

Progress in Precision Muon Physics

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Tsung-Dao Lee Institute, Shanghai Jiao Tong University

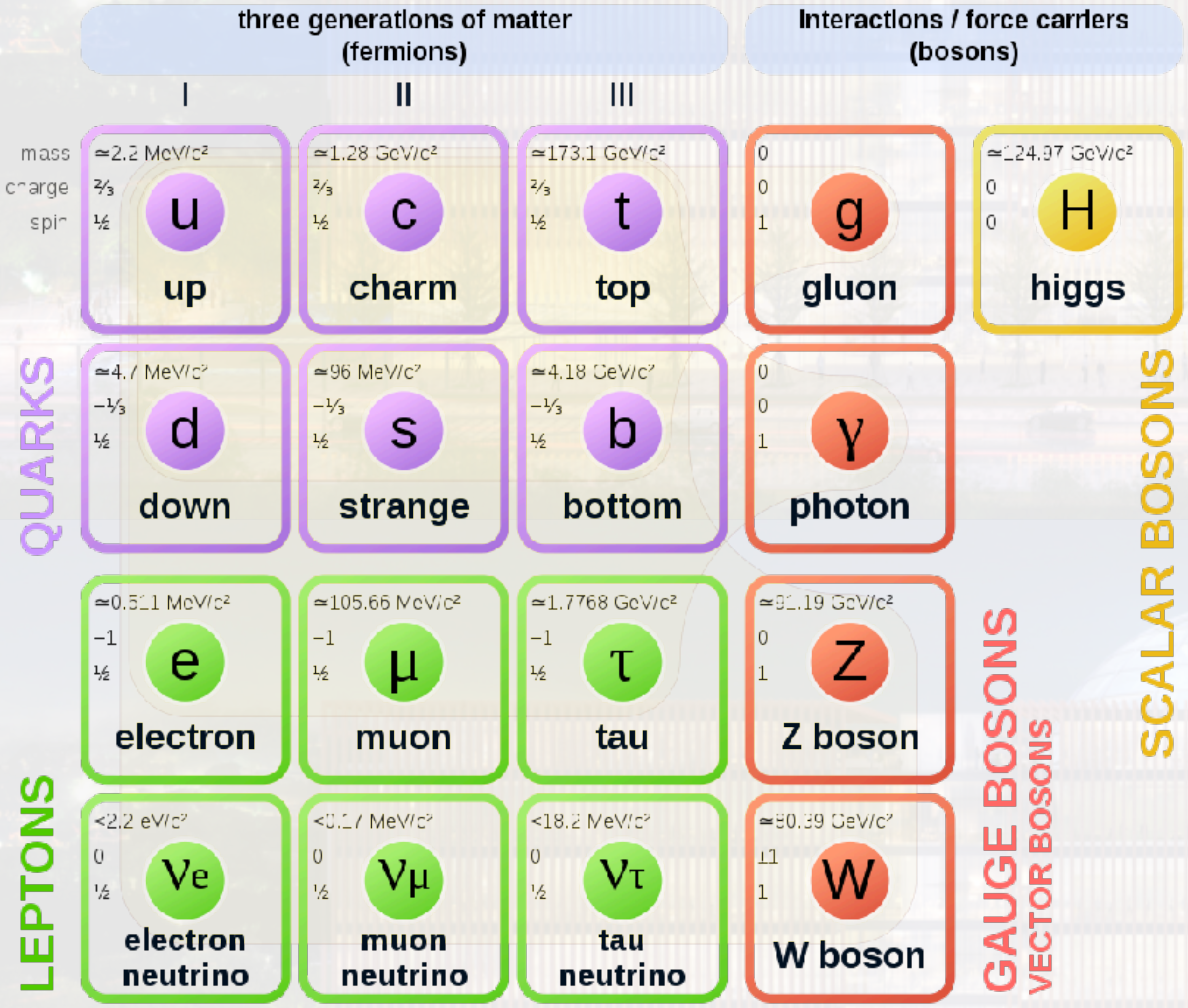
3rd workshop on "Physics at the high-intensity hadron accelerator in China"

7-8 Dec, 2019

Goal of this talk

- Muon as a probe for New Physics
- Overview of muon facilities and physics programs
    - The muon g-2 puzzle and experiments at Fermilab and J-PARC
    - The frozen-spin technique and muEDM at PSI
- Outlook

New Physics beyond the Standard Model



The SM has been a very successful theory

- However, it could not account for
  - Neutrino Oscillation
  - Baryon Asymmetry of the Universe (BAU)
  - Dark Matter & Dark Energy
- There exist several μ-related puzzles
  - Muon anomalous magnetic moment (g-2)
  - Proton radius (from μp lamb shift)
  - B-meson anomalies Br(B->Kμμ)/Br(B->Kee)
- Muons are sensitive probes of NP
  - Explore various observables!
  - Can be created copiously!

Lepton observables

- In the Standard Model:
  - Massless neutrinos
  - Conservation of lepton numbers and lepton flavors
  - Tiny leptonic EDMs (at 4-loop level, $d_e \sim 10^{-38}$ e cm)
  - Precise calculation of g-2 possible

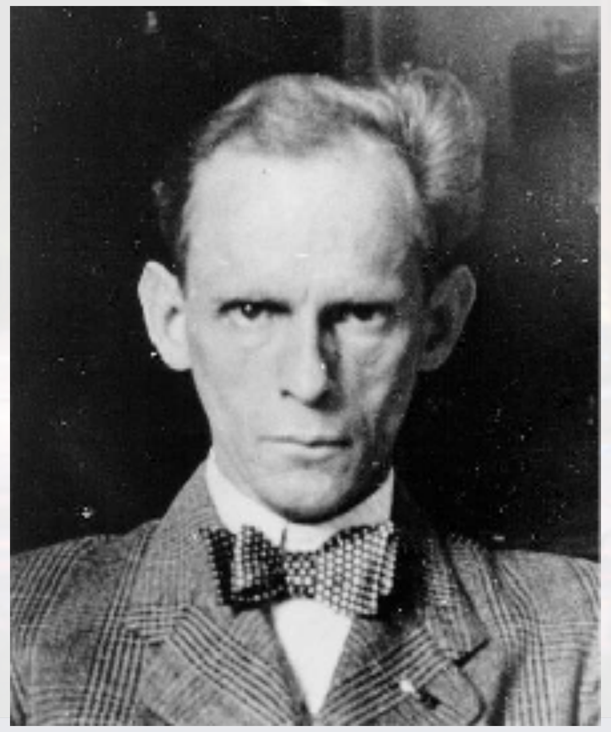
- SM + neutrino oscillation (minimal extension)
  - Total lepton number is conserved
  - How about lepton flavor? Is charged LFV possible? $BR(\mu \rightarrow e\gamma) \sim 10^{-54}$
  - How about CP? Is EDM large enough? Contributions from δ_{CP} at 2-loop level, $d_e \sim 10^{-35}$ e cm
  - Precise calculation of g-2 possible

Good news for experimentalists!

Observation of signals above = New Physics!

Muon history [86 years!]

- First observed in 1933 from Cosmic Ray: Paul Kunze, Z. Phys. 83, 1 (1933)



"A particle of uncertain nature"

University of Rostock, Germany

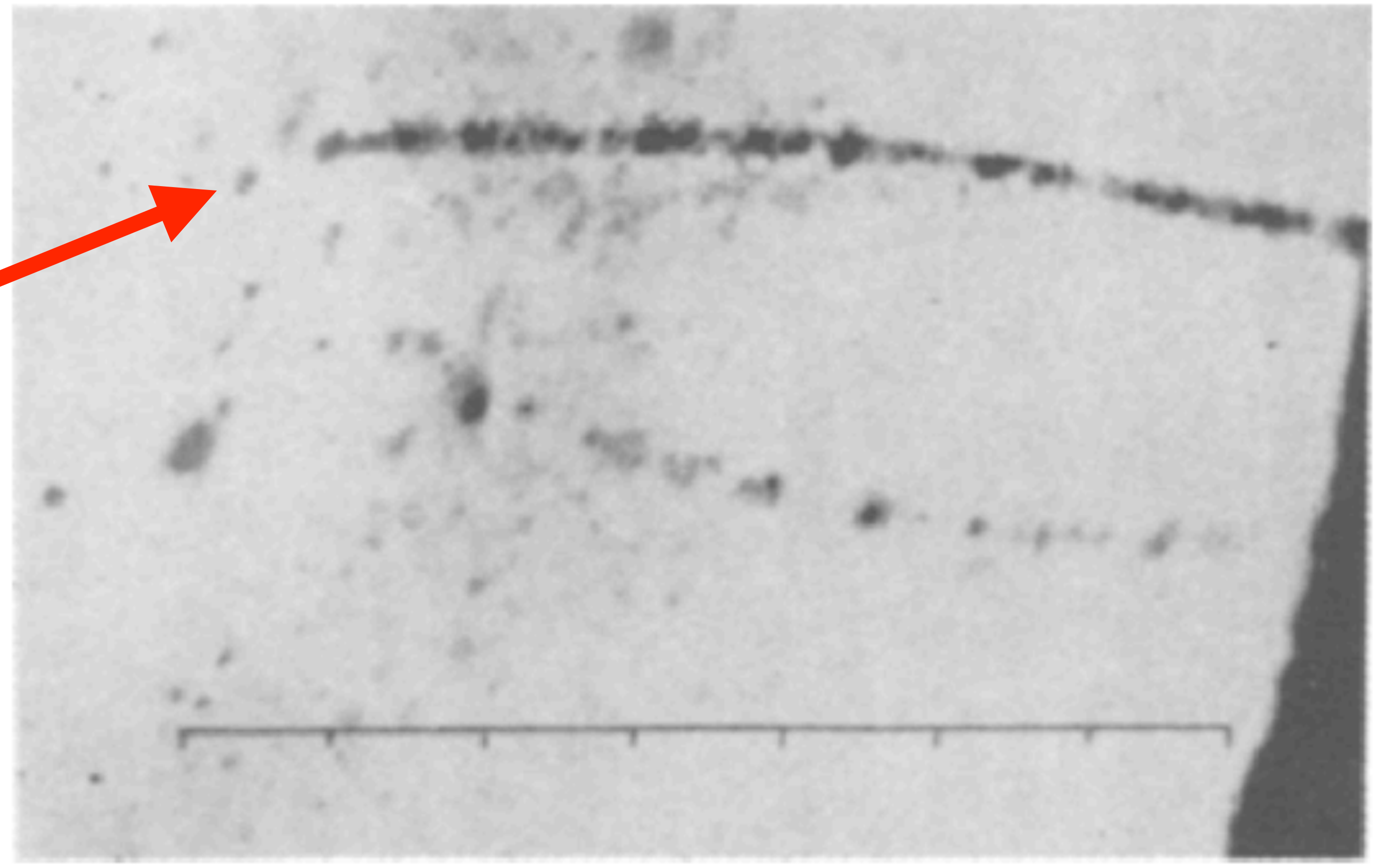


Fig. 5.
Doppelspur als Resultat einer vermutlichen Kernexplosion. 7-fache Vergrößerung. Untere Spur = Elektron von 37 000 000 V. Natur der oberen positiven Korpuskel nicht sicher bekannt.

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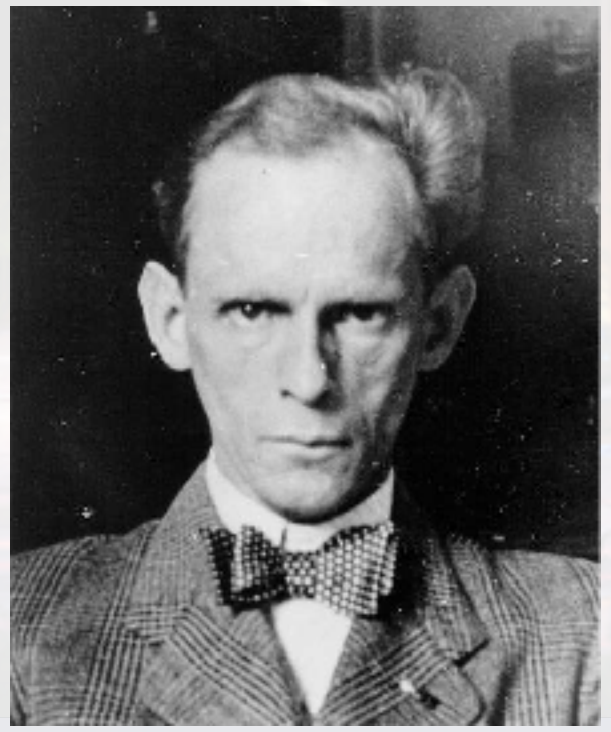

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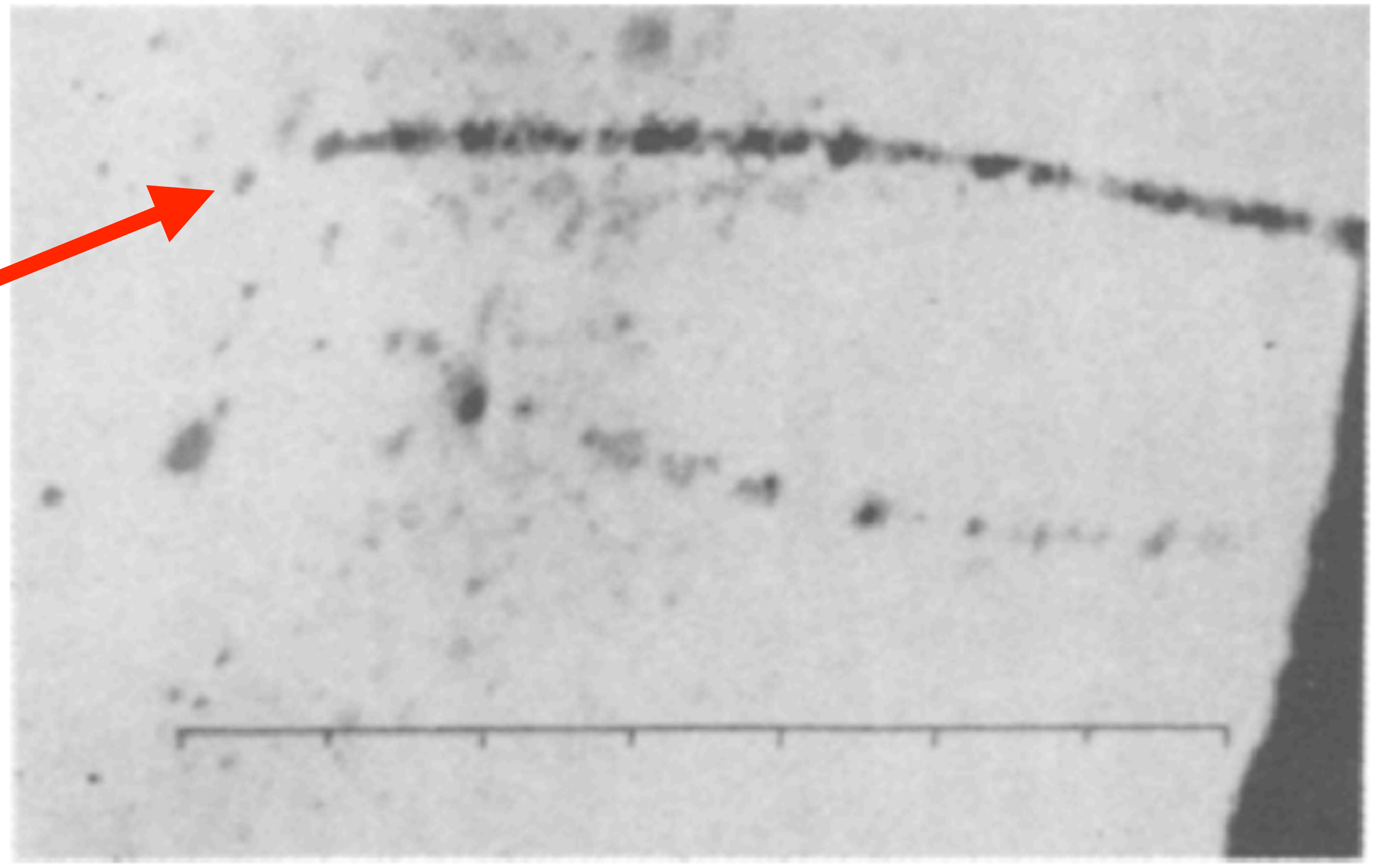

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At that time the full power level of the electricity station was still so low that always when Kunze operated his cloud chamber – about 500000 Joules in the time of a second, normally in some minutes distance – the whole electricity net of the town went down for about half of a second: The copper coil produced practically a short

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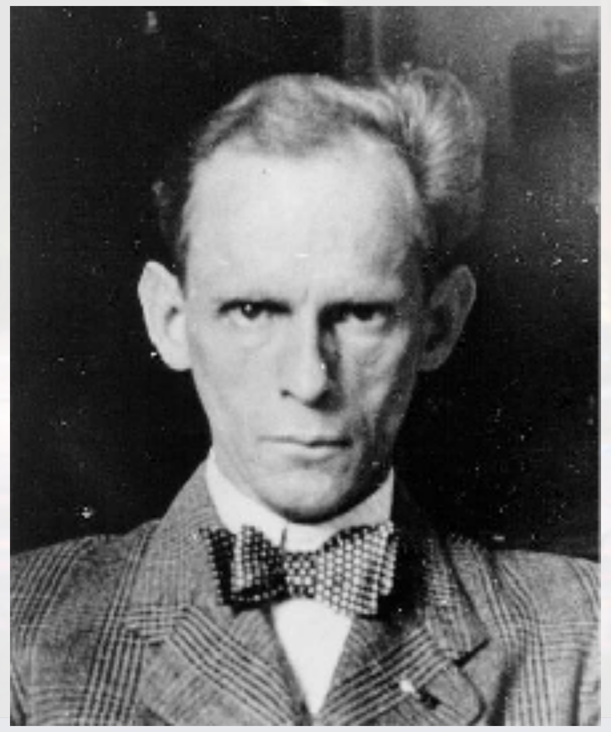

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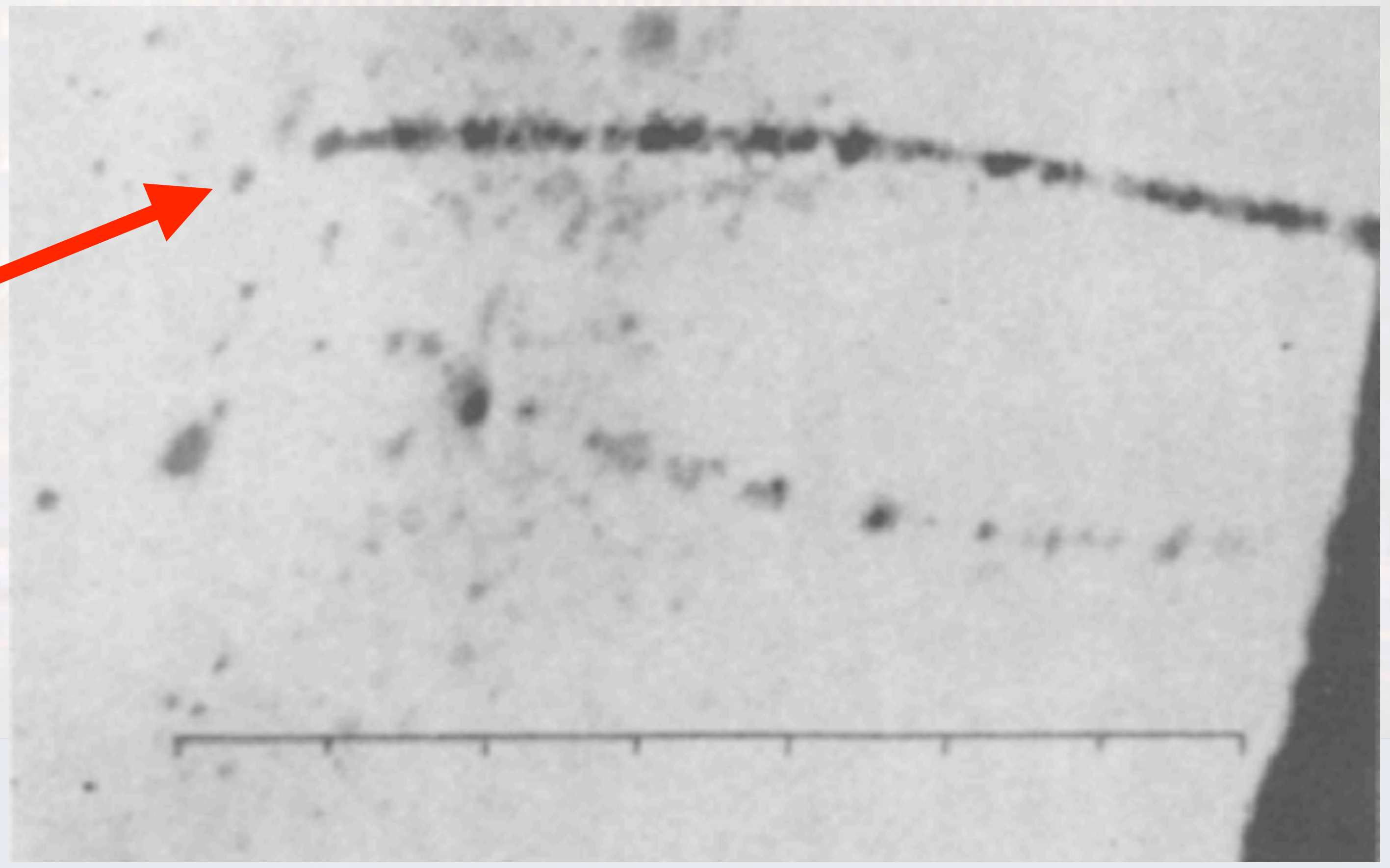

- First identified in 1936 by Seth Neddermeyer and Carl Anderson

MAY 15, 1937 PHYSICAL REVIEW VOLUME 51

Note on the Nature of Cosmic-Ray Particles

Seth H. Neddermeyer and Carl D. Anderson
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

Measurements[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory, we have taken about 6000 counter-tripped photo-

Muon properties

- Mass ~ 207 m_e
  - $(m_\mu/m_e)^2$ ~ 43,000 times more sensitive to new physics through quantum loops
- Lifetime ~ 2.2 μs at rest
  - Most precise particle lifetime ever measured (1 ppm by MuLan), G_F (0.5 ppm)
- Primary production: p + target $\rightarrow \pi^+ \rightarrow \mu^+ \nu_\mu$
  - Polarized naturally
- Primary decay: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
  - Purely weak decay
- Magnetic moment, g-factor
  - Precisely calculated and measured

$$\vec{\mu} = g \frac{e}{2m} \vec{S}$$

- Forms exotic atoms
  - Muonium (μ^+e^-), muonic hydrogen (μ^-p), muonic helium (μ^-He), …

Muon facilities around the world

Comparison of muon facilities

* Planned, # for Muon g-2

Region	Facility	Proton Energy [GeV]	Proton Intensity [MW]	μ^+/s	μ^-/s	Beam structure
Asia	J-PARC	3.0	1.0 (design)	2×10^8	1×10^7	Pulsed (25 Hz)
	CSNS*	1.6	0.1 (design)	$\sim 10^7$?	$\sim 10^7$?	Pulsed (2.5 Hz)
Europe	PSI	0.59	1.3	2×10^8	2×10^7	DC (CW)
	RAL-ISIS	0.8	0.16	6×10^5	7×10^4	Pulsed (50 Hz)
North America	FNAL#	8.89	0.7 (NOvA+g-2)	5×10^5	2×10^5	Pulsed (11.5 Hz)
	TRIUMF	0.52	0.075	$\sim 10^6$	$\sim 10^6$	DC (CW)

[Talk by K. Kirch on activities at PSI, J.Y. Tang on EMuS]

Probing New Physics with muons in 3 ways

Exotic events

$\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$, $\mu^-N \to e^-N$

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$\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$, $\mu^-N \to e^-N$

