muon charged lepton flavour violation, muon and proton EDMs

Joost Vossebeld

Inputs from: Mark Lancaster, Themis Bowcock, Alex Keshavarzi, Graziano Venanzoni

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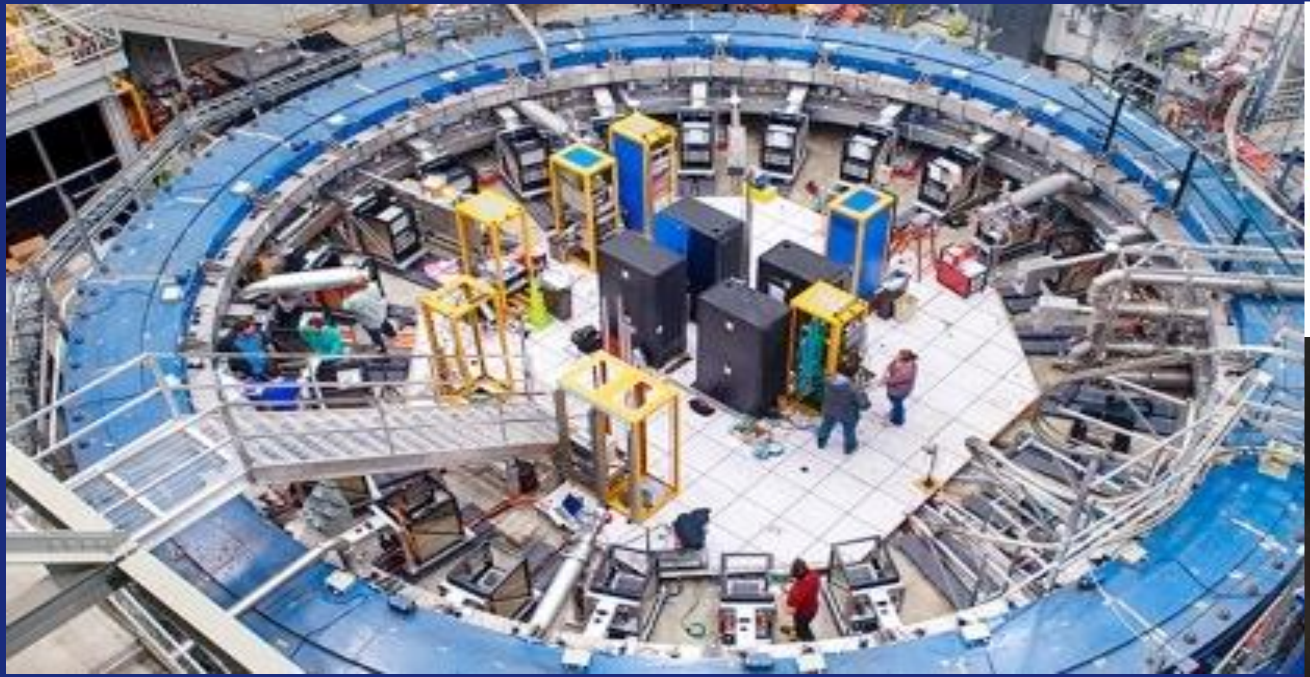
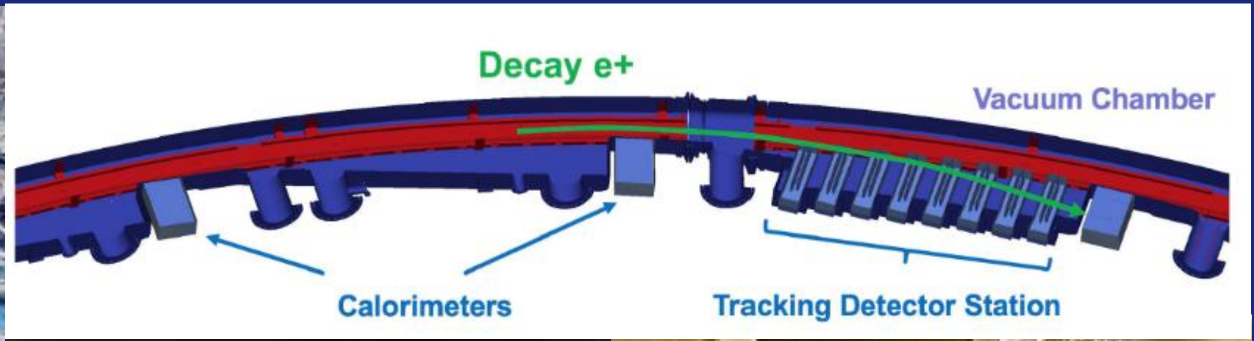
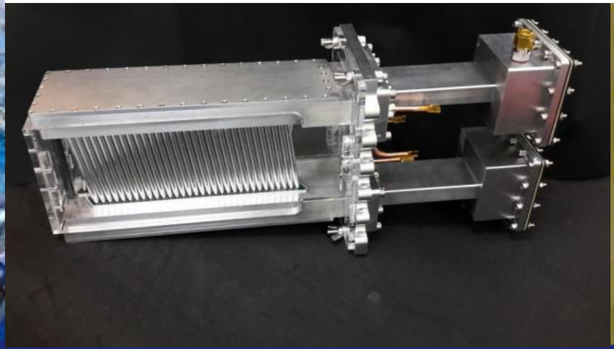
1. Muon magnetic moment: the g-2 puzzle
2. Storage ring Electric Dipole Moment (EDM) measurements (muons, protons)
3. Lepton Flavour Violation in muon decays

Fermilab g-2

→(Cockcroft, Lancaster, Liverpool, Manchester, UCL)





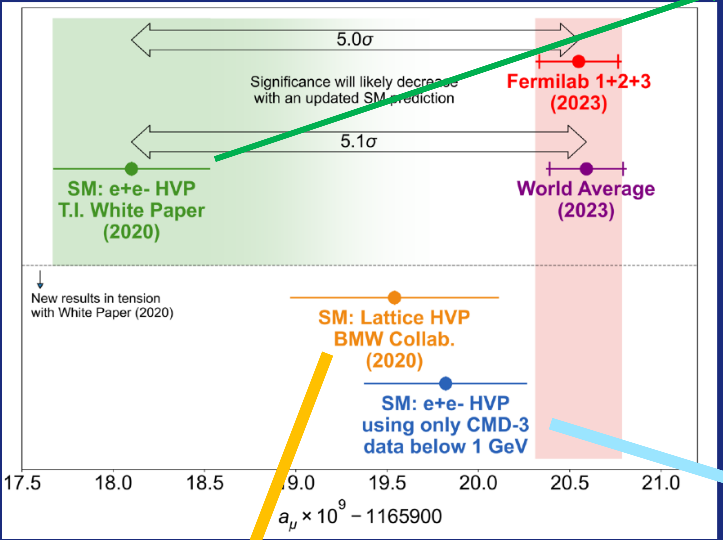


UK groups provided the two in-vacuum strawtube tracking stations for improved understanding of beam dynamics and to increase sensitivity.

Increased statistics and reduced systematics w.r.t previous BNL experiment.

Datataking is now completed (2023), with final results expected in 25/26.

g-2 puzzle

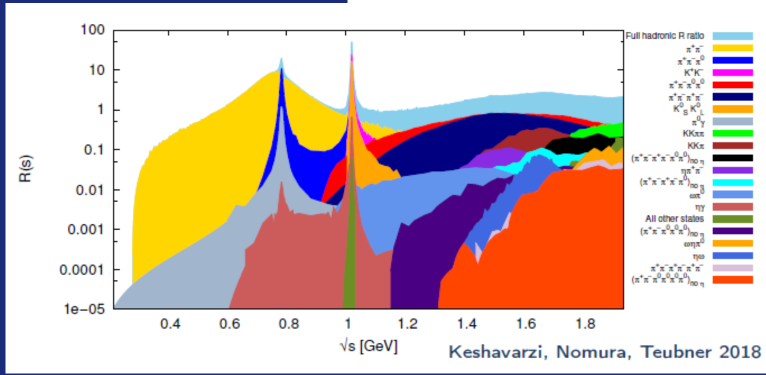


Dispersive theory predictions use optical theorem to determine $\mathbf{a_\mu^{HLO}}$ (hadronic contribution a_μ)

$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to hadr}(s)K(s)\,ds$$

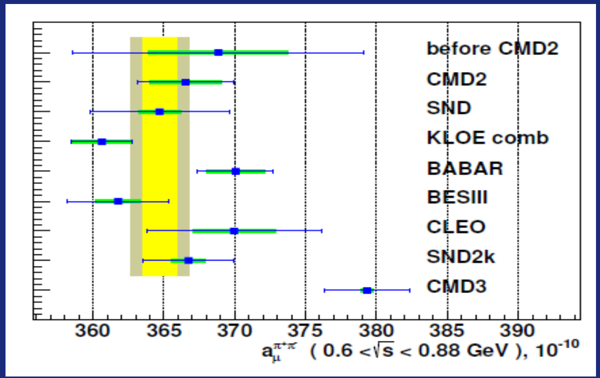
$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)(s/m^2)} \sim \frac{1}{s}$$

$e^+e^- \to hadrons$



BMW collaboration (2020) lattice calculation yields higher value of $\mathbf{a_\mu^{HLO}}$.

