The UK Muon Physics Programme
g–2, CLFV & μEDM

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IOP 2024, Liverpool

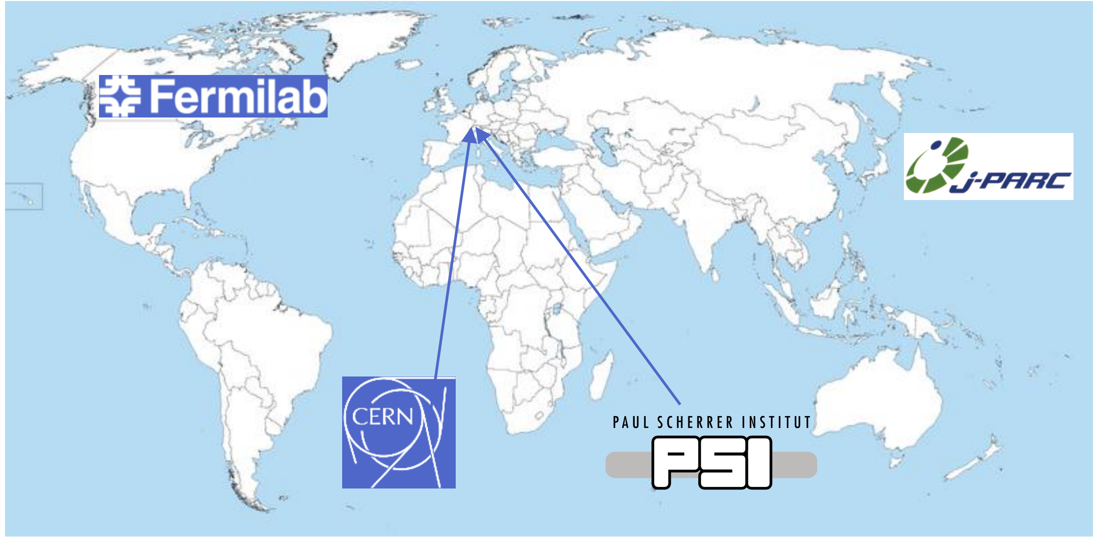
9th April 2024

Muon Physics in the UK

- Charged Lepton Flavour Violation (CLFV)
  - Fermilab: Mu2e
  - JPARC: COMET
  - PSI: Mu3e, MEG-II

- The g-2 puzzle
  - Fermilab g-2 experiment
  - MUonE experiment at CERN
  - Theory effort

- Muon Electric Dipole Moment (μEDM)
  - Fermilab g-2 experiment
  - PSI μEDM Experiment

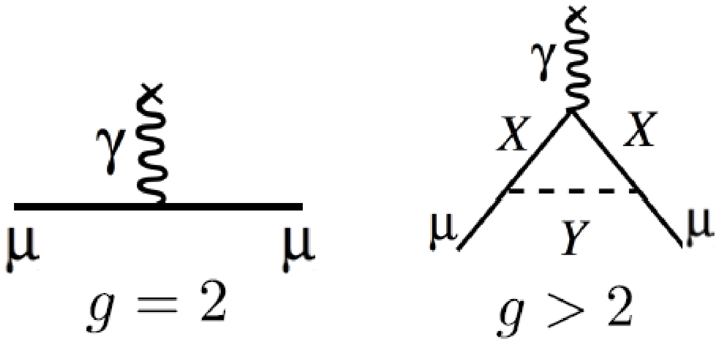


The Muon g–2 Puzzle

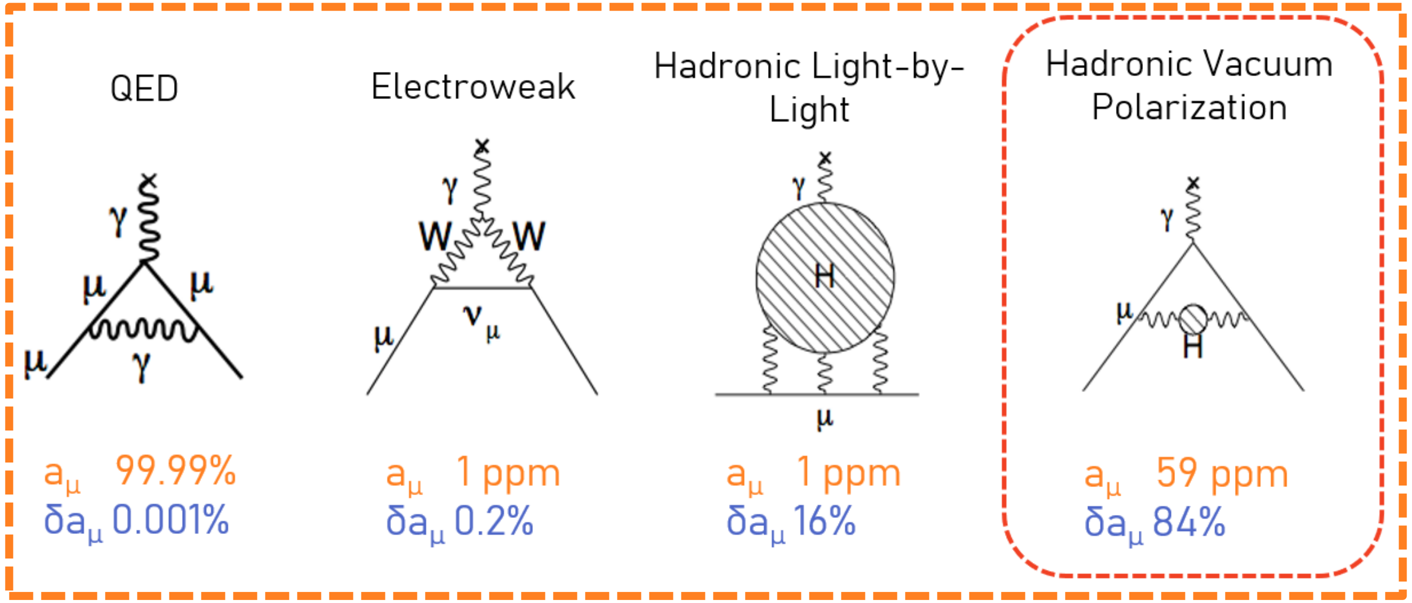
Muon g-2: Testing the Standard Model

- For a spin-1/2 particle: spin couples to external B-field → torque (precession)
- Magnetic moment determined by dimensionless quantity *g*
- Size of *g* determined by virtual loop interactions

Torque in B-field	Magnetic Moment
$\vec{\mu} \times \vec{B}$	$\vec{\mu} = g\frac{e}{2m}\vec{S}$



Define: $$a_\mu = \frac{g-2}{2}$$



Contributions from all SM → and beyond…?

Measuring g-2

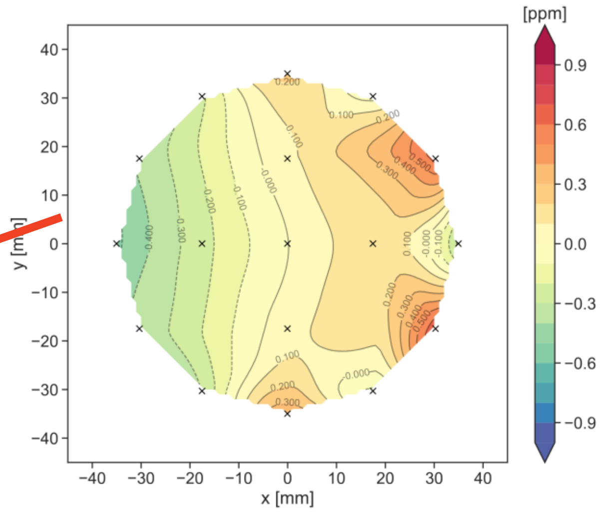
See parallel talks by Ce Zhang and Lorenzo Cotrozzi (Wednesday Session F)

a_μ obtained from ratio of two frequencies

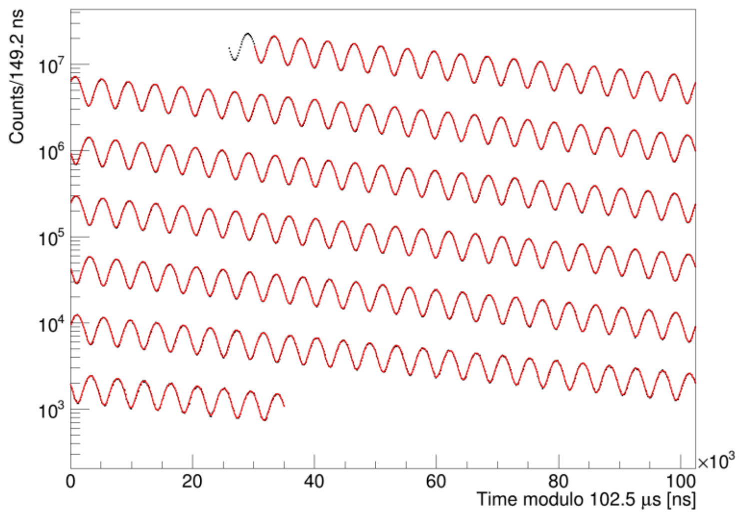
$$a_\mu \propto \frac{\omega_a}{\widetilde{\omega}_p}$$

Measure each with equal precision (70 ppb)

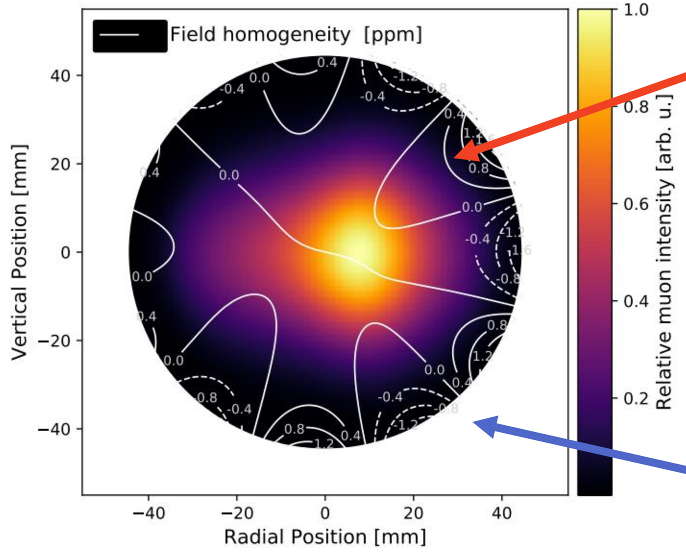
Magnetic field measurement
PhysRevA.103.042208



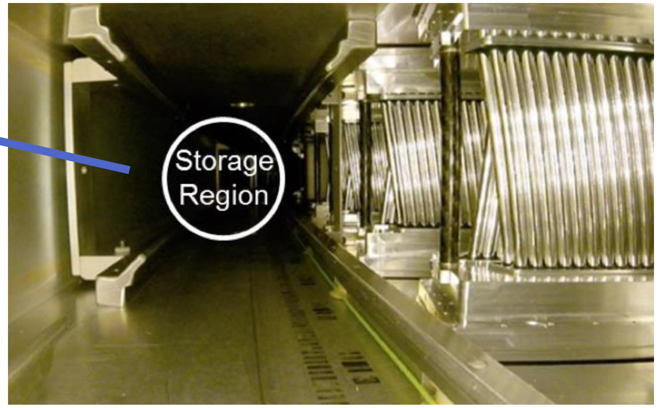
PhysRevD.103.072002



Muon spin precession frequency ω_a



Muon weighted magnetic field ω_p



Straw tracking detectors: JINST-17-P02035

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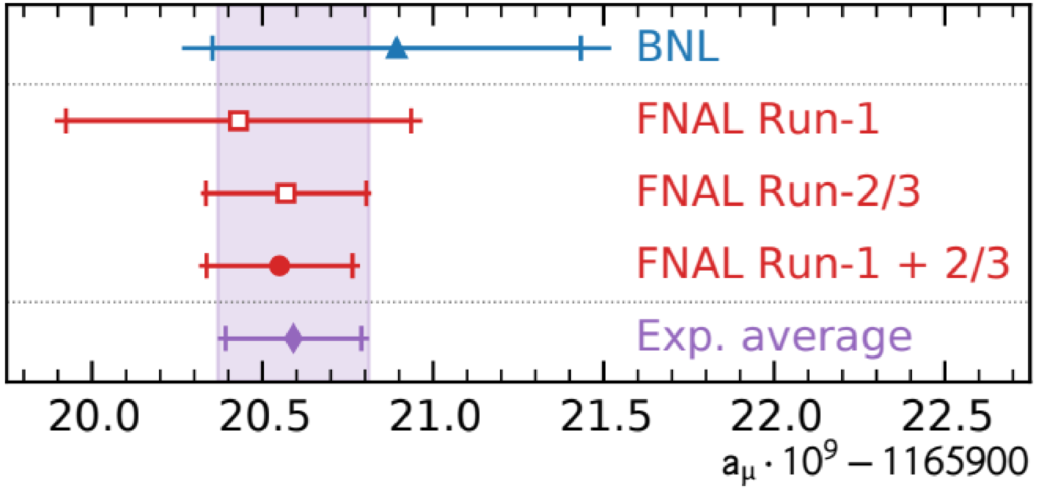
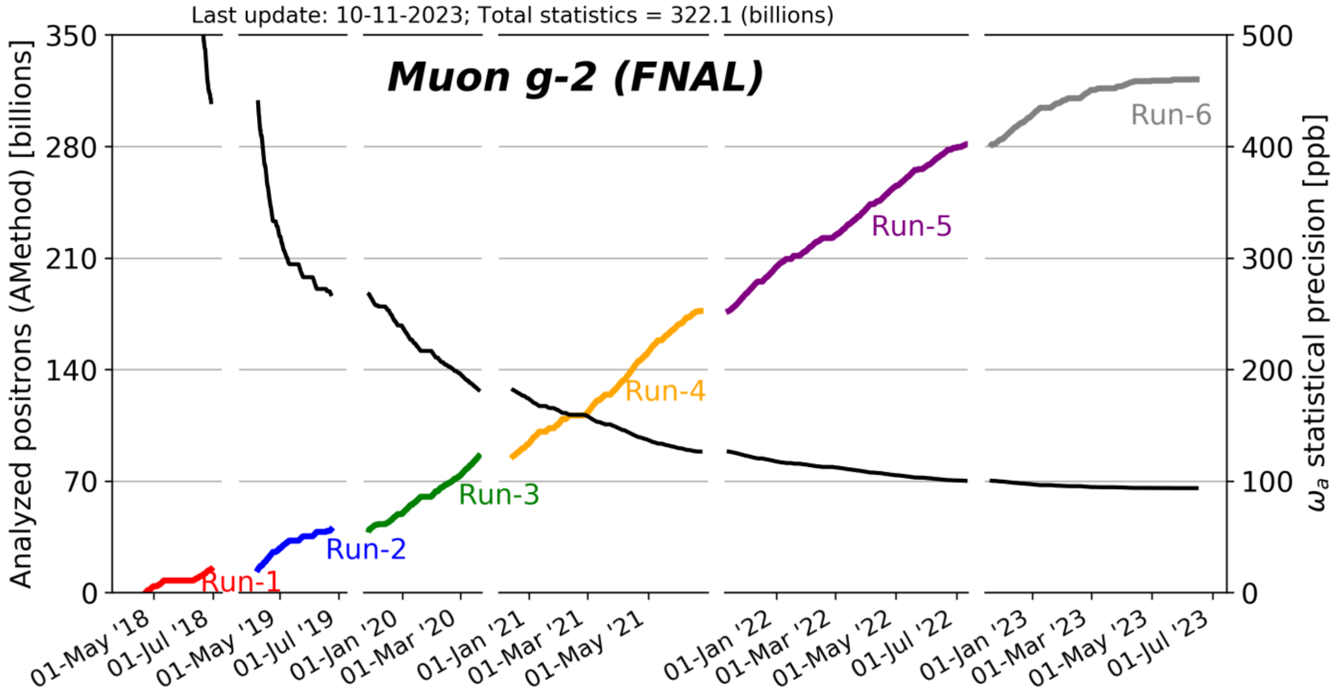
Status of the Fermilab g-2 experiment

