# Muon Experiments

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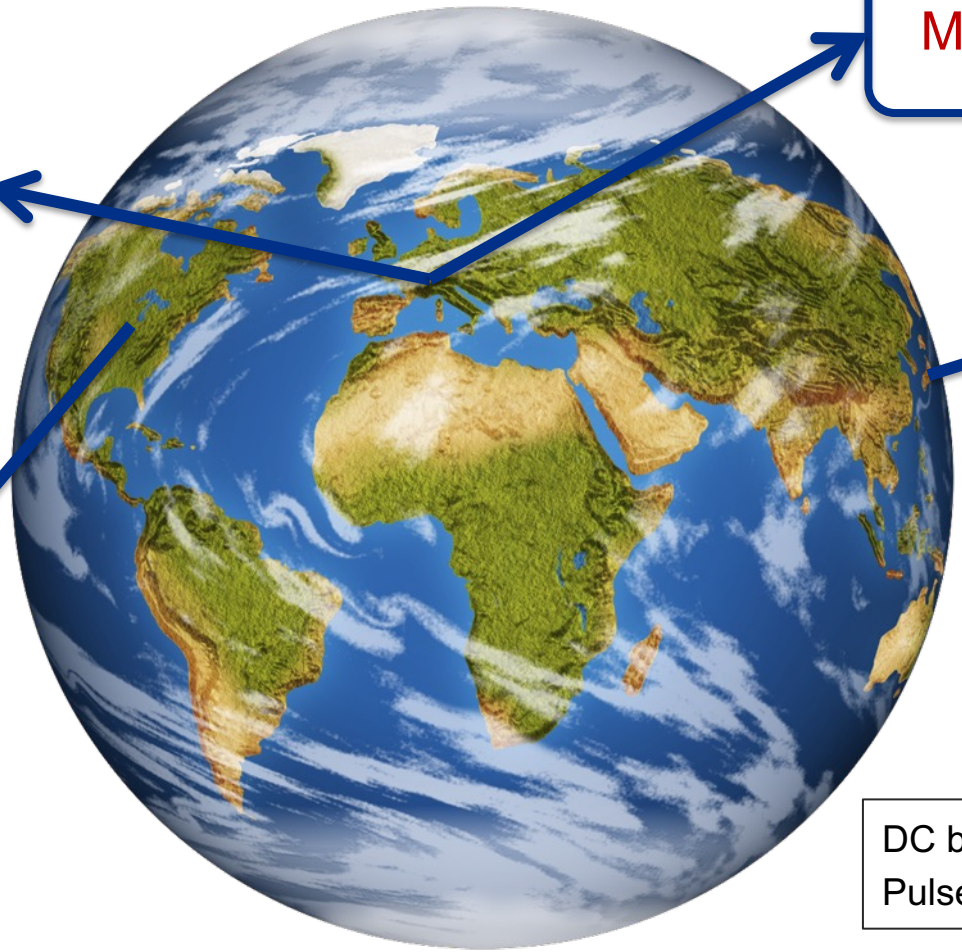
# Muon Experiments at all PP Facilities



**CERN**
MUonE

**PSI**
MEG
MuMass
CREMA
MUSE
Mu3e
MuEDM

**J-PARC**
DeeMe
Museum
COMET
g-2

**FNAL**
g-2
Mu2e
Mu2e-II
AMF
$M^3$

DC beams: $10^8$ $\mu$/sec
Pulsed beams: $10^{10}$ $\mu$/sec

UK: Birmingham, Bristol, Glasgow, Imperial, Lancaster, Liverpool, Manchester, Oxford, Sussex, UCL
Also lot of (g-2) theory work in UK: Edinburgh, Glasgow, Liverpool, Manchester, Plymouth, Southampton

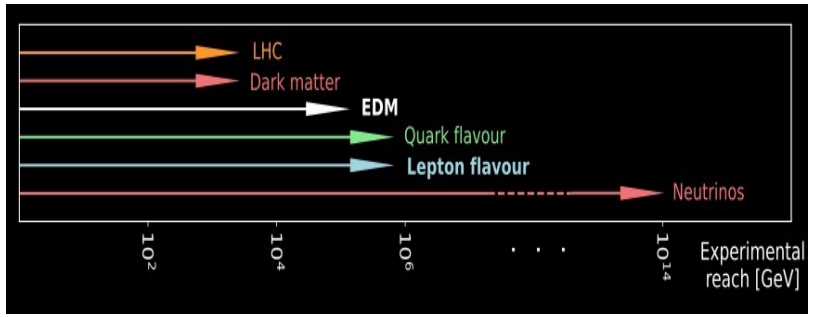
Also LHCb, ATLAS, CMS doing CLFV (particularly $\tau$) & LFU & PIONeer at PSI.

