Status and prospects on muon $g-2$ and lepton flavor violation

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INFN PISA

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Introduction

Muon $g-2$

- sub-ppm theory prediction
- sub-ppm experimental uncertainty
- precise Standard Model test
  - discrepancy $\Rightarrow$ New Physics
- to search for high-energy New Physics, $(g-2)_\mu$ test more powerful than e and τ
- many activities on-going
  - direct measurements
  - measurements for theory prediction
  - dispersive theory prediction
  - lattice QCD theory prediction

Muon magnetic anomaly a_μ

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

Lepton flavour violation

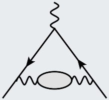
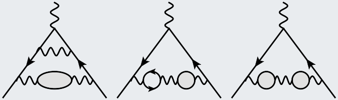
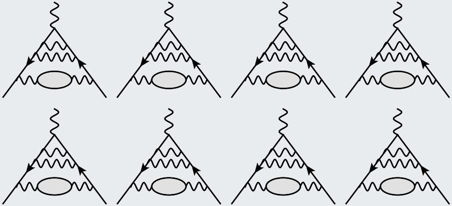
- theory predicts extreme suppression [e.g. $\mathcal{B}(\mu \to e\gamma{\sim}10^{-54}$]
- experiments very sensitive
- valuable tool to search for New Physics
- μ LFV more effective than e or τ
- τ LFV modes essential to study NP models
- many muon and tau searches on-going

a_μ theory prediction to 0.37 ppm [Muon $g-2$ theory initiative, Dec 2020]

- doi:10.1016/j.physrep.2020.07.006

Contribution	Section	Equation	Value $\times 10^{11}$	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
HVP LO (e^+e^-)	Sec. 2.3.7	Eq. (2.33)	6931(40)	Refs. [2–7]
HVP NLO (e^+e^-)	Sec. 2.3.8	Eq. (2.34)	−98.3(7)	Ref. [7]
HVP NNLO (e^+e^-)	Sec. 2.3.8	Eq. (2.35)	12.4(1)	Ref. [8]
HVP LO (lattice, $udsc$)	Sec. 3.5.1	Eq. (3.49)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	Sec. 4.9.4	Eq. (4.92)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	Sec. 4.8	Eq. (4.91)	2(1)	Ref. [31]
HLbL (lattice, uds)	Sec. 5.7	Eq. (5.49)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	Sec. 8	Eq. (8.10)	90(17)	Refs. [18–30, 32]
QED	Sec. 6.5	Eq. (6.30)	116 584 718.931(104)	Refs. [33, 34]
Electroweak	Sec. 7.4	Eq. (7.16)	153.6(1.0)	Refs. [35, 36]
HVP (e^+e^-, LO + NLO + NNLO)	Sec. 8	Eq. (8.5)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	Sec. 8	Eq. (8.11)	92(18)	Refs. [18–32]
Total SM Value	Sec. 8	Eq. (8.12)	116 591 810(43)	Refs. [2–8, 18–24, 31–36]
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	Sec. 8	Eq. (8.14)	279(76)	

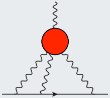
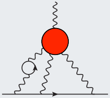
Contributions to a_μ: QCD HVP (hadronic vacuum polarization)

	a_μ contribution $[10^{-11}]$	order
	6931 $\pm$ 40	HVP,LO
	-98.3 $\pm$ 7	HVP,NLO
	12.4 $\pm$ 1	HVP,NNLO

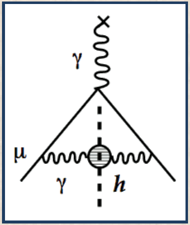
terminology

LO = "leading order", NLO = "next to leading order", NNLO = "next to next to leading order"

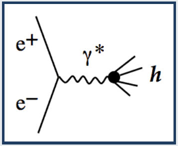
Contributions to a_μ: QCD HLbL (hadronic light-by-light)

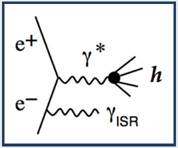
	a_μ contribution $[10^{-11}]$	order
	92 ± 19	HLbL,LO
	2 ± 1	HLbL,NLO

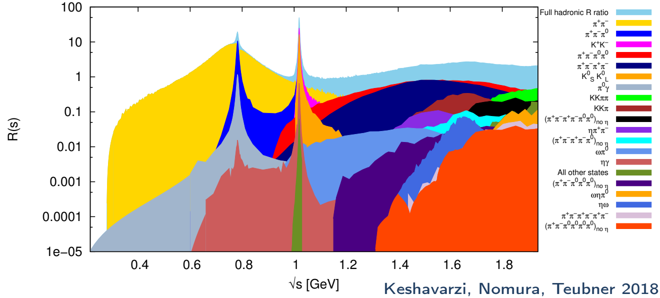
Calculation of QCD HVP,LO contribution to a_μ



using measurements of $e^+e^- \to$ hadrons cross-section (or $\tau \to$ hadrons ν decay)

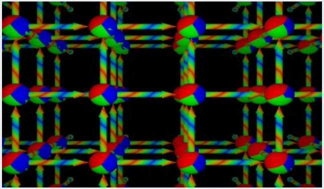






Keshavarzi, Nomura, Teubner 2018

using numeric calculations on discretized space-time (lattice QCD)



a_μ test more powerful than a_e to search for high energy New Physics

a_e test more precise than a_μ test

$$\frac{\Delta(a_\mu^{\text{exp}} - a_\mu^{\text{th}})}{\Delta(a_e^{\text{exp}} - a_e^{\text{th}})} \sim 2000$$

but

a_μ test more sensitive than a_e test for "typical" high-energy New Physics models

$$\frac{\Delta a_\mu^{\text{New Physics}}}{\Delta a_e^{\text{New Physics}}} \sim \frac{m_\mu^2}{m_e^2} \simeq 43000$$

experiment and theory uncertainties contributions to a_μ test before April 2021

	δa_μ [ppm]	δa_e [ppb]
experiment	0.54	0.24
theory	0.37	0.20
- α_{QED}	0.00	0.20
- QED	0.00	0.01
- EW	0.01	0.00
- QCD	0.37	0.01
- HVP	0.34	
- HLbL	0.15	

- note: using less precise α_{QED}(Cs 2018) because of inconsistency with α_{QED}(Rb 2020)

Motion and spin precession of muon in uniform magnetic field

muon spin precession relative to momentum

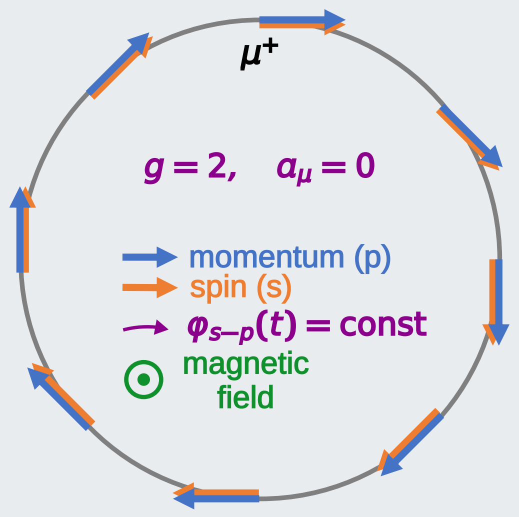
$$\omega_s - \omega_c = \omega_a$$

$$\boxed{-g_\mu \frac{eB}{2m_\mu} - (1-\gamma)\frac{eB}{m_\mu\gamma}} - \boxed{-\frac{eB}{m_\mu\gamma}} = \boxed{-a_\mu \frac{eB}{m_\mu}}$$

Larmor + Thomas precessions — cyclotron frequency — no γ!

- frequency measurements best for precision
- magnetic field NMR measurement also frequency proton spin precession, $\hbar\omega_p = 2\mu_p B$
- angle between momentum and spin: $\varphi(t) = \omega_a t$

polarized muons in magnetic storage ring



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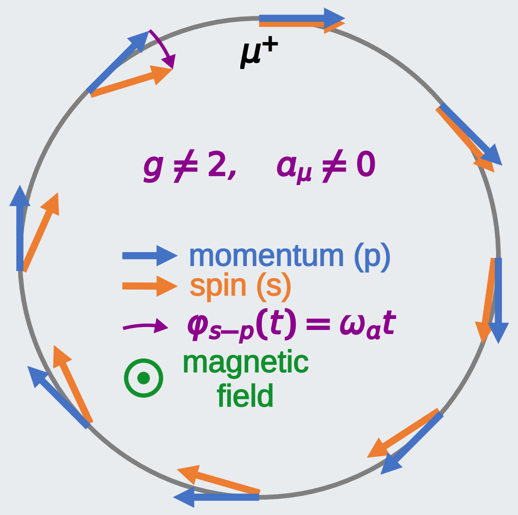


Beam focusing in storage ring, magic energy

beam focusing

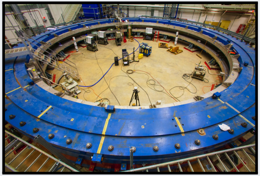
- weak horizontal focusing provided by uniform magnetic field
- weak vertical focusing with electric field quadrupoles
  (associated E-field horizontal de-focusing overridden by magnetic focusing)

magic energy

- $$\vec{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})}_{E\text{-field correction}} - \underbrace{a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta} \cdot \vec{B}\right)\vec{\beta}}_{\text{pitch correction}} \right]$$
- magic energy, corresponding to $p_\mu^{\text{magic}} = 3.094\,\text{GeV}$ and $\gamma = 29.3$, zeroes E field correction

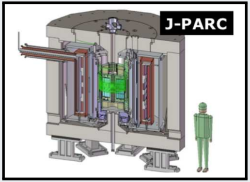
magic energy

- CERN 1975-, BNL, FNAL



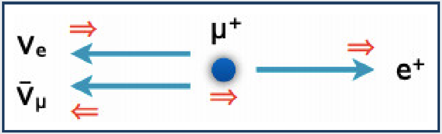
$E = 0$, ultra-cold muons

- J-PARC E34

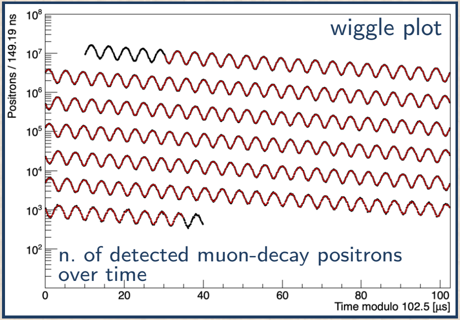


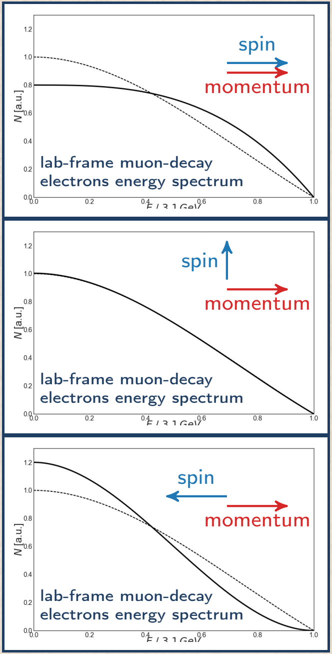
Rate of high-energy muon-decay electrons modulated with $\cos \omega_a t$

- because of parity violation in muon decay, decay electrons peak along muon spin