See parallel talks by Ce Zhang and Lorenzo Cotrozzi (Wednesday Session F)

- Run-2/3 data consistent with Run-1 and BNL
- Factor >2 in statistical and systematic uncertainty
- Surpassed TDR goals in statistics and systematics
- Another reduction by factor of 2 in statistical uncertainty from Run-4/5/6
- Expect final result in 2025



Phys. Rev. Lett 131.161802 (October 2023)
Detailed Report: arXiv 2402.15410 (Feburary 2024)



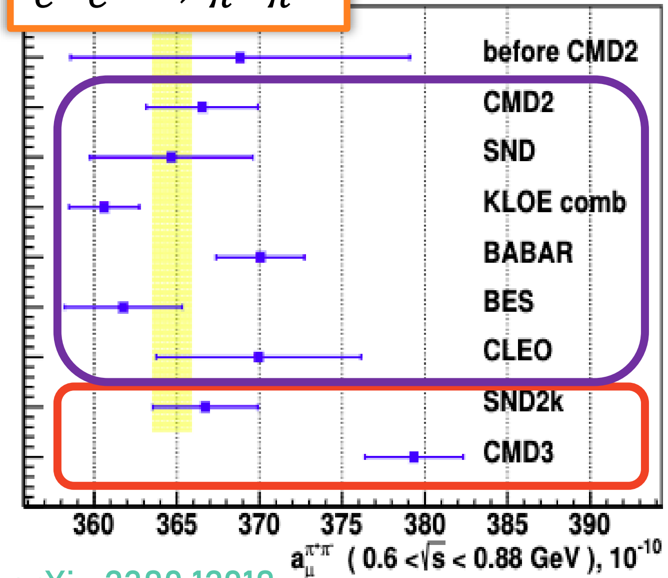
- UK is a leading group in the experiment
- Analysis roles: magnetic field, beam dynamics, spin precession, muon EDM search
- Hardware: straw tracker and DAQ
- Simulation: beamline modelling

The g-2 puzzle: comparison with SM theory

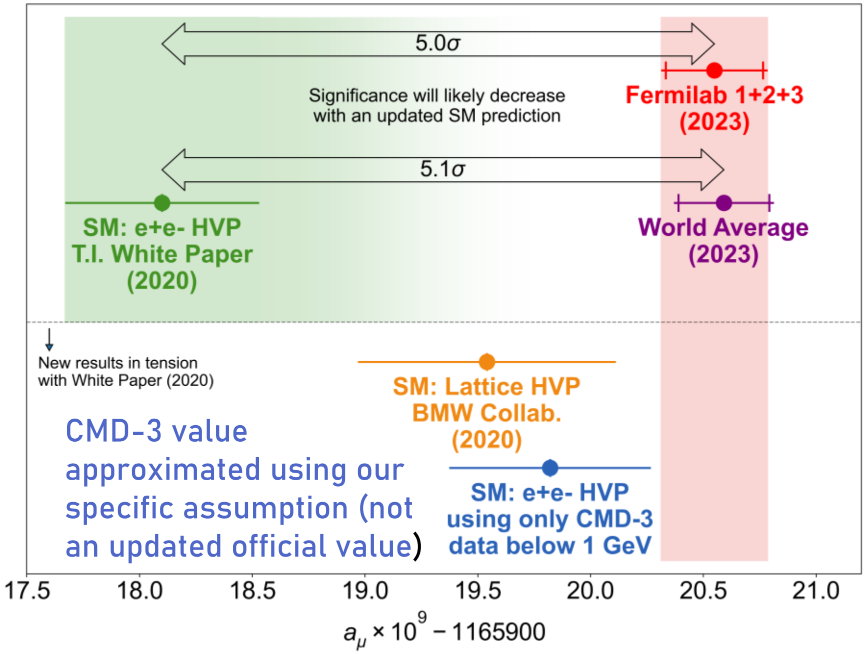
Tensions between alternative theoretical values of a_μ^{SM} must be resolved

- 5σ discrepancy between g-2 experiment a_μ^{EXP} (2023) and Theory Initiative SM prediction (a_μ^{SM}) from 2020. However:
  - Traditional SM prediction uses data-driven approach with e^+e^- data
  - Novel analytical calculation (lattice QCD) disagrees with data-driven calculation
  - Recent result from the CMD-3 detector disagrees with other experiments

$e^+e^- \rightarrow \pi^+\pi^-$

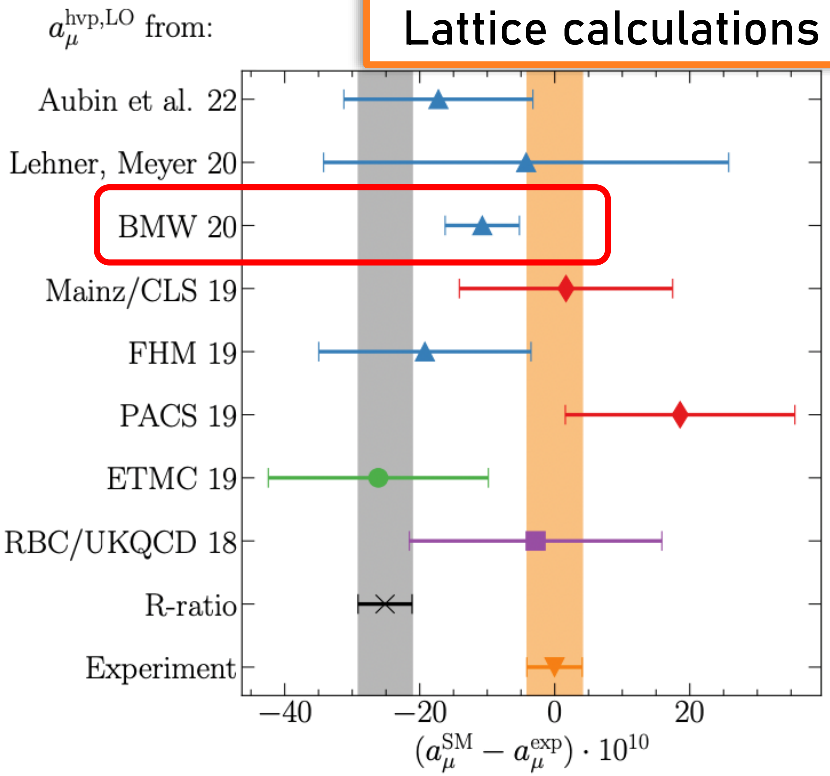


arXiv 2309.12910



CMD-3 value approximated using our specific assumption (not an updated official value)

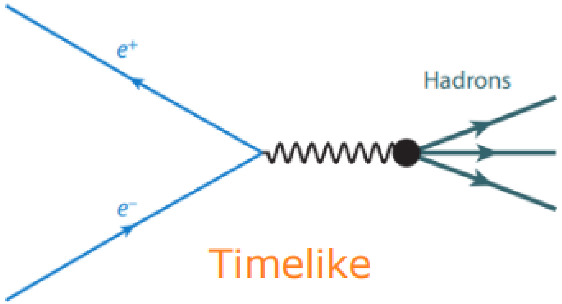
Lattice calculations



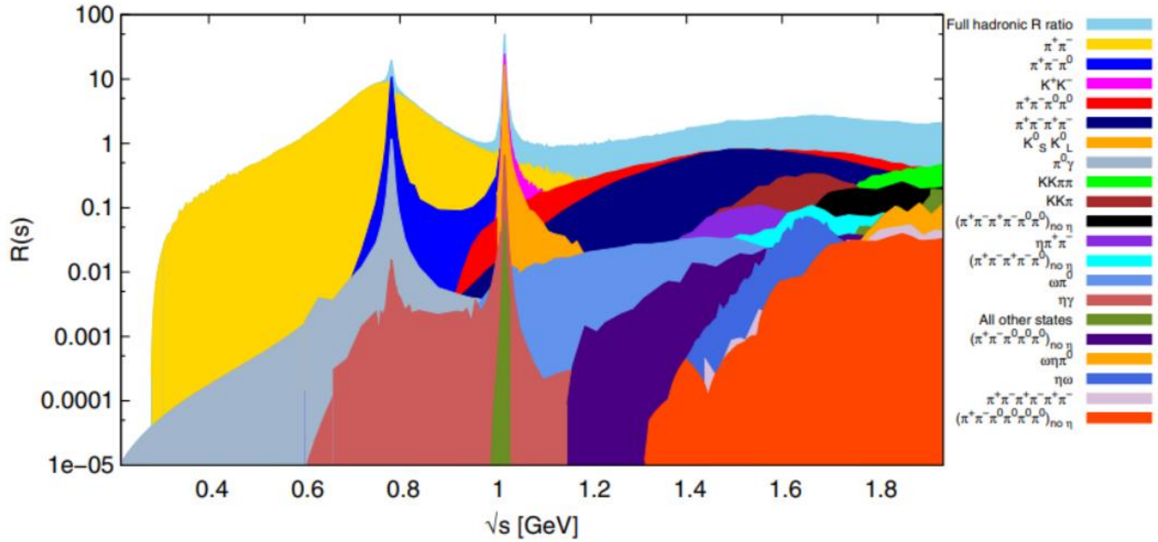
Spacelike vs timelike

See poster by Giorgia Cacciola (Tuesday)

Dispersive approach: relate a_μ to hadronic cross section data

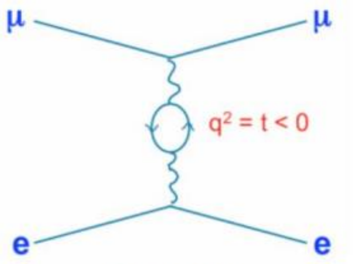


Timelike

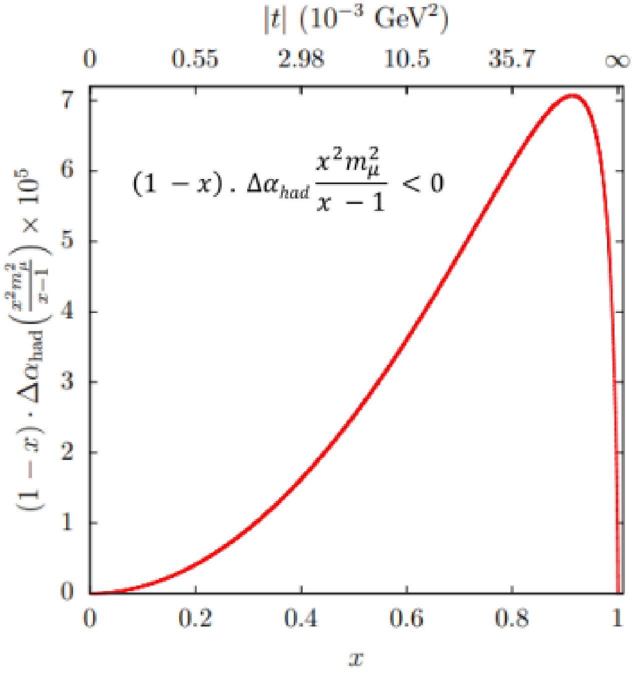


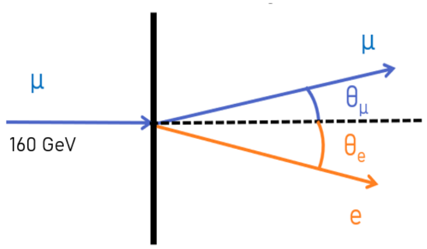
- Combine data from all hadronic channels
- Data from different experiments (KLOE, BaBAR, CMD3, …)
- Resonances → difficult to integrate

MUonE: directly measure a_μ^{HLO} from shape of μe → μe cross-section



Spacelike





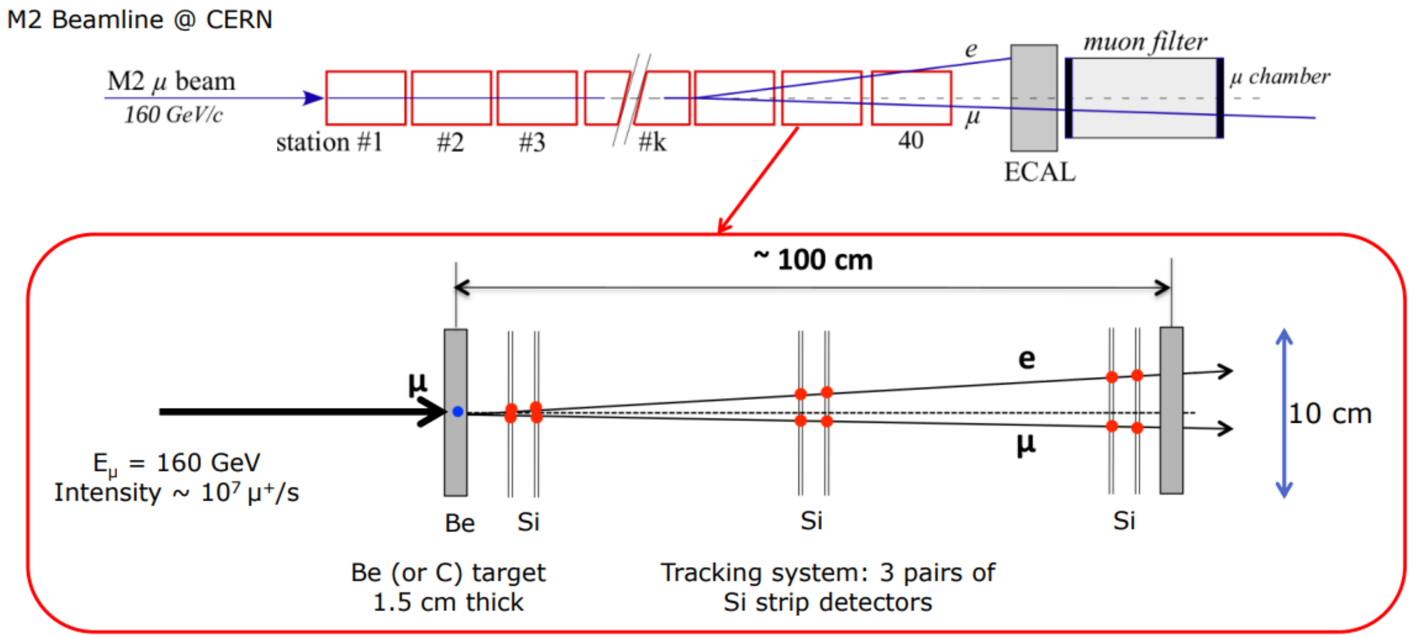
Measure muon and electron scattering angles