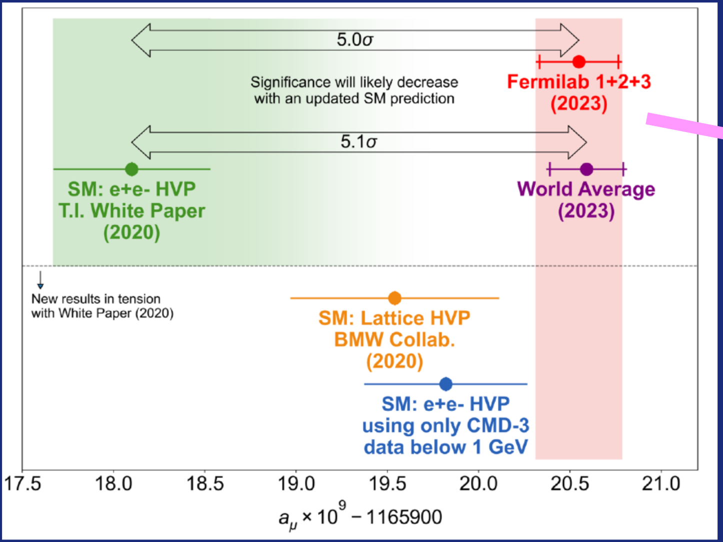
2022 CMD-3 measurement of $e^+e^- \to \pi^+\pi^-$, would lead to higher value for $\mathbf{a_\mu^{HLO}}$ (but is in tension with previous measurements).



We are left with a confusing picture that needs resolution!

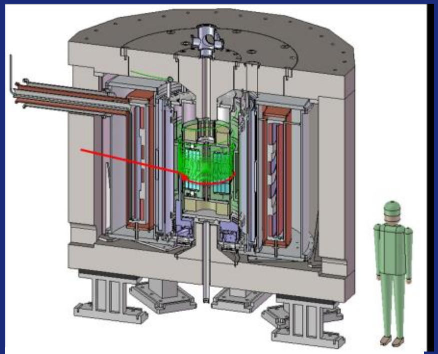
Understanding the theory predictions is critical for precision physics.

g-2 puzzle … what next?



g-2 measurements:

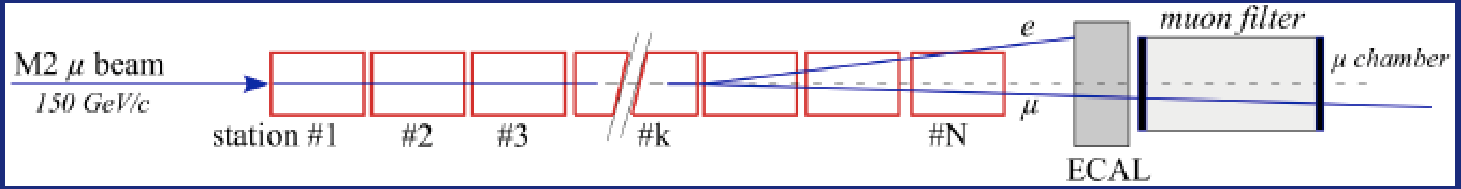
- Final FNAL g-2 results 25/26.
- Independent measurement of g-2 with the JPARC-E34 experiment (starting in 2027).

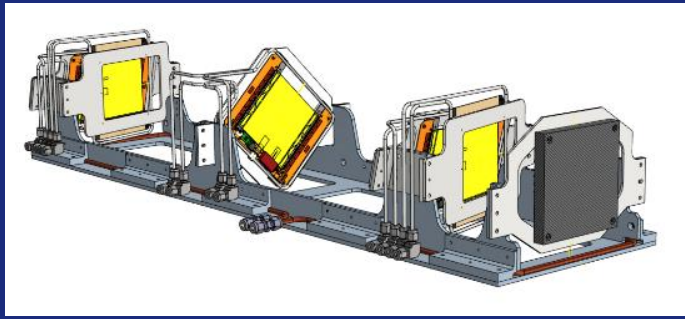


JPARC E34 experiment

Theory:

- New lattice predictions (even closer agreement with measurement)
- Dispersive predictions, work on experimental inputs:
  - New measurements in progress:
    - KLOE → new analysis of $e^+e^- \to \pi^+\pi^- \gamma$ →(Liverpool)
    - BES-III → fully inclusive measurement $e^+e^- \to hadrons$ in ISR events
  - MUonE → indendent determination of a_μ^{HLO} in muon-electron scattering →(Imperial, Liverpool)



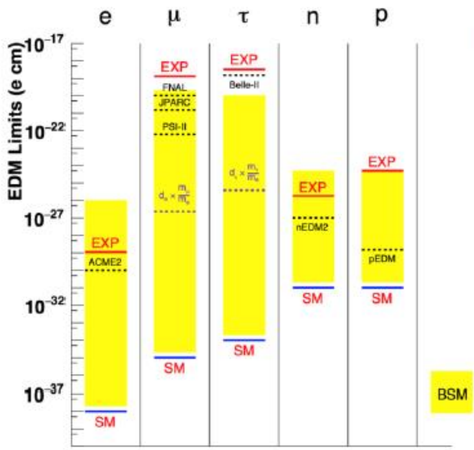


Storage ring Electric Dipole Moments (protons and muons)

Why EDMs?

Slide from Alex Keshavarzi

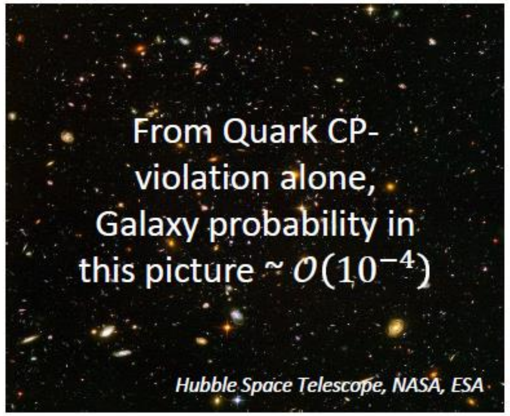
Robust precision test of the SM



Predicted values are immeasurably small in the SM.

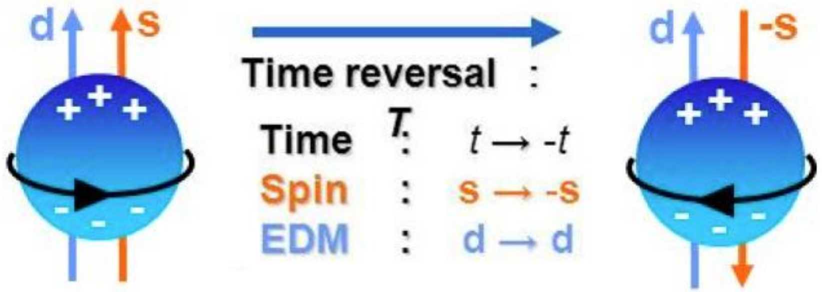
Universe's matter-antimatter asymmetry

Need new sources of CP violation.



Why EDMs?

Permanent EDM Violates both T & P Symmetries

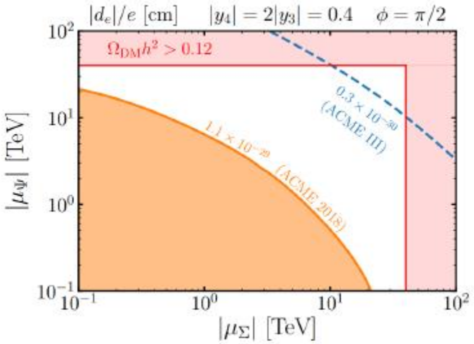


EDM, $d \neq 0$:
T-violation = CP-violation

Non-zero EDM = BSM physics + CP-violation.

Dark matter

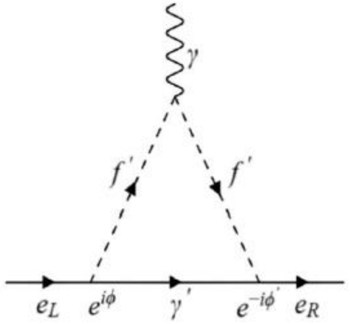
DM models predict large EDMs.



At minimum, can greatly constrain parameter space.

New physics sensitivity

BSM effects are loop-induced.



Sensitive to a wide range of interactions and energy scales.

alexander.keshavarzi@manchester.ac.uk @alexkeshavarzi

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Muon EDM

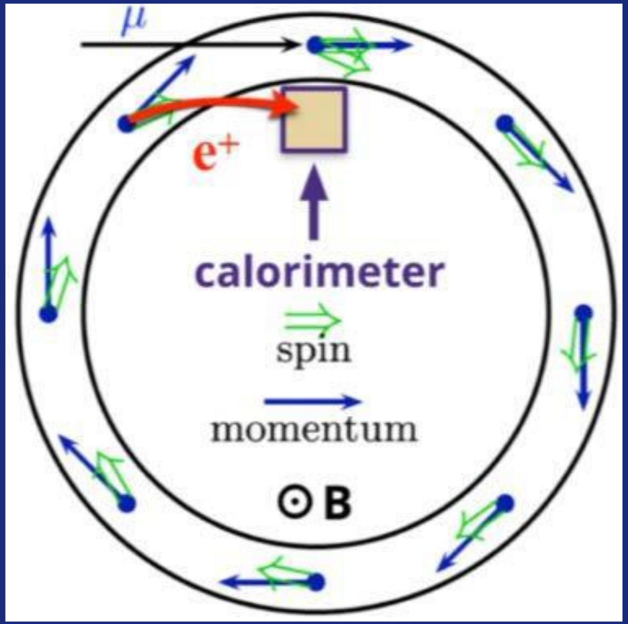
Reminder: storage ring measurement of g-2

In the magnetic field, if $g \neq 2$, the spin direction rotates differently from the momentum.

