Muon $g-2$ Experiments:
From Fermilab and J-PARC to Future Opportunities

Ce Zhang

Particle Physics Annual Meeting

22/05/2026

UNIVERSITY OF LIVERPOOL

LEVERHULME TRUST

Liverpool contributions span all aspects for muon g-2

Fermilab (completed) | **J-PARC** (ongoing) | **R&D** for Future Exp.

Experiments (this talk)

Muon $g\mathrm{-}2$:
One of the Key Topics in Muon Physics

Theory (SM) predictions (next talk by Fedor)

Data-driven approach

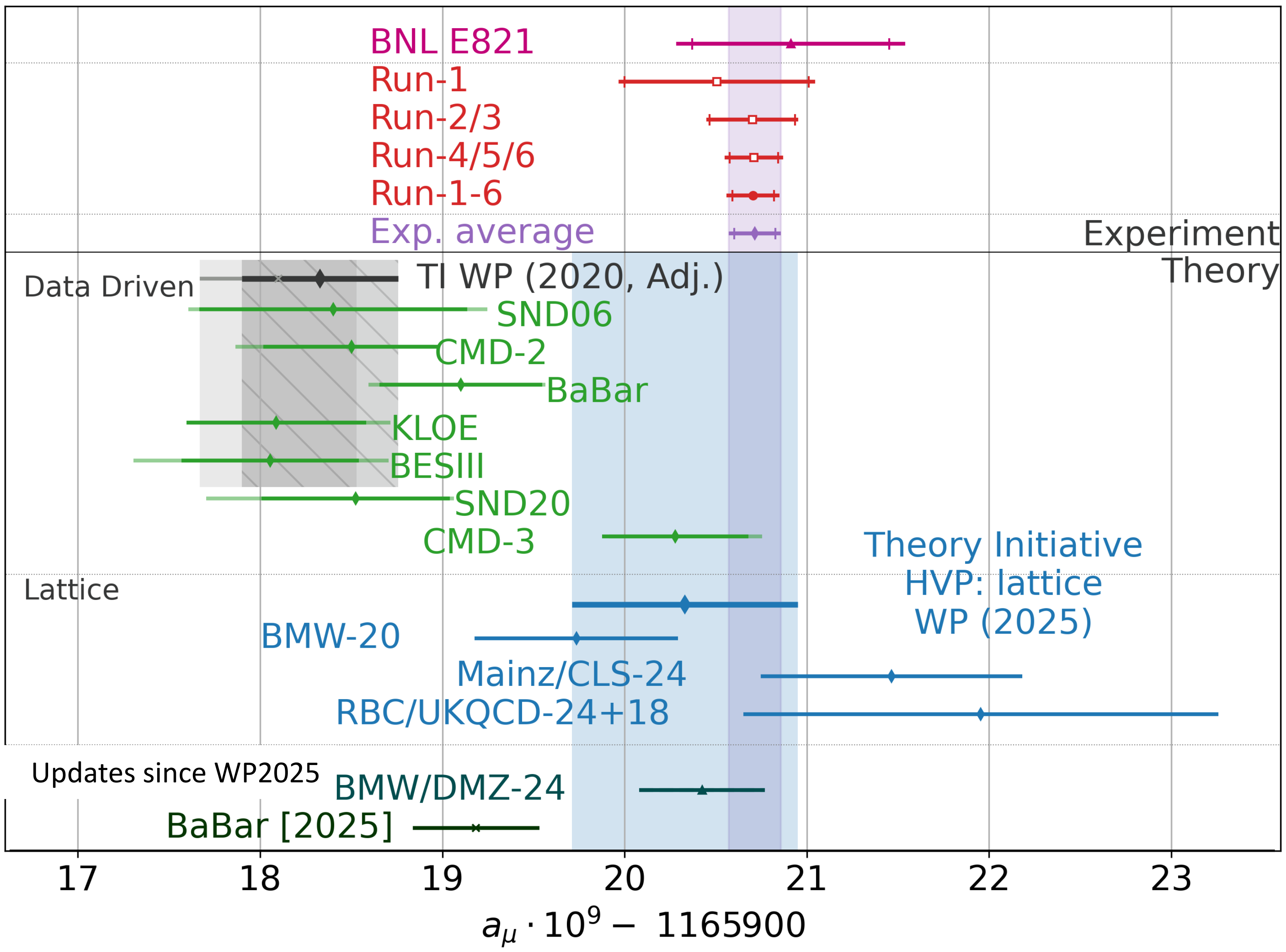
- Dispersive evaluation: **KNTW, …**
- Inputs from e+e- data: **KLOE, …**

Lattice QCD approach

- **UKQCD,**
- …

Novel approach: MUonE (for LO-HVP)

Current Status: Experiment vs Theory



Fermilab g-2: a Breakthrough

2008 – Proposal

The New (g − 2) Experiment:

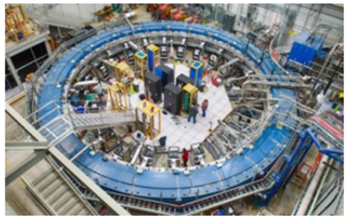
A Proposal to Measure the Muon Anomalous

Magnetic Moment to ±0.14 ppm Precision

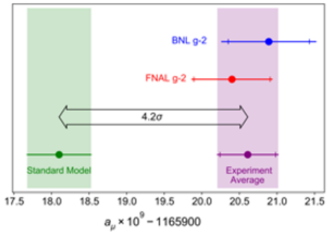
2012 – Muon g-2 Critical Decision-0

2013 – The Big Move

2017 – 1st muon beam



2021 – First g-2 result

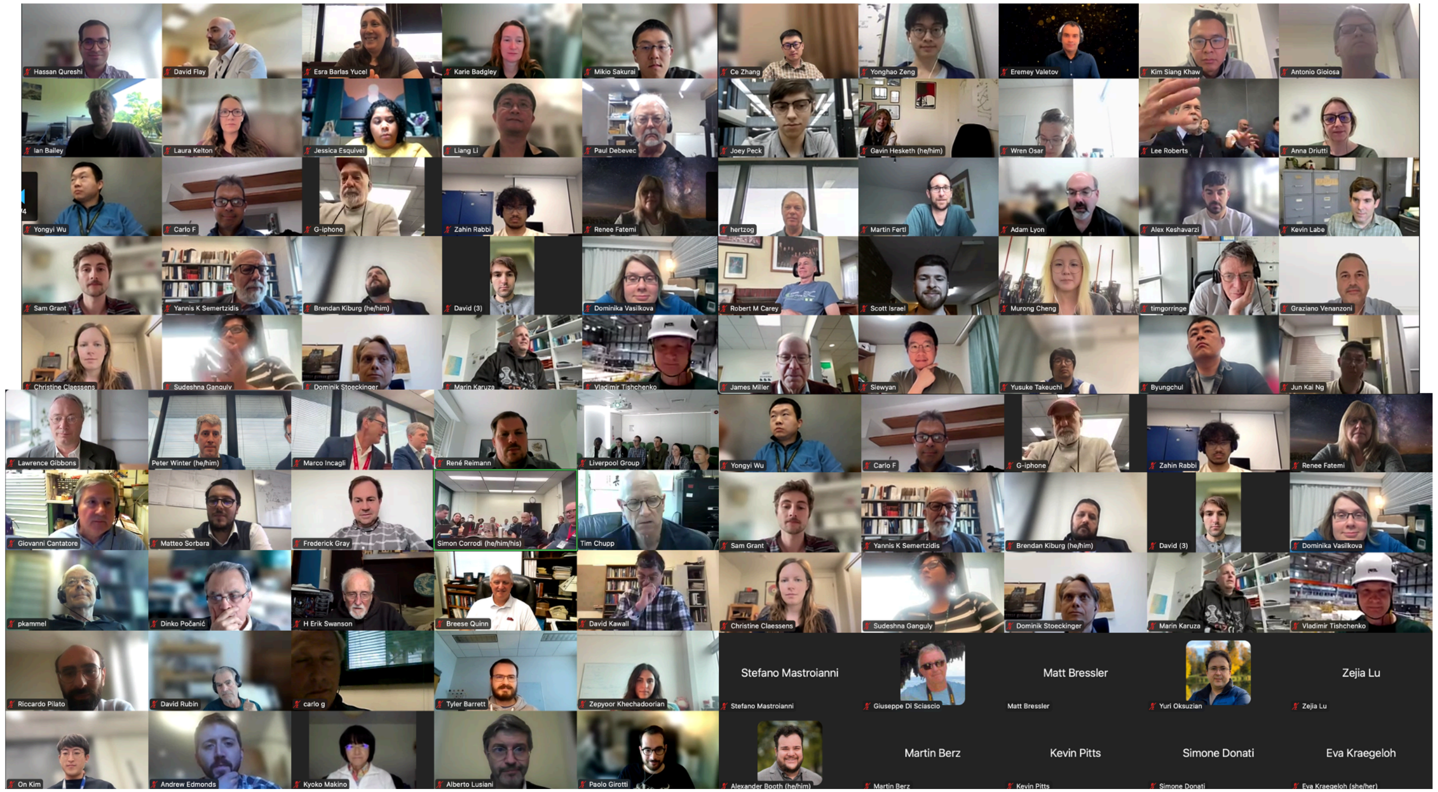


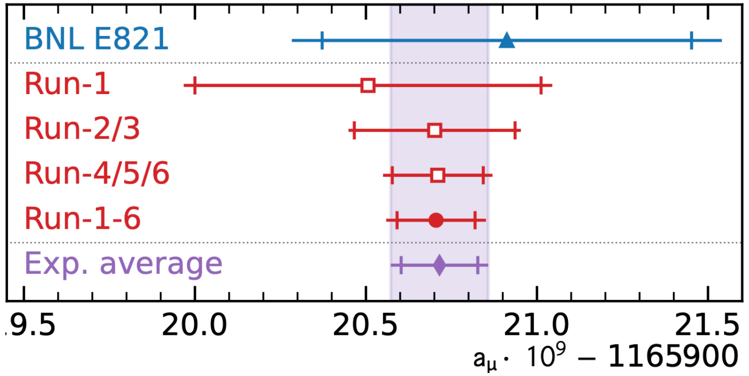
2023 – End of data taking and second result

2025 – Final g-2 result

Fermilab g-2: a Breakthrough

- Final value unblinded on 20th May 2025, a result that will stand for many years.

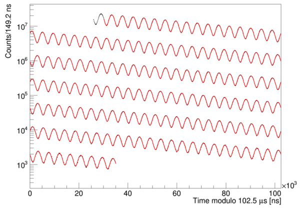




Phys. Rev. Lett. **135**, 101802

Fermilab g-2: a Breakthrough

- Liverpool contributions to the final result analysis by **early-career members**:



Precession analysis:
Lorenzo Cotrozzi, Estifa'a Zaid, Ce Zhang (slow-term task force leader)

Beam Dynamics corrections:
Elia Bottaloco (BD coordinator)

Muon 'g-2' ← $a_\mu = \dfrac{\omega_a (1 + C_e + C_p + C_{ml} + C_{pa})}{< \omega_p(x,y,\phi) \times M(x,y,\phi) > (1 + B_k + B_q)}$

Field measurement: Saskia Charity (Field coordinator)

- Liverpool is also leading the EDM analysis (Joe Price, Dominika Vasilkova, Katie Ferraby) and involved in other New Physics (DM & CPT) activities.