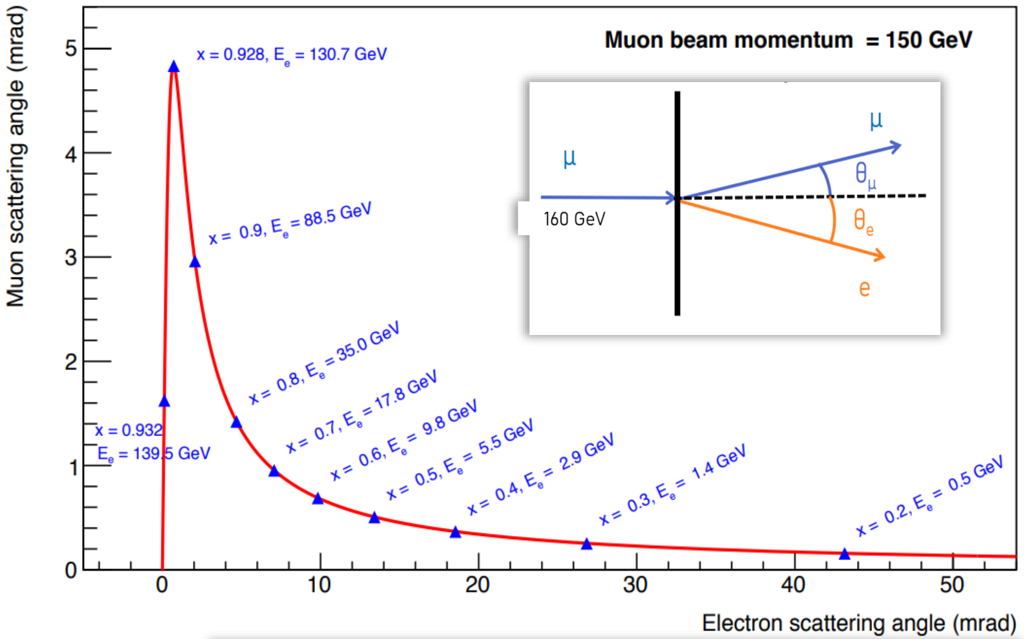
- Smooth integral (no resonances)
- One measurement for whole term

MUonE experiment design

See parallel talk by Riccardo Pilato (Wednesday Session F)

High-precision tracking detectors required to measure small scattering angles





Extract a_μ directly from correlation between outgoing angles for elastic events

Detector design requirements

- Alignment: Relative position within a station must be stable at 10 μm
- Material effects: control multiple scattering at 1% level → minimise material
- Uniform efficiency over full energy range, as close to 100% as possible

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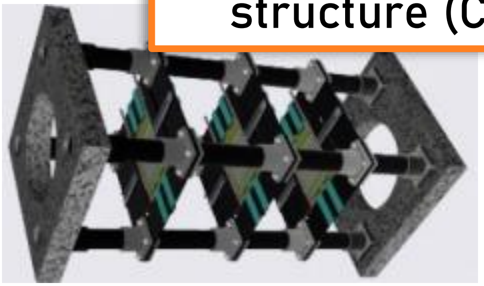
MUonE status and UK contribution

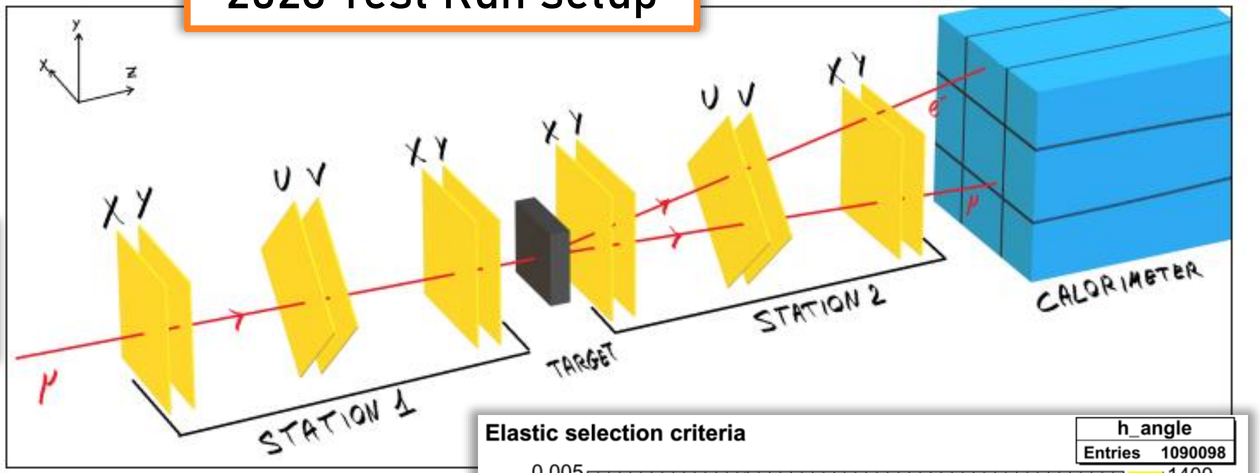
See poster by Clement Devanne (Monday)

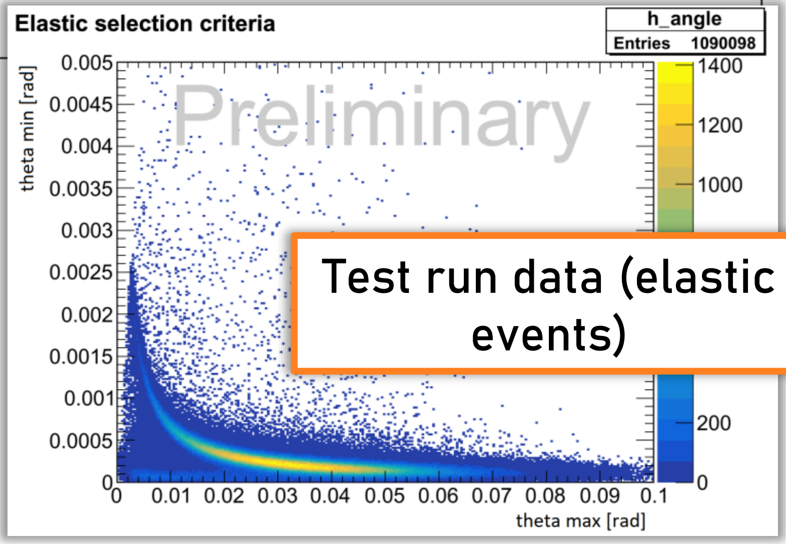
Tracking planes (CMS 2S modules)

Low CTE support structure (CF)



2023 Test Run setup





Test run data (elastic events)

- UK leading detector development (based on CMS 2S)
- Leading involvement in the Physics analysis
- Major theory involvement → state-of-the-art MC generators
- 2-module Test Run in 2023 → analysis underway
- Technical proposal to SPSC in 2024
- Aim for first physics run in 2025 with a reduced setup
- Full data-taking (40 stations) planned for 2029 after LS3 → 0.3% uncertainty

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Muon EDM Experiments

Muon EDM current limits

- Charged particles might have an intrinsic electric dipole moment (EDM) analogous to magnetic dipole moment (MDM) → heavily suppressed in SM

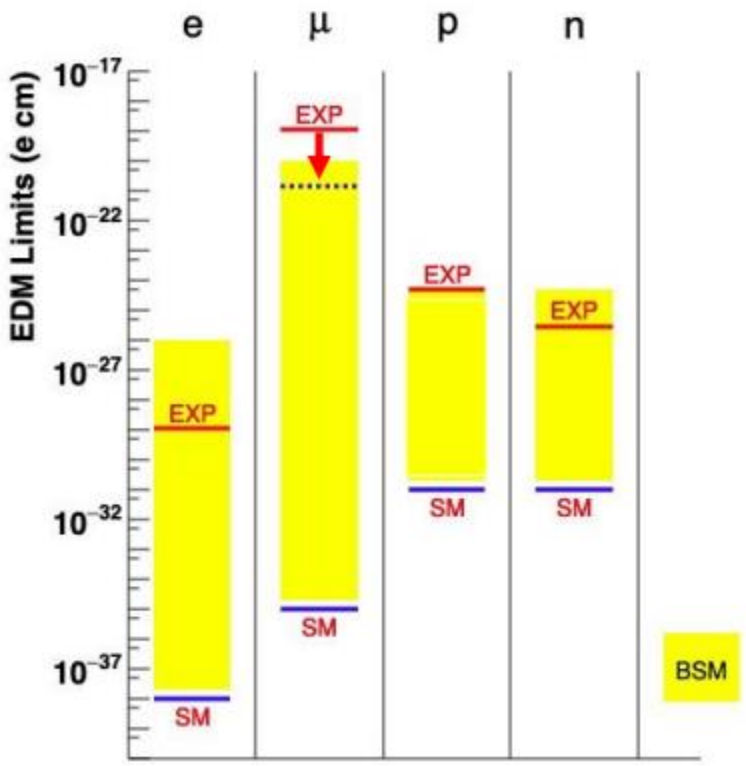
$$H = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

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

MDM

$$\vec{d} = \eta \frac{Qe}{2mc} \vec{S}$$

EDM



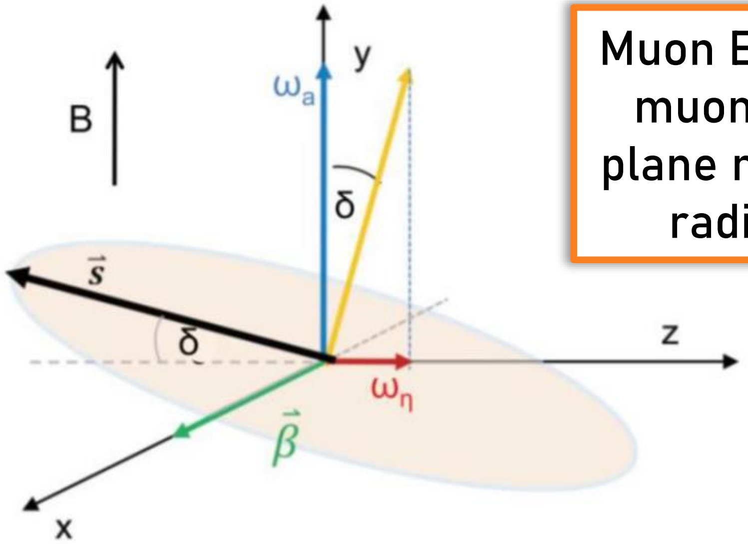
- SM d_μ out of experimental reach (10^{-34} e.cm)
- $\vec{d} \cdot \vec{E}$ is CP-odd → source of CP violation in leptons
- Current best limit set by BNL g-2 experiment: 1.9 x10^{-19} e.cm

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

Muon EDM in the g-2 experiment

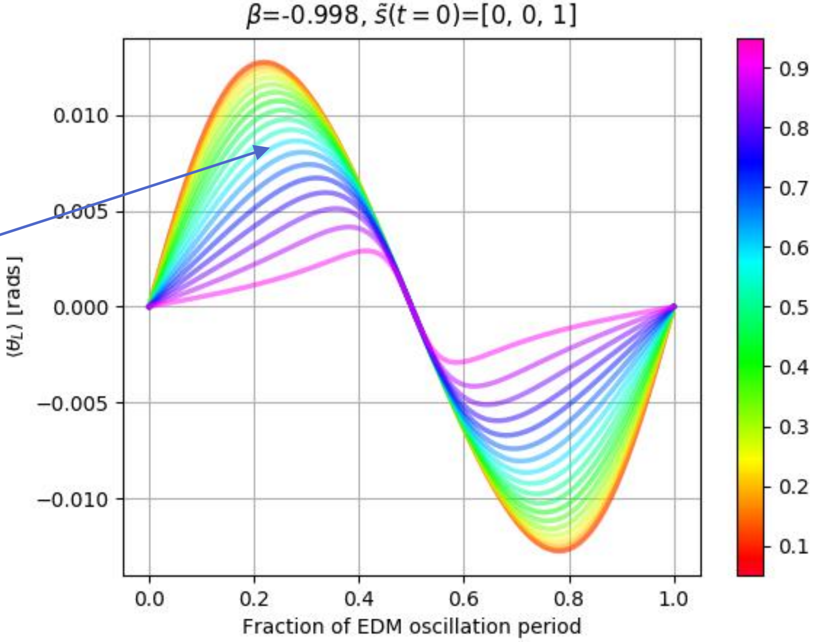
See parallel talk by Lucy Bailey (Wednesday Session F)
See poster by Katie Ferraby (Tuesday)

- UK leading analysis roles on muon EDM search
- Tracking detectors (UK-built) → crucial for analysis of vertical angle signal
- Improvements in tracking algorithms led by UK teams
- Run-1 sensitivity: ~BNL limit
- Run-2/3 (3x statistics): d_μ ~6 x 10^{-20} e.cm
- Target sensitivity (Runs 1-6): d_μ ~1 x 10^{-20} e.cm



Muon EDM would tilt muon precession plane radially (like a radial B-field)

Medium-energy e+ have highest sensitivity to d_μ



Signal: up-down oscillation in trajectories of emitted decay e^+

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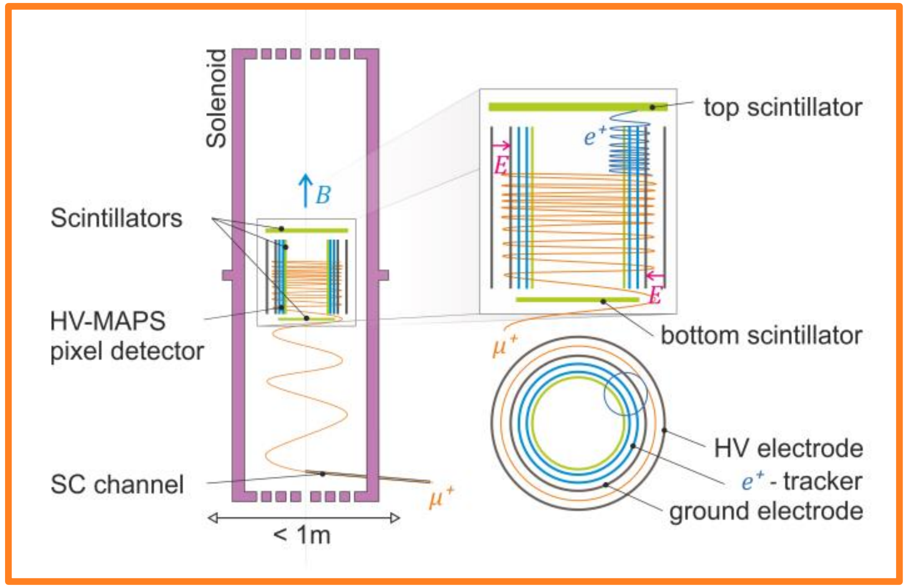
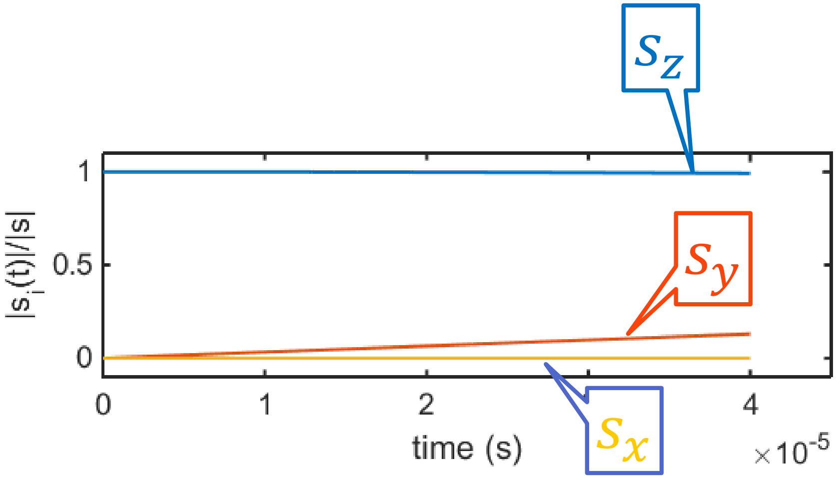
muEDM at PSI

