Recent progress in muon electric and magnetic dipole moments

Kim Siang Khaw（许金祥）

中国物理学会高能物理分会学术年会

11 Aug 2022

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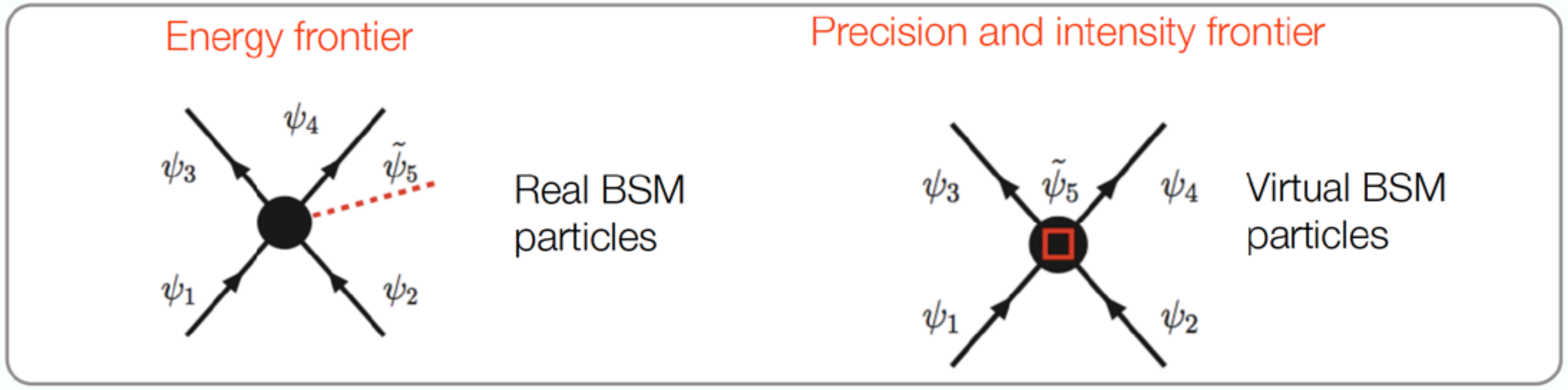
A recent review on muon g-2: Nucl. Phys. B 975 (2022) 115675

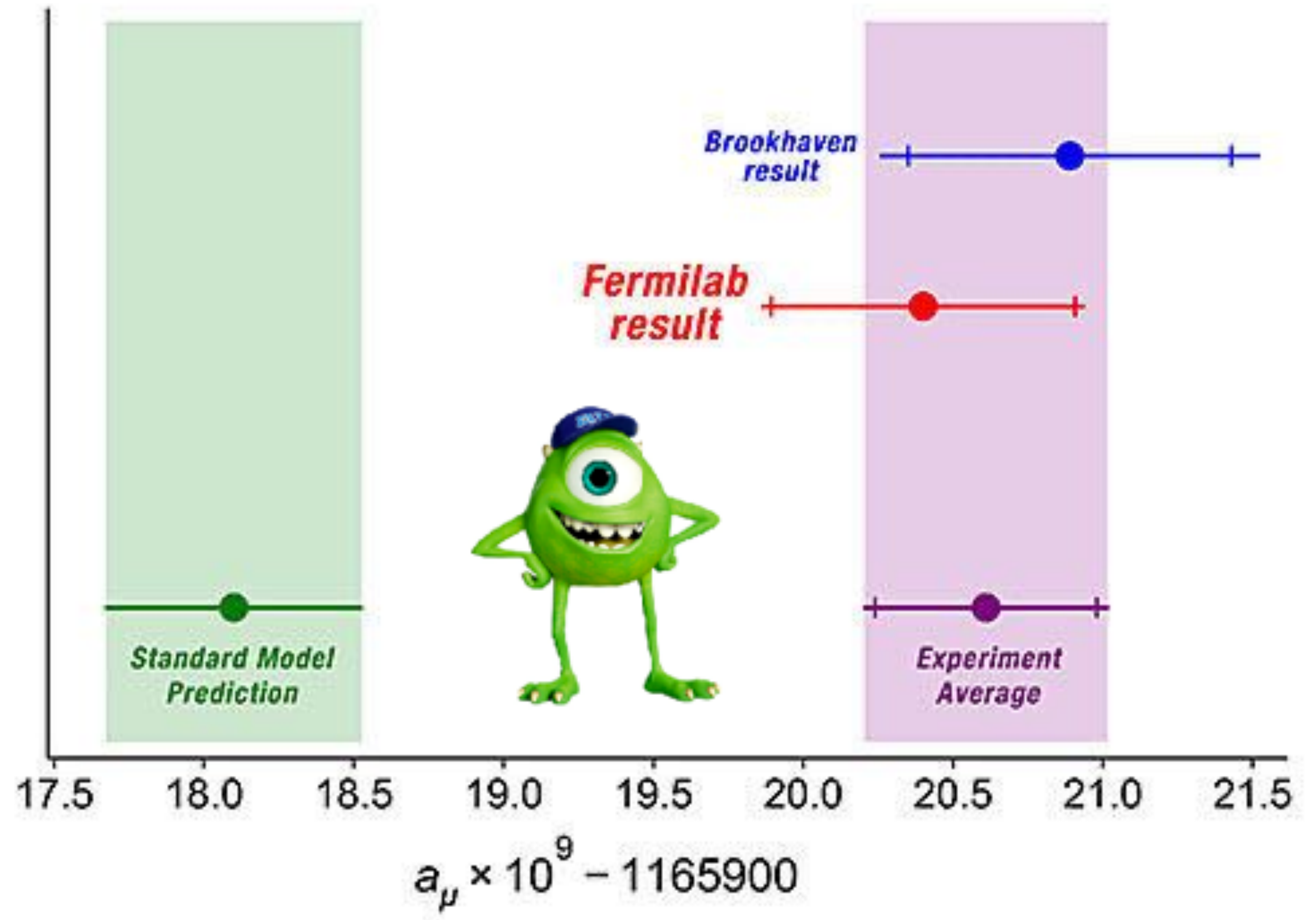
Probing BSM with muons

Apr 7, 2021

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm
Muon g-2 Collaboration • B. Abi (Oxford U.) et al. (Apr 7, 2021)
Published in: Phys.Rev.Lett. 126 (2021) 14, 141801 • e-Print: 2104.03281 [hep-ex]
pdf links DOI cite claim 904 citations

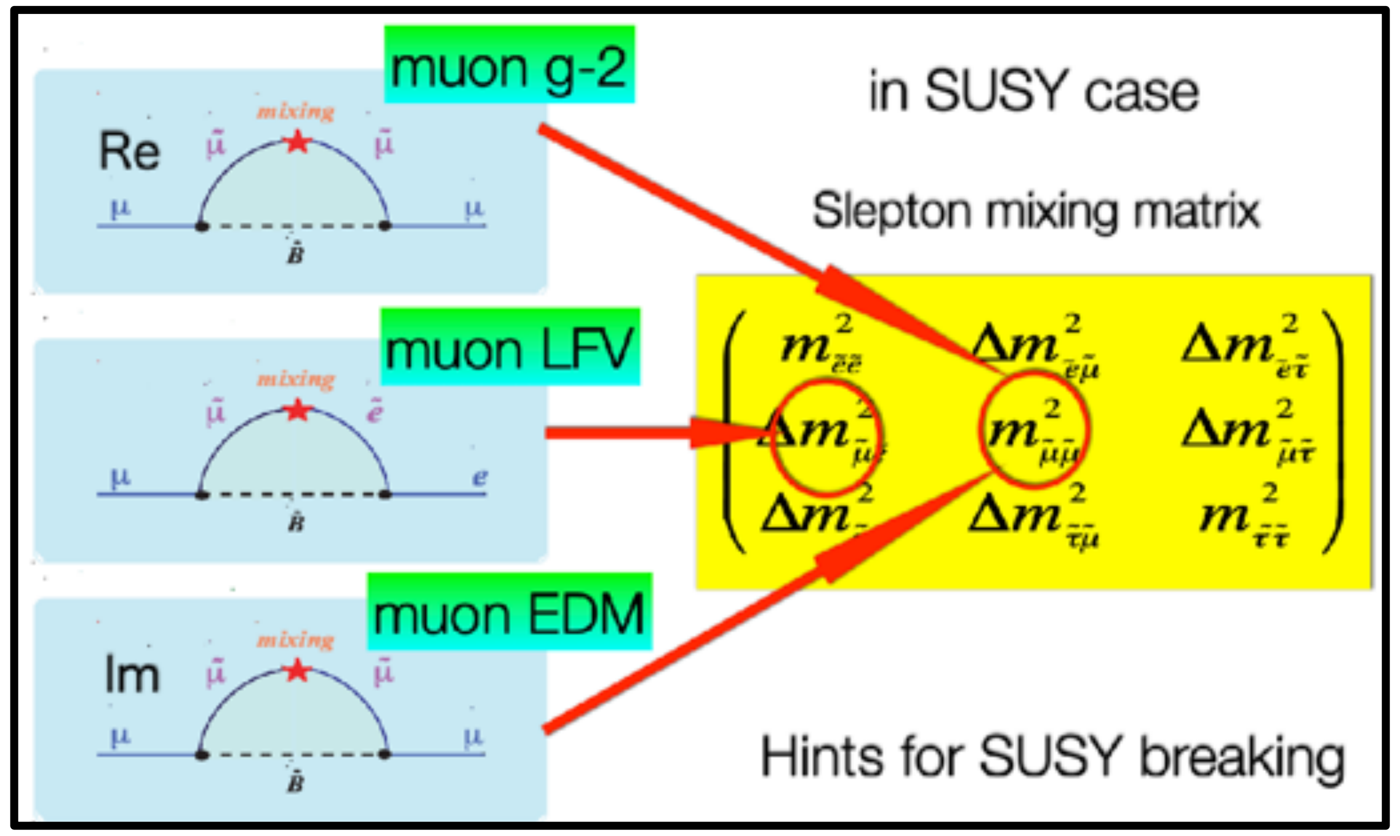
- Muon is a very sensitive probe for BSM physics
- The Muon Trio in Precision and Intensity Frontiers
  - *g-2, EDM, charged lepton flavor violation (cLFV)*





Unveil new physics

Probe energy scale otherwise unreachable E > 1000 TeV



Courtesy Yoshitaka Kuno

Very active research area!

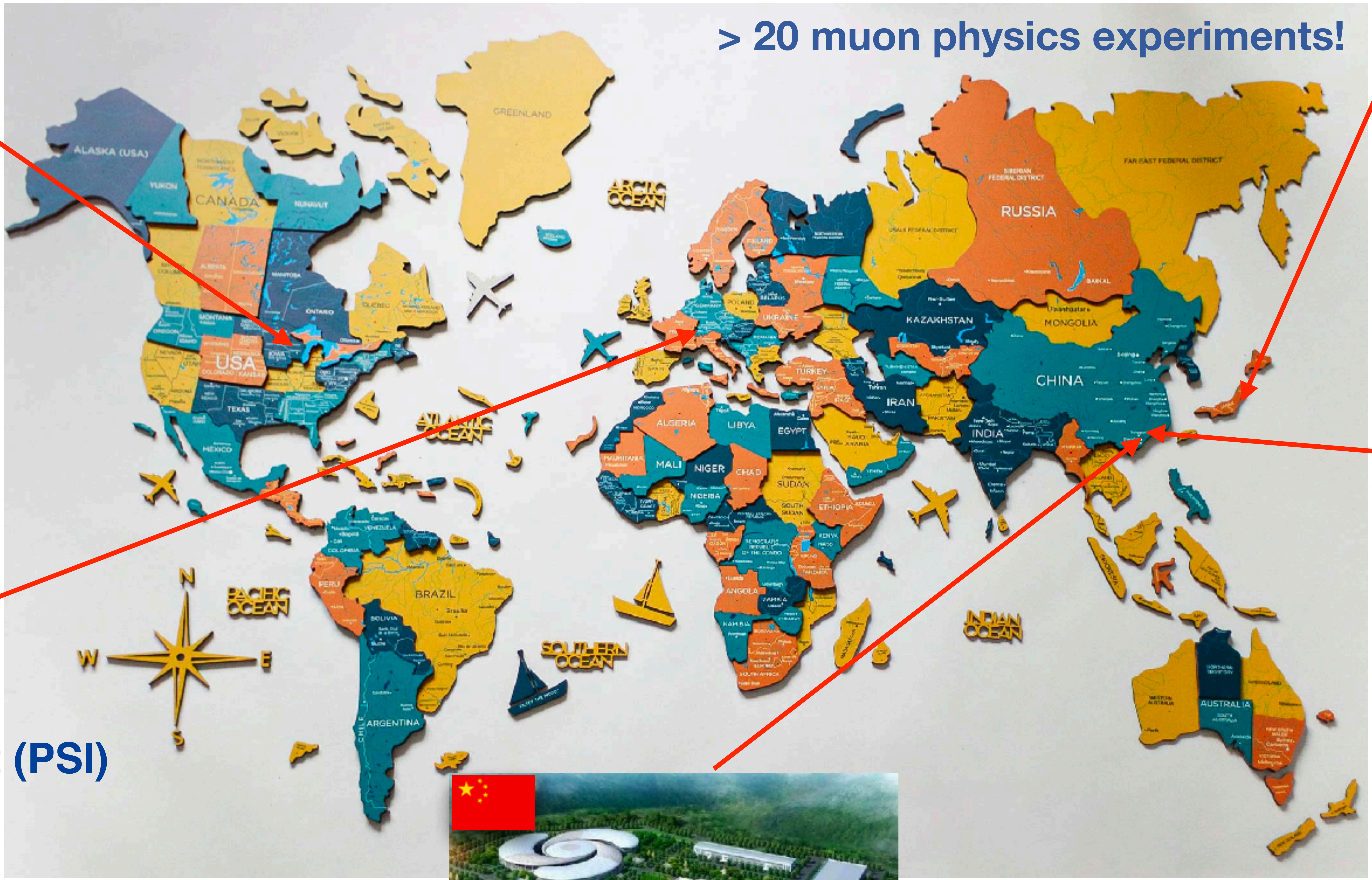
Tsung-Dao Lee Institute

Fermilab

Muon g-2 (SJTU)
Mu2e (SYSU)

Paul Scherrer Institut (PSI)

muEDM (SJTU)
MEG II, Mu3e,
MUSE, CREMA, etc



> 20 muon physics experiments!

J-PARC

Muon g-2/EDM (PKU)
COMET (IHEP), DeeMe,
Mu HFS/1S-2S, etc

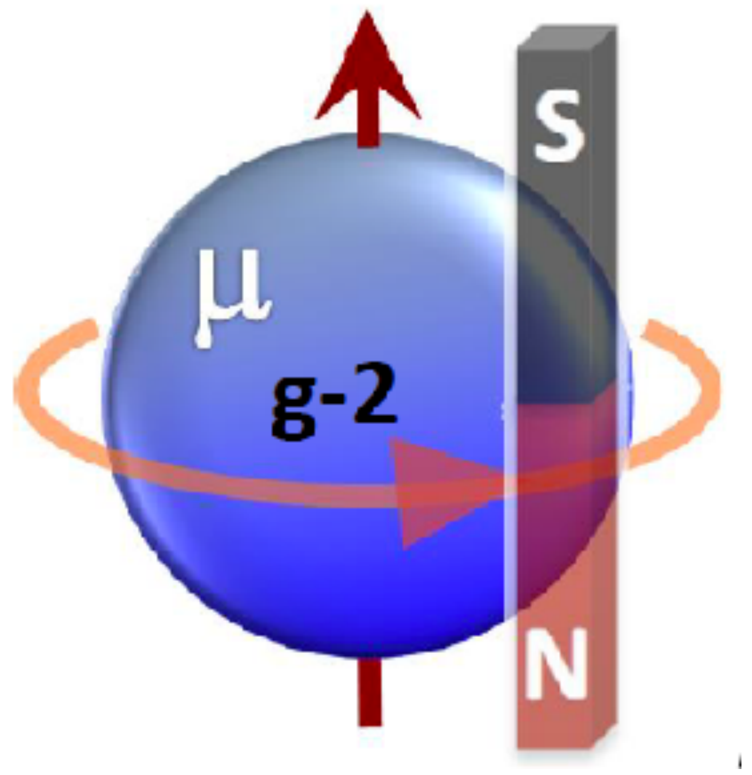
中国散裂中子源

MACE (IHEP, SYSU)

中国强流重离子加速器装置

Next generation muon g-2/EDM

The Muon Moments: g-2 and EDM

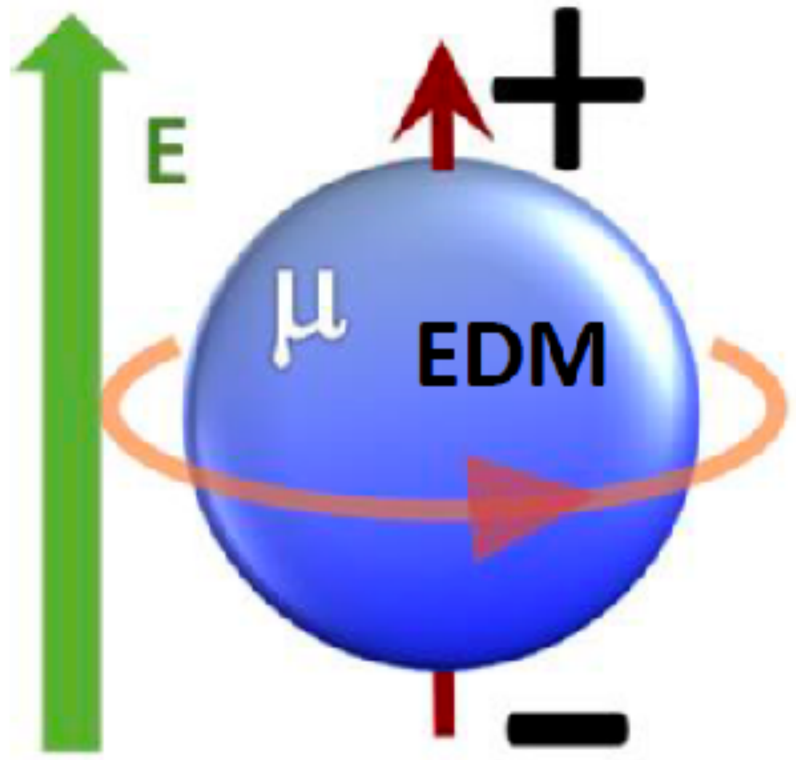


$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

- g-2 can be calculated and measured to very high precision
  - SM Theory: 370 ppb
  - Fermilab experiment: 460 ppb

百万分之一以上的精度!

- Precision test of SM calculations
  - Sensitive to 4-loop QED, QCD, and EW
- The difference between theoretical and experimental values probes BSM physics
  - Complementary to LHC searches



$$\vec{d} = \eta\frac{e}{2m}\vec{s}$$

- A search for new physics which is essentially “background-free”
  - The contribution from SM’s CKM matrix is too small (d ~ 10^{-42} e cm)
  - Current limit d ~ 10^{-19} e cm
- Many BSM models predict large EDMs
  - Complementary to LHC searches
- Baryon asymmetry in the universe (BAU) requires more CPV
  - EDMs are good probes of BSM CPV

Standard Model Prediction of a_μ

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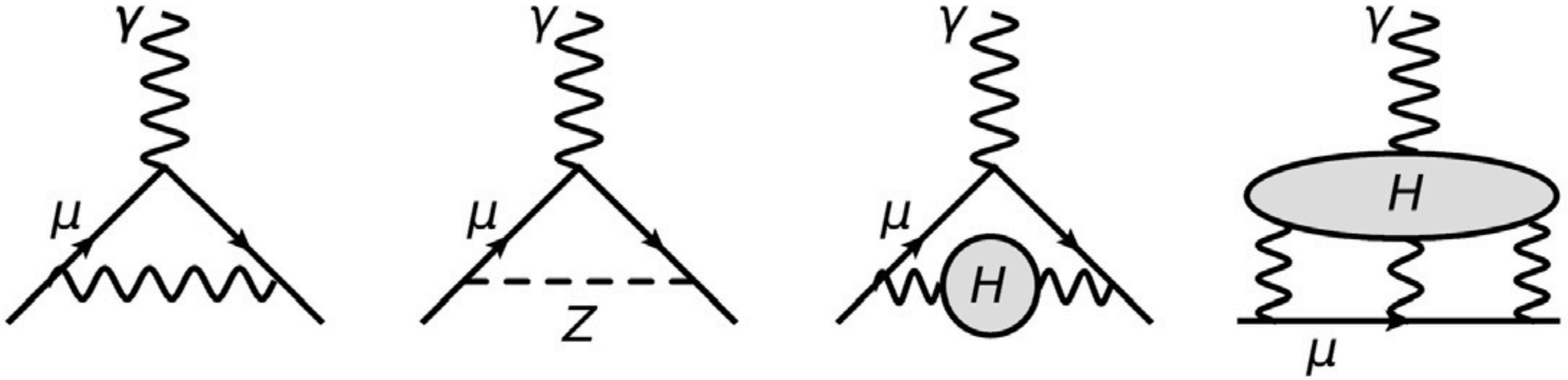
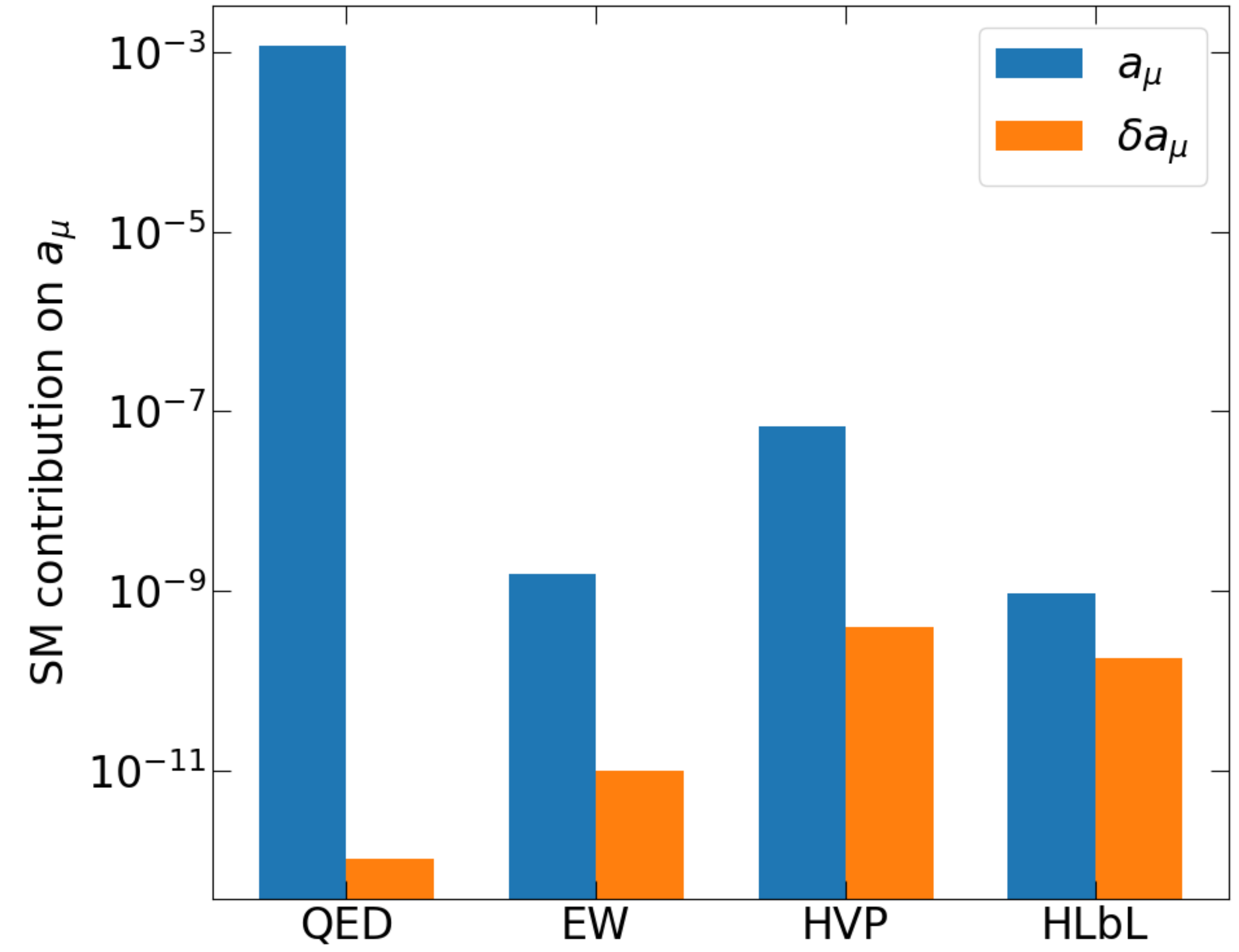


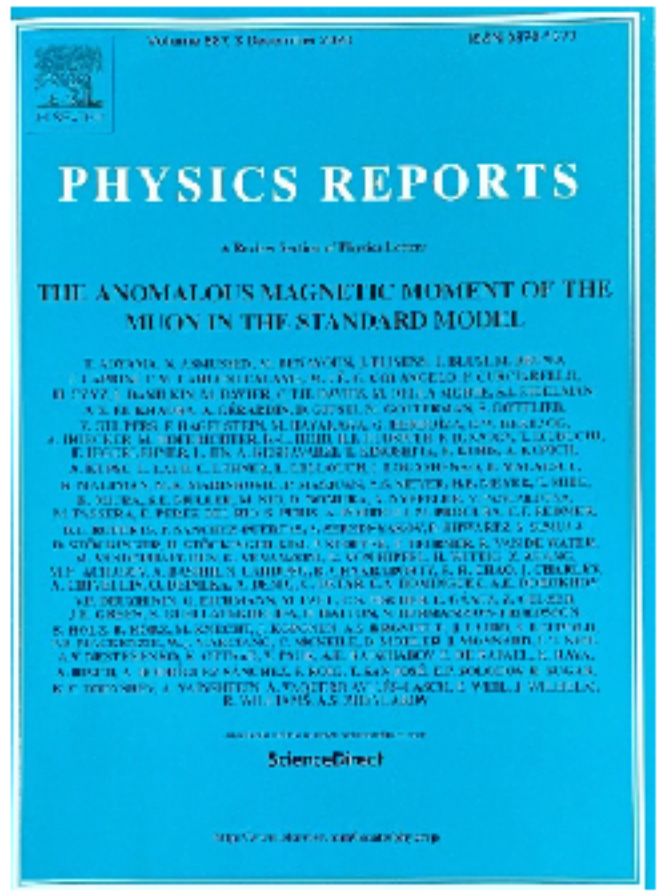
QED EW HVP HLbL



强子真空极化

$$a = \frac{g-2}{2}$$

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP,\ LO}} + a_\mu^{\mathrm{HVP,\ NLO}} + a_\mu^{\mathrm{HVP,\ NNLO}} + a_\mu^{\mathrm{HLbL}} + a_\mu^{\mathrm{HLbL,\ NLO}}$$
$$= 116\,591\,810(43) \times 10^{-11}$$ (370 ppb)