Education & Outreach

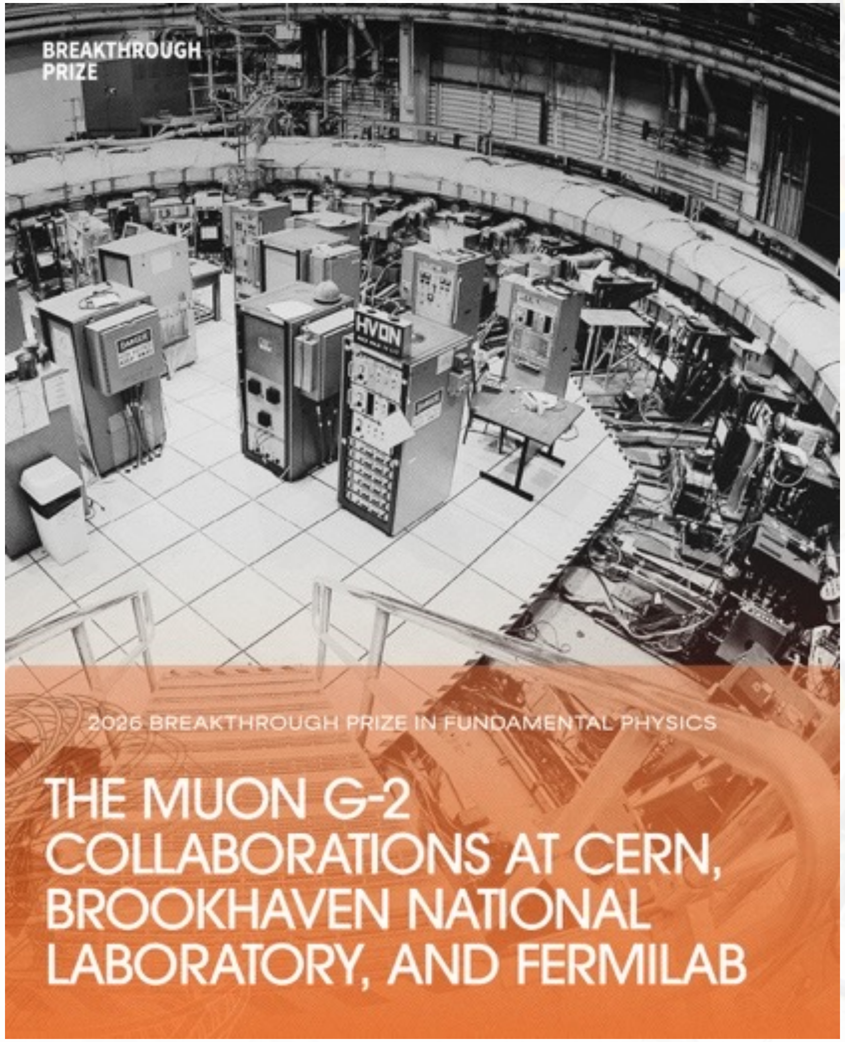
Panel Discussion at the British Science Festival
Universal secrets: Unpacking particle physics

Graziano Venanzoni (University of Liverpool), Saskia Charity (University of Liverpool), Mark Thomson (CERN) and Jocelyn Monroe (University of Oxford).

A g-2 exhibition at The Yoko Ono Lennon Centre for BSF

Pub(lic) talk at Pint of Science this week by Elia Bottalico

Fermilab g-2: a Breakthrough



- Breakthrough Prize in Fundamental Physics 18th April 2026
- Liverpool members are:

  Talal Albahri, Elia Bottalico, Themis Bowcock, John Carroll, Saskia Charity, Lorenzo Cotrozzi, Katie Ferraby, Tabitha Halewood-Leagas, Alex Herrod, Anthony Hibbert, Barry King, Stephen Maxfield, David Newton, Riccardo Pilato, Joe Price, David Sim, Tony Smith, David Tarazona, Thomas Teubner, Kayleigh Thomson, William Turner, Dominika Vasilikova, Graziano Venanzoni, Mark Whitley, Andy Wolski, Mike Wormald, Estifa'a Zaid, Cedric Zhang.

  We dedicate the award to the memory of the Barry King, Stephen Maxfield and David Newton.

Fermilab g-2: the magic-γ approach

- Muon's motion is very nearly planar and the momentum is very nearly the ideal one, but both effects are not perfect and require corrections:

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

We need electric quadrupoles

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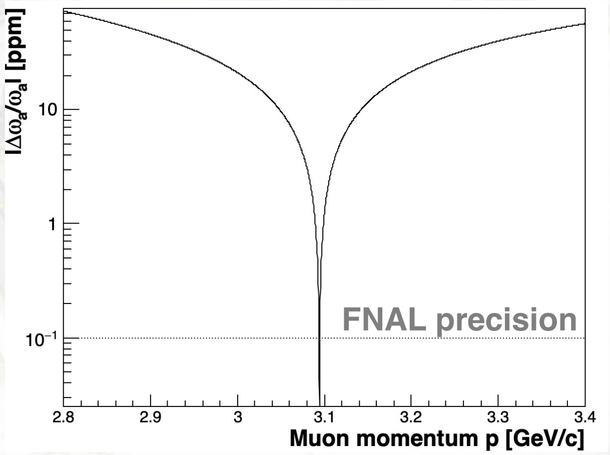
0 if "in plane"

→ Term cancels at 3.094 GeV/c, the "Magic γ"

Achievable Precision vs Muon P



Beyond the Fermilab Muon g–2

Reaching the precision limit
(stat ≈ syst ~100 ppb)

$$\frac{\Delta\omega_a}{\omega_a} \propto \frac{1}{\gamma B P \sqrt{N}}$$

$$\left(a_\mu - \frac{1}{\gamma^2 - 1}\right) \frac{\vec{\beta} \times \vec{E}}{c}$$

E field 'issue' → **'Magic γ'** → **muon at 3.1 GeV/c**
B = 1.45 T → **CERN/BNL/FNAL Muon g-2**

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E field 'issue' ↓

remove E-field? → **How to focus (store) muons?**

Beyond the Fermilab Muon g–2

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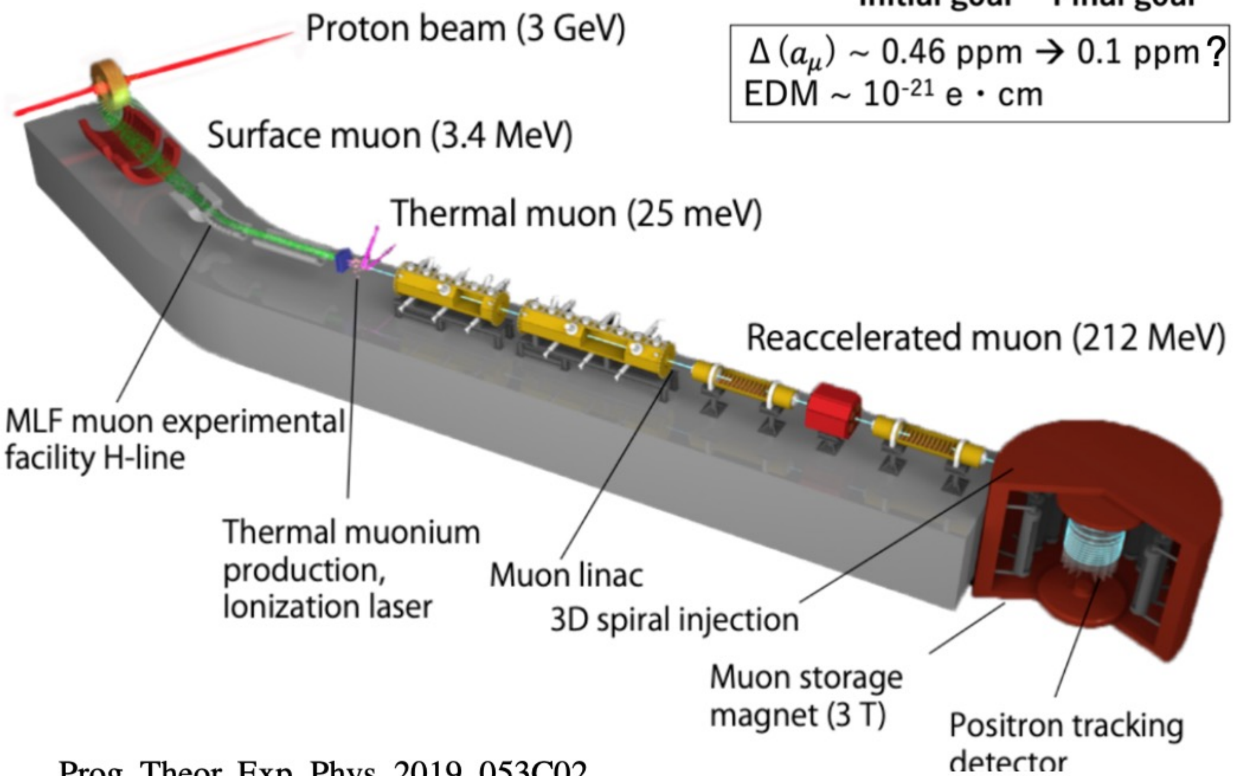
E field 'issue' → **'Magic γ'** → **muon at 3.1 GeV/c, B = 1.45 T** → **CERN/BNL/FNAL Muon g-2**

E field 'issue' ↓ **remove E-field?** → **How to focus (store) muons?**

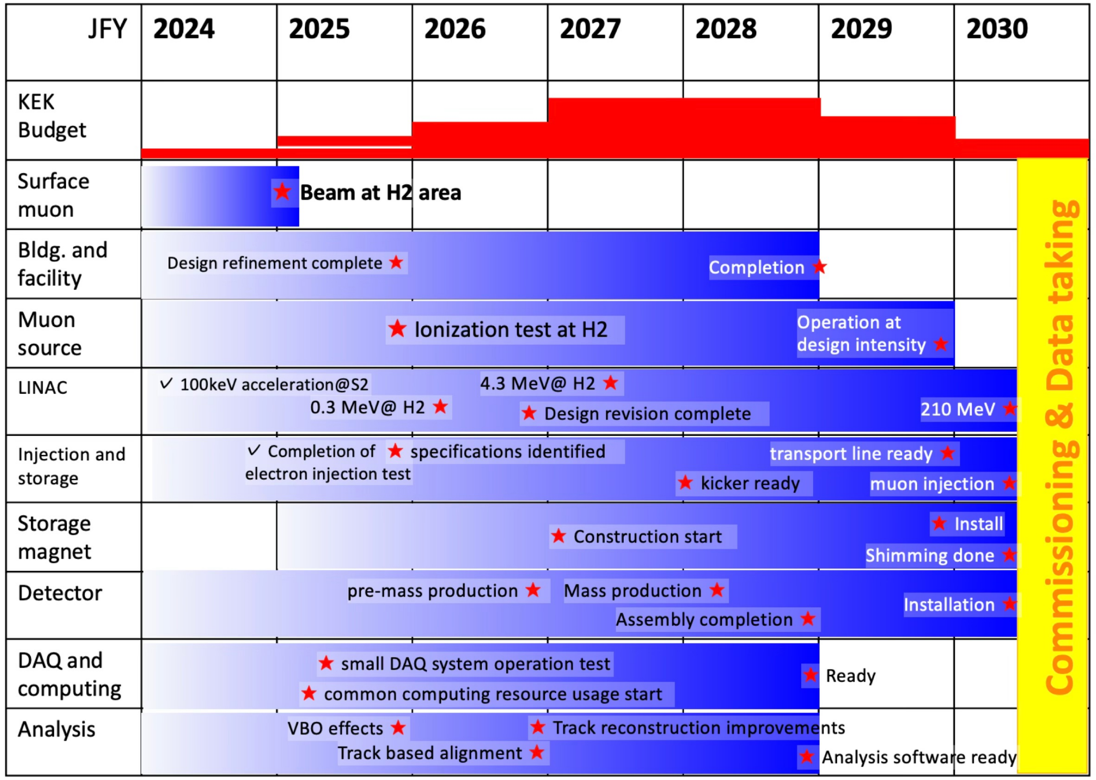
- → **novel muons** (even storable w/o an E field) → **J-PARC g-2**
- → **novel focusing fields** (capable of focusing conventional muons) → **Propasals at HIAF, PSI, ...**

J-PARC g-2: Current Status

	Initial goal	Final goal
$\Delta(a_\mu)$	~ 0.46 ppm →	0.1 ppm ?
EDM ~ 10^{-21} e · cm		



Prog. Theor. Exp. Phys. 2019, 053C02



Aiming at 2030+, but may be **subject to a step-by-step implementation scenario (funding issue):**

- 1st step(2027-2031?)
- 2nd step (203X) for a full realization

J-PARC g-2: Current Status

- Liverpool has officialy joined J-PARC Muon g-2/EDM collaboration in 2025

CM30 (June 2025 @ J-PARC)

CM31 (Dec 2025 @ Hiroshima)

Liverpool collaborators: Elia Bottalico, Lorenzo Cotrozzi, Fedor Ignatov, Riccardo Nunzio Pilato, Thomas Teubner, Jonathan Tinsley, Graziano Venanzoni, Estifa'a Zaid, Ce Zhang

J-PARC g-2: Current Status

Support letter to KEK DG

The Muon $g-2$ Theory Initiative
Steering Committee

December 14, 2025

Dr. Shoji Asai
Director General
Inter-University Research Institute Corporation
High Energy Accelerator Research Organization (KEK)
1-1 Oho, Tsukuba, Ibaraki, 305-0801
Japan

Dear Asai-san,

We are writing to express our strong support for J-PARC's muon $g-2$/EDM experiment, which proposes a highly innovative measurement of the muon anomalous magnetic moment, $g-2$. Confronting its precision measurement with theoretical predictions constitutes one of the most important low-energy tests of the Standard Model (SM) of particle physics.

