High Intensity Muon Beam Physics

IOP Institute of Physics

HEPP & APP Annual Conference 2022

3-6 April 2022, Rutherford Appleton Laboratory STFC, Oxfordshire, UK

Mark Lancaster

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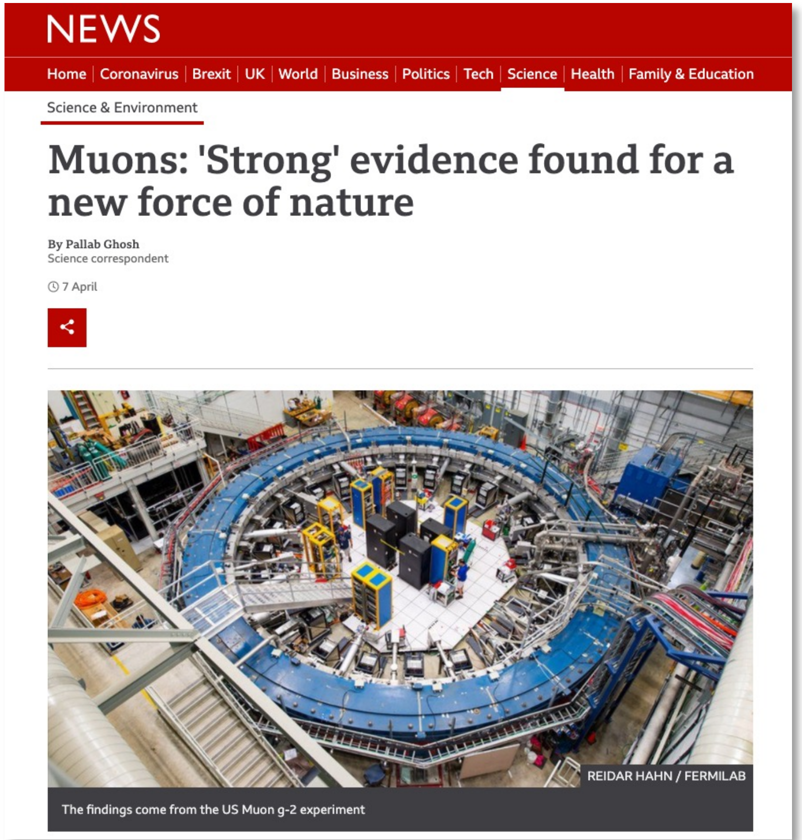
ATLAS/CMS
B-Factories
Theory
ν Experiments
Muon Experiments



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Science & Environment

Muons: 'Strong' evidence found for a new force of nature

By Pallab Ghosh
Science correspondent

7 April

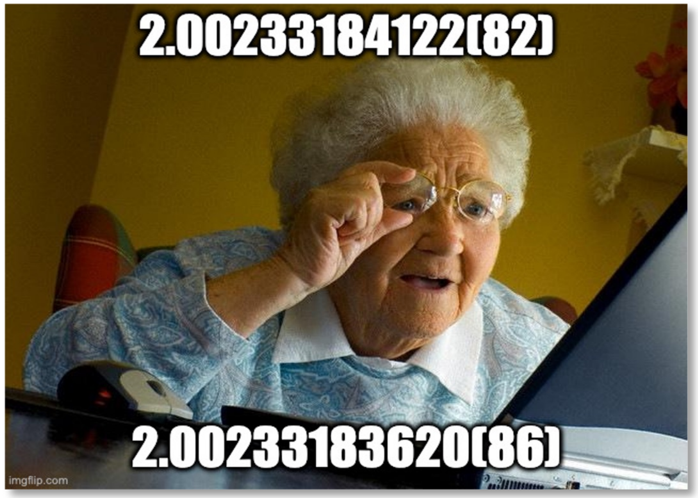
REIDAR HAHN / FERMILAB

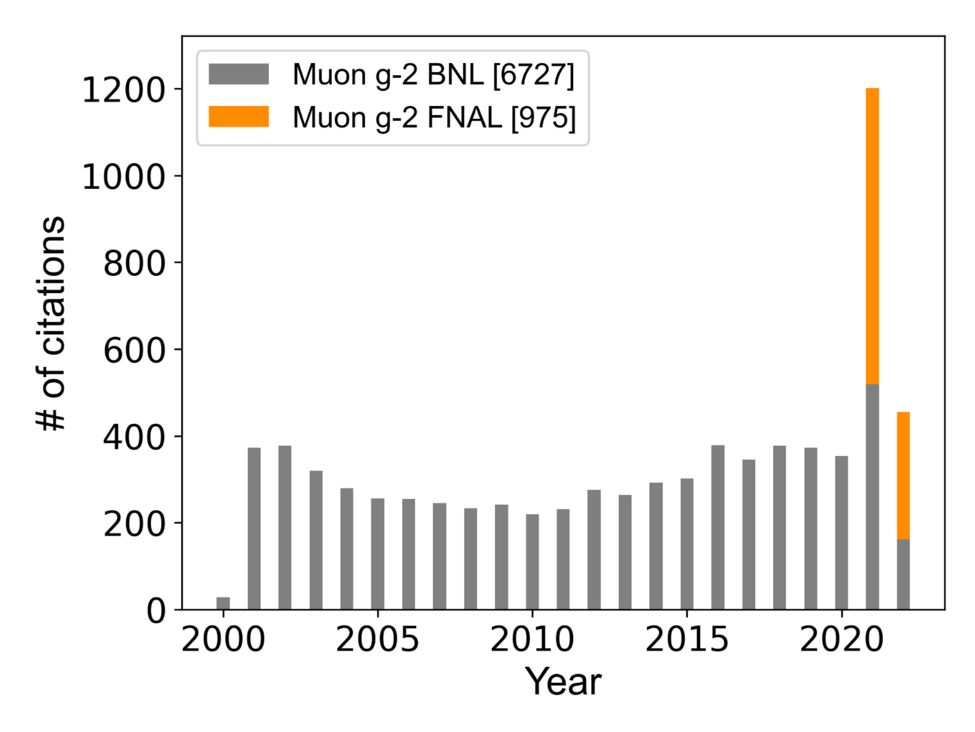
The findings come from the US Muon g-2 experiment

'Last Hope' Experiment Finds Evidence for Unknown Particles

27

Today's long-anticipated announcement by Fermilab's Muon g-2 team appears to solidify a tantalizing conflict between nature and theory. But a separate calculation, published at the same time, has clouded the picture.





$ 0.5-1B of Muon Experiments

PSI
MEG
MuMass
CREMA
MUSE
Mu3e
MuEDM

CERN
MUonE

J-PARC
DeeMe
Museum
COMET
g-2

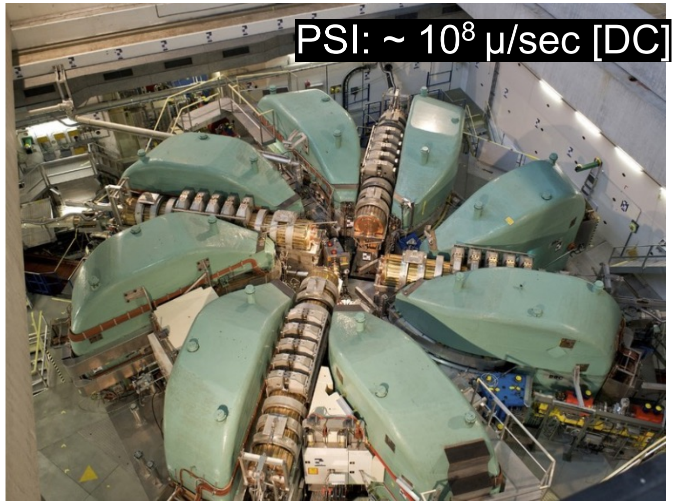
FNAL
g-2
Mu2e

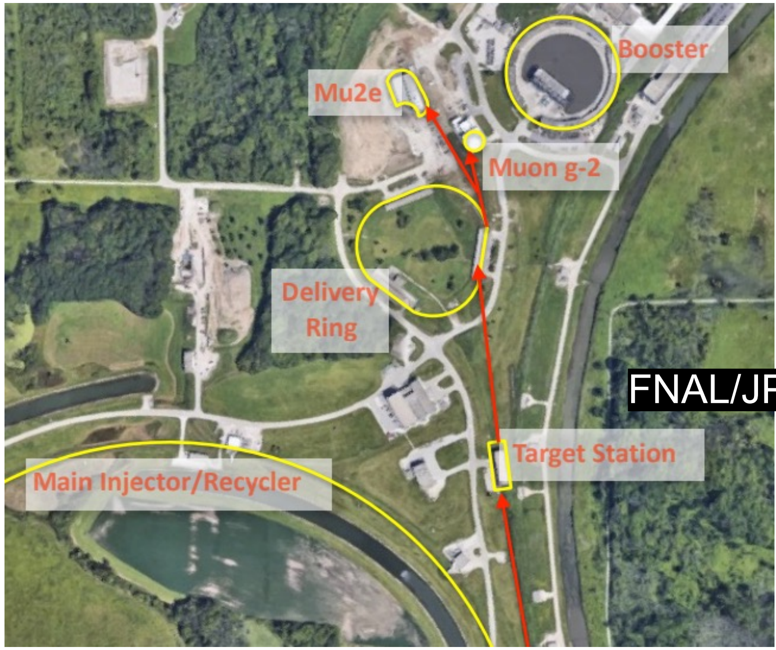
Two Types of Measurement

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)

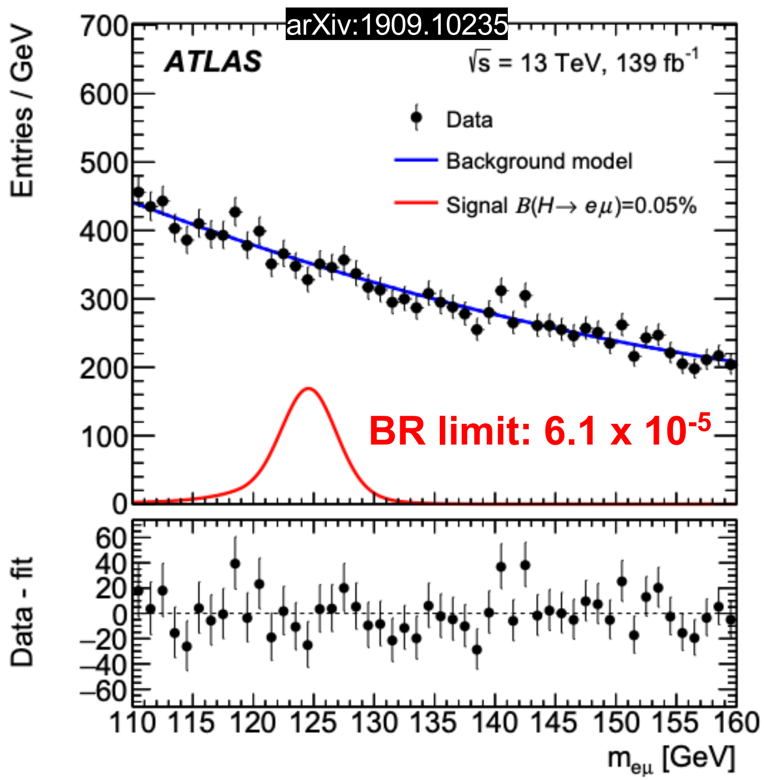


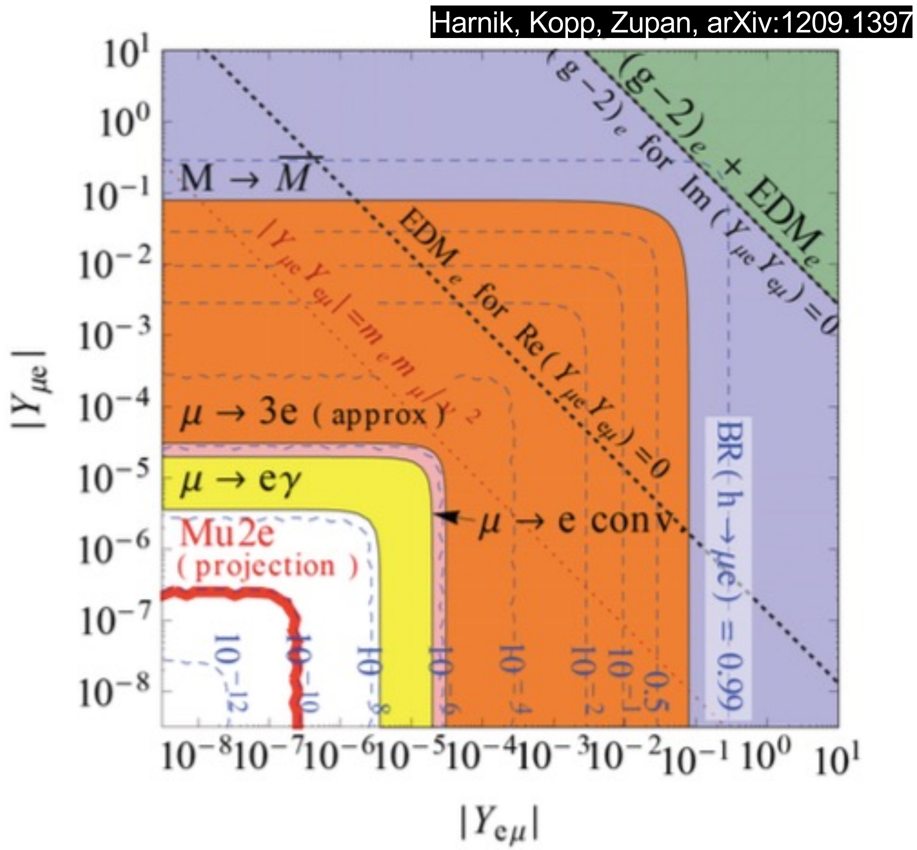


FNAL/JPARC: ~ 10^{10} μ/sec [Pulsed]

Why Muons ?