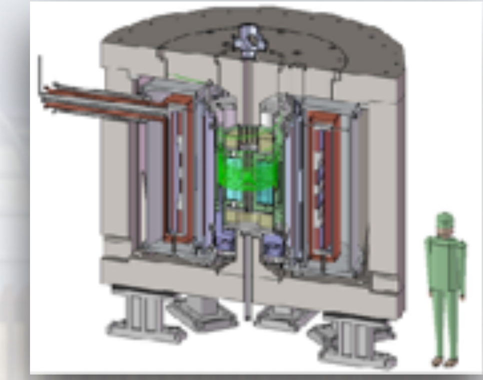
$\mu^+ \to e^+\gamma$	$BR < 4.2 \times 10^{-13}$	10^{-14}(MEG)
$\mu^+ \to e^+e^+e^-$	$BR < 1.0 \times 10^{-12}$	10^{-16}(Mu3e)
$\mu^- N \to e^- N$	$R_{\mu e} < 7.0 \times 10^{-13}$	10^{-17}(Mu2e, COMET)

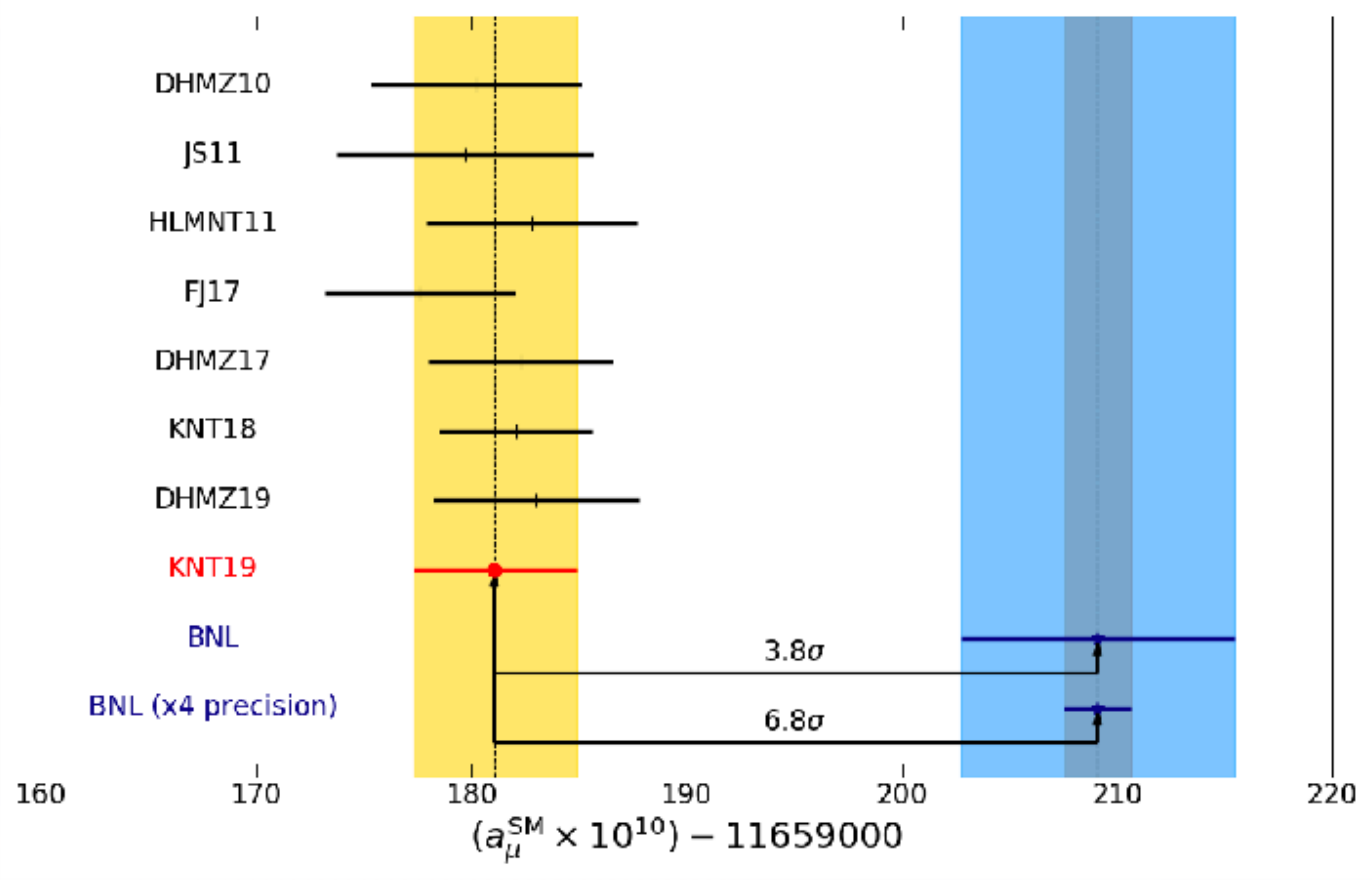
Probing New Physics with muons in 3 ways

Exotic events

$\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$, $\mu^-N \to e^-N$

Precise measurement





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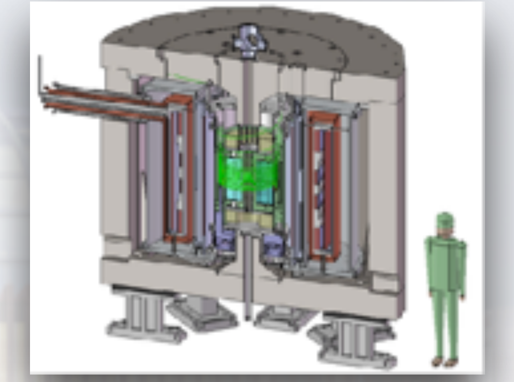
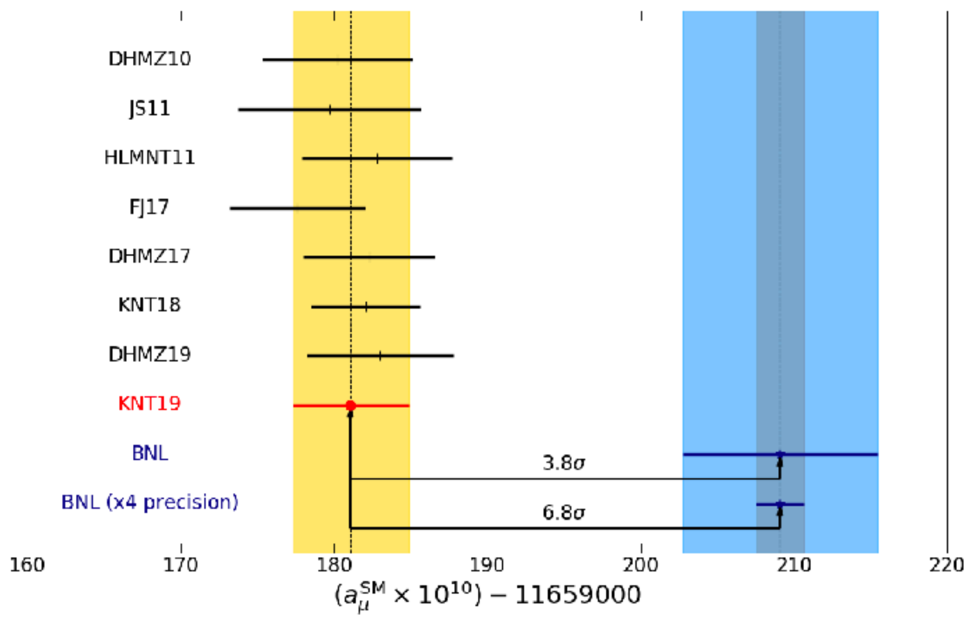
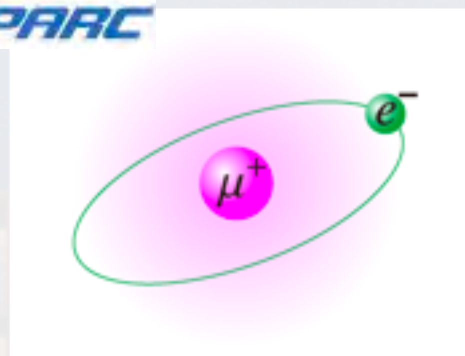




Precise measurement on exotic atoms



M 1S-2S (RAL, 1999): 2 455 528 941.0(9.8) MHz

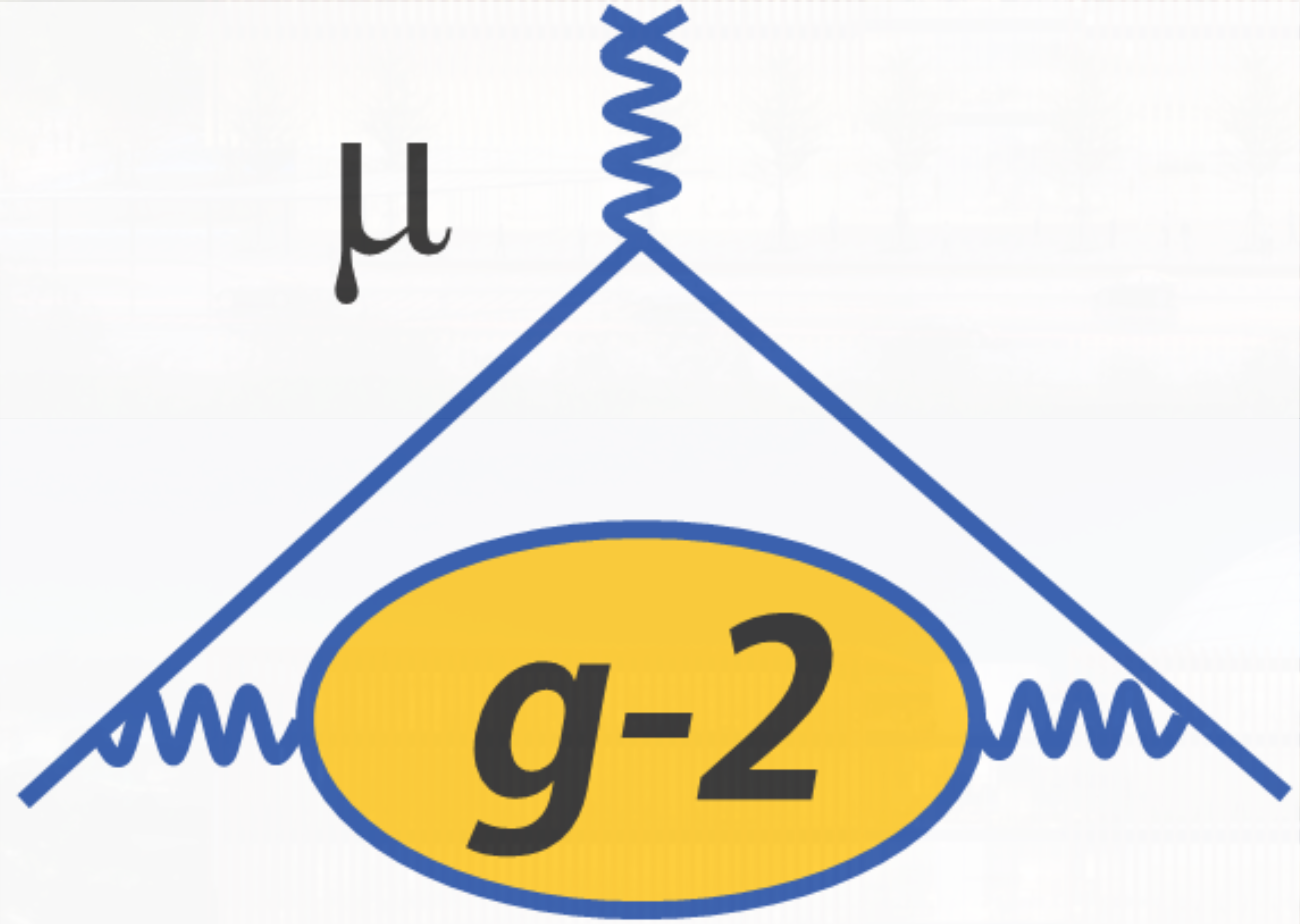
Target : 10 kHz (1 ppt)

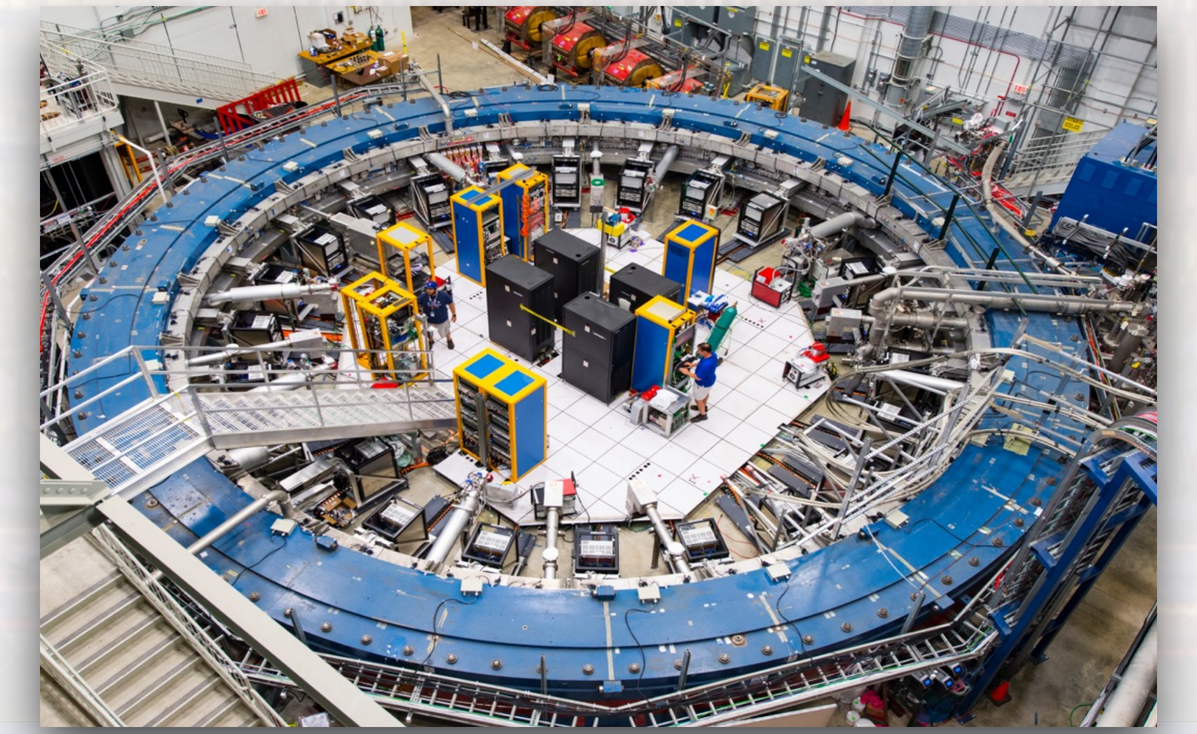
Overview of muon physics programs (non-exhaustive list)

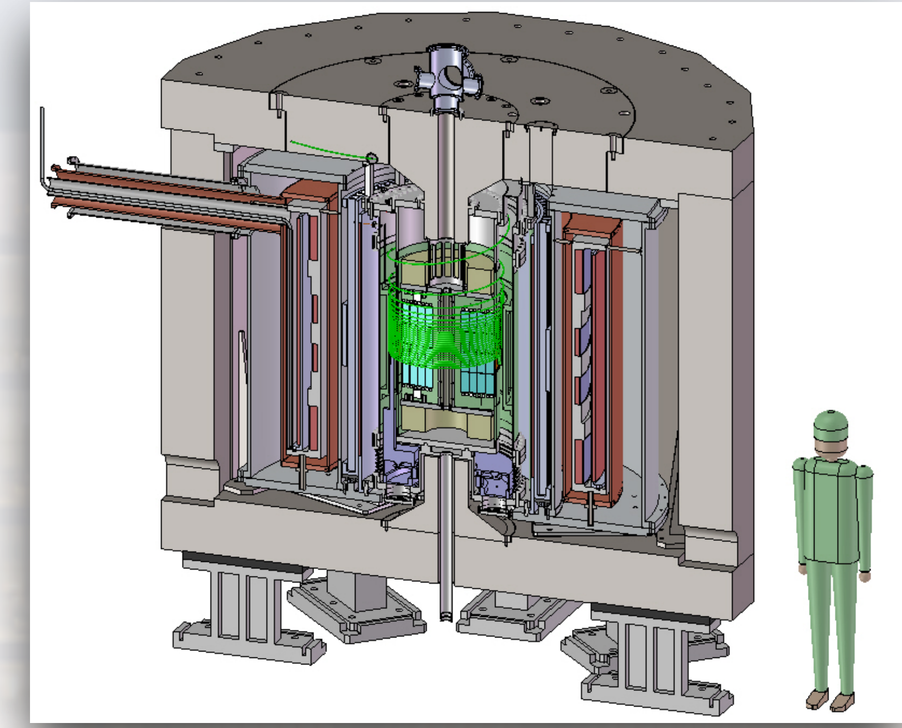
Region	Facility	Collaboration	Physics	Target/Sensivitiy
Asia	J-PARC	Muon g-2/EDM	Lepton moments	$\delta a_\mu \sim$ 450 ppb, $d_\mu \sim 10^{-21}$ e cm [this talk]
	J-PARC	COMET	cLFV	$R_{\mu e} \sim 10^{-18}$ [Talk by C. Wu, Y. Kuno]
	J-PARC	Mu-Mubar	cLFV	Feasibility study [KEK muon workshop 2019]
	J-PARC	MuSEUM	M 1S-HFS, BS-QED	$\delta\nu \sim 10^{-9}$
	J-PARC	Mu 1S-2S	M 1S-2S, BS-QED	$\delta\nu \sim 4 \times 10^{-12}$
	CSNS	Mu-Mubar	cLFV	[Talk by S. Zhou, Y. Bao]
Europe	PSI	muEDM	Lepton moments	5×10^{-23} e cm [this talk]
	PSI	MEG, MEG-II	cLFV	$Br(\mu \to e\gamma) < 6 \times 10^{-14}$ [Talk by S. Ritt]
	PSI	Mu3e	cLFV	$Br(\mu \to eee) < 10^{-16}$ [Talk by C. Wu]
	PSI	Mu-MASS	M 1S-2S, BS-QED	$\delta\nu \sim 4 \times 10^{-12}$
	PSI	CREMA	1S-HFS of μp, TPE	$\delta\nu \sim 10^{-6}$
North America	FNAL	Muon g-2 (E989)	Lepton moments	$\delta a_\mu \sim$ 140 ppb, $d_\mu \sim 10^{-21}$ e cm [this talk]
	FNAL	Mu2e	cLFV	$R_{\mu e} \sim 10^{-18}$ [Talk by Y. Wang]

[Talk by L.W. Chen on Mu2e with CiADS]

