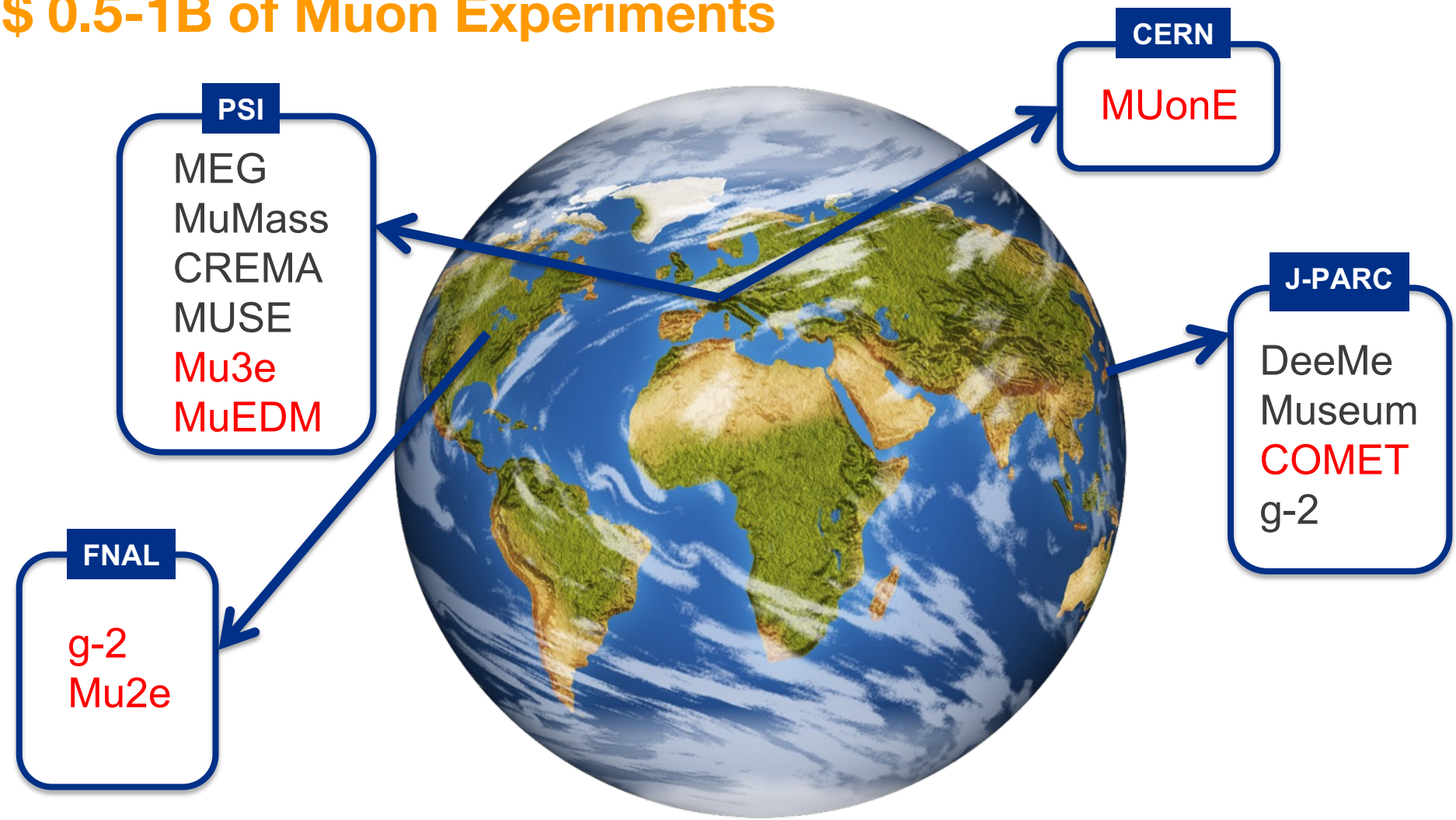
Precision Muon/LFV and EDMs

Mark Lancaster

MANCHESTER 1824
The University of Manchester

$ 0.5-1B of Muon Experiments



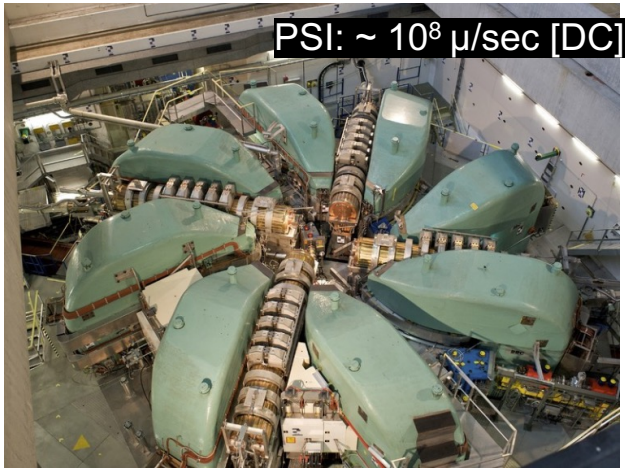
UK: Bristol, Cockcroft, Imperial, Lancaster, Liverpool, Manchester, Oxford, UCL involved in 6 experiments
Also lot of (g-2) theory work in UK: Edinburgh, Glasgow, Liverpool, Manchester, Plymouth, Southampton

Two Types of Measurement

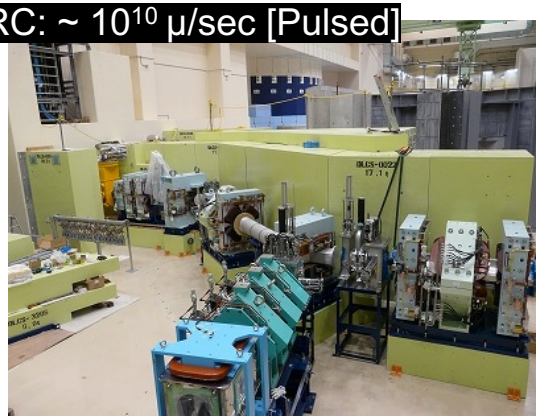
Looking for a deviation from precise SM prediction e.g. (g-2), LFU

Looking for a signal that is essentially zero in the SM

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

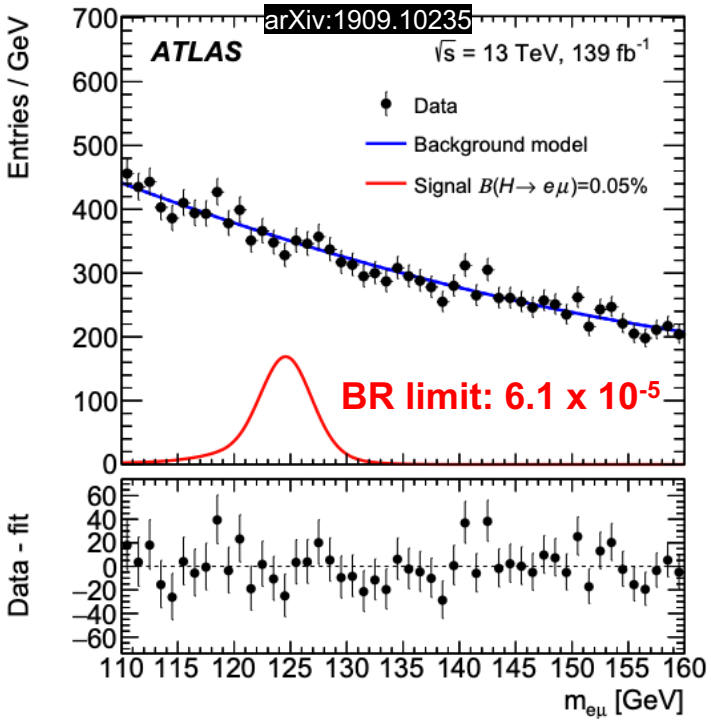


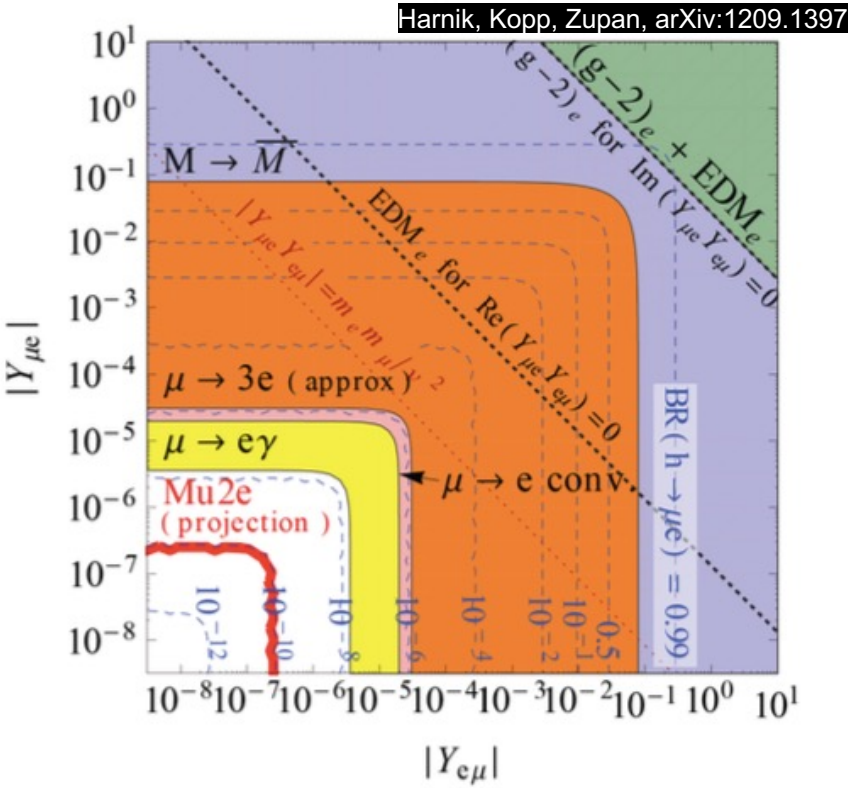
FNAL/JPARC: ~ 10^{10} μ/sec [Pulsed]



Why Muons ?

