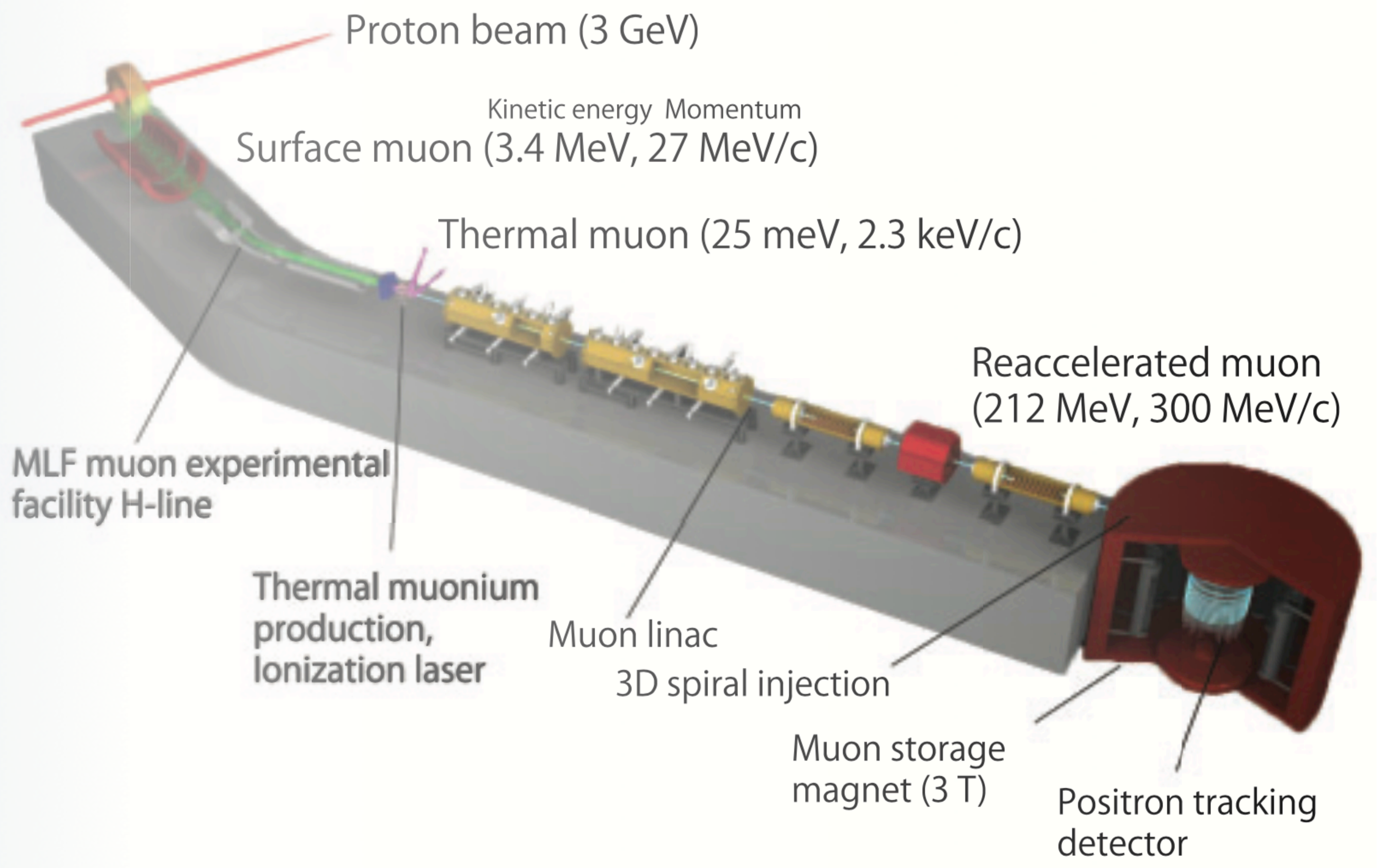
Rethinking Muon $g-2$/EDM at J-PARC: The Change, and The Challenges

Cedric

Liverpool Muon Group Meeting

March 2025



Rethinking Muon $g-2$/EDM at J-PARC: The Change, and The Challenges

- **This was my PhD project nearly 3 years ago:**
  - Things evolve rapidly - I may not cover the very latest updates;
  - I am not covering all aspects but will focus on the motivation and challenges.

Rethinking Muon $g-2$/EDM at J-PARC: The Change, and The Challenges

- **This was my PhD project nearly 3 years ago:**
  - Things evolve rapidly - I may not cover the very latest updates;
  - I am not covering all aspects but will focus on the motivation and challenges.
- **The need for a new experiment** - a historical and technological view;
- **Muon cooling** - the key to all the downstream differences;
- **New ideas** - potential collaboration in Liverpool.

The need for a new experiment:

A history of precision battles

Graziano - Muon Workshop, Liverpool, Nov 2022

History: the first measurement of g_μ

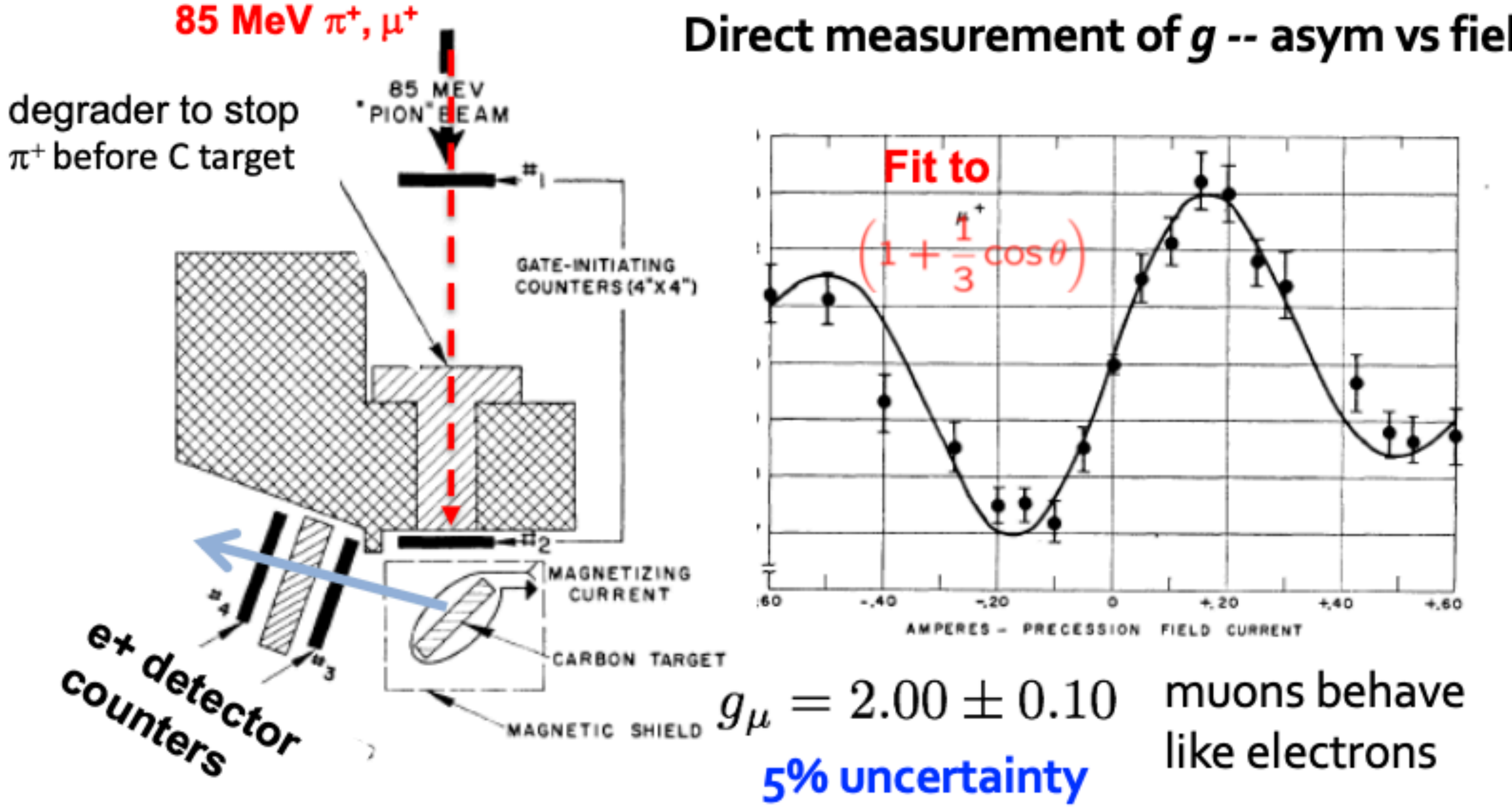
Muon g-2

- 1957: Garwin, Lederman, Weinrich at Nevis (Just after Yang and Lee parity violation paper - confirmation)

85 MeV π^+, μ^+

degrader to stop π^+ before C target

Direct measurement of *g* -- asym vs field



$$g_\mu = 2.00 \pm 0.10$$

5% uncertainty

muons behave like electrons

21

The CERN muon g-2 experiments (1960-1979)

Muon g-2

F. Farley, E. Picasso The Muon (g−2) Experiments at CERN
Ann. Rev. Nucl. Part. Sci. 29 (1979) 243-282

The history of the muon $(g-2)$ experiments
B. Lee Roberts* SciPost Phys. Proc. 1, 032 (2019)

Review
The 47 years of muon $g-2$
F.J.M. Farley[a,*], Y.K. Semertzidis[b]
[a] Yale University, New Haven, CT 06520, USA
[b] Brookhaven National Laboratory, Upton, NY 11973, USA
Received 30 October 2003

Fig. 10. The first experimental magnet in which muons were stored at CERN for up to 30 turns. Left to right: Georges Charpak, Francis Farley, Bruno Nicolai, Hans Sens, Antonio Zichichi, Carl York and Richard Garwin.