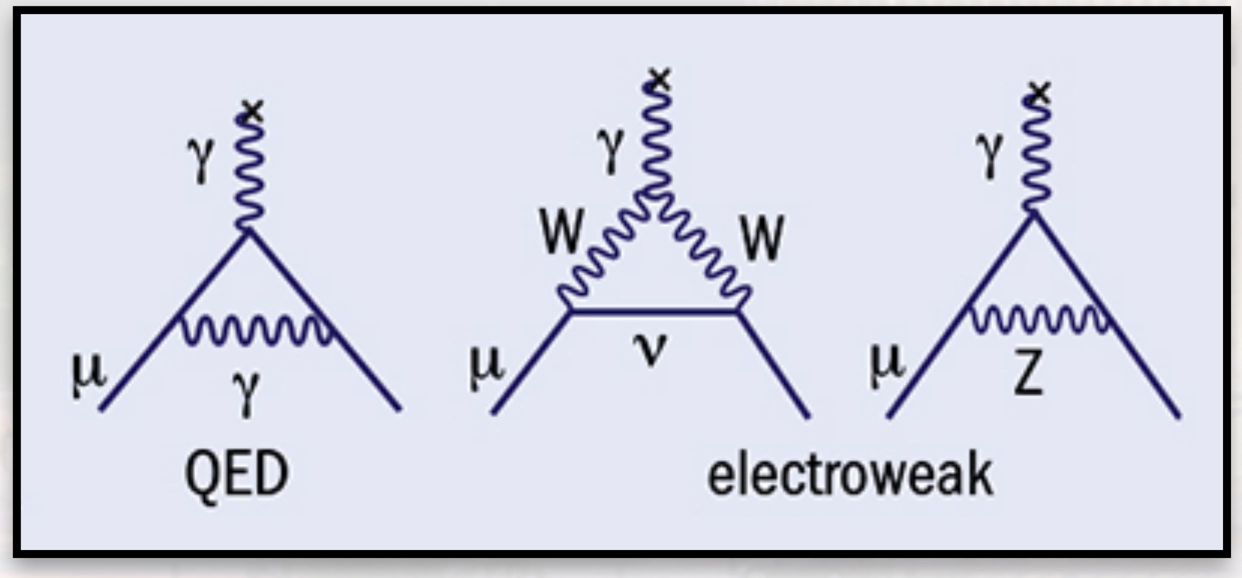
Let’s get back to muon g-2

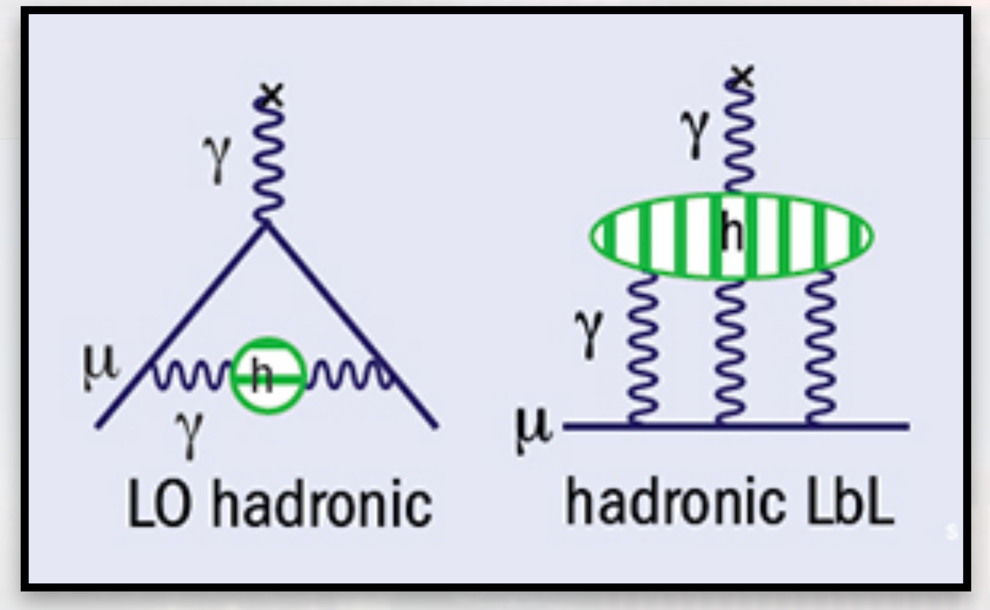






The muon g-2 puzzle

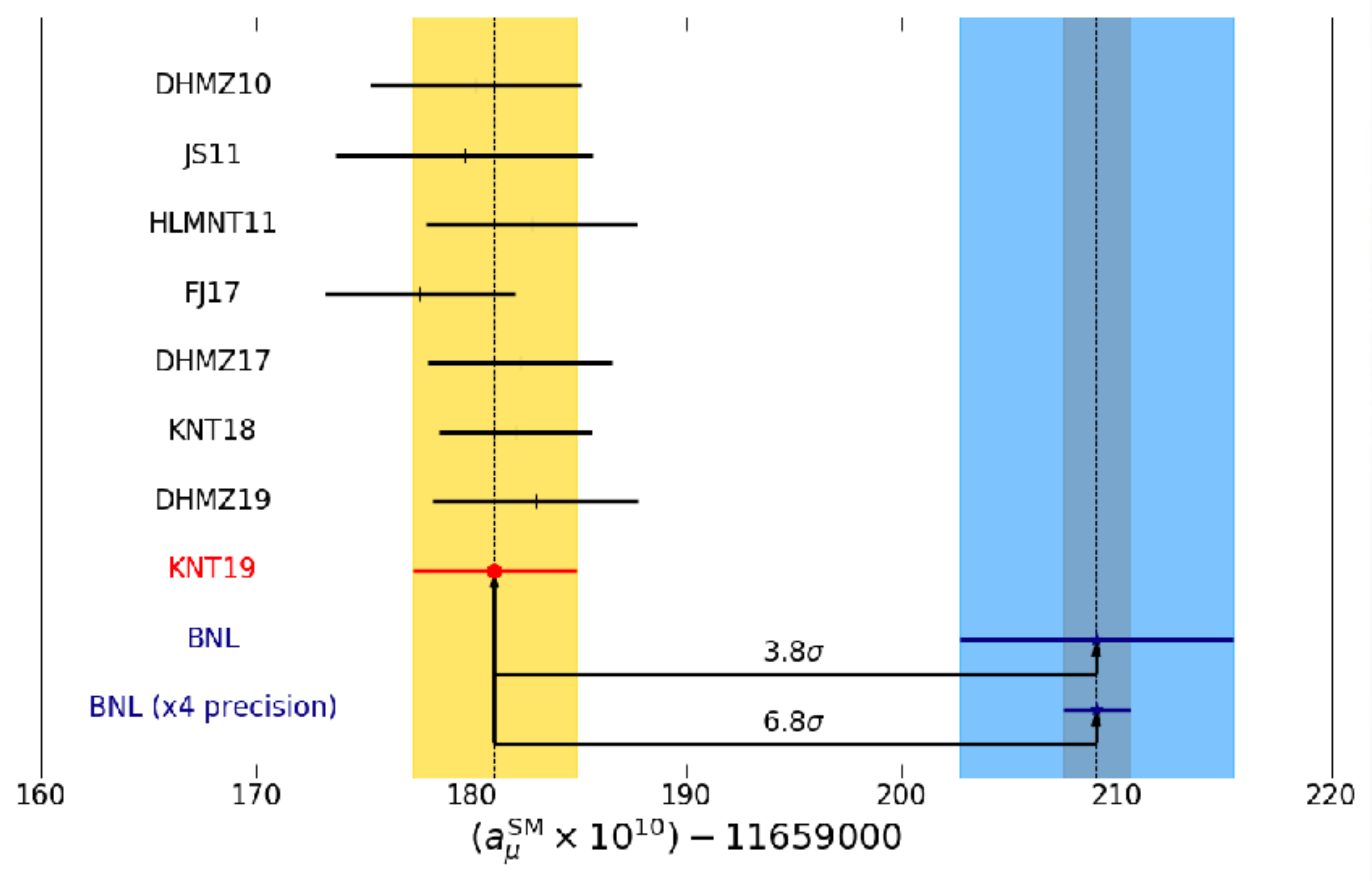




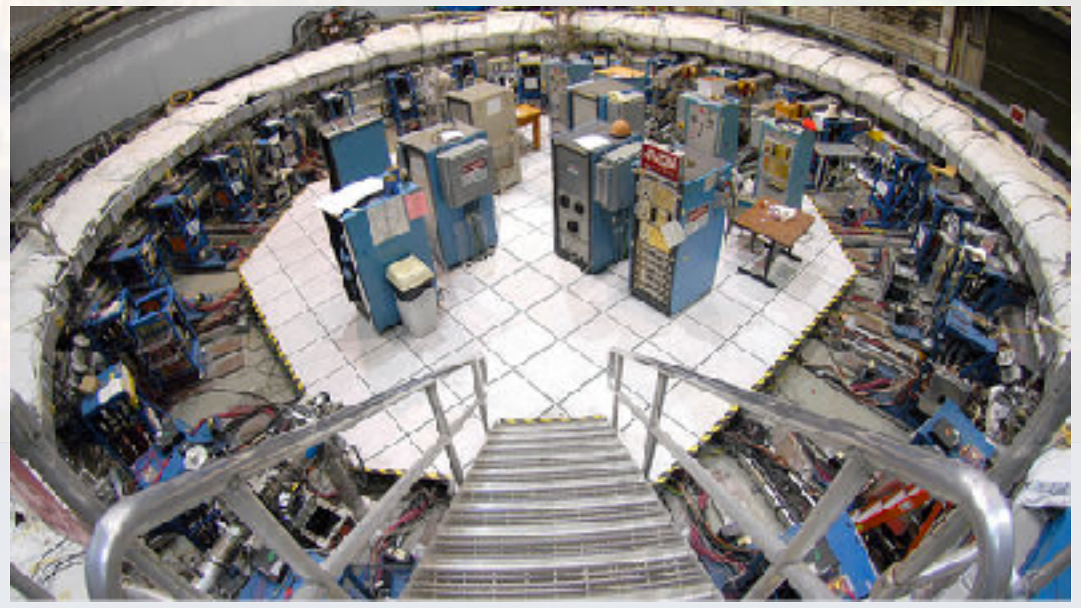
300 ppb

predictions

experiments



A. Keshavarzi, *et al.*, Phys. Rev. D 97, 114025 (2018)
A. Keshavarzi, *et al.*, arXiv:1911.00367

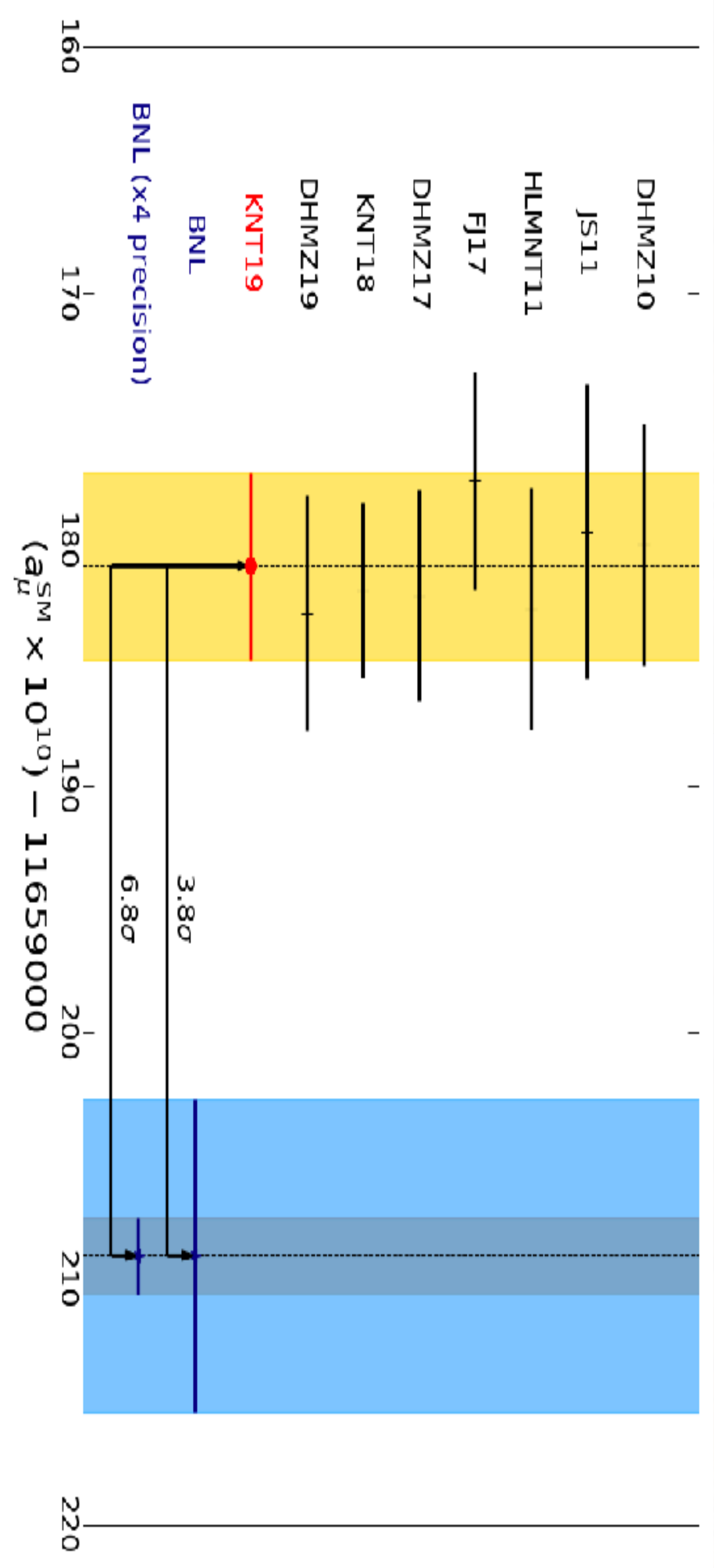


G.W. Bennett *et al.*, PRD 73, 072003 (2006)

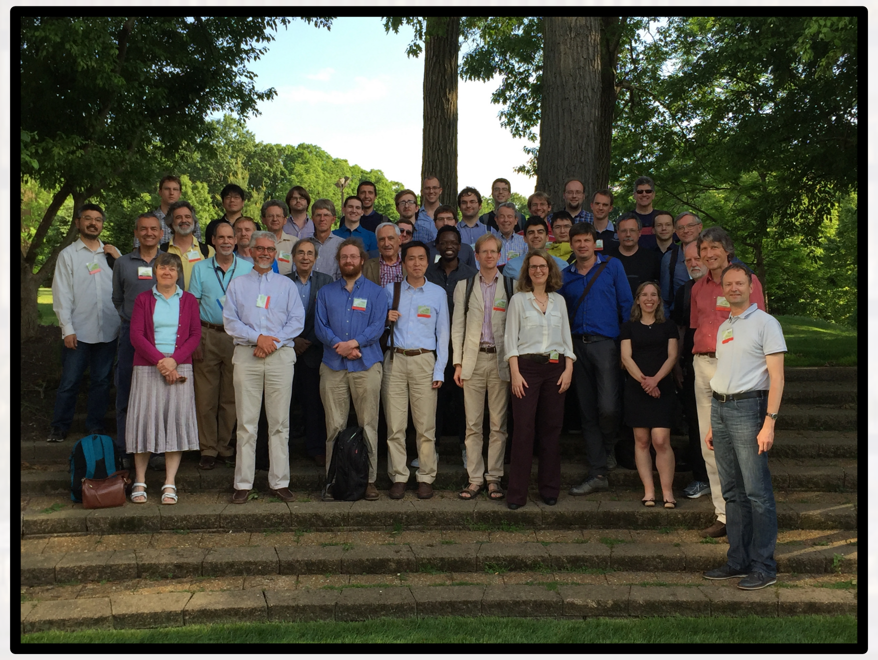
540 ppb

Discrepancy persisting for ~ 20 years !!!

Timeline for muon g-2 community



2017



1st muon g-2 theory initiative
(held at close to Fermilab)

2018

2019

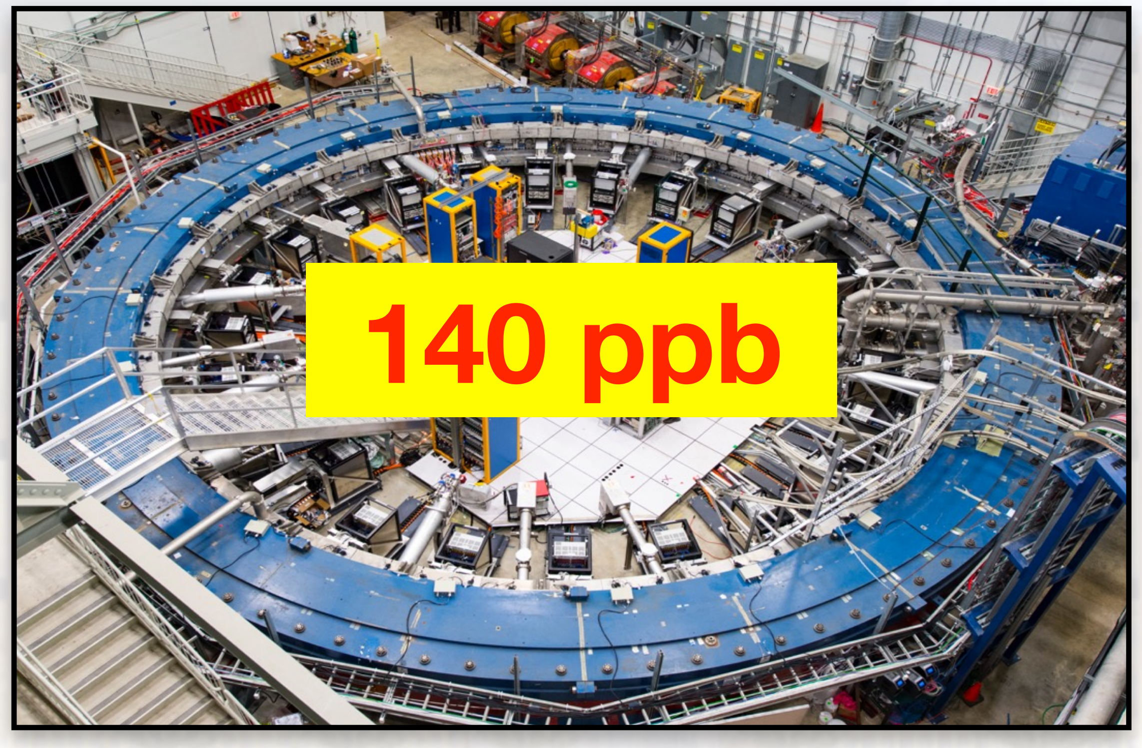
INT Workshop
Hadronic contribution to (g-2)
Sep 9-13, 2019
UW, Seattle

2020

White Paper g-2 theory

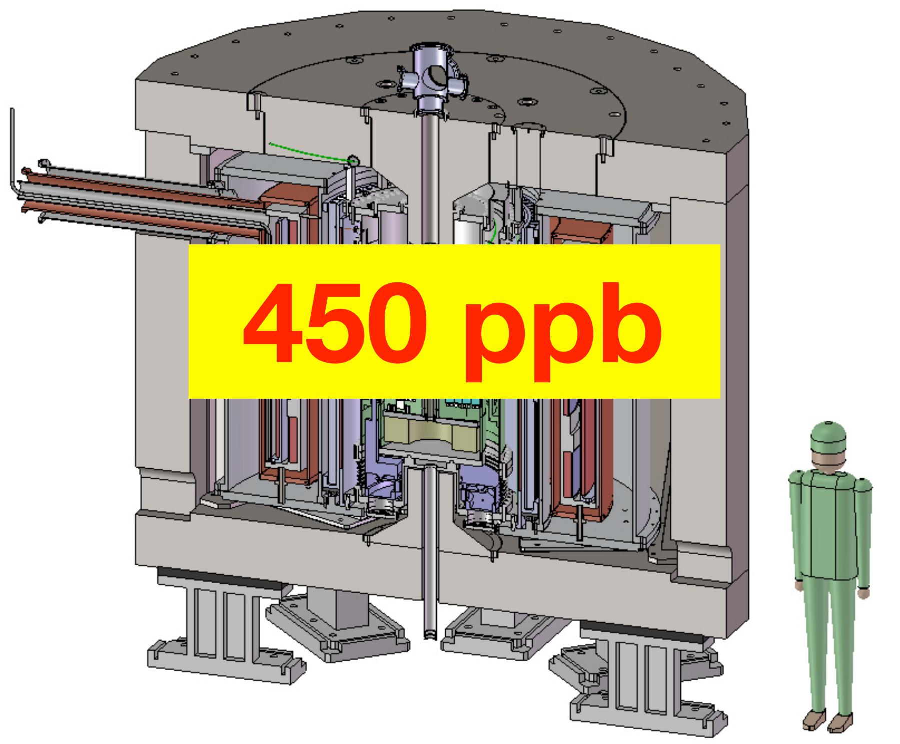
4th muon g-2 theory initiative
KEK, Tsukuba

2018 ~ 2021++

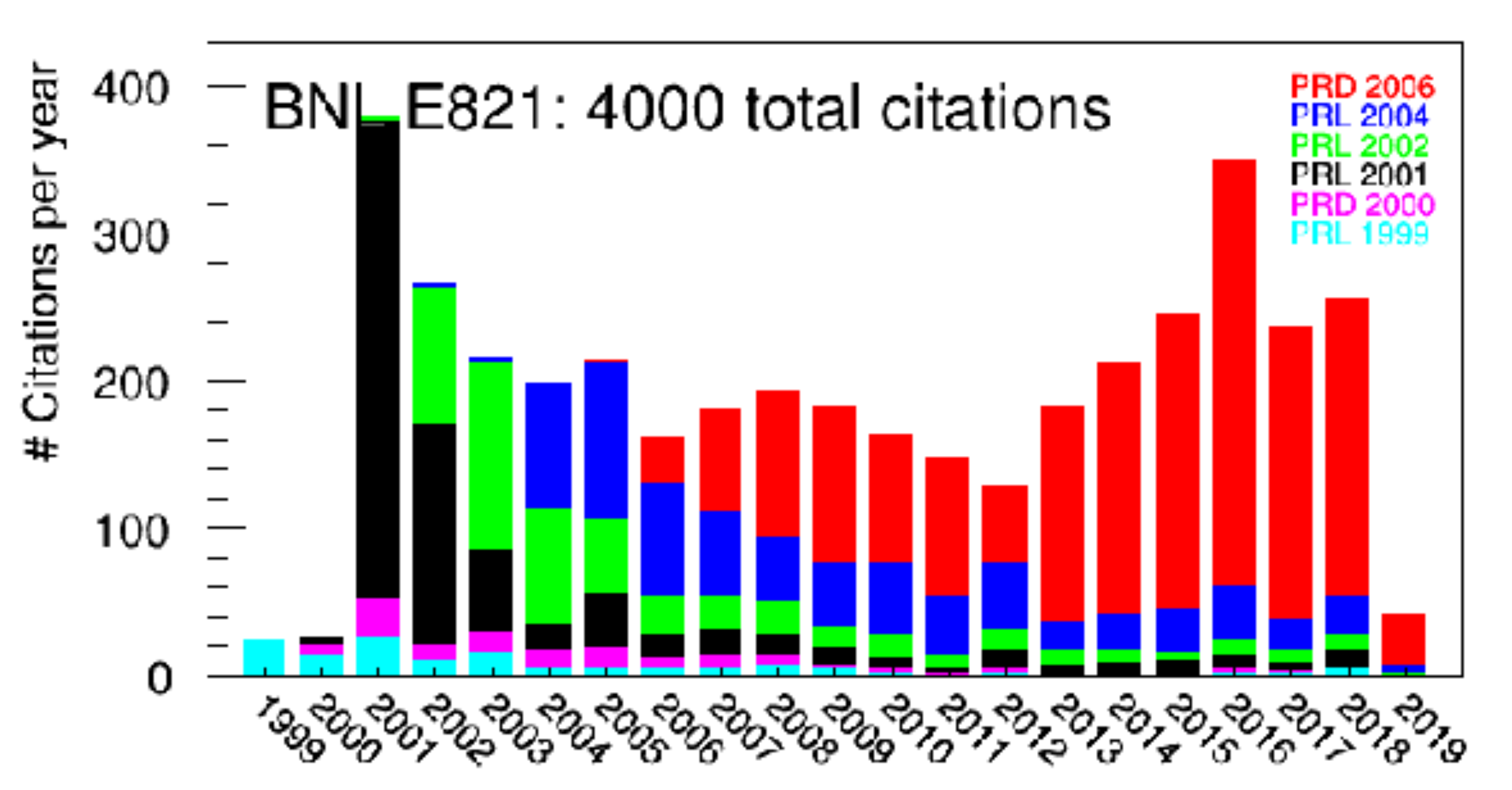


Fermilab E989

2024 ~ 2026



J-PARC E34



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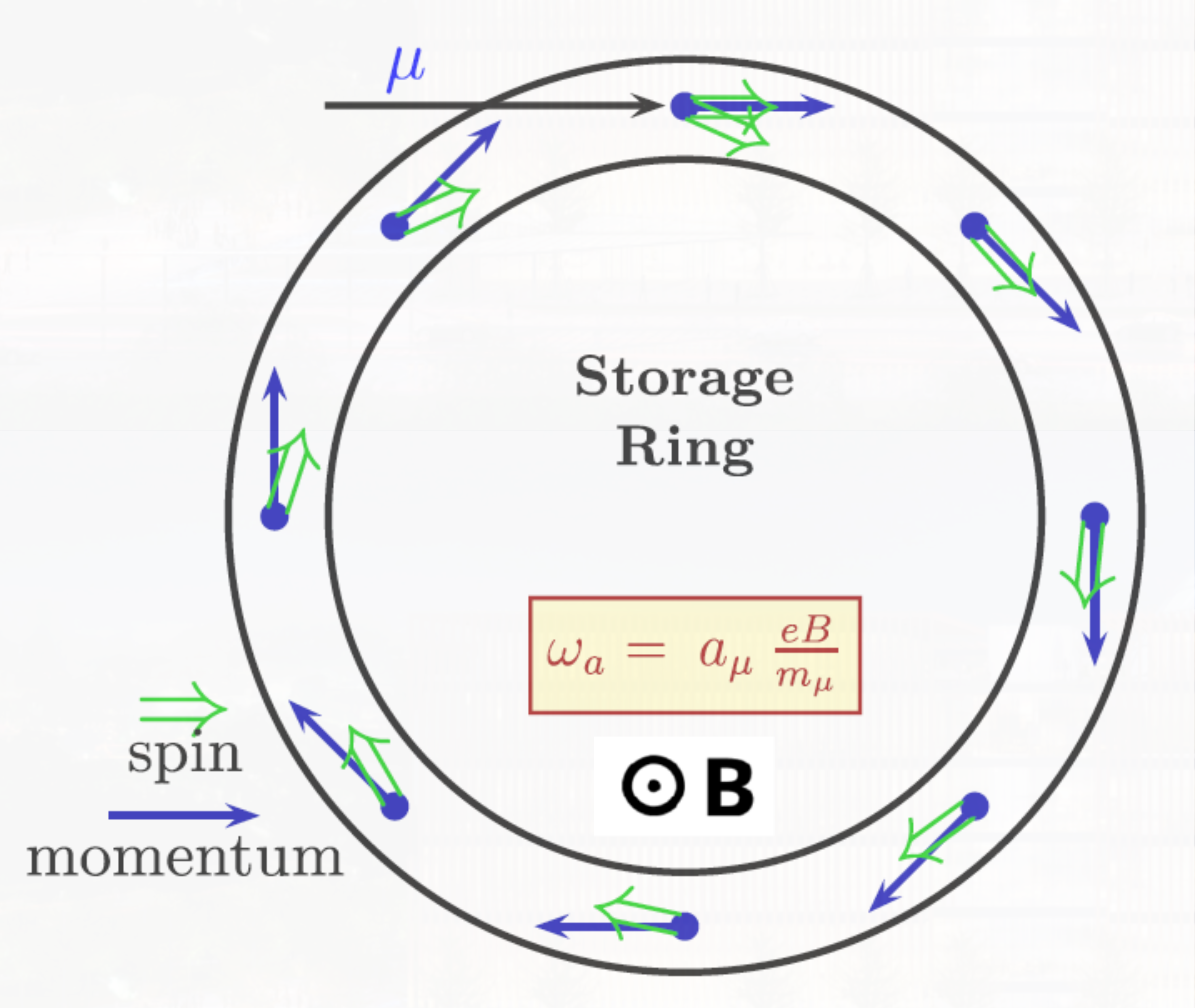
Principle of muon g-2 experiment



