

Precision Physics

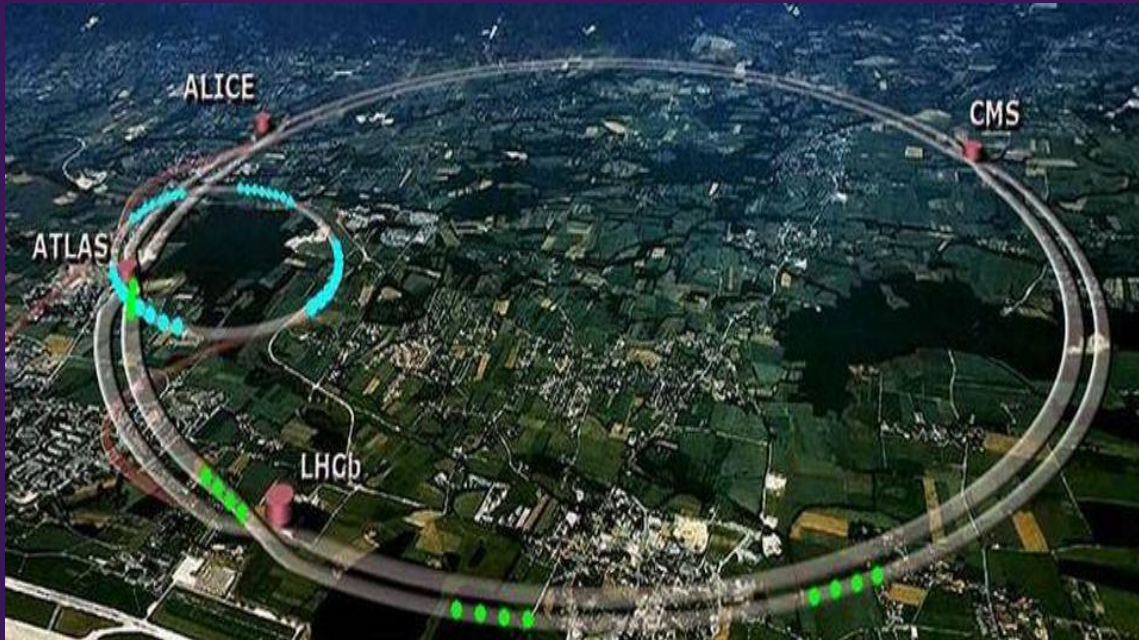
Rebecca Chislett

IoP APP and HEPP Conference
9th April 2026



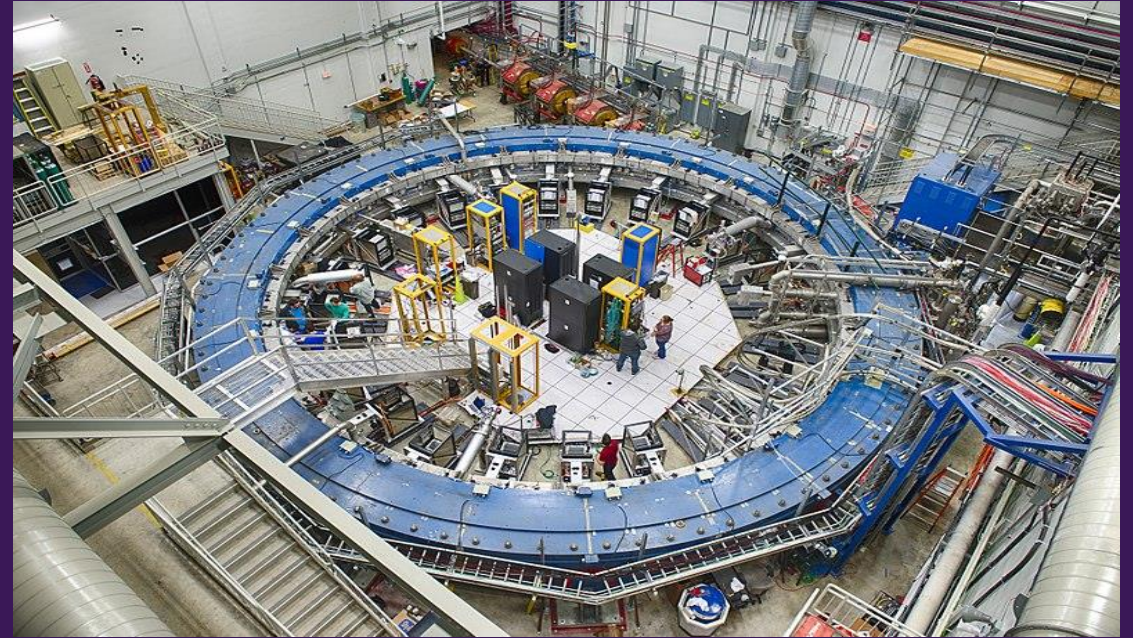
The Search for New Physics

High energy frontier



$$E = mc^2$$

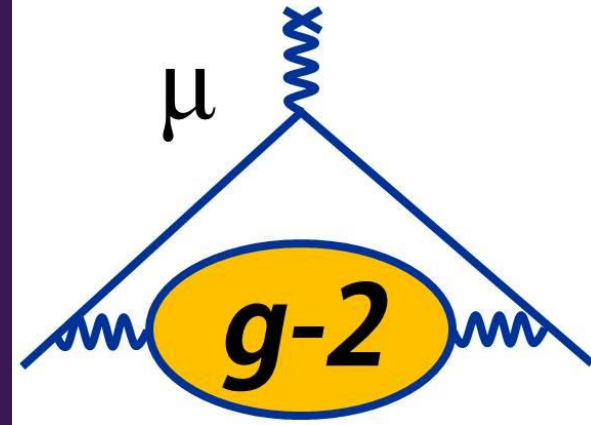
High intensity/precision frontier



$$\Delta E \Delta t \geq \frac{1}{2} \hbar$$

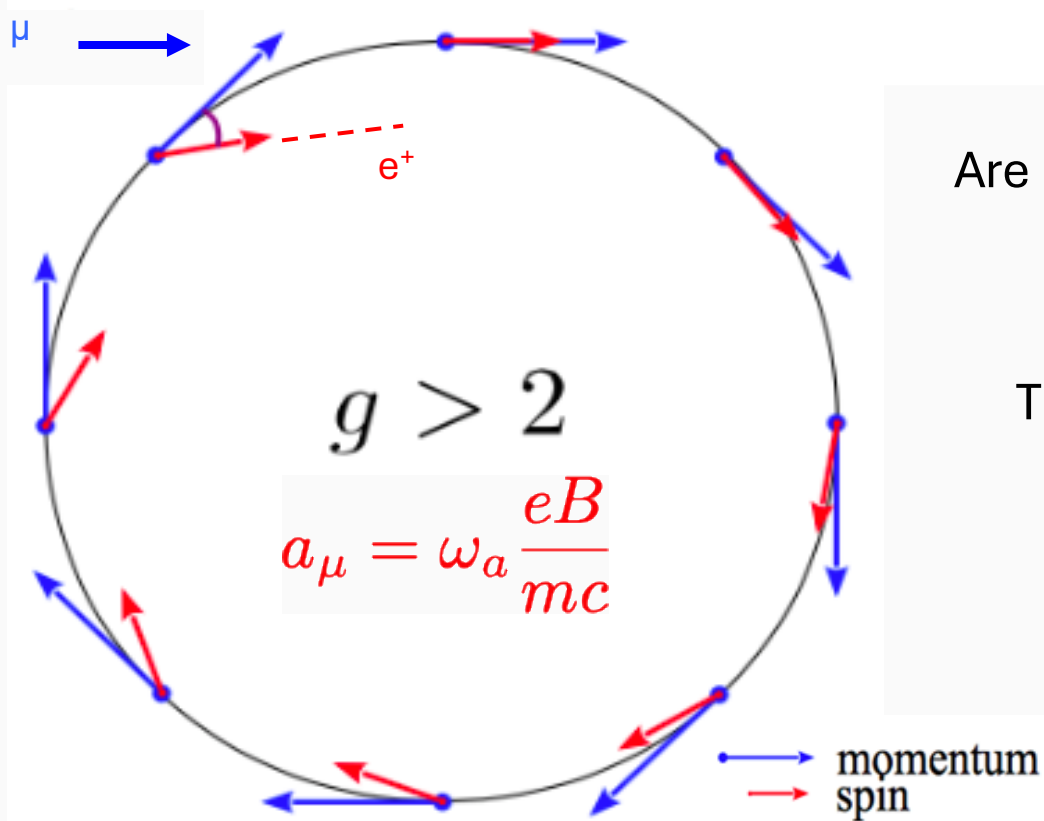
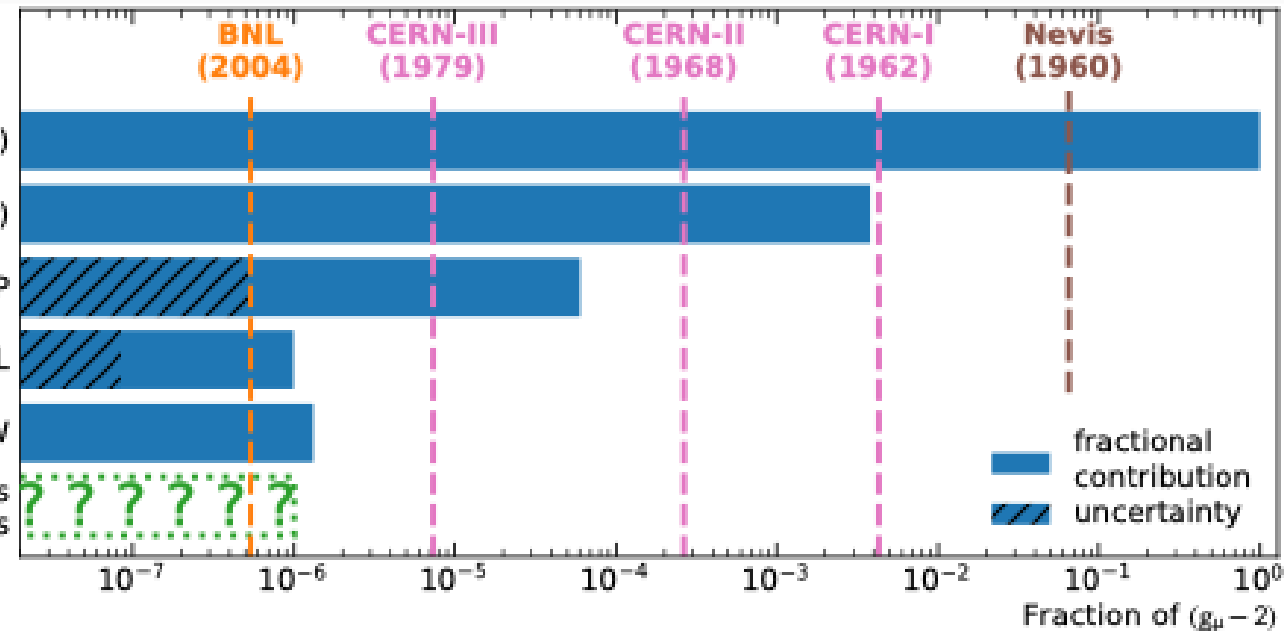
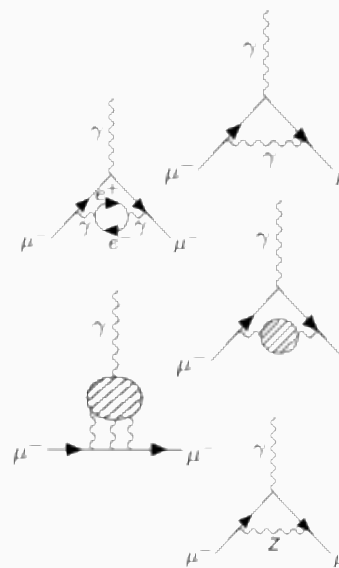
Precision measurements give access to high masses through quantum fluctuations
Availability of intense muon beams allows for large increases in precision in the muon sector
Probes new physics at the hundreds-thousands TeV scale

Fermilab Muon $g-2$ Experiment



Muon g-2

The interaction of a muon with a magnetic field can be both measured and theoretically predicted to an extremely high precision



Are **new particles or forces** showing up (in the experiment) that are not in the **Standard Model** (calculation)?

The experiment actually measures two frequencies

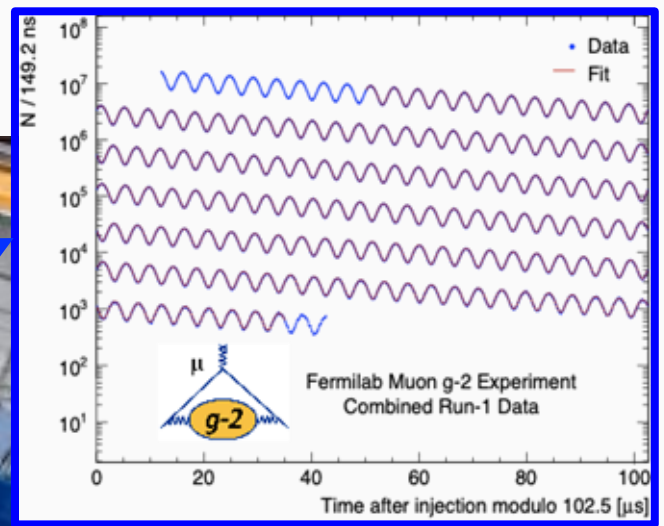
$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Annotations: 3ppb (above ω_a), 0.0003ppb (above μ_p), 22ppb (below μ_e), 2 (below g_e).

What we measure

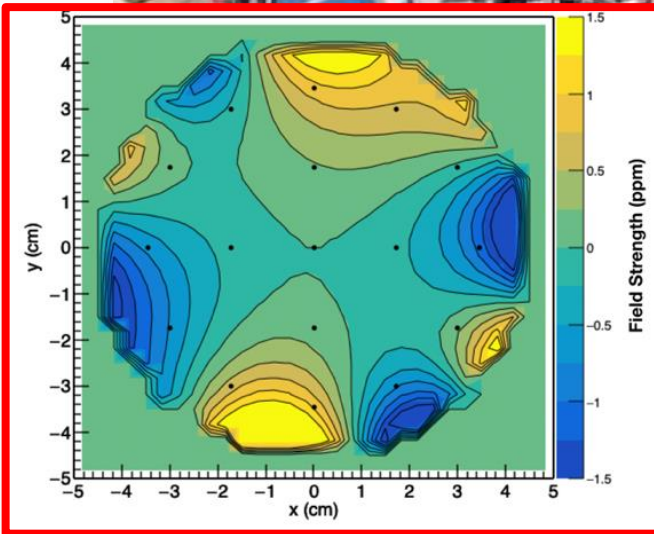
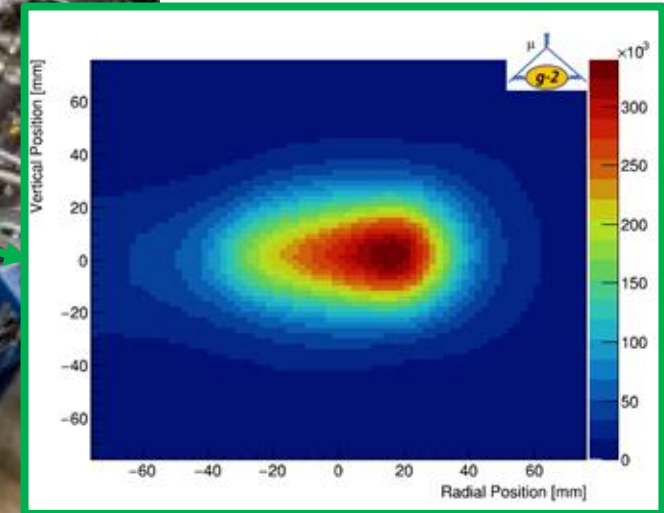
Measurement Principle

Anomalous Precession
Frequency, ω_a



$$a_\mu \propto \frac{\omega_a}{\langle \omega'_p \times M_\mu \rangle}$$

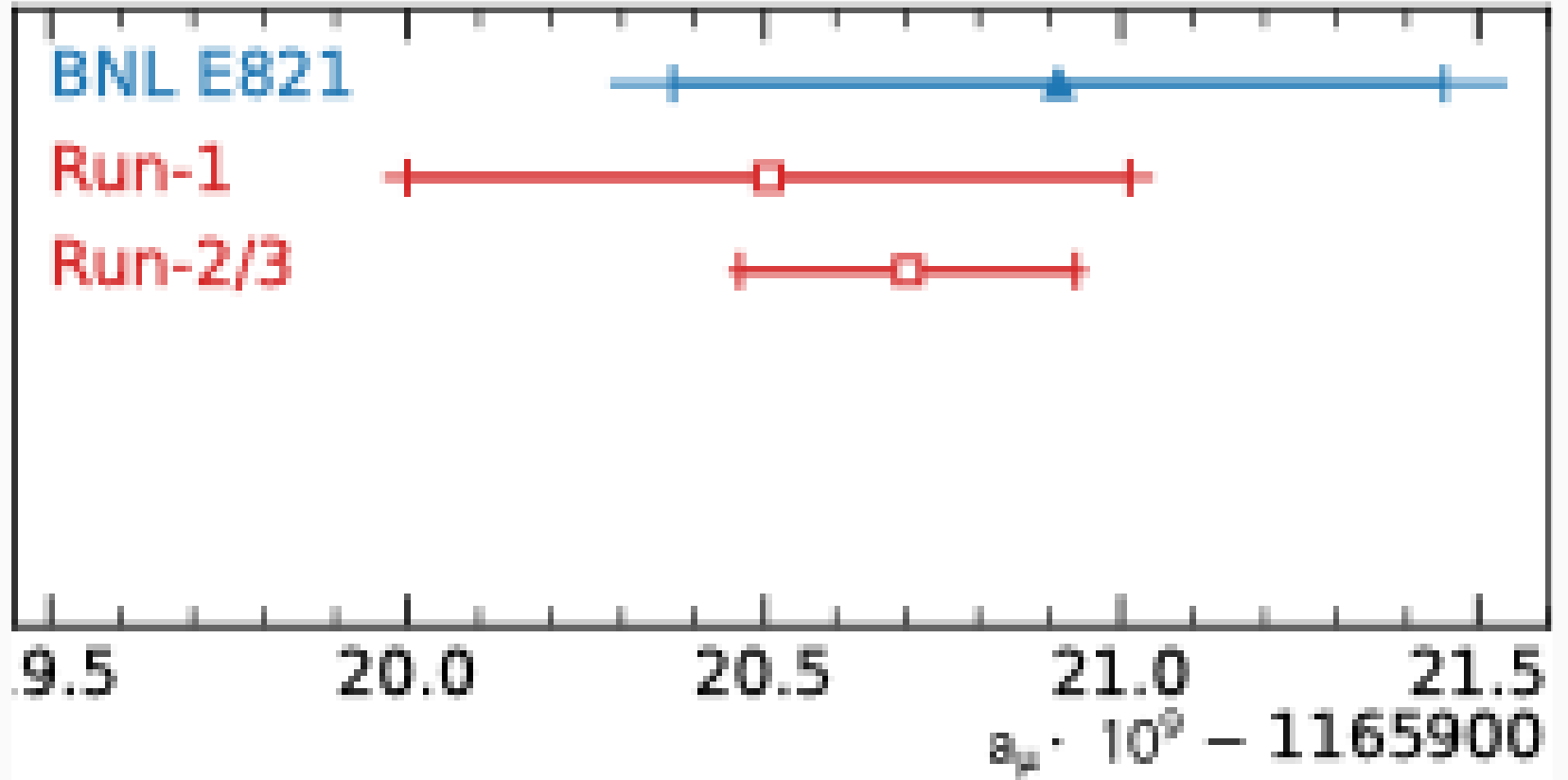
Muon Distribution, M_μ



Magnetic Field Map, ω'_p

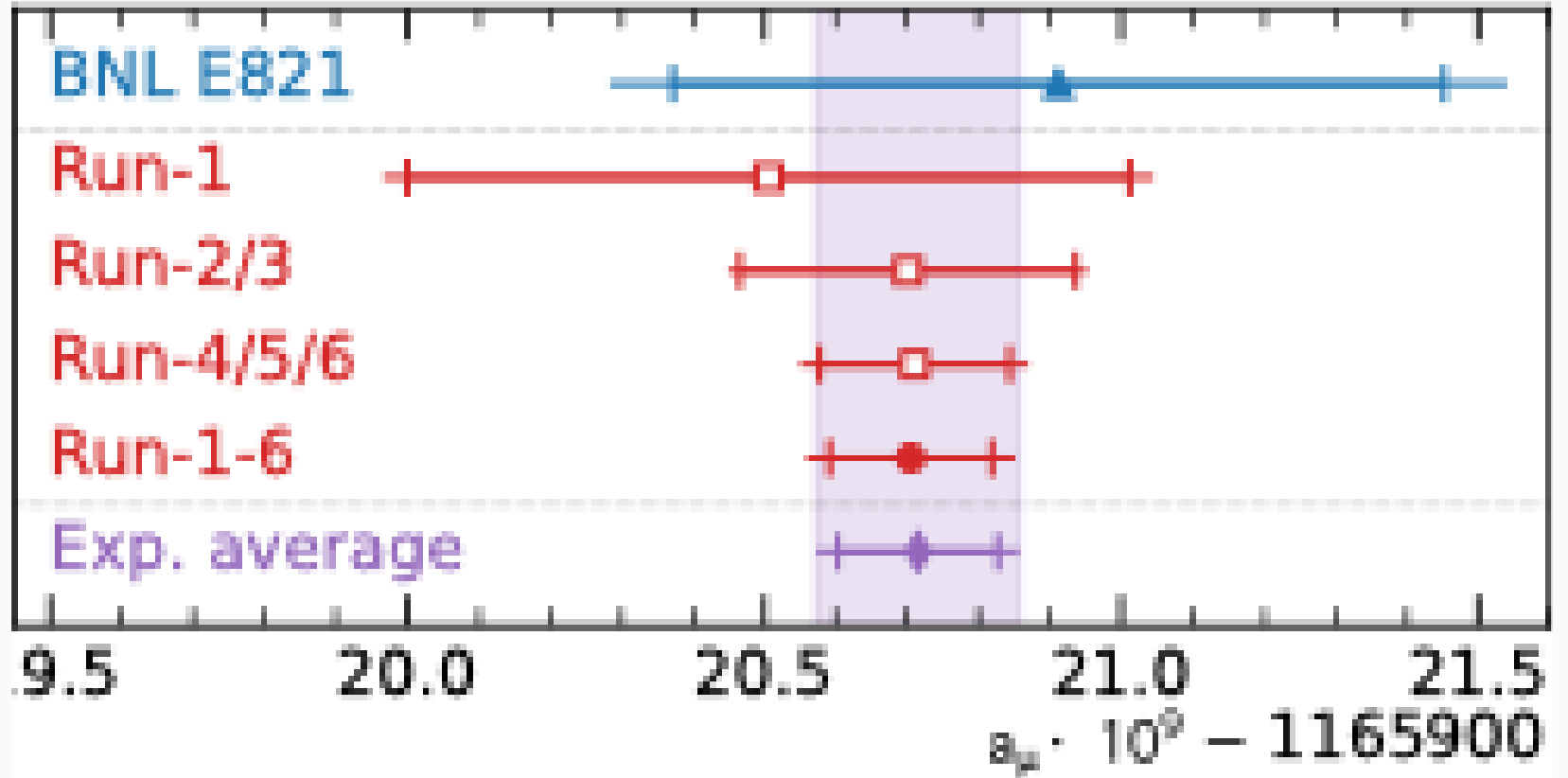
Results

(prior to last year)