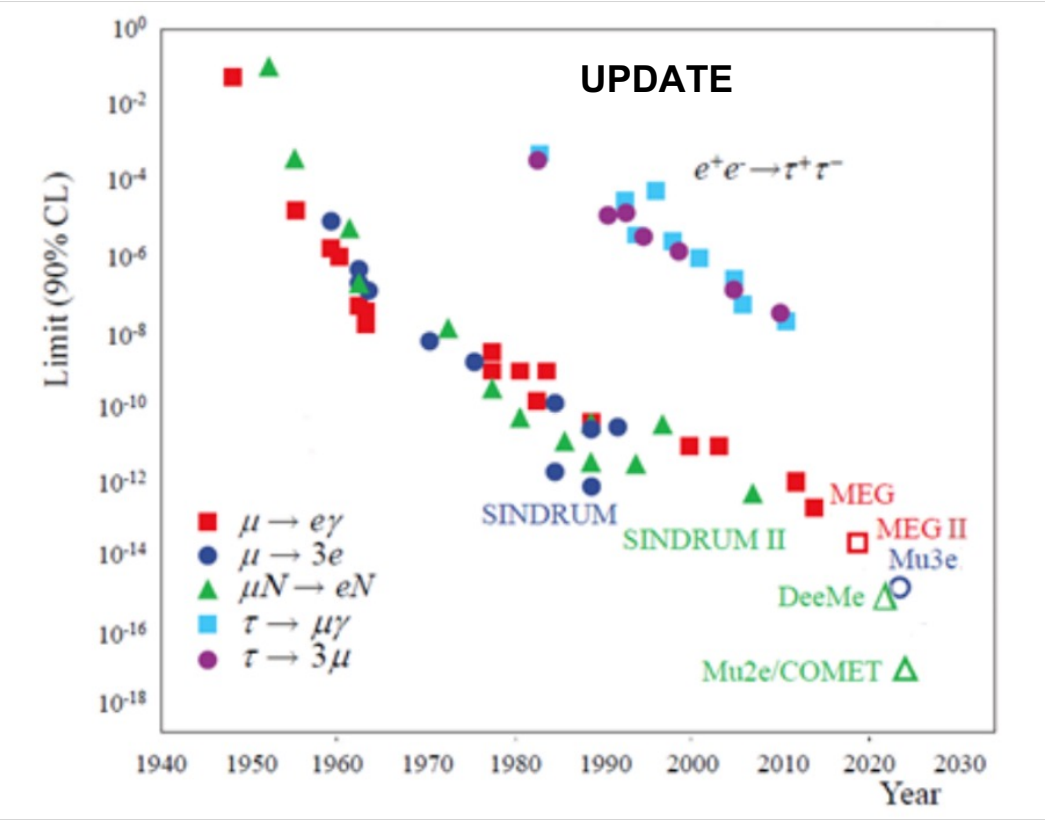
# Two Types of Measurement

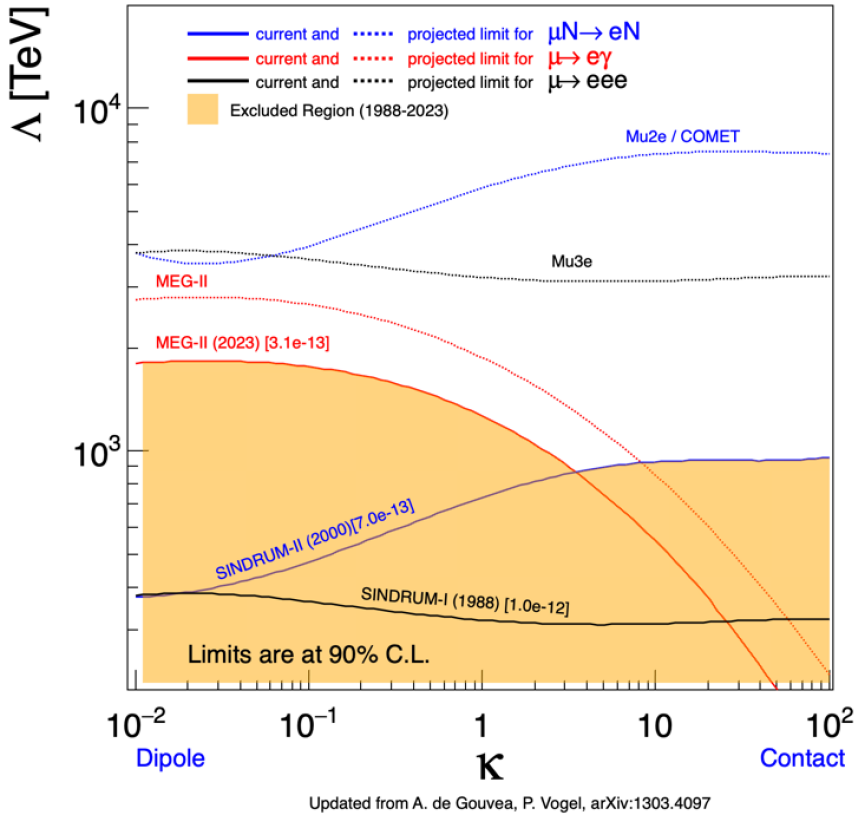
Looking for a deviation from precise SM prediction e.g. (g-2), LFU

Looking for a signal that is essentially zero in the SM

e.g. muon electric dipole moment (EDM) or charged lepton flavour violation (CLFV)



