80 keV acceleration of Mu$^-$($\mu^+e^-e^-$)

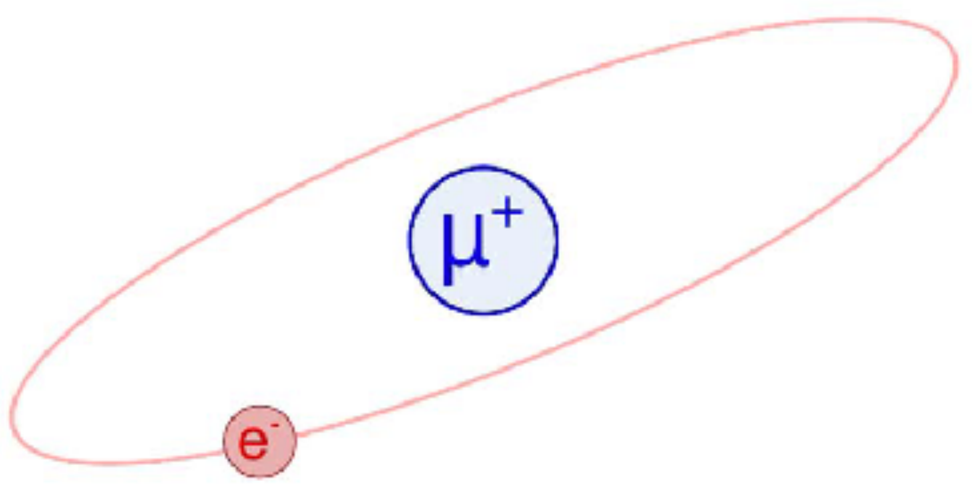


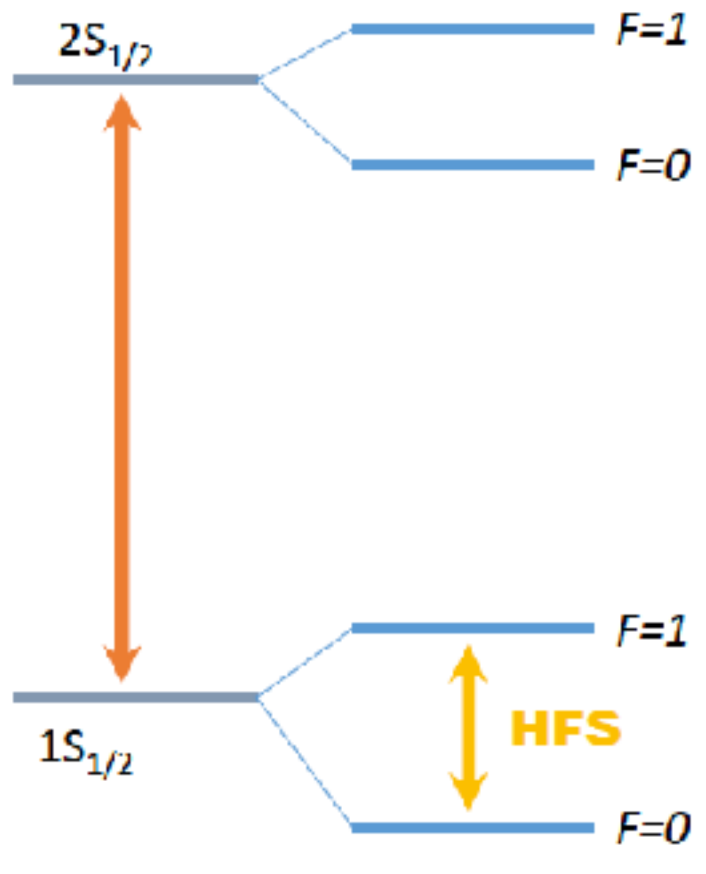
Demonstrated acceleration of Mu-
Next: demonstration of acceleration of μ+