$\omega_a = \omega_s - \omega_c$ is the anomalous precession frequency.

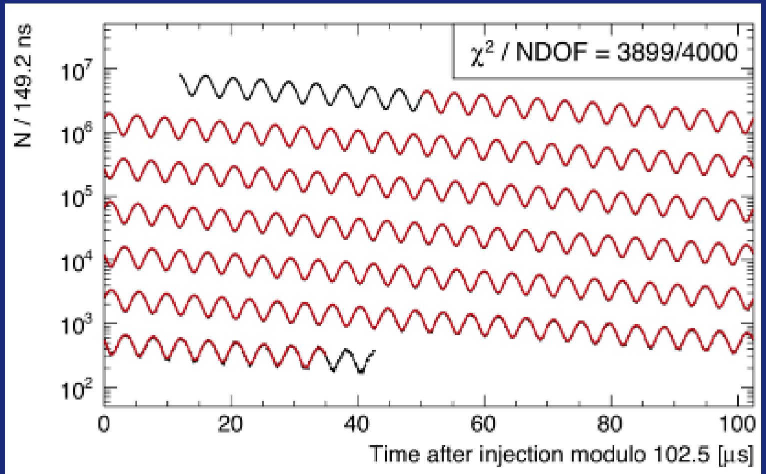
$$\vec{\omega}_a = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

Second term can be reduced to 0 when P_μ = 3.1 GeV (“magic momentum”)



Muon polarisation measured from direction of emitted positrons

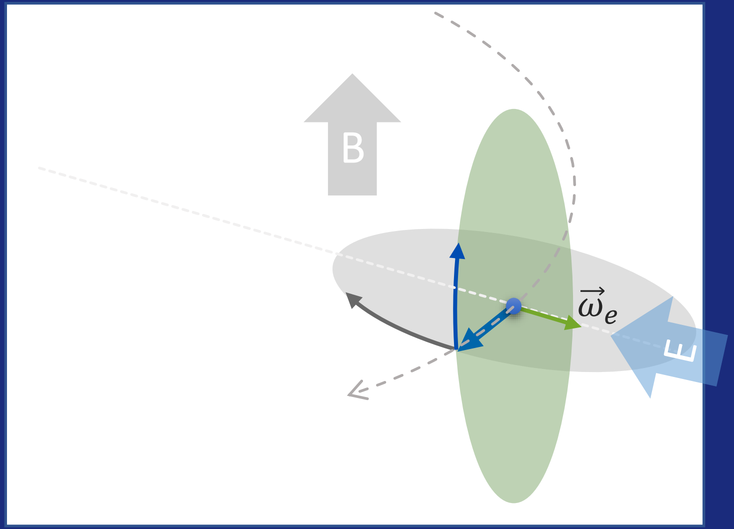
The precession leads to the so-called wiggle plot from which ω_a is extracted.



Electric dipole moments in a storage ring experiment

A non-zero muon or proton EDM causes a tilt in the precession plane.

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



This leads to a small up-down oscillation of the spin, that follows the anomalous g-2 precession frequency. (This is used to measure muon EDM in g-2 experiments.)

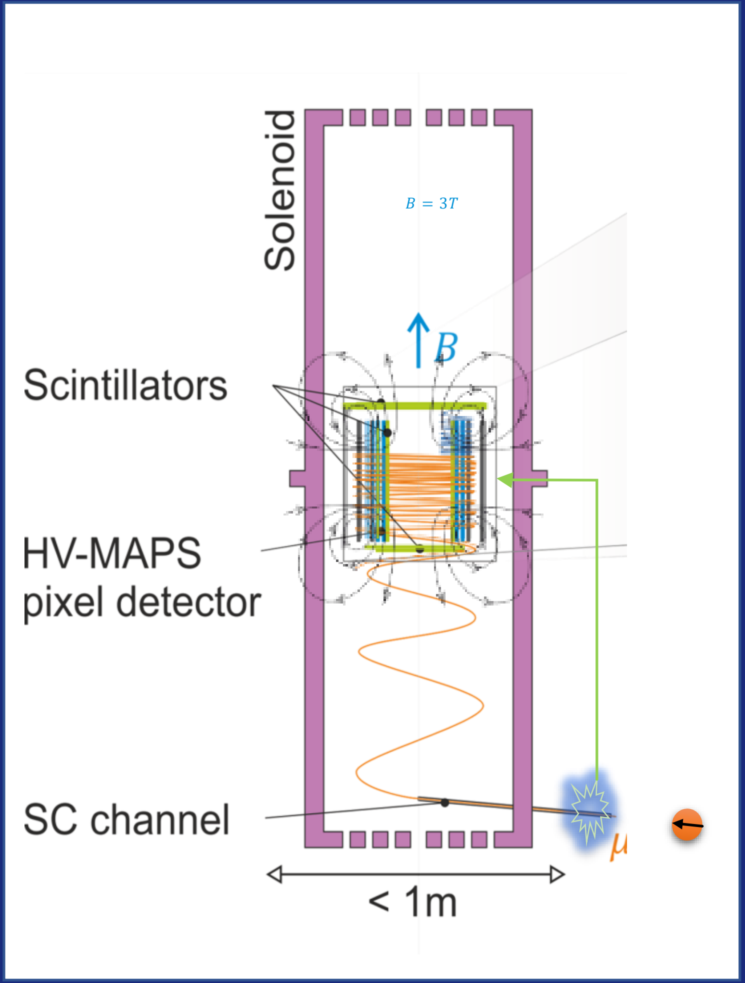
- **BNL g-2:** $|d_\mu| < 1.9 \times 10^{-19}$ e.cm (95% C.L.)
- **FNAL g-2:** *expected limit* $|d_\mu| < 2.1 \times 10^{-20}$ *e.cm (95% C.L.)*
- **JPARC-E34 g-2:** *expected limit:* $|d_\mu| < 1.5 \,.\, 10^{-21}$ *e·cm (95% C.L.)*

Frozen Spin Method: with a suitable radial electric field ($E \cong aBc\beta\gamma^2$) the g-2 precession can be removed, allowing a much larger out of plane spin precession to build up. leaving only the out of plane precession due to d_μ.

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

μEDM experiment at PSI

→(Liverpool, Manchester, UCL)



PSI μEDM experiment: first to exploit "frozen spin"

- Muon injected in compact magnet
- Kicker magnet locks muons in orbit
- Trackers measure the in/out (g-2) and up-down asymmetry (d_μ) of emitted positrons.

Phase 1 (start 2026)

- Demonstrate muon injection and stable orbits in the magnet
- Instrument magnet to measure g-2 precession and demonstrate it can be removed using the frozen spin method.
- First measurement of d_μ with $\boldsymbol{\sigma(d_\mu) \sim 3 \times 10^{-21}}$ ***e.cm***

Phase 2 (> 2030):

- Full experiment in custom-built magnet
- High precision measurement: $\boldsymbol{\sigma(d_\mu) \sim 6 \times 10^{-23}}$ ***e.cm*** *(factor ~3000 improvement on today's limit)*

Proton EDM

Proton Electric Dipole Moment

Slide from Alex Keshavarzi
See also: https://arxiv.org/abs/2409.14996

Robust precision test of the SM

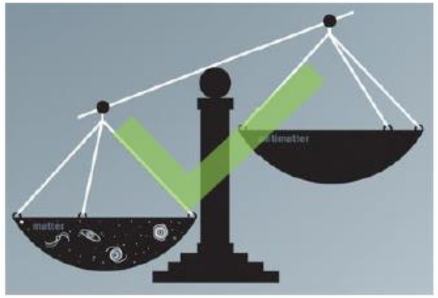
$$\mathcal{L}_{QCD} = (\dots) + \boxed{\frac{g^2}{32\pi^2}\bar{\theta}\tilde{G}^a_{\mu\nu}G^{\mu\nu a}}$$

→ CP-violating

Non-zero nucleon (N) Electric Dipole Moment (EDM) →
$|\vec{d}_N| = \vartheta(\theta)$.

Solve the Strong CP problem.

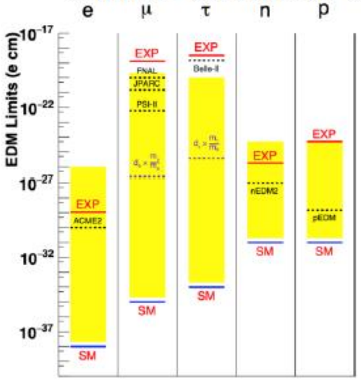
Universe's matter-antimatter asymmetry

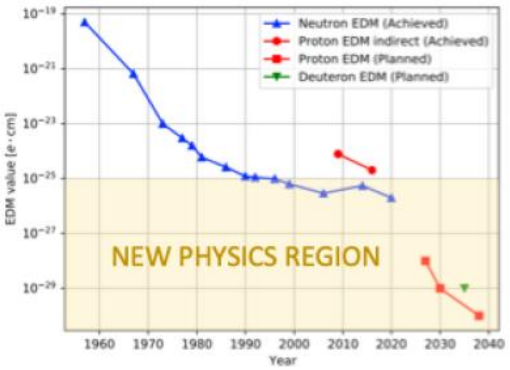


Confirmed proton EDM = model-independent CP violation.

