Muon $g-2$/EDM experiment at J-PARC
日本 μ 子反常磁矩 $(g-2)$ 与电偶极矩测量实验

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- **Introduction**
  - Muon anomalous magnetic moment
  - Recent result from Fermilab
- **Muon $g-2$/EDM experiment at J-PARC**
  - Overview
  - R&D highlights
  - Roadmap
- **Summary**

Muon anomalous magnetic moment

- The Hamiltonian for the spin 1/2 particle (charge e and mass m) in the external electromagnetic field is

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

Magnetic dipole moment

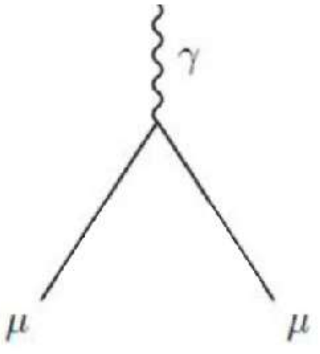
$$\vec{\mu} = g\frac{e\hbar}{2m}\vec{S}$$

Electric dipole moment

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

- $\vec{\mu}$ is proportional to gyromagnetic ratio (g), which is predicted to be $g = 2$ by Dirac equation.
- But quantum fluctuations gives **the anomaly of muon** a_μ:

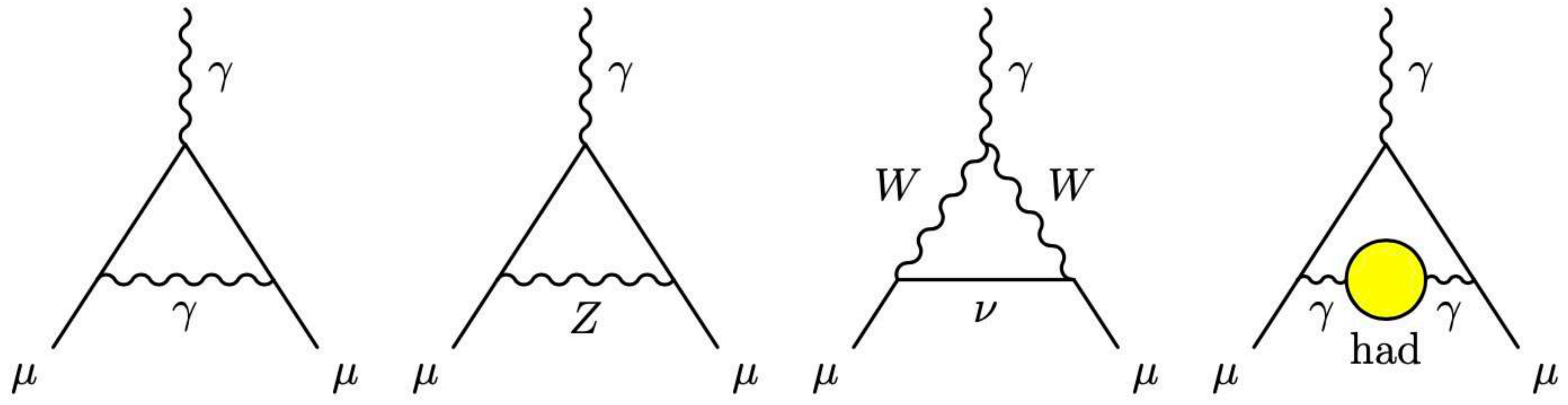
$$a_\mu \equiv \frac{g_\mu - 2}{2}$$



Muon anomaly

- In the standard model, muon anomaly a_μ is calculated from each contributions:

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm Had}$$



QED Electro-weak Hadronic

First-order QED correction:

$$a^{(2)} = \frac{\alpha}{2\pi} = 0.001\,161\,40\ldots$$

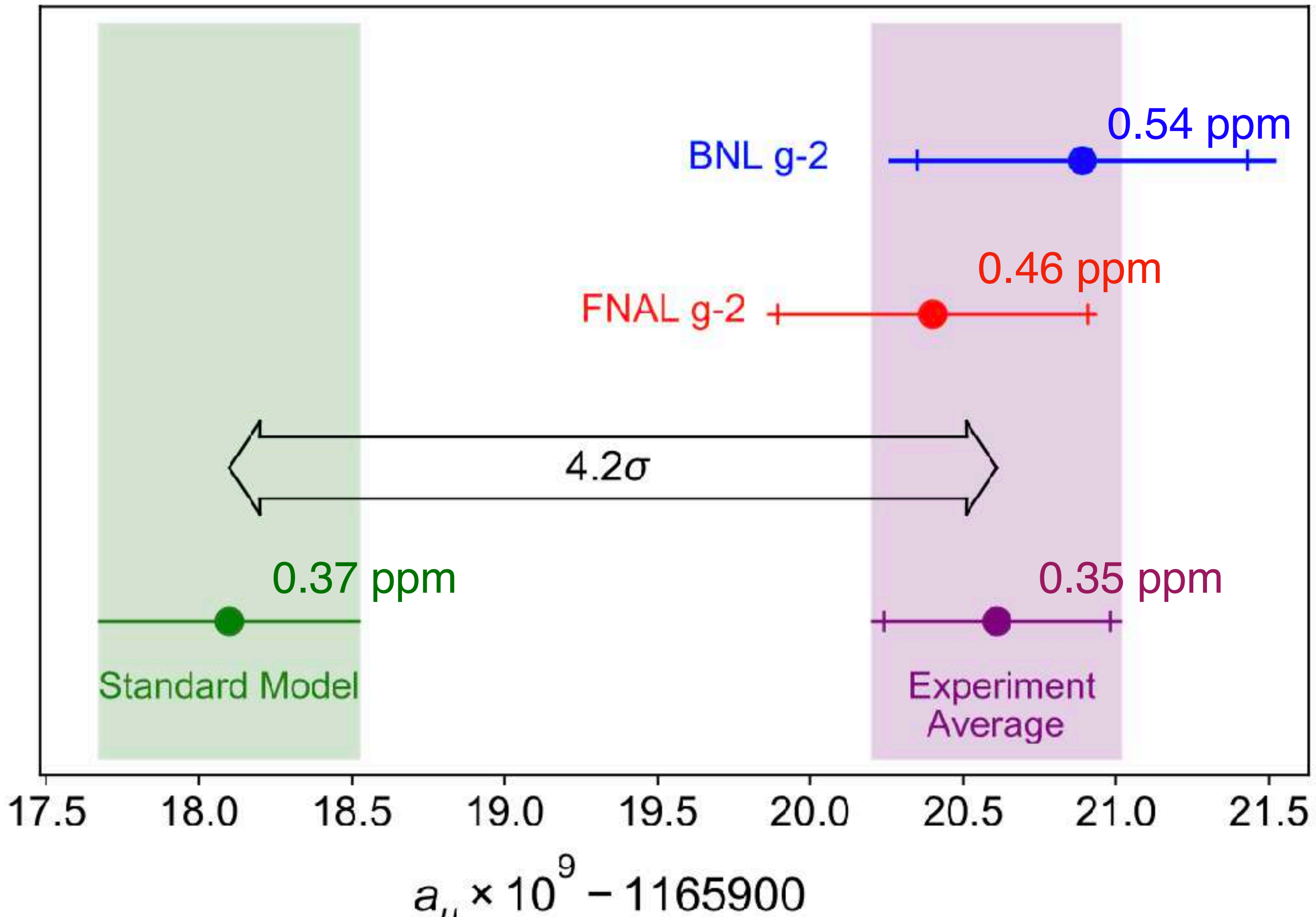
[J. Schwinger, Phys Rev 73 (1948) 416]

Muon anomaly

- In the standard model, muon anomaly a_μ is calculated from each contributions:

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}}$$

- Recent result from Fermilab shows 4.2 σ tension between a_μ^{EXP} and a_μ^{SM}



a_μ(BNL)	$116592092(63) \times 10^{-11}$	0.54 ppm
a_μ(FNAL)	$116592040(54) \times 10^{-11}$	0.46 ppm
a_μ(EXP)	$116592061(41) \times 10^{-11}$	0.35 ppm
a_μ(SM)	$116591810(43) \times 10^{-11}$	0.37 ppm

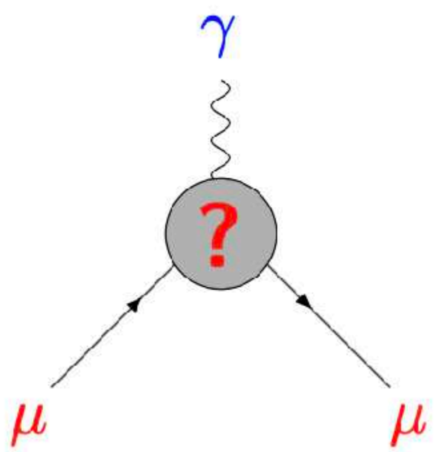
Phys Rev Lett.126.141801

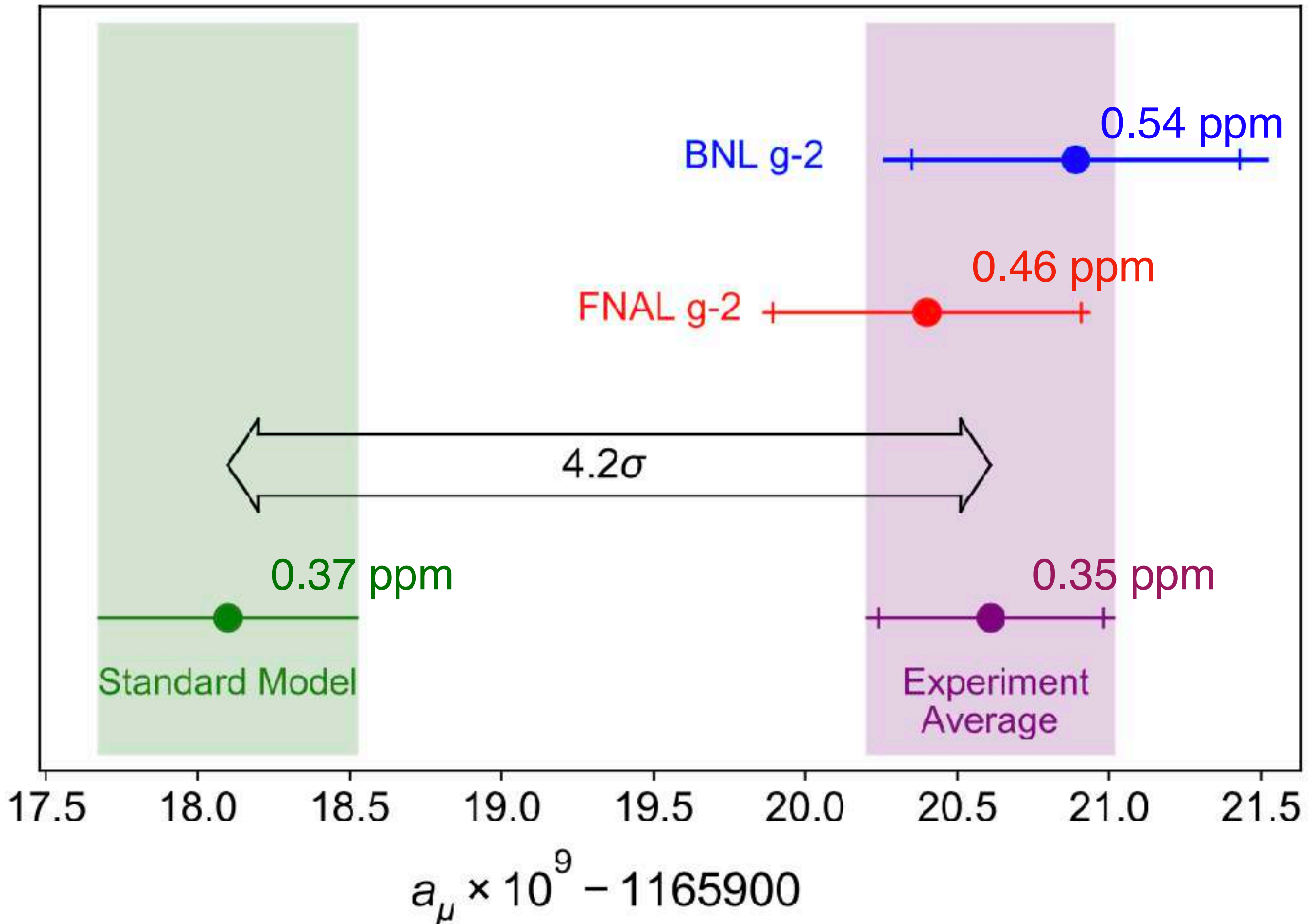
Muon anomaly

- New physics contribution to a_μ ?

$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}} + a_\mu^{\mathrm{NP}}?$$

Unknown particles
SUSY, MSSM…





Phys Rev Lett.126.141801

Why muon?

New physics effects enhanced by

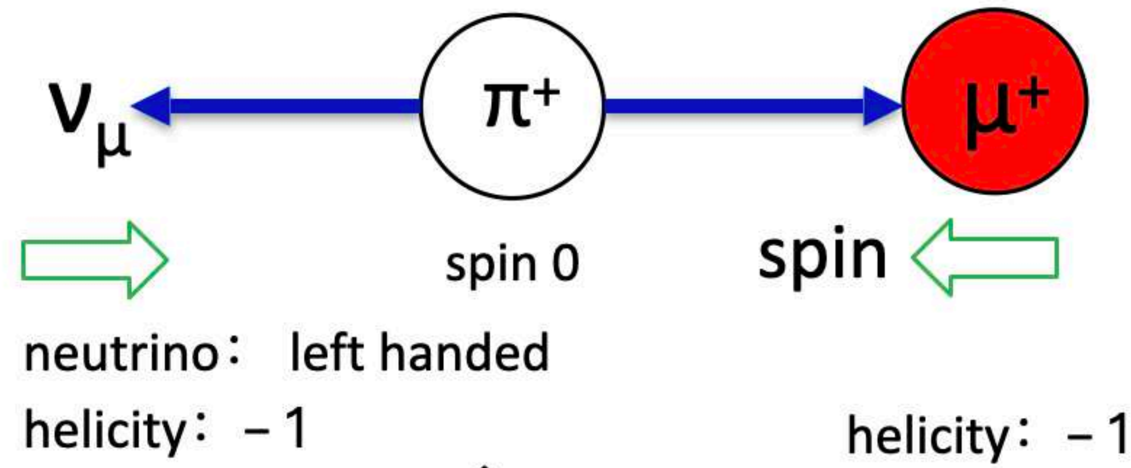
$$\delta a_\ell \propto m_\ell^2 / M^2_{?(\mathrm{NP})}$$

Muon is more sensitive by a factor

$$(m_\mu / m_e)^2 \approx 4.3 \cdot 10^4$$

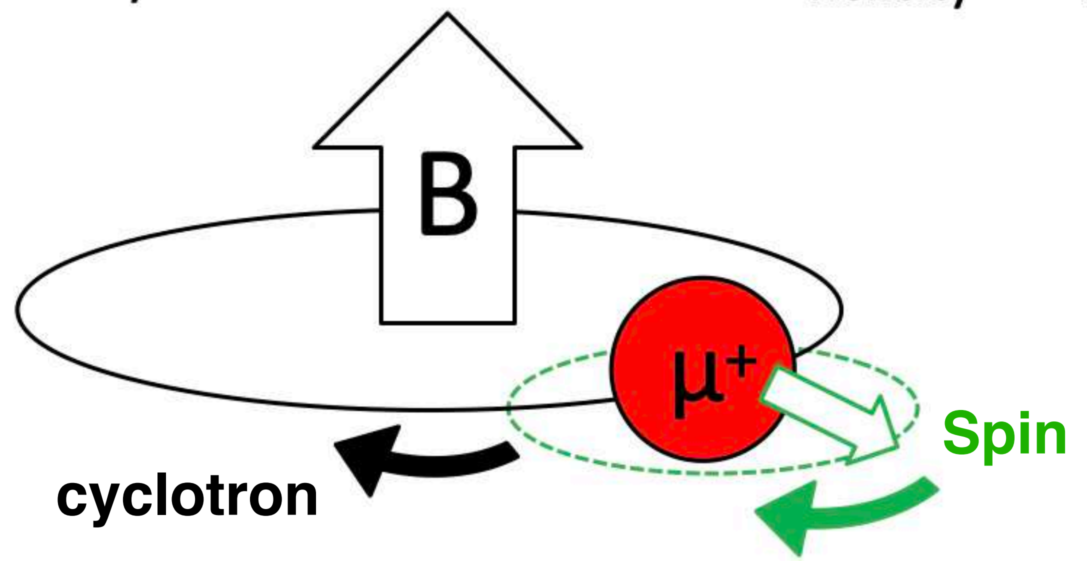
Experimental determination of a_μ

1. Prepare a polarized muon beam.



2. Store in a magnetic field (muon's spin precesses)

$$\omega_a = \omega_S - \omega_C = -\underbrace{\tfrac{1}{2}(g-2)}_{a_\mu}\frac{eB}{m}$$



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

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

(Larmor) (Thomas)

Measure two quantities: ω_a, B

Experimental determination of a_μ

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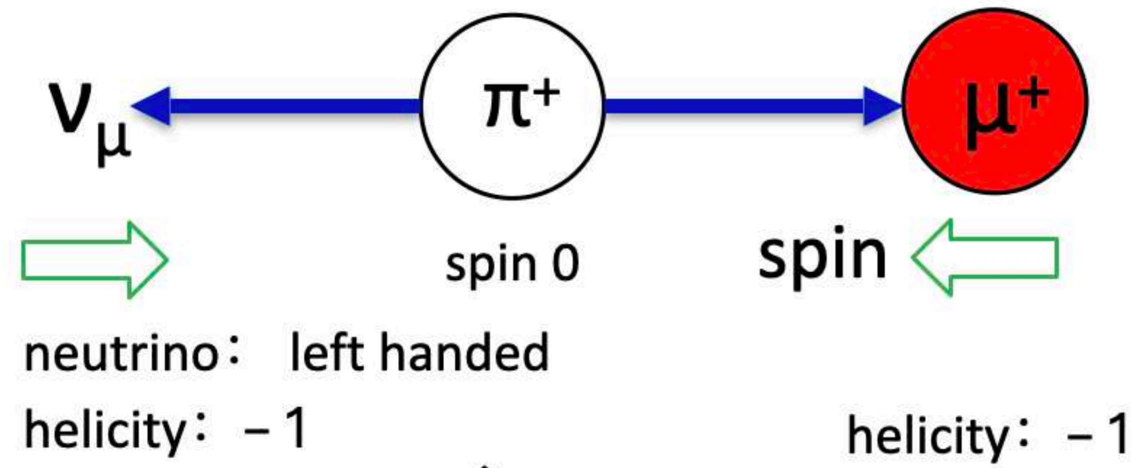

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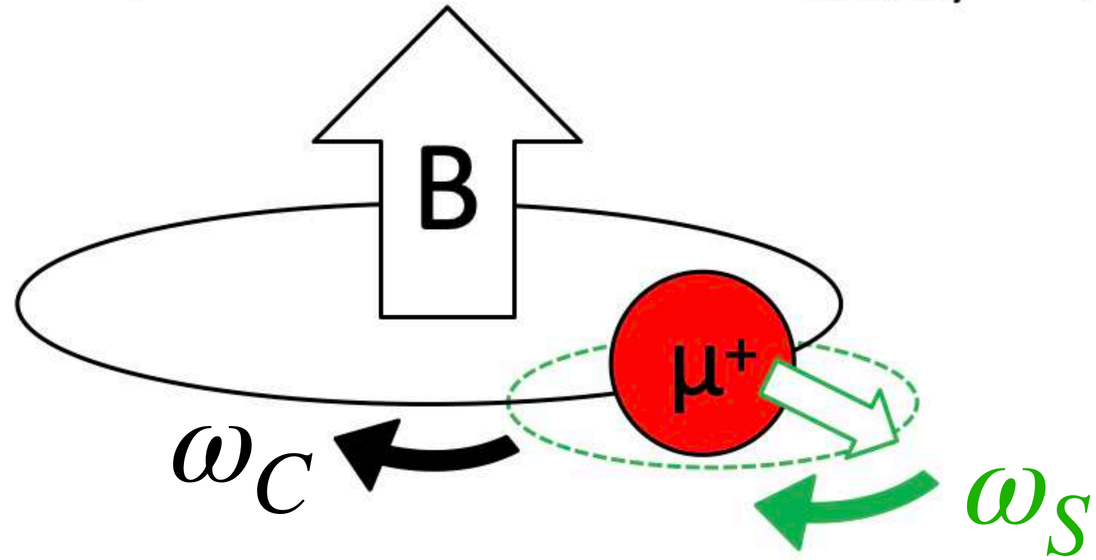
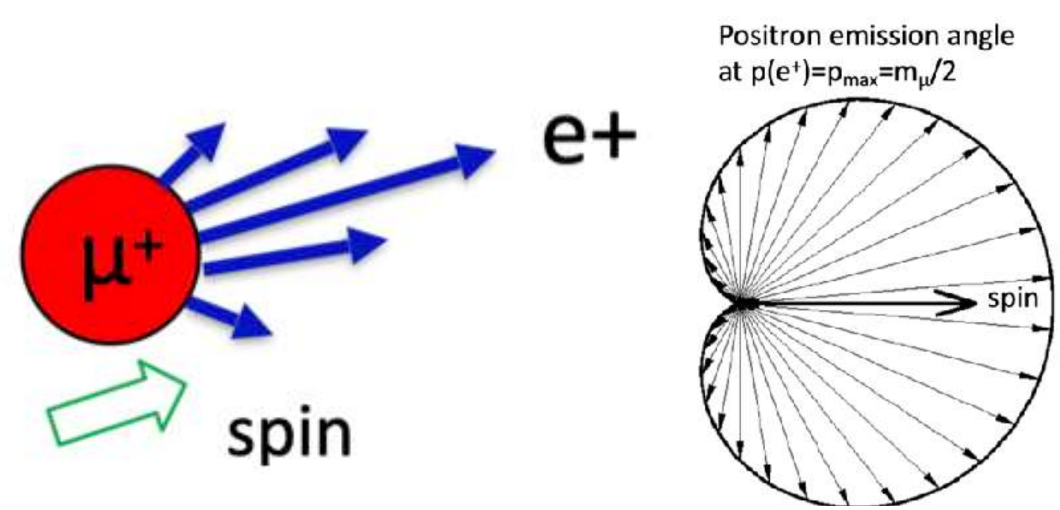


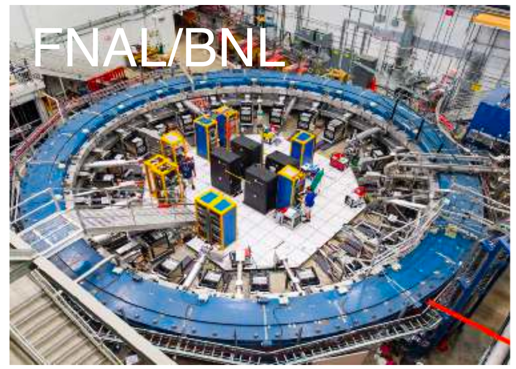
3. Detect a decay positron

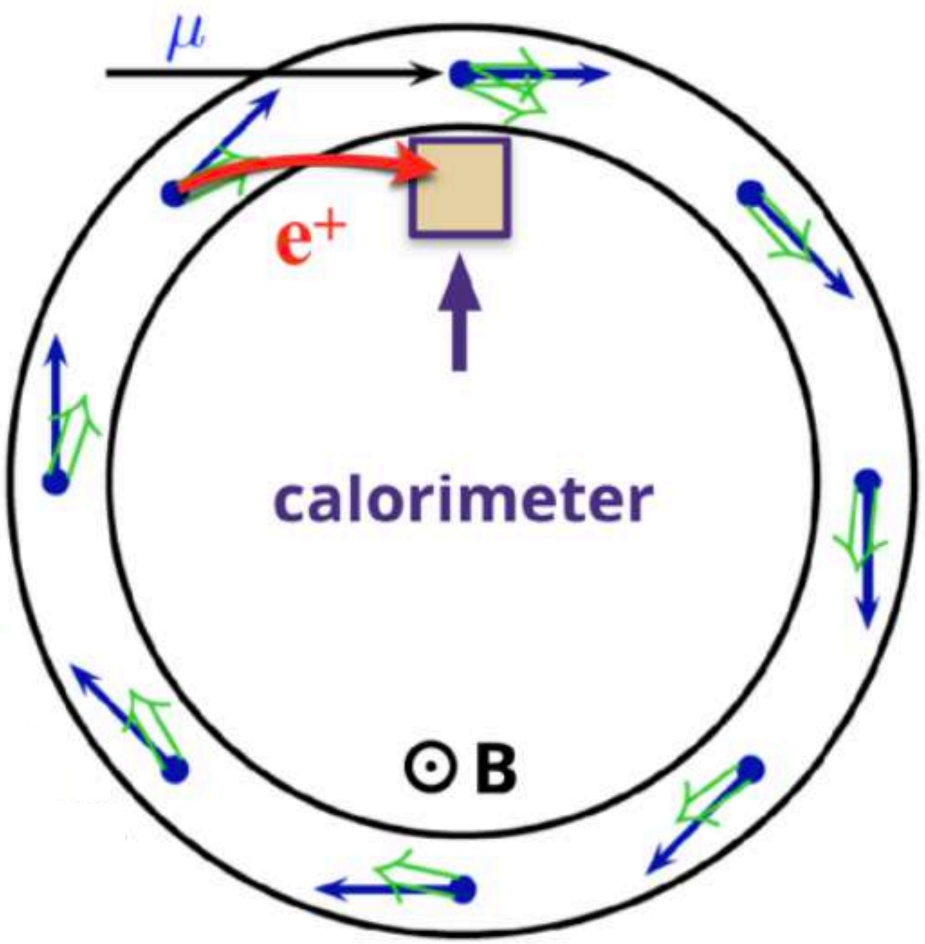
(Higher energy positron tends to emit along muon's spin direction).