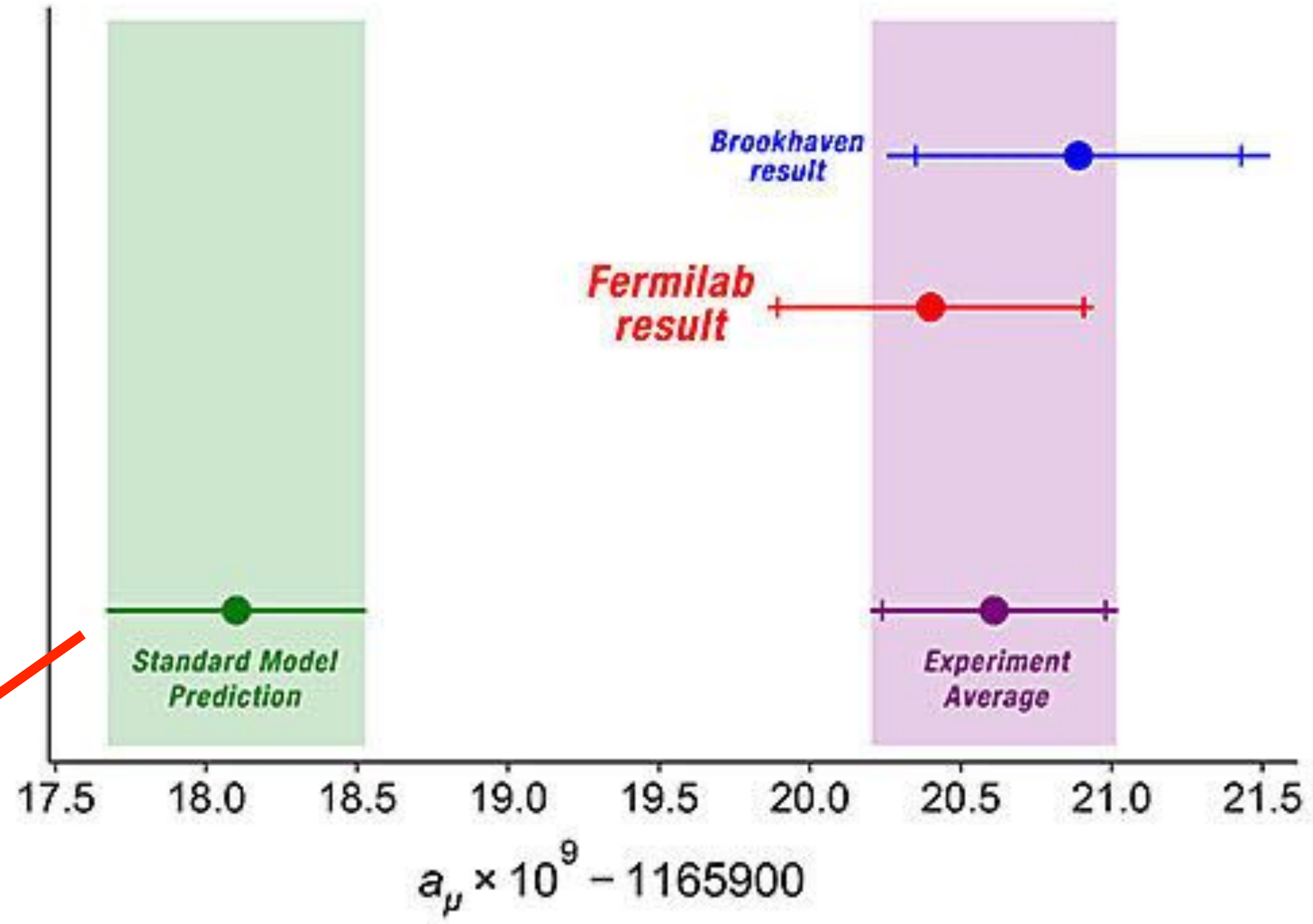


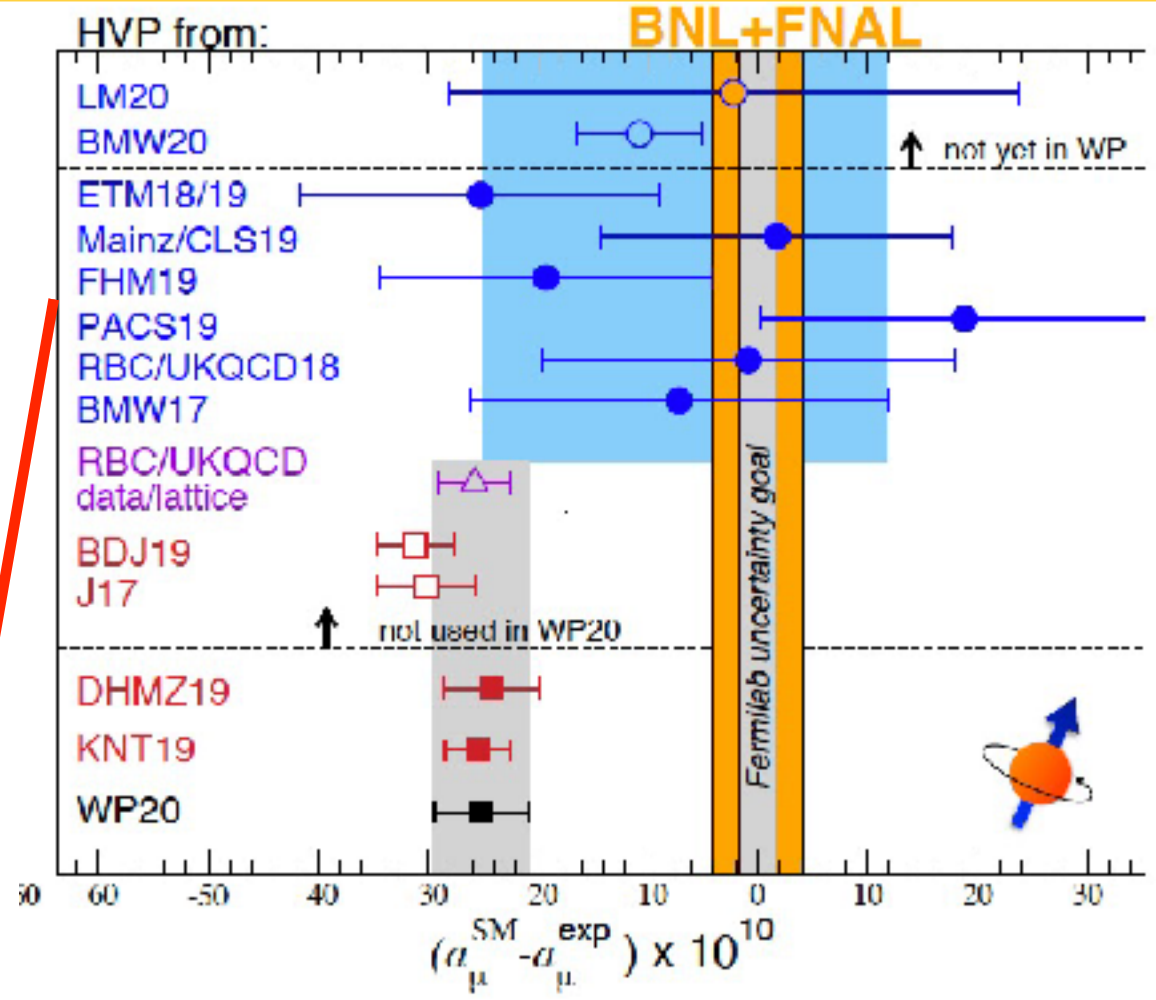
Theory Initiative White Paper: T. Aoyama et al. Phys. Rept. **887** (2020)

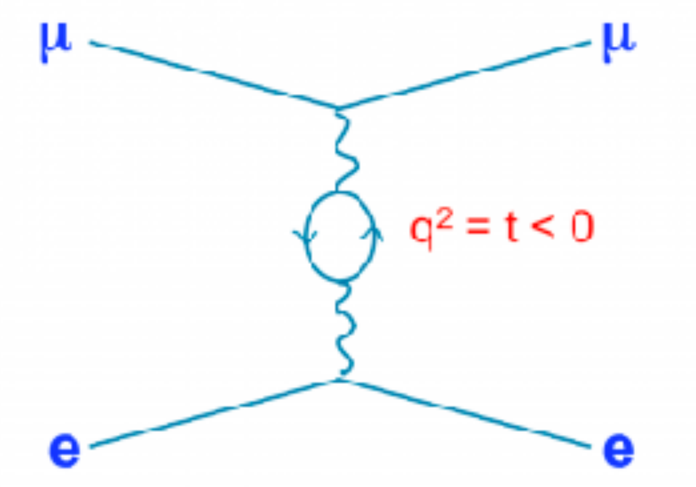
More on HVP contributions

Theory initiative: estimate of ~2025 to sort all this out

New results from CMD-3, BaBar, BES-III and Belle-II expected!

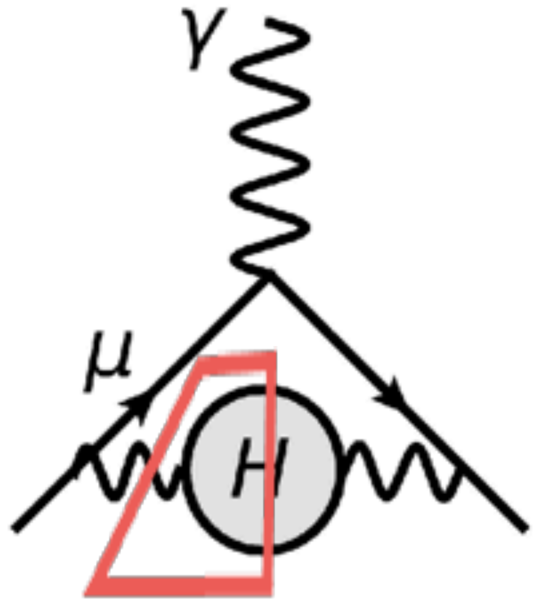


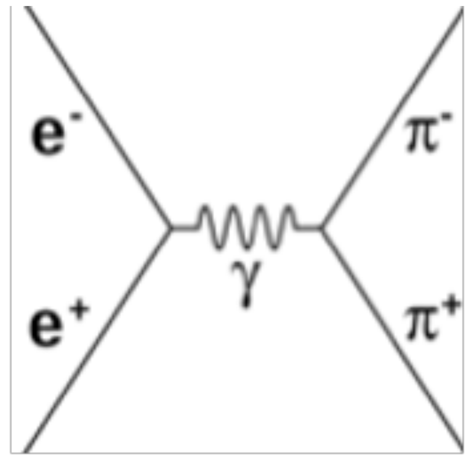




Very important cross check!
First run: 2022-2024

1) Dispersion relation + low energy e⁺e⁻ -> hadrons

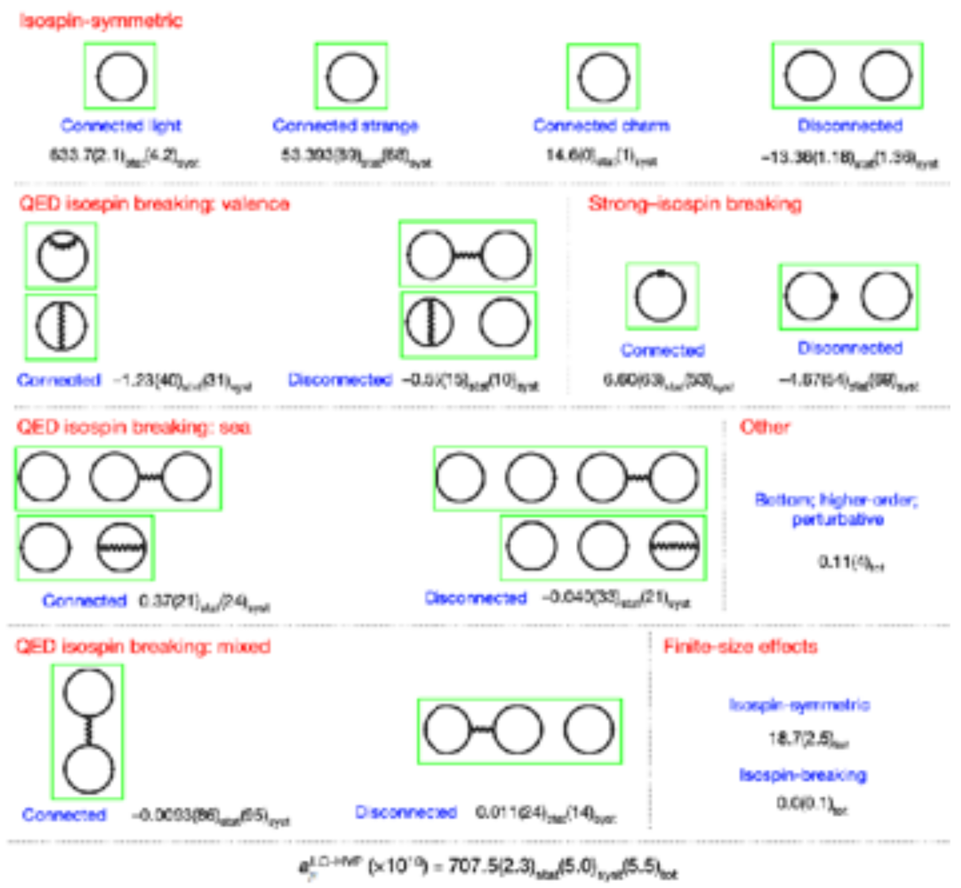




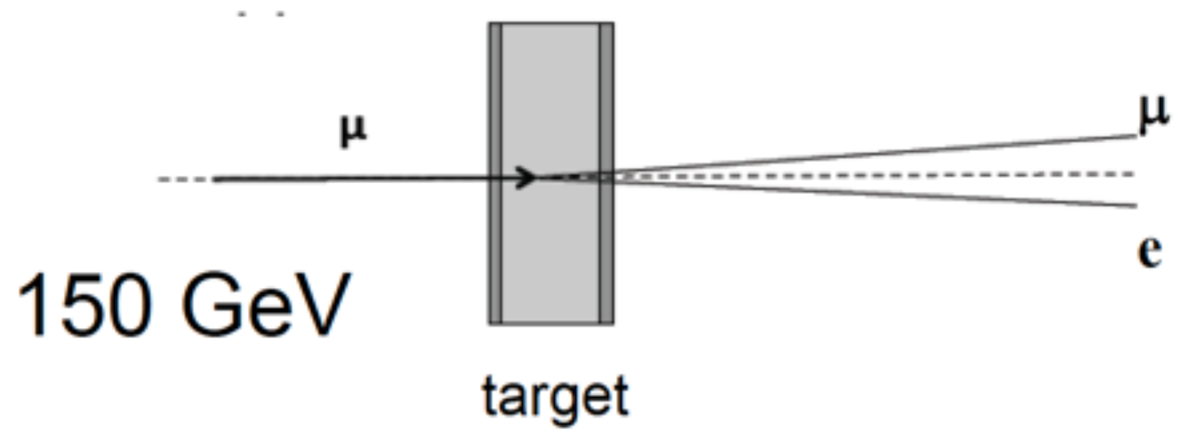
e⁺e⁻ to hadrons

$$a_\mu^{\text{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\text{th}}}^{\infty} ds\, \frac{1}{s}\hat{K}(s)\sigma_{\text{had}}(s)$$

2) Lattice QCD + supercomputers



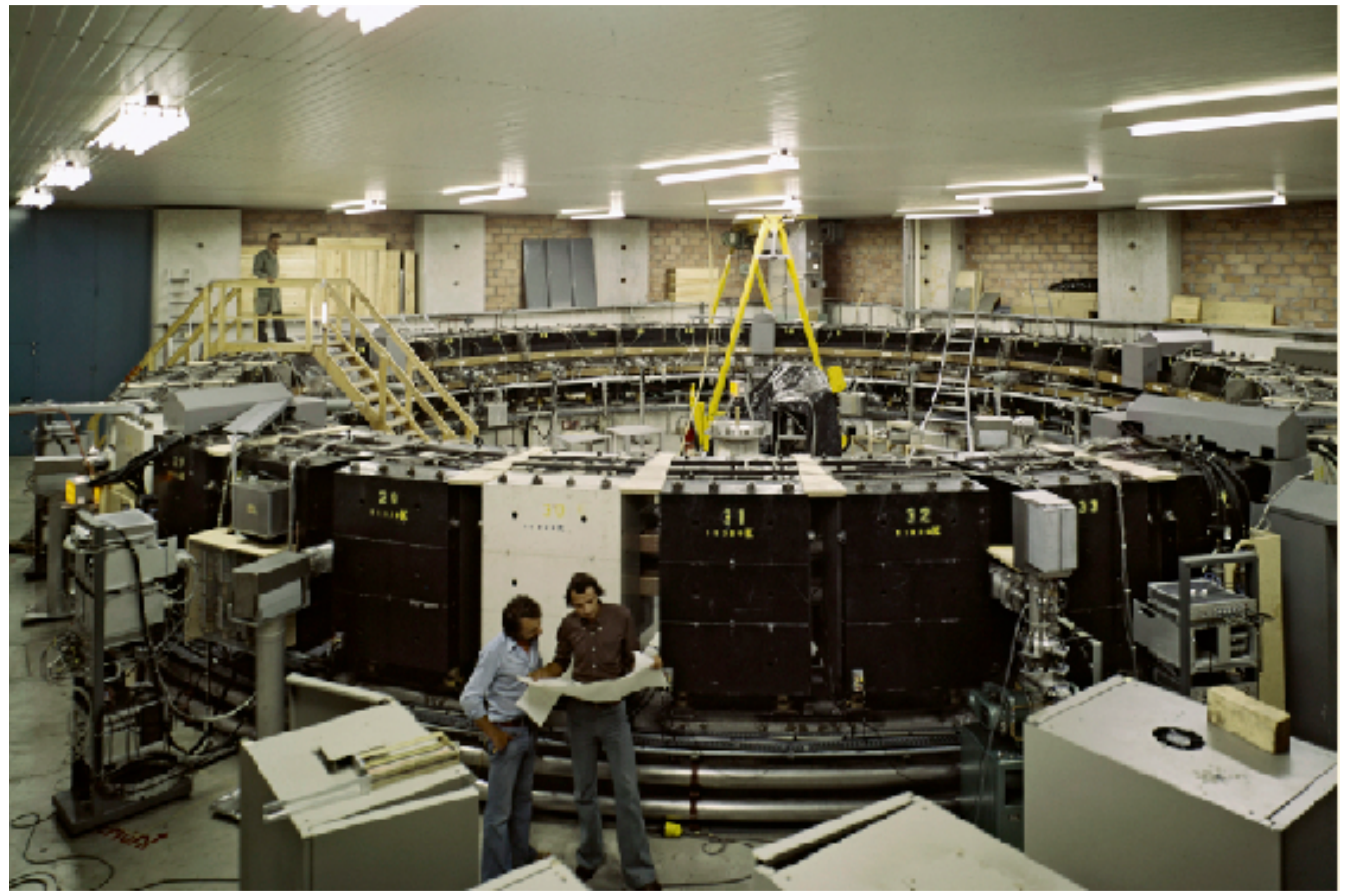
3) Dispersion relation + muon scattering on electrons



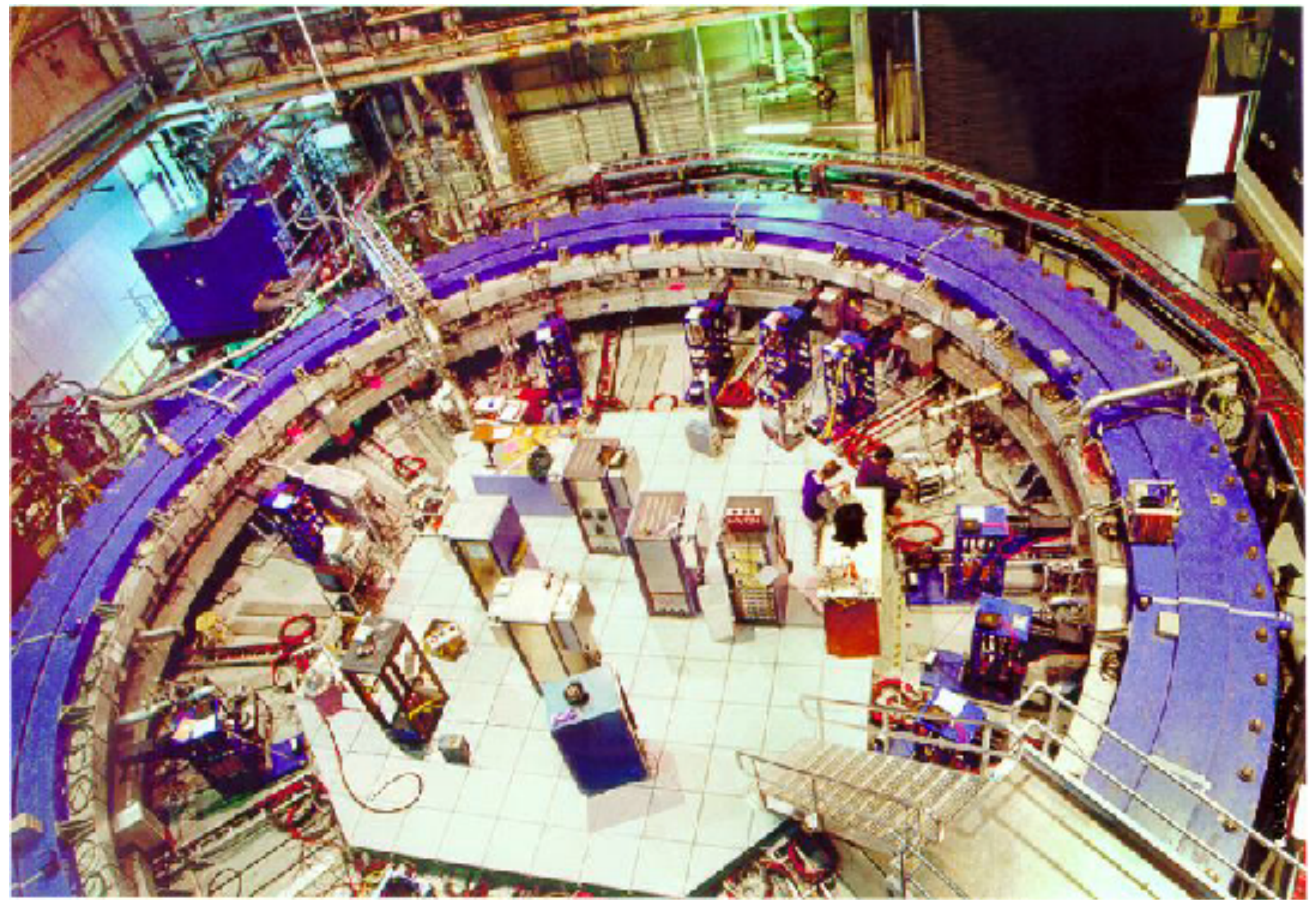
Phys. Lett. B 746 (2015), 325

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\cdot\Delta\alpha_{had}\left(-\frac{x^2 m_\mu^2}{1-x}\right)$$

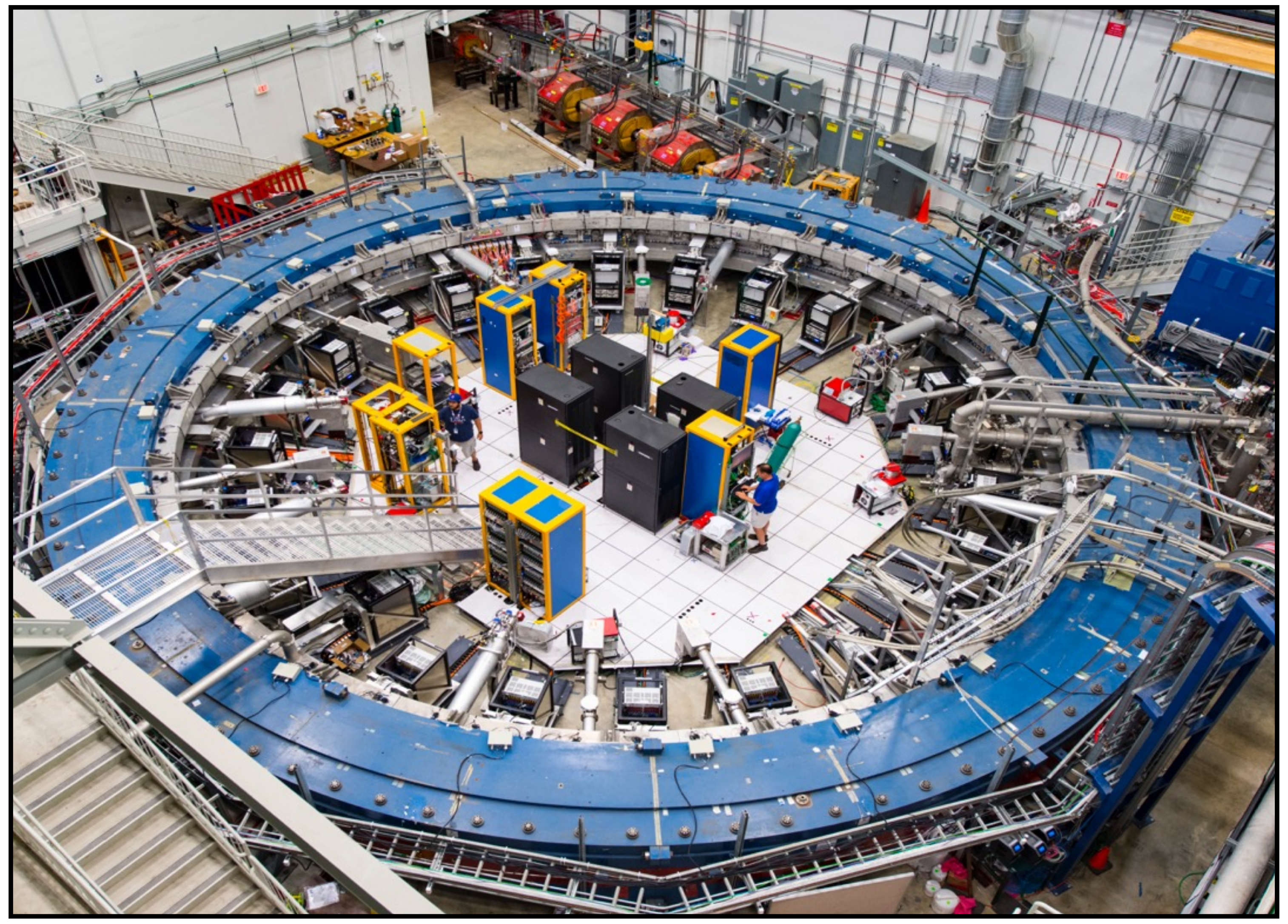
Four generations of storage rings



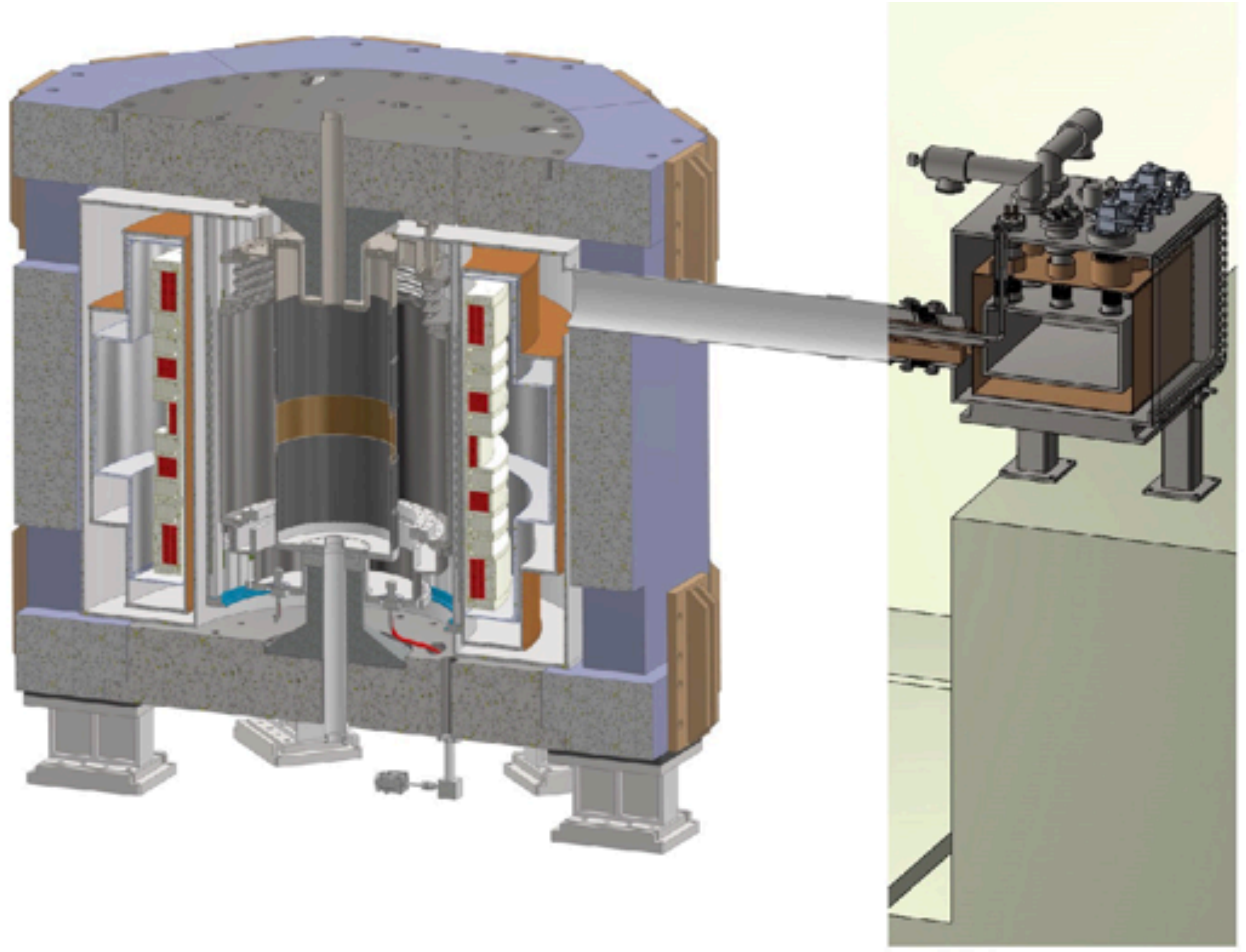
CERN
1960-1970s
7.3 ppm
(completed)