- Run 2/3 had 4.6 times more data than run 1 with a more than two-fold increase in precision
- Many improvements in the Run 4/5/6 analysis

Results 2025



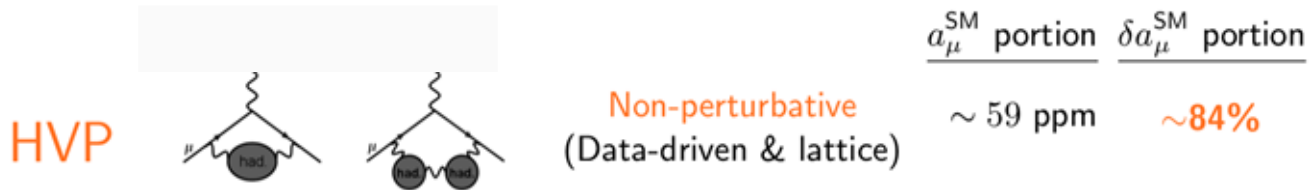
$$a_\mu(\text{Run-4/5/6}) = 0.001165920710(162)$$

$$a_\mu(\text{Run-1-6}) = 0.001165920705(148)$$

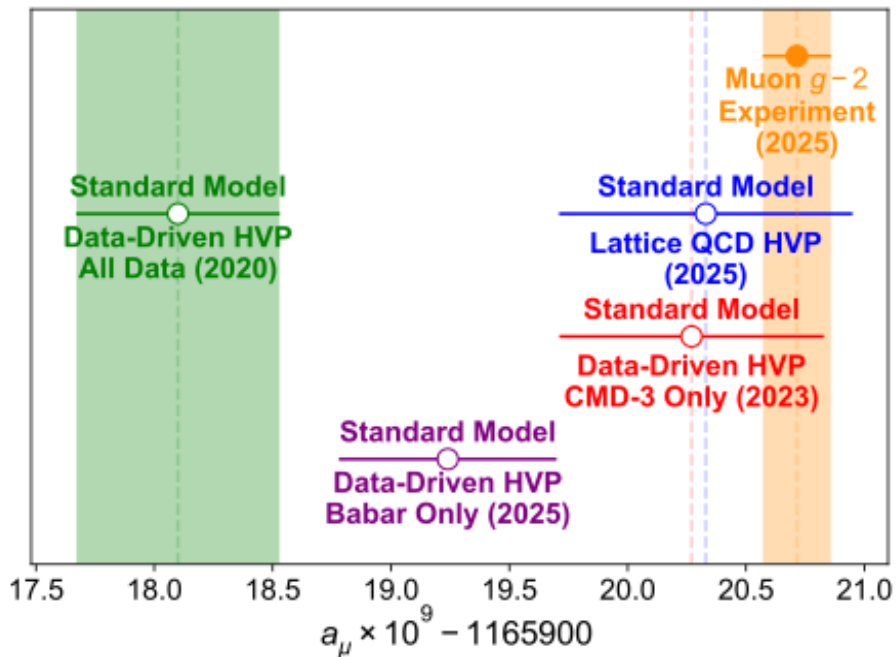
- Results in excellent agreement
- Run-4/5/6 uncertainty reduced by 1.8 times over Run-1/2/3
- New world average reduces BNL E821 uncertainty by a factor of 4.4

Comparison with Theory

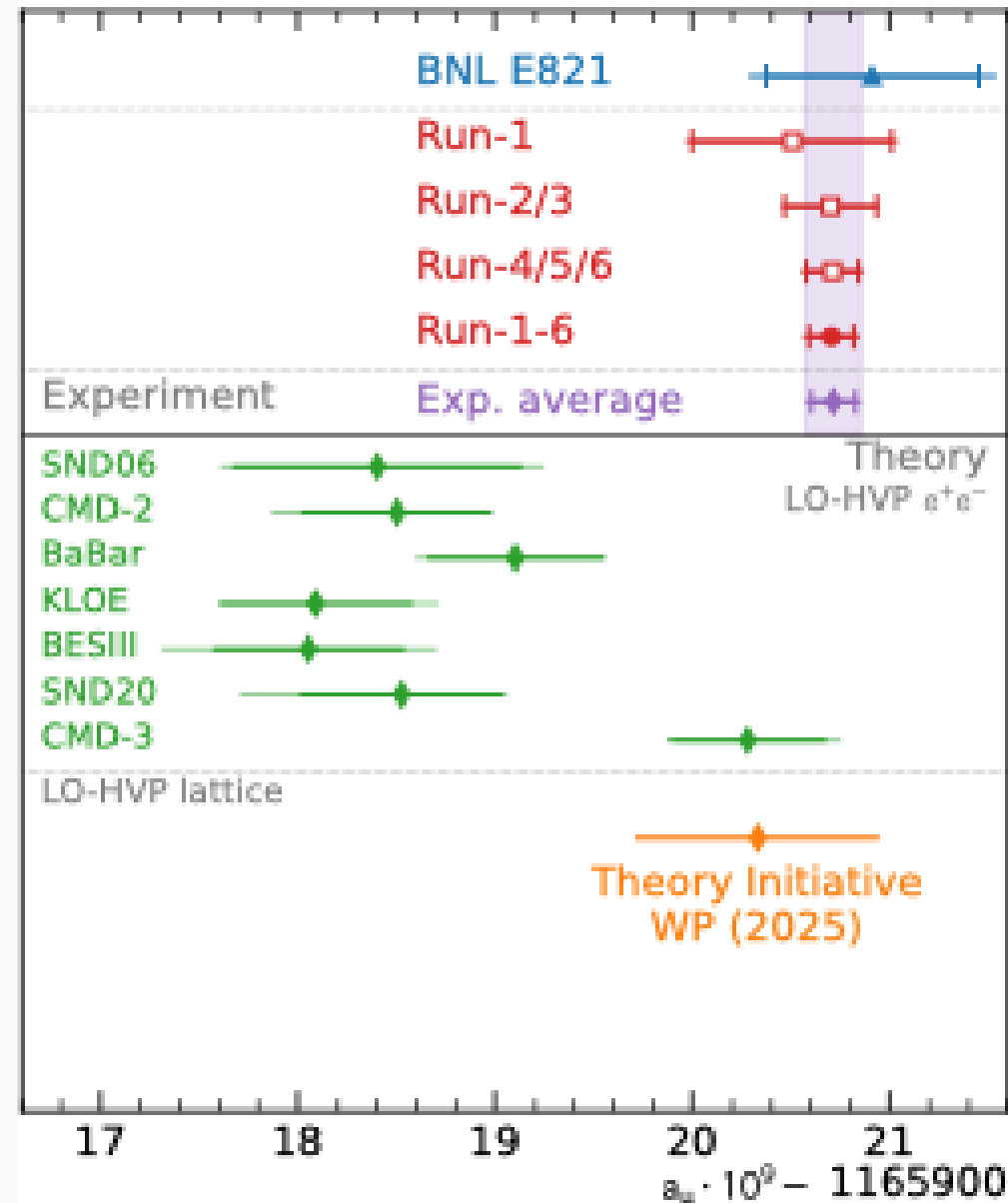
$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}}$$



Hadronic Vacuum Polarisation (HVP) = hadronic running of photon propagator.



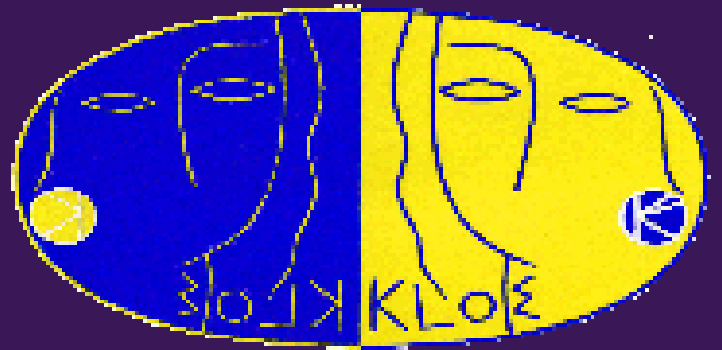
Severe tension exist between cross section measurements, and between data and lattice QCD:



To be continued (over next few years)...

KLOE $\pi^+\pi^-\gamma$

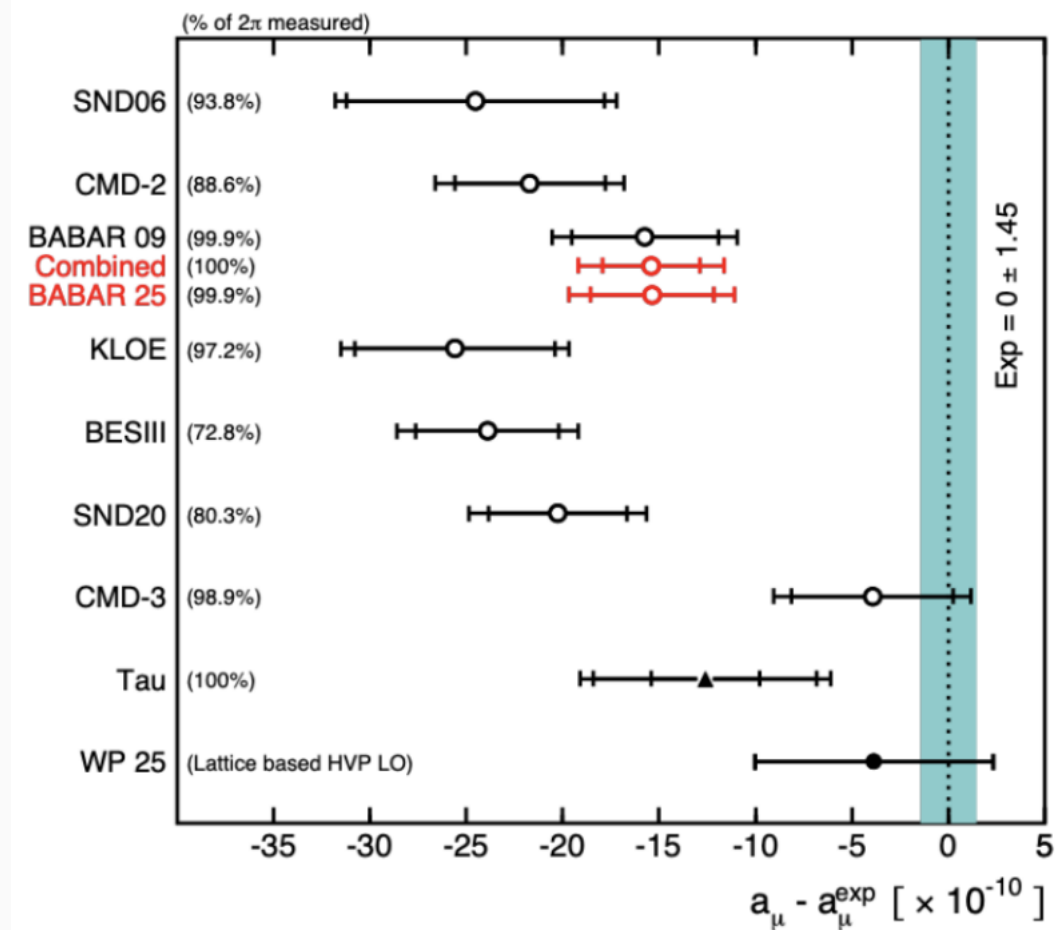
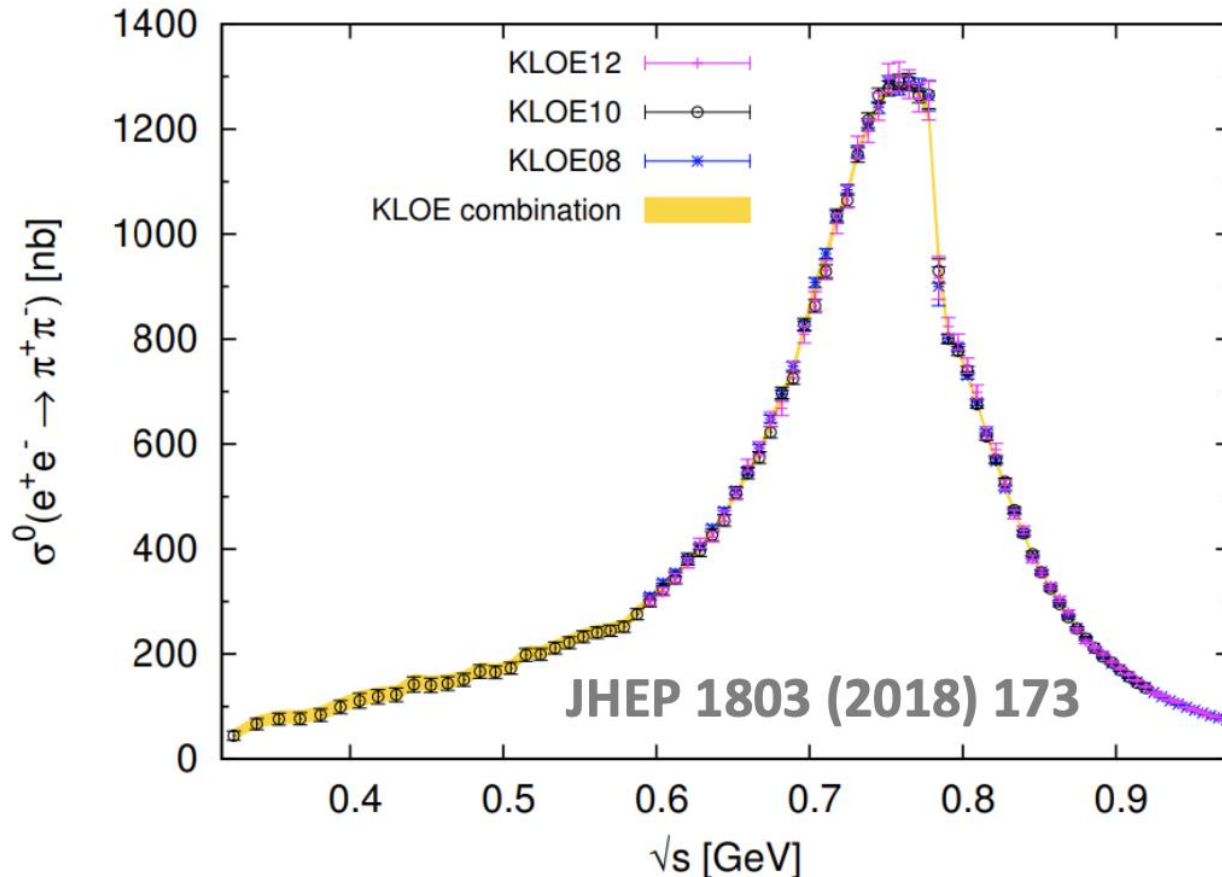
Talk at 10.45am today
Niels Vestergaard



Thanks to Fedor Ignatov and Lorenzo Cotrozzi

KLOE-nxt $\pi^+\pi^-\gamma$ analysis

- e+e- collider run on ϕ peak (~ 1020 MeV)
- Drift chamber + EM calorimeter inside 0.52T B field
- Aiming for 2 fold improvement on uncertainty



1.7 fb⁻¹ from 2004/2005 data not yet analysed – 7x more data than published analyses!