Frequency ω_a extraction in Fermilab

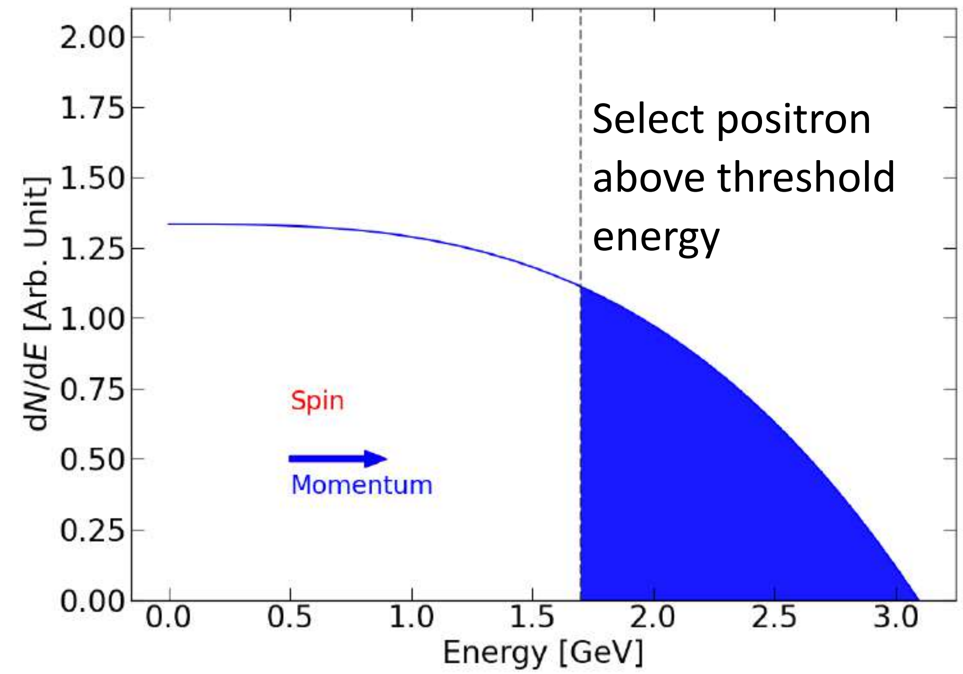
$$\omega_a = a_\mu \frac{eB}{m}$$

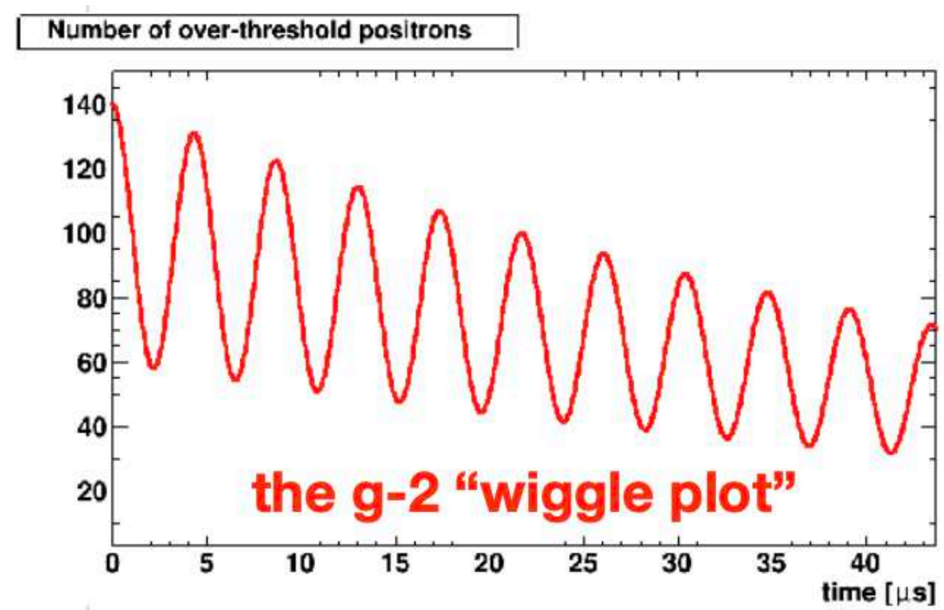




spin — Rotation by ω_s

momentum — Rotation by ω_c

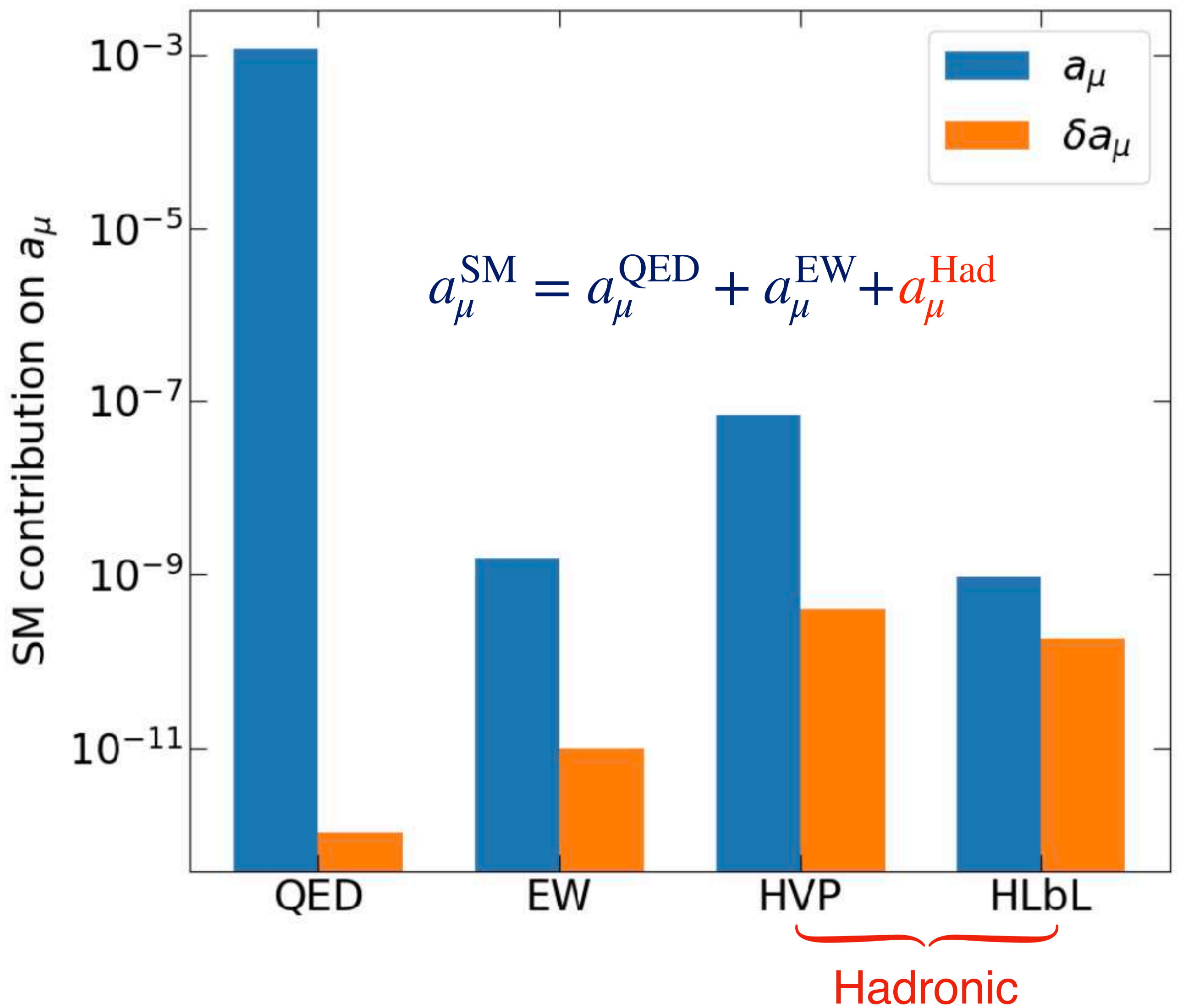


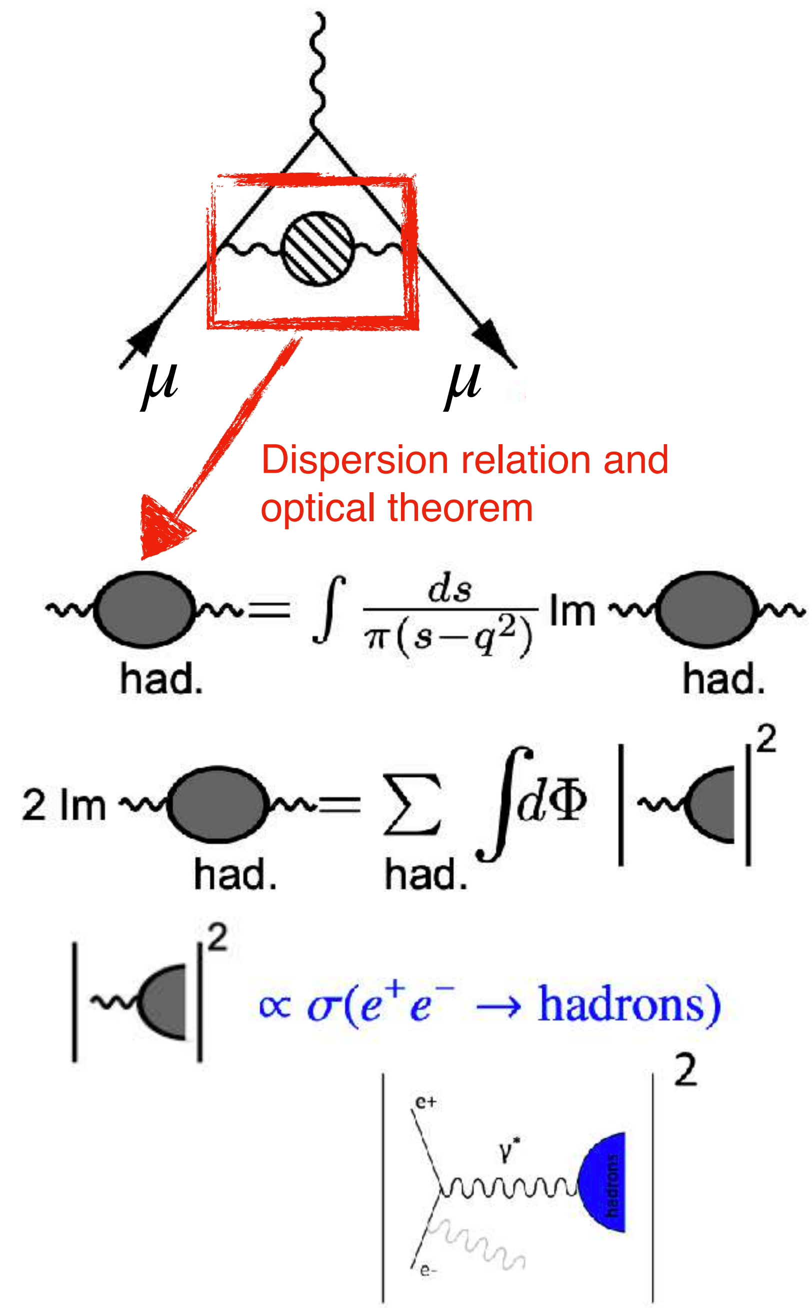


$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$

Theory initiative to determine $a_\mu^{\rm SM}$

- In the theory $a_\mu^{\rm SM}$, hadronic contribution is the most changeling part
- At low energy pQCD is not useful, either LQCD or exp. data is needed.





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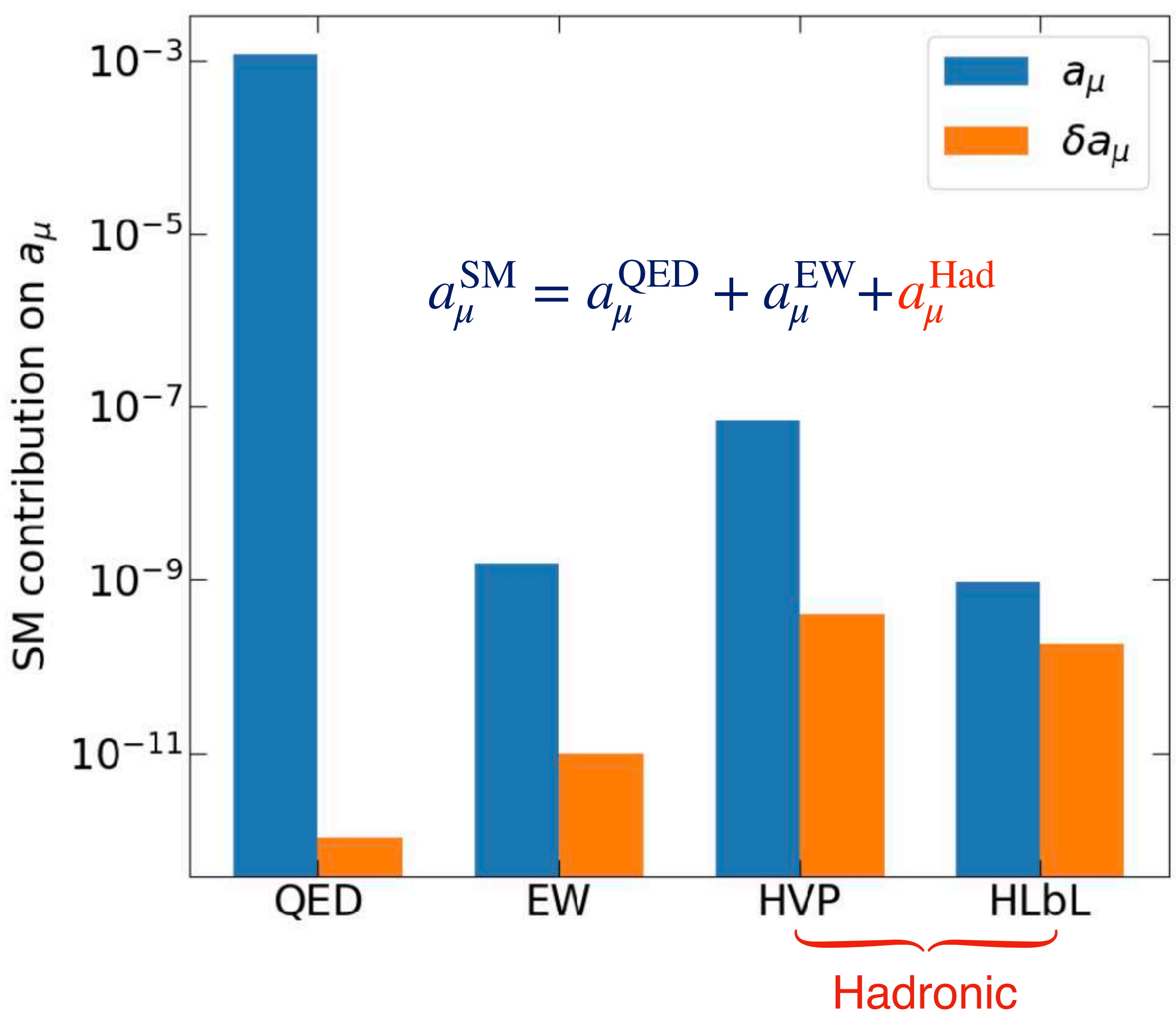
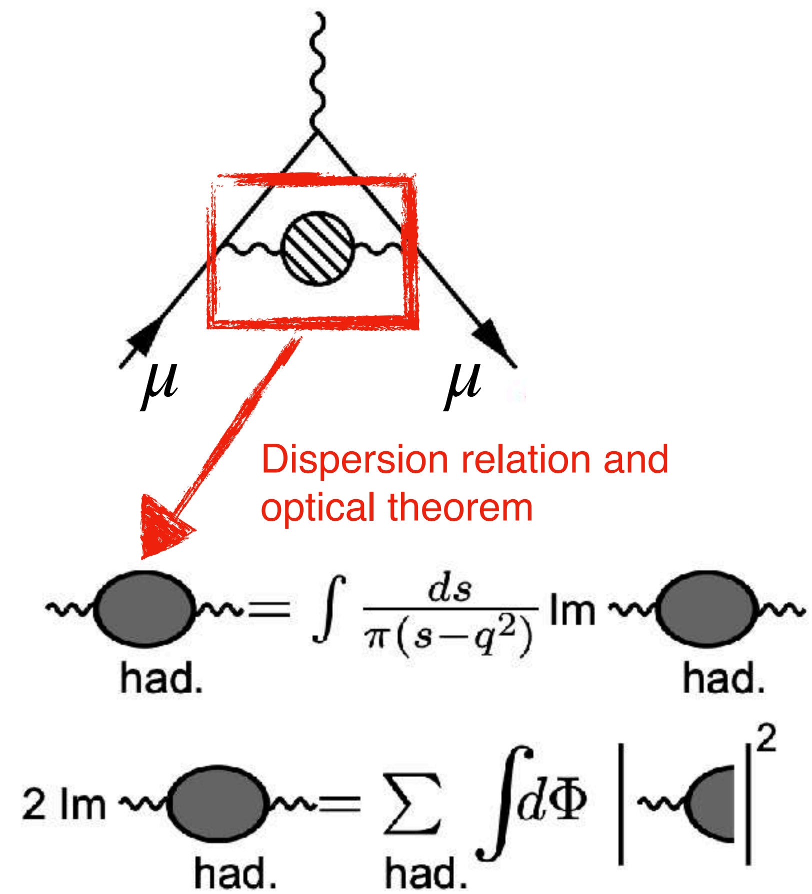
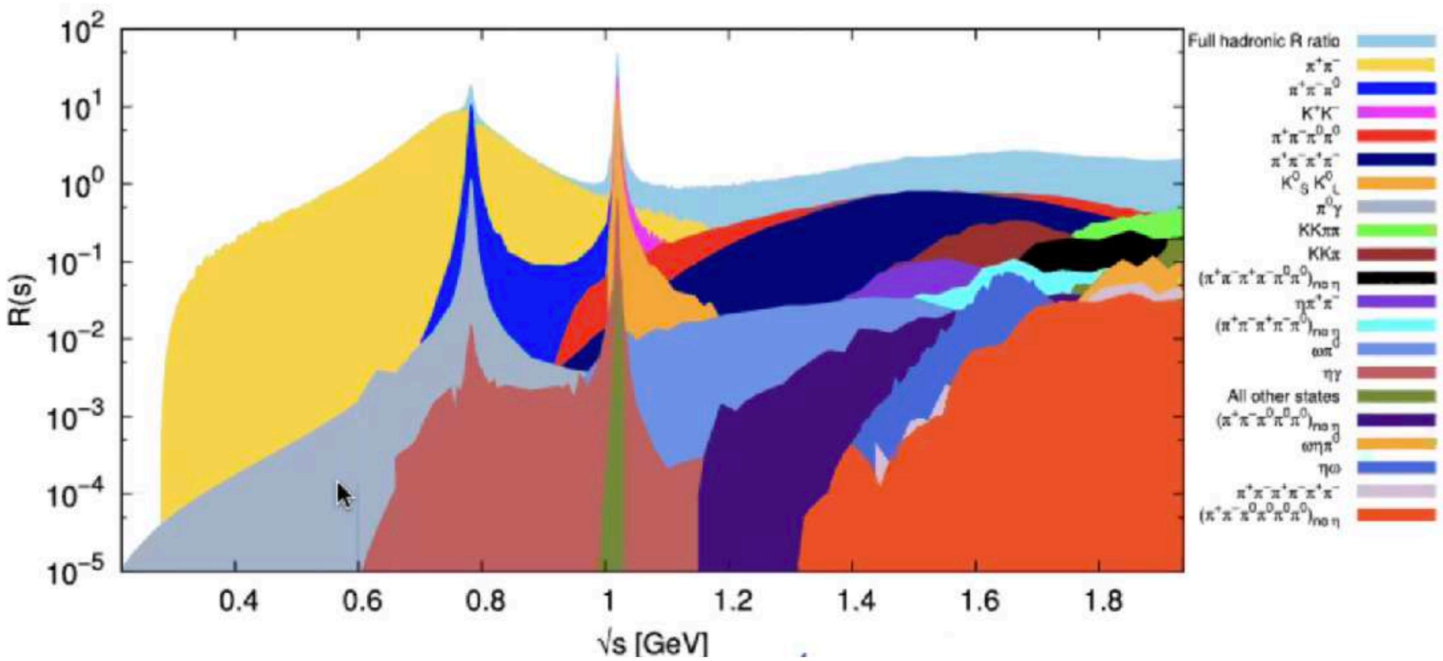