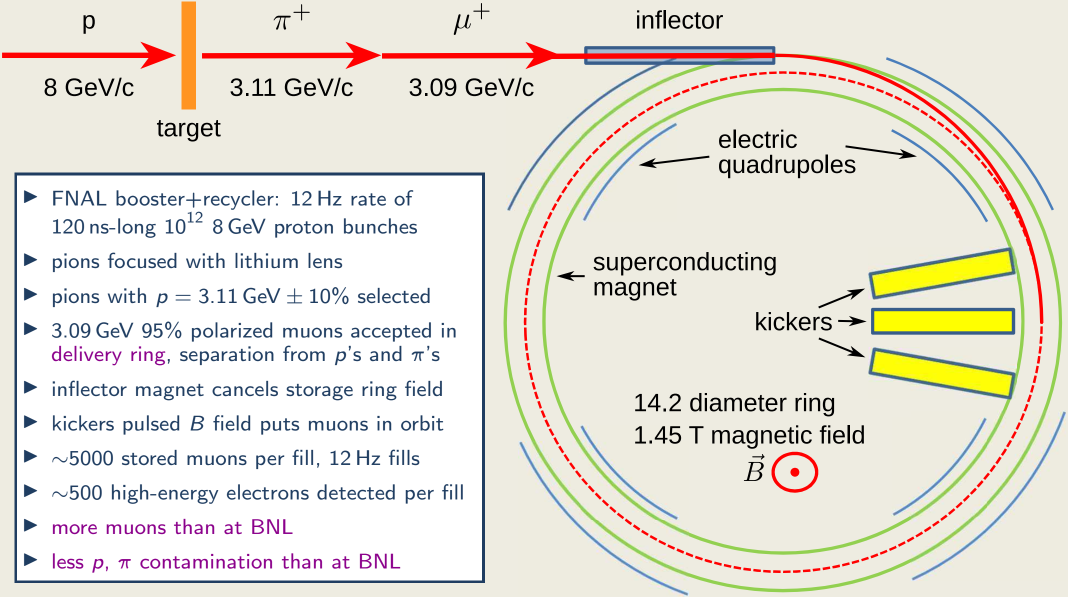


- electrons decaying along muon momentum have highest energy in laboratory frame
- $N_e(E_e > E_t) = N_{e0} e^{-t/\tau_\mu} (1 + A \cos \omega_a t)$





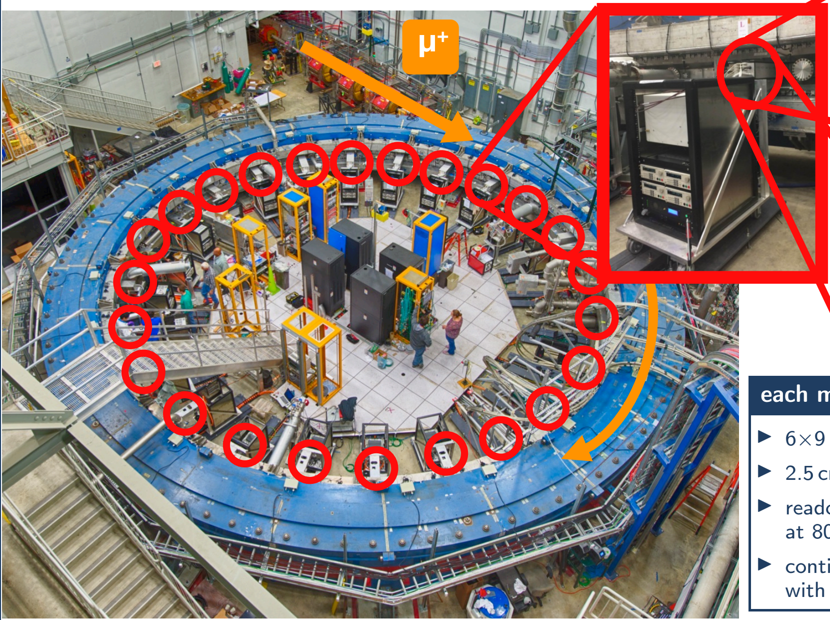
Muon production, storage and decay at FNAL Muon $g-2$ exp. (E989)

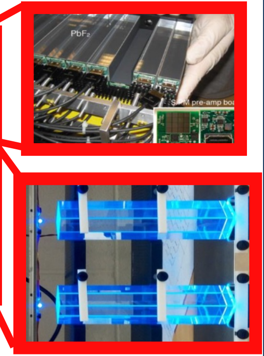


- FNAL booster+recycler: 12 Hz rate of 120 ns-long 10^{12} 8 GeV proton bunches
- pions focused with lithium lens
- pions with $p = 3.11$ GeV $\pm$ 10% selected
- 3.09 GeV 95% polarized muons accepted in delivery ring, separation from p's and π's
- inflector magnet cancels storage ring field
- kickers pulsed B field puts muons in orbit
- $\sim$5000 stored muons per fill, 12 Hz fills
- $\sim$500 high-energy electrons detected per fill
- more muons than at BNL
- less p, π contamination than at BNL

FNAL accelerator complex for Muon $g-2$

24 calorimeter modules

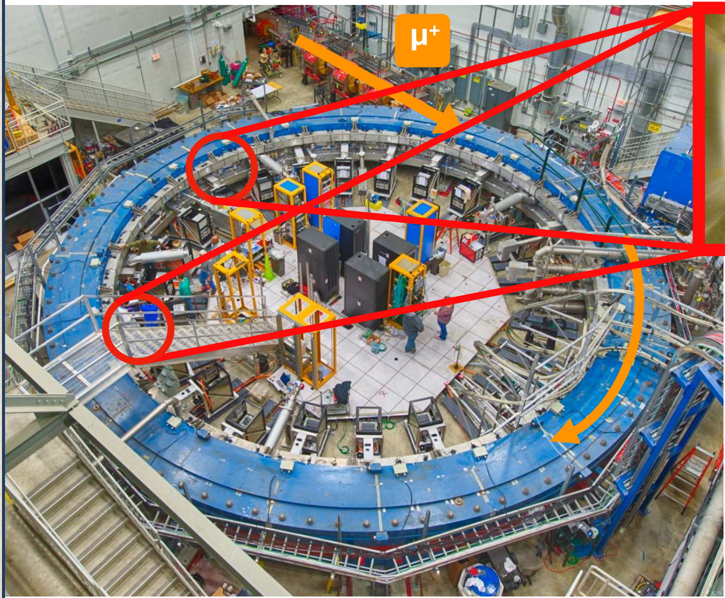




each module

- $6{\times}9$ PbF_2 crystals array
- $2.5\,\text{cm}{\times}2.5\,\text{cm}{\times}14\,\text{cm}$, $15\,X_0$
- readout Cherenkov light at 800 MHz with SiPMs
- continuos gain monitoring with laser system pulses

Two tracker modules



each tracker

- 8 modules
- 128 straw chambers each
- trace back muon decay points

Calculation of the muon magnetic anomaly

$$a_\mu = \left[\frac{\omega_a}{\tilde{\omega}'_p(T)}\right] \cdot \left[\frac{\mu'_p(T)}{\mu_e(\mathrm{H})}\right] \left[\frac{\mu_e(H)}{\mu_e}\right] \left[\frac{m_\mu}{m_e}\right] \left[\frac{g_e}{2}\right]$$

measurements by the Muon $g-2$ collaboration

- ω_a — precession of muon spin relative to momentum rotation in magnetic field
- $\tilde{\omega}'_p(T)$ — precession frequency of shielded proton spin in spherical water sample at $T = 34.7\,°\mathrm{C}$ in muon-beam-weighted magnetic field, $\tilde{\omega}'_p(T) = \langle \omega'_p(T)(x, y, \varphi) \times M(x, y, \varphi) \rangle$

notation

- $\mu'_p(T)$ — magnetic momentum of proton in spherical water sample at 34.7 °C
- $\mu_e(\mathrm{H})$ — magnetic momentum of electron in hydrogen atom

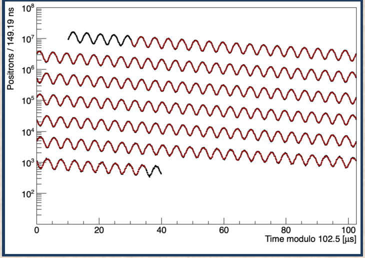
external measurements

- $\mu'_p(T)/\mu_e(H)$ — 10.5 ppb precision, Metrologia 13, 179 (1977)
- $\mu_e(H)/\mu_e$ — 100 ppt (for n. digits) theory QED calculation, Rev. Mod. Phys. 88 035009 (2016)
- m_μ/m_e — 22 ppb precision — CODATA 2018 fit, primarily driven by LAMPF 1999 measurements of muonium hyperfine splitting, Phys. Rev. Lett. 82, 711 (1999)
- $g_e/2$ — 0.12 ppt, PDG 2023

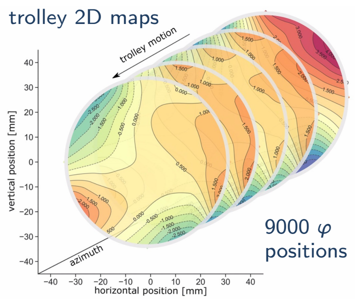
Conceptual formula for $R'_\mu(T) = \omega_a/\tilde{\omega}'_p(T)$

$$R'_\mu(T) = \frac{\omega_a}{\tilde{\omega}'_p(T)} \overset{\text{conceptually}}{=} \frac{\omega_a^{\rm m}\ \left(1 + C_e + C_p + C_{\rm ml} + C_{\rm pa} + C_{\rm dd}\right)}{\langle \omega'_p(T)(x,y,\varphi) \times M(x,y,\varphi)\rangle\ \left(1 + B_k + B_q\right)}$$

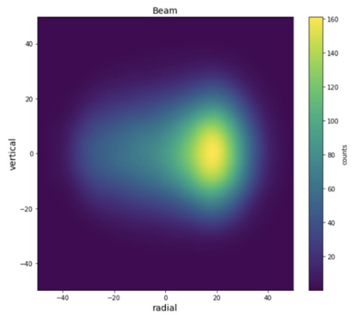
$\omega_a^{\rm m}$ - muon-spin precession