Can be produced in large numbers and live long enough

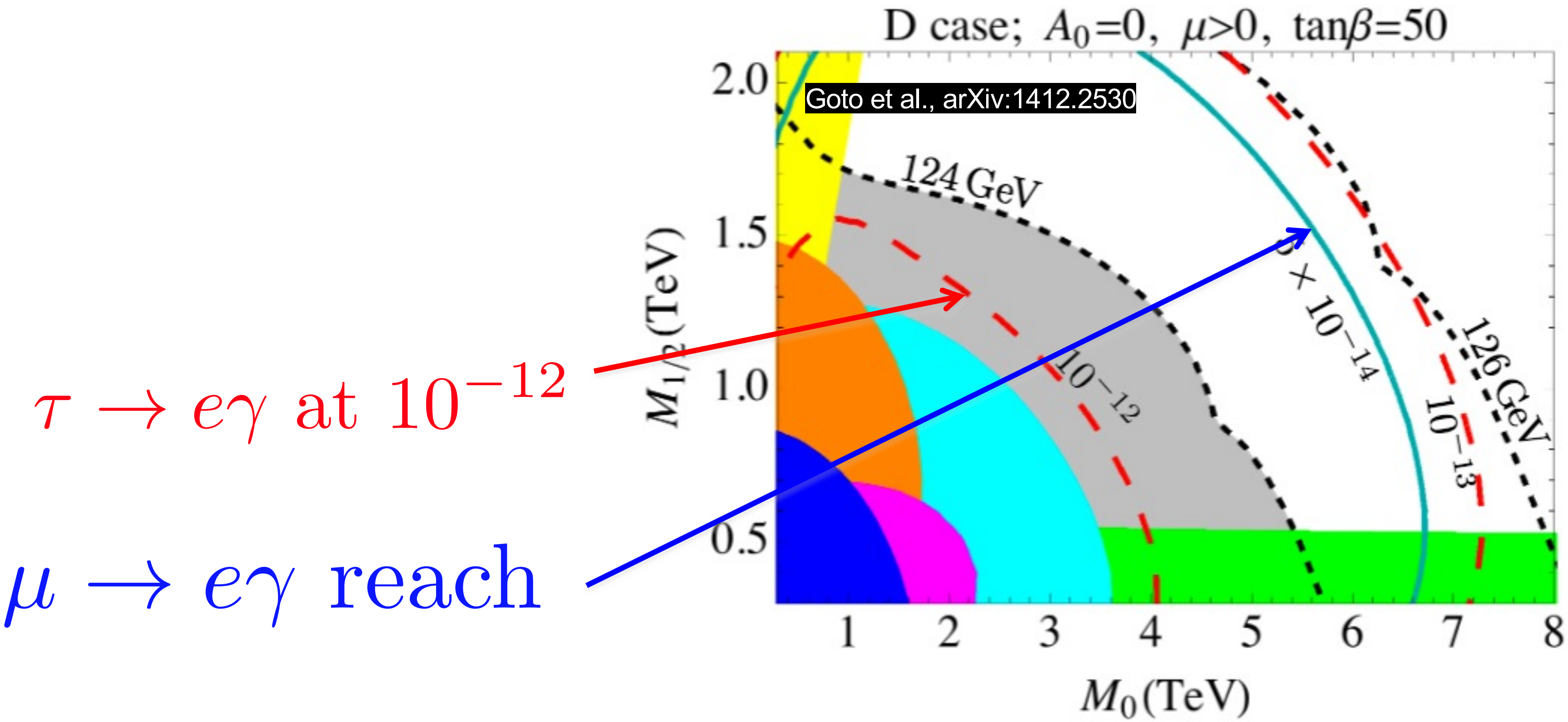




Mu2e/COMET have sensitivity to BR ($h \to \mu e$) of 10^{-10}

Comparison with Taus

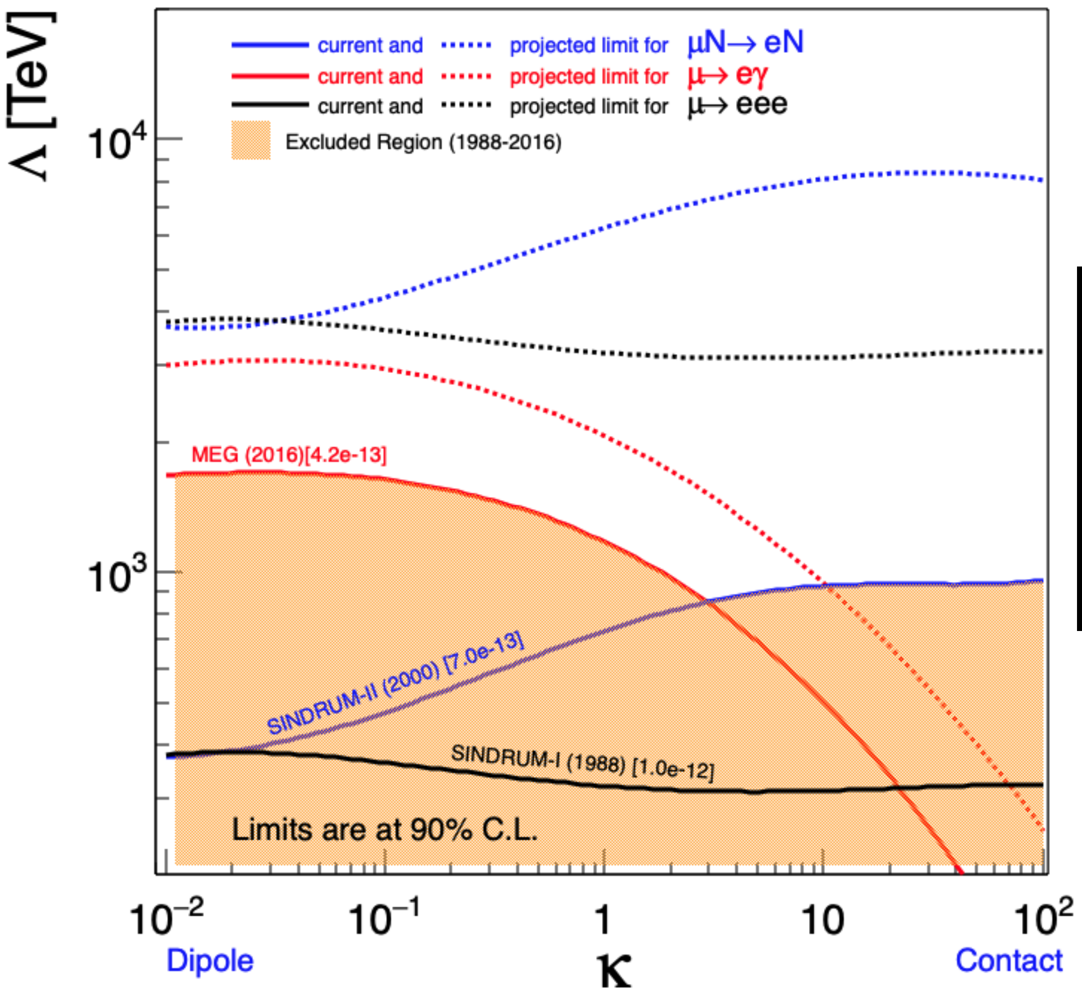
To probe similar regions of parameter space typically requires the τ BR sensitivity to be O(10^3) beyond near-future capabilities.



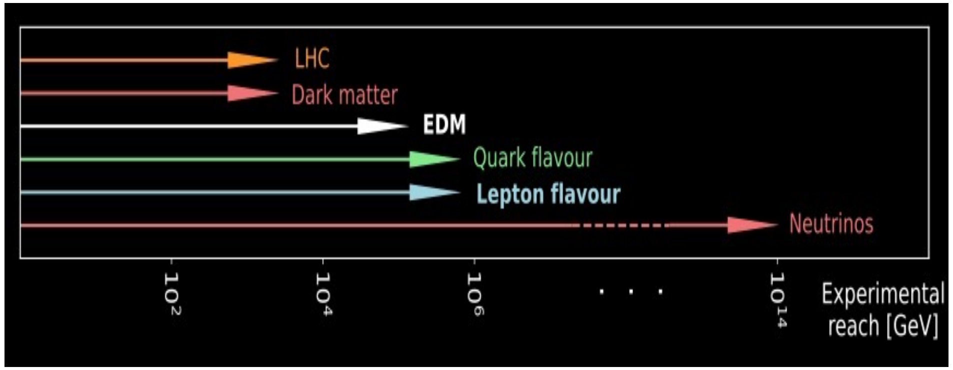
BUT It is vitally important that τ-interactions as well as μ-interactions are studied.

The 3rd generation may well be peculiar.

Access to high mass scales

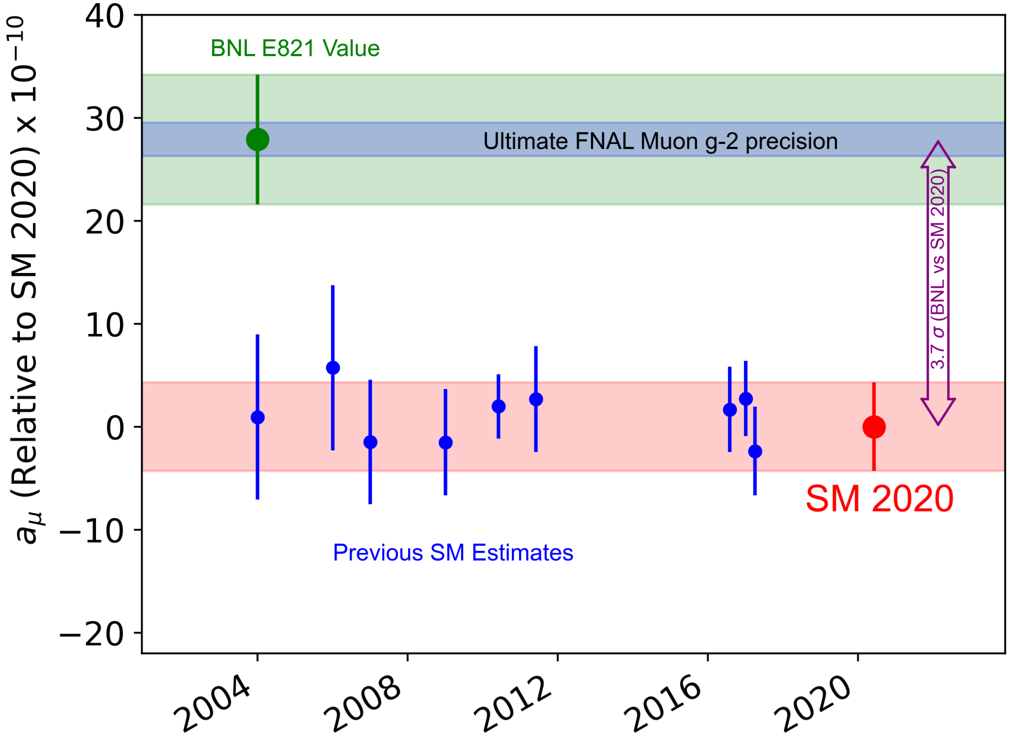


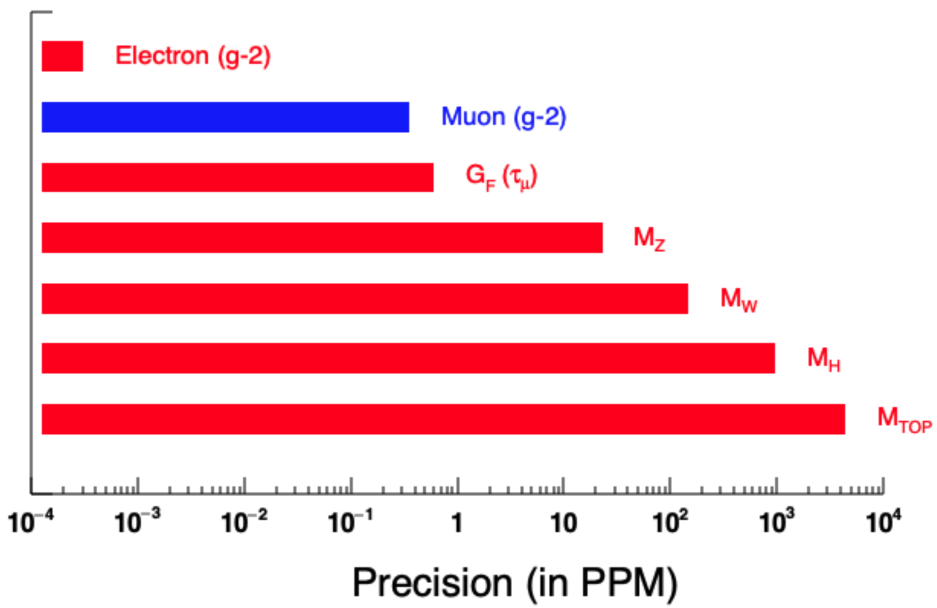
Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097



Muon g-2

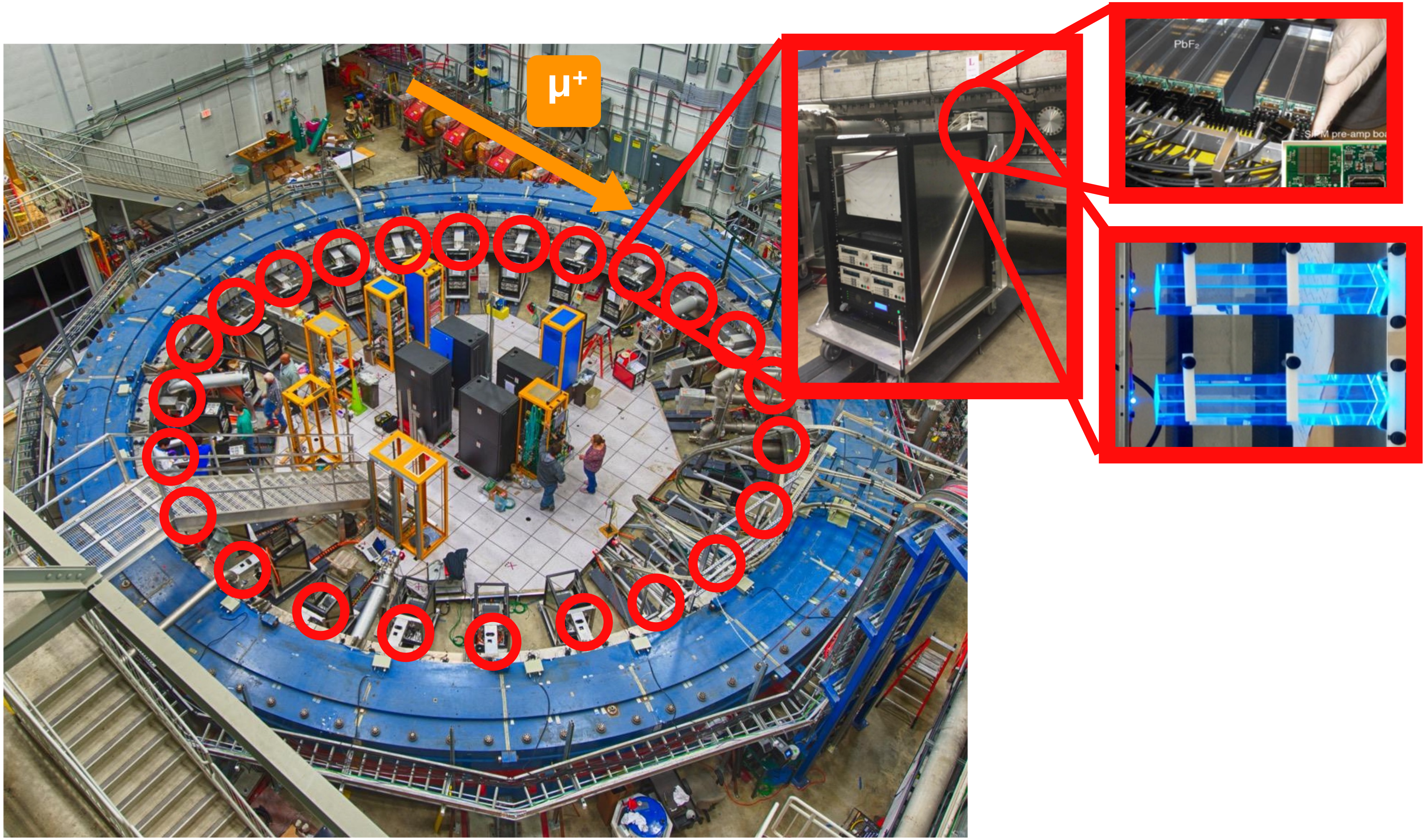
Most precise quantity measured at a particle accelerator





Latest FNAL measurement based on a dataset of similar size to BNL ~ 10 billion μ^+

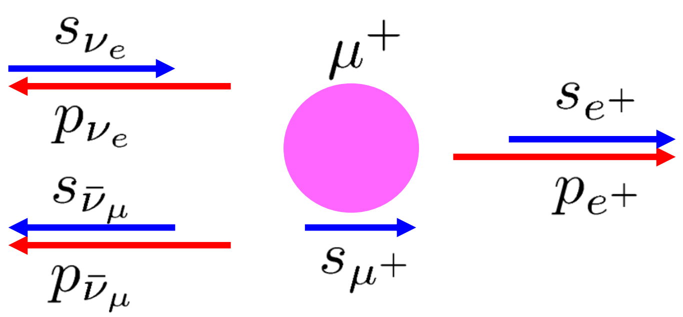
FNAL g-2 Experiment

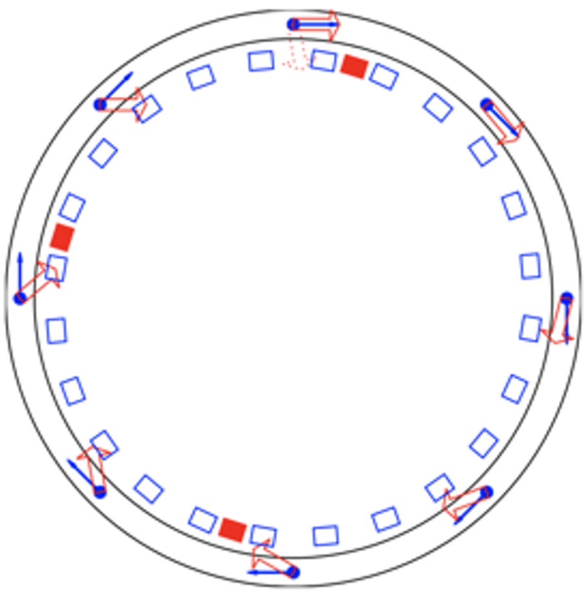


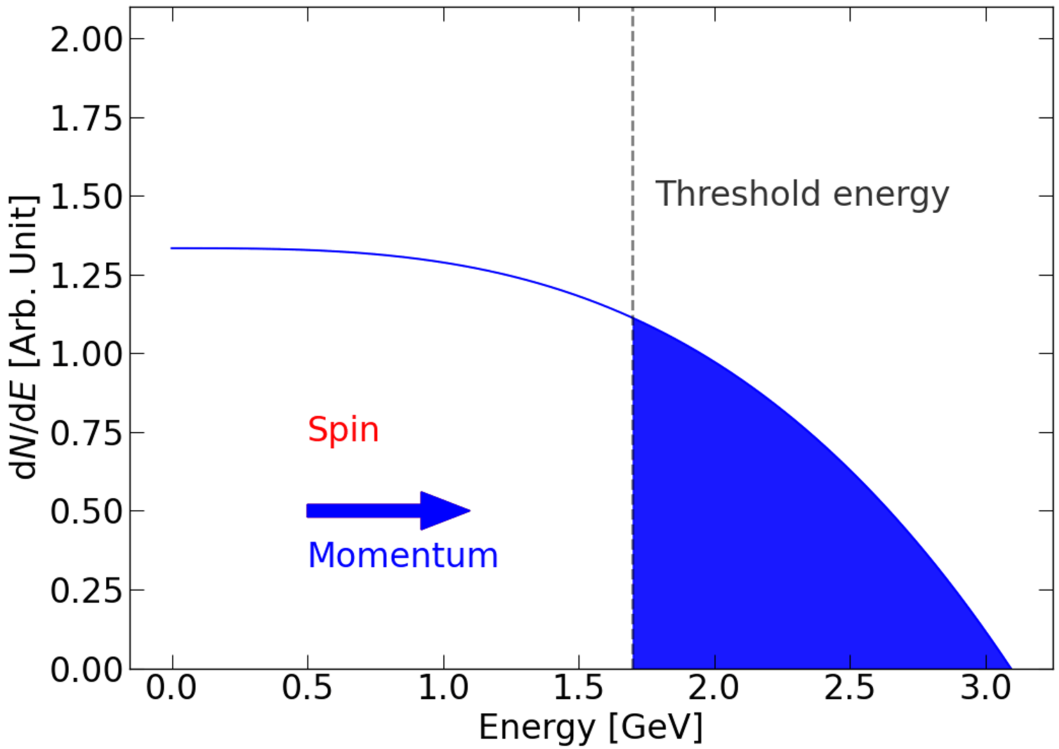
Measuring ω_a

$$\Delta\omega = \left(\frac{g-2}{2}\right)_\mu \frac{eB}{mc} = a_\mu \frac{eB}{mc}$$