BNL
1990-2000s
0.54 ppm
(completed)



Fermilab
2009-2023
0.14 ppm
(in progress)



J-PARC
2009-2030s
0.45 ppm
(under construction)

Muon g-2 Collaboration

(>200 collaborators, 35 institutes, 7 countries)

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS
- KAIST

Russia

Budker/Novosibirsk
JINR Dubna

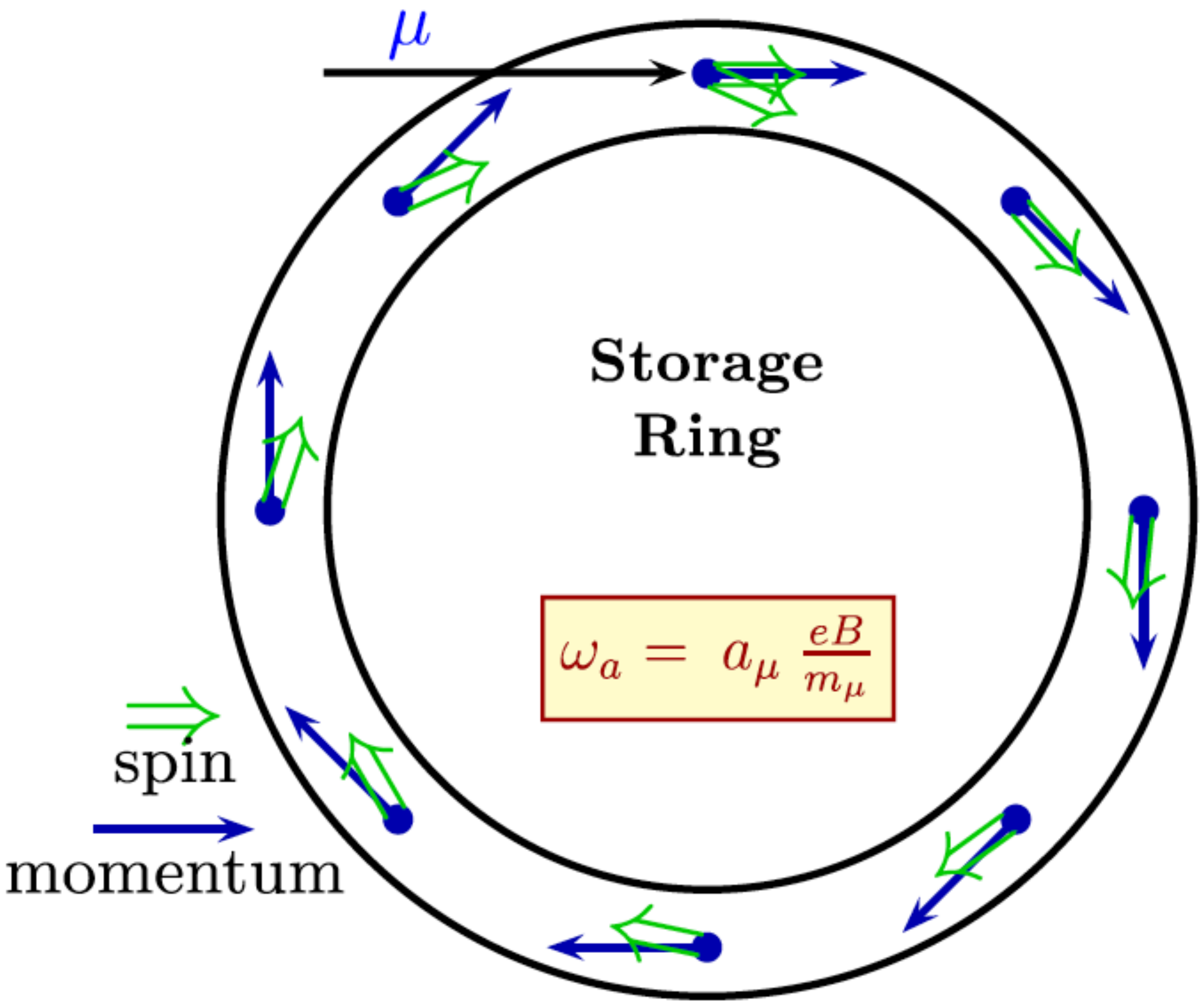
United Kingdom

Lancaster/Cockcroft
Liverpool
Manchester
University College London

We include: Particle-, Nuclear-, Atomic-, Optical-, Accelerator-, and Theoretical Physicists
And we combine our effort to measure a single value, g-2, to 140 ppb (BNL - 540 ppb)!

Muon g-2 collaboration meeting at Elba, Summer 2019

Principle of g-2 measurement



Larmor Thomas Cyclotron

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

Anomalous precession frequency

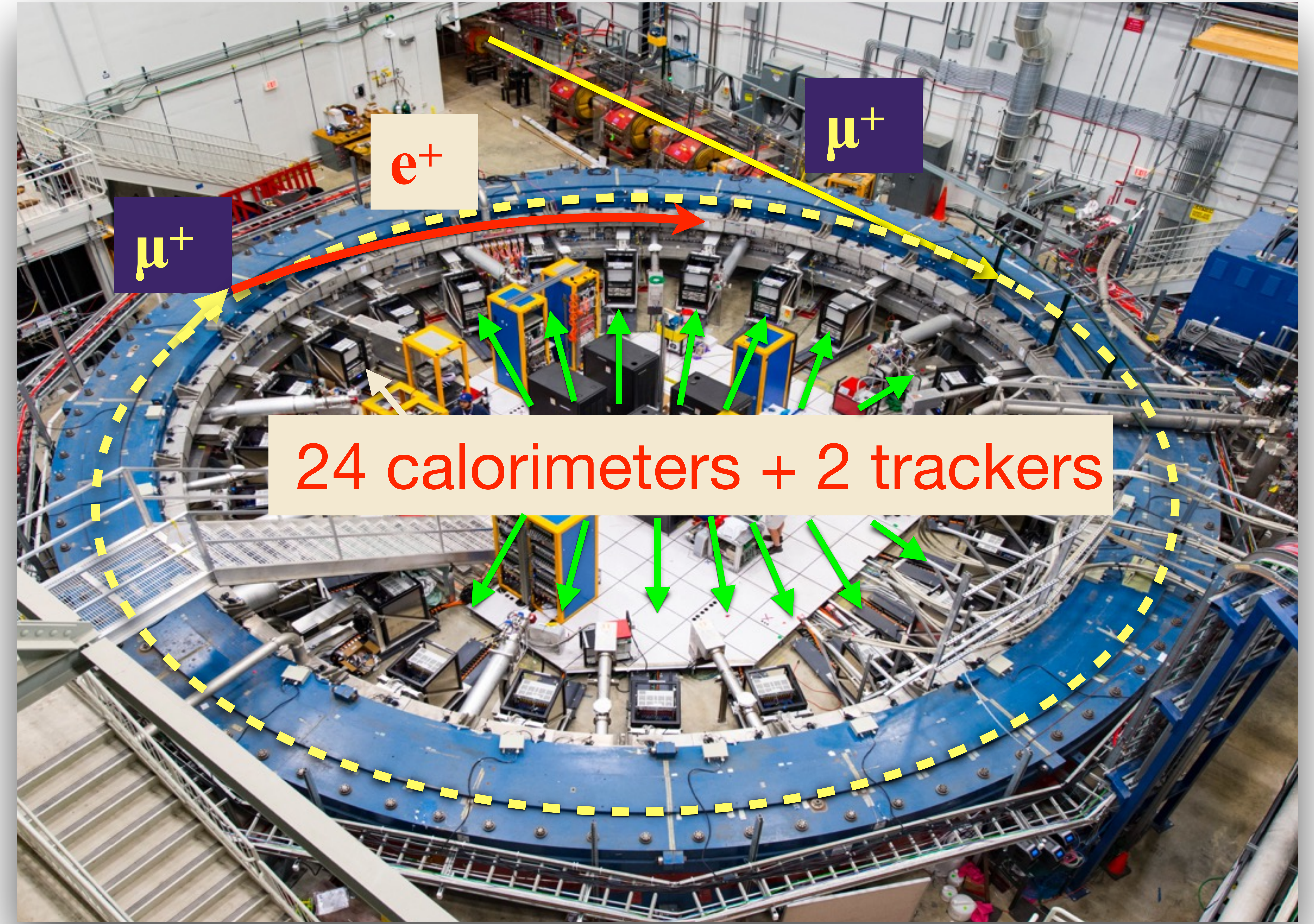
$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$

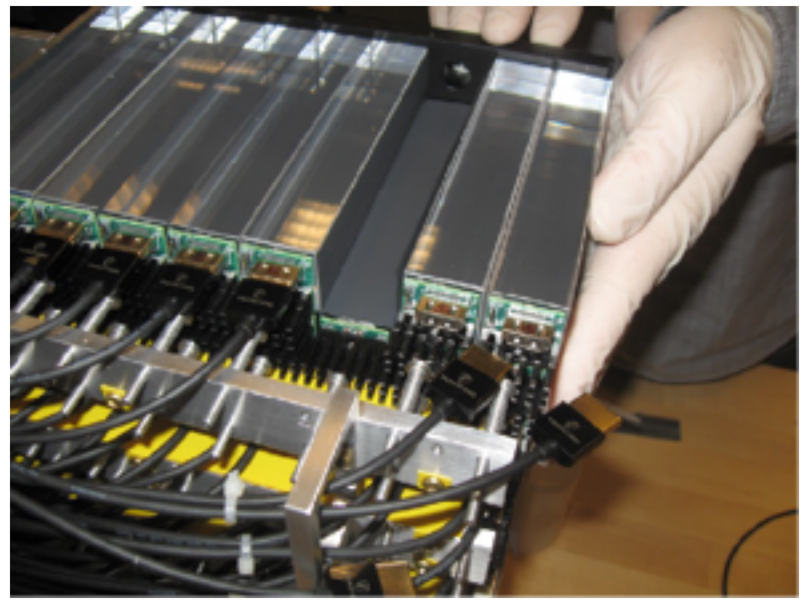
measure difference in frequency precisely

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

homogenous field and precise field measurement

A grand view of the g-2 ring

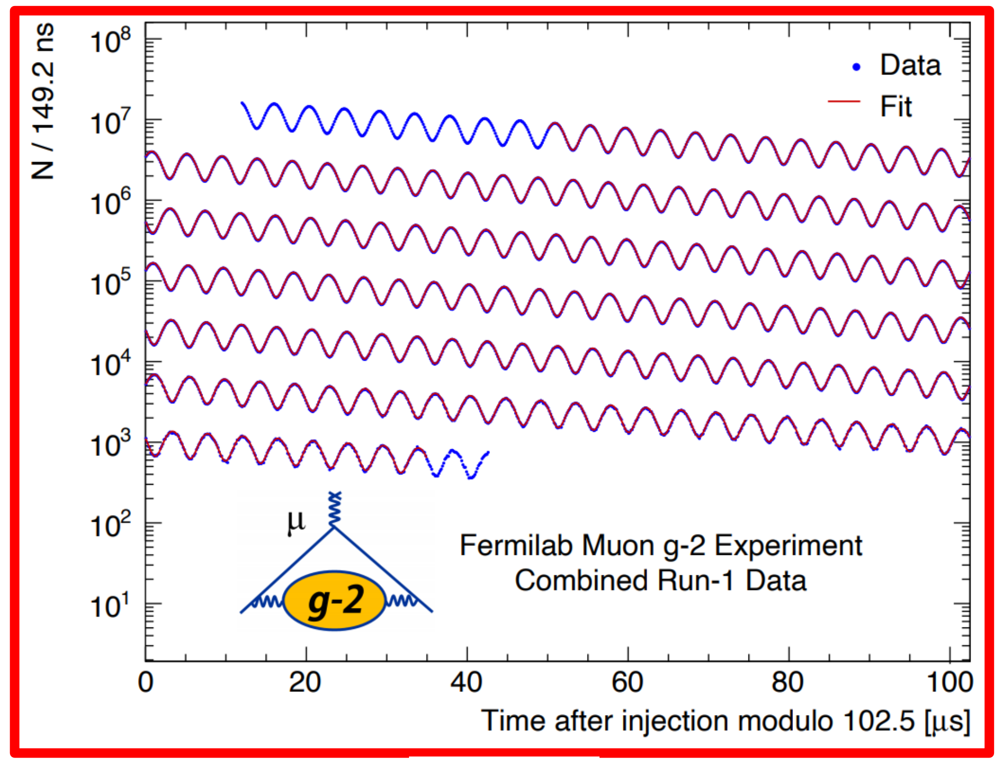


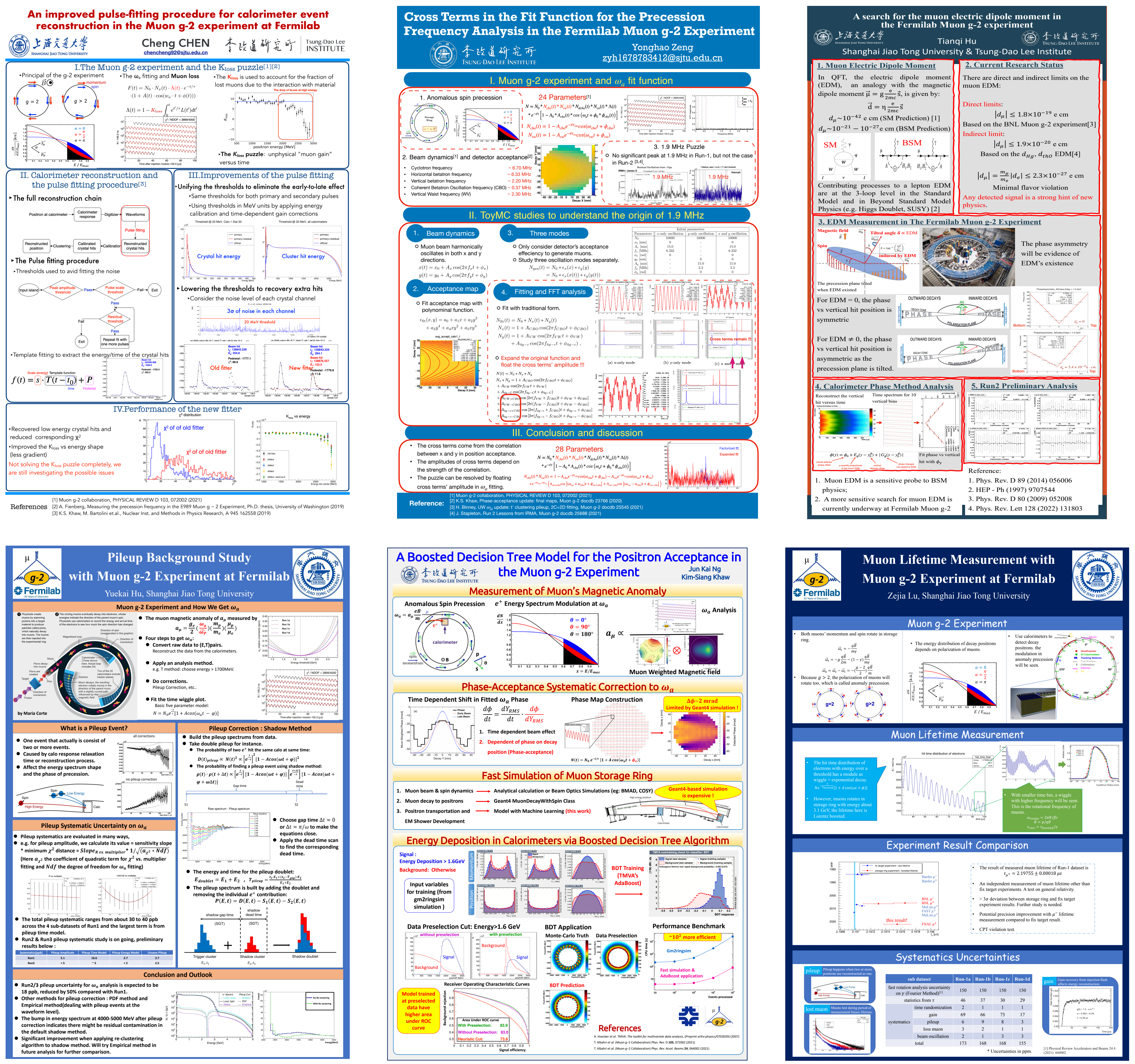


1. Inject muon beam into the storage ring and store them
2. Monitor the magnetic field with fixed and trolley probes
3. Detect positrons with calorimeters and trackers

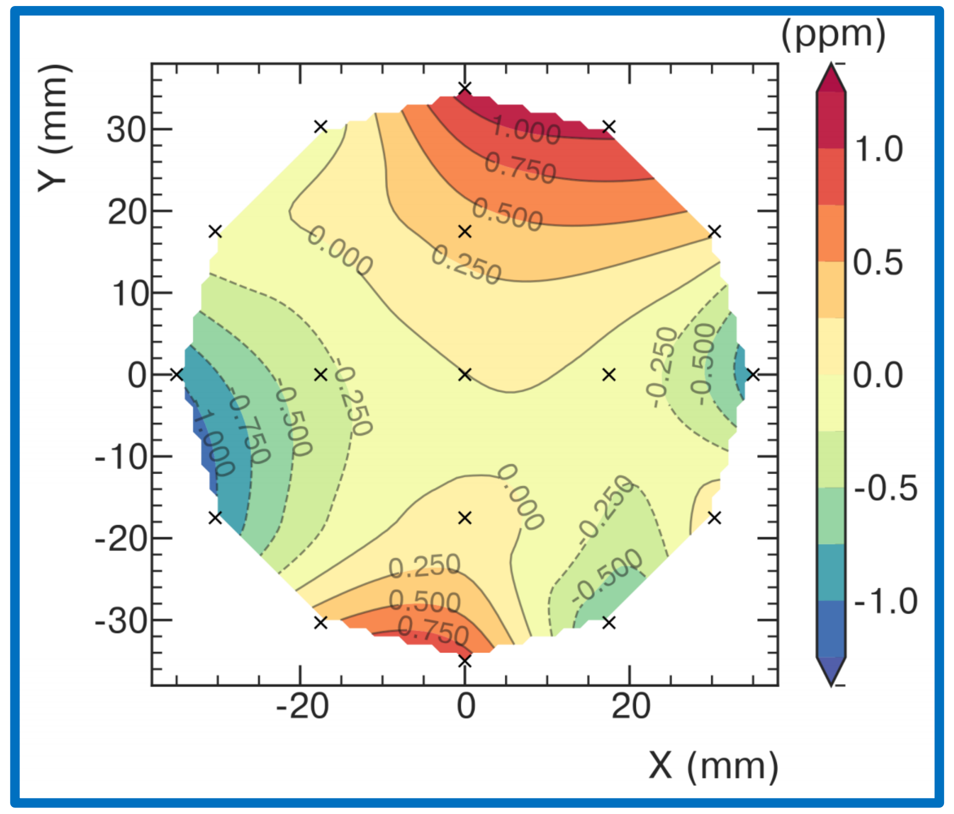
Visualizing the measurements

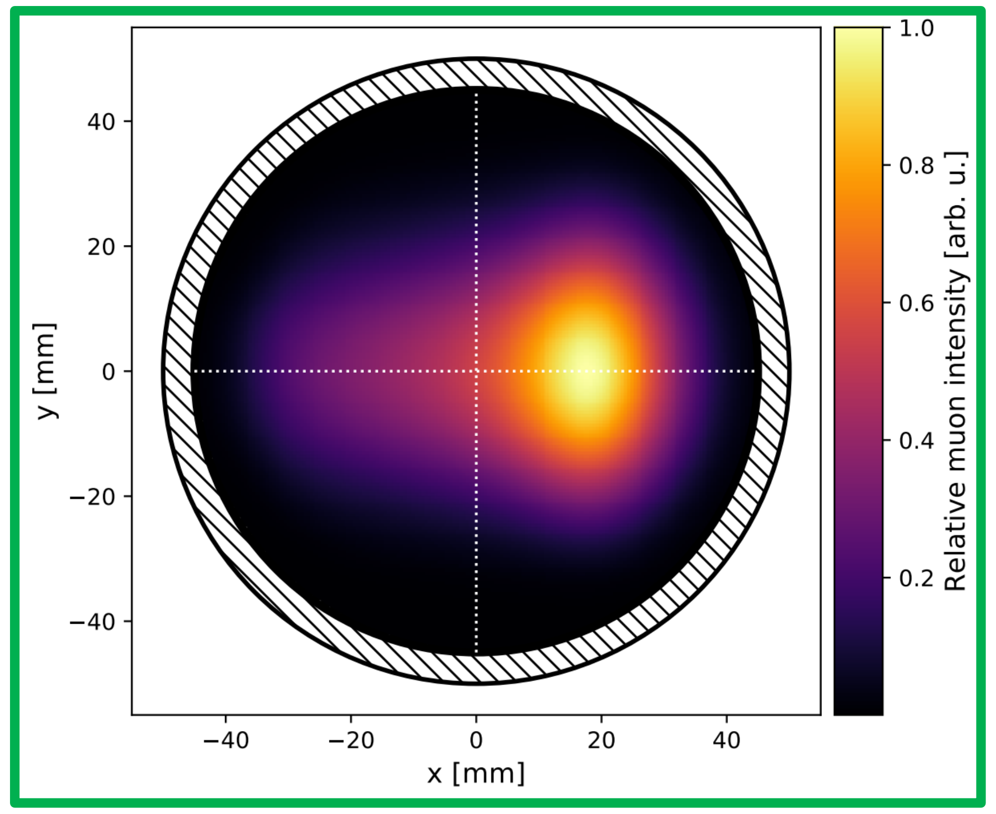
Details of analysis in poster session yesterday!





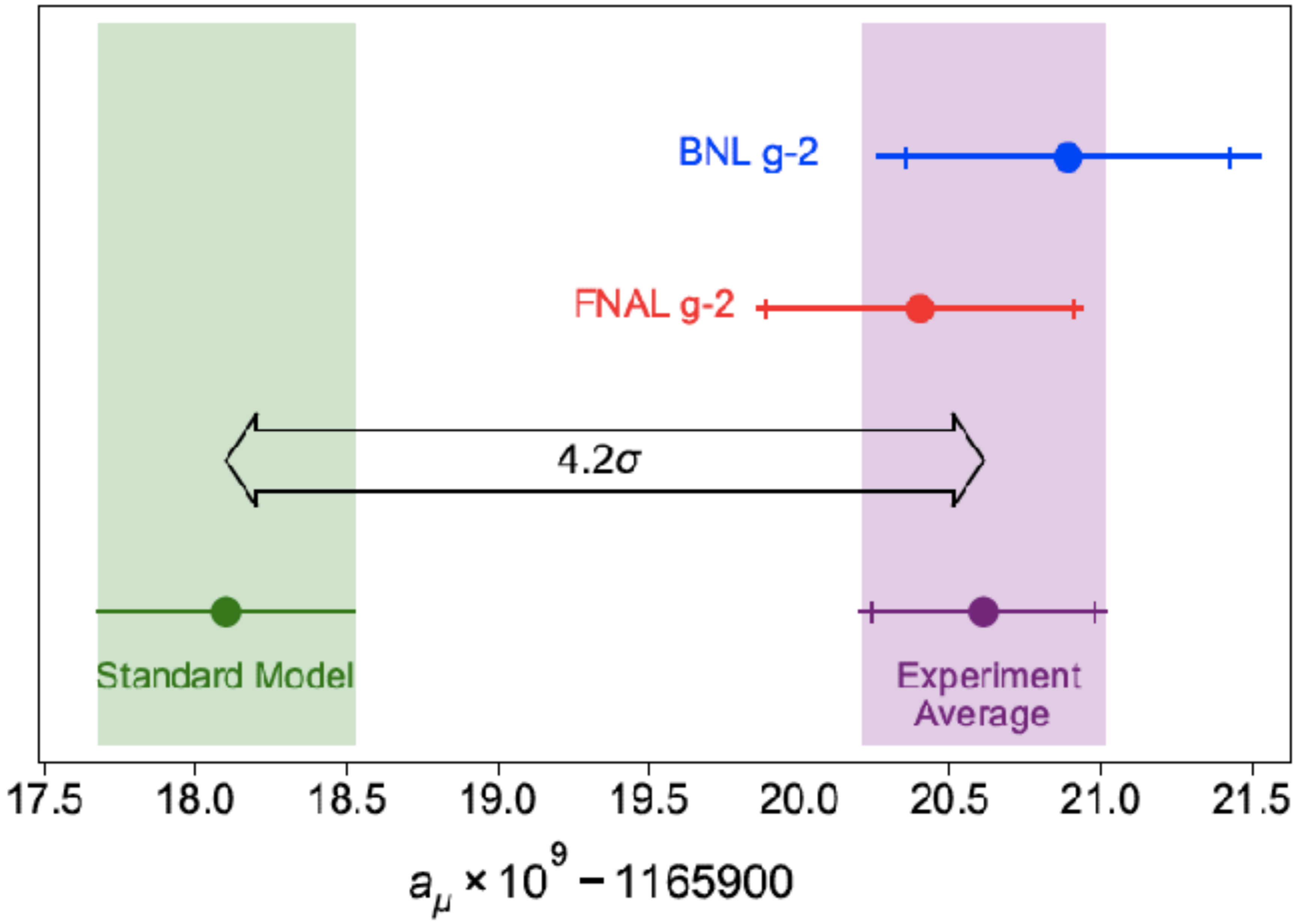
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle\ \omega_p(x,y,\phi)\times M(x,y,\phi)\ \rangle(1 + B_k + B_q)}$$





https://indico.ihep.ac.cn/event/16065/timetable/#20220810.detailed

Run-1 result (Apr 2021)



Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a (statistical)	–	434
ω_a (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{calib}\langle\omega'_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_q	-17	92
B_k	-27	37
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total	–	462


4 中国科学报 2021年4月15日 星期四 综合

缪子反常磁矩实验：见证新物理？

实现多色光纤束无透镜衍射成像

发现结直肠癌治疗新靶标

Current status

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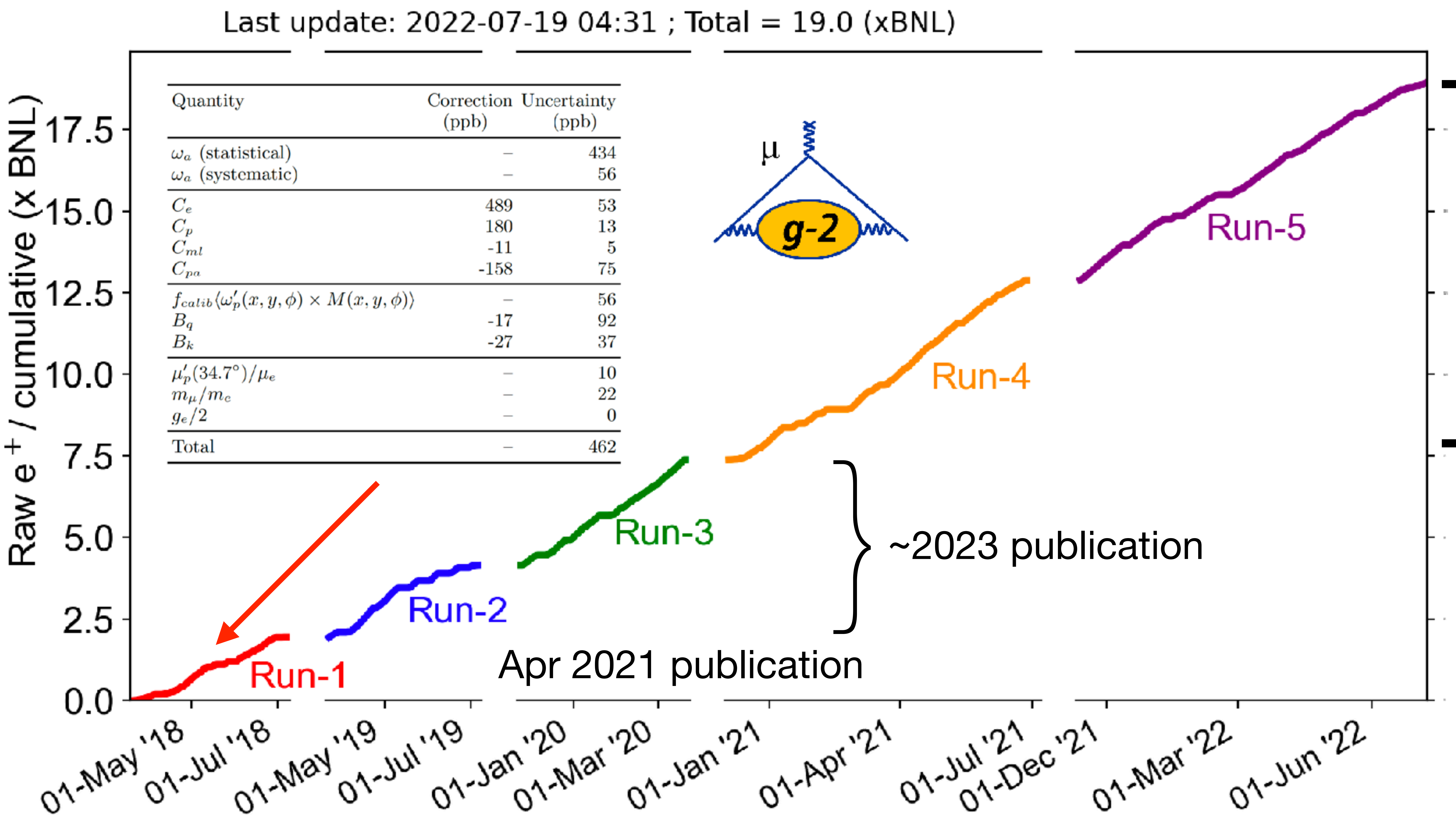

