Muon g-2 @ J-PARC

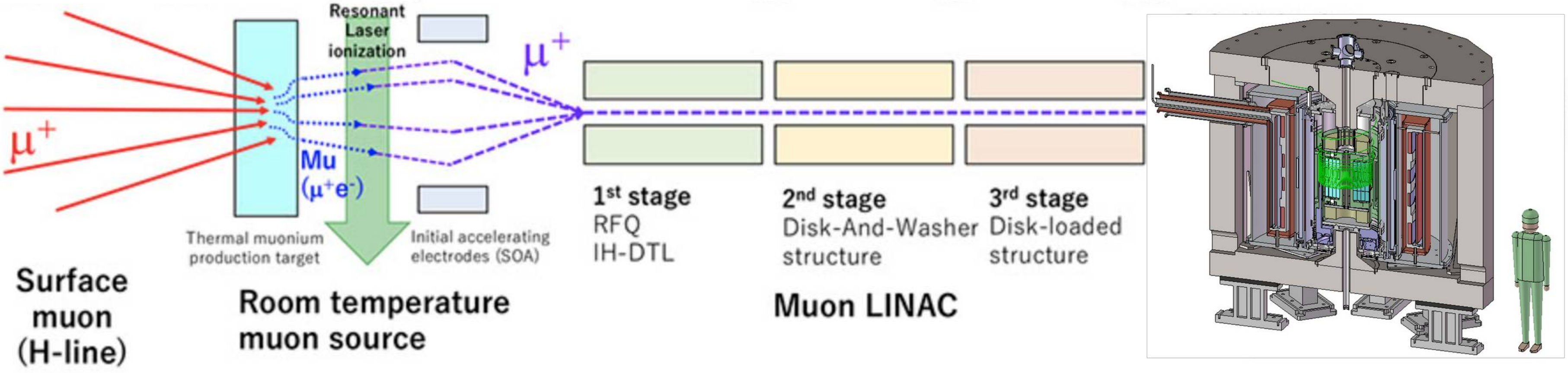
Gerco Onderwater
on behalf of the J-PARC E34 Collaboration

Flavour Physics Conference, Quy Nhon, VN, 19 Aug 2025

Maastricht University

Experiment E34 @ J-PARC

Part of a wide-range muon physics programme

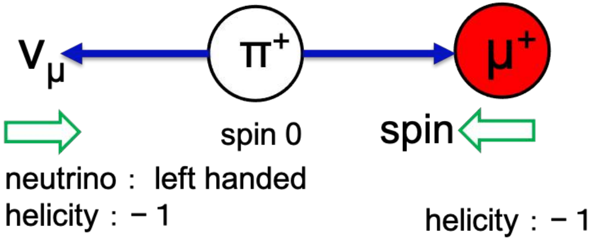


Aim: competitive measurement of muon g-2 and EDM

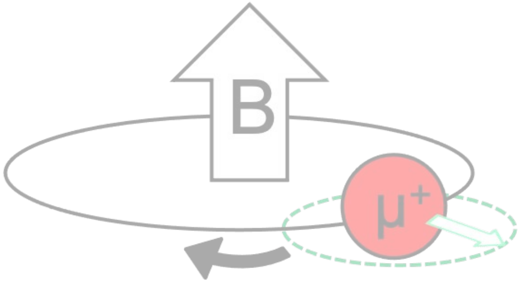
https://g-2.kek.jp/overview/

Elements of an MDM or EDM Expt

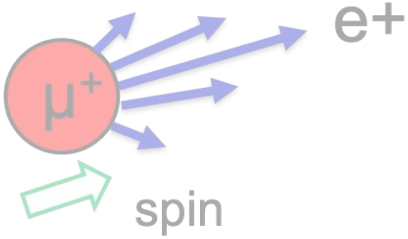
Polarized Muon Production



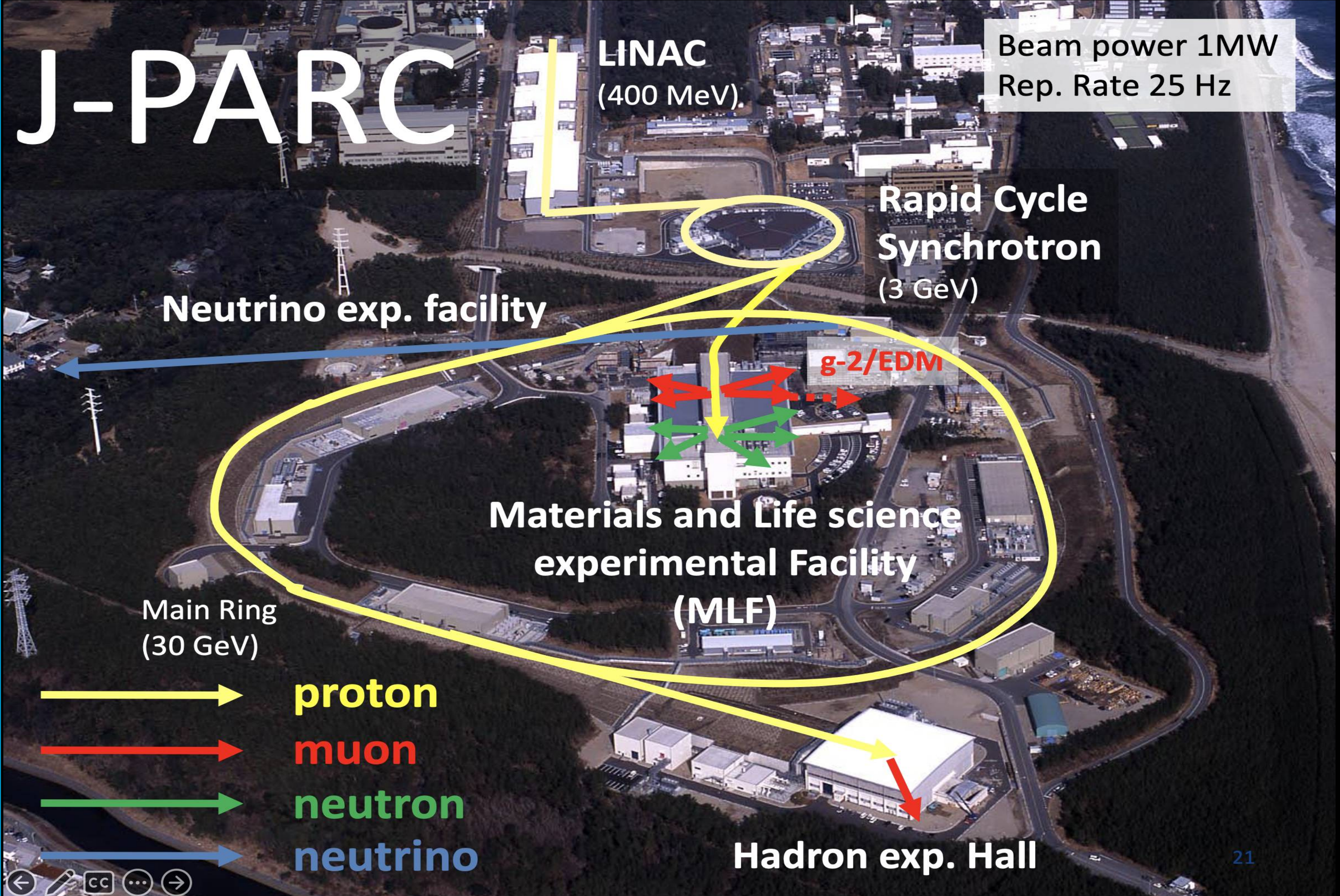
Storage & Spin Precession

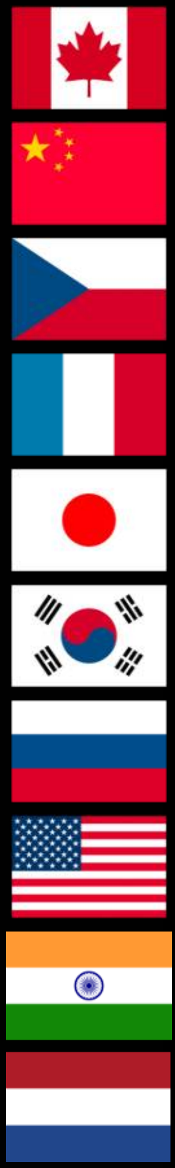


Detection of Spin Orientation

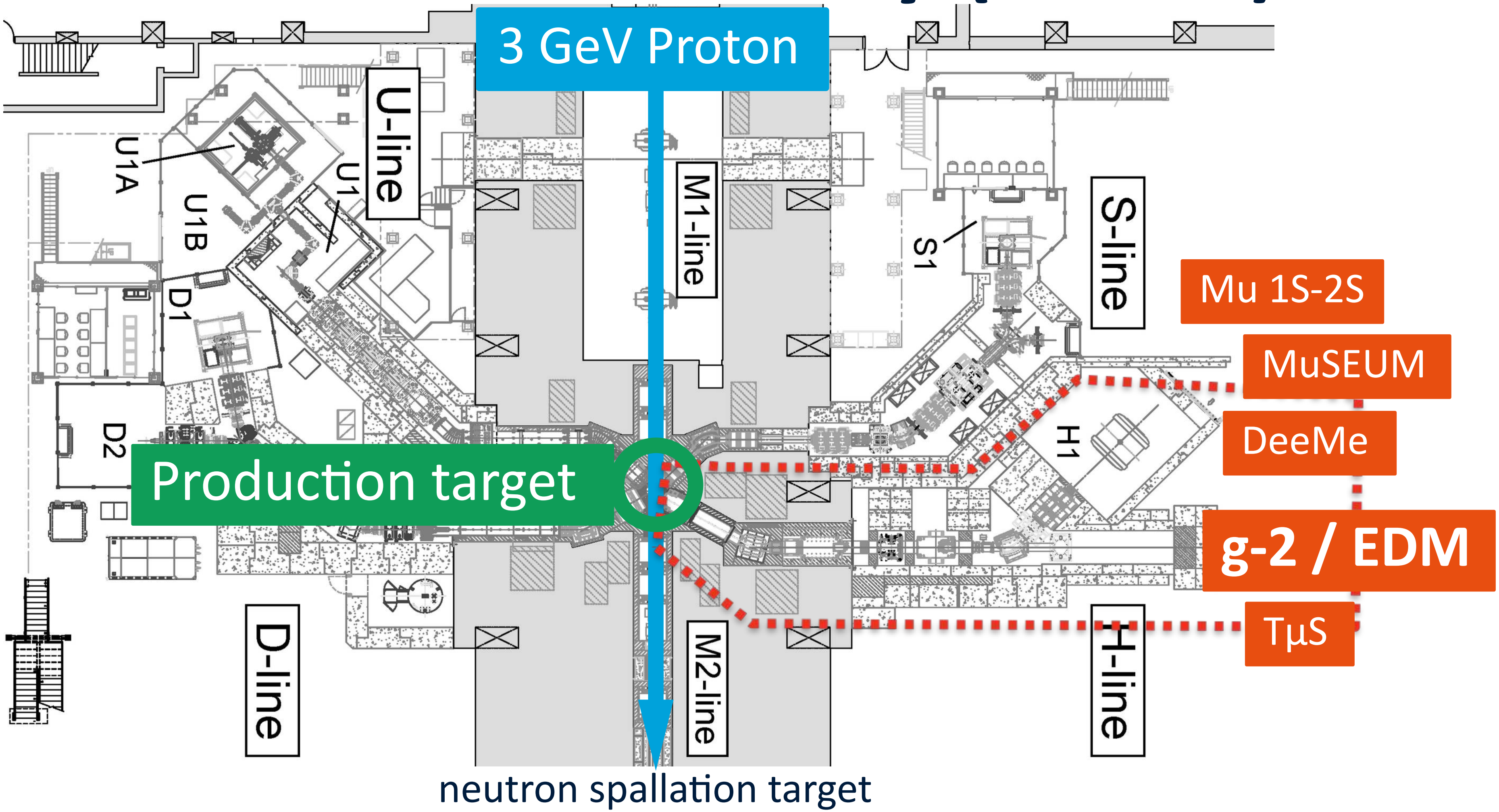


J-PARC

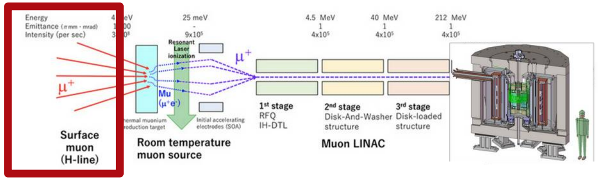

LINAC
(400 MeV)
Beam power 1MW
Rep. Rate 25 Hz
Rapid Cycle
Synchrotron
(3 GeV)
Neutrino exp. facility
g-2/EDM
Materials and Life science
experimental Facility
(MLF)
Main Ring
(30 GeV)
proton
muon
neutron
neutrino
Hadron exp. Hall
21