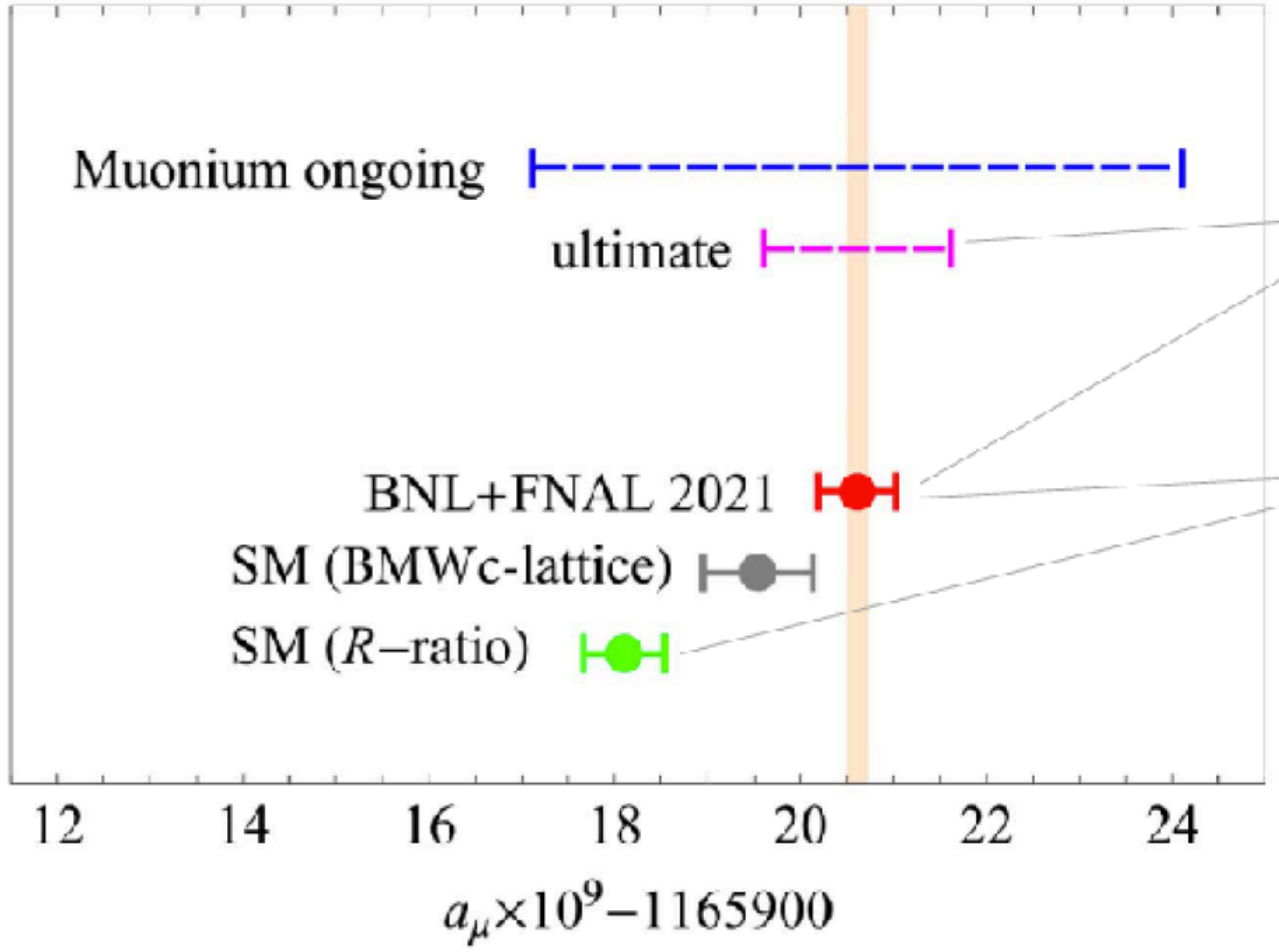
Muon g-2 from muonium spectroscopy

Tsung-Dao Lee Institute

Phys.Rev.Lett. 127 (2021) 25, 251801







A value of a_μ^{Mu} at $\mathcal{O}(1\text{ppm})$ is not competitive to current spin-precession measurements

However, it may help to understand the origin of the $\sim 2\text{ppm}$ difference between (R-ratio) SM and experiment

Ground-state HFS theory

$$\nu_{\text{HFS}} = \frac{16}{3}(1 + a_\mu)\frac{m_e}{m_\mu}\frac{R_\infty c\alpha^2}{(1+m_e/m_\mu)^3}[1 + \delta_{\text{HFS}}]$$