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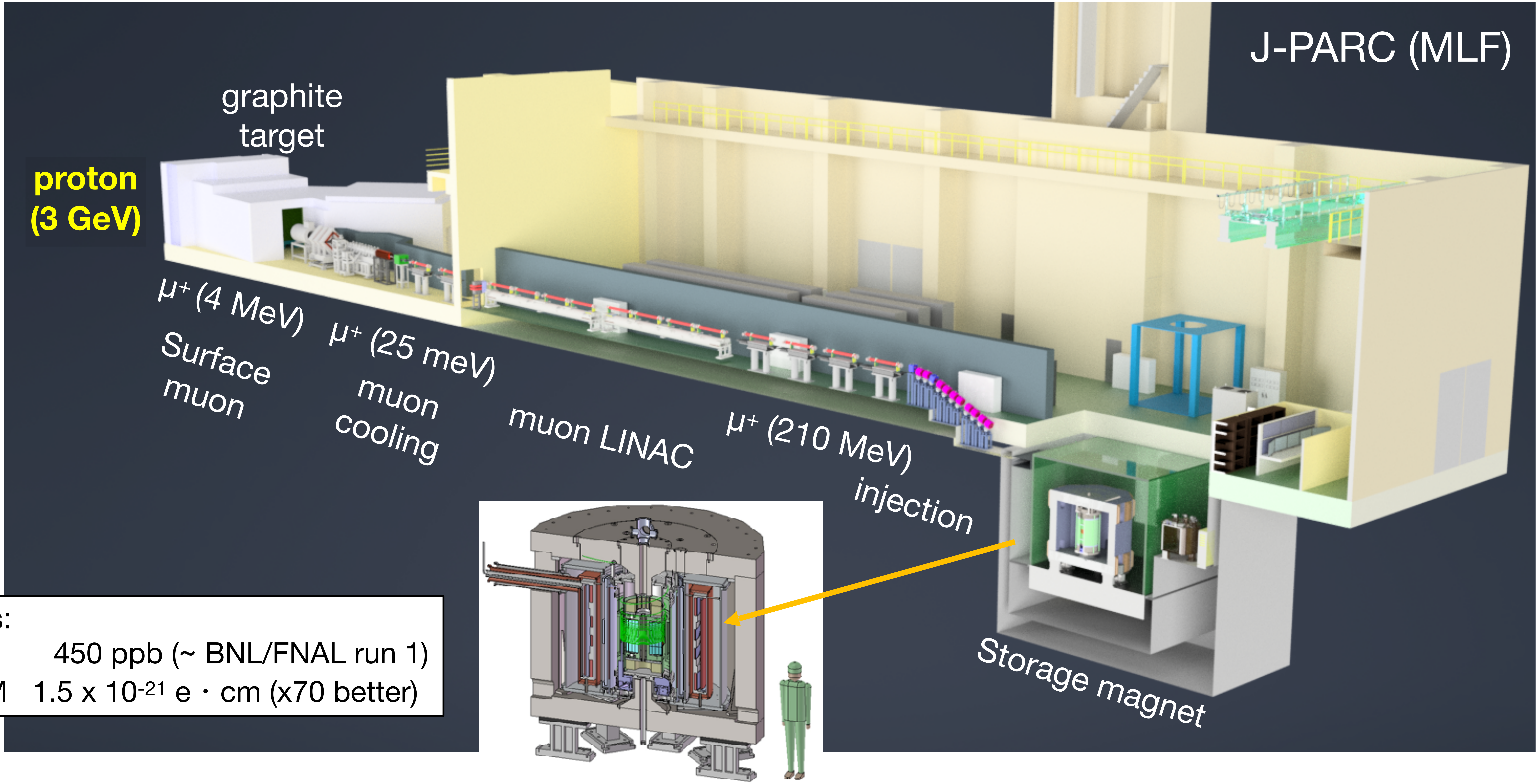
$\mu_p'(34.7°)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total	–	462

~2023 publication

~2024/2025 publication

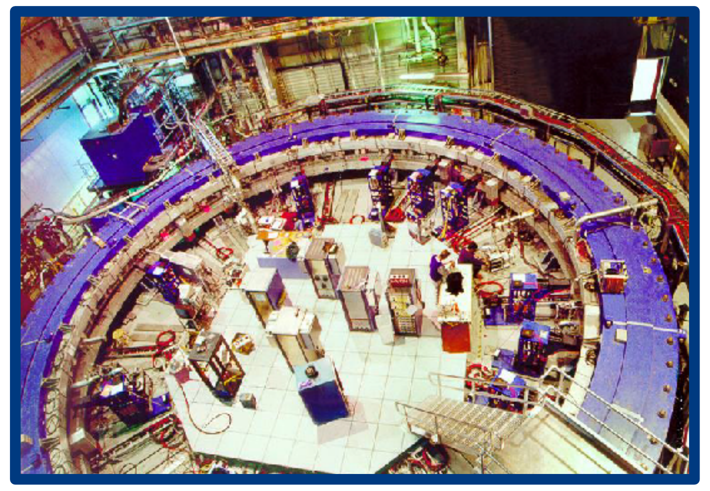
Run-6 will start this Fall
(More stats + systematic runs)

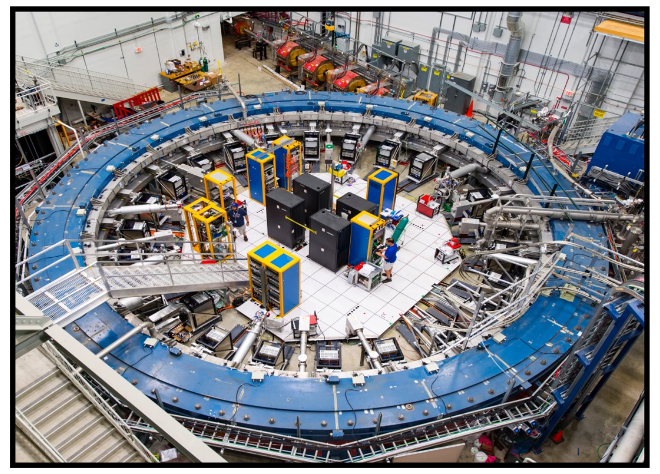
J-PARC Muon g-2/EDM

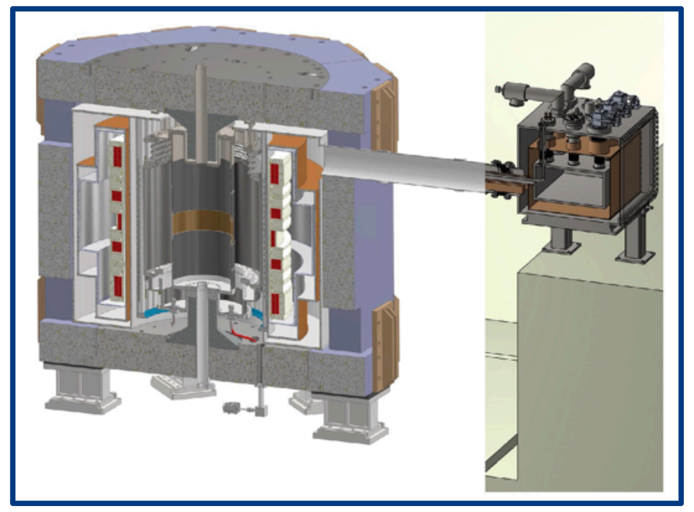


Goals:
g-2 450 ppb (~ BNL/FNAL run 1)
EDM 1.5×10^{-21} e · cm (x70 better)

Fermilab vs J-PARC

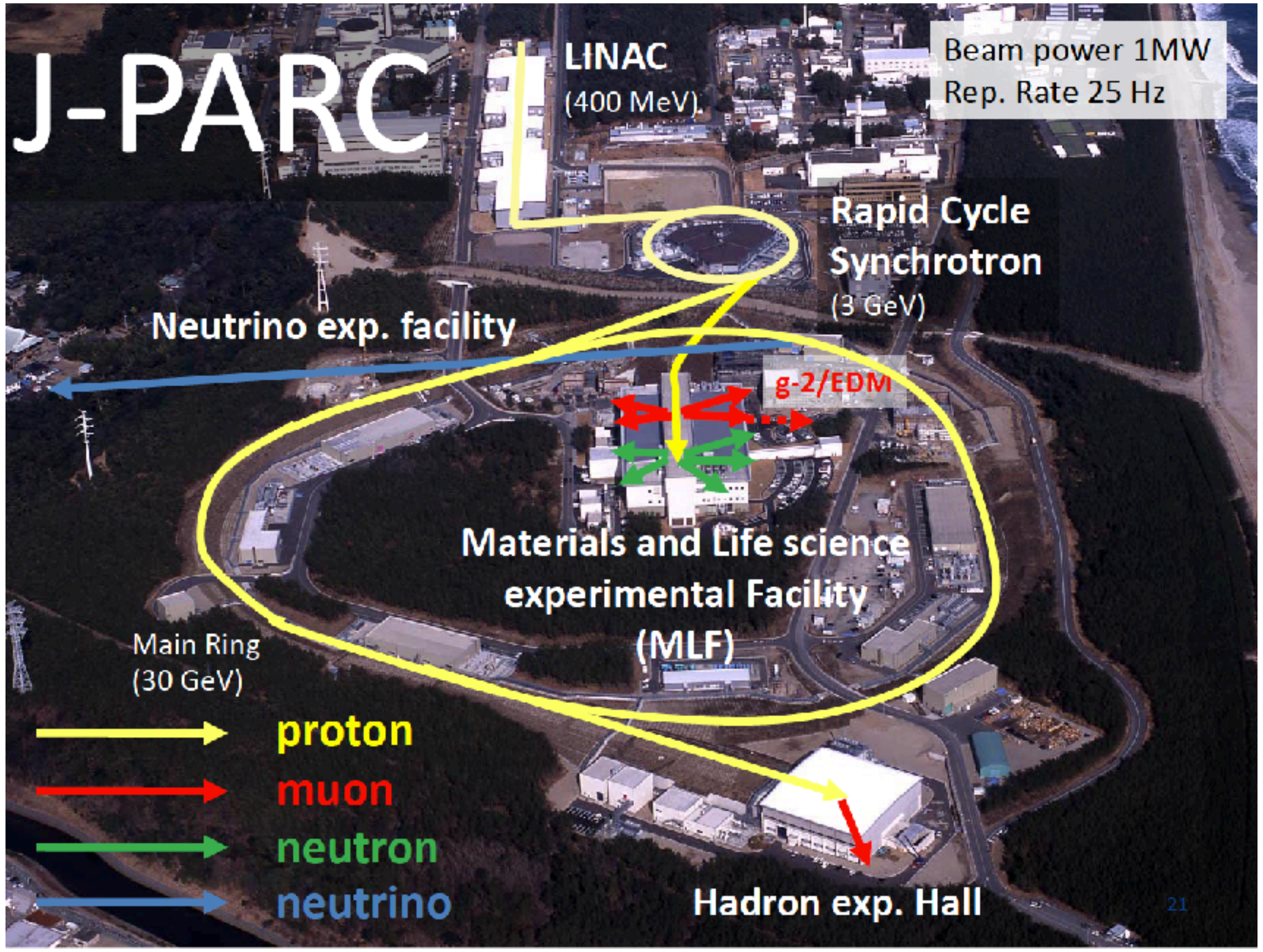


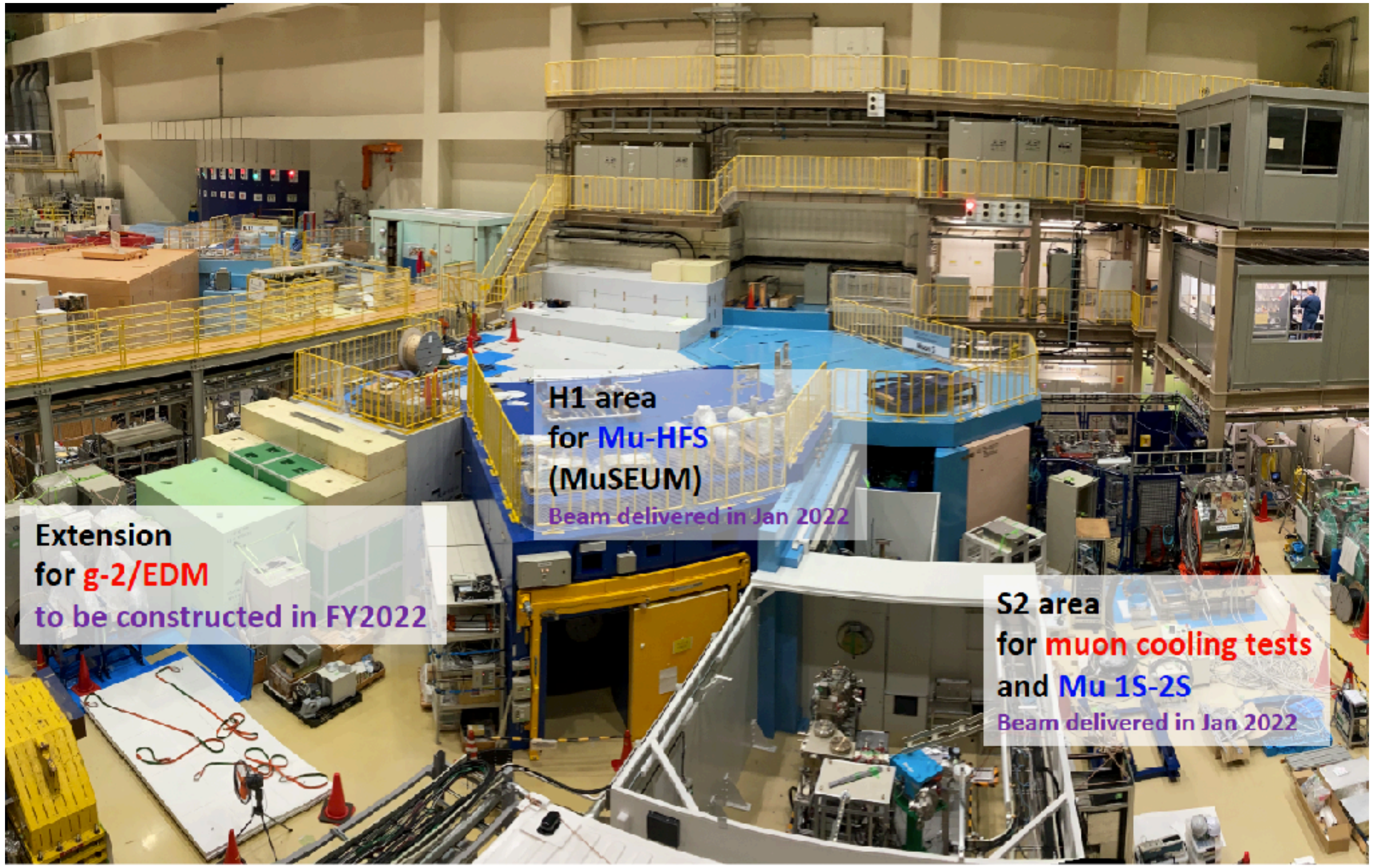




	BNL-E821	Fermilab-E989	J-PARC-E34
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	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

Current status: experimental hall





T. Mibe, Schwinger Fest 2022

Current status First beam to H1 area (Jan 15, 2022)

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Construction of surface muon beamline (H-line)

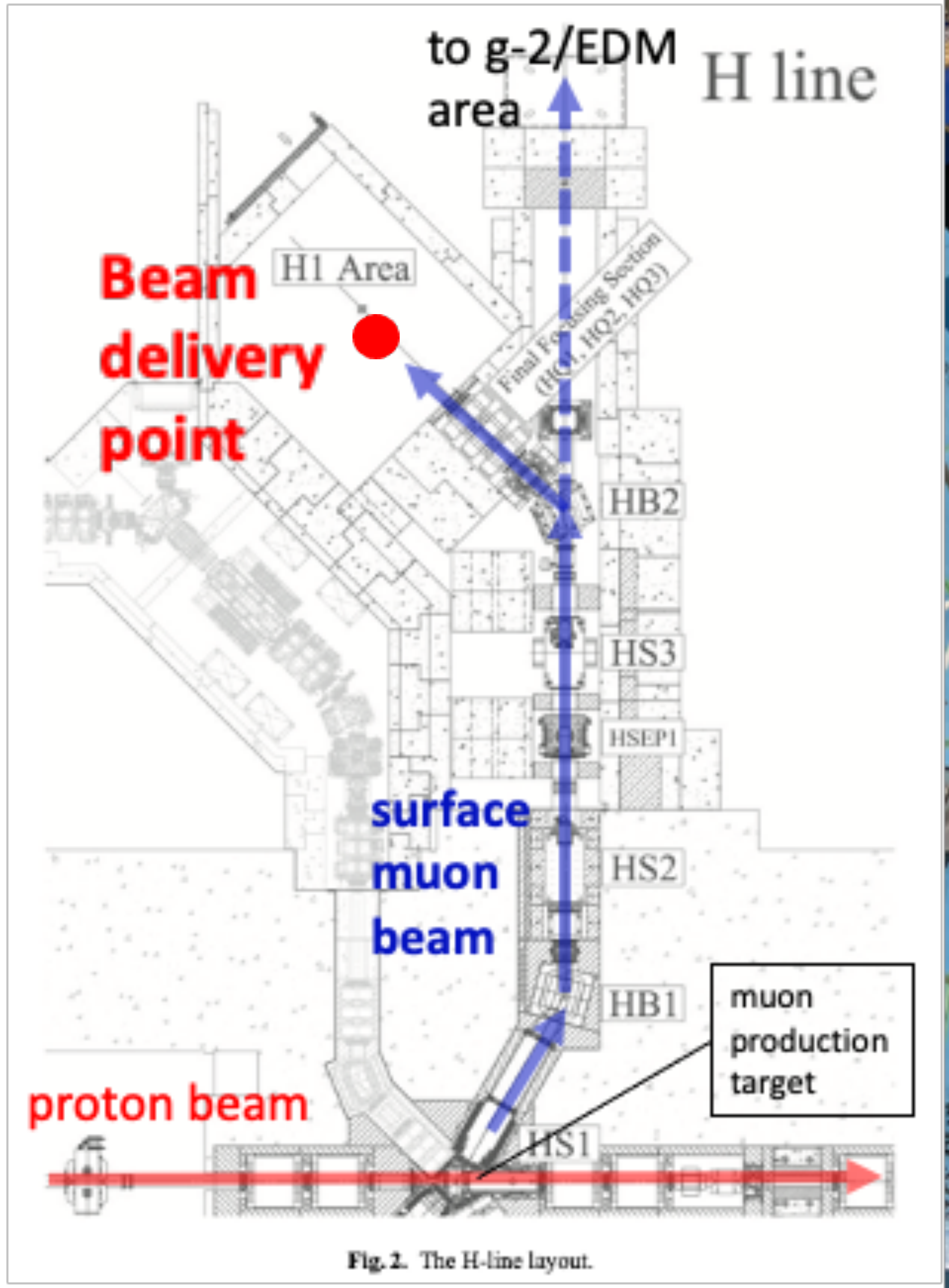
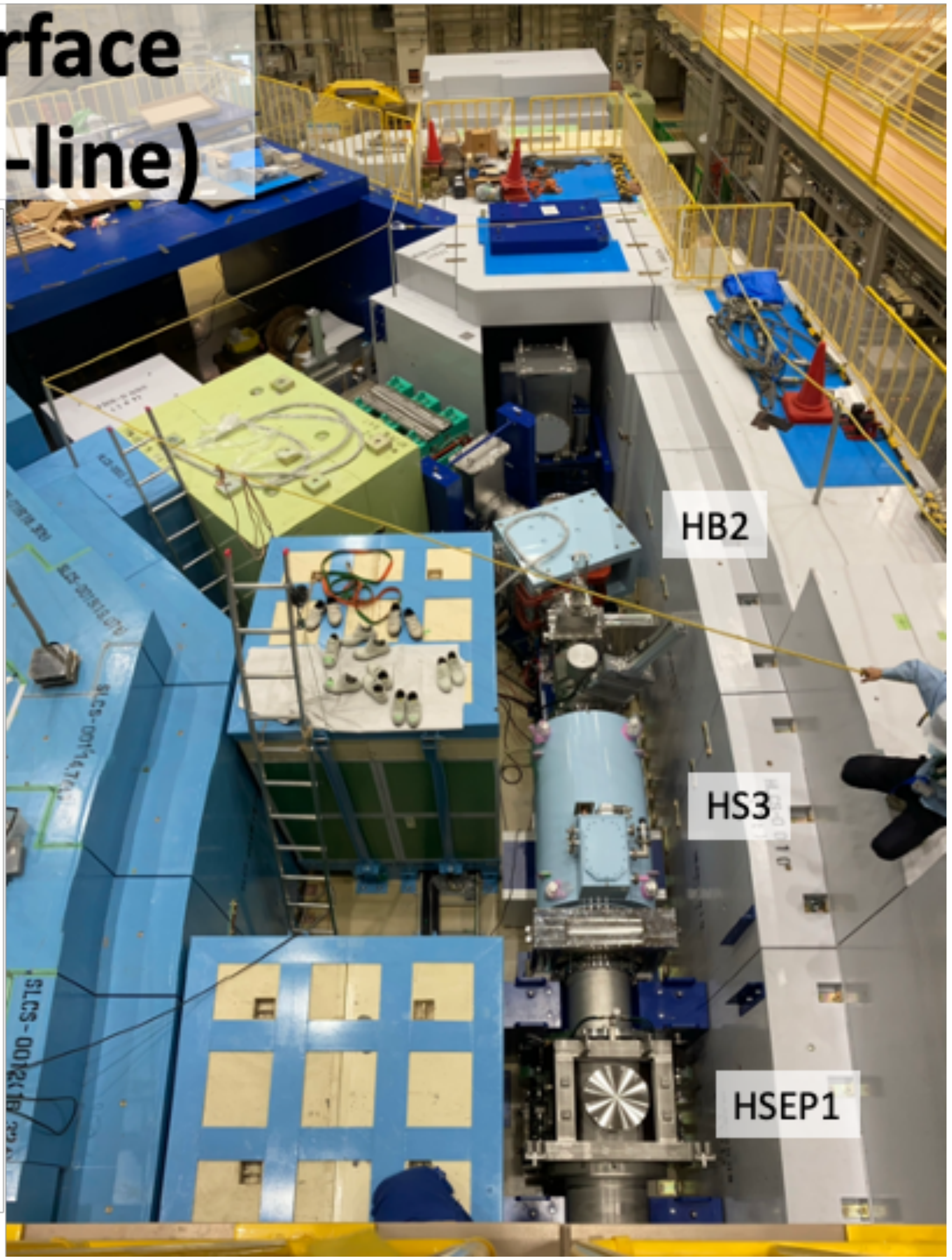
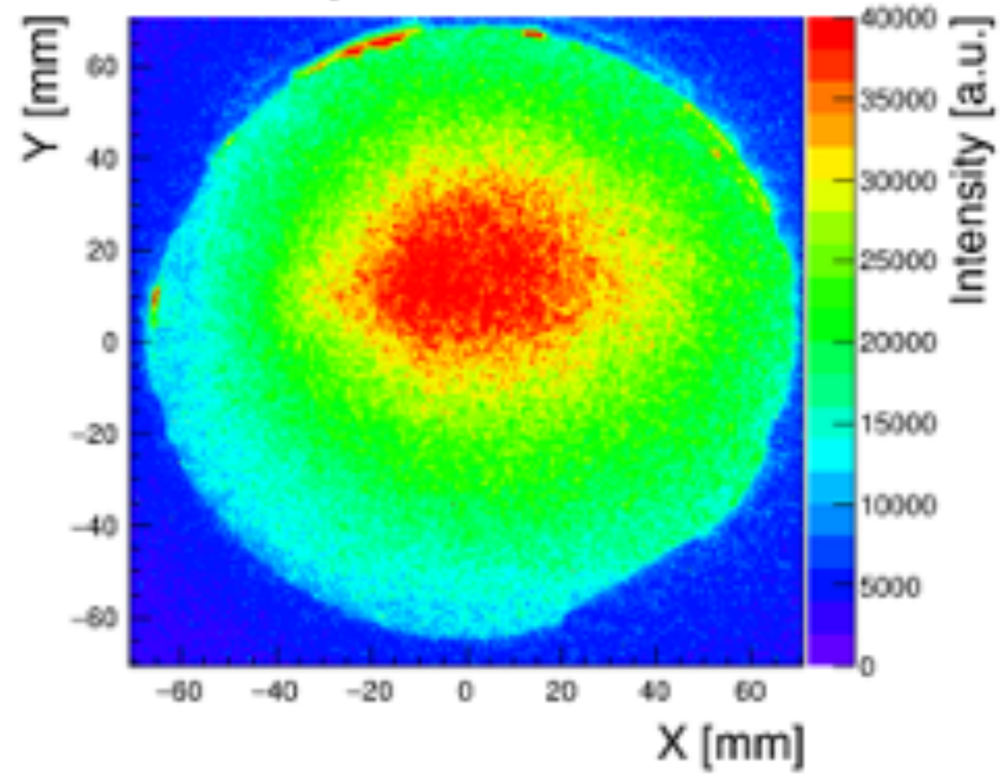


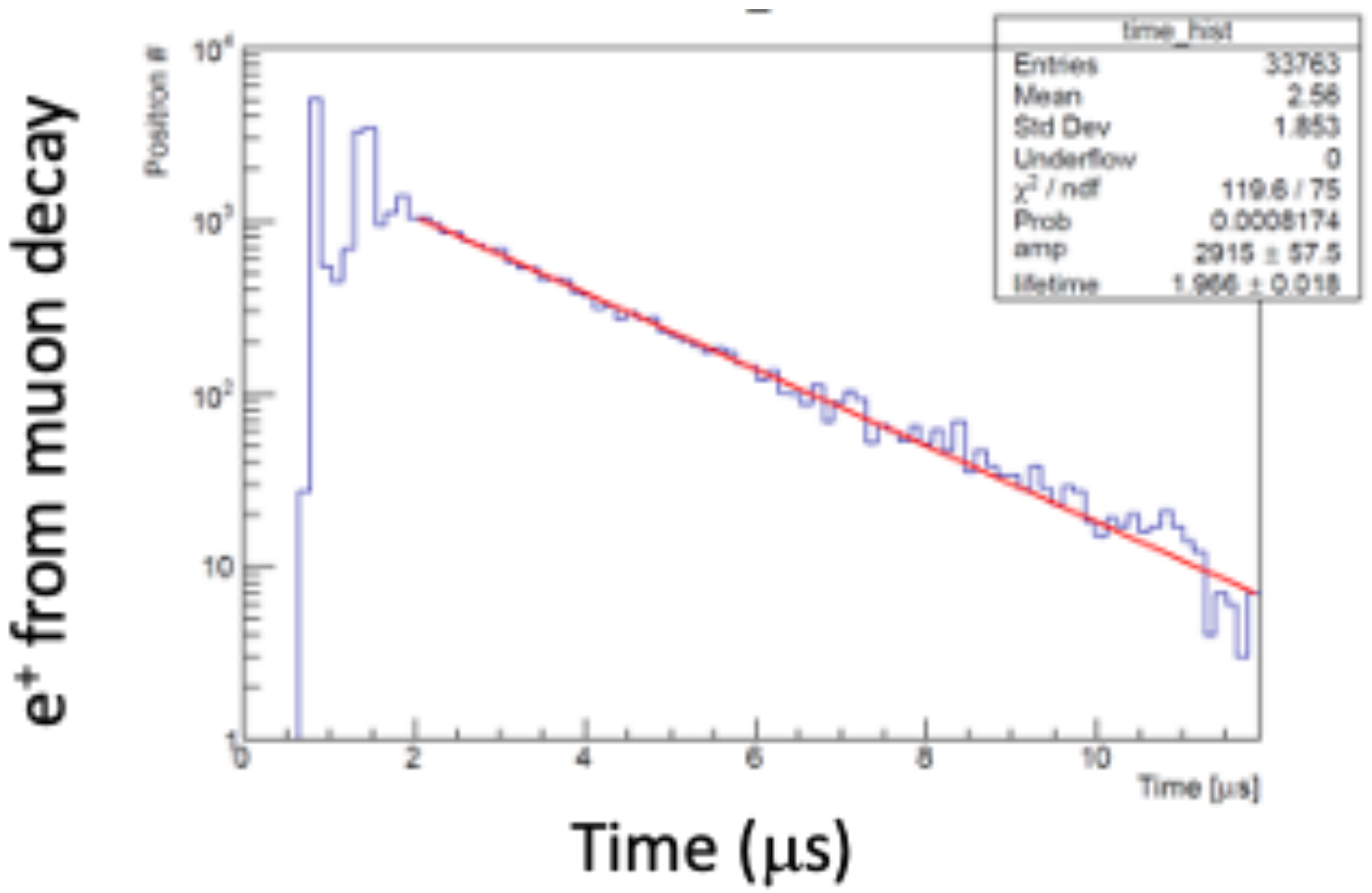
Fig. 2. The H-line layout.