KLOE12: 0.3%_{stat} \oplus 0.2%_{th} \oplus 0.7%_{syst} = \sim 0.8%_{total}

KLOE-nxt goal: 0.1%_{stat} \oplus 0.2%_{th} \oplus 0.3%_{syst} = \sim 0.4%_{total}

MUonE Experiment

Talks at

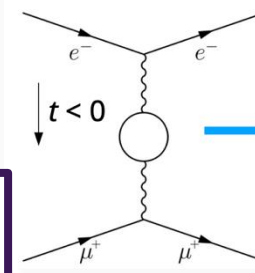
3.45pm yesterday - Giorgia Cacciola

11.15am today - Clement Loic Devanne



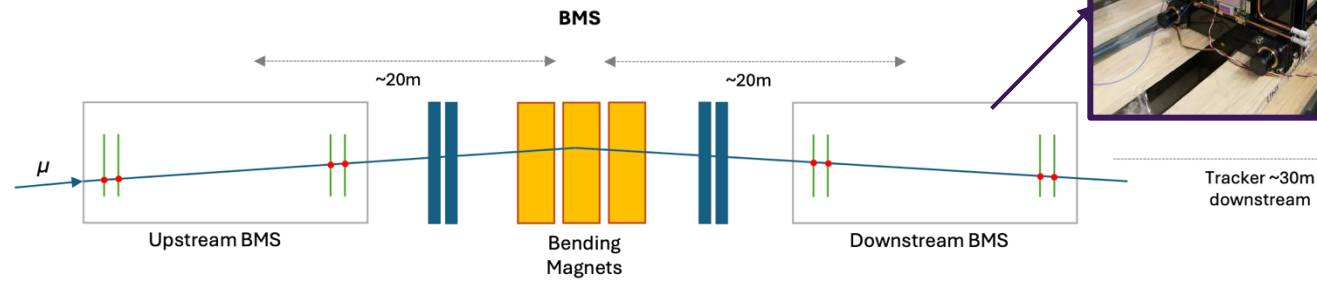
Thanks to Saskia Charity and Riccardo Pilato

The MUonE Experiment

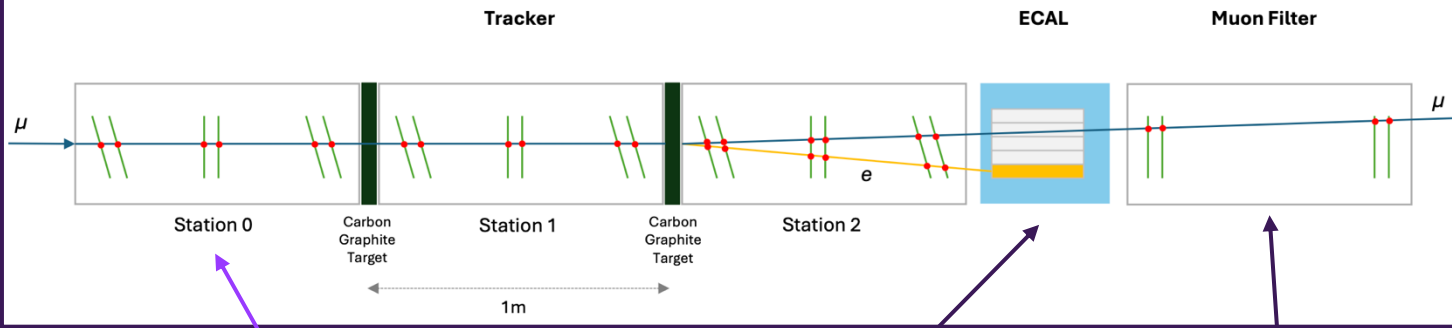


$$a_{\mu}^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx (1-x) \Delta\alpha_{had}[t(x)]$$

Single measurement of leading-order HVP term, a_{μ}^{HLO} , in spacelike domain via elastic scattering process $\mu e \rightarrow \mu e$



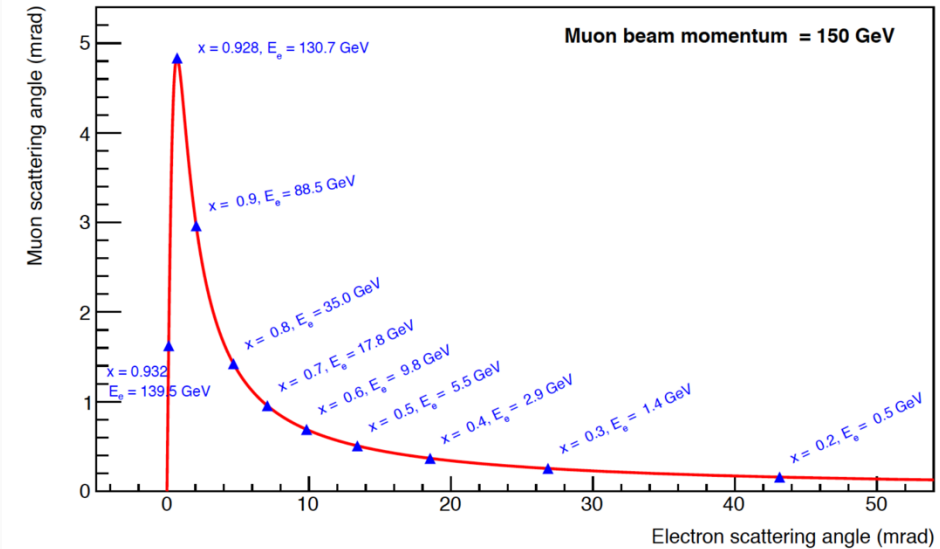
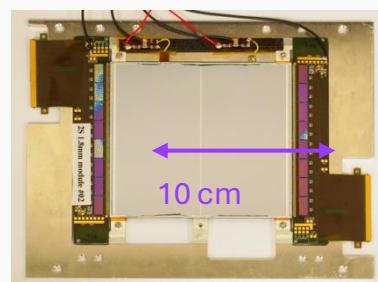
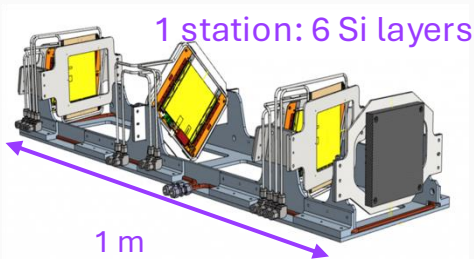
Phase-I (June - Aug 2025) setup - 3 stations + BMS + ECAL + Muon Filter



ECAL: PID, remove possible hadronic particle contamination

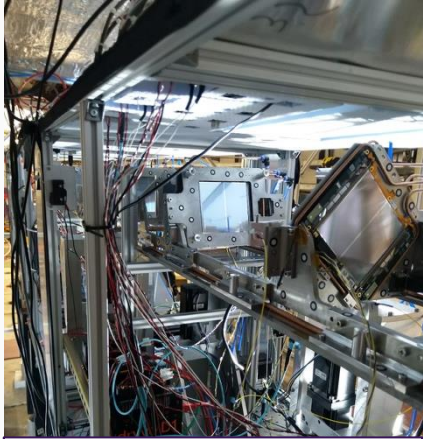
Muon Filter: improved PID

CMS 2S Si modules



Experiment in the M2 beamline at CERN-SPS using 160 GeV μ^+

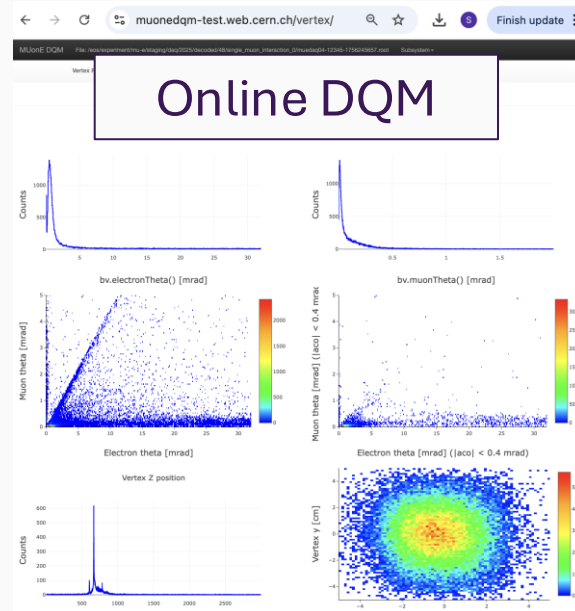
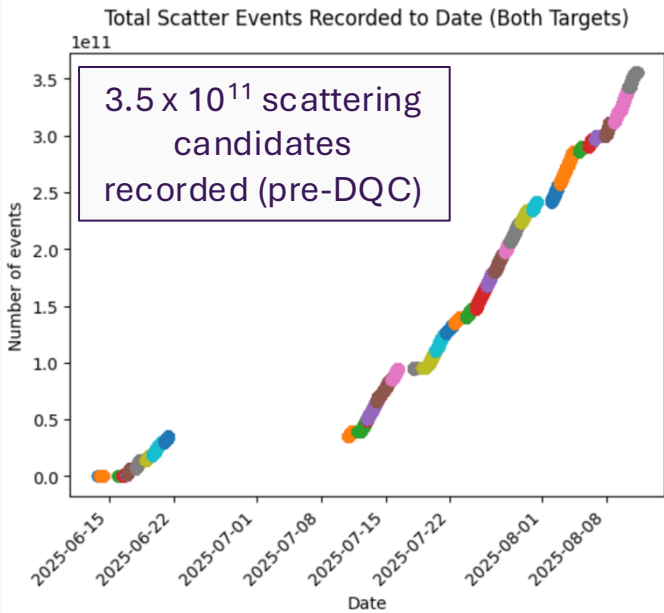
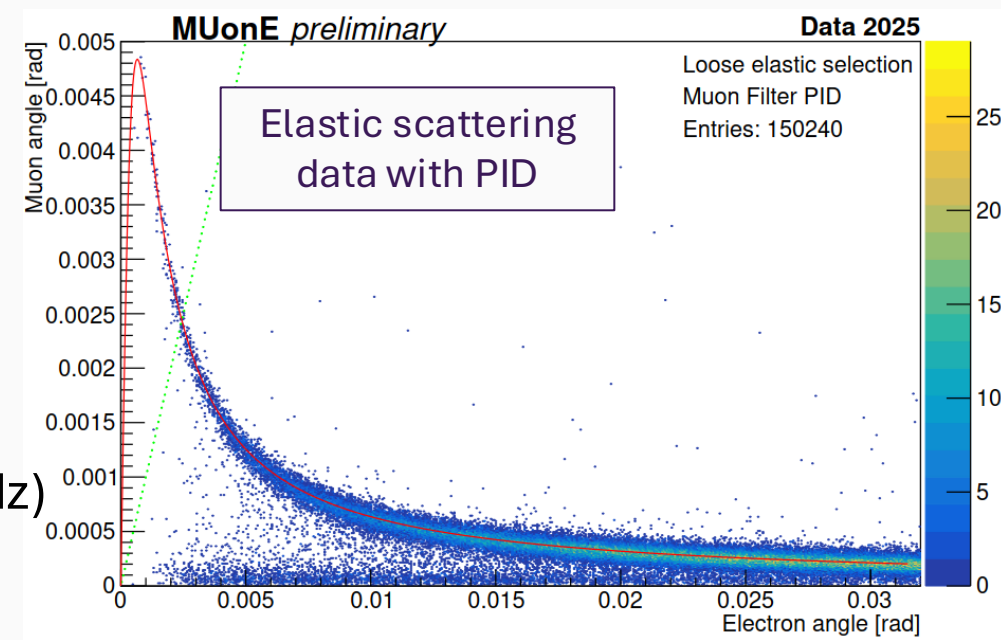
MUonE Highlights and Plans



MUonE in the SPS beamline

2025 Test Run 3 stations, June – Aug (3 months)

- First test of all systems included in DAQ, final design configuration, full rate (40 MHz)
- First test of **online event selection** based on event topologies
- Proof of principle measurement of $\Delta\alpha^{\text{lep}}$
- Preliminary measurement of $\Delta\alpha^{\text{had}}$ to 20%

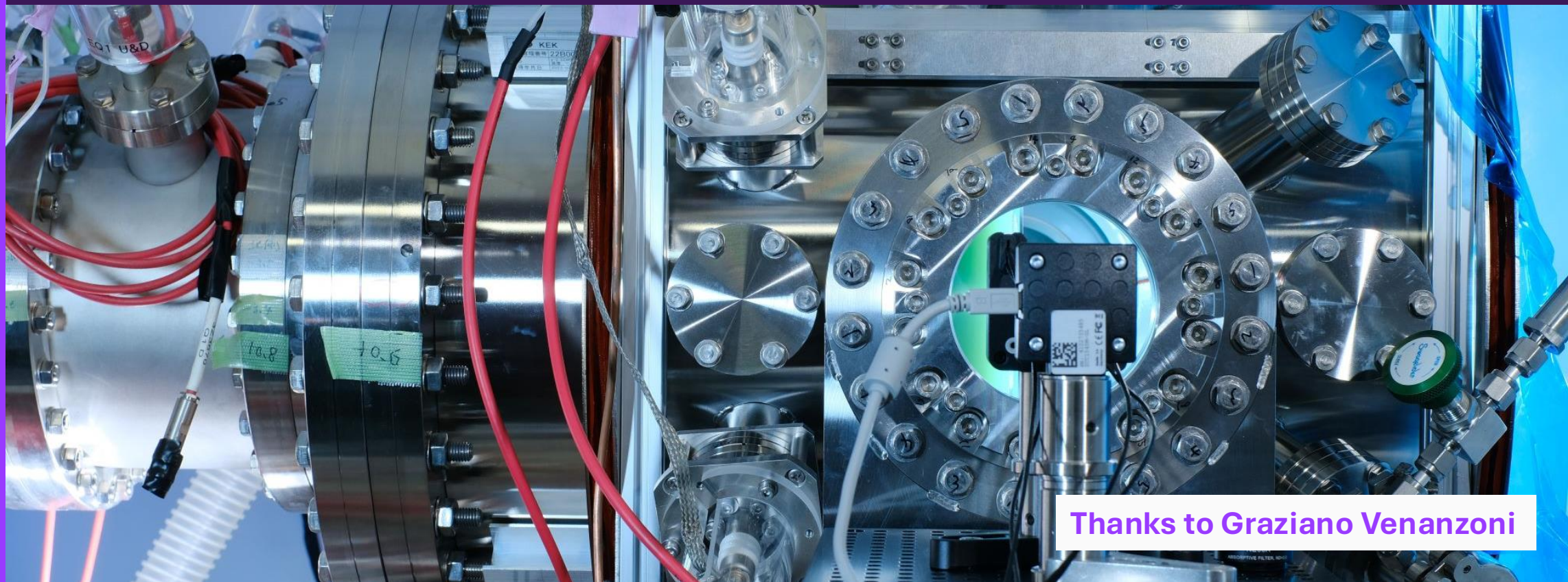


Full experiment ~2030: 40 stations, 3yrs

- Aim: measure a_μ^{HLO} to <0.5% (competitive)
- **Stringent systematic requirements**
 - 10 μm longitudinal alignment
 - Multiple scattering 1%
 - Uniform efficiency over full angular range
 - Measure beam energy with ~few MeV precision



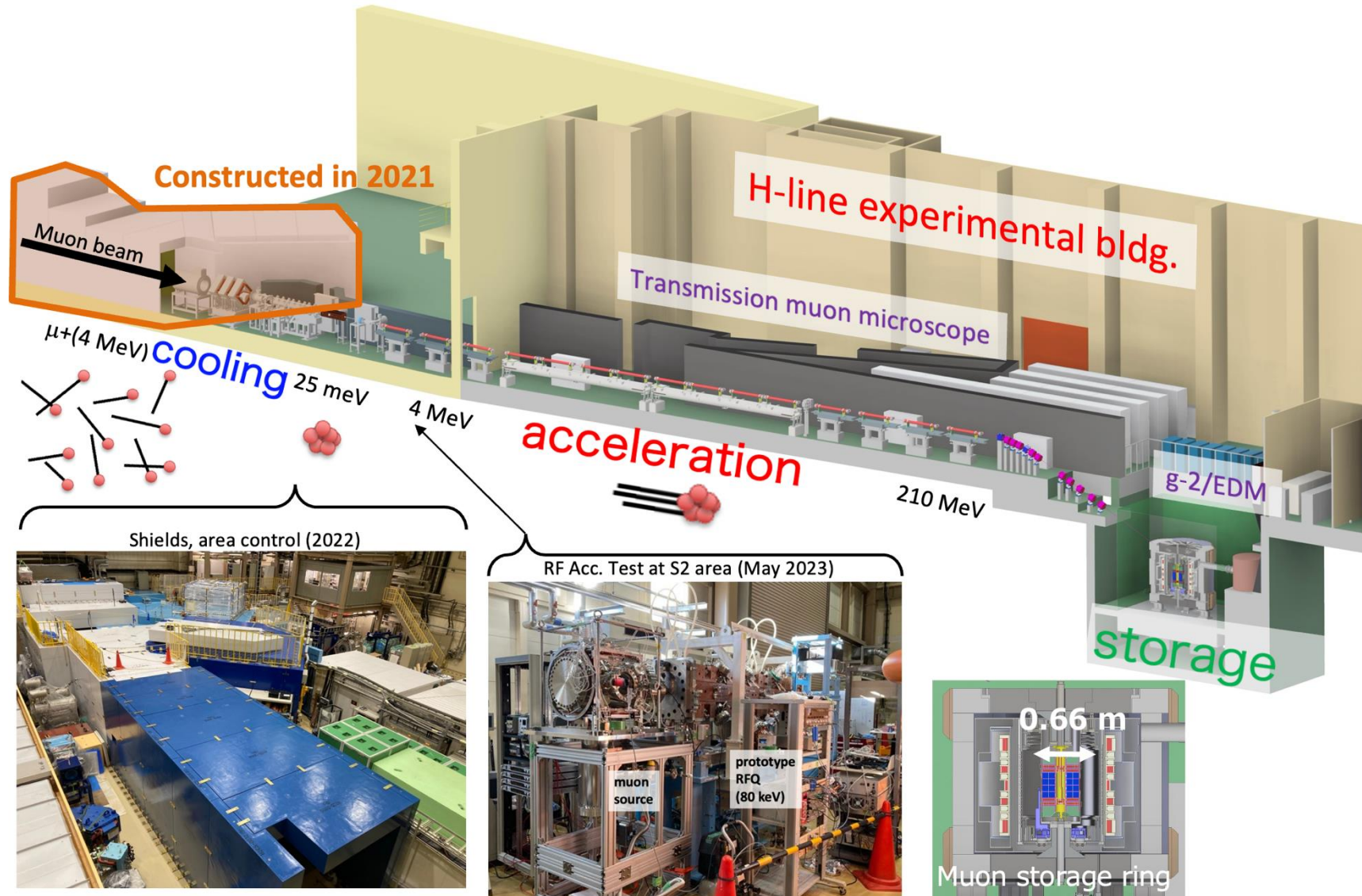
J-PARC Muon g-2 Experiment



Thanks to Graziano Venanzoni

Muon g-2 at J-PARC (E34)

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \frac{e}{mc} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right]$$



- Low emittance muon beam (**1/1000**)
- Muon acceleration to **300 MeV/c**
- **No E field**
- 3D spiral injection: Good injection efficiency (**x10**)
- Compact storage ring (**0.66m, 1/20, B=3T**)
- Tracking detector
- Excellent sensitivity to **muon EDM ~ 100 times** better than the previous limit
- **Different systematics**

Towards High Sensitivity

The statistical precision on the anomalous precession frequency ω_a is:

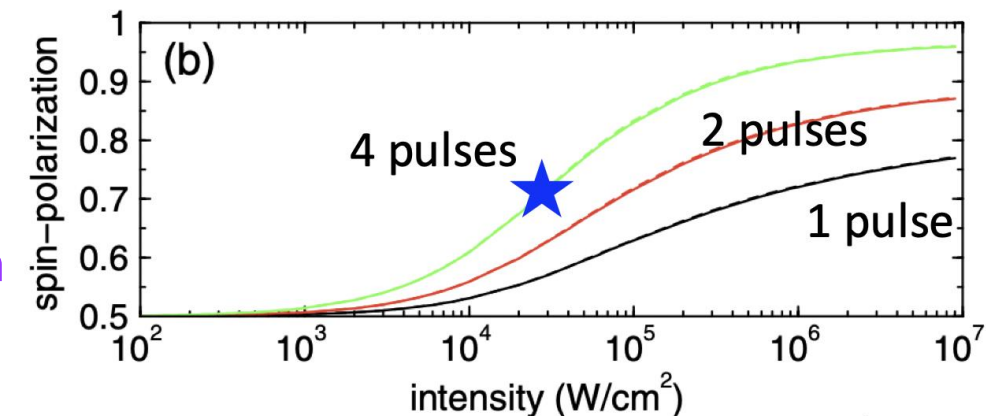
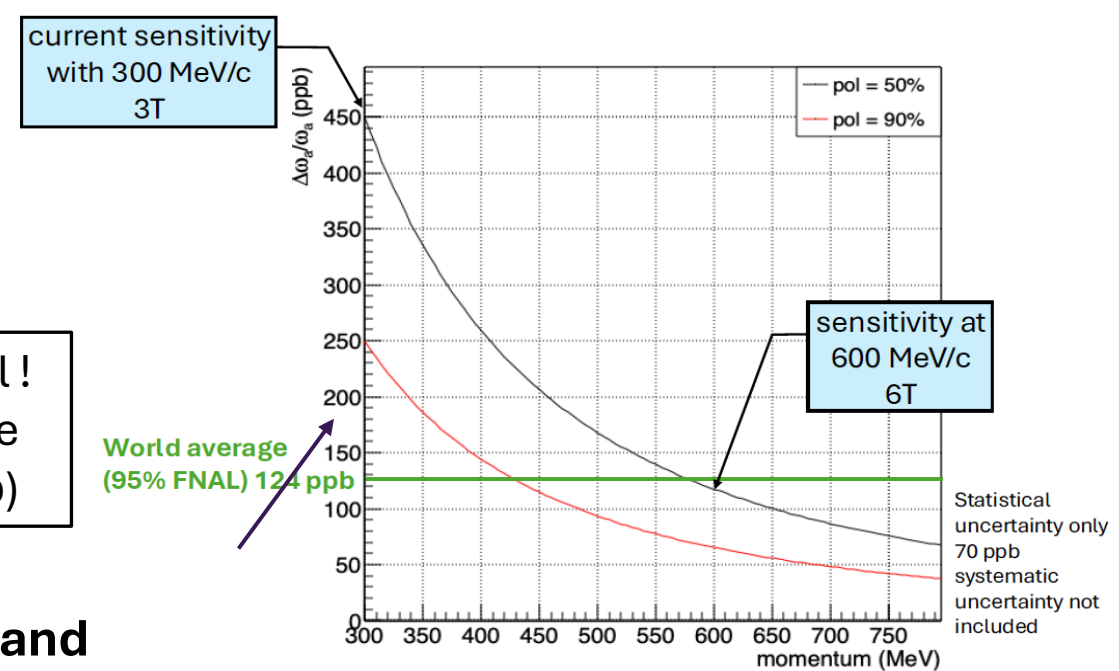
$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P} \sqrt{\frac{2}{NA^2}}$$

Significant effort in Liverpool!
(G. Venanzoni co-chair of the High Sensitivity Study Group)

- **Doubling both momentum (from 300 to 600 MeV/c) and magnetic field to 6 T (to keep the muon orbit unchanged)**
⇒ **x4** improvement in ω_a precision.
- **Polarization (P), linear dependence:**
 - Current polarization: 50%
 - Possible improvement: **75%** (realistically) → **x1.5** gain in total precision.