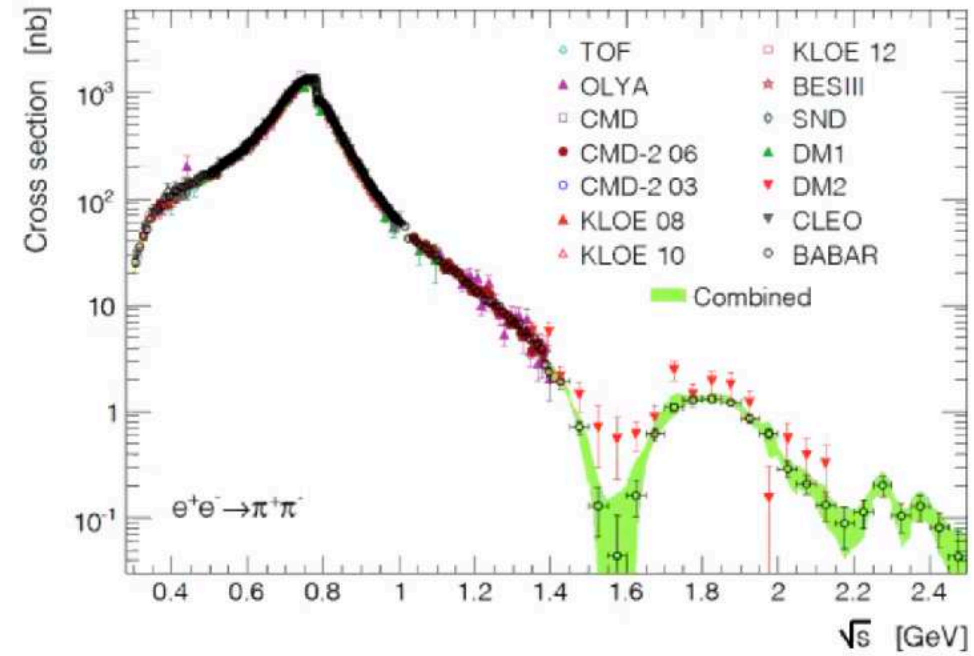


$$a_\mu^{\rm hvp} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} ds \, \frac{R_{\rm had}(s)\, \hat{K}(s)}{s^2},$$

$$R_{\rm had}(s) = \sigma(e^+e^- \to \text{hadrons}) \Big/ \frac{4\pi\,\alpha(s)}{(3s)}$$

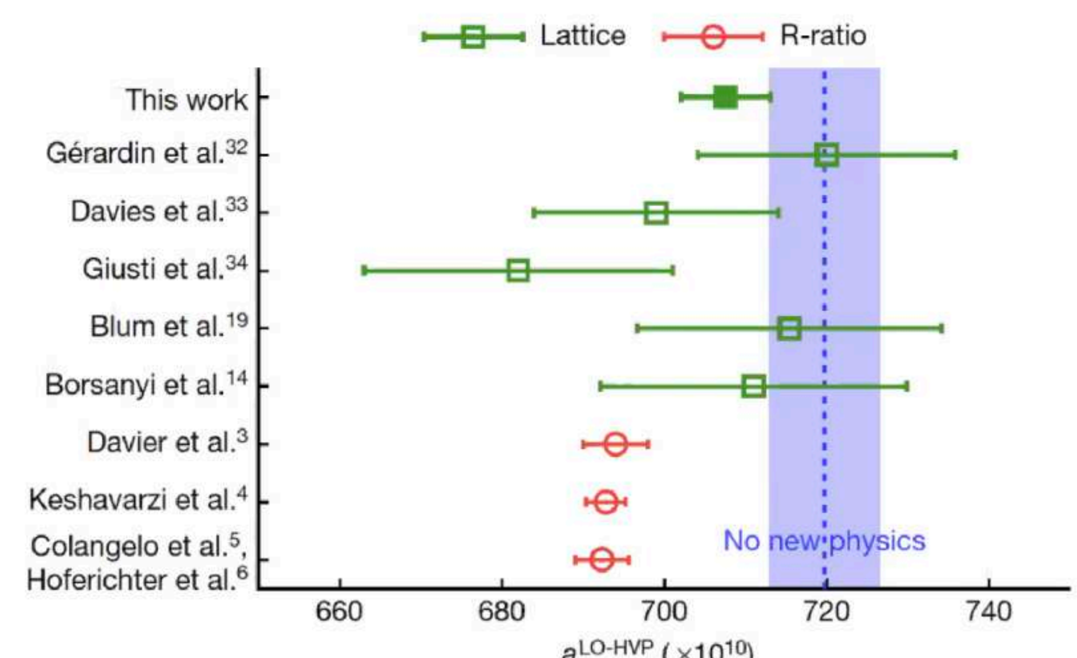
Theory initiative to determine a_μ^{SM}

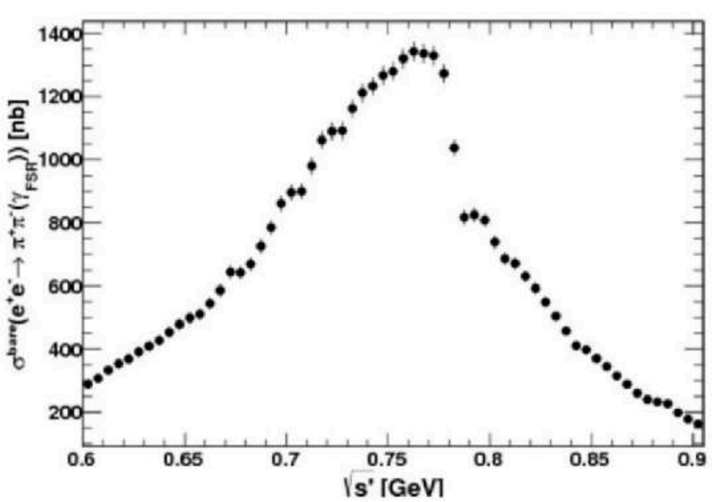




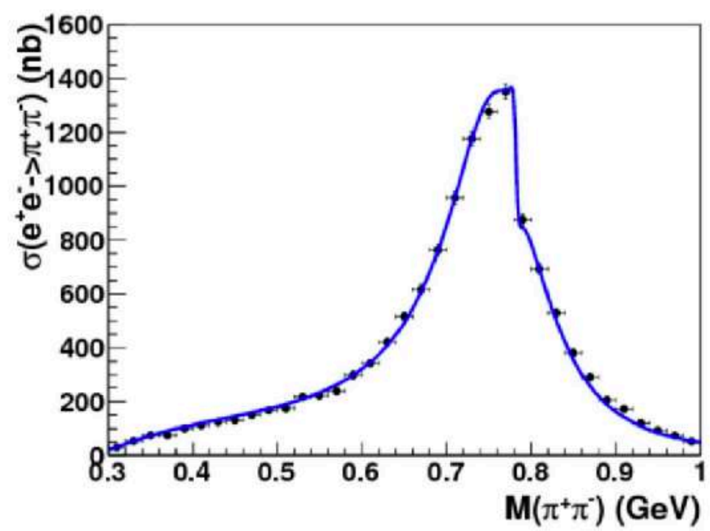
Use experimental data for cross section ratio $R_{\mathrm{had}}(s)$

Various Theoretical Calculations





BESIII data



CLEO-c data

π+π− data from BESIII and CLEO-c is critical

Borsanyi et al (BMWc), Nature 2012

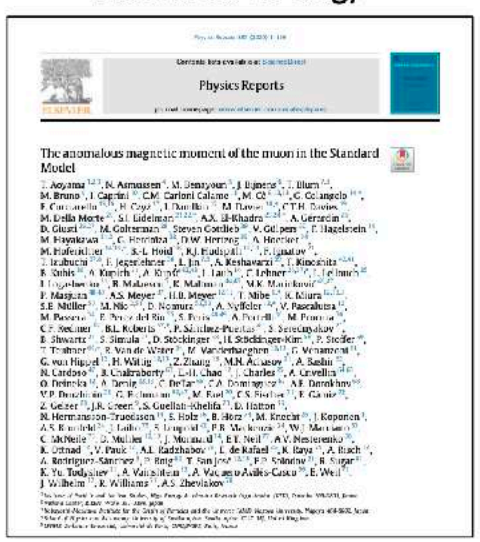
Theory initiative to determine $a_\mu^{\rm SM}$

The muon g-2 theory initiative

A group of 170 experts came to a consensus on **a single value** of muon g-2 in the standard model.

The white paper

Phys. Rep. 887 (2020) 1-166
(Submitted 15 June
Accepted 29 July
Published 14 Aug)

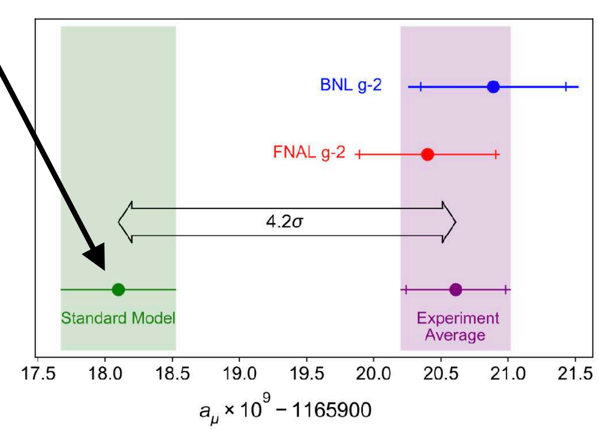


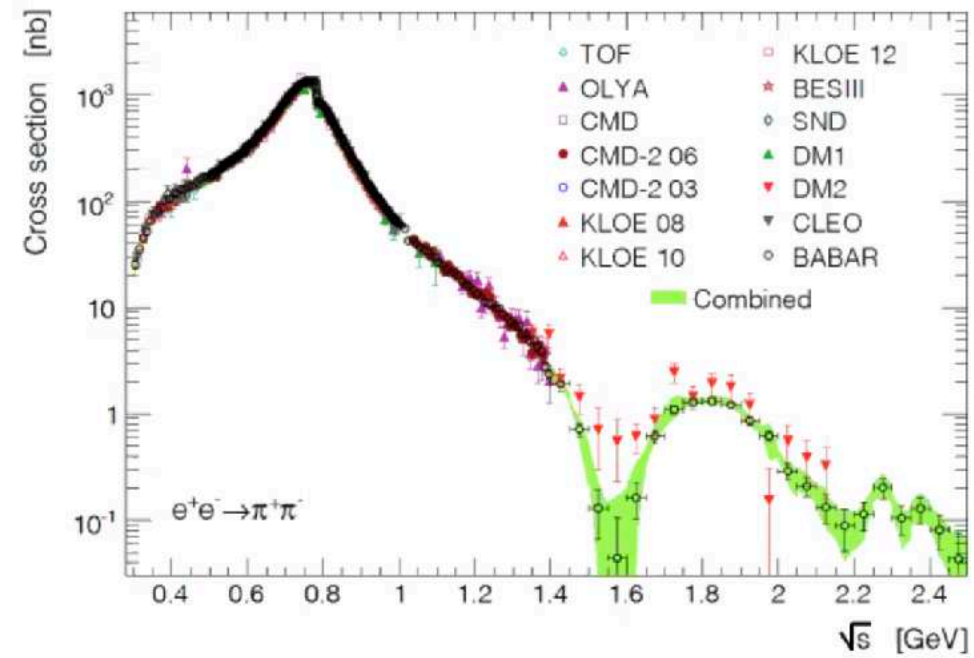
2017 workshop in Fermilab
2018 workshop in Mainz
2019 workshop in Seattle
~~2020~~→2021 workshop in KEK (online)

Supported by the KEK-IPNS theory center

https://www-conf.kek.jp/muong-2theory/index.html

$$a_\mu^{\rm SM} = 116591810(43) \times 10^{-11}$$





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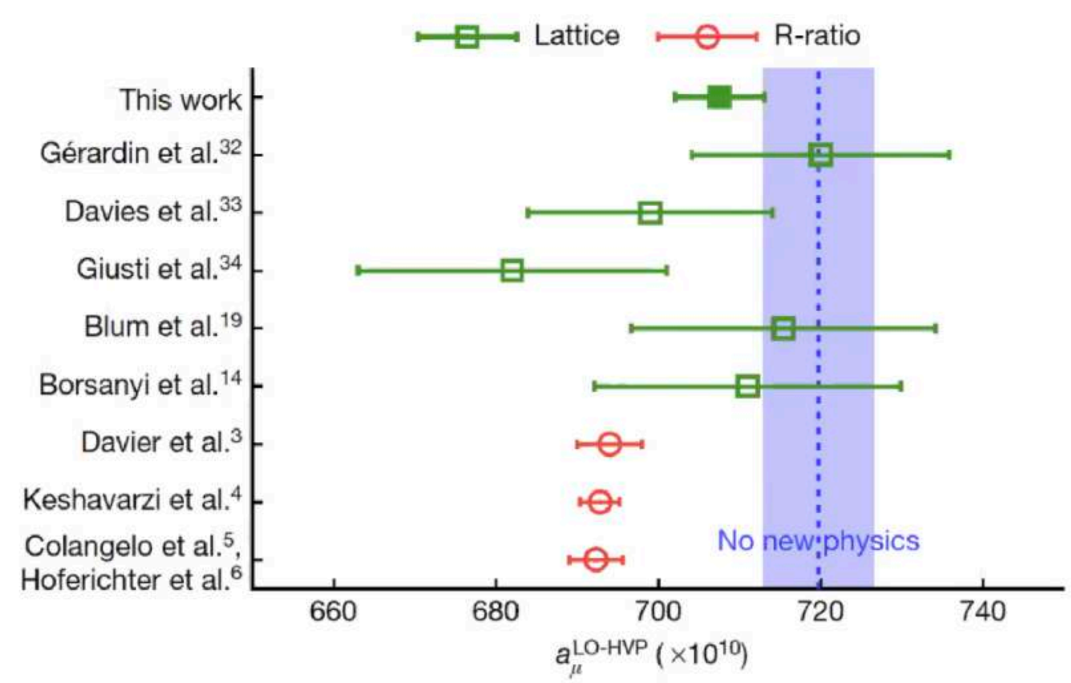

Borsanyi et al (BMWc), Nature 2012

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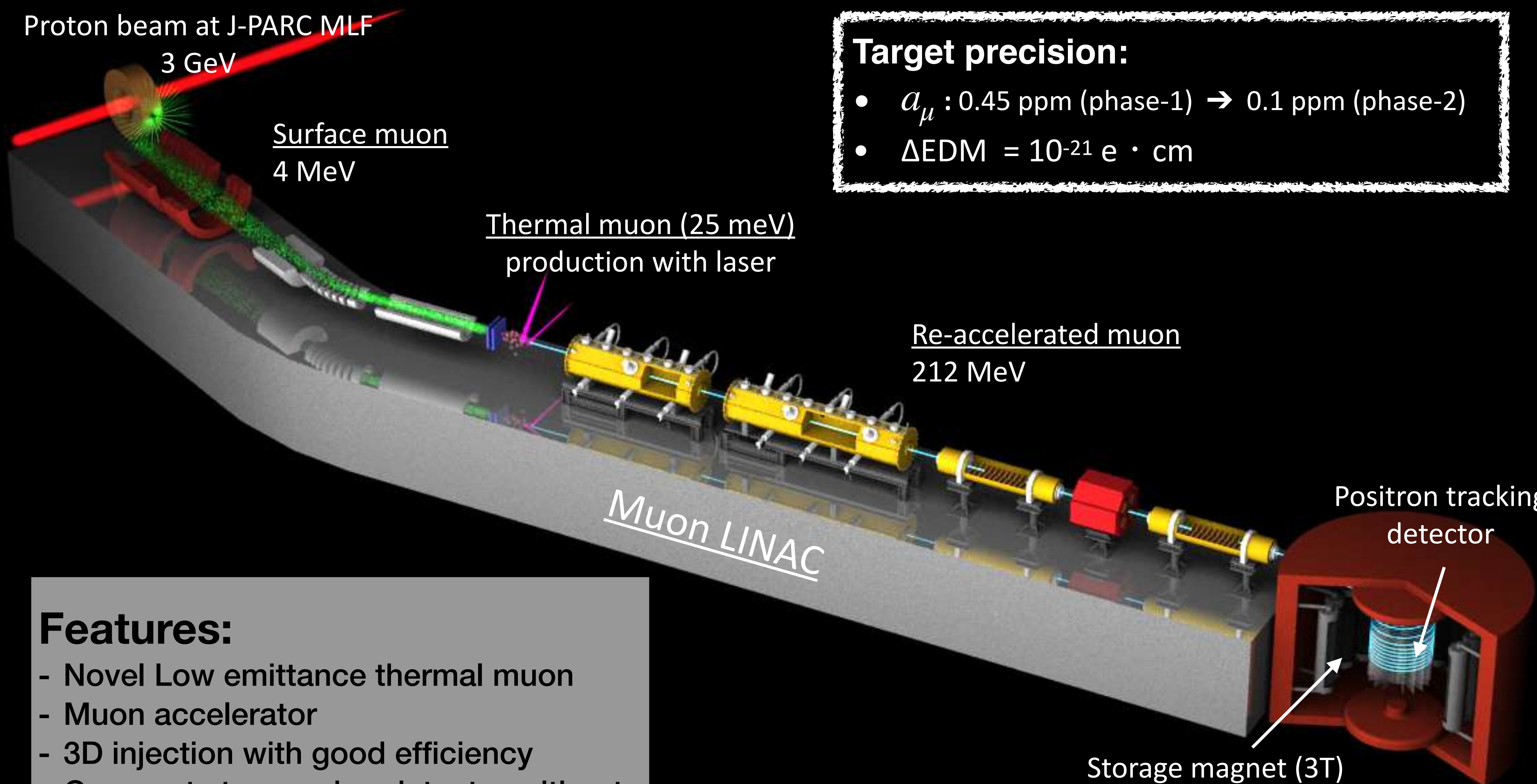
New muon $g-2$/EDM experiment in Japan



Target precision:

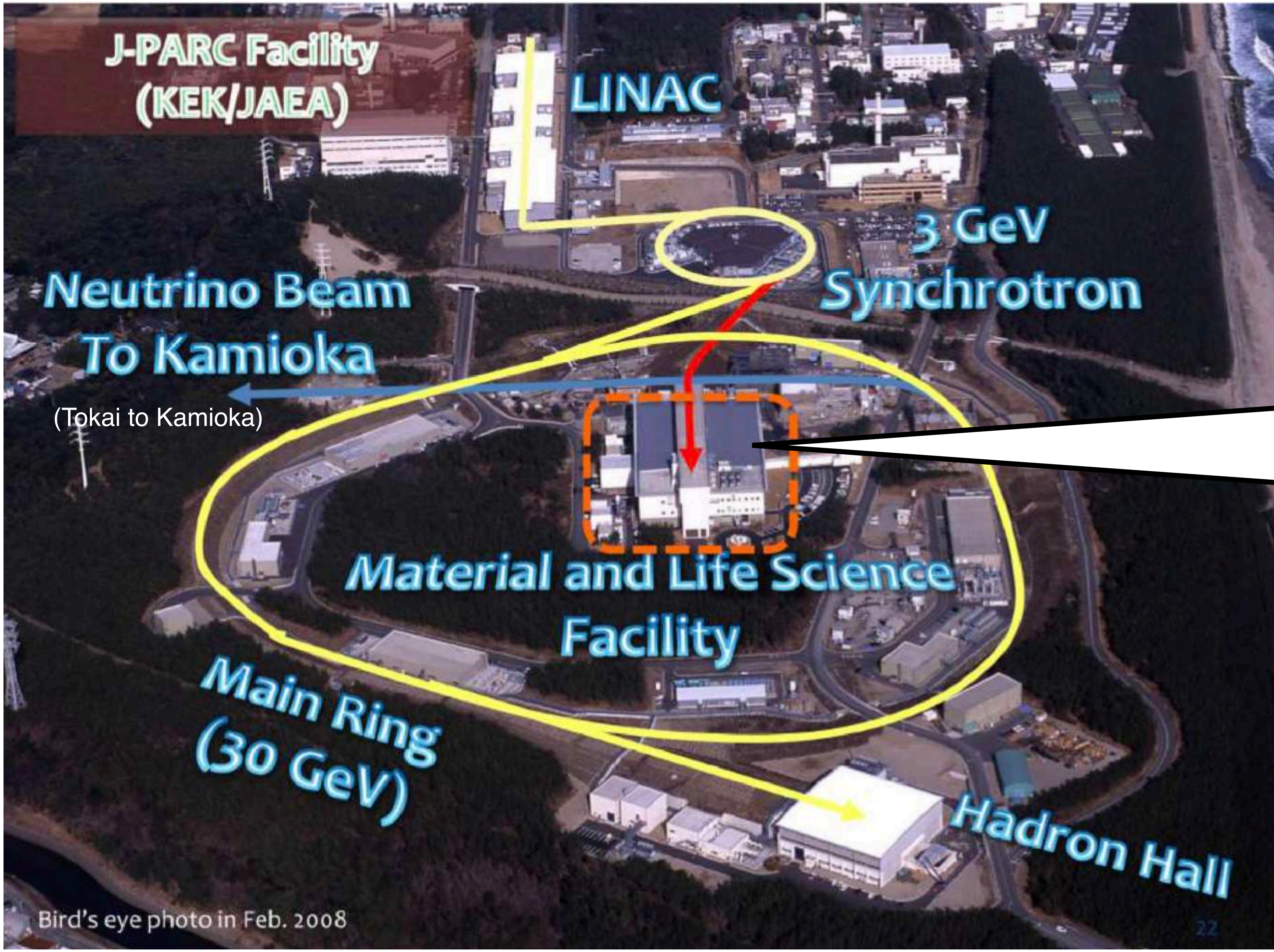
- a_μ : 0.45 ppm (phase-1) ➔ 0.1 ppm (phase-2)
- ΔEDM = 10^{-21} e・cm

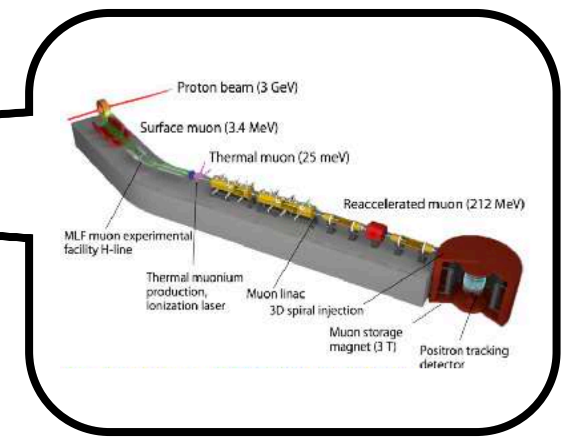
Features:

- Novel Low emittance thermal muon
- Muon accelerator
- 3D injection with good efficiency
- Compact storage ring detector without strong focusing