Prog. Theor. Exp. Phys. 2018, 113G01



Beam profile

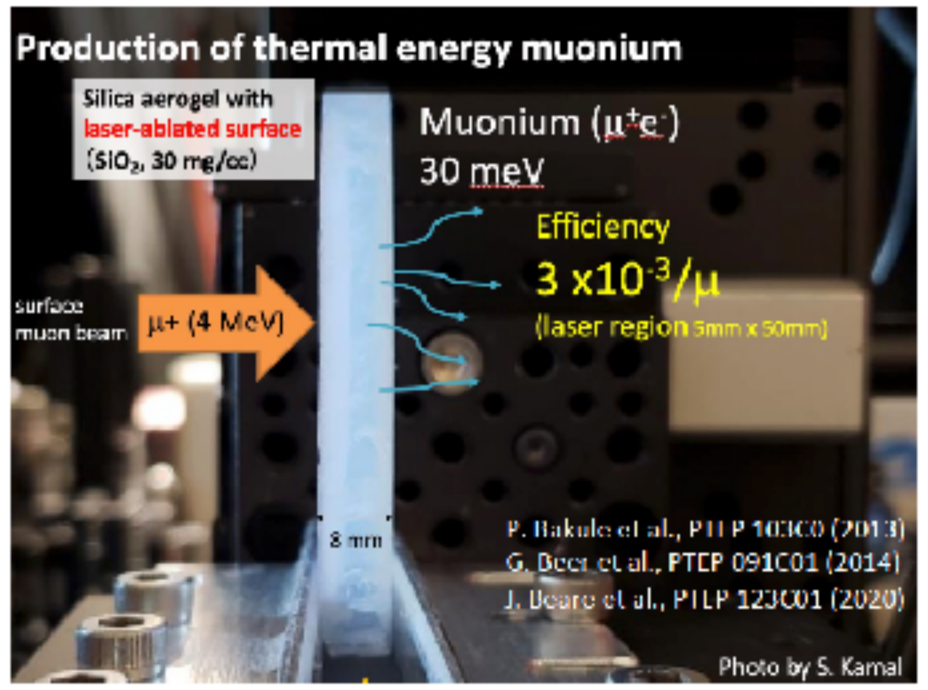


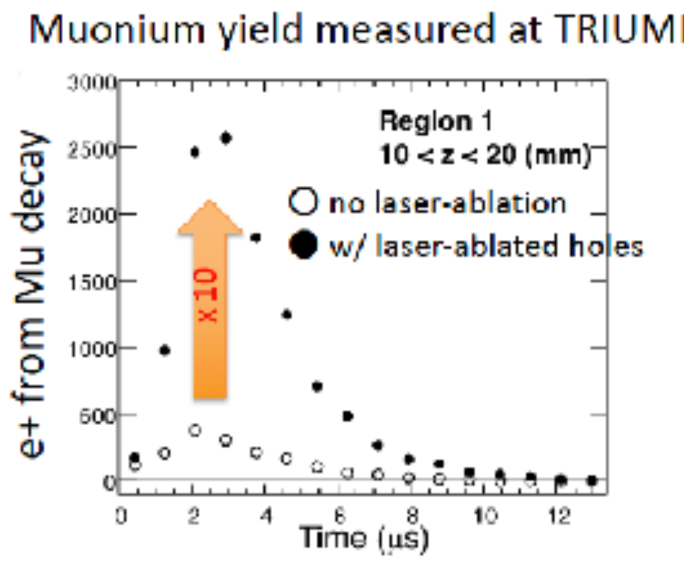


Intensity ~70% of expected in H1 area with partial currents to capture solenoids

Schedule and milestone

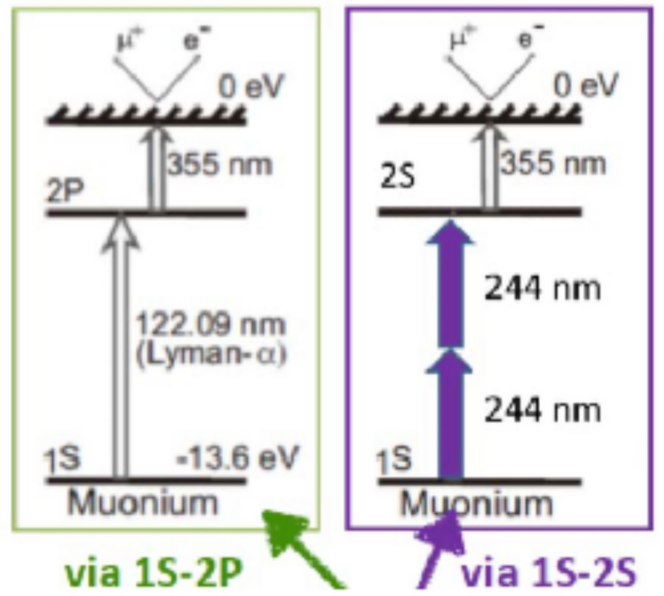
	2021	2022	2023	2024	2025	2026	2027 and beyond
KEK Budget							
Surface muon	★ Beam at H1 area			★ Beam at H2 area			Commissioning / Data taking
Bldg. and facility		★ Final design			★ Completion		
Muon source	★ Ionization test @S2			★ Ionization test at H2			
LINAC		★ 80keV acceleration@S2		★ 4.3 MeV@ H2	★ fabrication complete	★ 210 MeV	
Injection and storage		★ Completion of electron injection test				★ muon injection	
Storage magnet				★ B-field probe ready	★ Install	★ Shimming done	
Detector		★ Quoter vane prototype	★ Mass production ready			★ Installation	
DAQ and computing		★ grid service open ★ common computing resource usage start	★ small DAQ system operation test	★ Ready			
Analysis			★ Tracking software ready	★ Analysis software ready			



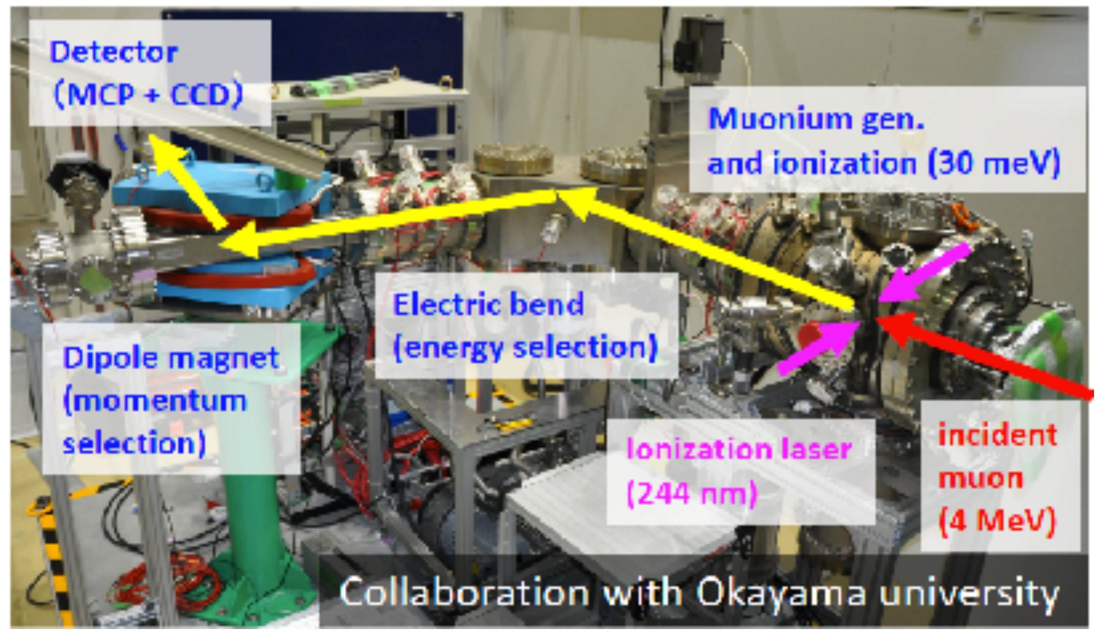


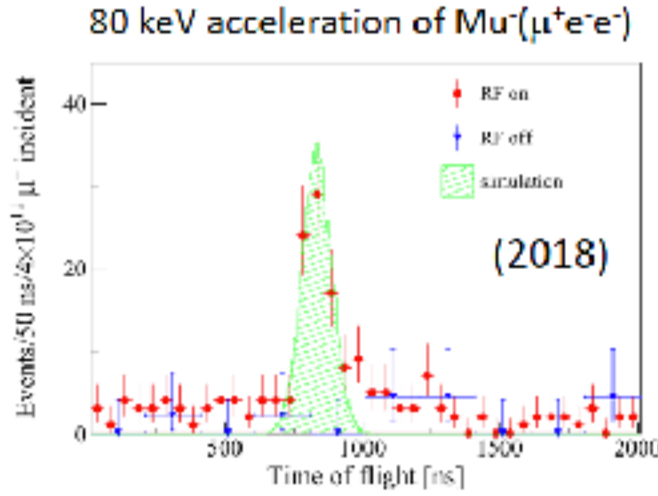
Sufficient efficiency to achieve Δa_μ~450ppb

Schemes of ionization



Our version of "Steven Chu's" experiment at J-PARC

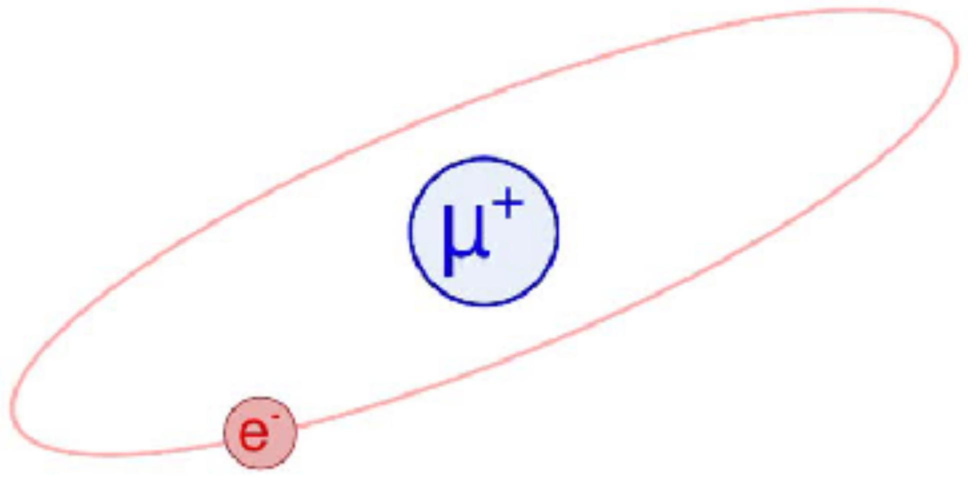


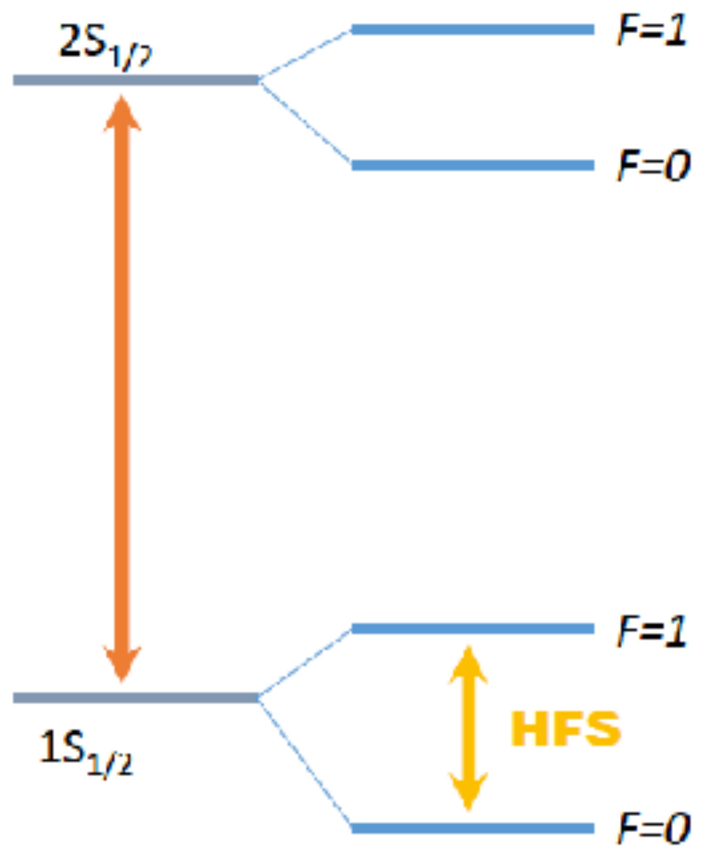


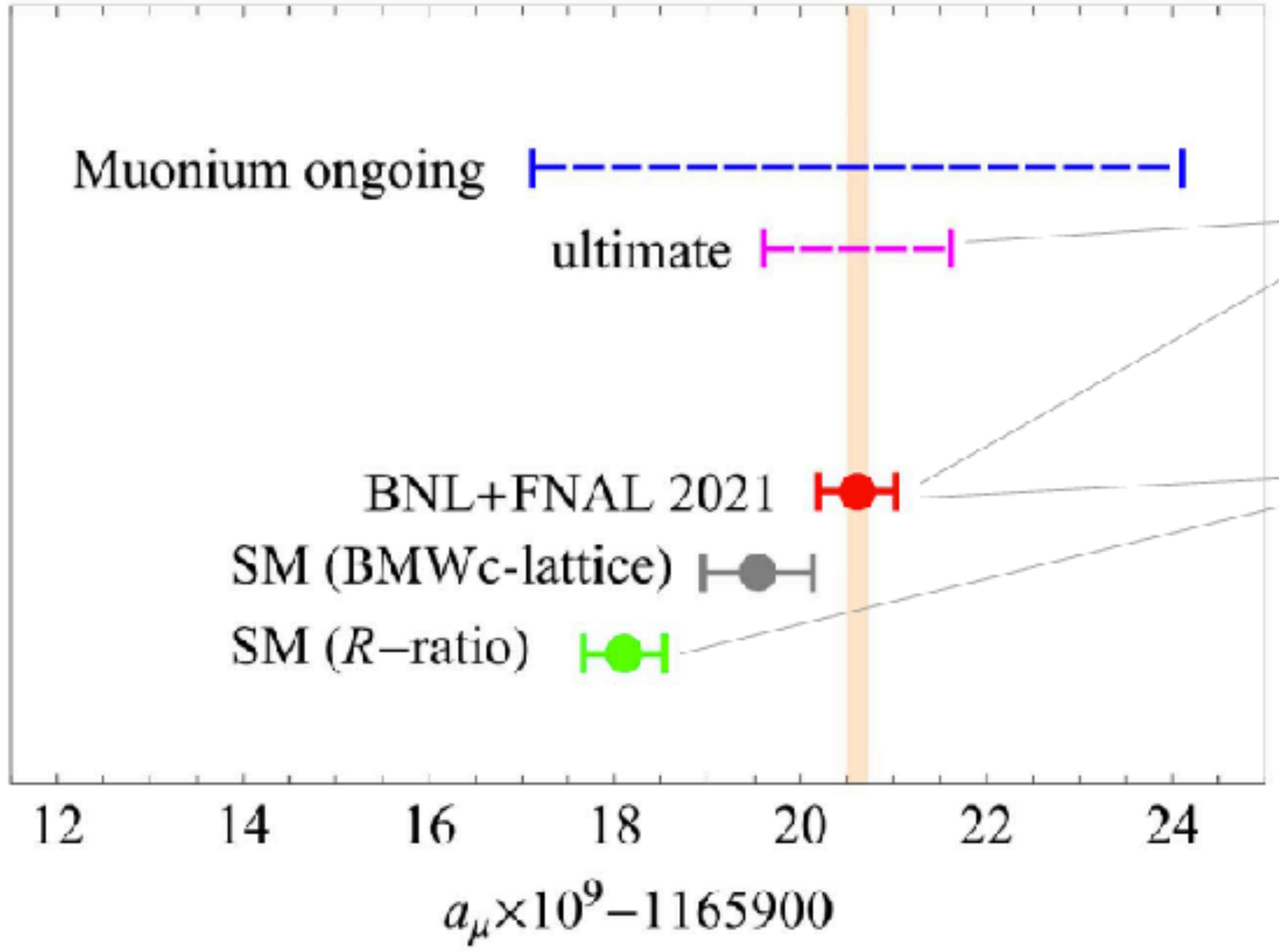
Demonstrated acceleration of Mu-
Next: demonstration of acceleration of μ+

Muon g-2 from muonium spectroscopy

Phys.Rev.Lett. 127 (2021) 25, 251801







A value of a_μ^{Mu} at $\mathcal{O}(1\mathrm{ppm})$ is not competitive to current spin-precession measurements

However, it may help to understand the origin of the $\sim 2\mathrm{ppm}$ difference between (R-ratio) SM and experiment

Ground-state HFS theory

Rydberg constant $R_\infty = \alpha^2 m_e c/(2h)$

fine-structure constant

nonrelativistic **Fermi energy** from H_{HFS}

$$\nu_{\mathrm{HFS}} = \frac{16}{3}(1+a_\mu)\frac{m_e}{m_\mu}\frac{R_\infty c\alpha^2}{(1+m_e/m_\mu)^3}[1+\delta_{\mathrm{HFS}}]$$

electron-muon mass ratio

$\mathcal{O}(\alpha)$ correction

[CODATA 2018 + refs therein]

Z-exchange $-65\ \mathrm{Hz}$

$$\delta_{\mathrm{HFS}} = \delta_{\mathrm{Dirac}} + \delta_{\mathrm{rad}} + \delta_{\mathrm{rec}} + \delta_{\mathrm{rad-rec}} + \delta_{\mathrm{weak}} + \delta_{\mathrm{had}}$$

hadronic vacuum pol. $= 237.7(1.5)\ \mathrm{Hz}$

relativistic (exact)

antimuon charge $Z=1$

radiative known up to $\mathcal{O}(Z\alpha^4)$ including a_e

recoil known up to $\mathcal{O}[(m_e/m_\mu)(Z\alpha)^3]$

$\sim 60\ \mathrm{Hz}$ uncertainty

radiative-recoil known up to $\mathcal{O}[(m_e/m_\mu)\alpha^3]$

$\sim 10\ \mathrm{Hz}$ uncertainty

Total TH uncertainty $\sim 70\ \mathrm{Hz}\ (16\mathrm{ppb})$

dominanted by (yet) uncalculated QED corrections at three-loop order

[Eides-Shelyuto IJMPA 2016]

1S-2S theory

nonrelativistic energy (including recoil)

$$\nu_{\mathrm{1S-2S}} = \frac{3}{4}\frac{R_\infty c}{(1+m_e/m_\mu)}[1+\delta_{\mathrm{1S-2S}}]$$

$\mathcal{O}(\alpha^2)$ correction

[CODATA 2018 + refs therein]

rescaling hydrogen formulae with the muon mass and removing nuclear finite size and pol. effects

vacuum pol. known up to $\mathcal{O}[\alpha(Z\alpha)^4]$

2+3 photon exchange known up to $\mathcal{O}[\alpha^3(Z\alpha)^4]$

muon self-E

$$\delta_{\mathrm{1S-2S}} = \delta_{\mathrm{Dirac}} + \delta_{\mathrm{rel-rec}} + \delta_{e\mathrm{SE}} + \delta_{\mathrm{VP}} + \delta_{2\gamma} + \delta_{3\gamma} + \delta_{\mathrm{rad-rec}} + \delta_{\mu\mathrm{SE}}$$

relativistic (exact)

relativistic-recoil known up to $\mathcal{O}[(m_e/m_\mu)(Z\alpha)^4]$

electron self-E $\mathcal{O}[\alpha(Z\alpha)^4]$ known

radiative-recoil known up to $\mathcal{O}[(m_e/m_\mu)\alpha(Z\alpha)^3]$

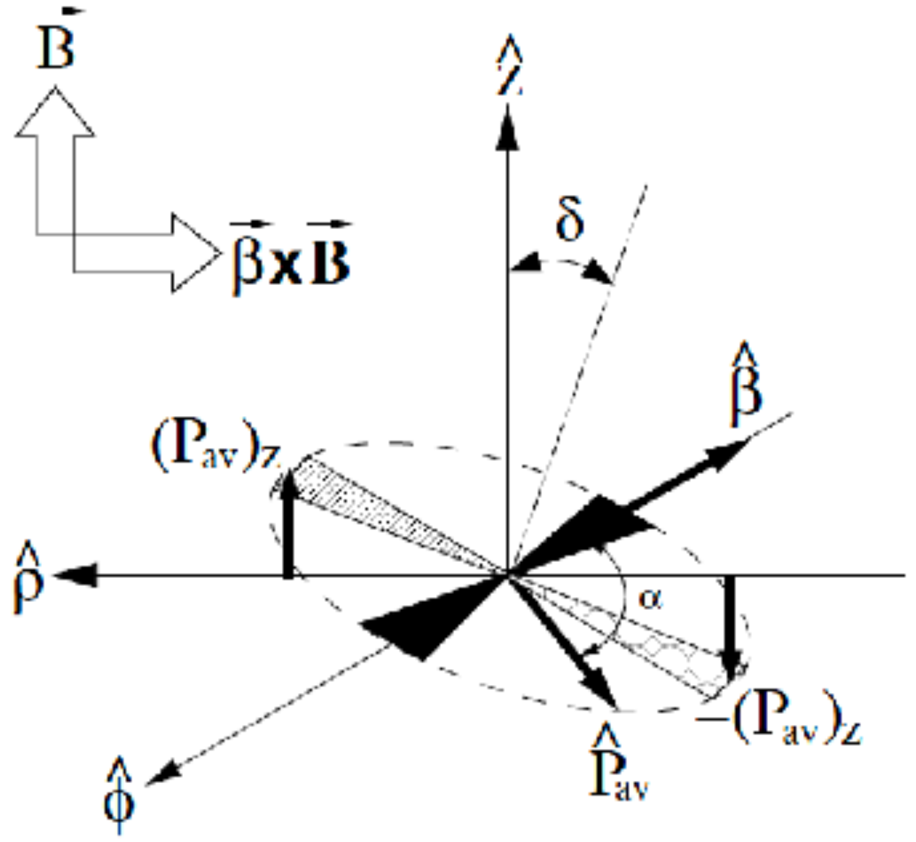
Total TH uncertainty $\sim 20\ \mathrm{kHz}\ (8\mathrm{ppt})$

from (yet) uncalculated QED (rad-rec) corrections at three-loop order

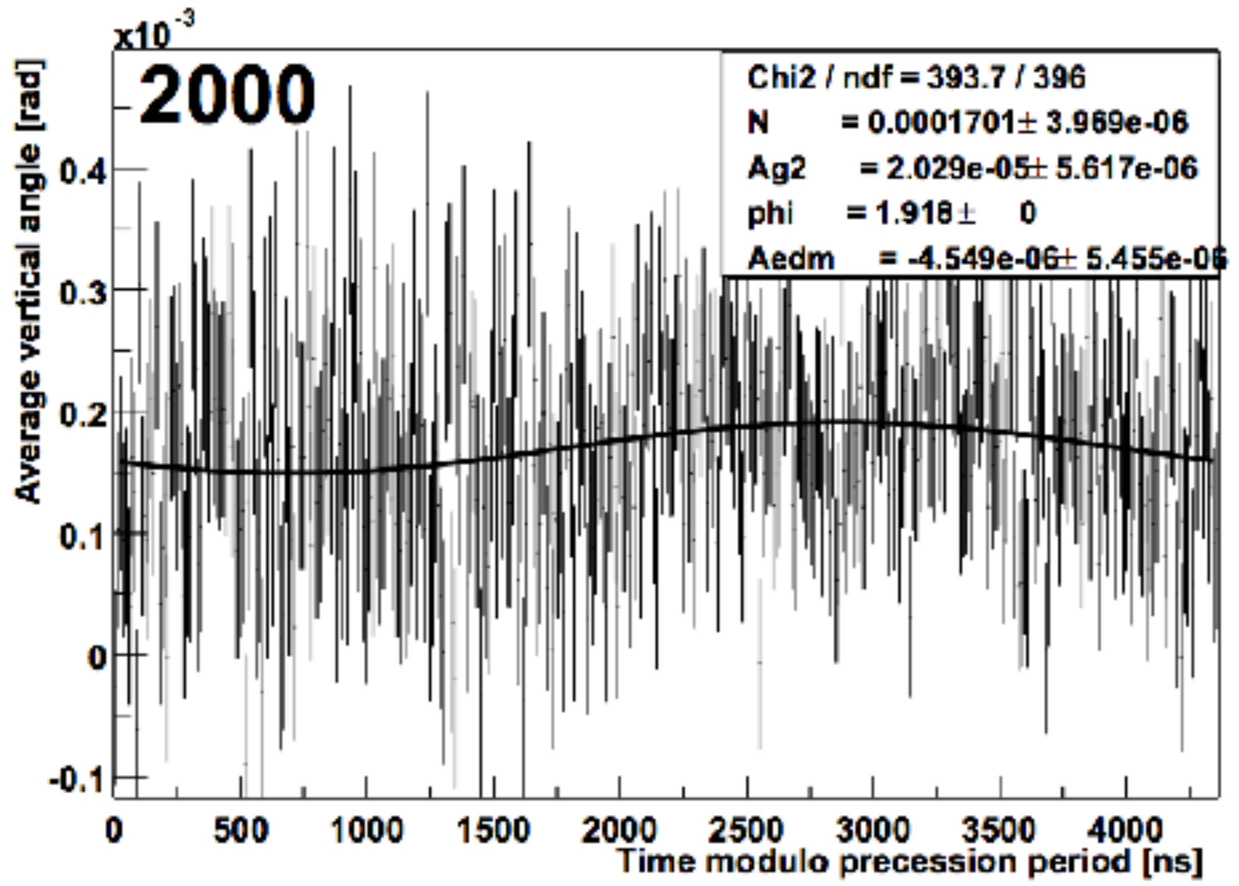
[Karshenboim et al. PLB 2019]

