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groningen

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and engineering

van swinderen institute for
particle physics and gravity

Measuring Muon Moments @ JPARC

(on behalf of the JPARC E34 Collaboration)

Gerco Onderwater

Flavour Vietnam 2022

Plan

Context

Muon Magnetic Moment

J-PARC Experiment

Conclusion

Setting the stage

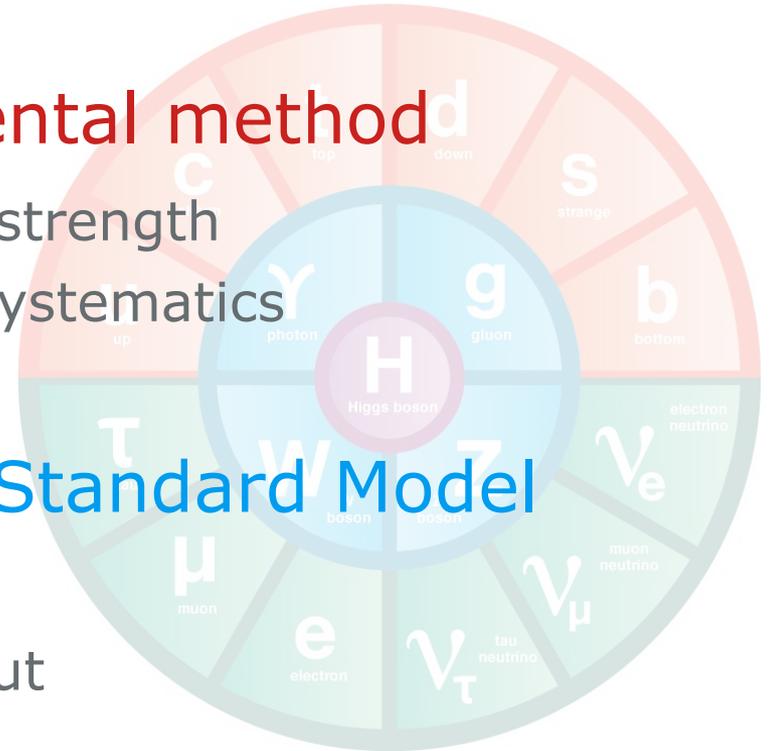
$$\text{Anomaly} = \text{Experiment} - \text{Theory}$$

Need (ultra-)precise experimental method

- high sensitivity: maximal signal strength
- high specificity: robust against systematics

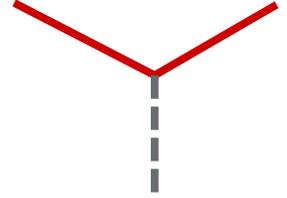
Need (ultra-)precise theory : Standard Model

- ideally from first principle
- based on high-quality model input

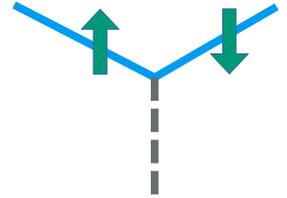


Lepton Moments

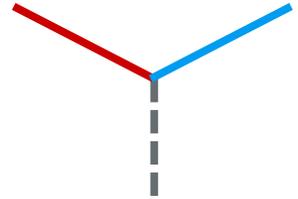
Monopole Moments \rightarrow flavour universal?



Dipole Moments \rightarrow flavour universal?



Transition Moments \rightarrow flavour mixing?



Monopoles

		$q_e q_{\bar{\mu}} = (-1 \pm 10^{-9}) e^2$
Electric charge \mathbf{Q}	$\nu_{e,\mu,\tau}: 0^*$	$e,\mu,\tau: -1e^{**}$
Magnetic charge	0^{***}	
Weak charge \mathbf{Q}_w	$\nu_{e,\mu,\tau}: -1$	$e,\mu,\tau: -1 + 4\sin^2\theta_w$
Color charge	$0^?$	

for neutral flavour conserving interaction \rightarrow earlier talks on e.g. R(X)

* Atthar et al., 10.1016/j.pnpnp.2022.103947 (2022)

** V. Meyer *et al.*, DOI: 10.1103/PhysRevLett.84.1136 (2000)

*** R. Abbasi et al. (IceCube Collaboration), DOI: 10.1103/PhysRevLett.128.051101 (2019)

Dipoles

Magnetic DM μ → allowed in the SM → this talk

Electric DM d → breaks P and T, so CP → $d_{\ell,SM} \leq O(10^{-38} \text{ e}\cdot\text{cm})$

$$|d_e| < 1.1 \times 10^{-29} \text{ e}\cdot\text{cm}^*$$

$$|d_\mu| < 1.8 \times 10^{-19} \text{ e}\cdot\text{cm}^{**}$$

$$\text{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17} \text{ e}\cdot\text{cm} \quad \text{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17} \text{ e}\cdot\text{cm}^{***}$$

↑
or CPT/Lorentz

Weak DM ****

$$|\text{Re } \mu_\tau^W| < 1.14 \times 10^{-3}, \quad |\text{Im } \mu_\tau^W| < 2.65 \times 10^{-3}$$

$$|\text{Re } d_\tau^W| < 0.91 \times 10^{-3}, \quad |\text{Im } d_\tau^W| < 2.01 \times 10^{-3} \quad \rightarrow \text{break P and T}$$

* Andreev *et al.*, DOI: 10.1038/s41586-018-0599-8 (2018)

** Bennett *et al.*, DOI: 10.1103/PhysRevD.80.052008 (2008)

*** Inami *et al.*, DOI: 10.1016/S0370-2693(02)02984-2

**** Heister *et al.*, DOI: 10.1140/epjc/s2003-01286-1

Transition Moments

Electromagnetic → flavour conserving?

" $Q_{\ell\ell'}$ ": 0

Too many tests to mention ...

→ see many talk at this conference

Weak → ($\ell \leftrightarrow \nu_\ell$) allowed, ($\ell \leftrightarrow \nu_{\ell'}$) forbidden?

FCCC

Fermi coupling constant $G_{F,\mu} = g_\mu^2/4\sqrt{2}M_W^2 = 1.1663787(6)\times 10^{-5} \text{ GeV}^{-2*}$

HFLAV^{**}: $g_\tau/g_\mu = 1.0009(14)$, $g_\tau/g_e = 1.0027(14)$, $g_\mu/g_e = 1.0019(14)$

FCNC

$g_{\ell\ell'} = 0$, $g_{\nu\ell\nu\ell'} = 0$

Neutrino Mixing → ($\nu_\ell \leftrightarrow \nu_{\ell'}$) allowed, ($\ell \leftrightarrow \ell'$) forbidden?