Prog. Theor. Exp. Phys. 2019, 053C02

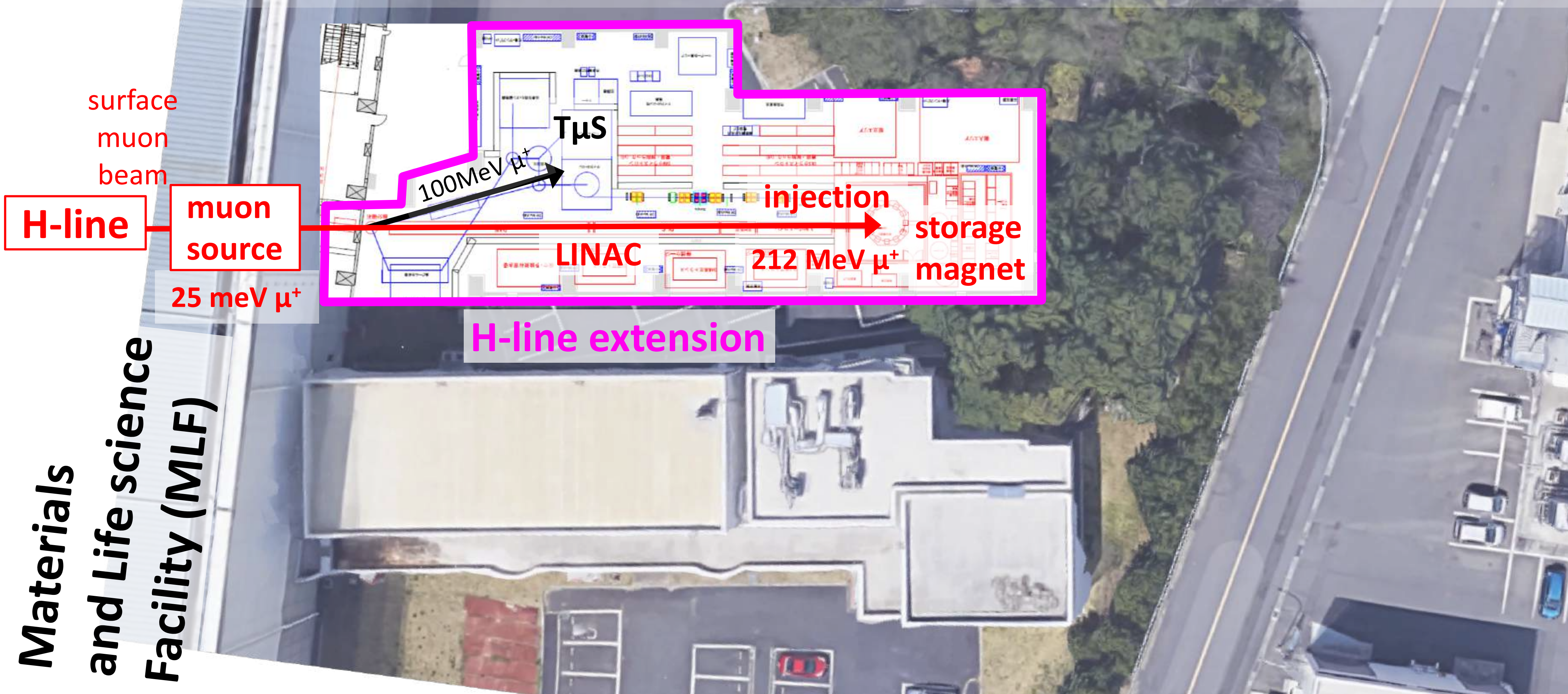
Japan proton accelerator research complex (J-PARC)

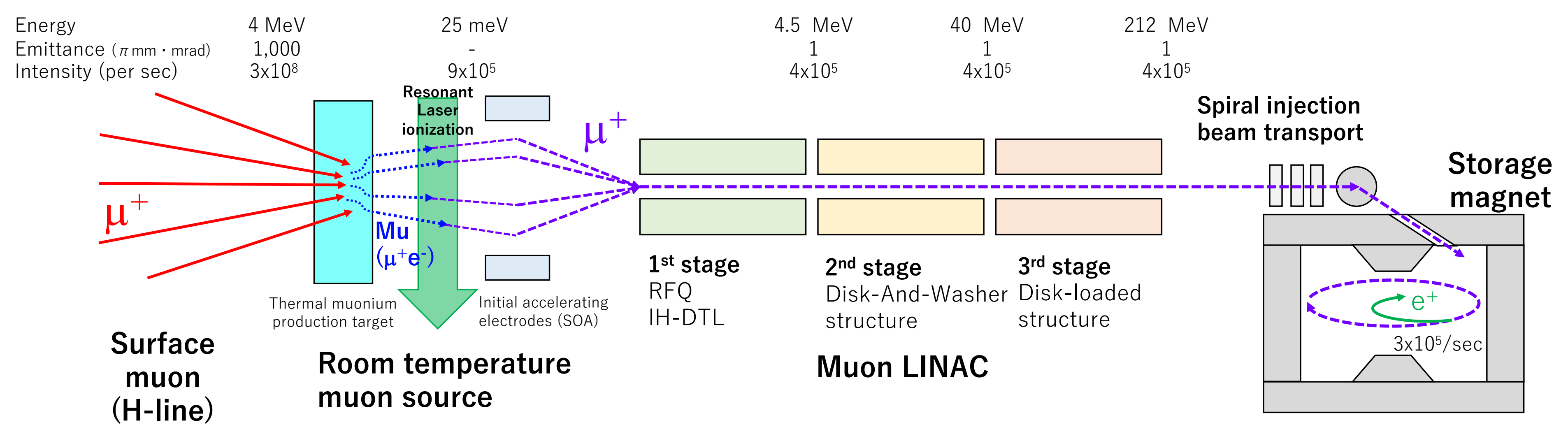




Location of our experiment

Muon g-2 and EDM experiment at J-PARC





New muon $g-2$/EDM experiment in Japan

- **Our experiment is completely different from BNL/FNAL approach!**
- In the E-B field, the more general form of spin precession vector:

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

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Magic "γ": $a_\mu = \frac{1}{\gamma^2 - 1}$

BNL E821 approach
γ=30 (P=3 GeV/c)

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

FNAL E989

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Directly remove E field!

BNL E821 approach

γ=30 (P=3 GeV/c)

J-PARC approach

E = 0 at any γ

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

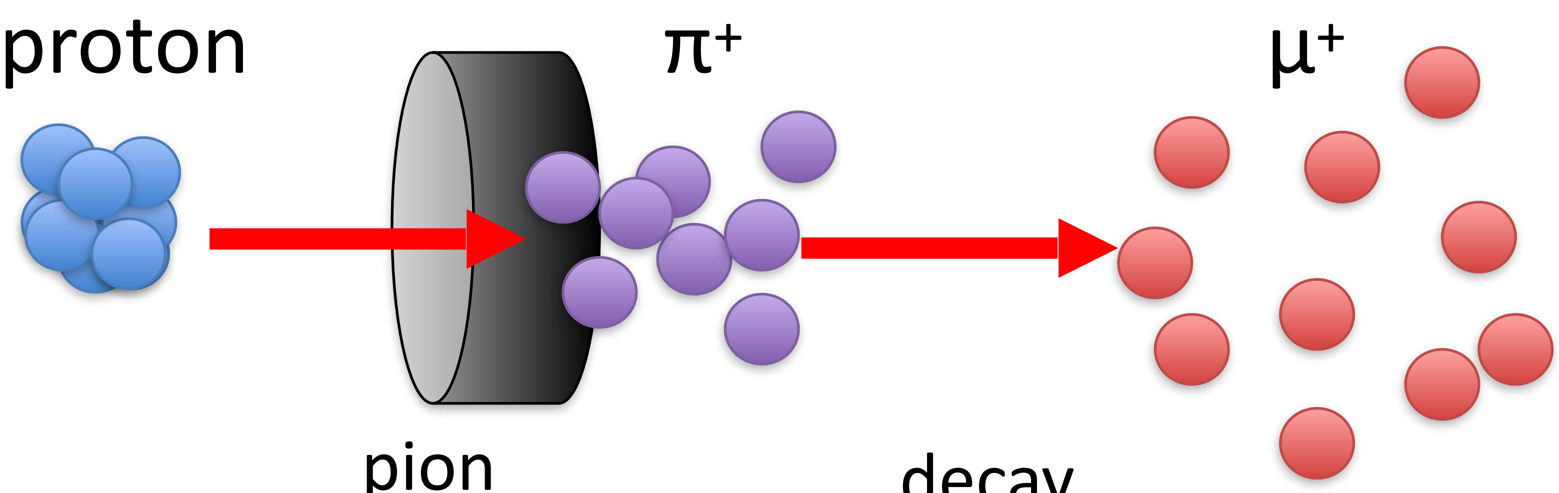
FNAL E989

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

J-PARC E34

Muon beam at BNL/FNAL

Conventional muon beam



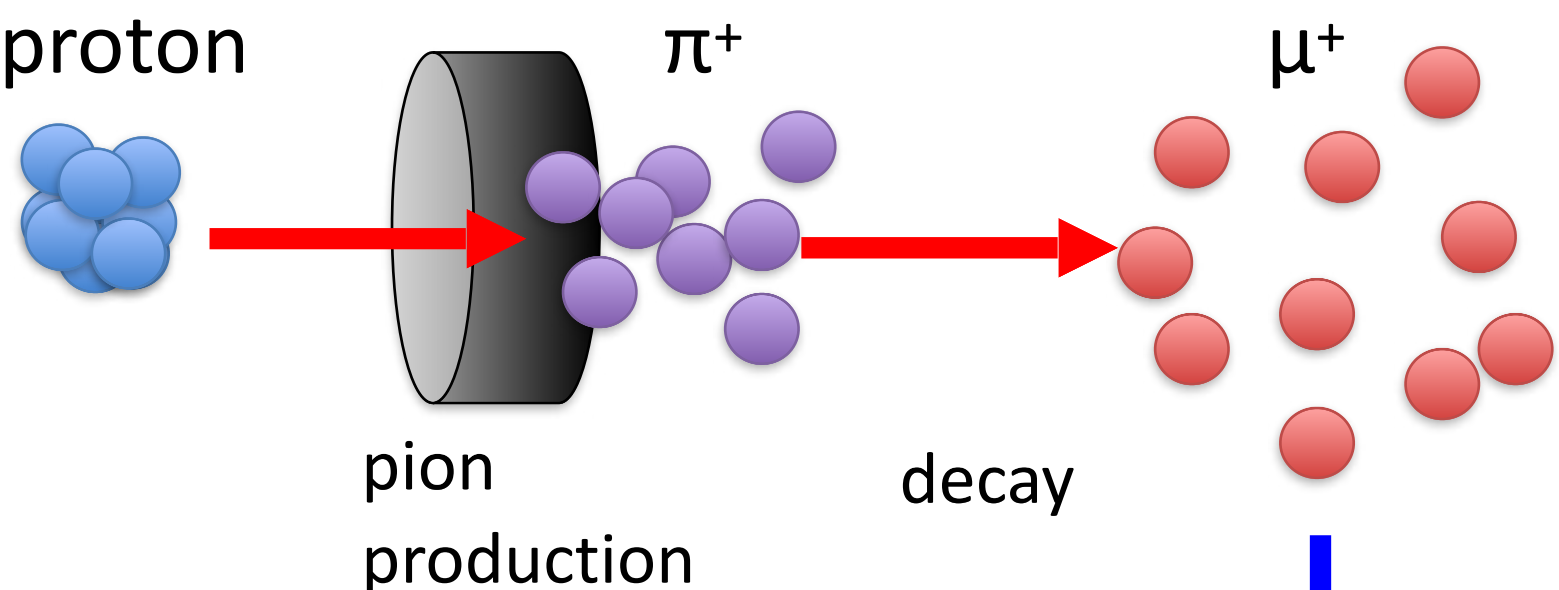
emittance

~1000π mm・mrad

Strong focusing Muon loss BG π contamination

Novel thermal muon beam at J-PARC

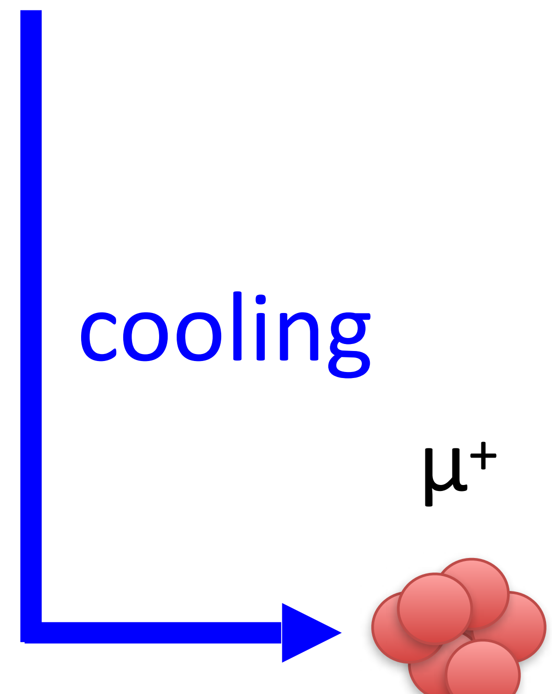
Conventional muon beam



emittance

~1000π mm・mrad

Strong focusing
Muon loss
BG π contamination



Thermal muon beam

emittance

1π mm・mrad

Free from any of these

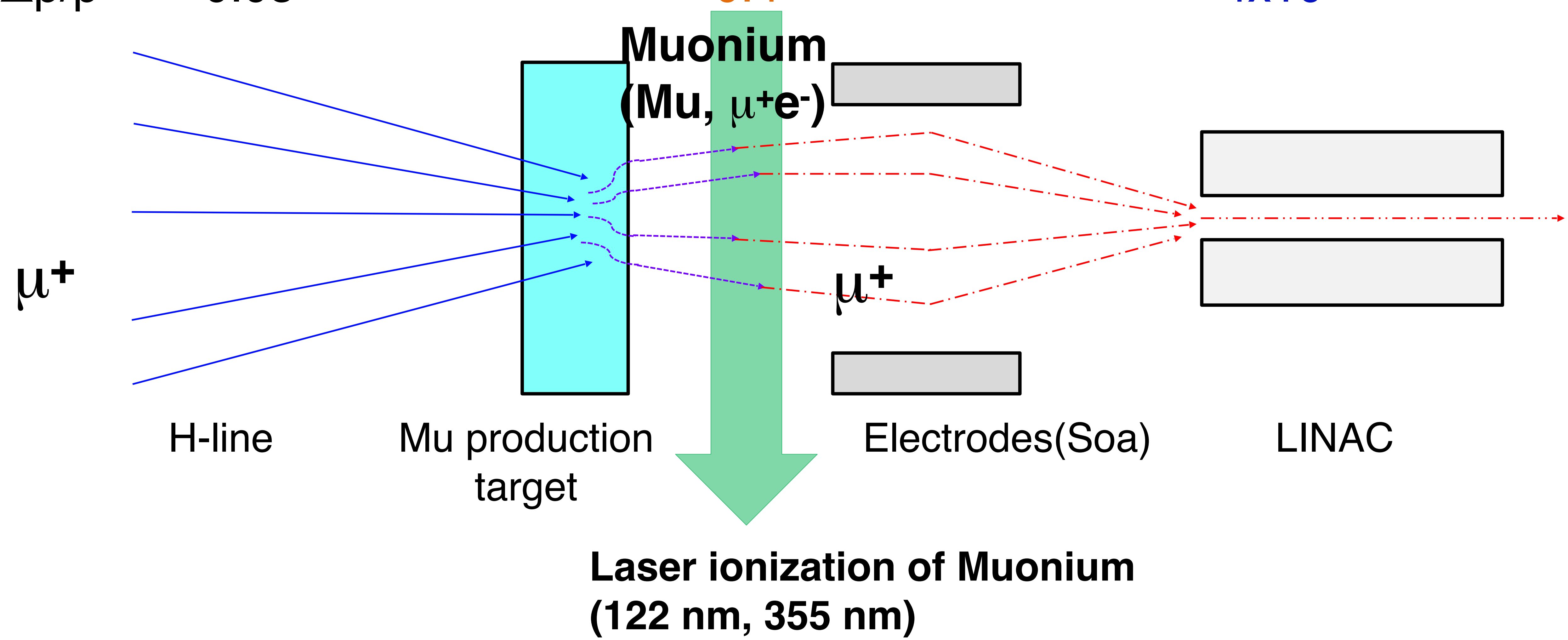
Re-accelerated thermal Muon beam

<u>Requirement for zero E-field:</u>

Muons should be kept stored without E-focusing

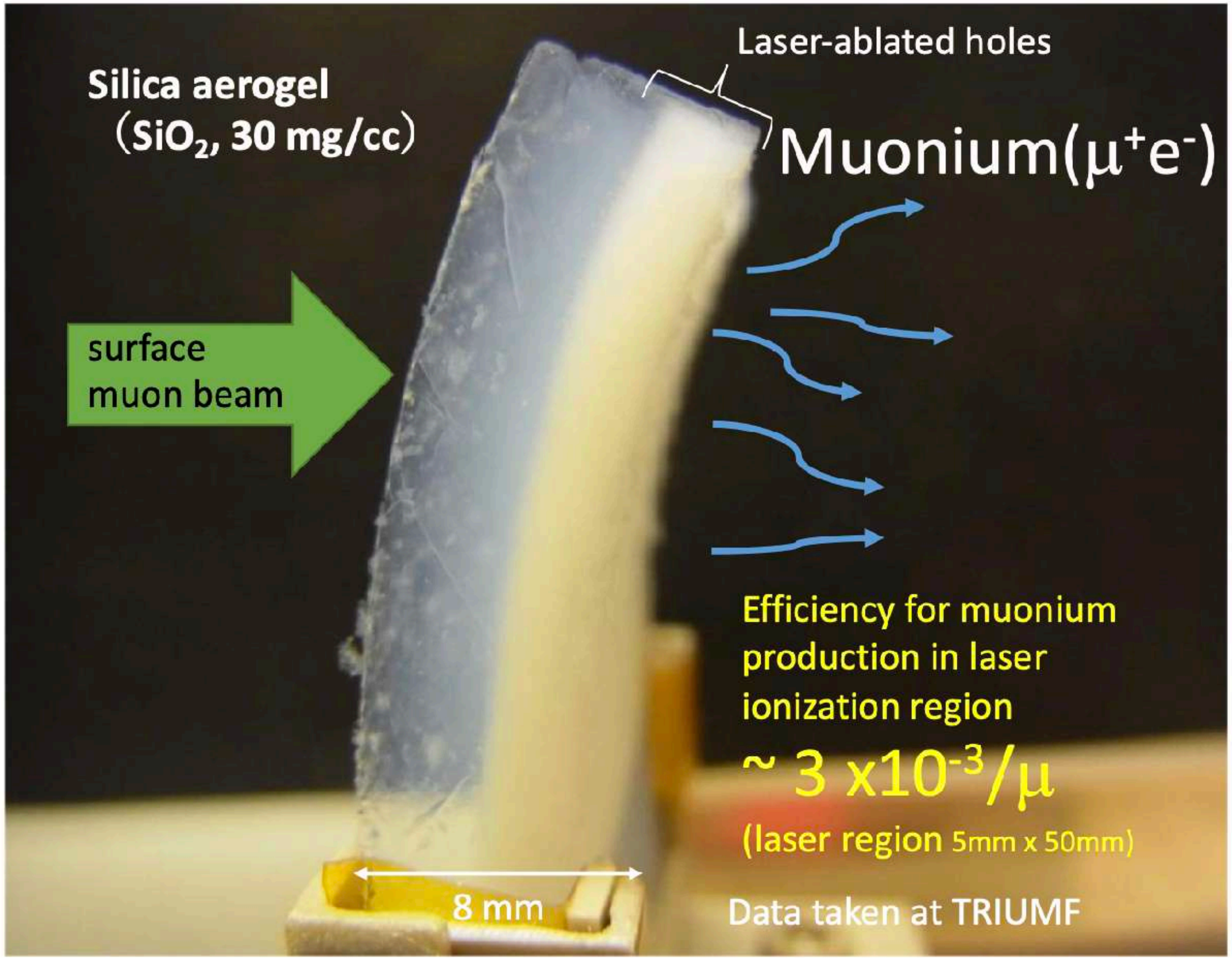
→Beam with ultra-small transverse dispersion, i.e. $\Delta p_T/p \sim 0$

	surface muon	thermal muon	accelerated muon
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	4×10^{-4}

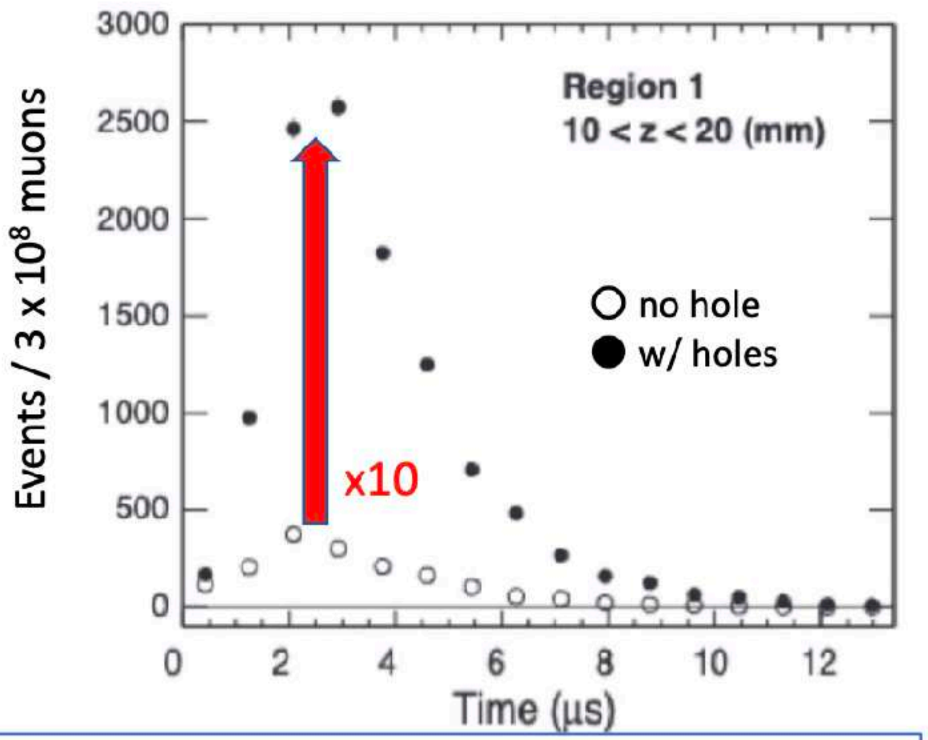


Development of thermal muon source

- Muonium yield from silica aerogel has been confirmed
- Novel technique of laser-ablated aerogel was used to enhance the Mu yield



P. Bakule et al., PTEP 103C0 (2013), G. Beer et al., PTEP 091C01 (2014)



Need muonium to diffuse out of target before decay. Yield increased to 3% !