Rydberg constant $R_\infty \equiv \alpha^2 m_e c/(2h)$

fine-structure constant

nonrelativistic **Fermi energy** from H_{HFS}

electron-muon mass ratio

$\mathcal{O}(\alpha)$ correction [CODATA 2018 + refs therein]

$$\delta_{\text{HFS}} = \delta_{\text{Dirac}} + \delta_{\text{rad}} + \delta_{\text{rec}} + \delta_{\text{rad-rec}} + \delta_{\text{weak}} + \delta_{\text{had}}$$

relativistic (exact)

antimuon charge $Z = 1$

radiative known up to $\mathcal{O}(Z\alpha^4)$ including a_e

recoil known up to $\mathcal{O}[(m_e/m_\mu)(Z\alpha)^3]$ ~ 60 Hz uncertainty

radiative-recoil known up to $\mathcal{O}[(m_e/m_\mu)\alpha^3]$ ~ 10 Hz uncertainty

Z-exchange -65 Hz

hadronic vacuum pol. $= 237.7(1.5)$ Hz

Total TH uncertainty ~ 70 Hz (16ppb) dominanted by (yet) uncalculated QED corrections at three-loop order

[Eides-Shelyuto IJMPA 2016]

1S-2S theory

$$\nu_{1S-2S} = \frac{3}{4}\frac{R_\infty c}{(1+m_e/m_\mu)}[1 + \delta_{1S-2S}]$$

nonrelativistic energy (including recoil)

$\mathcal{O}(\alpha^2)$ correction

[CODATA 2018 + refs therein]
rescaling hydrogen formulae
with the muon mass and removing
nuclear finite size and pol. effects

$$\delta_{1S-2S} = \delta_{\text{Dirac}} + \delta_{\text{rel-rec}} + \delta_{eSE} + \delta_{\text{VP}} + \delta_{2\gamma} + \delta_{3\gamma} + \delta_{\text{rad-rec}} + \delta_{\mu SE}$$

vacuum pol. known up to $\mathcal{O}[\alpha(Z\alpha)^4]$

2+3 photon exchange known up to $\mathcal{O}[\alpha^3(Z\alpha)^4]$

muon self-E

relativistic (exact)

relativistic-recoil known up to $\mathcal{O}[(m_e/m_\mu)(Z\alpha)^4]$

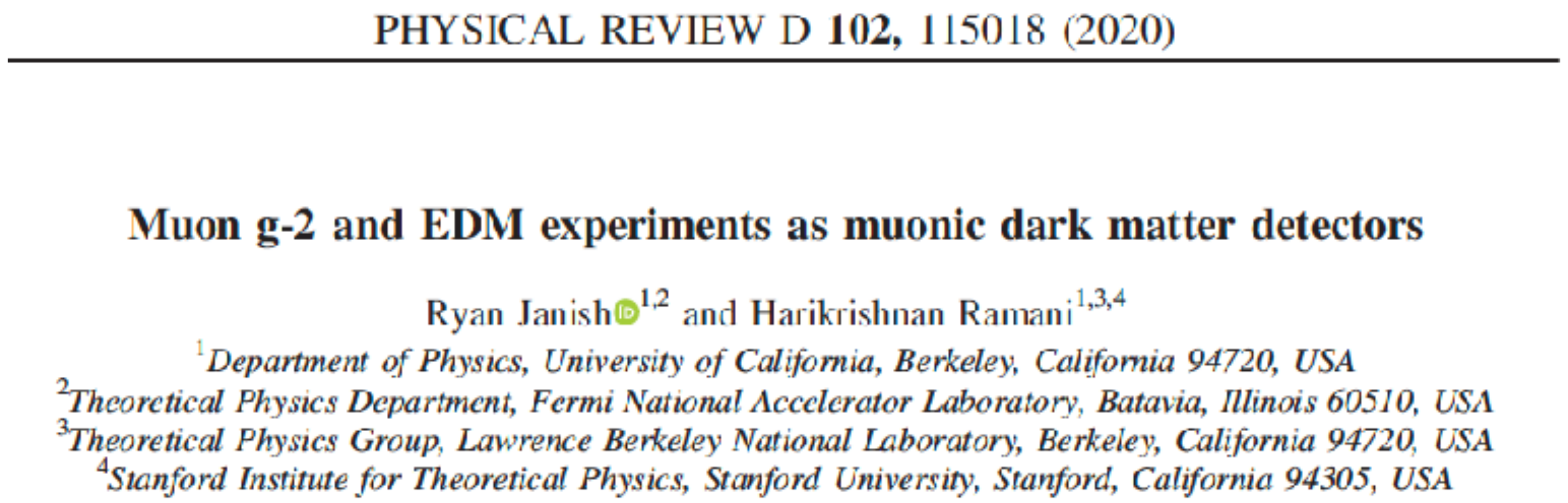
electron self-E $\mathcal{O}[\alpha(Z\alpha)^4]$ known

radiative-recoil known up to $\mathcal{O}[(m_e/m_\mu)\alpha(Z\alpha)^3]$

Total TH uncertainty ~ 20 kHz (8ppt) from (yet) uncalculated QED (rad-rec) corrections at three-loop order