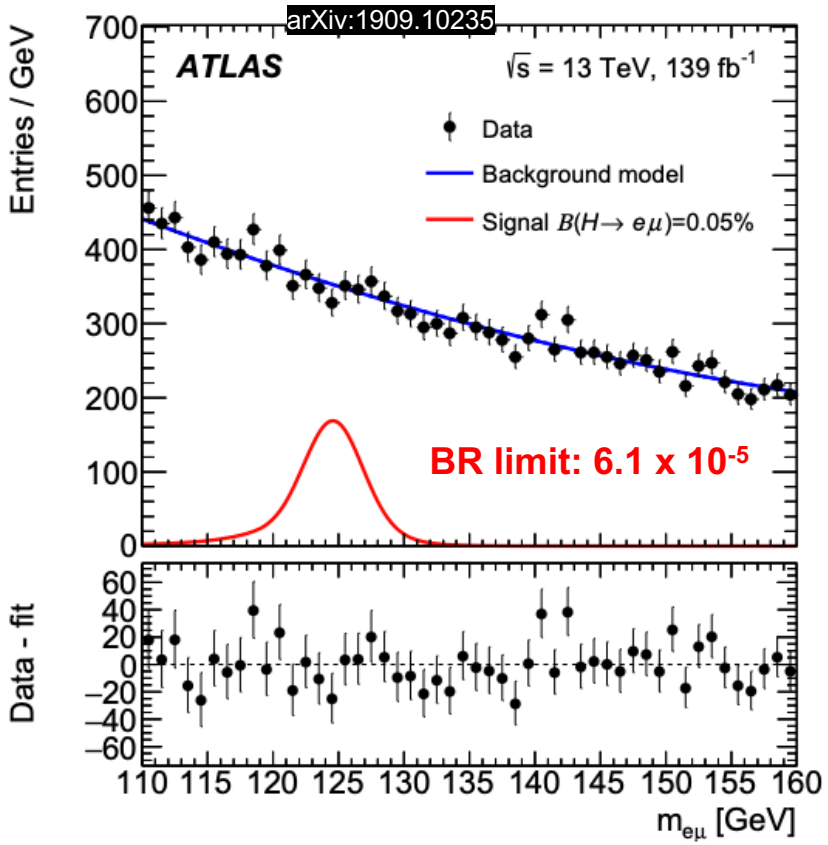



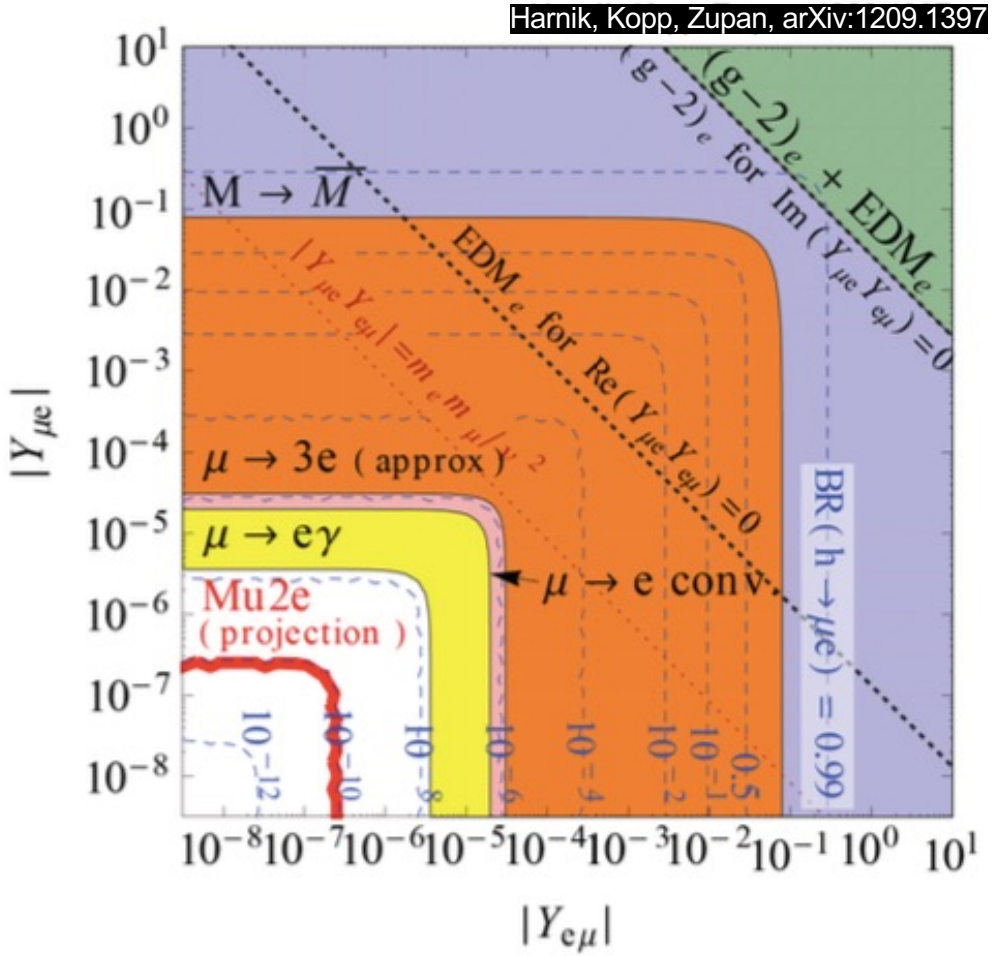




Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

# Why Muons ?

Can be produced in large numbers and live long enough




Mu2e/COMET have sensitivity to BR ($h \rightarrow \mu e$) of $10^{-10}$

# Current Generation of Experiments

FNAL g-2 data taking is complete and a final result in ~ 1 year.
Final precision will be x2 better than current (2023) publication and x5 better than BNL.