Sample	Laser-ablated structure (pitch)	Vacuum yield (per 10^3 muon stops)
Flat	none	3.72 ± 0.11
Flat (Ref. [7])	none	2.74 ± 0.11
Laser ablated	500 μm	16.0 ± 0.2
Laser ablated	400 μm	20.9 ± 0.7
Laser ablated	300 μm	30.5 ± 0.3

Development of thermal muon source

- Now, a demonstration experiment 244 nm laser is being prepared at J-PARC
- It will be world's first time to generate thermal muon by this approach!
- Except for the muon g-2, such thermal muon source has wide application for other muon-related precision experiment

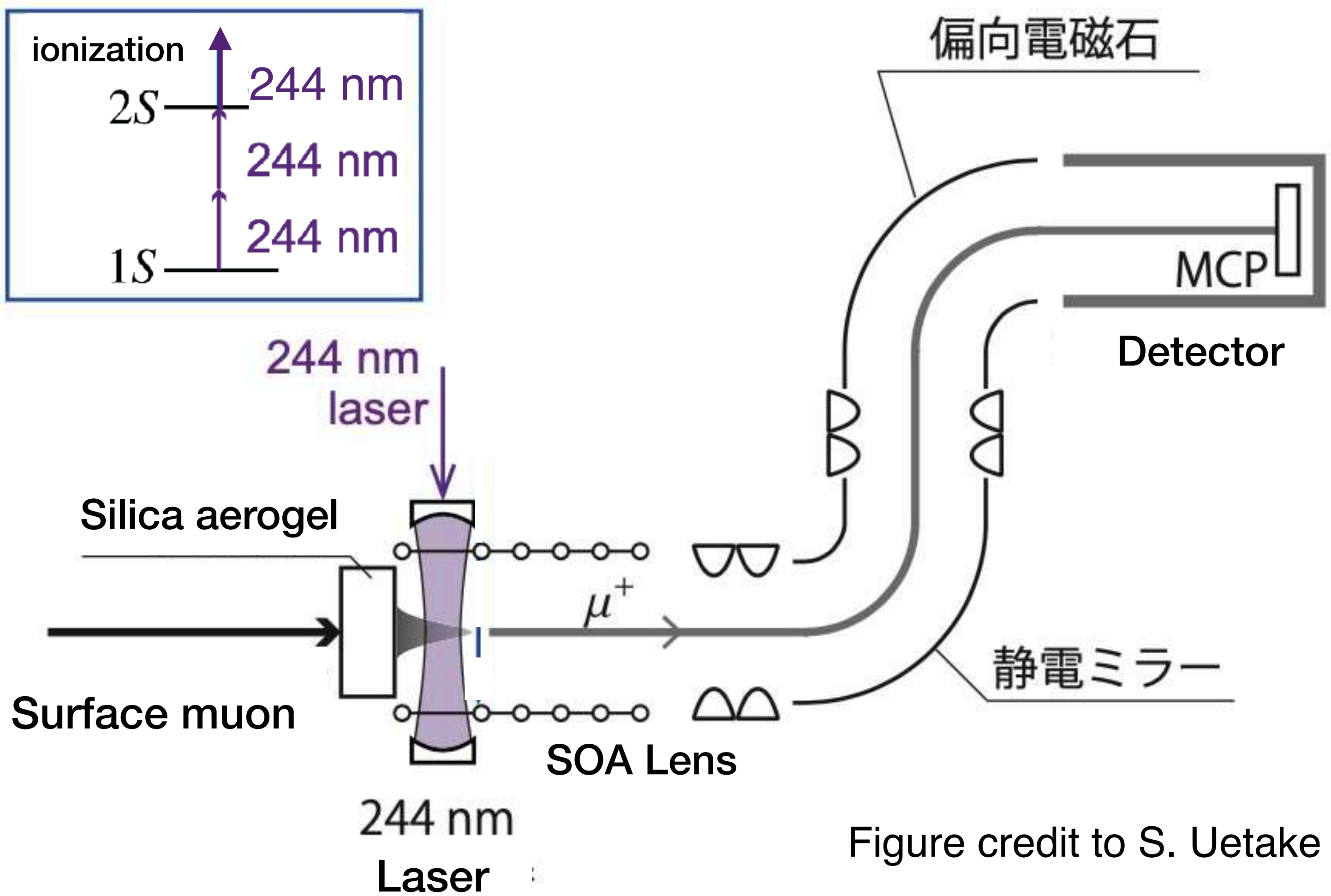
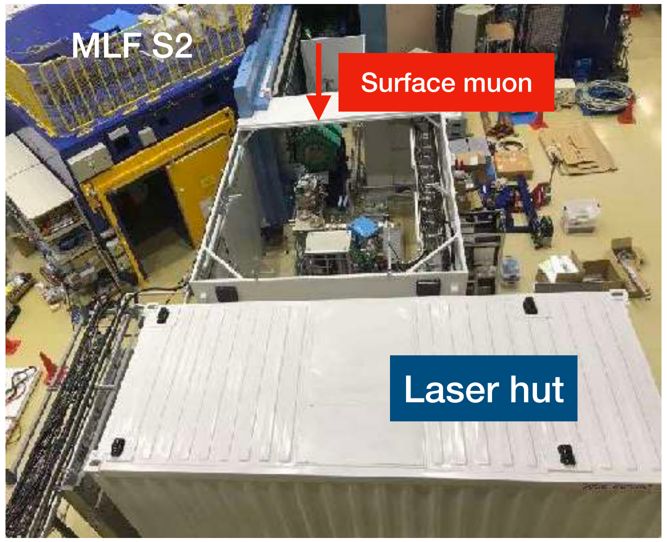
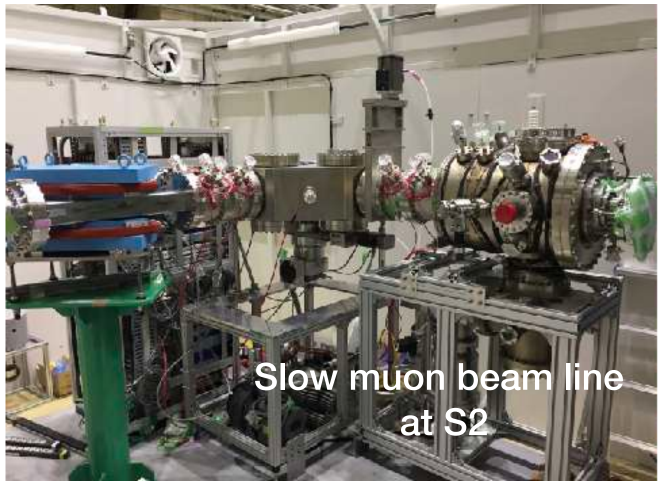
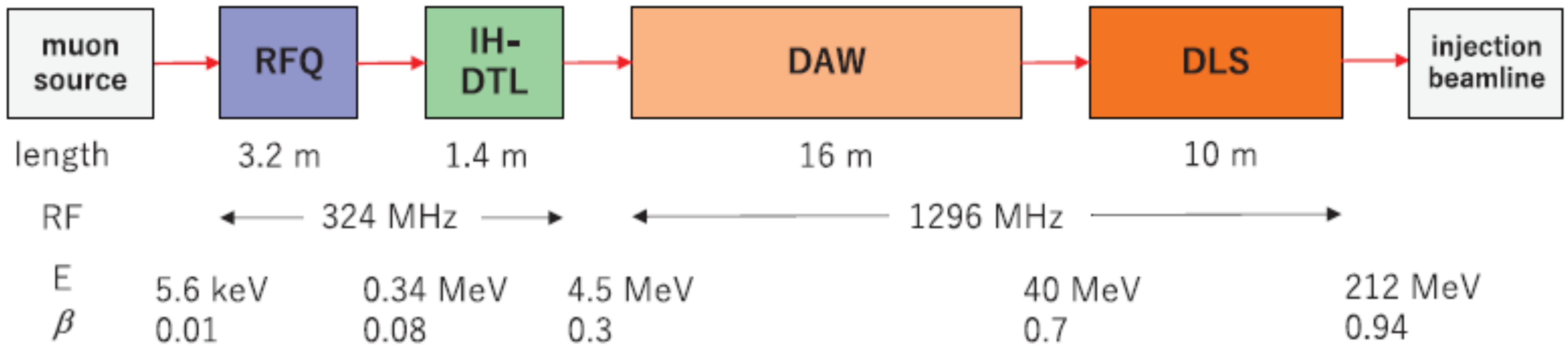


Figure credit to S. Uetake

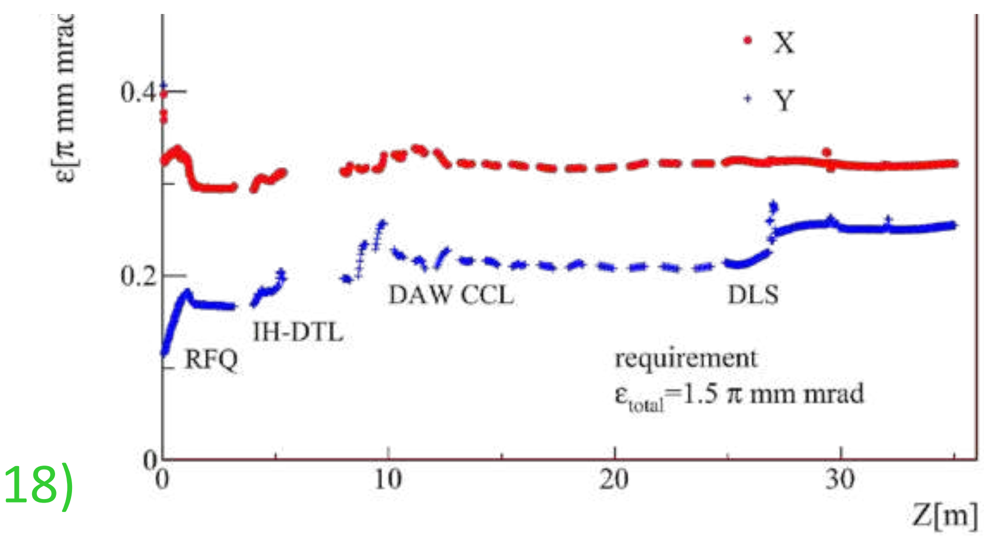




Muon acceleration (LINAC)

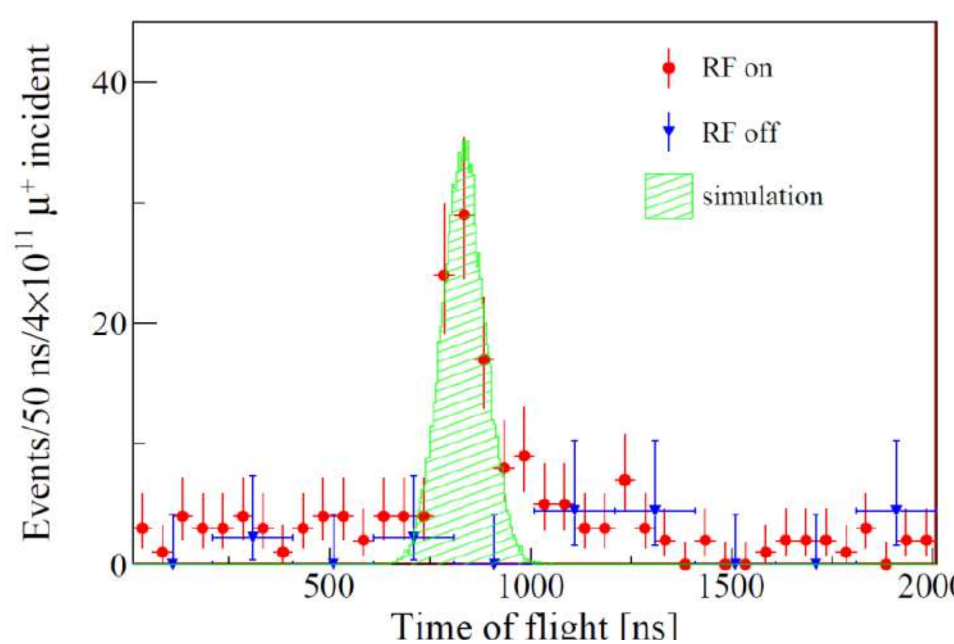


End to end simulation
- transmission loss ~7% + decay loss
- emittance growth is small

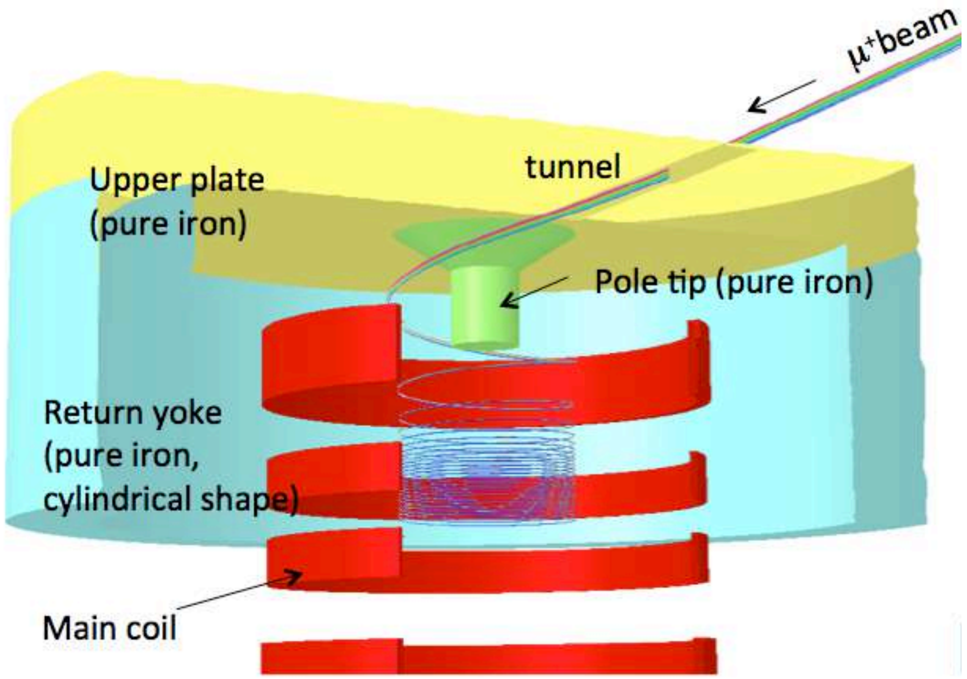


First muon acceleration with RFQ!

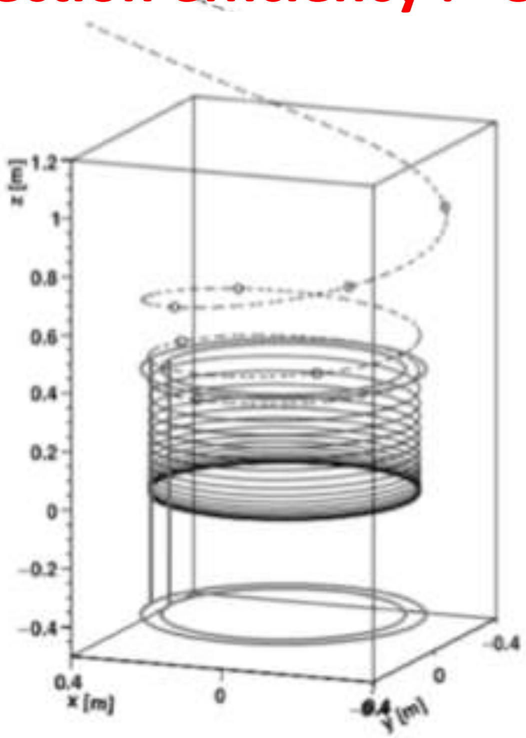
S. Bae et al., Phys. Rev. Accel. Beams 21, 050101 (2018)



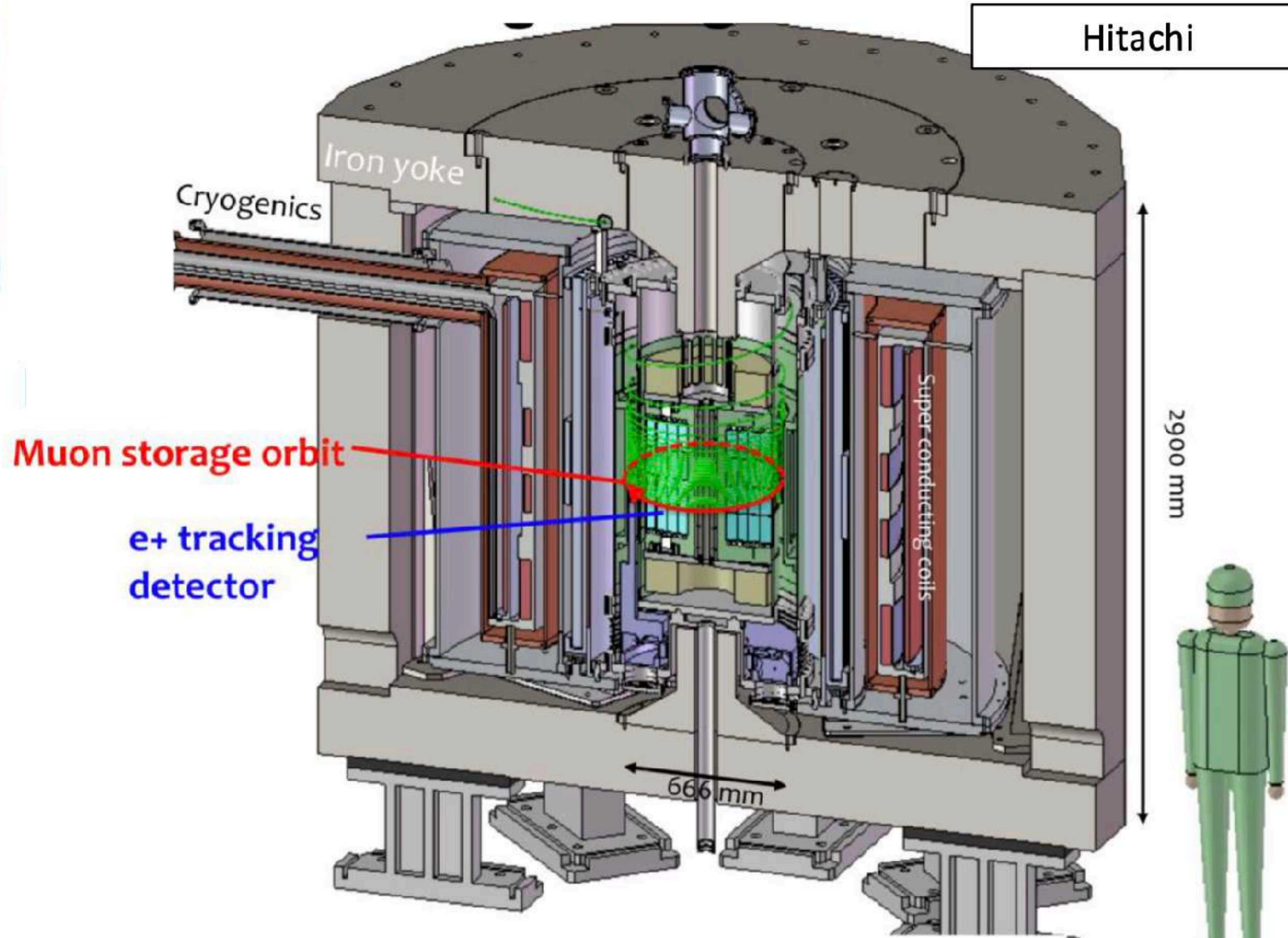
Muon injection and storage



Injection efficiency : ~85%



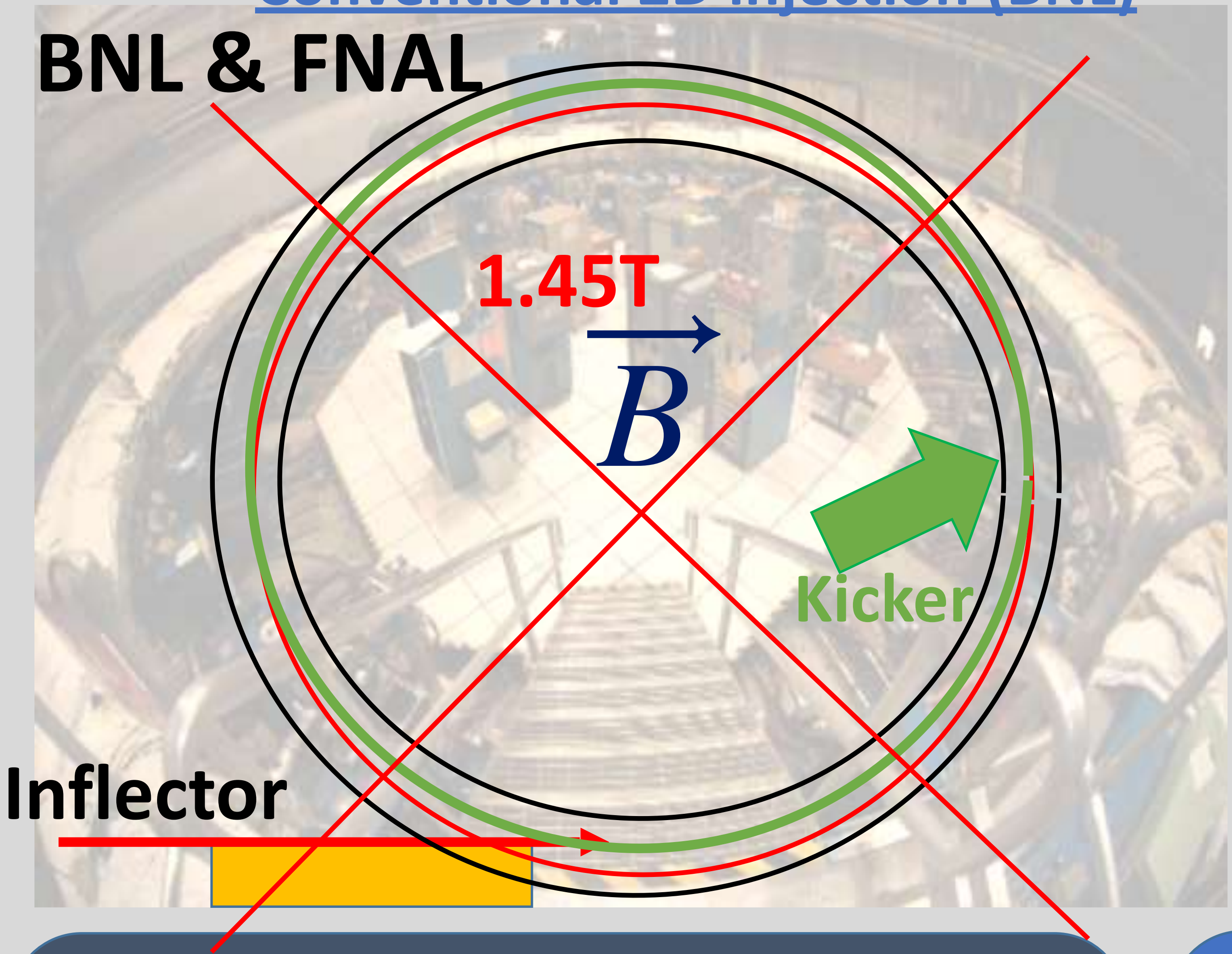
H. Iinuma et al., Nucl. Instr. And Methods. A 832, 51 (2016)



M. Abe et. al., Nuclear Inst. and Methods in Physics Research A 890, 51 (2018)

Why inject beam 3D spirally?

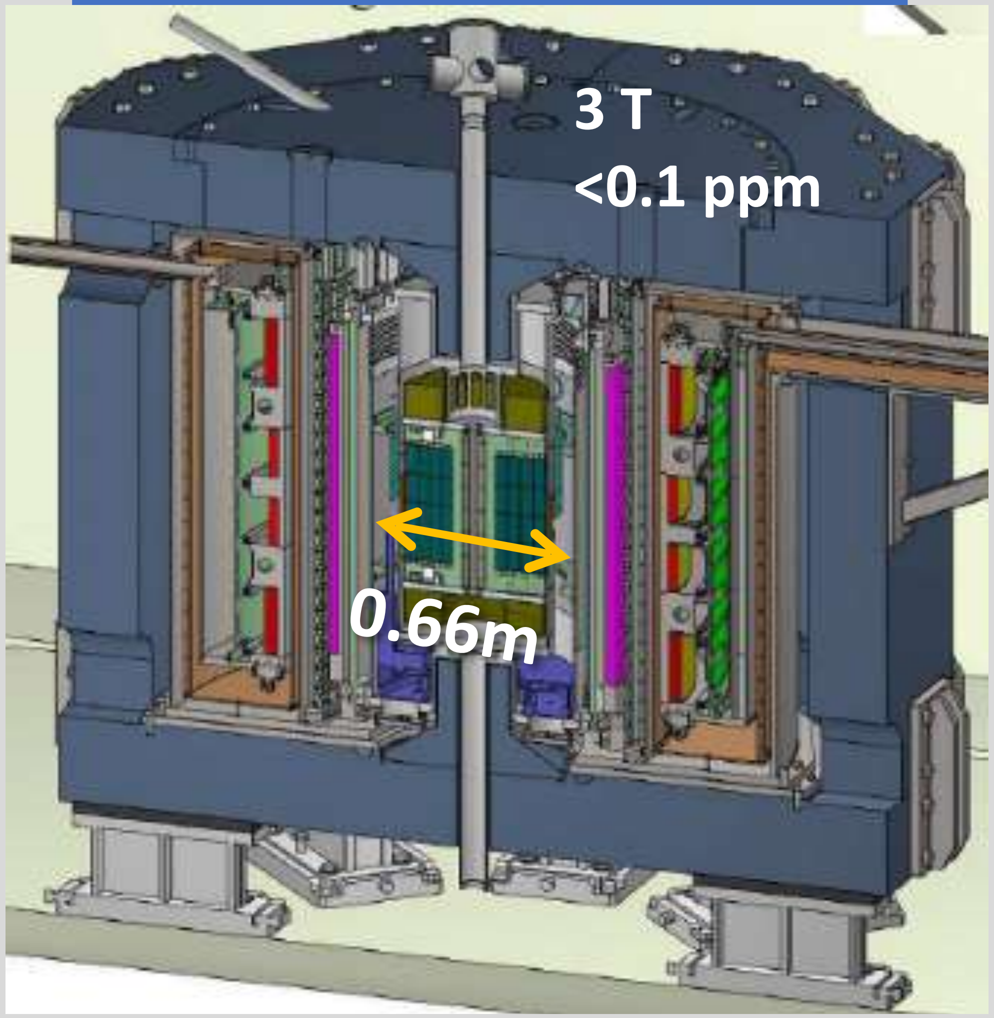
Conventional 2D injection (BNL)



14 m orbit, To avoid beam hit at inflector (77 mm), kick angle become 10.8 mrad within 149 ns.