The experimental world average is dominated by the Fermilab Muon $g-2$ experiment, based on the same experimental method as all $g-2$ experiments in the last 50 years starting from the CERN III experiment. While its value agrees with the SM prediction based on lattice-QCD calculations for the hadronic-vacuum-polarization (HVP) contribution, the uncertainty on the theoretical prediction is four times larger than that of the experiment. The decision in the 2025 White Paper of the Muon $g-2$ Theory Initiative to rely solely on lattice QCD for the HVP contribution is due to unsolved puzzles on the SM theory side, particularly issues concerning the experimental inputs in the dispersive method, and their resolution may have profound implications for the comparison. In short, the question "Does the SM agree or disagree with the experimental value of the muon's anomalous magnetic moment?" has not yet been satisfactorily answered.

Recent changes in the SM prediction have shown that a well-established method (the dispersive approach) for determining the HVP contribution has been challenged by an innovative and independent approach, namely lattice QCD. The aim of the J-PARC muon $g-2$/EDM experiment is precisely this: to provide an independent verification of the method employed in the direct measurements of the muon $g-2$ over several decades.

Thanks to significant ongoing efforts both using data-driven, dispersive techniques and lattice QCD, the Muon $g-2$ Theory Initiative anticipates substantial improvements in the SM prediction in the coming months and years. This includes, crucially, comparisons among the different methods, as detailed in the 2025 White Paper that summarizes the status of the SM prediction at this point in time. These new results will be compiled in another White Paper, planned to appear before the end of this decade.

As the theoretical picture sharpens, the forthcoming J-PARC measurement will provide essential new experimental input that represents an independent validation based on a distinct, complementary methodology. As the case of the SM prediction shows, independent checks are of vital importance in this endeavor, but for a conclusive validation the J-PARC experiment should strive to match the precision of the Fermilab experiment. We, therefore, strongly support recent efforts by the collaboration towards this goal.

In summary, the J-PARC muon $g-2$/EDM experiment, with its innovative methodology, is in the unique position to test the existing muon $g-2$ measurements, which are the culmination of 50 years of experimental development. Its timely completion would have an amplified impact on the comparison between SM theory and experiment, which will sharpen the constraints on physics beyond the SM. This view is widely shared within the Muon $g-2$ Theory Initiative, as indicated in the 2025 White Paper.

We thank you very much for your attention.

Sincerely,
Gilberto Colangelo (Universität Bern)
Achim Denig (Johannes Gutenberg-Universität Mainz)
Aida X. El-Khadra (University of Illinois Urbana-Champaign)
Martin Hoferichter (Universität Bern)
Christoph Lehner (Universität Regensburg)
Laurent Lellouch (Aix Marseille Université)
B. Lee Roberts (Boston University)
Thomas Teubner (University of Liverpool)
Hartmut Wittig (Johannes Gutenberg-Universität Mainz)
…
…

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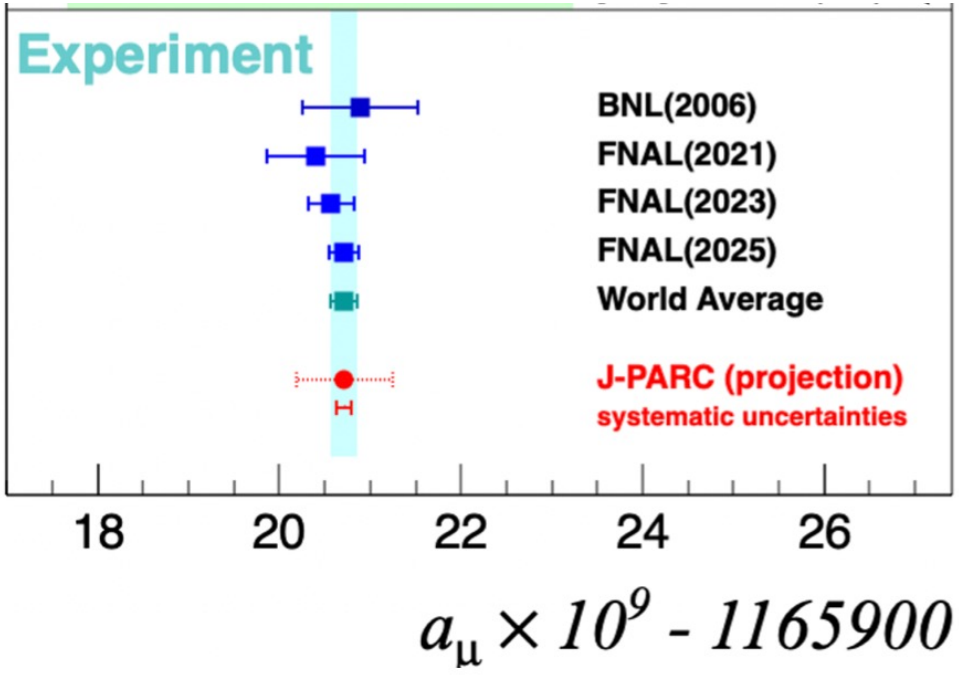
230 signers from the international community

J-PARC g-2: Liverpool Contributions

- The precision for J-PARC g-2 (phase-I) only matches BNL level (~0.4 ppm) due to the lack of statistics:



We started studies to improve the precision (goal: surpass the FNAL precision)

$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P}\sqrt{\frac{2}{NA^2}}$$

High Sensitivity Study Group (HSSG) has been established. Graziano (Liverpool) is leading this effort with Tsutomu

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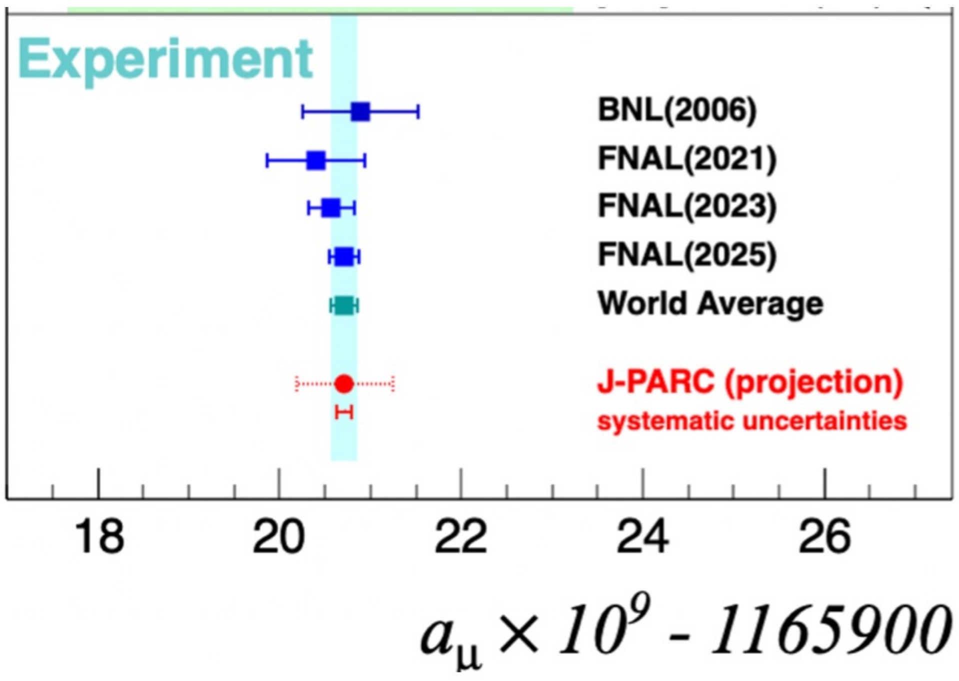
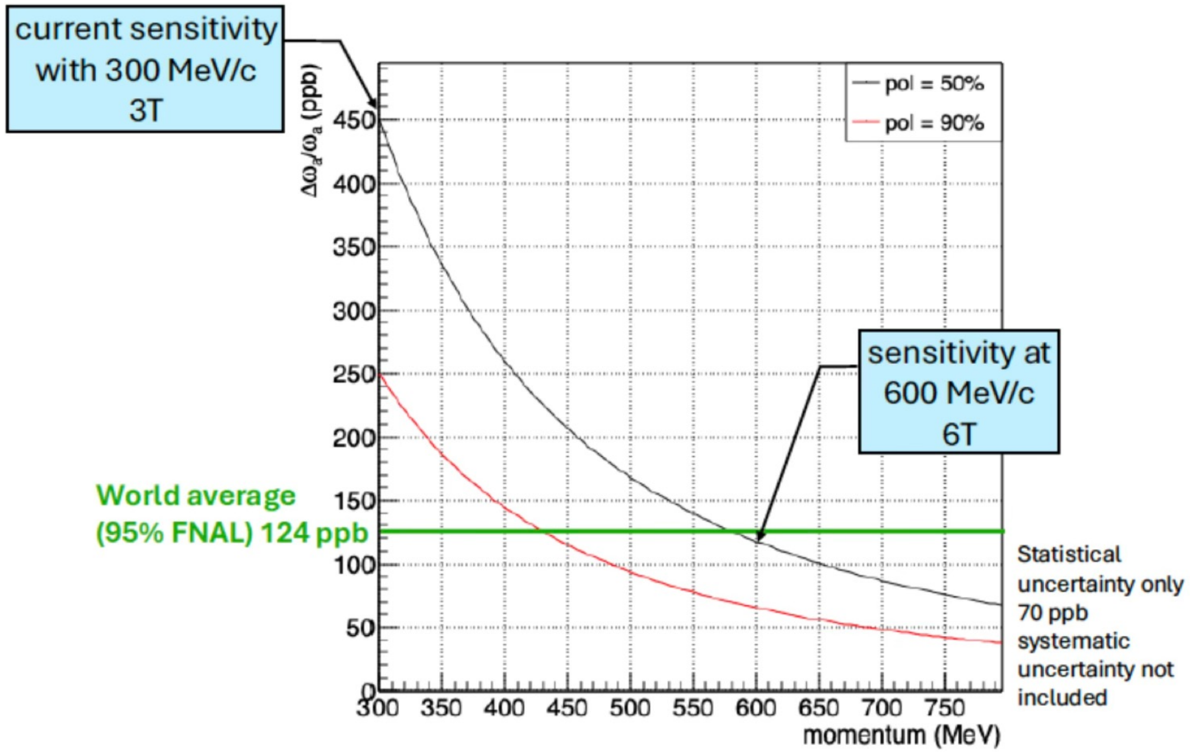