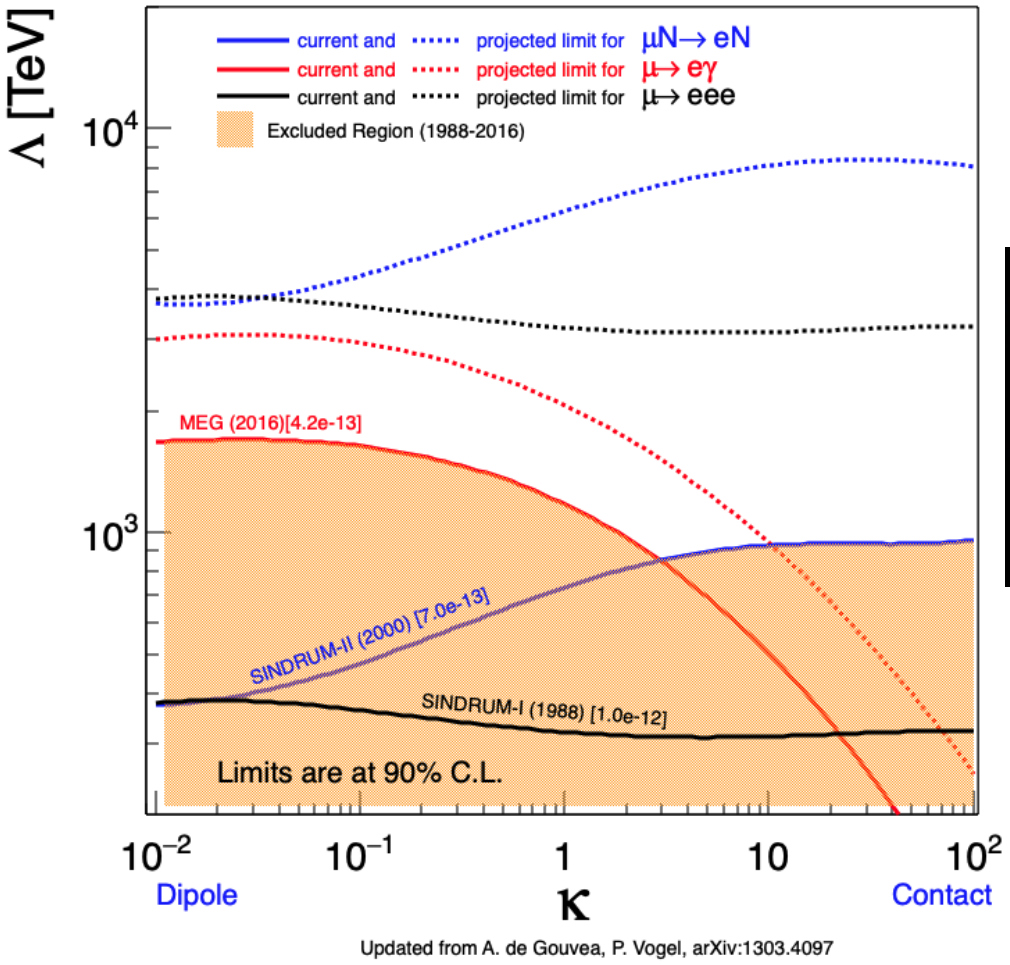
Can be produced in large numbers and live long enough



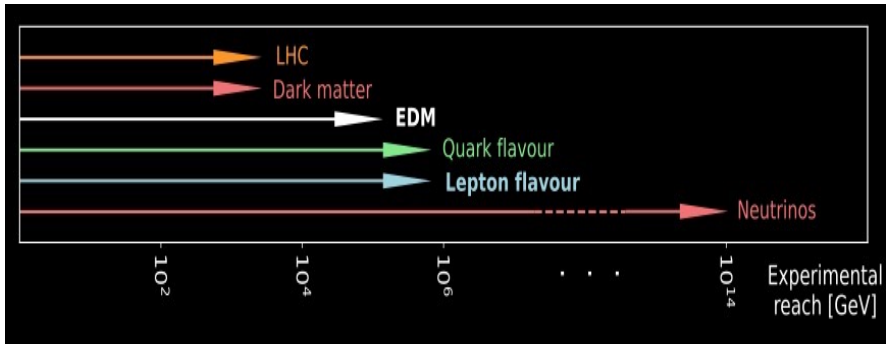


Mu2e/COMET have sensitivity to BR ($h \rightarrow \mu e$) of 10^{-10}

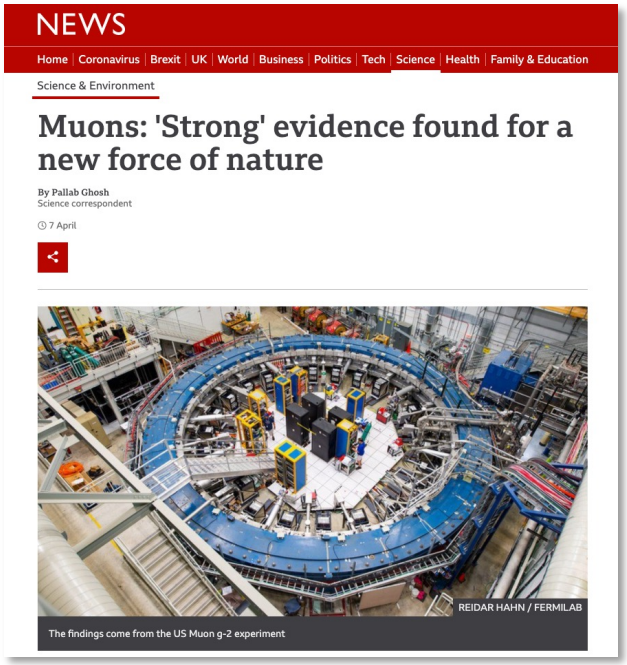
Access to high mass scales

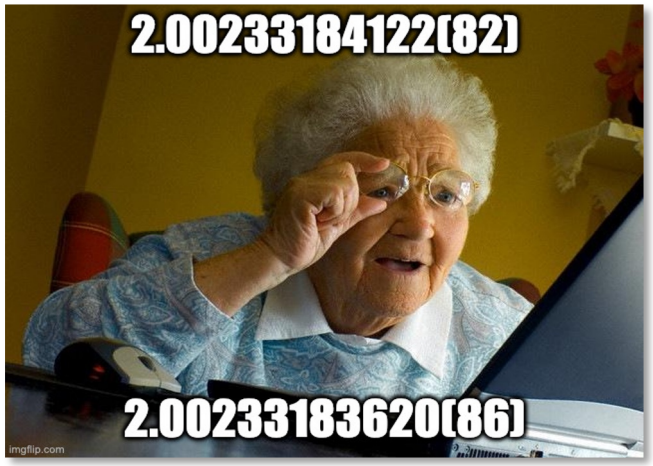


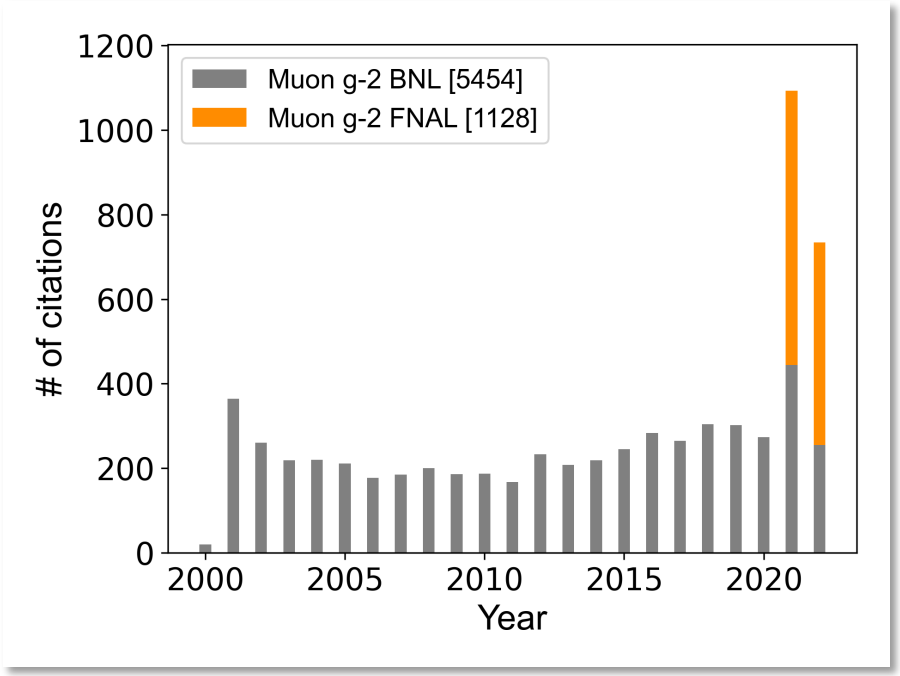
Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097