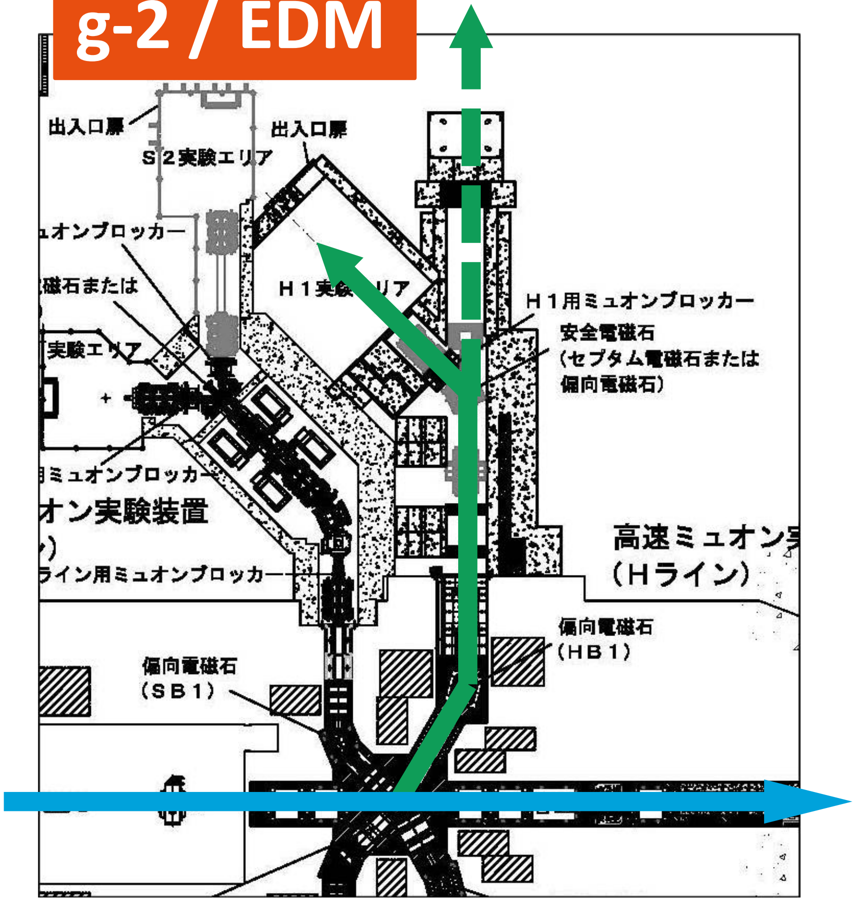
Muon Science Facility (MUSE)

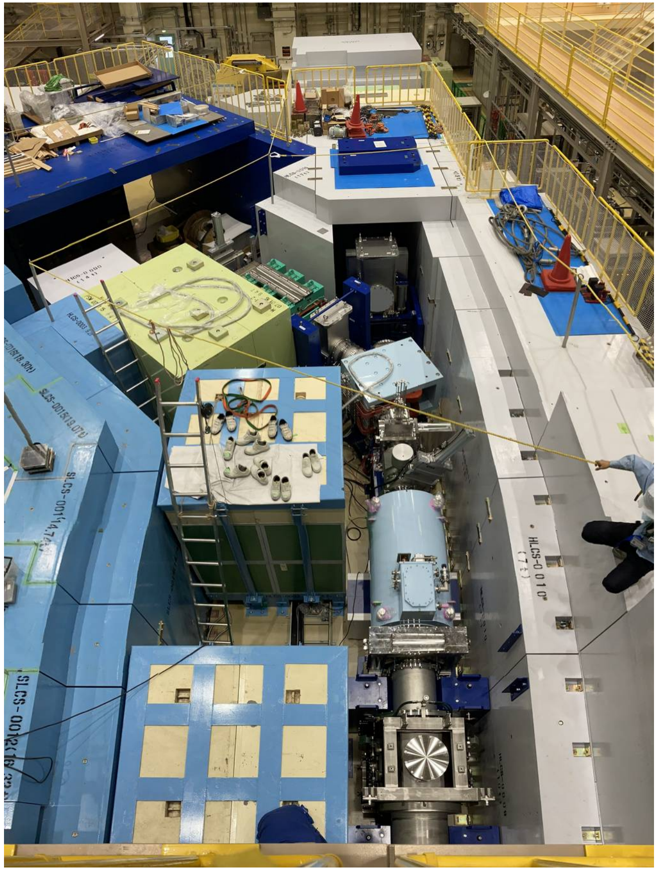


H1 & H2-Beamlines

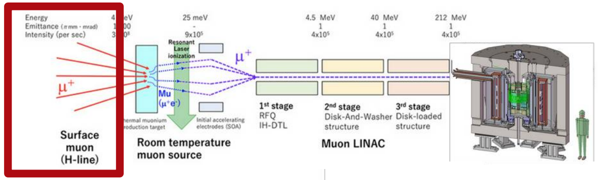


g-2 / EDM

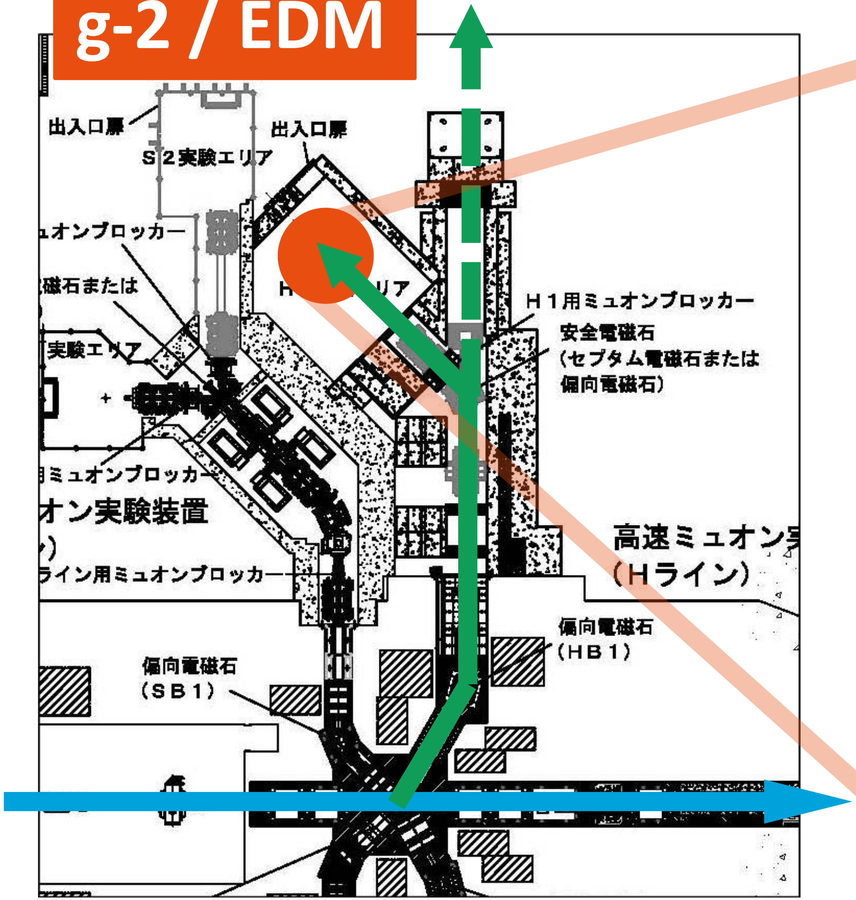


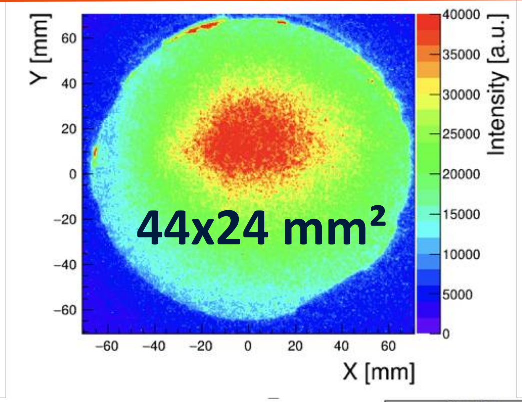


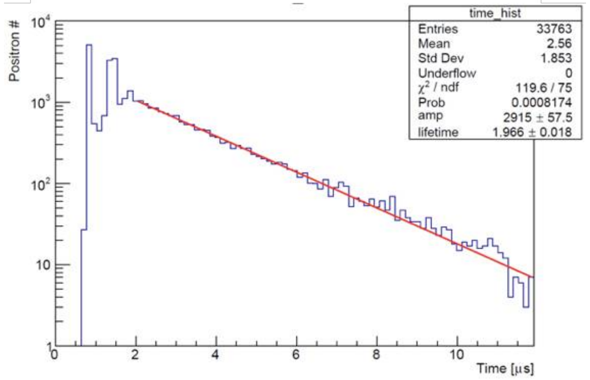
First beam (Jan. 2022)



g-2 / EDM

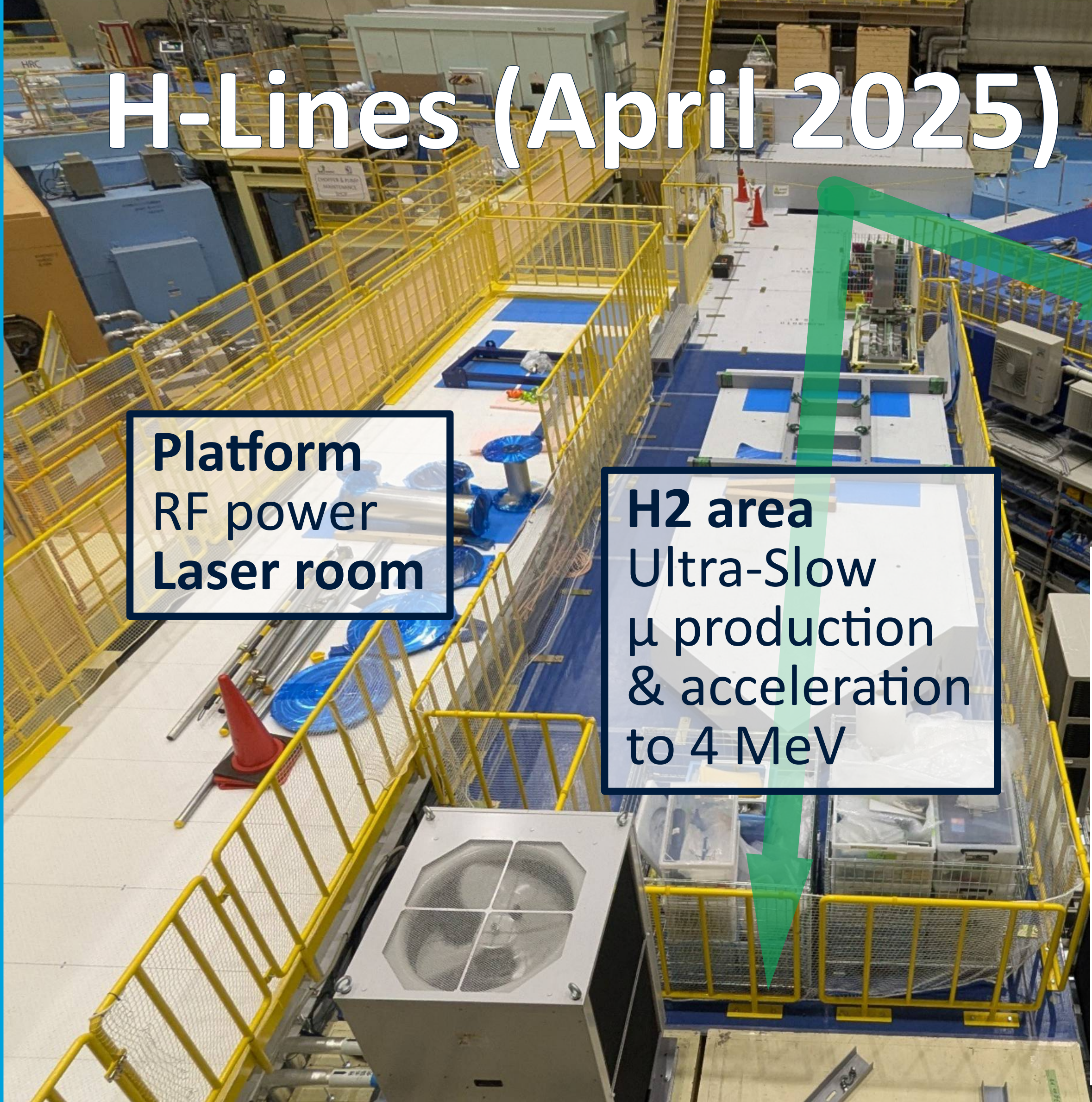


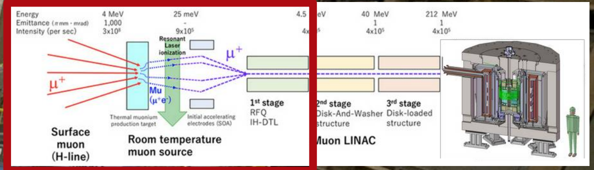




7x10^7/s @ 28 MeV/c, 730 kW

H-Lines (April 2025)