	ν_1	ν_2	ν_3
ν_e			
ν_μ			
ν_τ			

* Tishchenko *et al.*, DOI: 10.1103/PhysRevD.87.052003 (2013)

** Amhis *et al.*, DOI: 10.48550/arXiv.2206.07501 (2021)

Muon (Magnetic) Dipole Moment

(Anomalous) Magnetic Moment

Magnetic moment defined as

$$\vec{\mu} = g \frac{e \hbar}{2mc} \hat{\sigma} = 2(1+a) \frac{e \hbar}{2mc} \hat{\sigma} \quad a \equiv \frac{g-2}{2}$$

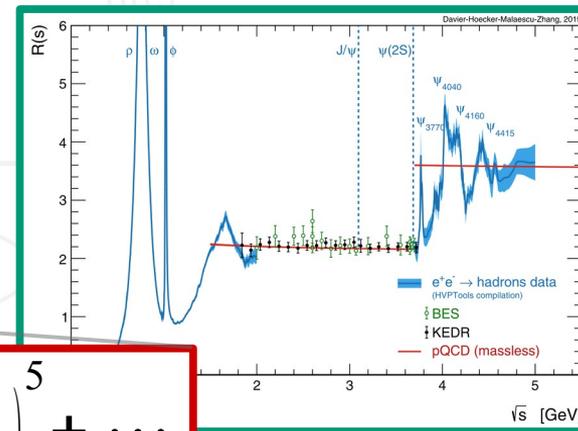
$$a_l^{new} = \kappa \left(\frac{m_l}{\Lambda} \right)^2$$

Anomaly from loops w/ all interactions

$$a_l = a_l^{QED} + a_l^{QCD} + a_l^{QFD} + a_l^{new}$$

$$a_l^{QED} = a_1 \left(\frac{\alpha}{\pi} \right) + a_2 \left(\frac{\alpha}{\pi} \right)^2 + a_3 \left(\frac{\alpha}{\pi} \right)^3 + a_4 \left(\frac{\alpha}{\pi} \right)^4 + a_5 \left(\frac{\alpha}{\pi} \right)^5 + \dots$$

calculable from first principles



Standard Model Predictions

x 10 ¹¹	QED		Hadronic		Weak	
	Value	± Error	Value	± Error	Value	± Error
a _e	<u>115965217.988</u>	± 0.023	<u>0.1683</u>	± 0.0012	<u>0.003053</u>	± 0.000023
a _μ	<u>116584718.931</u>	± 0.104	<u>6937</u>	± 44	<u>153.6</u>	± 1.0
a _τ	117324000	± 2000	350100	± 5000	47400	± 500

Experimental sensitivity*

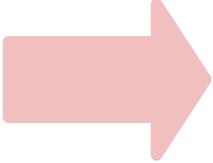
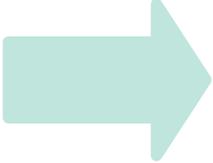
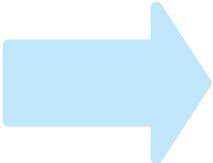
Aoyama, Kinoshita, and Nio, DOI: 10.3390/atoms7010028 (2019)

Aoyama *et al.*, DOI: 10.1016/j.physrep.2020.07.006 (2020)

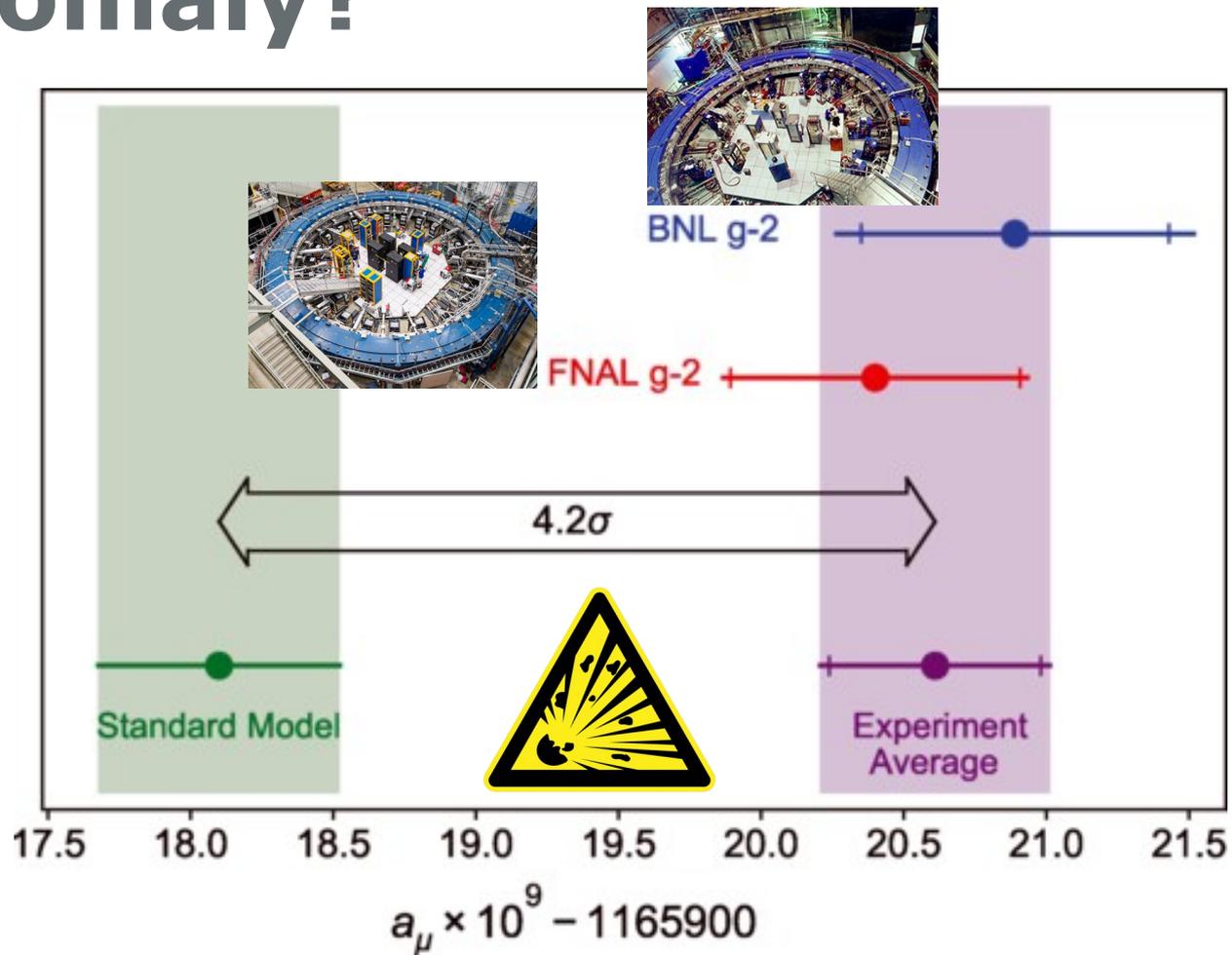
Eidelmann and Passera, DOI: 10.1142/S0217732307022694 (2007)