[Karshenboim et al. PLB 2019]

Muonphilic dark matter



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Muon g-2 and EDM experiments as muonic dark matter detectors

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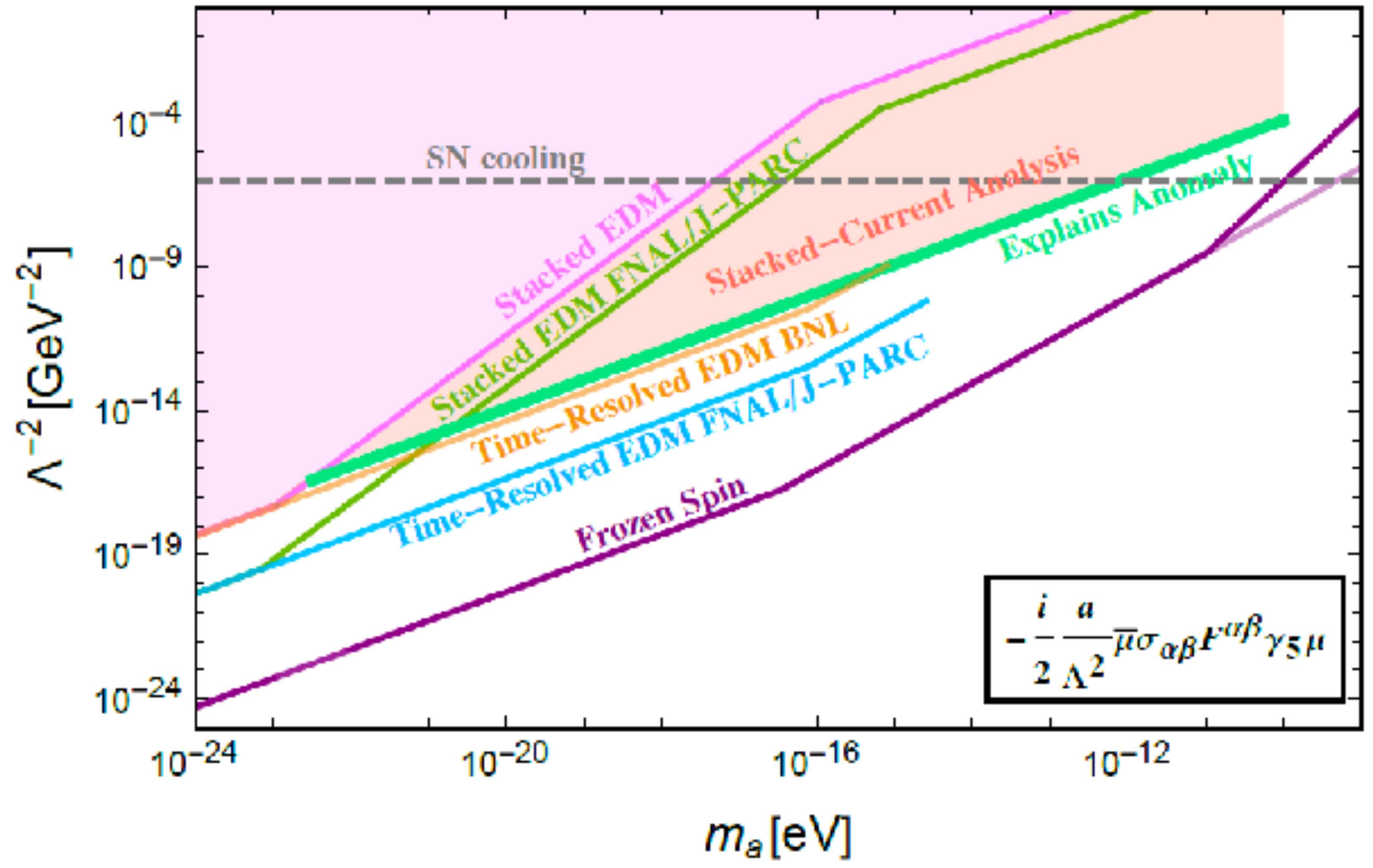
[4]*Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*