Why Proton EDM?

First ever direct proton EDM measurement.
Improve on current (indirect) limit by at least $\mathcal{O}(10^4)$.

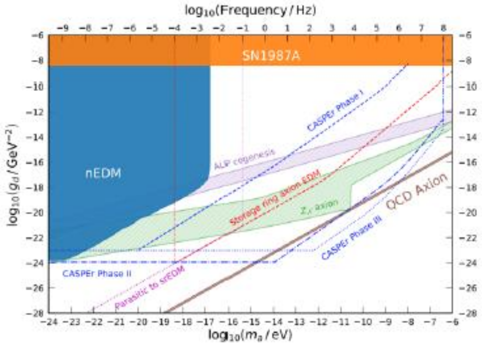




Only EDM measurement with potential to probe SM limit.

Dark matter

Oscillating pEDM = axionic DM.



Probes axion field...
Freq: 1 mHz → 1MHz
Mass: 10^{-7} eV → 10^{-22} eV

New physics sensitivity

Far-reaching complimentary to wider programme.

$\mathcal{O}$(PeV) mass scale:
$\phi^{NP} \sim 1,\ \Lambda_{NP} \sim 3 \times 10^3$ TeV.
[e.g. LHC/FCC.]

Light, weak new physics:
$\Lambda_{NP} \sim 1$ GeV, $g \lesssim 10^{-5}$, $\phi^{NP} \sim 10^{-10}$.
[e.g. LZ, LDMX, FASER, SHiP.]

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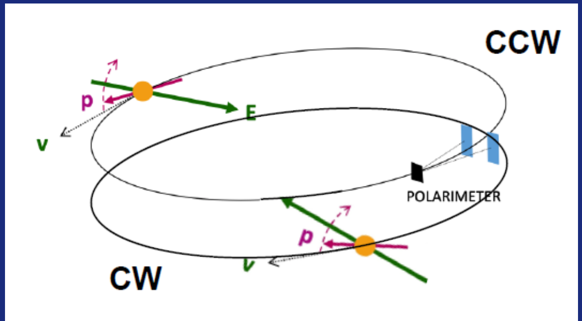
alexander.keshavarzi@manchester.ac.uk @alexkeshavarzi

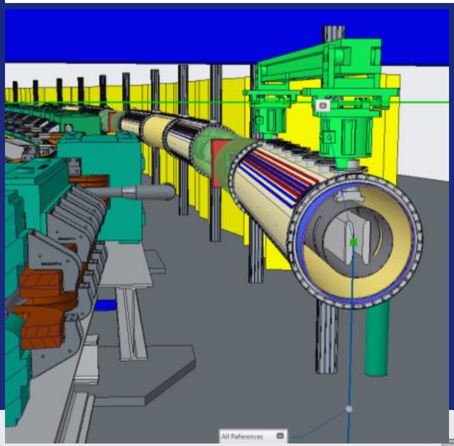
Storage-ring proton EDM measurement at BNL

Proposed facility to achieve sensitivity $\sigma(d_p) \sim 10^{-29}$ e.cm (4 orders improvement on today's limit → 10^3 TeV physics reach)



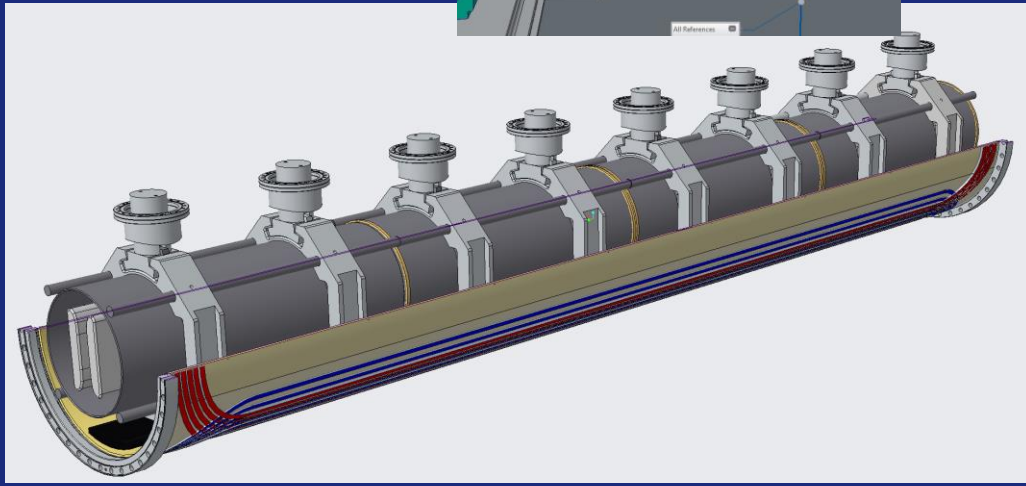
Mixed electric and magnetic storage beam, co-located in the 800m AGS booster tunnel at BNL.

Benefit from availability of high intensity polarized sources for protons, deuterons, ^{3}He.



Status:

- Experiment design and modelling complete.
- Measurement techniques and key systematics understood.
- Prototype components under construction.
- Moving to TDR stage, operation possible mid 2030s
- UK involvement →(**Liverpool, Manchester, …)**
  - Precision beam studies
  - Polarimeter development
  - Prototype high field electrostatic deflector section



Muon Charged Lepton Flavour Violation

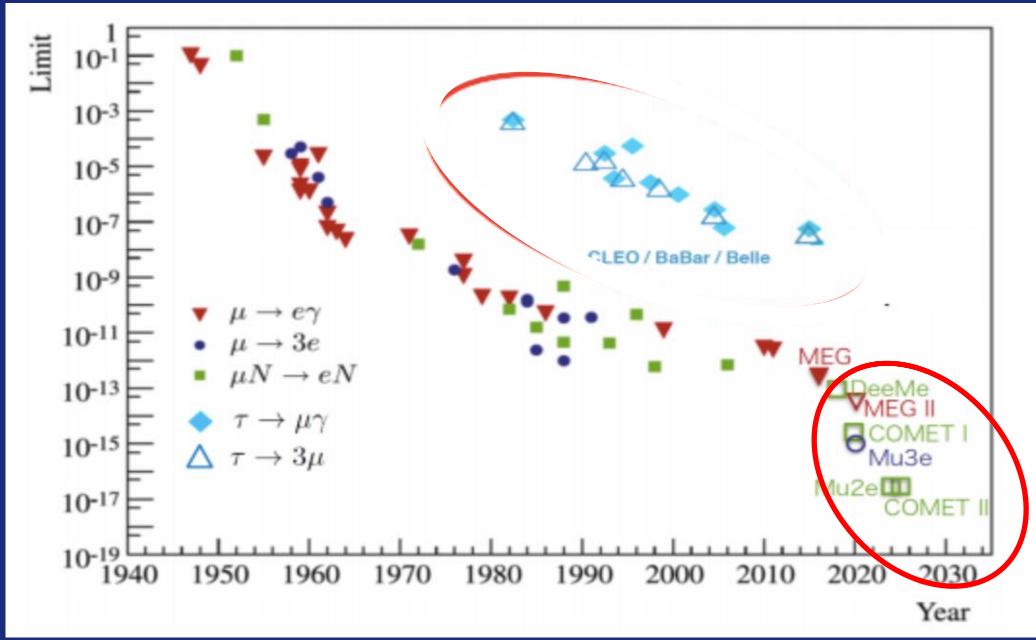
Charged Lepton Flavour Violation in Muon decays

The absence of direct charged lepton flavour violation in SM appears accidental, but it can appear naturally in NP theories.

The heavily suppressed SM rate for CLFV decays through neutrino oscillations makes it ideal decay to look for NP.

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$

If charged lepton flavour is violated, we could see muon decays to $e\gamma$, *eee* and direct $\mu \to e$ in muonic atoms.



Planned experiments increase muon CLFV sensitivity by ~4 orders over the next 10 years.

	Best limits	Projected sensitivities (90%CL)
$\mu \to e\gamma$	$< 4.3\text{x}10^{-13}$ MEG (PSI)	$6\text{x}10^{-14}$ MEG II (PSI)
$\mu \to eee$	$< 1.\text{x}10^{-12}$ SINDRUM (PSI)	$4\text{x}10^{-15}$ Mu3e I (PSI) $1\text{x}10^{-16}$ Mu3e II (PSI)
$\mu N \to eN$	$< 7.0\text{x}10^{-13}$ SINDRUM II (PSI) μ Au $\to$ e Au	$6\text{x}10^{-17}$ Mu2e (FNAL) $7\text{x}10^{-15}$ COMET I (J-PARC) $6\text{x}10^{-17}$ COMET II (J-PARC)

$\mu \rightarrow$ eee and $\mu \rightarrow e\gamma$ at PSI

Positive muons are stopped on a target and decay at rest.