Muon g-2



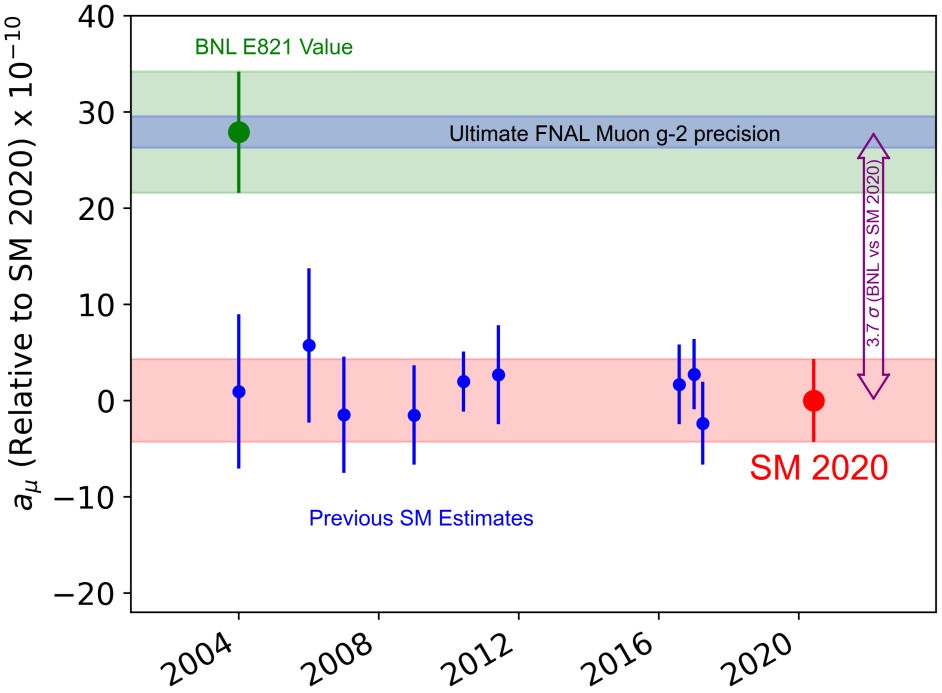


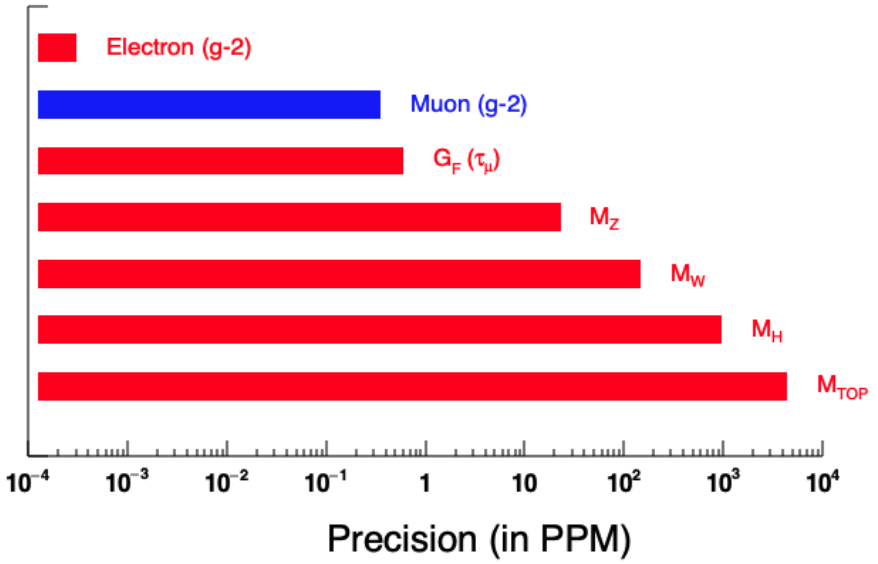


Cockcroft, Lancaster, Liverpool, Manchester, UCL

Muon g-2

Most precise quantity measured at a particle accelerator

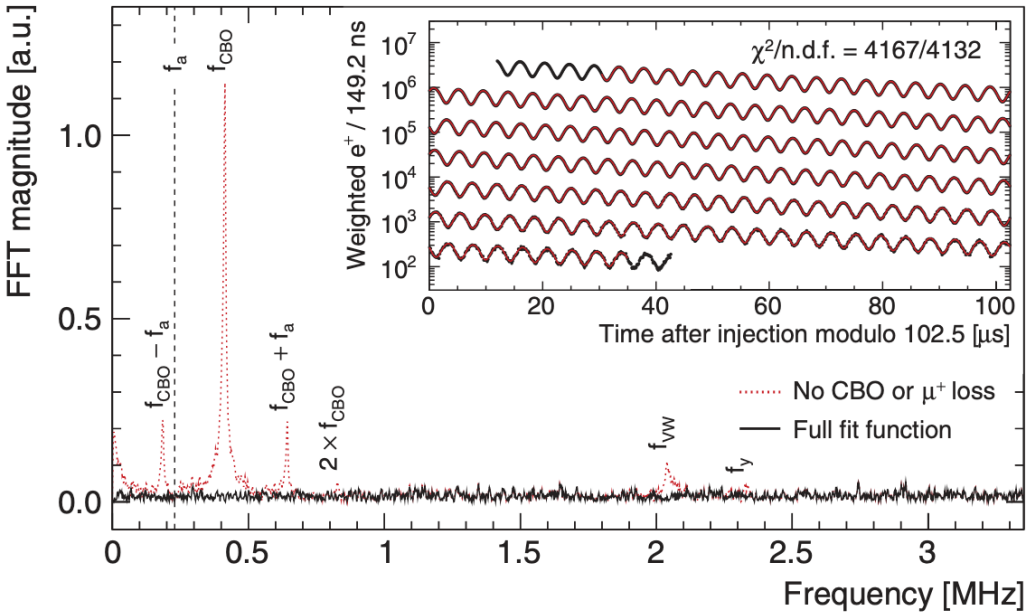


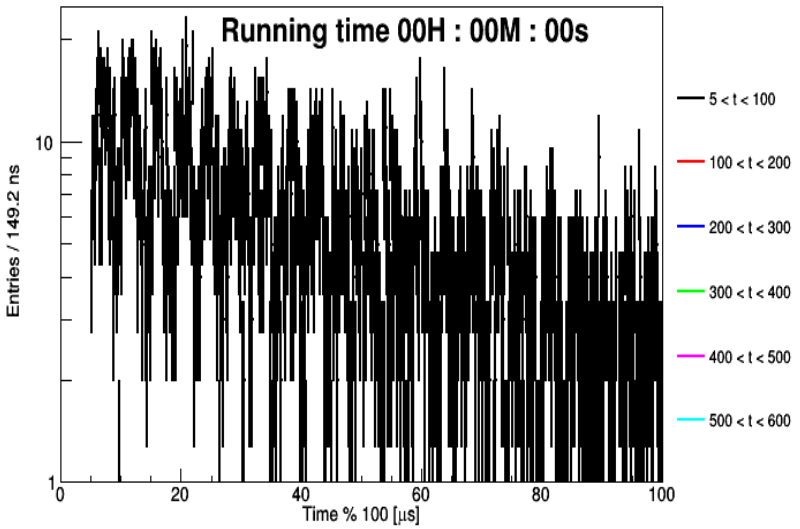


2021 FNAL measurement based on a dataset of similar size to BNL ~ 10 billion μ^+
SM predictions stable until day after 2021 measurement PRL ….

Cockcroft, Liverpool, Manchester, UCL

Result from a 22 Parameter Fit





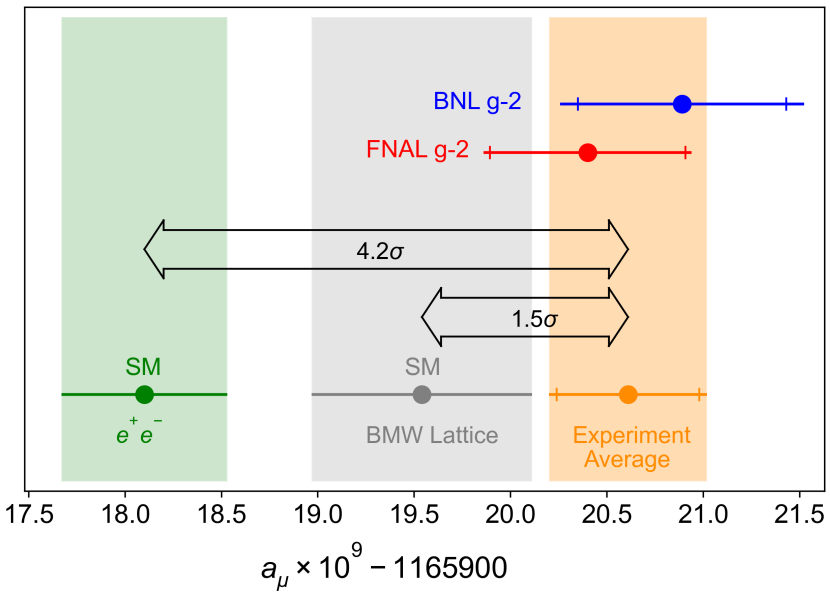
Statistical uncertainty : 434 ppb

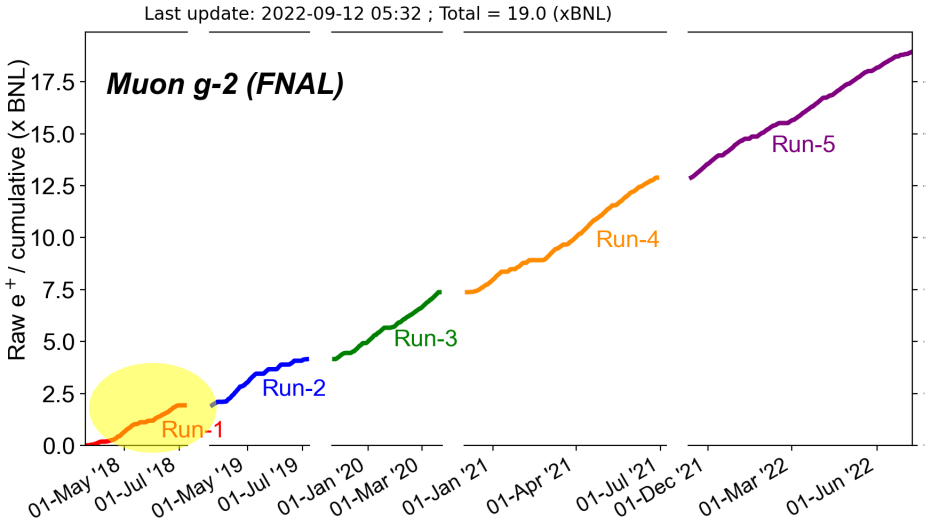
Largest correction to data is : 489 ppb (total correction is 456 ppb)

Total systematic uncertainty : 157 ppb (aim was 100 ppb)

Deviation from e^+e^- SM (with BNL) : 2150 ppb

Next FNAL measurements





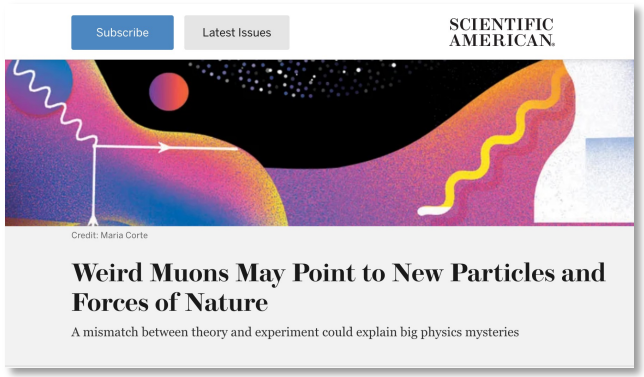
Exp-SM discrepancy (with e^+e^-): 2150 ± 350 (expt) ± 370 (theory) ppb
is of comparable size to the SM EWK contribution to g-2.