JPARC g-2 (~ 2029 start) is systematically very different but will only have the precision of BNL.

MEG-II has begun data taking : will conclude 2026. Needs new ideas/detectors to improve.

COMET, Mu3e, Mu2e all coming online 2025-2027 and ultimately will extend CLFV sensitivity by $x10^4$.
Conclude ~ 2033 when systematics limited → new ideas/detectors

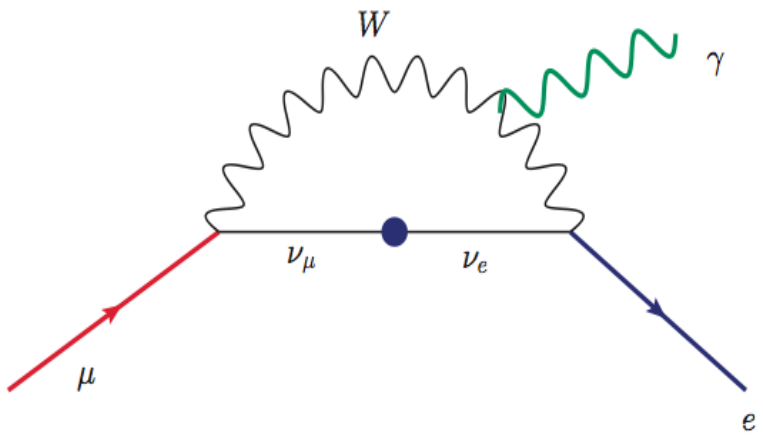
Mu3e benefits significantly from HIMB PSI upgrade (ready 2029/30) as does MuEDM.

Plenty of BSM ideas out there but the actual measurements (unlike g-2) don't really need much SM theory input since SM predictions are O(30) (CLFV), O(10) (EDMs) orders of magnitude below experimental sensitivity …

Many more details on current status in Saskia Charity's (IoP Talk)

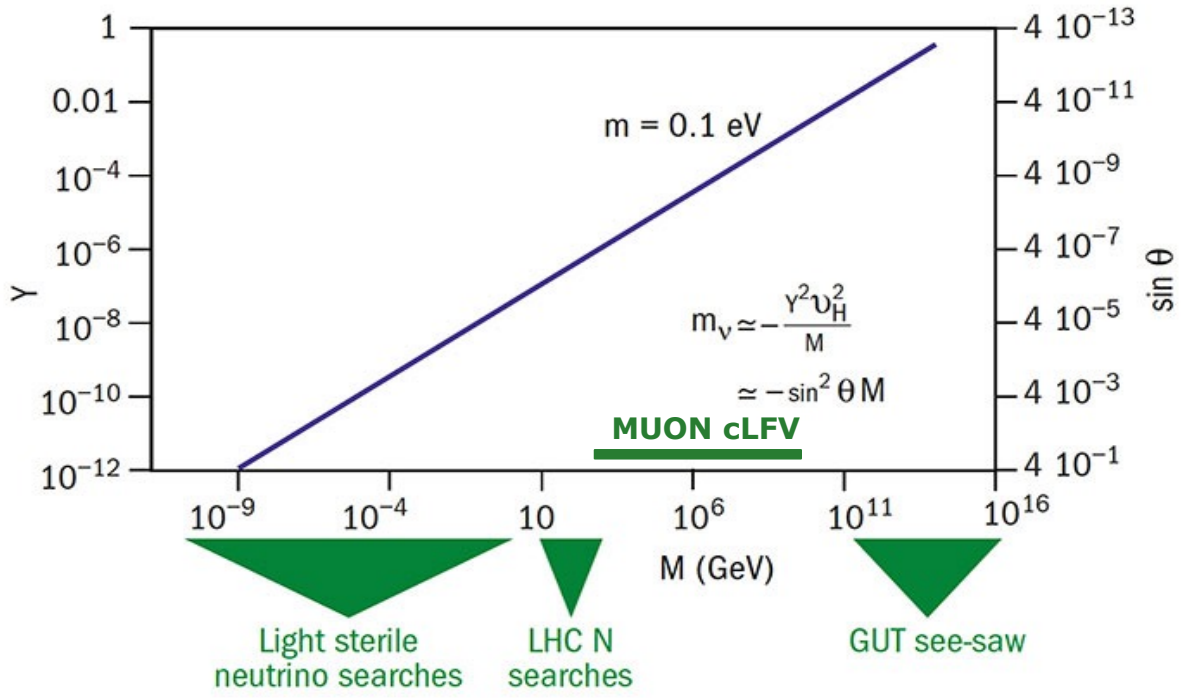
# Synergies : science

In SM: neutrino oscillations (masses) are intimately connected with charged lepton flavour violation