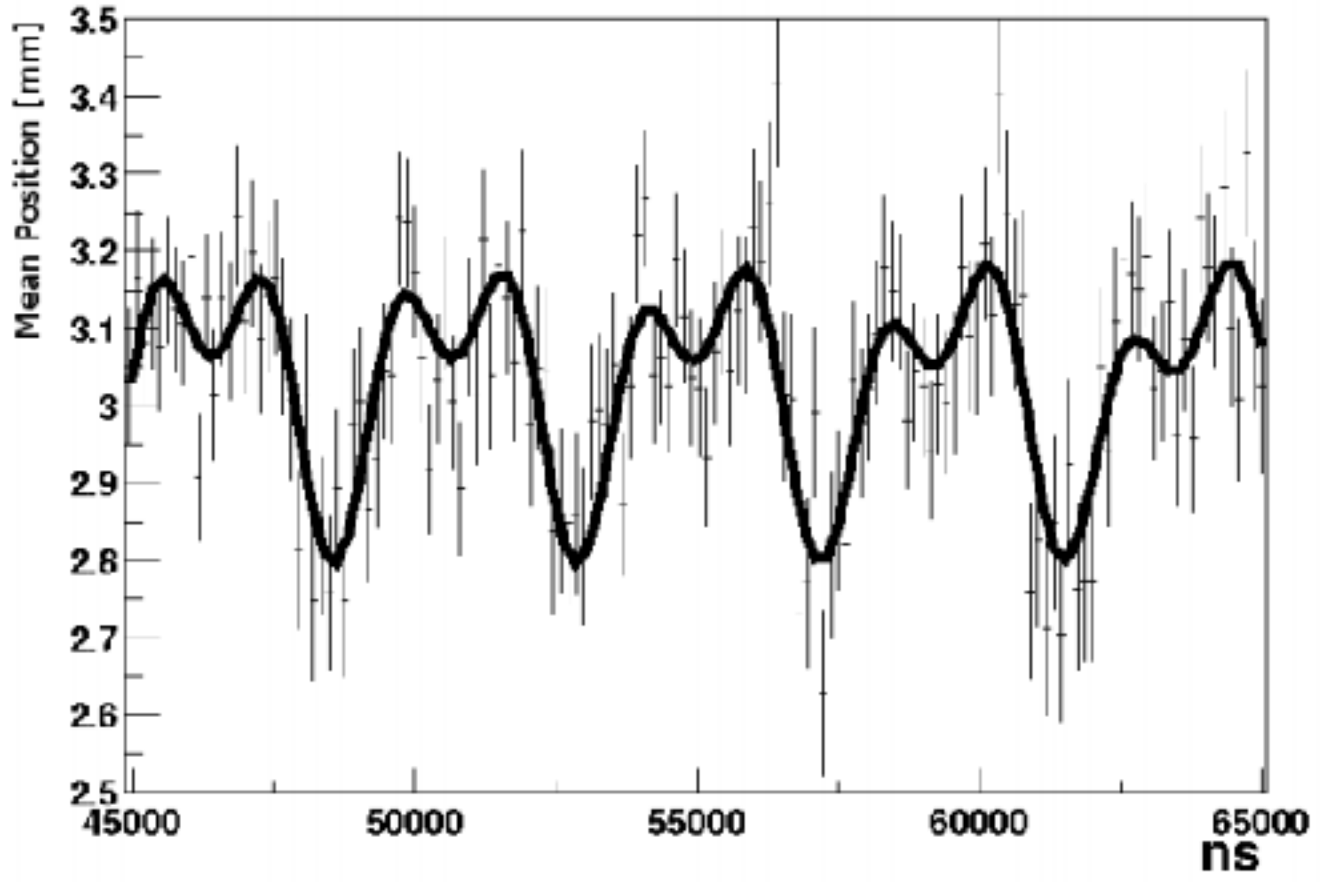
BNL/Fermilab Muon EDM search

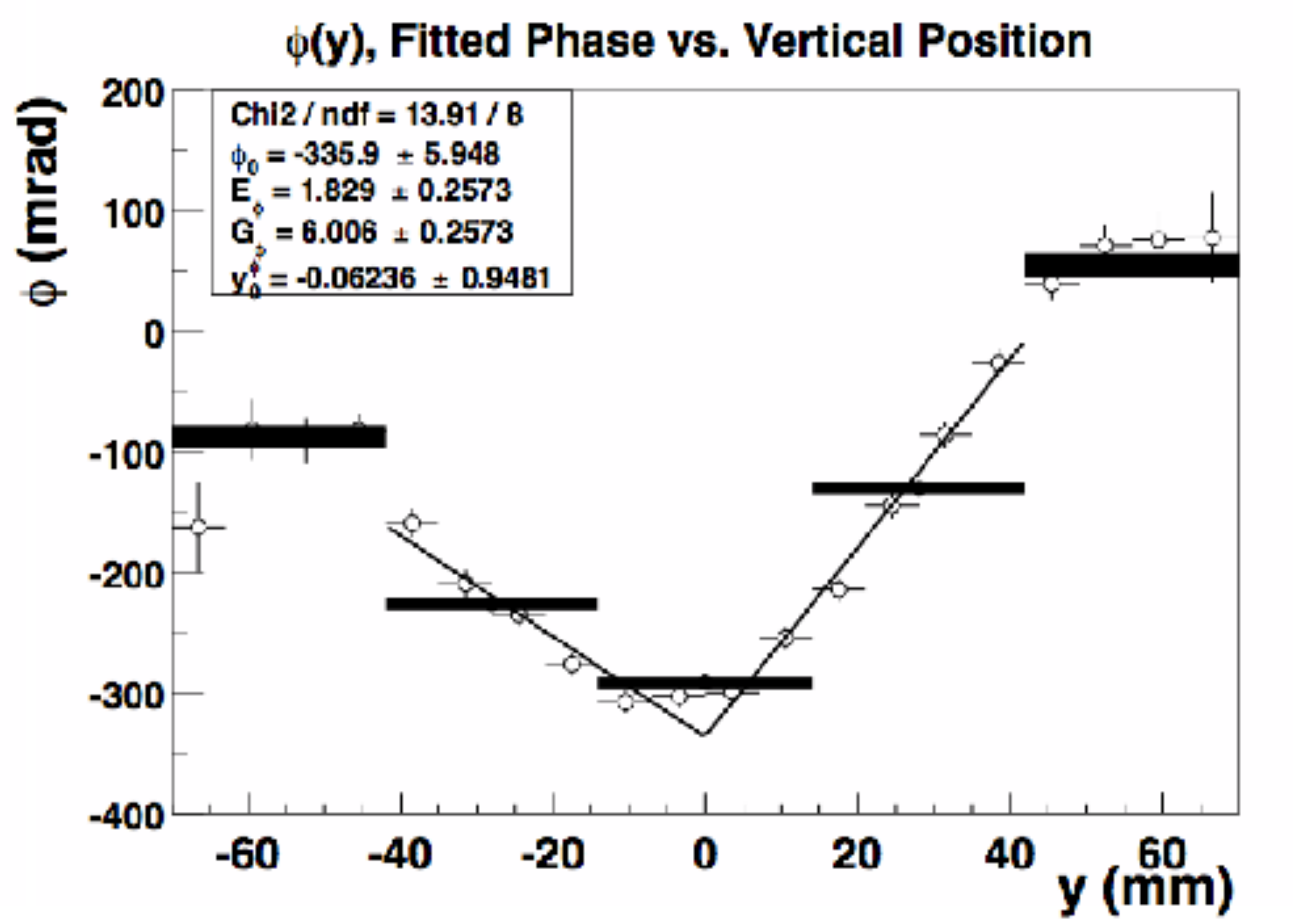
PRD 80 (2009) 052008



- Three approaches from BNL/FNAL experiment:
  - Vertical Angle Oscillation (Tracker)
  - Vertical Position Oscillation (Calorimeter)
  - Vertical Phase Gradient (Calorimeter)







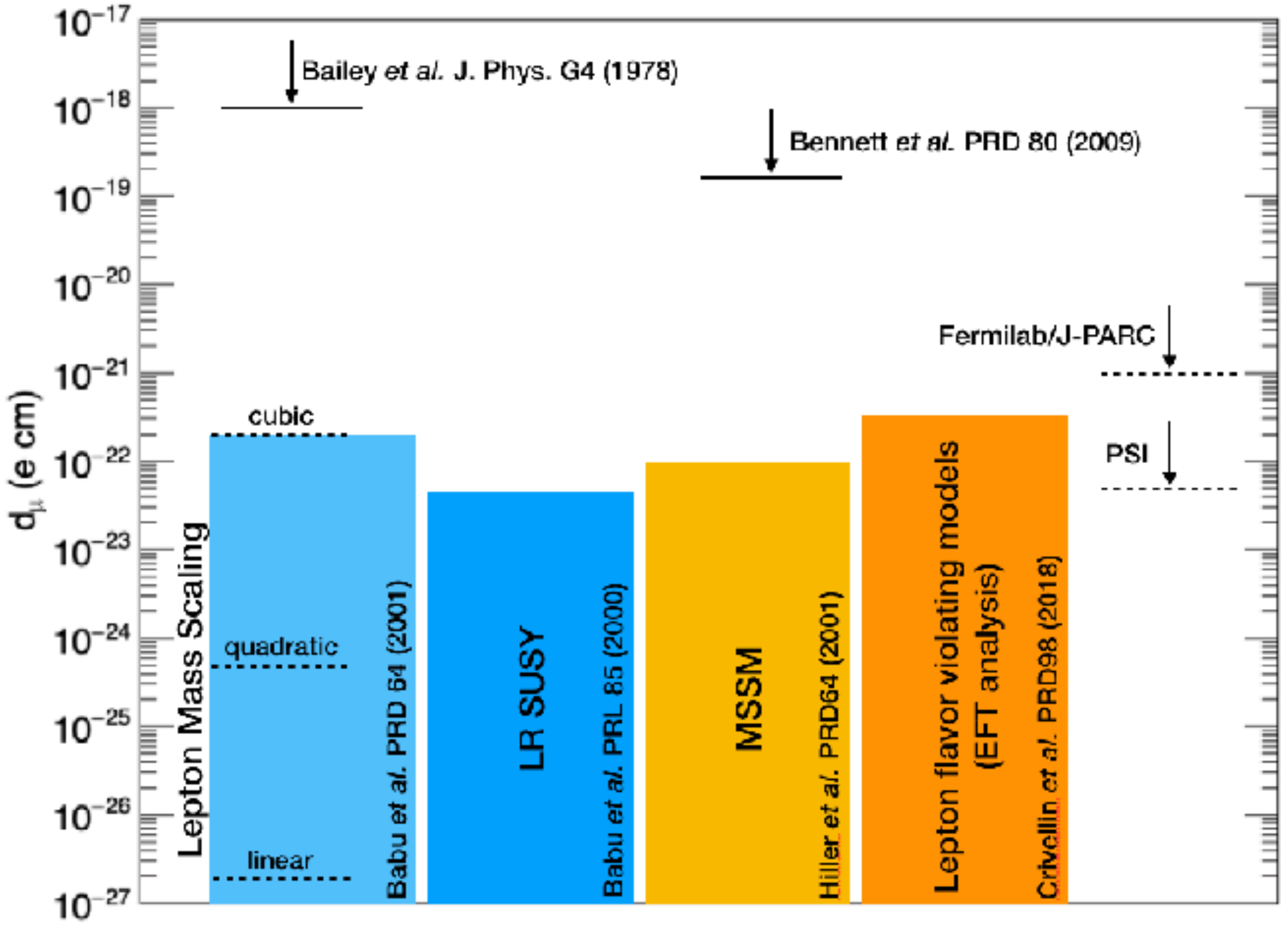
$$\theta(t) = M + A_\mu \cos(\omega t + \Phi) + \boxed{A_{\mathrm{EDM}} \sin(\omega t + \Phi)}$$

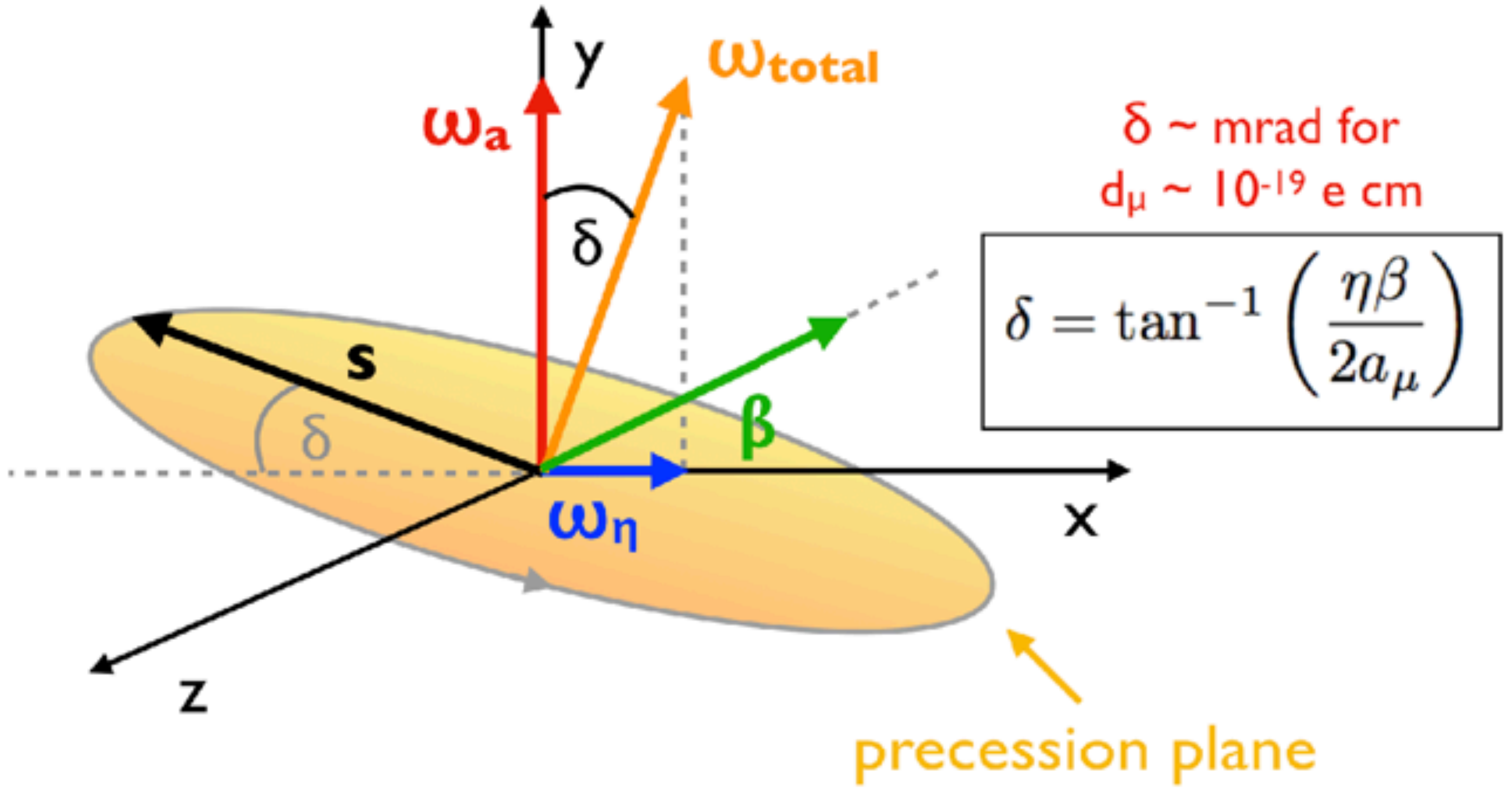
$$f(t) = K + [\boxed{S_{g2}\sin(\omega t)} + C_{g2}\cos(\omega t)] + e^{-(t/\tau_{\mathrm{CBO}})} \times [S_{\mathrm{CBO}} \sin(\omega_{\mathrm{CBO}}(t-t_0) + \Phi_{\mathrm{CBO}}) + C_{\mathrm{CBO}} \cos(\omega_{\mathrm{CBO}}(t-t_0) + \Phi_{\mathrm{CBO}})] + M e^{-(t/\tau_M)}$$

$$\phi(y) = \phi_0 + \boxed{E_\phi (y - y_0^\phi)} + |G_\phi (y - y_0^\phi)|$$

Can we going beyond 10^{-21} e cm?

- How can we improve the sensitivity of the muon EDM search?
- In the parasitic approach, the tilt angle is the limiting factor
- For an EDM below 10^{-21} e cm, it will be very challenging to measure this small angle (multiple scattering effect + systematics like alignment)





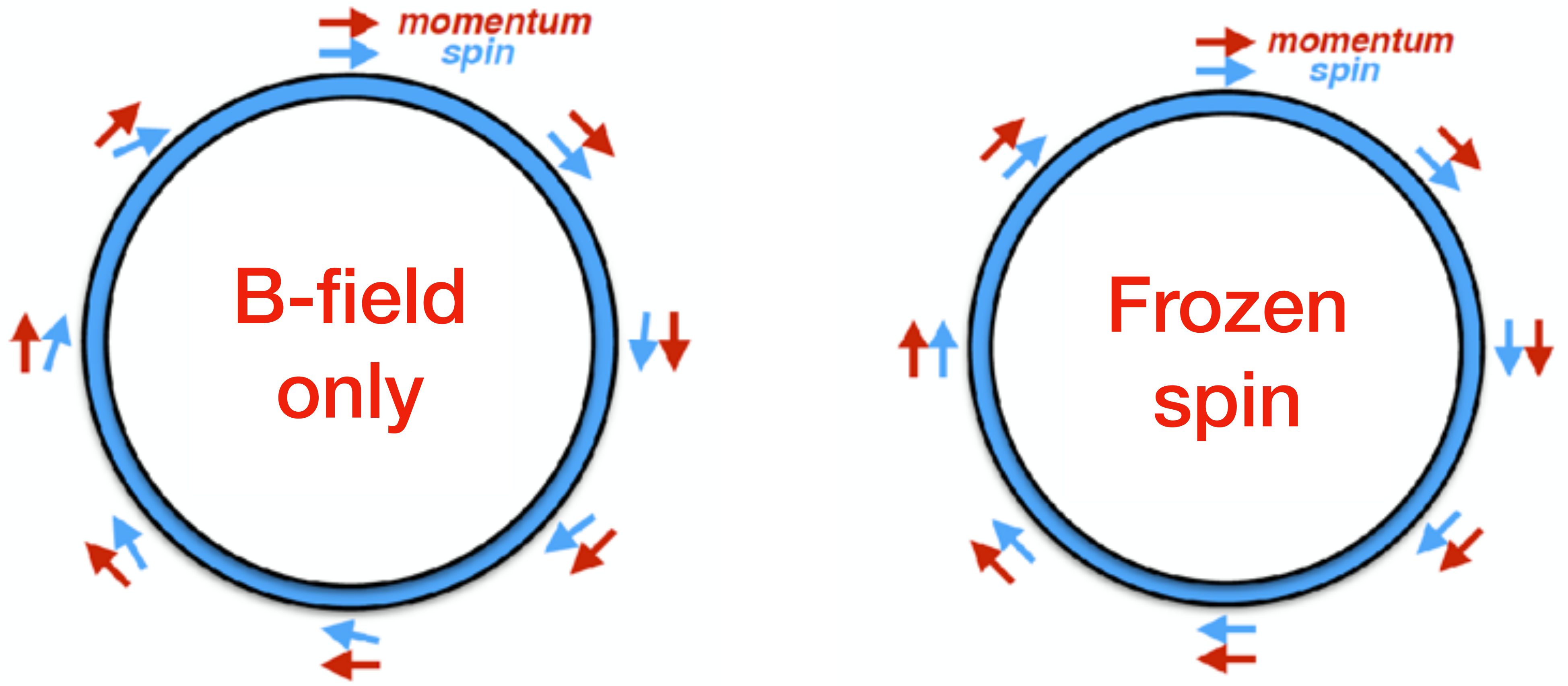
The "frozen-spin" technique

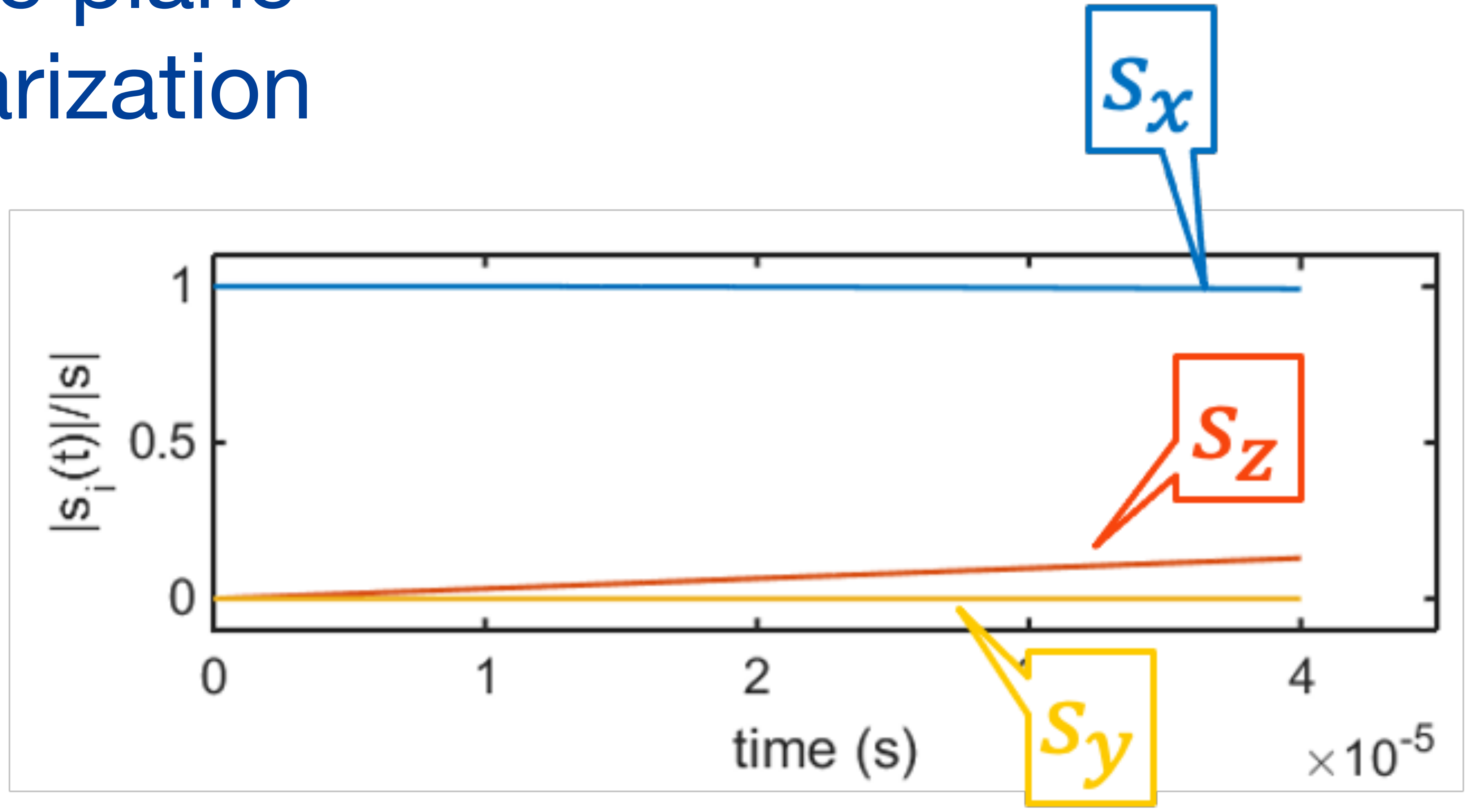
PRL 93 (2004) 052001

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

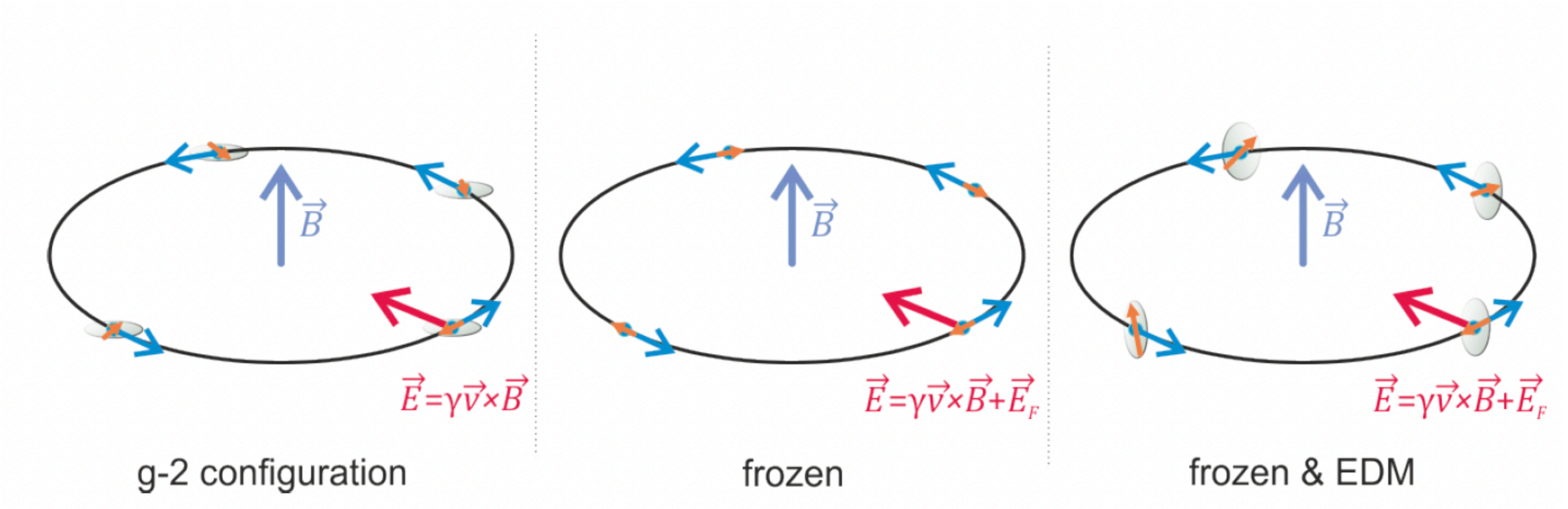
ω_a : g-2 ω_η: EDM

- Developed in 2004 for the muon
- Freeze g-2 component by applying a radial E-field of ~ **$aBc\beta\gamma^2$**
  → no anomalous precession in the storage plane
  → EDM causes an increasing vertical polarization





Putting everything together



Principle of the FS-EDM measurement

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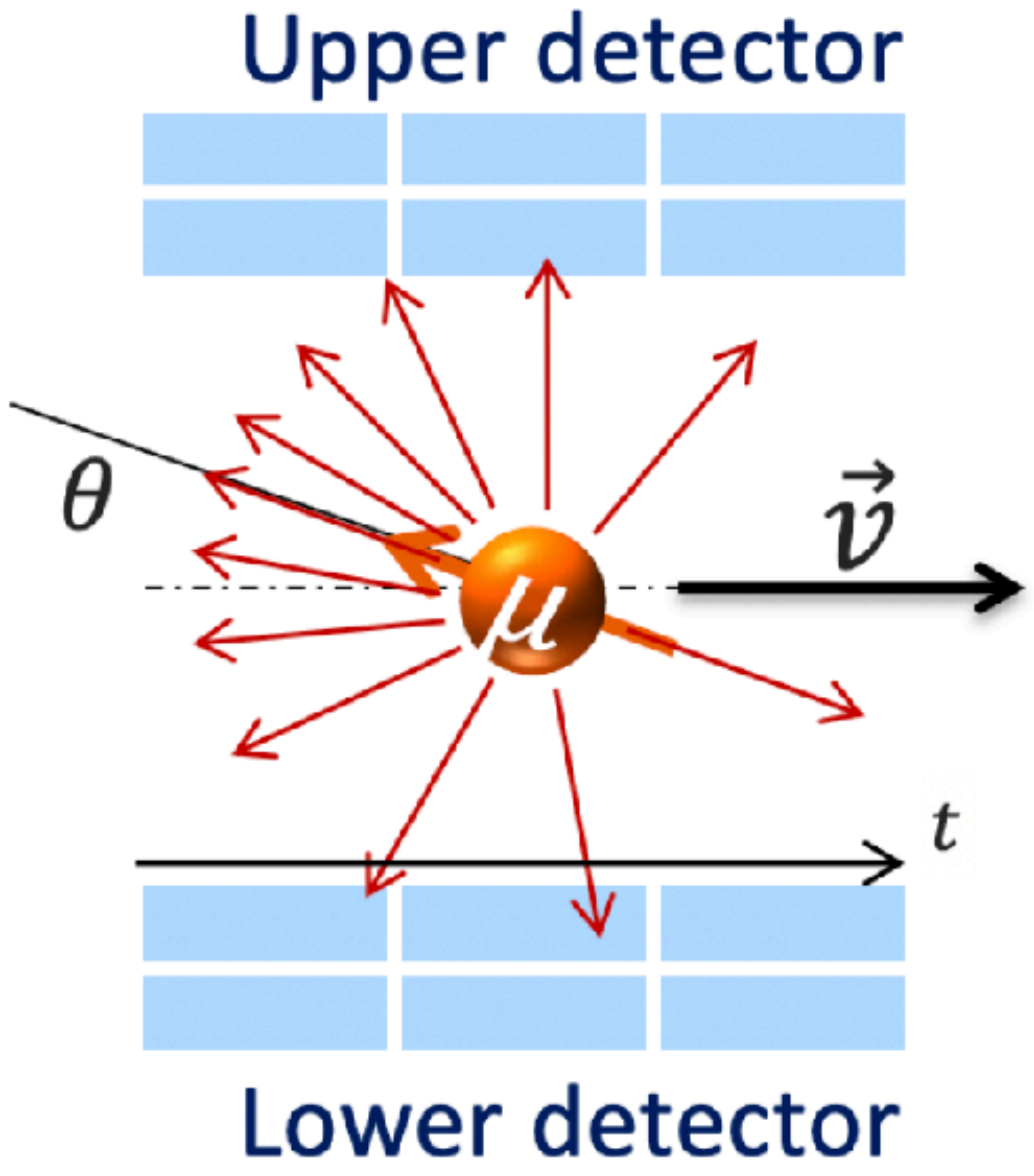
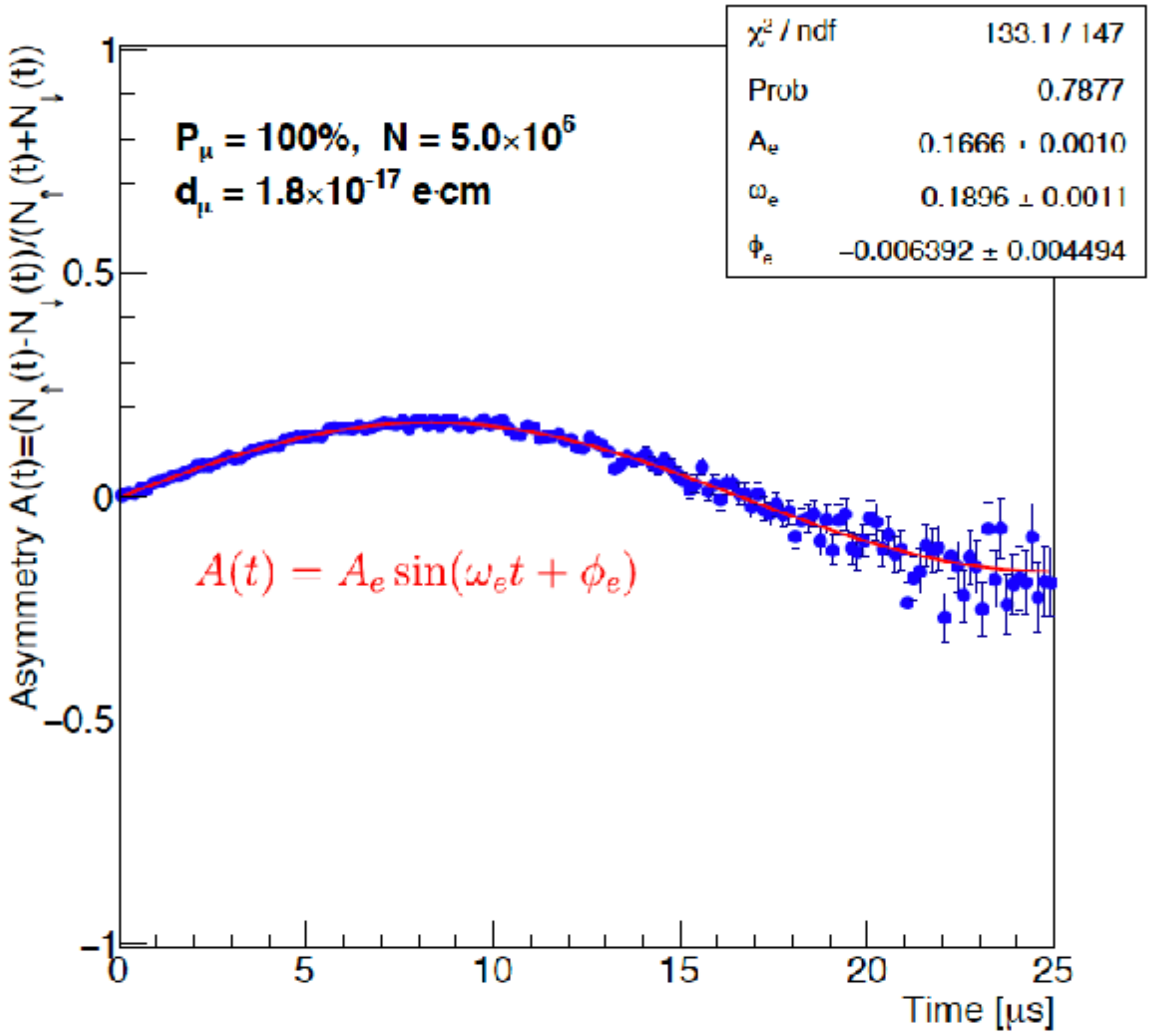
- Up-down asymmetry measured using upper and lower detectors





