Muon precision experiments
g-2, EDM and lepton flavour violation

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1. Muon magnetic moment, g-2: the puzzle
2. High sensitivity BSM searches / measurements
   a) Muon electric dipole moment
   b) Lepton flavour violation in muon decays

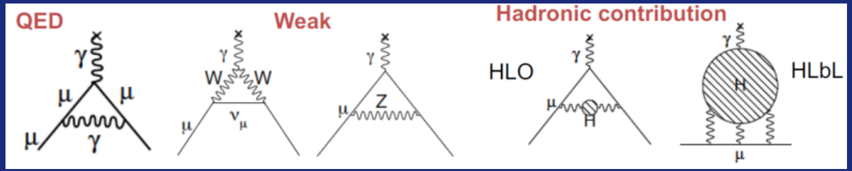
Why we measure the muon magnetic moment?

G Venanzoni, Workshop on Muon Precision Physics, Liverpool, 2022

$\vec{\mu} = g\frac{e}{2m}\vec{S}$ (Dirac theory predicts *g* = 2)

$a_\mu = (g-2)/2$

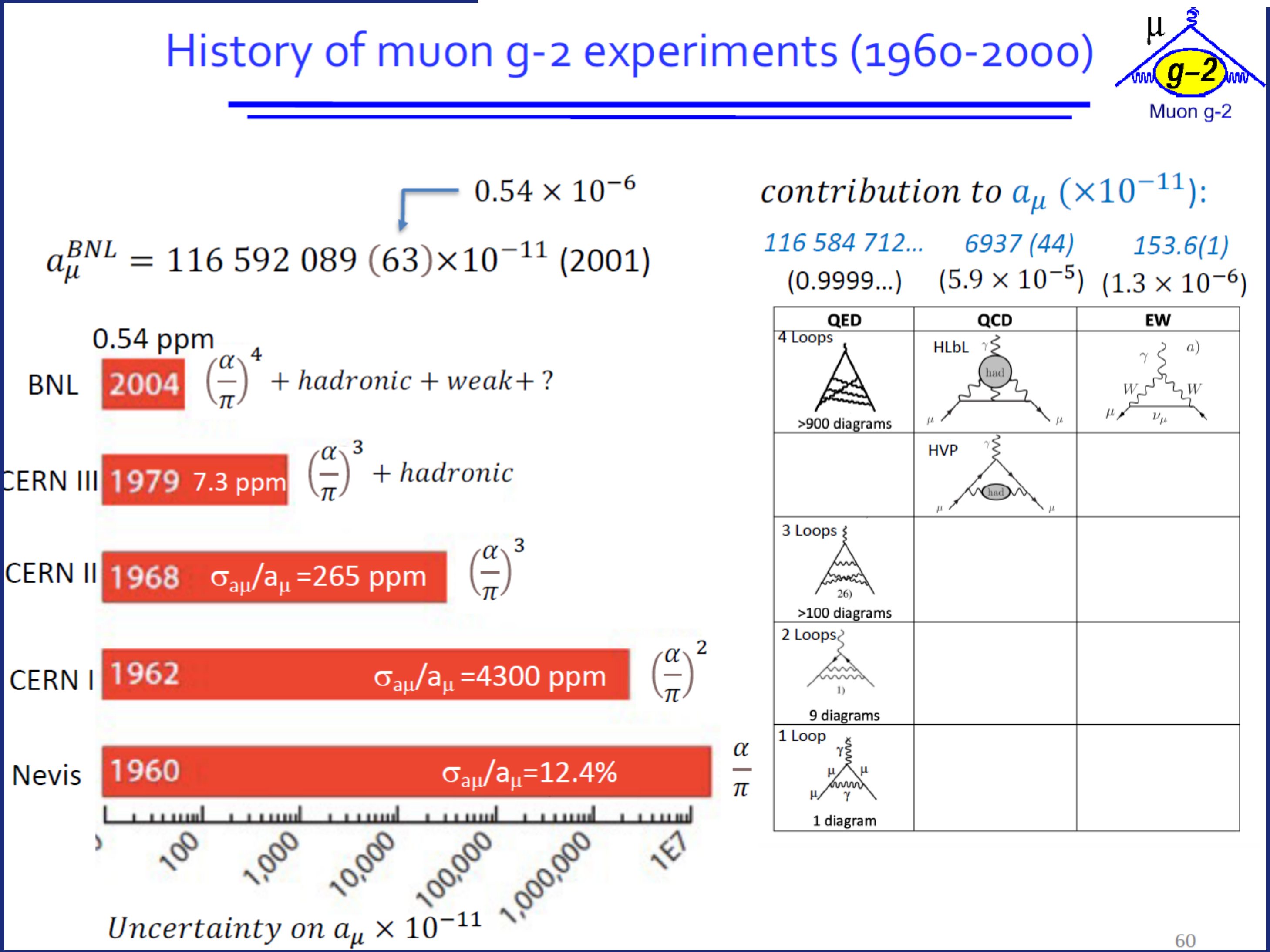
$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$ + ?



Can be calculated and measured with great precision (Phys. Rept. 887 (2020))

$a_\mu(\mathrm{SM})\ \ 116\,591\,810(43) \times 10^{-11}\ \ (0.37\,\mathrm{ppm})$

- precise test of SM effect to high orders
- sensitive test for BSM contribution

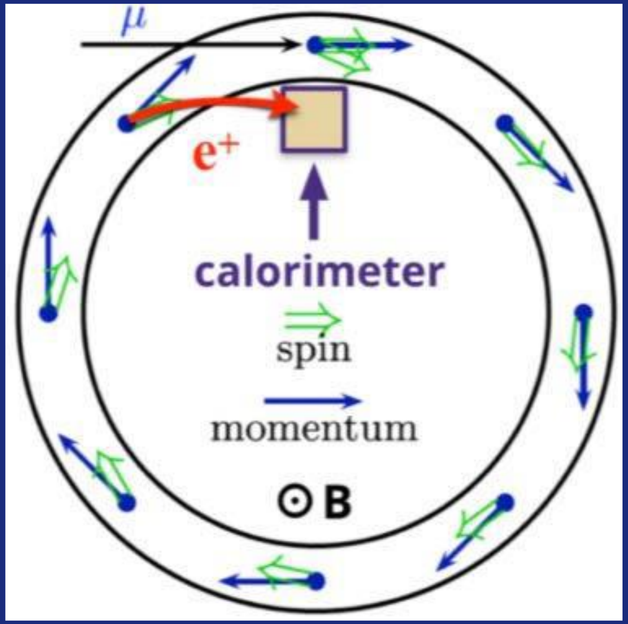


How we measure g-2

Since late 60s, most precise measurements of g-2 have been made in a storage ring experiments.
In the magnetic field, if $g \neq 2$, the spin direction rotates differently from the momentum.
$\omega_a = \omega_s - \omega_c$ is the anomalous precesion frequency.

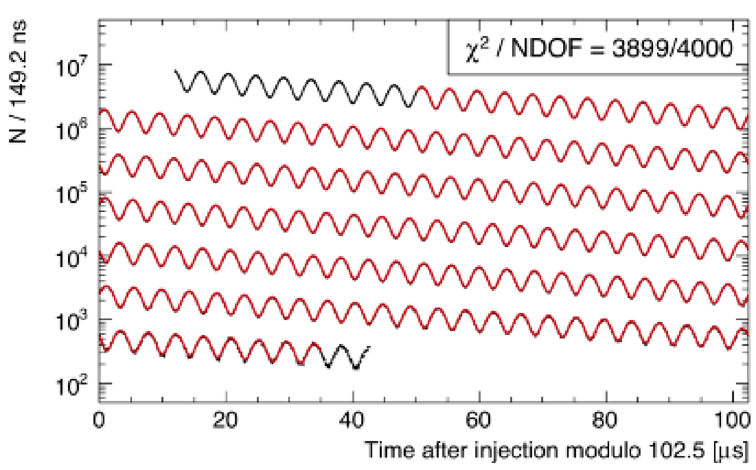
$$\vec{\omega}_a = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

Second term can be reduces to 0 when P_μ = 3.1 GeV ("magic momentum")



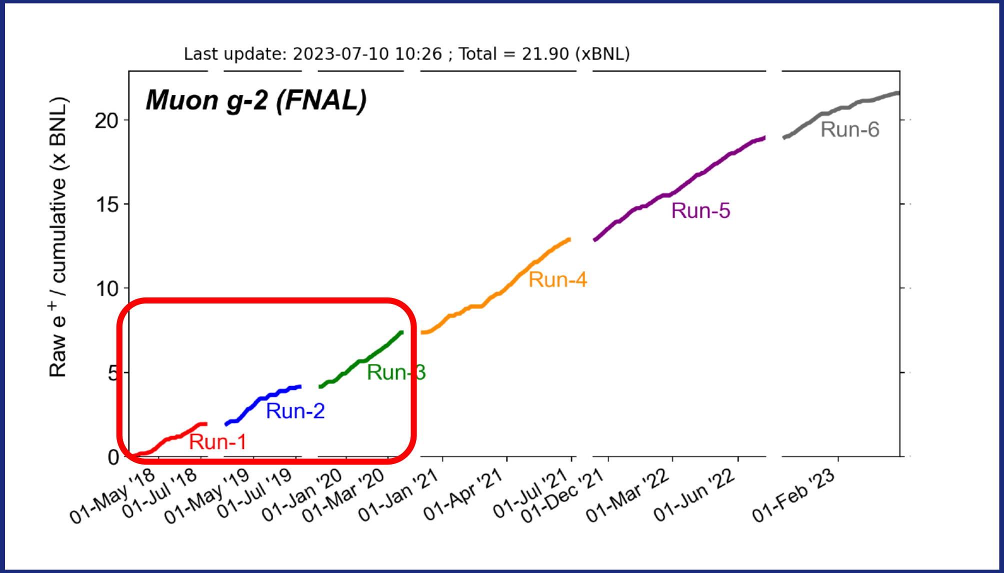
Muon spin precession leads to a rate fluctuation in (forward) emitted positrons.

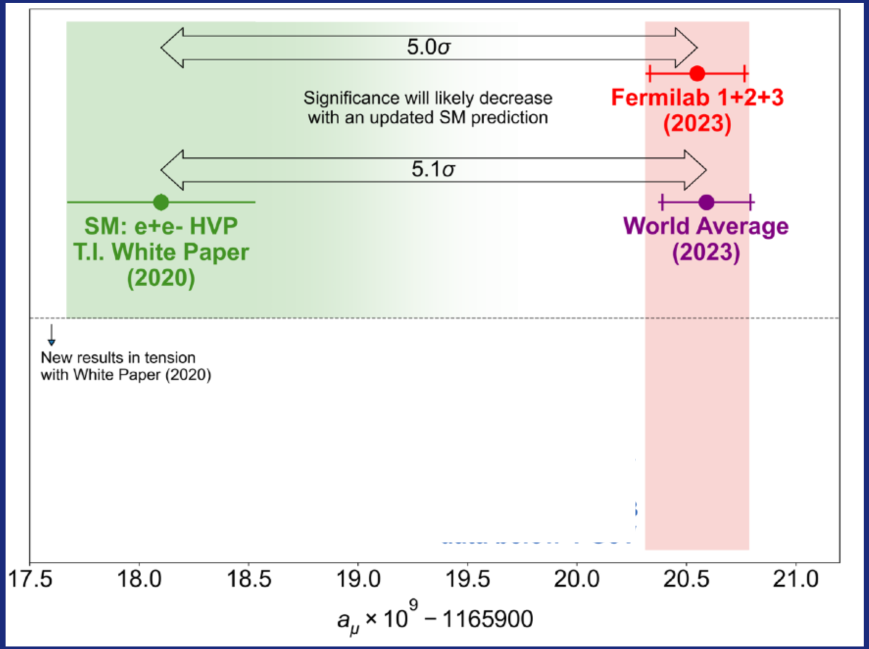
ω_a can be extracted from the oscillation in the rate plot.