Detection Reach for Muon EDM Coupling



PHYSICAL REVIEW D **103,** 055010 (2021)

Storage ring probes of dark matter and dark energy

Peter W. Graham,[1] Selcuk Hacıömeroğlu,[2] David E. Kaplan,[3] Zhanibek Omarov,[4,2]
Surjeet Rajendran,[3] and Yannis K. Semertzidis[2,4]
[1]*Stanford Institute for Theoretical Physics, Department of Physics,*
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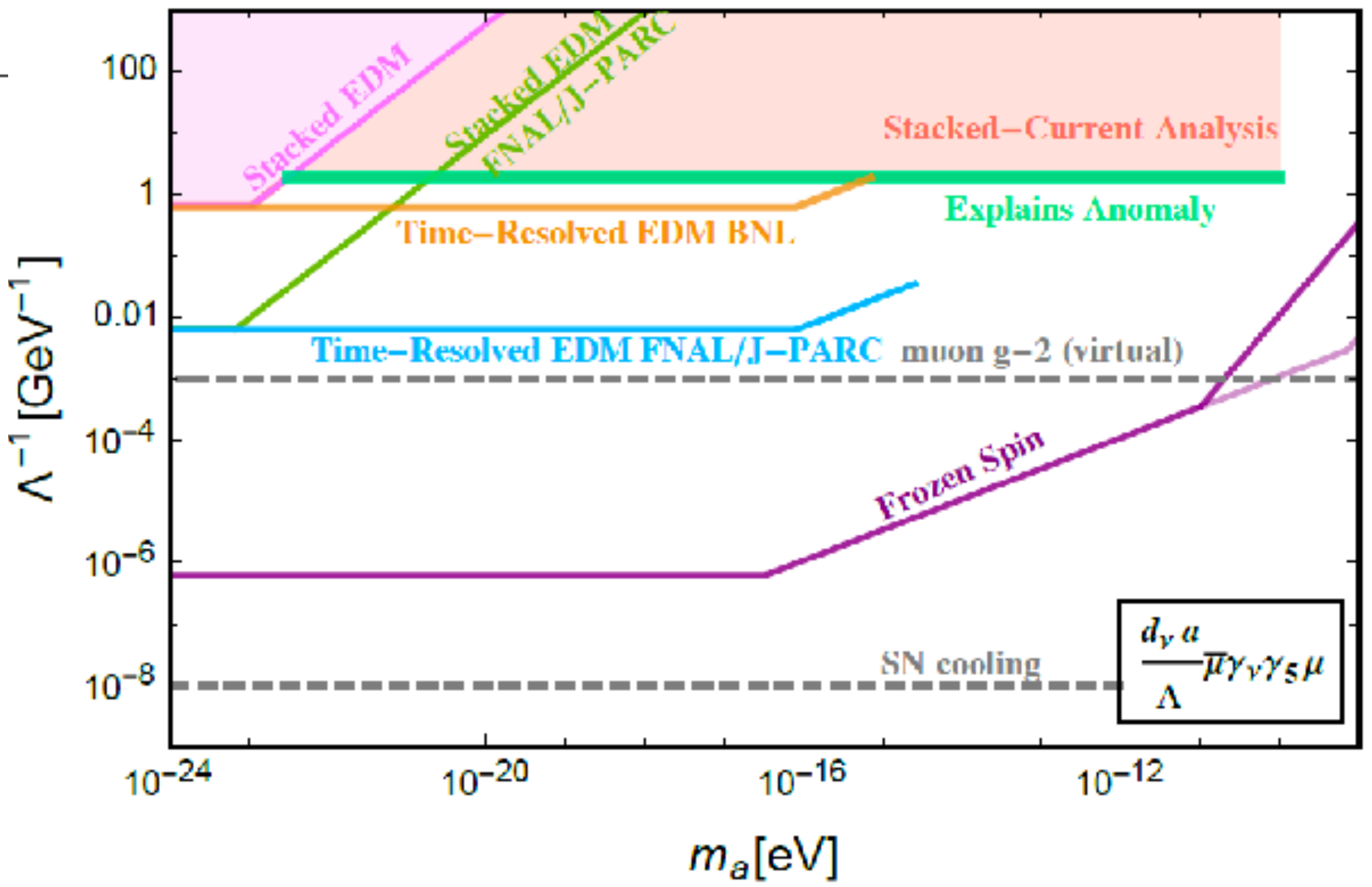
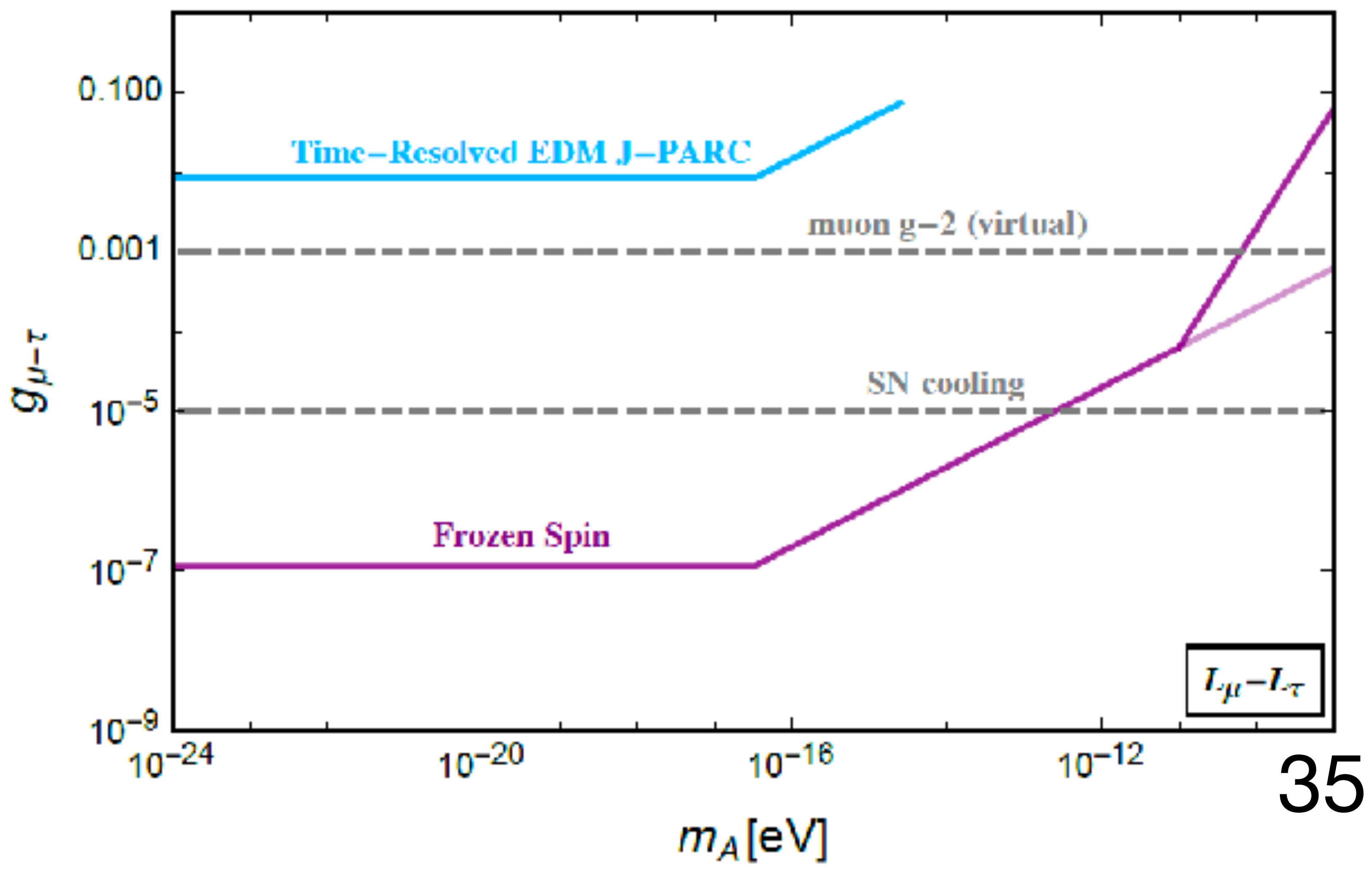
Daejeon 34051, Republic of Korea
[3]*Department of Physics & Astronomy, The Johns Hopkins University,*
Baltimore, Maryland 21218, USA
[4]*Department of Physics, Korea Advanced Institute of Science and Technology,*
Daejeon 34141, Republic of Korea