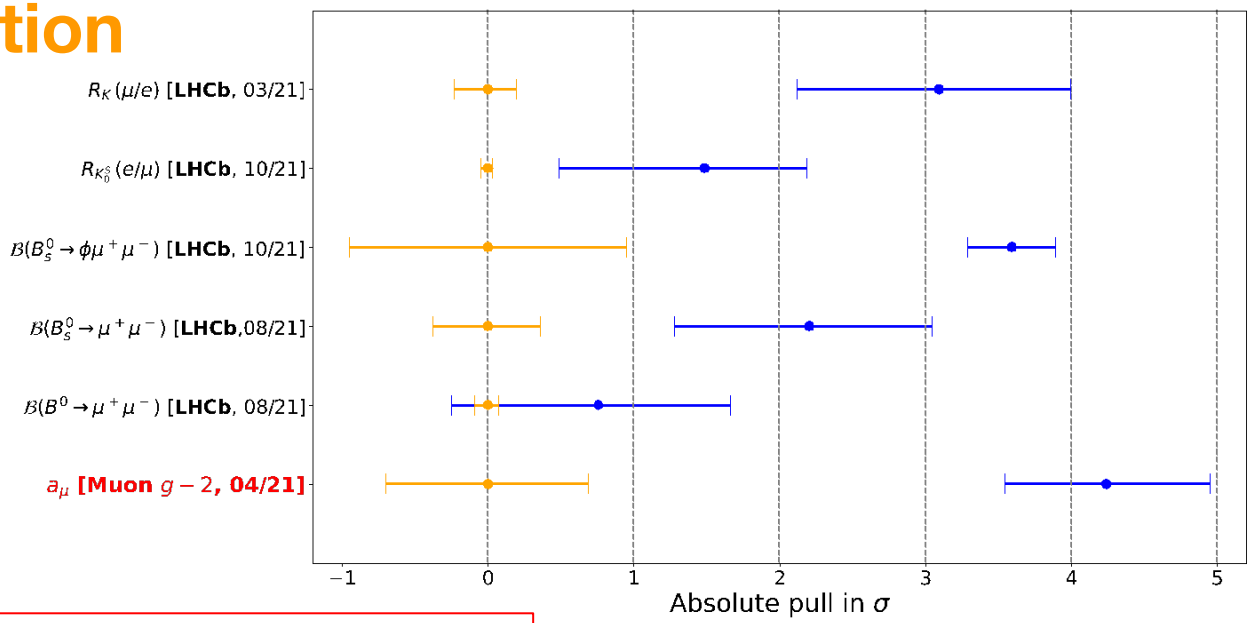
Much work on understanding the e^+e^- SM prediction vs lattice SM prediction

Run-2/3 will be published next year : should reduce statistical uncertainty by ~ 2 and so get uncertainty: 215 (stat.) ⊕ 100 (sys.) ~ 240 ppb (vs 460 ppb Run-1)

Final analsysis: including Runs-4/5/6 : stat. to be ~ same as syst i.e.100 ⊕ 100 ppb

Theory & Interpretation





"If you look at it in comparison to any other ideas, it's not worse than the others …."

"However, this dampening of supersymmetric enthusiasm is not entirely warranted…"

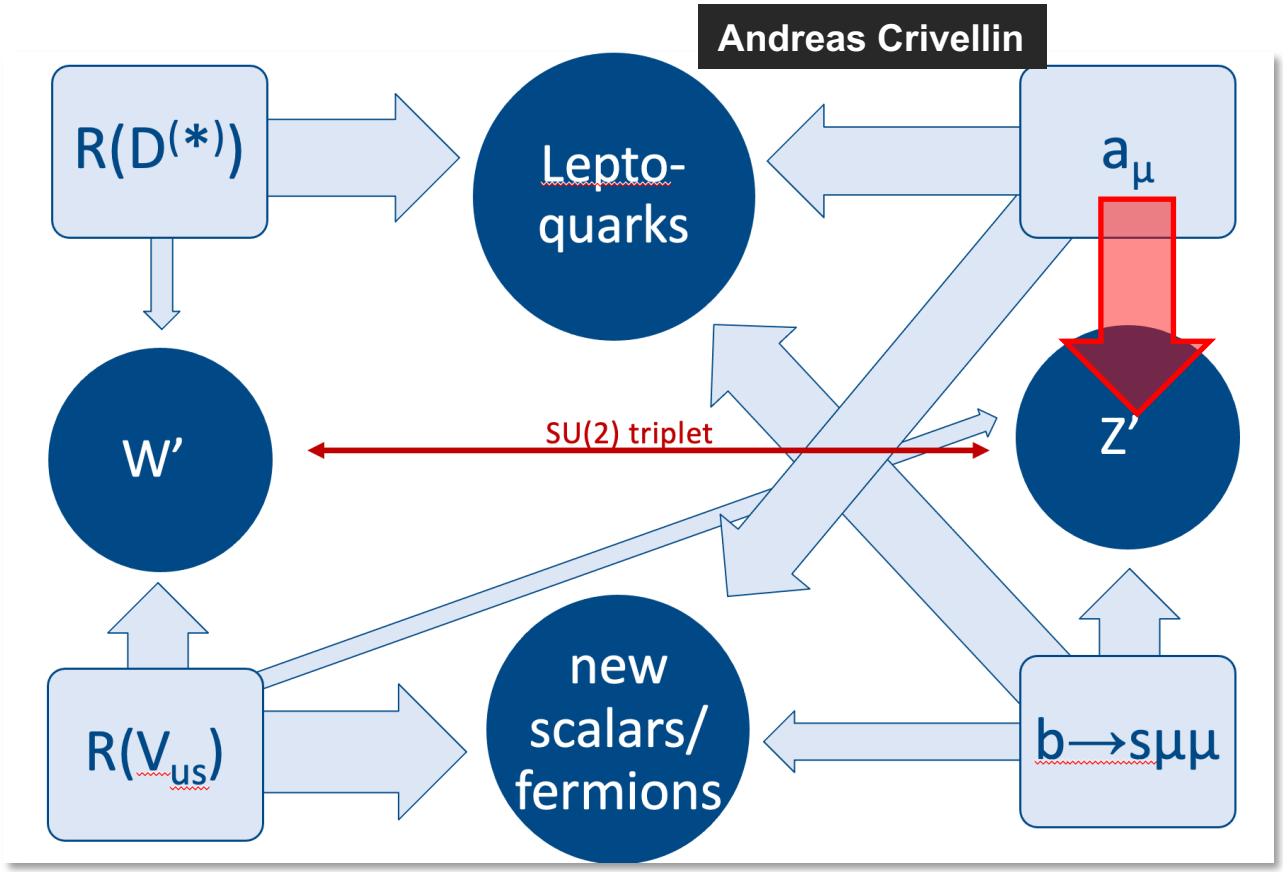
"I'm quite appalled by this procession of zombie SUSY models dragged out of their graves…"

"I think it has a very good chance to be real. But it's hard to pick a model - nothing strikes me as attractive"

Theory & Interpretation

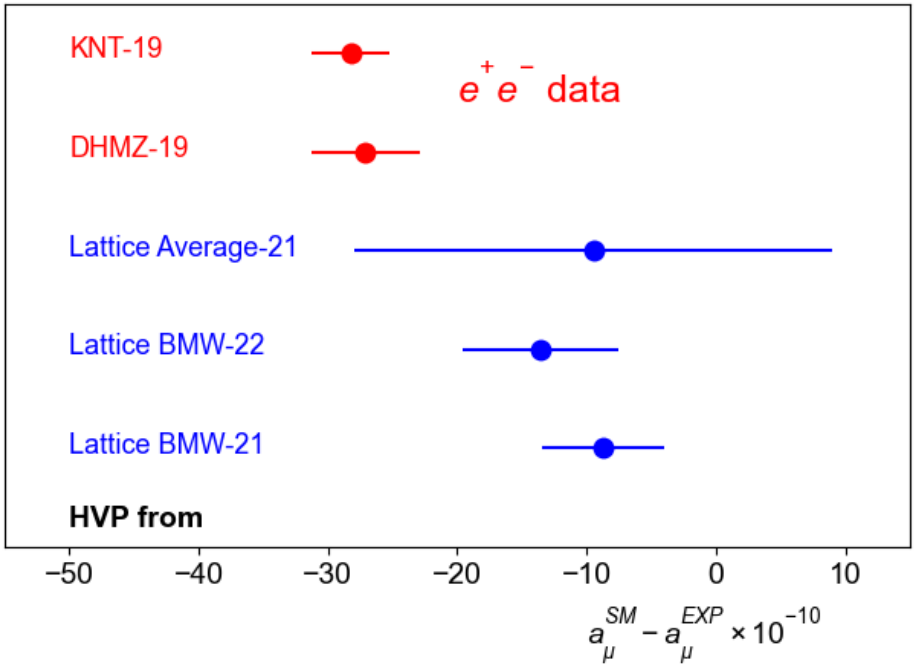
TeV Leptoquarks
Z', ALPs
LHC evading SUSY
Tweaked Higgs extensions ...

The fact that discrepancy is "large" (~ EWK contribution) and existing experimental constraints mean that BSM models tend to be in non-traditional parameter regions….