* Odom *et al.*, DOI: 10.1103/PhysRevLett.97.030801 (2007)

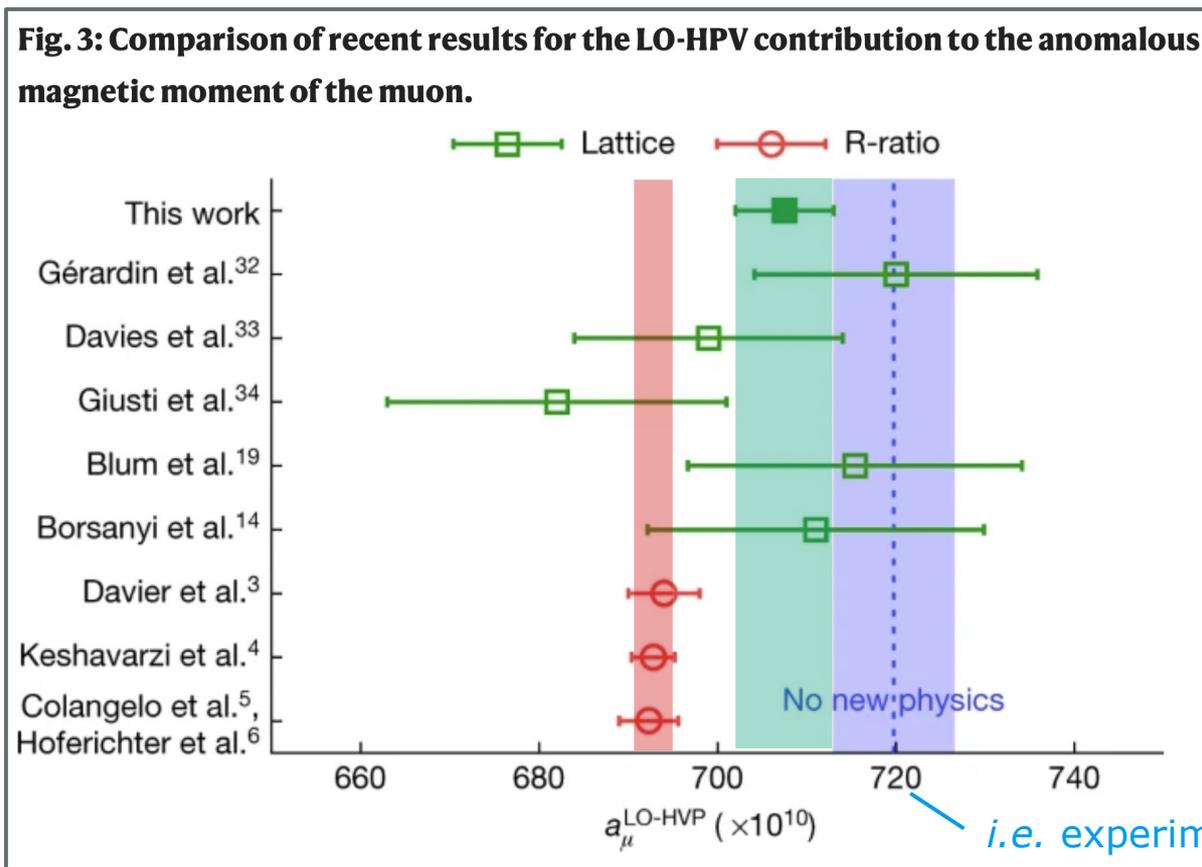
a_μ Experimental Results

		Year	a_μ	σ_{a_μ}	Ref.		
QED		1961	0.001145	0.000022	Charpak	CERN	
		1965	0.001162	0.000005	Charpak		
		1966	0.001165	0.000003	Farley		
		1969	0.001060	0.000067	Henry		
QCD		1972	0.00116616	0.00000031	Bailey		
		1975	0.001165895	0.000000027	Bailey		
		1979	0.001165910	0.000000012	Bailey		
		1979	0.001165936	0.000000012	Bailey		
QFD		1999	0.001165925	0.000000015	Carey		BNL
		2000	0.0011659191	0.0000000059	Brown		
		2001	0.0011659202	0.0000000015	Brown		
		2002	0.0011659204	0.0000000009	Bennett		
		2004	0.0011659214	0.0000000009	Bennett		
new?		2021	0.00116592040	0.00000000054	Abi	FNAL	

Anomaly?



Anomaly??