Backgrounds:

- **Non-CLFV backgrounds ($\mu \rightarrow ee e\nu\nu$ or $\mu \rightarrow e\nu\nu\gamma$)**

$\rightarrow$ excellent energy resolution ($E_{observed} = m_\mu$)

- **Combinatoric backgrounds**

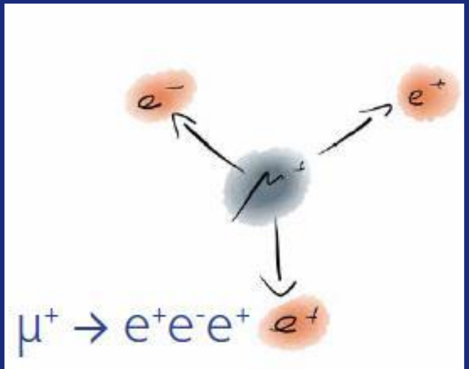
$\rightarrow$ DC muon beam and excellent timing

$\rightarrow$ excellent vertex resolution

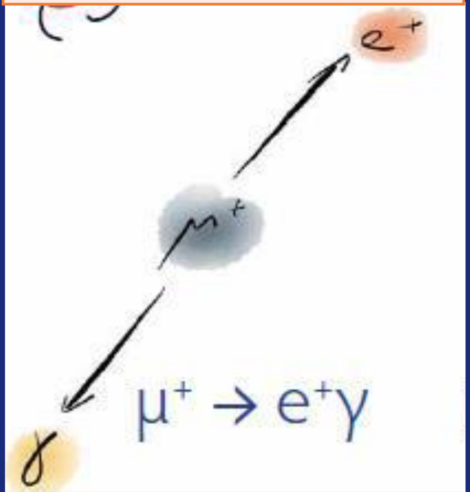
Muons created from high intensity proton beam at PSI

Currently πE5 beam line: 10^8 muons per second DC beam

After 2028 High Intensity Muon Beam (HIMB) will deliver 2×10^9 μ/s

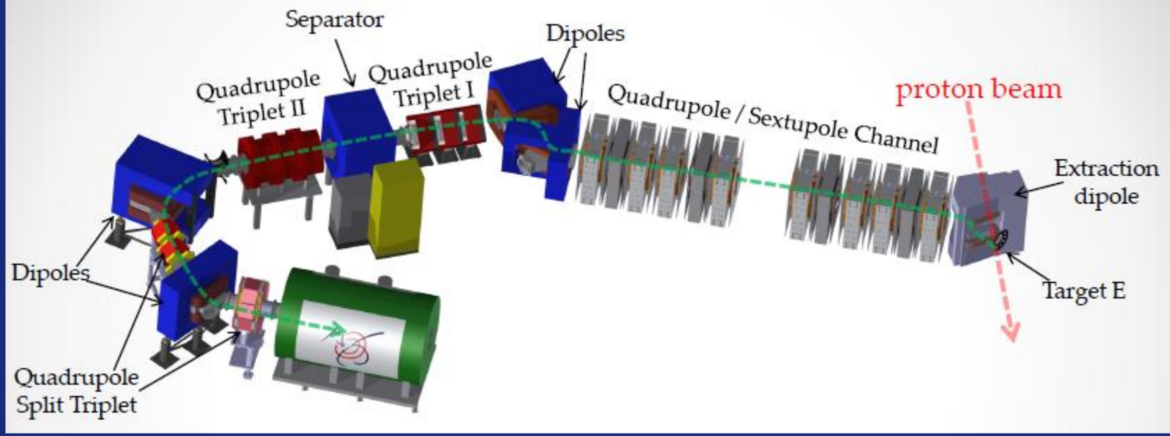


3 co-planar electrons
$\Sigma P_e = 0$, $\Sigma E_e = m_\mu$

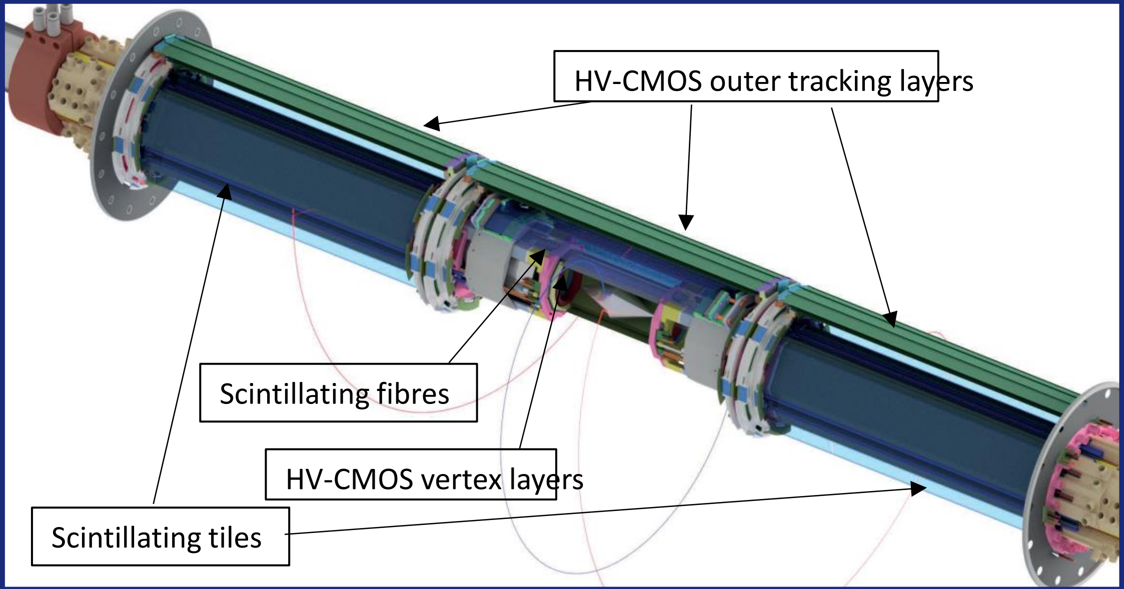


back-to-back electron and photon
$E_\gamma = E_e = ½ m_\mu$

Mu3e →(Bristol, Liverpool, Oxford, UCL)



UK contributes timing system and outer layers of the ultra-low mass (0.1%X_0) HV-CMOS pixel tracker.



Phase I experiment: BR($\mu \rightarrow eee$) < $2x10^{-15}$

- Construction is progressing → central detector operation in 2025.
- Physics from 2026.

Phase 2 experiment BR($\mu \rightarrow eee$) < $1x10^{-16}$

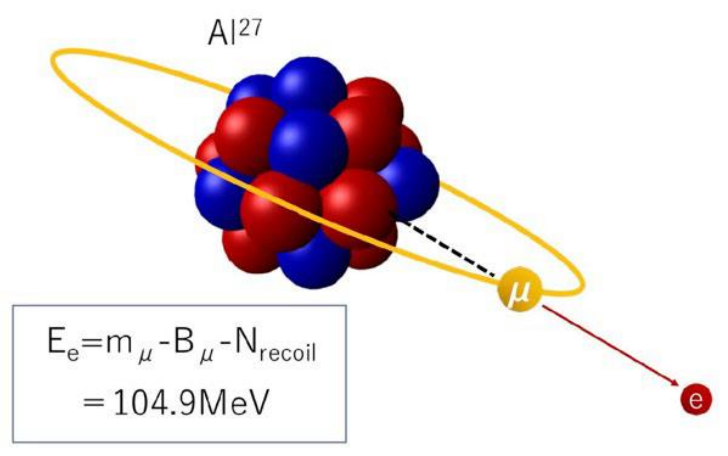
- Upgraded experiment to fully exploit the dedicated HIMB upgrade ($2x10^9$ μ/s)
- Start early ~2032/33,

$\mu N \rightarrow eN$ conversion experiments

Negative muons are stopped on a target and decay from muonic atoms

Backgrounds:

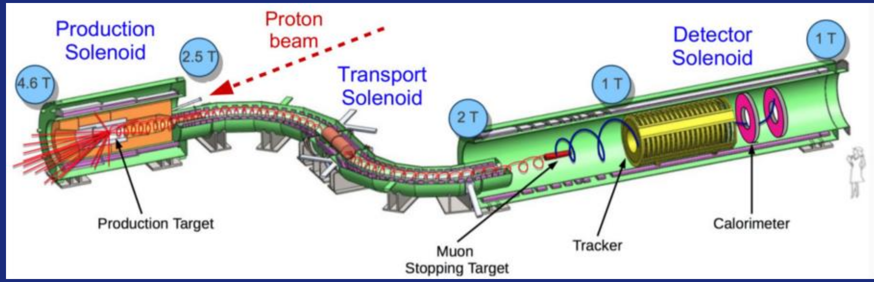
- Beam related backgrounds: prompt antiprotons, pions,..
  - → transport solenoid for high purity beam
  - → Pulsed beam + veto window after beam pulse
- Non-LFV muon decay in orbit → excellent electron energy resolution



Muon decay from muonic atom.
Monochromatic electron
$E_e = m_\mu - E_{binding} - E_{recoil}$

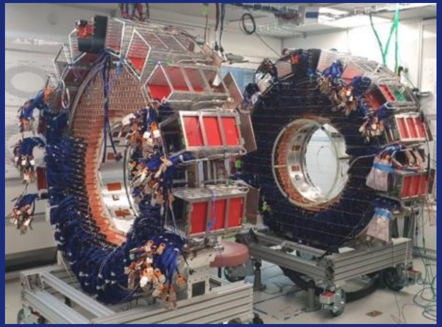
New experiments under construction at FNAL (Mu2e) and JPARC (COMET)

Mu2e →(Liverpool, Manchester, UCL)



Status Mu2e phase–1 (target sensitivity: 10^{-17})