Larmor | Thomas | Cyclotron

$$\omega_s = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$

$$\omega_c = \frac{eB}{\gamma m}$$

$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$

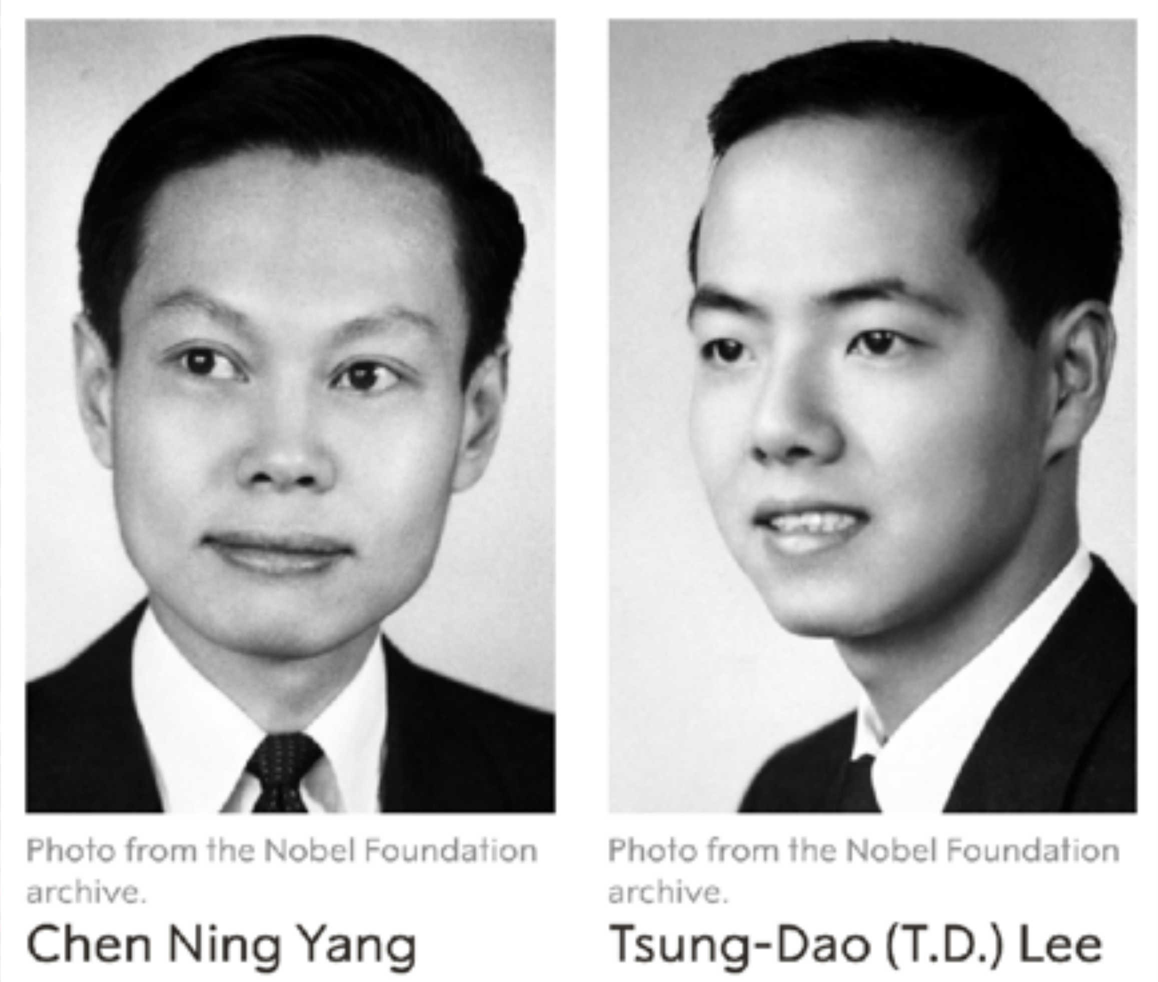
$$\omega_a = a_\mu \frac{eB}{m}$$

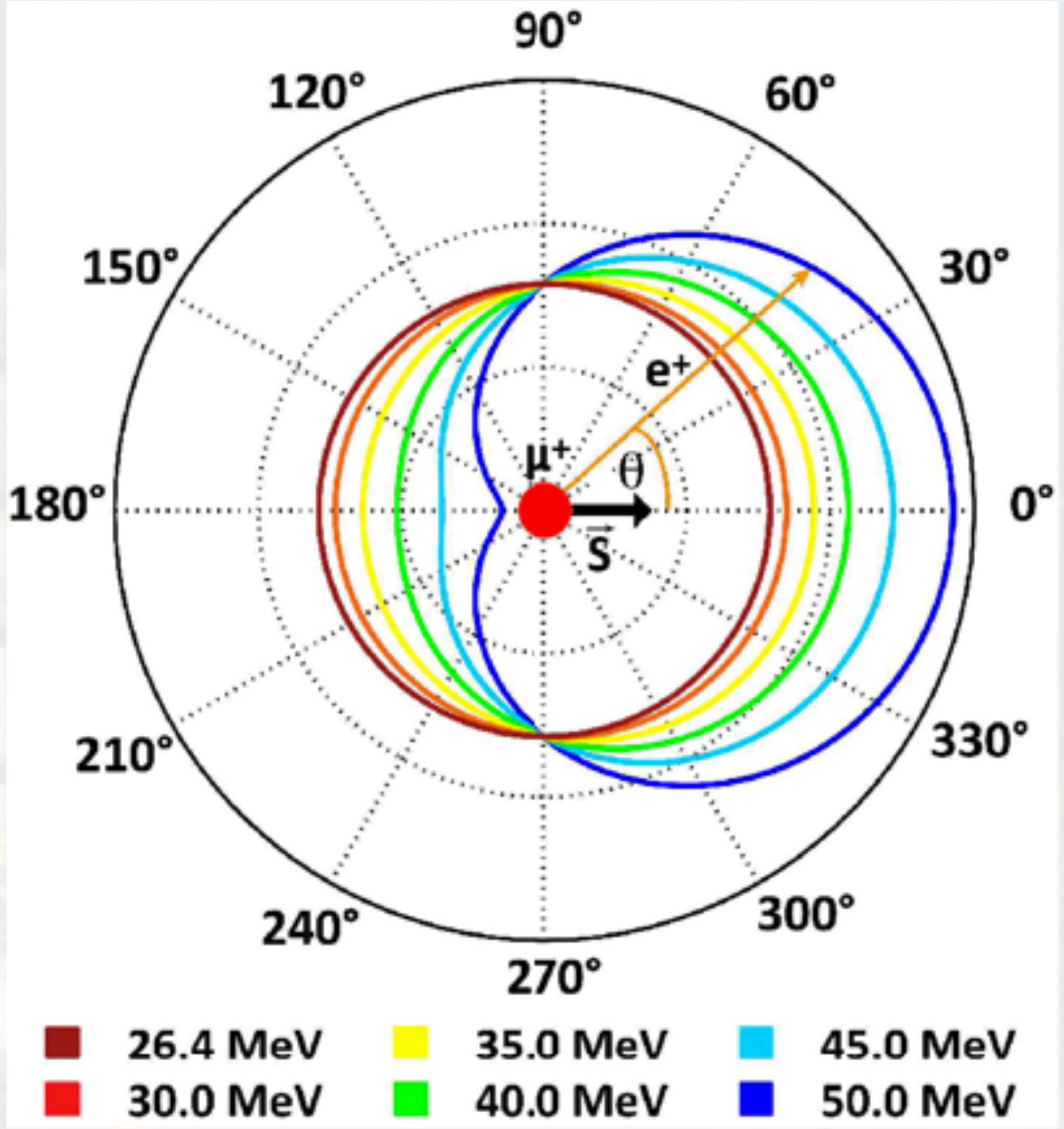
measure difference in frequency precisely

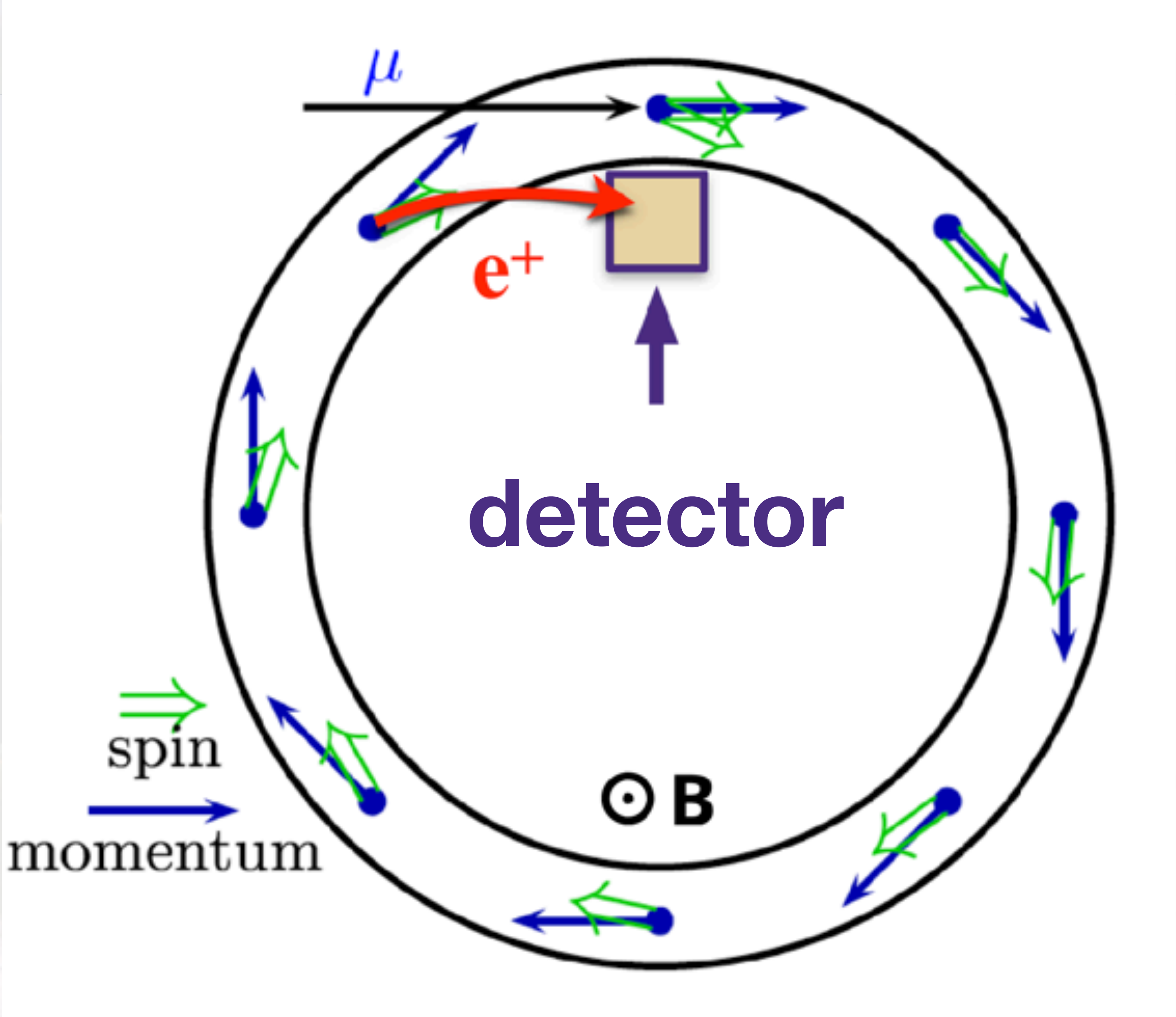
homogenous field and precise field measurement

Principle of muon g-2 experiment

$$\omega_a = a_\mu \frac{eB}{m}$$

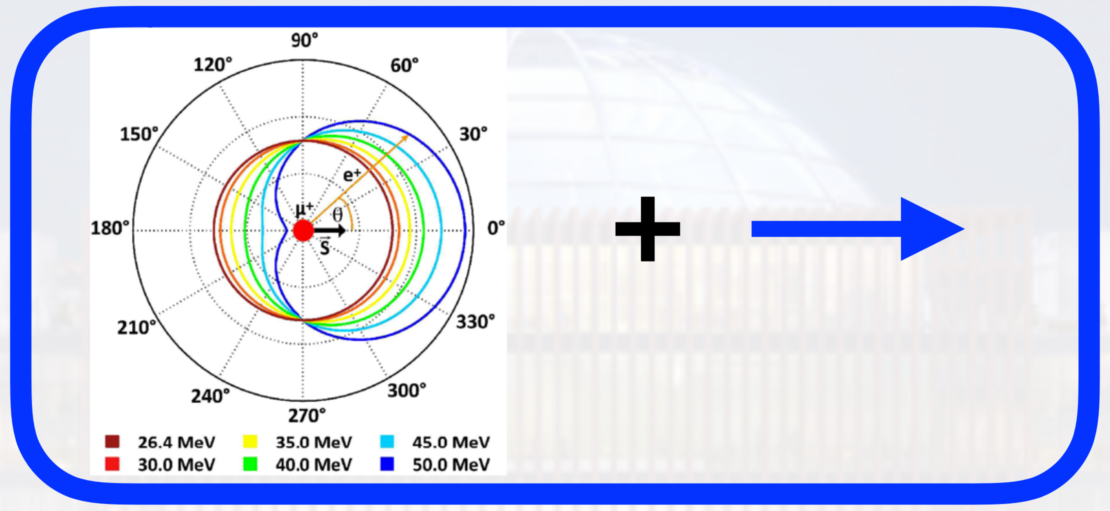


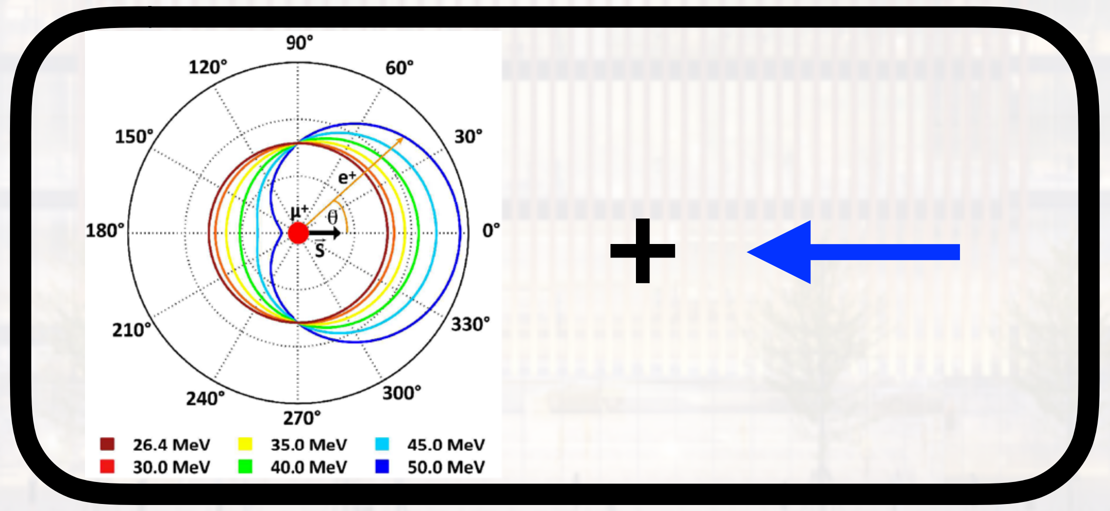


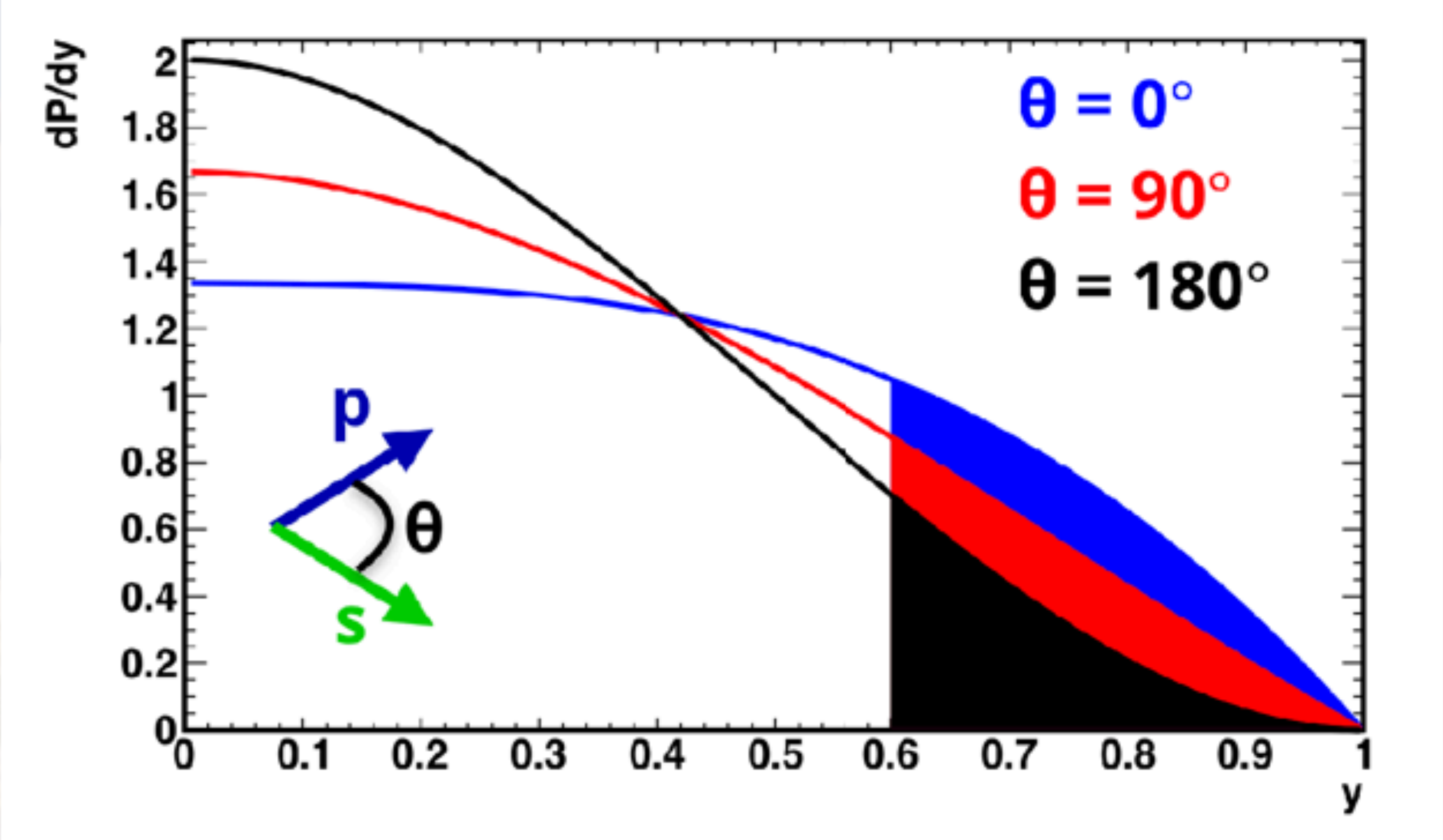


Parity violation in weak decay!

High energy positron follows muon spin! (rest frame)







BNL/FNAL vs J-PARC approach

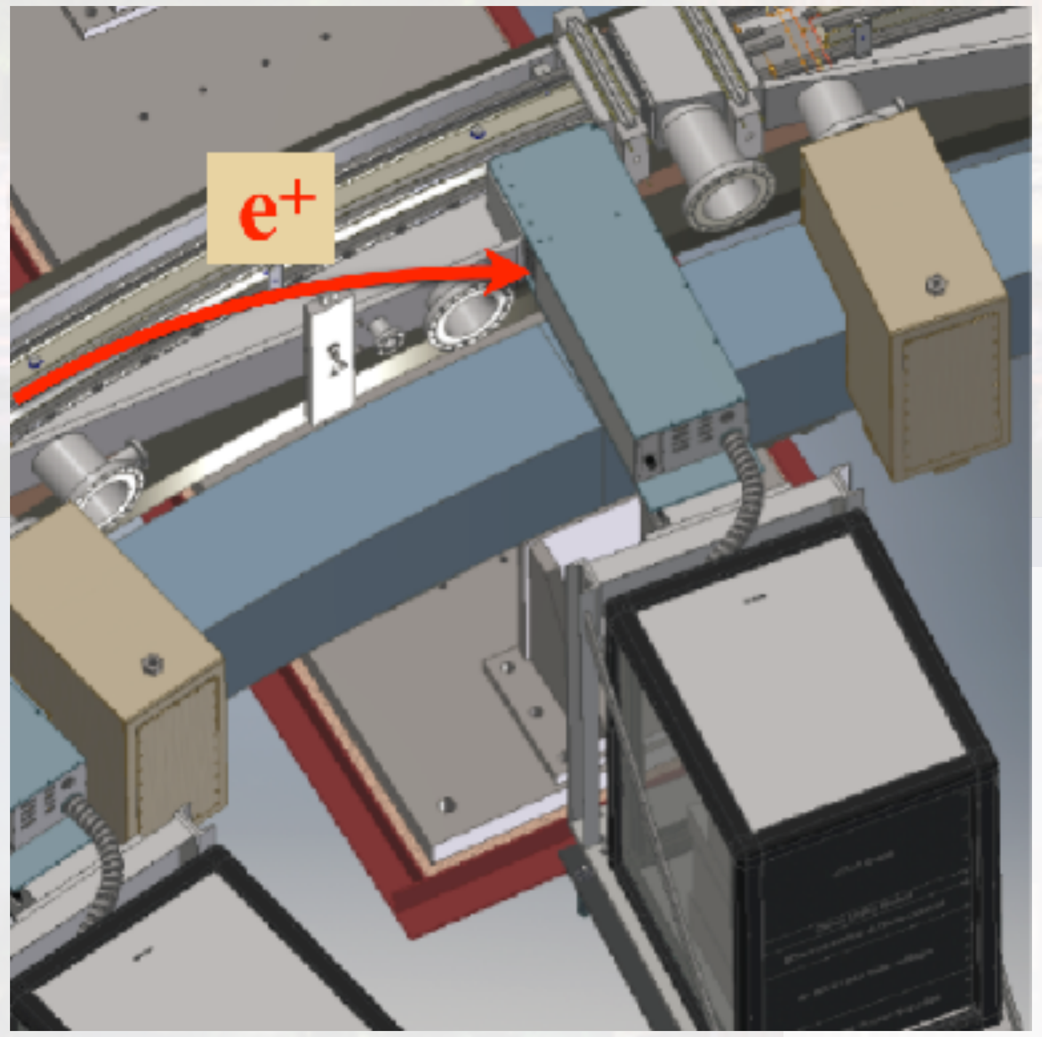
Very different systematics! Important confirmation of New Physics!