Internal tension



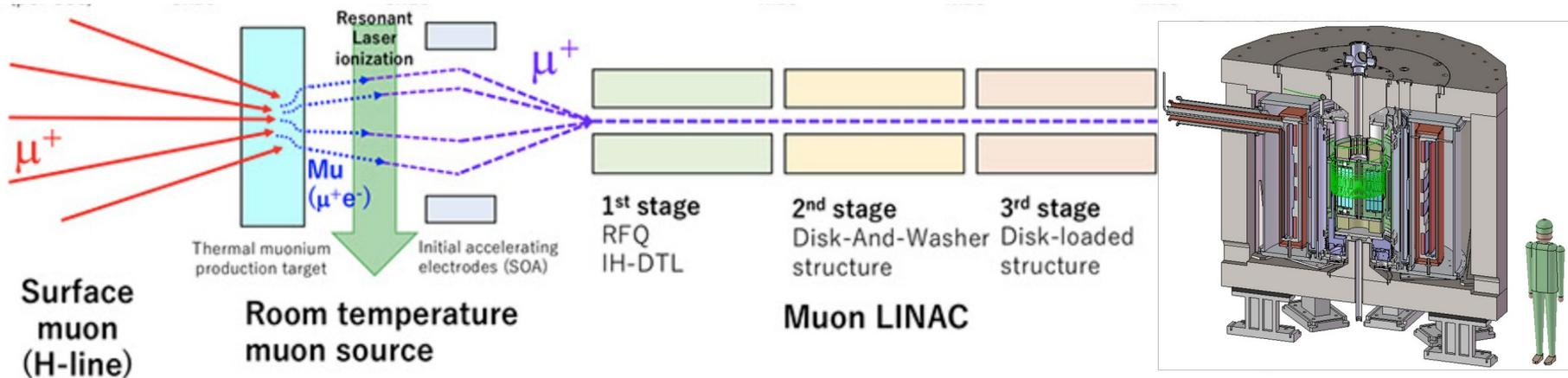
→ earlier talks

“they is g-2’s biggest issue”

i.e. experiment – other theory

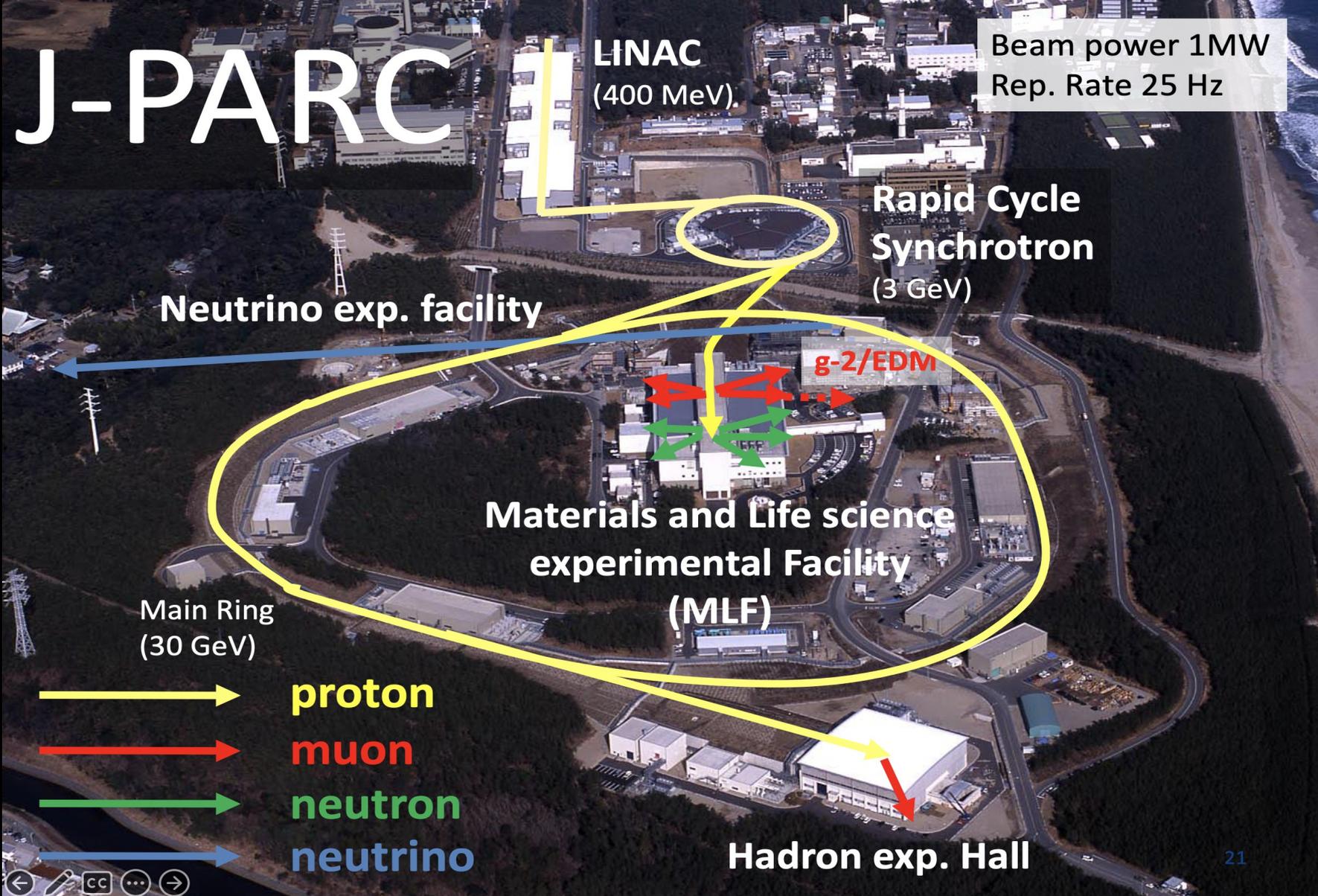
New Experiment E34 @ J-PARC

Part of a wide-range muon physics programme



Aim: competitive measurement of muon $g-2$ and EDM

J-PARC



LINAC
(400 MeV)

Beam power 1MW
Rep. Rate 25 Hz

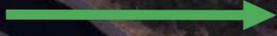
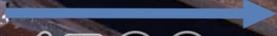
**Rapid Cycle
Synchrotron**
(3 GeV)

Neutrino exp. facility

g-2/EDM

**Materials and Life science
experimental Facility
(MLF)**

Main Ring
(30 GeV)

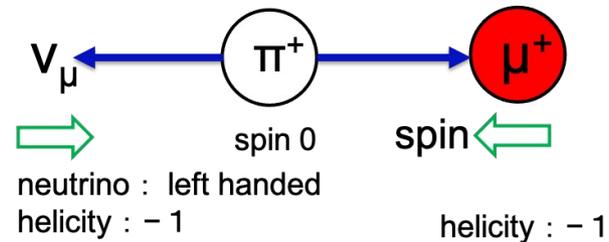
-  **proton**
-  **muon**
-  **neutron**
-  **neutrino**