$\omega'_p(T)(x,y,\varphi)$ - B field

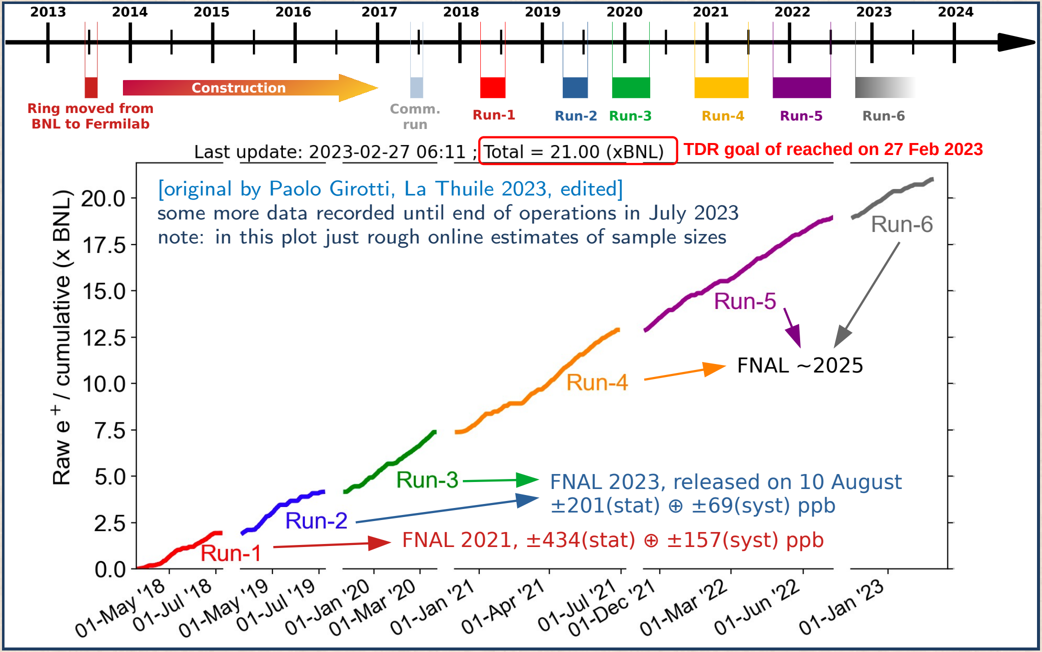


$M(x,y,\varphi)$ - μ^+ distribution

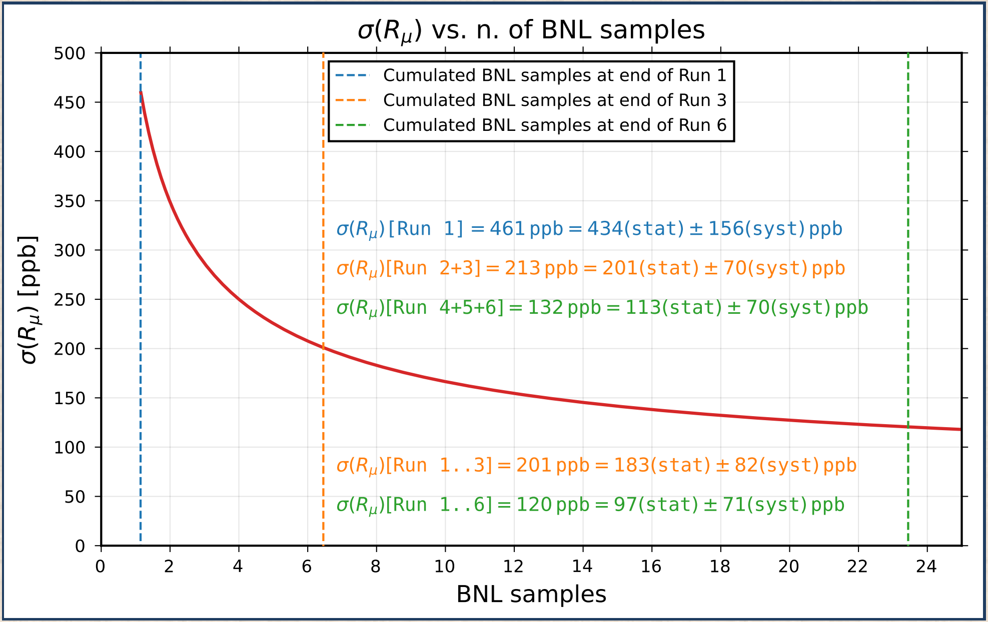


- ω_a: muon spin precession frequency
- C_x: corrections to ω_a for E field, pitch, muon loss, phase accetpance, differential decay
- $\omega'_p(T)$ precession frequency of shielded proton spin in spherical water sample at $T = 34.7\,^\circ\mathrm{C}$
- B_x: corrections to ω_p for quadrupole and kickers transient fields

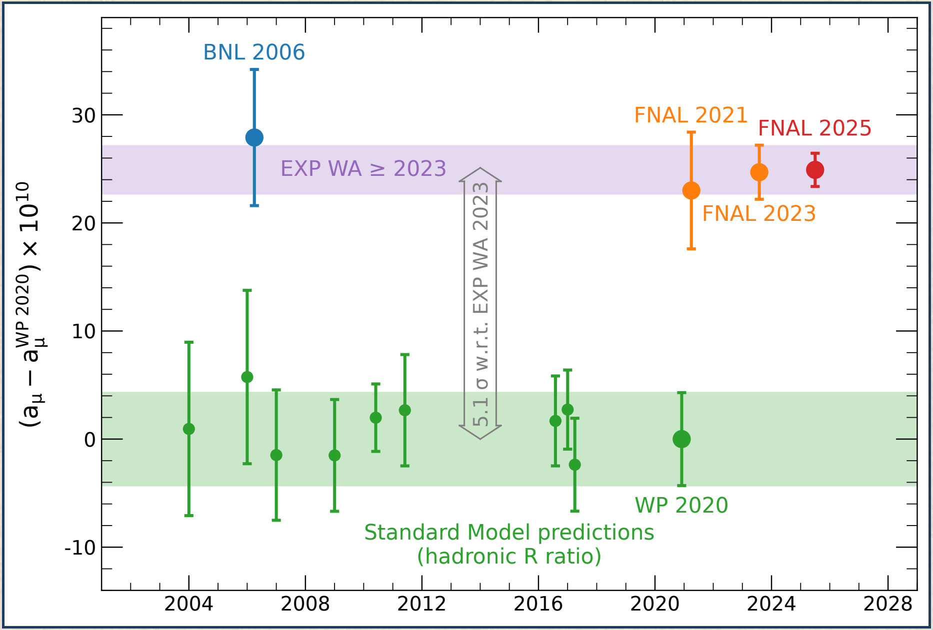
Data recorded by FNAL Muon $g-2$ experiment exceeded design goal



Expected future precision of FNAL Muon $g-2$ measurement



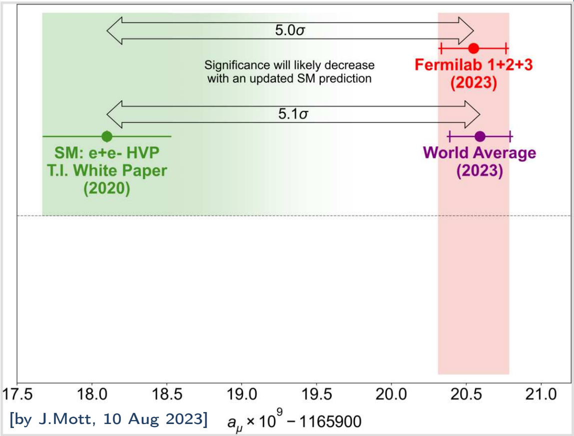
Muon $g-2$ test, after FNAL Run 2+3 measurement released in August 2023



Run 2+3 ω_a corrections and uncertainties

	Run 1 uncertainty	Run 2+3 uncertainty	design goal uncertainty
ω_a^m (statistical)	434	201	100
ω_a^m (systematic)	56	25	
- C_e	53	32	
- C_p	13	10	
- C_{pa}	75	13	
- C_{dd}	-	8	
- C_{ml}	5	3	
ω_a (total systematic)	109	44	70
$\omega'_p(T)$	56	46	
- B_q	92	20	
- B_k	37	13	
$\tilde{\omega}'_p(T)$ (total)	114	52	70
R_μ (total systematic)	157	70	100
external parameters	25	25	
total	462	215	140

Comparison with theory



[by J.Mott, 10 Aug 2023]

- large discrepancy with WP2020 prediction
- but new measurements not included in WP2020 expected to decrease significance of discrepancy

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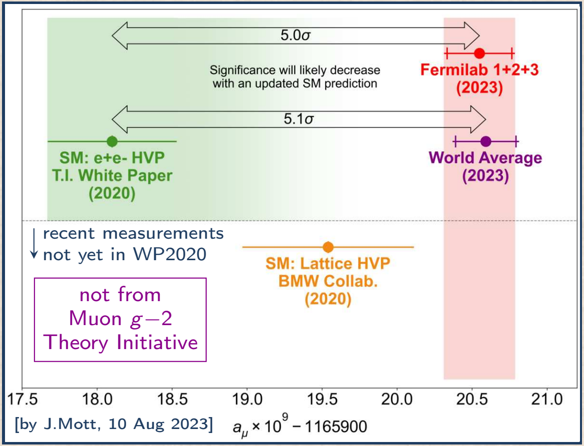

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- replace WP2020 $a_\mu^{\mathrm{HVP,LO}}$ estimate with BMW2020 lattice QCD calculation [A. Keshavarzi, Lattice 2023]
- replace WP2020 $a_\mu^{\mathrm{HVP,LO}}(\pi^+\pi^-)$ in [0.33, 1.0] GeV interval with CMD-3 $\sigma(e^+e^- \to \pi^+\pi^-)$ measurement [A. Keshavarzi, Lattice 2023] (this is a visual exercise, not an updated SM prediction)

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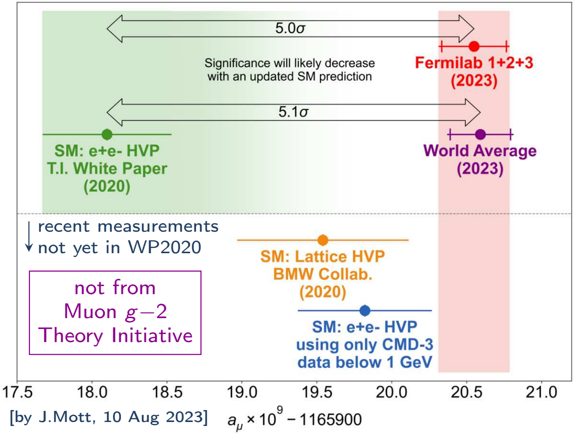

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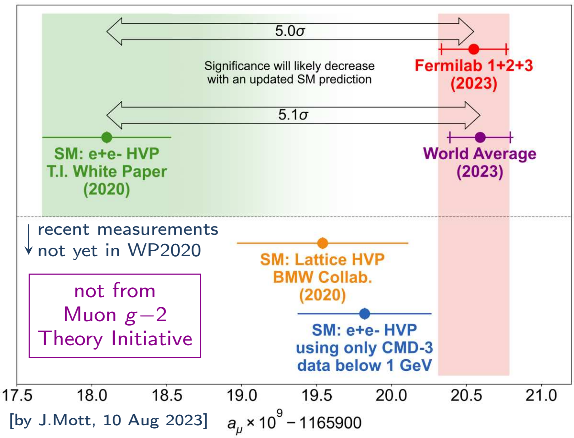

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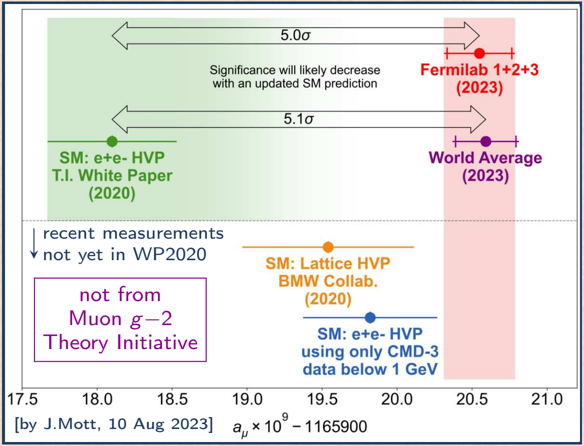

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- large ongoing effort to understand present poor consistency of theory predictions based on different inputs