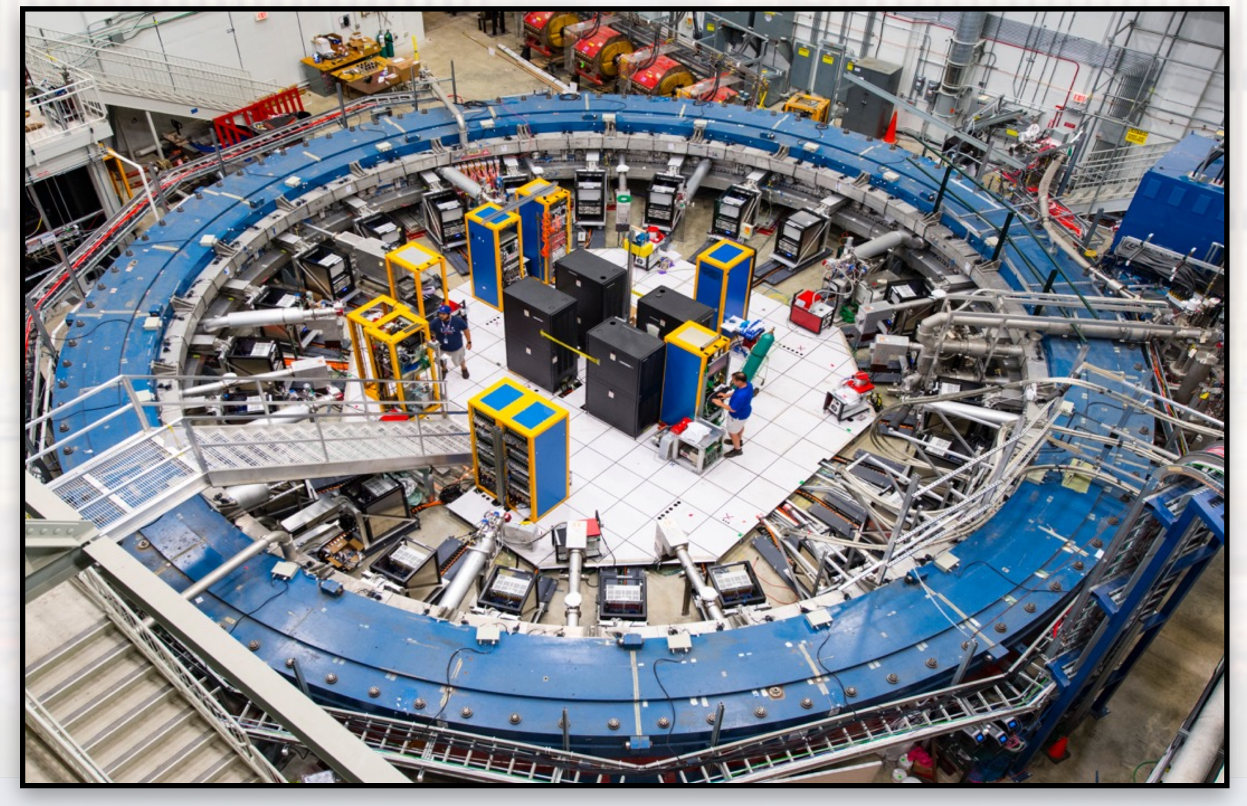
3.1 GeV/c μ^+

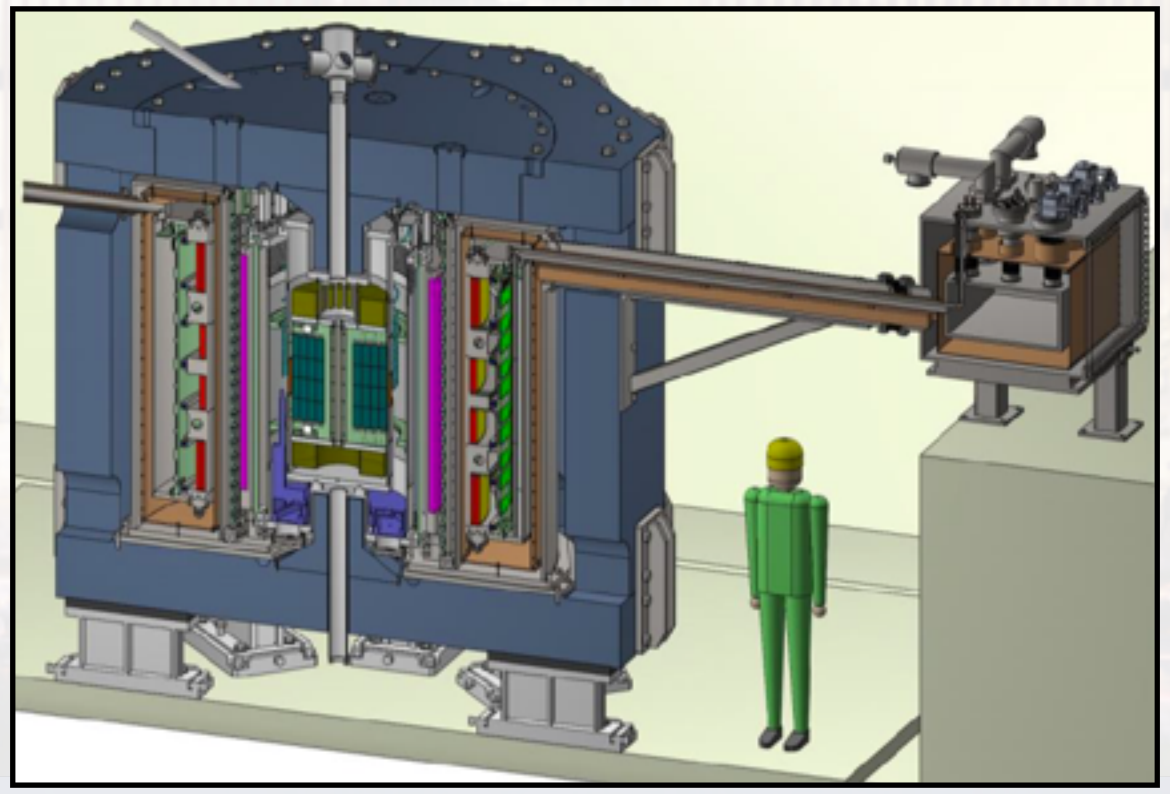
0.3 GeV/c μ^+

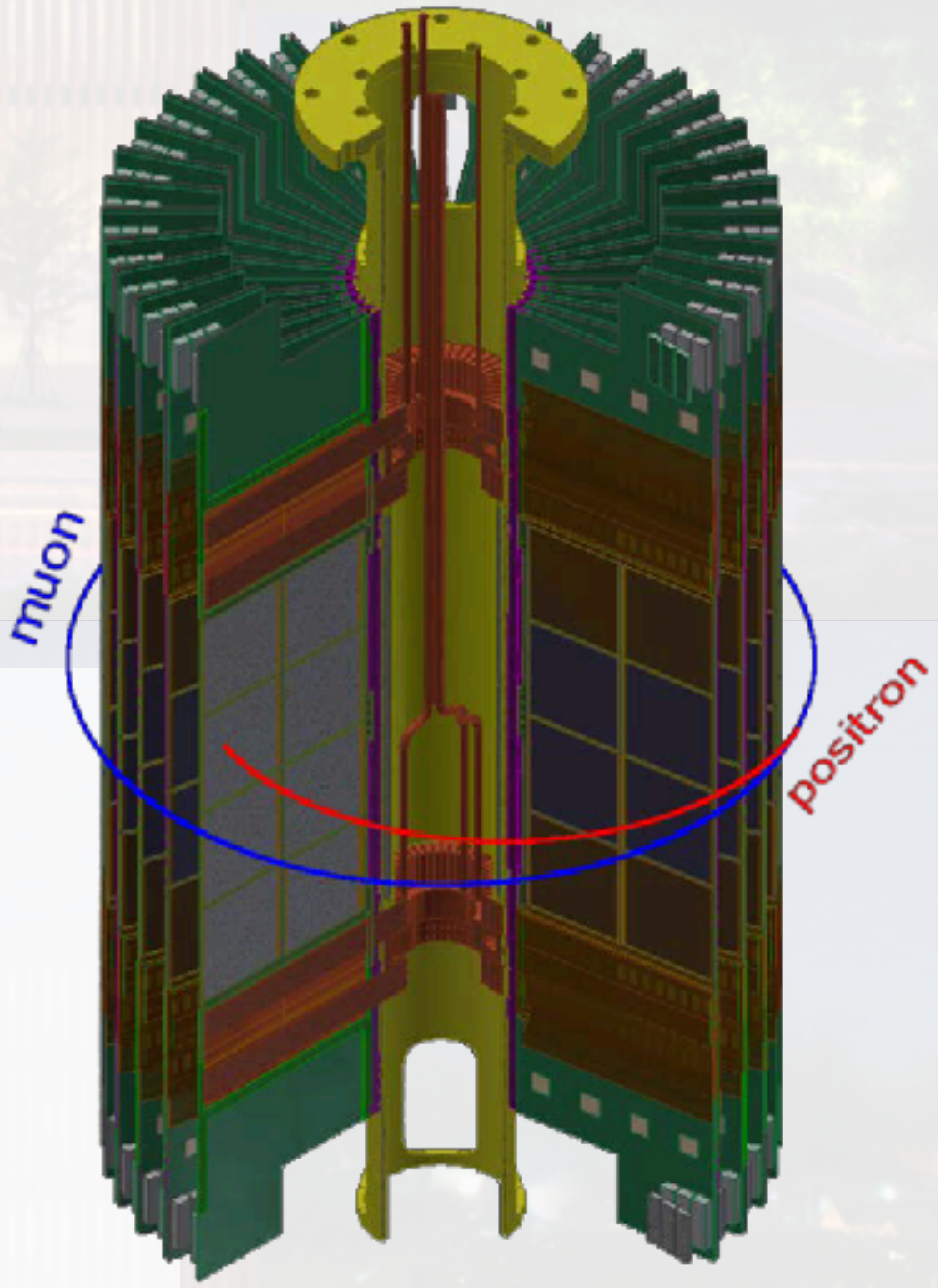
2018-2021++

2024-2026









Calorimetry

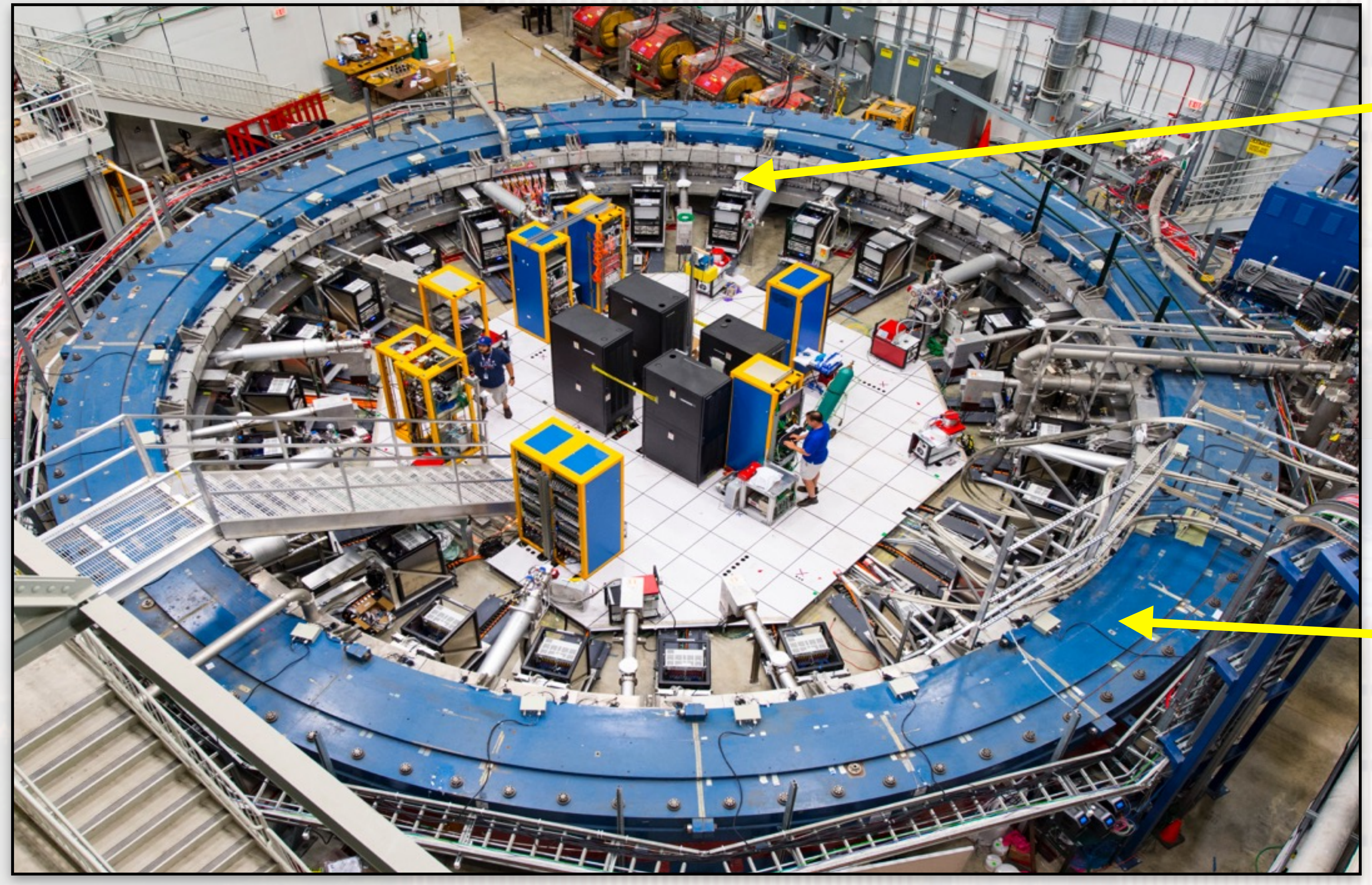
Tracking

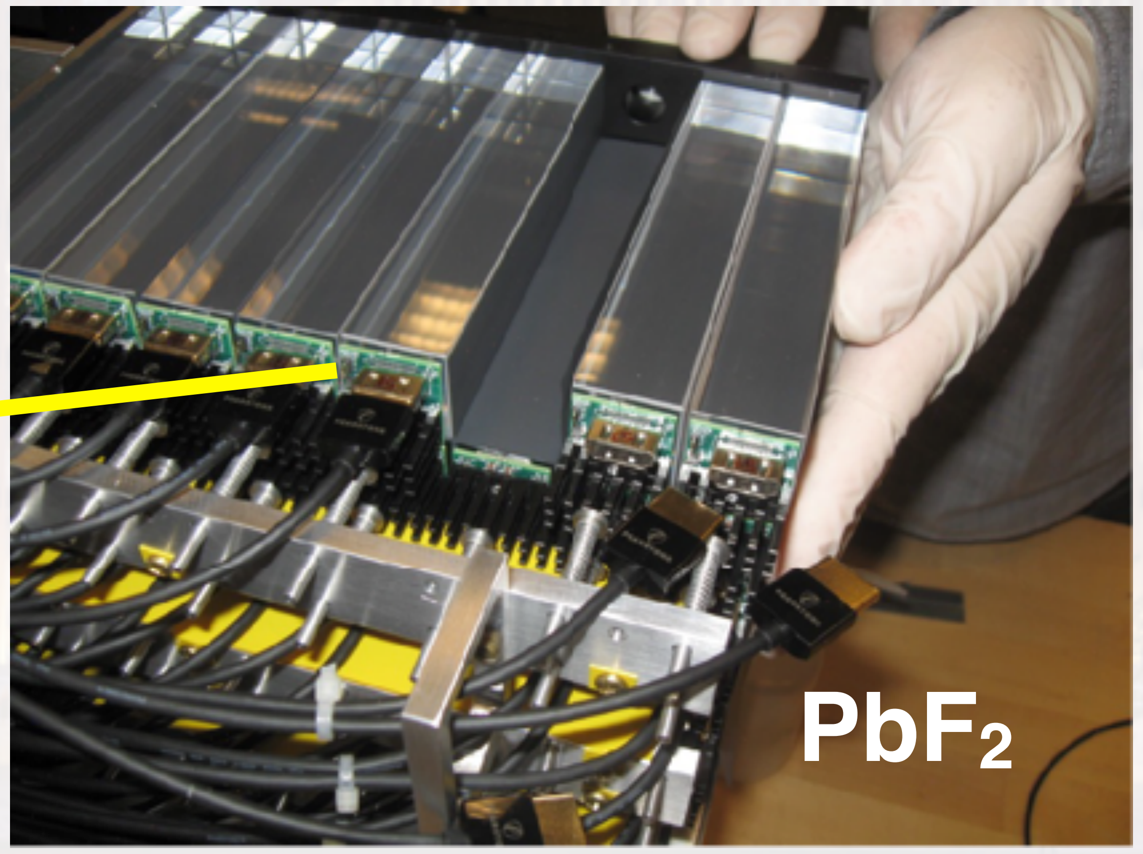
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.8×10^{11}	8.1×10^{11}

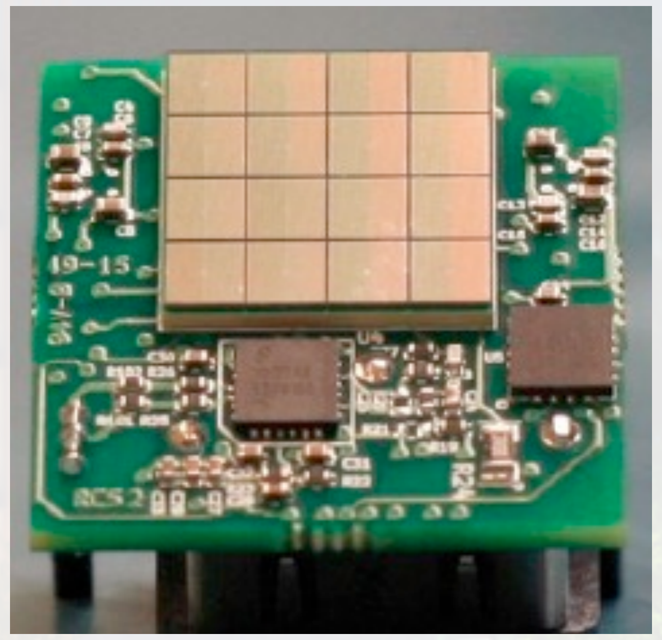
Gorringe and Hertzog, Progress in Nuclear and Particle Physics, *Volume 84 (2015) September 2015*