Fermilab g-2

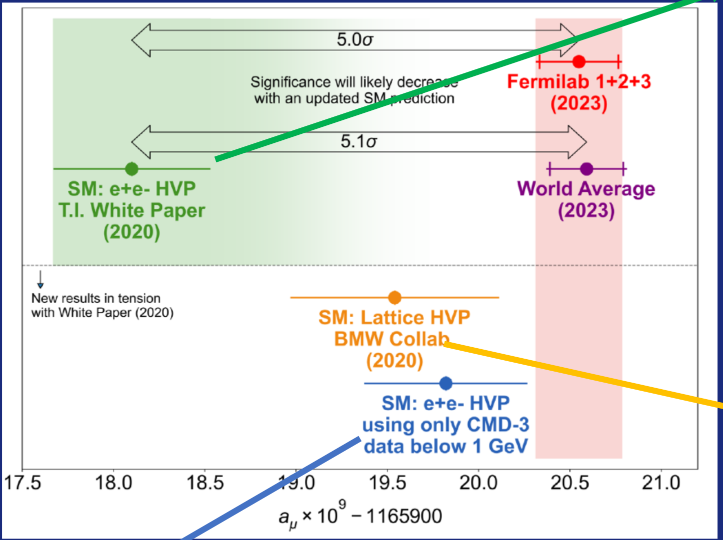
In 2013 BNL storage ring was moved to FNAL and re-instrumented, to do an experiment with higher statistics and improved systematics.
Final targeted precision 0.14 ppm



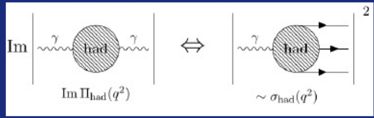


- Datataking was completed earlier this year (TDR Goal of 21 x BNL dataset achieved)
- Run 1, 2 and 3 analysis completed
  Result show 5.0 σ tension with SM predictions
- Analysis Run 4/5/6 started.
  Final results expected for 2025

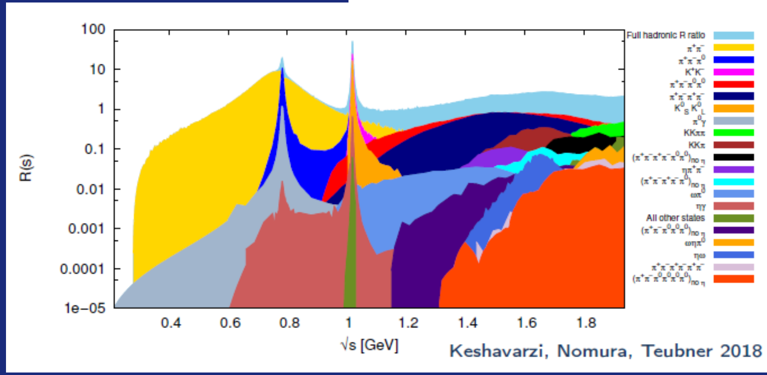
g-2 puzzle



Dispersive theory predictions use optical theorem to determine $\mathbf{a_\mu^{HLO}}$ (hadronic contribution a_μ)



$e^+e^- \to hadrons$



$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to hadr}(s)K(s)ds$$

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)(s/m^2)} \sim \frac{1}{s}$$

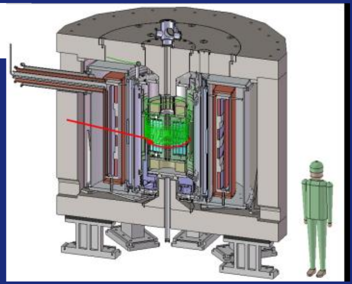
New CMD-3 measurement of $e^+e^- \to \pi^+\pi^-$, would also lead to to higher value $\mathbf{a_\mu^{HLO}}$, but are in tension with previous measurements (BABAR, KLOE).

BMW collaboration (2020) lattice calculation predicts higher value of $\mathbf{a_\mu^{HLO}}$ which would give closer agreement with data.

What next?

- Independent competitive measurement g-2 (JPARC-E34 experiment)
- Analysis of KLOE $e^+e^- \to \pi^+\pi^- \gamma$ data (not analysed previously)
- BES-III fully inclusive measurement $e^+e^- \to hadrons$ in ISR events in progress
- Higher order ISR corrections and implementation in better MC models
- MUonE at CERN – alternative determination of $\mathbf{a_\mu^{HLO}}$ in muon-electron scattering

JPARC E34 experiment



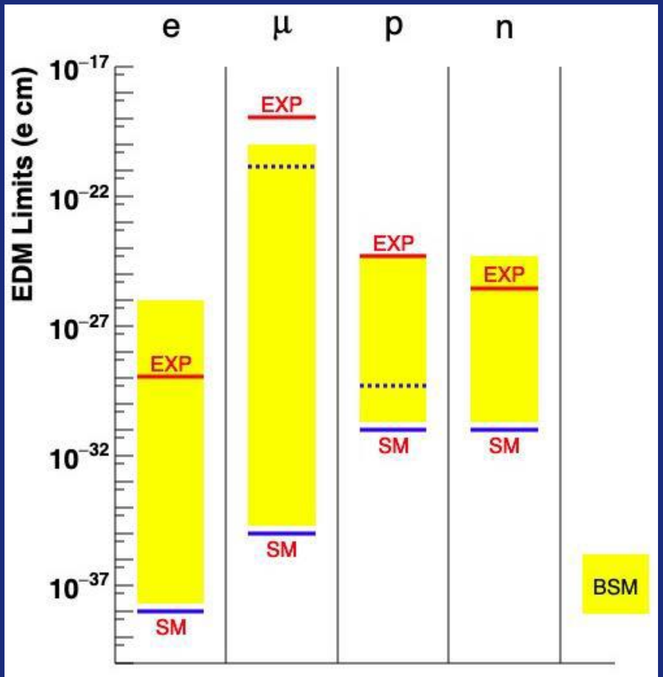
Muon electric dipole moment

Muon electric dipole moment

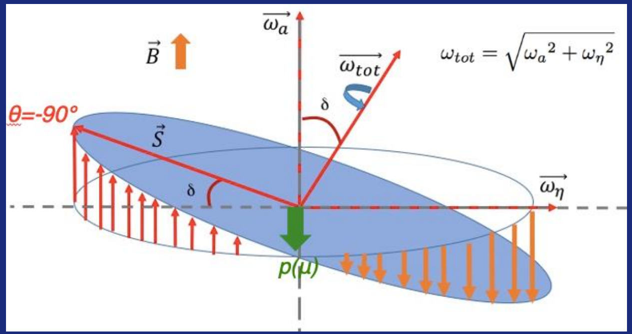
Why muon edm?

- SM muon EDM well below the range of current experiments.
- EDM measurement tests NP (non-zero e.d.m. in a fundamental particle with spin violates CP!)

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



A non-zero muon EDM causes a tilt in the precession plane, which can be measured from asymmetry in vertical decay angle of positrons.



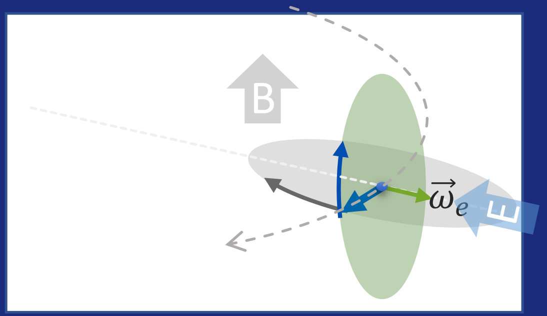
Muon EDM results (plans) from the g-2 experiments

- **BNL g-2 experiment:** $|d_\mu| < 1.9 \times 10^{-19}$ e.cm (95% C.L.)
- **FNAL g-2 experiment:** *expected limit* $|d_\mu| < 2.1 \times 10^{-20}$ *e.cm (95% C.L.)*
- **JPARC-E34 g-2 experiment:** *expected limit:* $|d_\mu| < 1.5 . 10^{-21}$ *e·cm (95% C.L.)*

A dedicated “frozen spin” μEDM experiment at PSI

Dedicated stored muon EDM measurement using the Frozen-Spin method

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



With a suitable radial electric field ($E \cong aBc\beta\gamma^2$) the g-2 precession can be removed, leaving only the out of plane precession due to d_μ.

PSI experiment: Muon injected in compact magnet – kicker magnet to lock muon in orbit – trackers to measure in/out (g-2) and up-down asymmetry (d_μ).

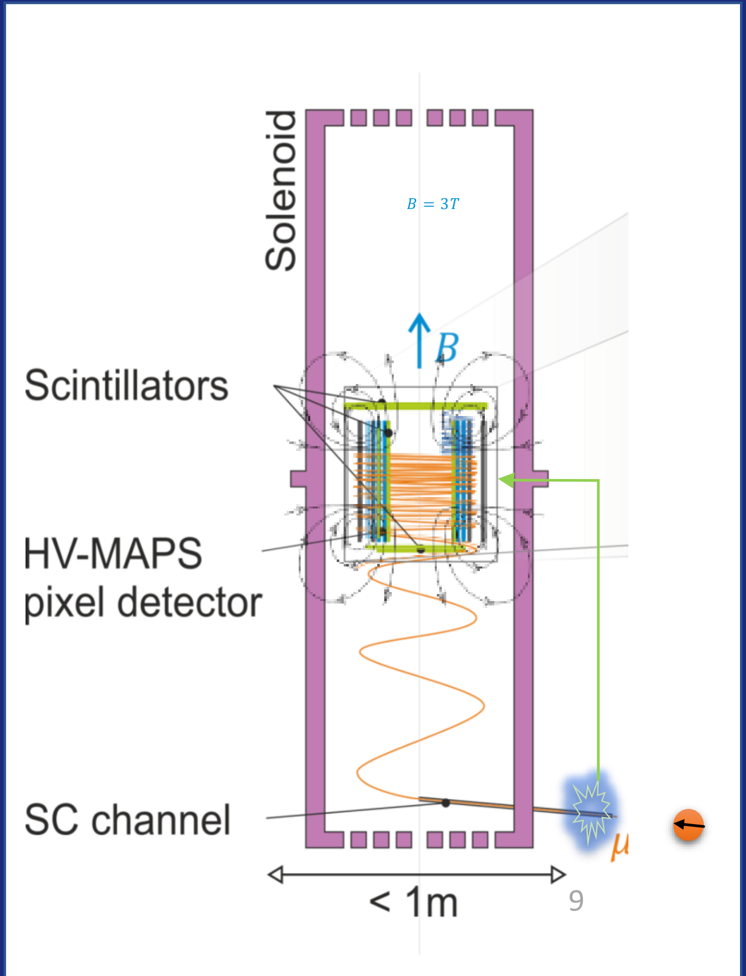
Phase I (start 2026)