Hadron exp. Hall

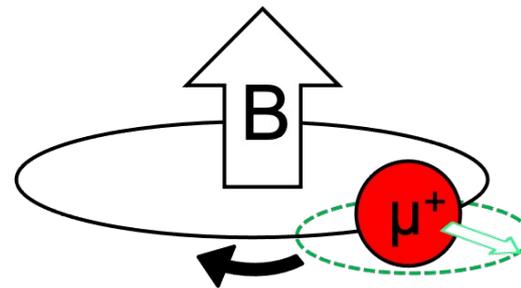


Elements of a MDM or EDM Expt

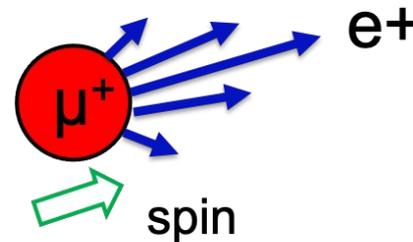
Polarized Muon Production



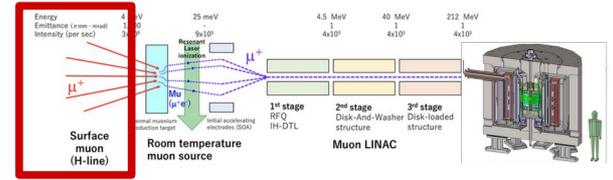
Storage & Spin Precession



Detection of Spin Orientation

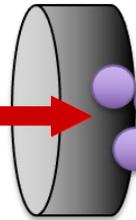


Production



↳ CERN

proton



pion production

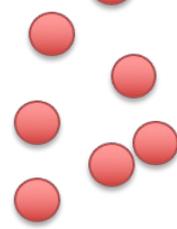
π^+



decay

↳ BNL FNAL

μ^+



cooling

↳ JPARC

μ^+



Emittance $\sim 1000\pi$ mm·mrad

Proton and pion contamination

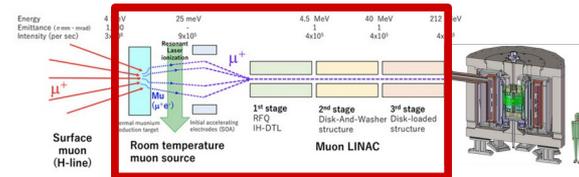
Need strong electric focussing

Need 'magic' $\gamma = \sqrt{1/a_\mu + 1} = 29$

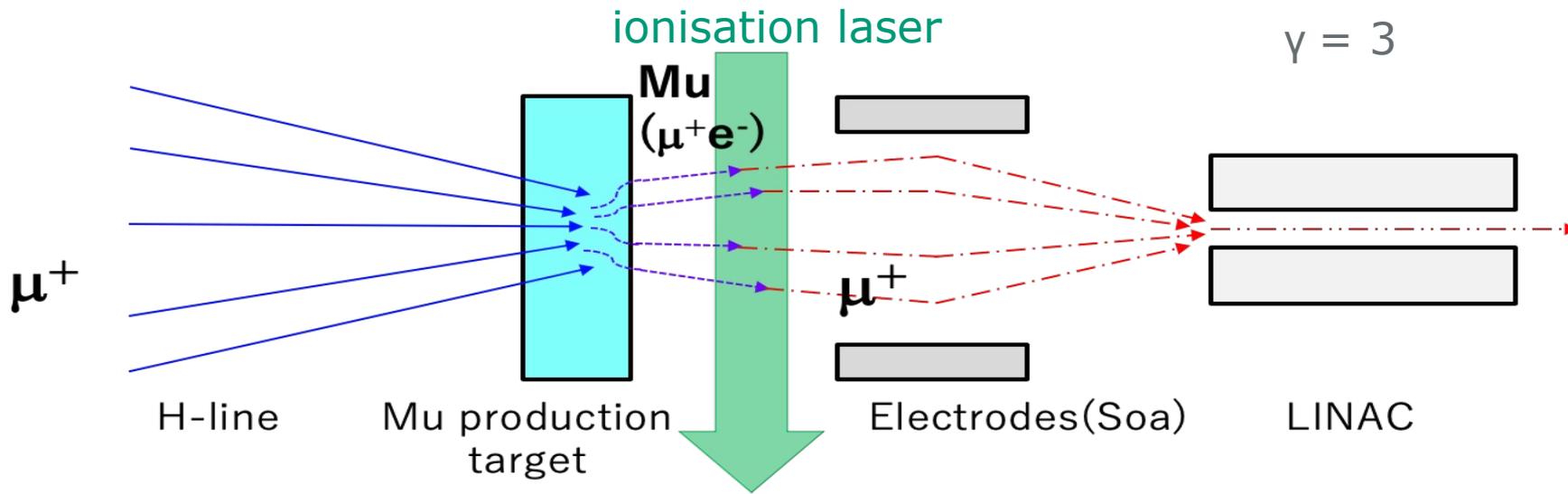
Muon loss

Emittance $\sim 1\pi$ mm·mrad
(after reacceleration)

Reacceleration



	surface muons	thermal muon	accelerated muons
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
$\Delta p/p$	0.05	0.4	0.0004



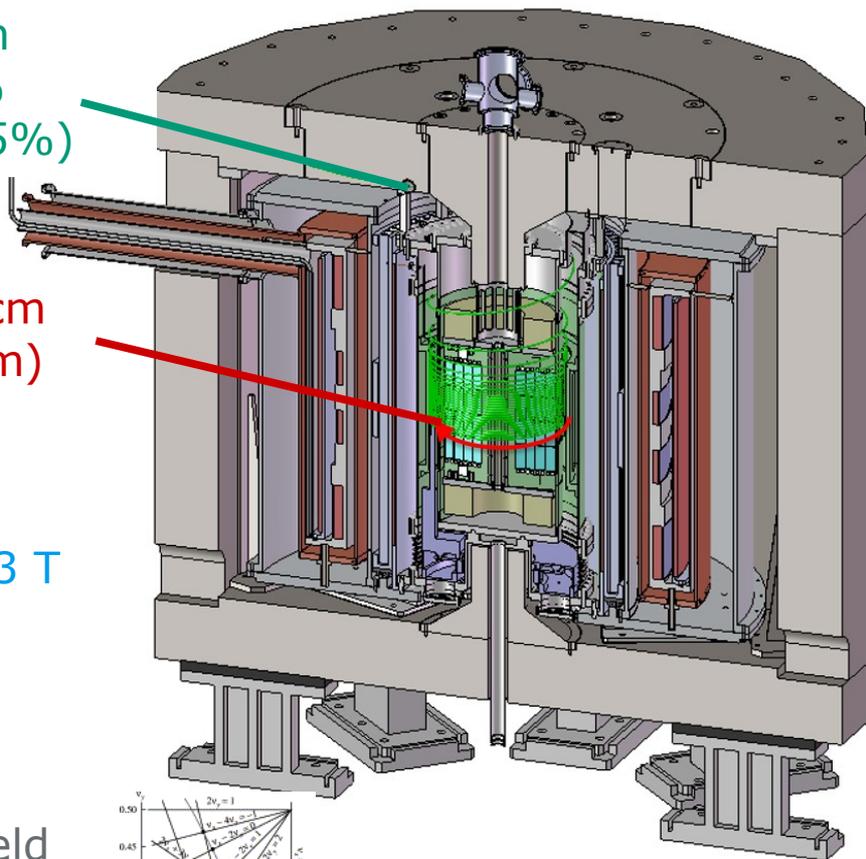
Cooling + LINAC : world's first muon accelerator