Injection efficiency : 3-5%(*)

J-PARC E34 storage magnet



0.66 m orbit kick angle is 233 mrad within 7.4 ns.
3 T is too high to be canceled by inflector.
Impossible by any existent technology.
Need to develop new 3D spiral injection!

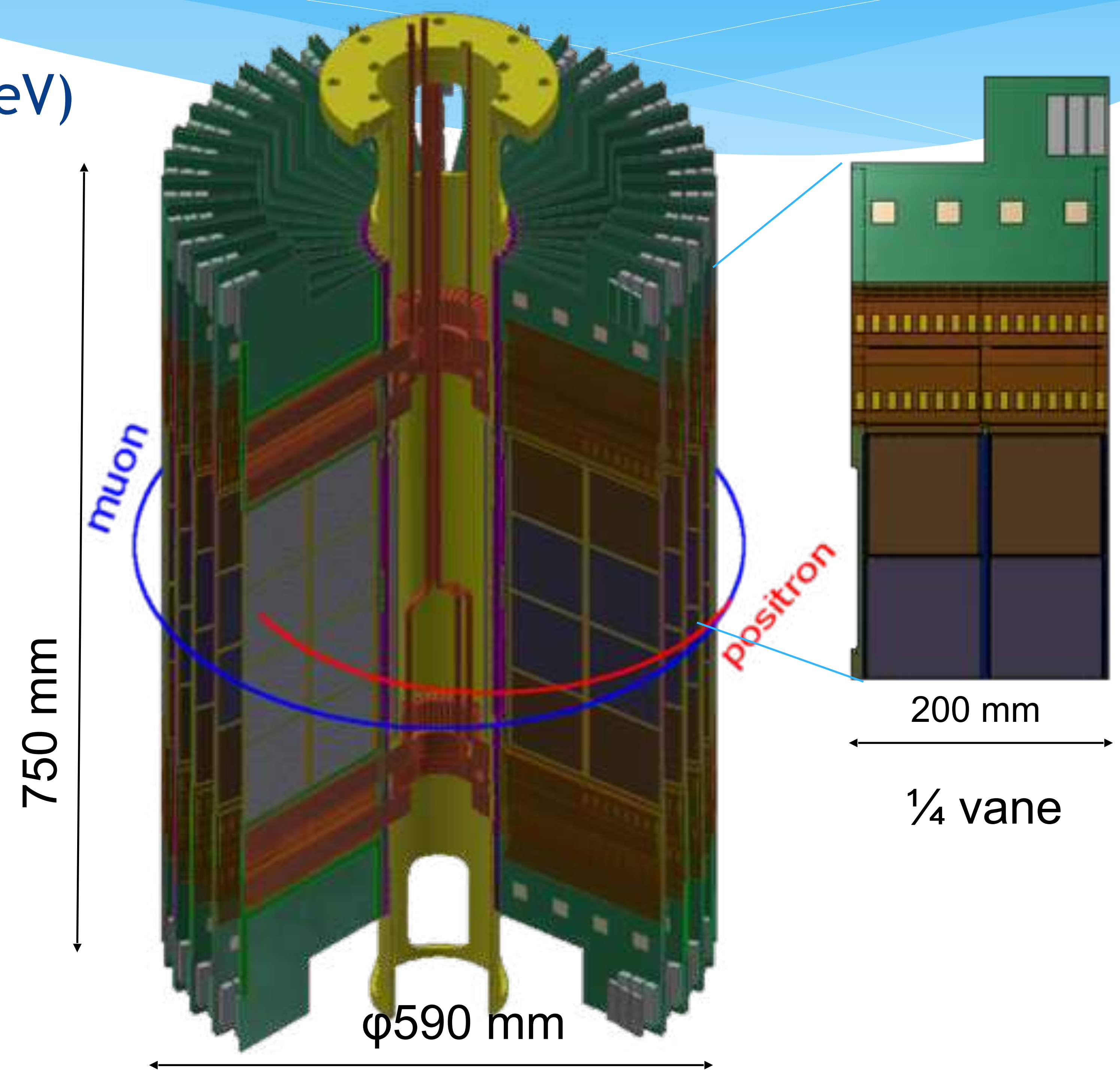
Injection efficiency : ~85%

(*) PRD73,072003 (2006)

Positron tracking detector

* Requirements
  * Detection of e+ (100<E<300 MeV)
  * Reconstruction of momentum vector
  * Stability over rate changes (1.4 MHz → 14 kHz)

* Specifications
  * Sensor: p-on-n single-sided strip
  * Number of vanes: 40
  * Number of sensors : 640
  * Number of strips : 655,360
  * Area of sensors : 6.24 m^2

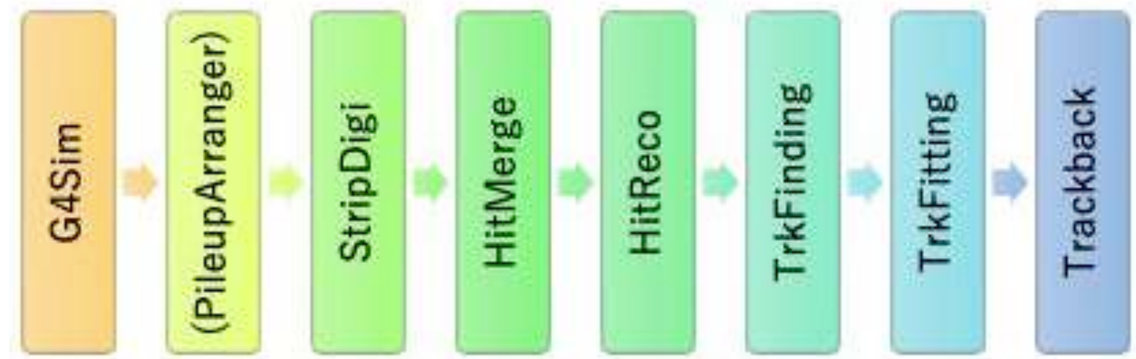


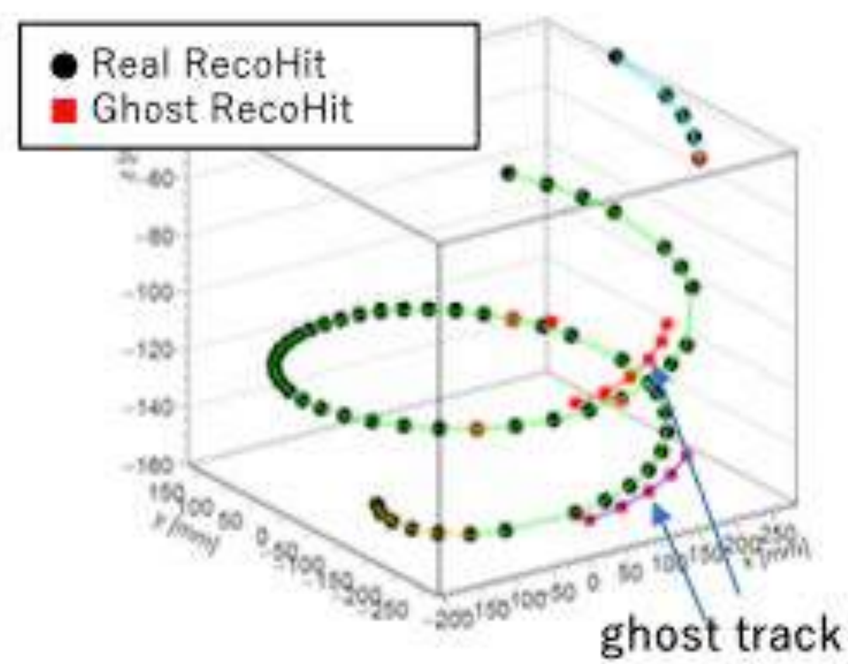
Software

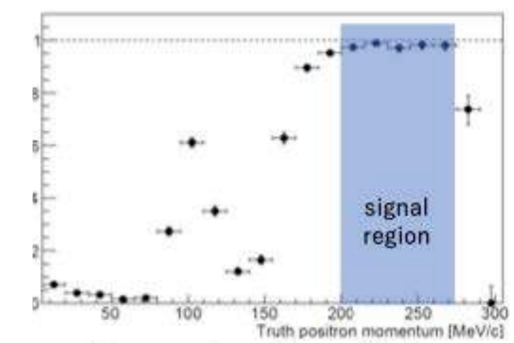
- **Positron track reconstruction**
  - A custom software framework "g2esoft" has been developed.
  - Developed improved tracking performance by connecting disconnected-tracklets, removing ghosts.
  - Evaluating rate-dependent effects in tracking performance.

- **End-to-end simulation**
  - Statistics increased from 16k muons to 1M (x100).
  - Analysis in progress to study various correlations.
  - Optimization of experimental conditions is in progress.

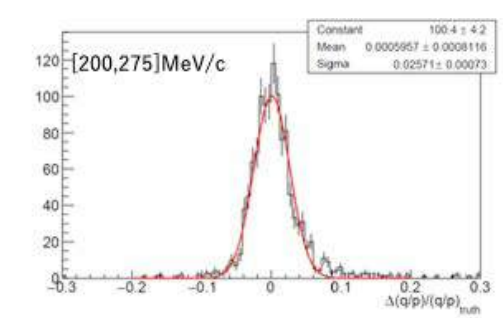
overview of g2esoft





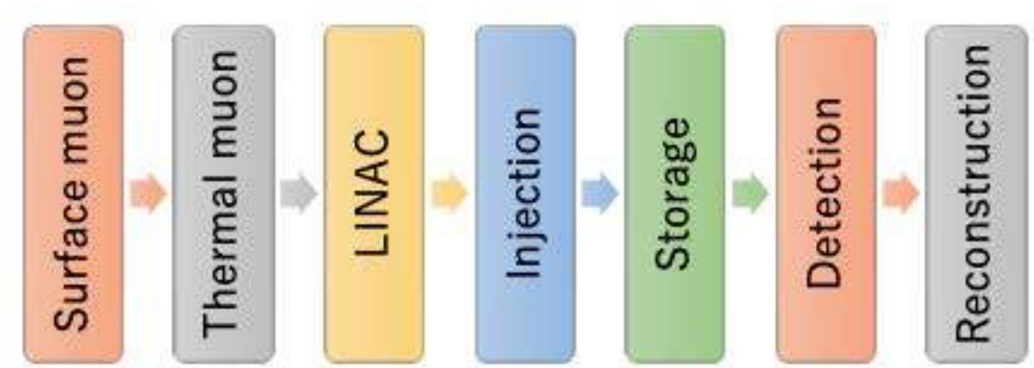


Reconstruction efficiency



Momentum resolution

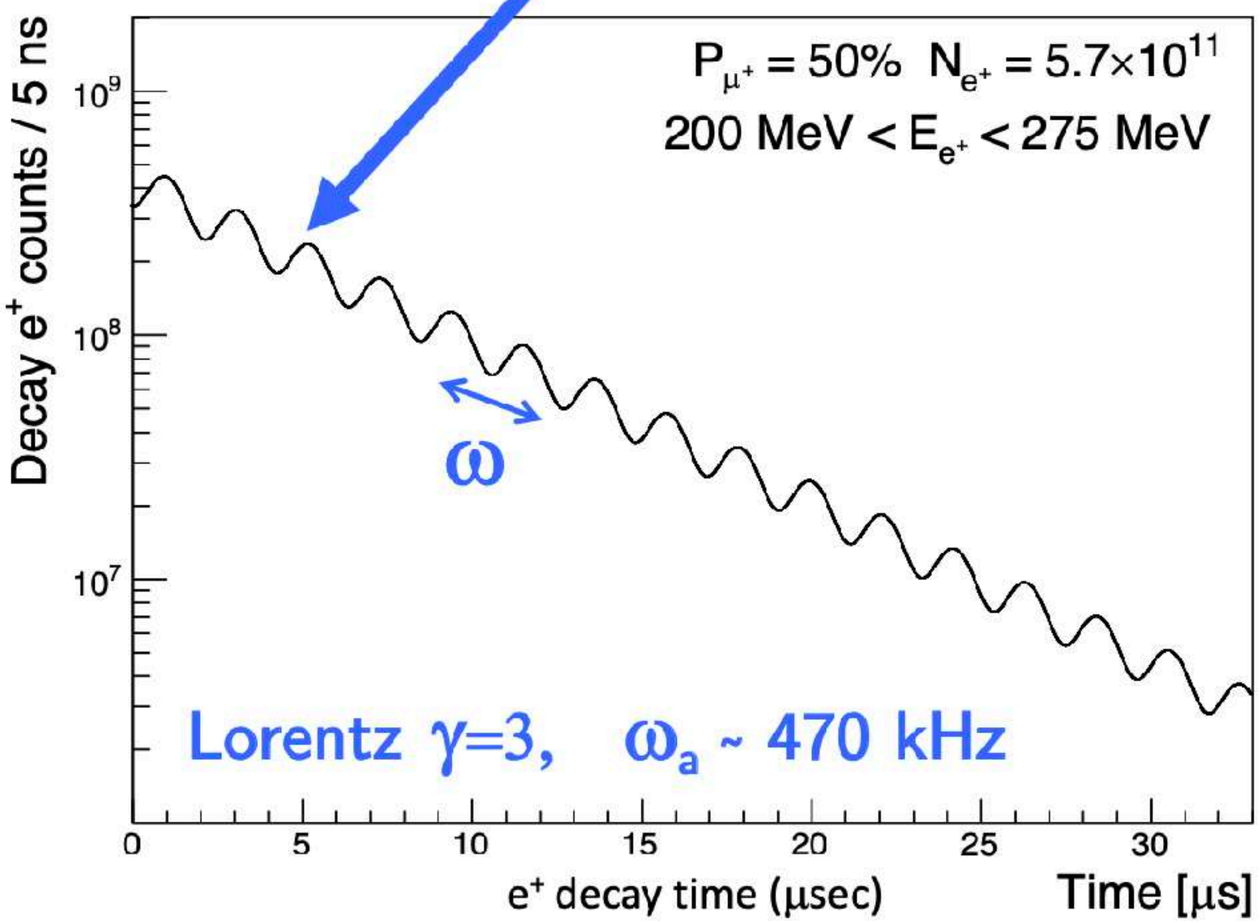
overview of end-to-end simulation

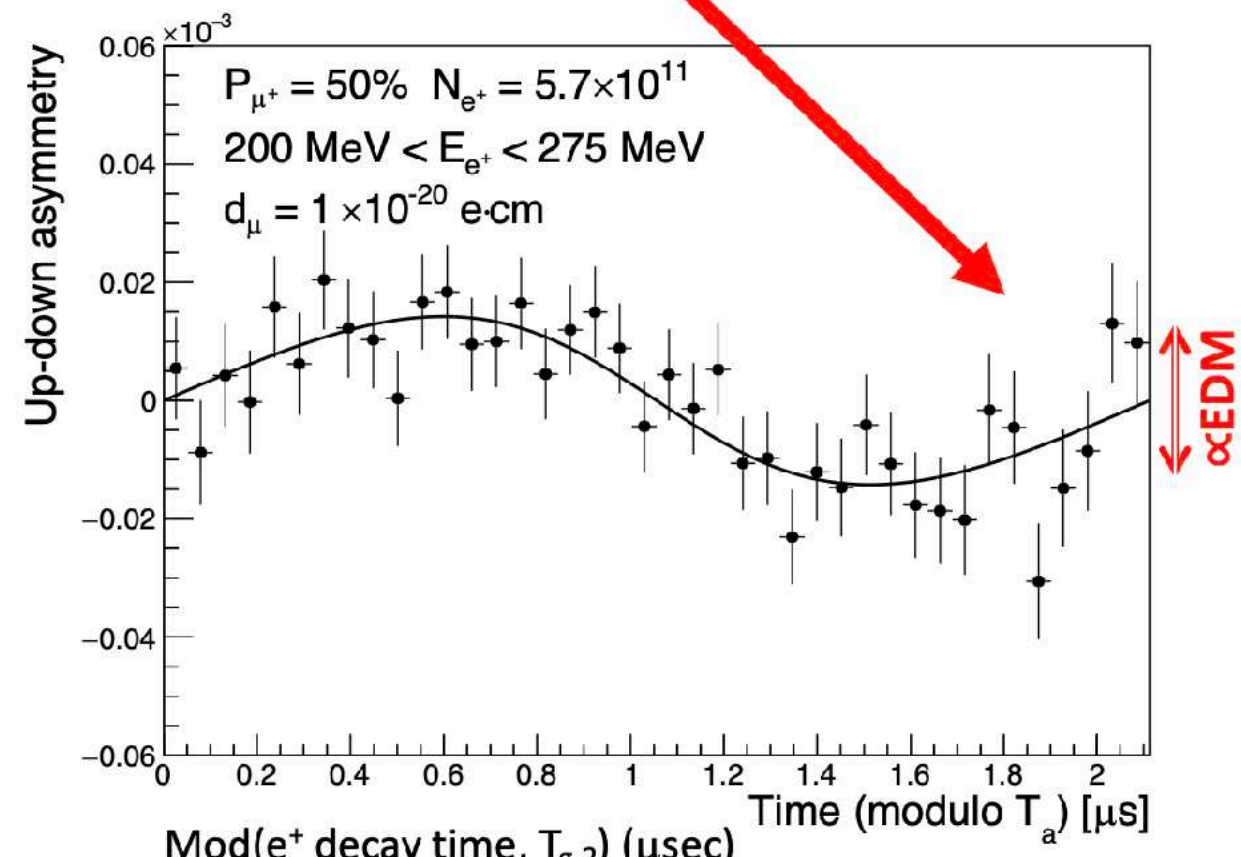


Expected results

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$$

Expected time spectrum of e^+ in $\mu \rightarrow e^+\nu\nu$ decay





Precision estimation & comparison

	Completed	Running	In preparation
	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 (Phase-0)
(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

Corrections, Uncertainties on g-2

Fermilab Run1

PRL 126, 141801 (2021)

Quantity		Correction Terms (ppb)	Uncertainty (ppb)		Fermilab goal	J-PARC estimate
ω_a^m (statistical)	スピン歳差運動 統計誤差	–	434		100	450
ω_a^m (systematic)	系統誤差	–	56			
C_e		489	53			
C_p	スピン歳差運動補正値・系統誤差	180	13			
C_{ml}		-11	5	108	70	<40
C_{pa}		-158	75			
$f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle$		–	56	114		
B_k	磁場測定　系統誤差	-27	37		70	56
B_q		-17	92			
$\mu_p'(34.7^\circ)/\mu_e$		–	10			
m_μ/m_e	変換に用いる物理量	–	22			
$g_e/2$		–	0			
Total systematic		–	157		100	<70
Total fundamental factors		–	25			
Totals		544	462		140	460

(108 = combined uncertainty of ω_a^m (systematic), C_e, C_p, C_{ml}, C_{pa}; 114 = combined uncertainty of f_{calib}, B_k, B_q)

21 x BNL

Towards ultimate test of the muon g-2 anomaly

T.Mibe, inspired by K. Jungmann's slide

$$\omega_a = a_\mu \frac{eB}{m}$$ ← MRI ← $$B = \frac{\hbar\omega_p}{2\mu_p}$$

ω_p B μ_{proton}

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\omega_a}{\omega_p} - \frac{\mu_\mu}{\mu_p}}$$

120 ppb

g-2

Fermilab E989

J-PARC E34 (our experiment)

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

3 ppb 22 ppb 0.3 ppt

μ_μ

m_μ

MuSEUM(J-PARC)

Mu-MASS(PSI), **new exp.(J-PARC)**

Mu HFS

Mu 1S-2S

m_μ

muonium

$$\Delta\nu_{\text{1S-HFS}} \simeq \frac{16}{3}\alpha^2 R_\infty \frac{\mu_\mu}{\mu_B}\left(1 + \frac{m_e}{m_\mu}\right)^{-3}$$

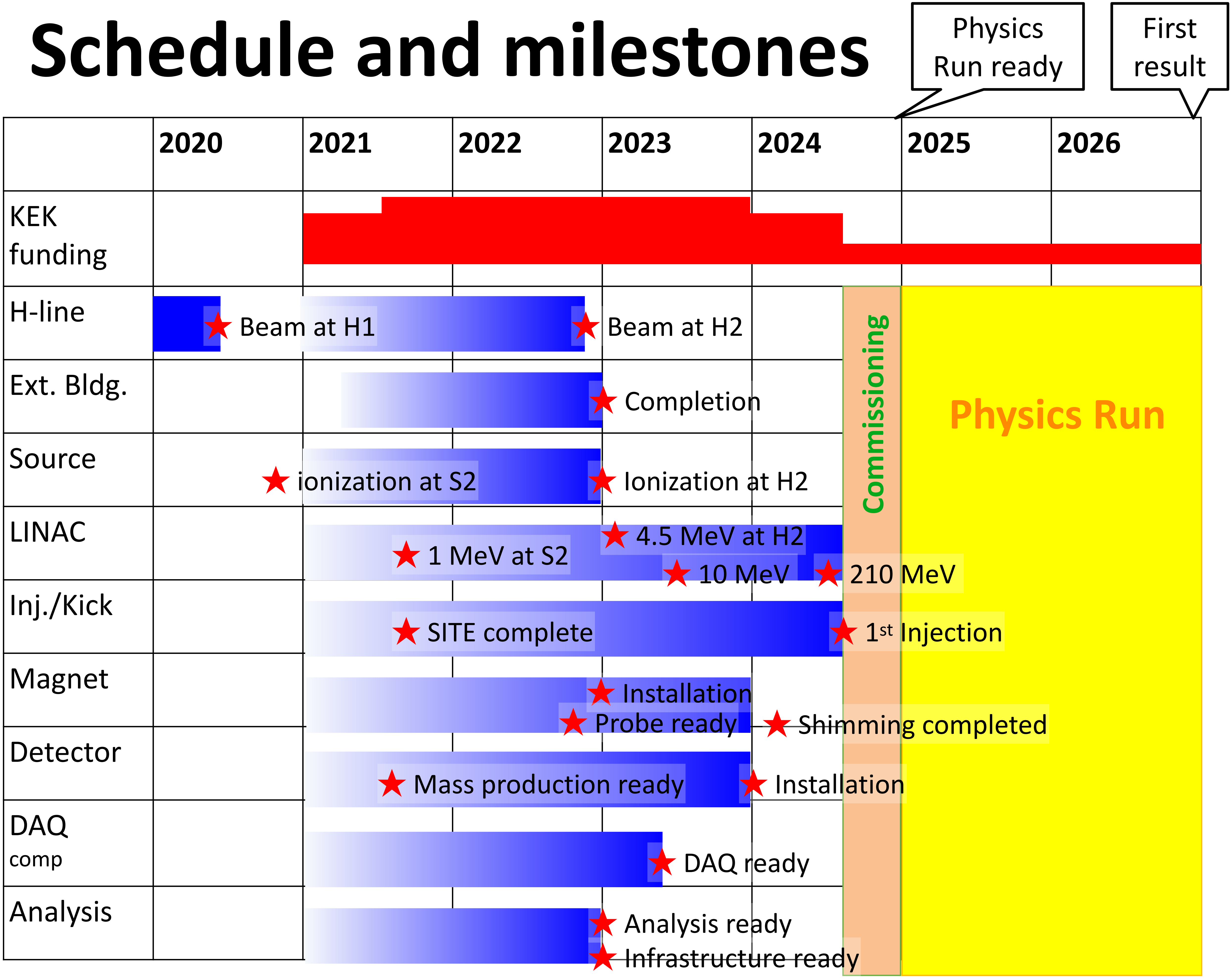
$$\nu_{34} - \nu_{12} \propto \frac{\mu_\mu}{\mu_p}$$

muonium

$$\Delta\nu_{\text{1S2S}} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1 + \frac{m_e}{m_\mu}\right)^{-1}$$

Three quantities are mutually correlated.
Closing a triangle with new experiments will establish ultimate precision.