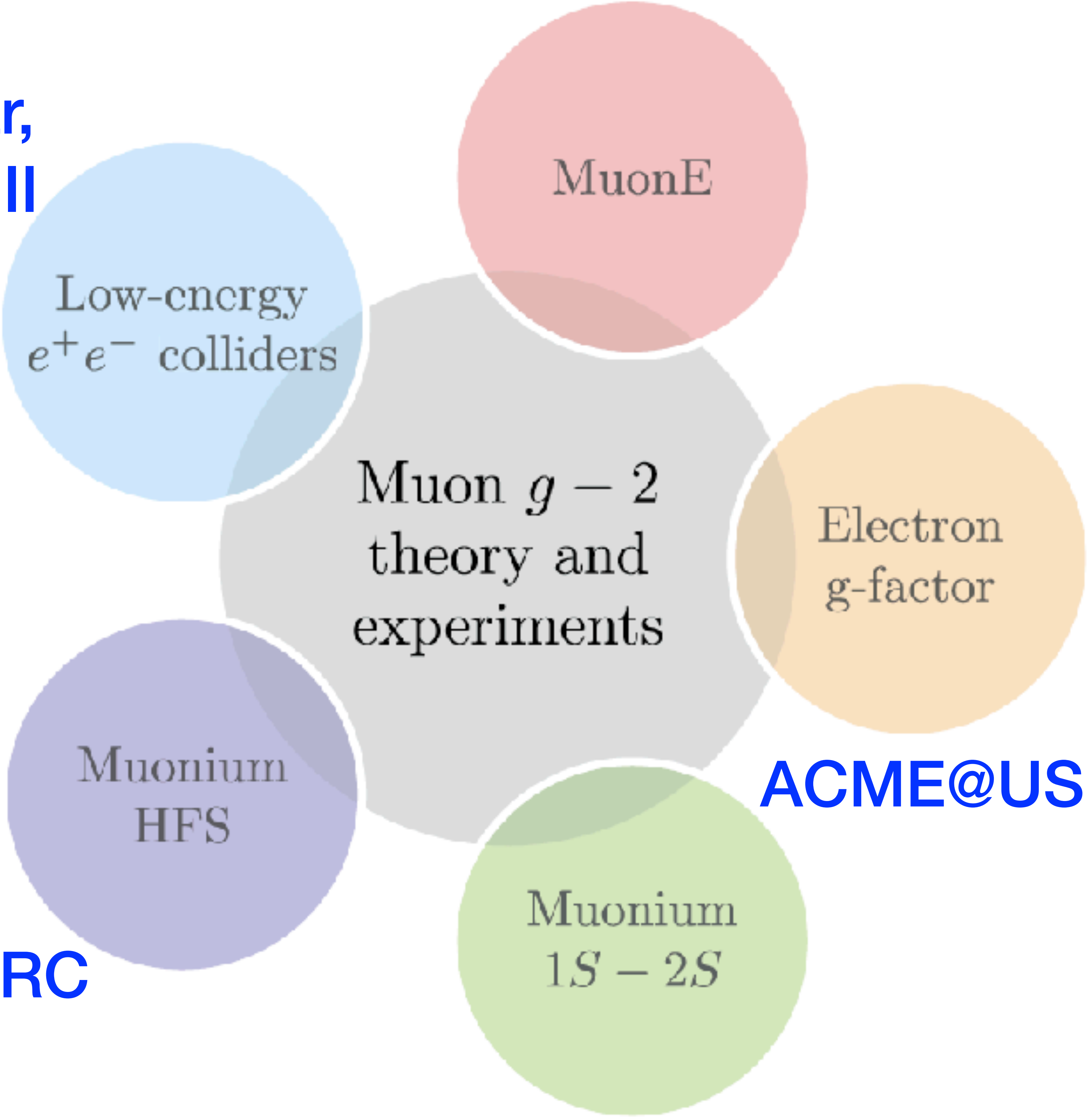
Detection Reach for ALP-Muon Wind



Muonic Vector DM



Rich physics program connected to muon g-2



Muon $g-2$ theory and experiments

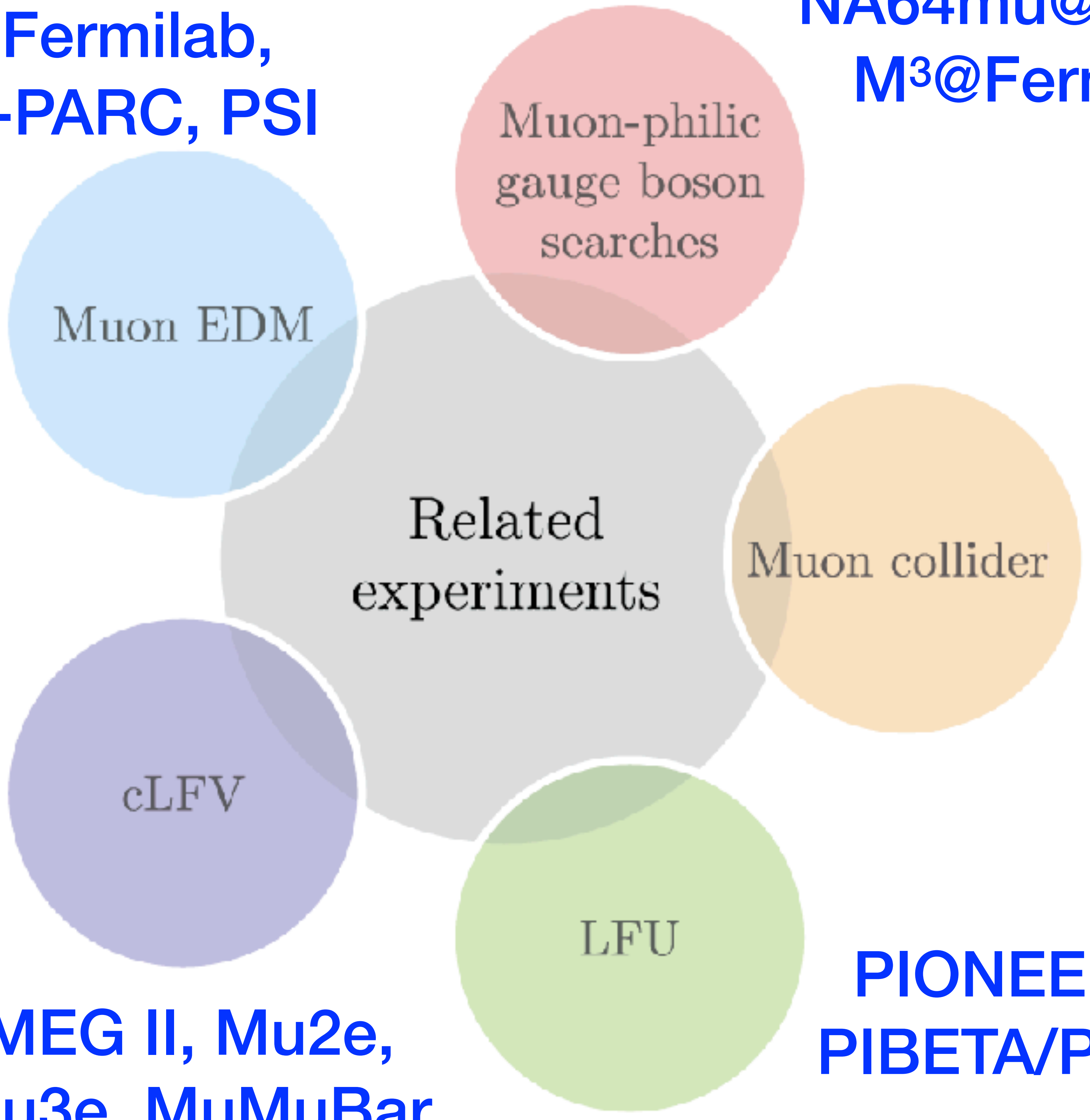
MuonE — CERN

Low-energy e^+e^- colliders — CMD-3, BaBar, BES-III, Belle-II

Electron g-factor — ACME@US

Muonium HFS — J-PARC

Muonium $1S-2S$ — MuMASS@PSI, J-PARC



Related experiments

Muon EDM — Fermilab, J-PARC, PSI

Muon-philic gauge boson searches — NA64mu@CERN, M^3@Fermilab

Muon collider — Very active field now!

cLFV — MEG II, Mu2e, Mu3e, MuMuBar

LFU — PIONEER@PSI, PIBETA/PEN@PSI

Many interesting and high-impact experiments for young students and postdocs!

Muonium 1S-2S + HFS @ PSI/J-PARC

Muon g-2 @ J-PARC

Muon g-2 @ Fermilab

muEDM @ PSI

MUonE @ CERN

Muon g-2
Theory Initiative

STAY TUNED!