Storage

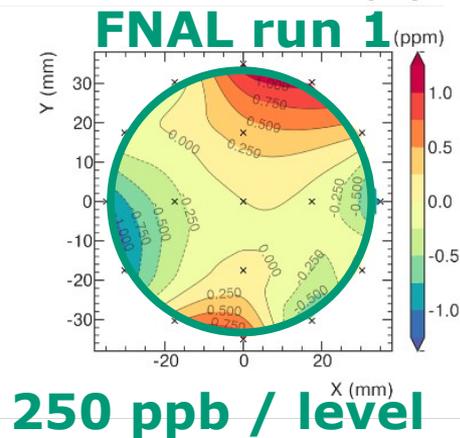
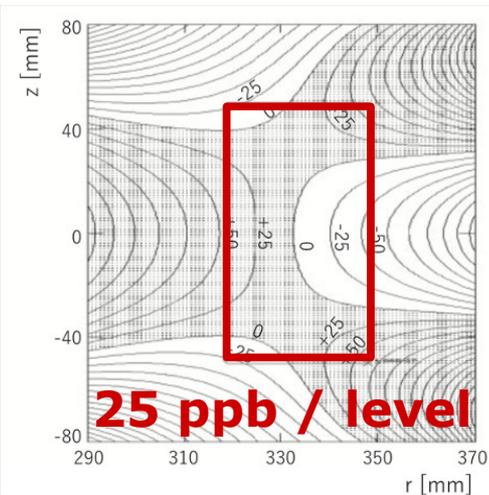
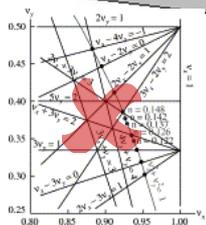
Vertical injection
 Efficiency $\pm 85\%$
 (vs. Horizontal 5%)

Muon orbit
 radius $R = 33$ cm
 (vs. $R = 711$ cm)

Magnetic field
 strength $B = 3$ T
 (vs. 1.45 T)

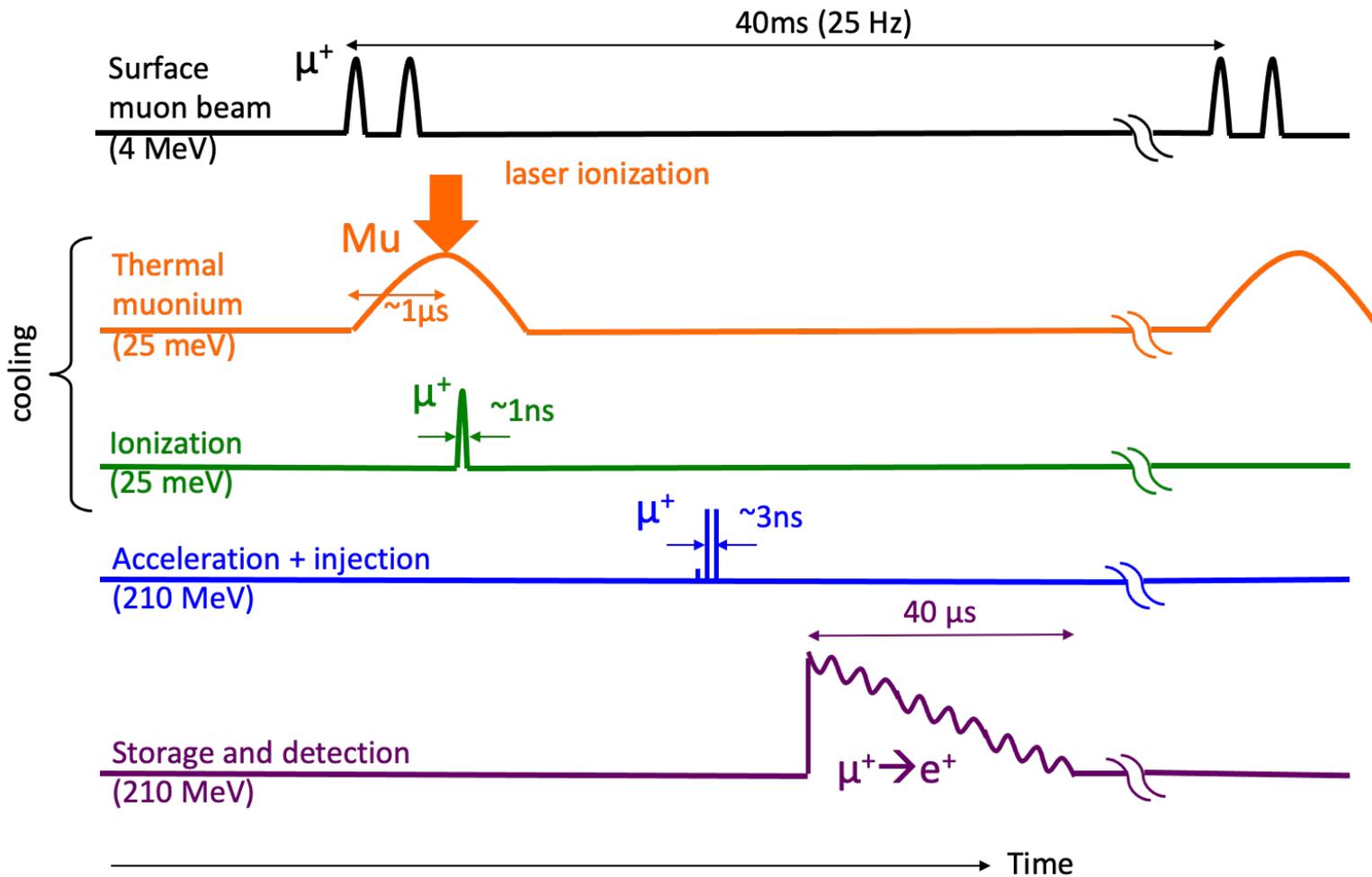


Electric quad-field
 strength $Q_E = 0$
 (vs. $Q_E = 1$ kV/cm²)