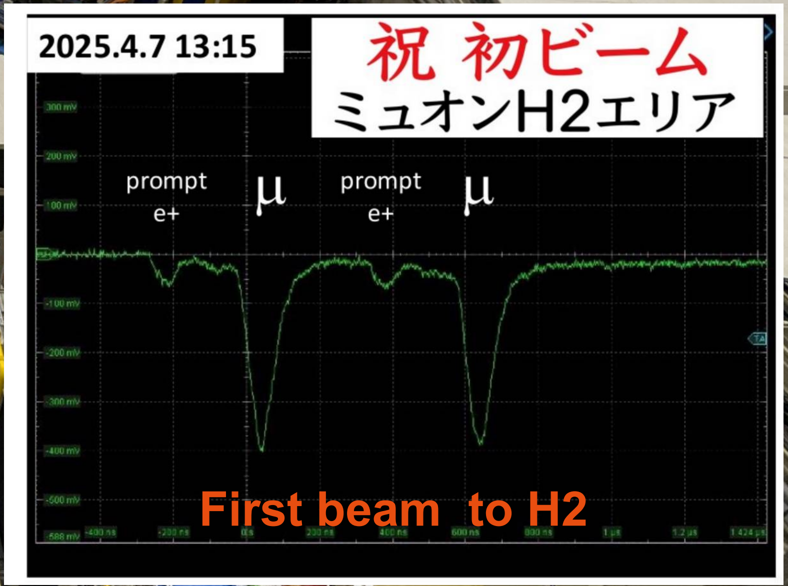




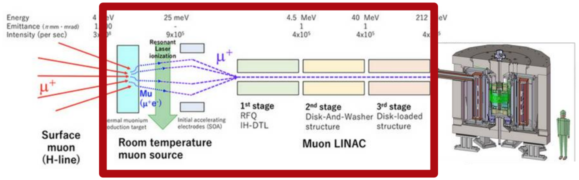
Platform
RF power
Laser room

H2 area
Ultra-Slow
μ production
& acceleration
to 4 MeV

H1 area
MuSEUM
DeeMe

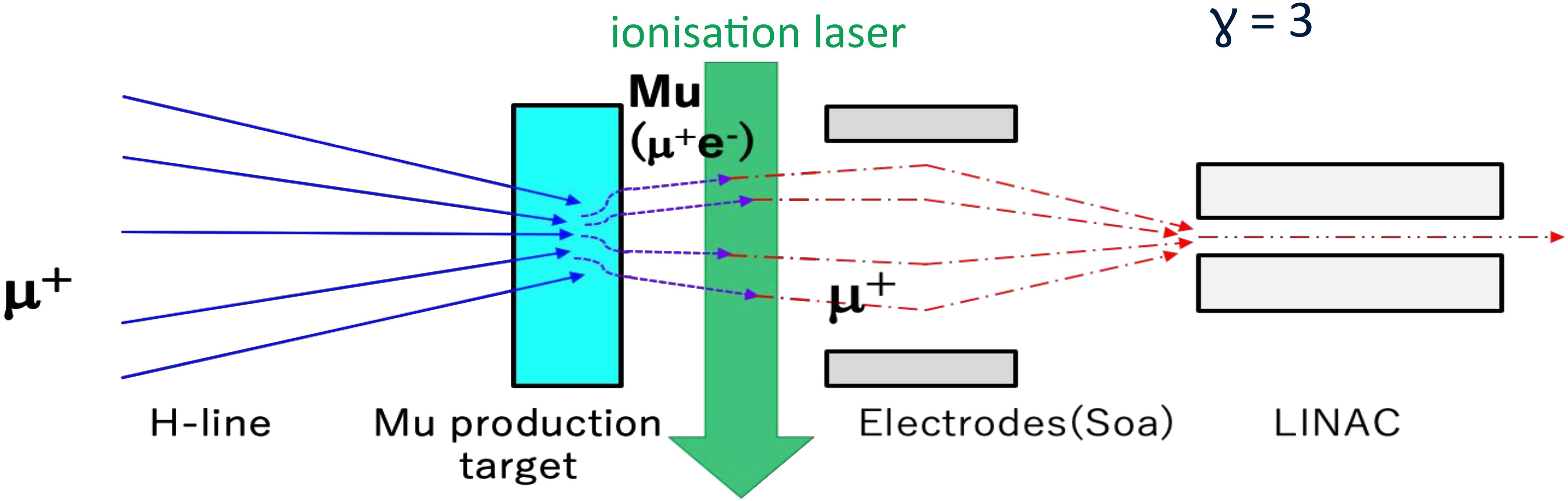


Muon Cooling



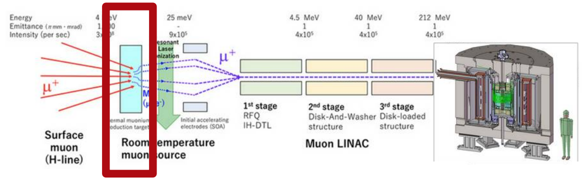
	surface muons	thermal muons	accelerated muons
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
Δp/p	0.05	0.4	0.0004

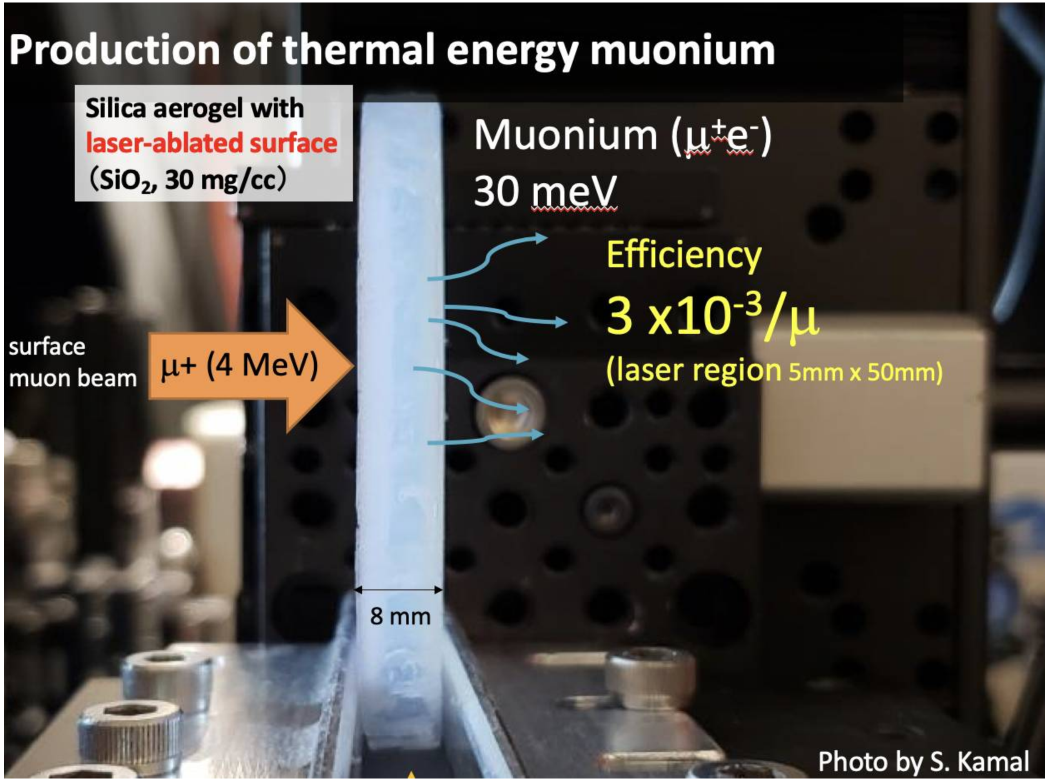
$\gamma = 3$



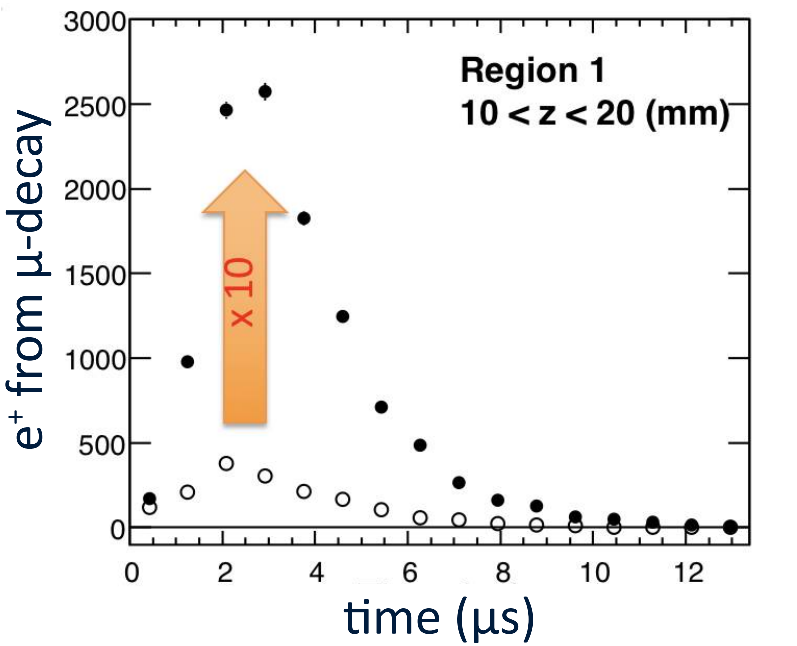
Cooling + LINAC : world's first muon accelerator

Muonium Production



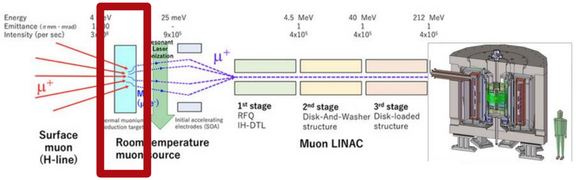


Muonium yield measured @ TRIUMF

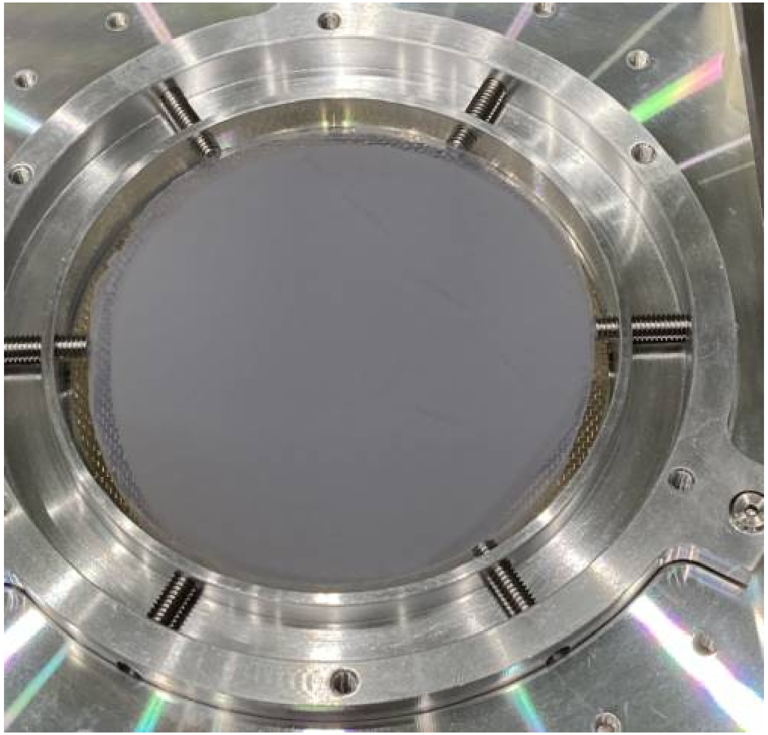


Sufficient to reach Δa_μ ~ 450 ppb

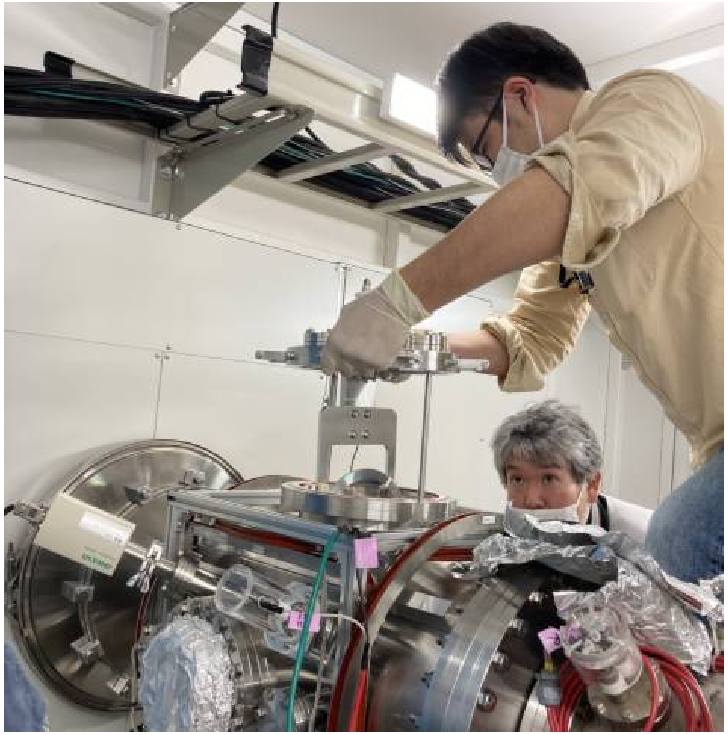
Muonium Production



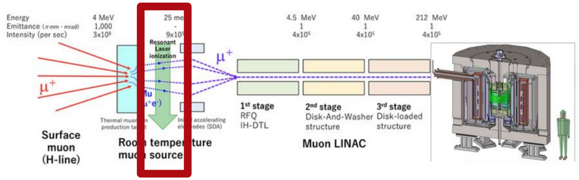
Laser ablated silica aerogel

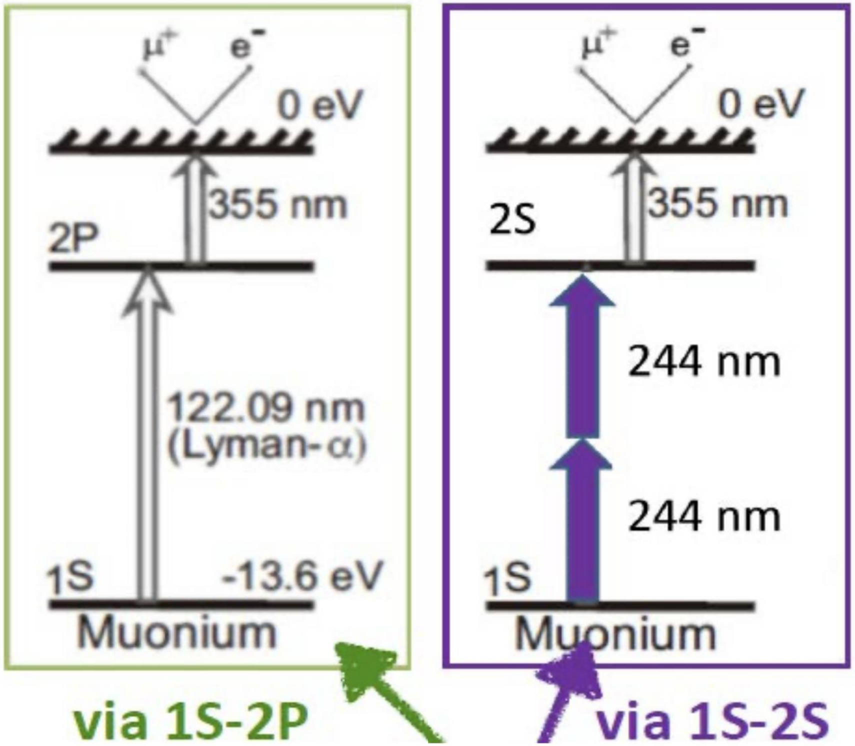


J-PARC S2 area (Feb. 2023)