They measure a_μ since the measure the spin relative to the momentum

$$\vec{\omega}_a = \omega_S - \omega_C = -\frac{Qe}{m} a_\mu \vec{B}$$

$a_\mu = (g_\mu - 2)/2 \sim g_\mu/1000$

23

From muon 'g' to 'g-2'

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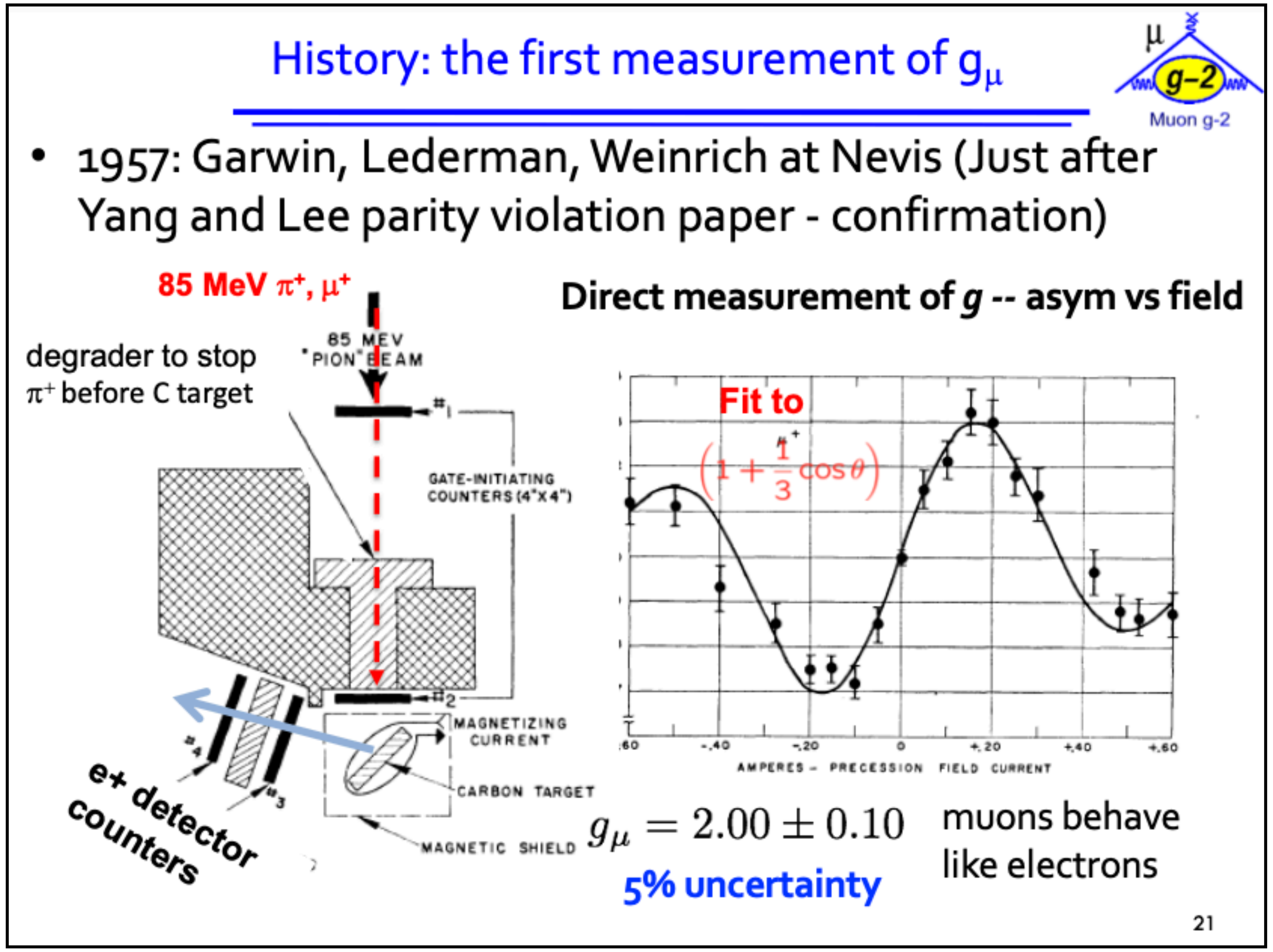
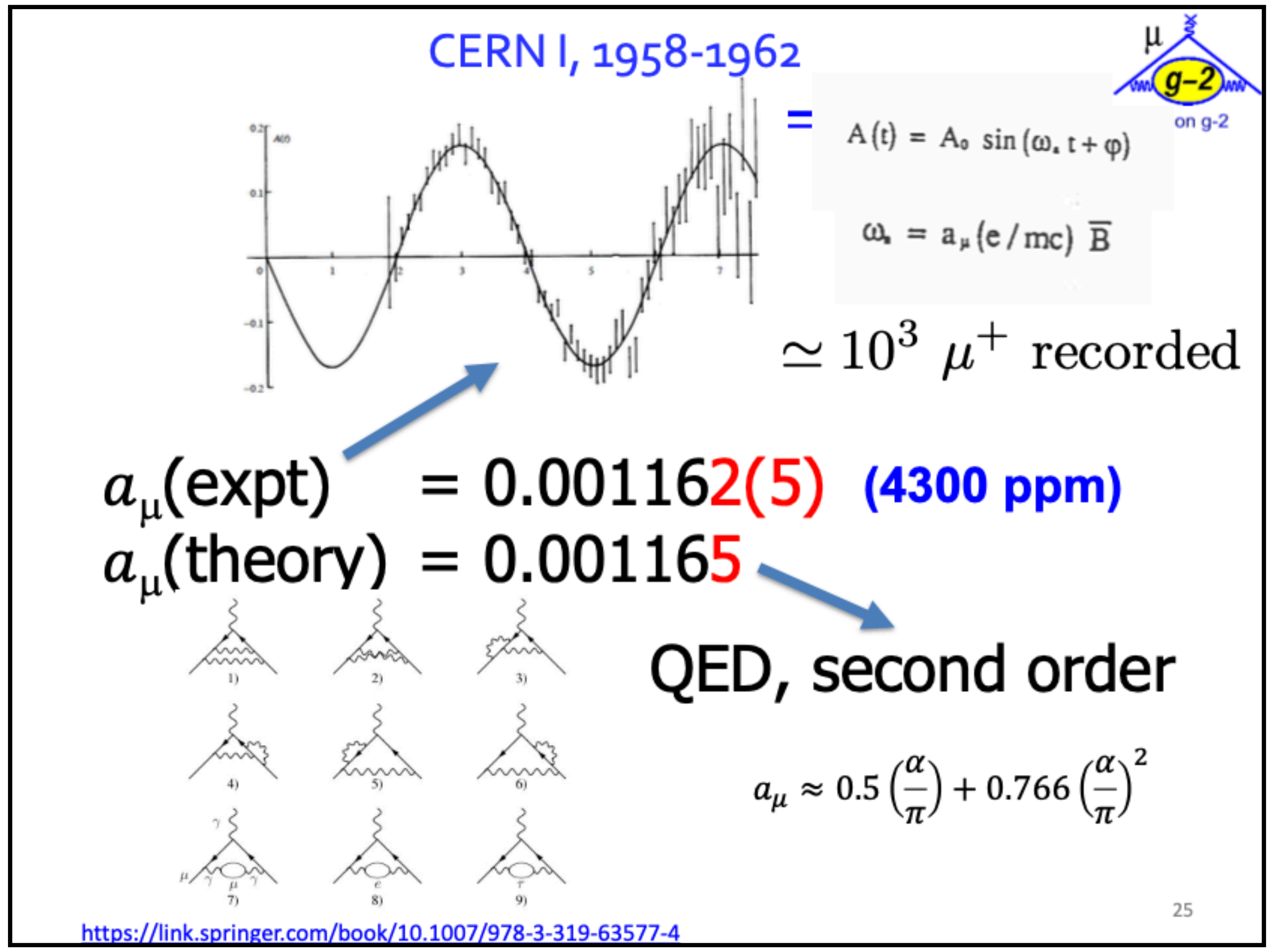
Graziano - Muon Workshop, Liverpool, Nov 2022





Generations of 'g-2' experiments at CERN have been marked by precision battles between theoretical predictions and experimental results.

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A history of precision battles

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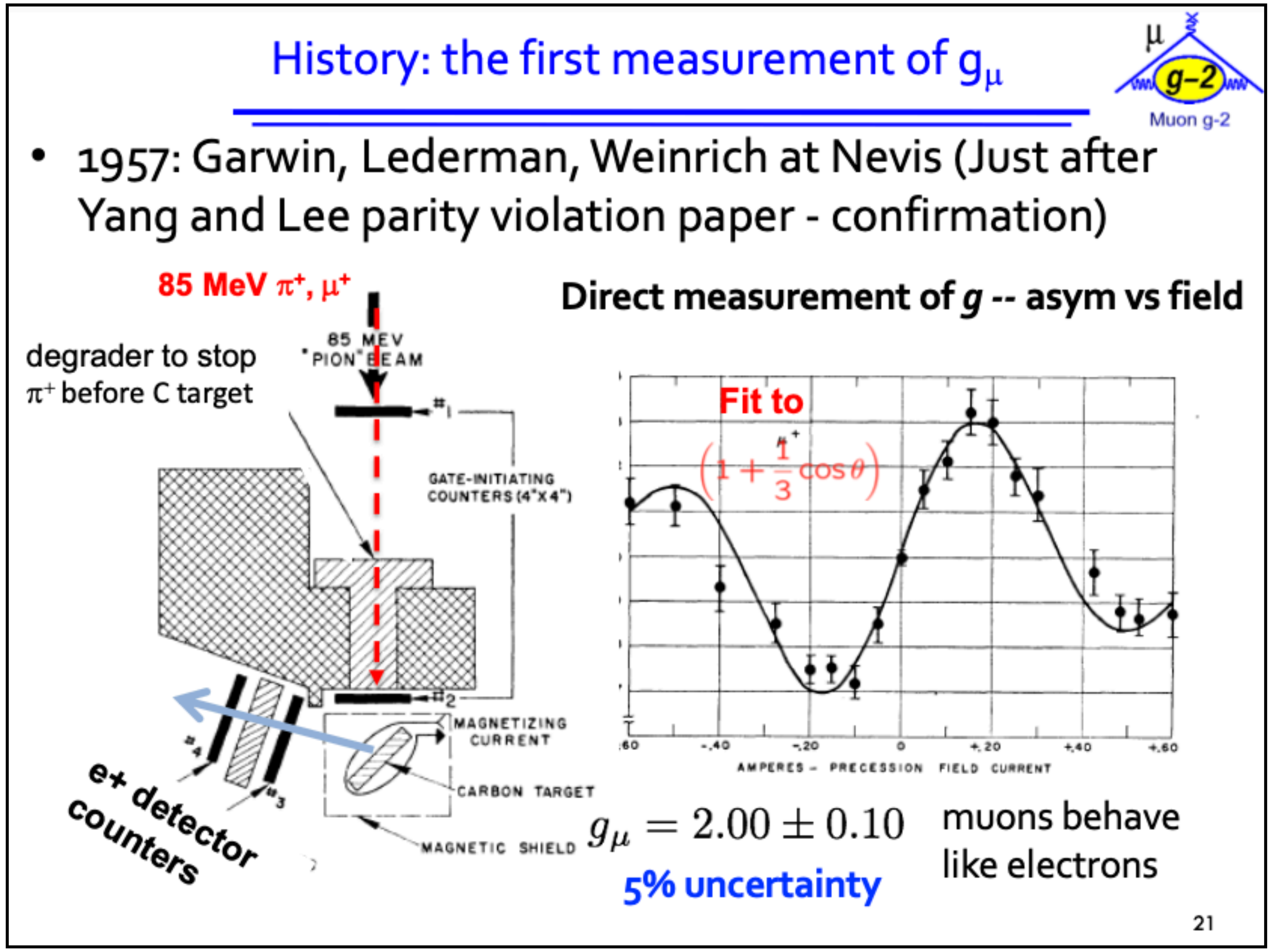