Abe *et al.*, DOI: 10.1016/j.nima.2018.01.026 (2018)
 Albahri *et al.*, DOI: 10.1103/PhysRevA.103.042208 (2021)
 Semertzidis *et al.*, DOI: 10.1016/S0168-9002(03)00999-9 (2003)

Experimental Cycle



Detection

In-field Si-strip Tracker / Spectrometer

40 vanes

@ 4 x 4 x (H+V) sensors / vane

@ 1024 strips / sensor

@ 5 cm x 190 μm / strip

@ 200 Mreads / s

-> (260 Tbits/s)

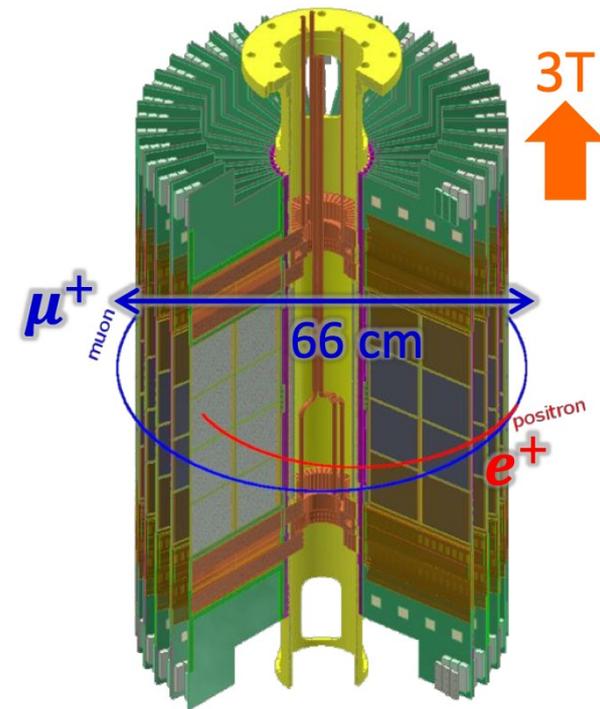
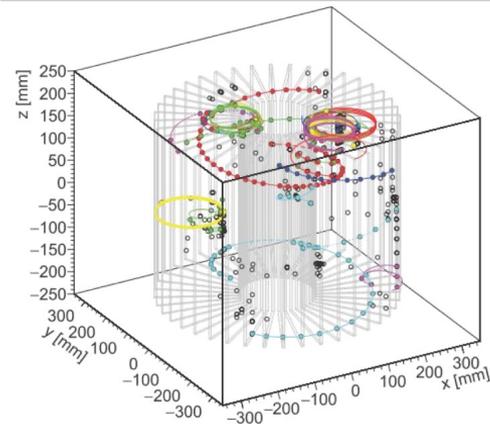
Detector Specs

Expected max. #e⁺'s 6/ns

Max. hit rate: 150 kHz / mm²

p > 200 MeV/c

dp/p = 8x10⁻⁴



Comparison

	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 μ s	2.11 μ s
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 · cm	–	1.5×10^{-21} e · cm
(syst.)	0.9×10^{-19} e · cm	–	0.36×10^{-21} e · cm

Systematics

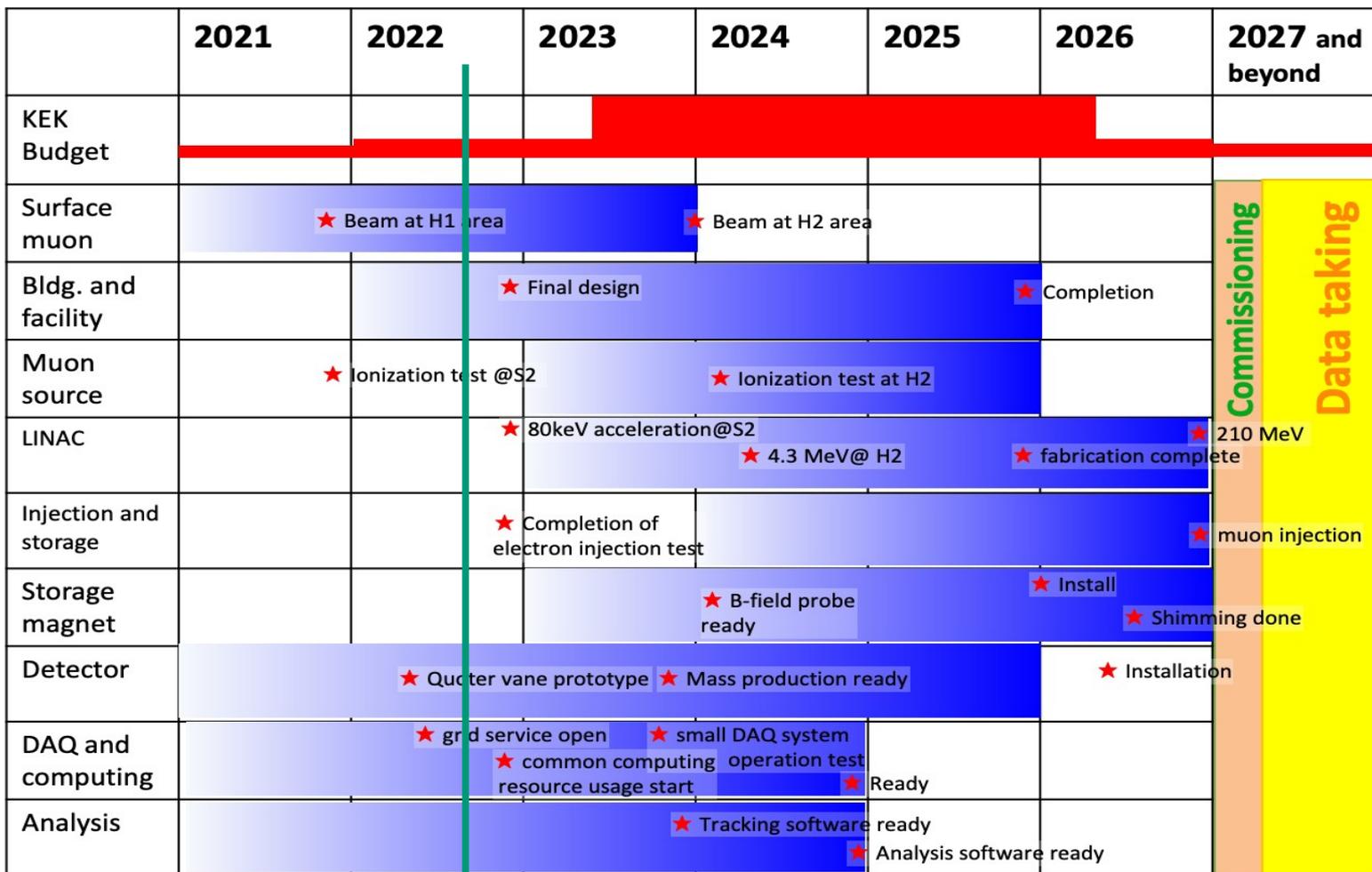
TABLE II. Values and uncertainties of the \mathcal{R}'_μ correction terms in Eq. (4), and uncertainties due to the constants in Eq. (2) for a_μ . Positive C_i increase a_μ and positive B_i decrease a_μ .