- e+ preferentially emitted in direction of muon spin



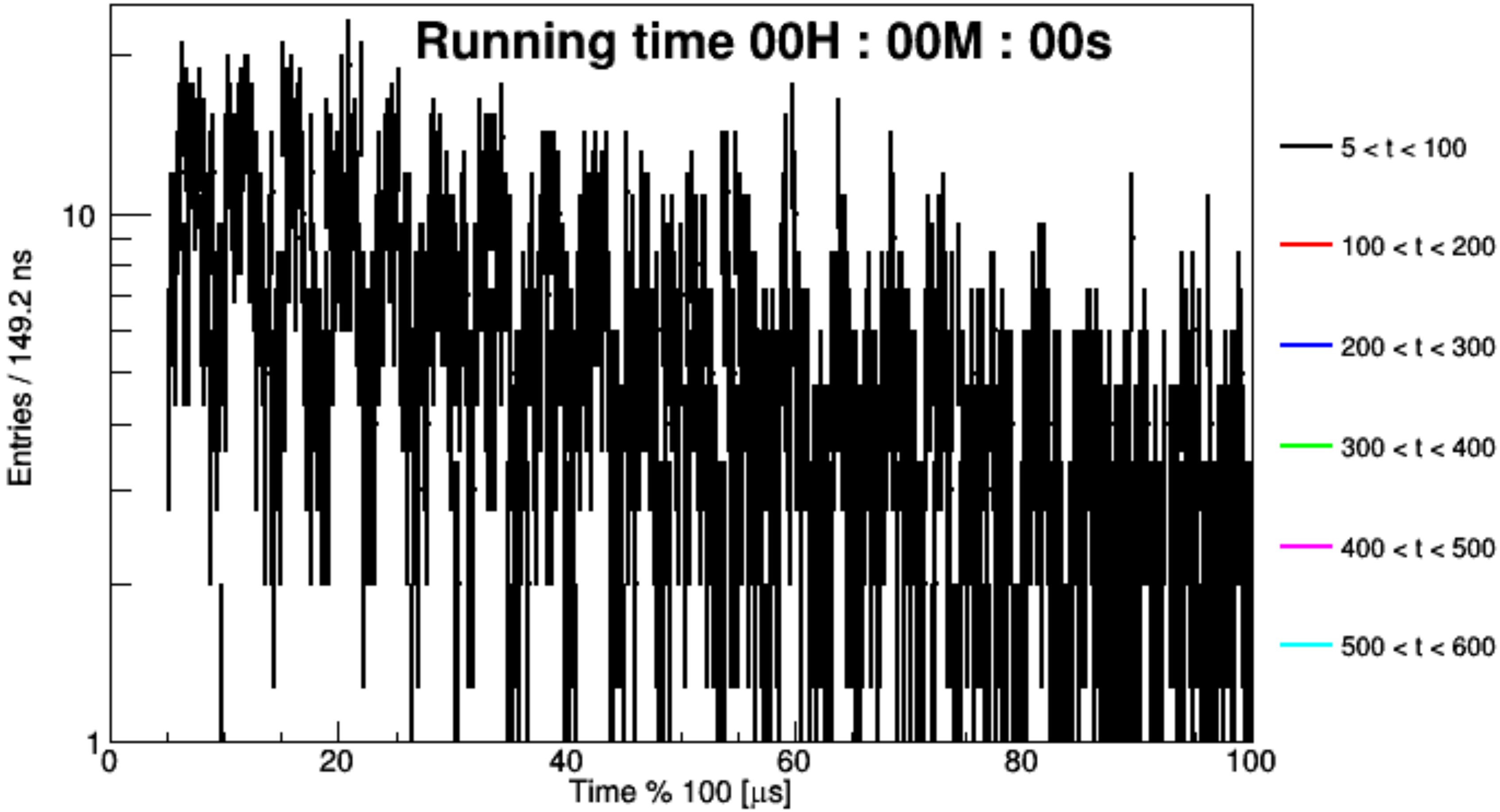




The number of high momentum positrons above a fixed energy threshold oscillates at precession frequency (ω_a)

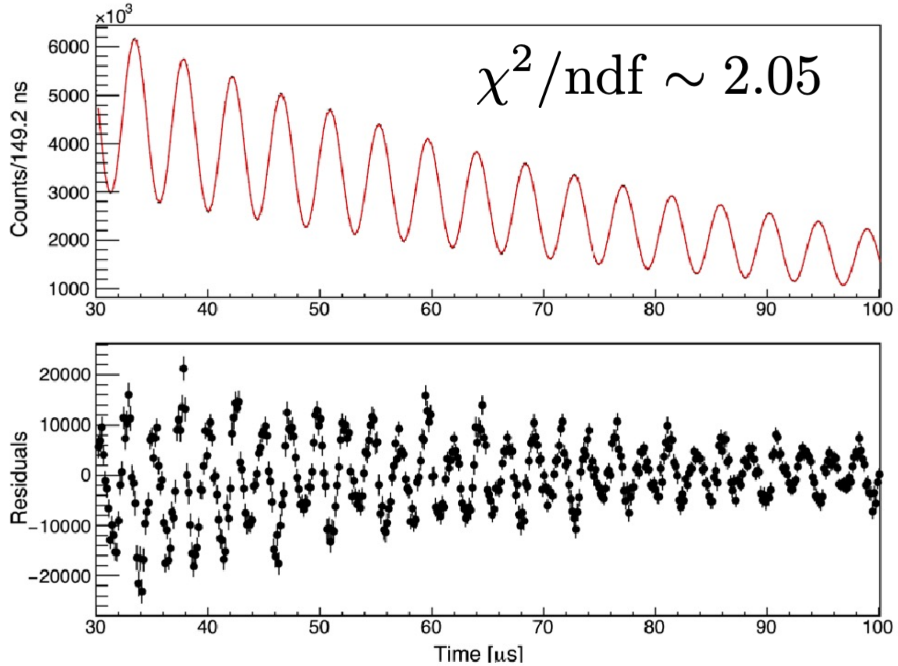
Simply count the number above an energy threshold vs time

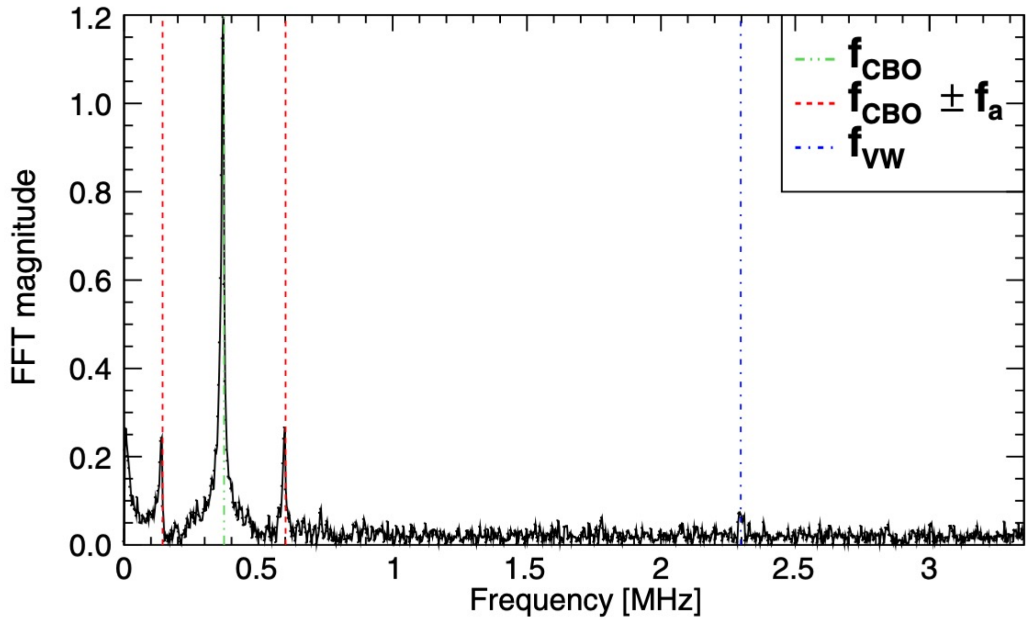
Precession in 1 hour of data



$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

Results of 5 parameter fit



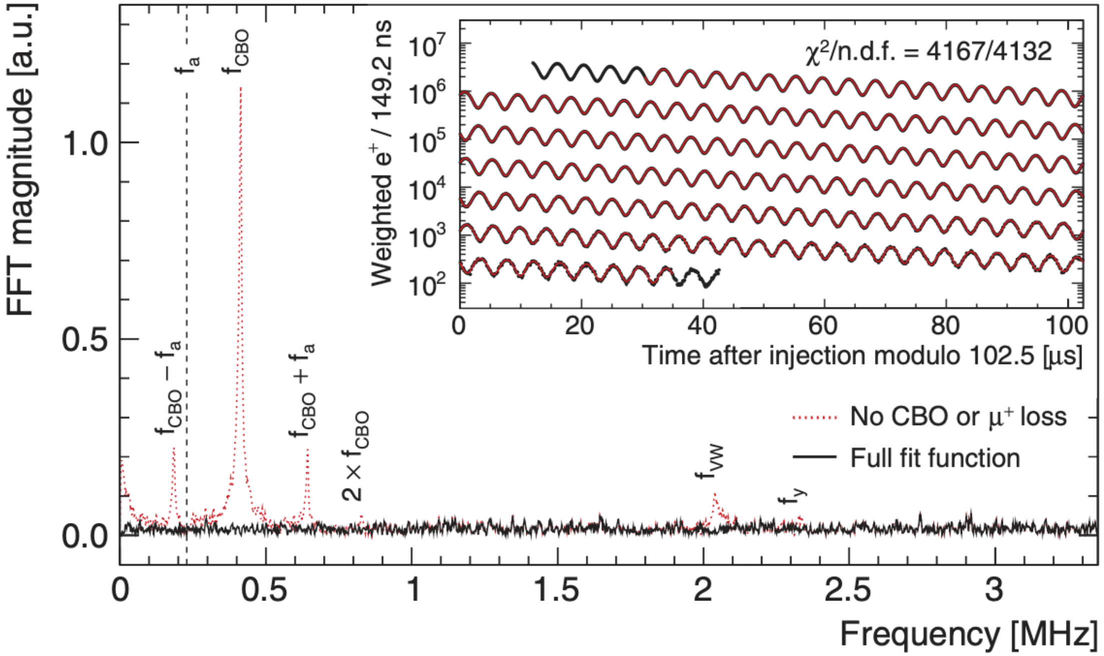


Add additional 17 terms in fit to describe:

- Muons lost from storage ring not by decaying
- Pileup (concurrent, multiple e^+ in same calorimeter crystal)
- Vertical and radial beam motion

And get $\chi^2/\mathrm{ndf} \sim 1.008$

Resulting 22 Parameter Fit



Phys. Rev. D 103, 072002 (2021)

Statistical uncertainty from this fit : 434 ppb

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

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

Deviation from SM (with BNL) : 2150 ppb

Systematic Uncertainties

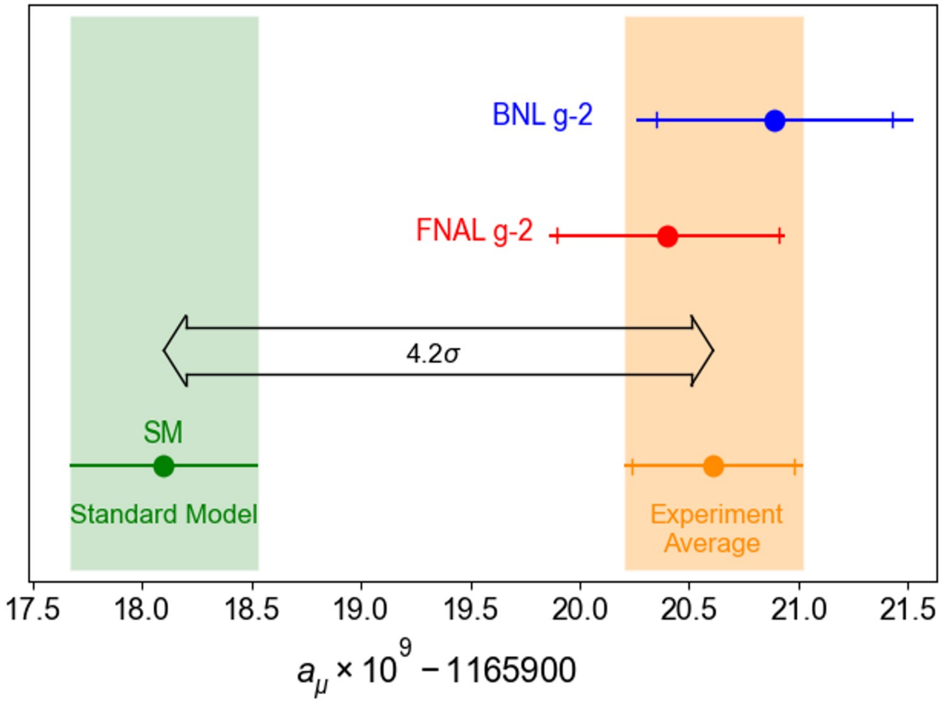
~ 80 effects considered significant in determining the systematic uncertainty. Dedicated runs taken for some of them e.g. at different beam momentum.

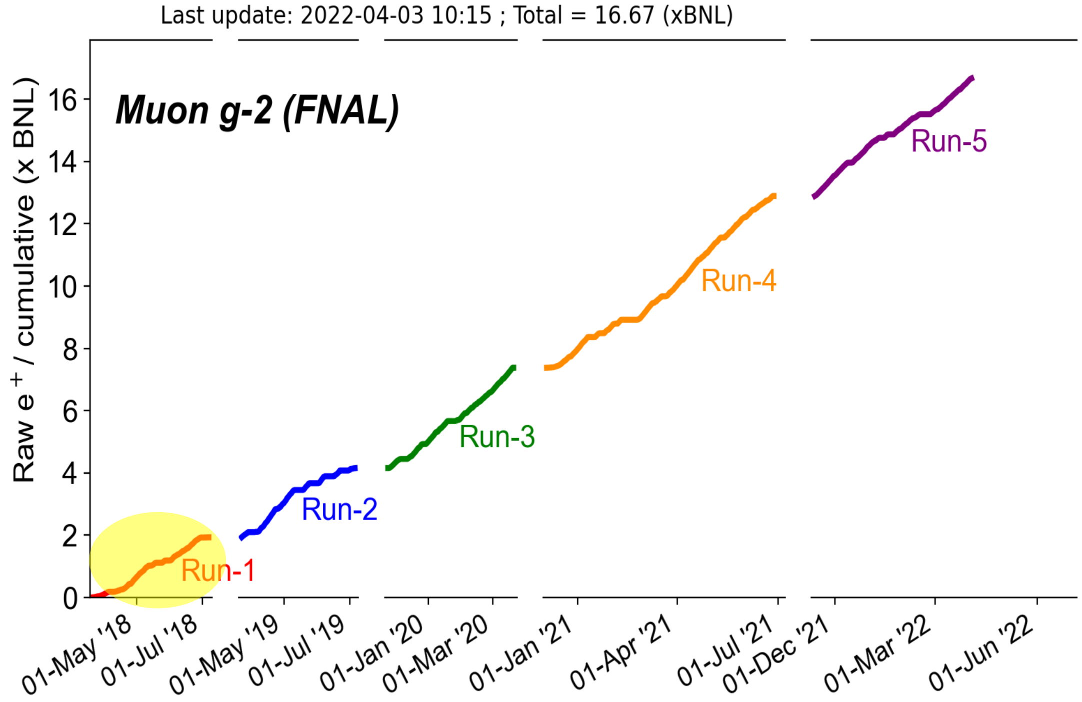
Total systematic uncertainty 157 ppb. Those above 30 ppb are below

Source	Systematic Uncertainty (ppb)	Improvements undertaken
Calorimeter pileup	35	
Beam Mean Momentum & Spread	53	Increased kicker voltage: 130-161 kV
Drift of beam over measurement	75	Replaced damaged quadrupole resistors
Transient B-field (from kicker)	37	Improved magnetometer
Transient B-field (from quadrupoles)	92	More extensive measurements / damping
Total	140	

Other effects at 10-20 ppb also significantly improved by better temperature control in the experimental hall.