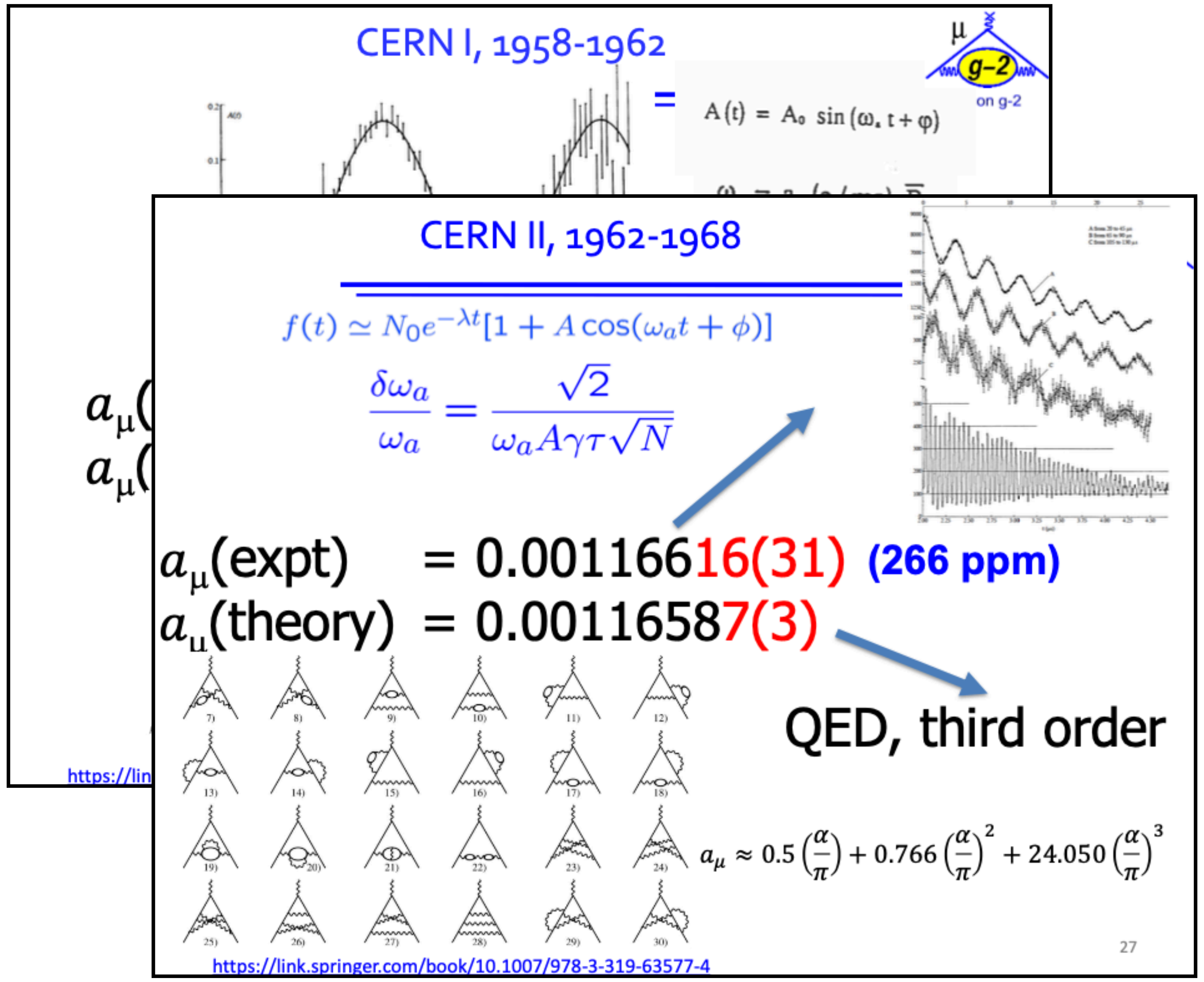

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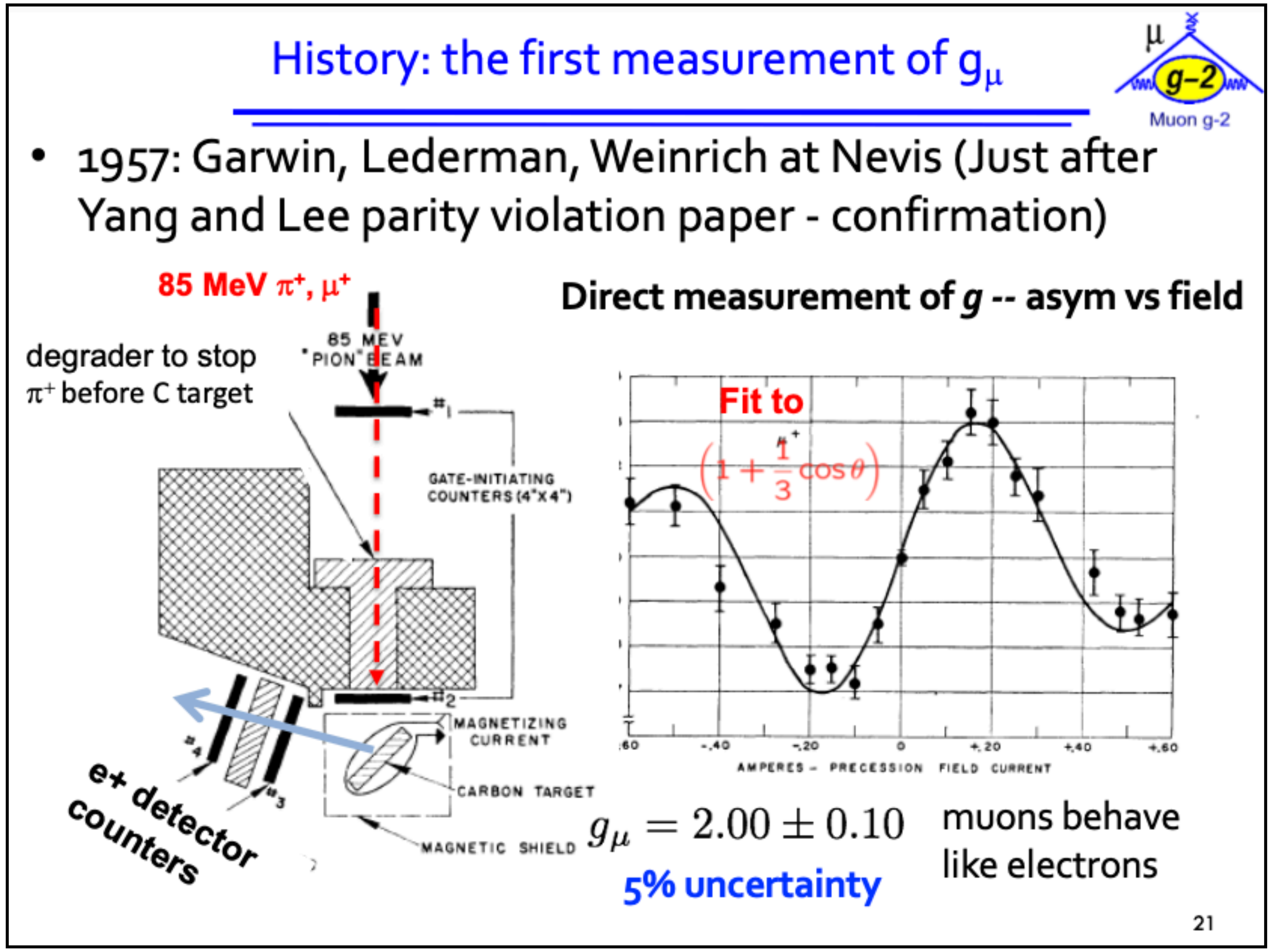