J-PARC g-2: Liverpool Contributions

- **HSSG group. Initial members:**
  - Graziano Venanzoni (Chair), Tsutomu Mibe
  - B-field and Injection : Shinji Ogawa, Ken'ichi Sasaki, Ce Zhang, Graziano Venanzoni (on behalf of ASG)
    + Lorenzo Cotrozzi (PDRA)
  - Acceleration: Masashi Otani, Elia Bottalico
  - High-Pol: Shusei Kamioka, Jonathan Tinsley + Shreya Pipraiya (PhD)
- **Mandate:**
  - Investigate potential / feasibility for higher sensitivity measurements
  - Establish pros and cons
  - Estimation of possible costs
  - Write a document (report)
- **Timeschedule:**
  - June 2026 to complete the studies; December 2026 to distribute (internally) the report. In case of success the report can be the base for an addendum/upgrade of the proposal

Saara Chikh

UNIVERSITY OF LIVERPOOL

A feasibility study for an increased main field of 6 T for the Muon $g-2$/EDM experiment at J-PARC

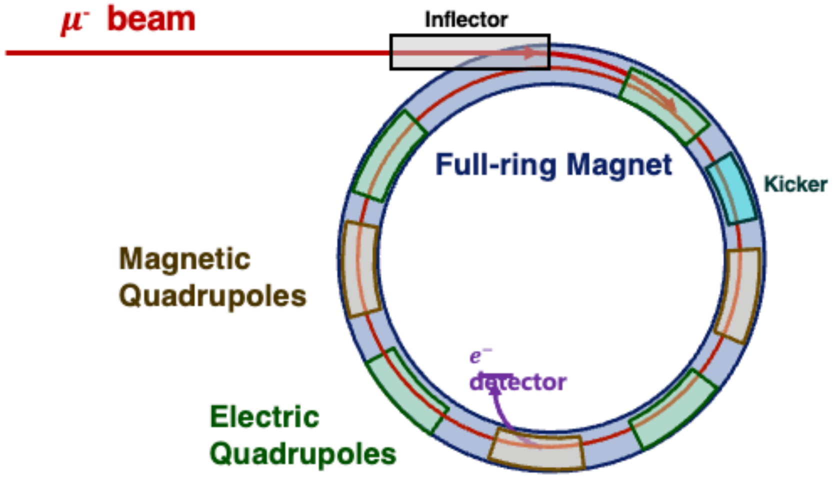
Saara Chikh
201641137

Department of Physics
Master of Physics Thesis
Supervised by Professor Graziano Venanzoni

April 2026

Future g-2: proposals

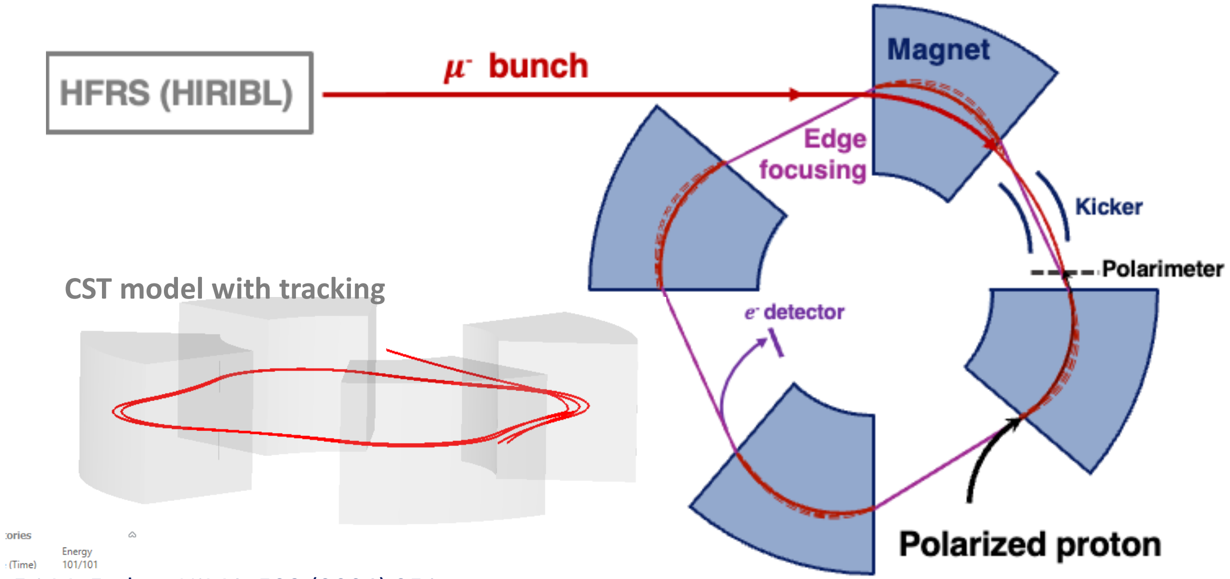
Concept 1) Hybrid weak focusing
higher-order B field cancels higher-order E-fields



$$\overrightarrow{\boldsymbol{\omega_a}} = -\boldsymbol{a_\mu}\frac{q}{m_\mu}\left(\vec{\boldsymbol{B}}_{\boldsymbol{0}} + \cdots\right) + \frac{q}{m_\mu}\left[\left(\boldsymbol{a_\mu} - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

On Kim and Yannis K. Semertzidis, Phys. Rev. Accel. Beams 25, 024001

Concept 2) Proton beam co-magnetometer
Edge-focusing from segmented B-field



F.J.M. Farley, *NIMA*, 523 (2004) 251
arXiv:2512.11486


arXiv > hep-ex > arXiv:2512.11486

High Energy Physics – Experiment

[Submitted on 12 Dec 2025 (v1), last revised 30 Mar 2026 (this version, v3)]

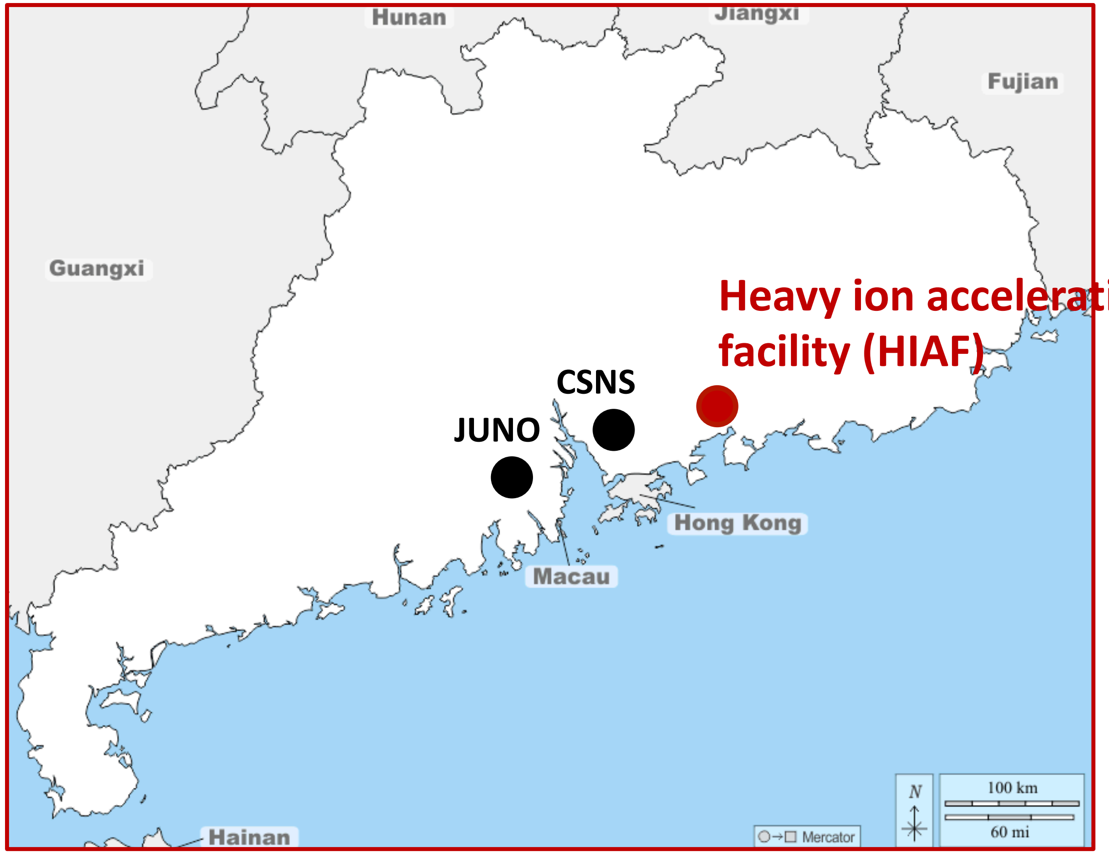
CANTON-μ Proposal: A Next-Generation Muon g − 2 Measurement at Sub-0.1 ppm Precision

Ce Zhang, Yu Xu, On Kim, Bingzhi Li, Guodong Shen, Liangwen Chen, Fedor Ignatov, Liang Li, Qiang Li, Xueheng Zhang, Zhiyu Sun

Currently under development by me and colleagues in Liverpool, IMP and beyond

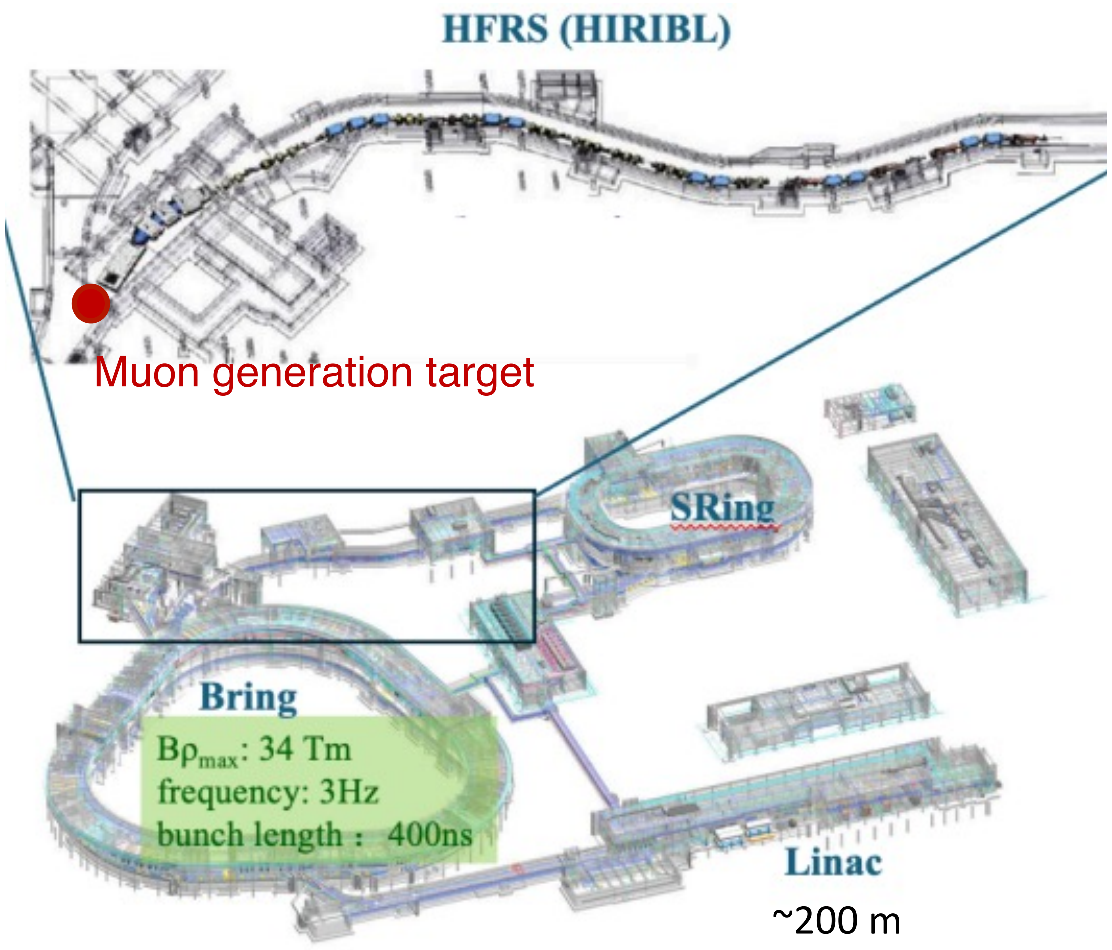
High-intensity muon source at China's HIAF