Quantity	Correction terms (ppb)	Uncertainty (ppb)	
ω_a^m (statistical)	...	434	
ω_a^m (systematic)	...	56 \rightarrow <36	: Pileup, (gain, CBO)
C_e	489	53 \rightarrow 10	: residual E-fields
C_p	180	13 \rightarrow 13	: pitch correction
C_{ml}	11	5 \rightarrow 2	: differential decay & (muon losses)
C_{pa}	-158	75 \rightarrow 0	: transverse muon distribution
$f_{\text{calib}} \langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$...	56 \rightarrow 49	: probe positioning & calibration
B_k	-27	37	
B_q	-17	92 \rightarrow <10	: kicker transients
$\mu'_p(34.7^\circ)/\mu_e$...	10	
m_μ/m_e	...	22	
$g_e/2$...	0	
Total systematic	...	157 \rightarrow <64	
Total fundamental factors	...	25	
Totals	544	462	

Abe *et al.*, DOI: 10.1093/ptep/ptz030 (2019)

Abi *et al.*, DOI: 10.1103/PhysRevLett.126.141801 (2021)

Schedule & Milestones



Commissioning

Data taking

Conclusion - I

Leptons excellent testing ground for flavour physics

- Rich palette of observables
- Ultra-precise predictions
- Extremely sensitive measurements

Long standing $\sim 3\sigma$ anomaly in muon $g-2$

- Experimental and theoretical uncertainty @ ppm level !!
- New experimental results expected from FNAL \rightarrow **100 ppb?!**
- Experiments consistent \rightarrow **but correlated**
- Steady progress in theory improvement
- Tension in (hadronic) theory \rightarrow **complicates interpretation**

Conclusion - II

New J-PARC g-2/EDM experiment

Alternative experimental method

pencil beam : cooled & re-accelerated positive muons

compact ring : stable & homogeneous magnetic field

in-field spectrometer : reliable & precise positron detection

Complementary systematic sensitivities

Surface muon beam delivered on Jan. 2022

Expected data taking starting in 2027

Electric Dipole Moments

EDMs need **P** and **T/CP** violation

SM leptonic EDMs from 4-loops w/ quarks are strongly suppressed

$$d_e \sim e(\alpha^2/\pi^4)G_F m_e f_e = 6 \times 10^{-29} f_e \text{ e}\cdot\text{cm}$$

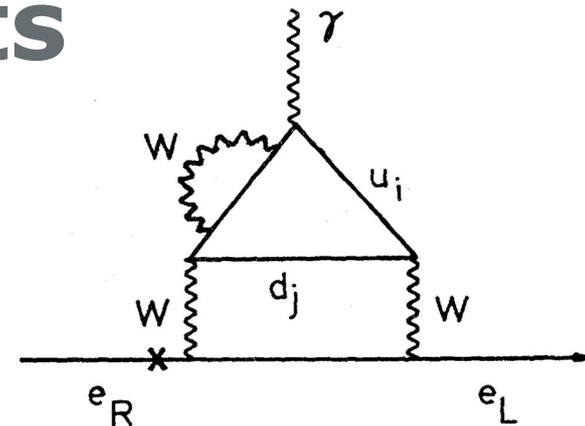
From lepton universality and (bounds on) neutrino masses

$$|f_e| \ll |f_q| \sim 10^{-9}$$

$$d_\mu^{SM} \approx \frac{m_\mu}{m_e} d_e^{SM}$$

Background-free probe for new sources of CP-violation

Probe via interaction with ultra-strong E-field

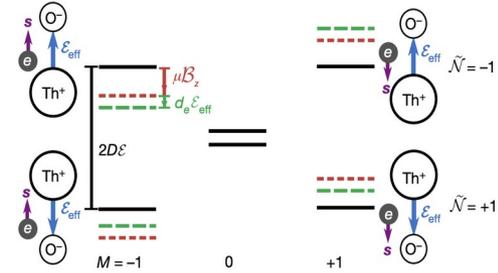


EDM

Electron

Internal E in molecule: **ThO** \rightarrow $E_{\text{eff}} = 8$ TV/m

$$|\mathbf{d}_e| < 1.1 \times 10^{-29} \text{ e}\cdot\text{cm} \text{ (90\% C.L.)}$$



Muon

Relativistic E: **g-2** \rightarrow $E_{\text{eff}} = \mathbf{v} \times \mathbf{B} = 0.5$ GV/m

$$|\mathbf{d}_\mu| < 1.8 \times 10^{-19} \text{ e}\cdot\text{cm} \text{ (95\% C.L.)}$$

Indirect from ^{199}Hg and ThO

$$|\mathbf{d}_\mu|_{\text{Hg}} < 6 \times 10^{-20} \text{ e}\cdot\text{cm}, \quad |\mathbf{d}_\mu|_{\text{ThO}} < 2 \times 10^{-20} \text{ e}\cdot\text{cm}$$