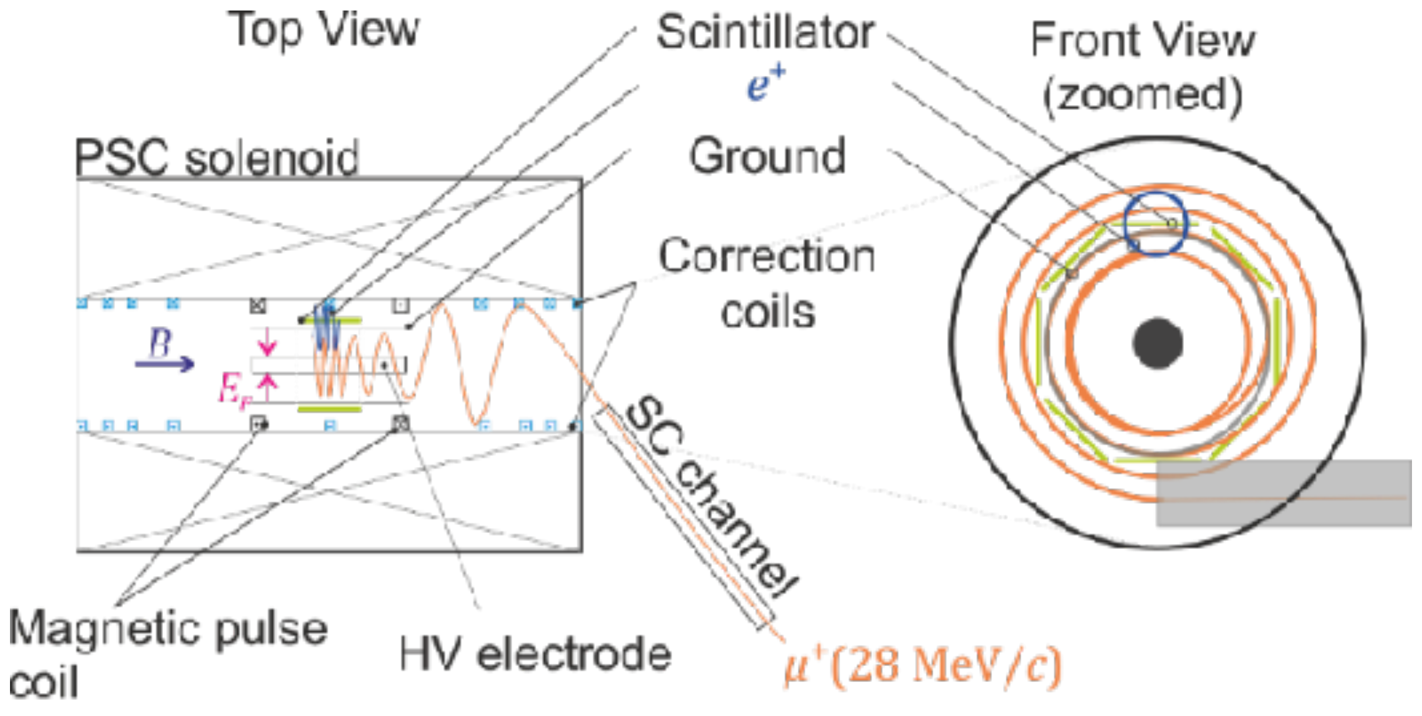
$$\sigma(d_\mu) = \frac{\hbar\gamma^2 a_\mu}{2PE_f\sqrt{N}\,\gamma\tau_\mu\,\alpha}$$

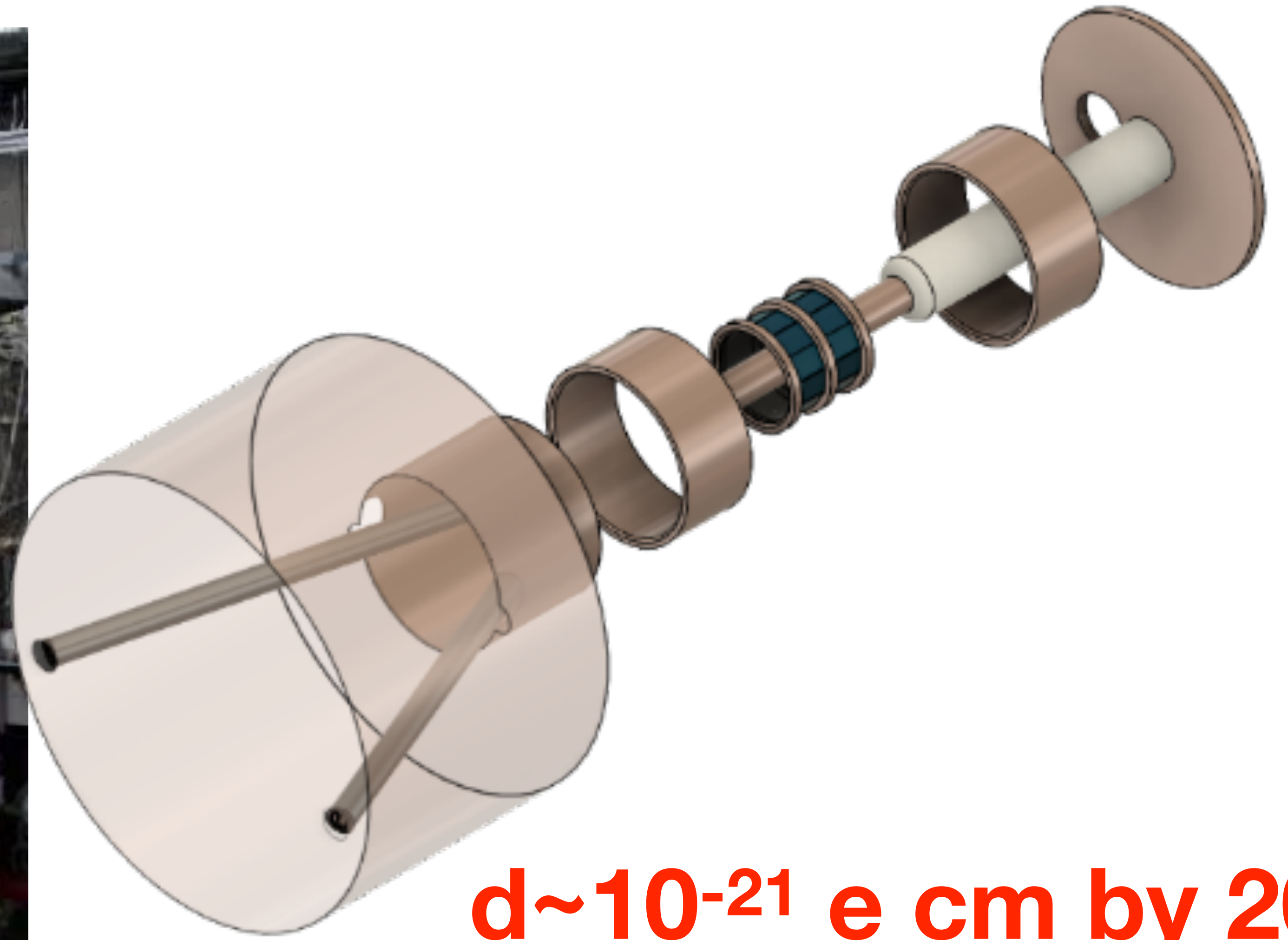
P := initial polarization
E_f := Electric field in lab
$\sqrt{N}$:= number of positrons
τ_μ := lifetime of muon
α := mean decay asymmetry

muEDM at PSI with the FS approach

Muon EDM search at PSI will commence in two phases:

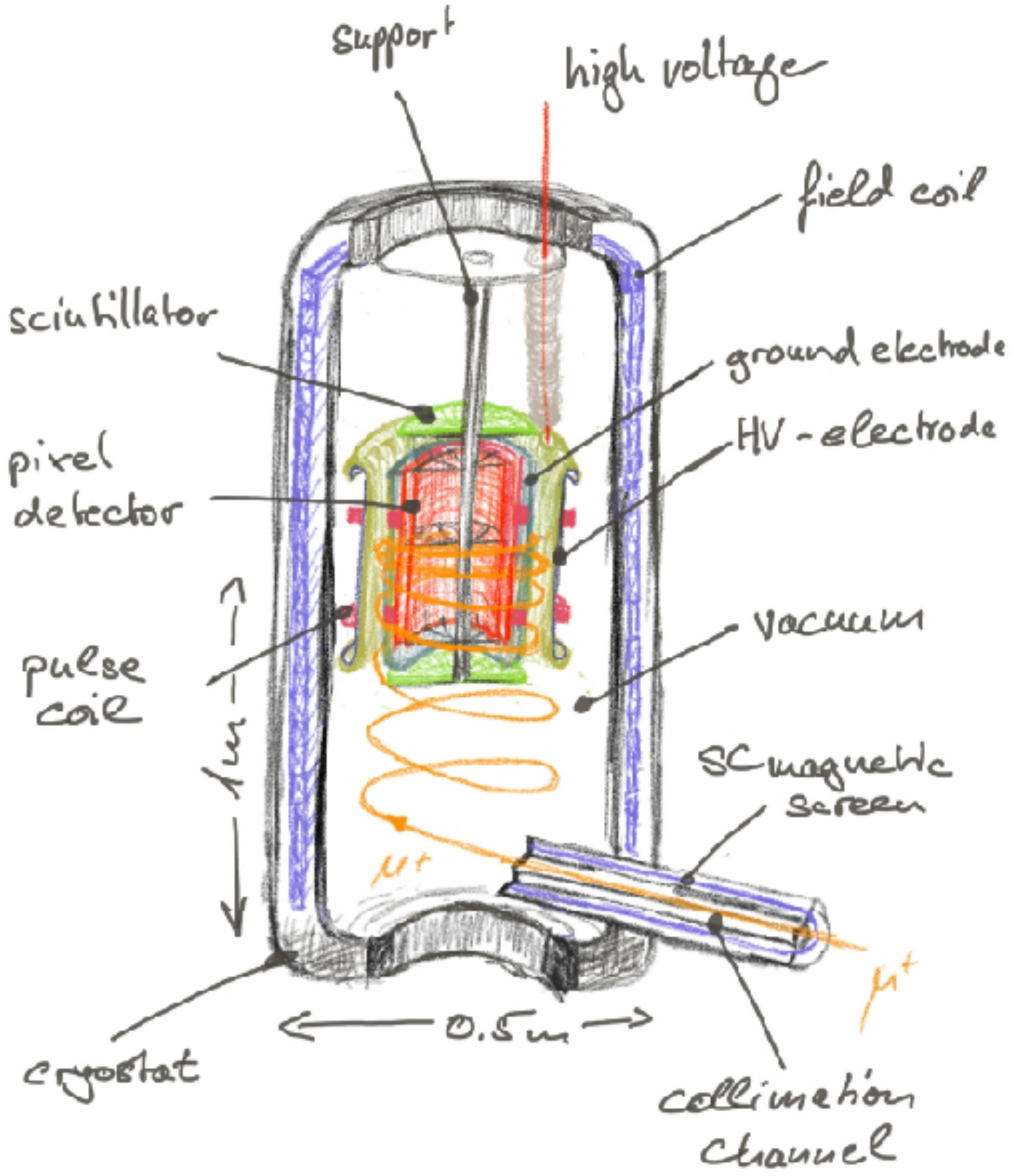
Phase 1 @ 28 MeV/c





d~10^{-21} e cm by 2026

Phase 2 @ 125 MeV/c



d~10^{-23} e cm by 2031

Potential beamlines for muEDM

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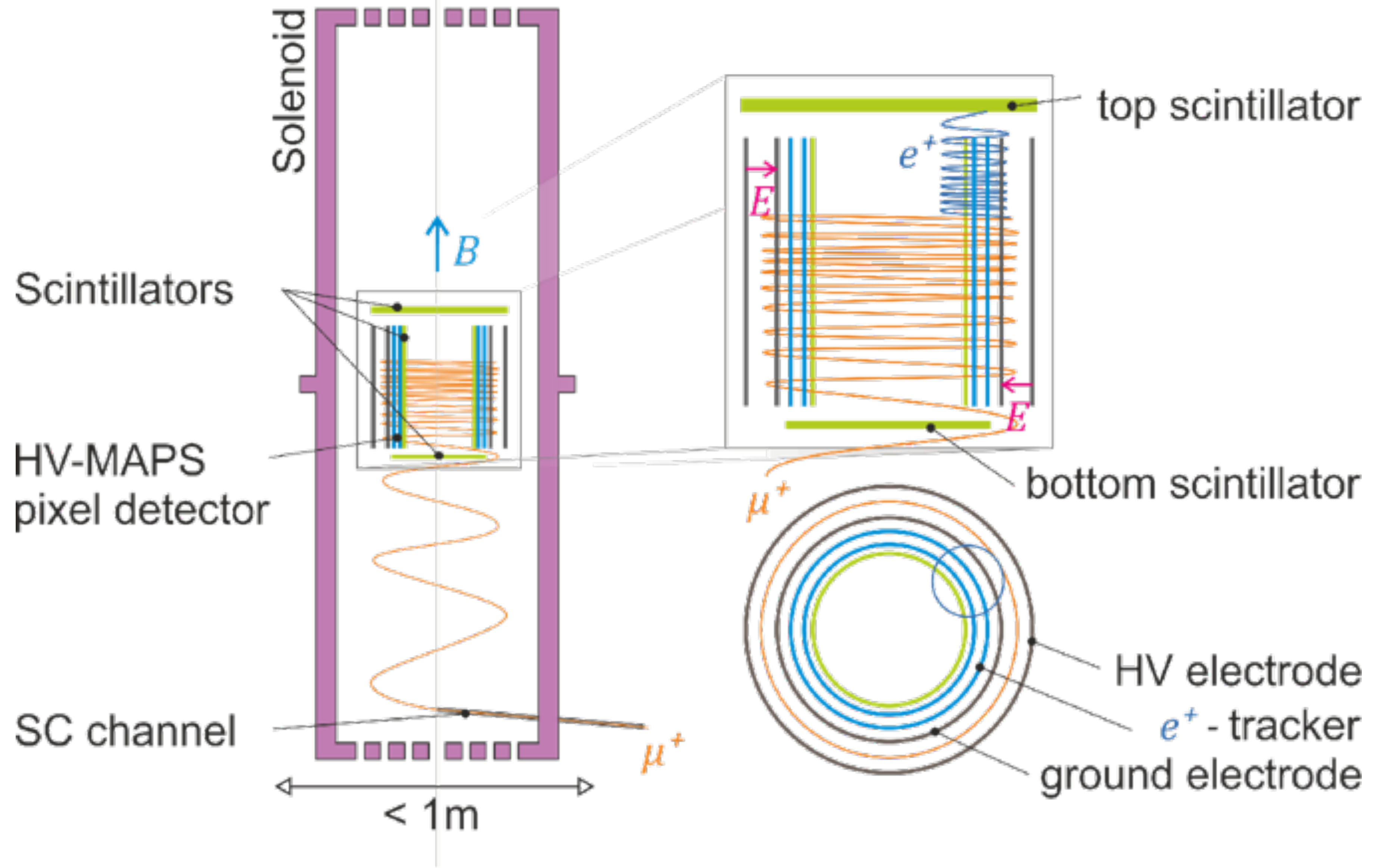
Phase 1 @ πE1
28 MeV/c, ~10^6/s

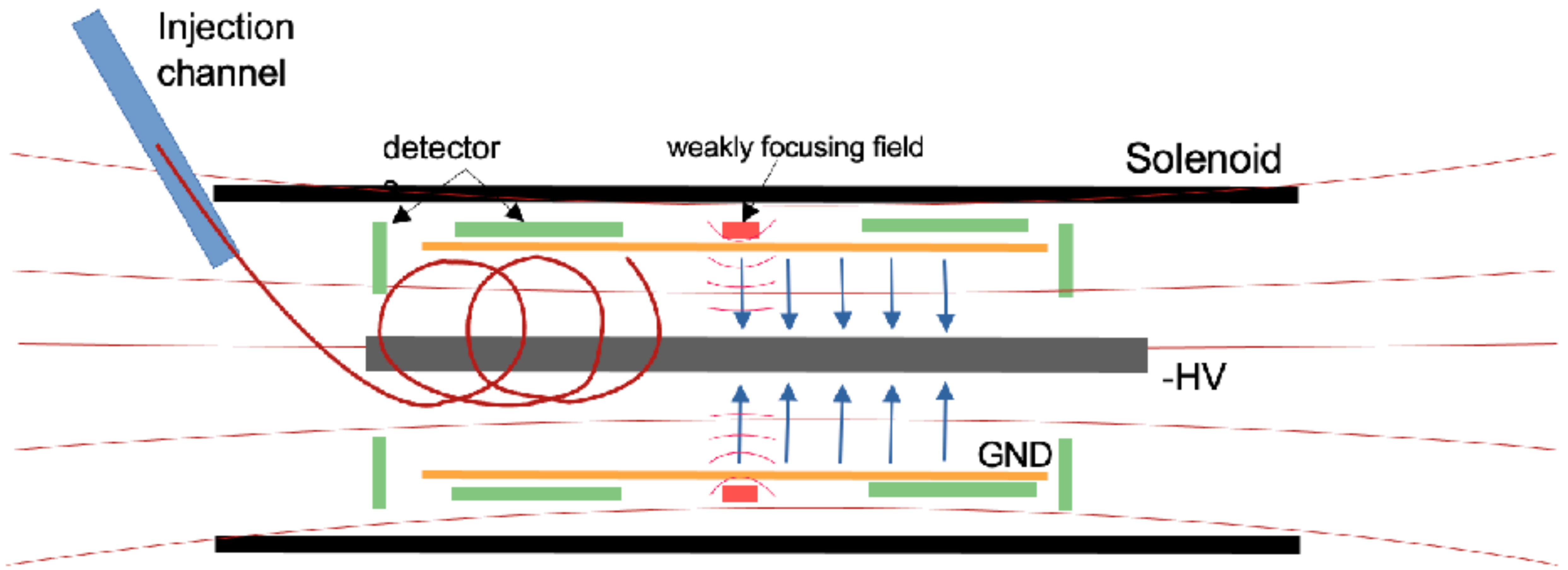
Phase 2 @ μE1
125 MeV/c, ~10^8/s

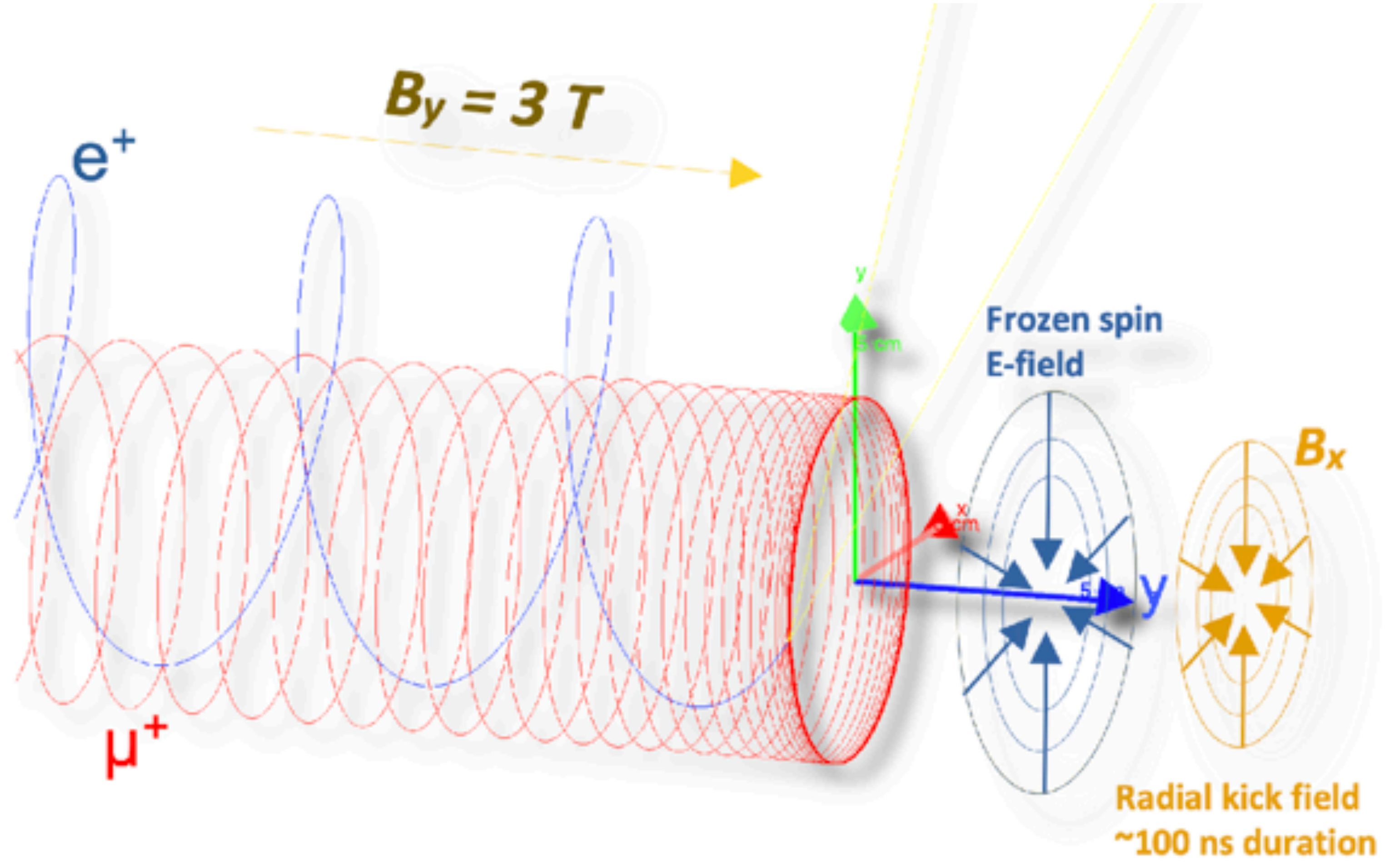
PSI Experimental Hall

The general experimental idea

- Muons enter the uniform magnetic field
- A radial magnetic field pulse stops them within a weakly focusing field where they are stored
- Radial electric field 'freezes' the spin so that the precession due to the g-2 is cancelled