Work is in progress to assess the feasibility of these upgrades.
Statistical goal → O(100 ppb) (systematic uncertainty ~ 70 ppb)

→ **Competitive with the Fermilab Muon g-2**



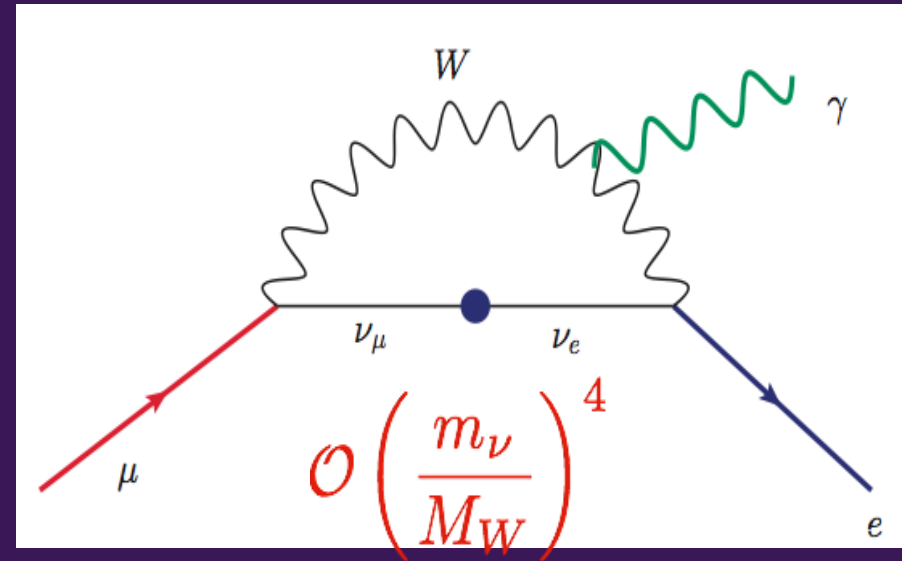
Optical pumping with train of laser pulse

Charged Lepton Flavour Violation

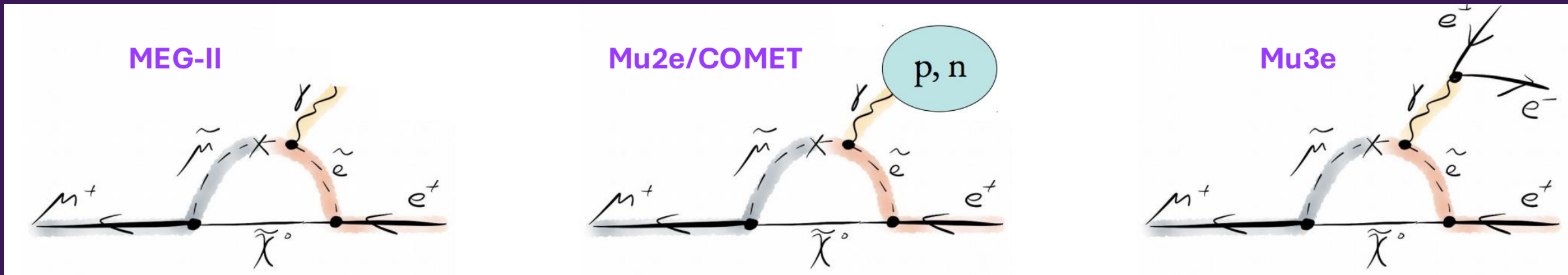
Observed in the neutral sector through neutrino oscillations

In the SM rate is $O(10^{-50})$

→ Any observation is a sign of new physics



Probes a wide range of different physics models



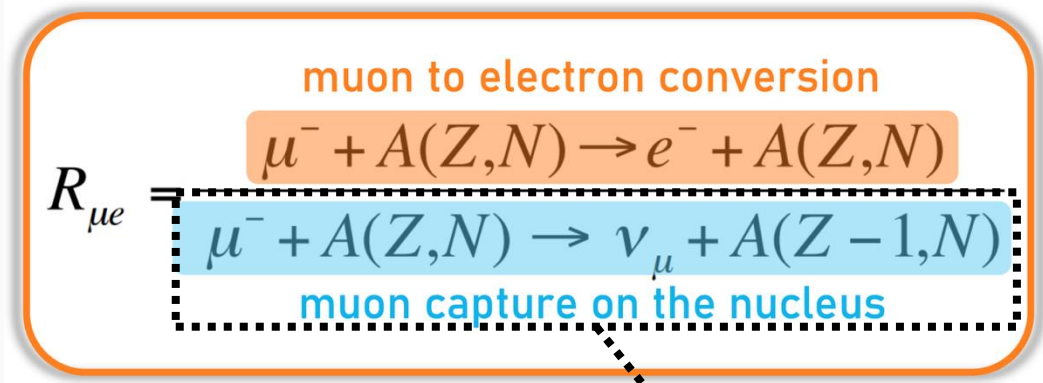
Mu2e



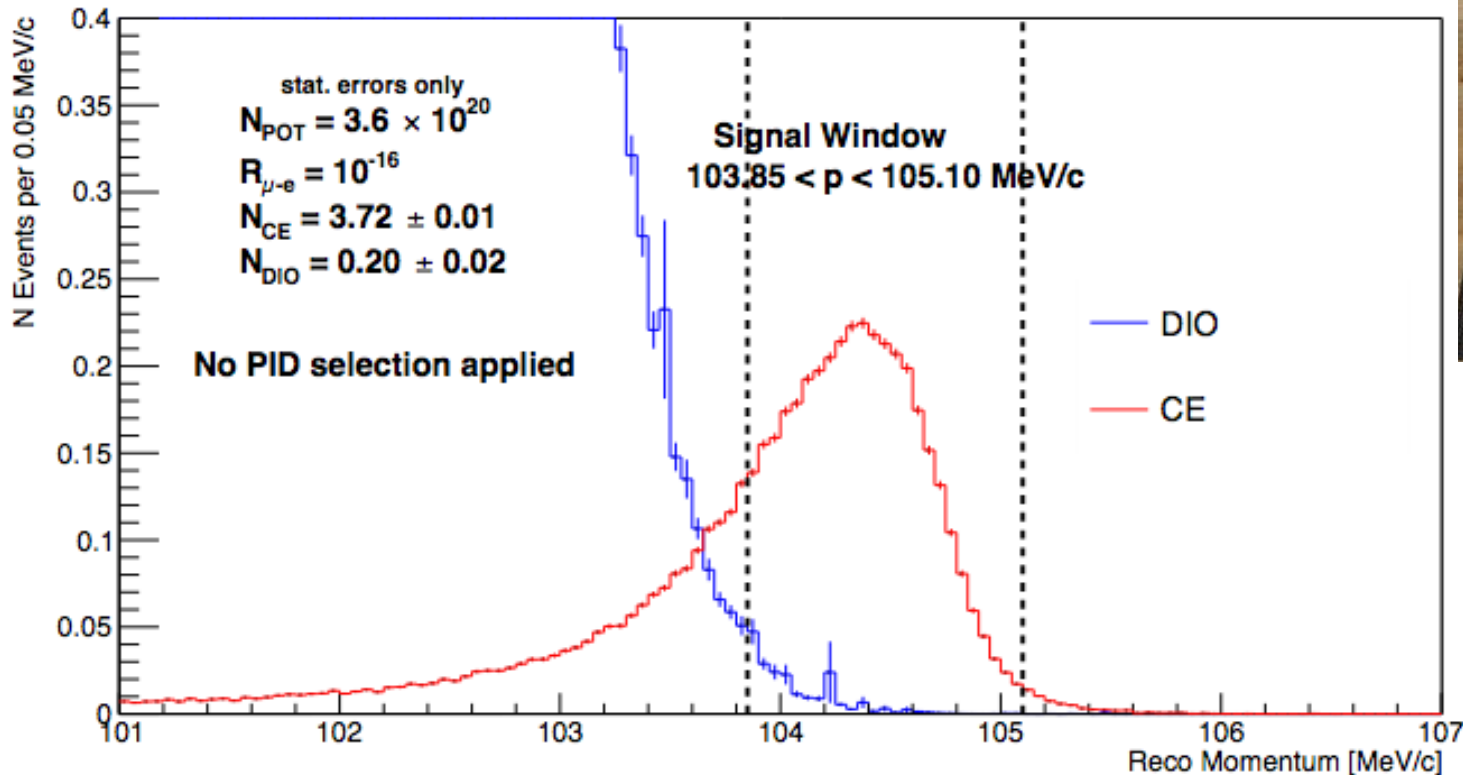
Mu2e

Searches for the neutrinoless conversion of a muon to an electron in the field of a nucleus

Aiming for an improvement of 10^4 on current limits

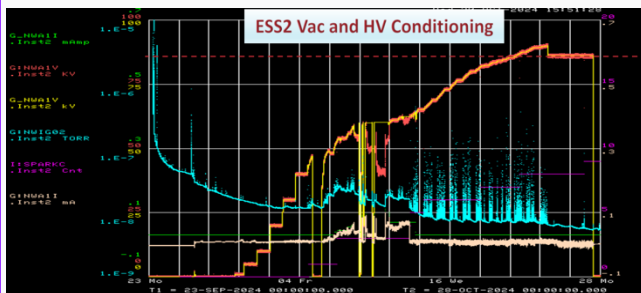
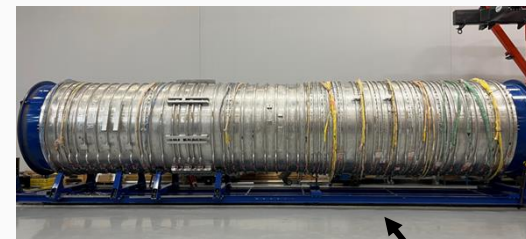
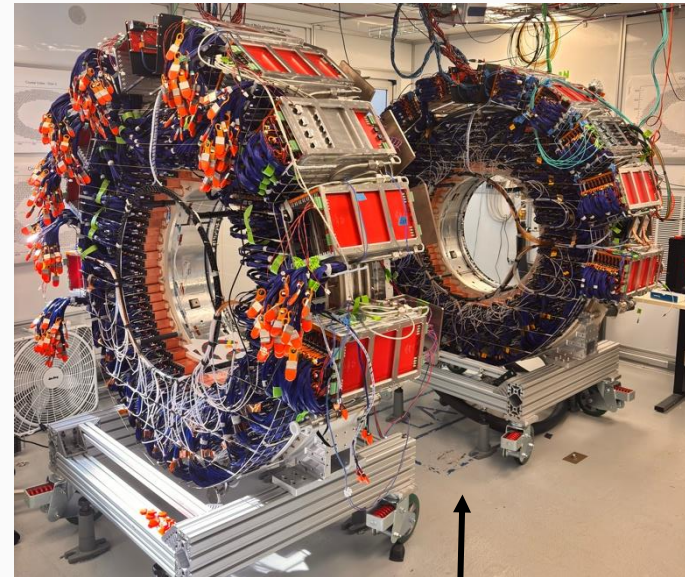
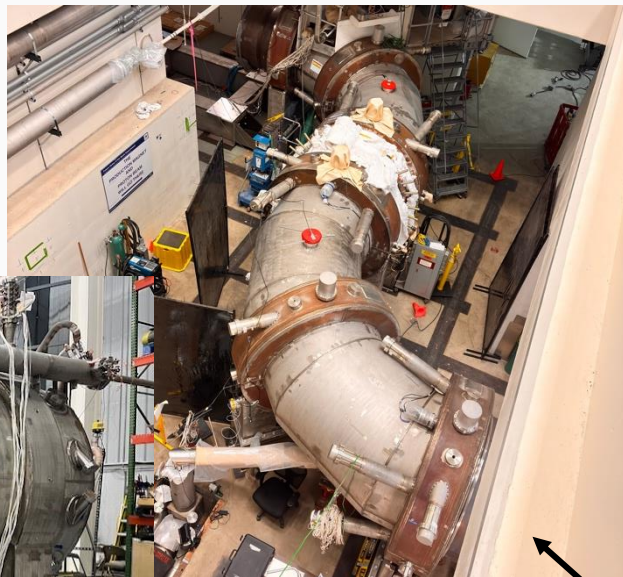


The UK is leading this measurement!

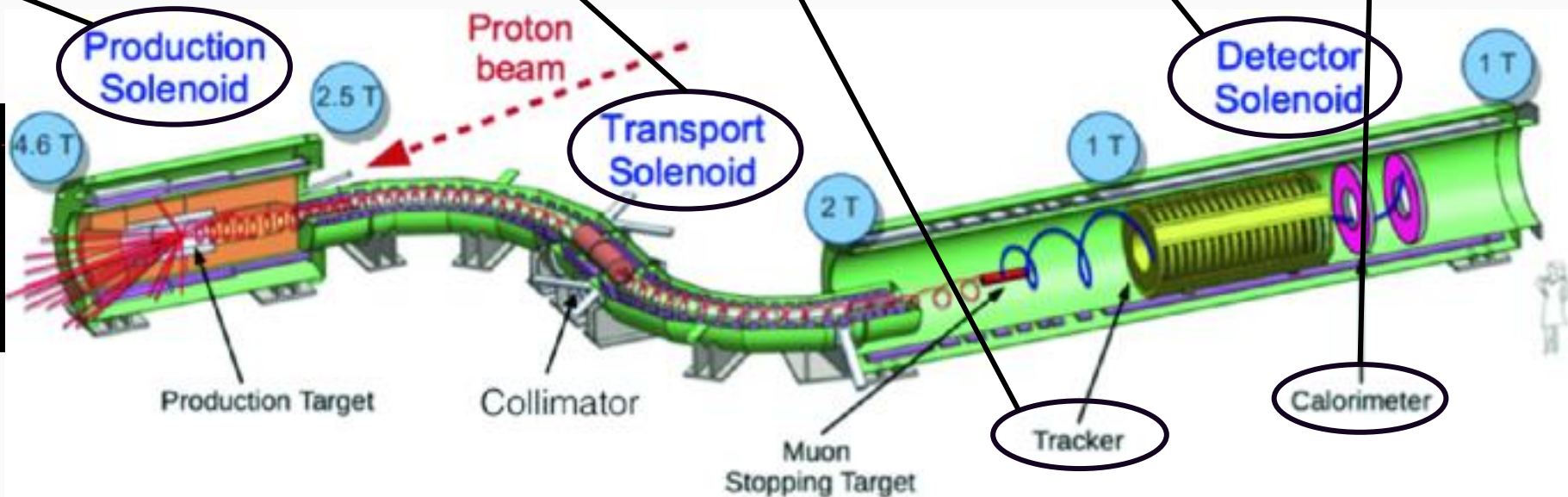


Commissioning + cosmic ray run in next year. First physics run before PIP-II shutdown will do $\mathcal{O}(10^3)$.

Mu2e



Beam commissioning in advanced stage



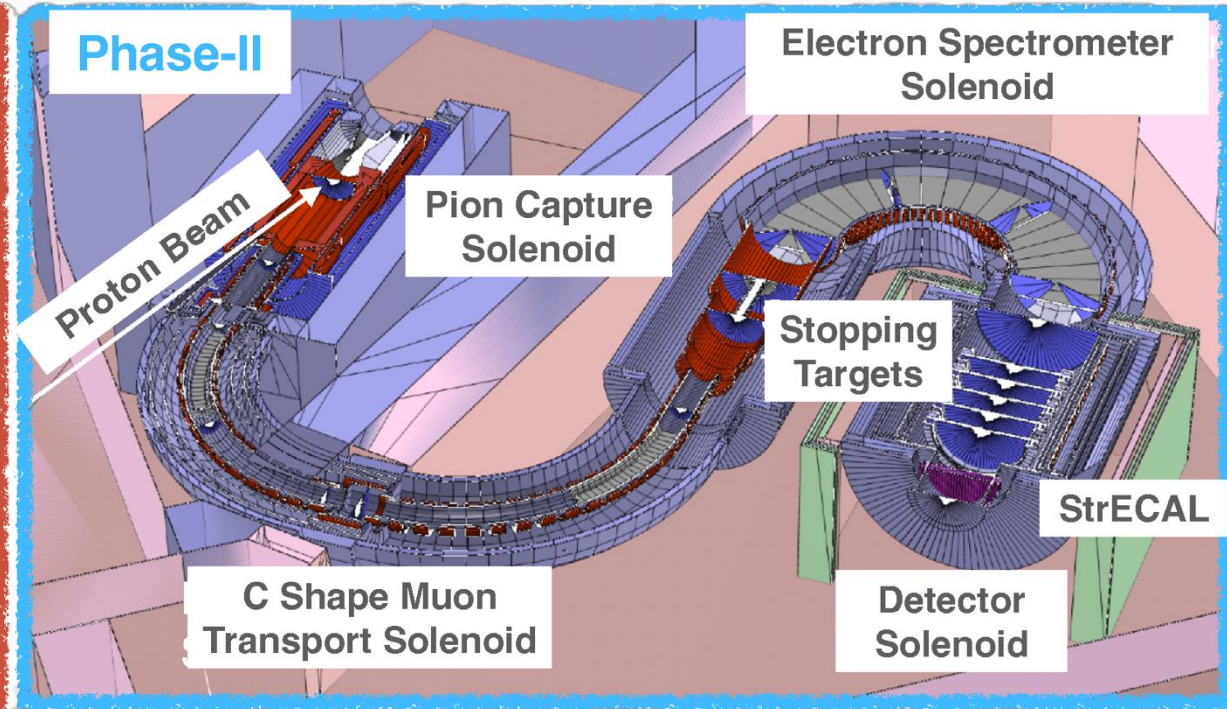
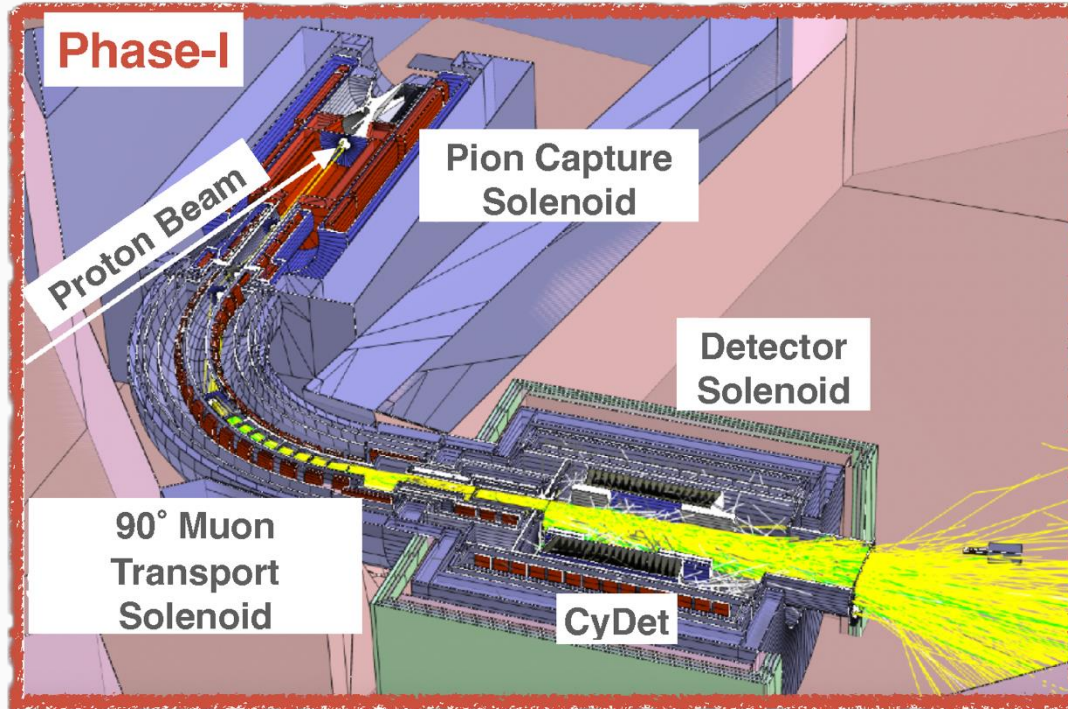
COMET