- Installation Production, Transport and Detector solenoids to complete in 2025.
- Solenoid commissioning 2025/2026.
- detector in-situ commissioning starting spring 2025.
- Beam commissioning 2026 and physics in 2027
- Continue operation after PIP-II shutdown



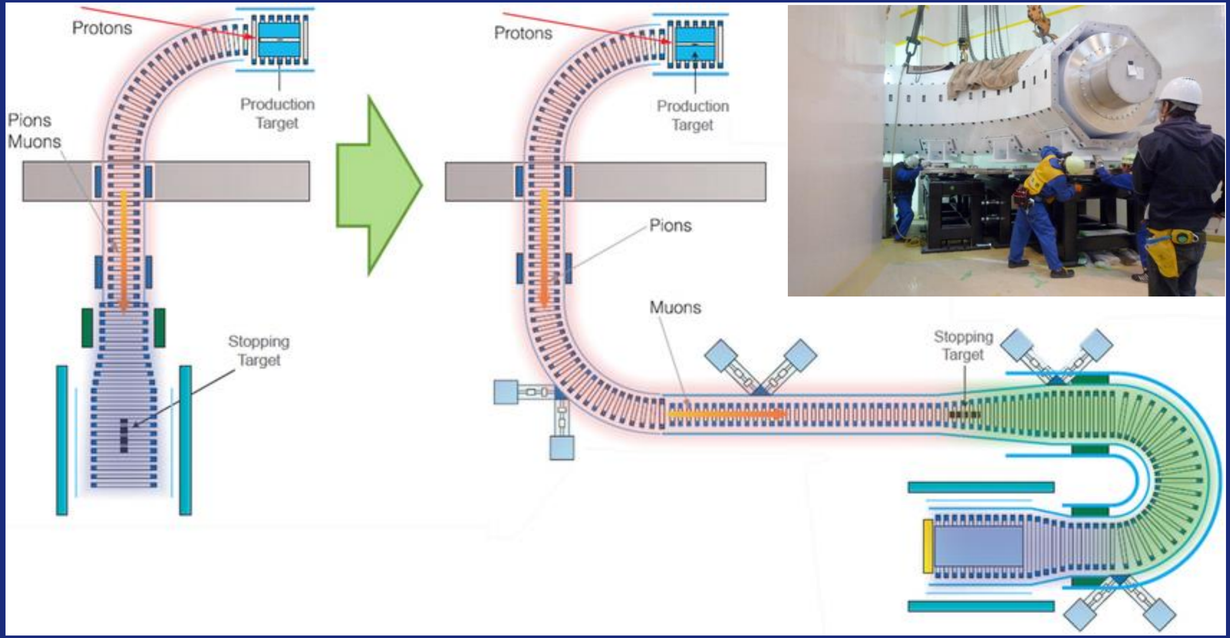
Mu2e phase-2 experiment ~mid 2030s

COMET →(Imperial)

Status COMET-1 (target sensitivity: $3x10^{-15}$)

- First beam on target in 2023
- Foreseen start in 2024…

COMET-2 (target sensitivity: $2x10^{-17}$)



Summary

- **Muon g-2** results still pose a puzzle that needs resolving.
- Experiments in preparation to greatly increase sensitivity to the **EDMs of muons and protons.** Important step towards first measurement of SM EDM value (for protons).
- CLFV experiments under construction will improve sensitivity to **charged lepton flavour violation in muon decays** by up to four orders of magnitude.

Precision measurement and rare decays searches remain a powerful tool to search for NP.

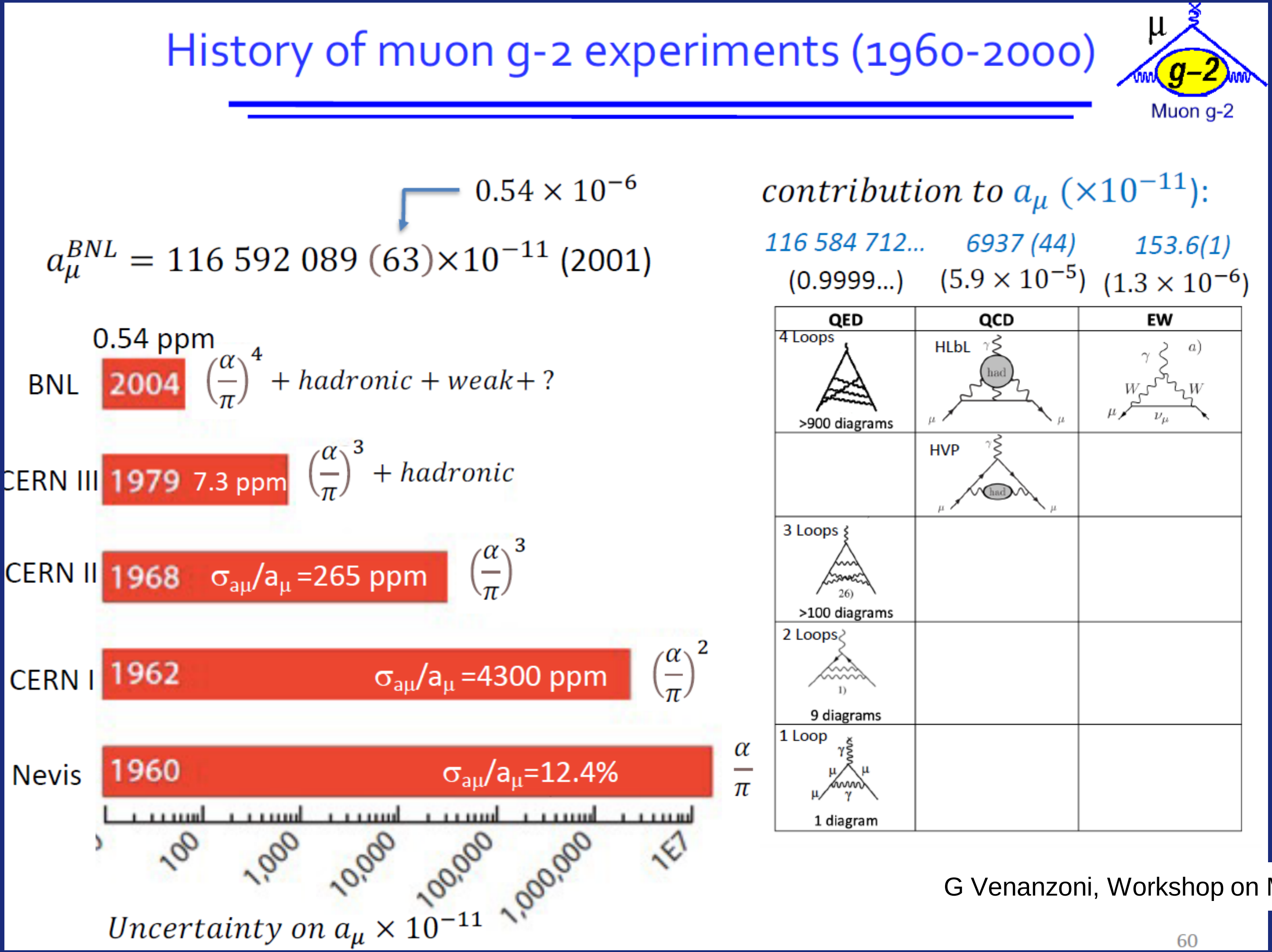
Continue to improve precision of fundamental measurements and sensitivity to ultra-rare decays

And … ensure we have theory predictions to a similar level

BACK-UP slides

Why we measure the muon magnetic moment?

SM test and BSM search with precision measurements



G Venanzoni, Workshop on Muon Precision Physics, Liverpool, 2022

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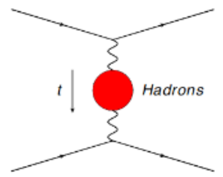
U. Marconi & R Pilato, Workshop on Muon Precision Physics, Liverpool, 2023

Proposed MUonE experiment at CERN

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

Phys. Rep. C 3 (1972), 193



The leading order hadronic contribution to a_μ can also be determined from the hadronic contribution to the running of the electro-magnetic coupling.

Muon-electron scattering is a clean way to measure this.

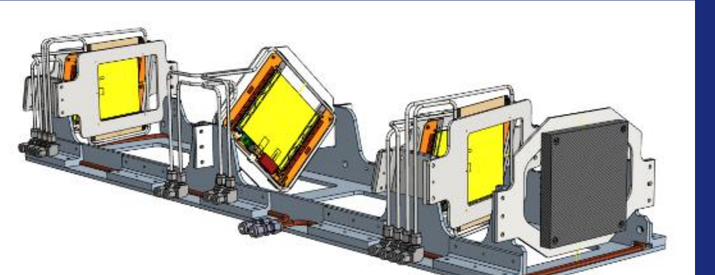
MUonE exploits 150 GeV muons at CERN to hit electrons at rest in a low Z target (Beryllium).