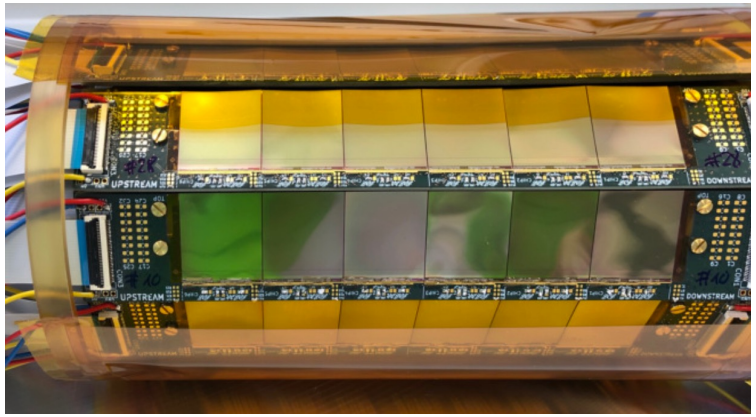

and also in BSM e.g. $\nu_{RH} \rightarrow l^- H^+$

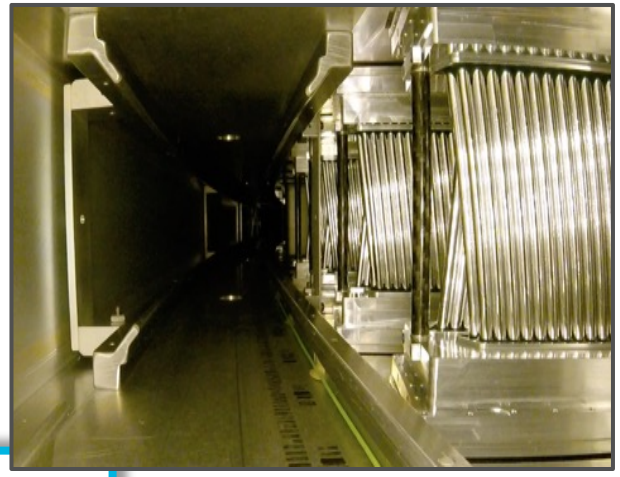
and thus to **extensions to the Higgs sector**