And …. low energy (keV-MeV) phenomena

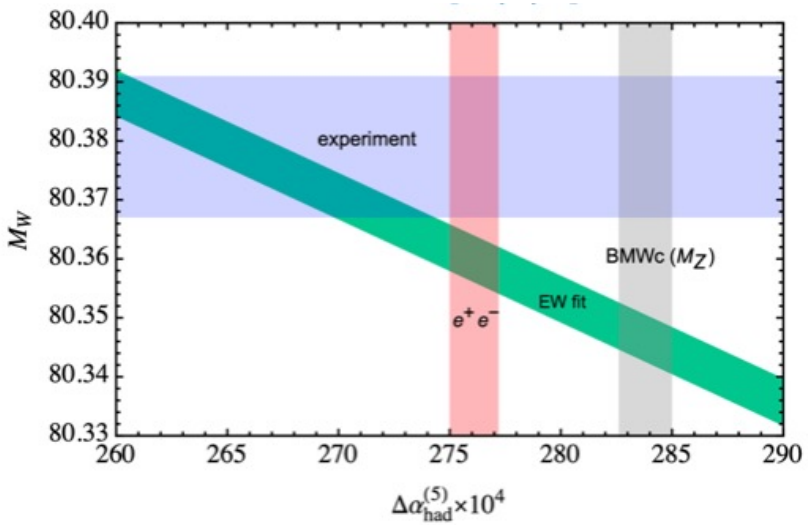
SM Prediction



Implication of BMW results is that there are issues with the e^+e^- measurements (below 0.7 GeV) or a flaw in the e^+e^- or lattice theory

If this is true then $\Delta\alpha^{(5)}_{\rm HAD}$ is affected and so are the global EWK fits since they use e^+e^- data

Tension in SM M_W, M_H vs measured M_W, M_H

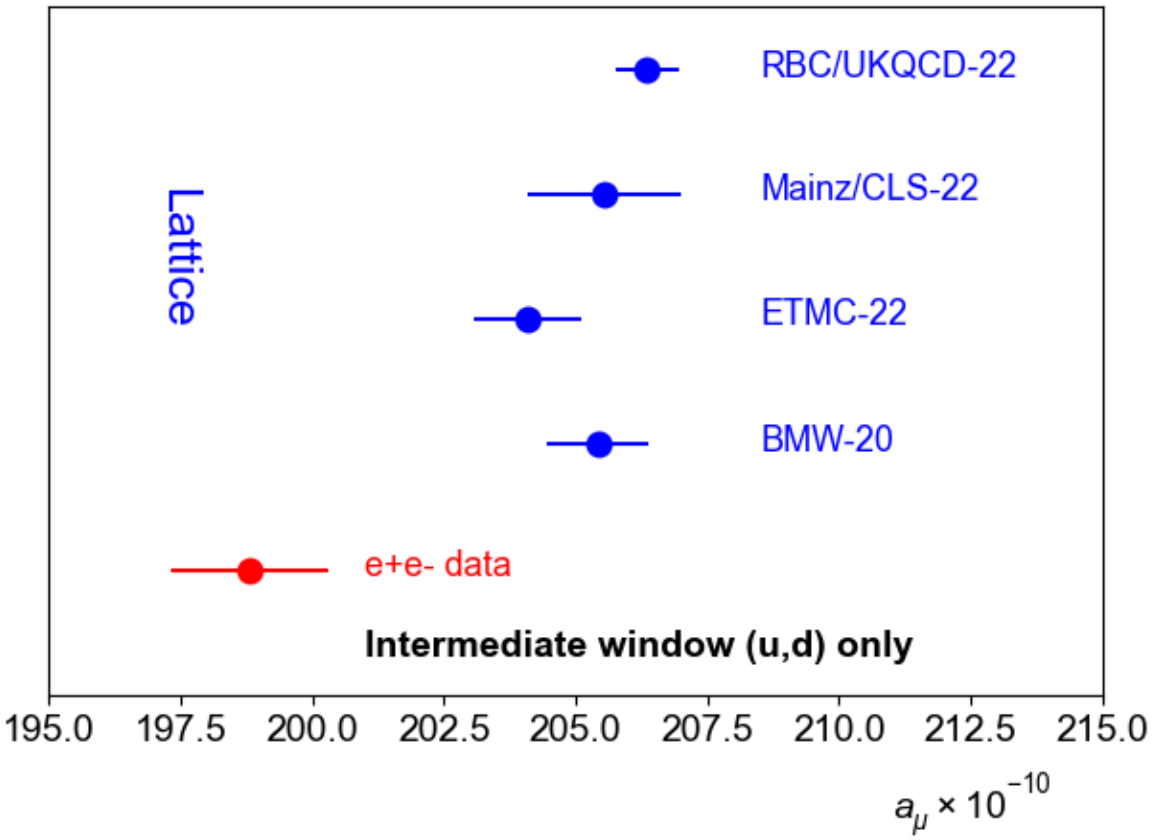


The analysis of e^+e^- data can be made to match the BMW lattice prediction if the measured cross sections below 0.7 GeV **are shifted by 7%.**

In this region there is data from 9 independent experiments: the most precise experiments (KLOE, BaBar, CMD, SND, ….) quote **cross section uncertainties of 0.5-1%...**

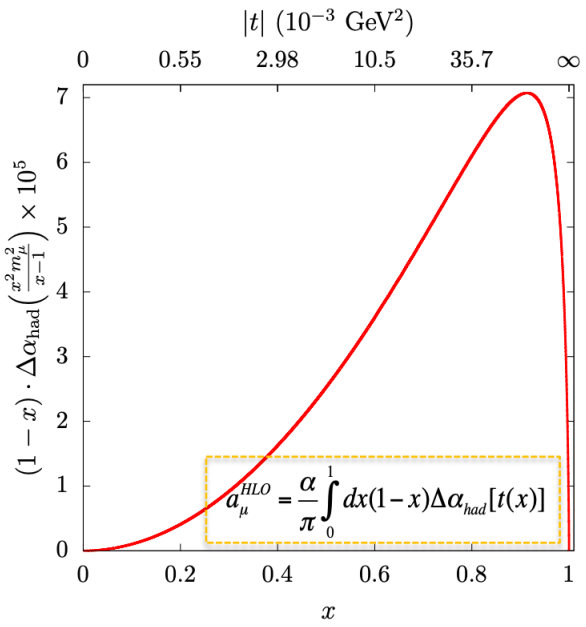
SM Prediction

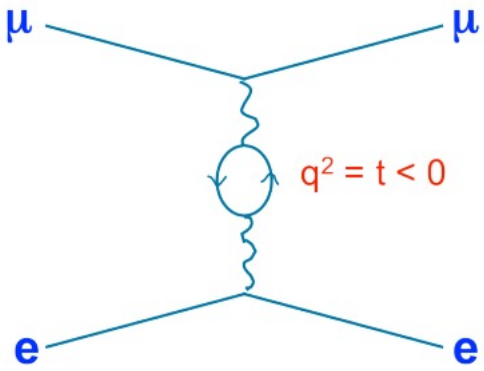
BMW is presently the only sub 1% (HVP) lattice calculation in the full kinematic region
Cross-checks recently performed but only **in limited** (30%) (distance) region.



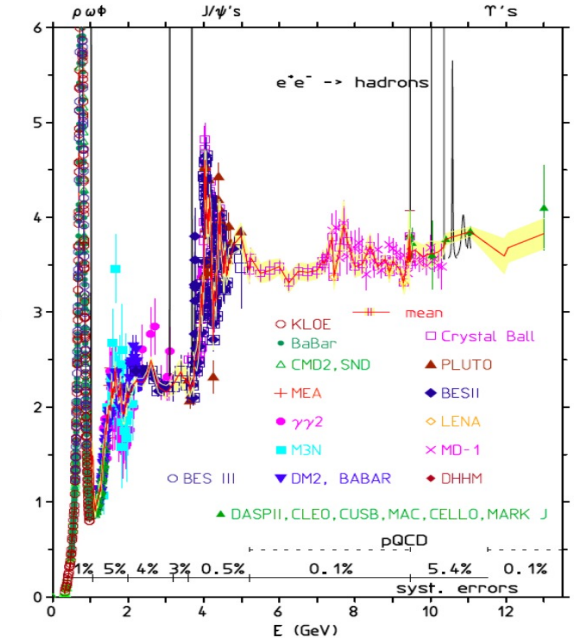
Lattice (full region) and e^+e^- determinations now being done blinded.

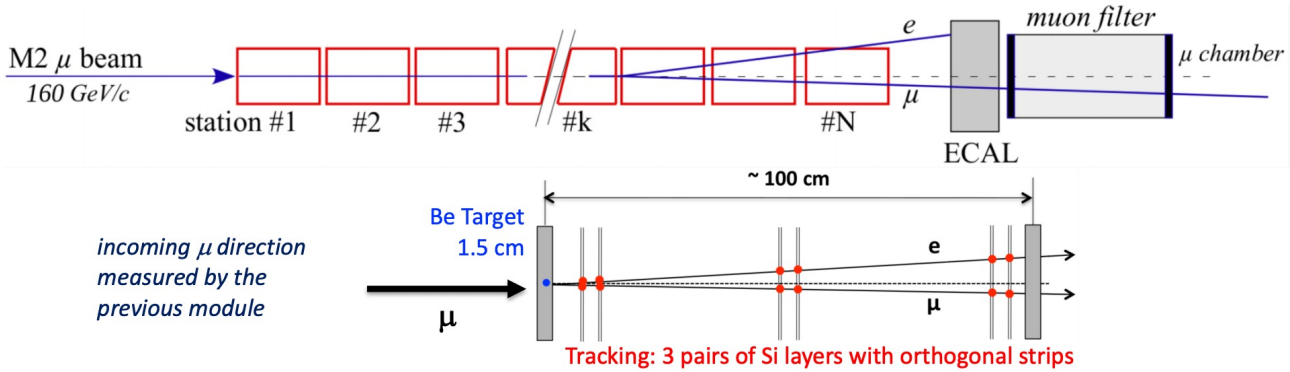
Cross checking the theory with experiment (MUonE)





$$\frac{d\sigma}{dt} \rightarrow \Delta\alpha_{\rm HAD}(t) \rightarrow a_\mu^{\rm HVP(LO)}$$