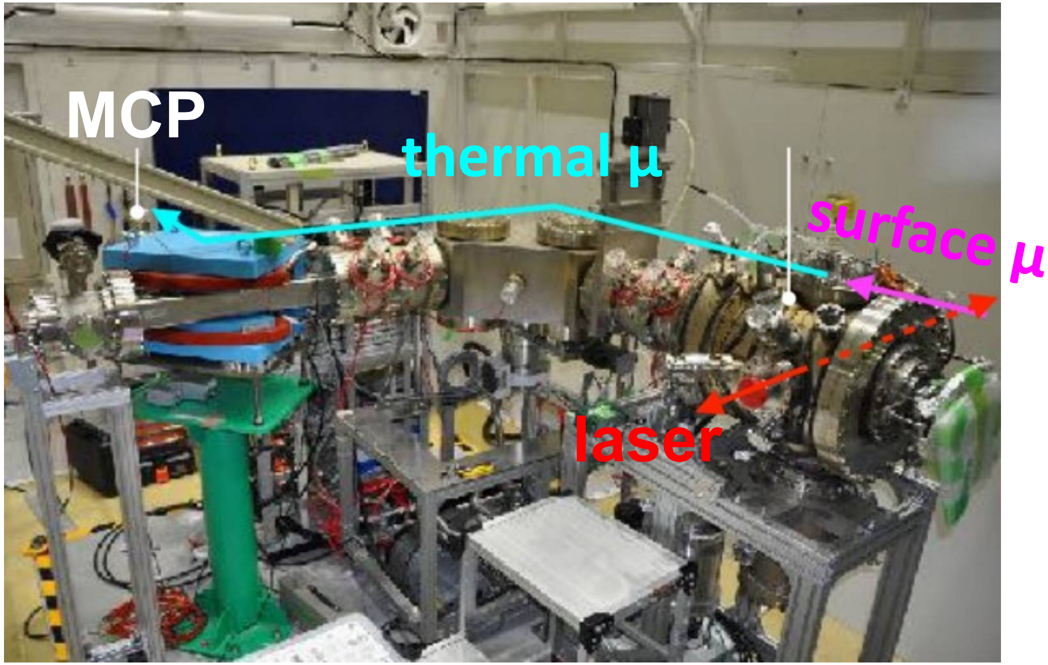


Muonium Ionisation



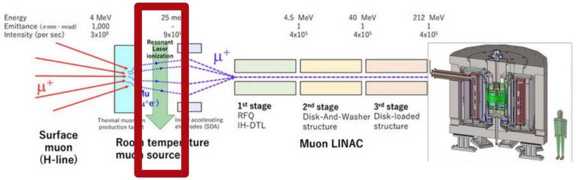


Ionisation test via 1S-2S

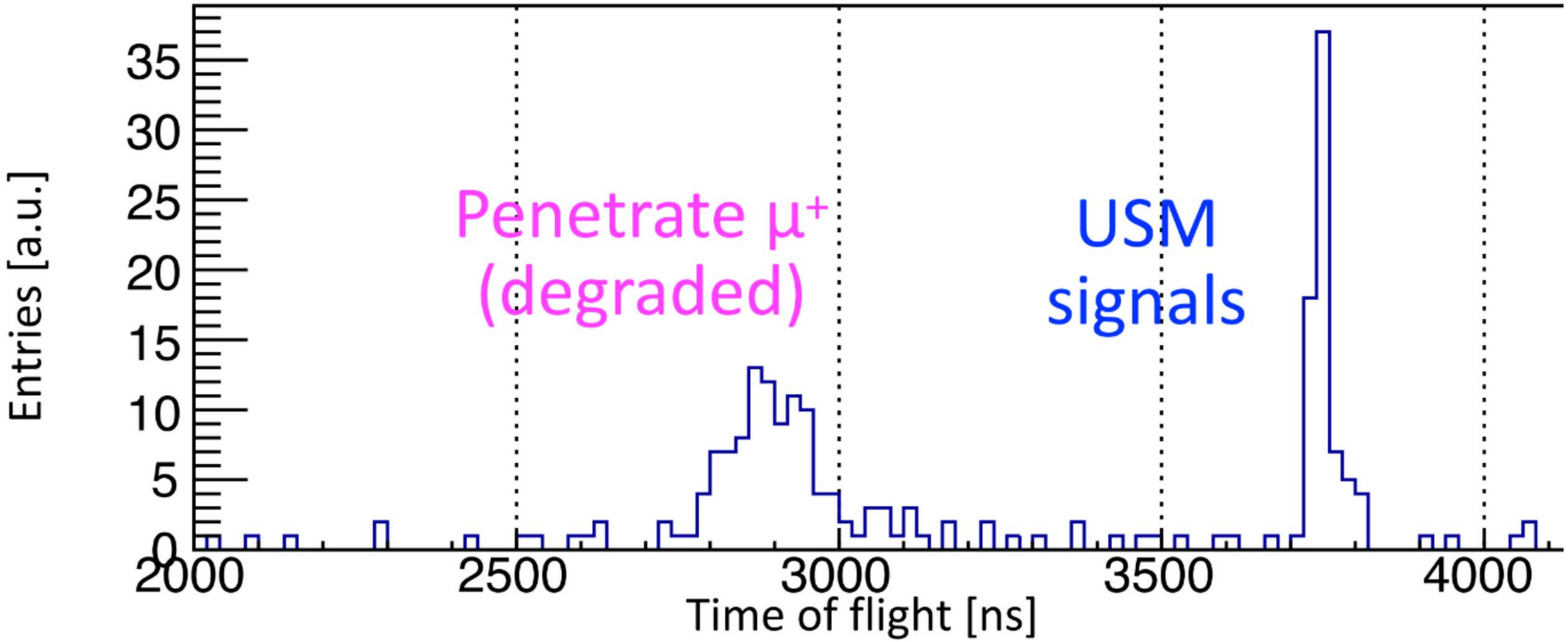


In collaboration w/ Okayama University (Uetake *et al.*)

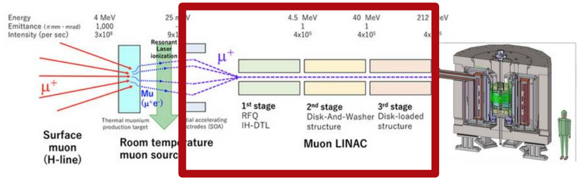
Ultra Slow Muon Demo

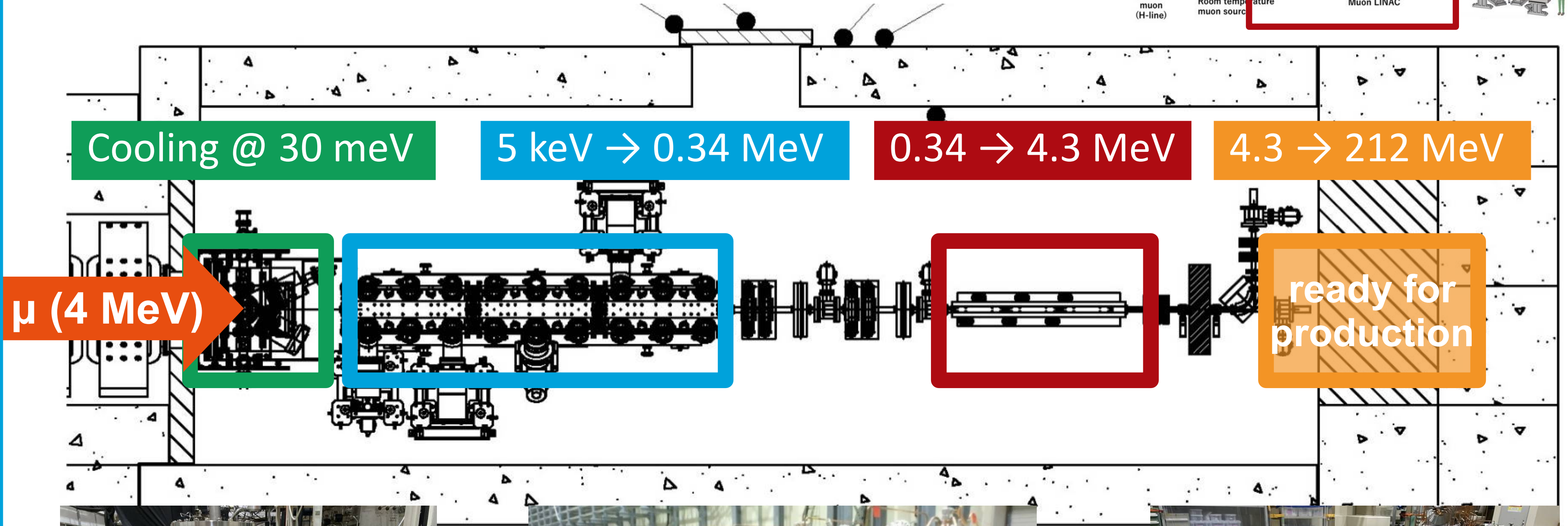


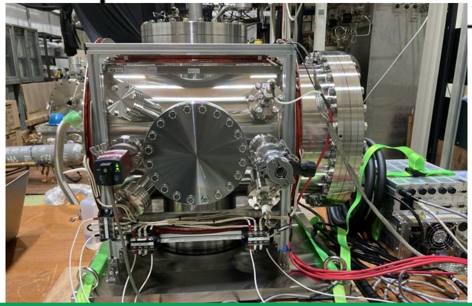
Thermal muon observed March '24



Muon Acceleration





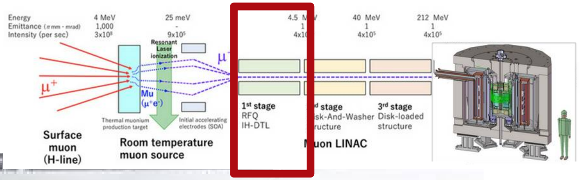


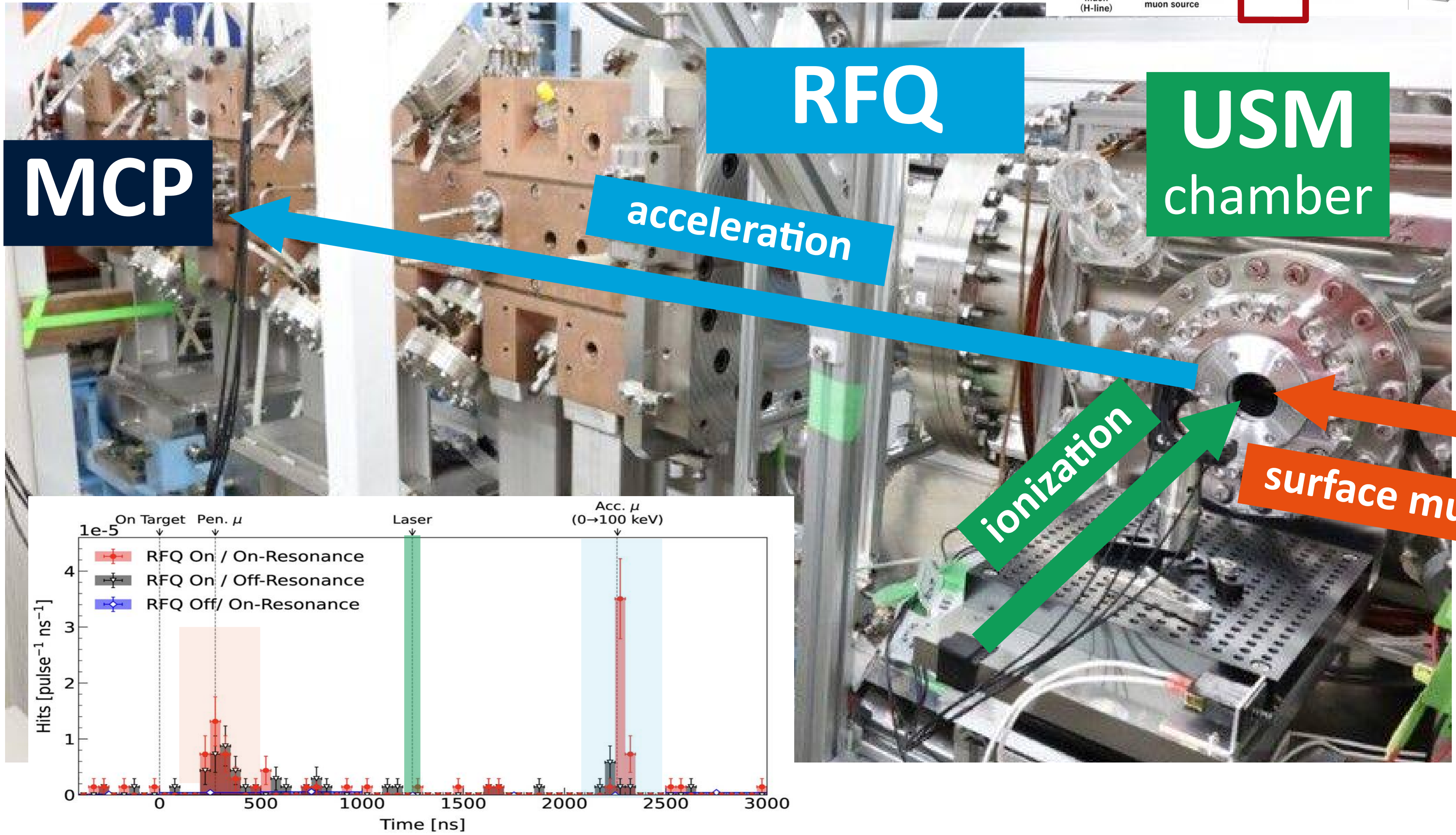
Mu chamber (ready)