Next FNAL measurements



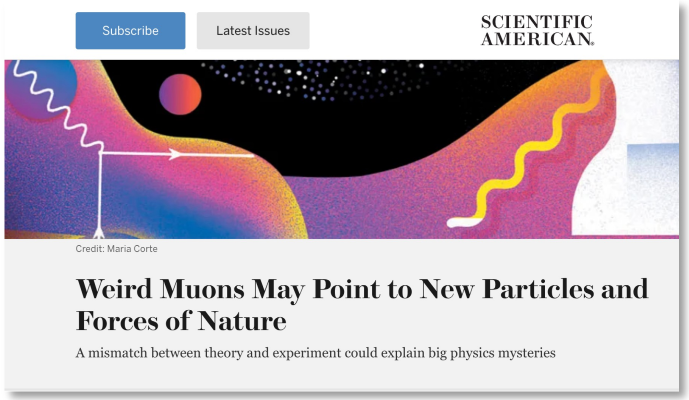


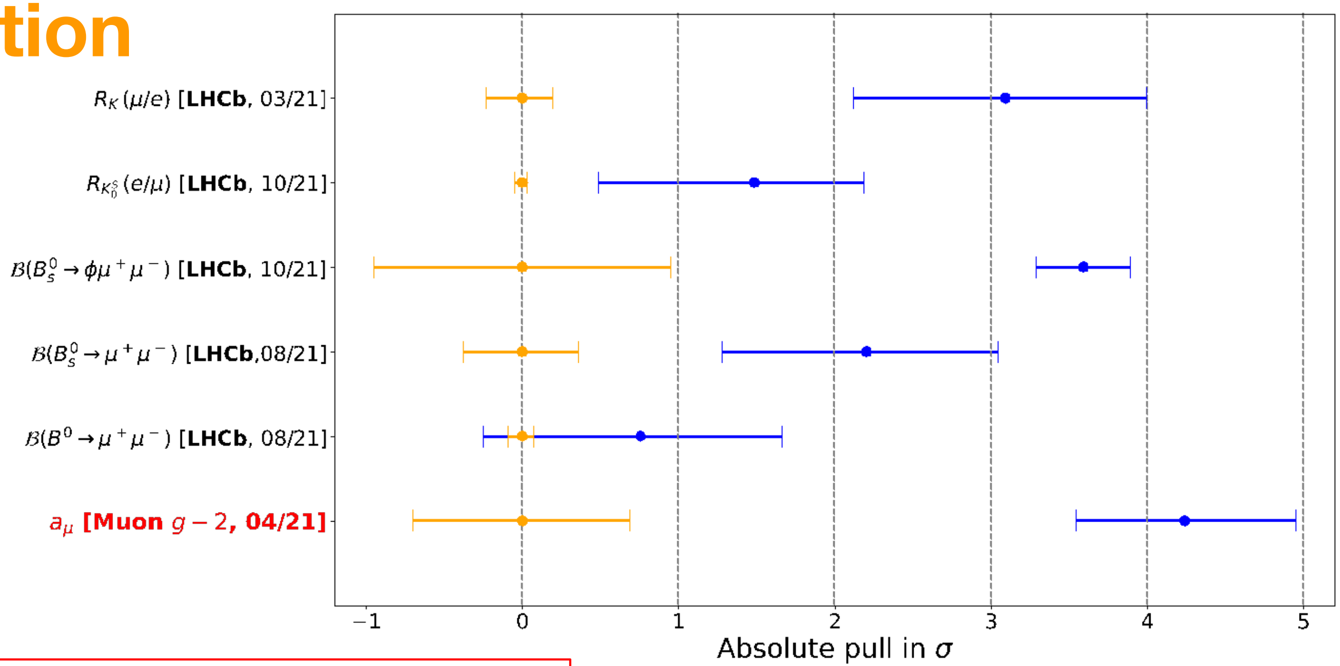
Exp-SM discrepancy: 2150 ± 350 (expt) ± 370 (theory) ppb (with BNL measurement)
Discrepancy is of comparable size to the SM EWK contribution to g-2.

Run-2/3 is now being analysed : should reduce statistical uncertainty by ~ 2 and so get uncertainty: 215 (stat.) ⊕ 100 (sys.) ~ 240 ppb (vs 460 ppb Run-1)

With final dataset (Run 1-6) expect stat. to be approx. 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…"

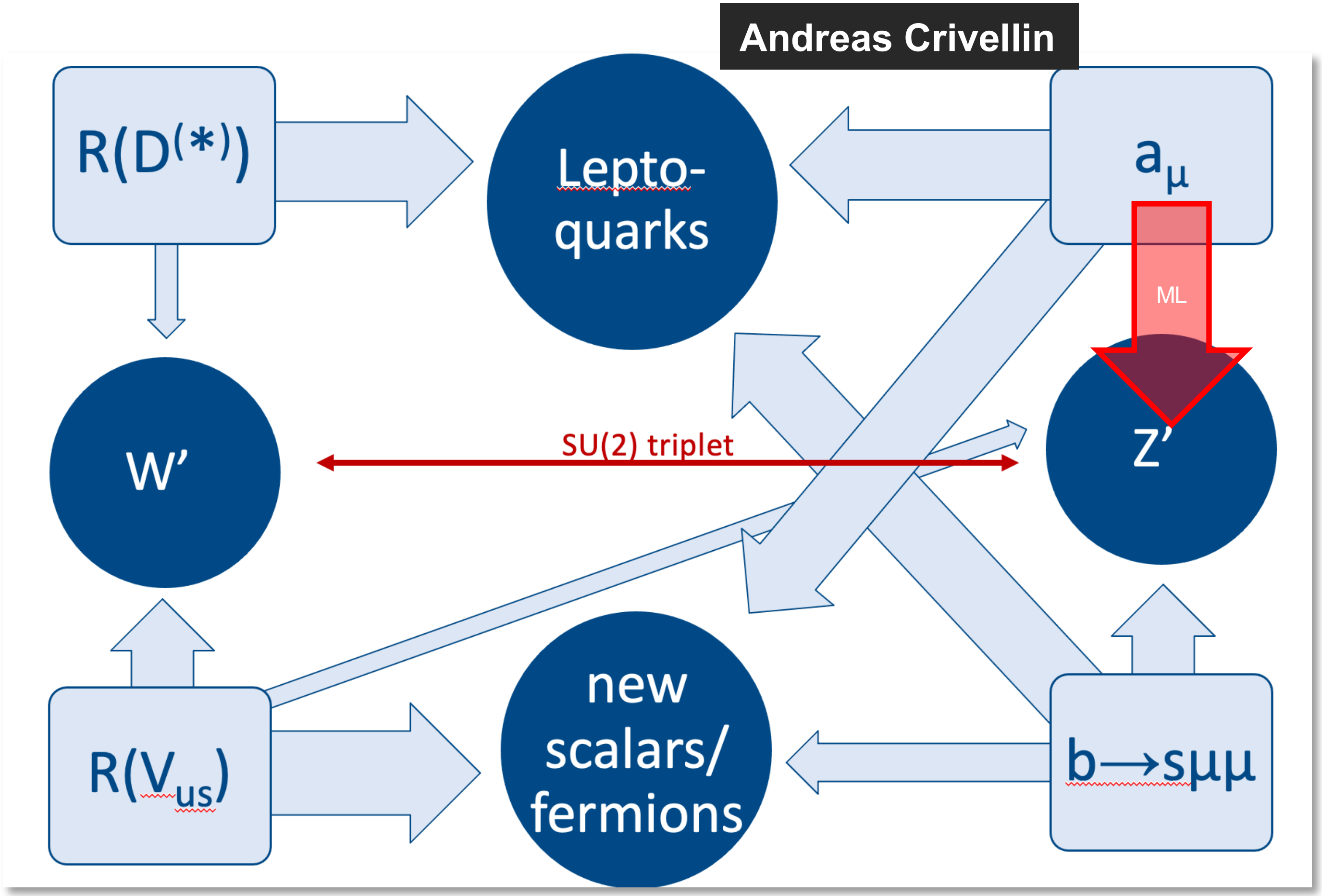
"I'm quite appalled by this procession of zombie SUSY models dragged out of their graves…"

"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

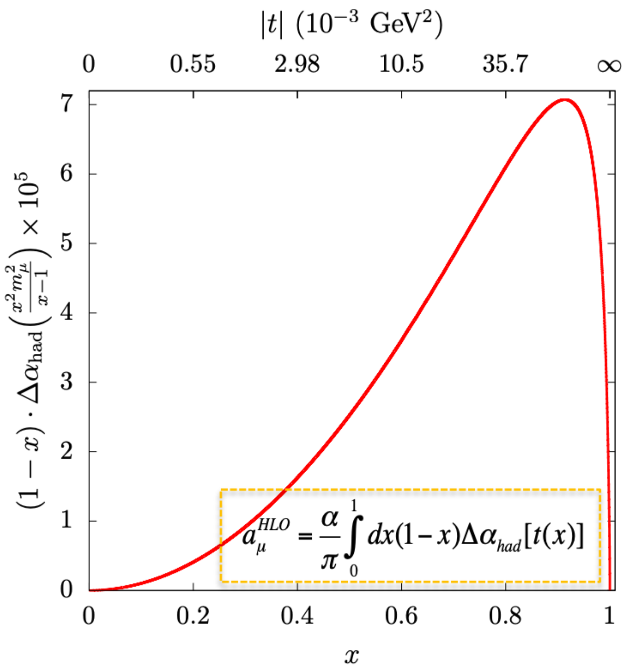
TeV Leptoquarks
Z', ALPs
LHC evading SUSY
Tweaked Higgs extensions ...

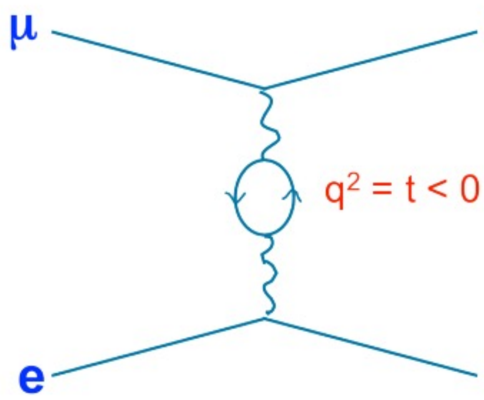
The fact that discrepancy is "large" (~ EWK contribution) and existing experimental constraints mean that BSM models tend to be in non-traditional parameter regions….

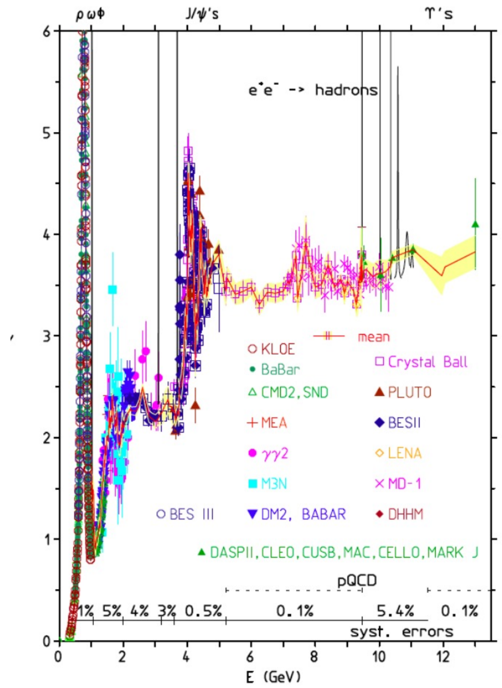


And …. low energy (keV-MeV) phenomena

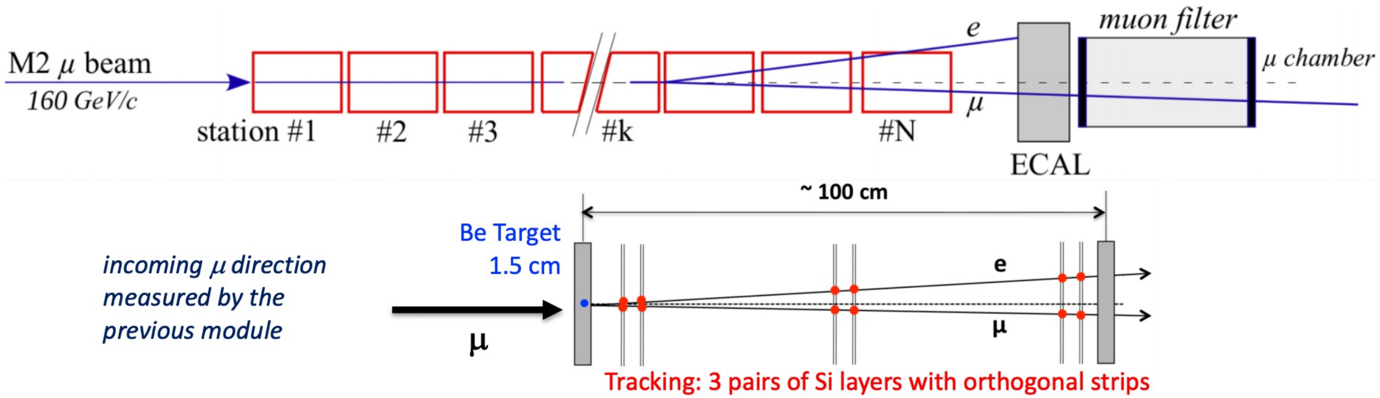
Cross checking the theory with experiment (MUonE)



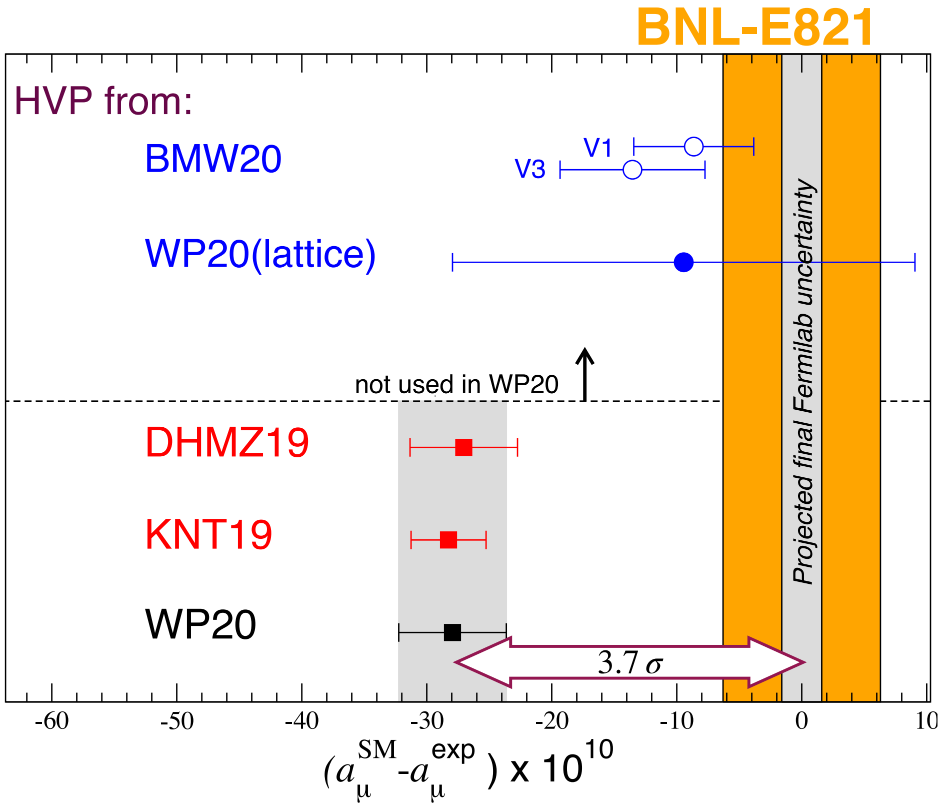




$$\frac{d\sigma}{dt} \rightarrow \Delta\alpha_{\mathrm{HAD}}(t) \rightarrow a_\mu^{\mathrm{HVP(LO)}}$$



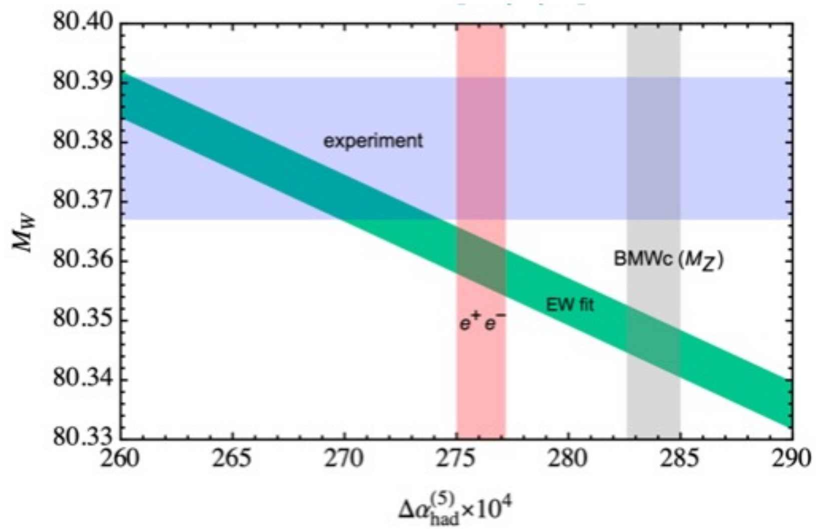
SM Prediction



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

If this is true then $\Delta\alpha^{(5)}_{\mathrm{HAD}}$ is affected and so are the global EWK fits

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%.**

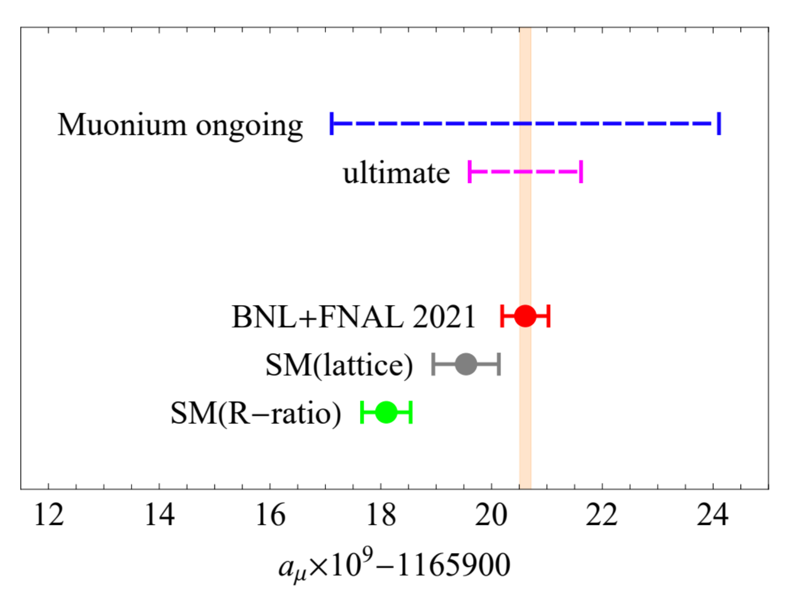
In this region there is data from 9 independent experiments: the most precise experiments (KLOE, BaBar, CMD, SND, ….) quote **cross section uncertainties of 0.5-1%...**

Muonium (μ^+e^-) Spectroscopy

Experiments at PSI (1S-2S) and JPARC (Hyperfine 1S splitting) provide key quantities: $\frac{m_\mu}{m_e}$ & $\frac{\mu_\mu}{\mu_p}$
allowing extraction of (g-2) from the data.