Target: 0.3% uncertainty on a_μ^{HLO}

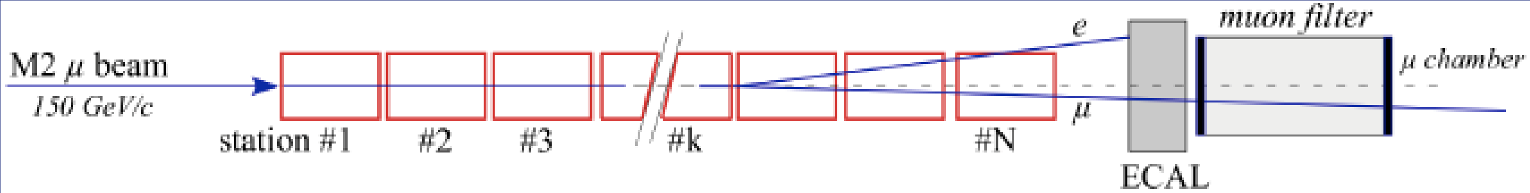
- Very challenging kinematics (θ_μ < 5 mrad, θ_e < 30 mrad, E_e > 1 GeV) require excellent angular resolution scattered electron and muon and(!) the incoming muon.

→ High resolution tracking and challenging tolerance on mechanical stability mechanical

→ 40 tracking stations, each with thin target and multiple silicon strip layers.

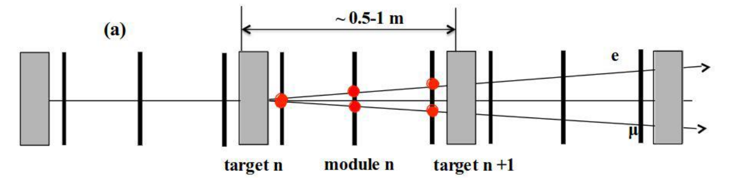


MUonE tracking station

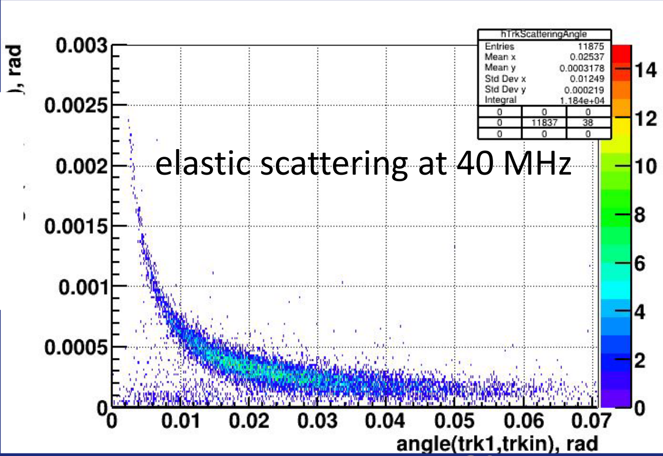


MUonE Schedule:

- 2023 demonstrator run
- Demonstrator run with ~10 stations before LS3
- Full experiment (40 stations) after LS3



2023 demonstration



Physics reach

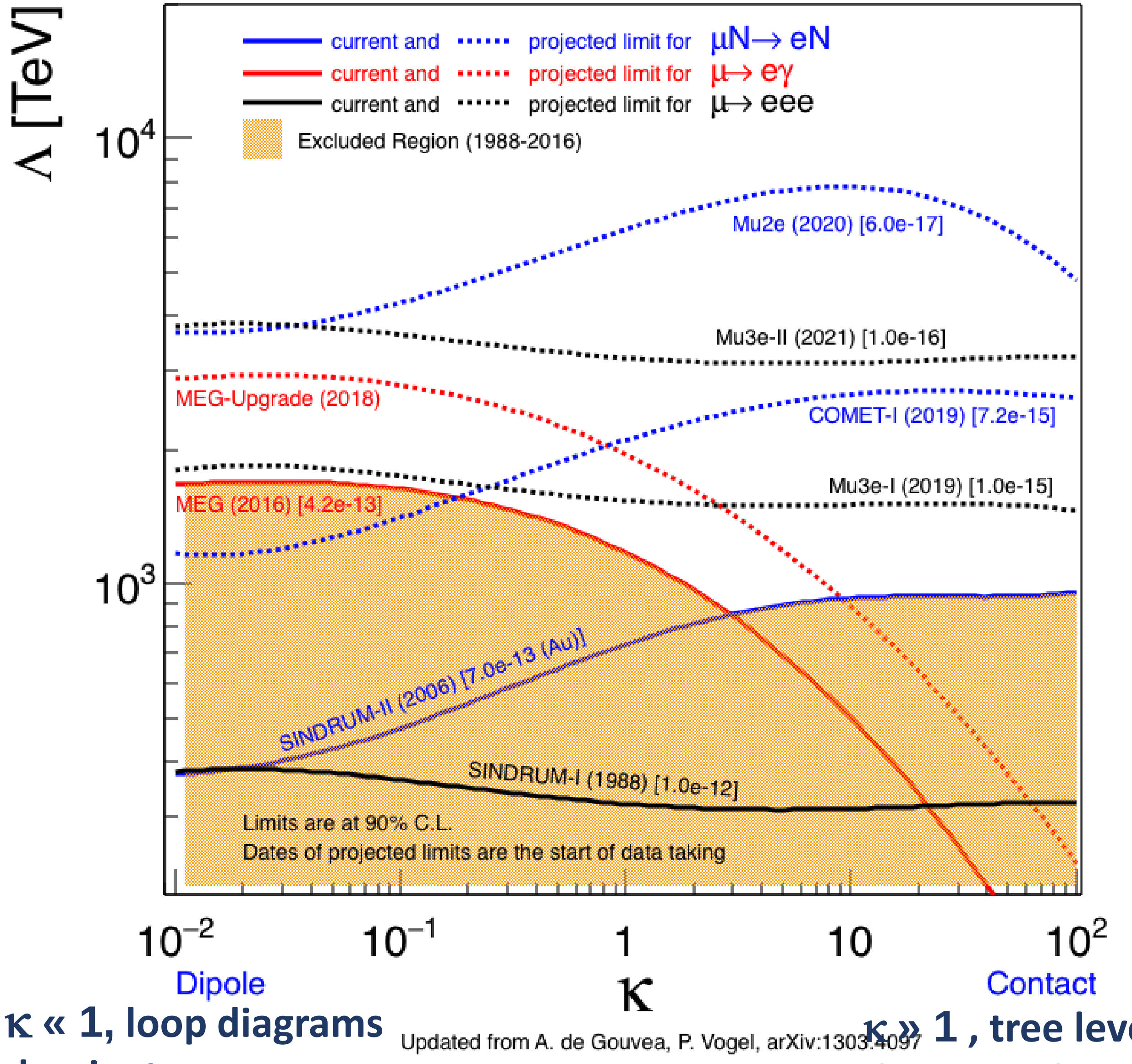
Highly model dependent. Different channels have varying sensitivity to different NP modes.

A comparison is possible with a generic Lagrangian model:

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c.\,.$$

CLFV experiments have sensitivity up to several PeV effective scale.

Update from de Gouvea & Vogel, Prog. in Part. and Nucl. Phys. 71 (2013).

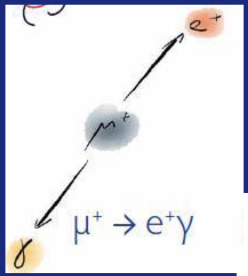


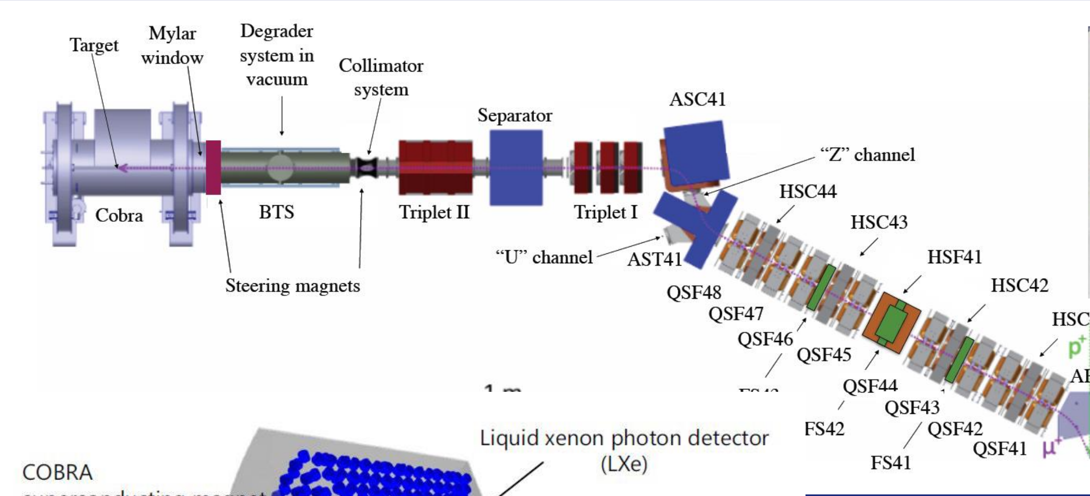
κ « 1, loop diagrams dominate

κ » 1 , tree level diagrams dominate

MEG-II: μ → eγ at PSI

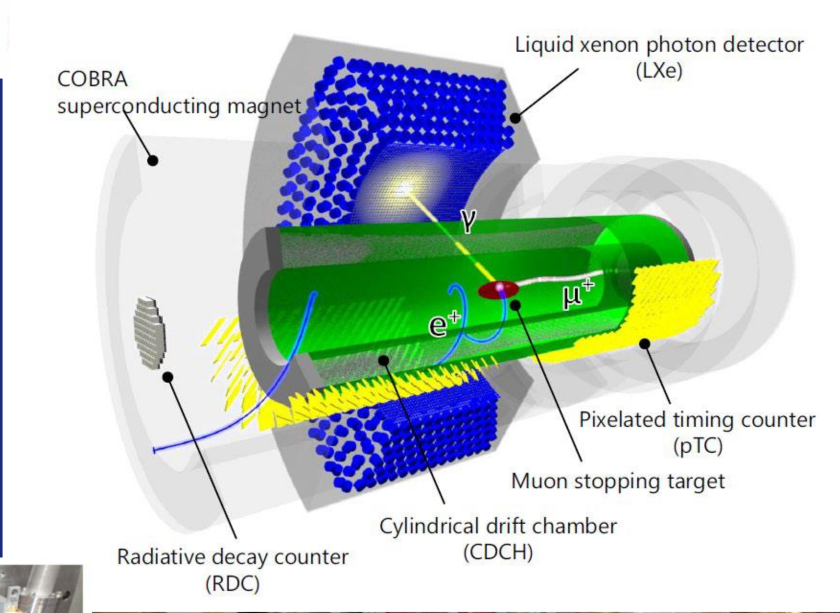
πE5 beam line delivers 28 MeV/c surface muons to experiment target