Aims:

1. Measure g-2 and demonstrate it can be switched off using the frozen spin method.
2. Possible first measurement of d_μ with ***σ(dμ) ~ 3 × 10⁻²¹ e.cm***

Phase-II (~ 2030):

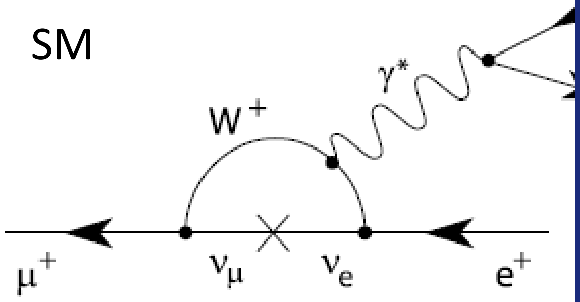
Target: ***$\sigma(d_\mu) \sim 6 \times 10^{-23}$ e.cm***



Muon Charged Lepton Flavour Violation

Charged Lepton Flavour Violation in Muon decays

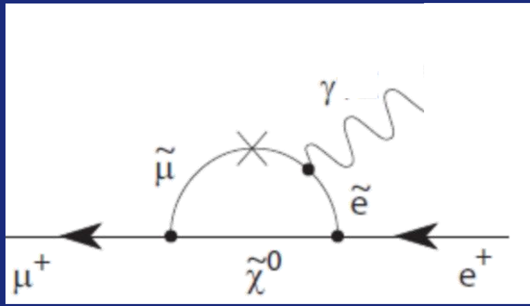
Heavily suppressed in the SM due to low neutrino mass.



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M_W^2}\right|^2 < 10^{-54}$$

Any observation of CLFV is evidence of NP.

Charged lepton flavour violation can appear naturally in NP theories.



CLVF μ-decay status

If charged lepton flavour is violated we might these muon decays:

$\mu \to e\gamma$,

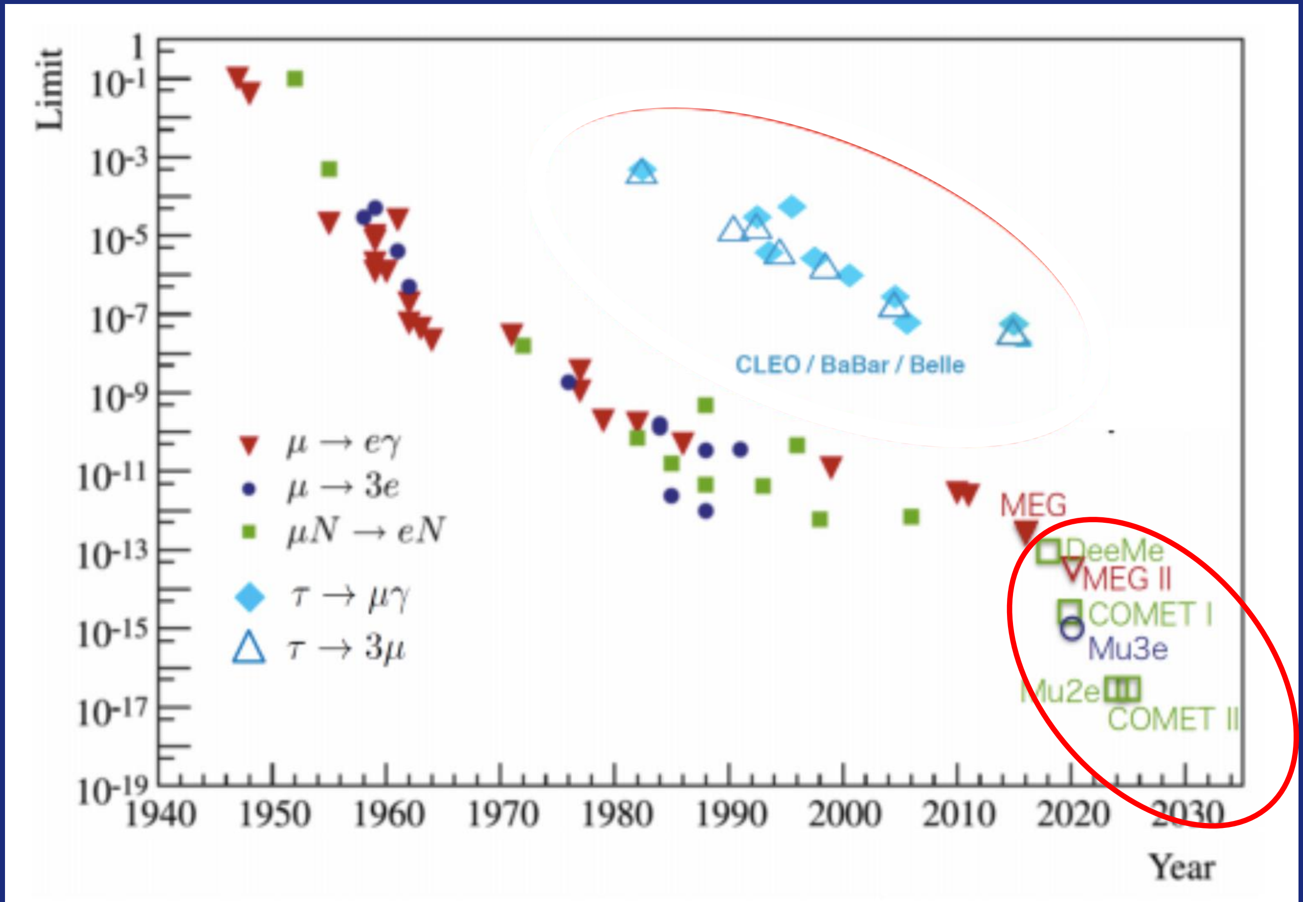
$\mu \to eee$

$\mu N \to eN$

First measurements shortly after discovery muon (showed muon was not an excited electron)

Experiments in preparation will push $\mu \to e$ sensitivity by up to four orders of magnitude over the next 5-10 years. #

This corresponds to at reach for NP up to O(PeV) mass scales, out of reach direct NP searches at colliders.



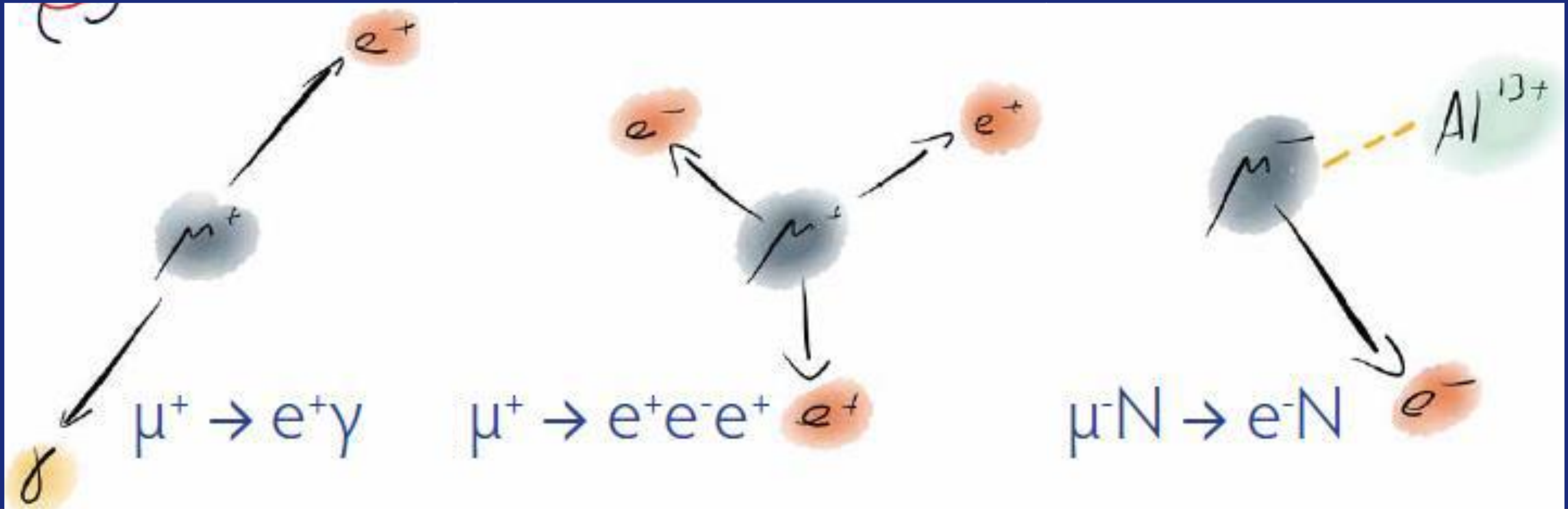
	Best limits	Projected sensitivities (90%CL)
$\mu \to e\gamma$	< 4.3x10^{-13} MEG (PSI)	6x10^{-14} MEG II (PSI)
$\mu \to eee$	< 1.0x10^{-12} SINDRUM (PSI)	4x10^{-15} Mu3e I (PSI) 1x10^{-16} Mu3e II (PSI)
$\mu N \to eN$	< 7.0x10^{-13} SINDRUM II (PSI) μ Au $\to$ e Au	6x10^{-17} Mu2e (FNAL) 7x10^{-15} COMET I (J-PARC) 6x10^{-17} COMET II (J-PARC)

CLFV Muon decay channels

If lepton flavour is violated there are three obvious muon decays to look for this.

Typically, muons are stopped on a target and decay at rest.