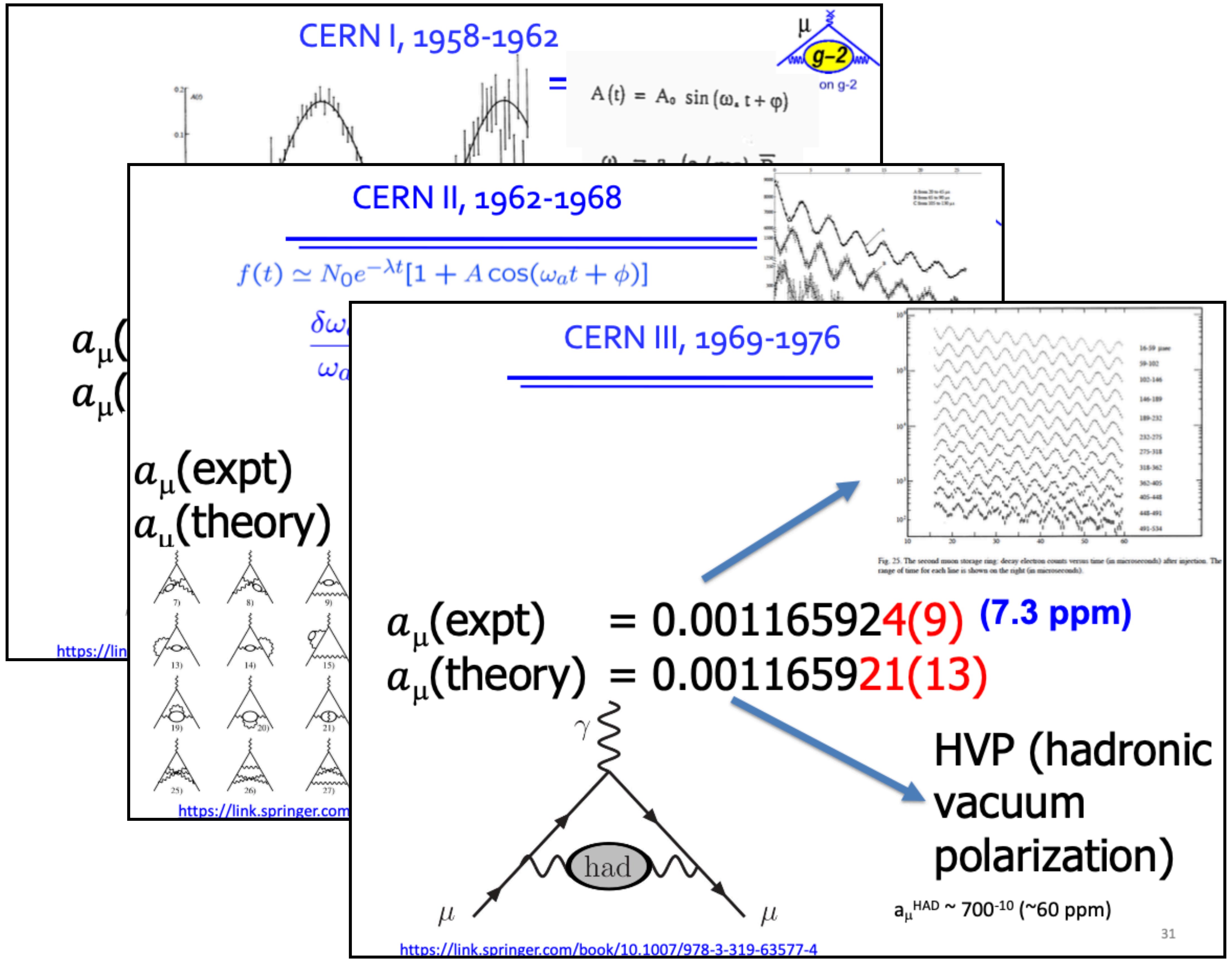

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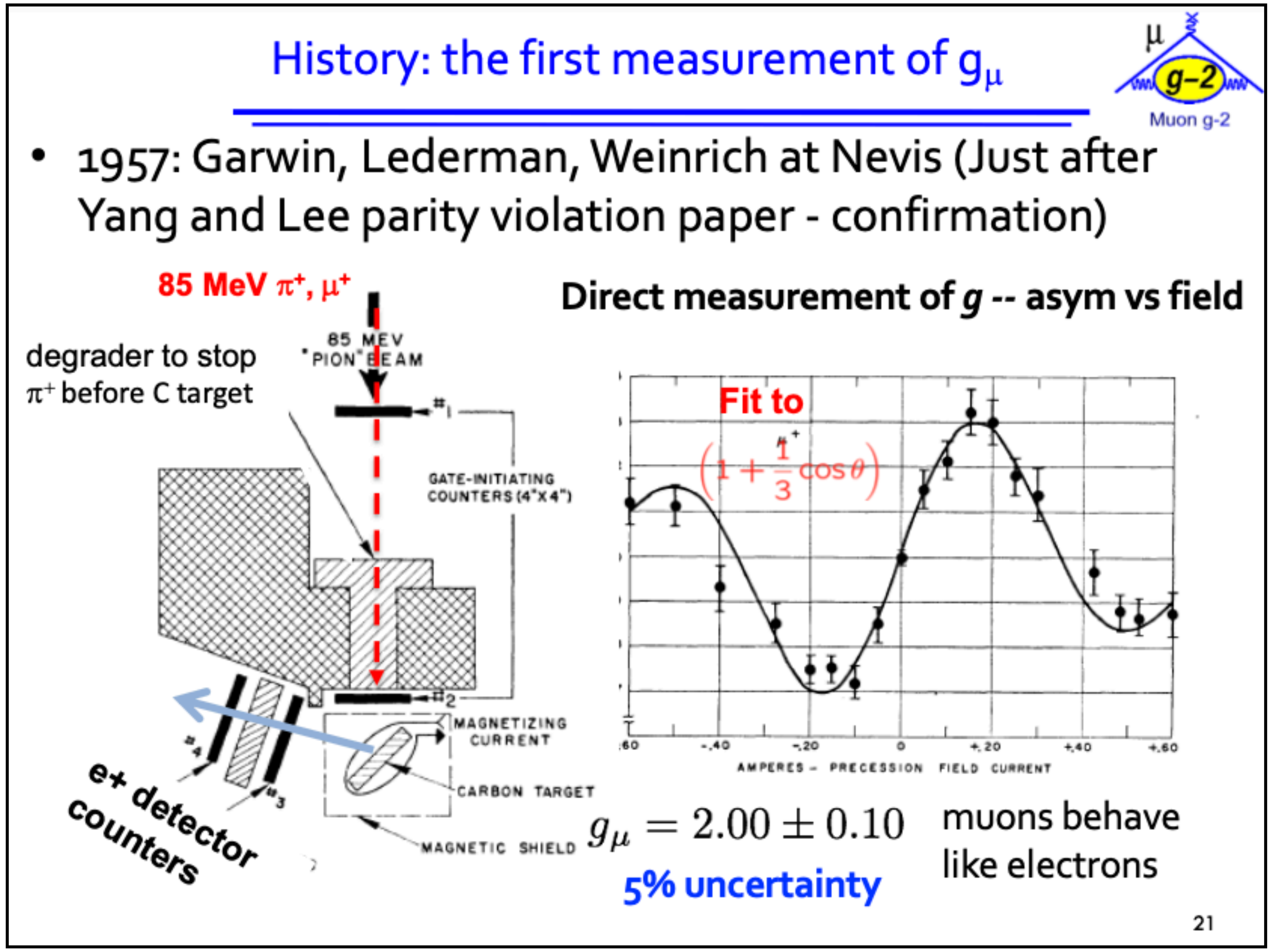
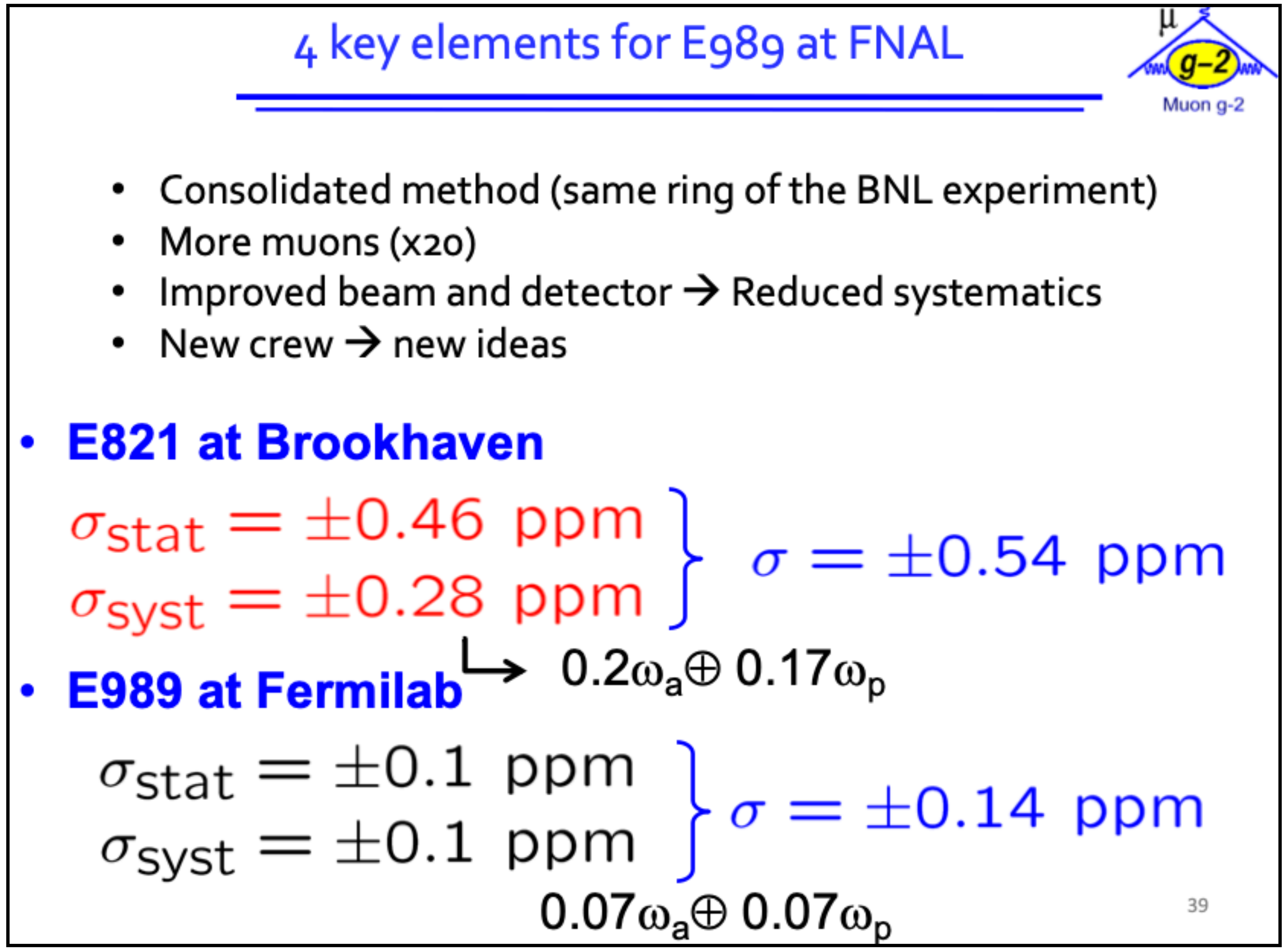
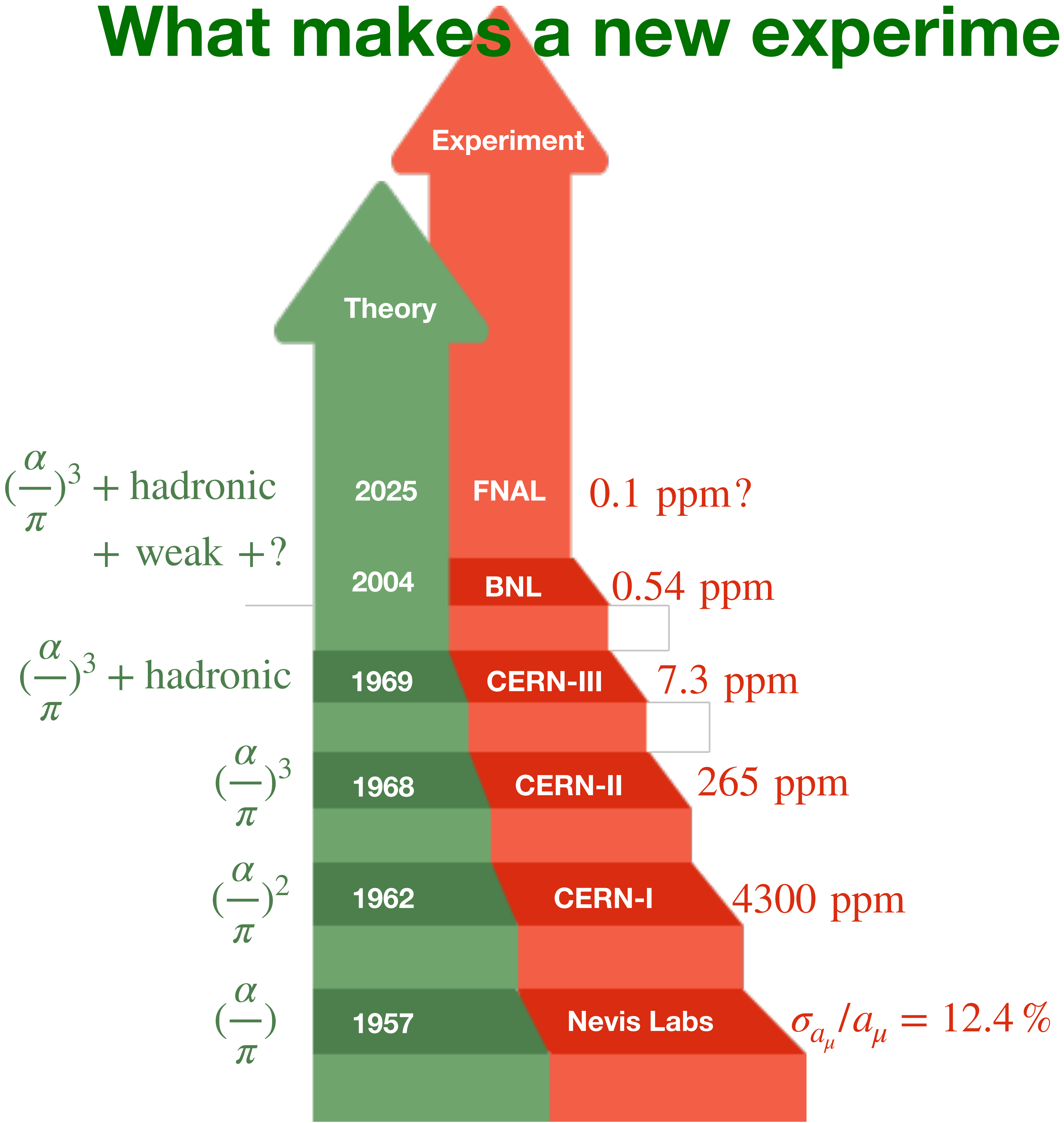




For generations of experiments, we need to consider both **systematic and statistical uncertainties**.

The need for a new experiment:

What makes a new experiment?