J-PARC Linac RFQ (ready)

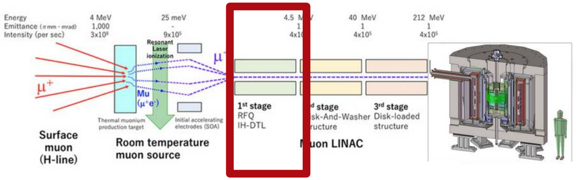
IH-DTL (ready; test '26/'27)

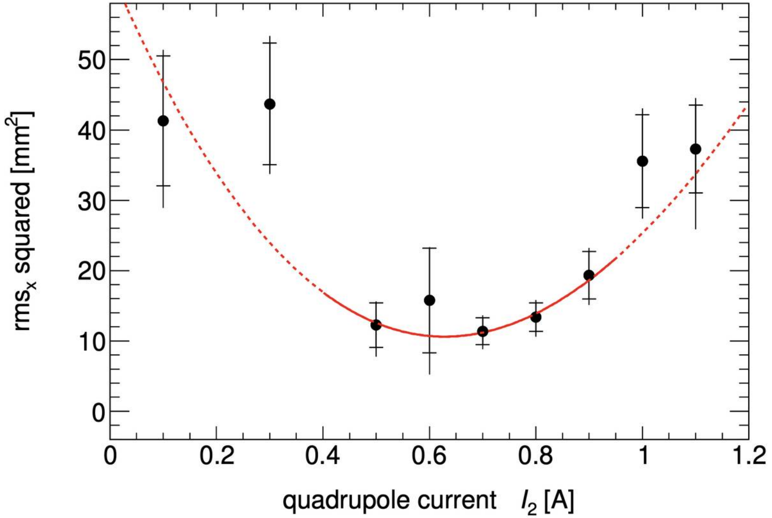
Cooled Accelerated μ‘s

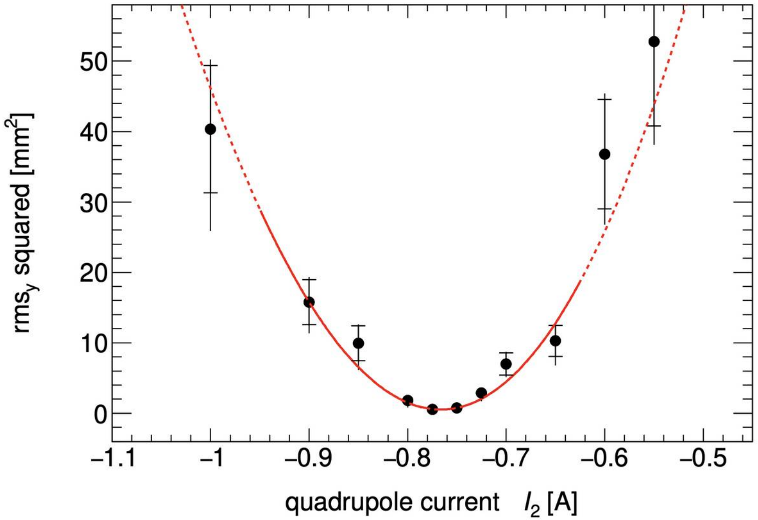




Cooled Accelerated μ‘s







$$\varepsilon_x = 170\,\pi\,\mathrm{mm\cdot mrad}$$

÷200

$$\varepsilon_x = \left(0.85 \pm 0.25\right)^{+0.22}_{-0.13}\,\pi\,\mathrm{mm\cdot mrad}$$

$$\varepsilon_y = 130\,\pi\,\mathrm{mm\cdot mrad}$$

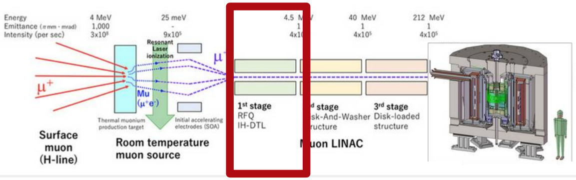
÷400

$$\varepsilon_y = \left(0.32 \pm 0.03\right)^{+0.05}_{-0.02}\,\pi\,\mathrm{mm\cdot mrad}$$

$$p = 30\,\mathrm{meV} \rightarrow 100\,\mathrm{keV}$$

$$dp/p = \left(1.10^{+0.02}_{-0.11}\right)\times 10^{-2}$$

arXiv:2410.11367



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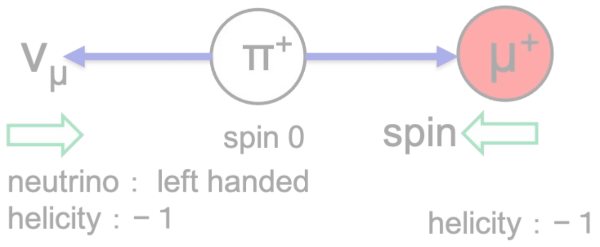
NEWS | 24 October 2024

Physicists tame fundamental muon particles into highly controlled beam for first time

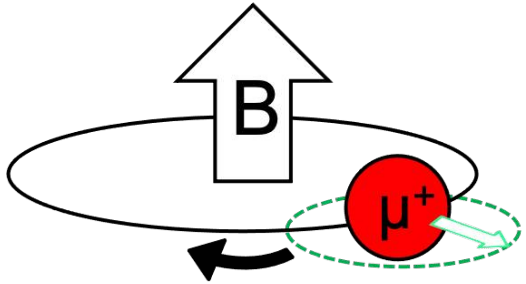
The milestone is an important step towards building smaller, cheaper particle colliders.

Elements of an MDM or EDM Expt

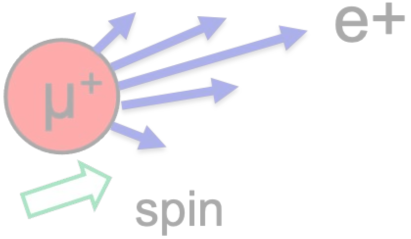
Polarized Muon Production



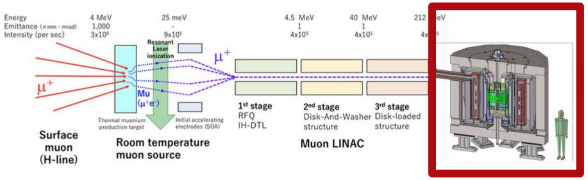
Storage & Spin Precession



Detection of Spin Orientation

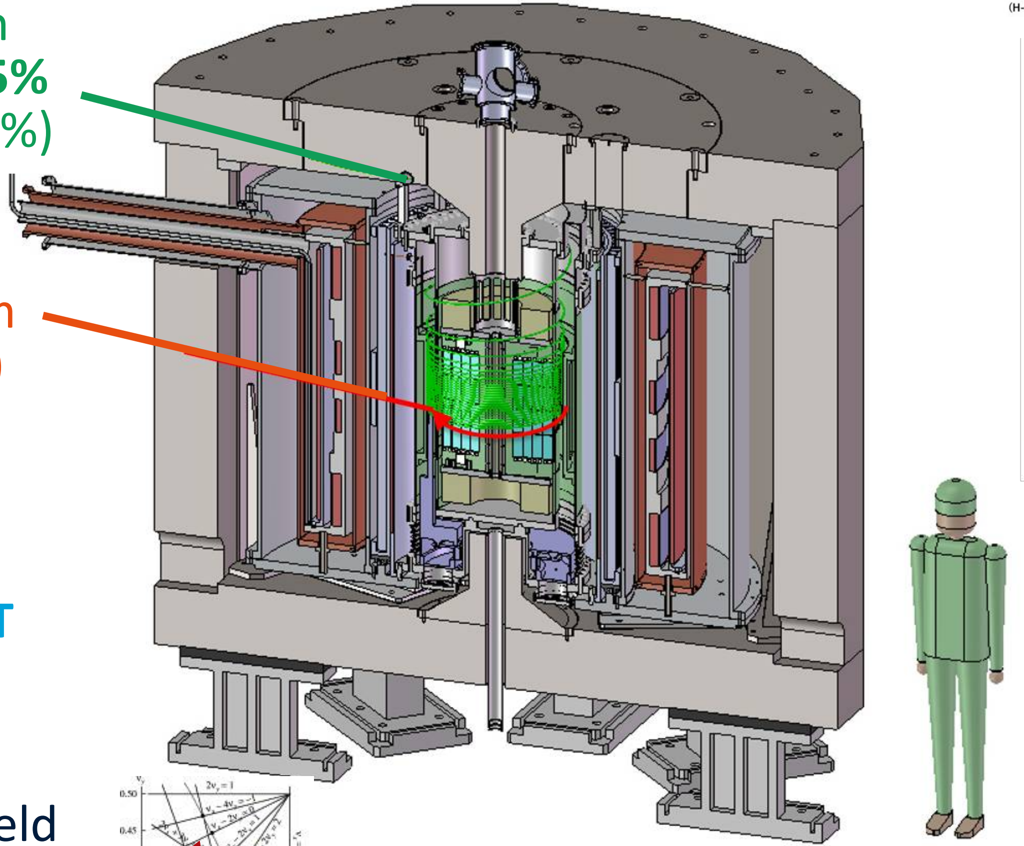


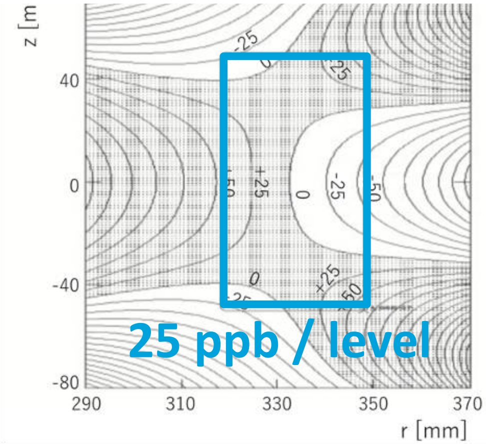
Storage



Vertical injection
Efficiency **η = 85%**
(*c.f.* Horizontal 5%)

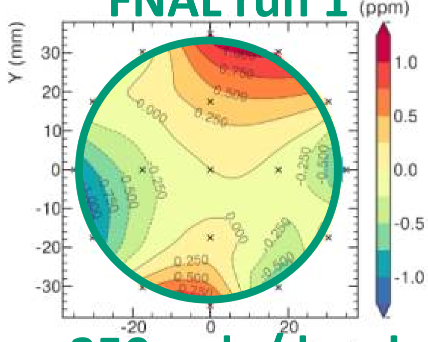
Muon orbit
radius **R = 33** cm
(*c.f.* R = 711 cm)





25 ppb / level

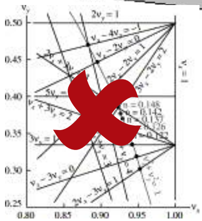
FNAL run 1



250 ppb / level

Magnetic field
strength **B = 3 T**
(*c.f.* 1.45 T)

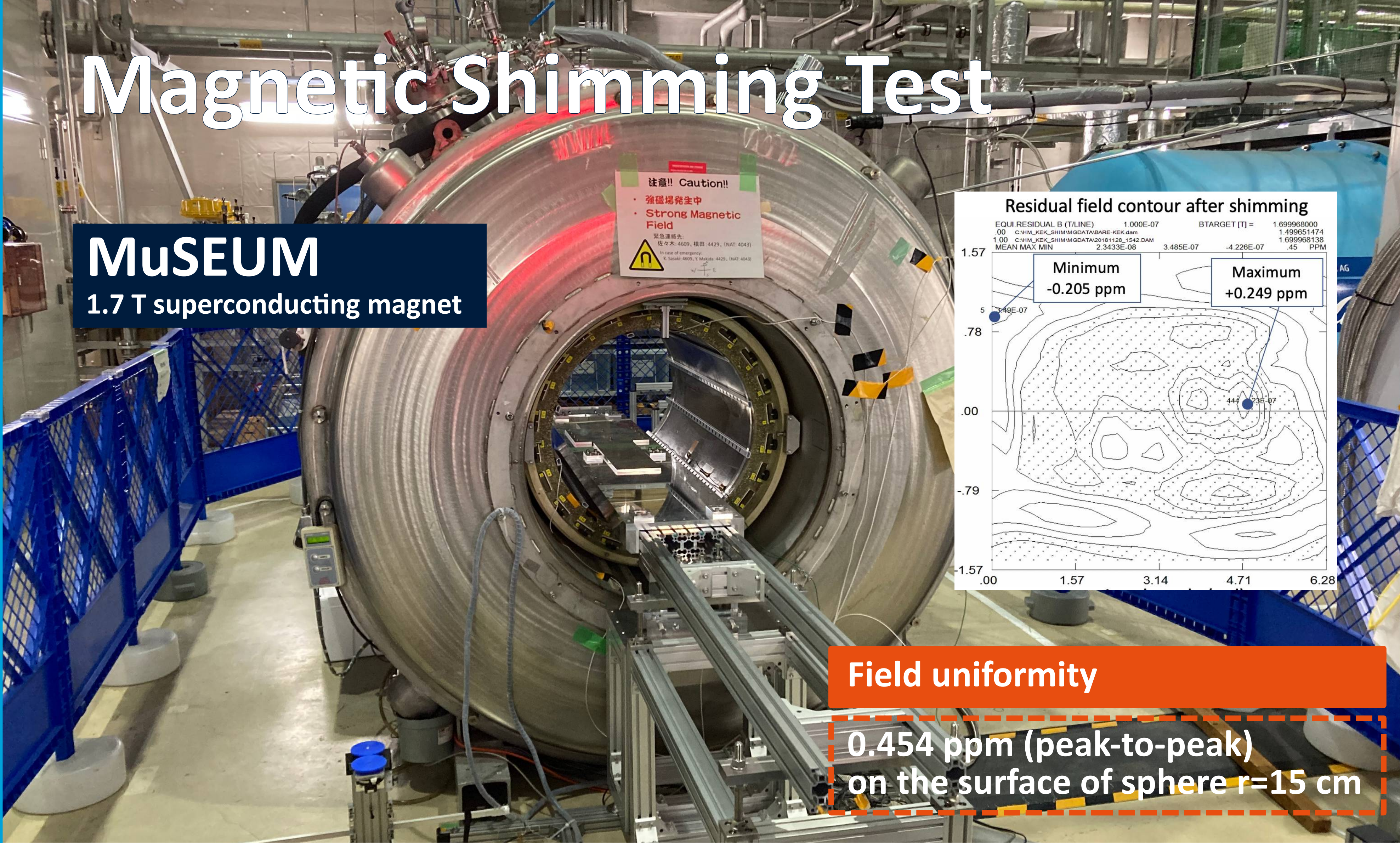
Electric quad-field
strength $Q_E = 0$
(*c.f.* $Q_E = 1\ \mathrm{kV/cm^2}$)