Muon $g-2$ test prospects

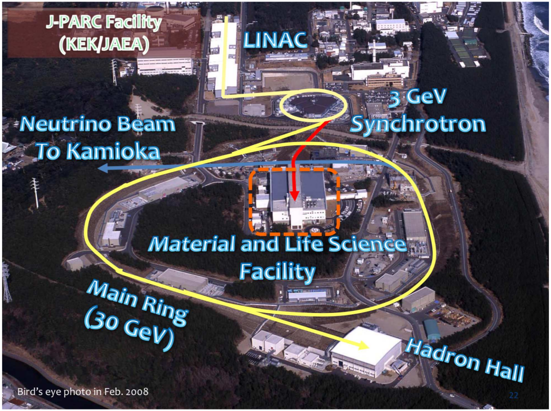
experimental measurement

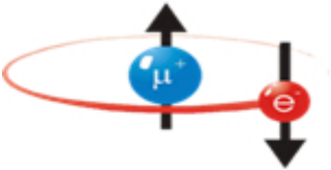
- a_μ to 0.12,ppm from FNAL-E989 complete dataset analysis by 2025
- a_μ to 0.45 ppm from J-PARC E34 with cold slow ($E = 300\,\text{MeV}$) muons in small 4 T NMR magnet
- a_μ to 3 ppm from Muonium spectroscopy PRL 127 (2021) 251801

theory prediction

- energy-scan scan $\sigma(e^+e^- \to \text{hadrons})$
  - CMD-3, SND
  - BES-III
- ISR technique $\sigma(e^+e^- \to \text{hadrons})$
  - *BABAR* $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$
  - Belle II (asymmetric-energy super B-factory)
  - BES-III, possibly Super Charm-Tau factories
  - analysis of KLOE data (Liverpool)
- MUonE: 160 GeV muons on e^- t-channel scattering, $a_\mu^{\text{HVP,LO}}$ to 0.5%
- Lattice QCD community will test and reproduce the BMW 2021 HVP contribution calculation
  - partial replications all confirmed BMW calculation
- Muon $g-2$ Theory Initiative group will verify and combine available measurement and calculations

J-PARC E34 Muon $g-2$/EDM experiment

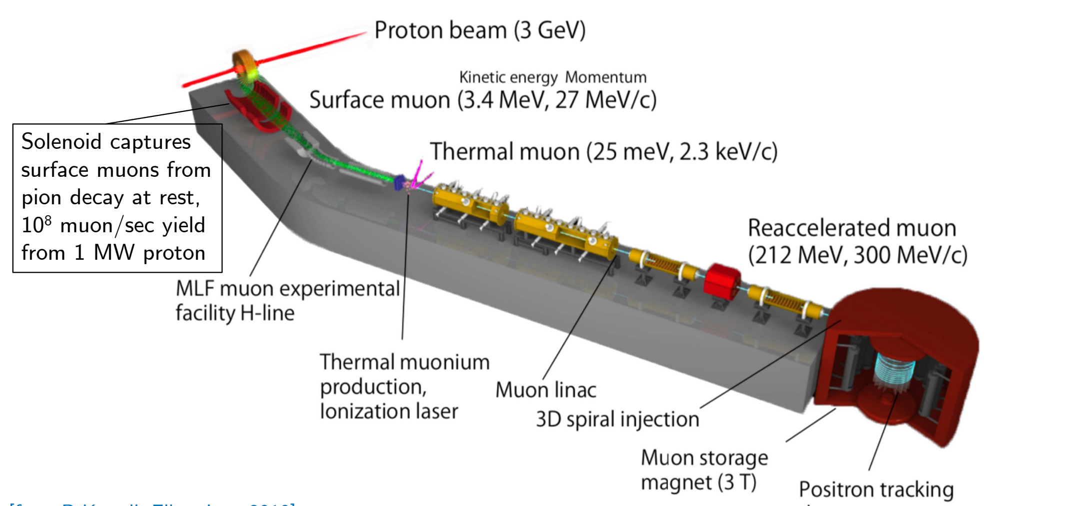




Slide Material: Tsutomu Mibe, Ken-ichi Sasaki, Koichiro Shimomura, Takayuki Yamazaki, Sohtara Kanda

[from D.Kawall, Elba, June 2019]

J-PARC E34 schematics



[from D.Kawall, Elba, June 2019]

J-PARC E34 features

Measure muon g-2 and EDM with ***significantly different methods*** from BNL/Fermilab experiments

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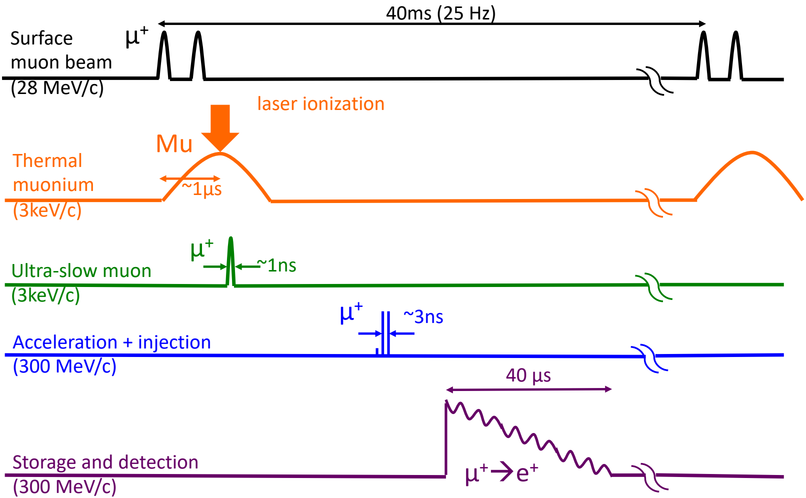
Features:

- Low emittance muon beam (1/1000)
- No strong focusing (1/1000):
  - Weak magnetic focusing, no/minimal E-field and pitch corrections
- Good injection efficiency (x 10)
- Compact storage ring (1/20):
  - B-field significantly more homogeneous and stable, easier to measure
- Tracking detector with large acceptance

[from D.Kawall, Elba, June 2019]

J-PARC E34 experimental sequence



Double pulse:
100 ns width
600 ns separation
$4\text{x}10^6$ μ^+/double pulse

Probability of Muonium in Laser Ionization Region:
$0.0034 = 0.52 \times (2.1\text{x}10^4 / 3.23 \times 10^6)$

50% polarized,
2000 – 8000 muons @ 25Hz
(kawall crude estimate)

[from D.Kawall, Elba, June 2019]

J-PARC E34 sensitivity

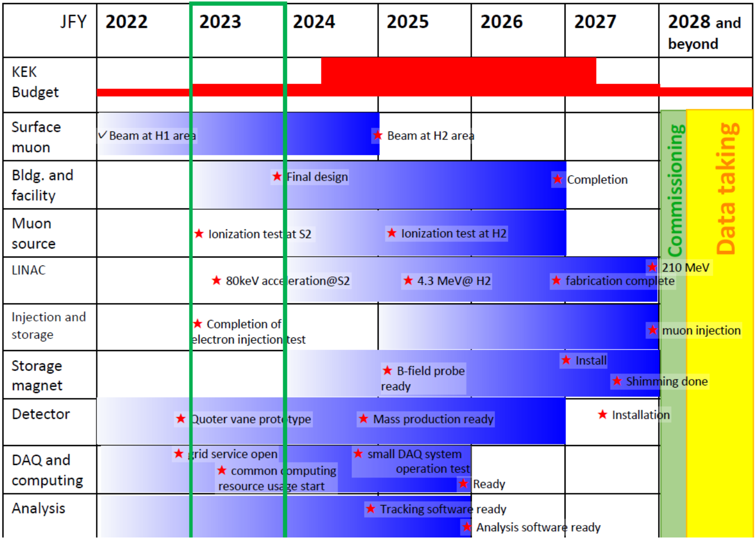
	BNL-E821	Fermilab-E989	Our Experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	0.2×10^{-19} $e \cdot$ cm	—	1.5×10^{-21} $e \cdot$ cm
(syst.)	0.9×10^{-19} $e \cdot$ cm	—	0.36×10^{-21} $e \cdot$ cm

[PTEP 2019 (2019) 5, 053C02]

J-PARC E34 schedule

Schedule

- Construction of experimental apparatus is ongoing aiming at the start of the experiment in 2028 JFY.

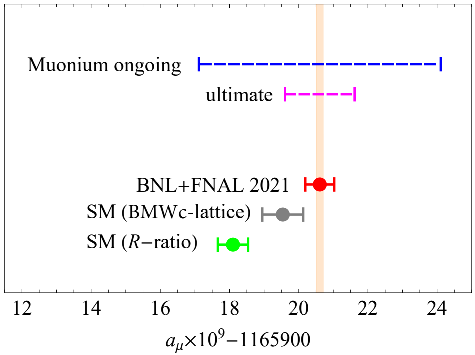


[Takashi Yamanaka, Bern, Sep 2023]

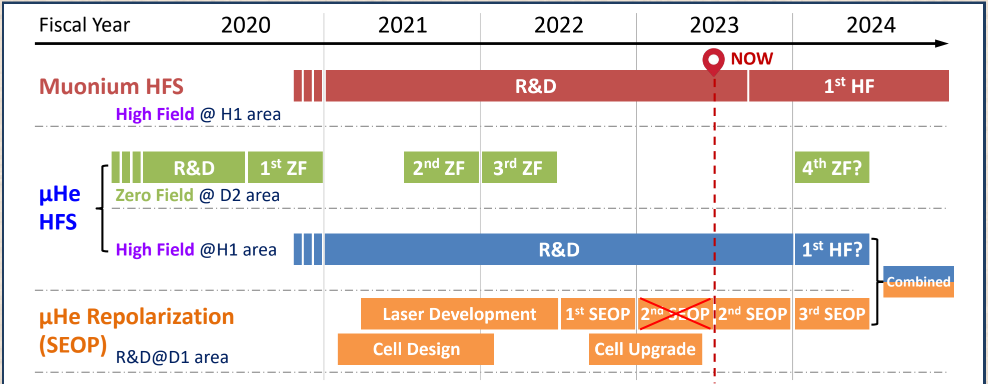
Muon $g-2$ from Muonium spectroscopy

- Delaunay, Ohayon, Soreqm, PRL 127 (2021) 251801: measure both a_μ and m_e/m_μ from
  - Muonium hyperfine splitting ν_{HFS}
    - J-PARC MUSEUM experiment
  - Muonium 1S-2S transition $\nu_{\text{1S-2S}}$
    - PSI Mu-MASS experiment
    - J-PARC Muonium 1S-2S experiment

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



J-PARC MuSEUM schedule



Current Goal

Statistical Improvement:

- H-line: 10x intensity (D-line)
- Runtime: 100 days

Systematic uncertainties:

- $\Delta\nu_{HFS}$: < 1.5 ppb
- μ_{μ}/μ_p : < 13 ppb

(estimation)

	Muonium
$\Delta\nu_{HFS}$	~ 2 ppb
μ_μ/μ_p	~ 20 ppb

Very Very Preliminary !!!

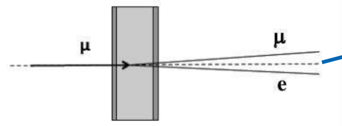
	μHe	μHe (SEOP)
$\Delta\nu_{HFS}$	~ 40 ppb	~ 6 ppb
μ_μ/μ_p	~ 400 ppb	~ 60 ppb

New Systematics !!!