$E_{observed} = m_\mu$ (no neutrinos)



back-to-back electron and photon $E_\gamma = E_e = \frac{1}{2} m_\mu$	**3 co-planar electrons** $\Sigma P_e = 0, \Sigma E_e = m_\mu$	**Muon decay from muonic atom. Monochromatic electron** $E_e = m_\mu - E_{binding} - E_{recoil}$

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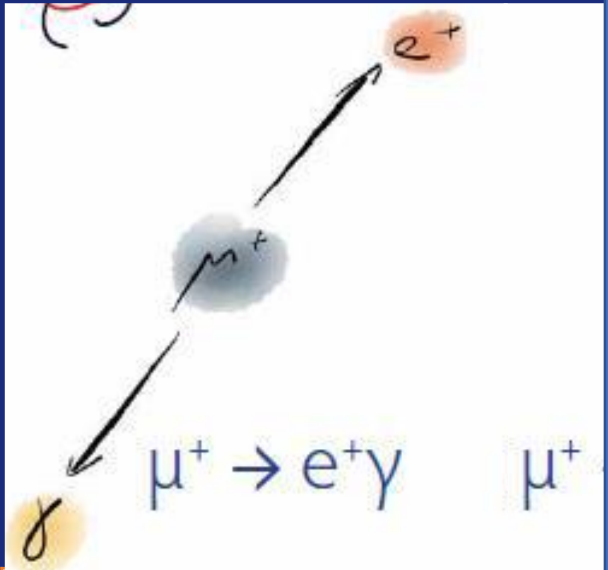


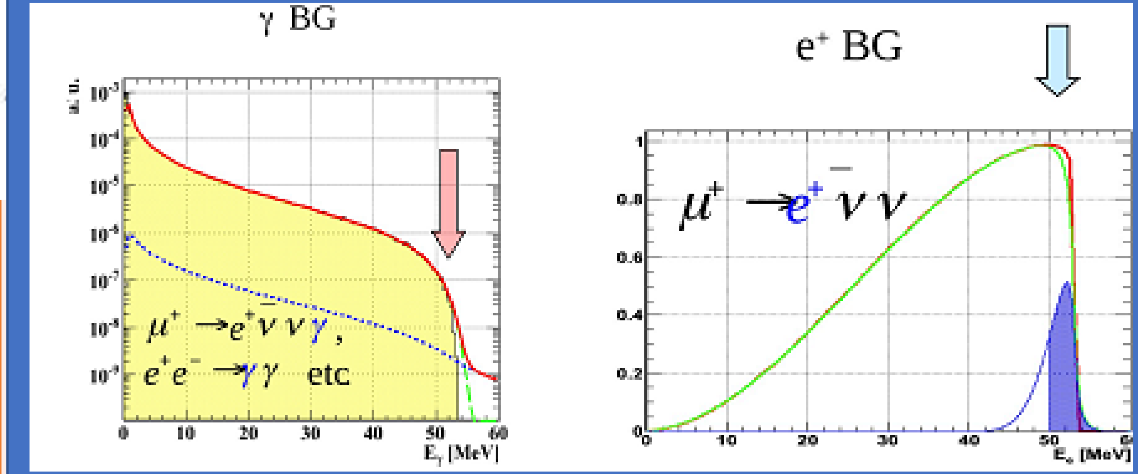
back-to-back electron and photon

$E_\gamma = E_e = ½\ m_\mu$

<u>Key backgrounds:</u>

At high rates, accidental eγ combinations are the dominant background.

DC beam



Need

- **Excellent electron and photon energy resolution**
- **Timing resolution**

MEG-II: $\mu \to e\gamma$ at PSI

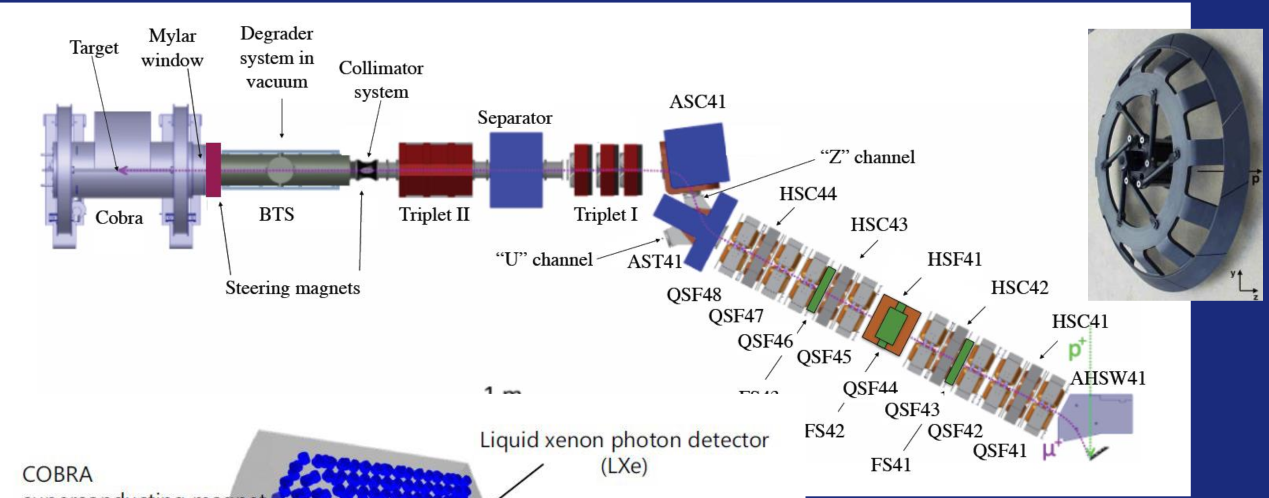
πE5 beam line delivers 28 MeV/c surface muons to experiment target

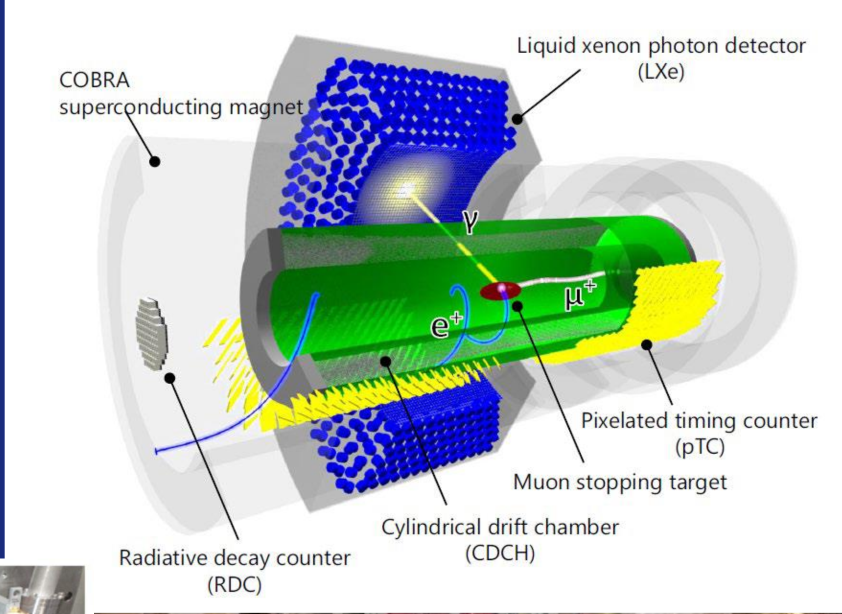
<u>Upgraded detector:</u>

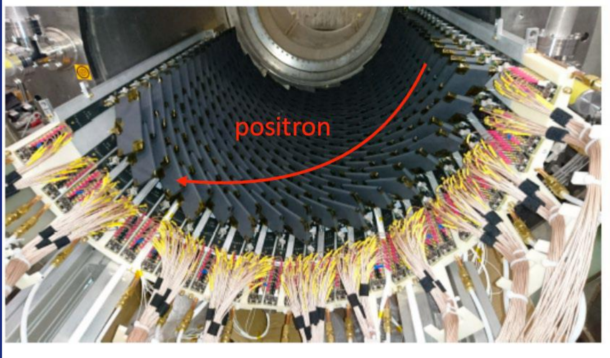
- 2 - 5 x10^7 μ-decays per second
- 800 liter LXe calorimeter for photon energies
- Cylindrical Drift Chamber for positron momentum
- Scintillating tile timing counters for accidental background rejection

Performance comparison MEG-II vs MEG

PDF parameters	Foreseen	Achieved	MEG
E_{e^+} (keV)	100	89	330
ϕ_{e^+}, θ_{e^+} (mrad)	3.7/6.7	4.1/7.1	8.4/9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.75/1.85	1.1/2.5
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.0/1.8	2.4/1.7
$u_\gamma, v_\gamma, w_\gamma$, (mm)	2.4/2.4/5.0	2.5/2.5/5.0	5/5/6
$t_{e^+\gamma}$ (ps)	70	78	122
Efficiency (%)			
ε_γ	69	63	63
ε_{e^+}	65	65	30
ε_{TRG}	≈99	82	







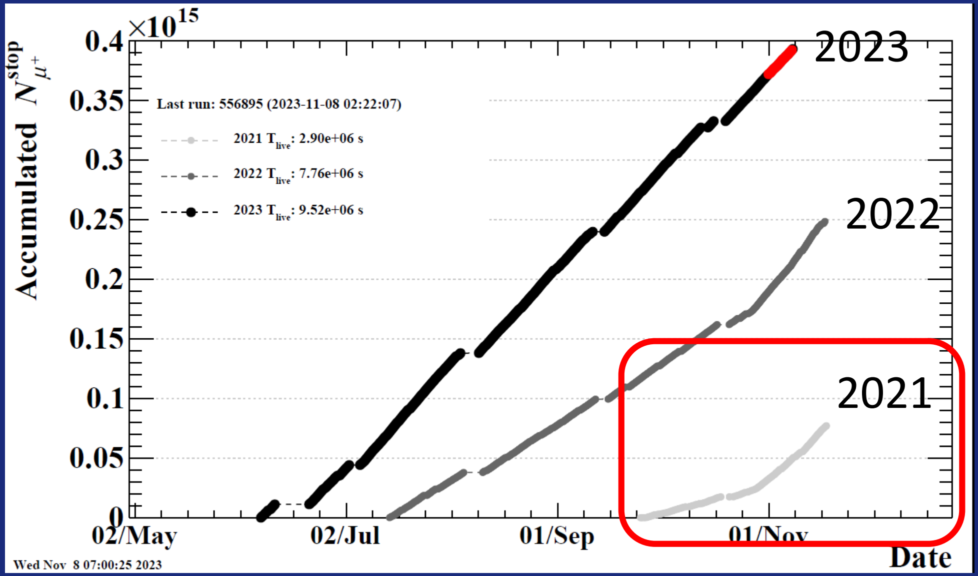
MEG-II status

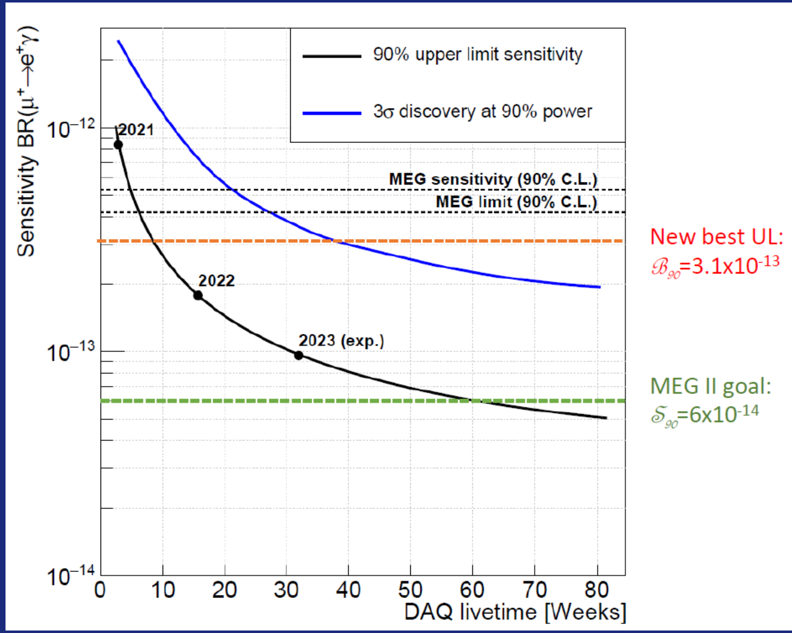
First MEG-II were published 2023:
BR($\mu \to e\gamma$) < **7.5 x 10^{-13}** (arXiv :2310.12614v2)

(Combined MEG + MEG-II: BR($\mu \to e\gamma$) < 3.1x10^{-13})

Continue to run until 2026.