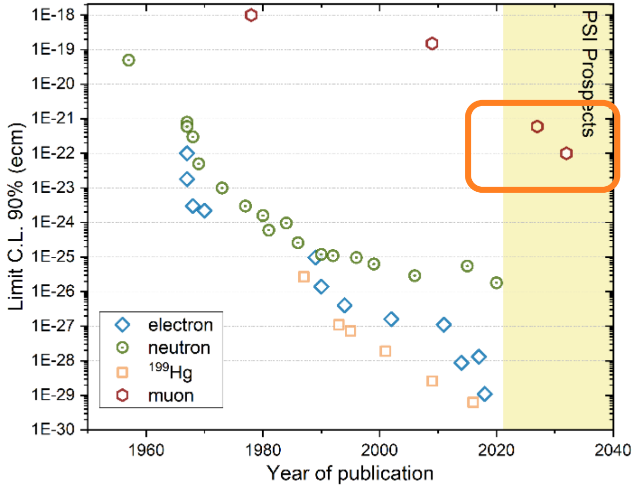
- New experiment using novel frozen spin technique: d_μ the only out-of-plane precession signal

- Stage 1
  - p_μ = 28 MeV/c ; B = 3T ; E = 0.3 MV/m
  - Demonstration of technique
  - Sensitivity: $d_\mu \sim 3 \times 10^{-21}$ e.cm
  - Completed prior to 2027 HIMB upgrade
- Stage 2
  - p_μ = 125 MeV/c; B = 3T; E=2.0 MV/m
  - Sensitivity: $d_\mu \sim 6 \times 10^{-23}$ e.cm
  - HV-MAPS positron tracker
  - ~early 2030s



UK contributions: DAQ, tracking, physics analysis and correction coils





Charged Lepton Flavour Violation

Charged Lepton Flavour Violation

- LFV observed in neutral sector → neutrino oscillations
- Mixing between charged leptons never observed
- CLFV suppressed in SM → Branching Ratio $\mathcal{O}10^{-54}$

$$BR\colon \mathcal{O}\left(\frac{m_\nu}{m_W}\right)^4$$

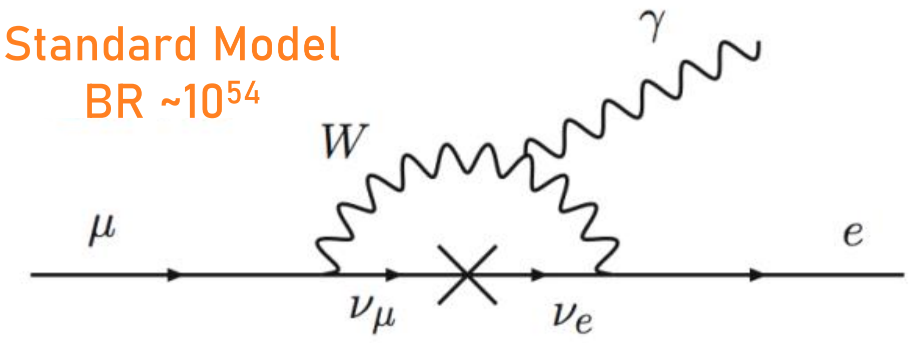
3 possible CLFV channels

$\mu \to e\gamma$	(MEG, MEG-II)
$\mu \to eee$	(mu3e)
$\mu N \to eN$	(COMET, mu2e)

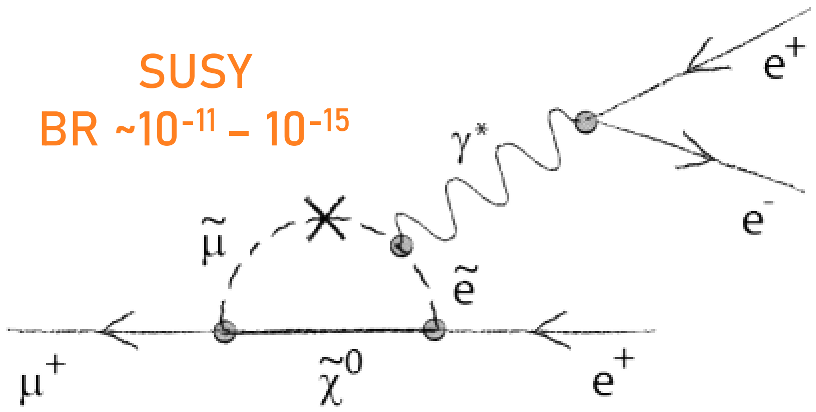
Observation of CLFV would be unambiguous sign of New Physics

- Ideal to search for rare CLFV decays in muon sector
  - clean decay modes (no SM background)
  - long lifetime
  - can be produced at high intensity

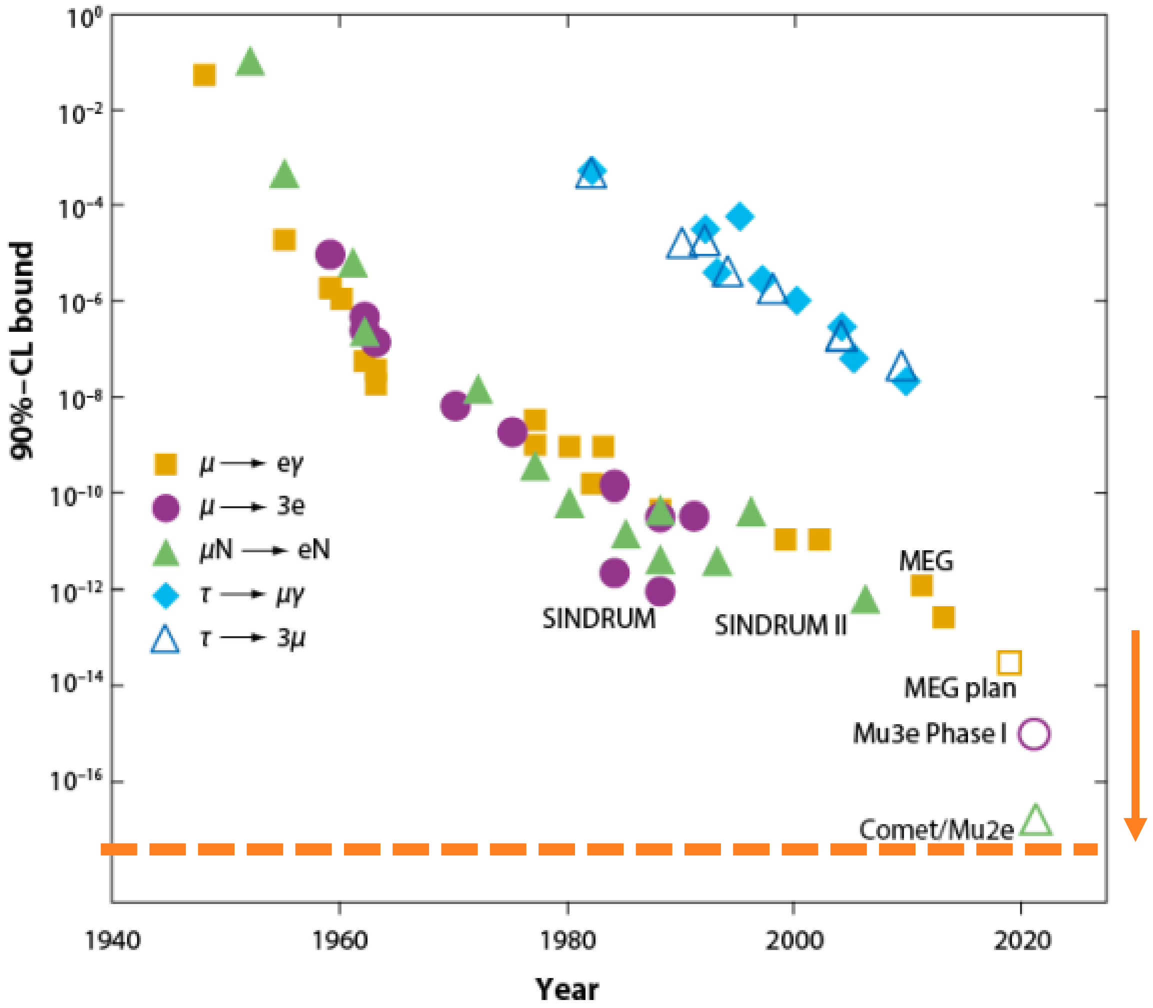
Standard Model
BR ~10^{54}



SUSY
BR ~10^{-11} – 10^{-15}



Current and projected limits on CLFV in muons

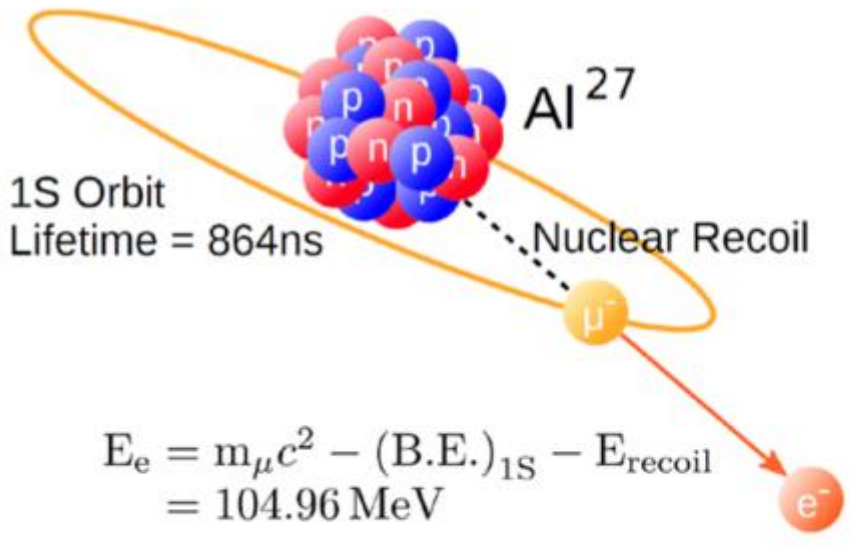


	Best limits	Projected sensitivities (90% CL)
$\mu \rightarrow e\gamma$	< 3.1×10^{-13} MEG + MEG II (PSI)	4×10^{-14} MEG II (PSI)
$\mu \rightarrow eee$	< 1.0×10^{-12} SINDRUM (PSI)	4×10^{-15} mu3e I (PSI) 1×10^{-16} mu3e II (PSI)
$\mu N \rightarrow eN$	< 7.0×10^{-13} SINDRUM II (PSI) $\mu Au \rightarrow eAu$	6×10^{-17} mu2e (FNAL) 7×10^{-15} COMET I (JPARC) 6×10^{-17} COMET II (JPARC)

μ → e sensitivity improved by four orders of magnitude in the next decade

μN → eN

COMET and mu2e search for μ → e conversion in the field of a nucleus



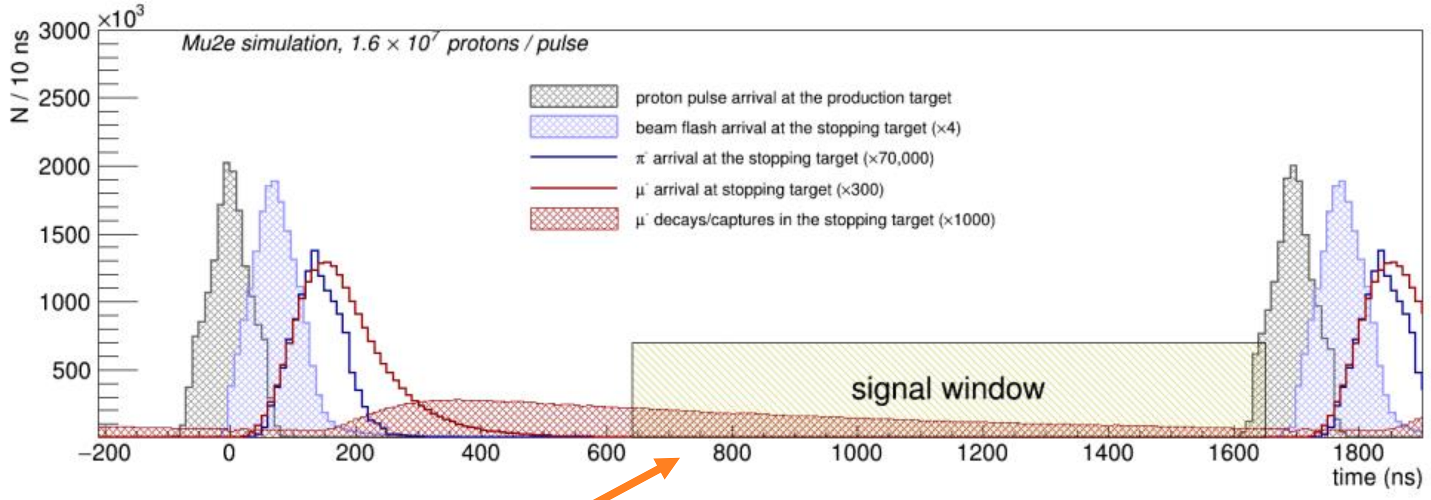
$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\,\text{MeV}$$

muon to electron conversion

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

muon capture on the nucleus

- Signal: a mono-energetic electron
- Requirements:
  - High intensity (stop 10^{18}) muons
  - << 1 background event



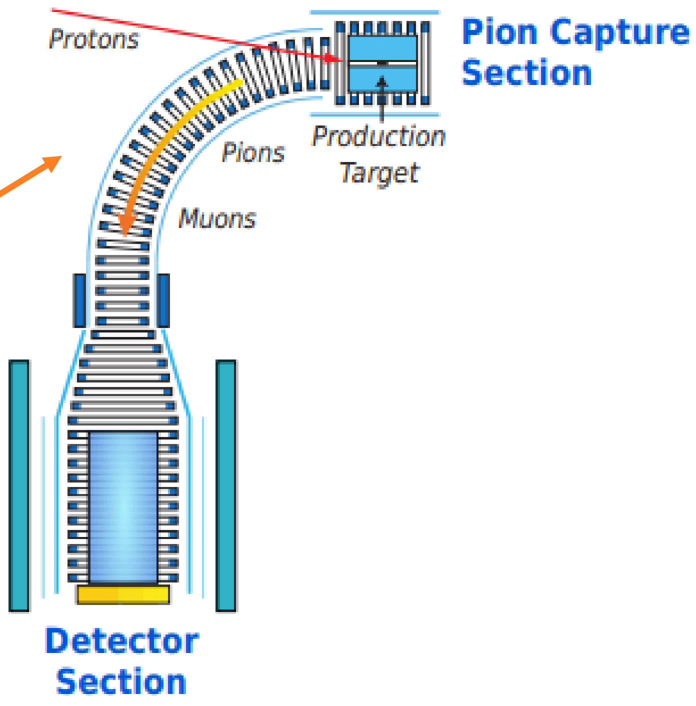
Long lifetime + pulsed beam → reduce prompt backgrounds