[Patrick Strasser, Bern, Sep 2023]

MUonE experiment

Extraction of $\Delta\alpha_{had}(t)$ from the ***shape*** of the $\mu e \to \mu e$ differential cross section

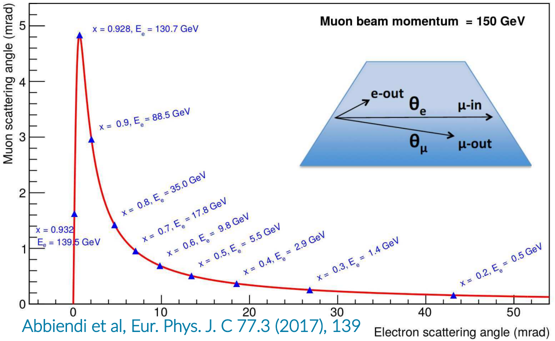


$$\frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$

From theoretical calculation

To be measured

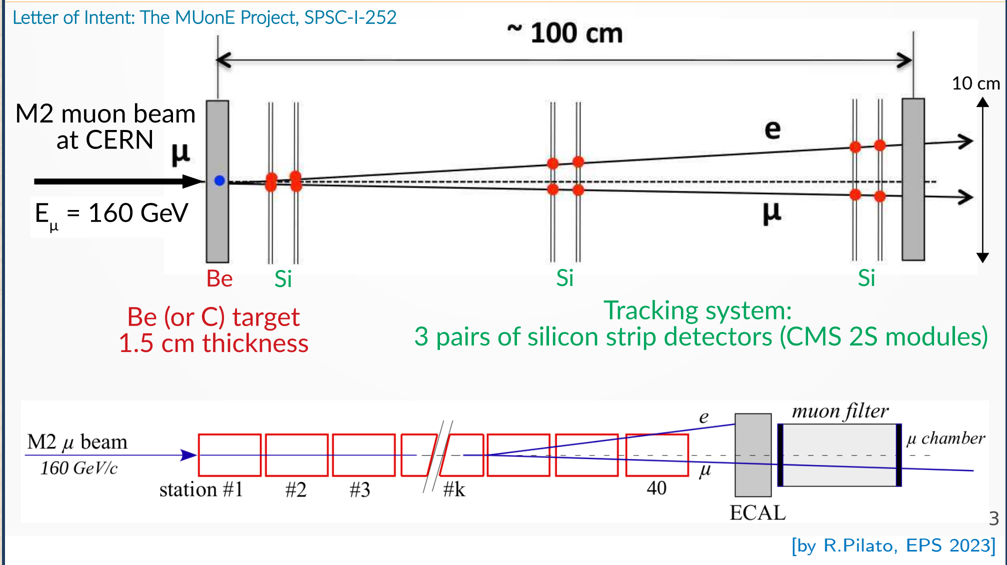
- Compute $a^{\rm HLO}$ using data from one single experiment.
- Correlation between muon and electron angles allows to select elastic events and reject background (μ N $\to$ μ N e^+e^-).
- Boosted kinematics: θ_μ < 5 mrad, θ_e < 32 mrad.



Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139 2

[by R.Pilato, EPS 2023]

MUonE experiment



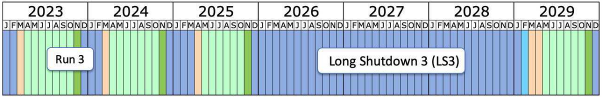
MUonE experiment

Conclusions and future plans

MUonE web site

- The new method proposed by MUonE to measure a^{HLO} is independent and competitive with the latest evaluations.
- Intense Beam Test activities in 2021-2022: first experience with detector in real beam conditions.
- 3 weeks Test Run in 2023: proof of concept of the experimental proposal using 2 tracking stations (pretracker + 1 station with target) and ECAL.
- Technical proposal in 2024 based on the results of the Test Run.
- Towards the full experiment: 5-10 stations before LS3 (2026). 2-4 months data taking: first measurement (few % precision) of a^{HLO}.
- Full apparatus (40 stations) after LS3 to achieve the target precision (~0.3% stat and similar syst).

The MUonE Collaboration gratefully acknowledges the contributions of the CMS Collaboration.



[by R.Pilato, EPS 2023]

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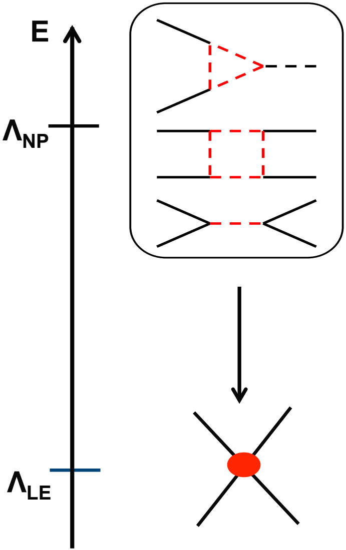
Charged Lepton Flavour Violation searches



- In the quest of New Physics, can be sensitive to very high scale:
  - Kaon physics: $\frac{s\bar{d}s\bar{d}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^5$ TeV
    [ε_K]
  - Charged Lepton Flavour Violation $\frac{\mu\bar{e}f\bar{f}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4$ TeV
    [$\mu \to e\gamma$]
- At low energy: lots of experiments e.g., *MEG*, *Sindrum, Sindrum II, BaBar*, *Belle*, *BESIII, LHCb, ATLAS* ⇒ huge improvements on measurements and bounds obtained and more expected e.g. *MEG, Mu3e, DeeMee, COMET*, *Mu2e, Belle II, LHCb, HL-LHC NA64, EIC, FC-ee, CEPC,STCF*
- Standard Model LFV extremely suppressed
  Detectable rates from New Physics Models

[adapted from E.Passemar, FPCP 2022]

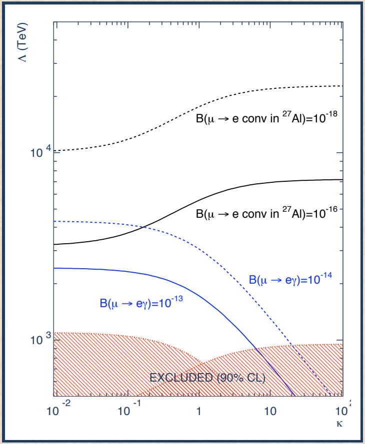
Muon Lepton Flavour Violation

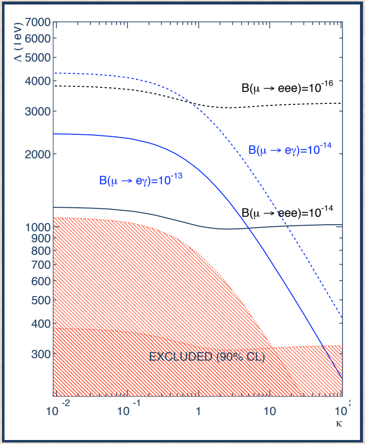
- effective theory for $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$ [Prog.Part.Nucl.Phys. 71 (2013) 75]

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

dipole term: SUSY, ...
$\mu \to e\gamma$, $\mu \to eee$

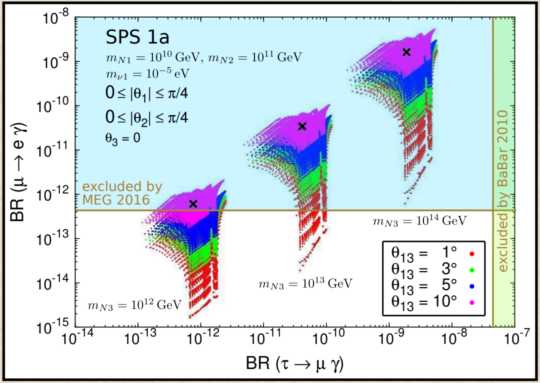
contact term, Z', leptoquark
$\mu N \to eN$, $\mu \to eee$
only via loops: $\mu \to e\gamma$





Also tau LFV searches probe & constrain New Physics models

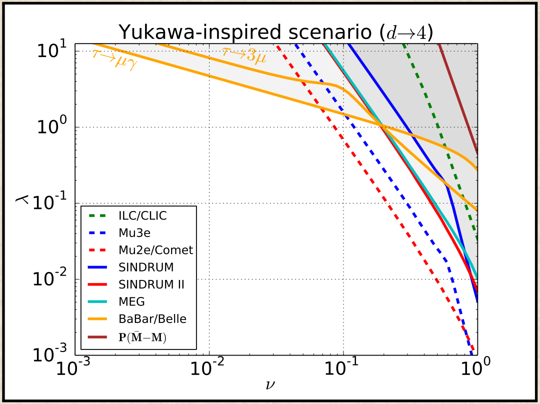
MSSM Seesaw
Antusch, Arganda, Herrero, Teixeira 2006



typical NP models

- $\mathcal{B}(\tau \to \mu\gamma) \sim 10\text{--}1000 \times \mathcal{B}(\mu \to e\gamma)$
- muon LFV searches more effective
- $(\theta_{13} \sim 8.5^{\circ})$

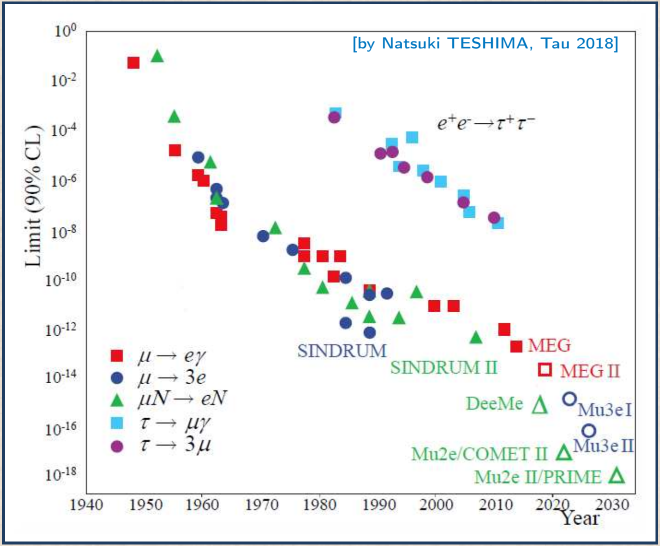
doubly charged scalar
Crivellin, Ghezzi, Panizzi, Pruna, Signer 2019



specific models / parameter space regions

- part of plot only constrained by tau LFV limits

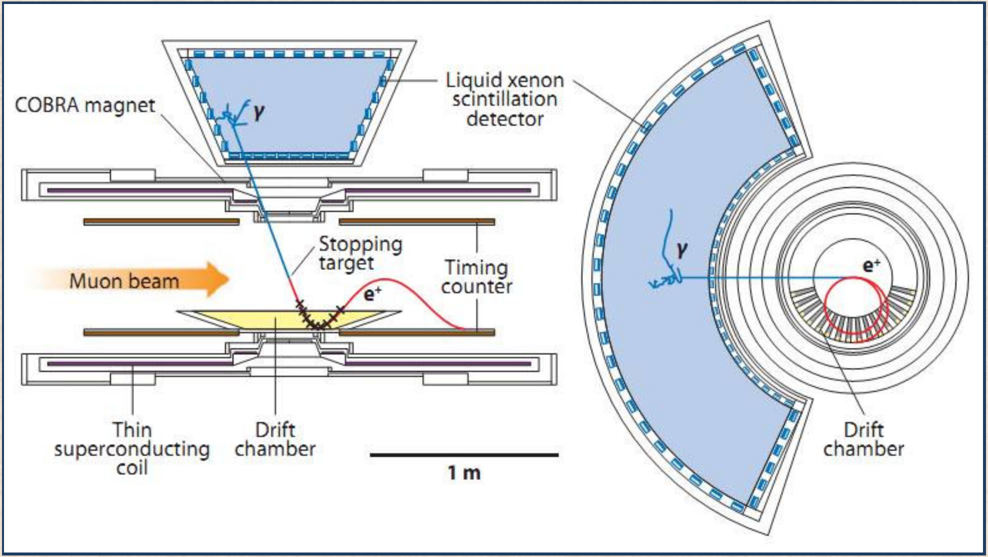
Muon LFV searches results and prospects



- recent MEG-II preliminary result, arXiv:2310.12614 [hep-ex], $\mathcal{B}(\mu^+ \to e^+\gamma) < 7.5{\cdot}10^{-13}$ (90% CL), combined with MEG 2016 $\mathcal{B}(\mu^+ \to e^+\gamma) < 3.1{\cdot}10^{-13}$ (90% CL)