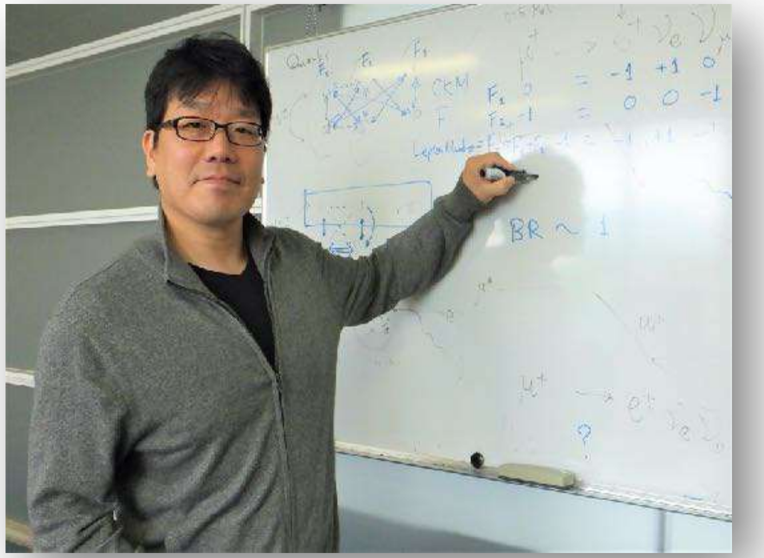
Schedule and milestones



Contact

www.g-2.kek.jp

齊藤　直人 (Naohito Saito)
Initiator of this experiment
naohito.saito@kek.jp

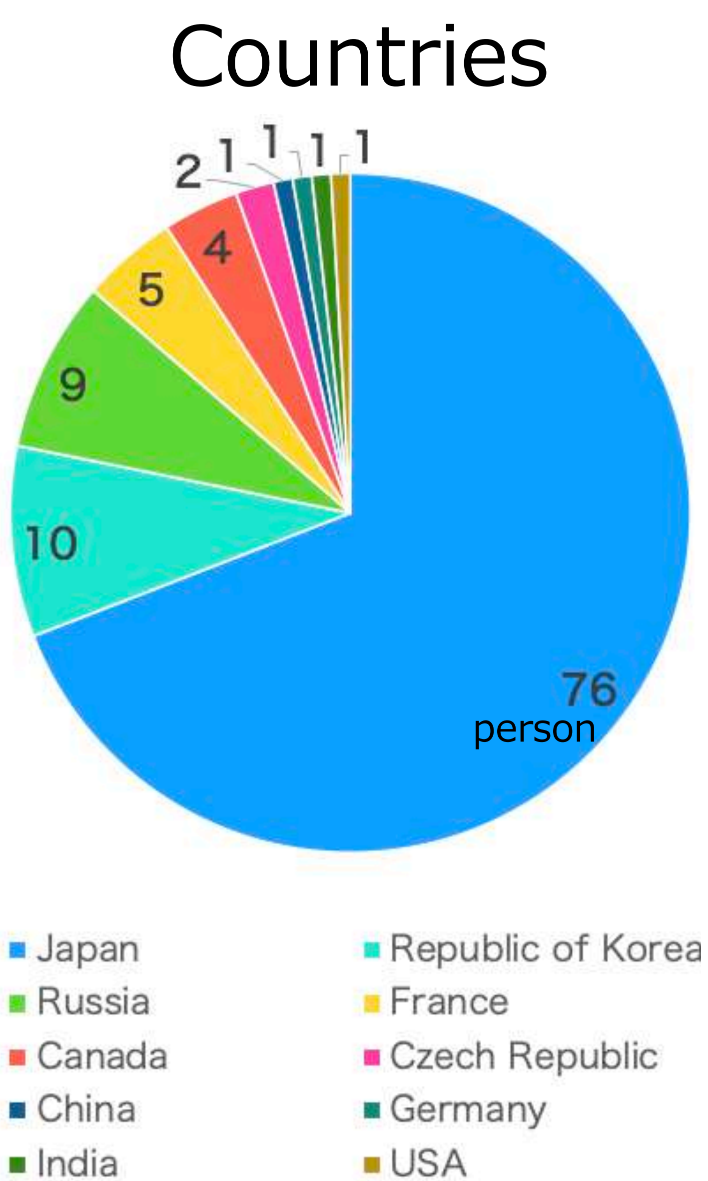


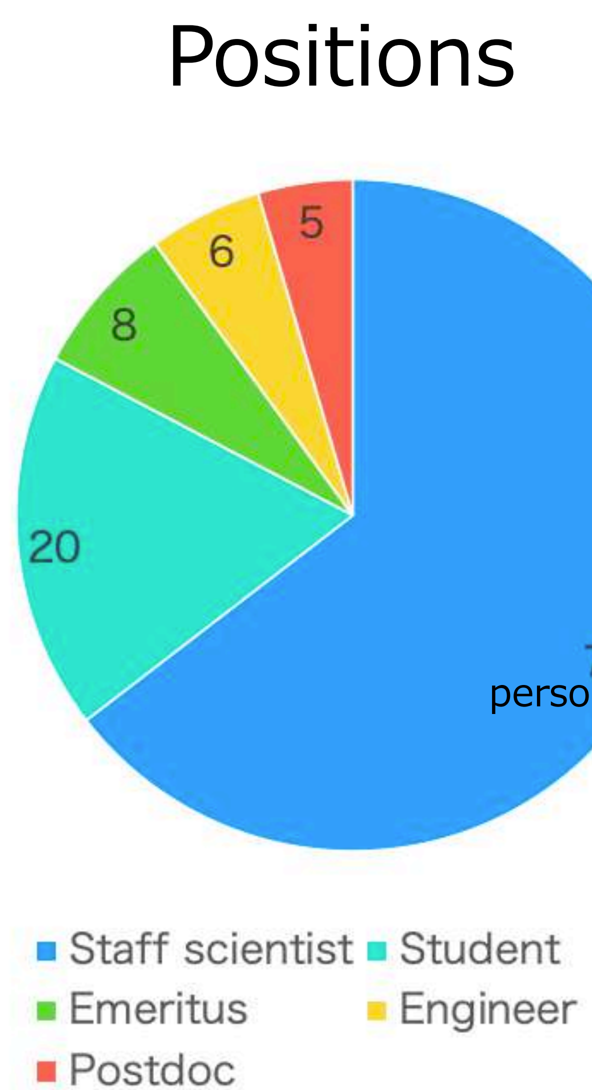
三部　勉 (Tsutomu Mibe)
Current spokesperson
mibe@post.kek.jp

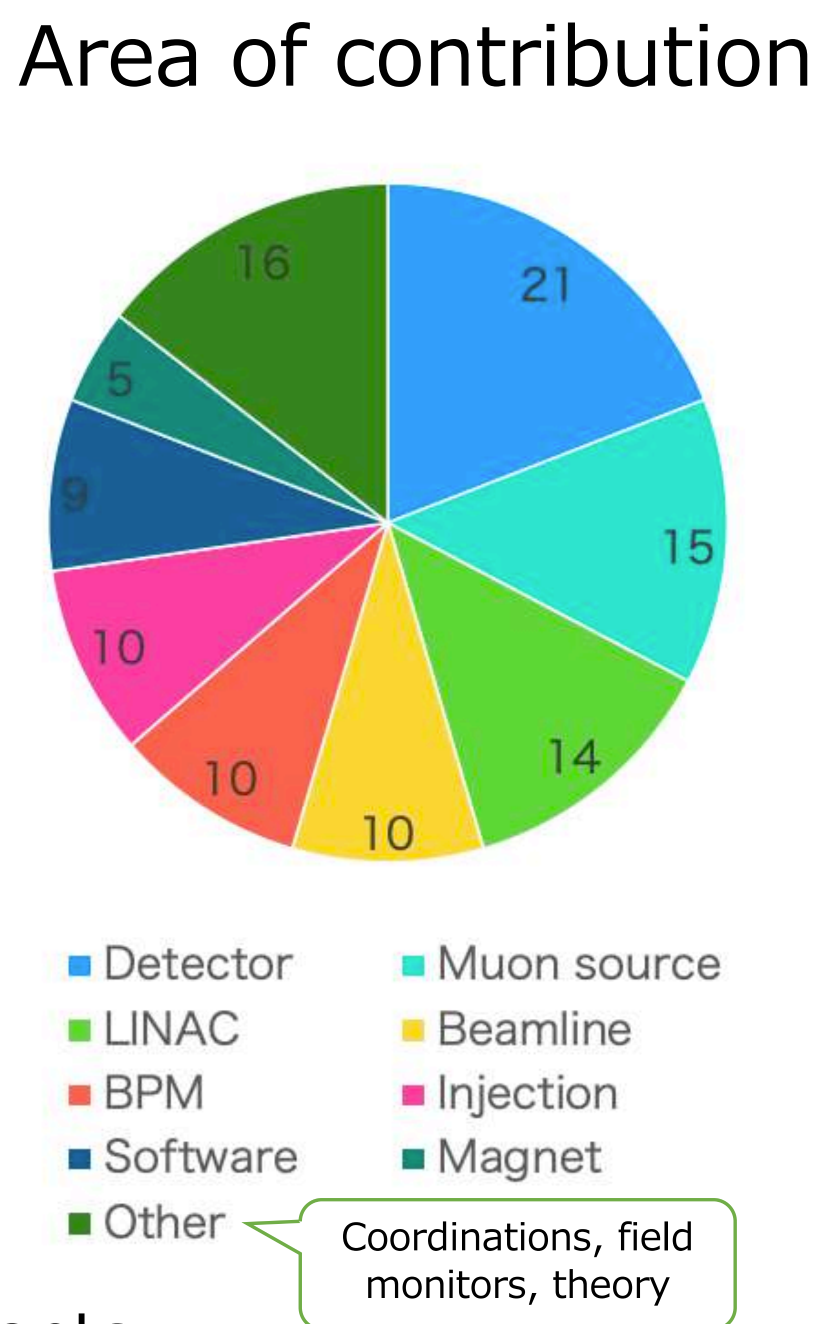
Distribution of human resource

From T. Mibe

110 active collaboration members







- 30% from outside of Japan.
- 65% staff scientists, 18% grad. students.
- Distributed over various subsystems

Summary

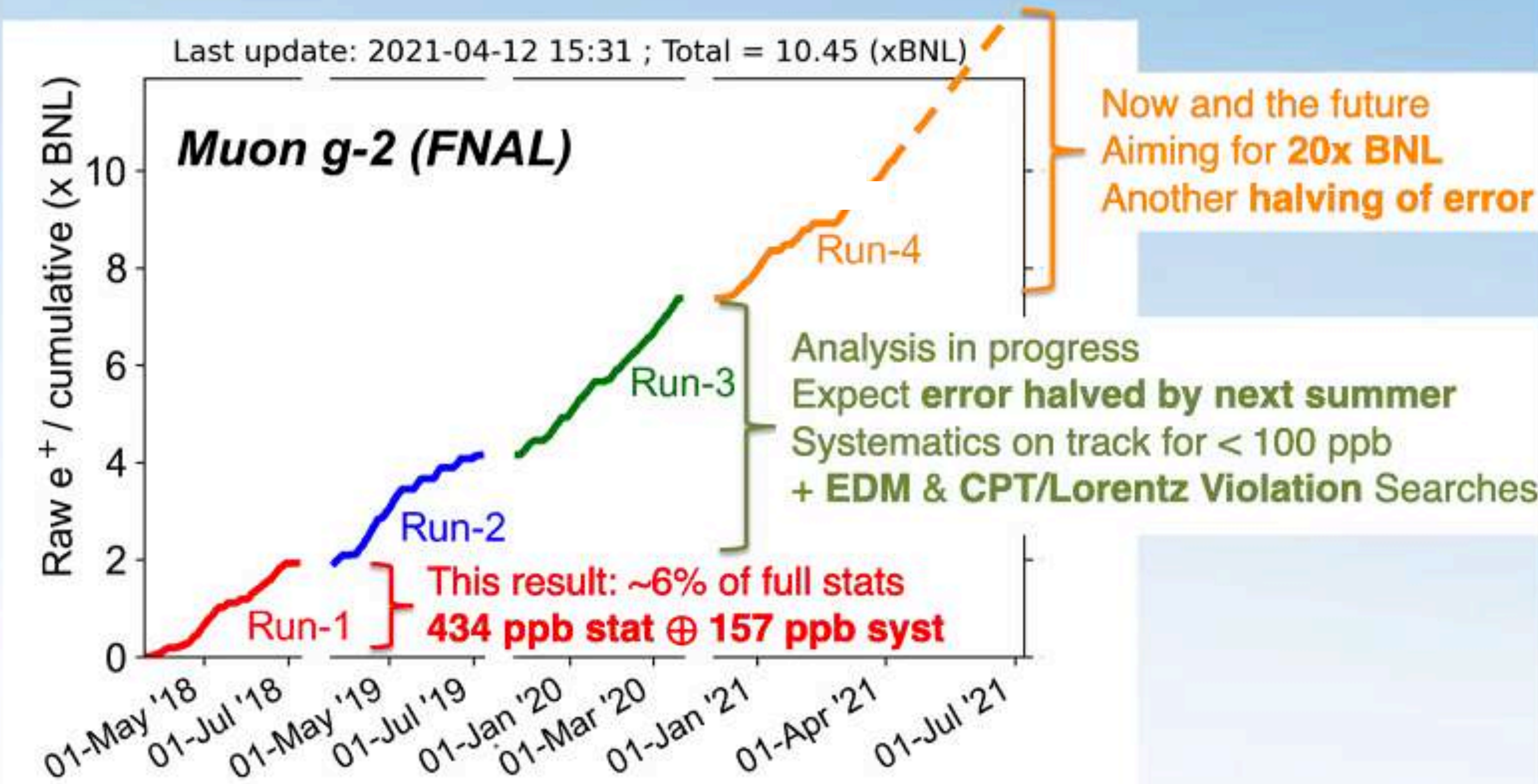
- The recent Muon $g-2$ result from Fermilab shows 4.2 σ deviation between the standard model prediction and the combined measurement.
- A new muon g-2 experiment has been proposed at J-PARC with different approach, aiming at final uncertainty of a_μ to be 100 ppb, comparable with FNAL final goal.
- In the new experiment, several novel techniques will be developed, including the re-accelerated thermal muon source, world's first muon RF acceleration, 3D beam injection scheme etc.
- Now, R&D phase is ending and construction phase is starting. Our experiment plan to start the physics run from 2025.

Thank you for your attention!

Backup

Outlook: Muon g – 2

- Future looks bright – there's much more data still to come



BOSTON UNIVERSITY

实际上的计算公式

其它更精确的基本常数

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$\tilde{\omega}'_p(T)$	Proton Larmor precession frequency in a spherical water sample. Temperature dependence known to < 1ppb/°C. Metrologia **13**, 179 (1977), Metrologia **51**, 54 (2014), Metrologia **20**, 81 (1984)
$\frac{\mu_e(H)}{\mu'_p(T)}$	Measured to 10.5 ppb accuracy at T = 34.7°C Metrologia **13**, 179 (1977)
$\frac{\mu_e}{\mu_e(H)}$	Bound-state QED (exact) Rev. Mod. Phys. **88** 035009 (2016)
$\frac{m_\mu}{m_e}$	Known to 22 ppb from muonium hyperfine splitting Phys. Rev. Lett. **82**, 711 (1999)
$\frac{g_e}{2}$	Measured to 0.28 ppt Phys. Rev. A **83**, 052122 (2011)

束流动力学修正

Corrections due to beam dynamics

$$R'_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

瞬态场修正

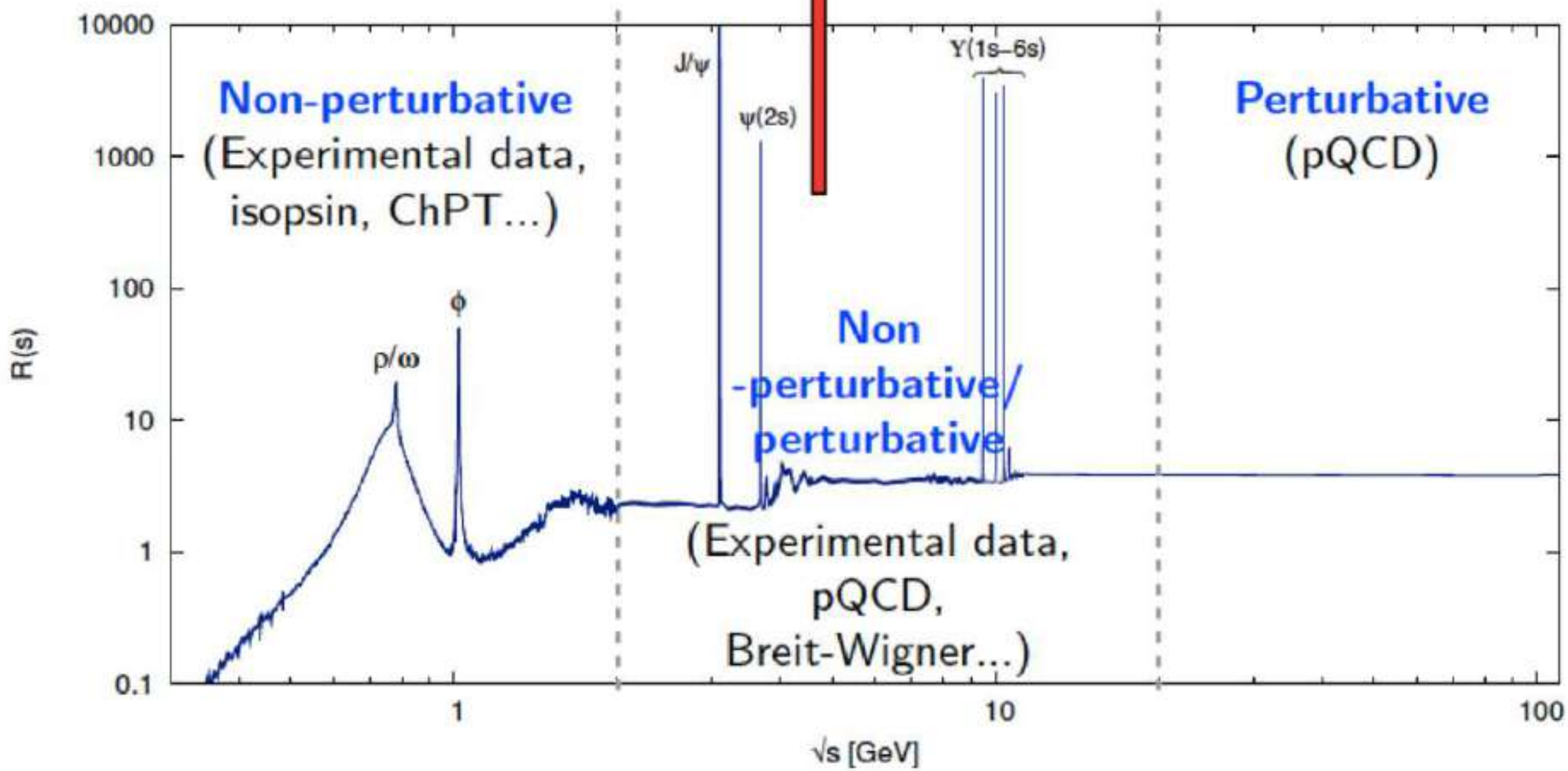
Corrections due to transient magnetic fields

$\tilde{\omega}'_p(T)$ = Proton Larmor precession frequency in a spherical water sample weighted for muon distribution

40

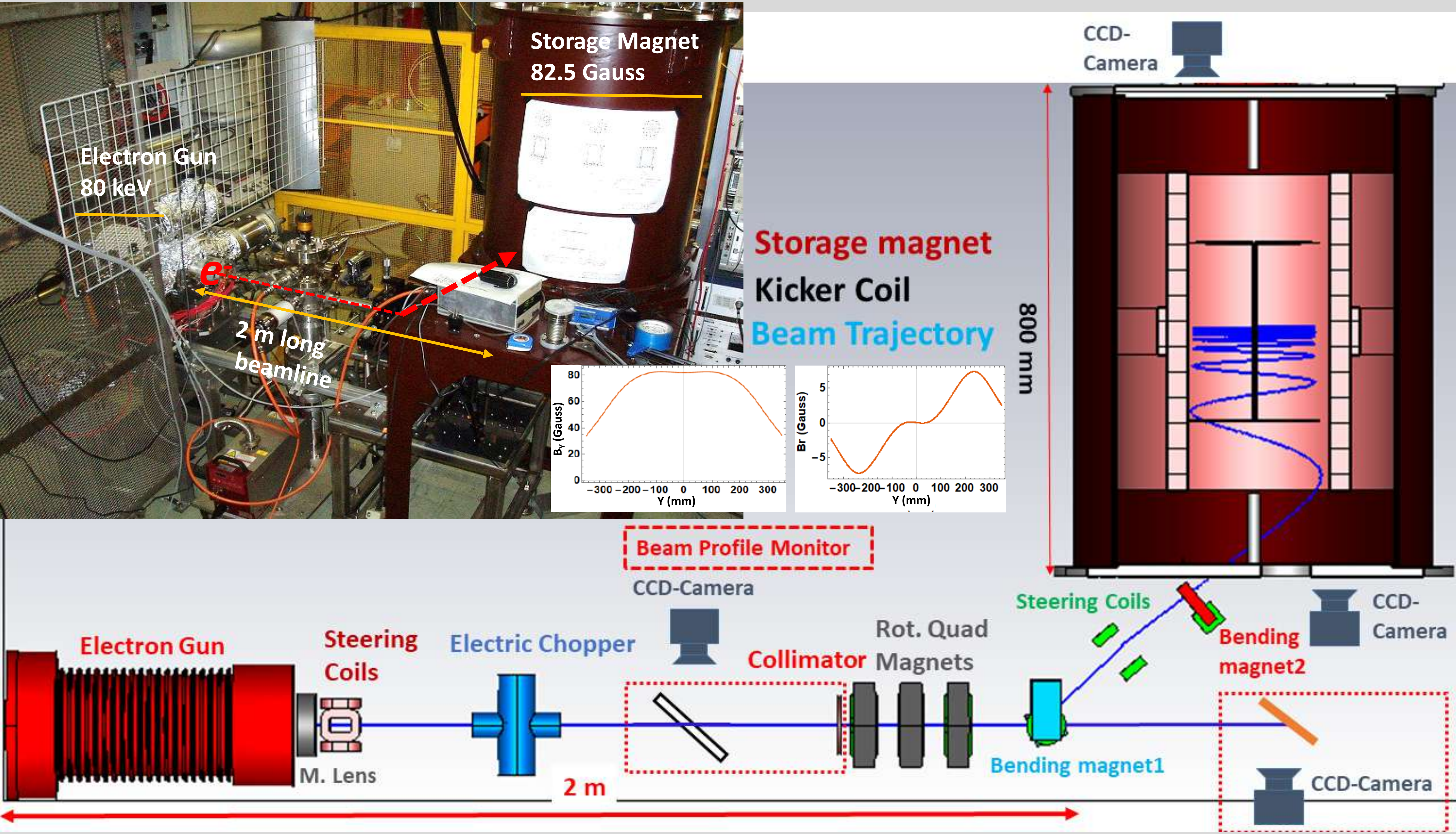
Building the hadronic *R*-ratio

$$a_\mu^{\mathrm{had,\,LO\,VP}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{\mathrm{d}s}{s}\,R(s)K(s), \text{ where } R(s) = \frac{\sigma^0_{\mathrm{had},\gamma}(s)}{4\pi\alpha^2/3s}$$