COMET Experiment at JPARC

$\mu N \rightarrow eN$

Phase-I (target 2026)

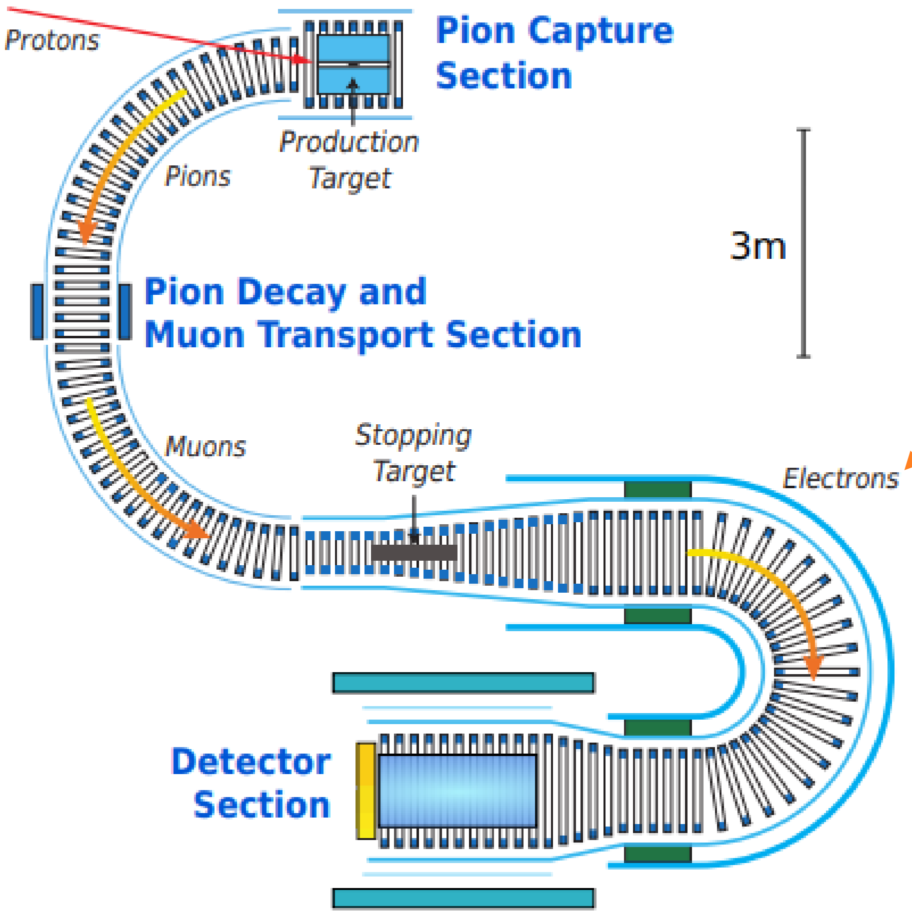
First bend for clean muon beam



- Sensitivity: $R_{\mu e} < 10^{-14}$
- 3.2 kW beam, 8 GeV
- TDR: DOI:10.1093/ptep/ptz125

Phase-II

Second bend to select electrons

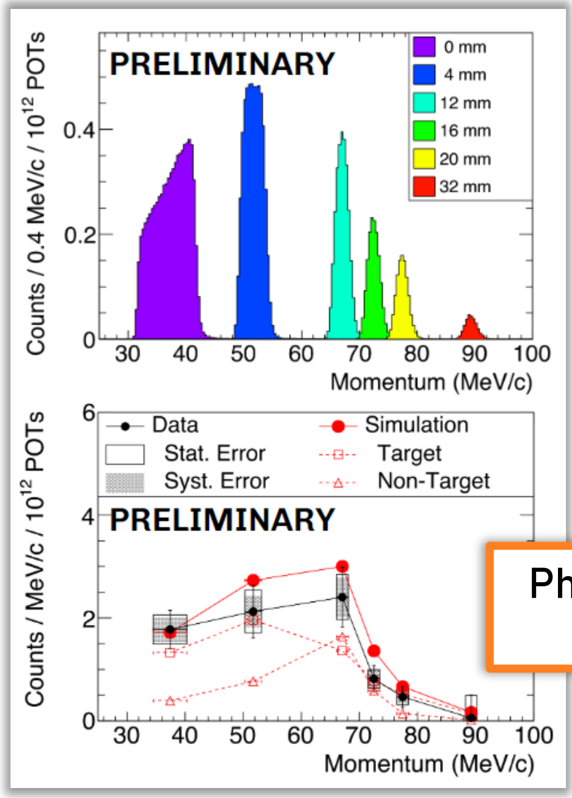


- Sensitivity: $R_{\mu e} < 10^{-17}$
- 57 kW beam, 8 GeV

COMET News: Phase-α data

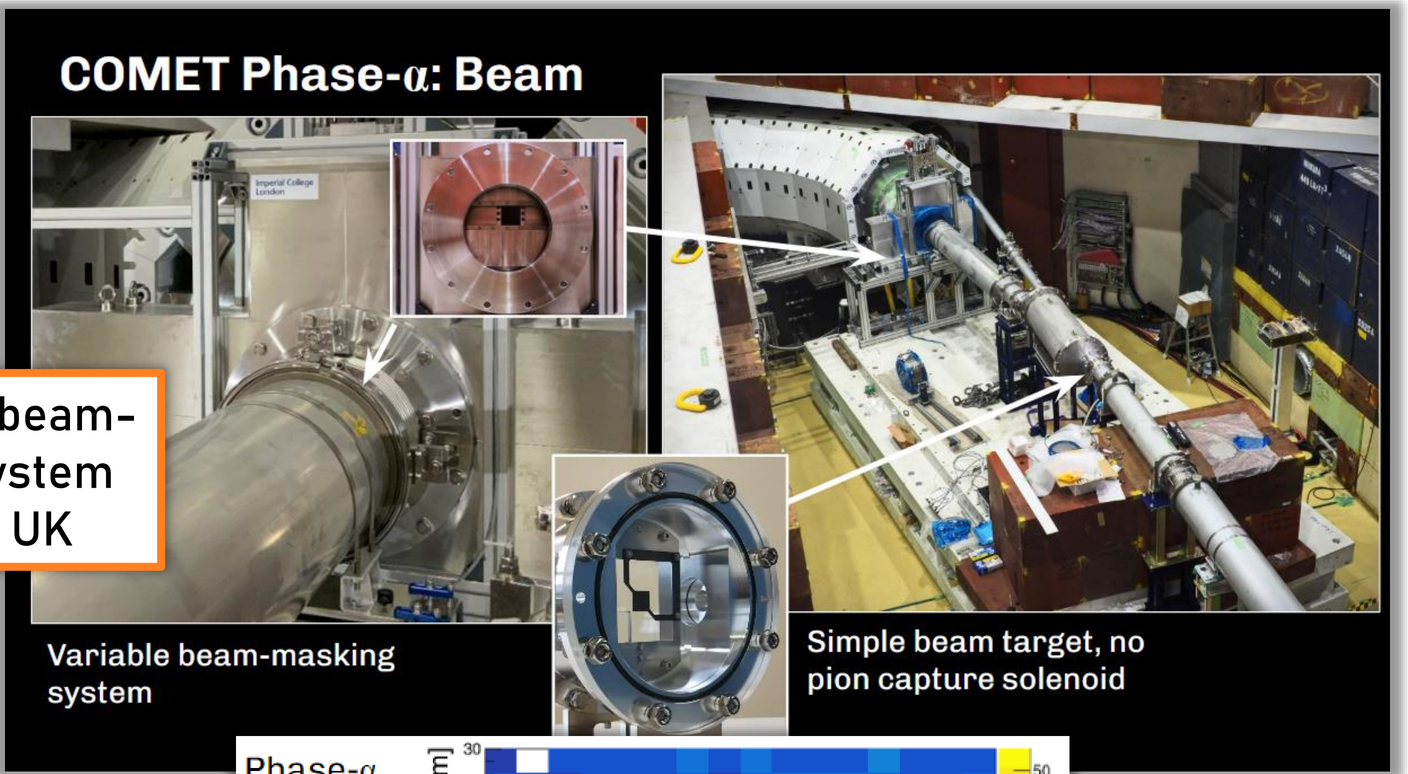
μN → eN

- Data-taking phase in early 2023
  - First beam in the new proton beamline
  - UK leading involvement in planning, operations and analysis
  - Analysis underway → successful "dress rehearsal" ahead of Phase-I

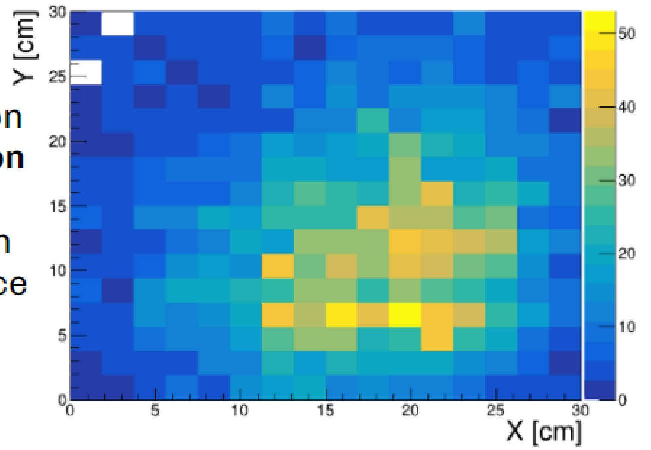


Variable beam-mask system led by UK

Phase-α data analysis



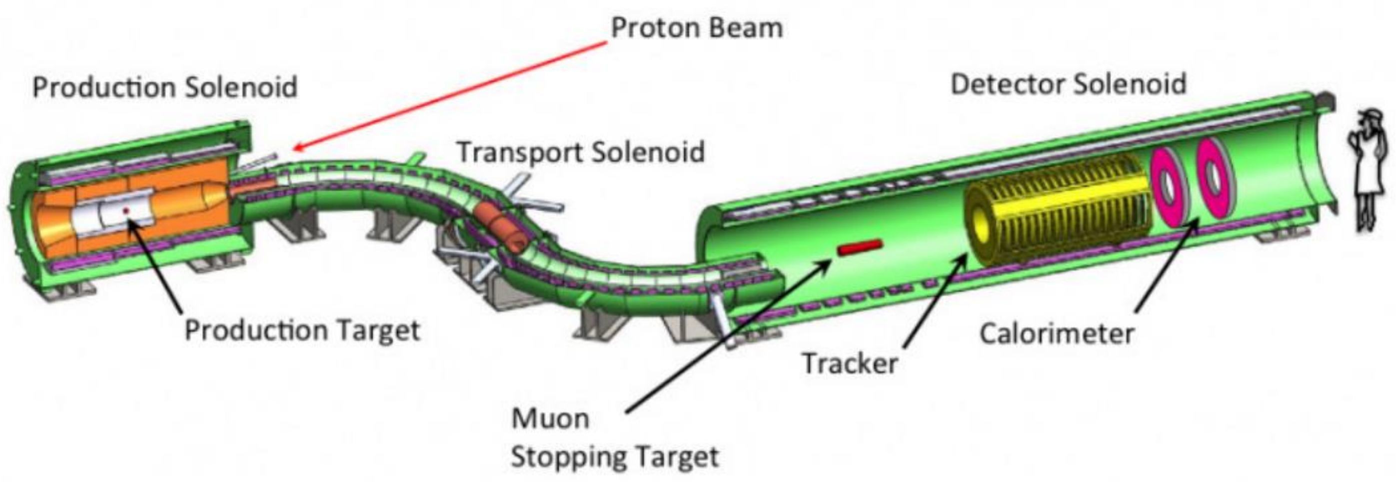
Phase-α position distribution in the **Muon Beam Monitor**, in coincidence with the **Range Counter**