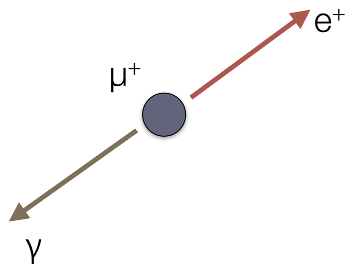
MEG experiment at PSI, search for $\mu \to e\gamma$

- PSI 28 MeV/c-momentum surface μ^+ beam, rate up to $R_\mu = 10^8/s$



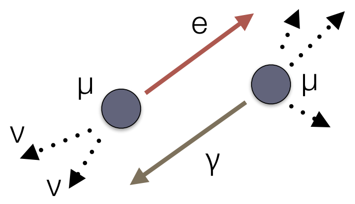
MEG experiment at PSI, search for $\mu \to e\gamma$

signal



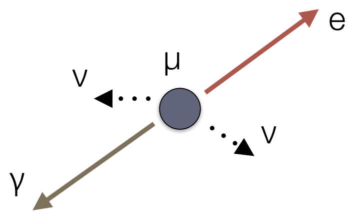
- $N \propto R_\mu$
- $E_\gamma = 52.8\,\text{MeV}$
- $E_{e+} = 52.8\,\text{MeV}$
- $\alpha_{e\gamma} = 180^\circ$
- $T_{e\gamma} = 0$

Accidental (Acc) background



- $N \propto R_\mu^2$
- $E_\gamma < 52.8\,\text{MeV}$
- $E_{e+} < 52.8\,\text{MeV}$
- $\alpha_{e\gamma} < 180^\circ$
- $T_{e\gamma} = \text{flat}$

Radiative Muon Decay (RMD)



- $N \propto R_\mu$
- $E_\gamma < 52.8\,\text{MeV}$
- $E_{e+} < 52.8\,\text{MeV}$
- $\alpha_{e\gamma} < 180^\circ$
- $T_{e\gamma} = 0$

note: in the data analysis $\theta_{e\gamma} = 180^\circ$ is simplified form of $\theta_{e\gamma} = 0$ and $\phi_{e\gamma} = 0$,
with $\theta_{e\gamma} = (\pi - \theta_e) - \theta_\gamma$ and $\phi_{e\gamma} = (\pi + \phi_e) - \phi_\gamma$

MEG experiment at PSI, search for $\mu \to e\gamma$

optimization

- optimal $R_\mu = 3{\cdot}10^7$ /s to suppress accidental background $\propto R_\mu^2$ [max $R_\mu = 1{\cdot}10^8$ /s]

analysis

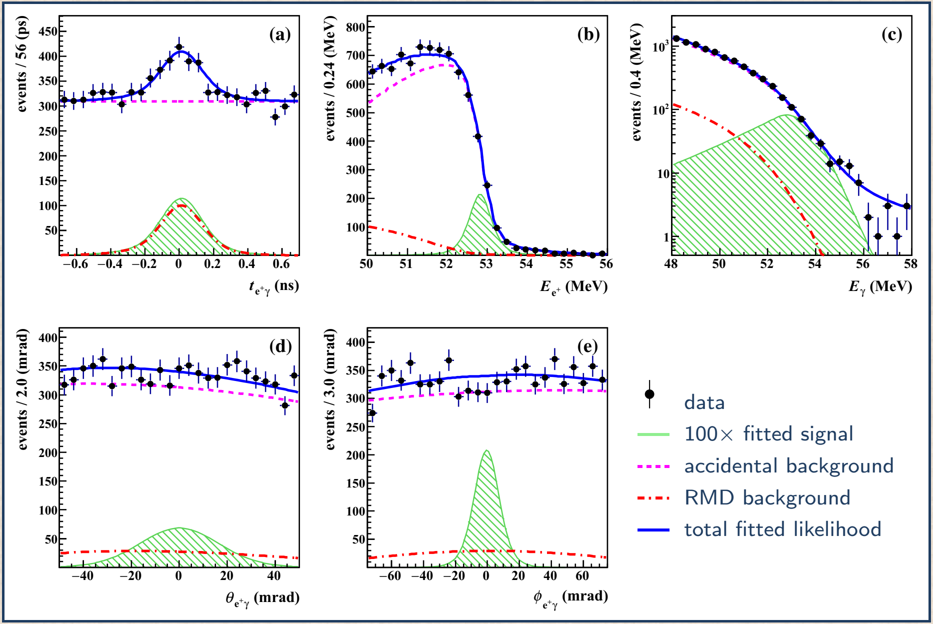
- loose selection of e^+, γ candidates with compatible detection times
- extended maximum likelihood fit with (simplified expression):

$$L(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{acc}}) = \frac{e^{-(N_{\textbf{sig}}+N_{\textbf{RMD}}+N_{\textbf{acc}})}}{N_{\text{obs}}!} \prod_{1}^{N_{\textbf{obs}}} \left(N_{\text{sig}}F_{\text{sig}}(x_i) + N_{\text{RMD}}F_{\text{RMD}}(x_i) + N_{\text{acc}}F_{\text{acc}}(x_i)\right)$$

N_{obs} = number of events in signal window; $x_i = E_\gamma,\quad E_{e+},\quad \theta_{e\gamma},\quad \phi_{e\gamma},\quad T_{e\gamma}$

- N_{RMD} and N_{acc} constrained to observed events in sidebands with Gaussian terms (not shown above)
- 90% confidence interval of N_{sig} using Feldman-Cousins approach with profile-likelihood ratio ordering
- N_μ in signal acceptance computed by counting Michel and radiative muon decays
- $1/N_\mu$(signal acceptance) $= (5.84 \pm 0.21){\cdot}10^{-14}$ (single event sensitivity)
- no significant signal found $\mathcal{B}(\mu \to e\gamma) < 4.2{\cdot}10^{-13}$ at 90% CL Eur.Phys.J.C 76 (2016) 434

MEG experiment at PSI, likelihood projections



MEG-II vs. MEG detector performances

2021 run → Achieved

Resolutions	Foreseen	Achieved	MEG	Ratio
E_{e^+} (keV)	100	89	380	X 4
ϕ_{e^+}, θ_{e^+} (mrad)	3.7/6.7	4.1/7.4	8.7/9.4	X 2 / X 1.5
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.7/2.0	1.2/2.4	X 2 / X 1.25
$E_\gamma(\%)$ $(w<2\,\text{cm})/(w>2\,\text{cm})$	1.7/1.7	2.0/1.8	2.4/1.7	X 1.2/ X 1.0
$u_\gamma, v_\gamma, w_\gamma$, (mm)	2.4/2.4/5.0	2.5/2.5/5.0	5/5/6	X 2/ X 2/ X 1.25
$t_{e^+\gamma}$ (ps)	70	78	122	X 1.6
Efficiency (%)				
ε_γ	69	62	63	X 1
ε_{e^+}	65	67	30	X 2.2
ε_{TRG}	≈99	80	99	X 0.8

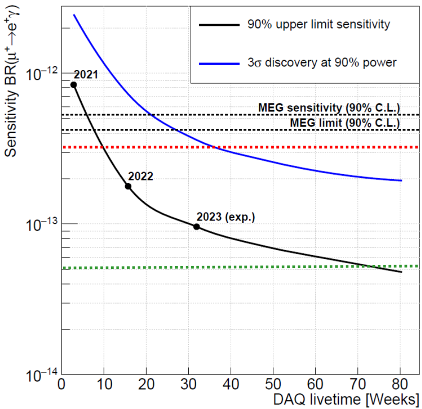
➢ **Better S/N**
➢ **Much smaller analysis windows**
➢ **Reduced computing time**

Fictitious, trigger efficiency for MEG in first data taking year was 69%. Effect of unstable operations in 2021 (different beam intensities, unstable photon detector energy thresholds …). **Foreseen efficiency reachable in stable data taking conditions**.

[F.Cei, Pisa, Oct 2023]

Future MEG + MEG-II sensitivity

An order of magnitude improvement in sensitivity wrt MEG is expected in about 80 weeks of DAQ livetime.

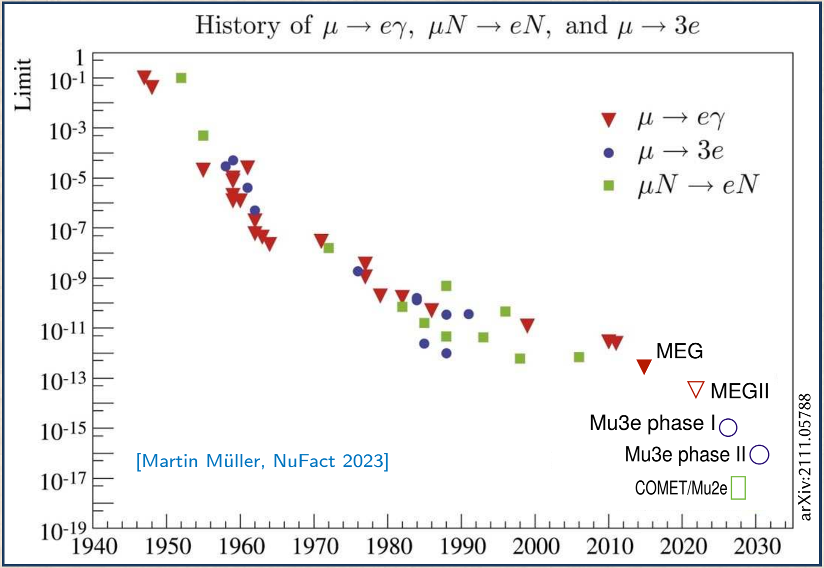


MEG+MEGII combined limit (90% C.L.)