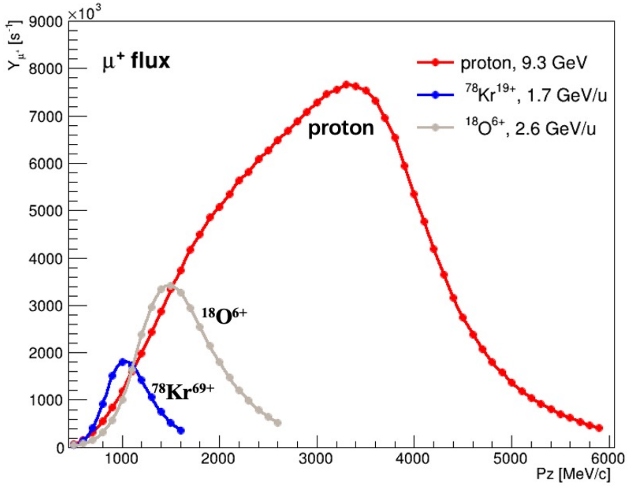
Guangdong ('Canton') area



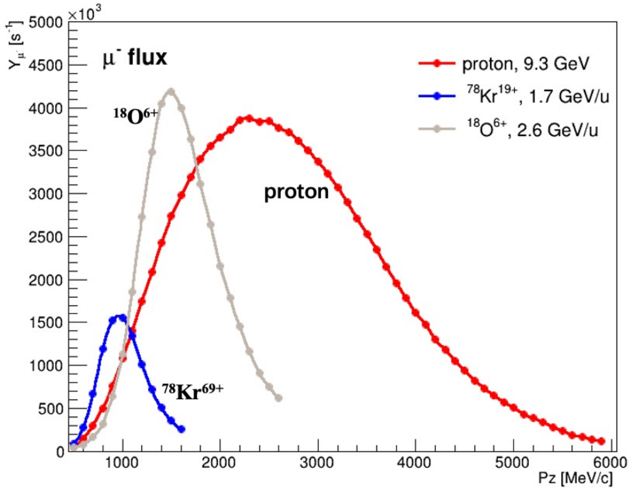
High-intensity muon source at China's HIAF

Currently under commissioning, providing competitive muon of both charges





positve muon



negative muon

- Maximum μ^+ flux： $8.2\times10^6/s$
  - projectile： proton
  - Pz： 3.5 GeV/c

w/ purification: $2.4\times10^5/s$

- Maximum μ^- flux： $4.2\times10^6/s$
  - projectile： $^{18}O^{6+}$
  - Pz： 1.5 GeV/c

w/ purification: $3.7\times10^5/s$

High-intensity muon source at China's HIAF

Facilities	CERN/BNL/FNAL	J-PARC	HIAF (HIAF-U)
Muons	3.1 GeV/c 10^5 /s	300 MeV/c 10^6 /s	2-4 GeV; 10^5 /s (HIAF) 10-20 GeV (upgrade, 2030+); 10^7 /s
Magnet	Full-ring magnet	Full-ring magnet	Sector magnet
Focusing	B-field & E-field	B-field	Edge B-field
Field calibration	NMR calibration	NMR calibration	Polarized proton & others
Precision	μ^+: 0.14 ppm (FNAL) μ^-: 0.7 ppm (BNL)	μ^+: 0.46 ppm → 0.1ppm (?)	μ^-/μ^+: 0.1 ppm → **0.05 ppm**

- The ideas for HIAF is also adaptable to other high intensity GeV muon facilities – BNL, FNAL, CERN, ...

For more details see slides by Philipp Schmidt-Wellenburg
https://indico.ph.liv.ac.uk/event/2133/

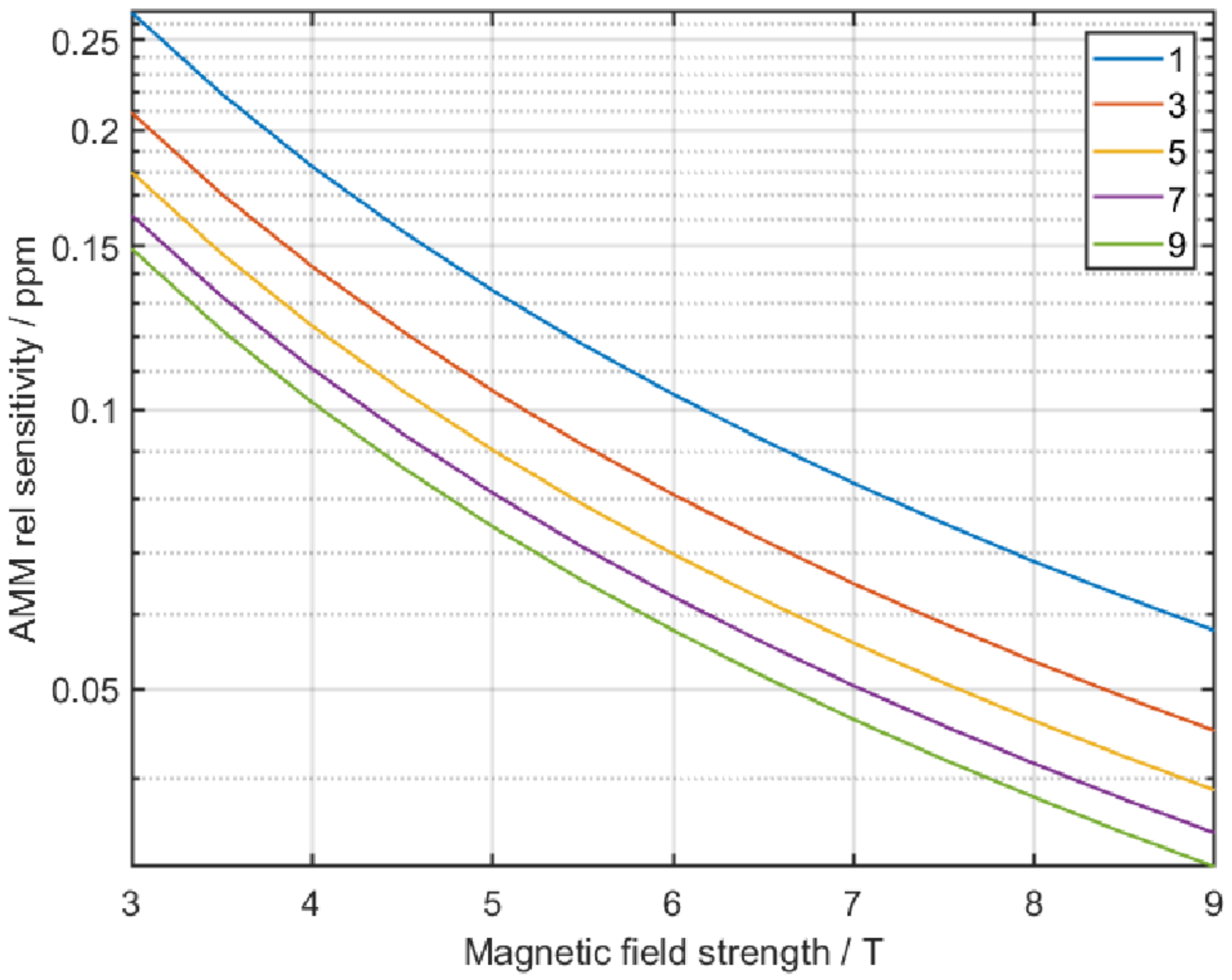
$(g-2)_\mu$ Prospects at PSI

PSI

- Statistics as in muEDM phase 2 (one year data)
  - blue: single muon
  - red: 3 muons – how?
- Same magnet, same detector, no electric field
- Prospects with new beamline solenoid to go to $p = 140\ \mathrm{MeV/c}$

Sensitivity: ~ 0.1 ppm statistically (4 years)

- Collaboration on magnet with JPARC and transport between institutes?



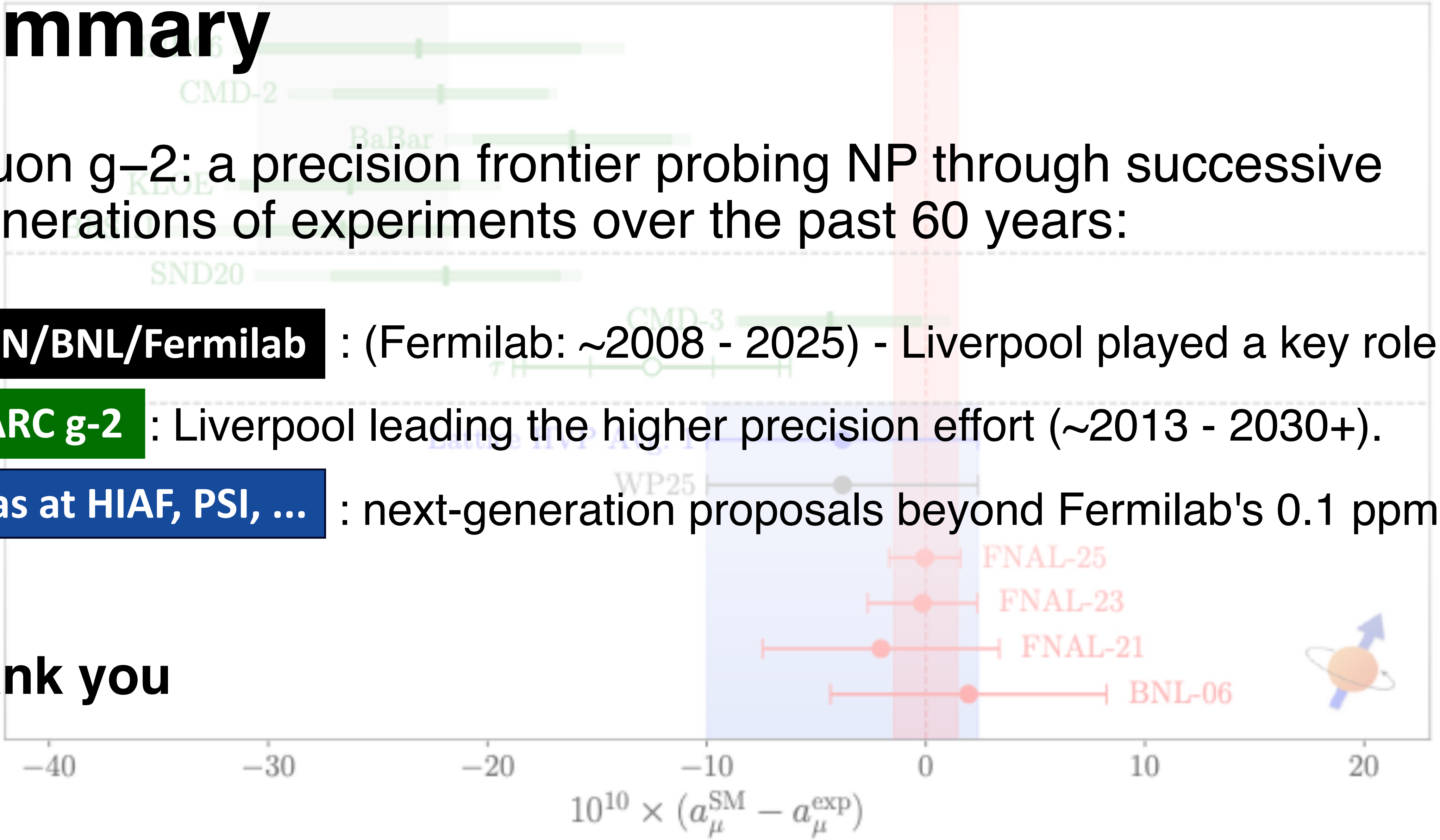
Summary

- Muon g–2: a precision frontier probing NP through successive generations of experiments over the past 60 years:

CERN/BNL/Fermilab : (Fermilab: ~2008 - 2025) - Liverpool played a key role.