Thanks to Yoshi Uchida

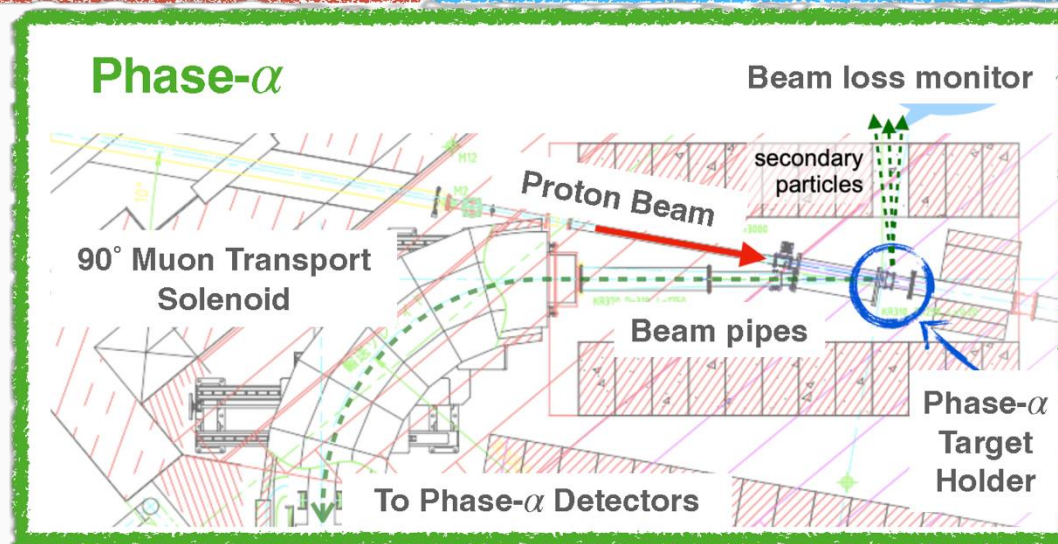
COMET

17-nation collaboration for muon-to-electron conversion at J-PARC aiming for 10^{-17} sensitivity



Phase-I data-taking scheduled for January 2028 aiming for 10^{-15} sensitivity

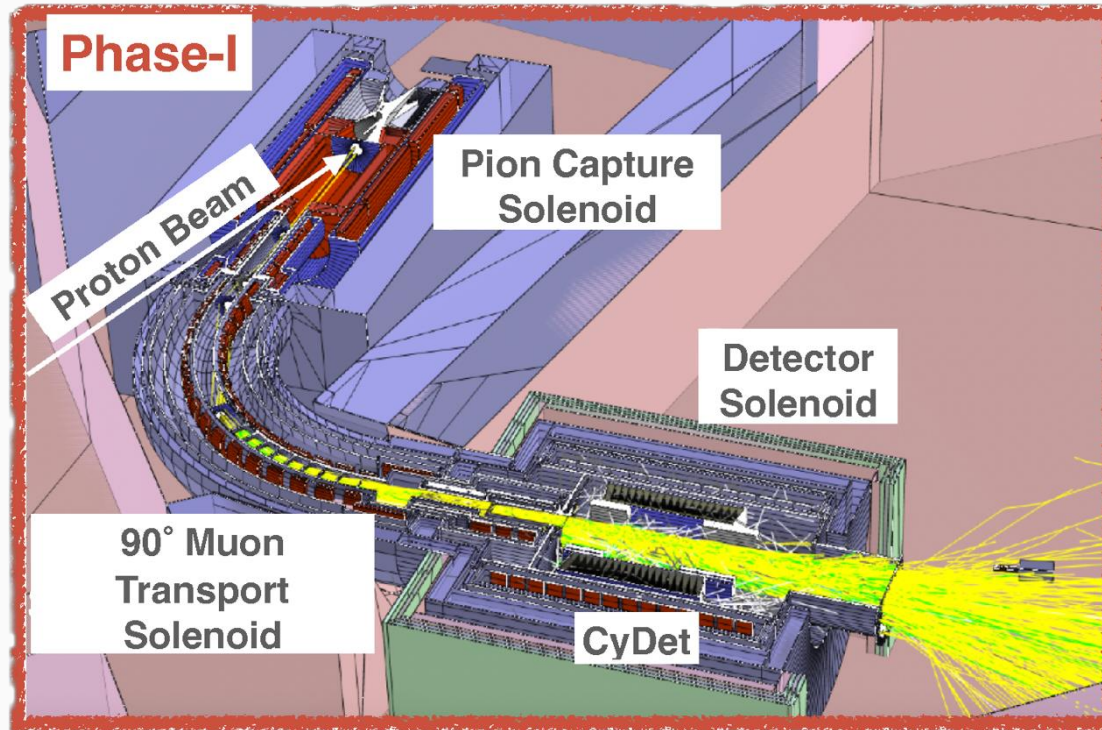
Starting with lower intensities, to understand novel muon production systems and detectors



“Phase- α ” commissioning took place in 2023 successfully; results soon to be published

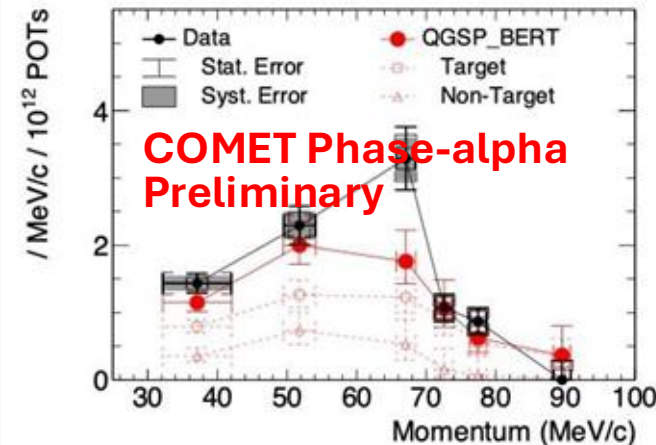
COMET Status

All magnets installed;
testing and field
measurements in progress



UK contributions include:

- Phase- α hardware and run coordination
- DAQ & Trigger Electronics Design
- Leadership in Software and Analysis
- Current Collaboration Board Chair and Run Coordinator (2/6 Executive Board positions)
- Future developments (Phase-II and PRISM)

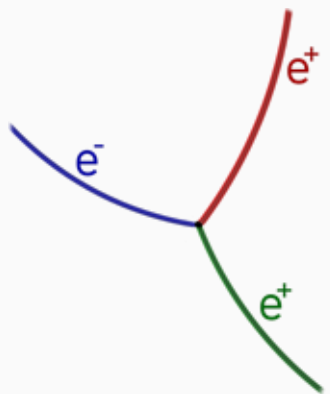


Mu3e



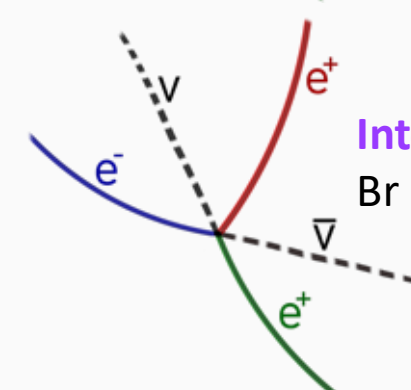
Thanks to Gavin Hesketh

Mu3e



Signal:

Coincident in space & time
 visible momentum = 0
 visible mass = m_μ

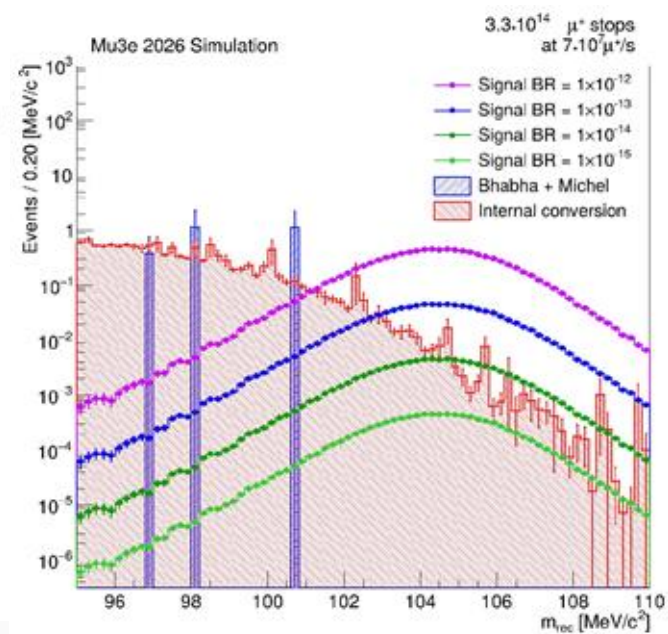
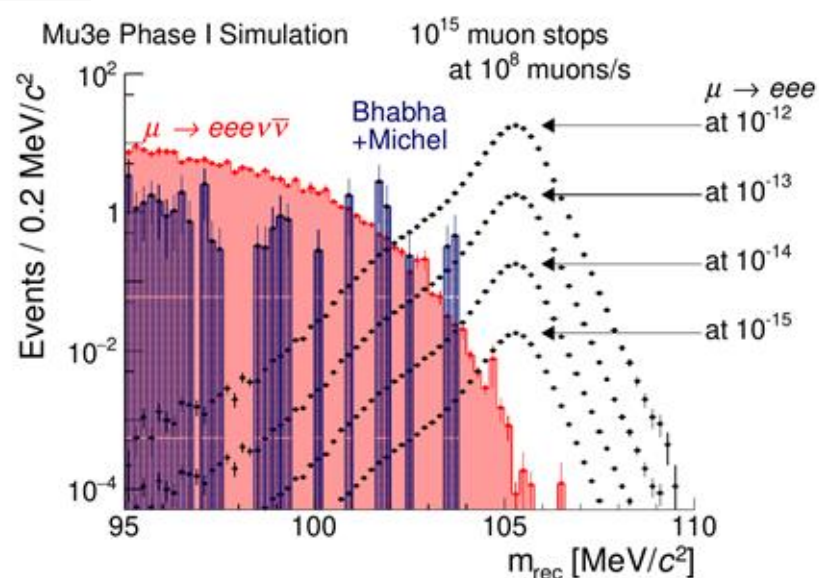
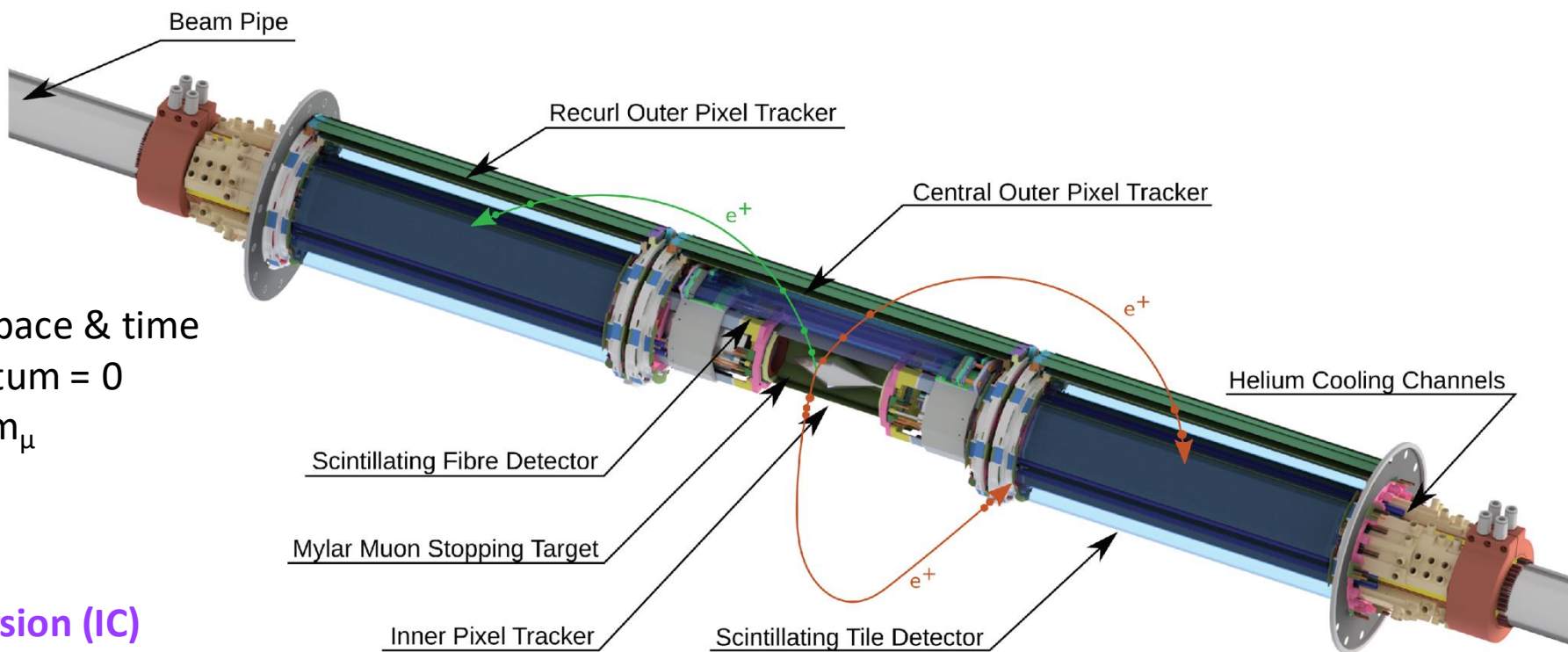
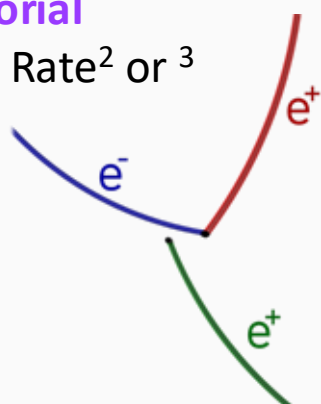


Internal conversion (IC)

$Br = 3.4 \times 10^{-5}$

Combinatorial

Scale with $Rate^2$ or 3



20 30 40 cm

Baseline design is 4 layers of pixels (2027 onwards)
 Can also push new limit with 3-layer



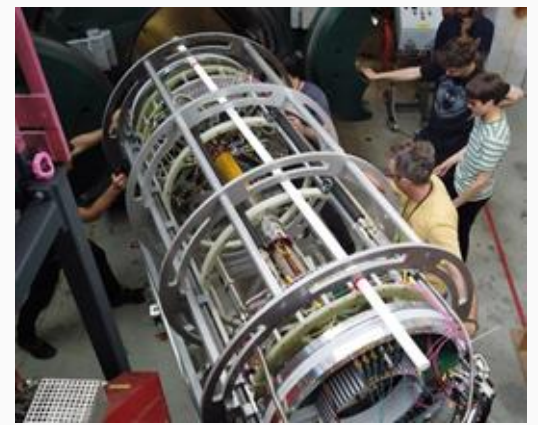
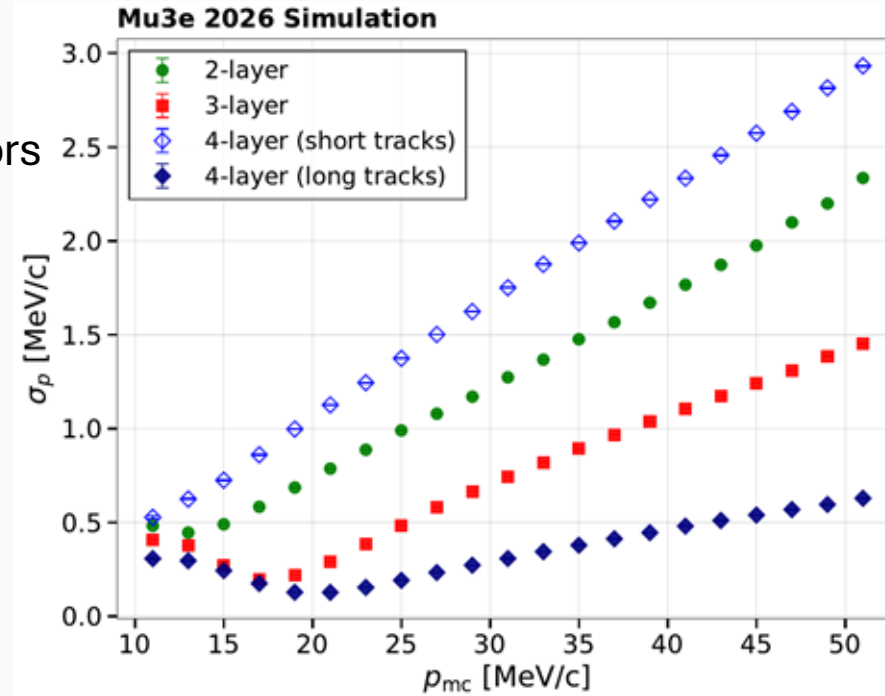
Mu3e Status and Plans

2025 commissioning data was incredibly useful:

- 2 pixel layers, partial fibre and tile detectors
- Construction, commissioning, operation
- DAQ, data quality, data processing
- Reconstruction and analysis

2026: First Physics Data!

- 3 pixel layers, complete fibre, downstream tiles
- Filter farm running in selection mode



2027: Surpass current limit (10^{-12})

- Phase-1 setup with 4-layers, major physics run

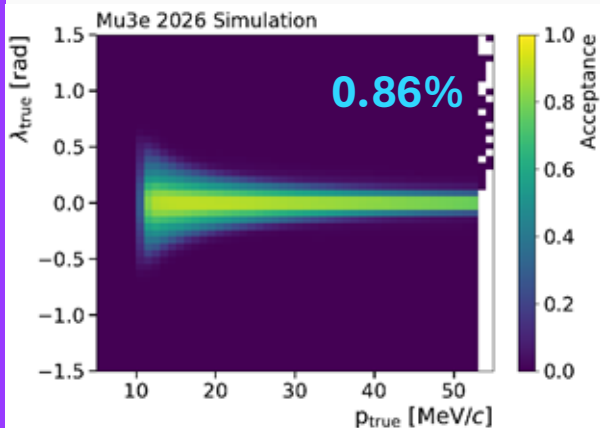
2028-29: PSI shutdown for beamline upgrade

2030: sensitivity of 10^{-15} , factor 1000 improvement

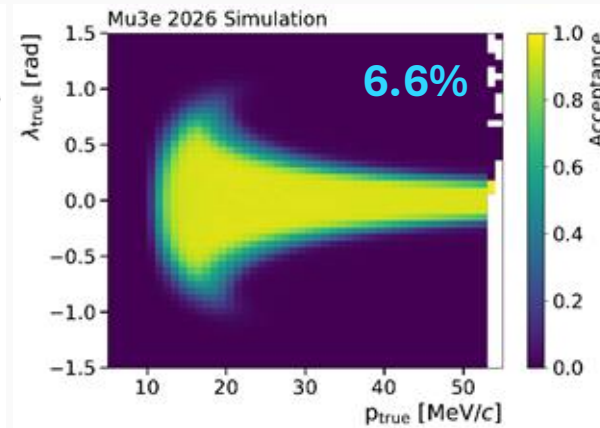
- Mu3e will run again with Phase-1 setup

Mid-2030: Phase 2 for ultimate sensitivity

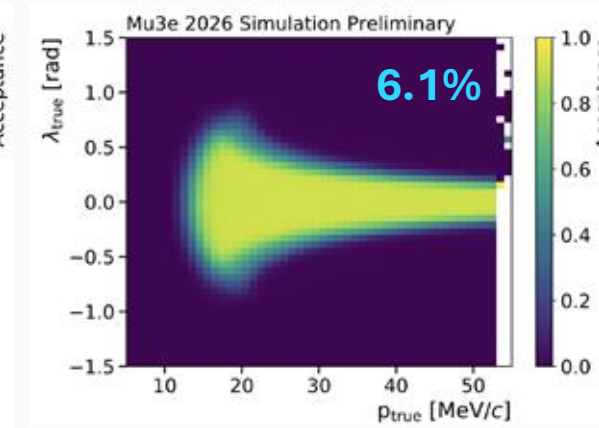
2 pixel layers (2025):



3 pixel layers (2026):



4 pixel layers (2027):



MEG-II

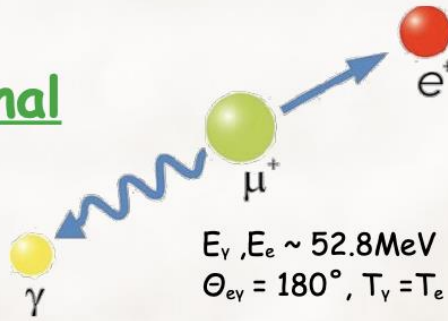


Thanks to Fedor Ignatov

MEG-II

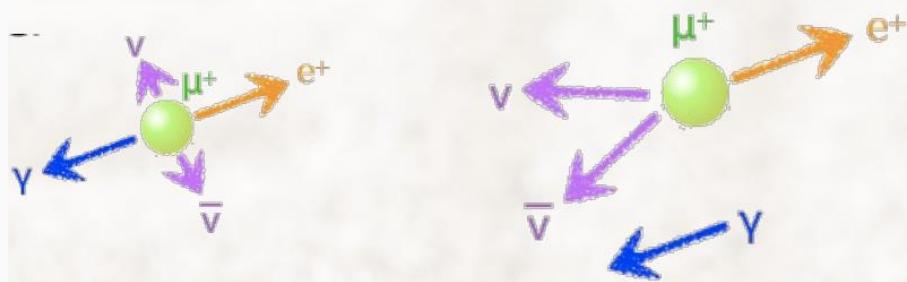
$$\mu^+ \rightarrow e^+ \gamma$$

Signal



RMD BG

Dominant Accidental BG



*Search for e^+ and γ correlated by time, direction, energy

COBRA superconducting magnet
1.3-0.5T

Liquid xenon detector (LXe) $\sigma_E/E \sim 2\%$

Geometrical acceptance 11%

DC μ beam
 $3-5 \times 10^7 \mu/s$

Radiative decay counter (RDC)