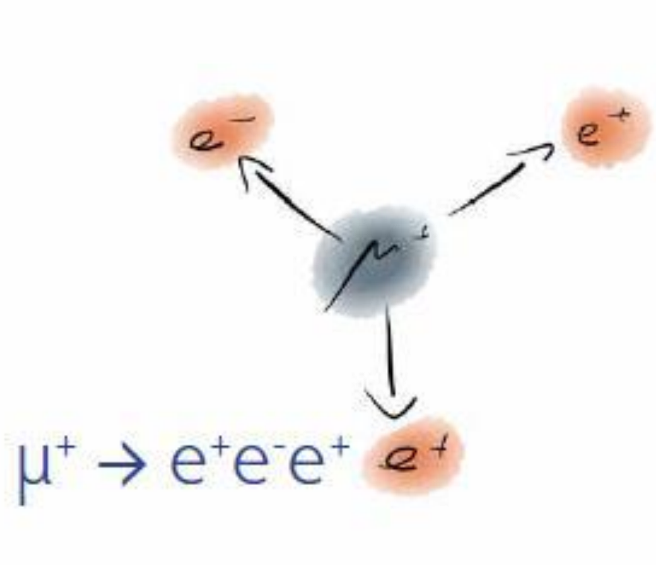
Final sensitivity goal is 6x10^{-14}





CLFV Muon decay channels

If lepton flavour is violated there are three obvious muon decays to look for this.



3 co-planar electrons
$\Sigma P_e = 0, \Sigma E_e = m_\mu$

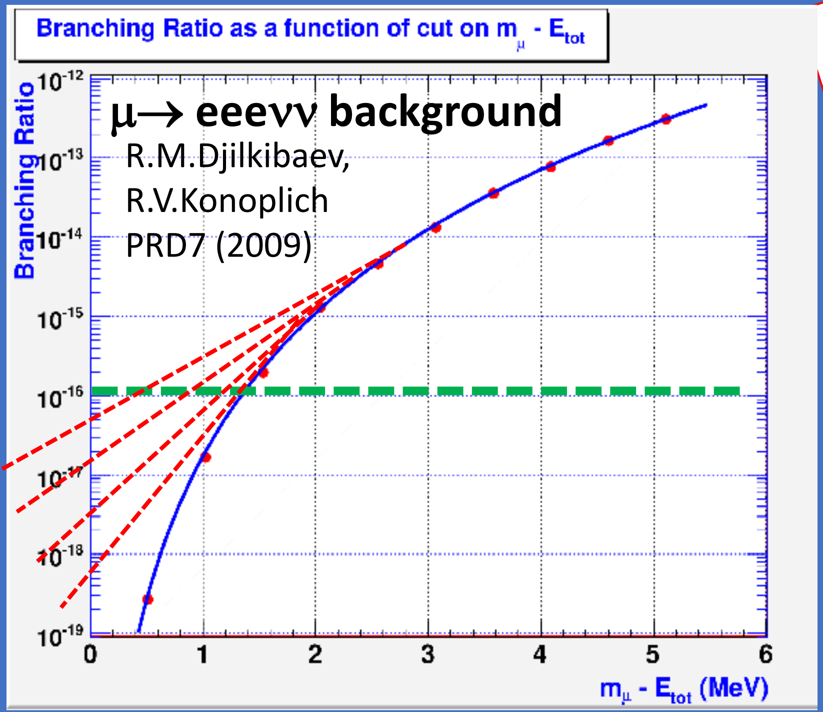
Typically, muons are stopped on a target and decay at rest.

$E_{observed} = m_\mu$ (no neutrinos)

Key backgrounds:

- **Radiative Michel decays ($\mu \to ee\nu\nu$)**
- **Accidental backgrounds: e^+ from $\mu \to e\nu\nu$ + e^+e^- pair from photon conversion or Bhabha events**

DC beam

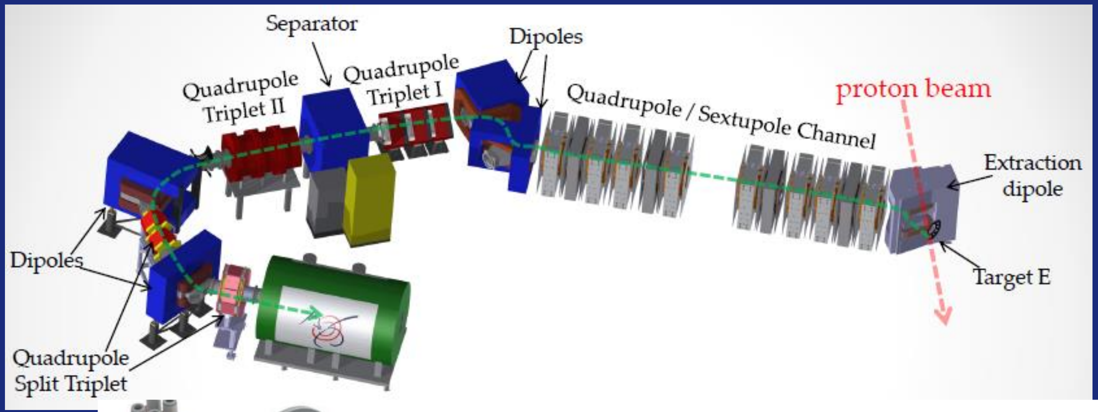


Need:

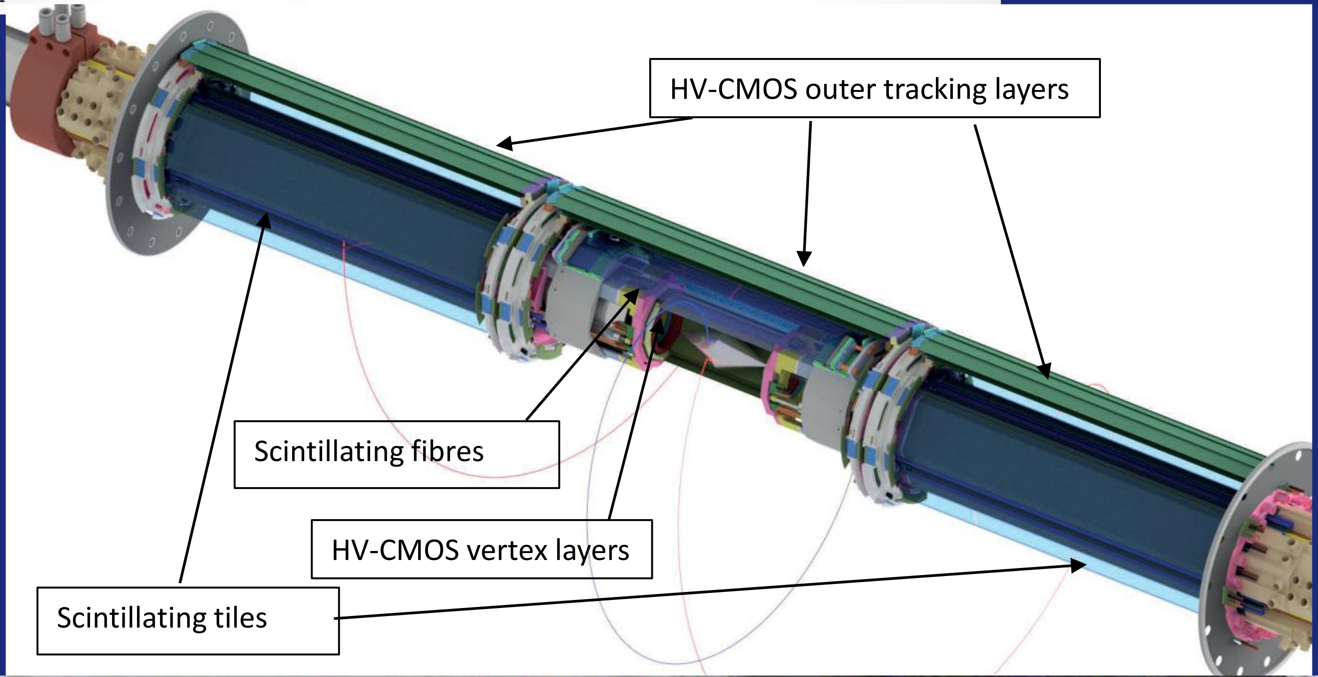
- **$\sigma(E_{tot}) < 1$ MeV**
- **Excellent vertex and timing resolution**

Mu3e: μ→eee at PSI

Mu3e will shares the πe5 beamline with MEG-II

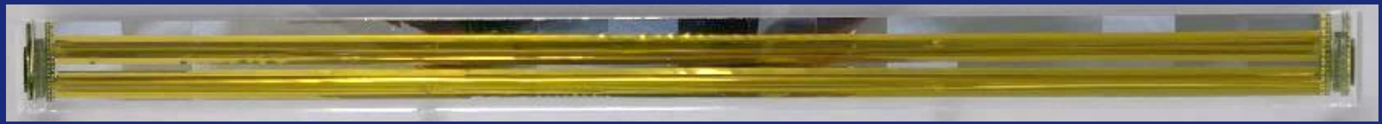


Inside mu3e up to 2x10^{9} μ/s are stopped on thin mylar target.



To achieve high resolution for low energy positrons/electrons (10-50 MeV) requires an ultra-low-mass tracker

- MuPix tracker (~0.1%X_0 per layer)
  - 50 μm HV-CMOS pixel sensors
  - Low mass supports
  - cooled with gaseous Helium
- Recoiling track concept



Scintillating fiber and tile detectors crucial for the reduction of combinatoric backgrounds

Mu3e status

Construction of the mu3e experiment is ongoing, to be completed in early 2025.

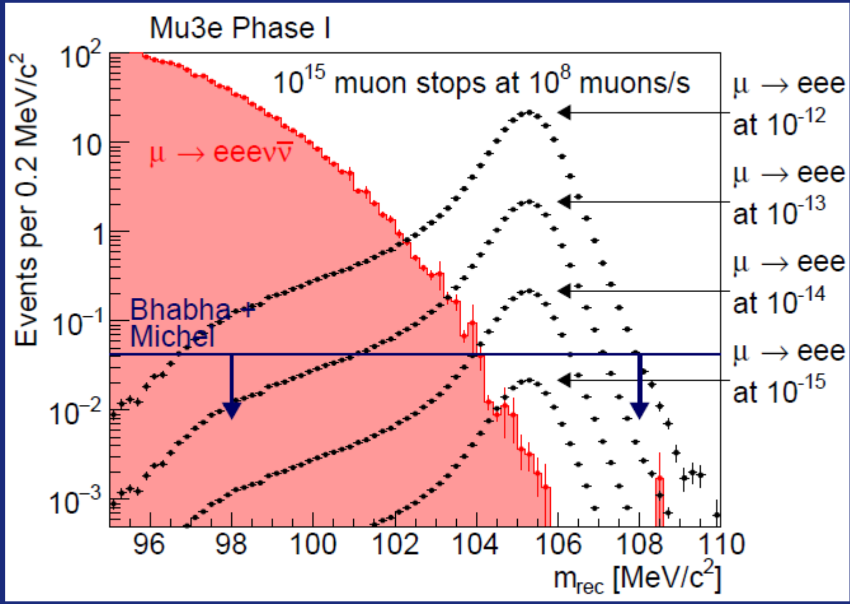
Phase I experiment

Start of Physics operation in 2026.