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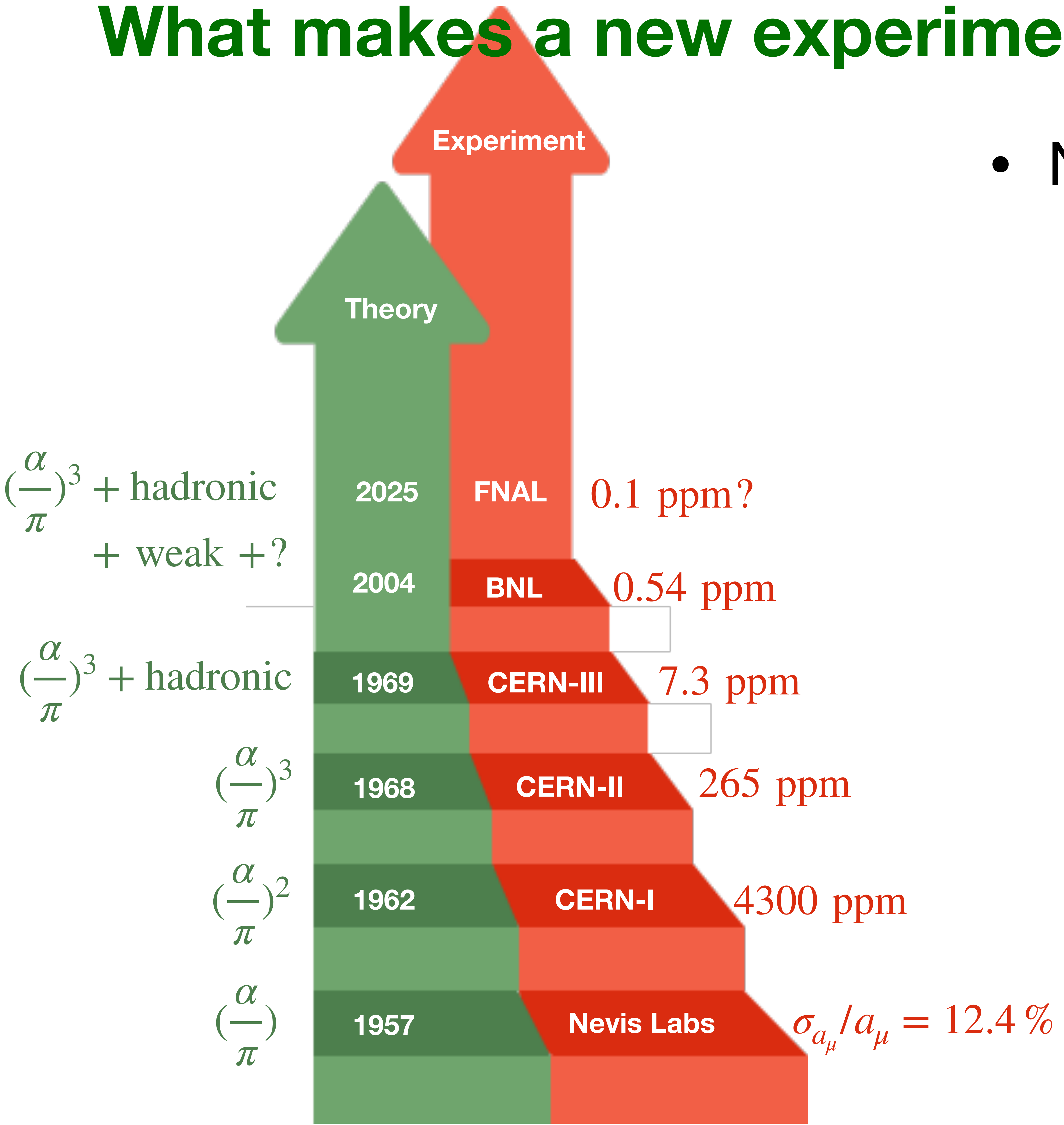

- New experimental ideas:

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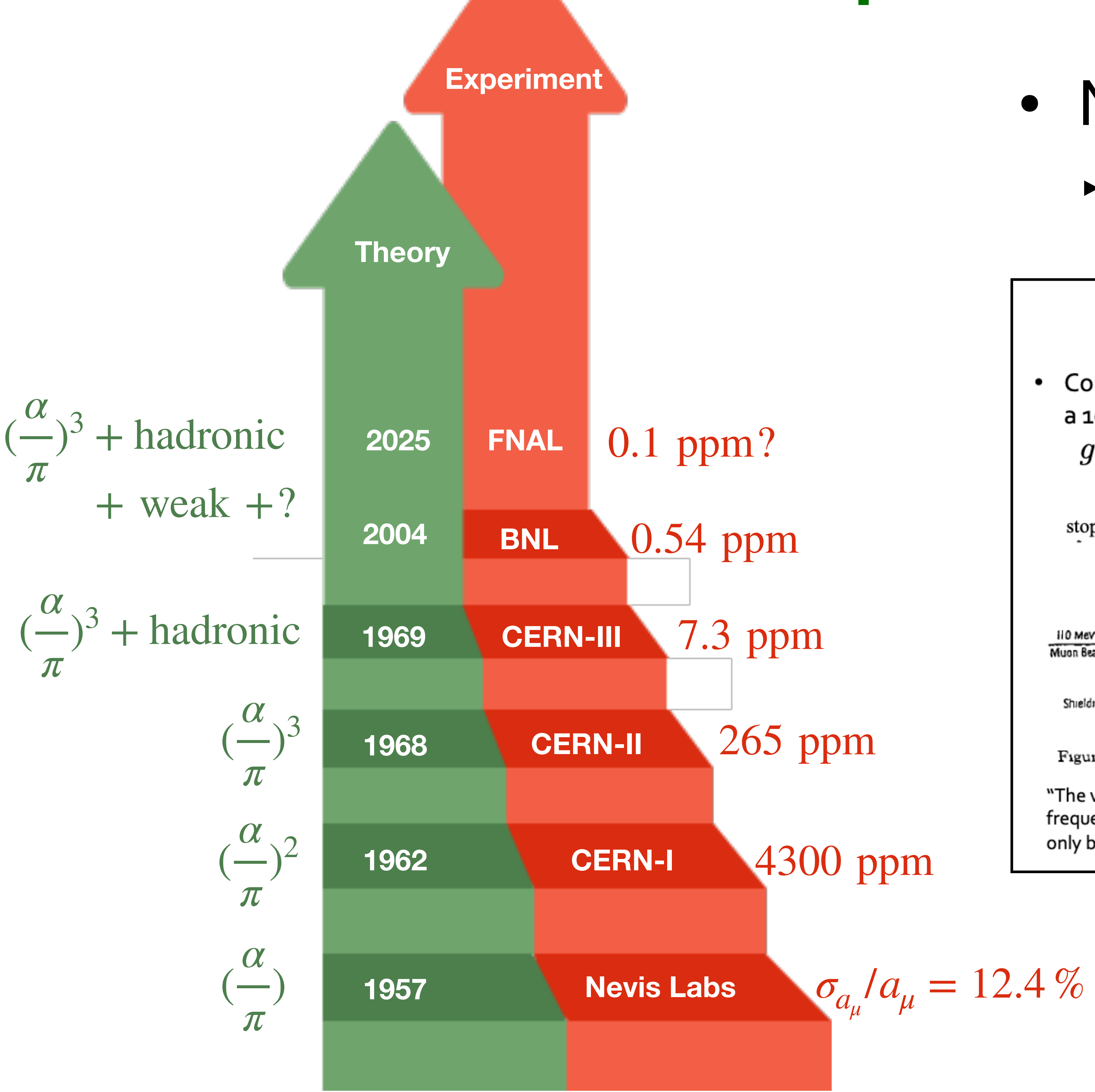
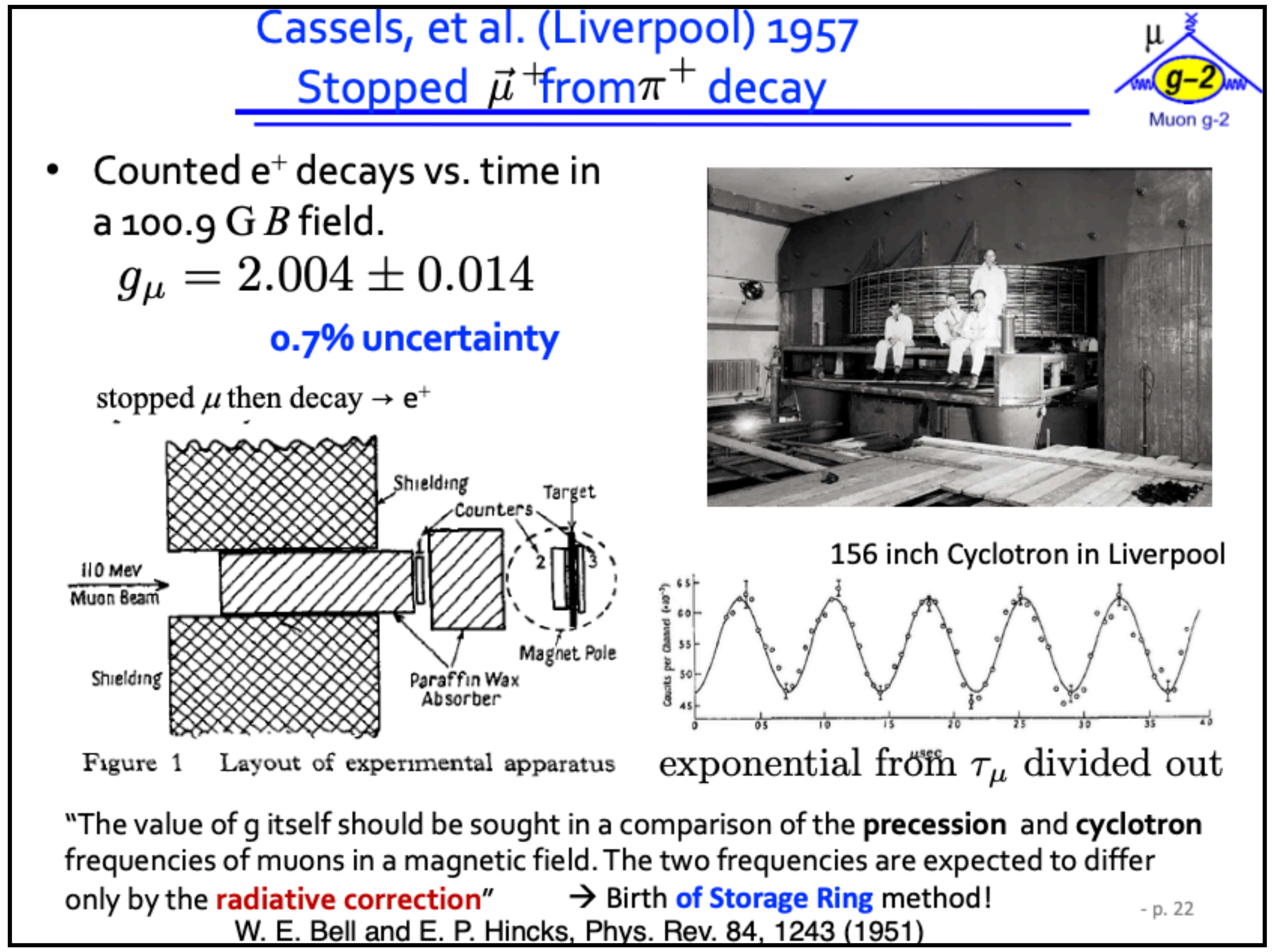
  - CERN-I: from ‘g’ to ‘g-2’ with storage ring method