FNAL Muon g-2 experiment: overview

24 calorimeters

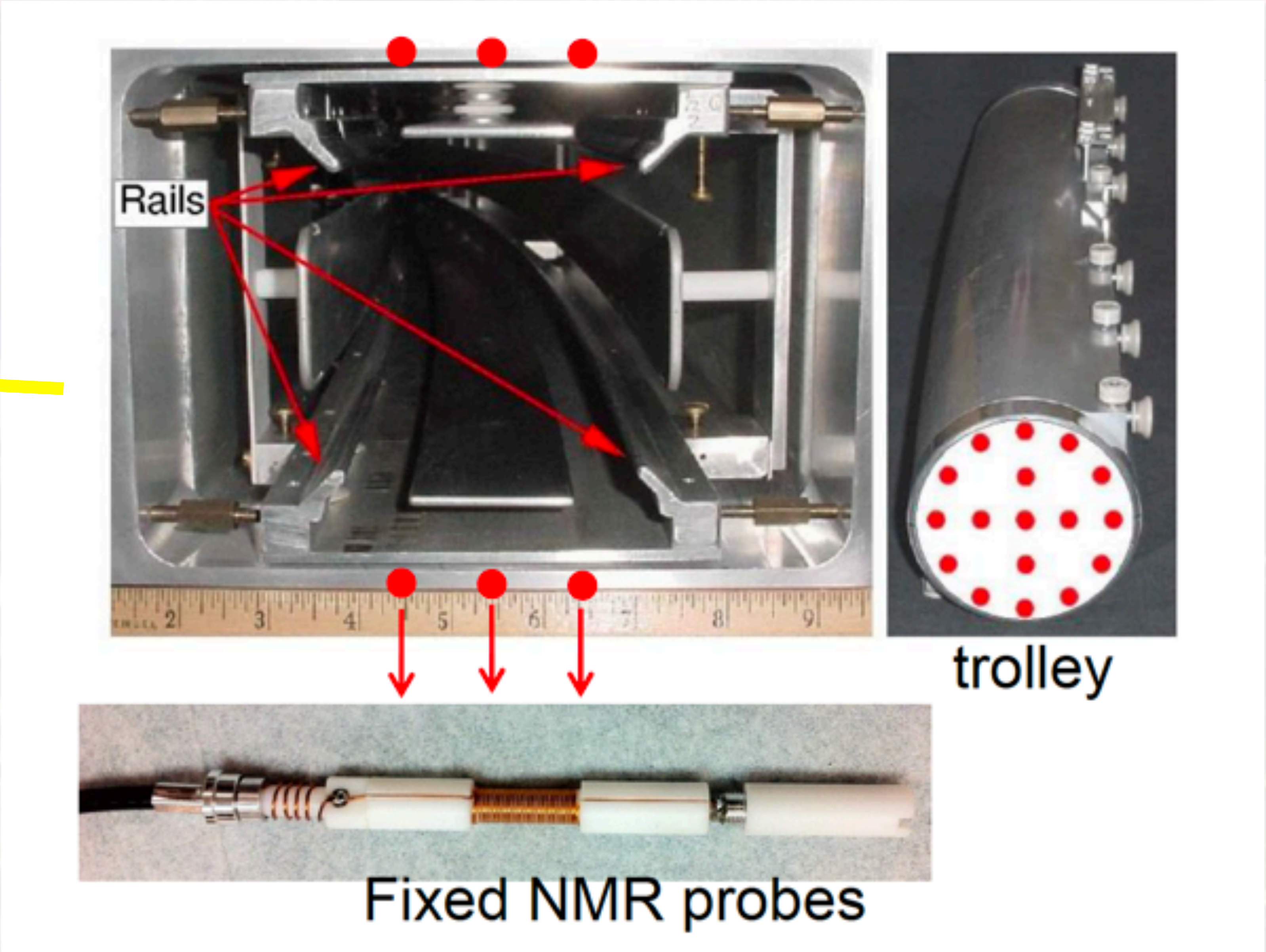






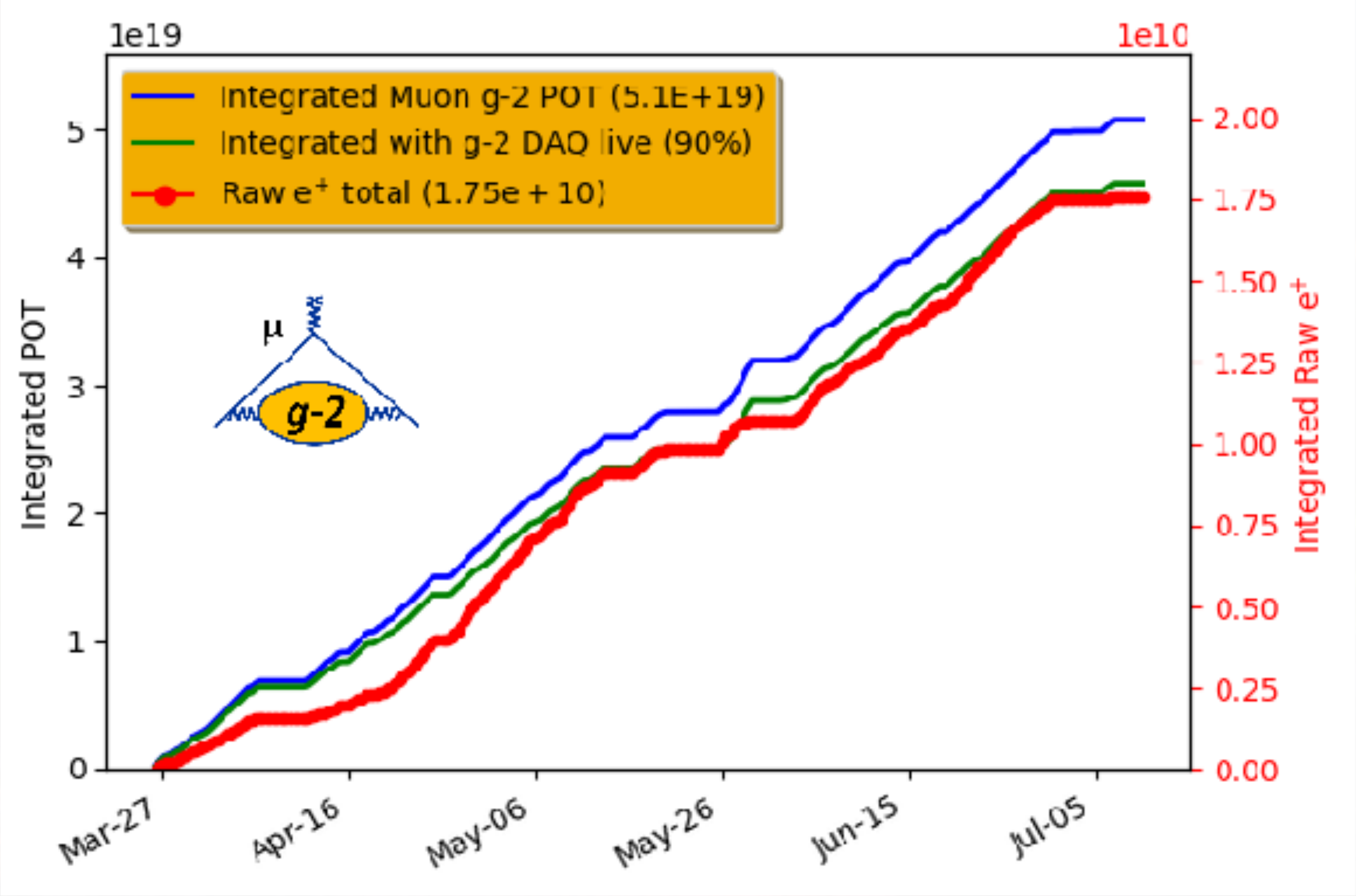
SiPM

~ 400 NMR fixed probes and trolley probes

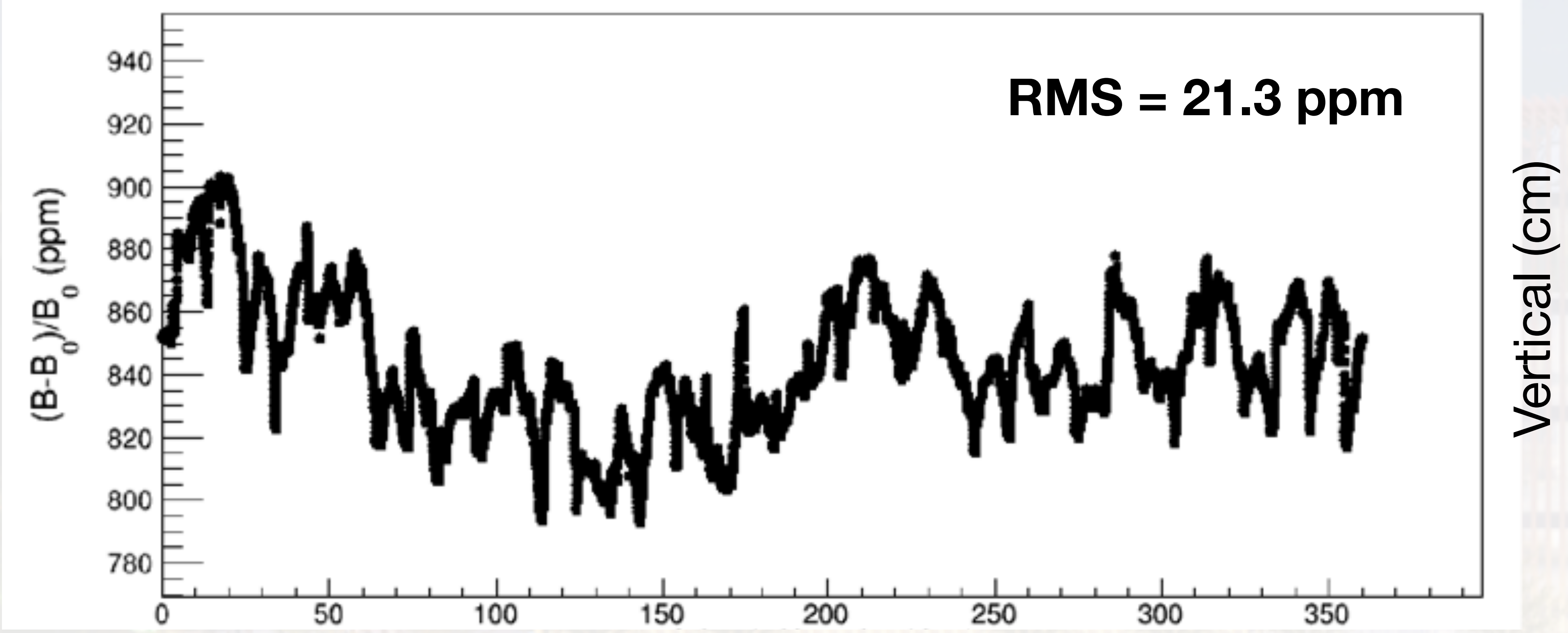


FNAL Muon g-2 experiment: run 1 overview

- Data taking period: Apr - Jul 2018
- Accumulated ~ 1.75x BNL statistics
- Projected ω_a stat. precision = 420 ppb (after DQ)
- Final ω_a & ω_p systematics ~ ?? ppb (work in progress)

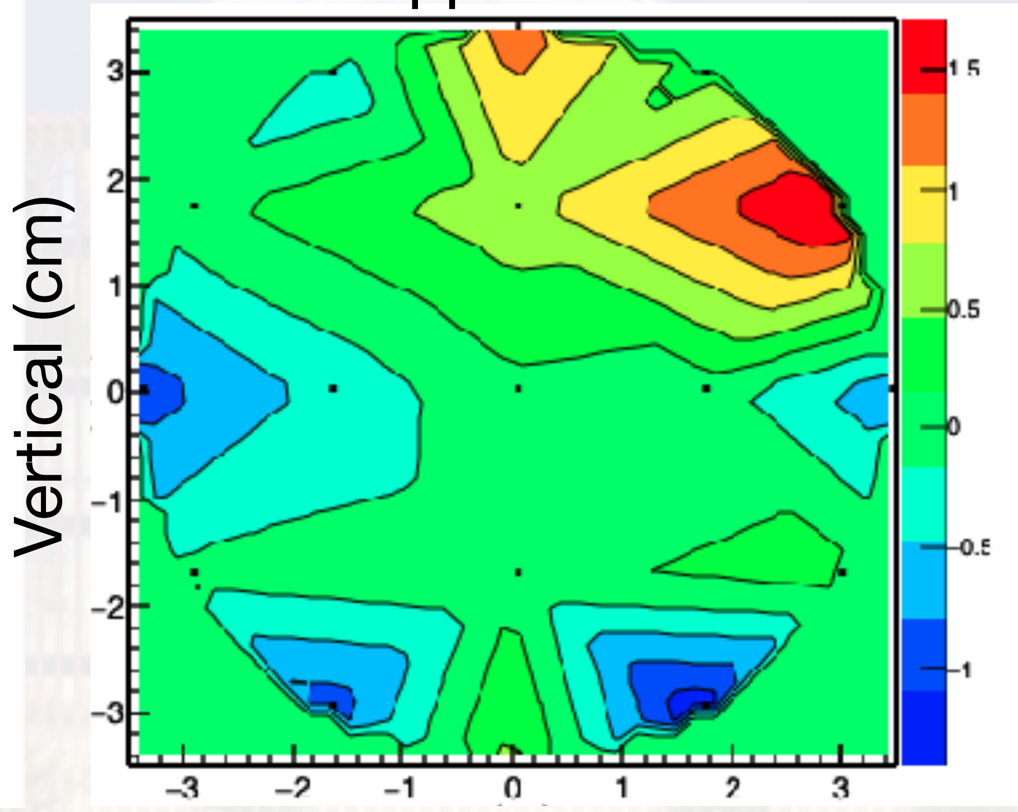


Dipole Moment

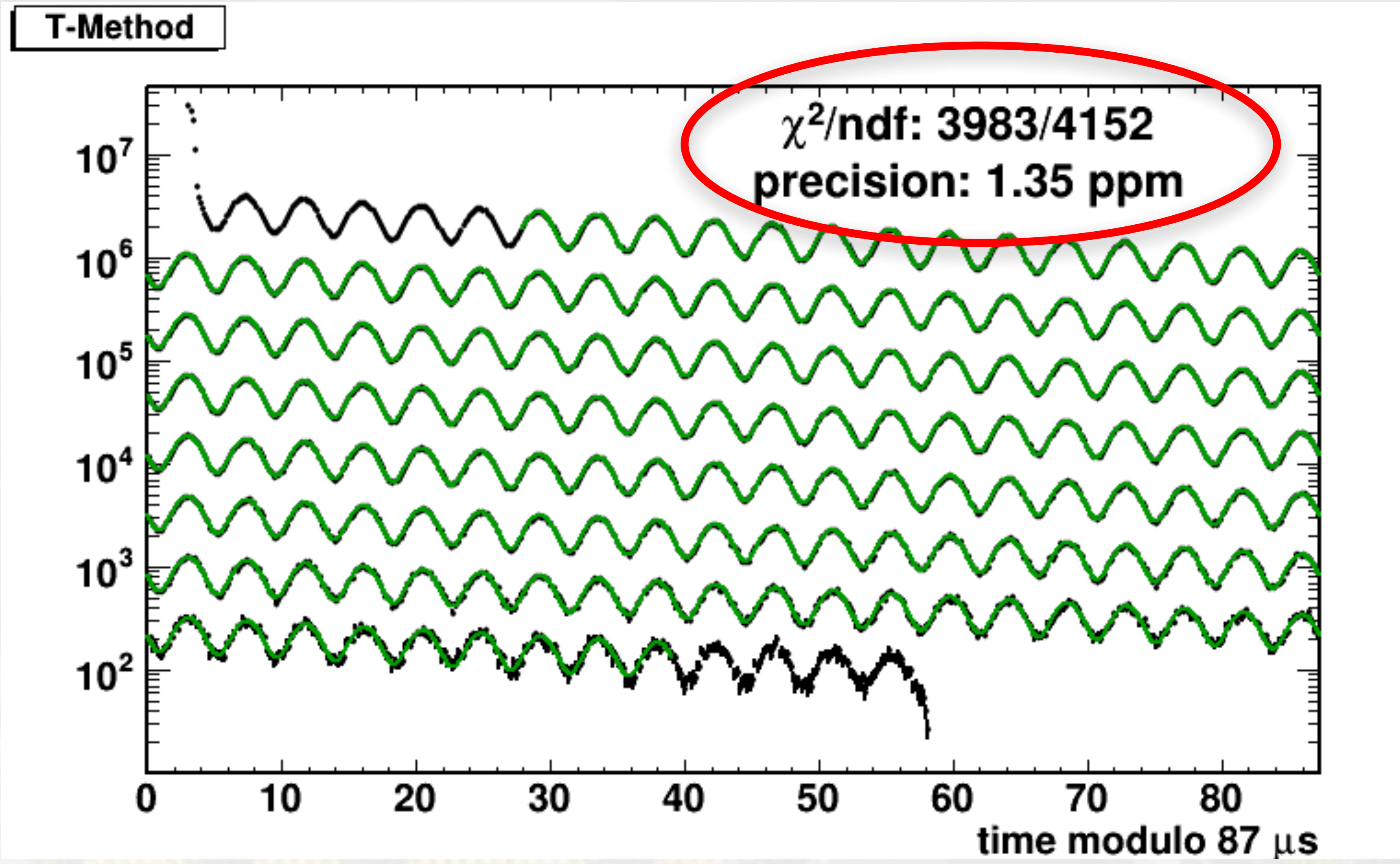


Azimuthal Position (deg)

Azimuthal average
250-ppb contours



R-R0 (cm)



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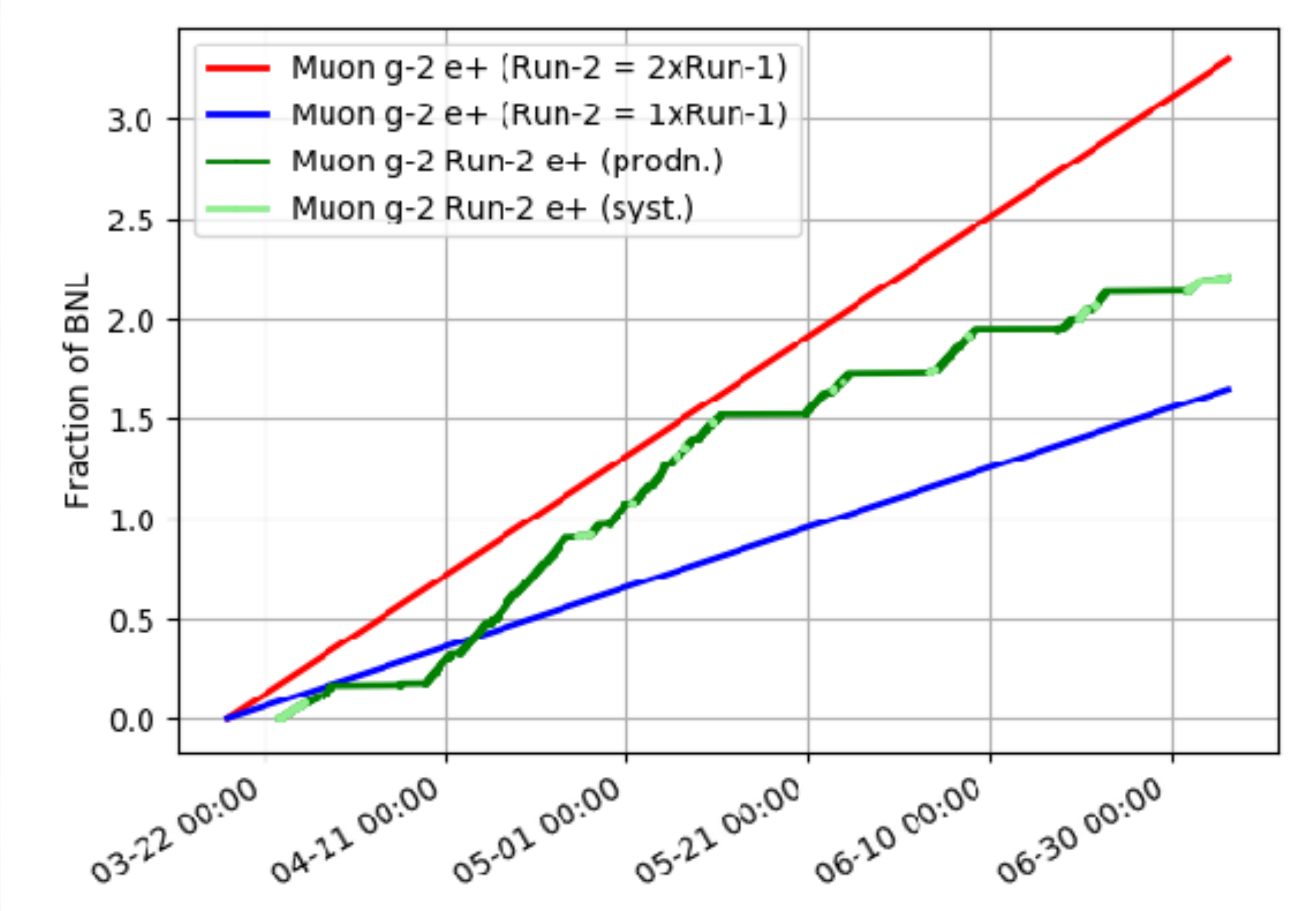
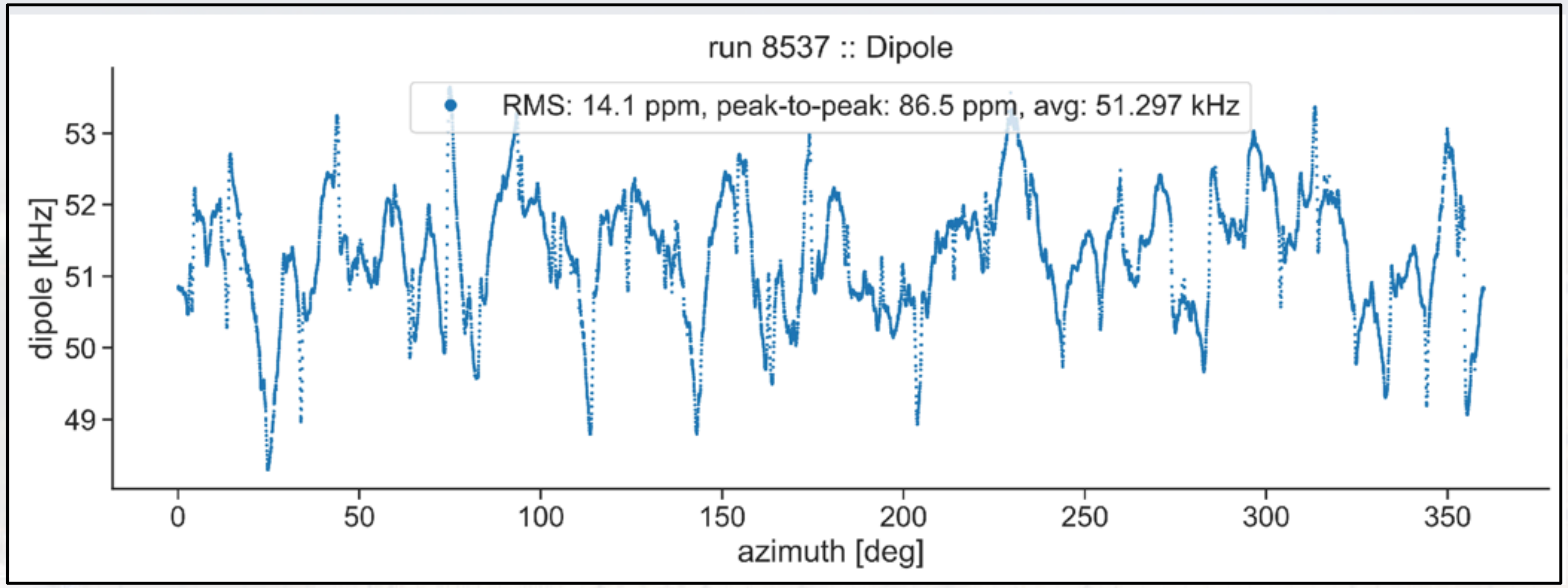
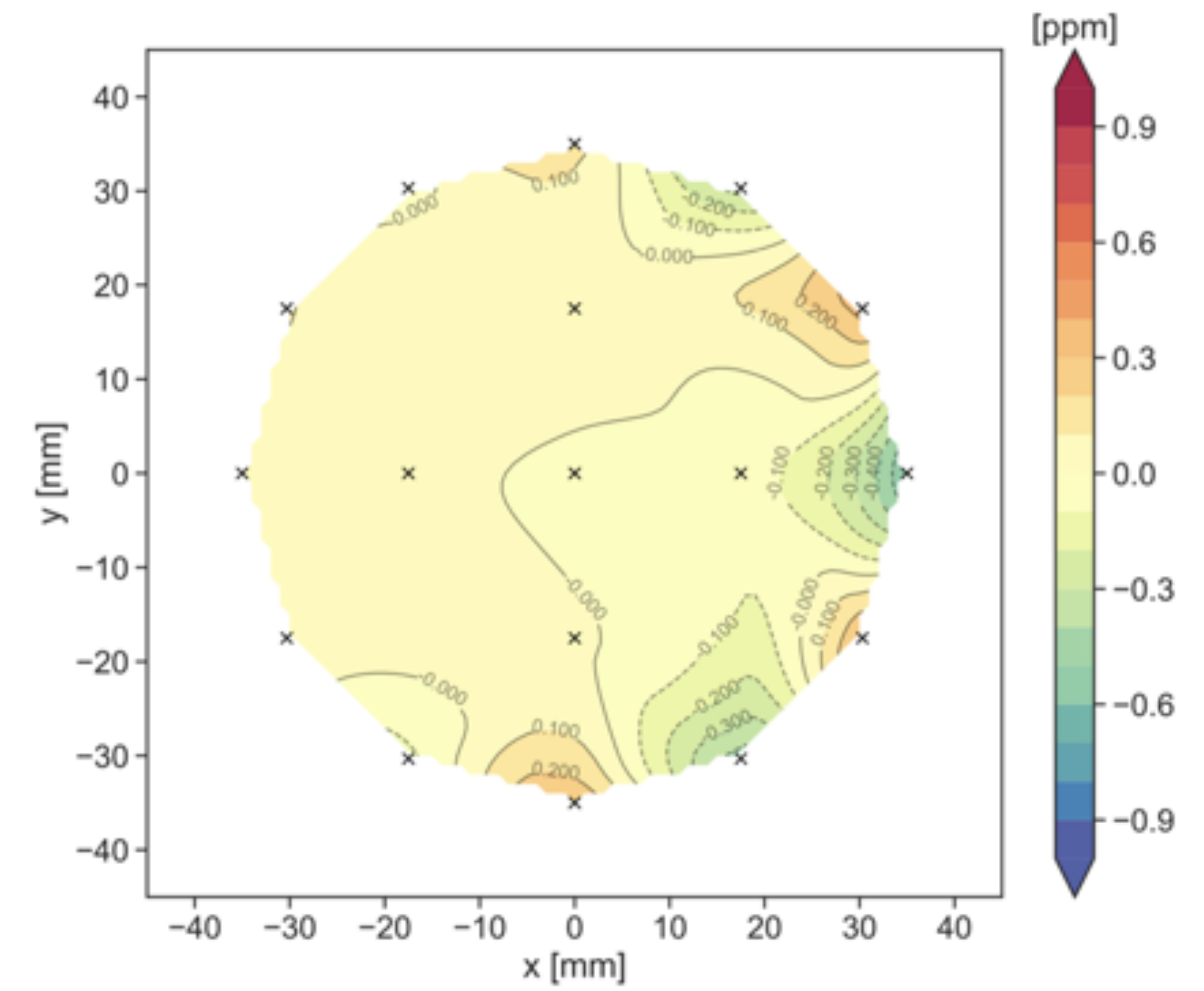
FNAL Muon g-2 experiment: run 2 overview

- Data taking period: Mar - July 2019
- Accumulated ~ 2.2x BNL statistics
- Expected ~ 2x BNL after DQ cuts
- Dipole moment ~ 14 ppm RMS