- substantial improvement on Sindrum limit (10^{-12}) based on first year of data.
- Completion phase-I around 2030 with sensitivity to BR($\mu \rightarrow eee$) < 2×10^{-15}

Phase 2 experiment upgrade

- 2×10^{9} μ/s after PSI HIMB upgrade
- Extended acceptance
- Fast silicon to control combinatoric backgrounds



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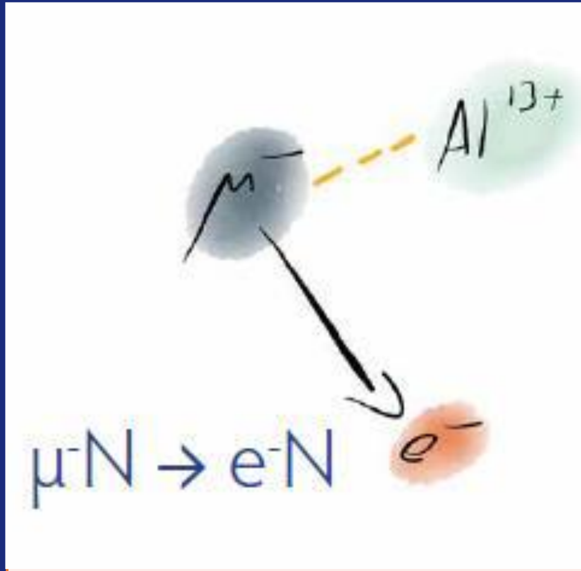


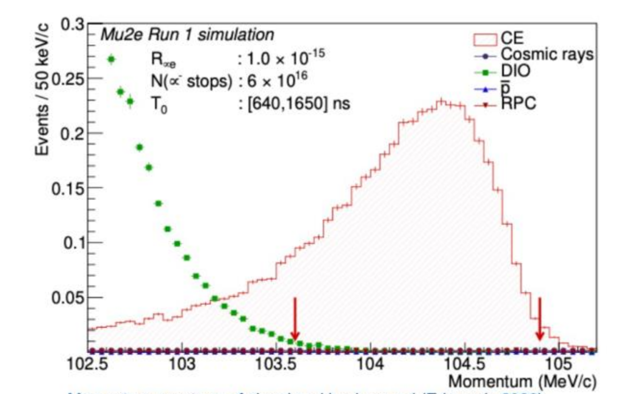
Muon decay from muonic atom. Monochromatic electron

$E_e = m_{\mu} - E_{binding} - E_{recoil}$

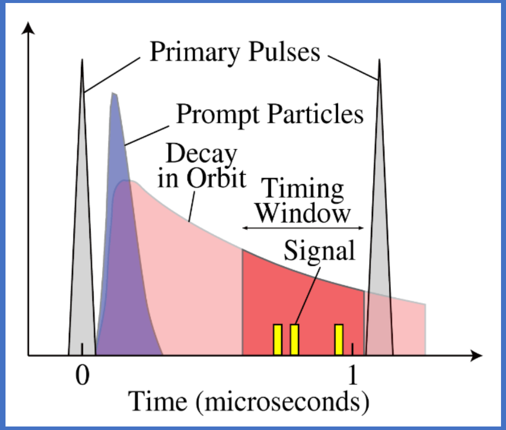
Key backgrounds:

- **Non-LFV muon decay in orbit**
- **Beam related backgrounds: prompt antiprotons, pions,..**

Pulsed μ^- beam



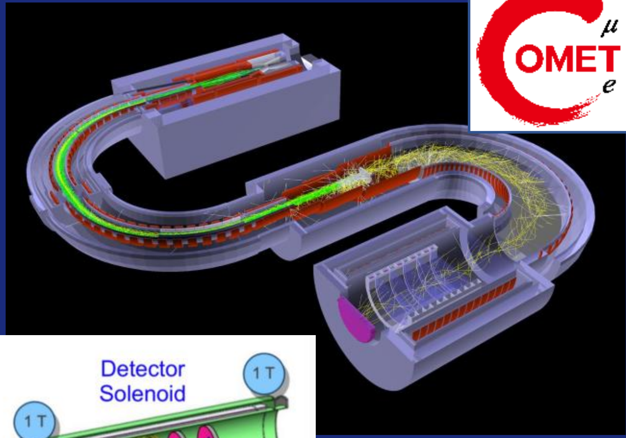
Momentum spectrum of signal and background (Edmonds 2023)



Need:

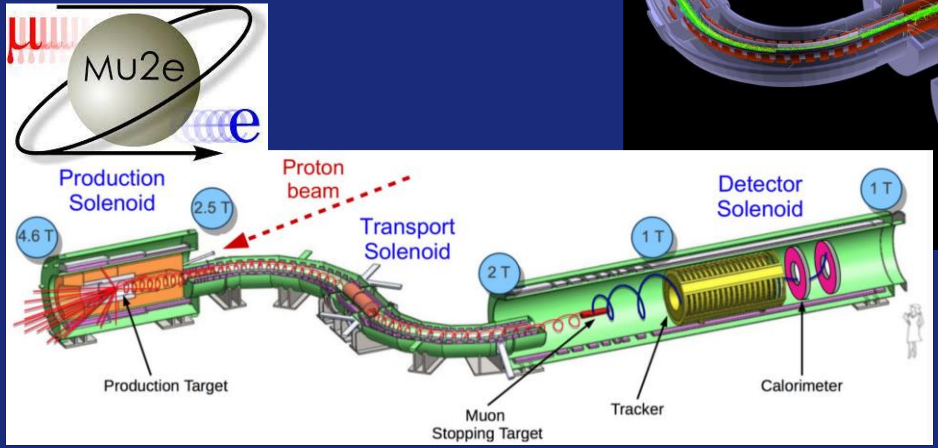
- **High purity beam**
- **Good momentum resolution**
- **Pulsed beam with delayed readout**

Mu2e (FNAL) & COMET (JPARC): $\mu N \rightarrow eN$ conversion



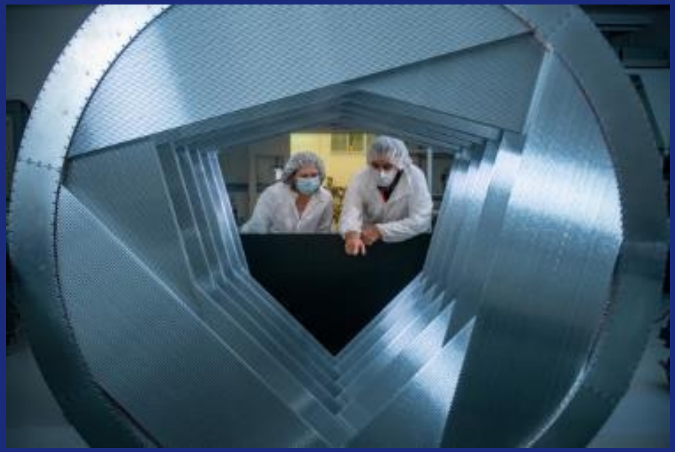
Two experiment under development with quite similar set-up and on similar schedule:
Mu2e at FNAL and COMET at JPARC
Similar muon beam set-up:

- Pulsed proton beam produces pions on target.
- Muons from pion decay captured with graded solenoid
- Curved transport solenoids to clean up muon beam



Description Mu2e

- Muons stopped on Aluminium target
- Hollow tracker in detector solenoid → no acceptance for low momentum electrons.
- Calorimeter (CsI) for energy measurement (key for residual muon background)



Mu2e schedule:

- Construction to complete in early 2026
- First physics in second half 2026
- Continue operation after PIP-II shutdown)

Phase 1 target is sensitivity of 10^{-16}

Summary

Exciting muon precision physics programme. I discussed only g-2, EDM and lepton flavour violation (there is more).

Muon g-2 results pose a puzzle that needs resolving. We observe >5σ discrepancy between data and theory, …… but unfortunately also discrepancies between different theory predictions of $\mathbf{a_\mu^{HLO}}$ and between experimental results that feed into $\mathbf{a_\mu^{HLO}}$.

Major focus across theory and new experiments to clarify this!

Sensitivity on the **Muon EDM** will be improved in steps with ultimate improvement of nearly four orders of magnitude possible from a dedicated experiment.

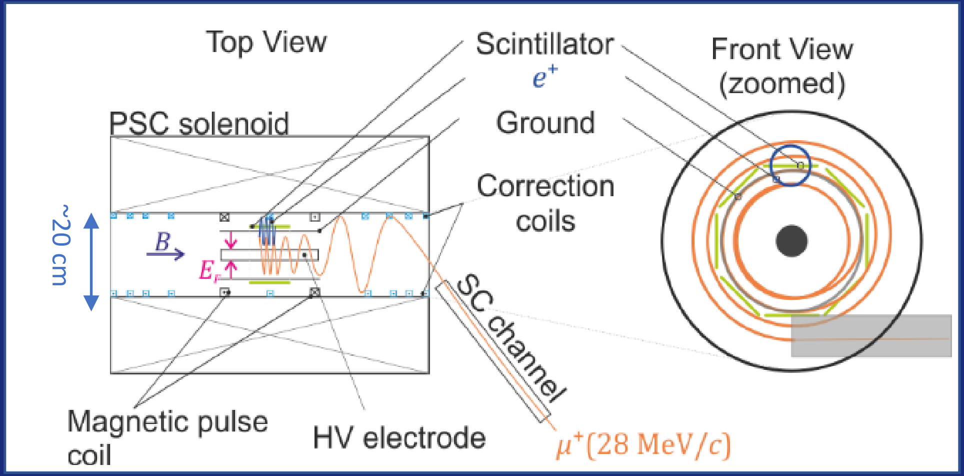
Current experiments and experiments under construction will improve sensitivity to **charged lepton flavour violation in muon decays** by up to four orders of magnitude.