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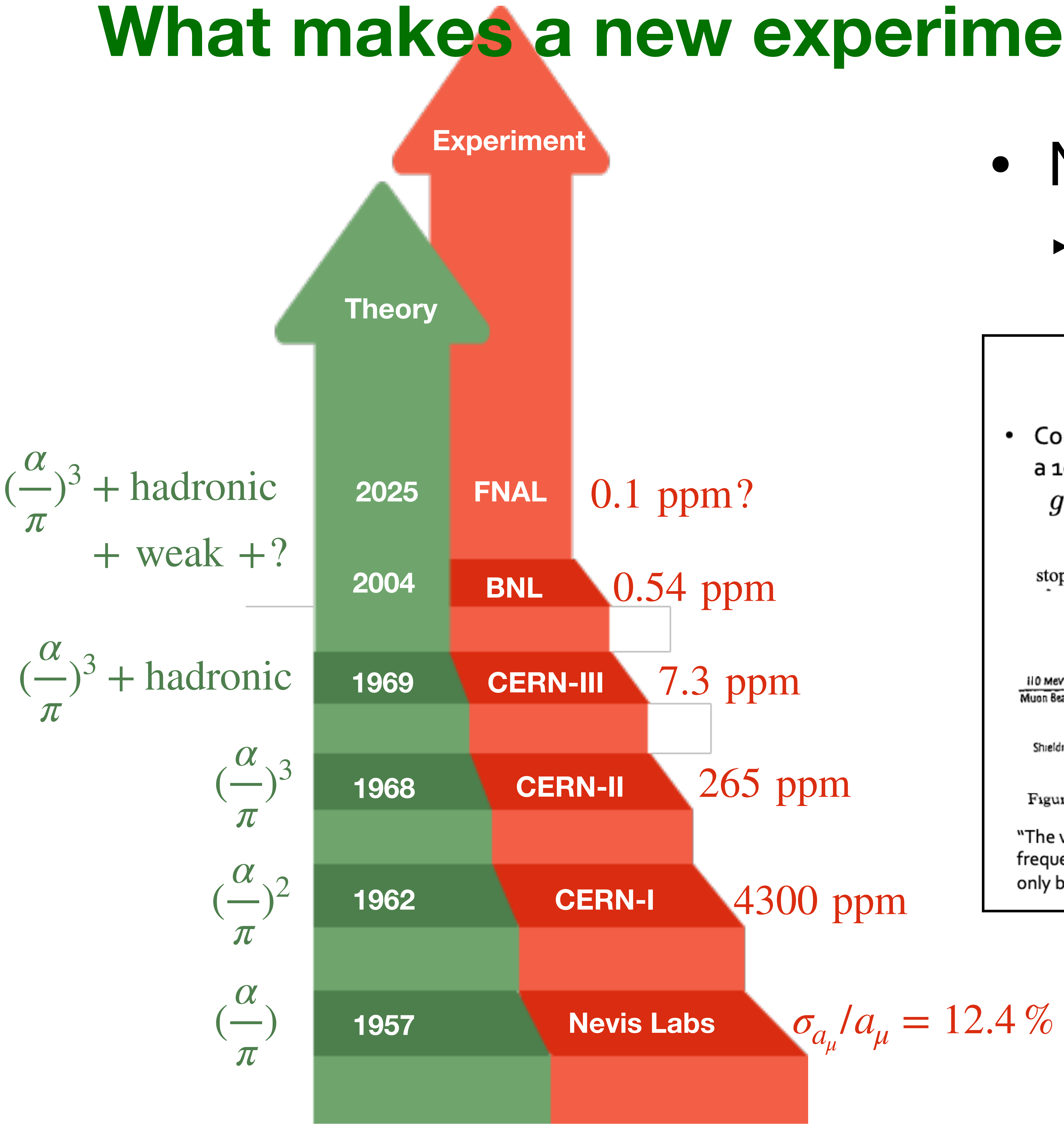

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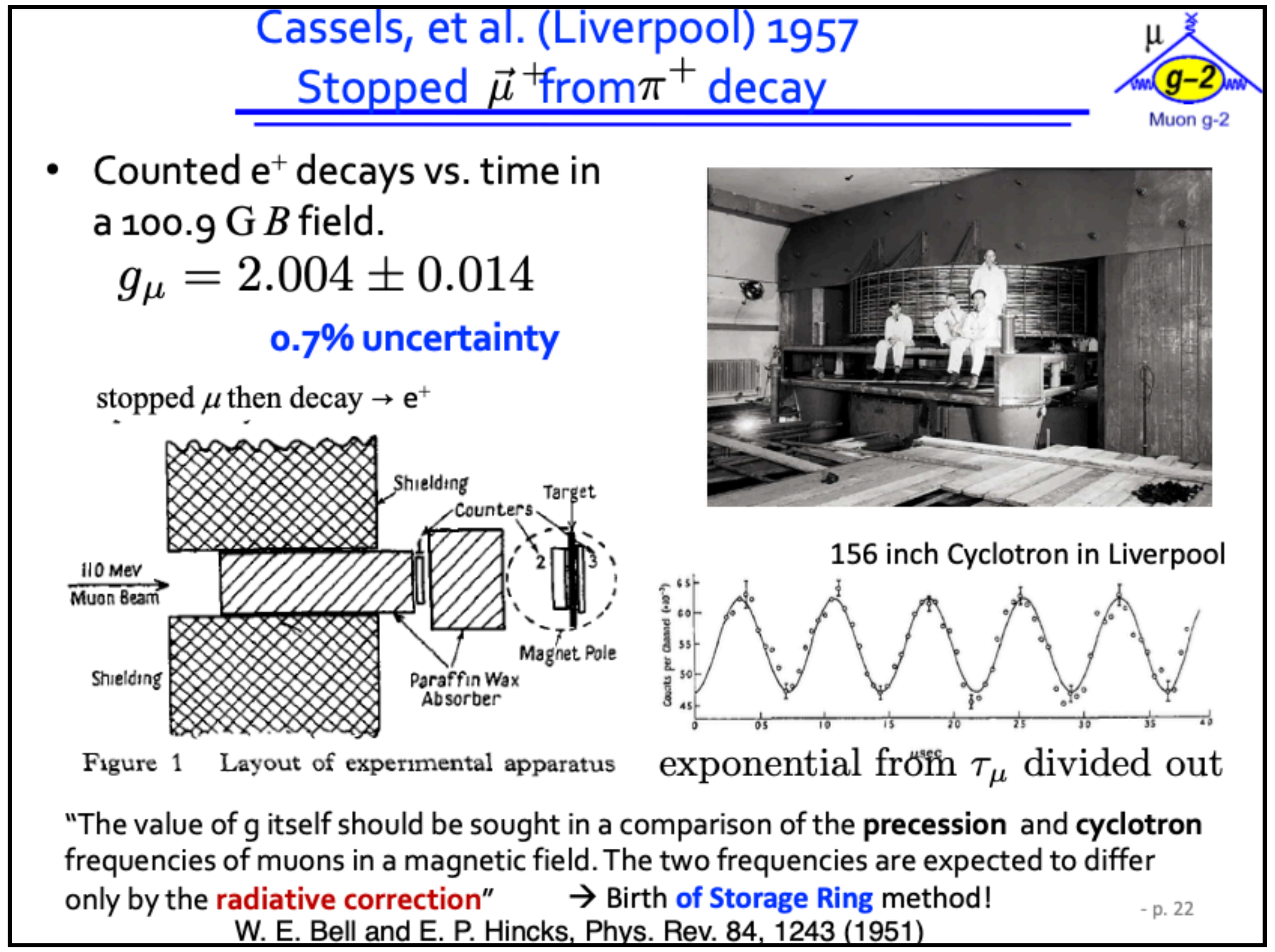
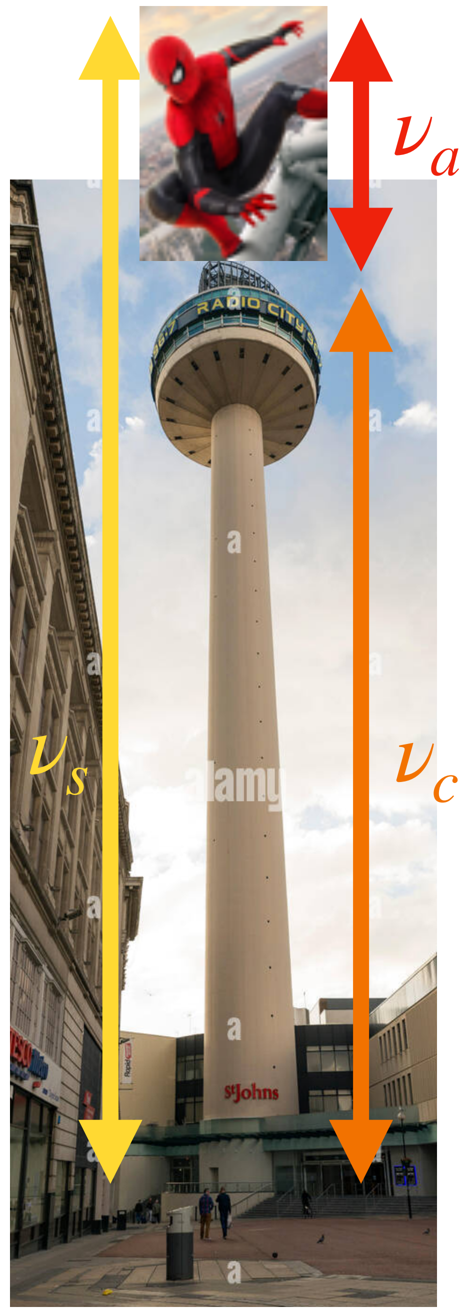