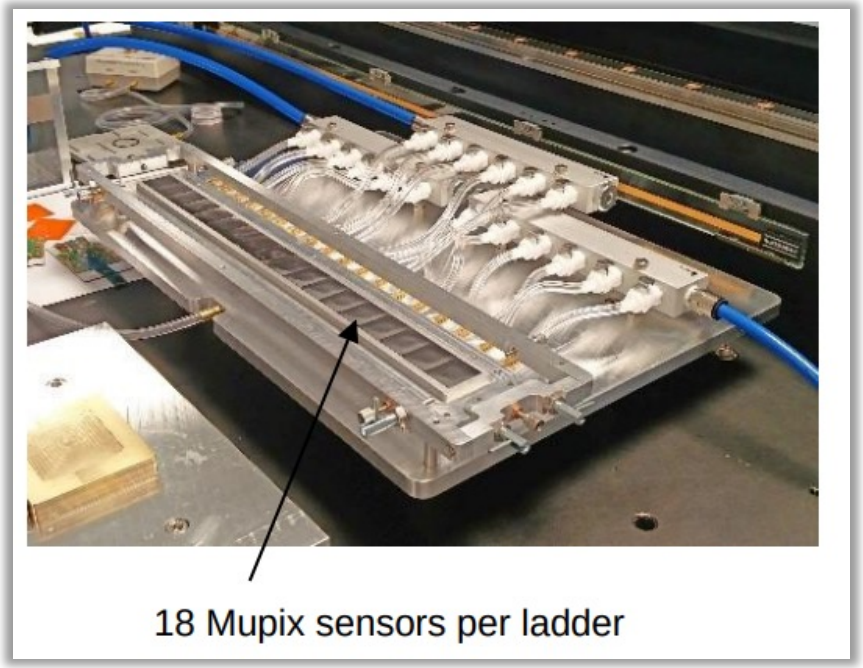


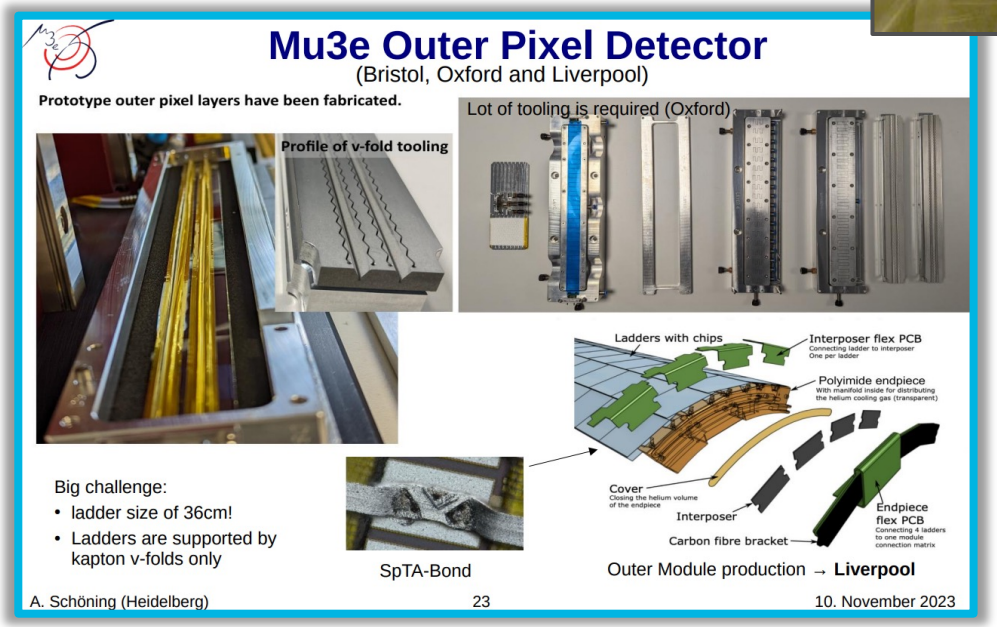
# Synergies : technology

All current and certainly future experiments rely on low-$X_o$ tracking (and LHC know-how)








We don’t have resources to re-invent the wheel…

# Future Projects

CLFV experiments: Mu2e/COMET/Mu3e/MEG (& MUONe) will essentially be complete on timescale of 10 years.

The future projects will be in two areas:
- next generation CLFV to improve sensitivity by x 10 – 1000
- EDMs : muon & proton : improve sensitivity by x $10^2$ ($\mu$) – $10^5$ (p)

This is a programme for the 2030s-2040s but R&D / demonstrators are required ahead of this.

Applications to STFC to support these activities will be incoming.

# Next Generation CLFV

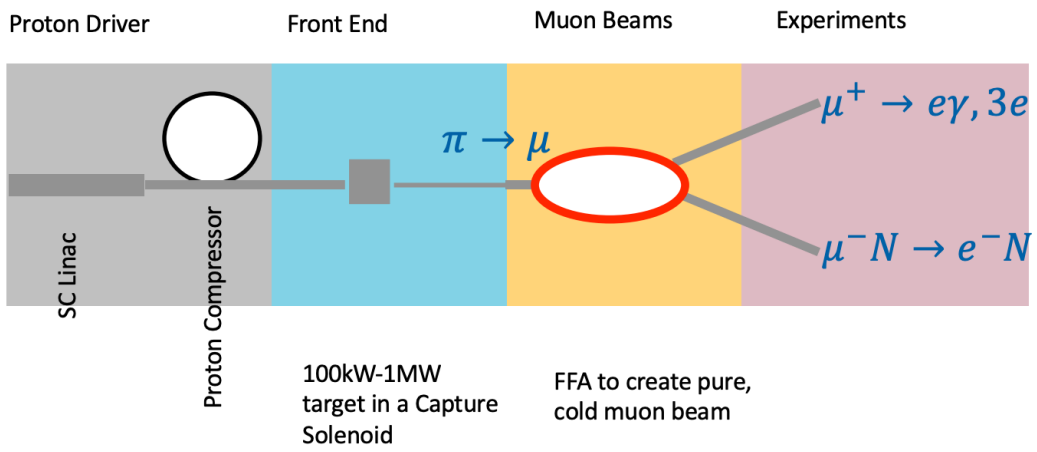
- Mu2e-II (2035-2040) can get x10 with same beam & better detectors
  - studies in this area, particularly low-mass tracking (e.g. very thin straws) are ongoing.

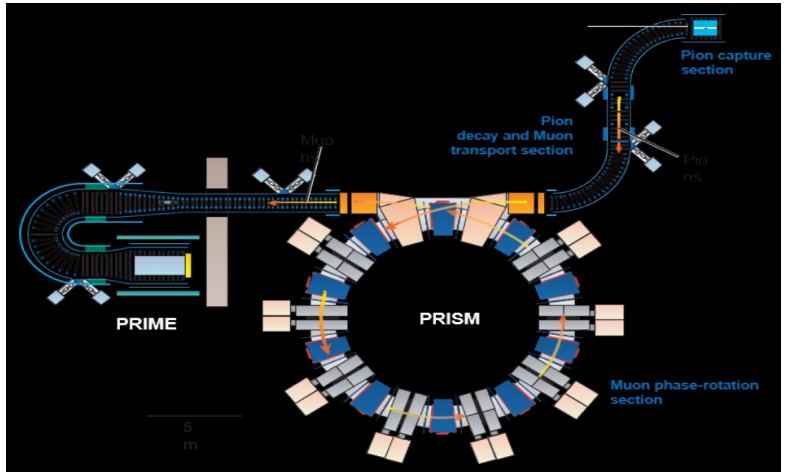
- Further improvement needs new facility e.g. AMF at FNAL or PRISM at JPARC : likely only one will be constructed and will require significant R&D / demonstrators and will have multiple CLFV experiments / detectors using the same beam.