They can also potentially achieve ppm sensitivity to (g-2) **arXiv: 2106.11998**

Needs factor of two improvement in the current experiments: Mu-MASS (PSI) and MuSEUM (JPARC) and x10 improvement in QED theory (radiative recoil in Lamb shift) to improve R_∞



parameter (unit)	quantity	u_r current	ongoing	ultimate
m_e/m_μ (ppb)	ν_{1S-2S}(exp)	825	0.84	0.34
	QED(1S-2S)	1.7	1.2	0.1
	R_∞	0.40	0.13	
	total	825	1.5	0.37
a_μ (ppm)	ν_{1S-2S}(exp)	708	0.73	0.29
	ν_{HFS}(exp)	10	1.9	0.77
	QED(1S-2S)	1.4	1.0	0.07
	QED(HFS)	14	1.9	0.2
	HVP(HFS)	0.29	0.16	
	R_∞	0.35	0.13	
	α	0.26	0.14	
	total	708	3.0	0.88

BSM effects are suppressed

Experimental limits mostly statistical in producing sufficient muonium atoms.

The other muon anomaly

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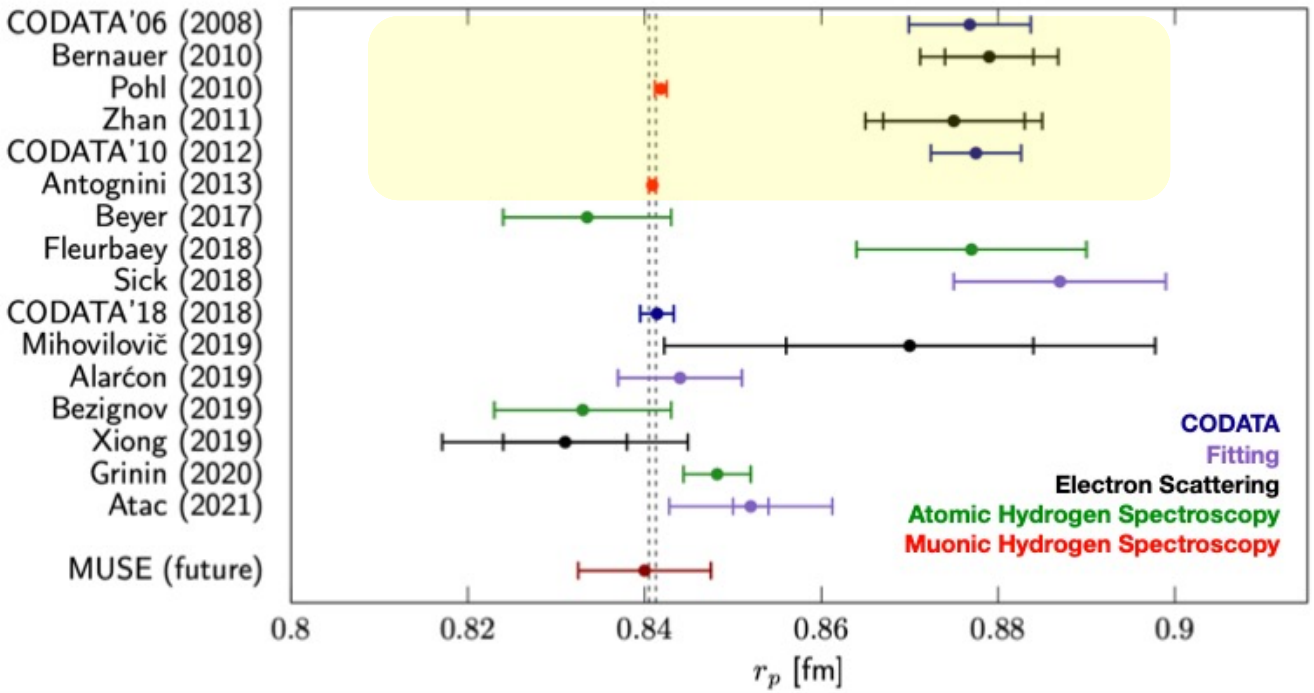
List of unsolved problems in physics

From Wikipedia, the free encyclopedia

Some of the major unsolved problems in physics are theoretical, meaning that existing theories seem incapable of explaining a certain observed phenomenon or experimental result. The others are experimental, meaning that there is a difficulty in creating an experiment to test a proposed theory or investigate a phenomenon in greater detail.

- Neutrino mass: What is the mass of neutrinos, whether they follow Dirac or Majorana statistics? Is the mass hierarchy normal or inverted? Is the CP violating phase equal to 0?[32][33]
- Strong CP problem and axions: Why is the strong nuclear interaction invariant to parity and charge conjugation? Is Peccei–Quinn theory the solution to this problem? Could axions be the main component of dark matter?
- Anomalous magnetic dipole moment: Why is the experimentally measured value of the muon's anomalous magnetic dipole moment ("muon g–2") significantly different from the theoretically predicted value of that physical constant?[34]
- Proton radius puzzle: What is the electric charge radius of the proton? How does it differ from gluonic charge?

Muonic hydrogen : proton radius



A small proton charge radius from an electron–proton scattering experiment

W. Xiong, A. Gasparian, […]Z. W. Zhao

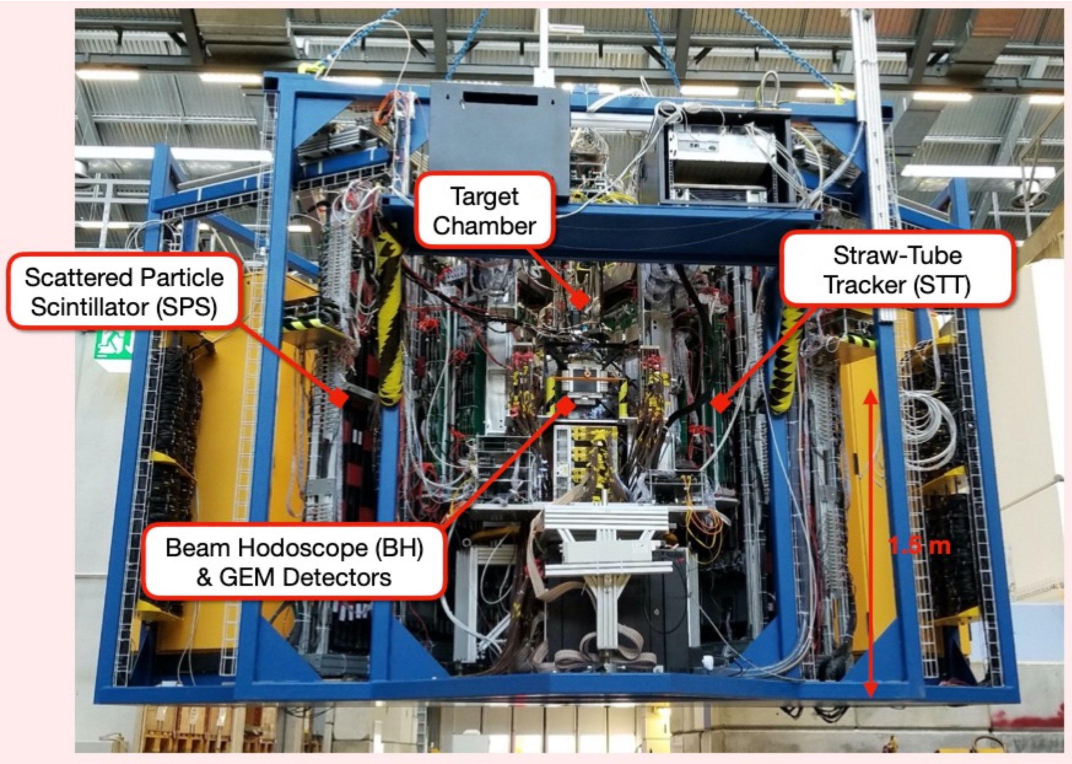
Nature **575**, 147–150(2019) | Cite this article

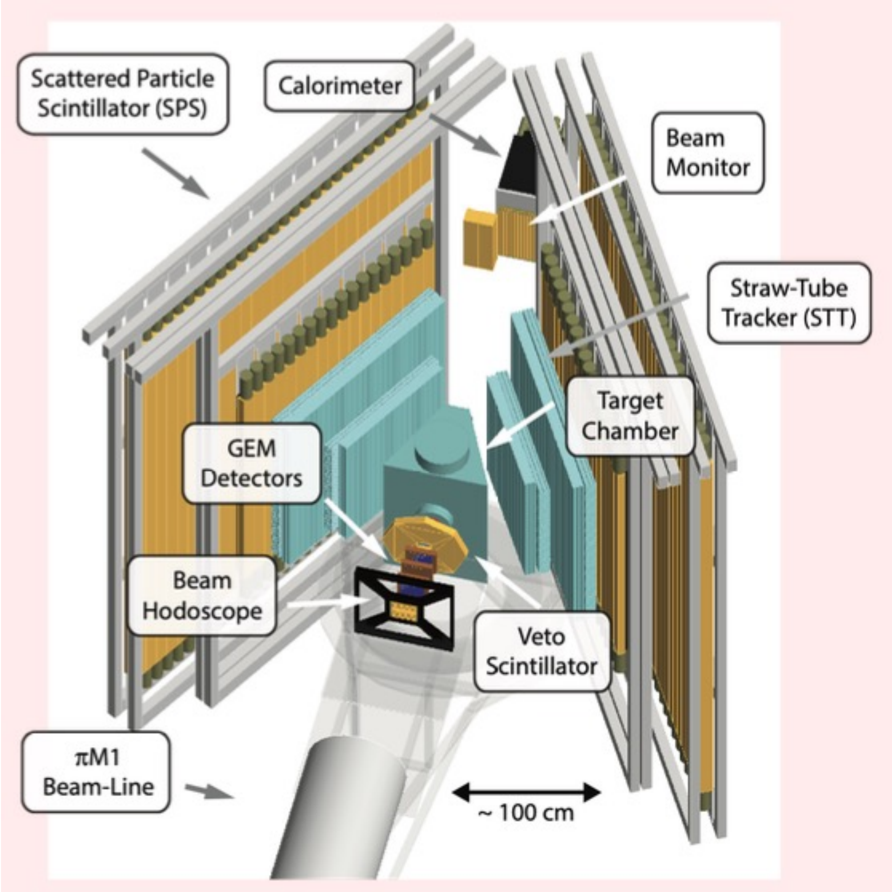
$$< r_p^2 >= -6\frac{dG_E}{dQ^2}|_{Q^2\to 0}$$

Most recent results point to a smaller radius, but there remain issues in the data, questions about the radiative corrections, and a lack of understanding about what might be wrong with earlier results

Muse Experiment at PSI

To measure $e^{+/-}p$ and $\mu^{+/-}p$ scattering with the same experiment : $0.002 < Q^2 < 0.08$ GeV^2 at the PiM1 beamline

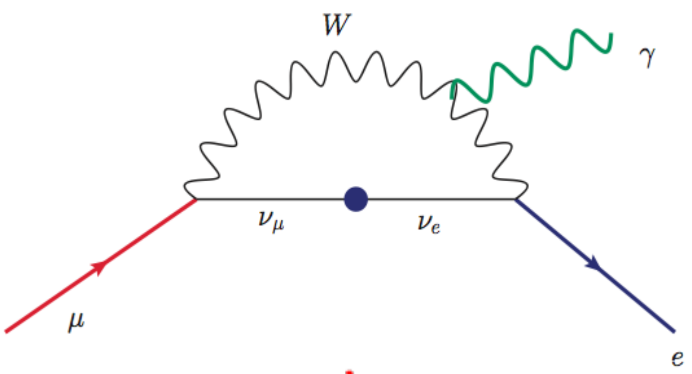




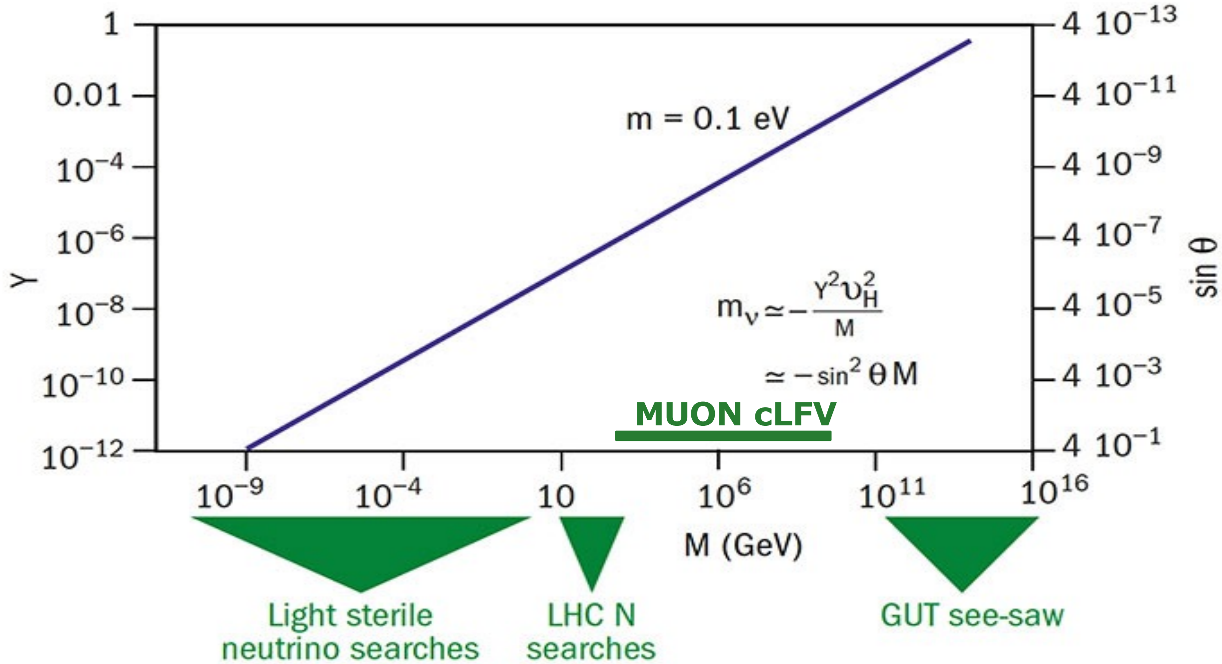
First data recently taken with more in 2022/3

Charged Lepton Flavour Violation (cLFV)

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



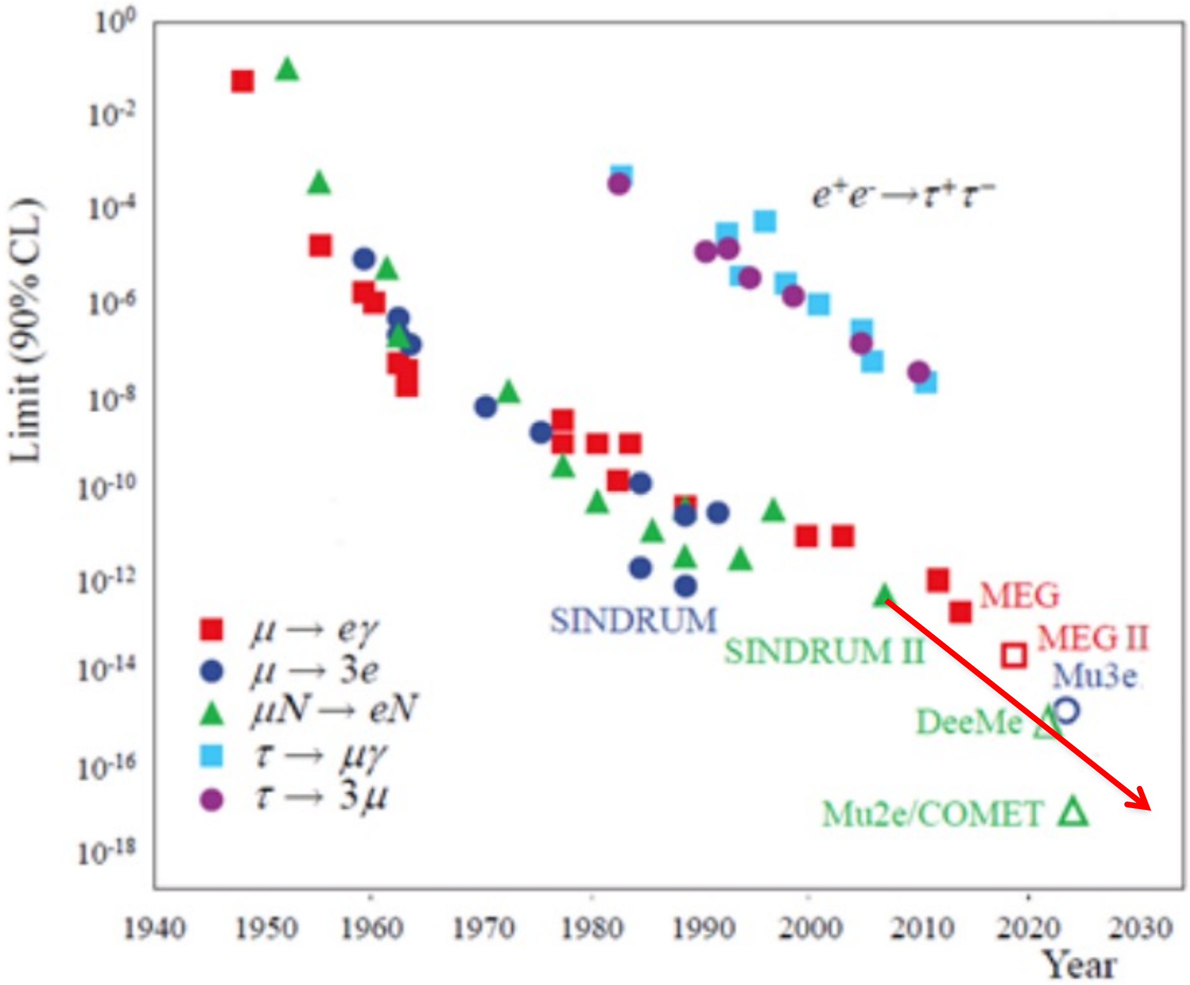
$$\mu \to e\gamma$$



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

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

Charged Lepton Flavour Violation (cLFV)