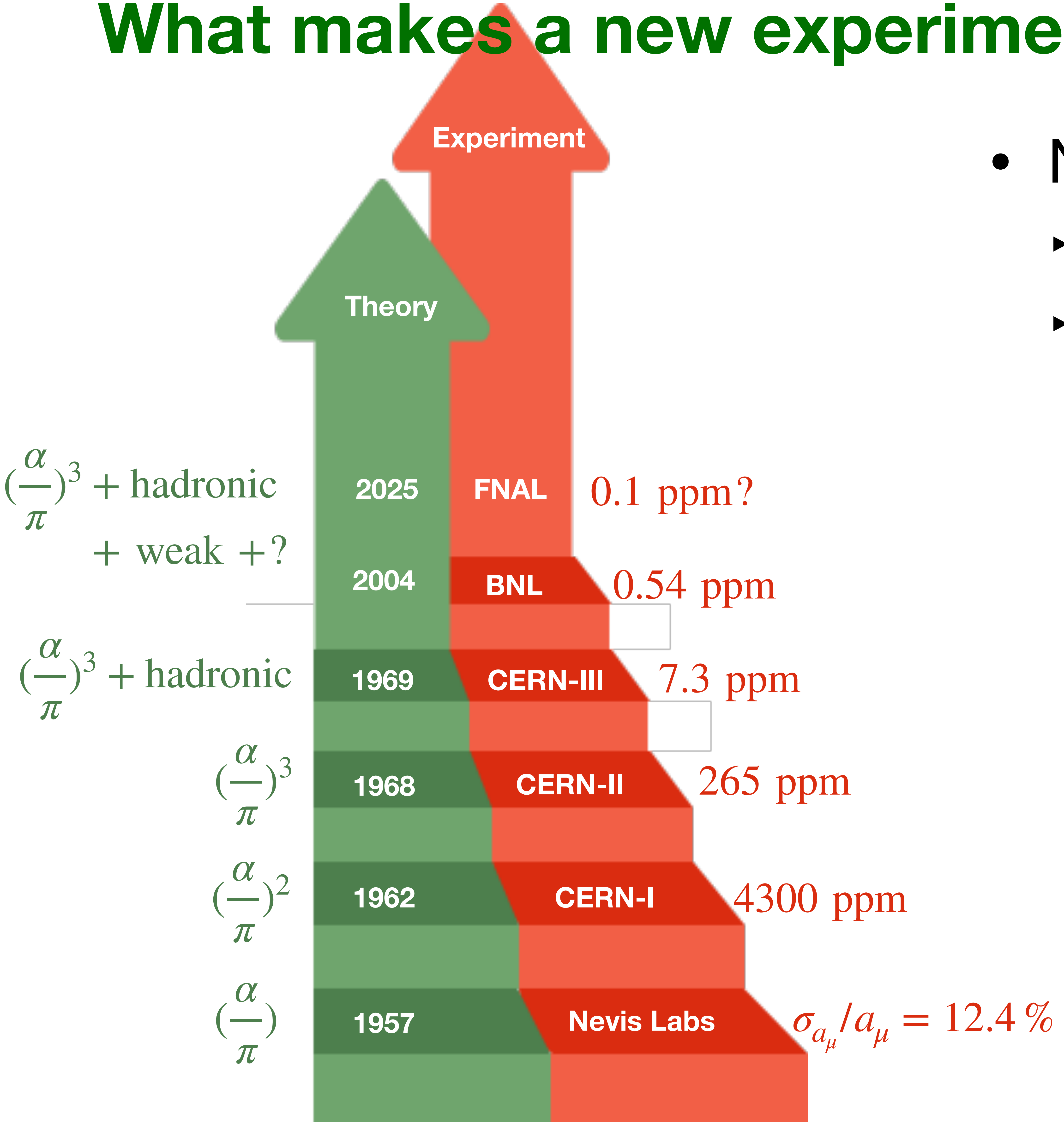
$$g/2 = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_a}{\nu_c}$$

(~1.001)

~1000 gain by measuring ν_a !

An experimental trick: subtract known quantities and focus only on the components with uncertainties that need resolution.

The need for a new experiment:
What makes a new experiment?



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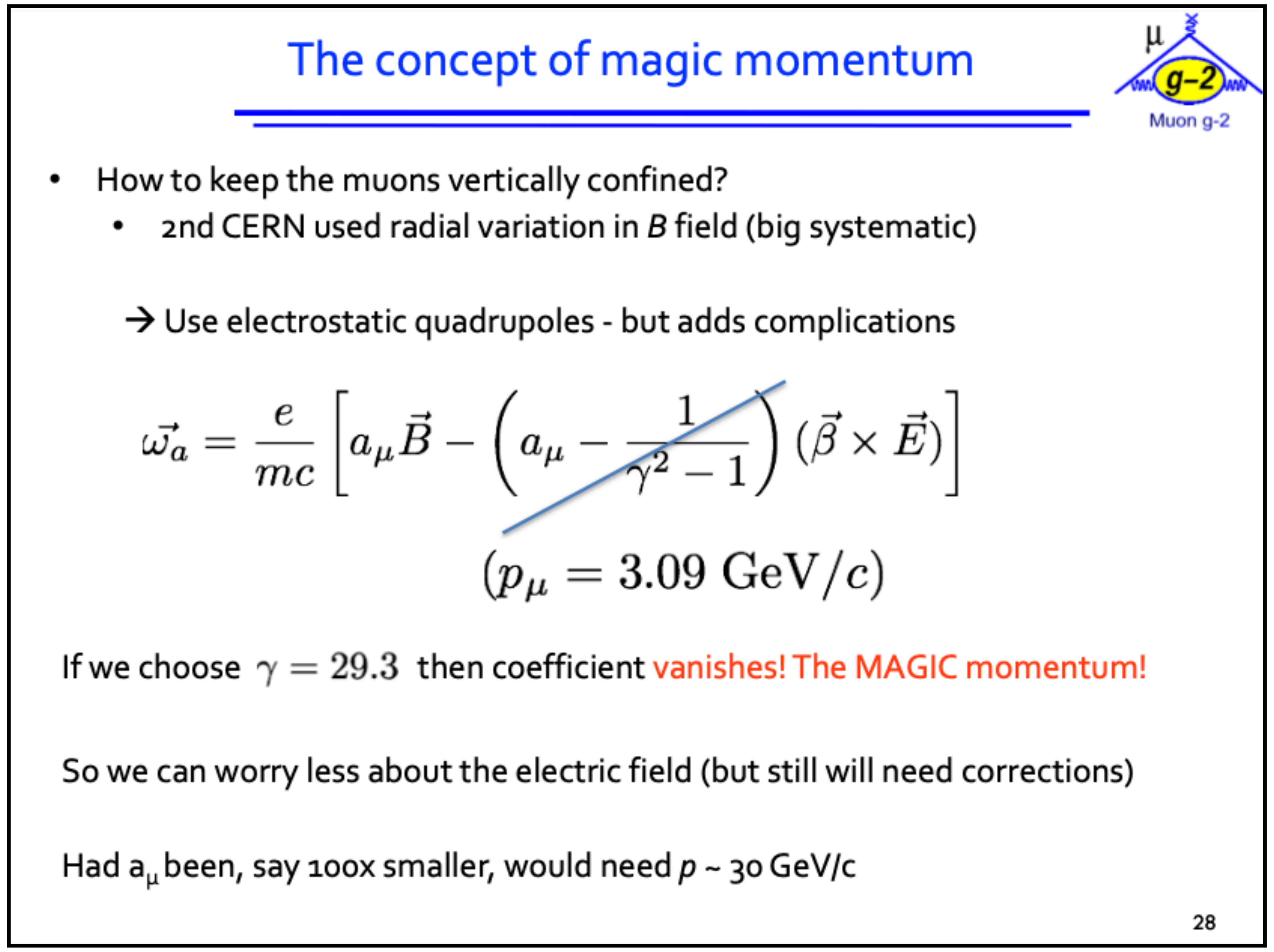


The concept of magic momentum

- How to keep the muons vertically confined?
  - 2nd CERN used radial variation in *B* field (big systematic)

→ Use electrostatic quadrupoles - but adds complications

$$\vec{\omega_a} = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

$$(p_\mu = 3.09\ \mathrm{GeV}/c)$$

If we choose $\gamma = 29.3$ then coefficient vanishes! The MAGIC momentum!

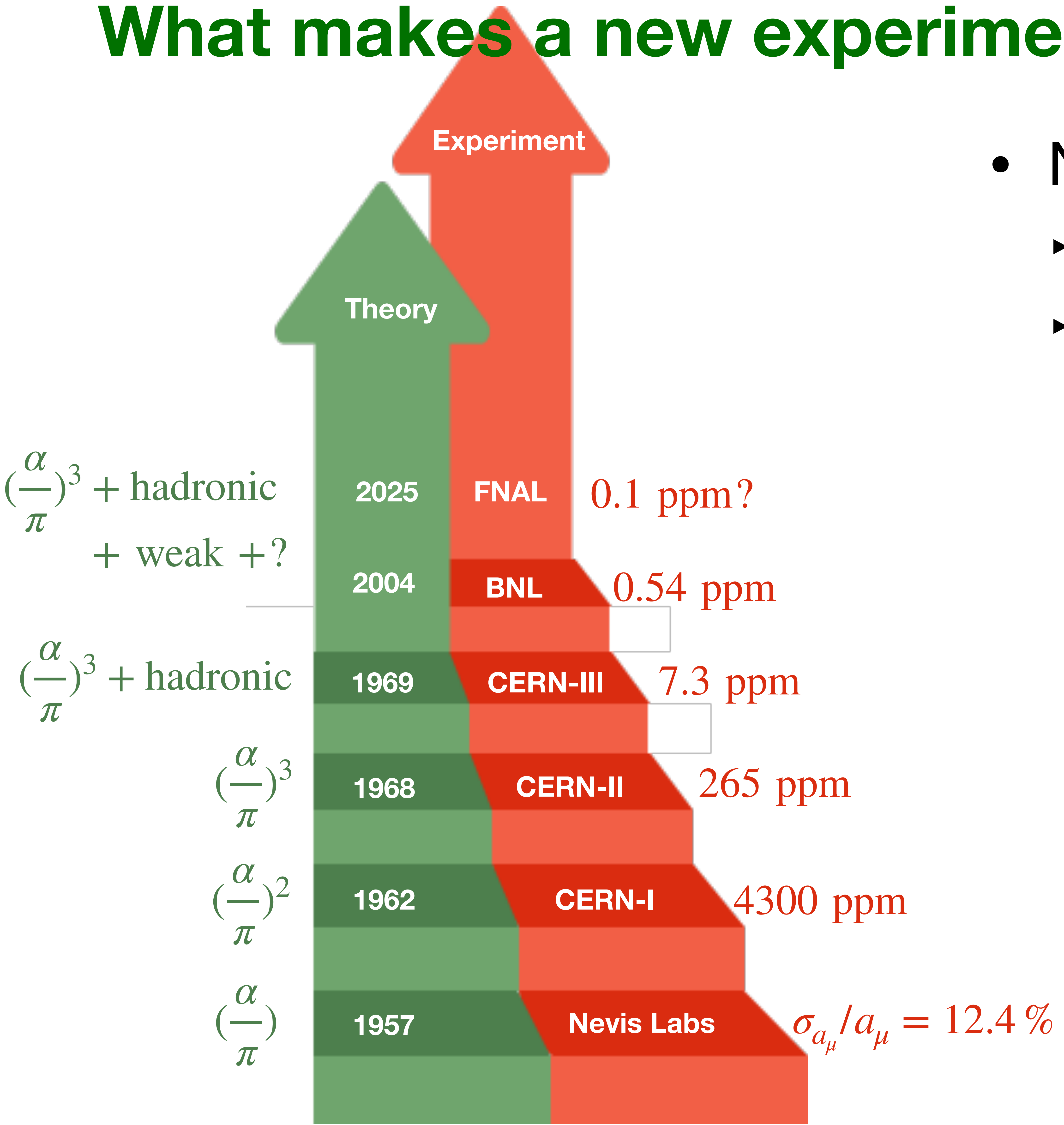
So we can worry less about the electric field (but still will need corrections)

Had a_μ been, say 100x smaller, would need *p* ~ 30 GeV/c

28

The need for a new experiment:

What makes a new experiment?