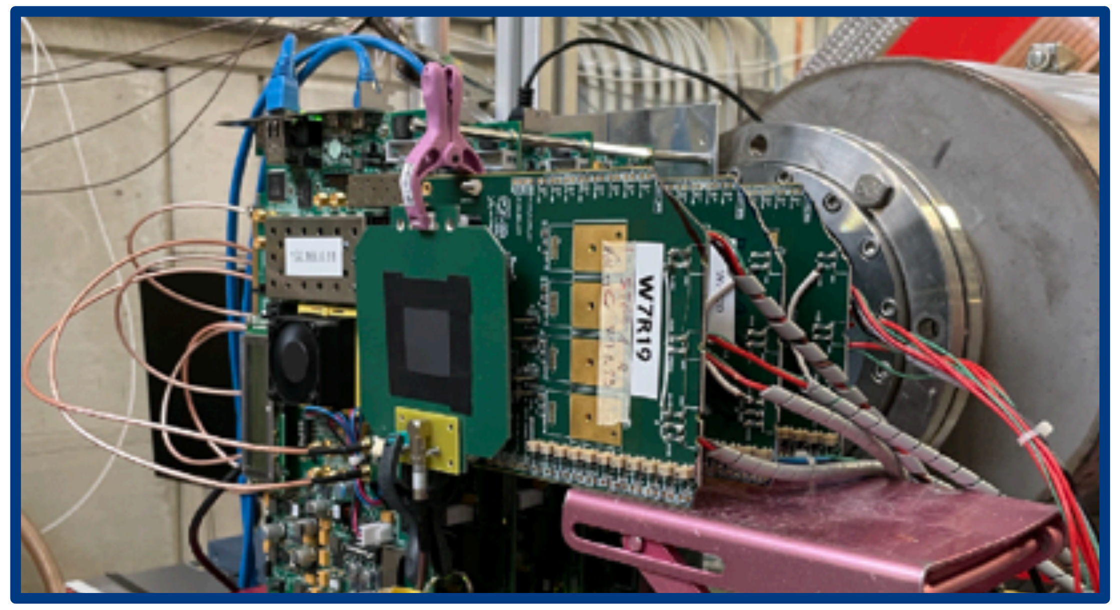


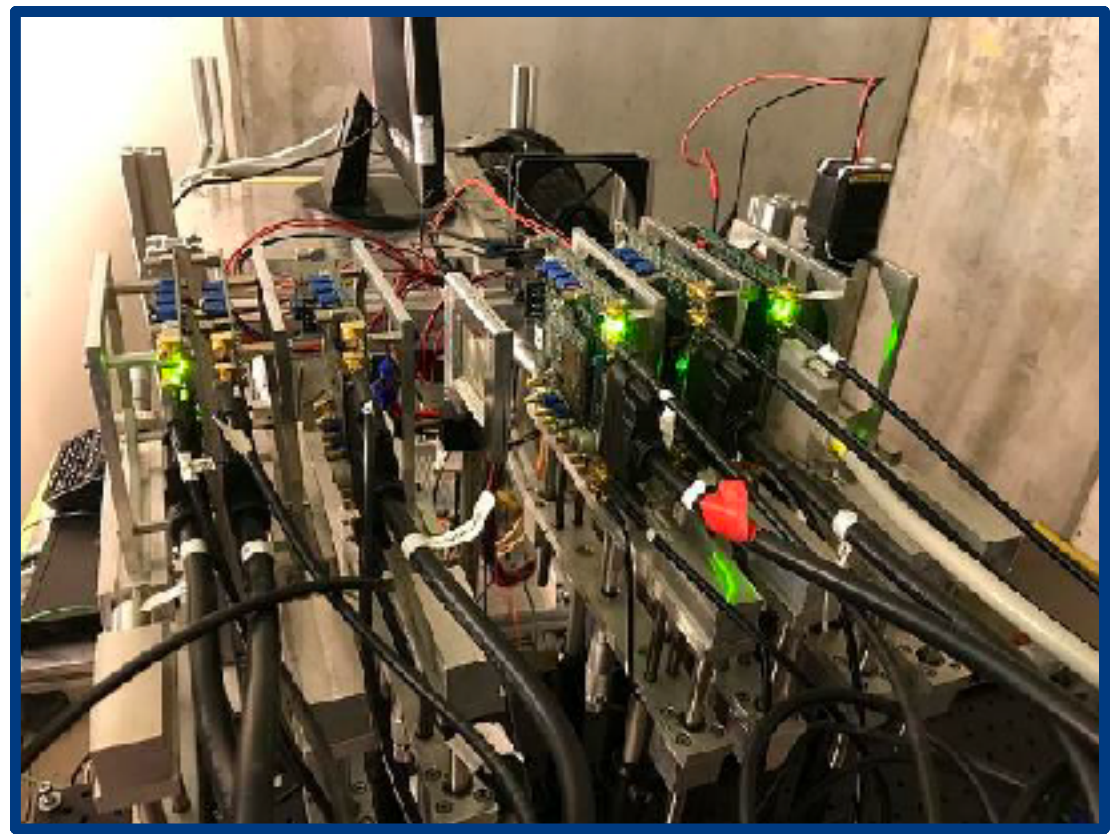


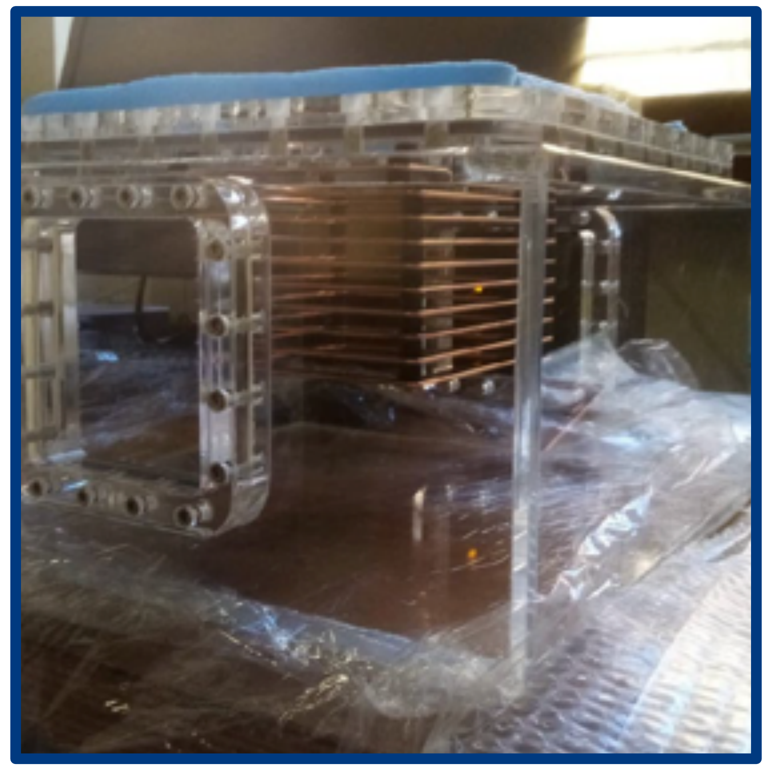


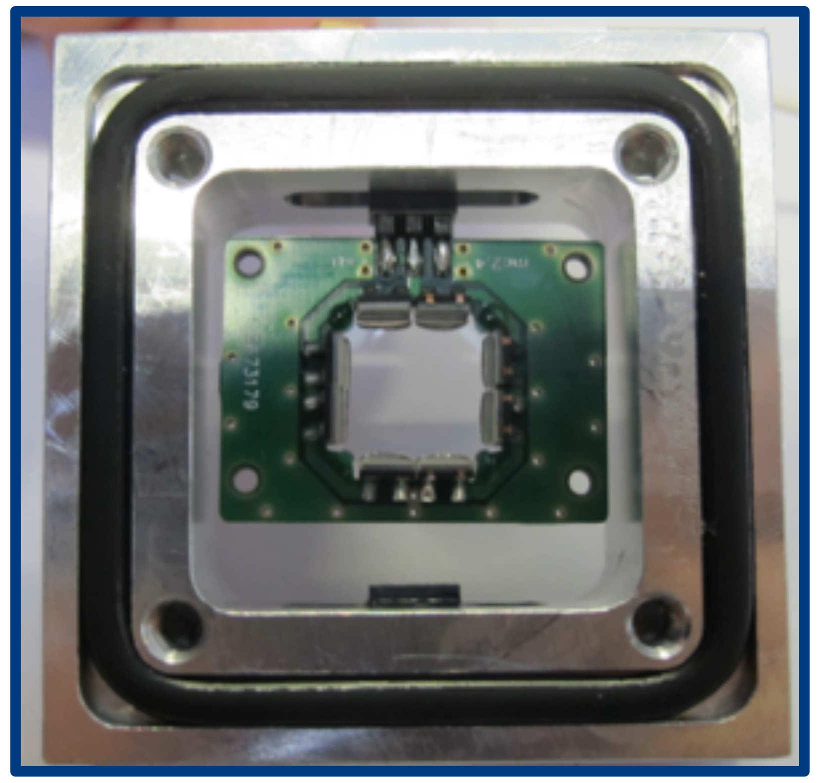
Annual beam tests at PSI

- PSI Beam Test 2019
  - Characterization of potential beam lines
- PSI Beam Test 2020
  - Study multiple scattering of positrons at low momenta
- PSI Beam Test 2021
  - Characterization of potential electrode material with positrons and muons
- PSI Beam Test 2022
  - Performance test of entrance/collimating channel
  - Performance test of TPC muon tagger/tracker









Projected Final Sensitivity of 10^{-23} e cm

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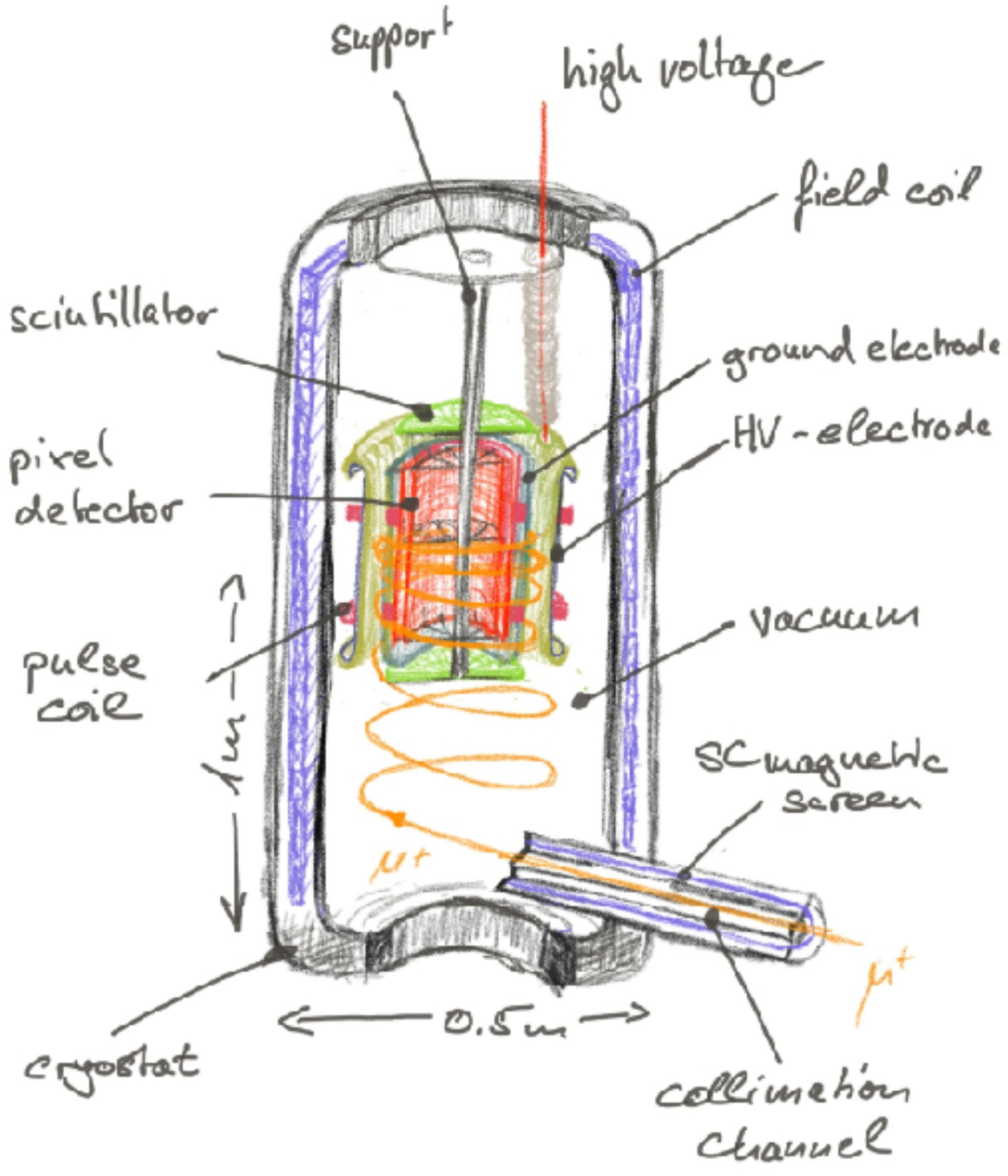
Key parameters	Symbols	Phase 1 @ 28 MeV/c	Phase 2 @ 125 MeV/c
Muon beam rate		2×10^{6} s^{-1}	1.2×10^{8} s^{-1}
After collimation		1×10^{6} s^{-1} (ε=50%)	1.2×10^{8} s^{-1} (ε=0.5%)
After beam injection		3 kHz (ε=0.3%)	480 kHz (ε=60%)
Gamma factor	γ	1.03	1.77
Initial polarization	P	0.95	0.95
Electric field	E_r	0.3 MV/m	2 MV/m
Positron detection rate		0.5 kHz	80 kHz
Muon decay asymmetry	α	0.3	0.3
Detections (200 days)	N	4×10^{11}	10^{12}
Sensitivity		**< 3×10^{-21} e cm**	**< 6×10^{-23} e cm**



$$\sigma(d_\mu) = \frac{\hbar \gamma^2 a_\mu}{2 P E_f \sqrt{N}\, \gamma \tau_\mu\, \alpha}$$

Collaboration activities

selected for funding, funded by SBFI

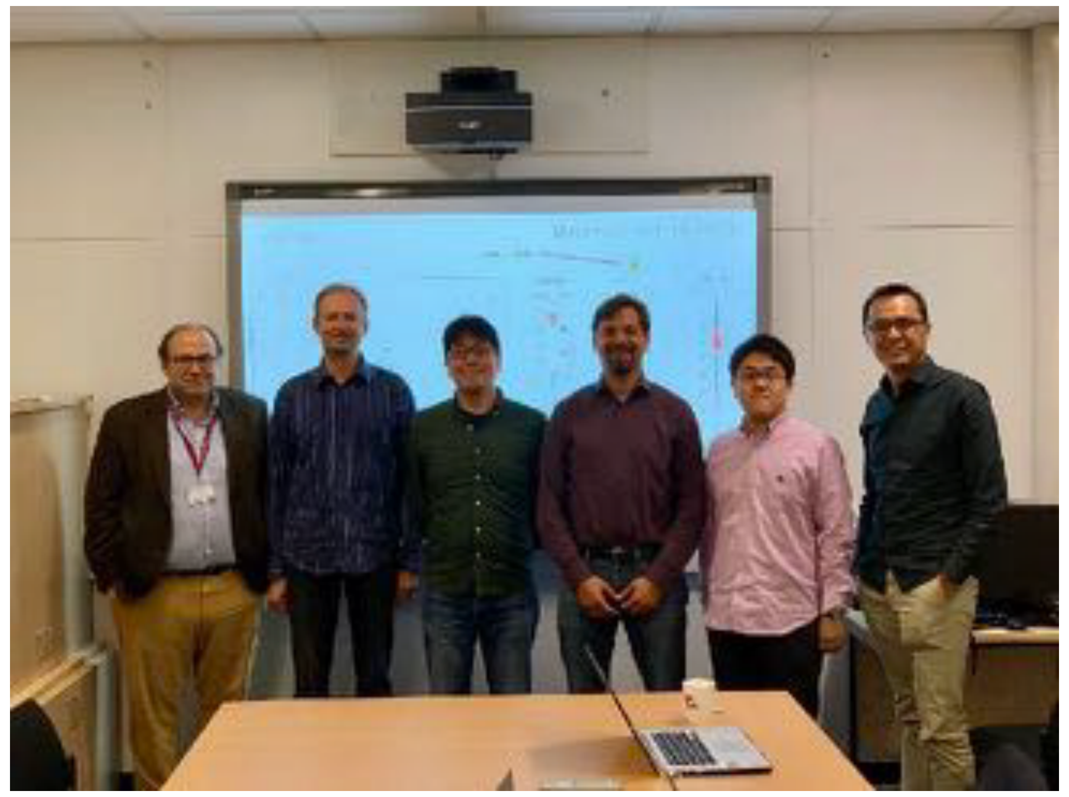
The muEDM – collaboration

Fonds national suisse

- A. Adelmann,[1,2] M. Backhaus,[1] C. Chavez Barajas,[3] N. Berger,[4] T. Bowcock,[3] A. Bravar,[5] C. Calzolaio,[2] L. Caminada,[2,6] G. Cavoto,[7] R. Chislett,[9] A. Crivellin,[2,6,10] C. Dutsov,[2] M. Daum,[2] M. Fertl,[11] M. Giovannozzi,[10] W.C. Griffith,[12] G. Hiller,[13] G. Hesketh,[9] M. Hildebrandt,[2] T. Hume,[2] A. Keshavarzi,[14] K.S. Khaw,[16,17] K. Kirch,[1,2] A. Kozlinsky,[4] A. Knecht,[2] M. Lancaster,[15] B. Märkisch,[18] F. Meier Aeschbacher,[2] F. Méot,[19] A. Papa,[2,20] J. Price,[3] F. Renga,[7,8] M. Sakurai,[1] P. Schmidt-Wellenburg,[2] M. Schott,[4,11] T. Teubner,[3] C. Voena,[7,8] J. Vossebeld,[3] and F. Wauters[4]

1 ETH, 2 Paul Scherrer Institut PSI, 3 University of Liverpool, 4 JGU, 5 Université de Genève, 6 University of Zurich, 7 Sapienza Università di Roma, 8 INFN, 9 UCL, 10 CERN, 11 Cluster of Excellence PRISMA+, 12 University of Sussex, 13 technische universität dortmund, 15 Manchester 1824 The University of Manchester, 16 上海交通大学 Shanghai Jiao Tong University, 17 李政道研究所 Tsung-Dao Lee Institute, 18 TUM, 19 Brookhaven National Laboratory "a passion for discovery", 20 Università di Pisa

国家自然科学基金委员会 National Natural Science Foundation of China (NSFC)



muEDM Workshop Pisa, May 2022

12 May 2022, 14:00 → 13 May 2022, 17:15 Europe/Zurich

250 (Dipartimento di Fisica&INFN)

Hotel list.pdf | muEDM_Pisameeti... | Short_PisaGuide.pdf | Zoom link for remot...

Registration: Participants — Register

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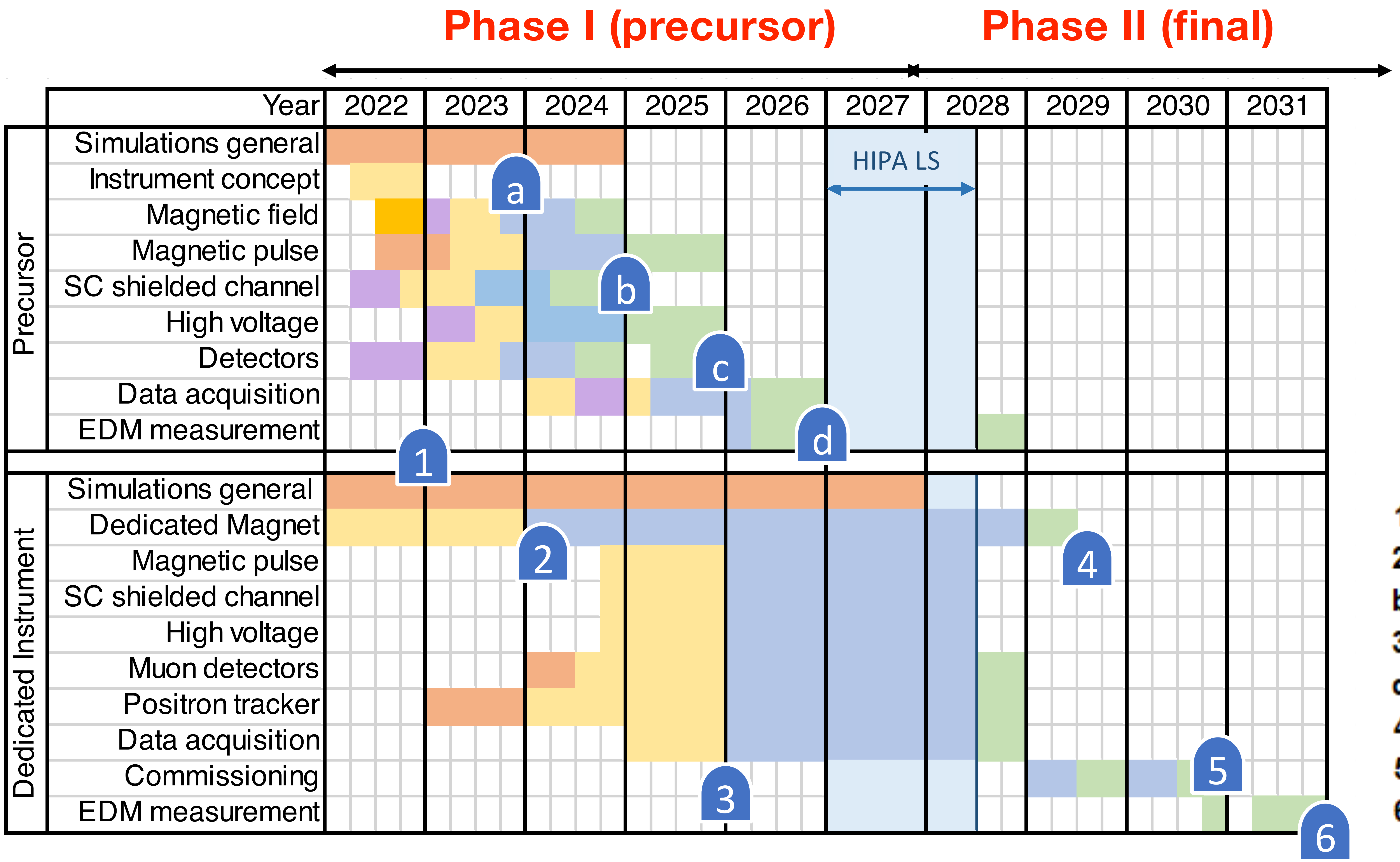
+ monthly meetings and online collaboration meetings in between

Schedule and milestone



Simulations
Conception/Design
Prototyping
Acquisition/Assembly
Tests/Measurements

1 Full proposal for both phases to CHRISP committee
2/a Magnet call for tender / precursor design fix
b Precursor ready for assembly/commissioning
3/c Technical design report / frozen spin demonstration
d First data for precursor muEDM
4 Magnet delivered, characterized and accepted
5 Successful commissioning / start of data taking
6 End of data acquistion for muEDM

Rich physics program connected to muon g-2

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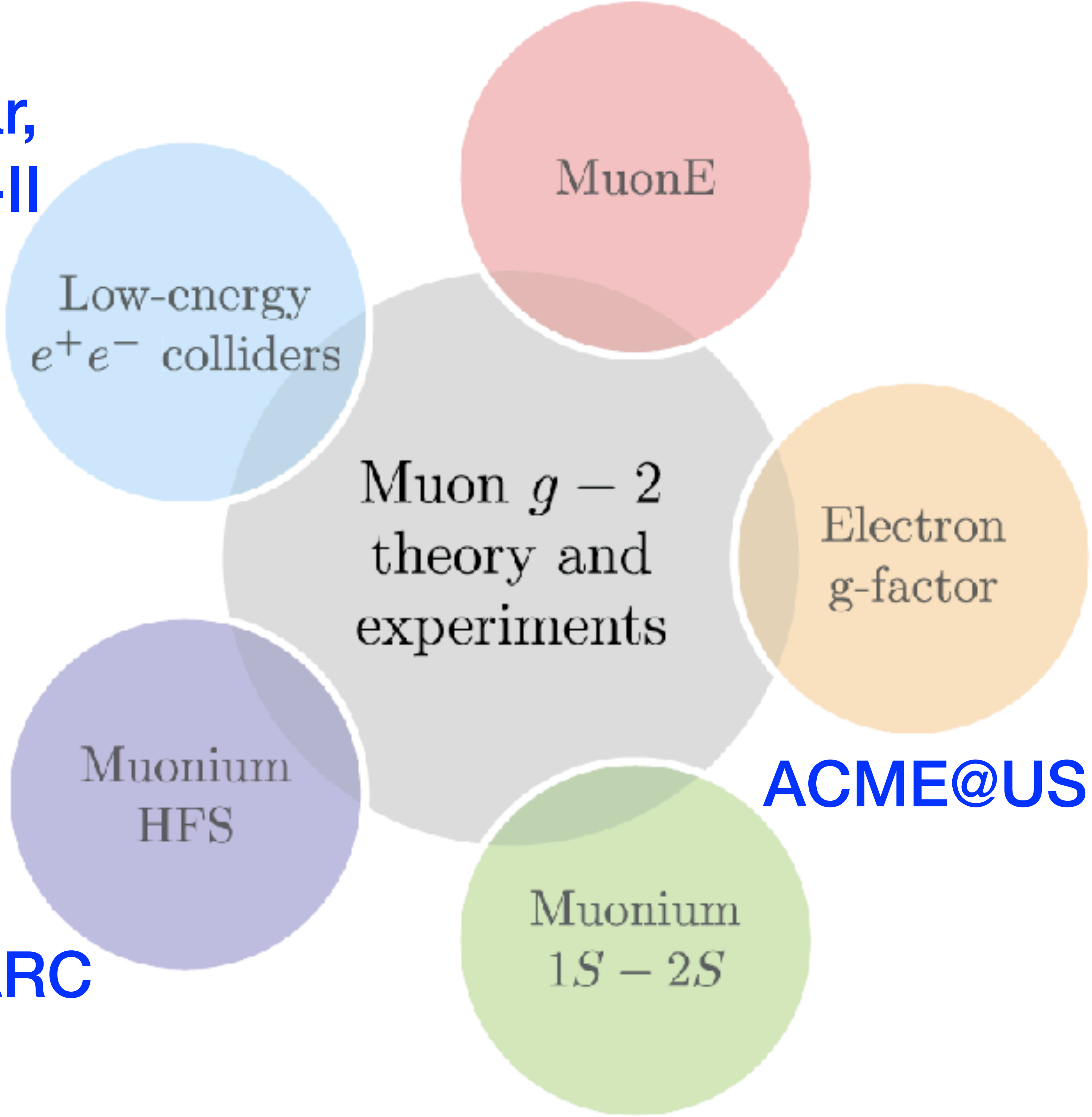
CERN

CMD-3, BaBar, BES-III, Belle-II



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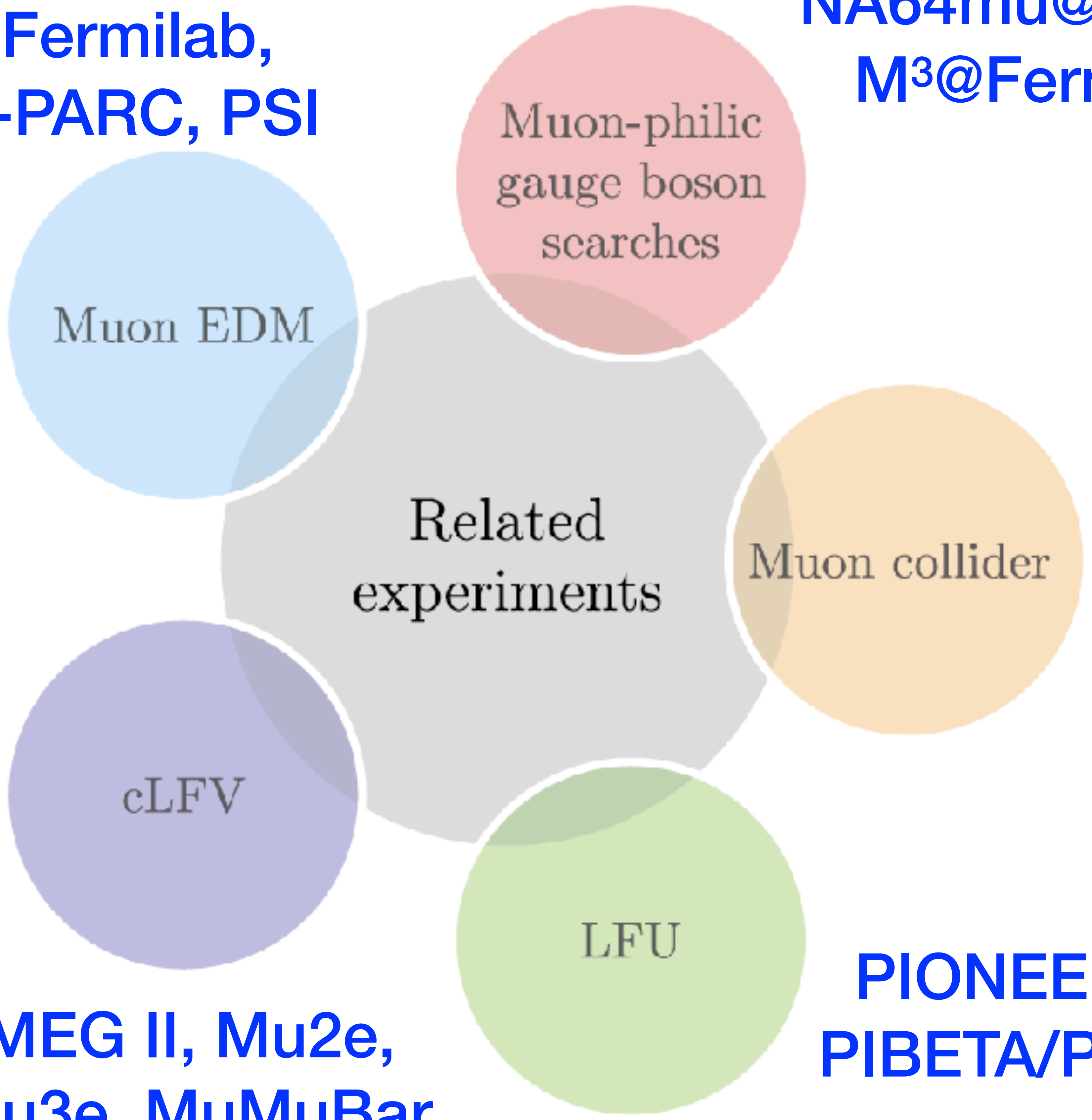
J-PARC

MuMASS@PSI, J-PARC

Fermilab, J-PARC, PSI

NA64mu@CERN, M³@Fermilab



Very active field now!

MEG II, Mu2e, Mu3e, MuMuBar

PIONEER@PSI, PIBETA/PEN@PSI

Many interesting and high-impact experiments for young students and postdocs!

ONE THING IS FOR SURE: THE HUNT IS ON, AND NEW DISCOVERIES ARE ON THE HORIZON.

Muonium 1S-2S + HFS @ PSI/J-PARC

Muon g-2 @ J-PARC

Muon g-2 @ Fermilab

muEDM @ PSI

MUonE @ CERN

Muon g-2
Theory Initiative

STAY TUNED!