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)

Magnetic Shimming Test

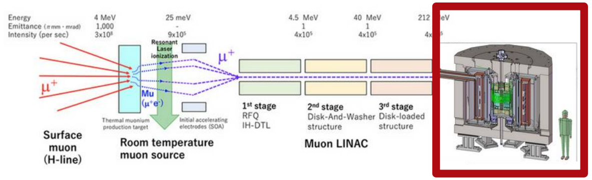
MuSEUM
1.7 T superconducting magnet

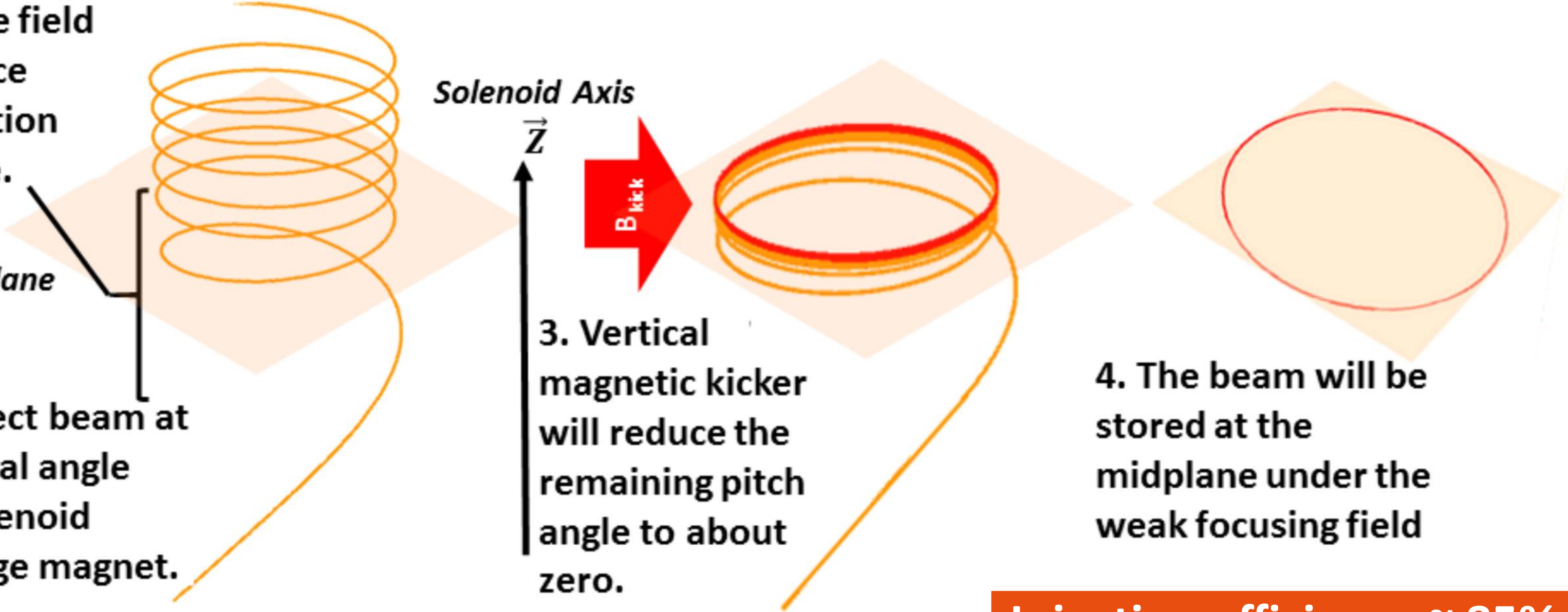


Field uniformity

0.454 ppm (peak-to-peak)
on the surface of sphere r=15 cm

Spiral Injection





2. Radial fringe field reduce injection angle.

1. Inject beam at vertical angle in solenoid storage magnet.

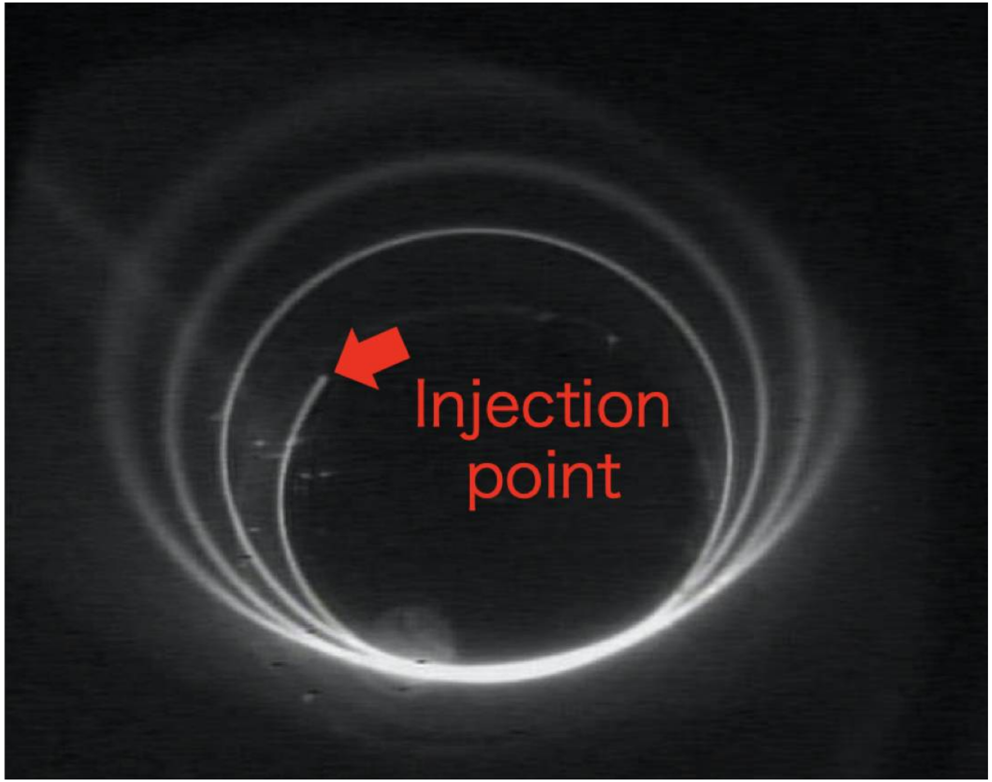
3. Vertical magnetic kicker will reduce the remaining pitch angle to about zero.

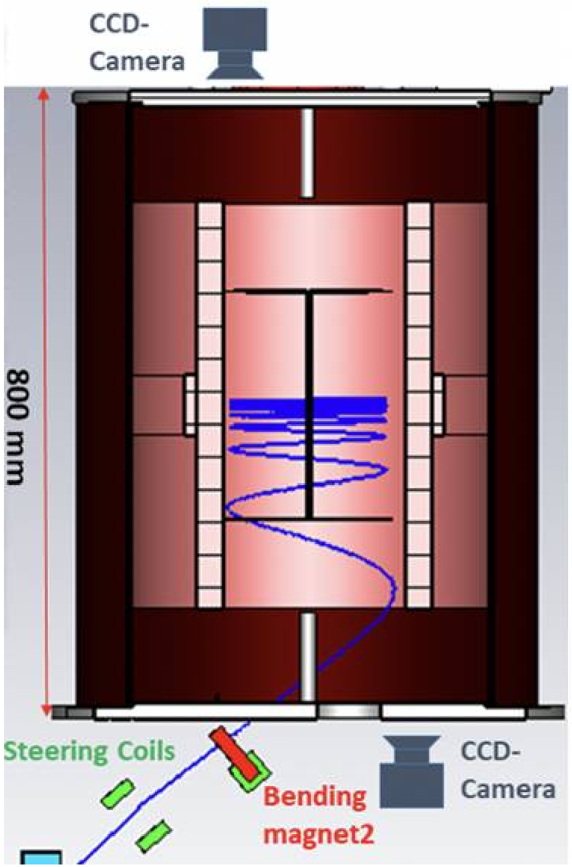
4. The beam will be stored at the midplane under the weak focusing field

Injection efficiency ~ 85%

Iinuma *et al.*, DOI: 10.1016/j.nima.2016.05.126 (2016)
Rehman et al., DOI: 10.18429/JACoW-LINAC2018-THPO017 (2017)
Oda *et al.*, DOI: 10.1109/TASC.2022.3164996 (2022)

Test w/ Electrons





R. Matsushita *et al.*, doi: 10.18429/JACoW-IPAC2023-MOPA118

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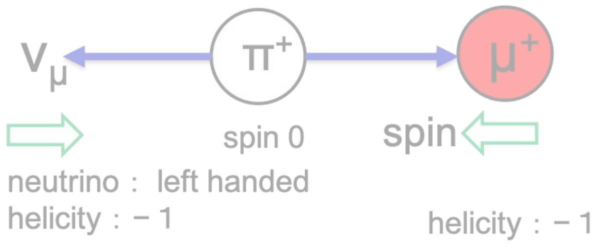
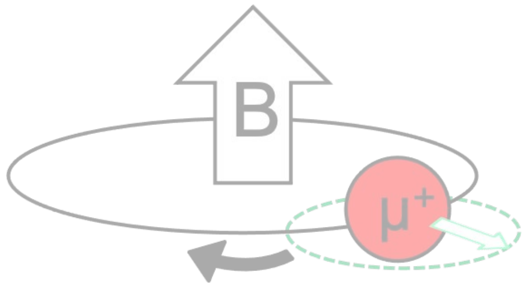
Polarized Muon Production



Storage & Spin Precession



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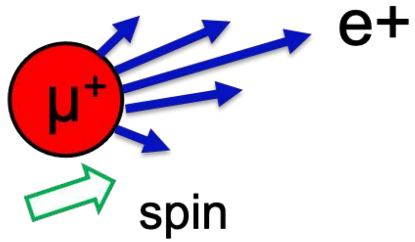
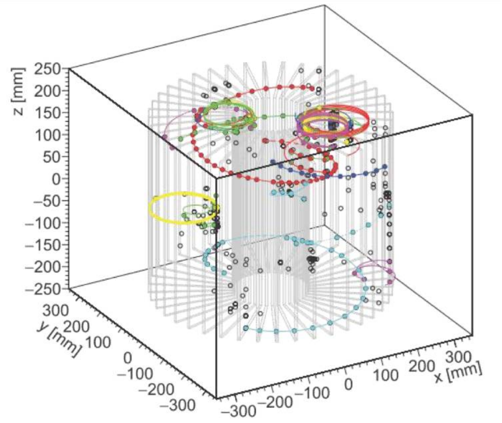
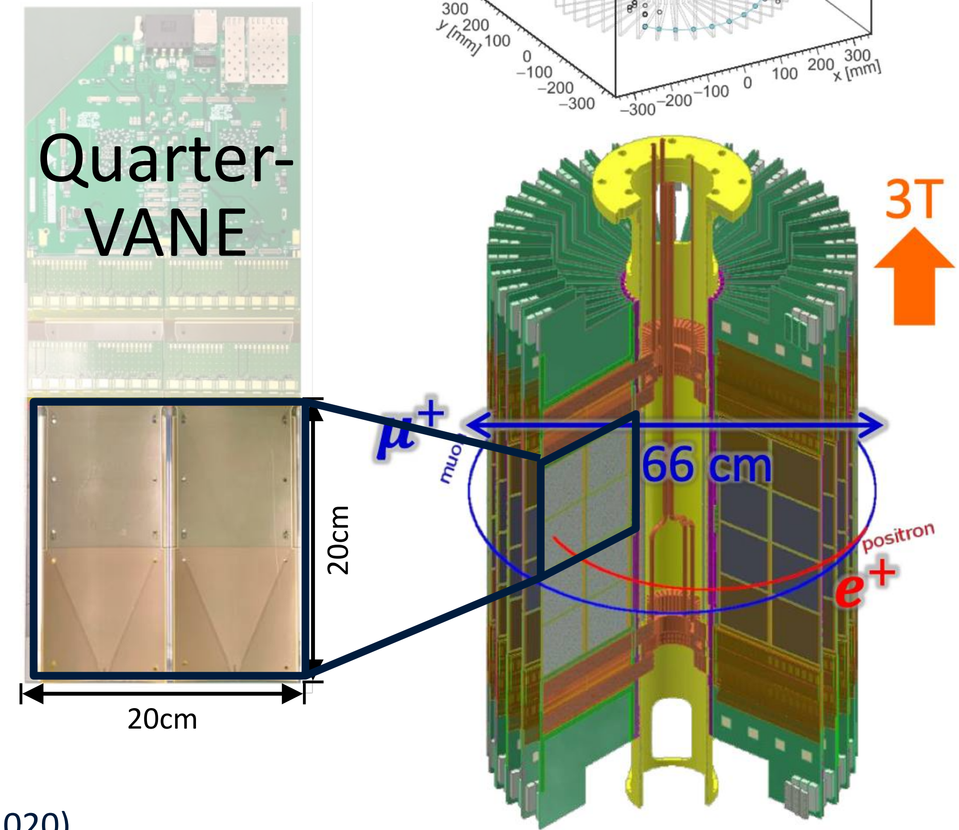