J-PARC g-2 : Liverpool leading the higher precision effort (~2013 - 2030+).

Ideas at HIAF, PSI, ... : next-generation proposals beyond Fermilab's 0.1 ppm.

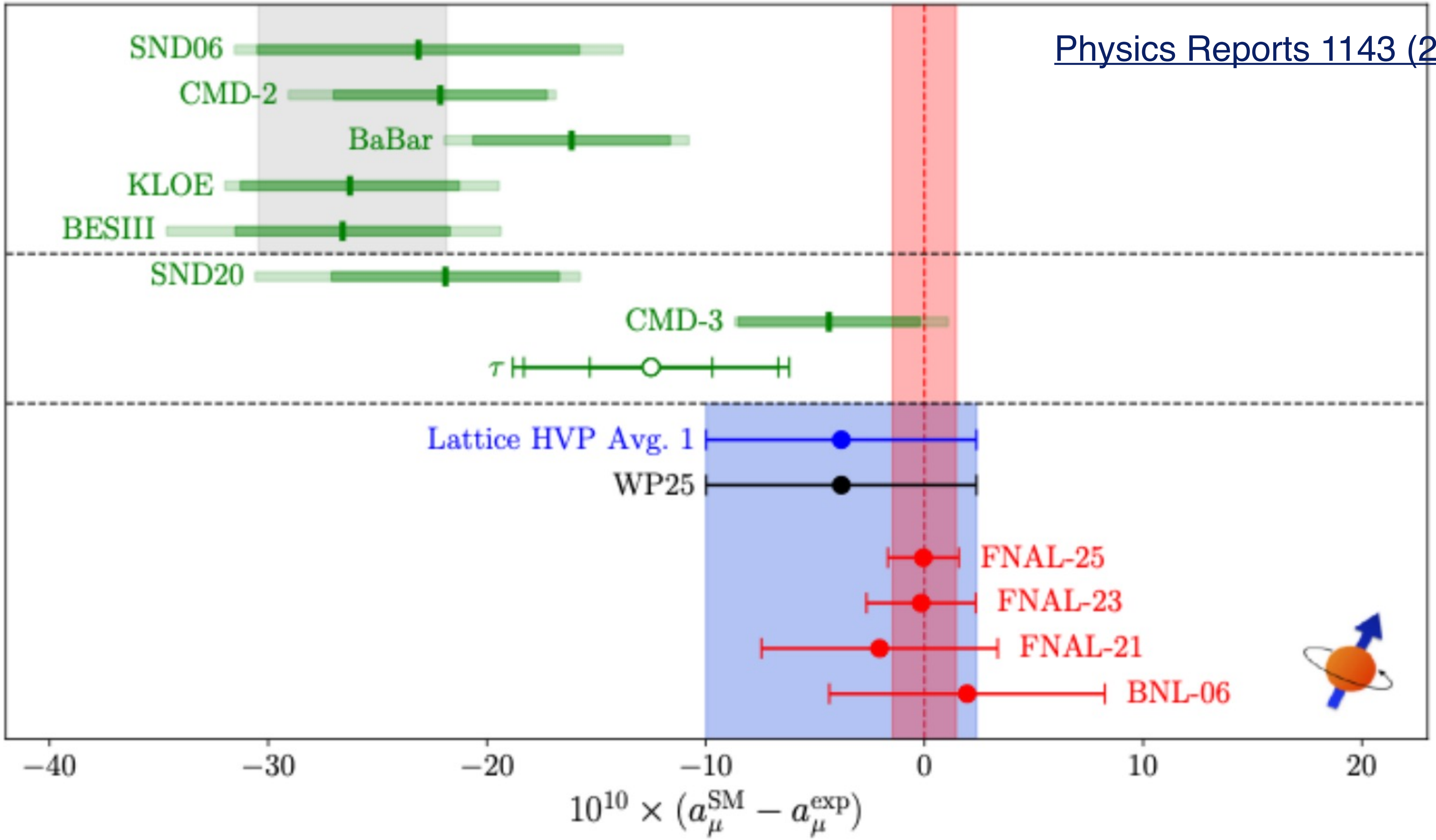


Thank you

Backup

LO-HVP from Lattice QCD approach - Theory Initiative White Paper 2025

Physics Reports 1143 (2025) 1-158



What can we probe given a 0.05 ppm?

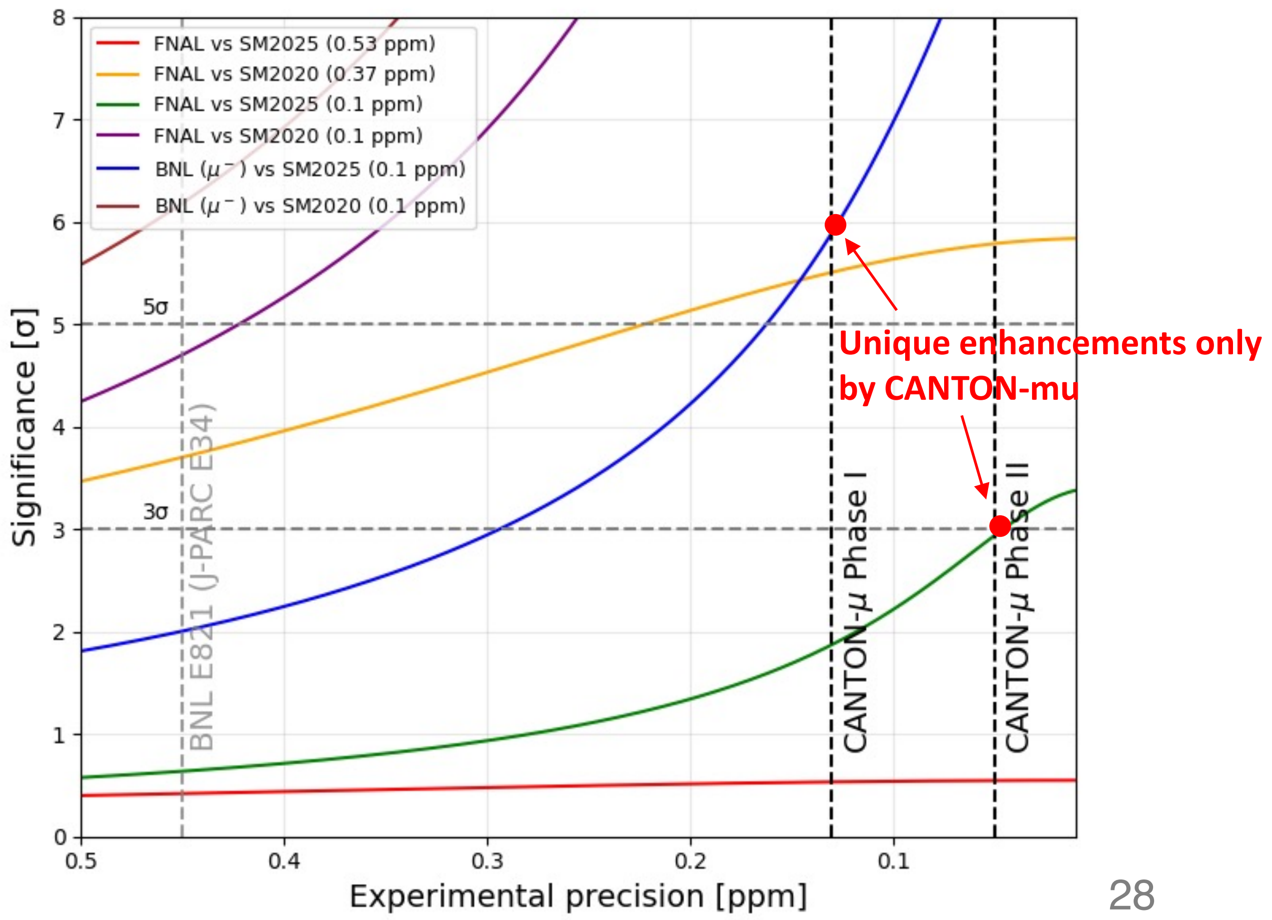
1) significance

New physics significance depends on the central values from both theory and experiment

$$\Delta a_\mu^{\mathrm{Exp-WP2020}} = 26.2(4.5) \times 10^{-10},$$

$$\Delta a_\mu^{\mathrm{Exp-WP2025}} = 3.8(6.3) \times 10^{-10}$$

- Phase-1 can reach 5σ for the exp central value centered on BNL (μ^-) vs. SM2025
- Phase-2 can reach $\sim 3\sigma$ for FNAL vs. SM2025 (assuming 0.1 ppm for theory)

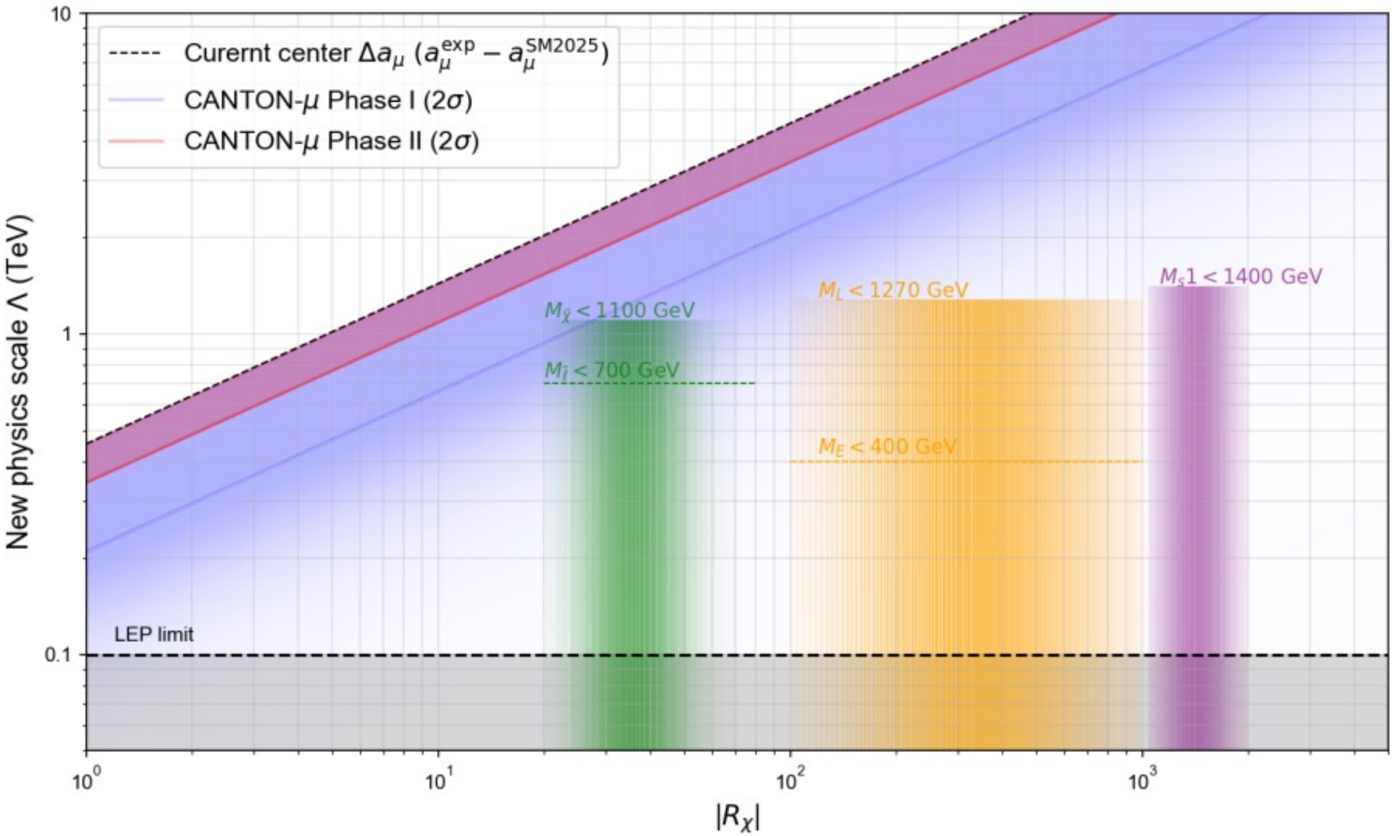


What can we probe given a 0.05 ppm?