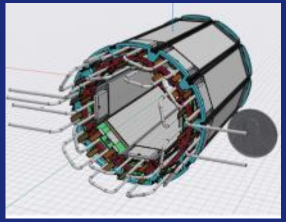
BACK-UP slides

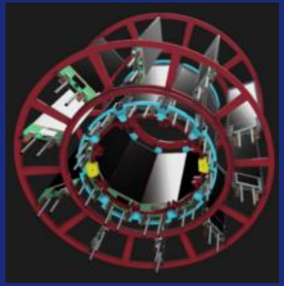
μEDM experiment at PSI

Stage 1

- $p_\mu = 28\ \mathrm{MeV}/c$; B=3T; E=0.3MV/m
- Demonstration of EDM frozen spin techniques
- Sensitivity d(μ) ~ $3 \times 10^{-21}\ e\mathrm{cm}$
- To be completed before 2027 HiMB upgrade

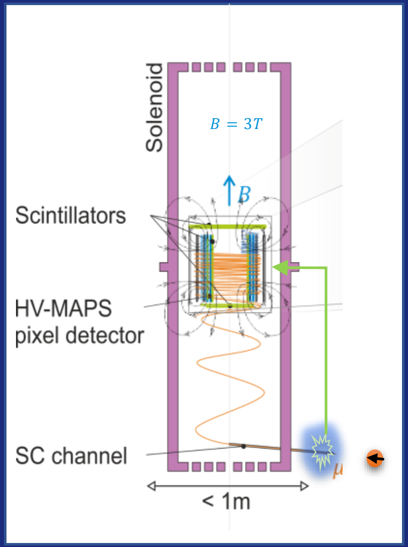


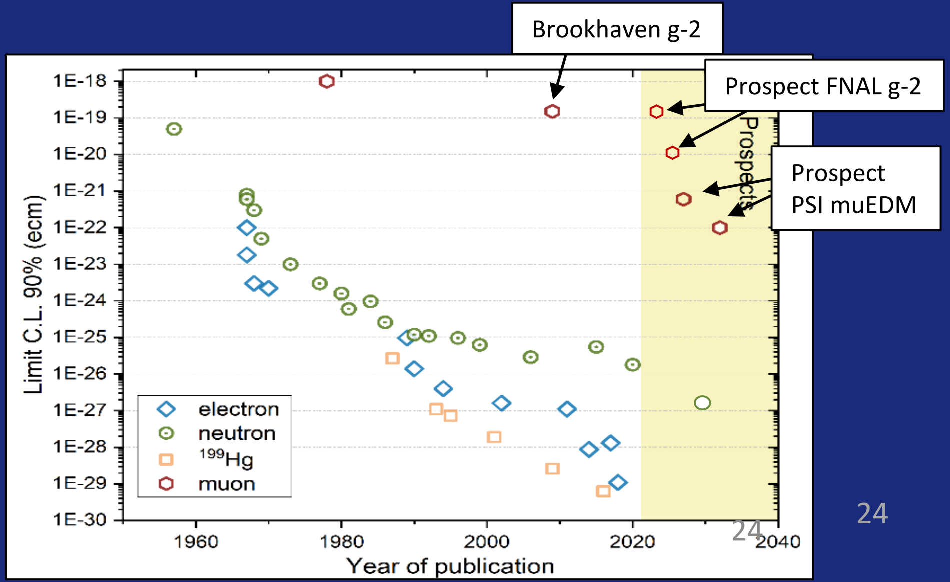




Stage 2

- $p_\mu = 125\ \mathrm{MeV}/c$; B = 3T; E = 2.0MV/m
- Sensitivity ~ $6 \times 10^{-23}\ e\mathrm{cm}$
- HV-MAPS positron tracker
- Start early 2030s



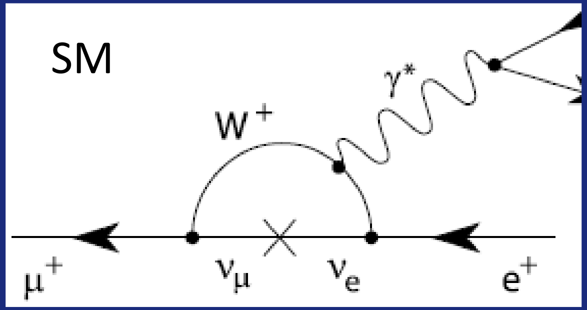


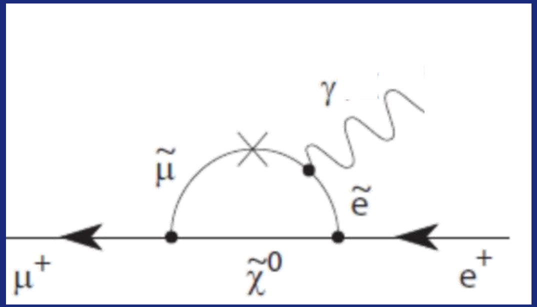
UK focus on general experiment development and positron tracker

Charged Lepton Flavour Violation in Muon decays

Heavily suppressed in the SM due to low neutrino mass.

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$





Any observation of CLFV is evidence of NP.

Charged lepton flavour violation can appear naturally in NP theories.

The long lifetime and clean decay modes make muon decays ideal to look for rare CLFV decays!

If charged lepton flavour is <u>not</u> conserved we expect to see:

- **μ → eγ,**
- **μ → eee**
- **μN → eN**

μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^- \overline{\nu}_e \nu_\mu$		$\approx 100\%$	
Γ_2	$e^- \overline{\nu}_e \nu_\mu \gamma$	[a]	$(6.0\pm0.5) \times 10^{-8}$	
Γ_3	$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[b]	$(3.4\pm0.4) \times 10^{-5}$	

Physics reach

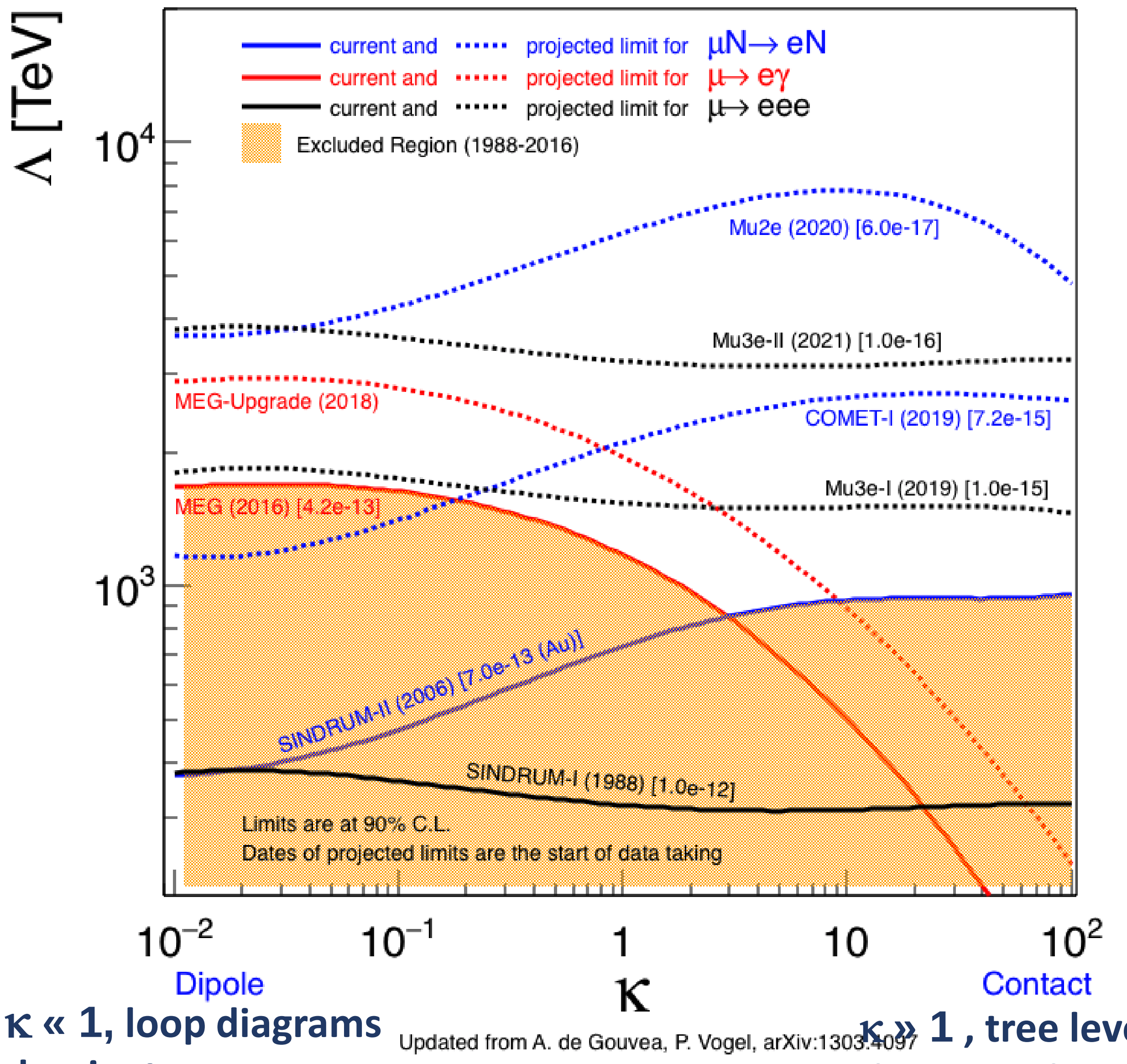
Highly model dependent. Different channels have varying sensitivity to different NP modes.

A comparison is possible with a generic Lagrangian model:

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c.\,.$$

CLFV experiments have sensitivity up to several PeV effective scale.

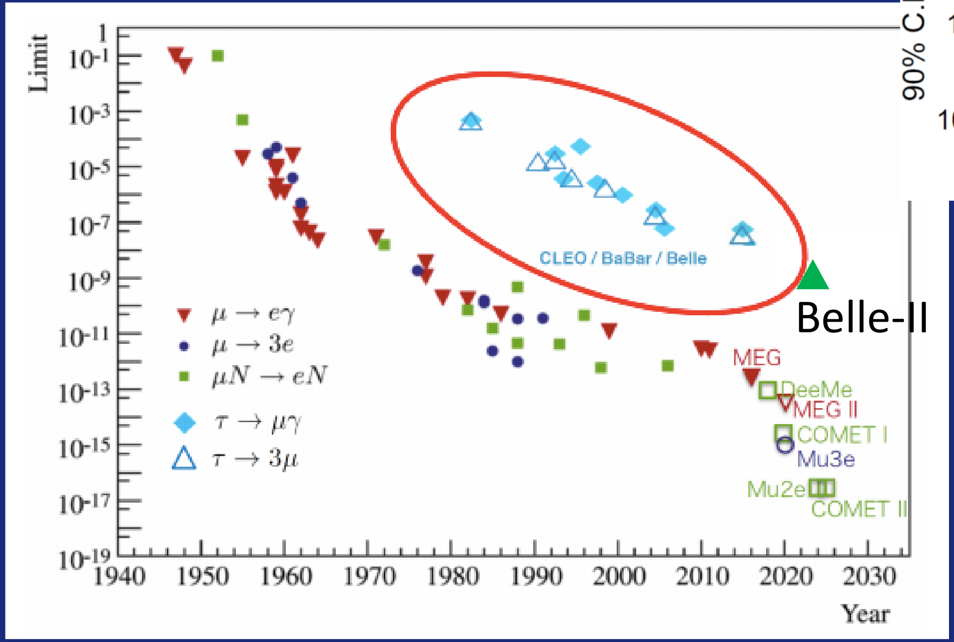
Update from de Gouvea & Vogel, Prog. in Part. and Nucl. Phys. 71 (2013).