Cylindrical drift chamber (CDCH) $\sim 1.6 \times 10^{-3} X_0, \sigma_e \sim 90 \text{ keV}$

Muon stopping target

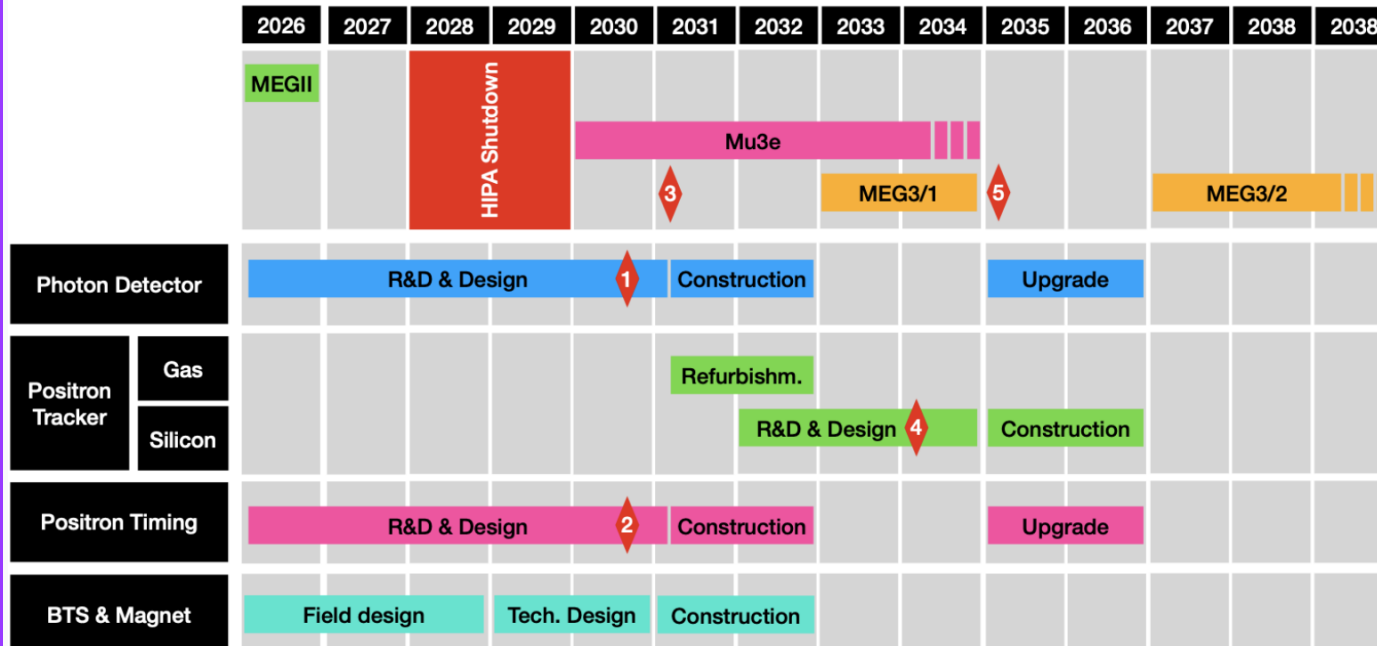
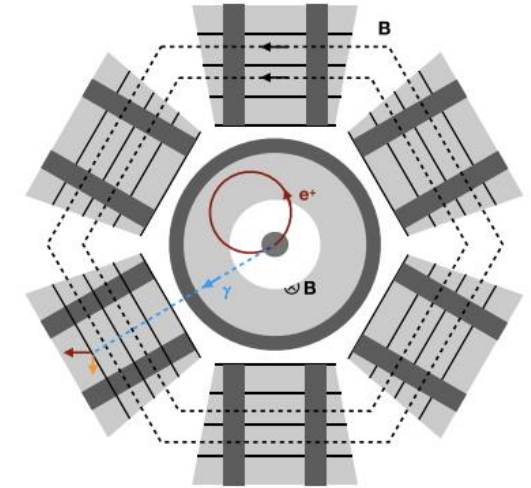
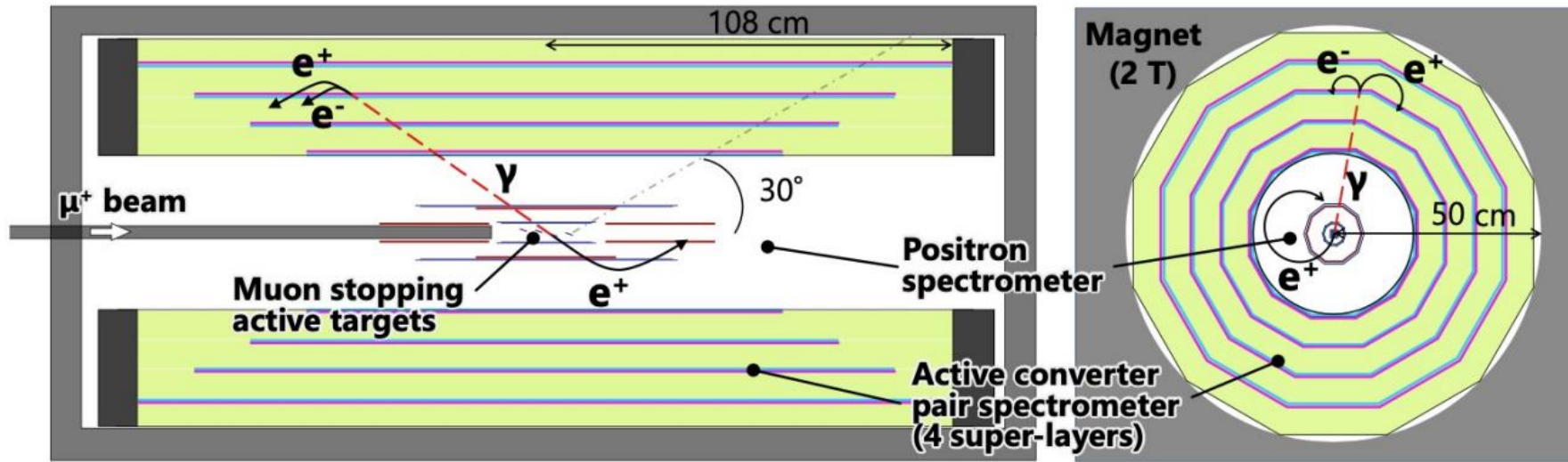
Pixelated timing counter (pTC) $\sigma_t \sim 35 \text{ ps}$

Final year of data taking (ran 2021–2026)

Published result 2021-22: limit 1.5×10^{-13} , final goal 0.5×10^{-13}



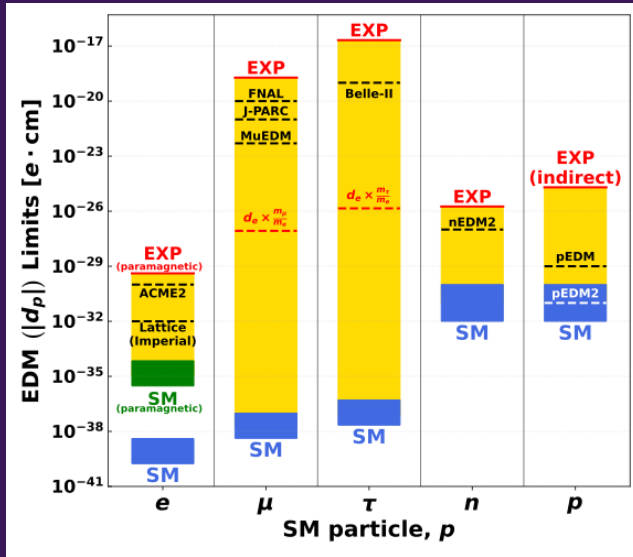
Future $\mu \rightarrow e\gamma$ experiment



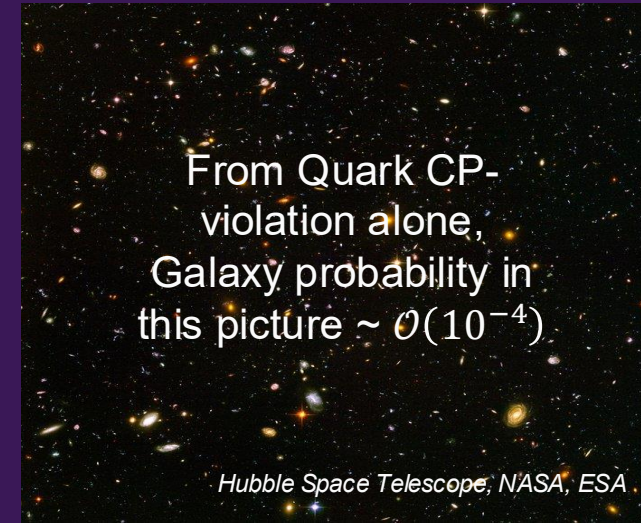
- Use PSI HIMB – 10^{10} muons per second
- Reuse Mu3e tracker (positron spectrometer)
- New technology calorimeter
- Aim for $2-3 \times 10^{-15}$ limit

Robust precision test of the SM

Predicted values are immeasurably small in the SM.

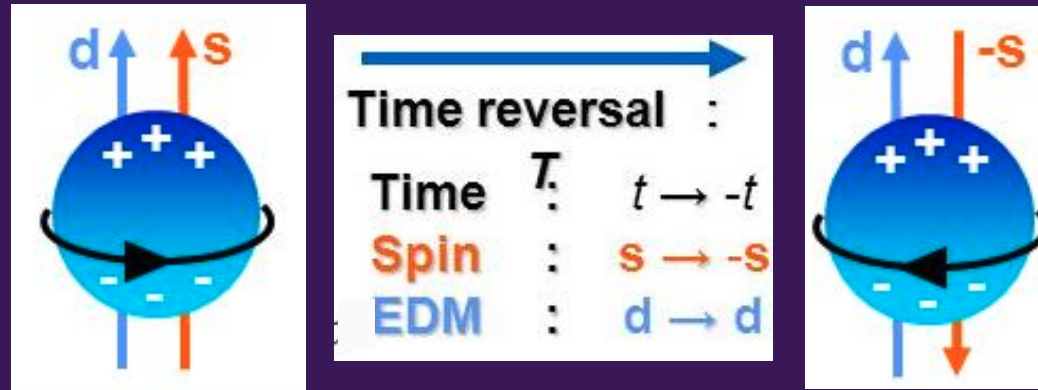


Universe's matter-antimatter asymmetry.
New CP violation.



Why EDMs?

Permanent EDM Violates both T & P Symmetries

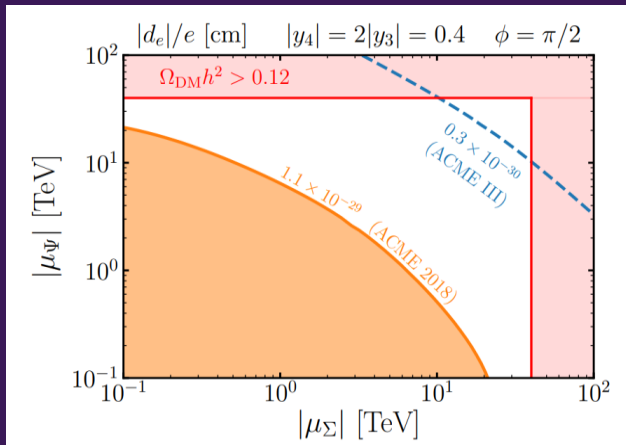


EDM, $d \neq 0$:
T-violation = CP-violation

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

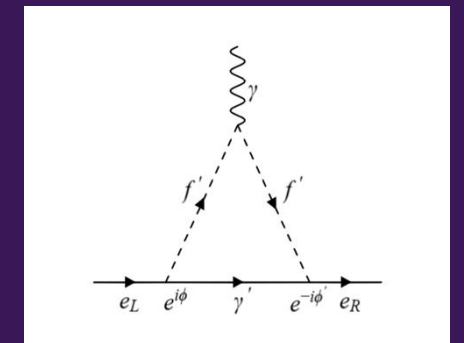
Dark matter

DM models predict large EDMs.



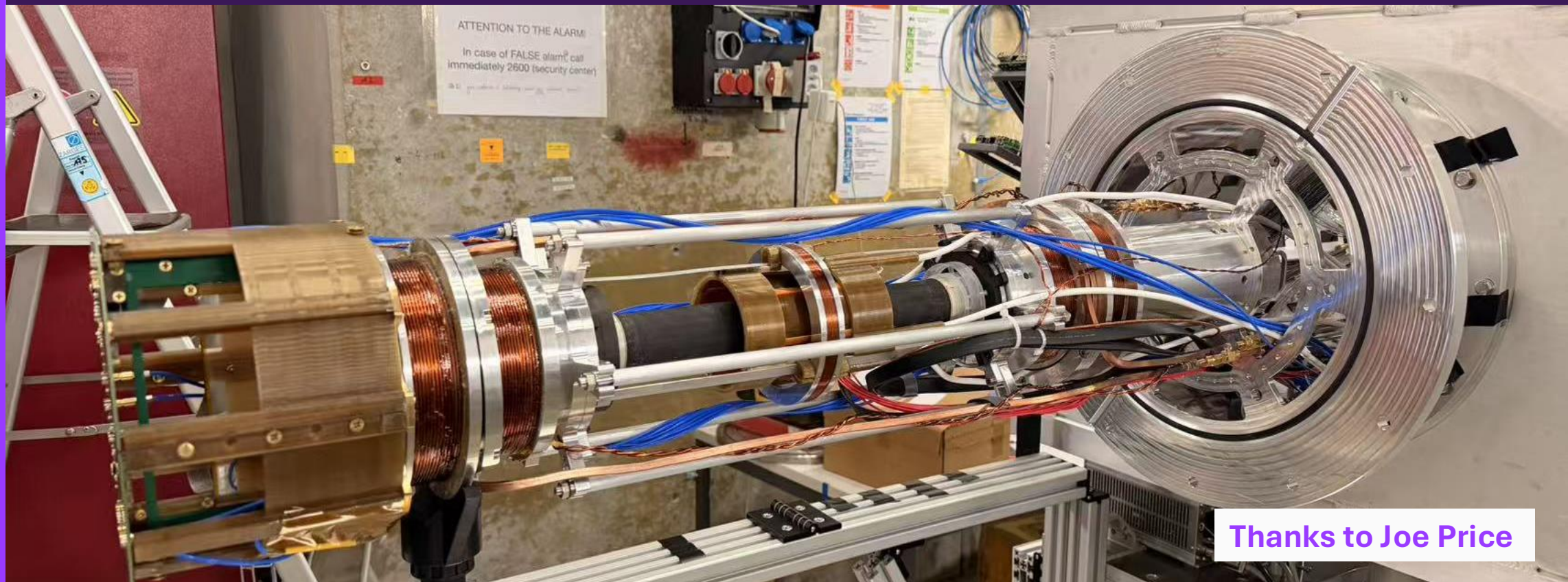
At minimum, can greatly constrain parameter space.

New physics sensitivity



Sensitive to a wide range of interactions and energy scales.

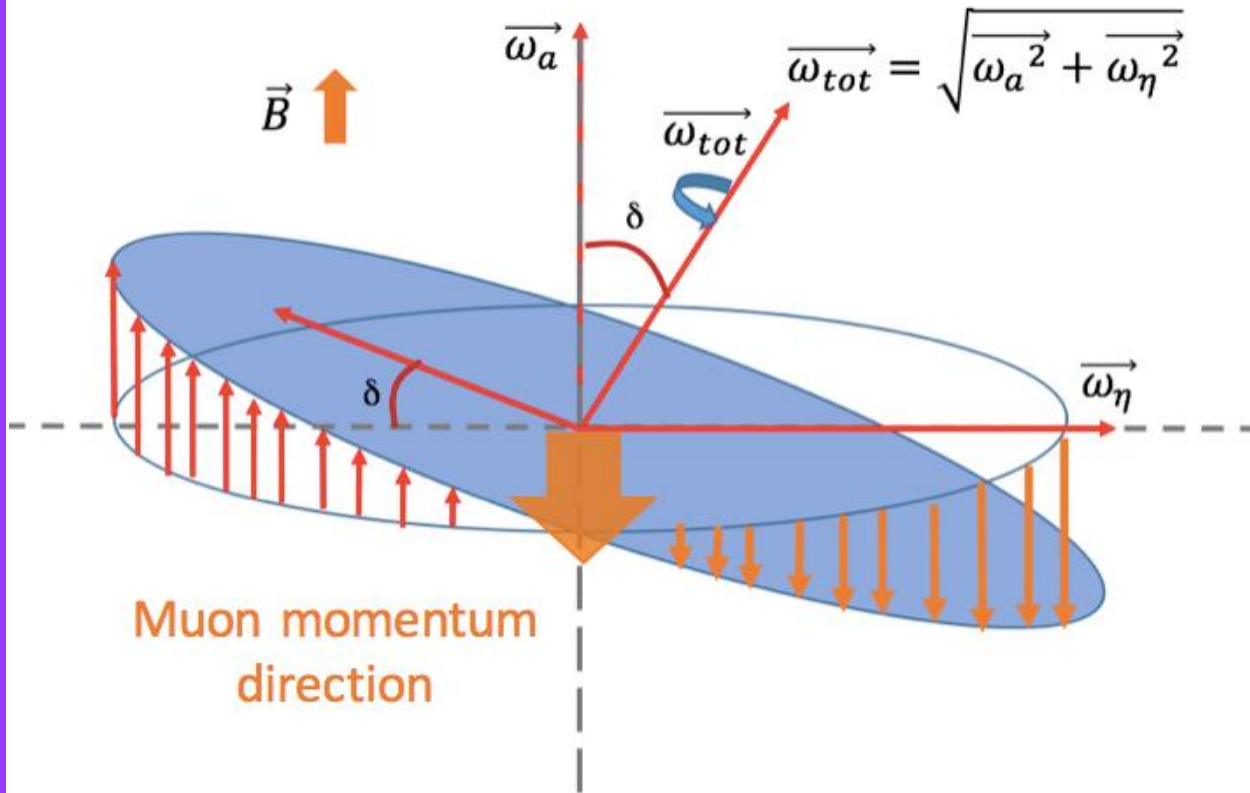
MuEDM



Thanks to Joe Price

MuEDM at g-2

An EDM tilts the precession plane towards the centre of the ring



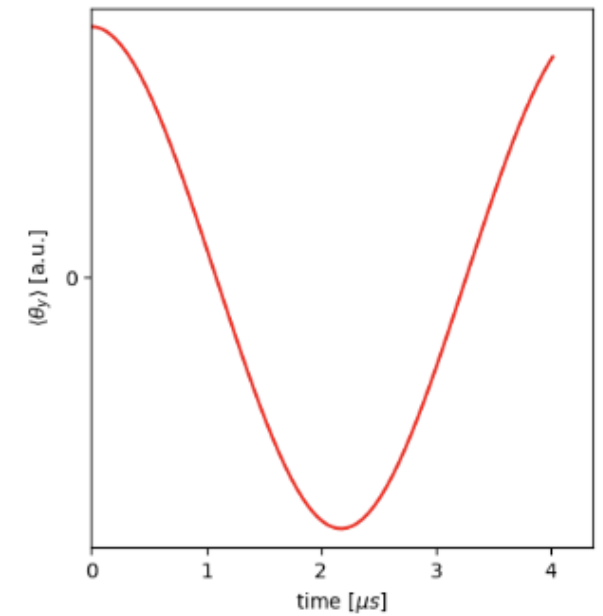
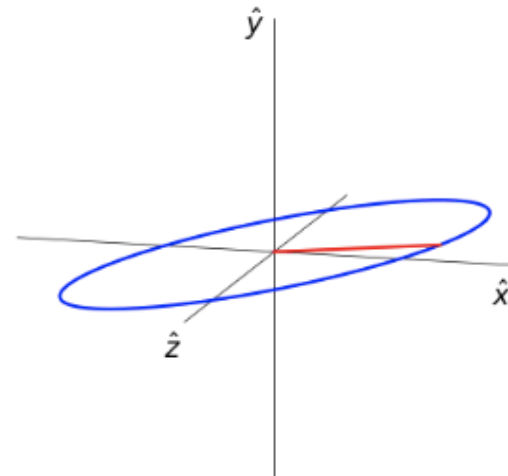
Vertical oscillation ($\pi/2$ out of phase)

$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = \underbrace{-\frac{Qe}{m} a \vec{B}}_{\text{MDM}} - \eta \frac{Qe}{2m} \left[\frac{\vec{E}}{c} + \underbrace{\vec{\beta} \times \vec{B}}_{\text{EDM}} \right]$$

Dominant term

The UK is leading the g-2 EDM analysis with the analysis of the run 2/3 data at an advanced stage

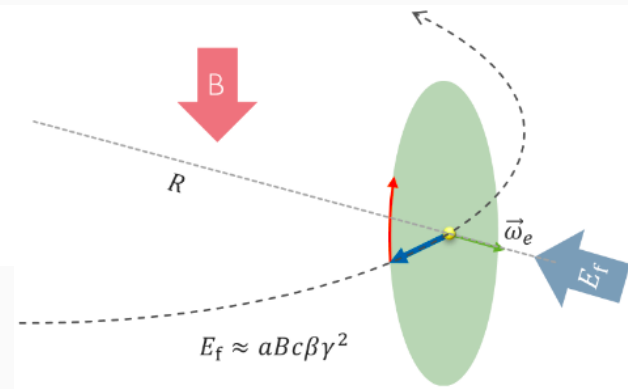
Expect a 5-fold improvement on the current limit!