> Develop plans for improving the Fermilab accelerator complex that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

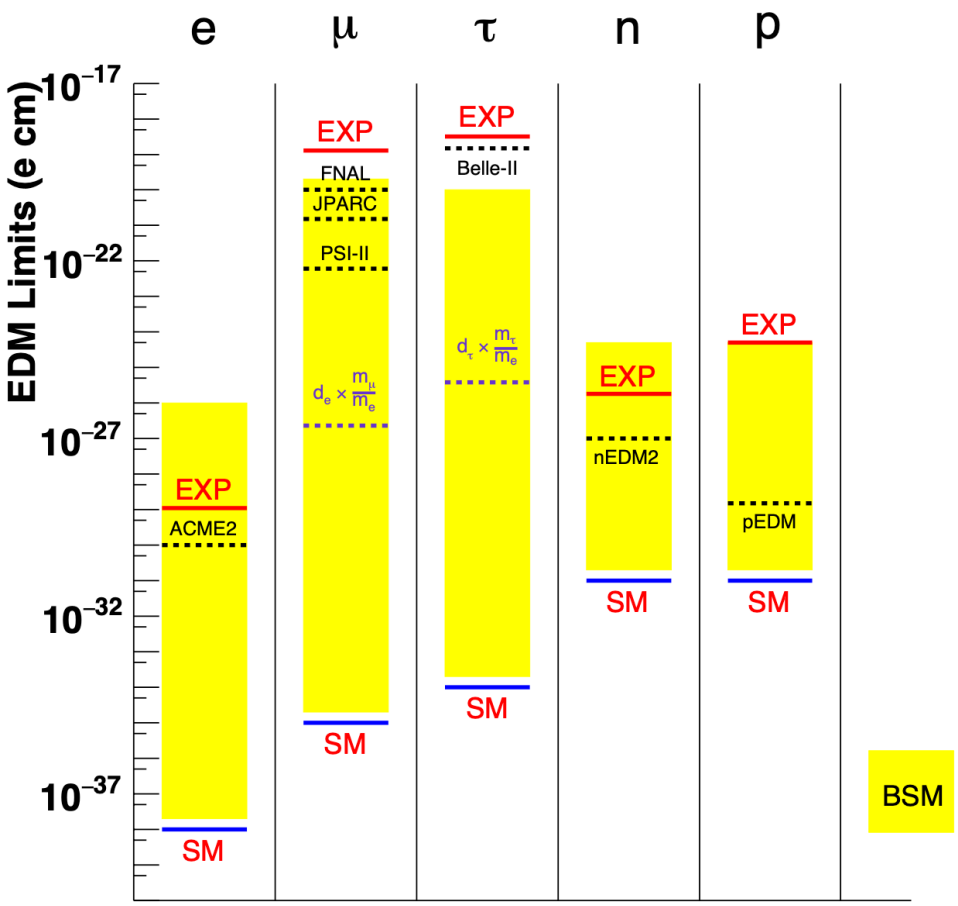
**US-P5**

Challenges: target (1MW beam); cooling (FFAGs); proton rebunching; low-$X_0$ detectors → synergy with Muon collider (NuStorm) & DRD detectors.

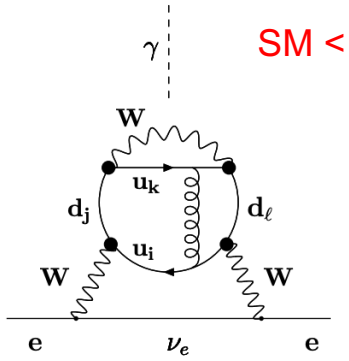


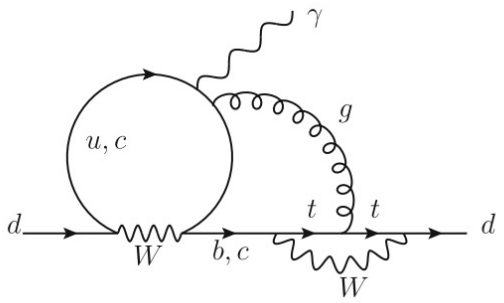



# Next Generation EDMs

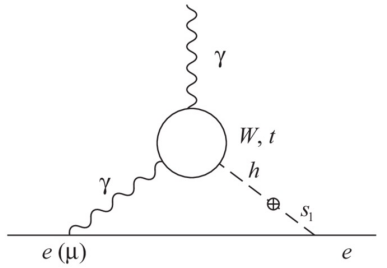



SM < $10^{-30}$ e.cm




BSM > $10^{-30}$ e.cm




So far only electron and neutron EDM measurements encroach into BSM territory.

Existing proton limits are extrapolated from nucleus measurement.