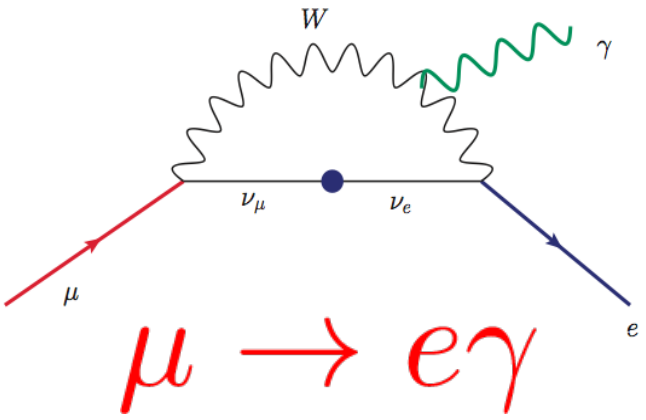
Imperial & Liverpool

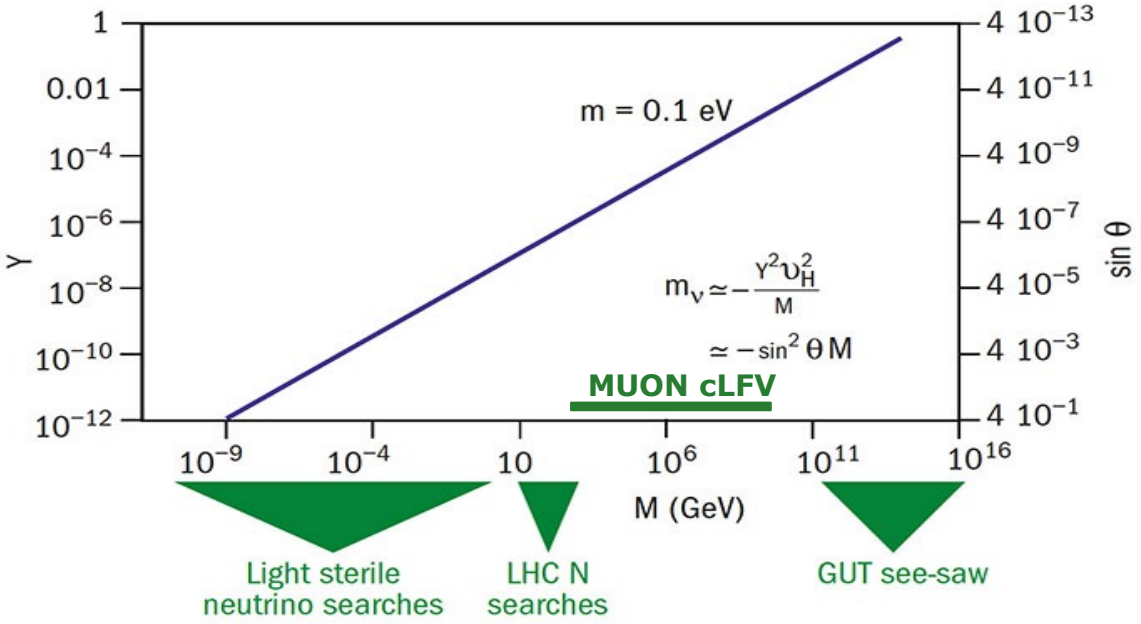
3 stations+calo test in 2023

Aiming to get 10 station data before LS3 in 2026.

Charged Lepton Flavour Violation (cLFV)

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

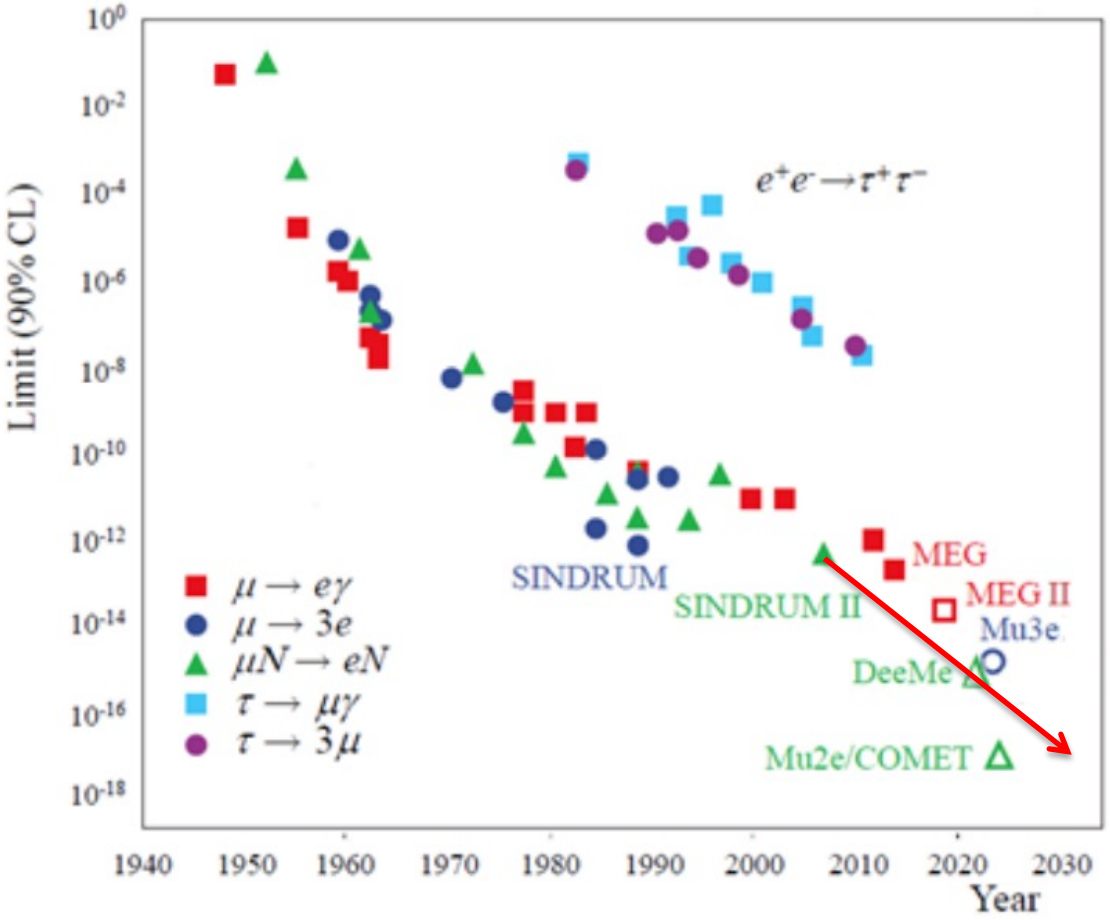




and also in BSM: $\nu_{RH} \rightarrow l^- H^+$

And thus to **extensions to the Higgs sector.**

Charged Lepton Flavour Violation (cLFV)



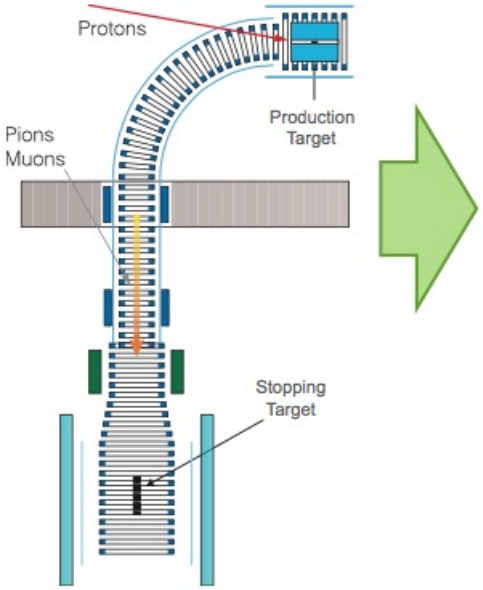
Ratio of the 3 different CLFV processes is model dependent and depend on model parameters.

O(10⁴) improvement driven by new technology

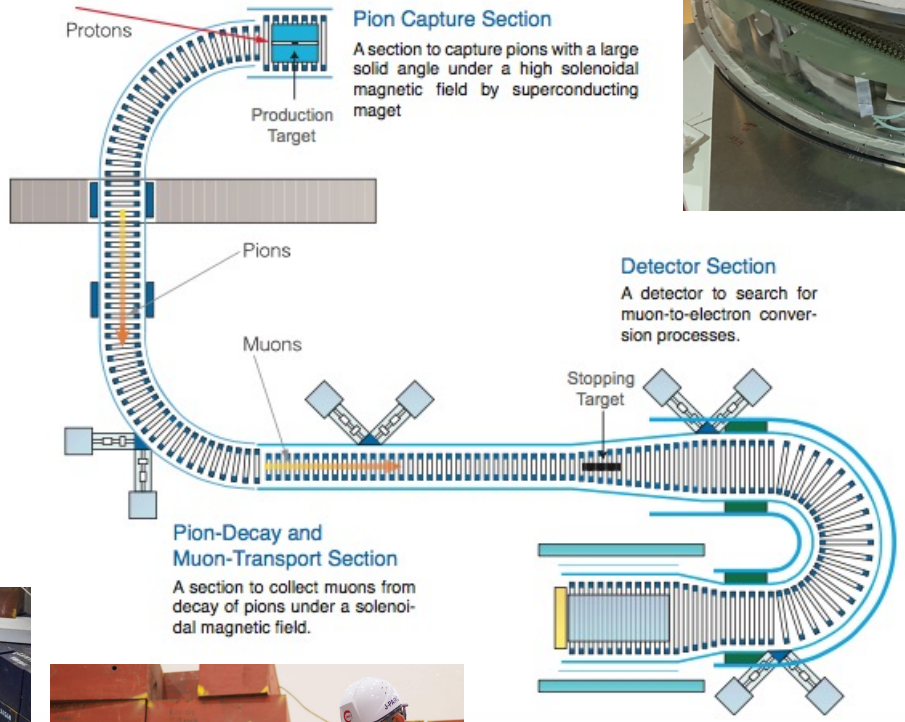
Being probed by MEG ($\mu^+ \to e^+\gamma$), Mu3e ($\mu^+ \to e^+e^-e^+$), DeeMe/COMET/Mu2e ($\mu^- N \to e^- N'$)