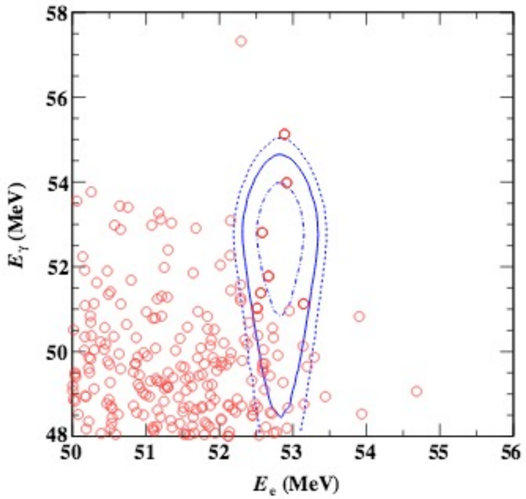


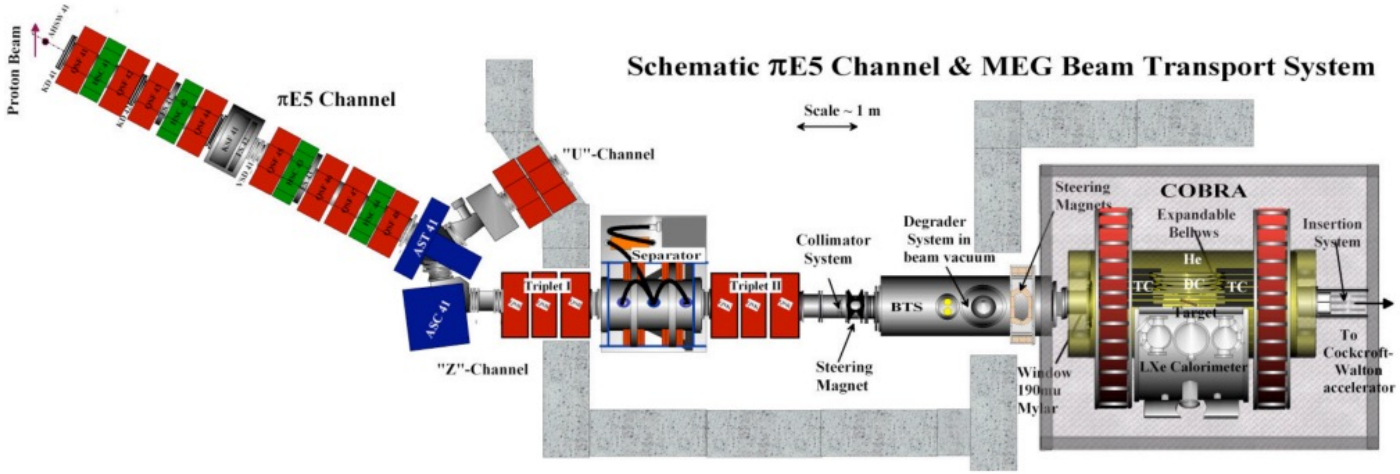
Ratio of the 3 different CLFV processes is model dependent and depend on model parameters.

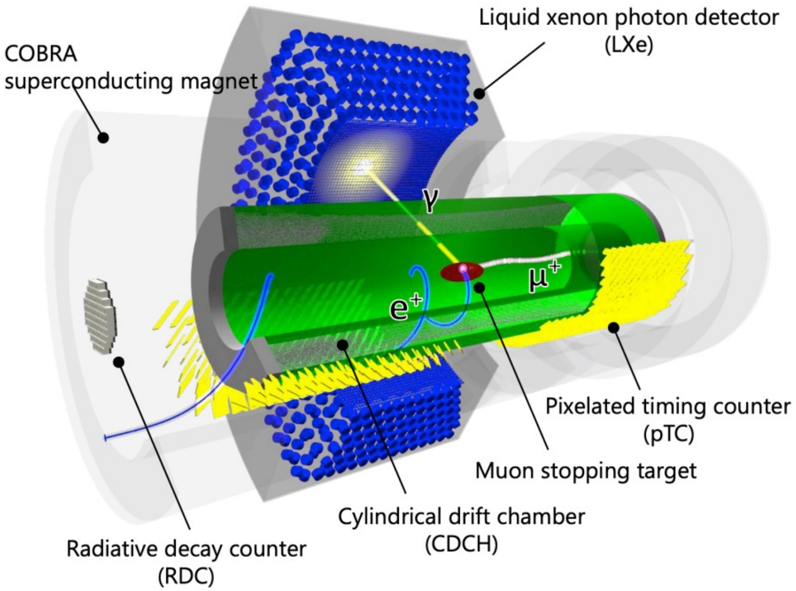
O(10⁴) improvement driven by new technology

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

MEG-II





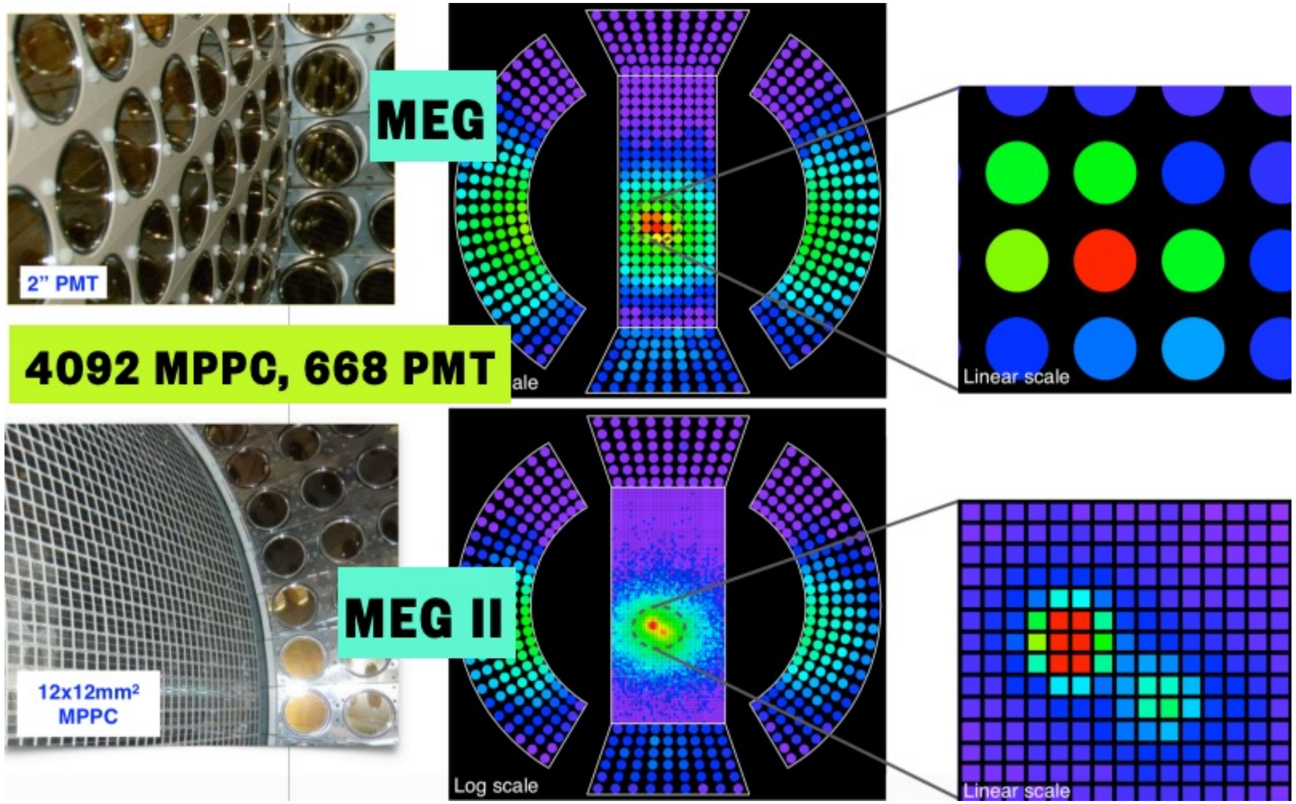


MEG-I (2016) : BR (μ→eγ) < 4.2 x10^{-13} (90%CL)

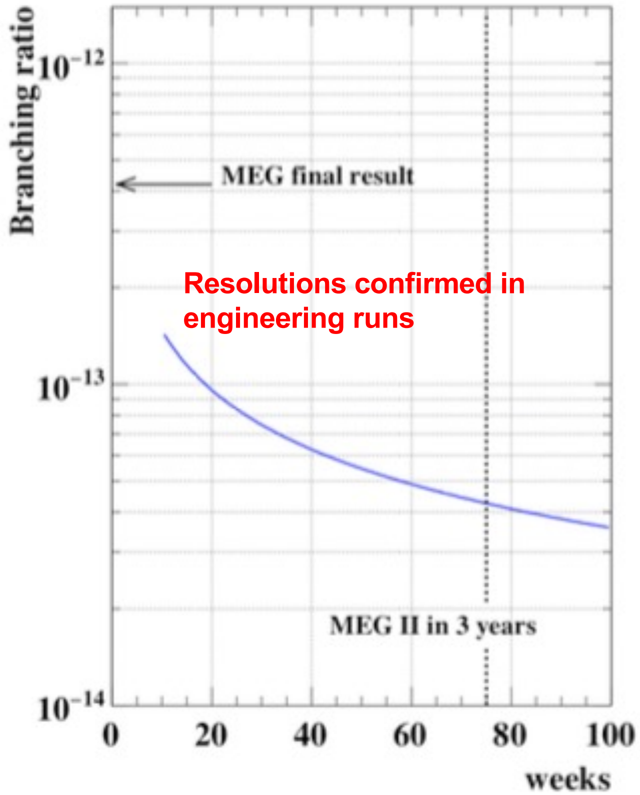
MEG-II to reach 6x10^{-14}

$$N_{\rm BG} = \left(\frac{R_\mu}{D}\right)^2 \Delta t_{e\gamma} \Delta E_e \left(\Delta E_\gamma\right)^2 \left(\Delta \Theta_{e\gamma}\right)^2$$

MEG-II

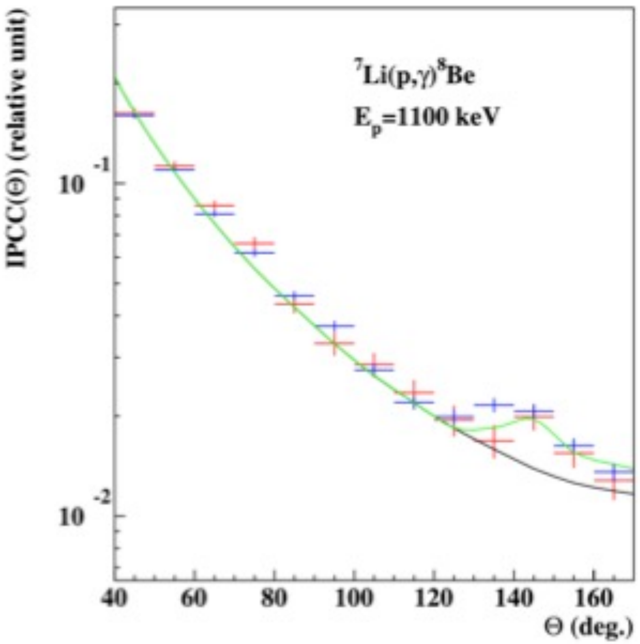


	MEG-I	MEG-II
$\sigma(E_e)$	380 keV	100 keV
$\sigma(t_{e\gamma})$	120 ps	70 ps
$\sigma(\phi_e)$	11 mrad	4 mrad
$\sigma(E_\gamma)$	1.6%	1 %
$\sigma(\theta_e)$	9 mrad	7 mrad



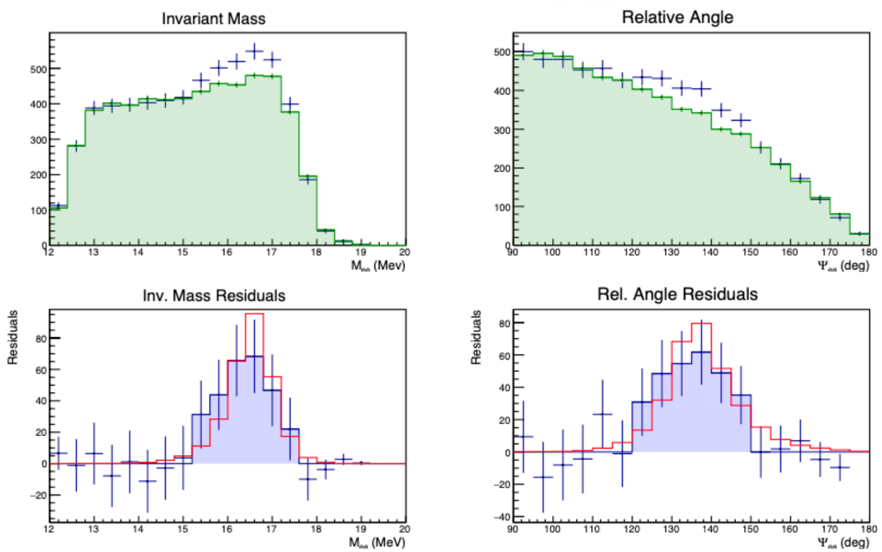
Improved detector resolution and granularity
Higher beam intensity achievable: 7 x 10^7 μ/s
New positron tracker
New detector for RMD
New TDAQ system
Improved photon detector

MEG-II : X(17)



J. Phys. Conf. Ser. **2018**, *1056*, 012028 (^{8}Be*)
J. Phys. Conf. Ser. **2020**, *1643*, 012001 (^{4}He*)

Possible interpretation : 17 MeV boson (BR ~ 6 x 10^{-6})

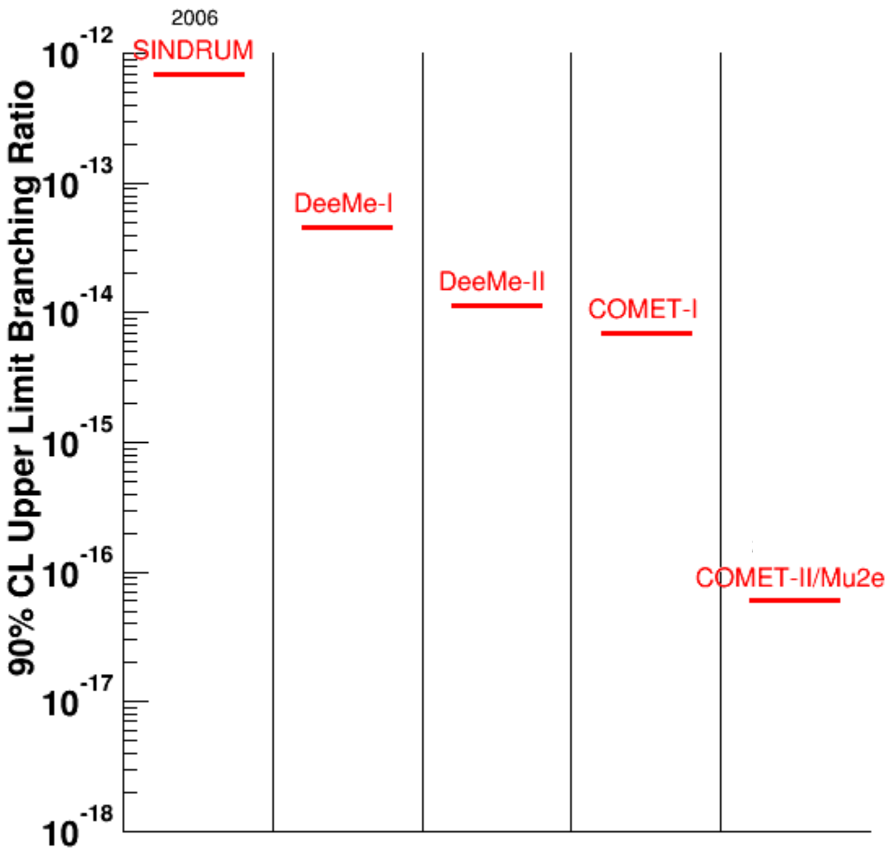


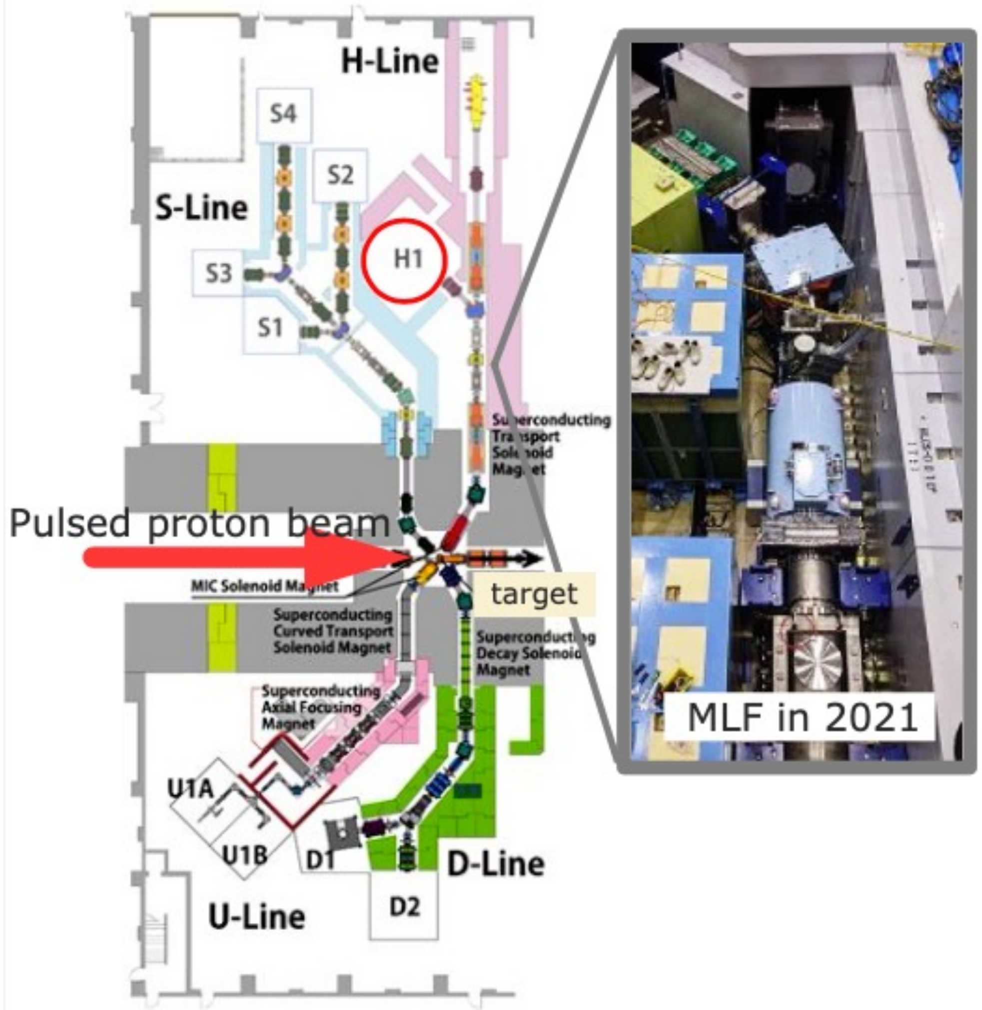
Li_2O layer on Cu substrate in PSI proton beam
MEG-II has improved resolution compared to Atomki

Data to be taken in 2022 prior to CLFV running.