## Motivation

Muon: 2nd generation particle, large value indicative of LFU-violation

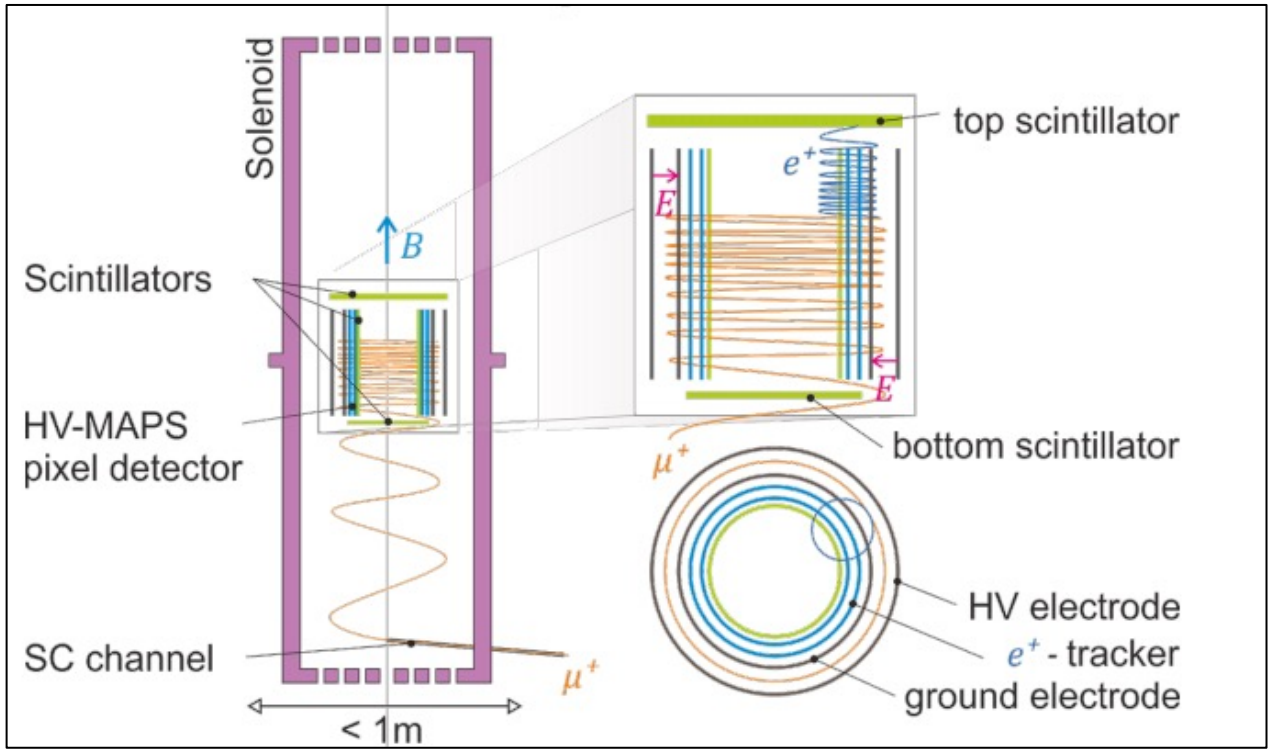
Proton: QCD axion, CP violating h-couplings, light DM.

# Muon EDM at PSI

”Frozen spin” technique disappears (g-2) using judicious p, E-field choice

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

**Signature: vertical oscillation**




**MuEDM Phase-1**
- verify frozen-spin condition can be achieved
- lateral injection, straw-tube tracker, $10^8$ μ/s

**MuEDM Phase-2 → x1000 over current limit**
- Vertical injection, thinned Si tracker, $10^{10}$ μ/s

Cockcroft, Lancaster, Liverpool, Manchester, UCL

# Proton EDM

Utilises similar frozen spin methodology & not using atoms but dedicated p=700 MeV polarized proton beam in an "electric" storage ring using electric quadrupoles of ~ 5 MV/m.

[arxiv.org/pdf/hep-ph/9506229]

We want some CP for baron asymmetry but we don't want too much !

- need to suppress CP from QCD dynamically which needs a QCD axion to exist which makes $\overline{\theta}_{\mathrm{QCD}}$ very small.
  - pEDM is sensitive to $\overline{\theta}_{\mathrm{QCD}}$ down to $10^{-13}$ (a factor of $10^{-3}$ below that from n-EDM.)
- need some BSM CP from loops

  → wide range of masses (GeV->PeV), phases & couplings → $d_p \sim (g^2/16\pi^2)\,(e\,m_q)/\Lambda^2_{\mathrm{NP}}\ \sin\phi^{\mathrm{NP}}\ \ e\cdot cm$

Oscillating pEDM signature → axionic dark matter [meV → peV] (DM: could all be QCD axion if mass O(100) $\mu$eV)

CP-violation in Higgs sector : can probe couplings $10^{-3}$ beyond what's possible with e-EDM.

**First Phase (can be now and in UK)**

- build a small demonstrator to prove that
  - quadrupoles can be built to operate at this field with required alignment precision
  - low mass silicon detector (polarimeter) to accurately measure vertical displacement of beam

**Second Phase**

- build the full storage ring (2030s), likely at BNL.

# Summary

FNAL g-2 is essentially complete and has surpassed its design goals : x5 BNL precision.

CLFVs and EDMs are a complementary probe for BSM (and even SM i.e. QCD axion) physics

Well established CLFV programme for the next ~ 10 years with significant UK leadership.
Important that this is supported through the various phases e.g. Mu3e-I → Mu3e-II

The future projects (2030++) will be in two areas:

- a single next generation muon CLFV facility to improve sensitivity by x 10 – 1000
- EDMs : muon & proton : improve sensitivity by x $10^2$ ($\mu$) – $10^5$ (p) using the frozen-spin technique.

But these need R&D / demonstrators in the short term and dedicated new facilities to be built in the longer term.