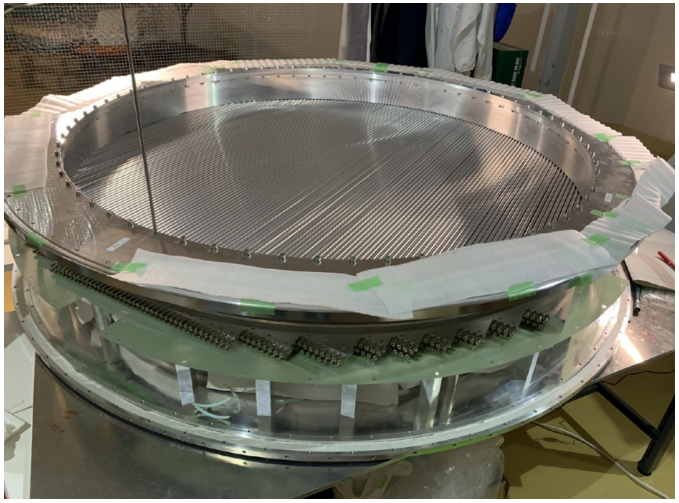
COMET @ JPARC

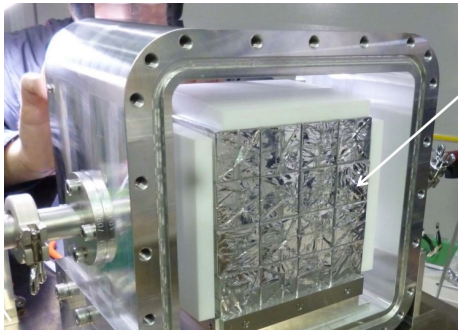
Phase-I

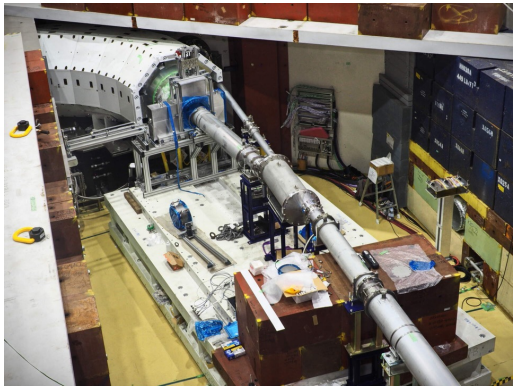


Phase-II

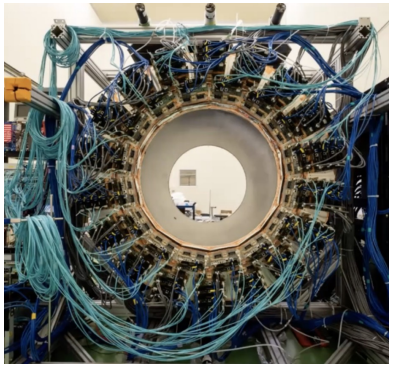






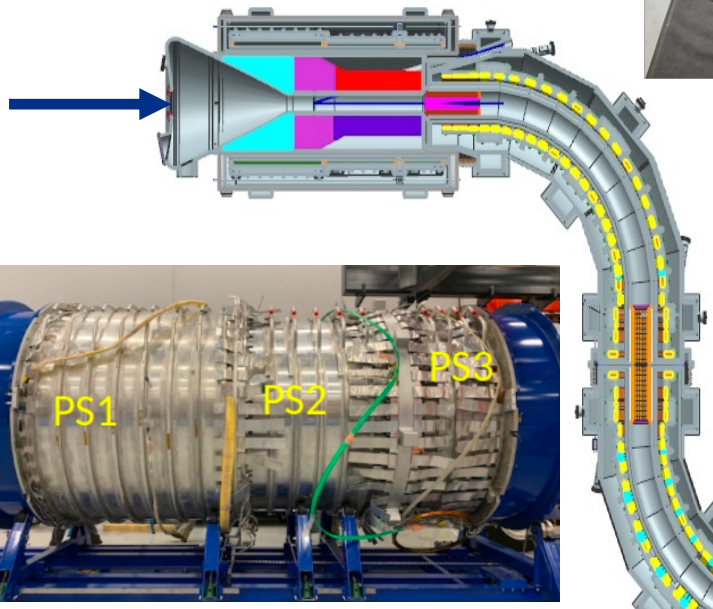


Imperial



Mu2e @ FNAL

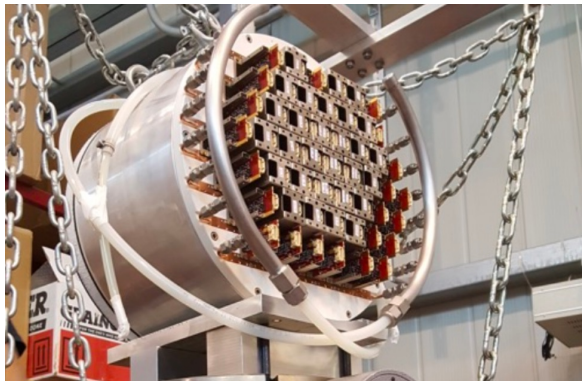
Production Solenoid



Transport Solenoid

Detector Solenoid &CRV

Tracker

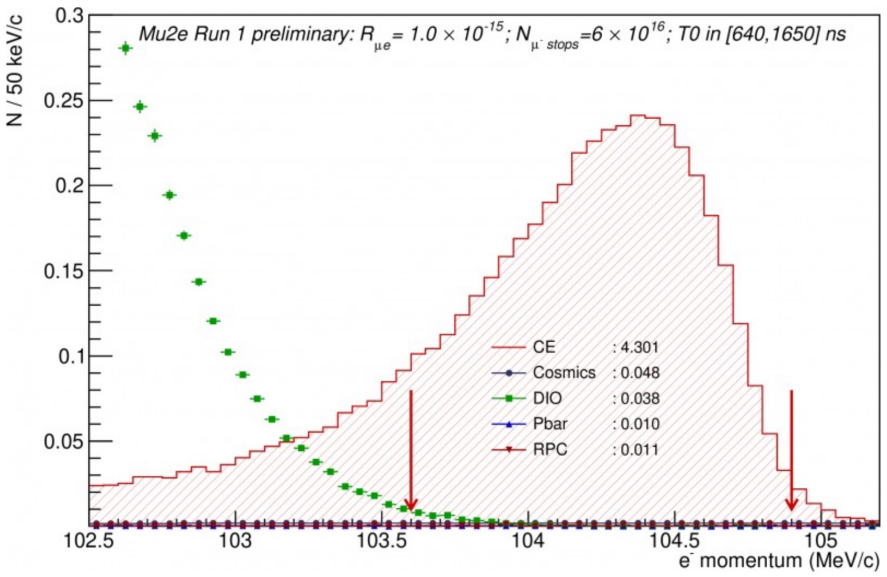


Al-Stopping Target

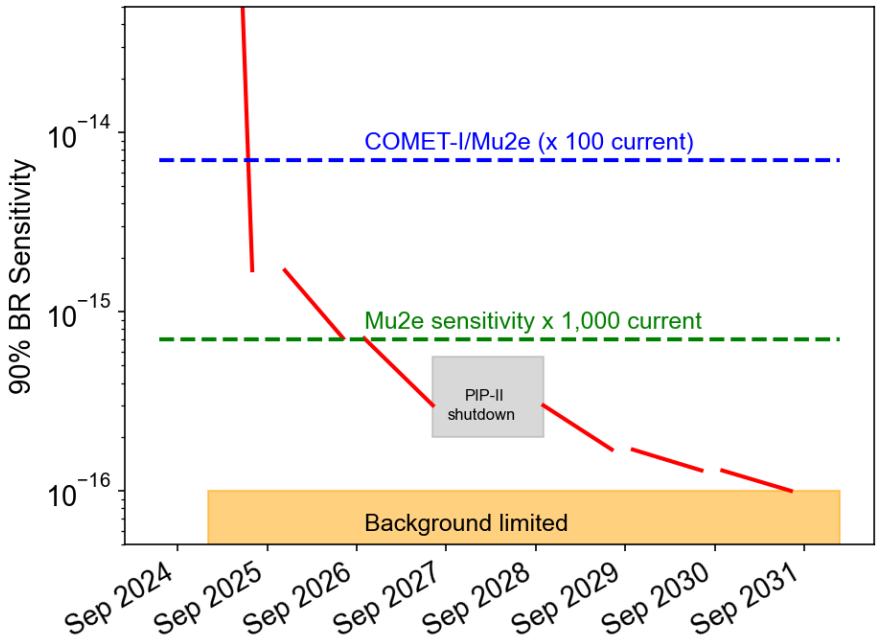
Calorimeter

Liverpool, Manchester, UCL

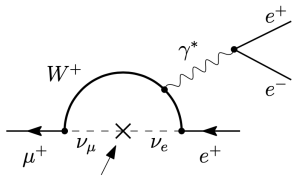
Mu2e / COMET-I



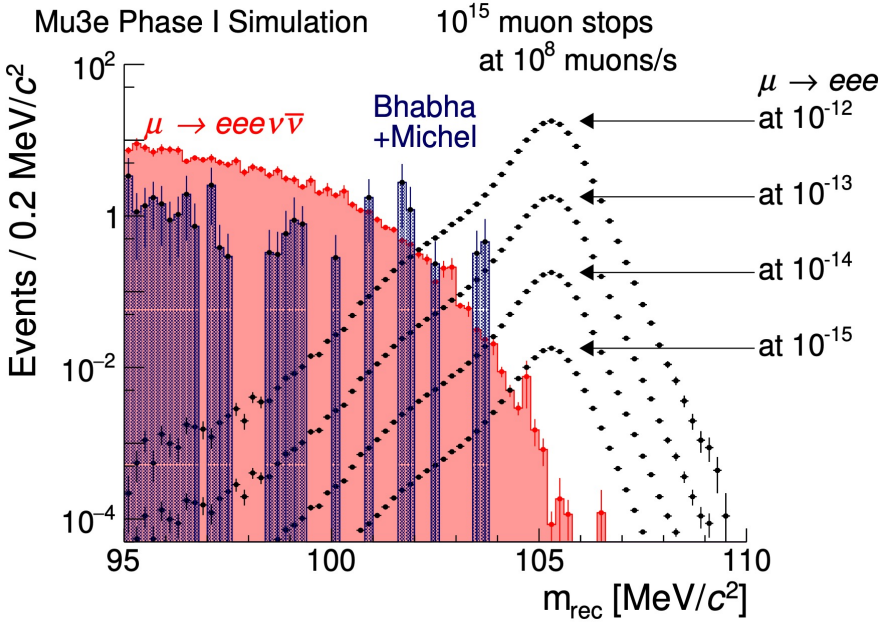
Beam commissioning 2023
Physics running 2024/25