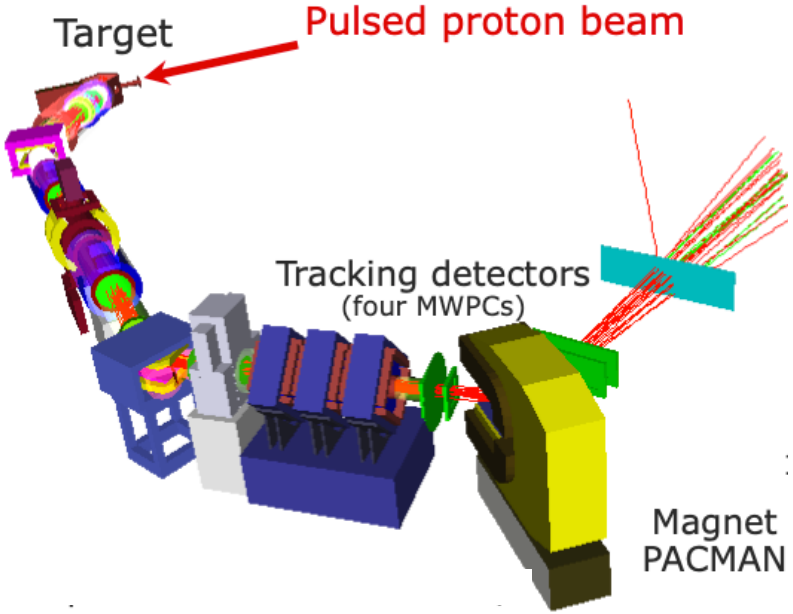
MEG-II GEANT4: mass resolution: 0.5 MeV

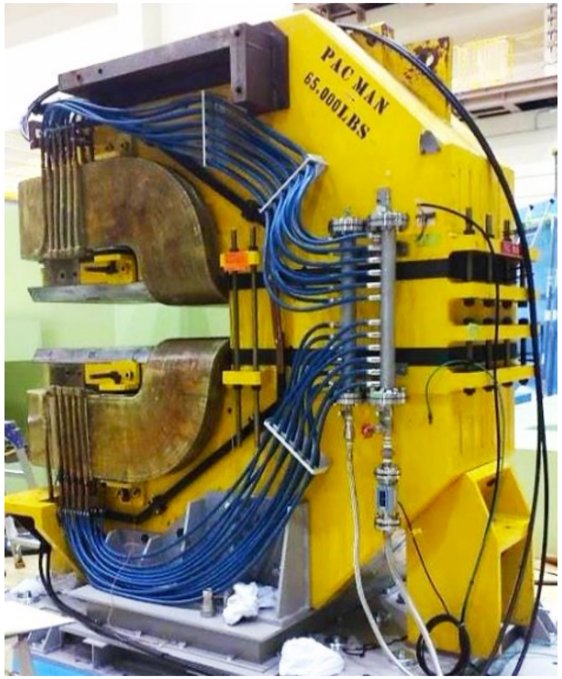
μN → eN′ : DeeMe

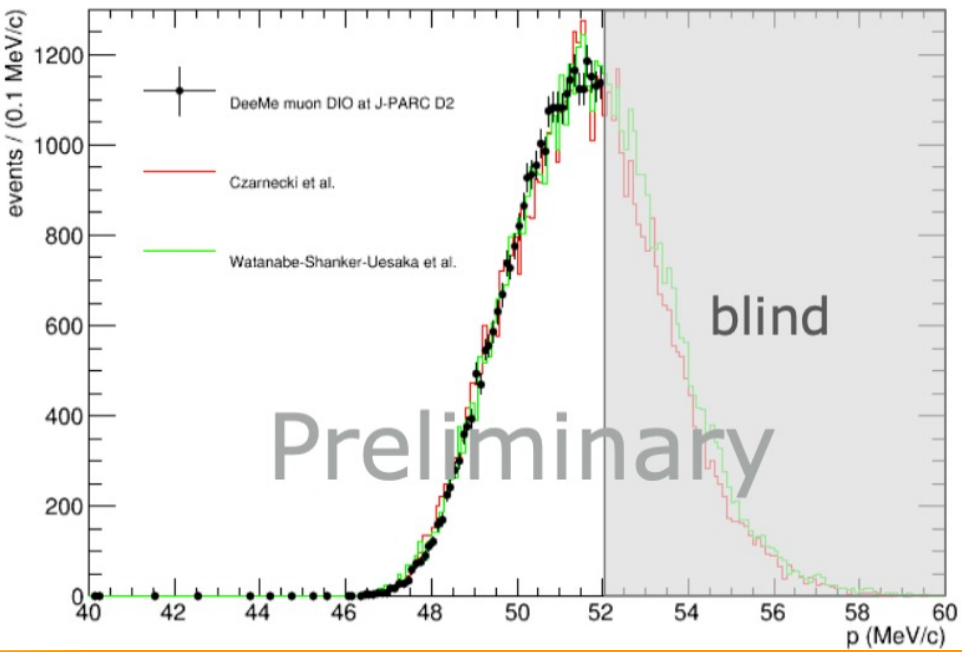

90% CL Upper Limit Branching Ratio
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
2006
SINDRUM
DeeMe-I
DeeMe-II
COMET-I
COMET-II/Mu2e


H-Line
S-Line
S4
S2
S3
S1
H1
Pulsed proton beam
target
MIC Solenoid Magnet
Superconducting Curved Transport Solenoid Magnet
Superconducting Decay Solenoid Magnet
Superconducting Axial Focusing Magnet
U1A
U1B
D1
D2
D-Line
U-Line
MLF in 2021