Positron Detection



In-field Si-strip Tracker

40 vanes
@ 4 x 4 x sensors / vane
@ 1024 strips / sensor
@ 5 cm x 190 µm / strip
@ 250 kreads / s (1 frame / 5 ns)



Spectrometer Specs

Expected max. #e⁺'s 6/ns, 30/frame
Max. hit rate: 150 kHz / mm²
p > 200 MeV/*c*
dp/p = 8×10^{-4}

Aoyagi *et al.*, DOI: 10.1088/1748-0221/15/04/P04027 (2020)

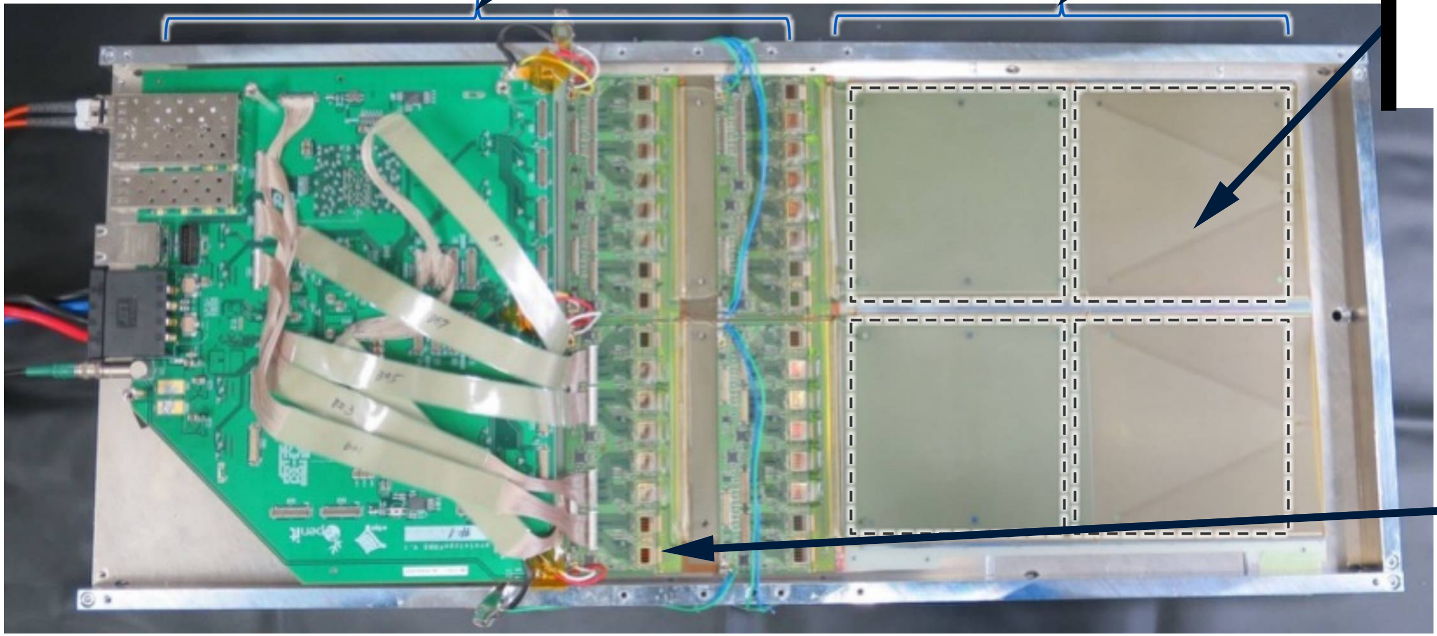
Detector Production

Rigid PCBs
Prototype made and being tested

Flexible PCBs
Mass production done

Silicon-Strip Sensor
Mass production ongoing

Readout ASIC
Mass production & QA done



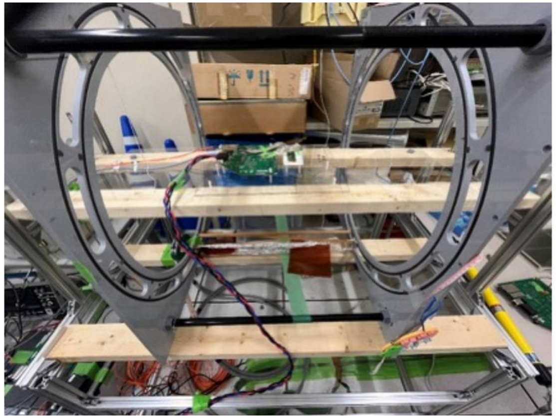
Detector Testing

Major components in mass production (partly completed)

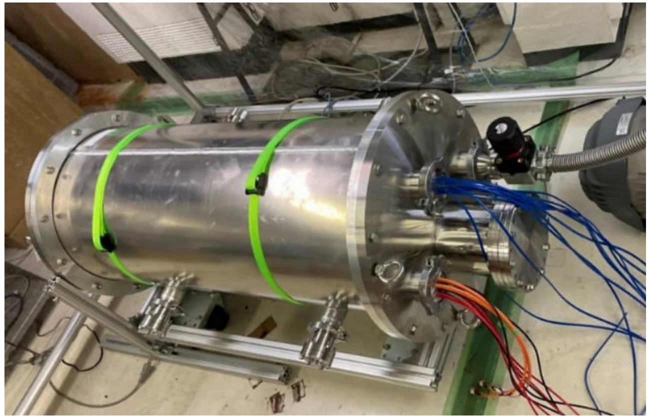
Prototype module ("quarter vane") assembled

Various operational tests are being performed using prototype:

Operation test
(static field)



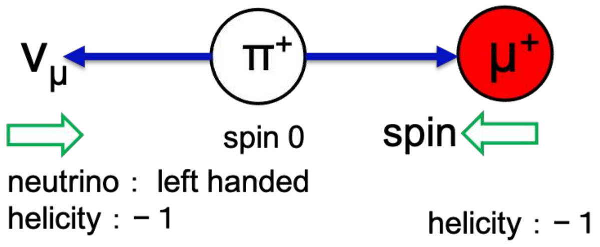
Operation test
(kicker field)



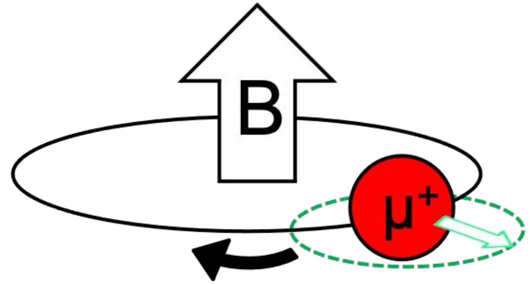
Cooling test

Elements of an MDM or EDM Expt

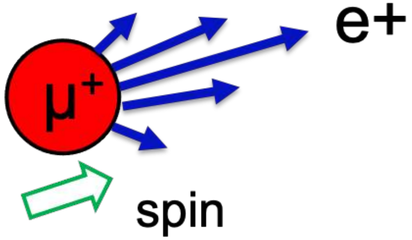
Polarized Muon Production



Storage & Spin Precession



Detection of Spin Orientation



Comparison of Specs

	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

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

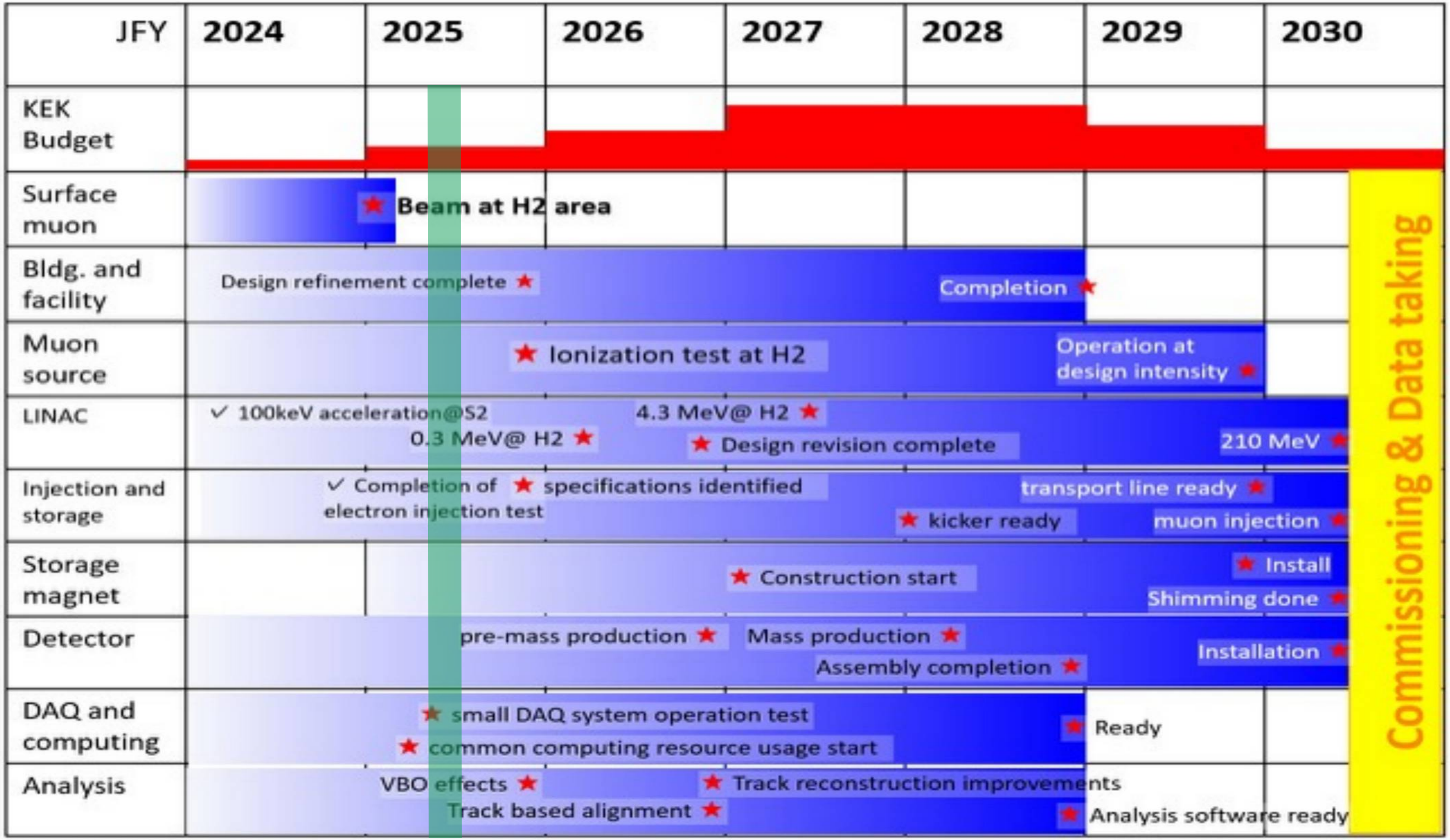
Systematics

TABLE II. Values and uncertainties of the $\mathcal{R}'_\mu$ 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.