Dipole Moment

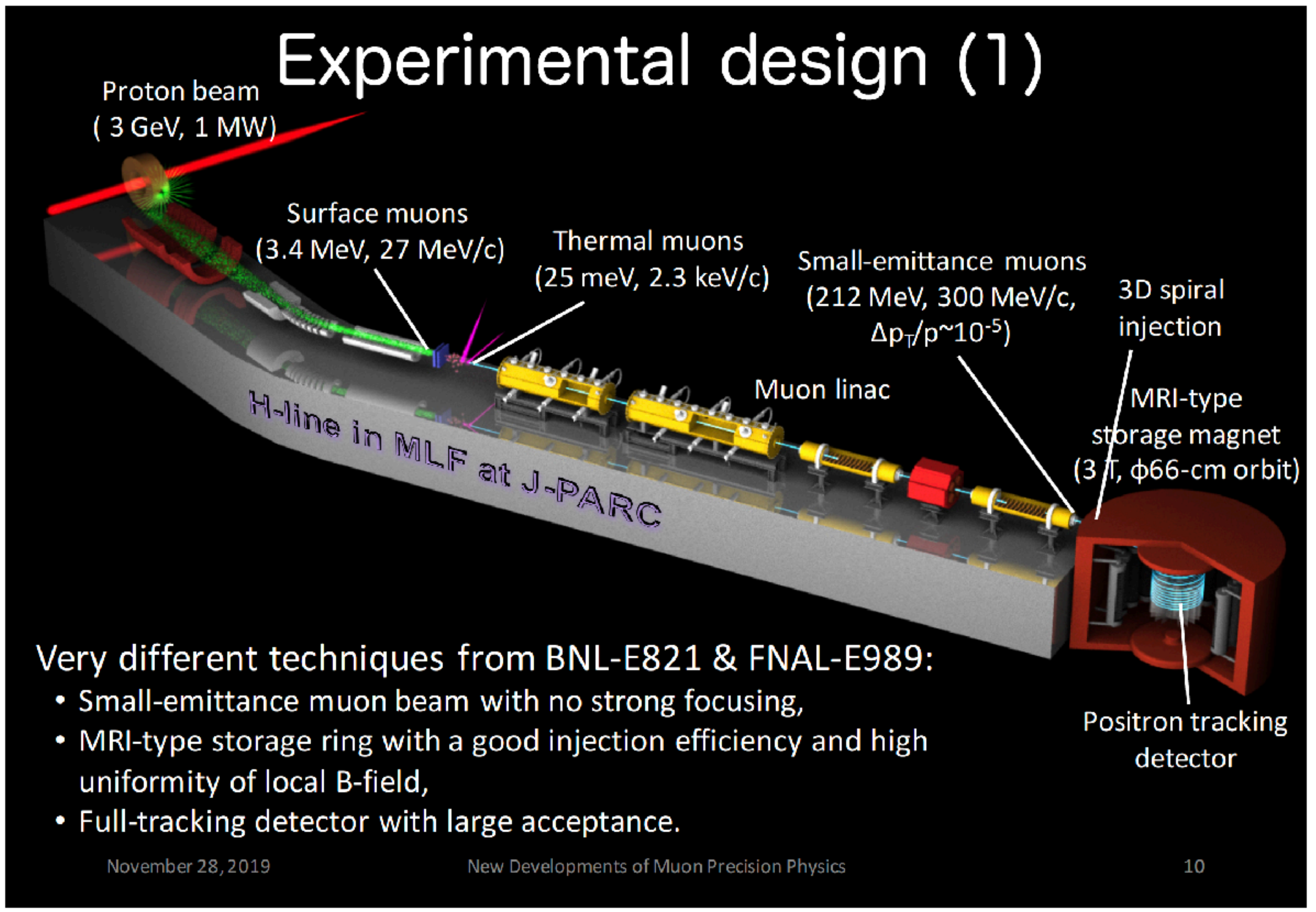


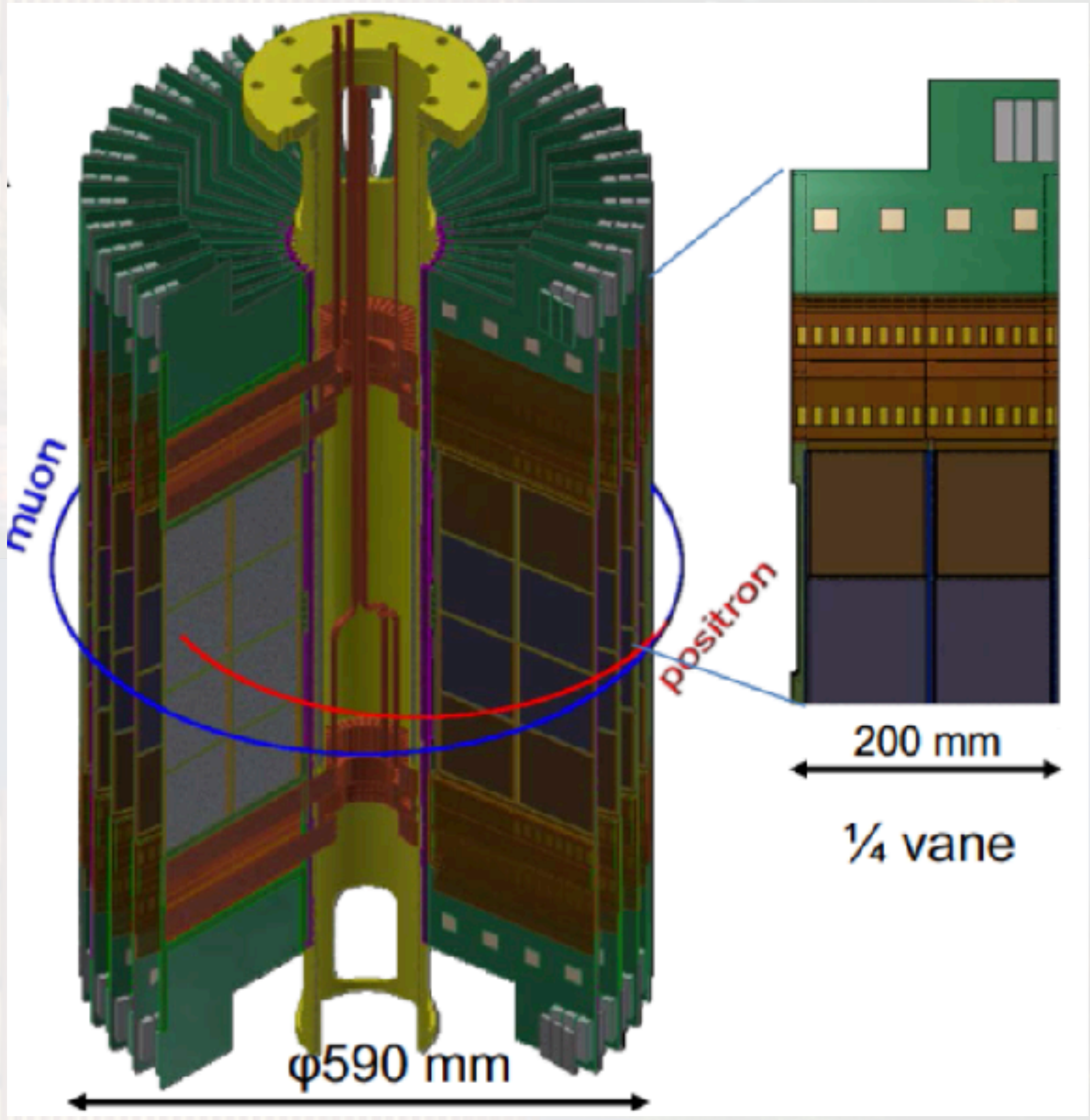


FNAL Muon g-2 experiment: status

- Run 1 in 2018 is completed with ~ 1.75x BNL statistics
- Will provide > 5σ sensitivity when combined with BNL result
- Run 2 in 2019 has ended and we collected 2.2x BNL statistics
- Run 3 (2019-2020) production will begin soon and our goal is 4.4x BNL statistics
- Based on most up-to-date FNAL time table
  - Run 4 (2020-2021) looks solid and Run 5 (2021-2022) is realistic

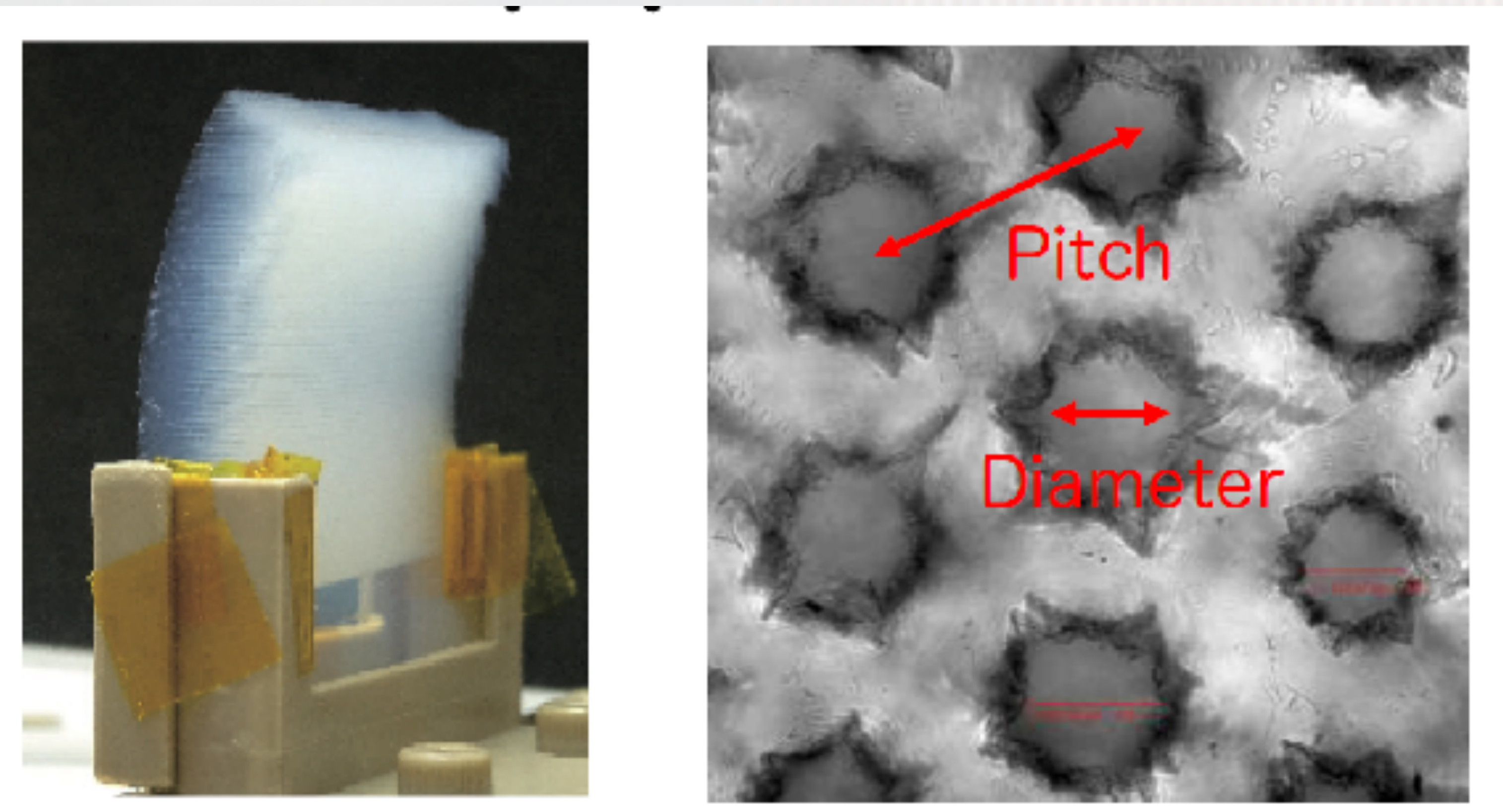
J-PARC Muon g-2/EDM experiment: overview



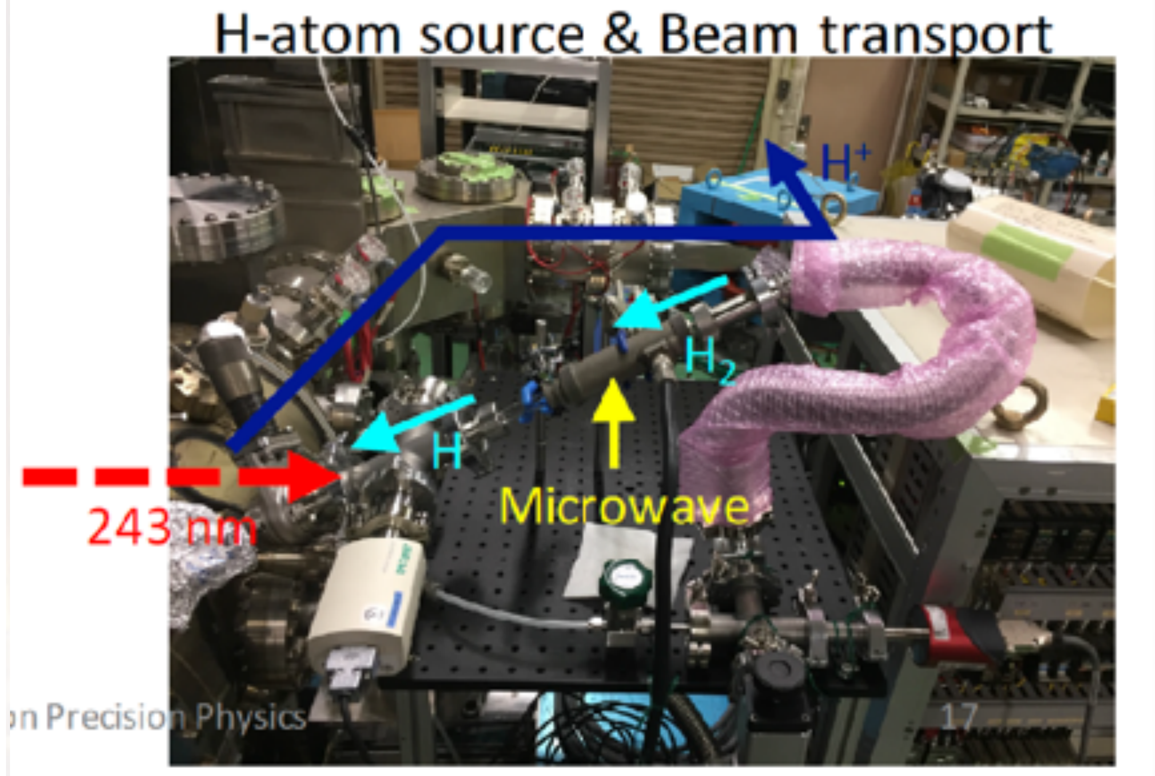


K. Suzuki,
KEK Muon Workshop 2019

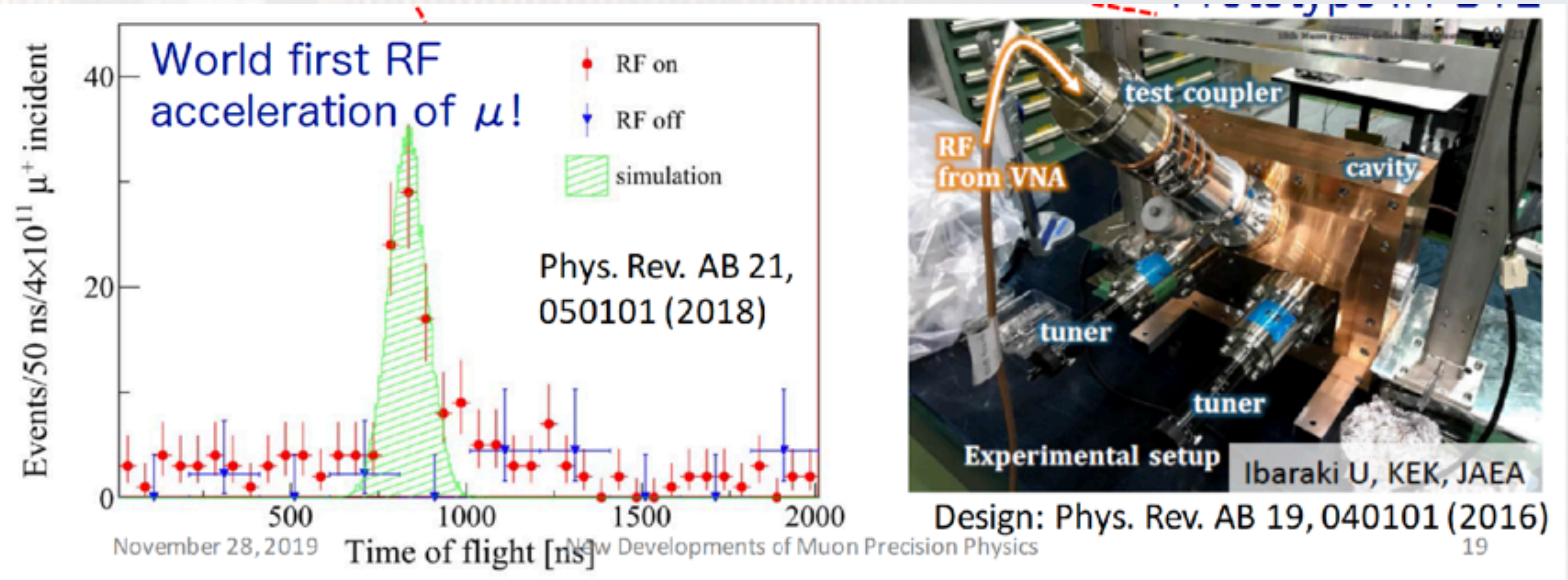
J-PARC Muon g-2/EDM experiment: status



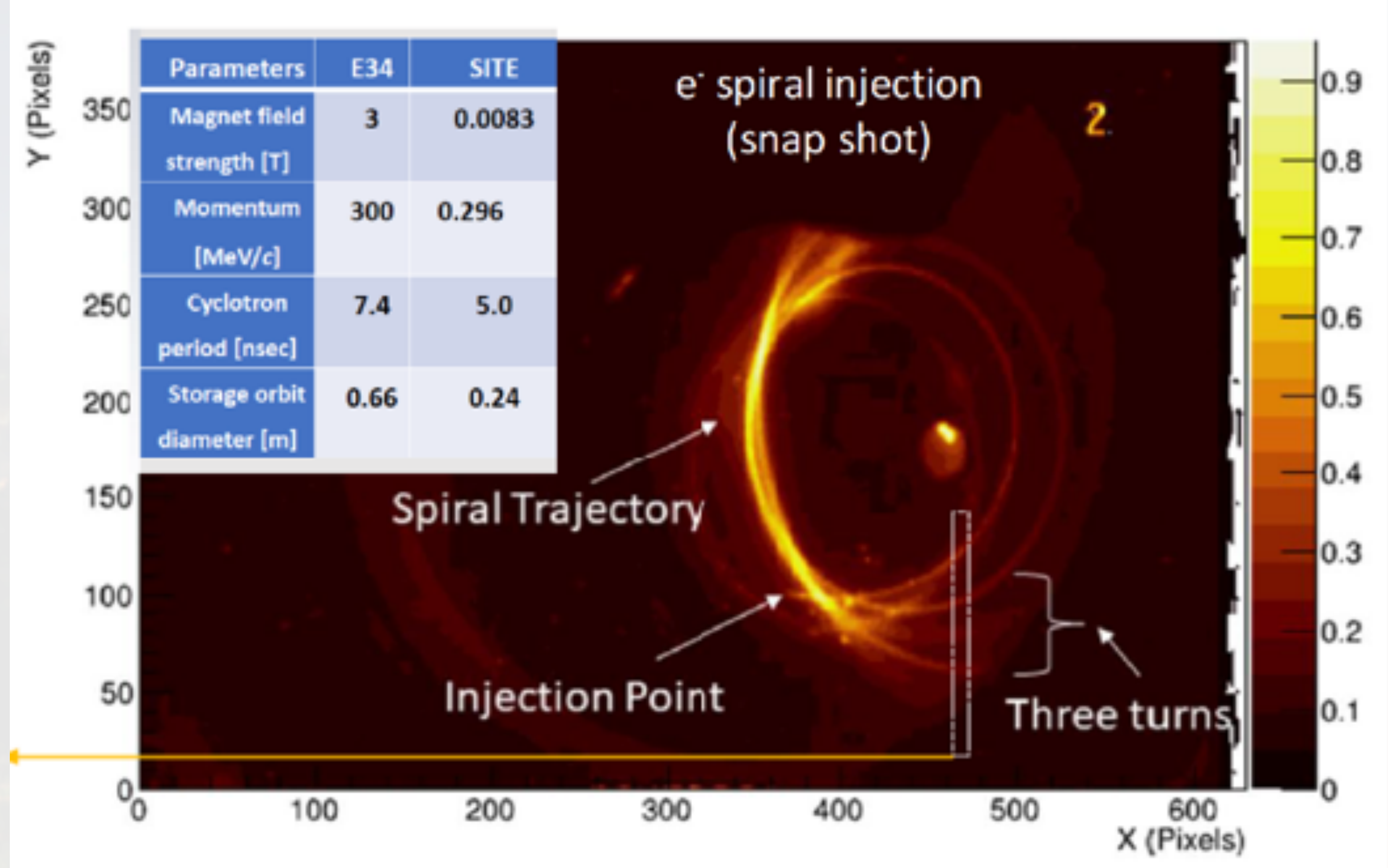
Muonium production



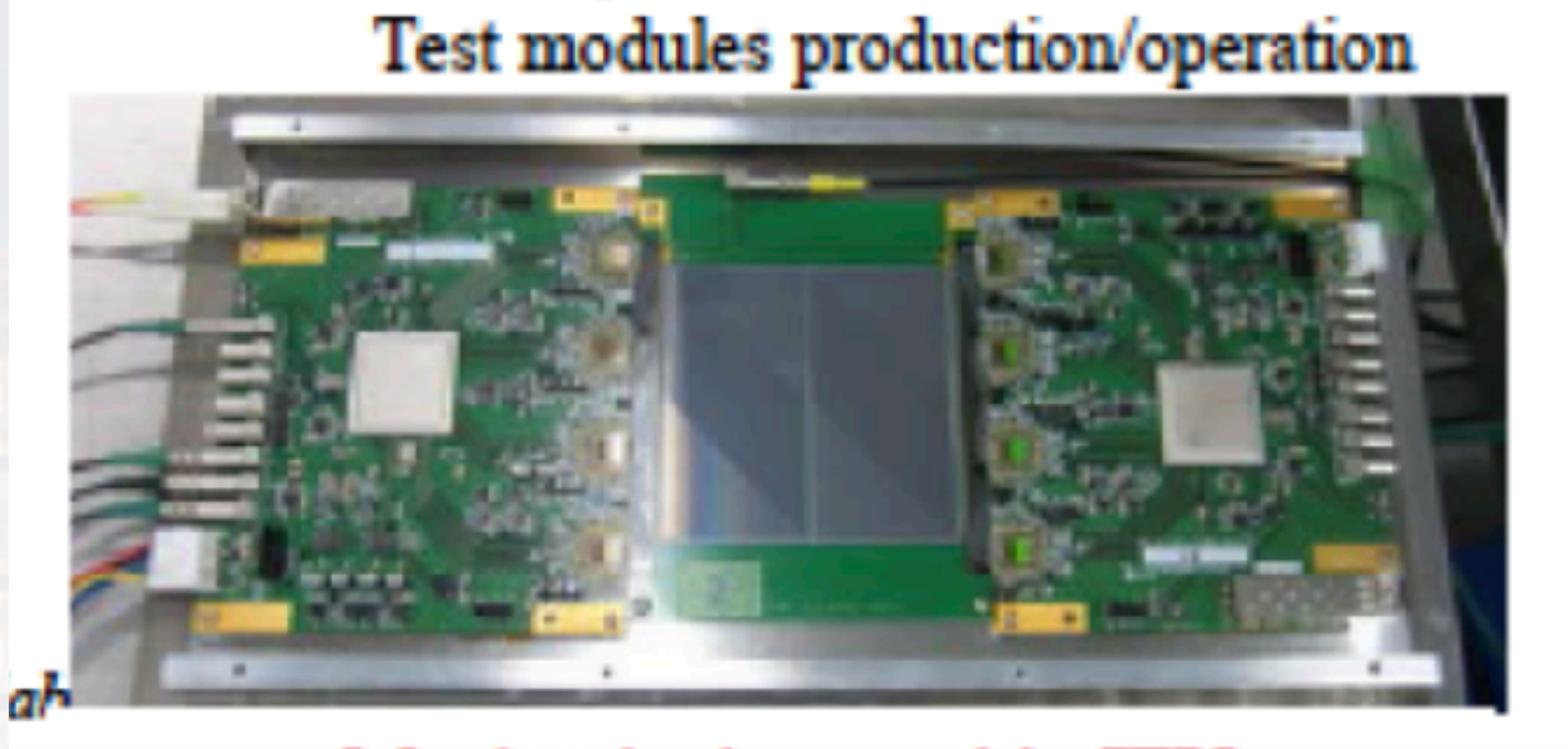
Ionization scheme



RF acceleration of muons



Spiral injection with e



Tracking module in test beam

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Frozen-spin technique for EDM search