2) New-Physics energy scale

- In the chiral enhancements, scaling behaviour for NP is parameteried as

$$\Delta a_\mu \sim R_\chi \times \frac{c_L c_R}{16\pi^2}, \frac{m_\mu^2}{\Lambda^2}$$

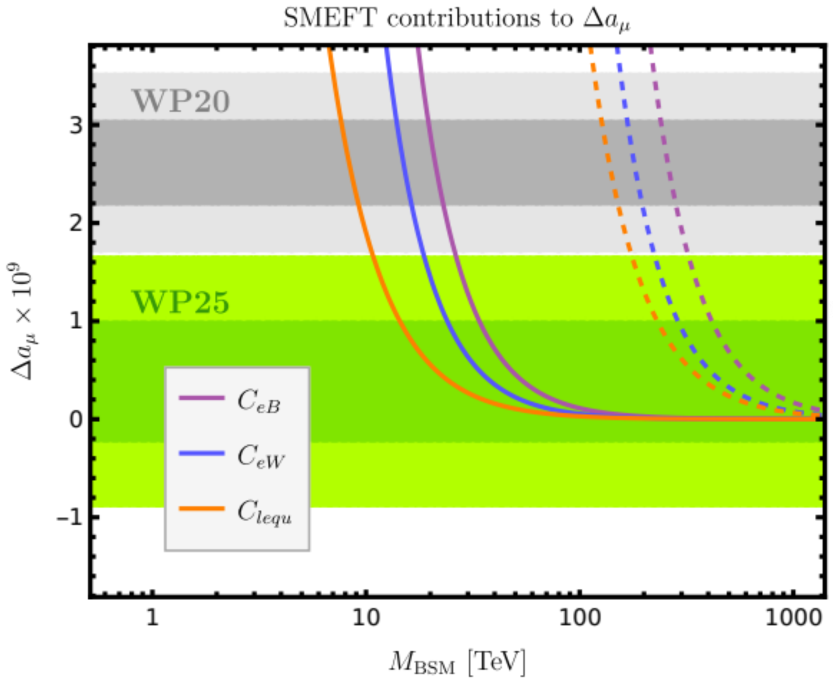


What can we probe given a 0.05 ppm?

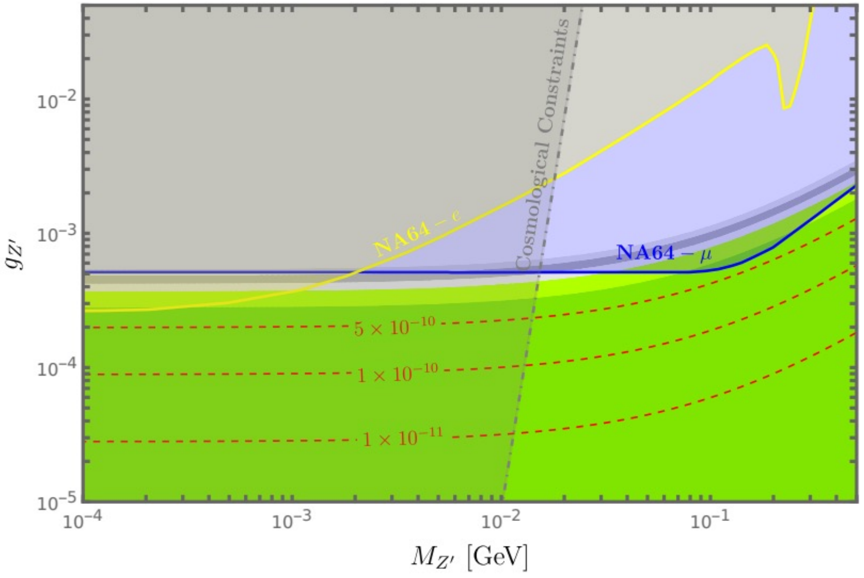
2) New-Physics energy scale

- An independent precise experimental result would decisively clarify the current WP20 vs WP25 puzzles over many NP models

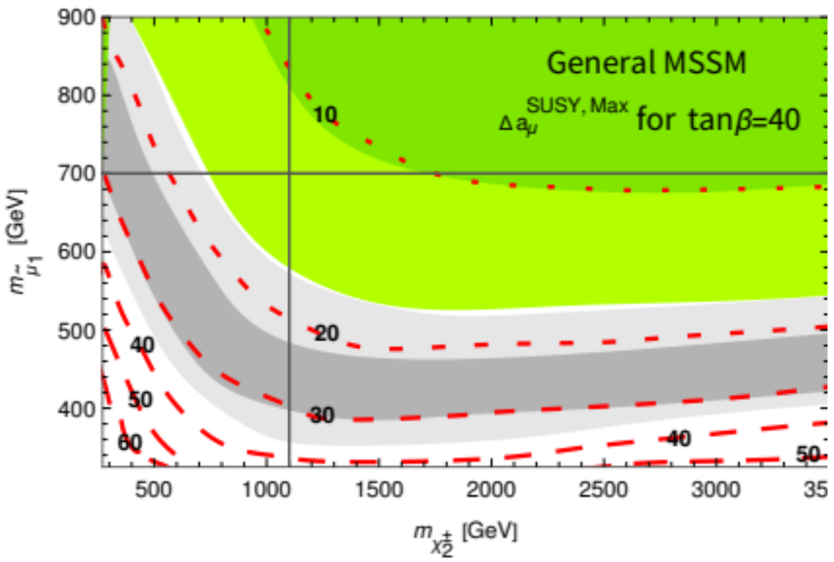
P. Athron et al., Prog.Part.Nucl.Phys. 148 (2026) 104225



SMEFT Wilson coefficients



Z prime constraint



SUSY MSSM contribution

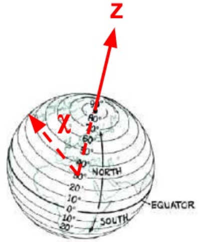
What can we probe given a 0.05 ppm?

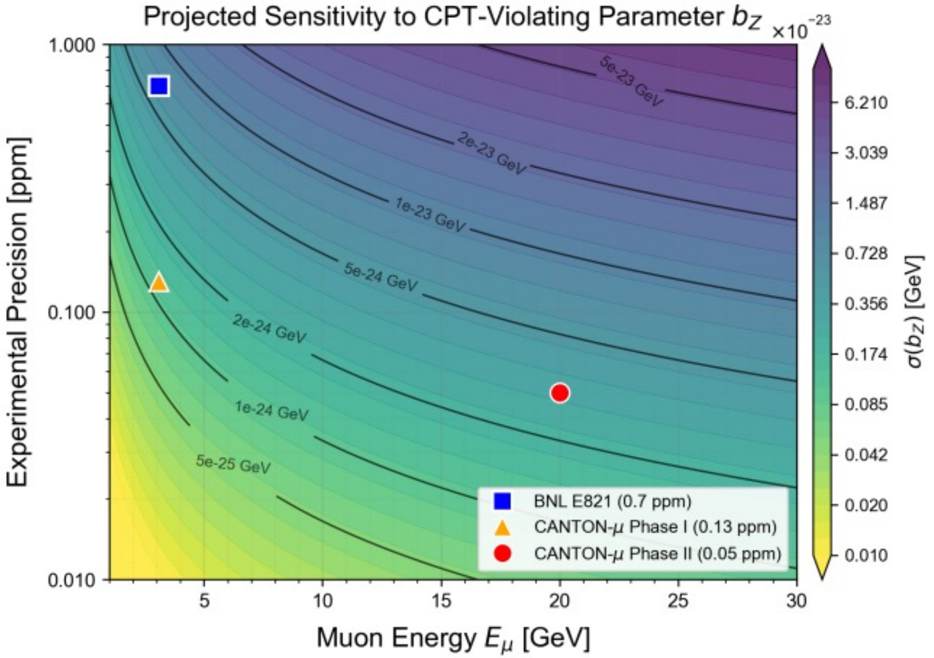
3) Unique CPT sensitivity

- SME Lagrangian:

$$\mathcal{L}' = -a_\kappa \bar{\psi}\gamma^\kappa\psi - b_\kappa \bar{\psi}\gamma_5\gamma^\kappa\psi - \frac{1}{2}H_{\kappa\lambda}\bar{\psi}\sigma^{\kappa\lambda}\psi + \frac{1}{2}ic_{\kappa\lambda}\bar{\psi}\gamma^\kappa \overleftrightarrow{D}^\lambda \psi + \frac{1}{2}id_{\kappa\lambda}\bar{\psi}\gamma_5\gamma^\kappa \overleftrightarrow{D}^\lambda \psi$$

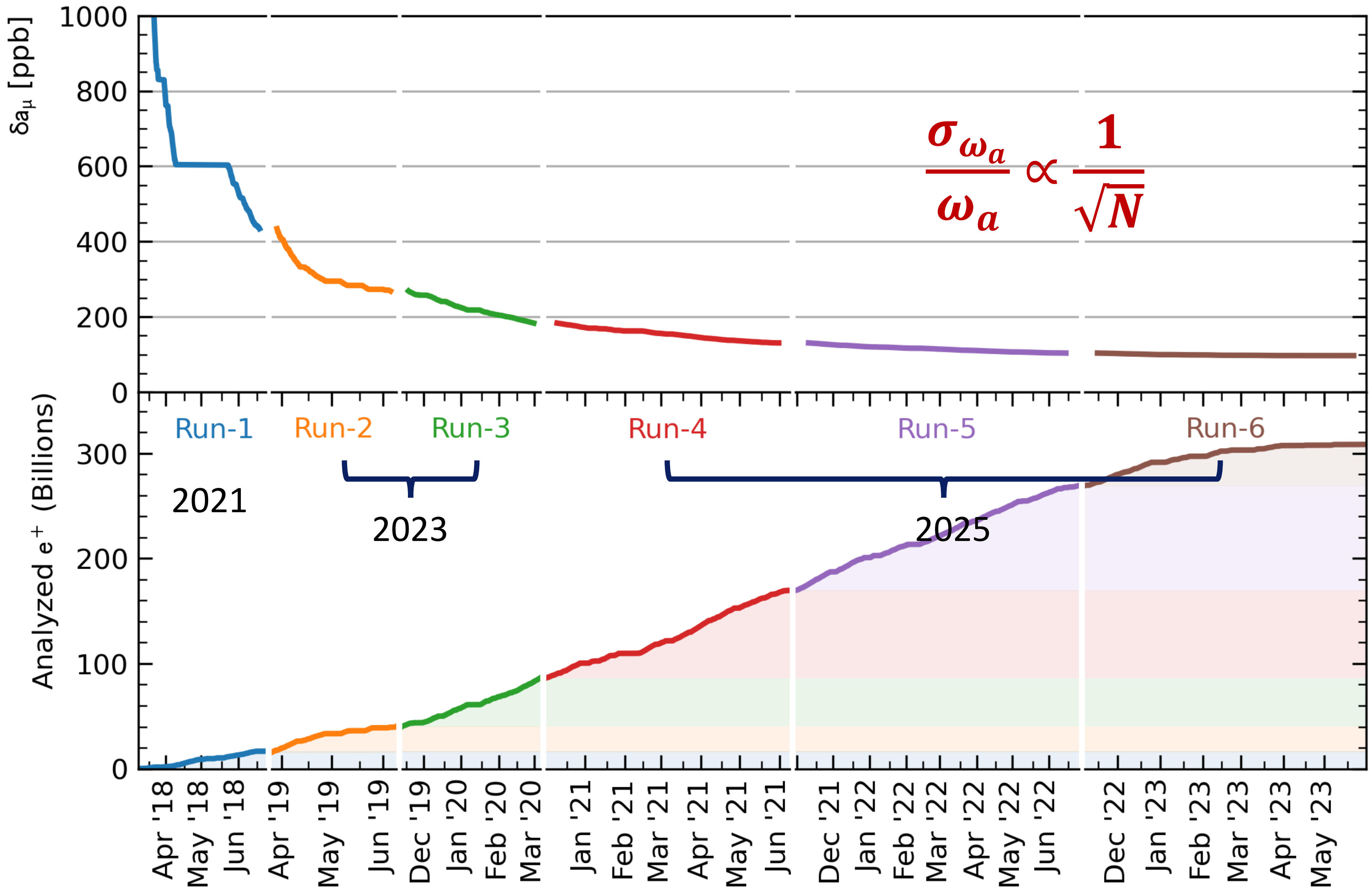
  - All terms violate Lorentz invariance
  - a_κ, b_κ are CPT-odd; others are CPT-even
- Predicts two CPT/Lorentz Violating signatures for muon g-2:
  - Gomes, Kostelecky, Vargas, Phys.Rev.D90:076009,2014
  - **Sidereal (or annual) variation in ω_a**
  - **Difference in ω_a between μ^+ / μ^-**
  - Use frame where Z is the orientation of the earth's axis relative to the fixed, distant stars, and χ is the colatitude (earth's precession negligible in our case)