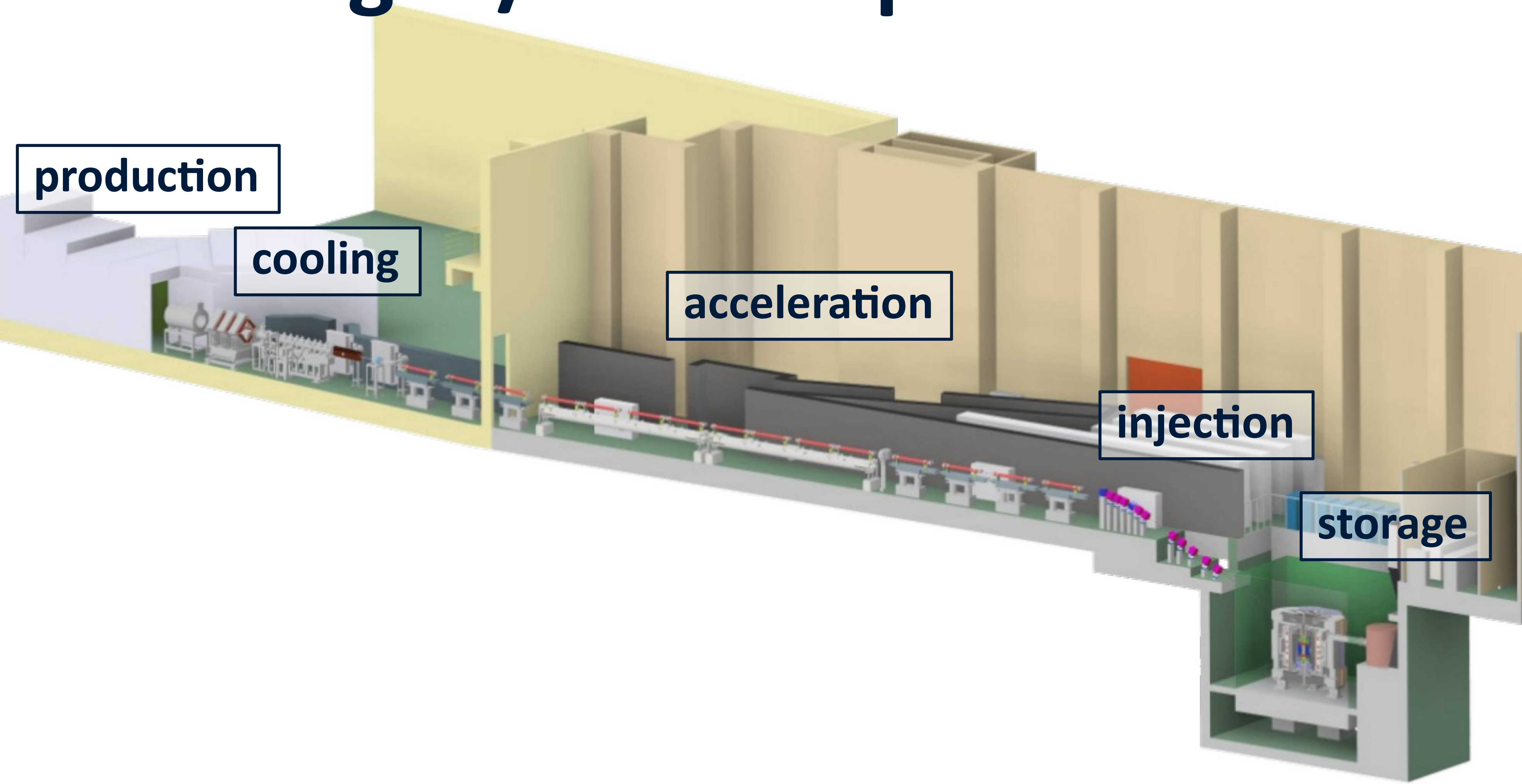
Quantity	Correction terms (ppb)	Uncertainty (ppb)		
ω_a^m (statistical)	⋯	434		
ω_a^m (systematic)	⋯	56	↦ <36	: Pileup, (gain, CBO)
C_e	~~489~~	53	↦ 10	: residual E-fields (no Quads)
C_p	~~180~~	13	↦ 13	: pitch correction
C_{ml}	~~−11~~	5	↦ 2	: differential decay & (muon losses)
C_{pa}	~~−158~~	75	↦ 0	: transverse muon distribution
$f_{\text{calib}} \langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$	⋯	56	↦ 49	: probe positioning & calibration
B_k	~~−27~~	37	↦ <10	: kicker transients
B_q	~~−17~~	92		
$\mu'_p(34.7°)/\mu_e$	⋯	10		
m_μ/m_e	⋯	22		
$g_e/2$	⋯	0		
Total systematic	⋯	157	↦ <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



Muon g-2 / EDM Experiment



Conclusion - I

Leptons excellent testing ground for flavour physics

Rich palette of observables

Ultra-precise predictions

Extremely sensitive measurements

Long standing anomaly in muon g-2

Experimental and theoretical uncertainty @ sub-ppm level **!!**

New experimental results from FNAL ↦ **127 ppb**

Experiments consistent ↦ but (somewhat) correlated

Steady progress in theory improvement

Tension in (hadronic) theory ↦ 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

Experiment getting ready for realization

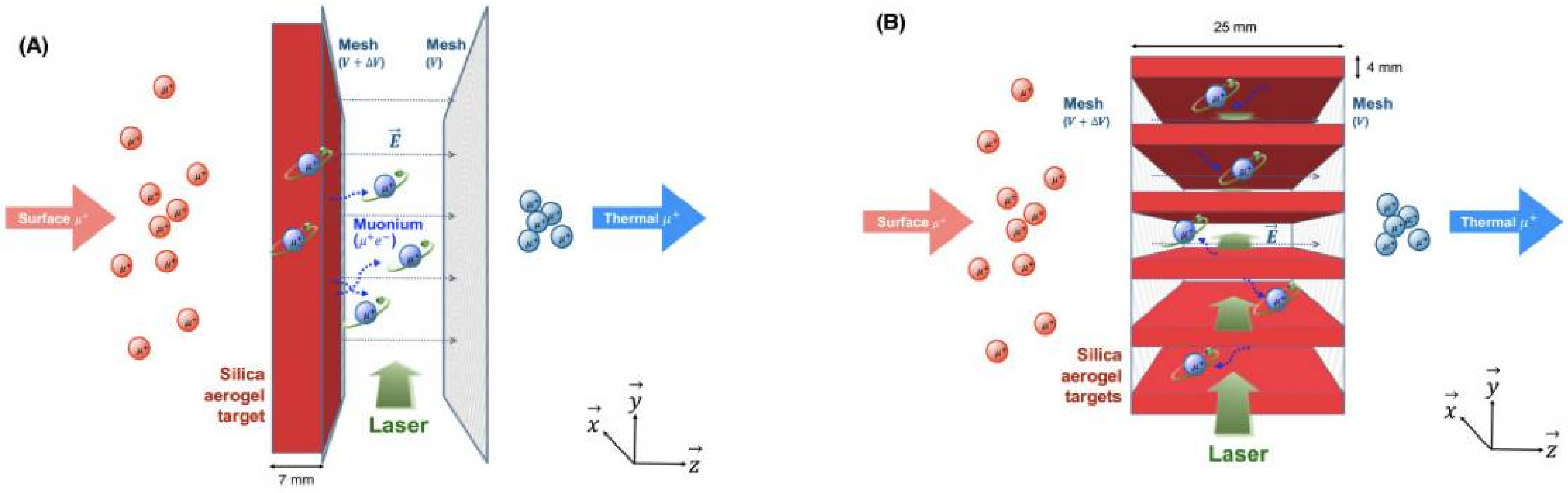
Expected data taking starting in 2030


Thank you for your attention
MAASTRICHT SCIENCE PROGRAMME

Comparison of Specs

	BNL-E821	Fermilab-E989	Our experiment	PSI
Muon momentum	3.09 GeV/c		300 MeV/c	125 MeV/c
Lorentz γ	29.3		3	1.57
Polarization	100%		50%	90%
Storage field	$B = 1.45$ T		$B = 3.0$ T	B=3.0 T, E=2MV/m
Focusing field	Electric quadrupole		Very weak magnetic	weak magnetic
Cyclotron period	149 ns		7.4 ns	3.8 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}	3.2×10^{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	$1\text{x}10^{-23}$ e·cm
(syst.)	0.9×10^{-19} $e \cdot$ cm	–	0.36×10^{-21} $e \cdot$ cm	?
	R = 280" (7112 mm)		R = 333 mm	R = 140 mm

Future source upgrade

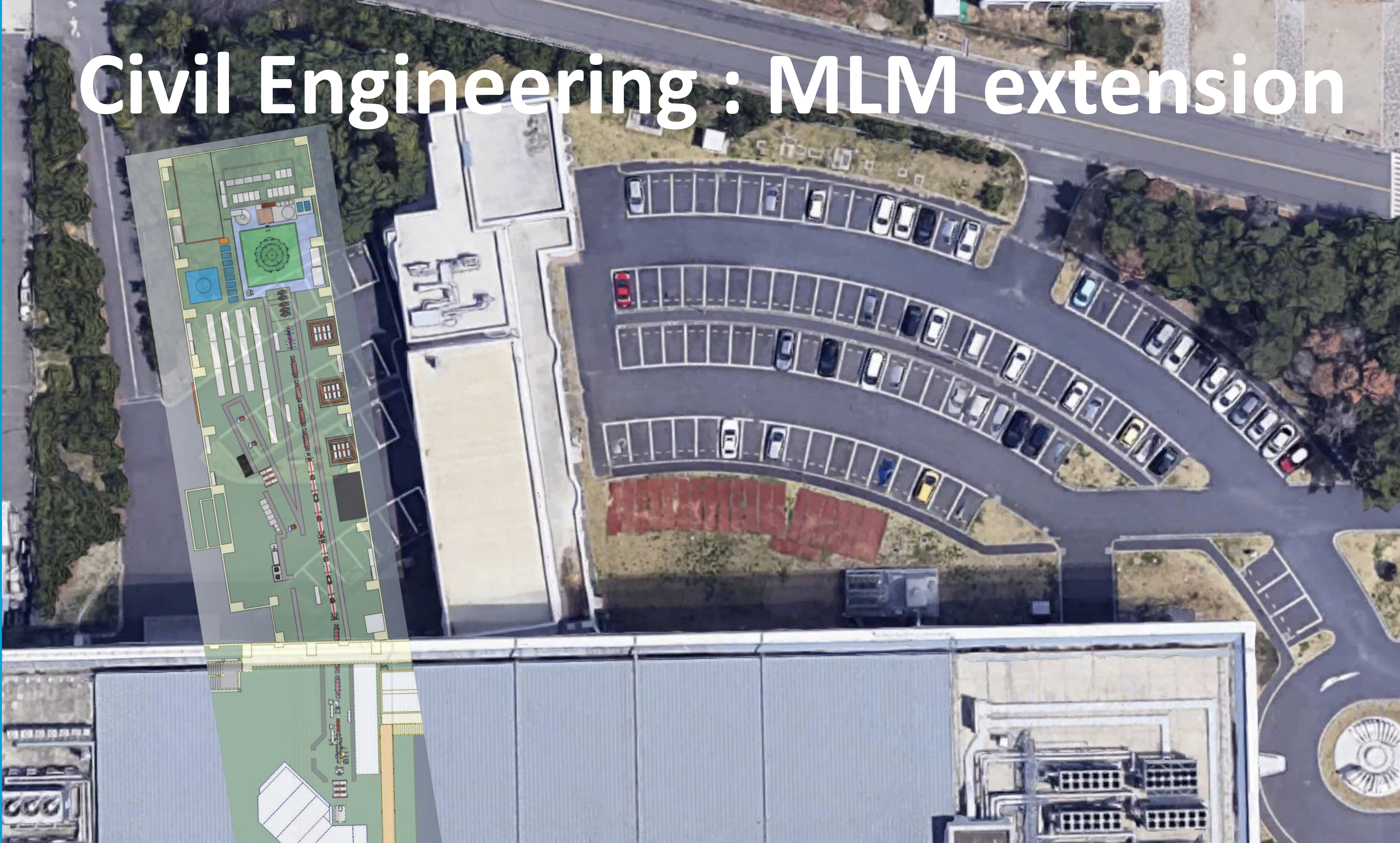


Intensity x 3.5

@ somewhat increased phase space

Zhang *et al.*, DOI: https://doi.org/10.1016/j.nima.2022.167443 (2022)

Civil Engineering : MLM extension



EDM sensitivity

Electron

Internal E in molecule: **HfF^+** → E_{eff} = 2300 GV/m

$|d_e| < 4.1 \times 10^{-30}$ *e*·cm (90% C.L.)

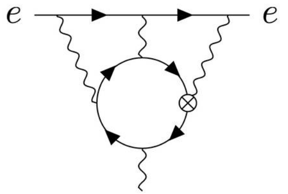
Muon

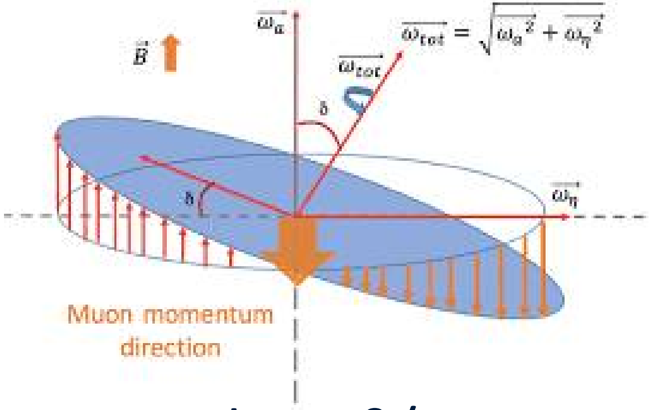
Relativistic E: **g-2** → E_{eff} = v x B = 0.5 GV/m

$|d_\mu| < 1.8 \times 10^{-19}$ *e*·cm (95% C.L.)

Indirect from ^{199}Hg and ThO

$|d_\mu|_{Hg} < 6 \times 10^{-20}$ *e*·cm, $|d_\mu|_{ThO} < 2 \times 10^{-20}$ *e*·cm





tilt ~ ηβ/2a

Aim: $|d_\mu| < 1.5 \times 10^{-21}$ *e*·cm (95% C.L.)

Roussy *et al.*, DOI: https://doi.org/10.48550/arXiv.2212.11841 (2022)
Bennett et al., DOI: 10.1103/PhysRevD.80.052008 (2009)
Ema, Gao, and Pospelov, arXiv:2108.05398 (2021)

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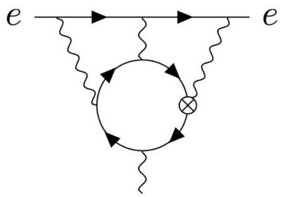

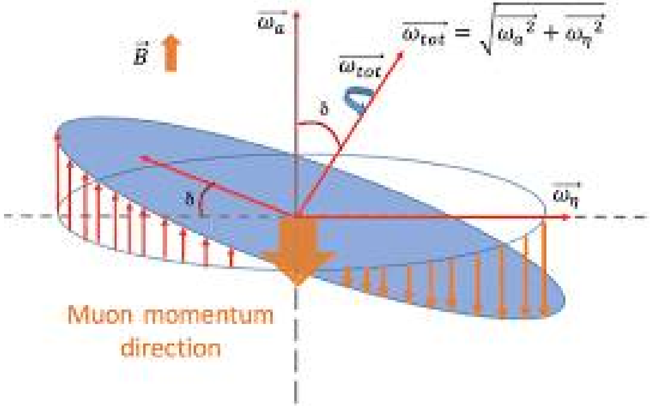

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