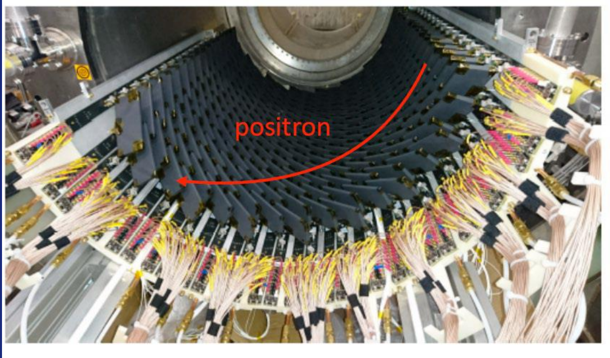
Upgraded detector:

- 2 - 5 x10^{7} μ-decays per second
- 800 liter LXe calorimeter for photon energies
- Cylindrical Drift Chamber for positron momentum
- Scintillating tile timing counters for accidental background rejection



Performance comparison MEG-II vs MEG

PDF parameters	Foreseen	Achieved	MEG
E_{e^+} (keV)	100	89	330
ϕ_{e^+}, θ_{e^+} (mrad)	3.7/6.7	4.1/7.1	8.4/9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.75/1.85	1.1/2.5
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.0/1.8	2.4/1.7
$u_\gamma, v_\gamma, w_\gamma$, (mm)	2.4/2.4/5.0	2.5/2.5/5.0	5/5/6
$t_{e^+\gamma}$ (ps)	70	78	122
Efficiency (%)			
ε_γ	69	63	63
ε_{e^+}	65	65	30
ε_{TRG}	≈99	82	



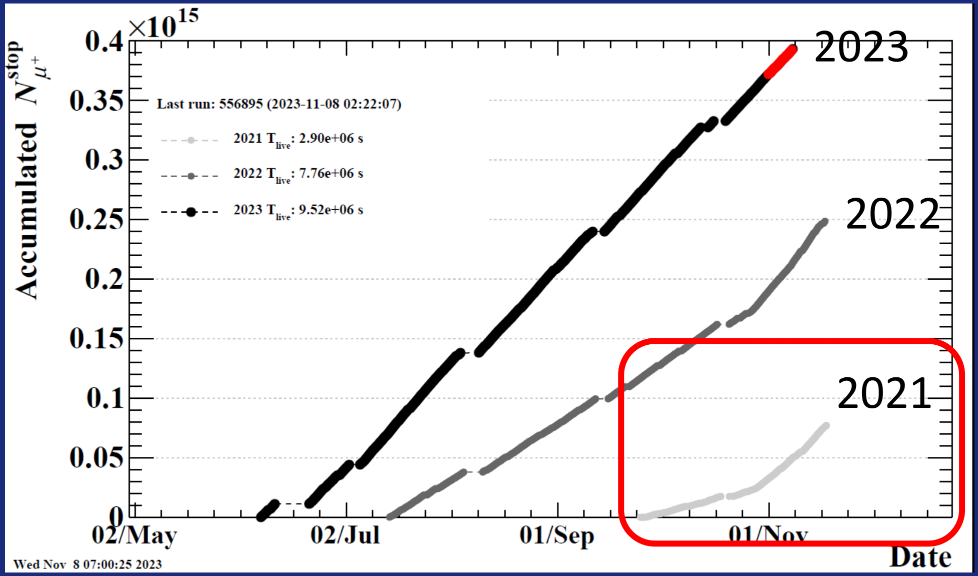
MEG-II status

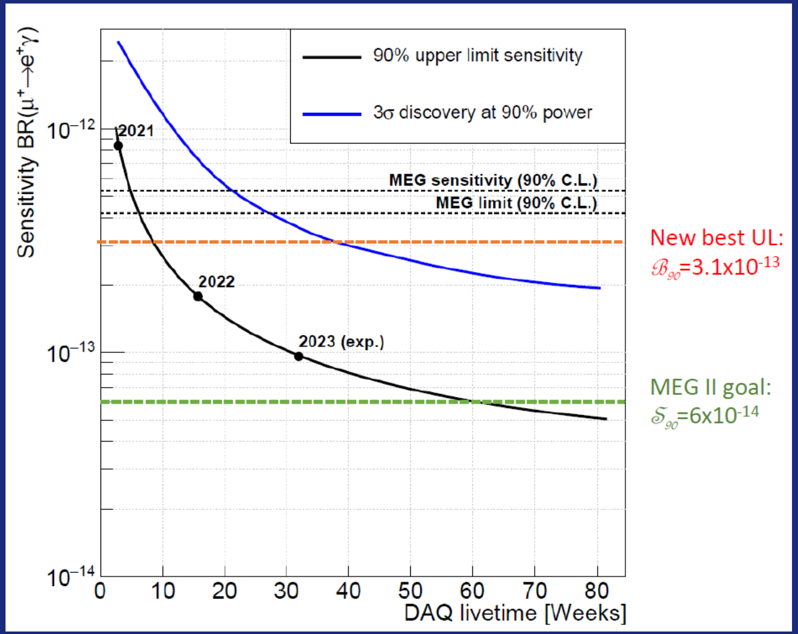
First MEG-II were published 2023:
BR($\mu \to e\gamma$) **< 7.5 x 10^{-13}** (arXiv :2310.12614v2)

(Combined MEG + MEG-II: BR($\mu \to e\gamma$) < 3.1x10^{-13})

Continue to run until 2026.

Final sensitivity goal is 6x10^{-14}





BNL pEDM experiment (from Alex Keshavarzi)

(Short) path to readiness

Main message: no showstoppers! Due diligence, physics case studies, moving to TDR phase…

Already completed…

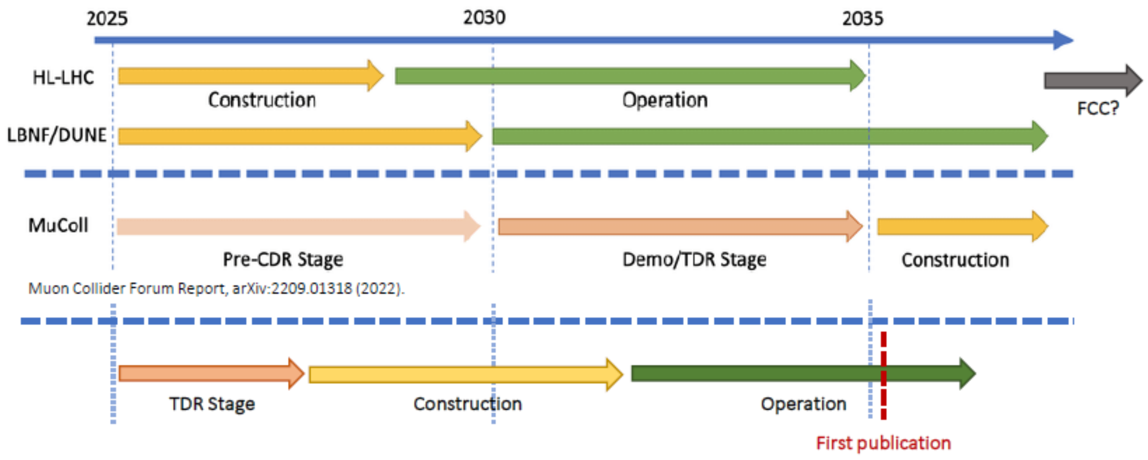
- Experiment design, engineering, modelling complete. ✅
- Prototype components under construction. ✅
- Measurement techniques understood. ✅
- Key systematics understood. ✅

Work to be done…

- Precision beams studies (Muon g-2 experts).
- Options for improved polarimetry (e.g. CMOS).
- Alignment system, methodology and studies.
- Simulate 10^3 particles for 10^3 seconds beam lifetime.
- More realistic costing (estimated $\mathcal{O}$(\$100M)).

Build community/collaboration!

- Increased involvement (you are invited!).
- New generation to start and finish experiment.



- From TDR to final publication in < 20 years.
- Can be started and finished by the new generation.
- Paramount physics drivers:
  - Strong CP problem. Baryon asymmetry. Dark matter.

- Requires high-intensity, polarised proton source.
  - Major capital investment + team to support it.
- BNL has it all, no new investment is needed there.
  - DOE/BNL still funding pEDM development through LDRD!

alexander.keshavarzi@manchester.ac.uk @alexkeshavarzi

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