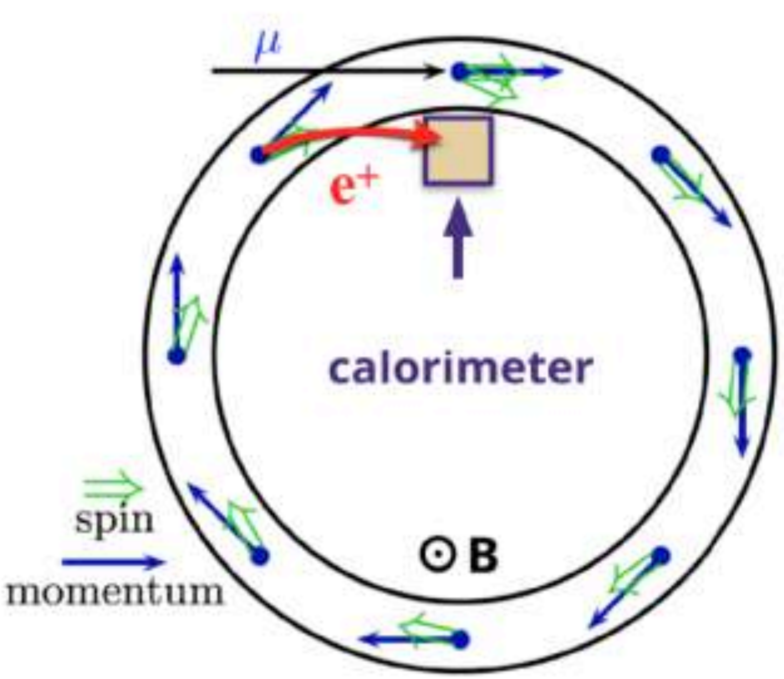
Spiral Injection Test Experiment (SITE)

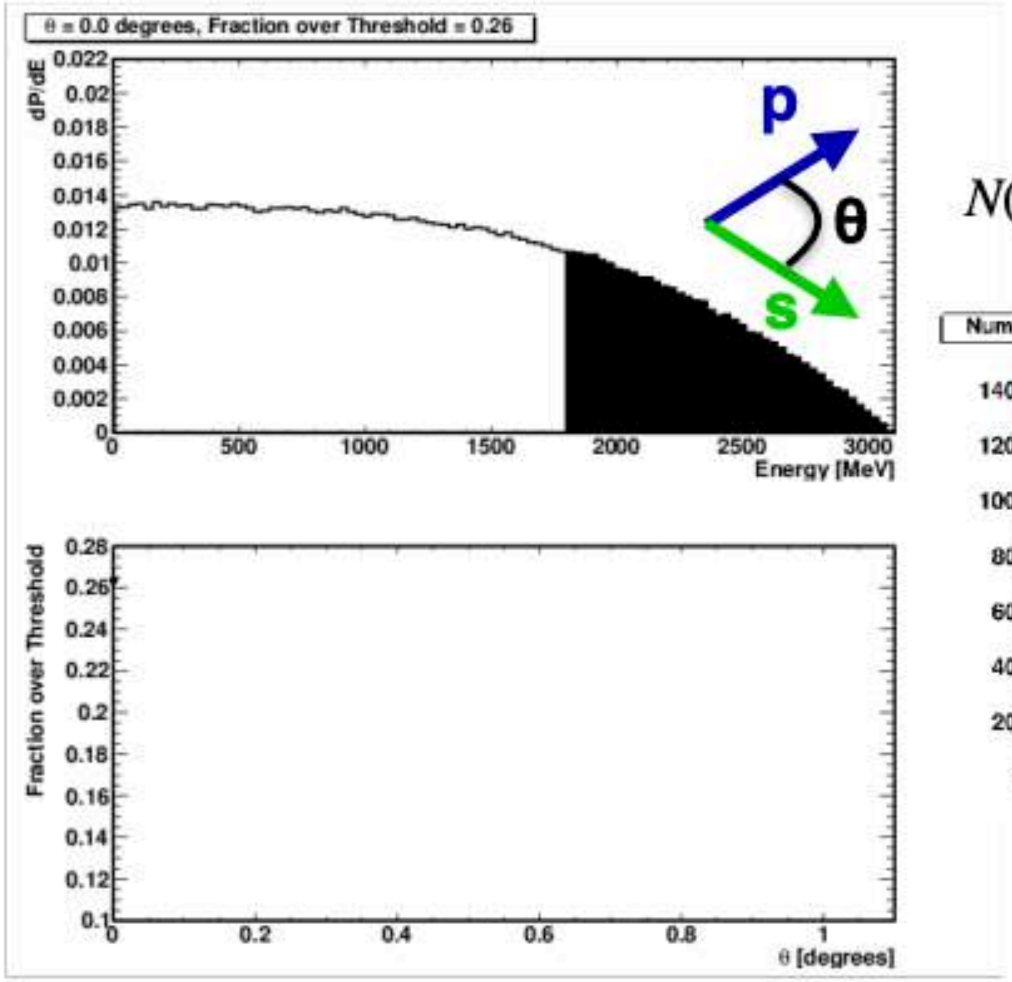
Spiral Injection Test Experiment Setup at KEK Tsukuba Campus



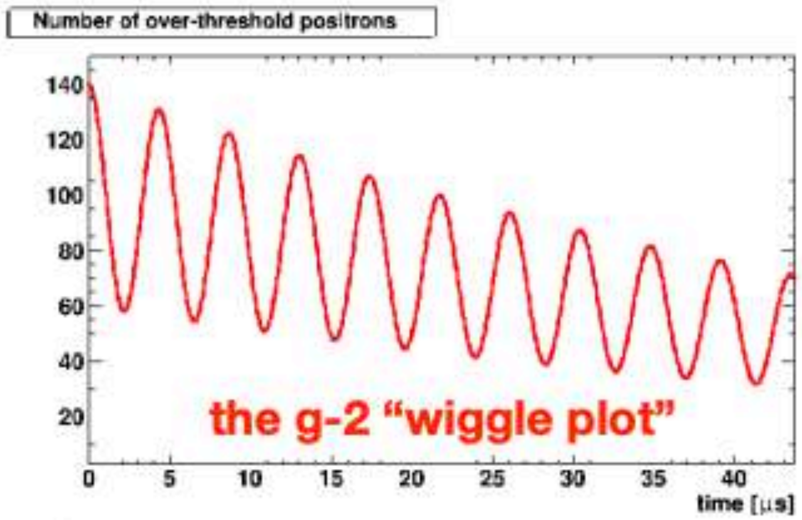
Frequency extraction: fitting the modulation

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

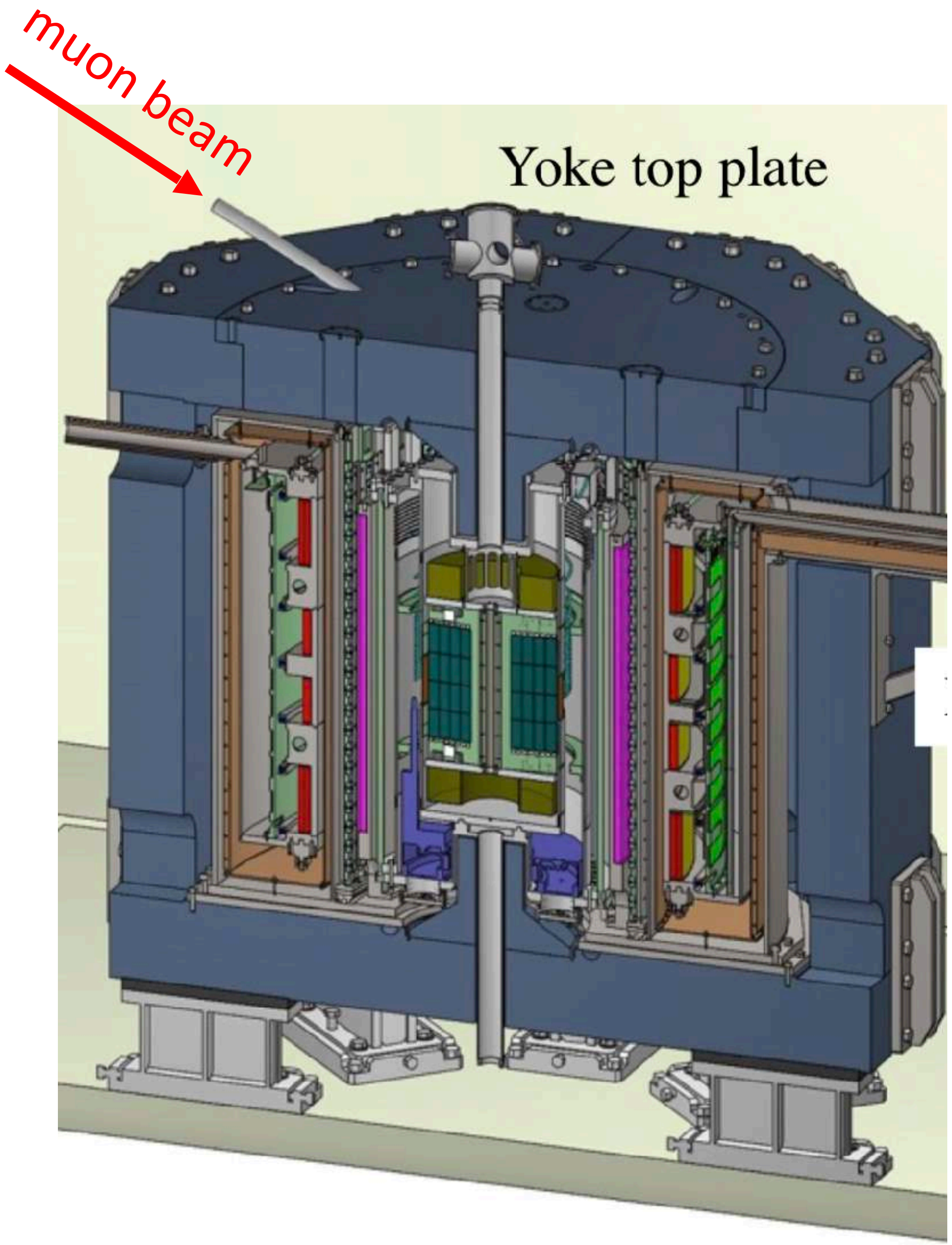




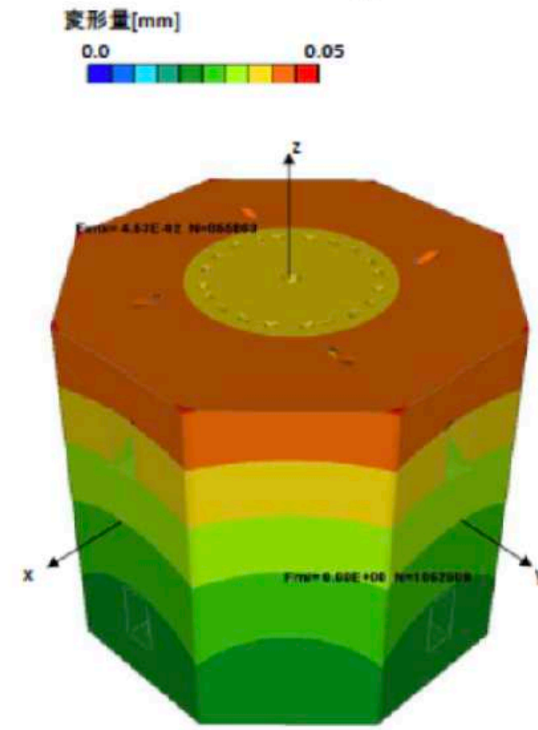
$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$



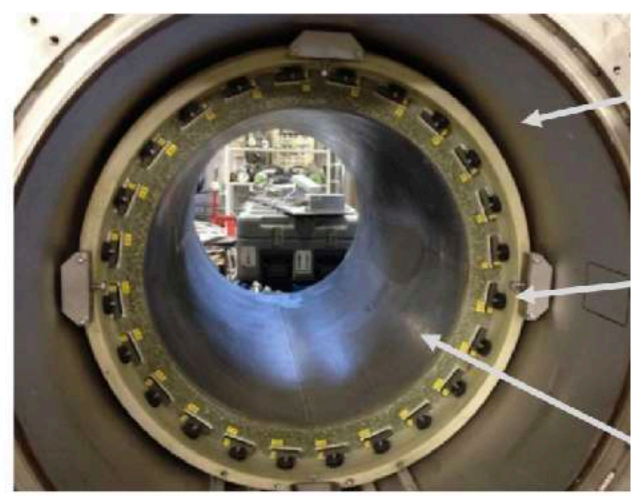
Storage magnet and field measurement

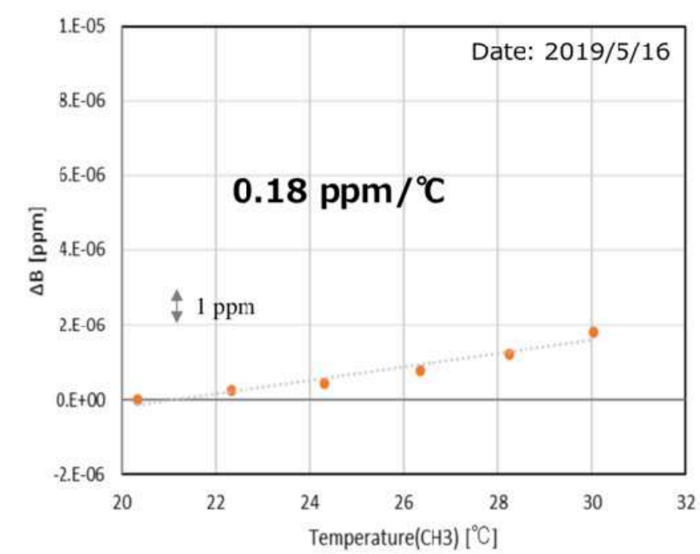


Thermal expansion of yoke has been simulated.

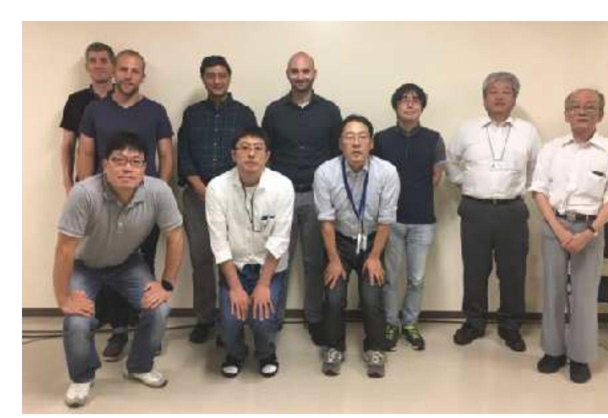


Temperature effect on B-field was evaluated by using a test magnet





US-Japan collaboration on cross calibration of B-field probes. Had a collaboration meeting at J-PARC, Sep 2019.



End-to-end simulations

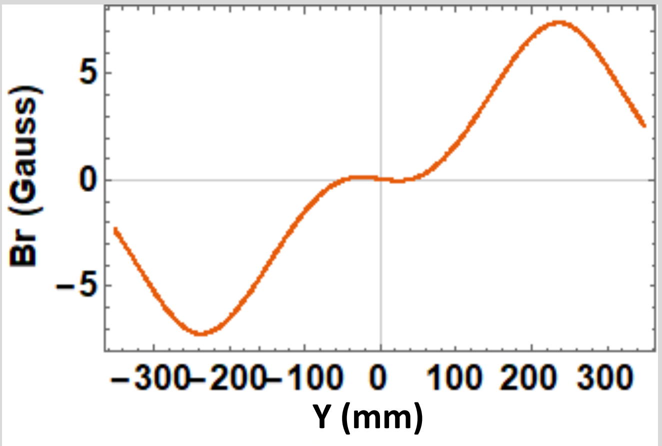
Current TDR (2017)

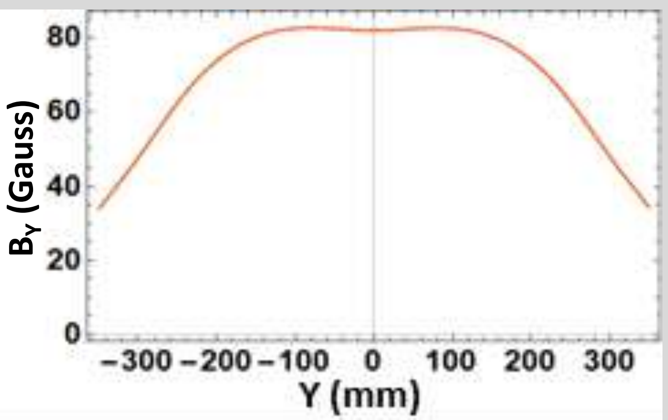
Table 14.1: *Efficiency and beam intensity*

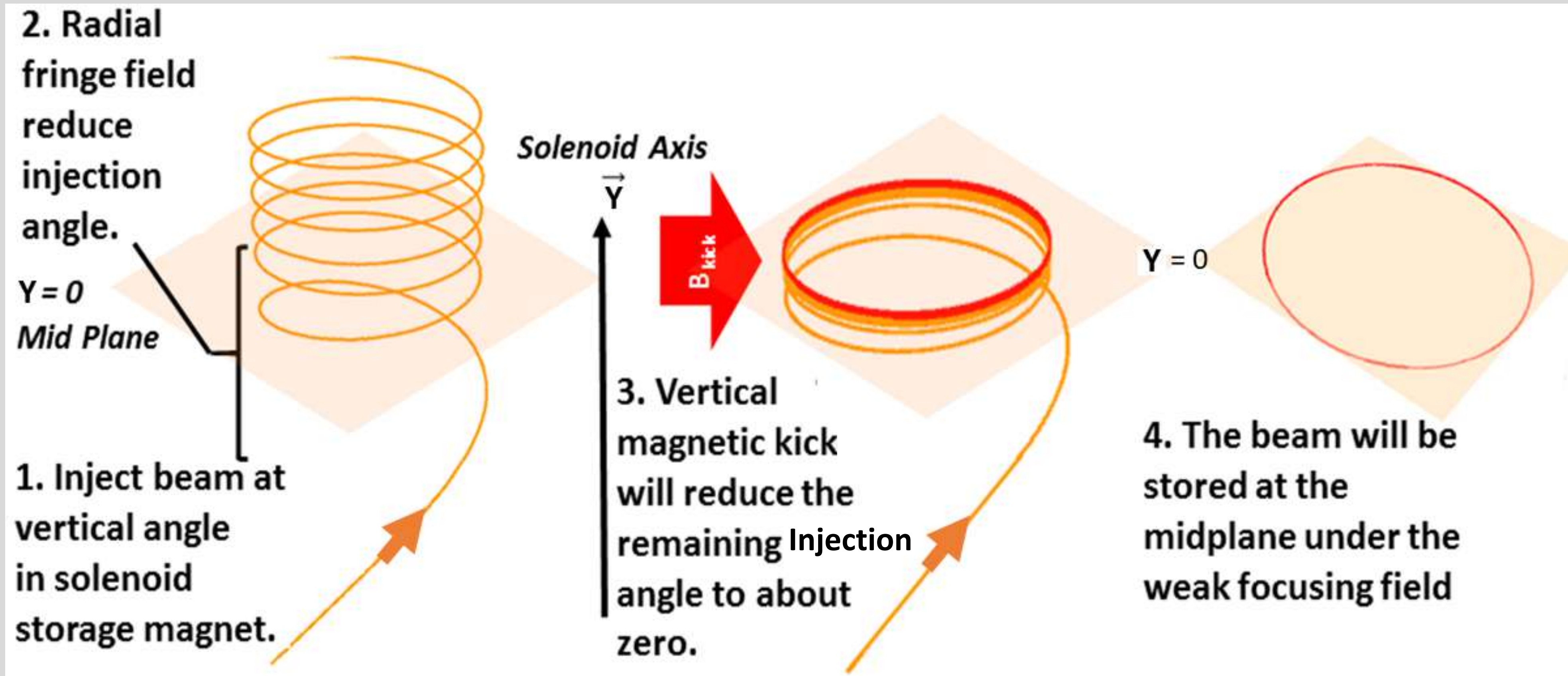
Quantity	Reference	Efficiency	Cumulative	Intensity (Hz)
Muon intensity at production target	[2]			1.99E+09
H-line transmission	[2]	1.62E-01	1.62E-01	3.22E+08
Mu emission	[3]	3.82E-03	6.17E-04	1.23E+06
Laser ionization	[4]	7.30E-01	4.50E-04	8.97E+05
Metal mesh	[5]	7.76E-01	3.49E-04	6.96E+05
Init.Acc.trans.+decay	[5]	7.18E-01	2.51E-04	5.00E+05
RFQ transmission	[6]	9.45E-01	2.37E-04	4.72E+05
RFQ decay	[6]	8.13E-01	1.93E-04	3.84E+05
IH transmission	[7]	9.87E-01	1.90E-04	3.79E+05
IH decay	[7]	9.89E-01	1.88E-04	3.75E+05
DAW transmission	[8]	9.95E-01	1.87E-04	3.73E+05
DAW decay	[8]	9.61E-01	1.80E-04	3.58E+05
High beta transmission	[9]	1.00E+00	1.80E-04	3.58E+05
High beta decay	[9]	9.88E-01	1.78E-04	3.54E+05
Injection transmission	[10]	8.5E-01	1.42E-04	2.83E+05
Injection decay	[10]	9.9E-01	1.41E-04	2.80E+05
Detector start time	[10]	9.27E-01	1.30E-04	2.60E+05
Muon at storage				2.60E+05

How to inject beam spirally?

To resolve technical challenges a new 3D Spiral Injection scheme has been invented







The Elegance and Advantages

- ➢Smooth connection between injection and storage sections: No need of Inflector
- ➢All in one storage magnet, which reduce source of error fields: No Quad
- ➢No need to kick within a single turn: Simple kicker

However

- ➢Unprecedented

Therefore, it is indispensable to prove the feasibility of this new scheme.

Experimental determination of $a_\mu = (g-2)/2$

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

ω_a : anomalous spin precession frequency

ω_p : proton's Lamor precession frequency

$$a_\mu = \frac{\boxed{\dfrac{\omega_a}{\omega_p}}}{\boxed{\dfrac{\mu_\mu}{\mu_p}} - \boxed{\dfrac{\omega_a}{\omega_p}}}$$

Present : 0.54ppm (BNL) → 140ppb (FNAL/J-PARC goal)
(→400ppb (J-PARC phase-I))

Present uncertainty ~ 0.12ppm (LANL) → 60ppb (MuSEUM goal)