DeeMe







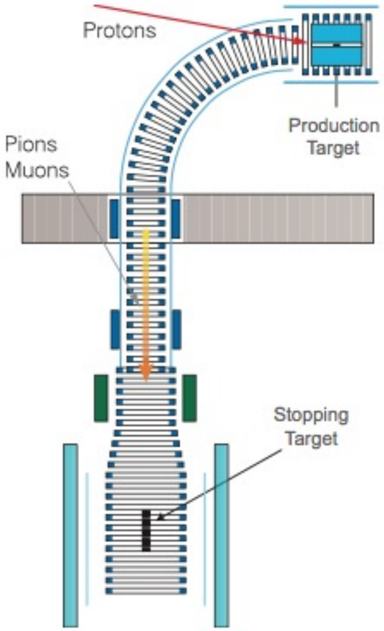
Phase-1 : C-target
Phase-2 : SiC target

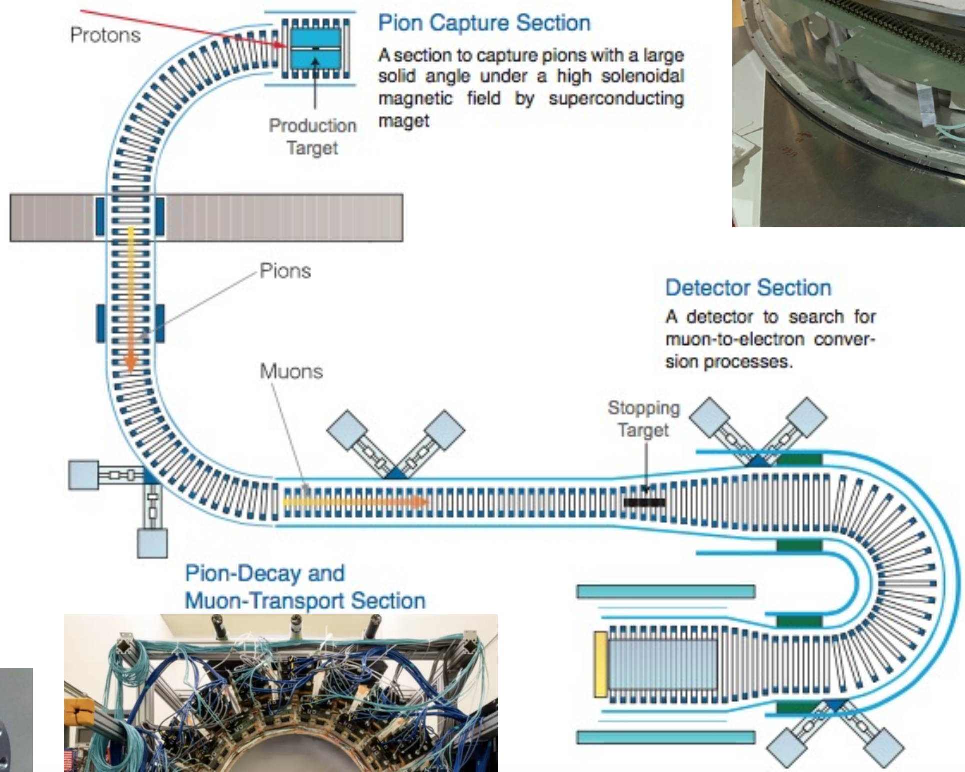
Expect x10 in sensitivity and then x100

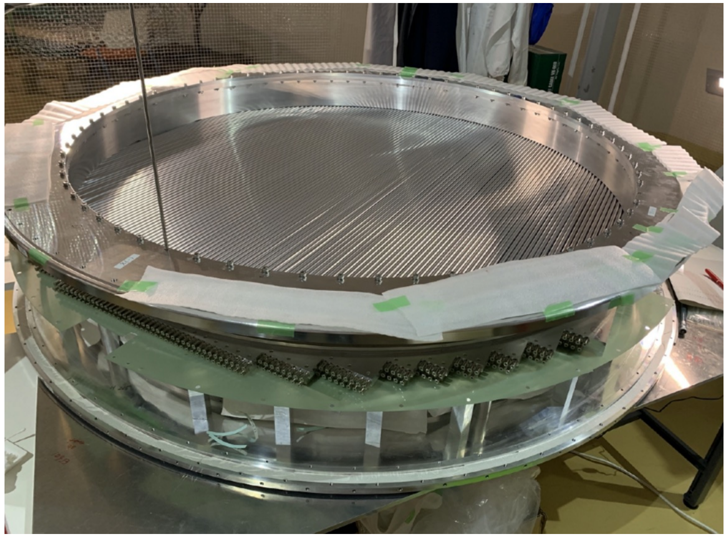
First running in 2022

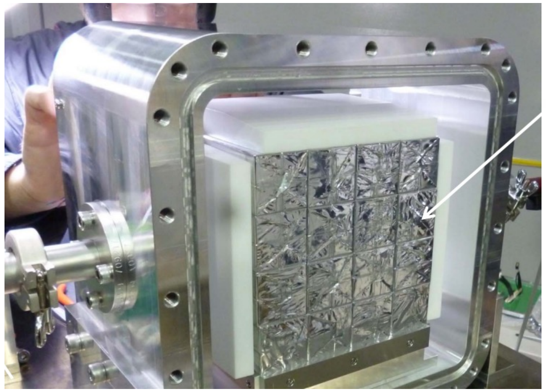
COMET

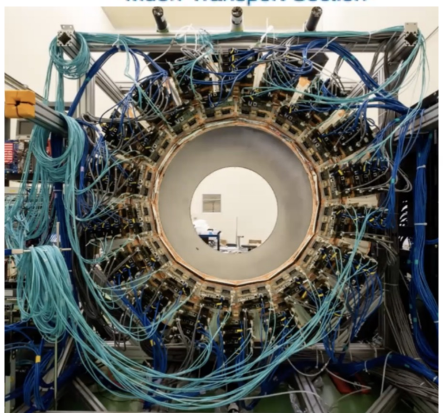
Phase-I **Phase-II**



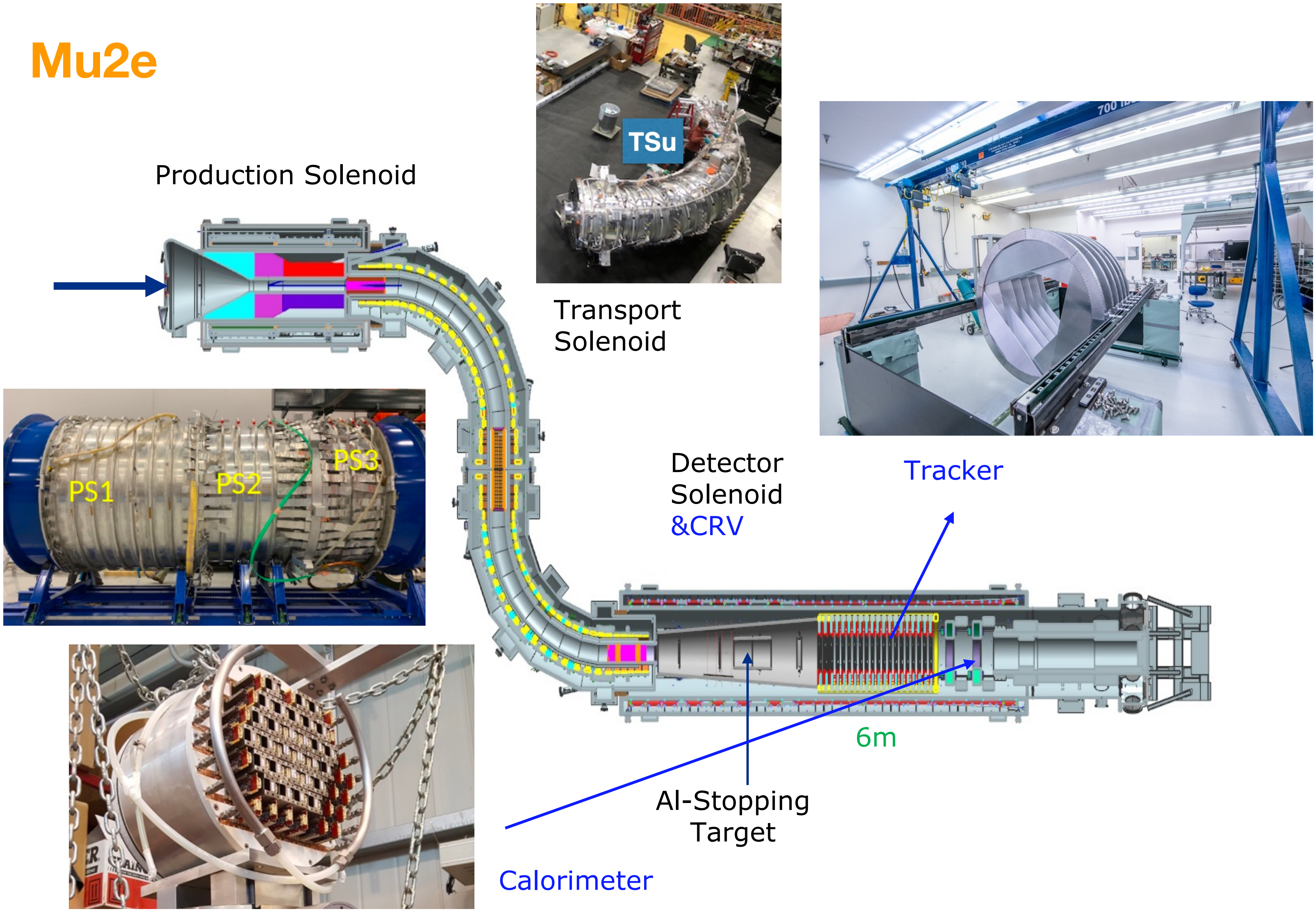




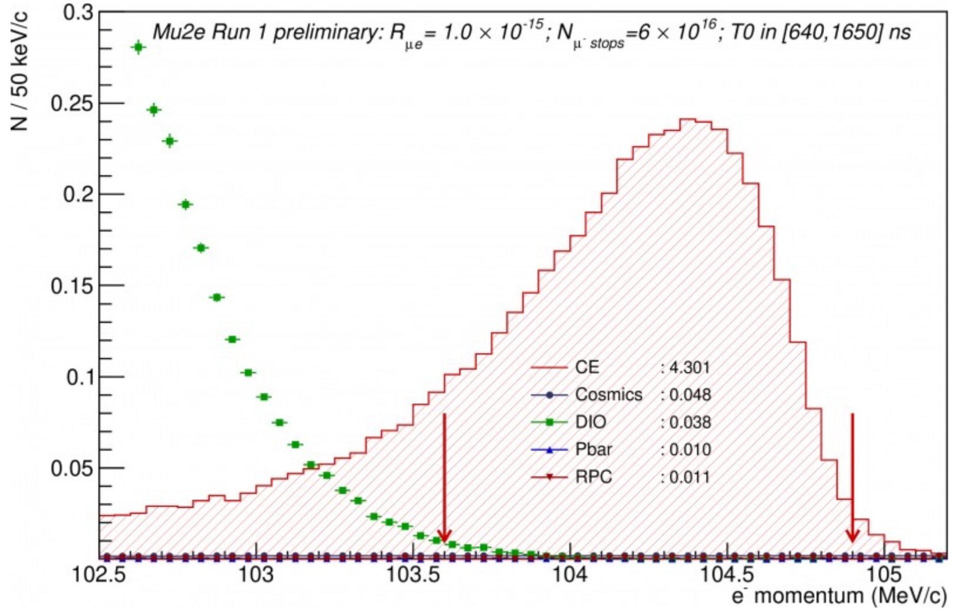




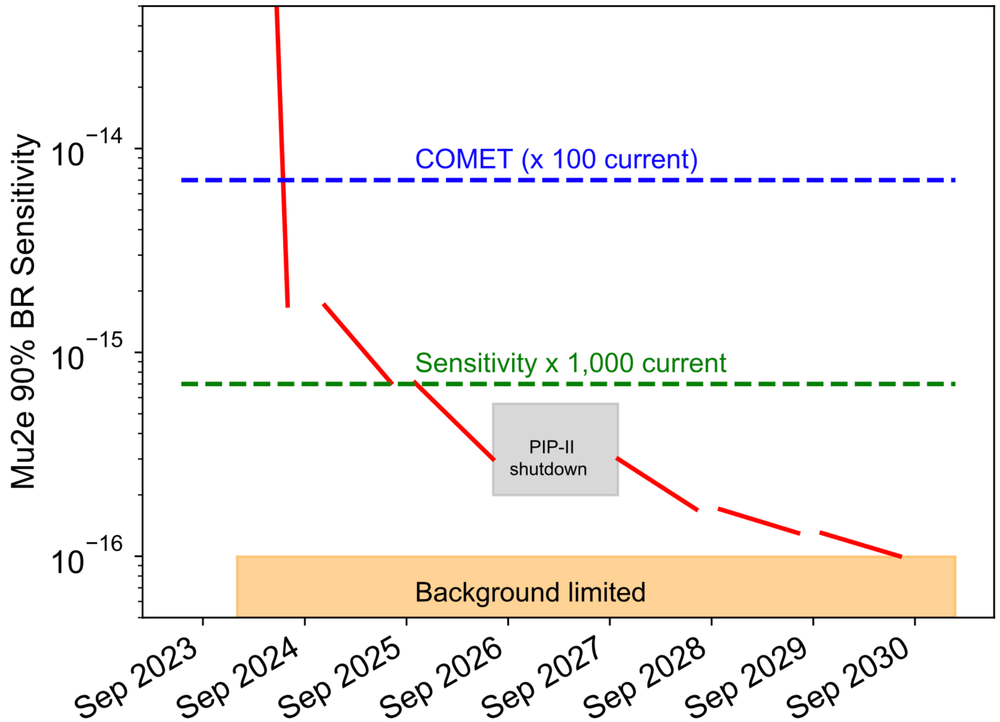
Mu2e


TSu
Production Solenoid
Transport Solenoid
PS1
PS2
PS3
Detector Solenoid
&CRV
Tracker
6m
Al-Stopping Target
Calorimeter

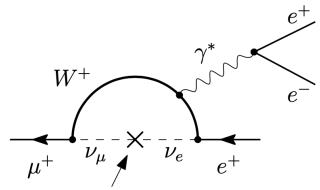
Mu2e / COMET-I



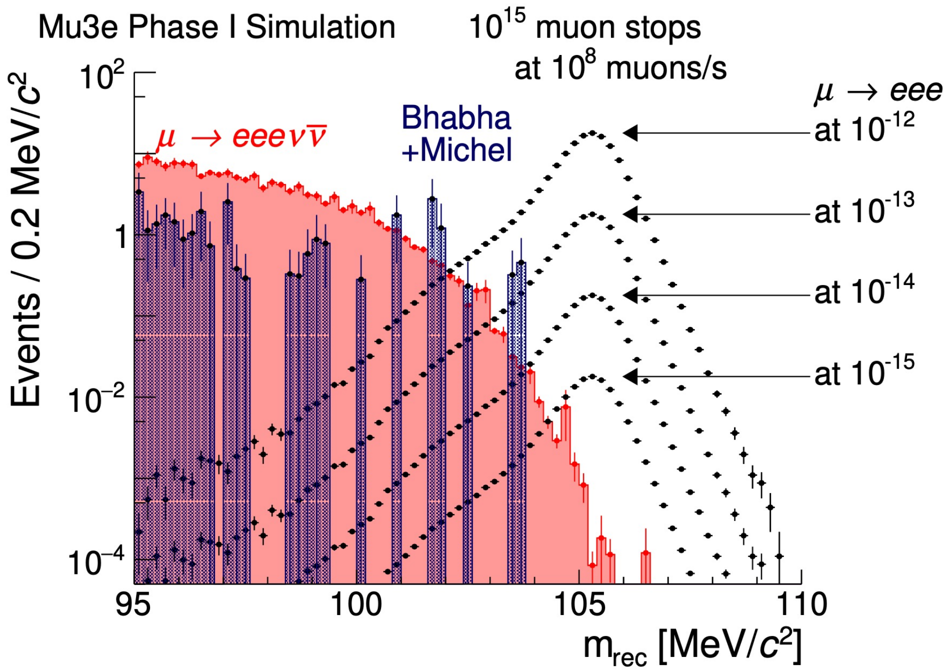
Beam commissioning 2023
Physics running 2024

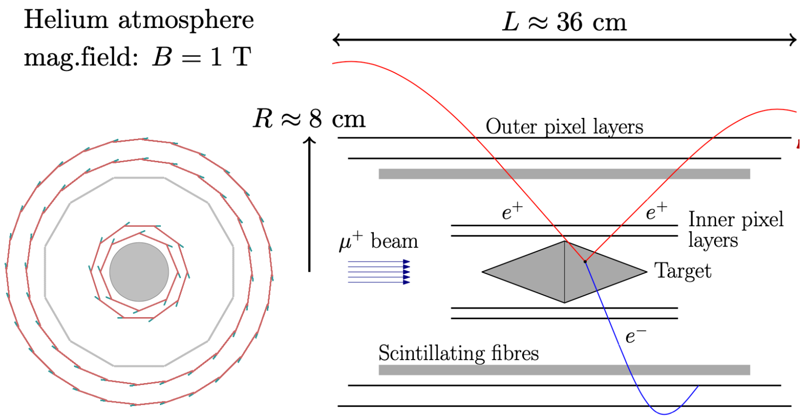


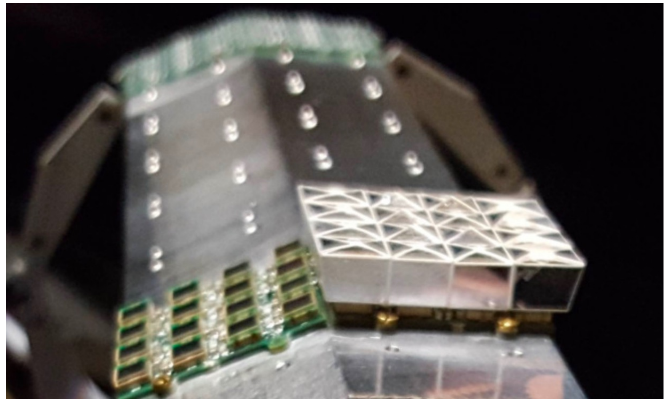
Mu3e

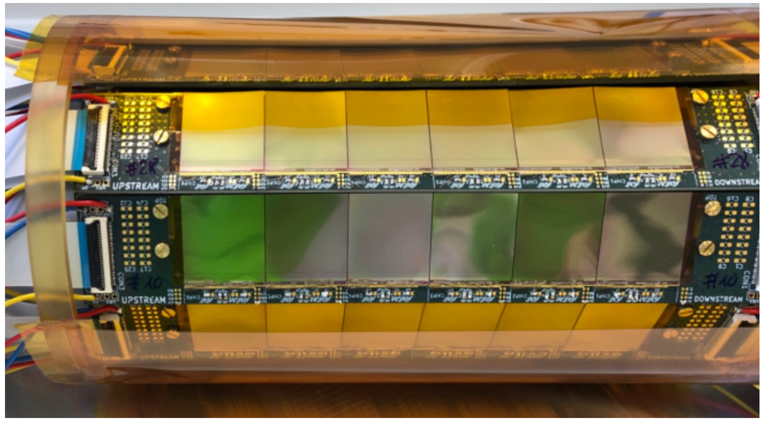


10^3 improvement in limit - Phase-I & further factor of ~ 10 with HIMB 10^{10} mu/sec upgrade









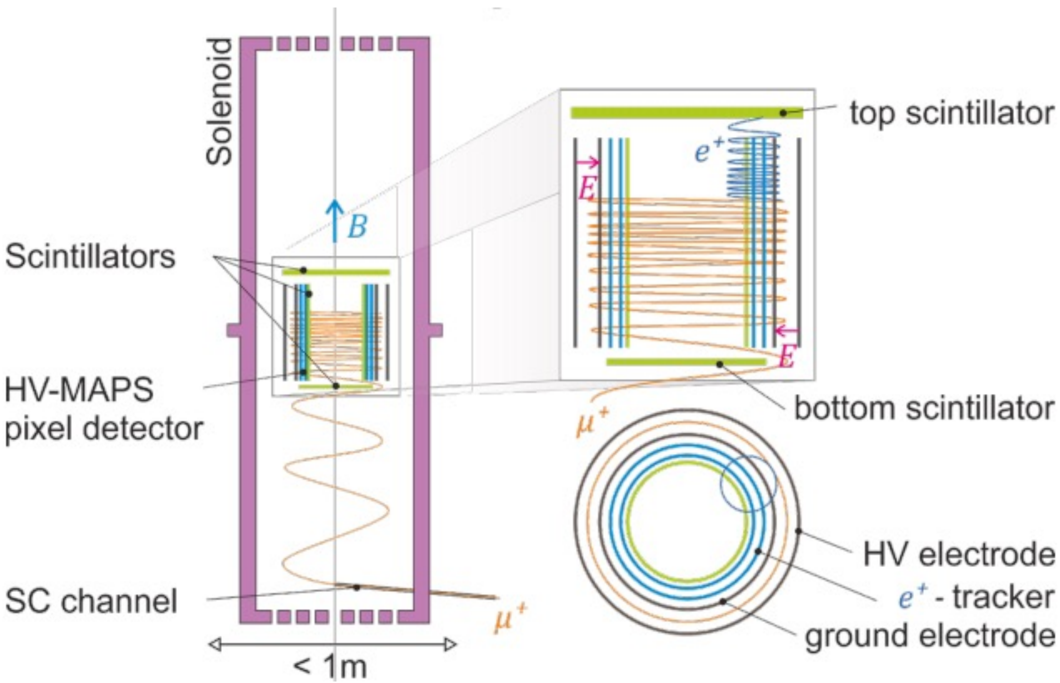
Commissioning now : physics run: 2024

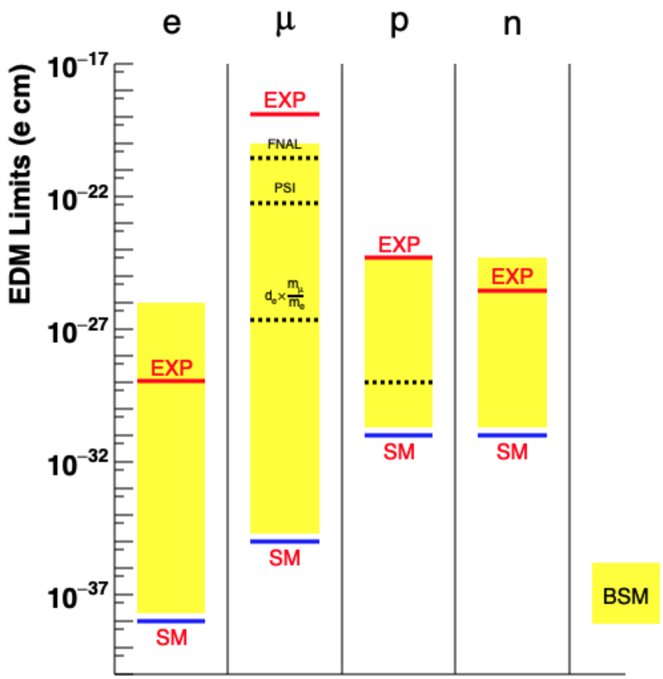
MuEDM at PSI

"Frozen spin" technique disappears (g-2) using judicious 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





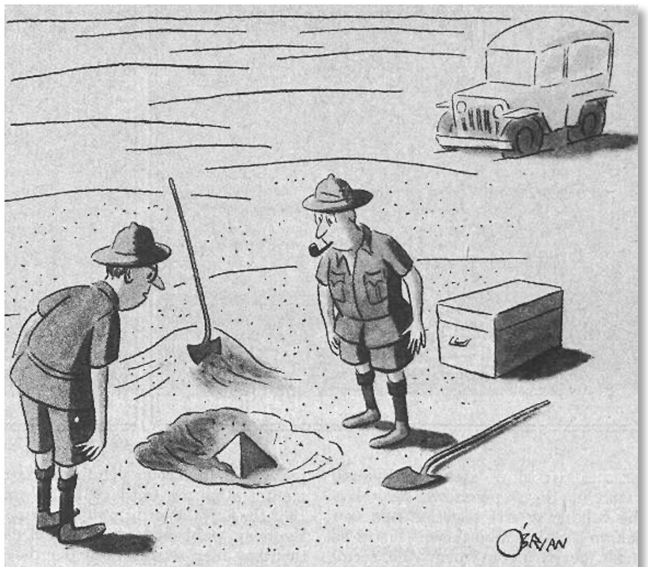
Conclusions

Interesting time for muon physics: strengthened evidence for deviation from SM in muon g-2 : 4.2σ

FNAL (g-2) already has x15 data of first publication and more to come.
Also much work being undertaken on the SM prediction.

MEG-II, DeeMe will have data in next year.

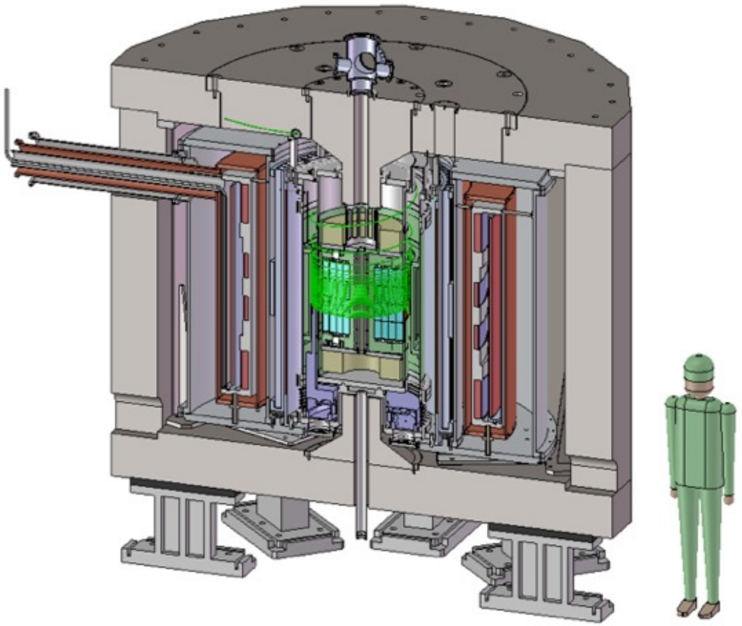
And then subsequently from Mu2e, COMET-I, Mu3e, JPARC g-2, Muon EDM

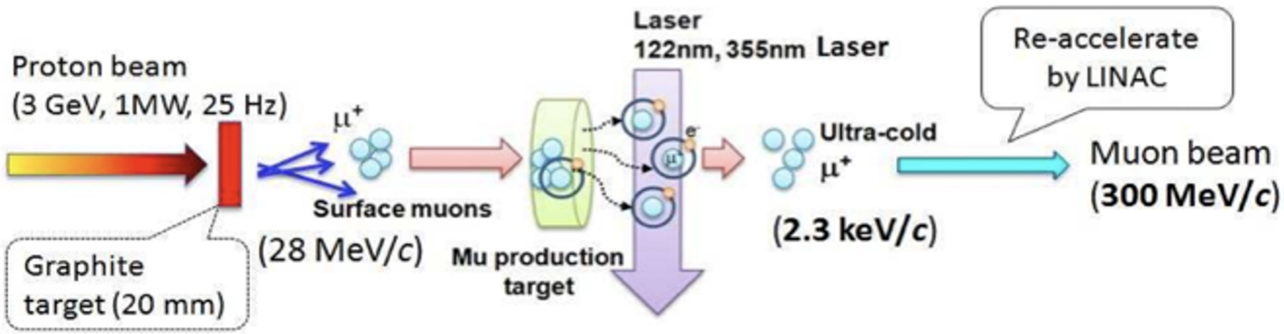


"This could be the discovery of the century.
Depending, of course, on how far down it goes"

Wed PM (Parallel)
George Sweetmore (g-2)
Dominika Vasilkova (g-2)
Roden Derveni (COMET)
Benjamin Gayther (Mu3e)

New Experiment / Methodology : JPARC g-2





See Friday's Plenary