5×10^{-4} sensitivity

[F.Cei, Pisa, Oct 2023]

Mu3e (PSI), search for $\mu \to 3e$

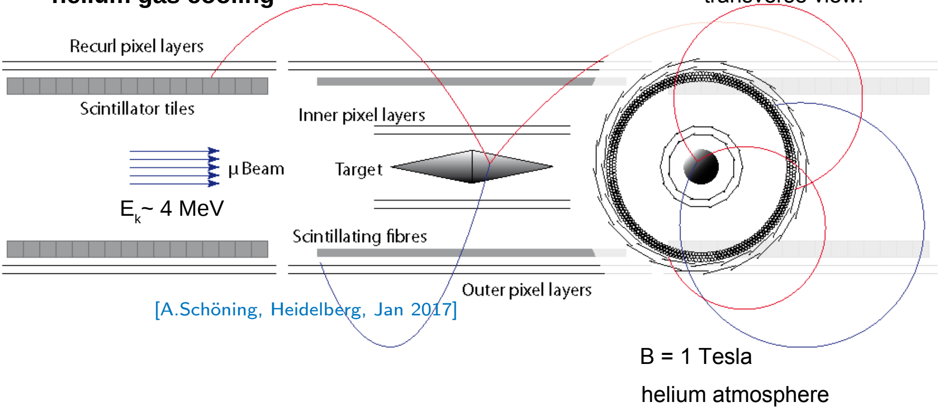


- phase 2 requires PSI High Intensity Muon Beam project

Mu3e design

Features:

- surface muons (p=29 MeV/c, DC) stopped on target at high rate: **10^8 - 10^9 /s**
- ultra thin **silicon pixel detector** (HV-MAPS) with **1 per mill radiation length** / layer
- high precision tracking using **recurling tracks** in strong magnetic field
- **fast timing** detectors (scintillating fibers & tiles)
- **helium gas cooling**



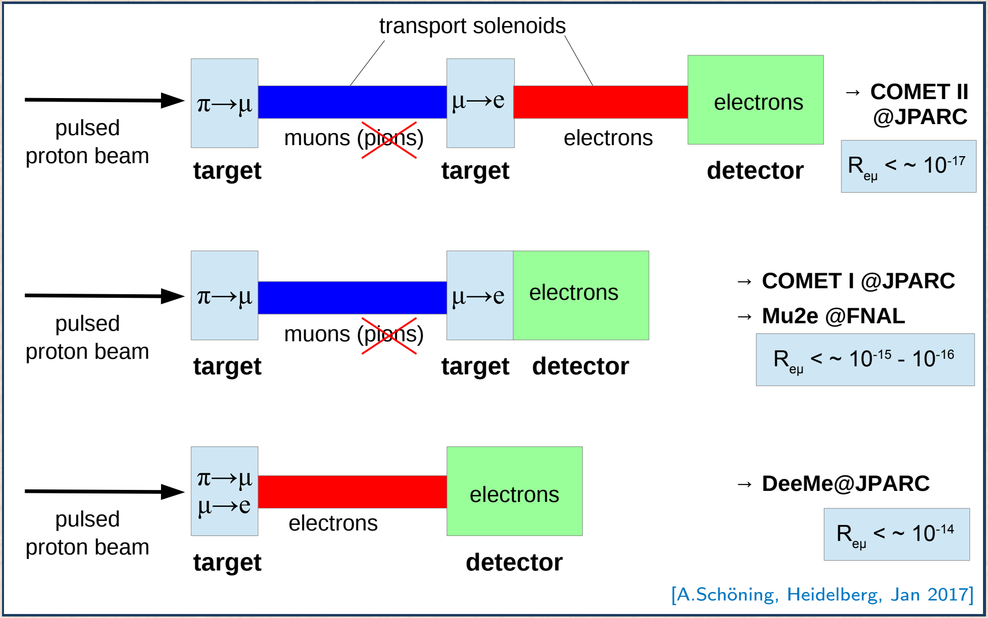
[A.Schöning, Heidelberg, Jan 2017]

Searches for muon conversion in nuclei, $\mu N \rightarrow eN$

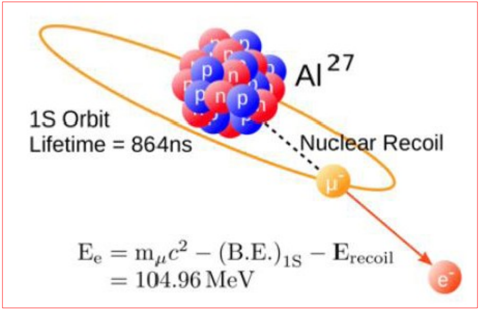
- DeeMe, C target, 1 year (JPARC, Japan), SES $\sim 1{\cdot}10^{-13}$
- DeeMe, SiC target, 4 years (JPARC, Japan), SES $\sim 5{\cdot}10^{-15}$
- Mu2e (FNAL, USA), SES $\sim 3{\cdot}10^{-17}$
- COMET-1 (JPARC, Japan), SES $\sim 3{\cdot}10^{-15}$
- COMET-2 (JPARC, Japan), SES $\sim 3{\cdot}10^{-17}$
- PRISM/PRIME (JPARC, Japan), SES $\sim 1{\cdot}10^{-18}$

note: $\mu N \rightarrow eN$ signature is 1 electron with $E_e \simeq m_\mu$ and does not suffer R_μ^2 accidental background

Searches for muon conversion in nuclei, techniques



Mu2e (FNAL)



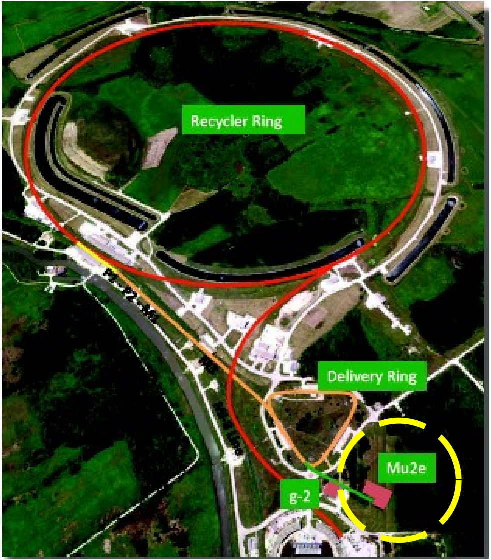
Mu2e searches for **Charged Lepton Flavor Violation (CLFV)** via the coherent conversion:

$$\mu^- + Al \rightarrow e^- + Al$$

Same channel as COMET, complementary to MEGII ($\mu^+ \rightarrow e^+\gamma$) and Mu3e ($\mu^+ \rightarrow e^+e^-e^+$)

[S. Di Falco, EPS-HEP2023]

Mu2e (FNAL)



Mu2e at
Fermilab Muon Campus

Mu2e **goal** is to improve by **a factor 10^4** the world's best sensitivity on:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$

SINDRUM II @PSI (2006, Au)*:

$$\mathbf{R_{\mu e} < 7 \cdot 10^{-13} \ (90\% \ CL)}$$

[S. Di Falco, EPS-HEP2023]

Mu2e (FNAL)

Background suppression: Radiative Pion Capture + other beam related bg

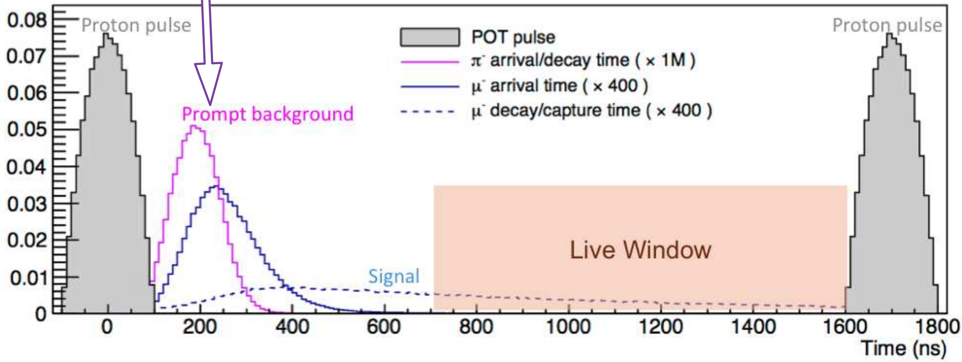
[Mete Yucel, Elba, 2022]

RPC : $\pi^- + N \rightarrow \gamma + N'$

$\gamma \rightarrow e^- + e^+$

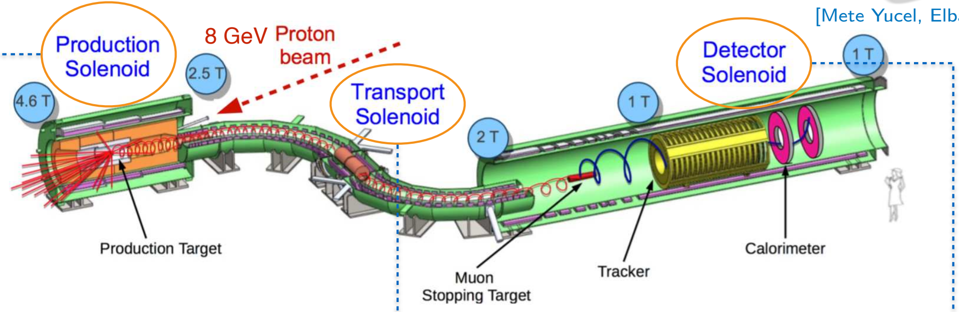
e^- **with enough momentum can fake conversion events**

- 8 GeV pulsed proton beam @ 1695 ns intervals.
- We wait 700 ns before taking C.E data to avoid most of the **prompt** background
  - Muonic Al lifetime = 864 ns.
- Out of time protons/ beam < 10^{-10}



Mu2e (FNAL)

[Mete Yucel, Elba, 2022]



- Direct low momentum pions/muons to transport solenoid.
- S-shaped geometry with collimators select low momentum and negatively charged particles.
- Houses muon stopping target, tracker & calorimeter.

Mu2e (FNAL)

Given the very low background level a **5σ discovery** will require Mu2e to observe just **5 events** of muon conversion

The $R_{\mu e}$ corresponding to a **5σ discovery** in Run 1 is:

$$R_{\mu e} = 1.1 \cdot 10^{-15}$$

Mu2e Run 1
5σ Discovery reach

If no events will be observed the **90% CL limit** will be:

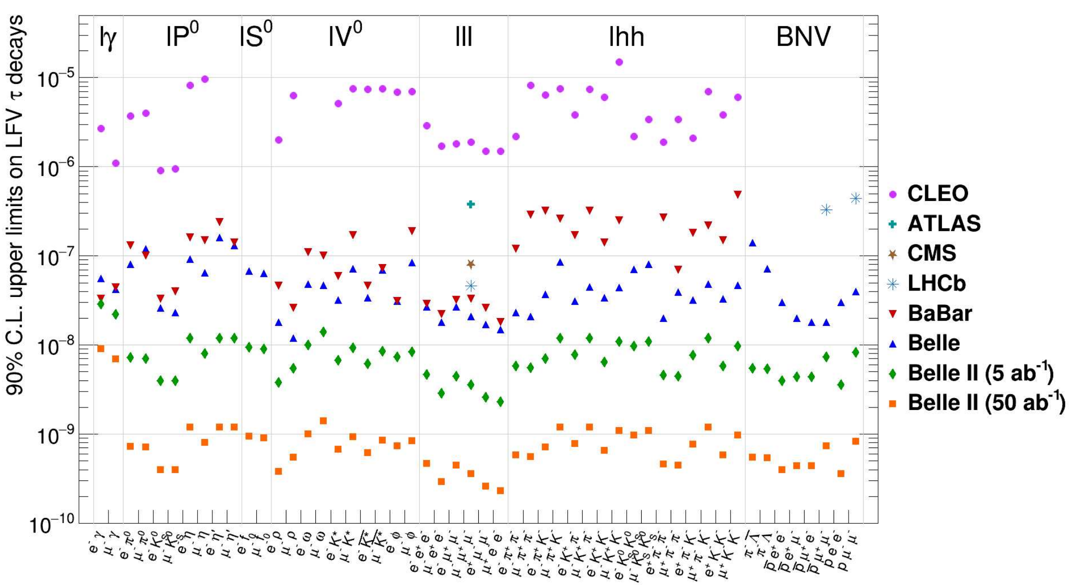
$$R_{\mu e} = 6.2 \cdot 10^{-16}$$

Mu2e Run 1
90% CL limit

that is more than **x1000** better than current best limit!