Slides from Yoshi Uchida

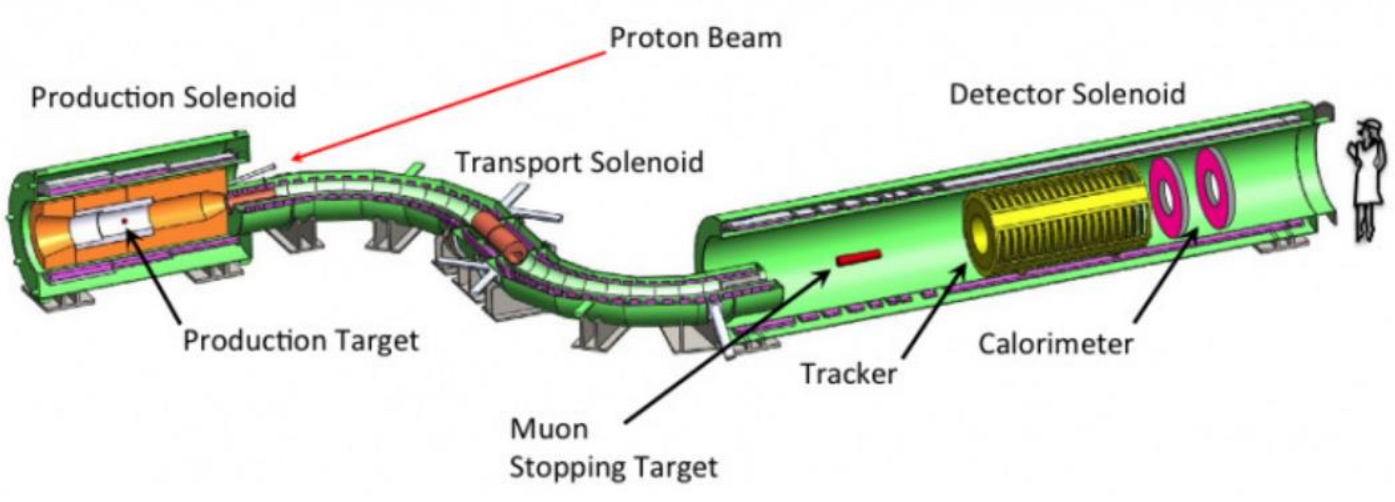
Imperial College London

The mu2e experiment at Fermilab $\mu N \rightarrow eN$



The mu2e experiment at Fermilab

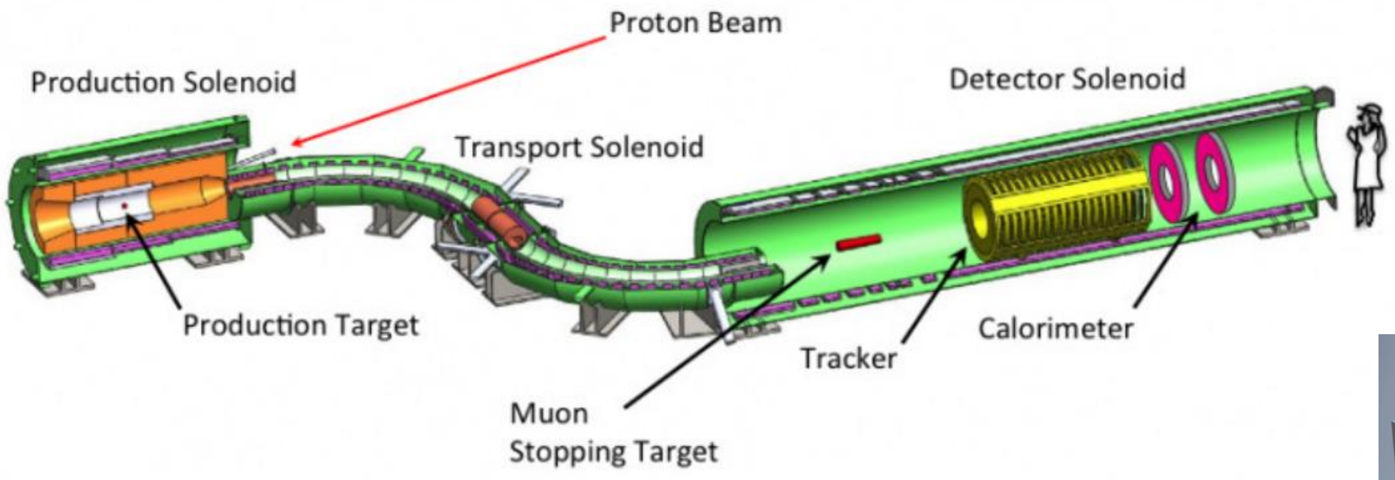
$\mu N \rightarrow eN$



Transport Solenoid completed

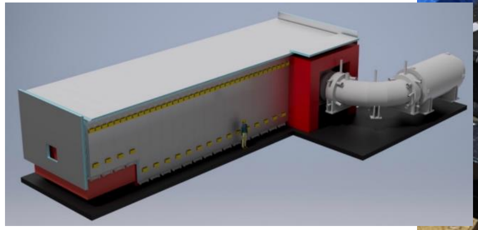
The mu2e experiment at Fermilab

μN → eN



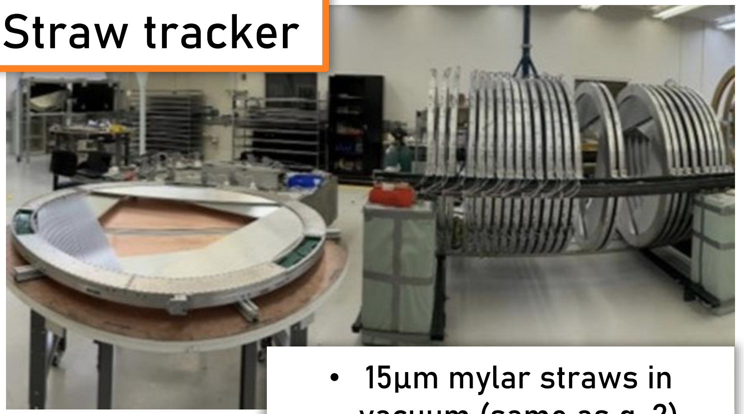
Cosmic Ray Veto

- ~1/day conversion-like electron from cosmic μ
- Require 99.99% efficiency



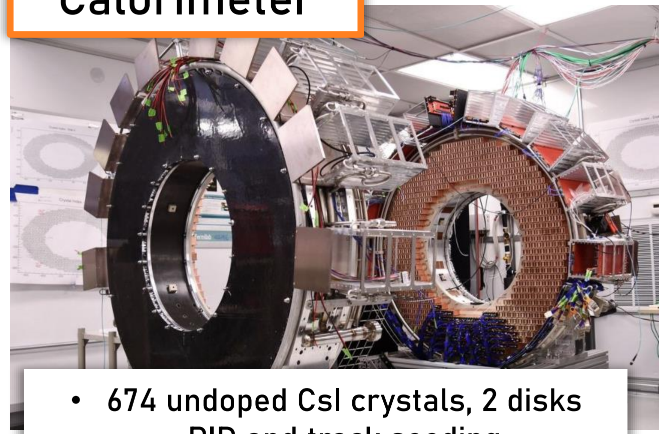
Transport Solenoid completed

Straw tracker



- 15μm mylar straws in vacuum (same as g-2)
- Better than 200 keV momentum resolution

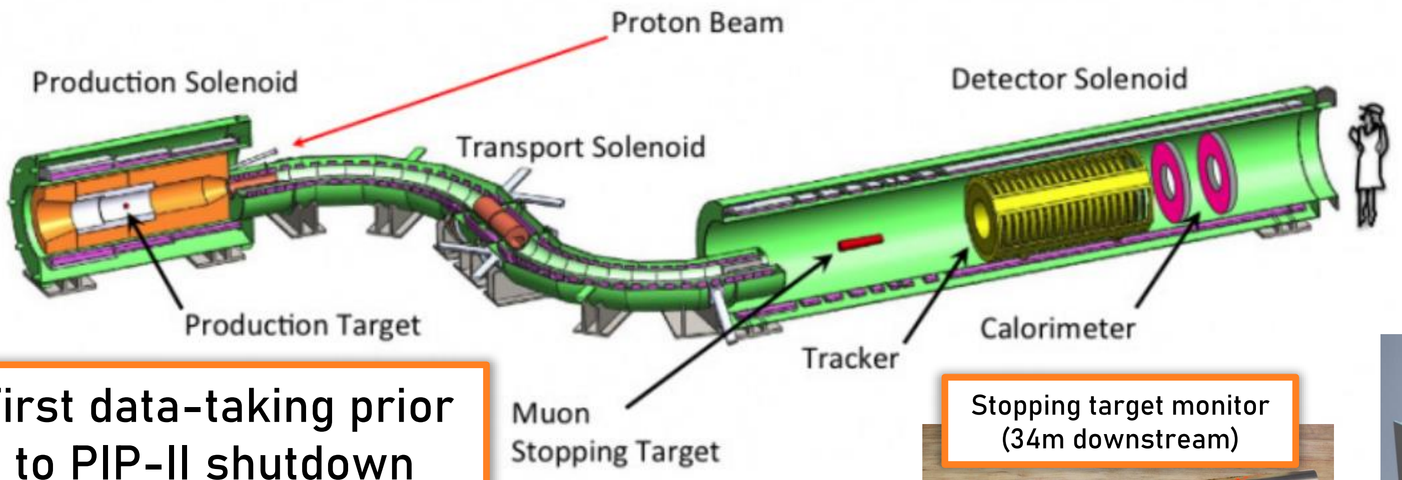
Calorimeter



- 674 undoped CsI crystals, 2 disks
- PID and track seeding
- 0.5 ns time, 10% energy, 1cm position

The mu2e experiment at Fermilab

μN → eN



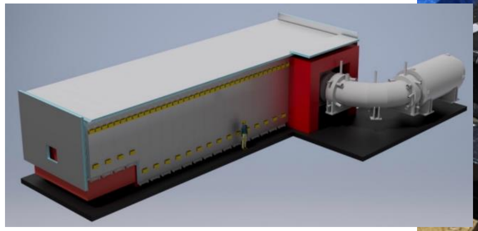
First data-taking prior to PIP-II shutdown

Transport Solenoid completed

Stopping target monitor (34m downstream)

Cosmic Ray Veto

- ~1/day conversion-like electron from cosmic μ
- Require 99.99% efficiency



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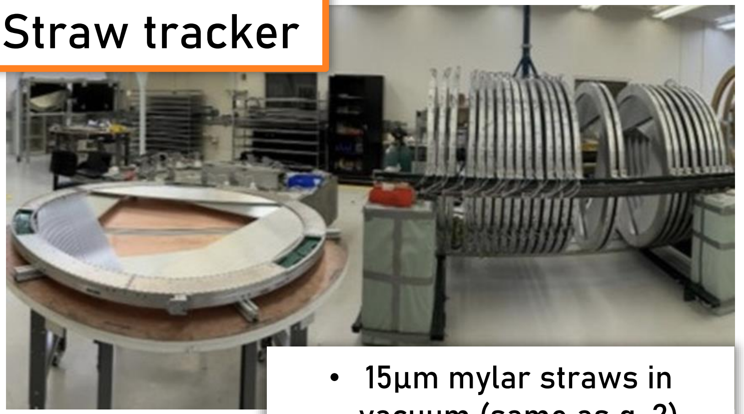

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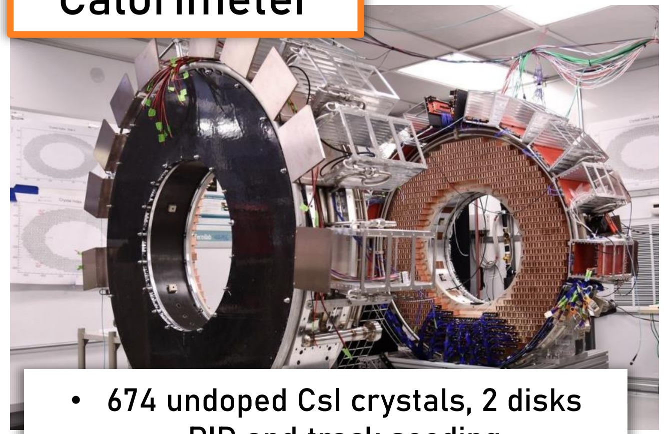
- Better than 200 keV momentum resolution

Calorimeter

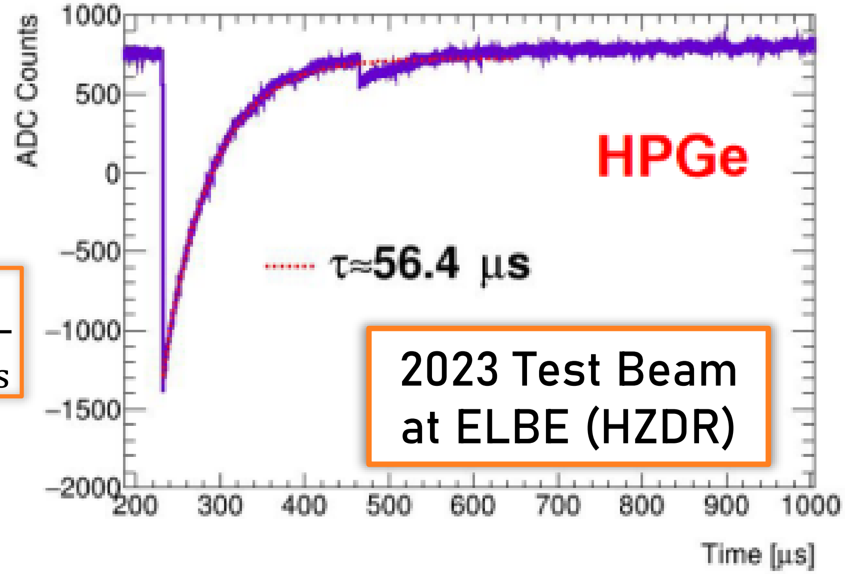


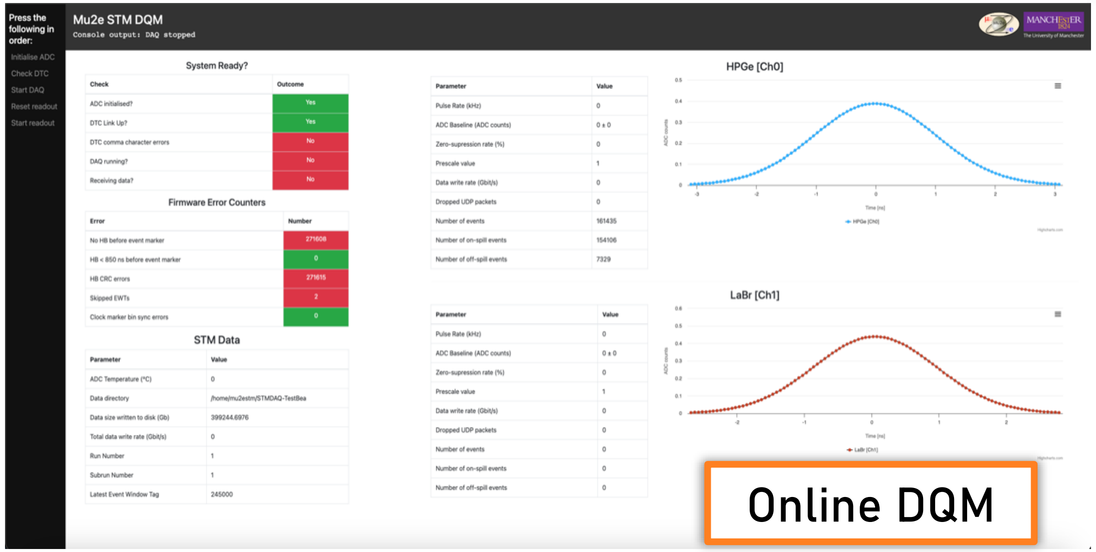
- 674 undoped CsI crystals, 2 disks
- PID and track seeding
- 0.5 ns time, 10% energy, 1cm position

Stopping target monitor (STM)

- STM determines the overall rate for normalisation ($N_{captures}$)
- Count characteristic γ- and x-rays
- UK leads the Stopping Target Monitor (STM) detector group
- Org chart roles in operations and commissioning of STM
- STM at Fermilab → ready for integration with other detectors and main DAQ
- UK leading role in DAQ integration for full experiment
  - Successful DAQ "dry run" completed early 2024

$$R_{\mu e} = \frac{N_{signal}}{N_{captures}}$$





Photos from Alex Keshavarzi

MANCHESTER 1824 The University of Manchester

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The mu3e experiment at PSI

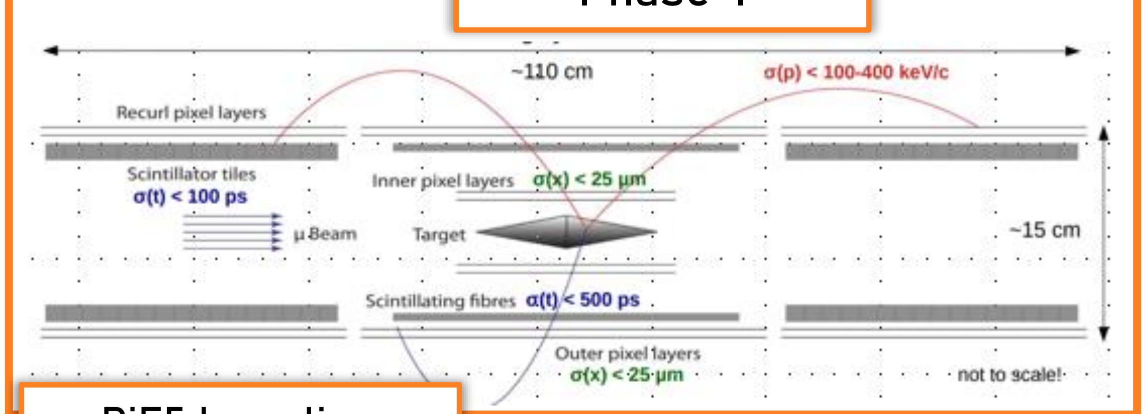
See poster by Charlie Kinsman (Tuesday)

μ → eee

- Current limit from SINDRUM (1986): BR < 10^{-12} (90% CL)
- DC proton beam produces pions on target
- Muons from pion decay → MEG and mu3e
- Muons stopped on thin mylar target
- Decay electrons tracked in ultra low-mass tracker
- Excellent time and vertex resolution required