MuEDM at PSI

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

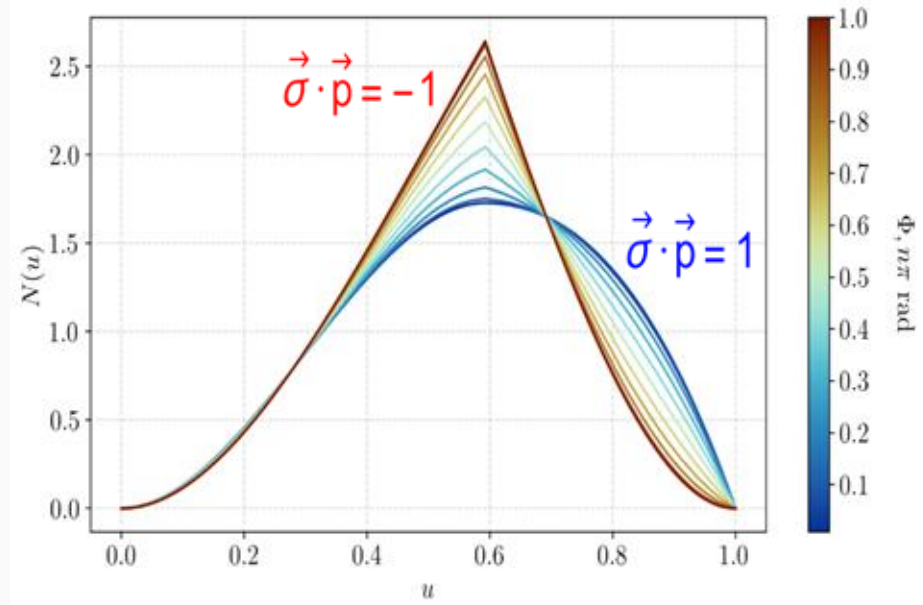
ω_a ω_e



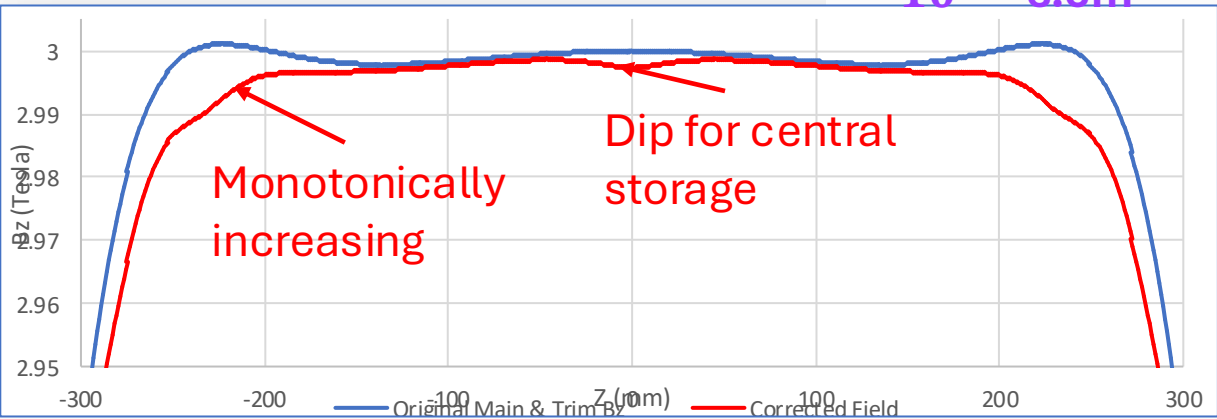
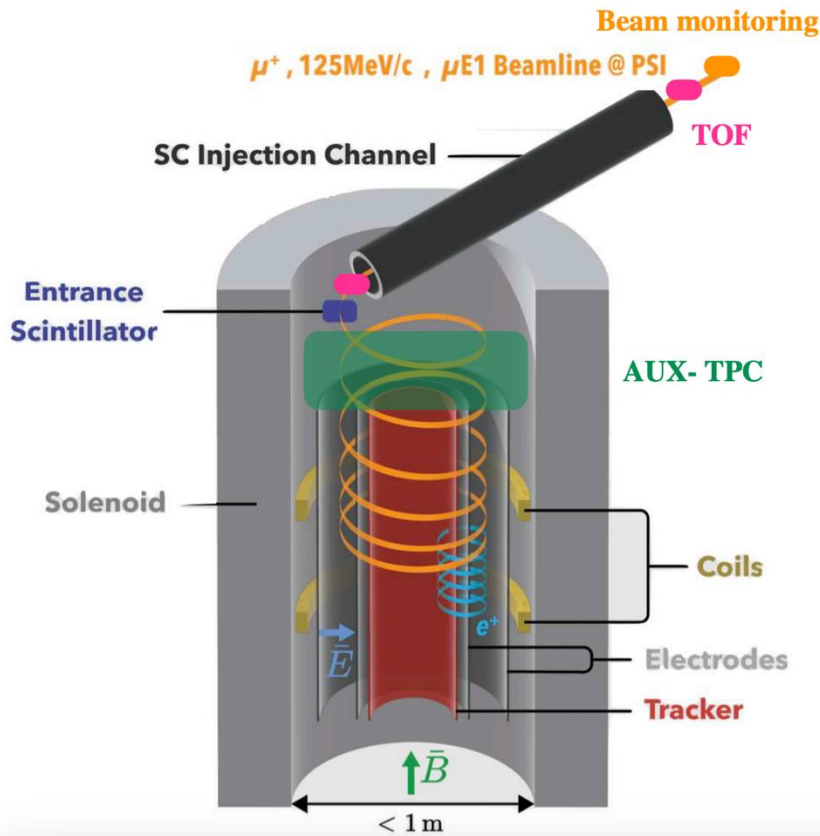
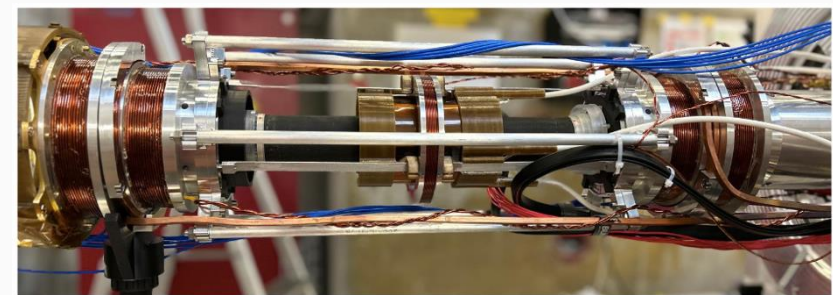
With **frozen spin** condition an EDM is the only cause of the precession

Spin can be frozen aligned, and anti aligned – changes momentum dependence
 Liverpool- simulation for positron momentum and angle weighting

Phase I: $d_\mu < 3 \times 10^{-21}$ e.cm
 Phase II: $d_\mu < 6 \times 10^{-23}$ e.cm



Correction coils for central storage UK deliverable (Daresbury)



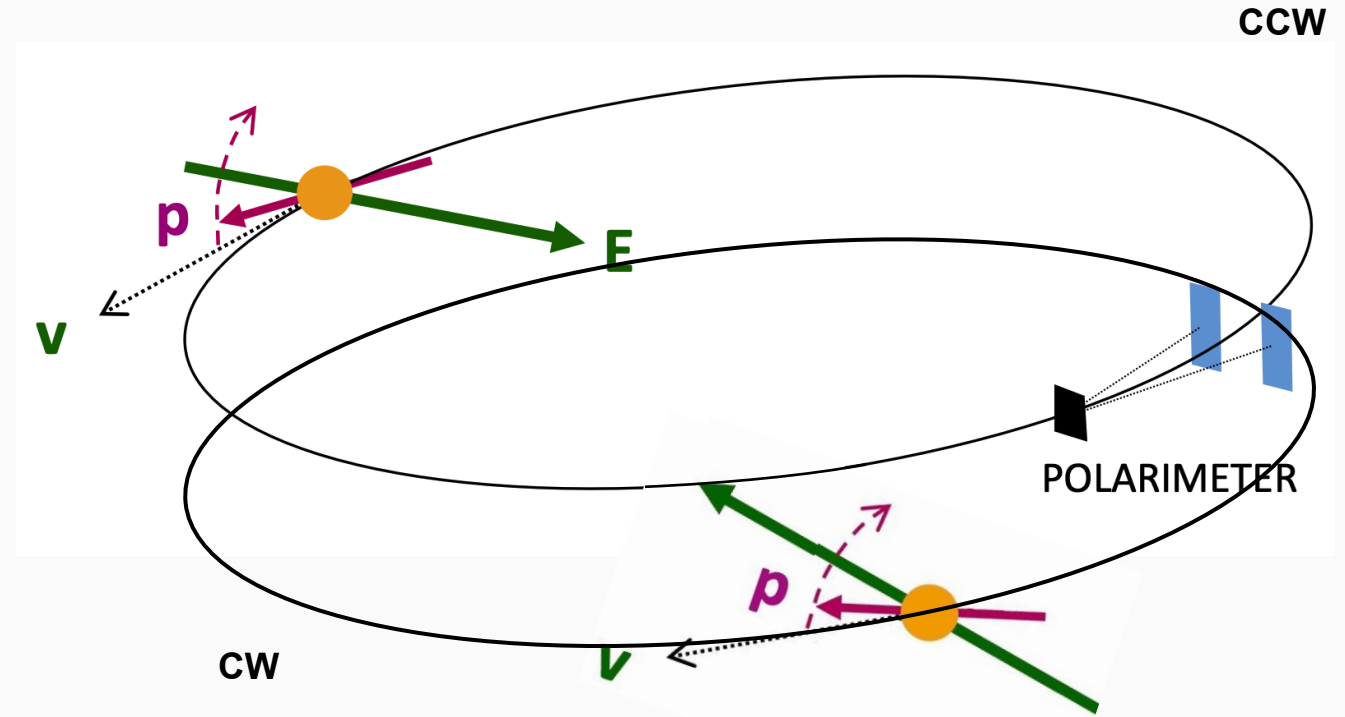
pEDM



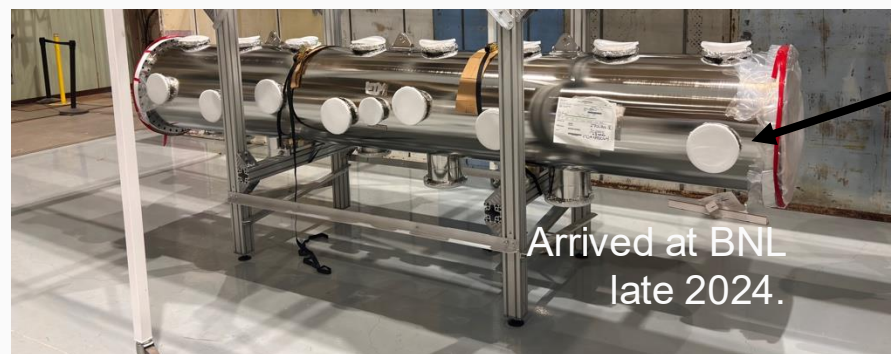
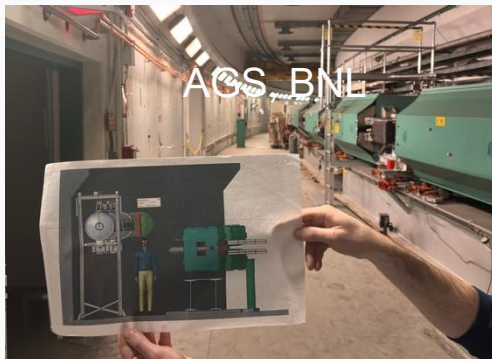
Thanks to Alex Keshavarzi

pEDM

- **First ever direct measurement** of the proton EDM
- Only current EDM experiment with **potential to probe SM prediction**
- pEDM phase-I will reach $10^{-29} e \cdot cm$ ($\mathcal{O}(10^4)$ improvement).
- High-intensity, polarised proton storage ring at **BNL's AGS tunnel**:
- Systematic error control via frozen-spin and CW/CCW storage.



- **UK leading electrostatic deflector and polarimeter development.**
- pEDM cost $\mathcal{O}(\text{£}100\text{M})$, TDR to completion < 20 years.



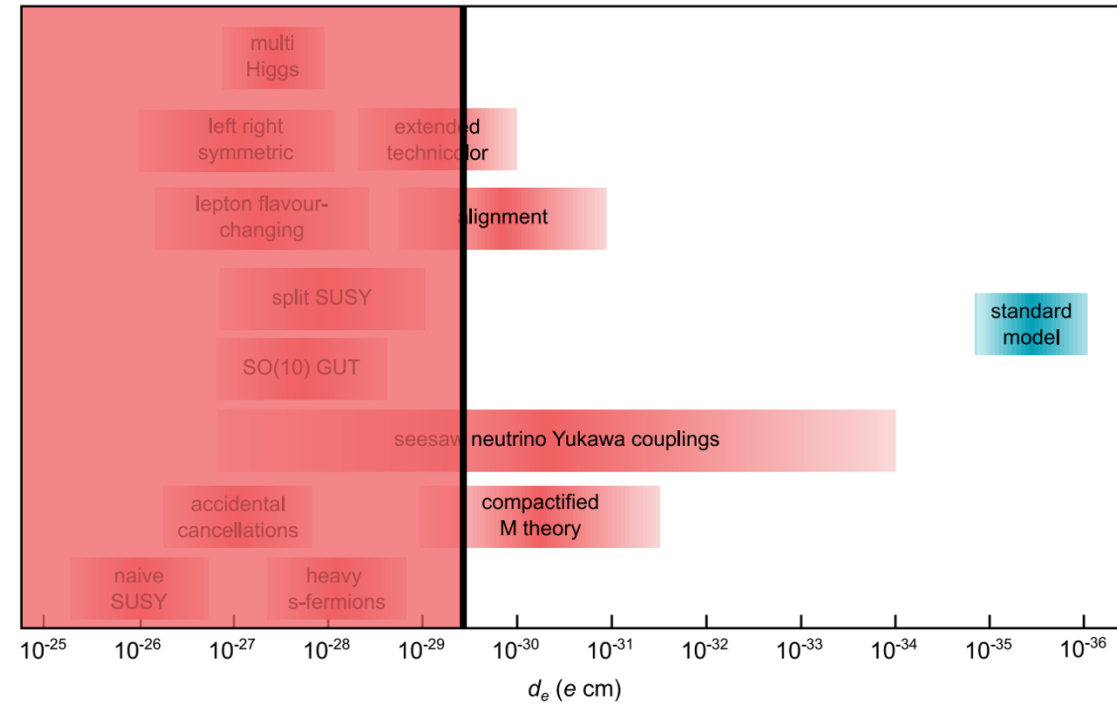
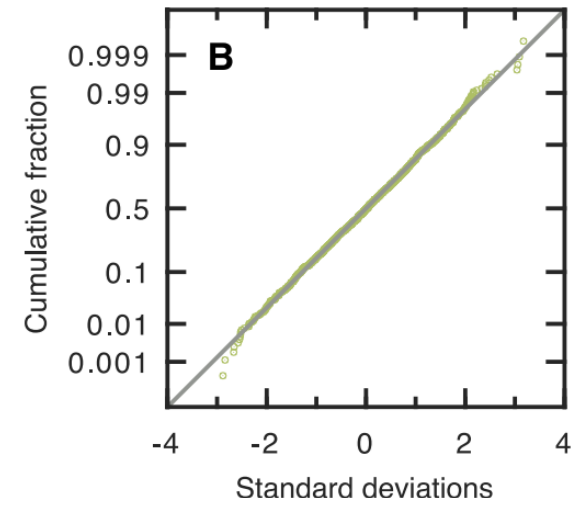
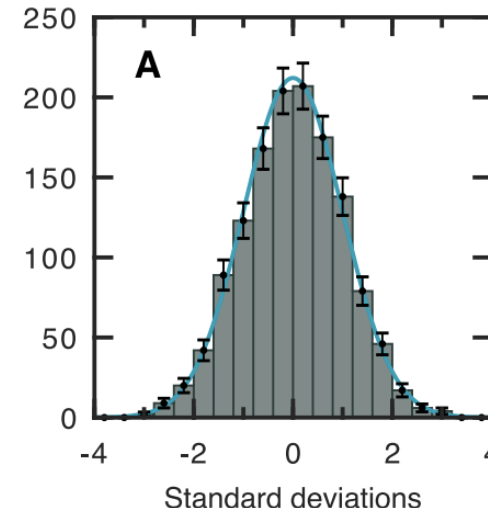
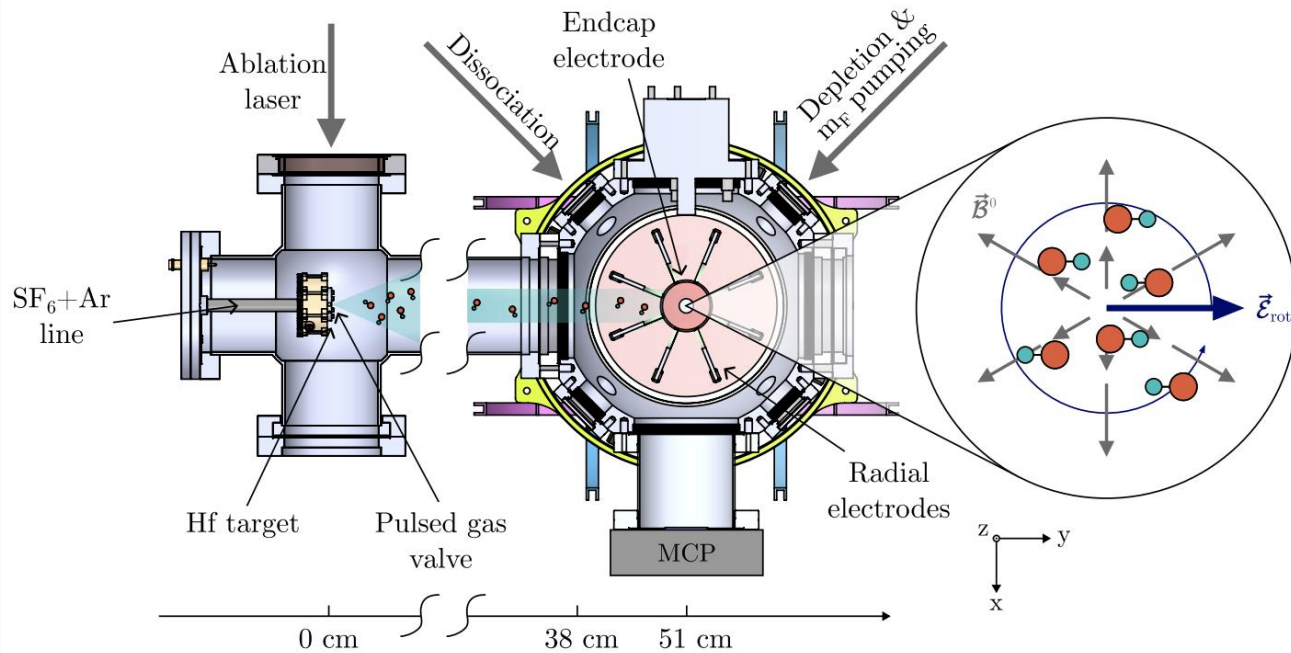
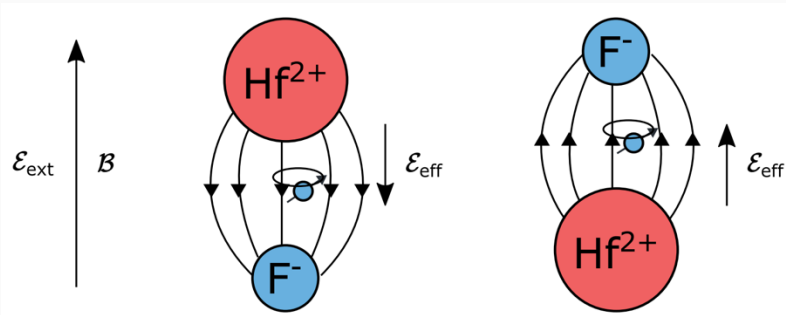
Comprehensive proton storage test at BNL in 2026. CDR in preparation now.