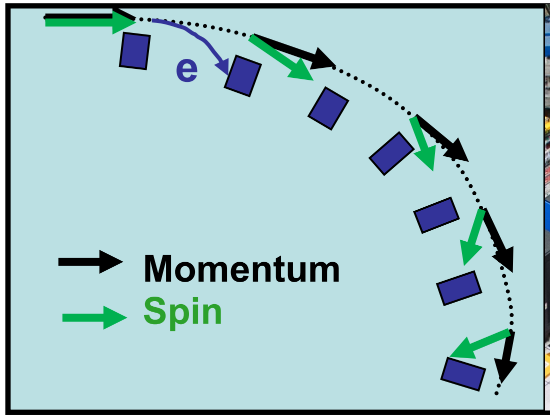


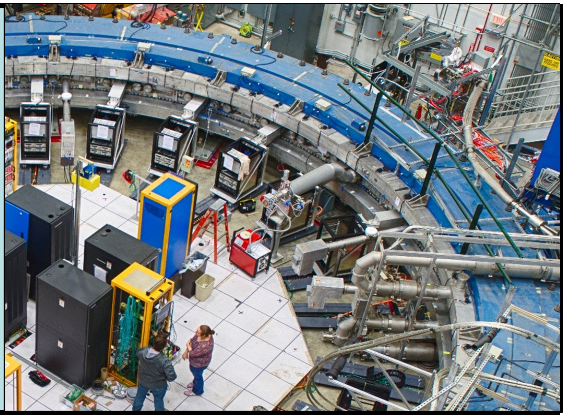
Facility	Latitude ϕ	Colatitude $\chi = 90° - \phi$
BNL	40.9°N	49.1°
Fermilab	41.9°N	48.1°
CERN	46.2°N	43.8°
J-PARC	36.5°N	53.5°
HIAF	23.1°N	66.9°

Statistics: After 6 years of running



The Basic Principle is Simple



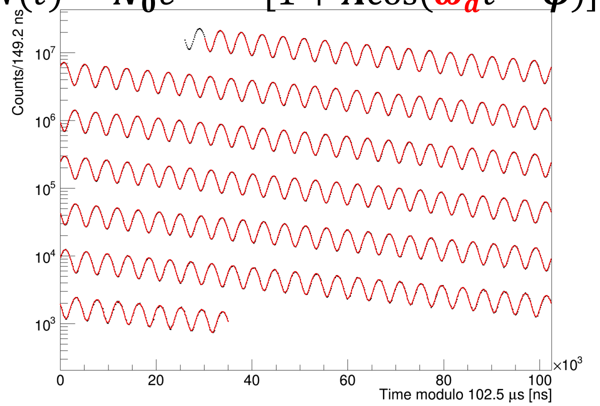


Determine difference between

- **spin precession frequency ω_S** and
- **cyclotron frequency ω_c**

for a (polarized) muon moving in a B field

$$N(t) = \boldsymbol{N_0} e^{(-t/\tau)}[1 + \boldsymbol{A}\cos(\boldsymbol{\omega_a} t - \boldsymbol{\phi})]$$



Measure these

$$\omega_S - \omega_c \equiv \omega_a = \frac{qB}{m} a_\mu$$

Extract

1. Measure $\boldsymbol{\omega_a}$: modulation of decay positron time spectrum
2. Measure $\boldsymbol{B}$: proton nuclear magnetic resonance (NMR)

$$\rightarrow 2\mu'_p(\mathrm{H_2O}, T_r)B = \hbar\omega'_p(\mathrm{H_2O}, \mathrm{T}_r)$$

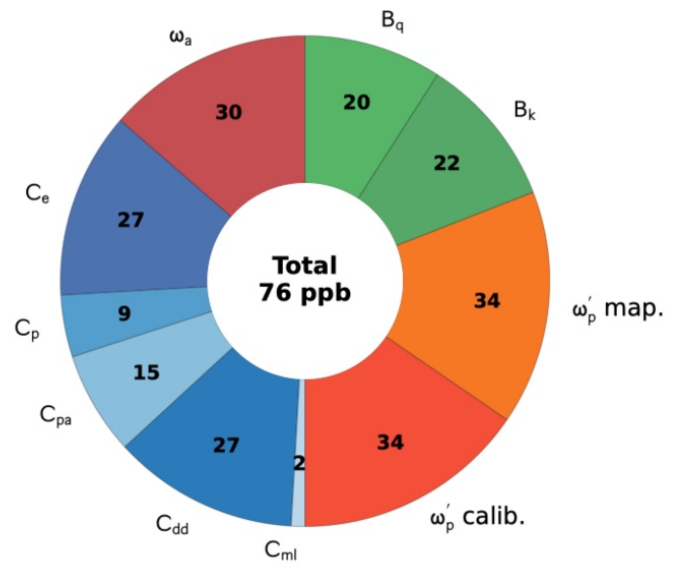
3. Extract a_μ

Final uncertainty budget

$$\frac{f_{clock}\,\omega_a^{meas}(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib}\langle \vec{x}(x,y,\phi)\times\omega_p(x,y,\phi)\rangle(1 + B_k + B_q)}$$

Run-4/5/6

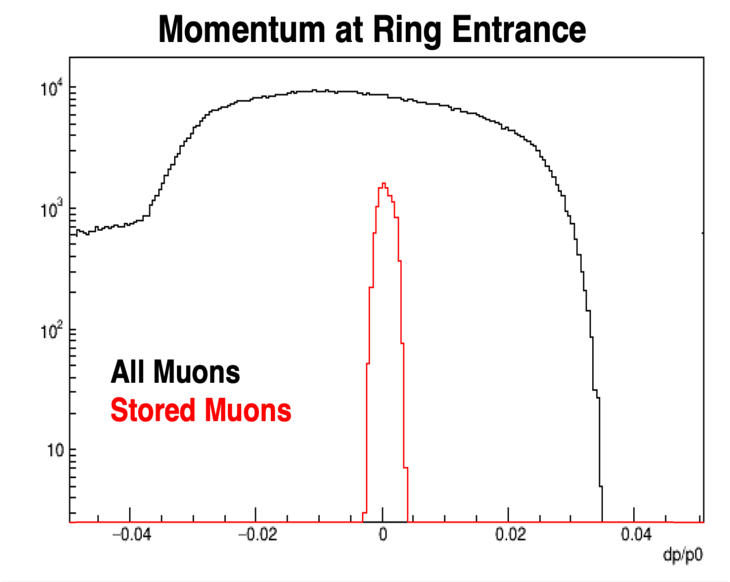
Quantity		Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)		...	114
ω_a^m (systematic)		...	30
C_e	Electric Field	347	27
C_p	Pitch	175	9
C_{pa}	Phase Acceptance	-33	15
C_{dd}	Differential Decay	26	27
C_{ml}	Muon Loss	0	2
$\langle\omega_p' \times M\rangle$ (mapping, tracking)		...	34
$\langle\omega_p' \times M\rangle$ (calibration)		...	34
B_k	Transient Kicker	-37	22
B_q	Transient ESQ	-21	20
μ_p'/μ_B		...	4
m_μ/m_e		...	22
Total systematic for $\mathcal{R}_\mu'$		...	76
Total for a_μ		572	139



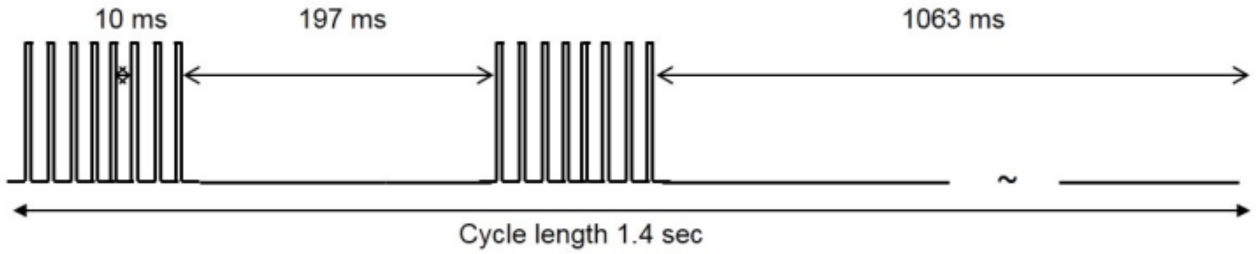
- TDR goal: 100 ppb ✓
- Systematics are "evenly" distributed:
  - No dominant source
  - Further improving would require to reduce in many categories **togerther!**
  - **How?**

How might we do better: more muons

$$\frac{\Delta\omega_a}{\omega_a} \propto \frac{1}{\gamma B P \sqrt{N}}$$



- Fermilab g-2 only stores **2% of incoming muons**
- A very tight momentum acceptance and time spread → required by the **magic momentum condition**.
- A better muon beam (e.g. lower emittance muon beam) would release the current acceptance requirement and also give smaller beam oscillations (smaller C_e & C_p)

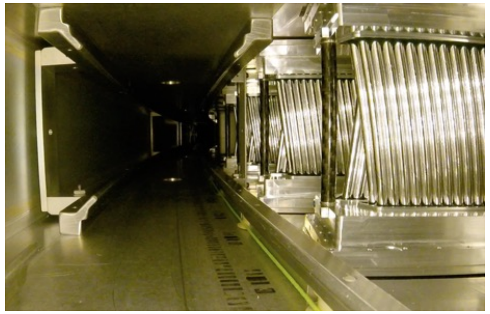


- Curent bunch structure:

11 Hz operation with 1 ms data-taking

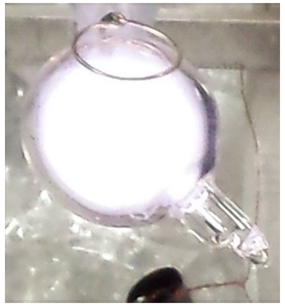
- Limited room for further improvement, given the accelerator constraints

Systematics improvement



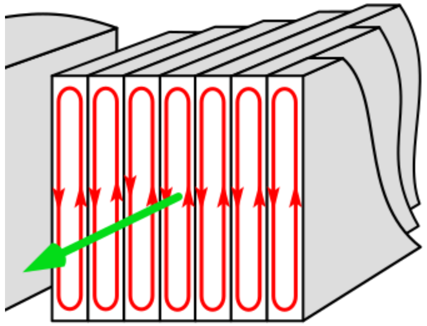
Replace calos with in-vacuo **silicon trackers**

- Removes/reduces **gain** & **pile-up** issues
- Azimuthal coverage reduces beam systematics



Improve field extraction

- Better calibration chain, mapping & use of ^3He
- $\delta(m_\mu/m_e)$ of 22 ppb will decrease with MuSEUM experiment



Design out transient fields

- Remove pulsed electrostatic quadrupoles
- Redesign vacuum chambers to control kicker eddy currents

slides courtesy: James Mott