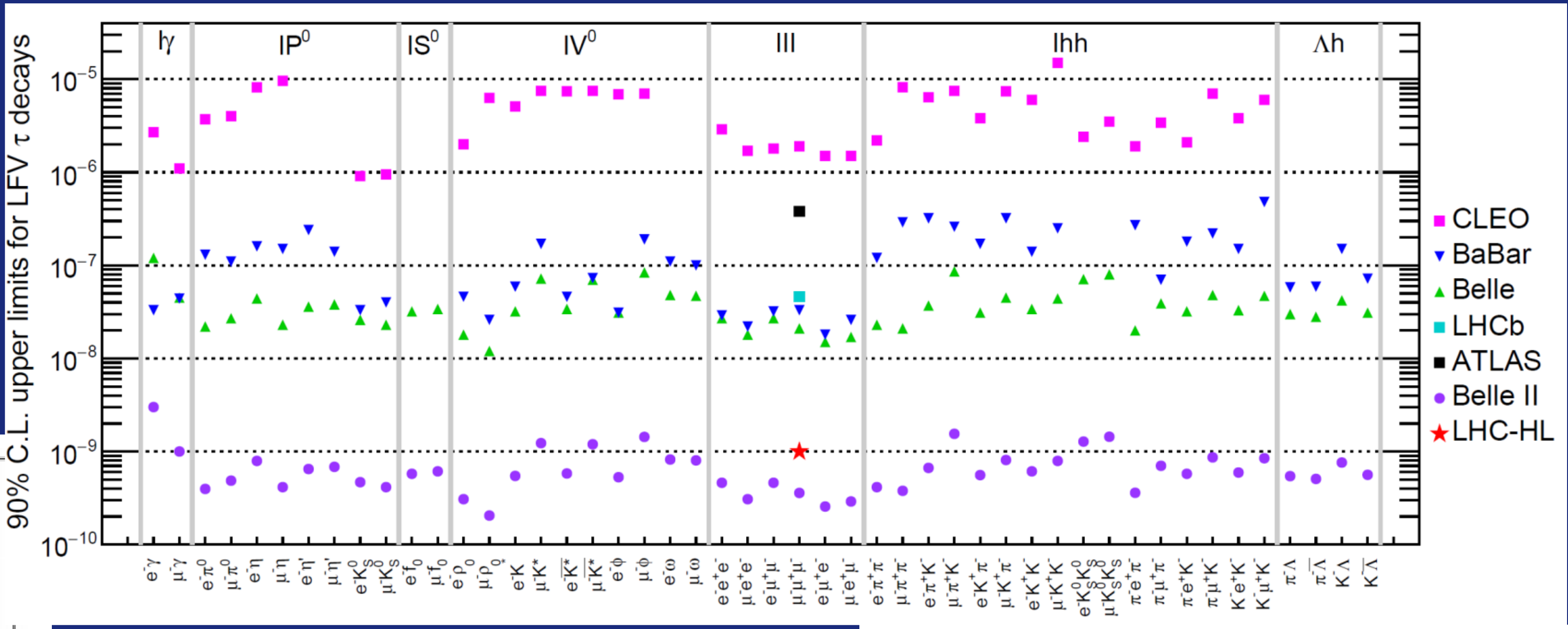


κ « 1, loop diagrams dominate

κ » 1 , tree level diagrams dominate

CLFV τ-decays





PDG 2019, "Tests of Conservation Laws"

Best τ limits from Belle and Babar, with improvements from Belle-II expected.

<u>Compared to muons:</u>

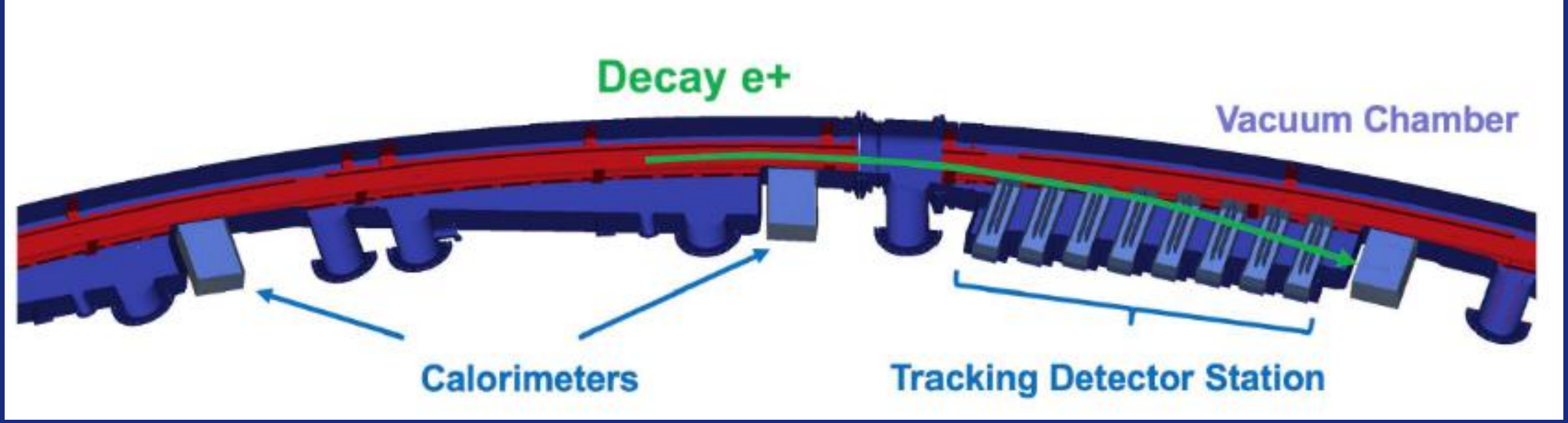
Shorter τ lifetime and more complex final states make it much harder to look rare decays due to new physics.

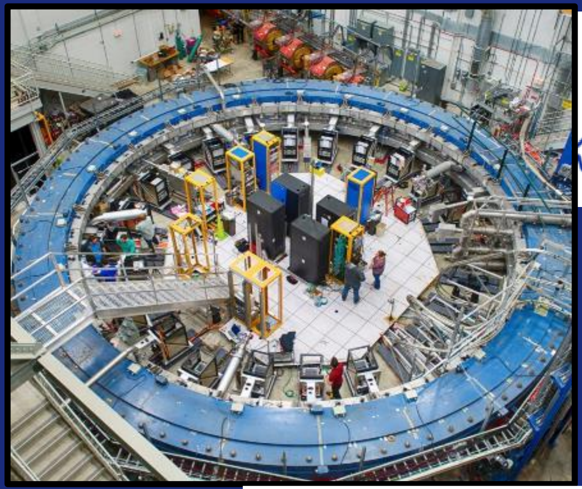
BR limits are several orders of magnitude higher.

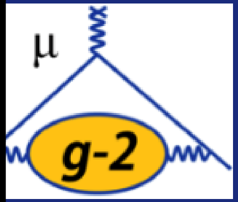
This is not compensated by higher tau mass unless NP has unexpected high power dependence on mass or is generation specific.

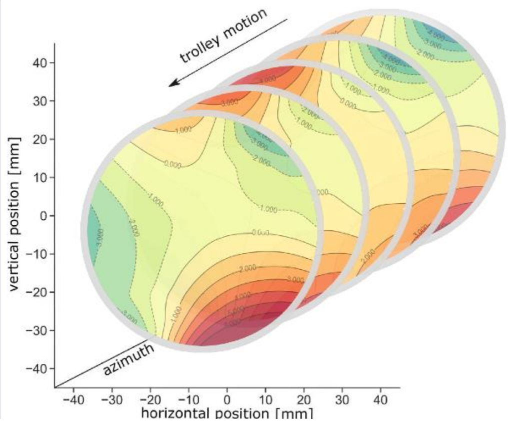
Fermilab g-2 experiment

In 2013 BNL storage ring was moved to FNAL and recommissioned, to do an experiment with higher statistics and improved systematics.









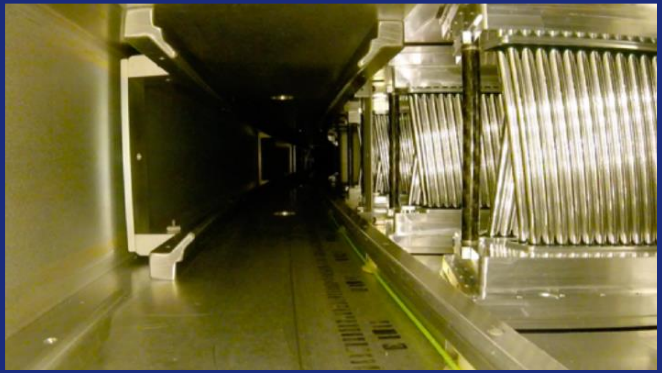
Magnetic field uniformity (<20ppm RMS)

Target: final uncertainly of 0.14 ppm

Critical parameters:

- Magnetic field uniformity
- Residual electric fields
- Beam dynamics and beam profile

Ring instrumented with 24 calorimeters and 2 tracking stations.

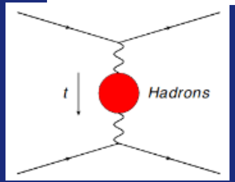


UNIVERSITY OF LIVERPOOL

Proposed MUonE experiment at CERN

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

Phys. Rep. C 3 (1972), 193



The leading order hadronic contribution to a_μ can also be determined from the hadronic contribution to the running of the electro-magnetic coupling.

Muon-electron scattering is a clean way to measure this.

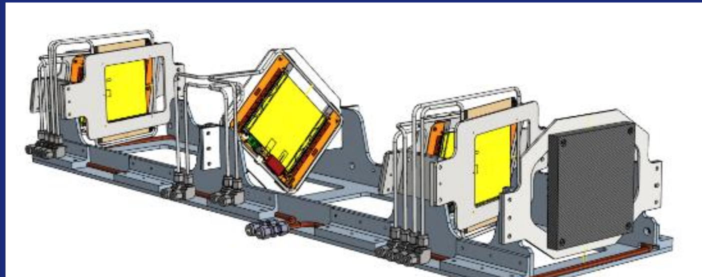
<u>MUonE</u> exploits 150 GeV muons at CERN to hit electrons at rest in a low Z target (Beryllium).

<u>Target: 0.3% uncertainty on a_μ^{HLO}</u>

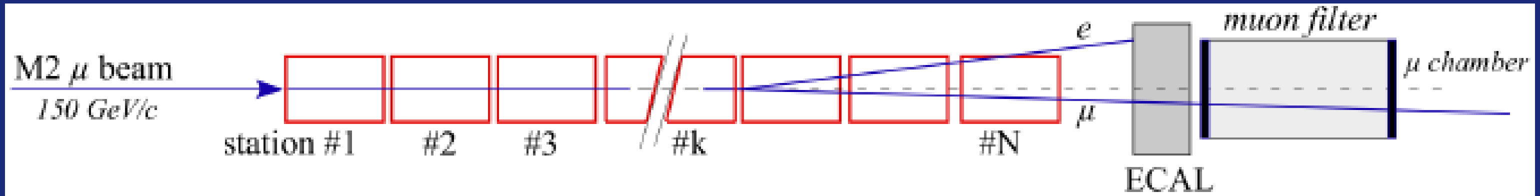
- Very challenging kinematics (θ_μ < 5 mrad, θ_e < 30 mrad, E_e > 1 GeV) require excellent angular resolution scattered electron and muon and(!) the incoming muon.

→ High resolution tracking and challenging tolerance on mechanical stability mechanical

→ 40 tracking stations, each with thin target and multiple silicon strip layers.

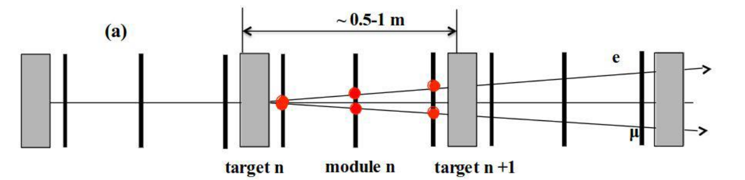


MUonE tracking station



<u>MUonE Schedule:</u>

- 2023 demonstrator run
- Demonstrator run with ~10 stations before LS3
- Full experiment (40 stations) after LS3



2023 demonstration