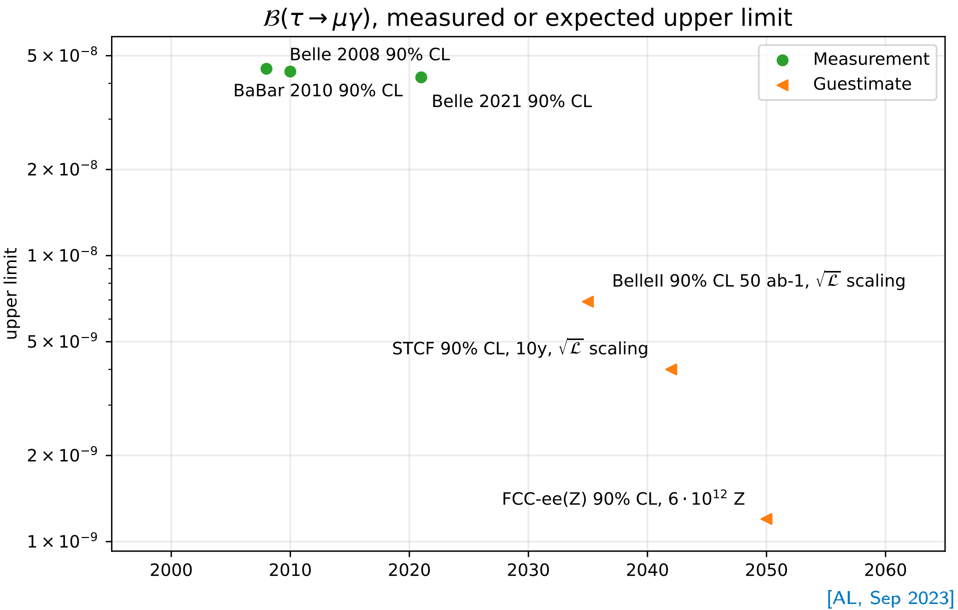
[S. Di Falco, EPS-HEP2023]

Tau LFV decay searches



[M.H.Villanueva, arXiv:2208.02723 [hep-ex]]

LFV search for $\tau \to \mu\gamma$



Conclusions

- in several ways, muon measurements are highly valuable for HEP progress
- LFV searches sensitive to very high energy possible New Physics
  - muon LFV searches most sensitive, tau LFV searches are complementary

End

Backup slides

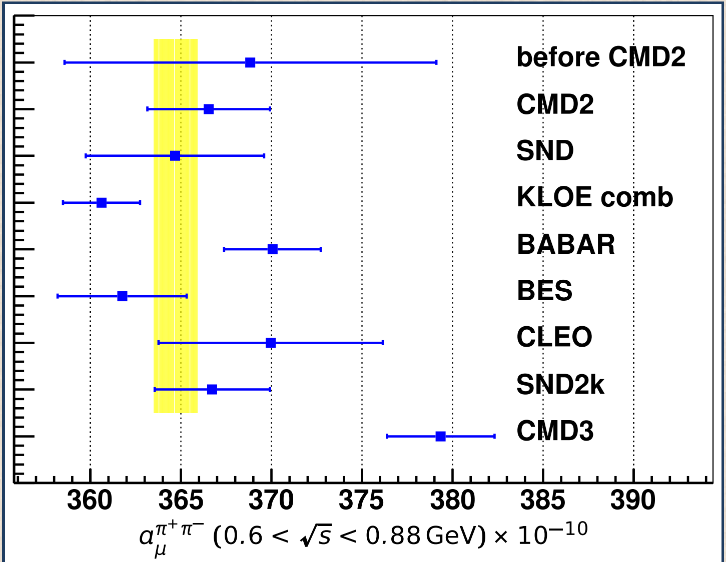
FNAL-E989 vs. BNL-E821

FNAL-E989 design precision, compared to BNL-E821 final report (2006)

	BNL E821 (2006)	FNAL E989 final goal	
ω_a statistical	460 ppb	100 ppb	$\times$21 detected muon decays ($1.6 \cdot 10^{11}$)
ω_a systematic	210 ppb	70 ppb	faster calorimeter with laser calibration, tracker
ω_p systematic	170 ppb	70 ppb	more uniform B, improve NMR measurement
external measurements	25 ppb	25 ppb	
total	540 ppb	140 ppb	

ω_a: measured muon spin precession frequency in magnetic field
ω_p: measured proton spin precession frequency to measure magnetic field

$a_\mu^{\rm HVP,LO}(0.6 < \sqrt{s} < 0.88\,{\rm GeV})$ from CMD-3



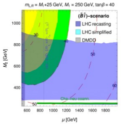
from F.V. Ignatov *et al.*, arXiv:2302.08834 [hep-ex]

Muon $g-2$ discrepancy and New Physics Models

Which models can still accommodate large deviation?

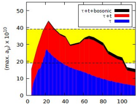
SUSY: MSSM, MRSSM

- MSugra. . . many other generic scenarios
- Bino-dark matter+some coannihil.+mass splittings
- Wino-LSP+specific mass patterns



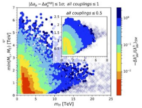
Two-Higgs doublet model

- Type I, II, Y, Type X(lepton-specific), flavour-aligned



Lepto-quarks, vector-like leptons

- scenarios with muon-specific couplings to μ_L and μ_R



Simple models (one or two new fields)

- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result
1	0	$(\mathbf{1},\mathbf{1},1)$	Ruled out: $\Delta a_\mu < 0$
2	0	$(\mathbf{1},\mathbf{1},2)$	Ruled out: $\Delta a_\mu < 0$
3	0	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Special cases viable
4	0	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
5	0	$(\bar{\mathbf{3}},\mathbf{1},1/3)$	Updated Sec. 3.2
6	0	$(\bar{\mathbf{3}},\mathbf{1},4/3)$	Ruled out: $\Delta a_\mu < 0$
7	0	$(\bar{\mathbf{3}},\mathbf{3},1/3)$	Ruled out: $\Delta a_\mu < 0$
8	0	$(\mathbf{3},\mathbf{2},7/6)$	Updated Sec. 3.2
9	0	$(\mathbf{3},\mathbf{2},2/3)$	Ruled out: $\Delta a_\mu < 0$
10	1/2	$(\mathbf{1},\mathbf{1},0)$	Ruled out: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1},\mathbf{1},-1)$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
12	1/2	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
13	1/2	$(\mathbf{1},\mathbf{2},-\frac{3}{2})$	Ruled out: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1},\mathbf{3},0)$	Ruled out: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
16	1	$(\mathbf{1},\mathbf{1},0)$	Special cases viable
17	1	$(\mathbf{1},\mathbf{2},-3/2)$	Ruled out: UV compl. $M_{Z'}$ limit

[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]

see also arXiv:2104.03691

Comparisons

Sigma deviation between different predictions/measurements

	FNAL 2023 (World Ave)	WP 2020	BMW	CMD-3
Exp	-			
WP 2020	5.0 (5.1)	-		
BMW	1.6 (1.7)	2.0	-	
CMD-3	1.4 (1.5)	2.8	0.4	-

- Comparisons are taken from the whole a_μ value.
- They're accurate when comparing to experiment
- But e.g. WP (2020) & BMW both include same H-LbL components and error, so significance of difference between them is a little underestimated (2.0 vs 2.2σ).

[by J.Mott, 10 August 2023]

HVP dispersive prospects

A. El-Khadra P5 town hall, 21-24 Mar 2023

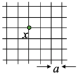
Ongoing work on experimental inputs:	Ongoing work on theoretical aspects:
• BaBar: new analysis of large data set in $\pi\pi$ channel, also $\pi\pi\pi$, other channels, other channels • KLOE: new analysis of large data in $\pi\pi$ channel, other channels • SND: new results for $\pi\pi$ channel, other channels in progress • BESIII: new results in 2021 for $\pi\pi$ channel, continued analysis also for $\pi\pi\pi$, other channels • Belle II: arXiv:2207.06307 (Snowmass WP) Better statistics than BaBar or KLOE; similar or better systematics for low-energy cross sections • STCF: arXiv:2203.06961 • Need blind analyses to resolve the tensions (esp. for $\pi\pi$ channel)	• Developing NNLO Monte Carlo generators (STRONG 2020 workshop https://agenda.infn.it/event/28089/) [➠ appendix] • radiative corrections using FsQED (scalar QED + pion form factor) • charge asymmetry (CMD-3 measurement) vs radiative corrections [Ignatov + Lee, arXiv:2204.12235] • development of new dispersive treatment of radiative corrections in $\pi\pi$ channel [Colangelo at al, arXiv2207.03495] • including τ decay data: requires nonperturbative evaluation of IB correction [M. Bruno et al, arXiv:1811.00508] **If the differences between experiments are resolved:** data-driven evaluations of HVP with $\sim 0.3\,\%$ feasible by ~2025

[by J.Mott, 10 August 2023]

Lattice HVP

A. El-Khadra P5 town hall, 21-24 Mar 2023

HVP: lattice



Ongoing work:

Evaluations of short-distance windows [ETMC, RBC/UKQCD]

Proposals for computing more windows:

- Use linear combinations of finer windows to locate the tension (if it persists) in $\sqrt{s}$ [Colangelo et al, arXiv:12963]
- Use larger windows, excluding the long-distance region $t \gtrsim 2\,\mathrm{fm}$ to maximize the significance of any tension [Davies at at, arXiv:2207.04765]

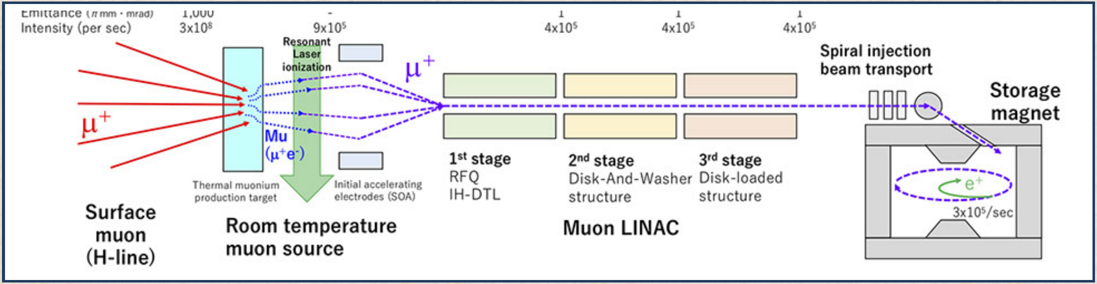
For total HVP:

- independent lattice results at sub-percent precision: coming soon!
- Including $\pi\pi$ states for refined long-distance computation (Mainz, RBC/UKQCD, FNAL/MILC)
- include smaller lattice spacings to test continuum extrapolations (needs adequate computational resources)

If results are consistent, Lattice HVP (average) with $\sim 0.5\,\%$ errors feasible by 2025

[by J.Mott, 10 August 2023]

Muon g-2/EDM experiment at J-PARC



- 50% polarized 300 MeV muons, small 3.0 T magnet
- no electric field, low focusing magnetic field
- silicon tracker instead of calorimetry
- uner construction aiming for data taking from 2028, 0.45 ppm statistical uncertainty goal
- taking data to demonstrate the muon cooling by using the laser ionization of muonium
- second phase with higher precision may be approved in future

g_e and α

- New measurement of g_e in 2023: 0.13 ppt on g_e

Measurement of the Electron Magnetic Moment

X. Fan, T. G. Myers, B. A. D. Sukra, and G. Gabrielse
Phys. Rev. Lett. **130**, 071801 – Published 13 February 2023

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.130.071801

- Ability to compare with prediction hampered by disagreement in the value of α:

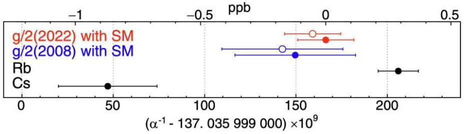


FIG. 5. SM prediction of α using μ/μ_B from this Northwestern measurement (red), and from our 2008 Harvard measurement (blue), with solid and open points for slightly differing C_{10} [40,41]. The α measurements (black) were made with Cs at Berkeley [38] and Rb in Paris [39]. A ppb is 10^{-9}.

[by J.Mott, 10 August 2023]