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

ω_a : AMM

BNL, FNAL: use γ = 29.3

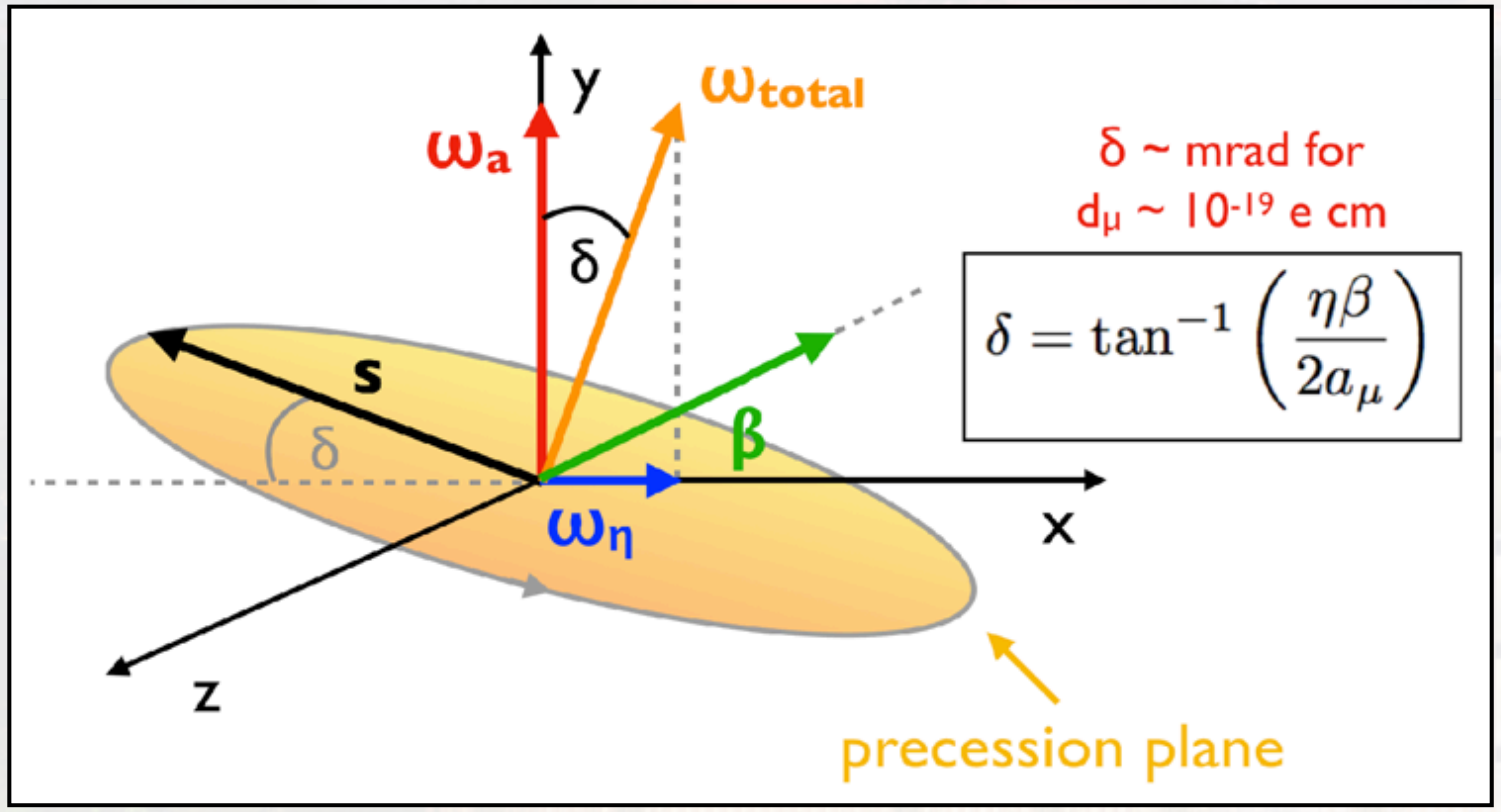
J-PARC: no E-field focusing

ω_η: EDM

J-PARC, PSI: E ~ $aBc\beta\gamma^2$

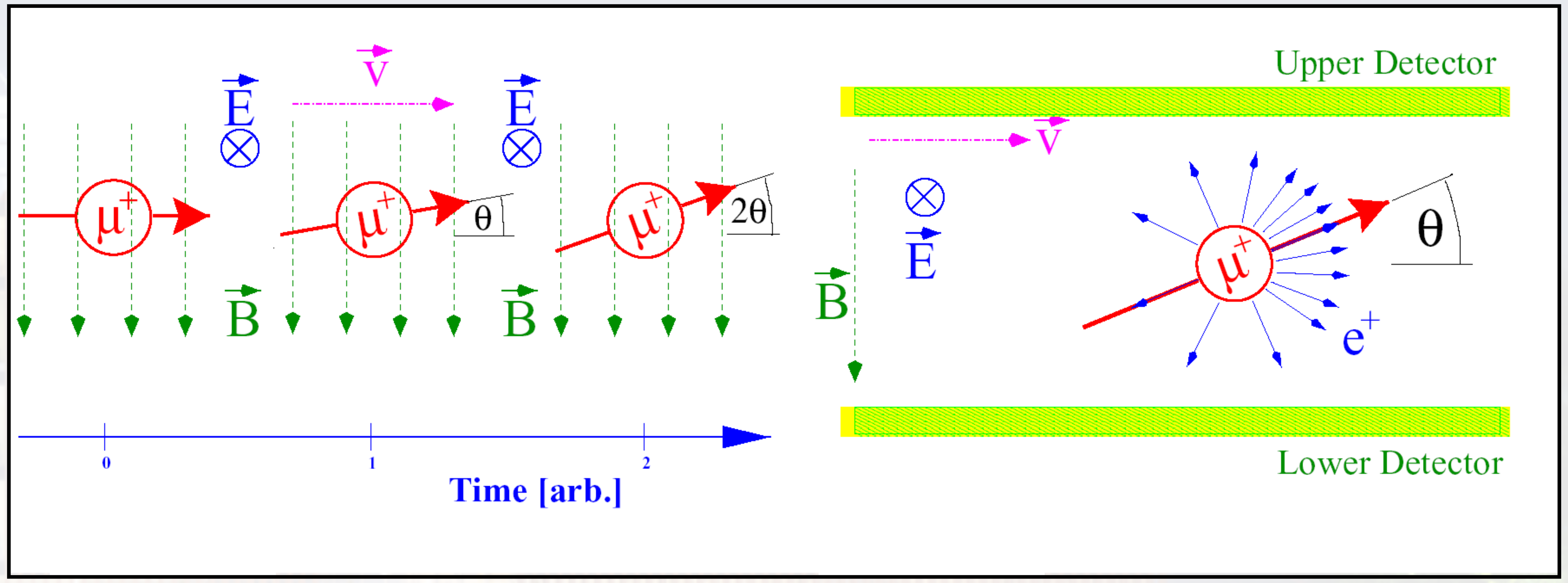
J-PARC: storage ring lattice, <R> ~ 11 m

PSI: compact storage ring, <R> ~ 0.3 m



The "parasitic" approach with g-2

(performed or proposed at BNL, FNAL and J-PARC)



The "frozen-spin" approach

(proposed at J-PARC, PSI)

First proposals at J-PARC and PSI

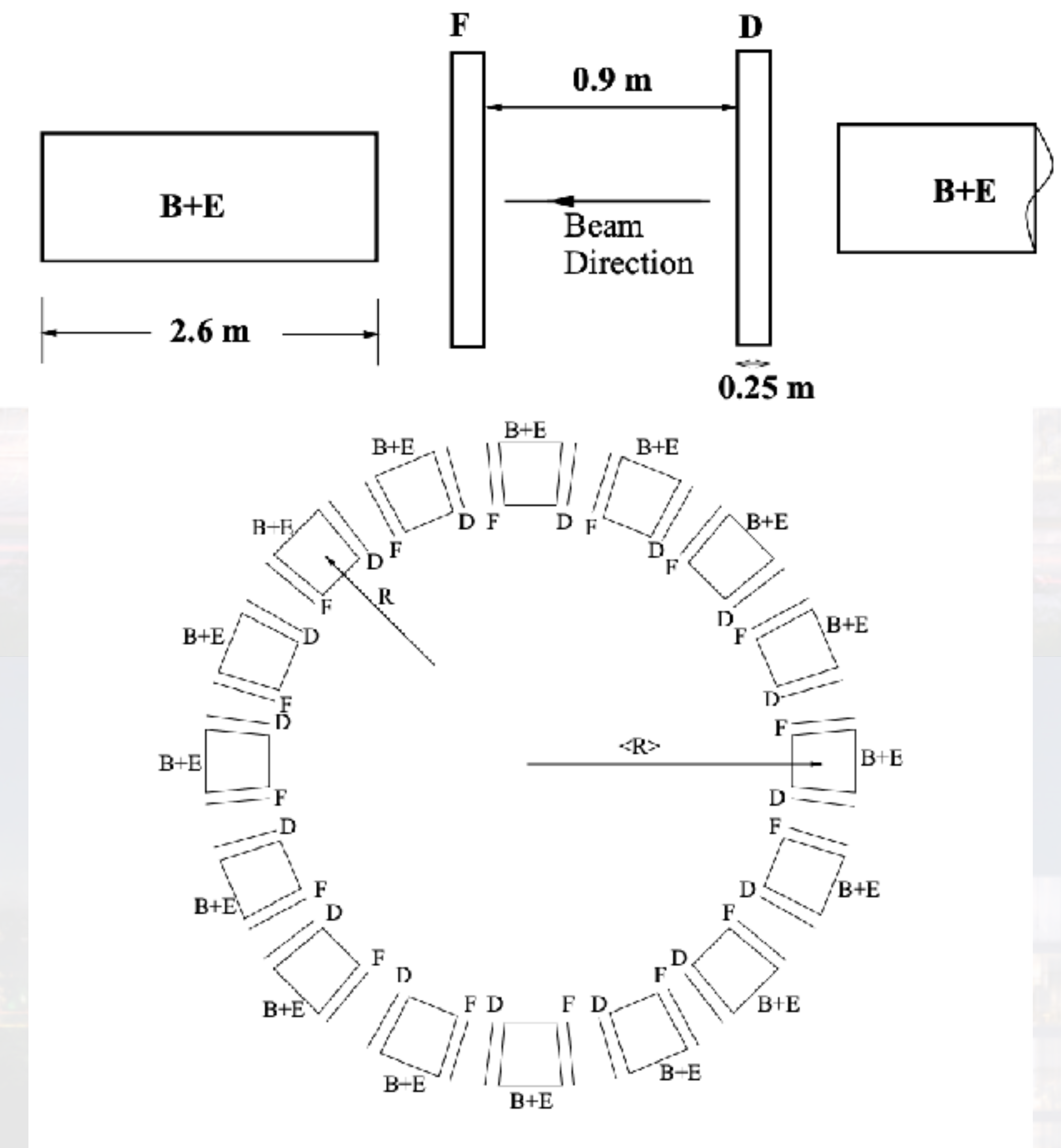
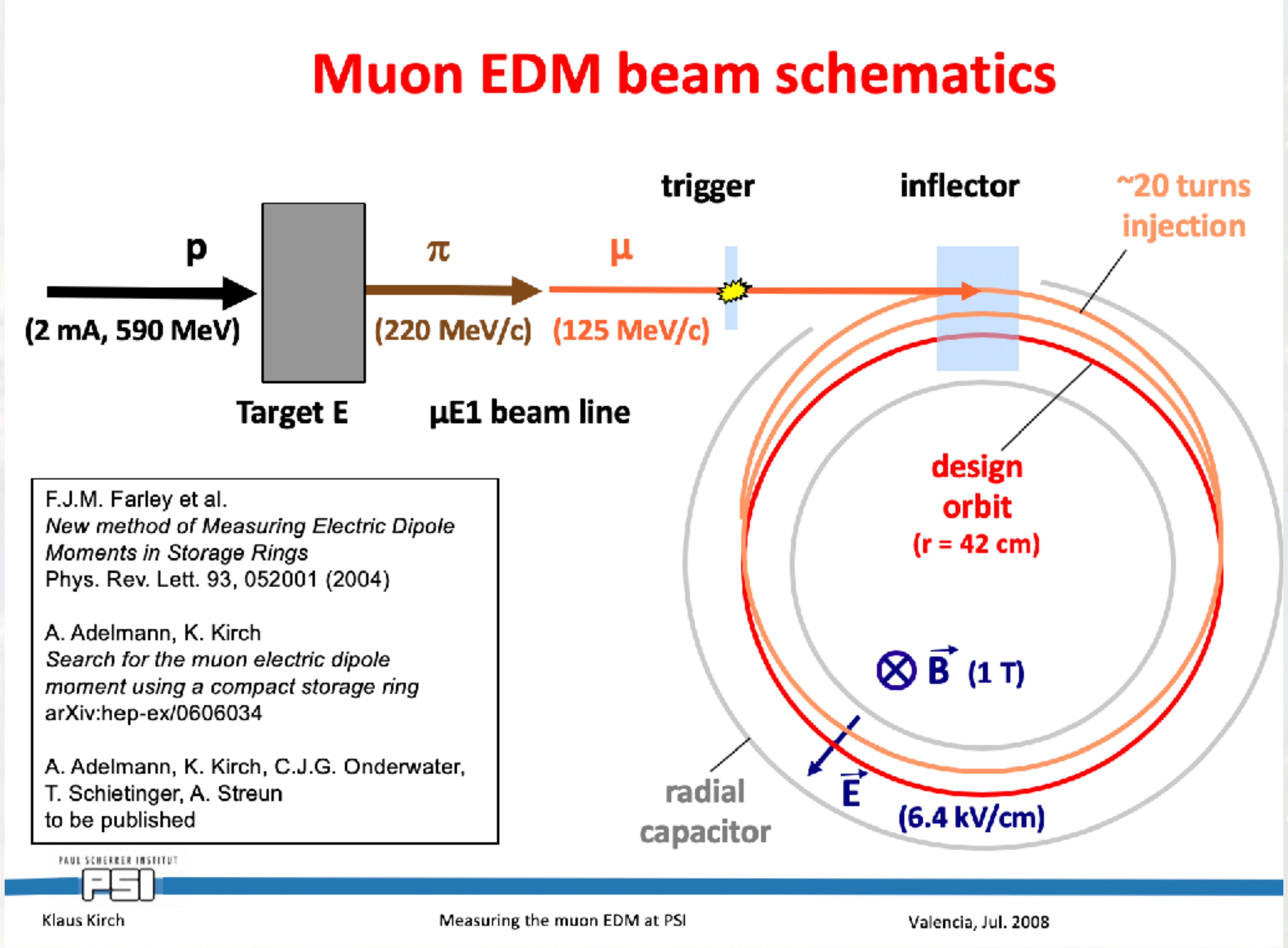


Figure 9: A schematic of the lattice (not to scale) of the EDM ring for the 0.5 GeV/c momentum case. $R \approx 6.5$ m, while the average radius around the ring, including regions with no dipole magnetic field, is $< R > \approx 11$ m.

J-PARC version (lattice)



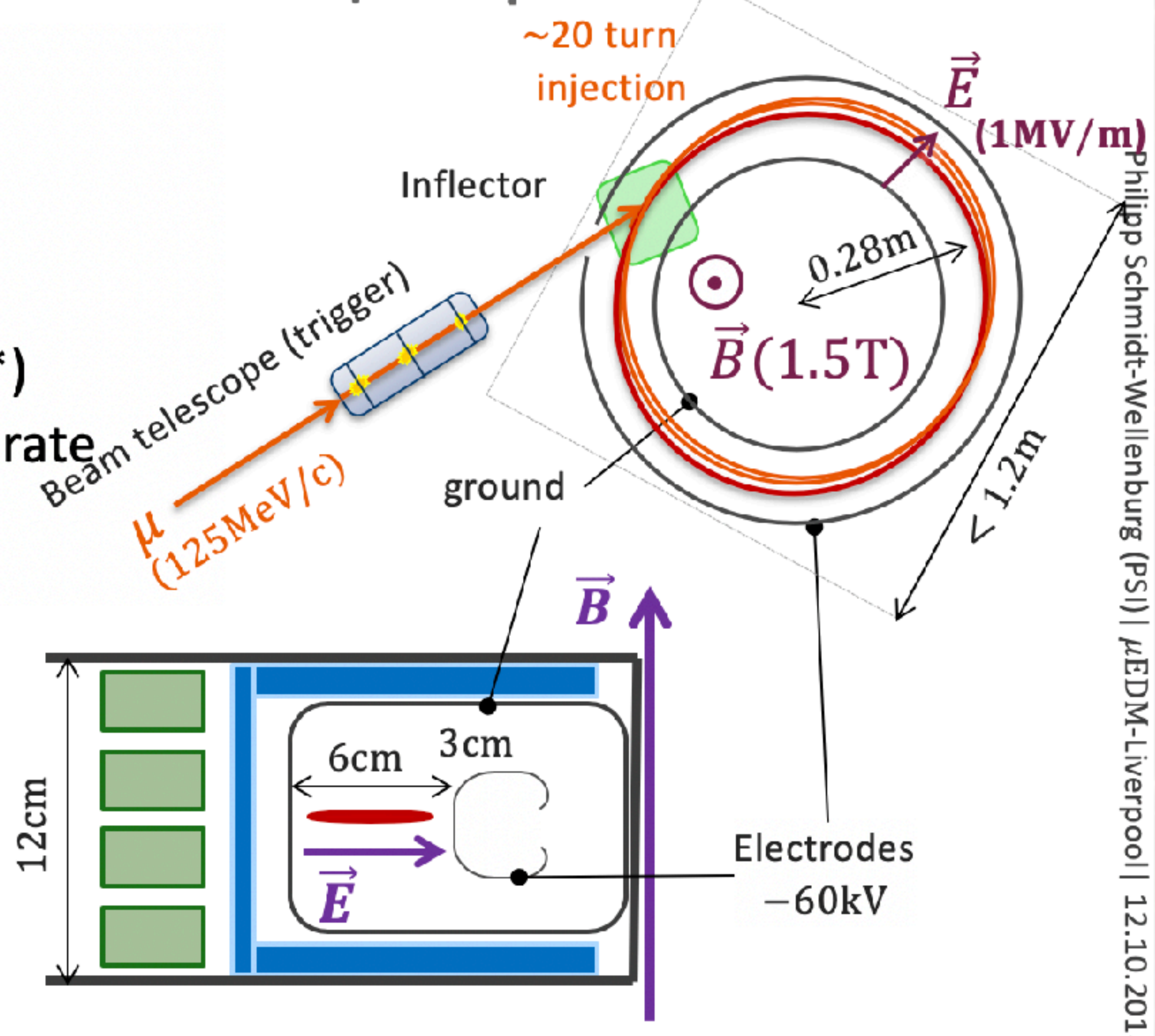
PSI version (compact storage ring)

Reincarnation of PSI version

PAUL SCHERRER INSTITUT PSI Proposal for a dedicated compact μ-EDM at PSI

- Weak focusing magnet
- Polarized μ −beam
- Trigger from beam telescope for start of inflector ramp (resonance ½ integer injection*)
- **One** muon at a time ~200kHz rate
- Tracking detector for positrons (resolution ~$0.25 \times 0.25 \text{mm}^2$)
- Optional calorimeter

Detector prototype:
Combination of scintillating tiles (timing) and thin MAPS (track,momentum)



A. Adelmann *et al.* JPG 37(2010)085001
* H. Yamada et al. NIMA467/368(2001)

Philipp Schmidt-Wellenburg (PSI) | μEDM-Liverpool | 12.10.2018

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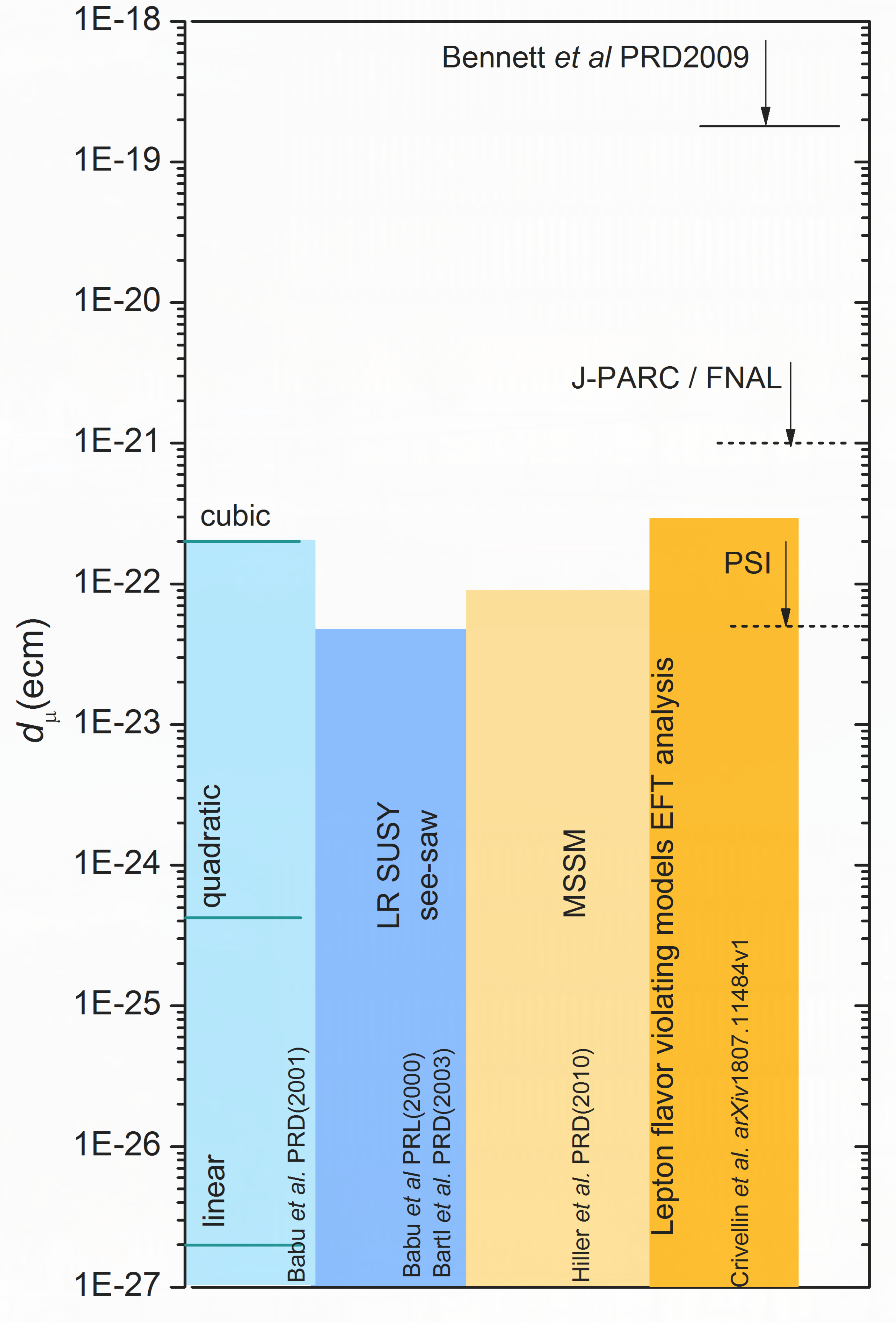
Projected sensitivity



Apply **frozen spin technique**

- PSI μE1: $2\times10^{8}\mu^{+}/s$ $\gamma = 1.57$
- Polarization from pion decay: $P = 0.9$
- Mean asymmetry of muon decay: $\alpha = 0.3$
- Compact conventional magnet:

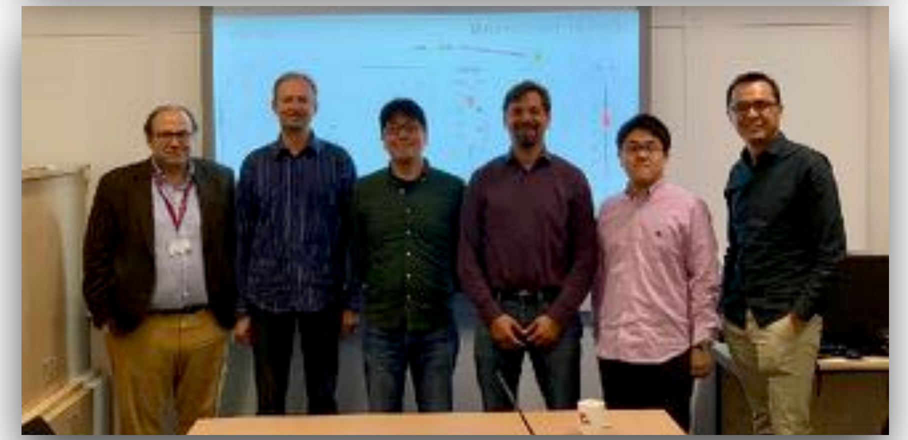
$$B = 1.5\,T \Rightarrow R = 0.28\text{m}, E = 10\text{MV/m}$$

PSI sensitivity (1 year):
$\sigma(d_\mu) < 5\times10^{-23}e\text{cm}$

- Detection rate: 200 kHz
- Run time: 2×10^{7} s

$\Rightarrow N = 4\times10^{12}$ positrons per year.

P. Schmidt-Wellenburg, muEDM Workshop Liverpool



Muon 

has not yet decayed *

> 80 years and going stronger than ever :

- ➢ more muons available 
- ➢ better quality beams
- ➢ more physics experiments considered
- ➢ more younger, enthusiastic physicists (young-in-heart)

⇒ looking forward to bright future

* after an article by V.W. Hughes and G. zu Putlitz (1984)

Klaus Jungmann, Workshop "New Developments of Muon Precision Physics“, Tsukuba, 27&28 Nov 2019