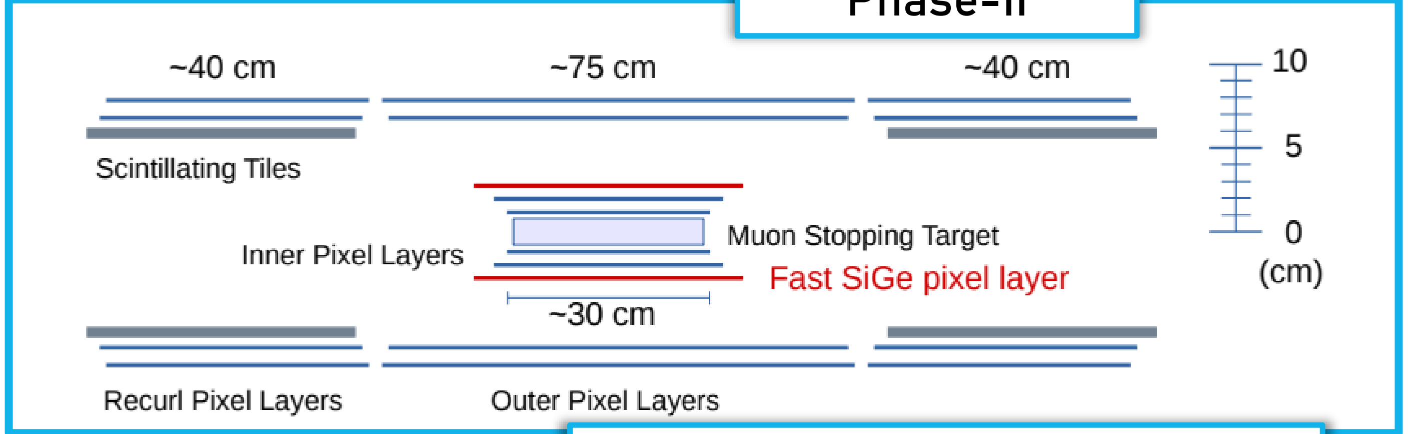
Sensitivity target
- Phase I: 10^8 μ/s, BR (μ→eee) < 2 x10^{-15}
- Phase II: BR (μ→eee) < 10^{-16}

Phase-I



- PiE5 beamline
- 10^8 μ/s

Phase-II

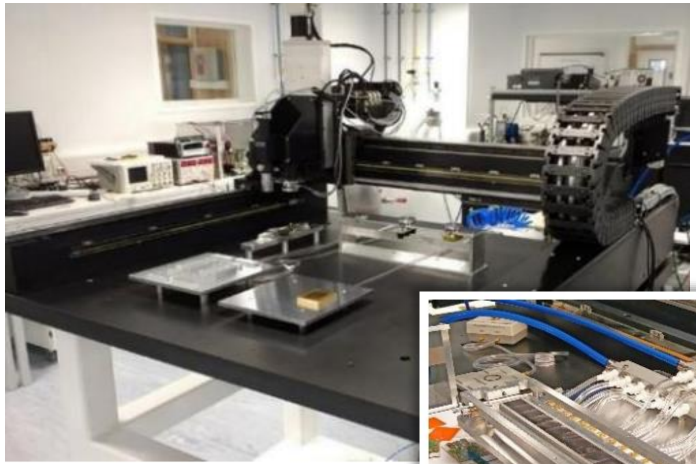


- HIMB: ~20x higher stopping rate
- >10^9 μ/s

Phase II vs Phase I
- Longer stopping target (10 cm → 30 cm)
- Thinner, smaller vertex detector → improve pointing resolution
- Longer pixel detector modules
- Faster timing / greater bandwidth

Mu3e Status and Experiment Design

See poster by Charlie Kinsman (Tuesday)



18 Mupix sensors per ladder

Phase-I: 2Y of physics data-taking between 2025 & 2026

UK leading physics analysis and detector development

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University of BRISTOL

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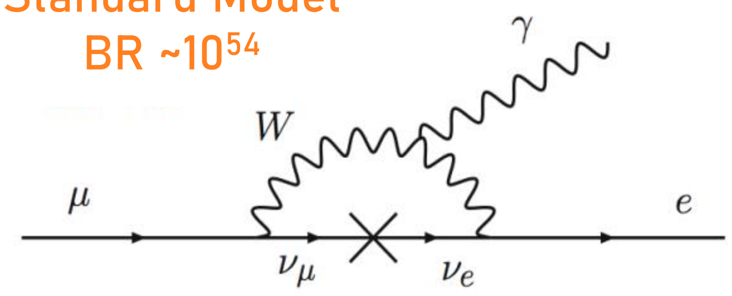
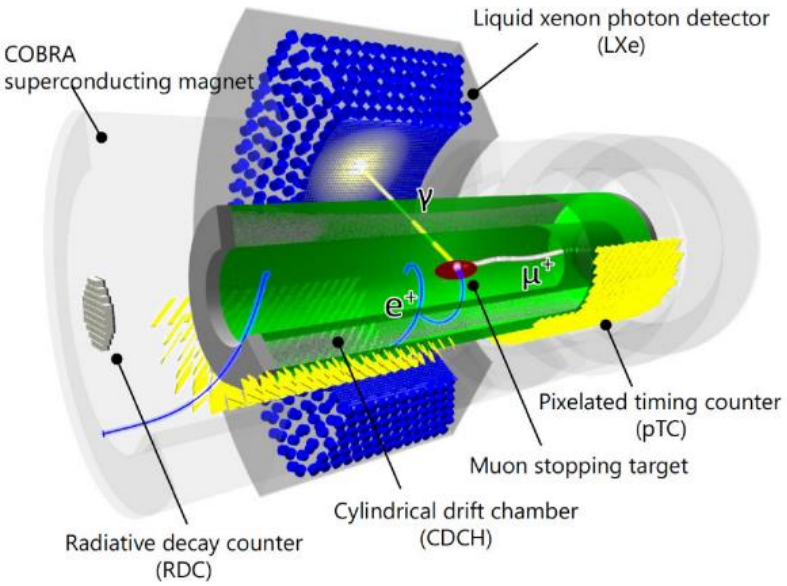
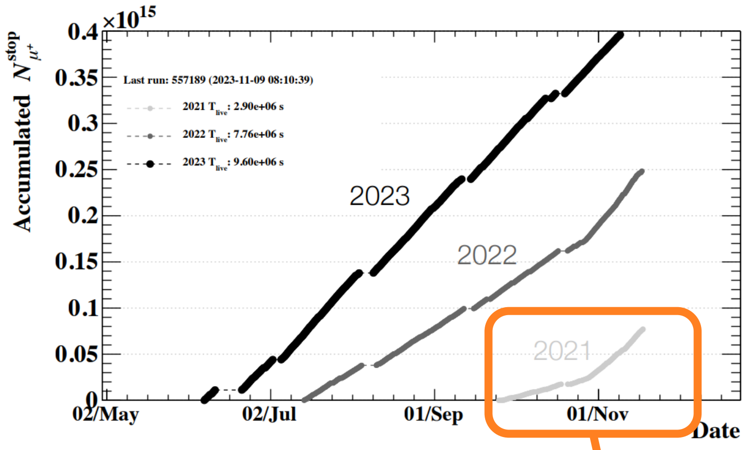
MEG-II at PSI: news and prospects

$\mu \rightarrow e\gamma$

Standard Model
BR ~10^{54}

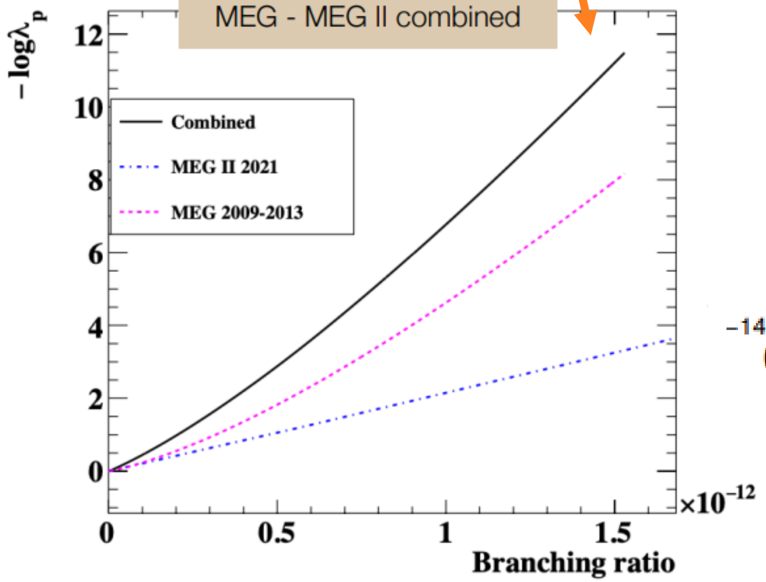


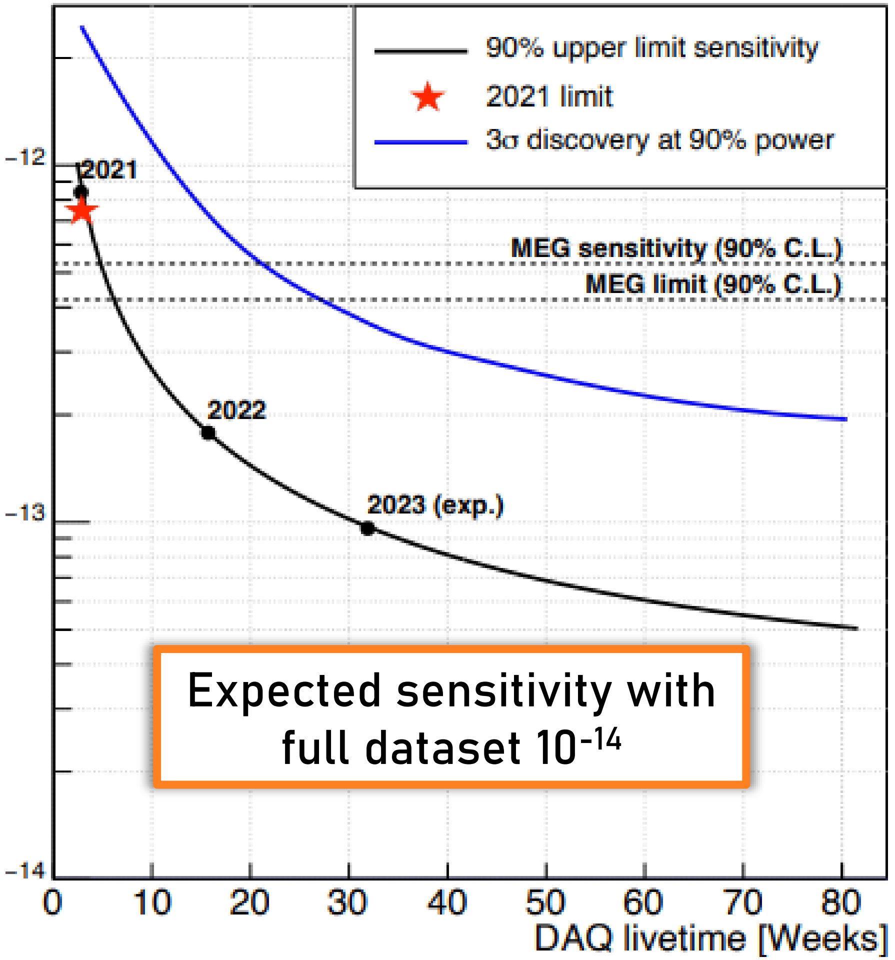




$BR_{sig} < 3.1 \times 10^{-13}$

MEG - MEG II combined





Expected sensitivity with full dataset 10^{-14}

EPJC **84**, 216 (2024)

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Summary

Summary

- FNAL g-2 experiment completed data-taking in Summer 2023
  - Published Run-2/3 result in 2023 with 0.2 ppm uncertainty
  - Analysis ongoing with full run-4/5/6 dataset → target final result in 2025
  - Muon EDM analysis underway → target sensitivity to d_μ with full statistics $d_\mu < 1 \times 10^{-20}$ e.cm
- MUonE experiment at CERN
  - directly measure a_μ^{HLO} to 0.3%
  - Major UK involvement for hardware and analysis
- Progress being made towards dedicated muEDM experiment at PSI
  - Full experiment in 2030, target sensitivity $d_\mu < 1 \times 10^{-22}$ e.cm
- CLFV experiments target 4 orders of magnitude improvement on current limits
  - Tight constraints on wide range of NP models

Many exciting results to come over the next 10 years

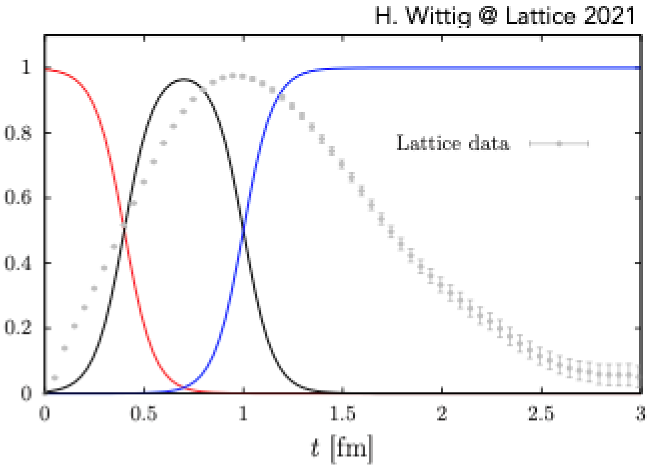
Thank you

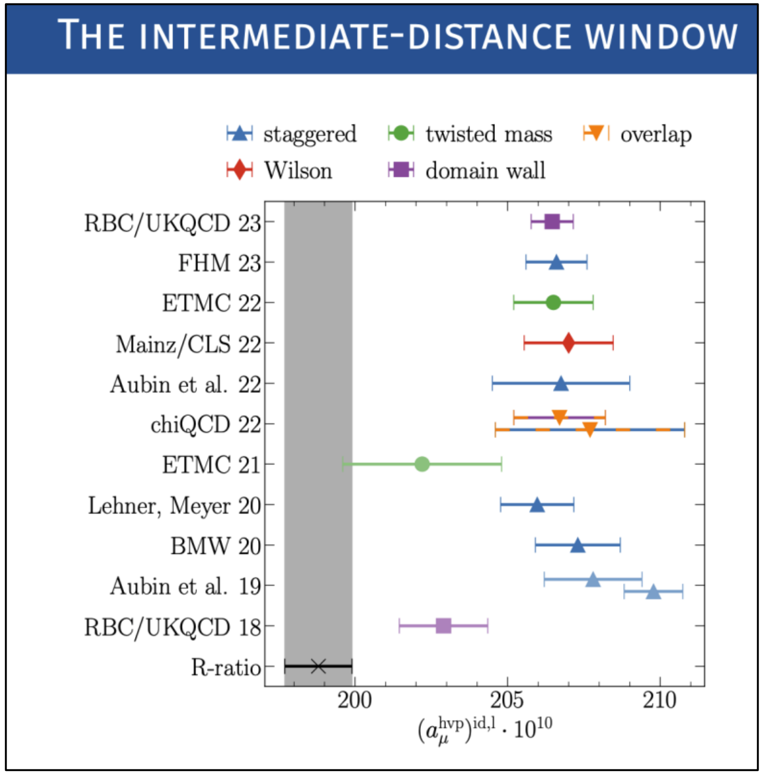
2nd Liverpool Workshop on Muon Precision Physics 2023 (MPP2023)