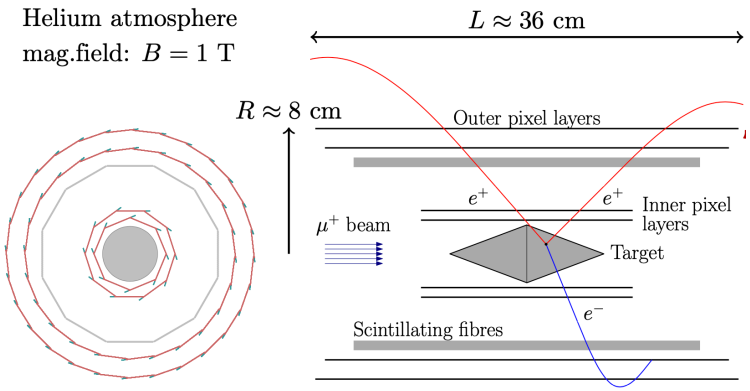


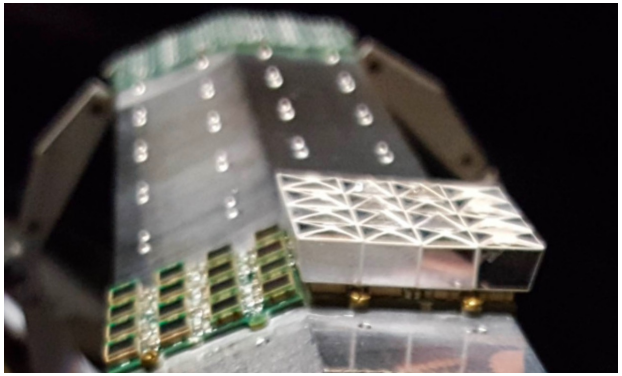
Mu3e

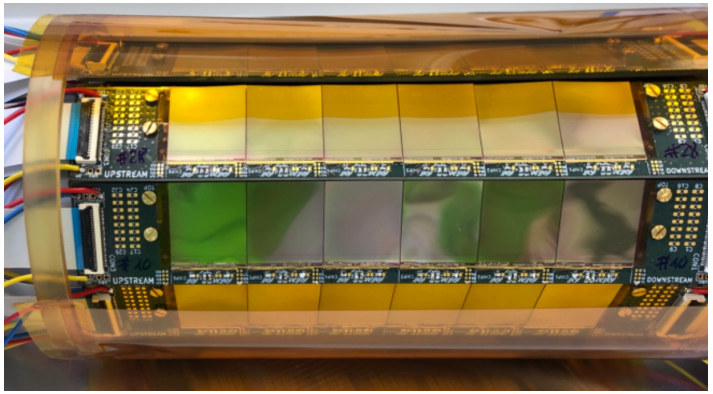


10^3 improvement in limit - Phase-I & further factor of ~ 10 (Phase-II) with HIMB 10^{10} μ/sec upgrade









Bristol, Liverpool, Oxford, UCL

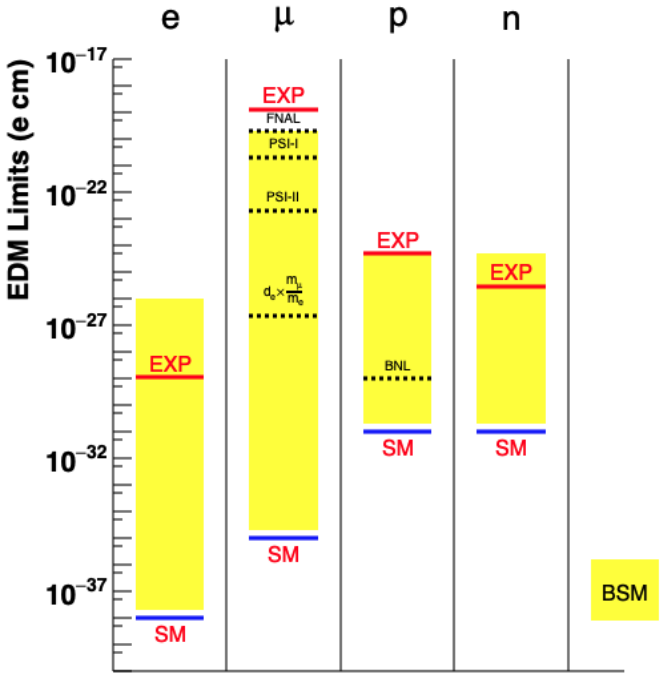
Commissioning now : physics run: 2025

MuEDM at PSI

LHCb / g-2 measurements hint that muon interactions may harbour BSM and lepton universality not sacred.

Motivates search beyond chirality flipping, flavour violating interactions to CP-violating interactions.

Enhancements beyond mass scaling possible in many BSM scenarios



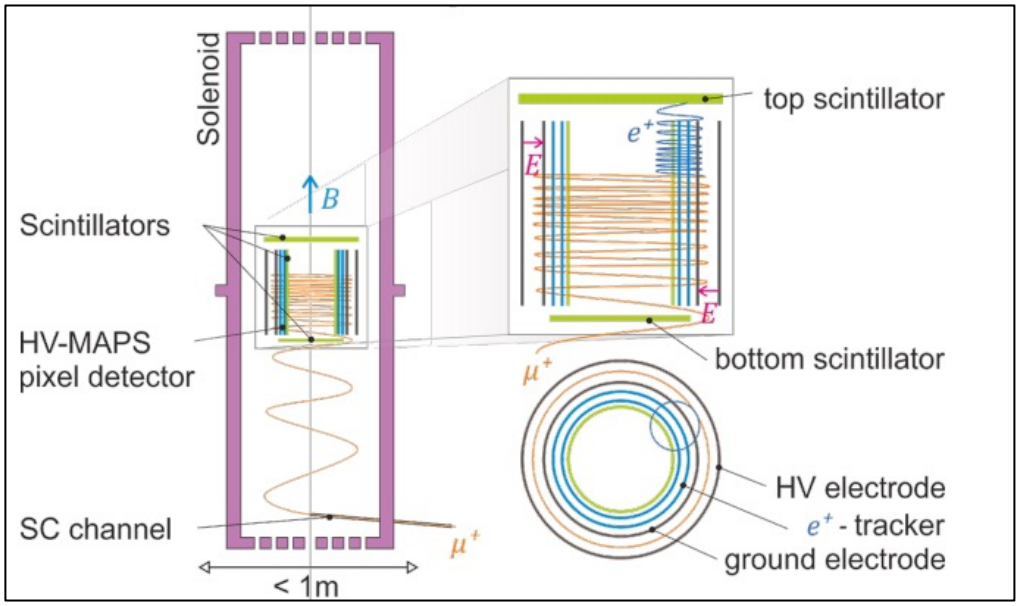
New experiment at PSI to extend x10 (Phase-I) beyond FNAL g-2 and then 2 more orders of magnitude in Phase-II using HIMB PSI upgrade to 2 x10^{-23} e.cm

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
- Vertical injection, thinned Si tracker, 10^{10} μ/s

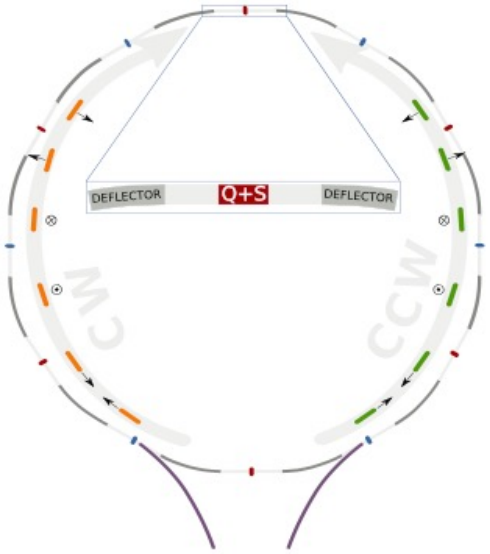
SoI to STFC for Phase-I submitted and proposal UKRI Infrastructure Fund for Phase-I/II

Cockcroft, Lancaster, Liverpool, Manchester, UCL

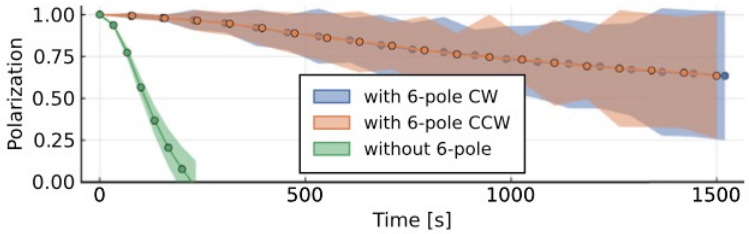
Proton EDM at BNL

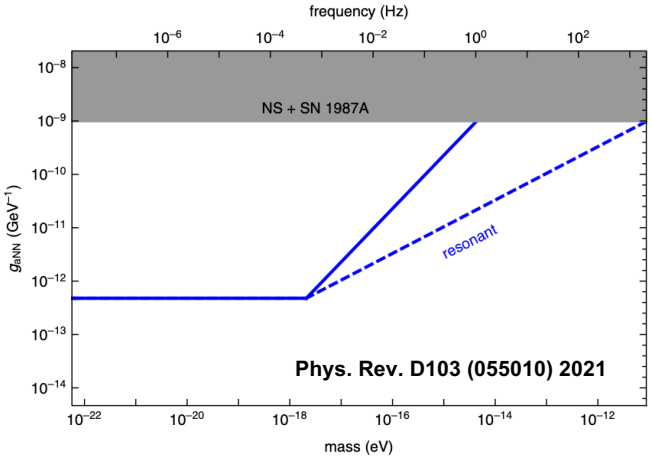
Utilises similar frozen spin methodology

Prior EDM measurements used atoms but 4 orders of magnitude (10^{-29} ecm) improvement by using dedicated proton storage ring : 700 MeV, 800m circumference, 4.4 MV/cm E-field.



UK proposing to build E-field electrodes: stability & alignment of which limit the EDM sensitivity





Also sensitive to axions over a wide region of parameter space

Conclusions

Interesting time for muon physics with a vibrant, leading UK involvement.

Final Muon g-2 results in next 2-3 years and Mu2e/COMET/Mu3e to start data taking - subject of bids to PPGP for exploitation.

Opportunity now to develop frozen spin EDM technique initially on muons (PSI) & then protons (BNL) to extend EDM sensitivities by 3-4 orders of magnitude.

Latter two and phase-2 of Mu3e subject of UKRI infrastructure bid : low-mass tracking.