eEDM



Thanks to Luke Caldwell

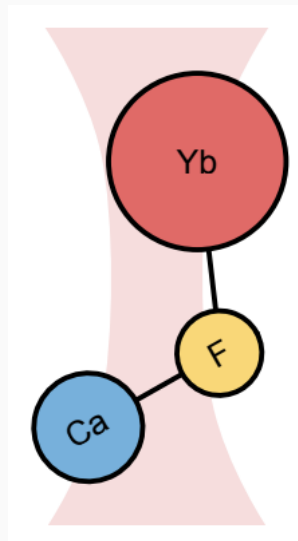
JILA eEDM



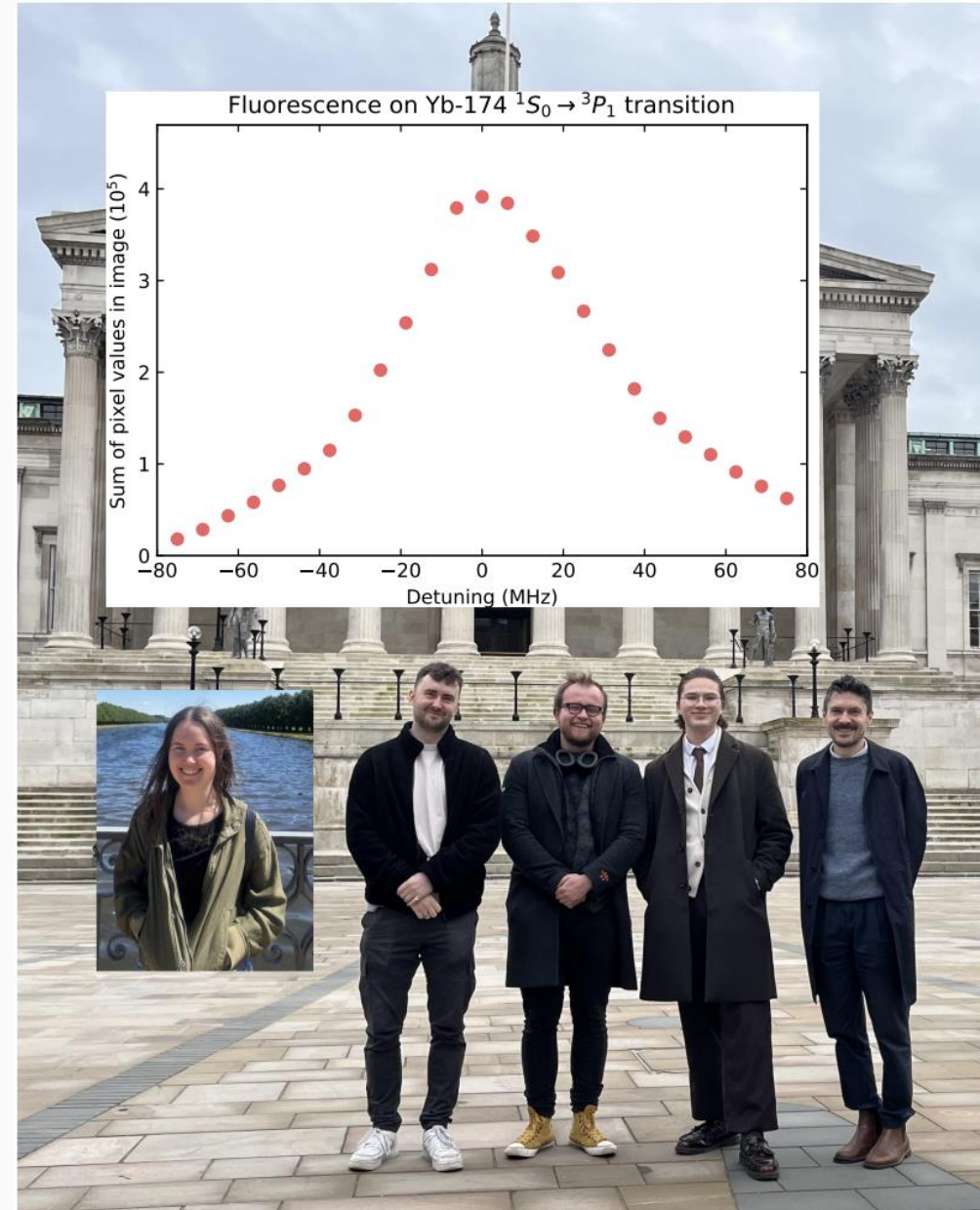
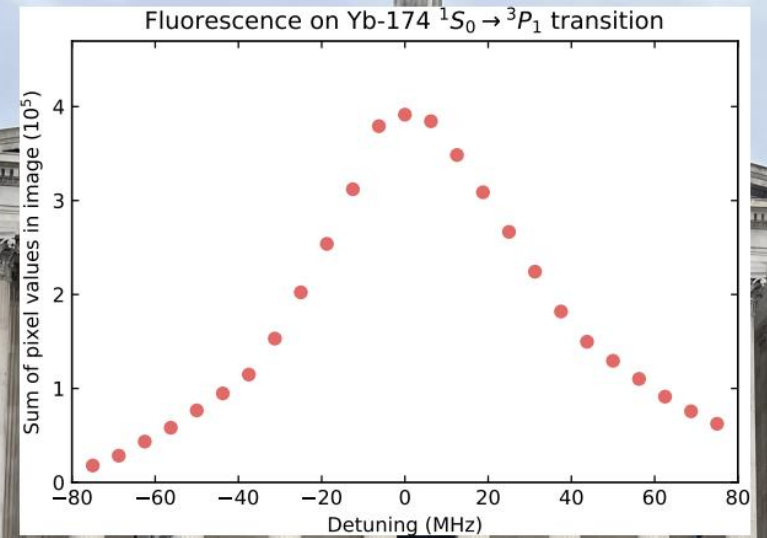
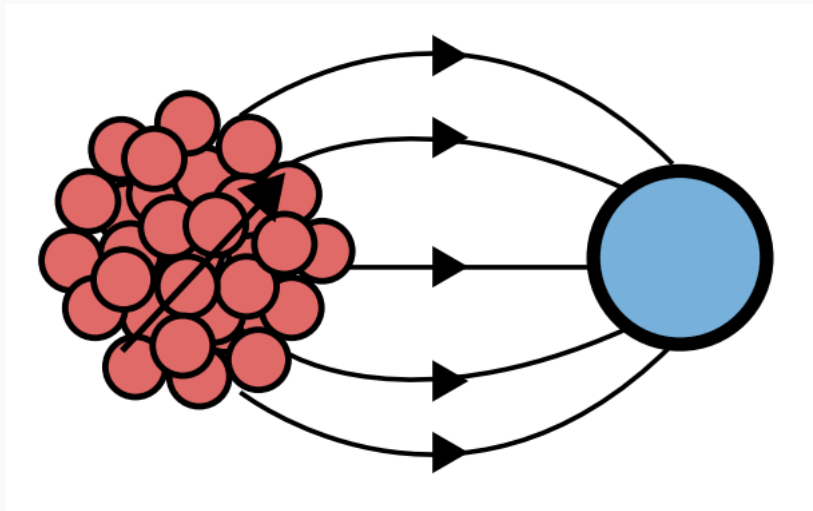
$$d_e = (-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-30} \text{ e cm}$$

$$d_e < 4.1 \times 10^{-30} \text{ e cm (90\% confidence)}$$

The future: probing nuclear CP violating moments



- Use heavy nucleus with spin embedded in polar molecule
- Looking at using ultracold, neutral YbCaF molecules
- Produce from separately laser-cooled species in optical tweezers

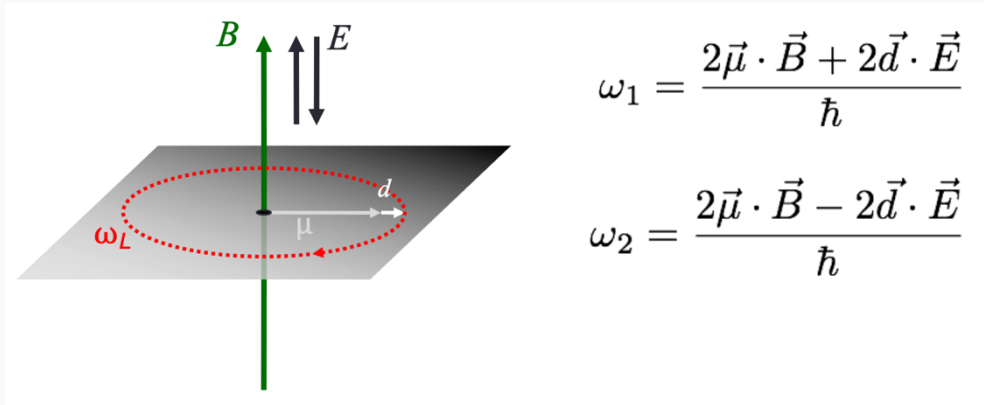


nEDM



Thanks to Clark Griffith

nEDM and n2EDM



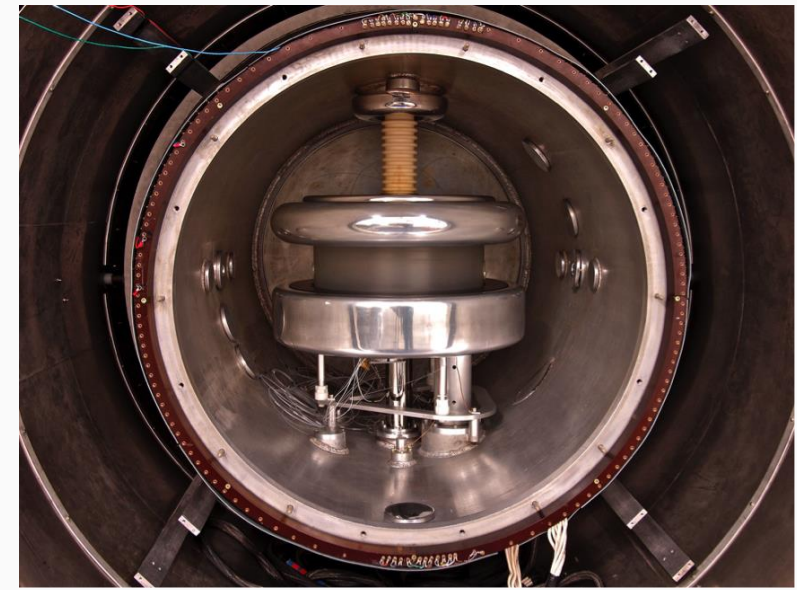
$$\omega_1 = \frac{2\vec{\mu} \cdot \vec{B} + 2\vec{d} \cdot \vec{E}}{\hbar}$$

$$\omega_2 = \frac{2\vec{\mu} \cdot \vec{B} - 2\vec{d} \cdot \vec{E}}{\hbar}$$

nEDM apparatus developed at RAL/Sussex at PSI UCN source

Store ultra cold neutrons in a trap

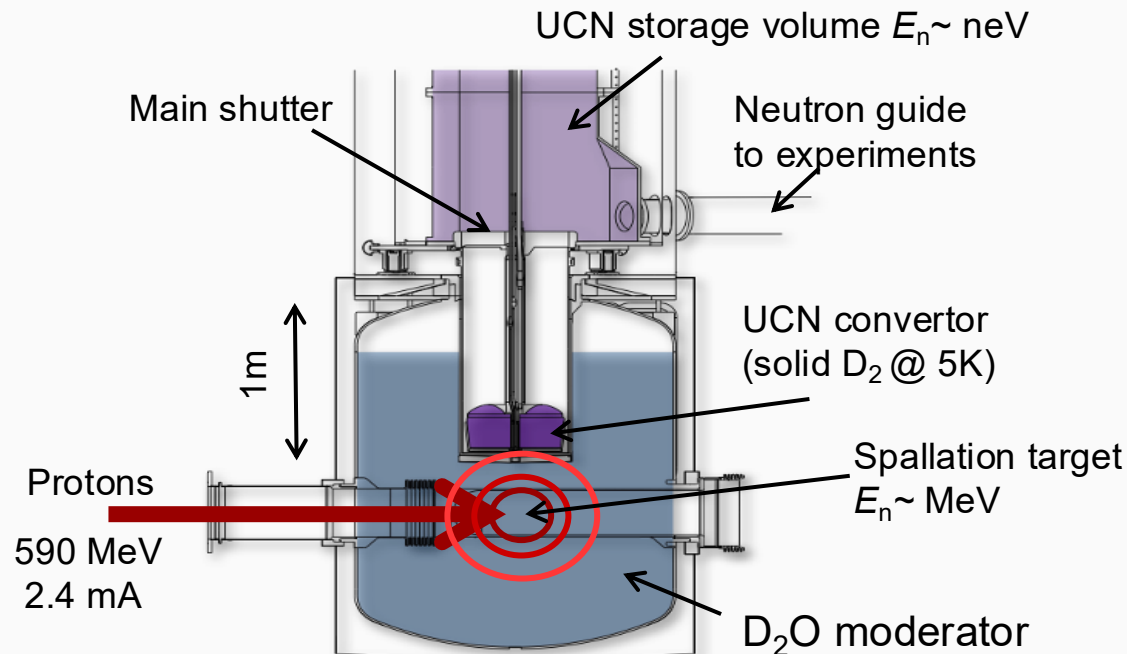
Apply a magnetic and electric field across the trap



An EDM would cause a change in the precession frequency when the E field is reversed

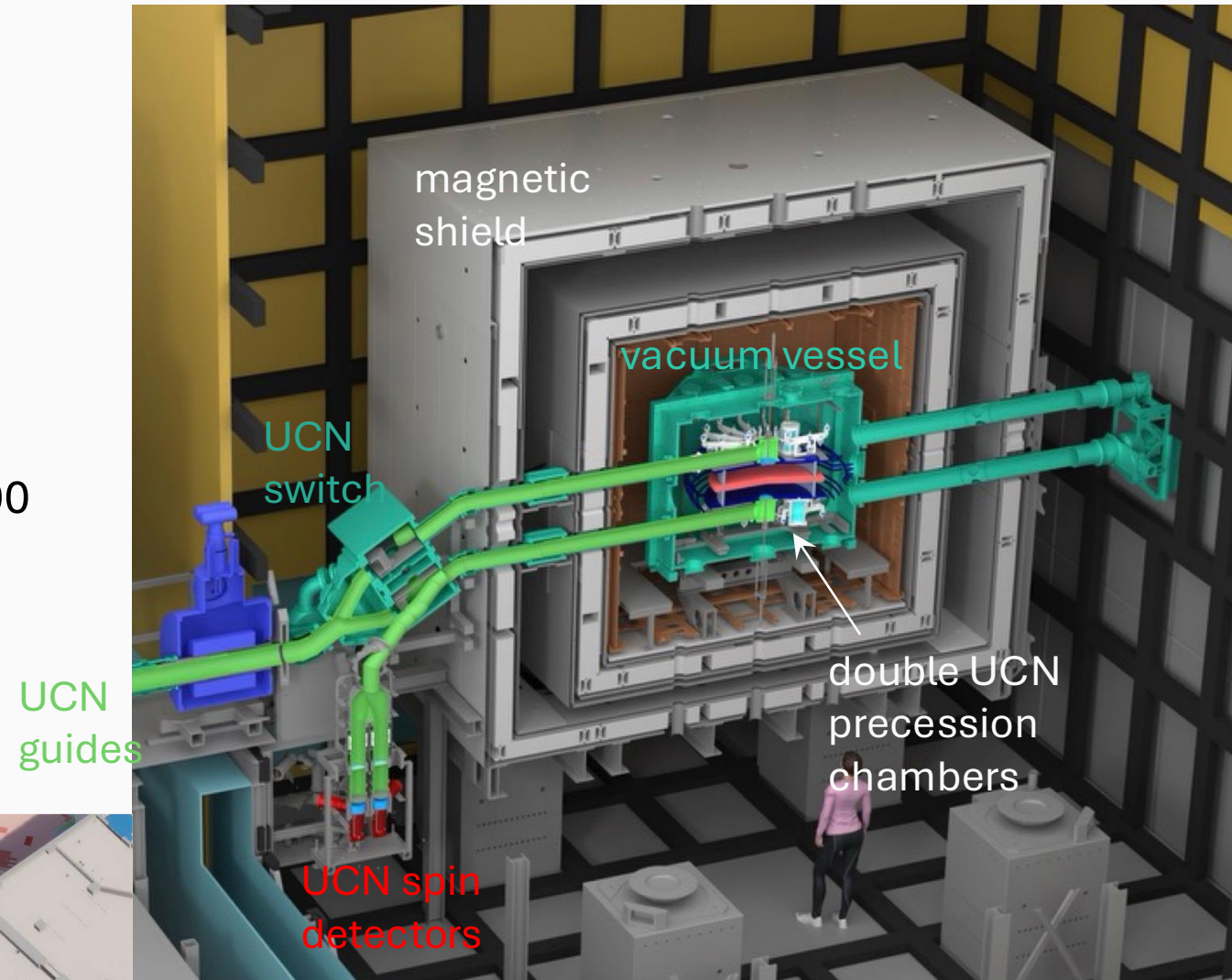
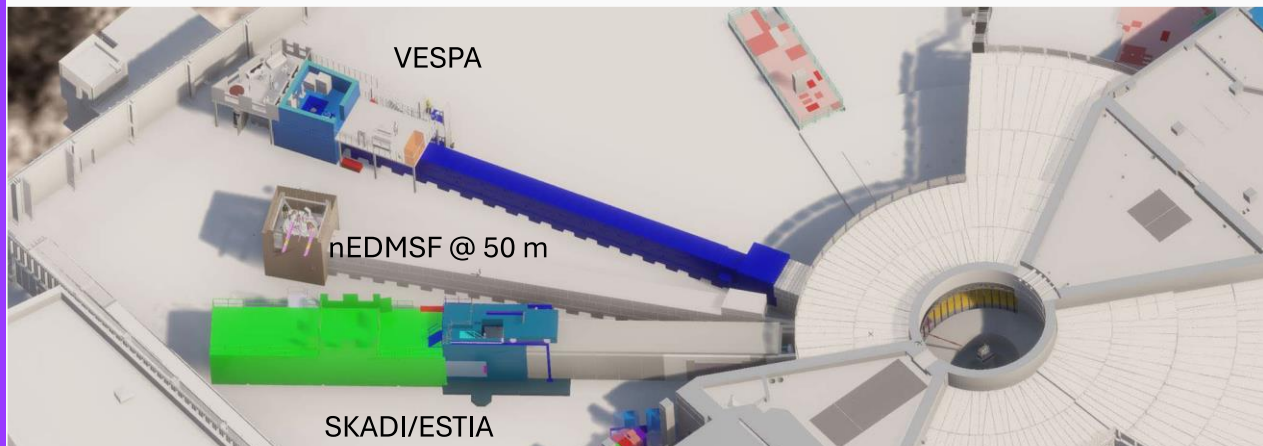
$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) e \text{ cm}$$

$$|d_n| < 1.6 \times 10^{-26} e \text{ cm (90\% CL)}$$



n2EDM and the future

- Double precession chambers
- Sussex leadership on magnetometry and systematics
- **nEDM data taking starting this year**
 - *projected sensitivity: 1×10^{-27} ecm* (500 days of data)



R&D ongoing for a cryogenic nEDM measurement in super fluid helium to reach 10^{-28} ecm sensitivity

Summary

- **Lots of exciting work in the field of precision physics – not enough time to cover everything!**
- Final result published from muon $g-2$ experiment at Fermilab reaching 127ppb. Lots of work ongoing to resolve theory discrepancies
- Charged lepton flavour violation experiments either running or about to start data taking aiming for large increases in sensitivity
- Many different efforts to measure particle EDMs with fantastic new results and improved limits expected soon

Thank you!