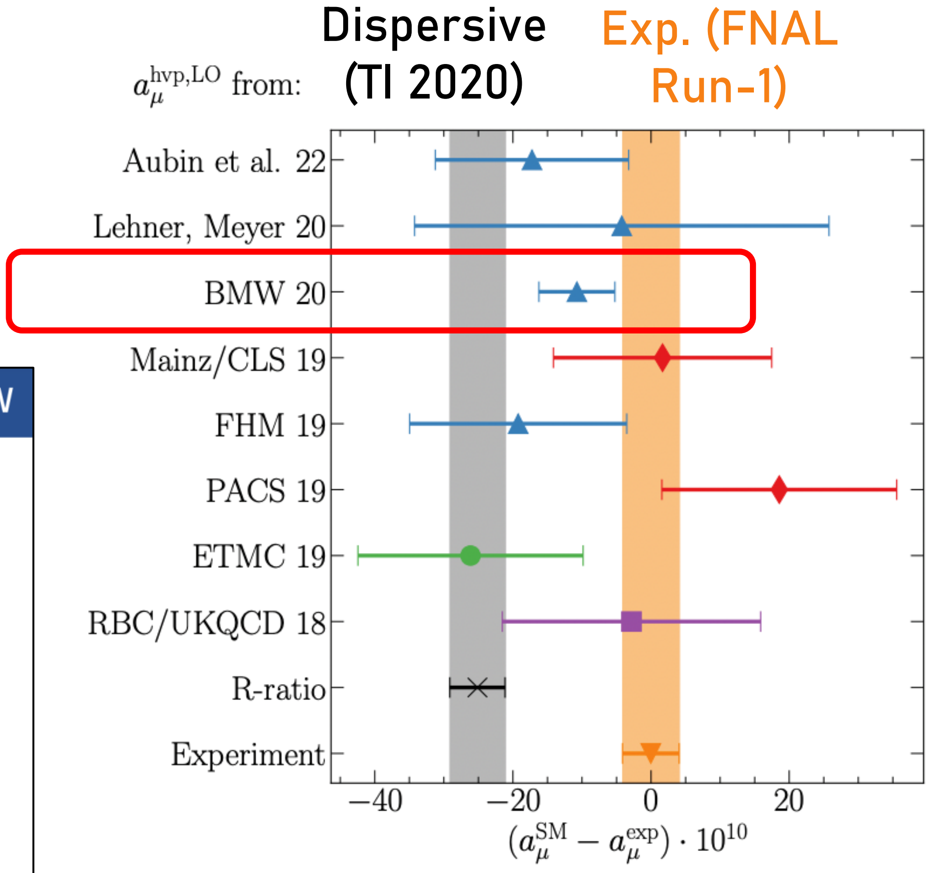
Extra Material

Lattice QCD

- Recent lattice QCD result also in tension with theory initiative value, agrees better with FNAL experiment
- Result being cross-checked in "intermediate window" by many groups
- Full calculation highly-anticipated







Data-driven determination of a_μ^{SM}

Dispersion relation

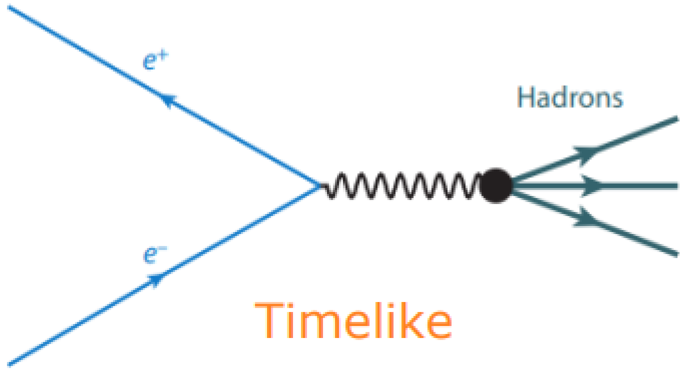
$$a_\mu^{\text{had,LO VP}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{ds}{s}R(s)K(s)$$

R-ratio

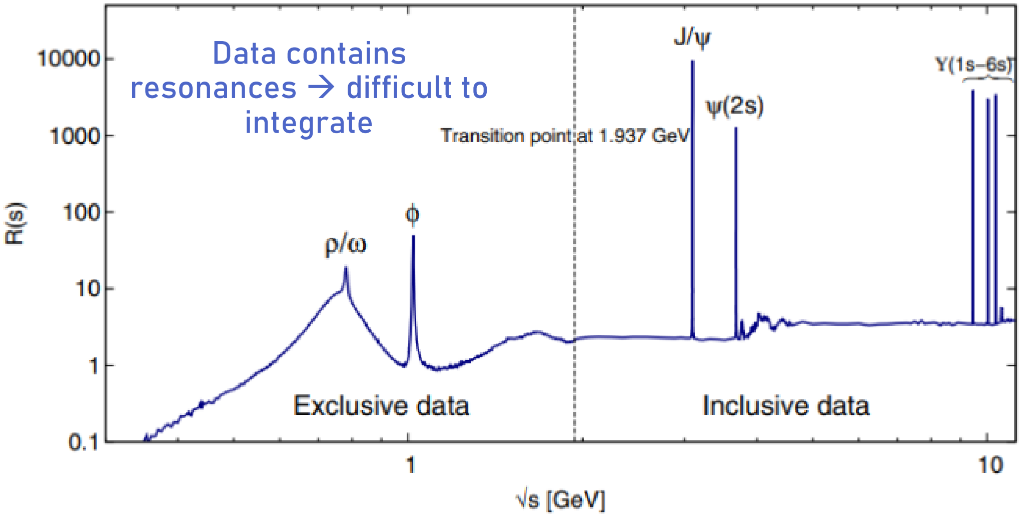
$$R(s) = \frac{\sigma^0_{\text{had},\gamma}(s)}{\sigma_{\text{pt}}(s)} \equiv \frac{\sigma^0_{\text{had},\gamma}(s)}{4\pi\alpha^2/(3s)}$$

Hadron production cross-section – measure at e^+e^- colliders

$$\sigma^0_{\text{had},\gamma}(s) \equiv \sigma^0\,(e^+e^- \to \gamma^* \to \text{hadrons} + \gamma)$$

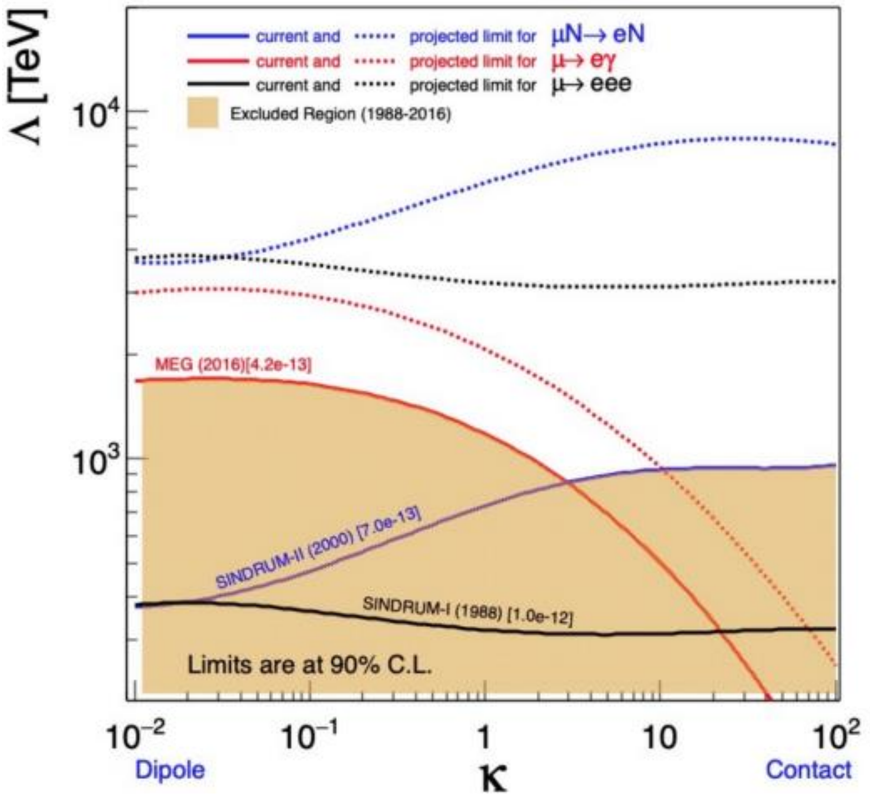


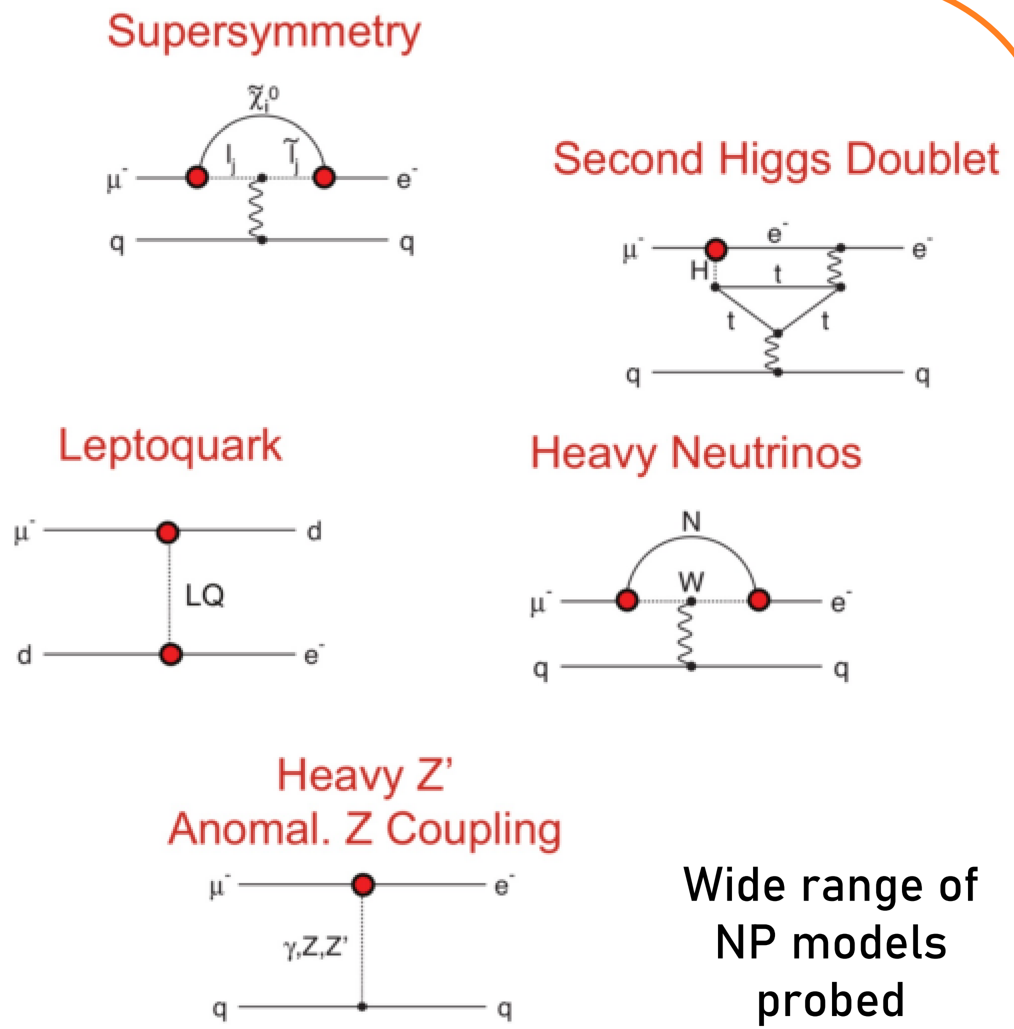
Timelike



From KNT PRD 97.114025

Probing NP with CLFV





Wide range of NP models probed

Mu3e at PSI

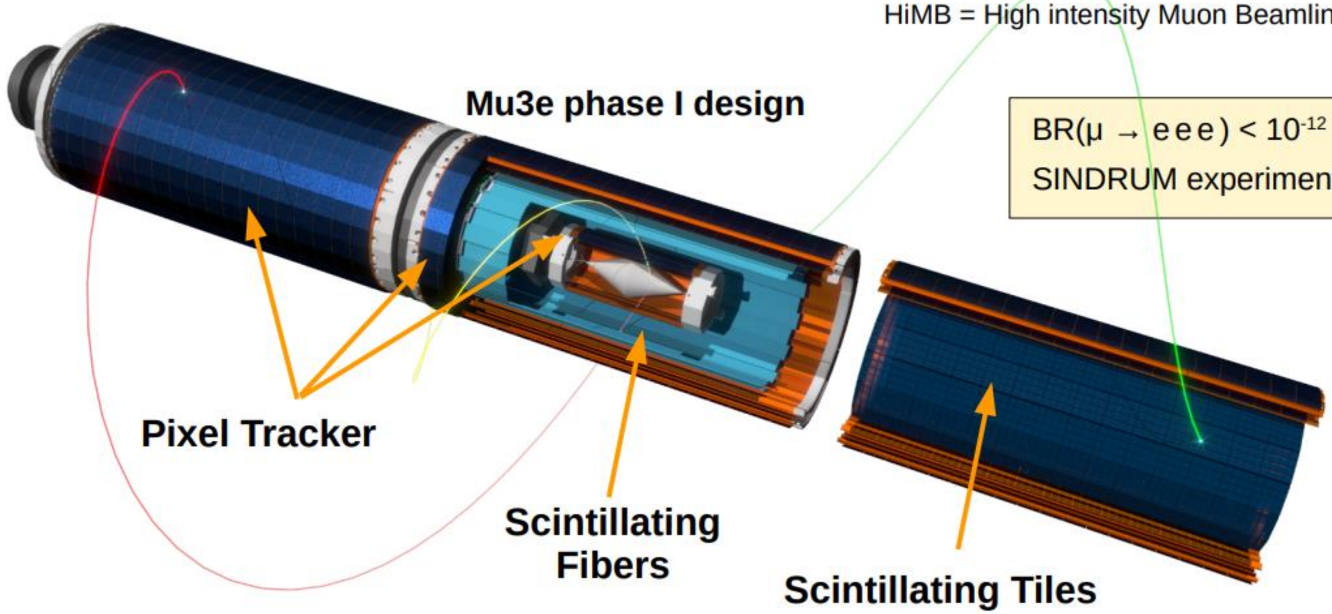
Mu3e Experiment

Aiming for single event sensitivity (SES) requires:

$BR(\mu \rightarrow eee) < 2 \cdot 10^{-15}$	(phase I)	→ 10^{8} muons/s	(PiE5 beamline)
$BR(\mu \rightarrow eee) < 10^{-16}$	(phase II)	→ $>10^{9}$ muons/s	(HIMB=High Intensity Beamline)

HiMB = High intensity Muon Beamline (under study)

$BR(\mu \rightarrow eee) < 10^{-12}$ (90% CL)
SINDRUM experiment (1986)



A. Schöning (Heidelberg) 5 10. N

United Kingdom

- Bristol
- Liverpool
- Oxford
- UC London

Summary & Schedule

- Pre-production of Mu3e sub-detectors has started for most systems
- In 2024, we expected the inner vertex detector and the timing system to be completed or almost completed
- For end of 2024, we are studying the possibility of a first physics run at low rate without outer pixel layers at high magnetic field
- Optimistically, the Mu3e phase I detector will be completed in 2025 and ready for data taking
- Design for Mu3e phase II at HIMB is starting now