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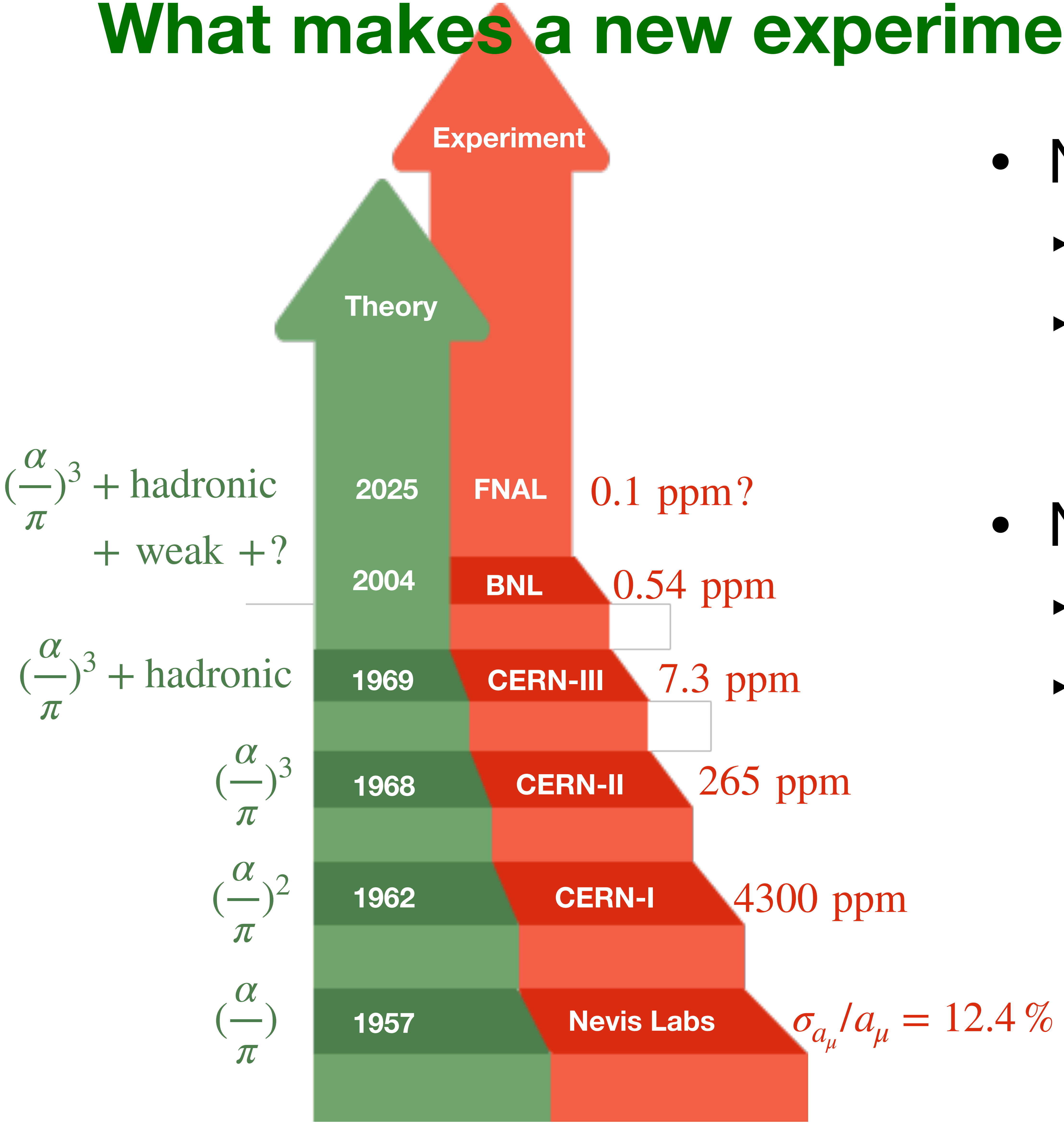

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  - Advanced detectors (tracker, laser, …)
  - RF field

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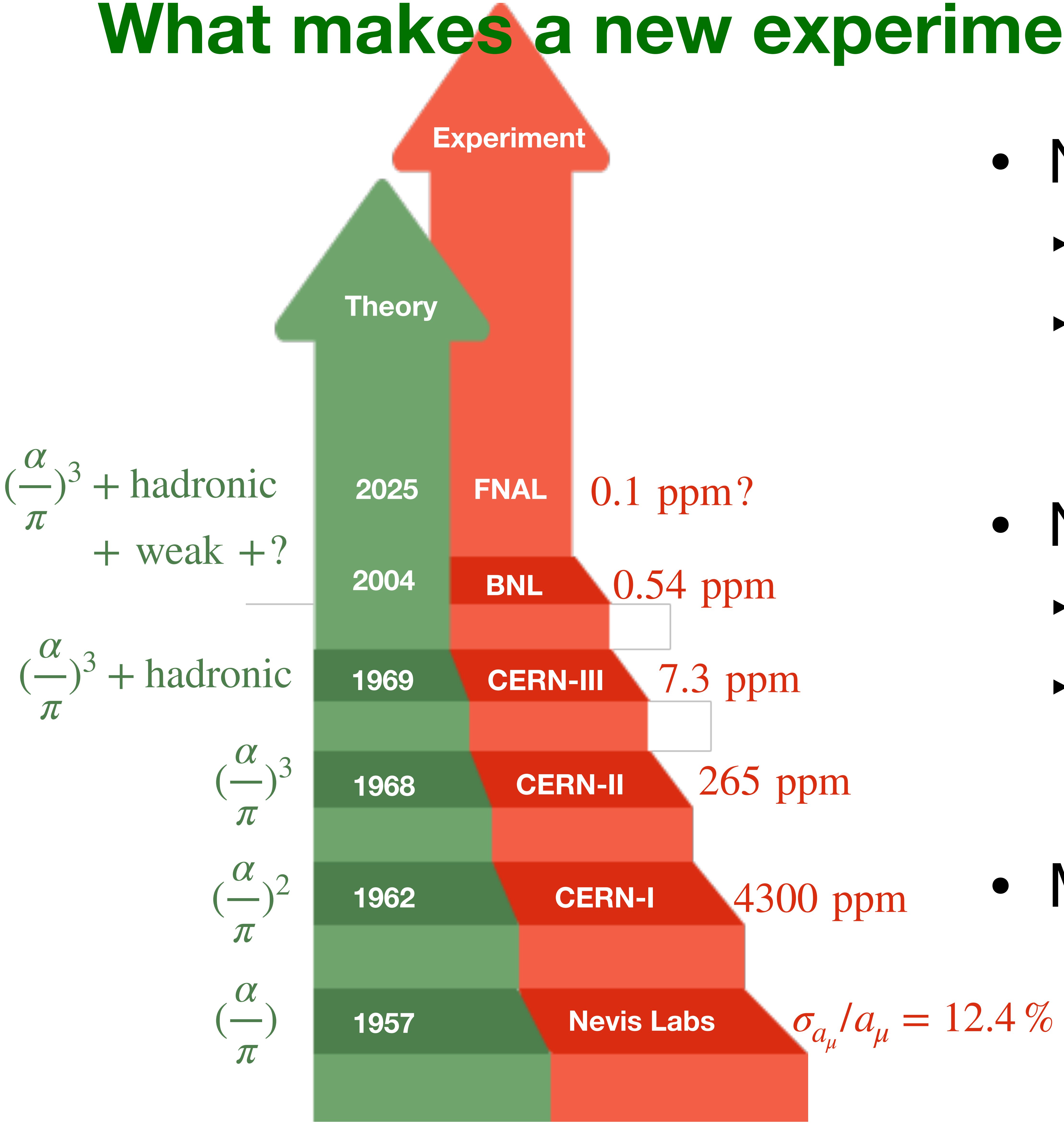

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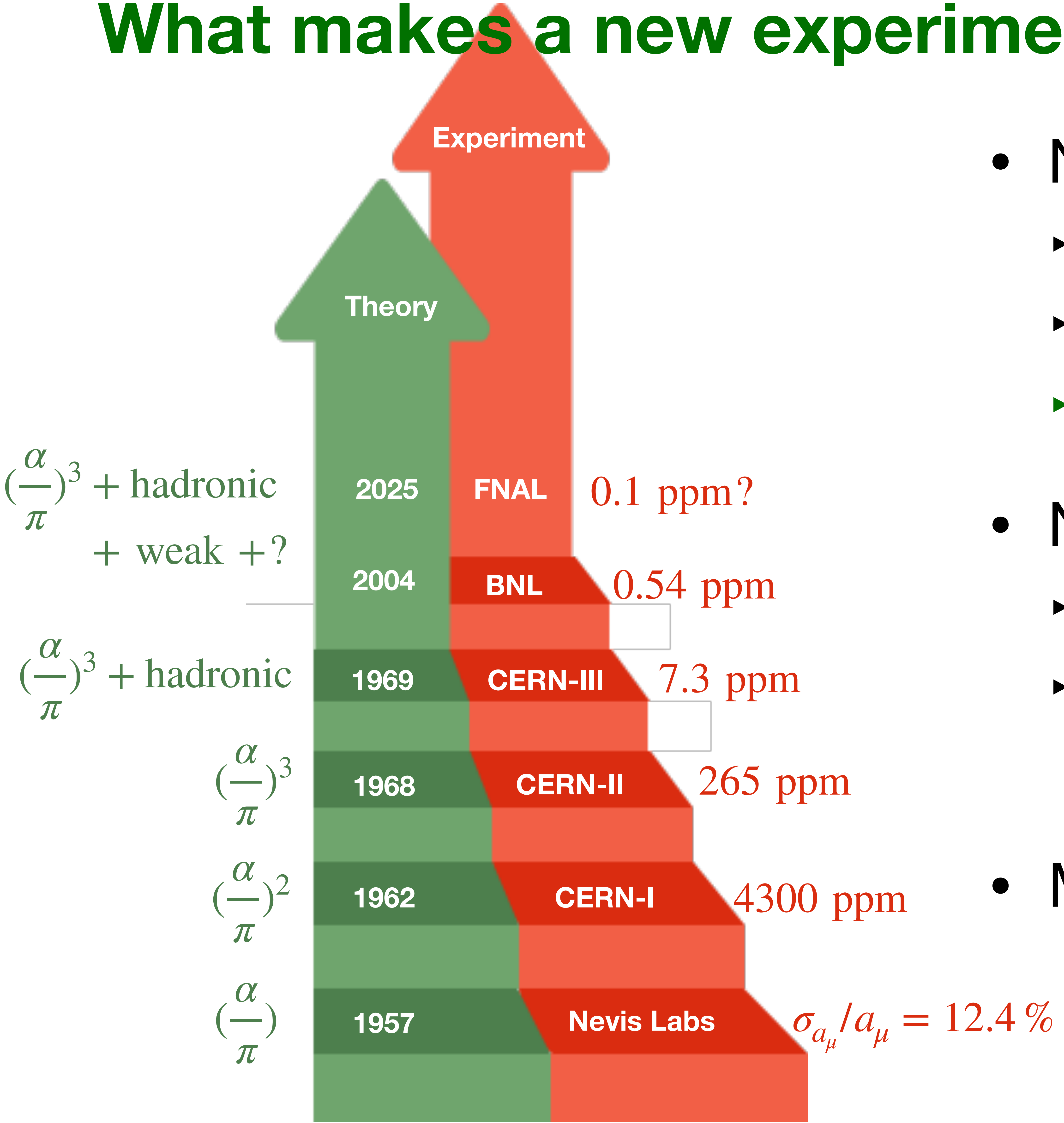

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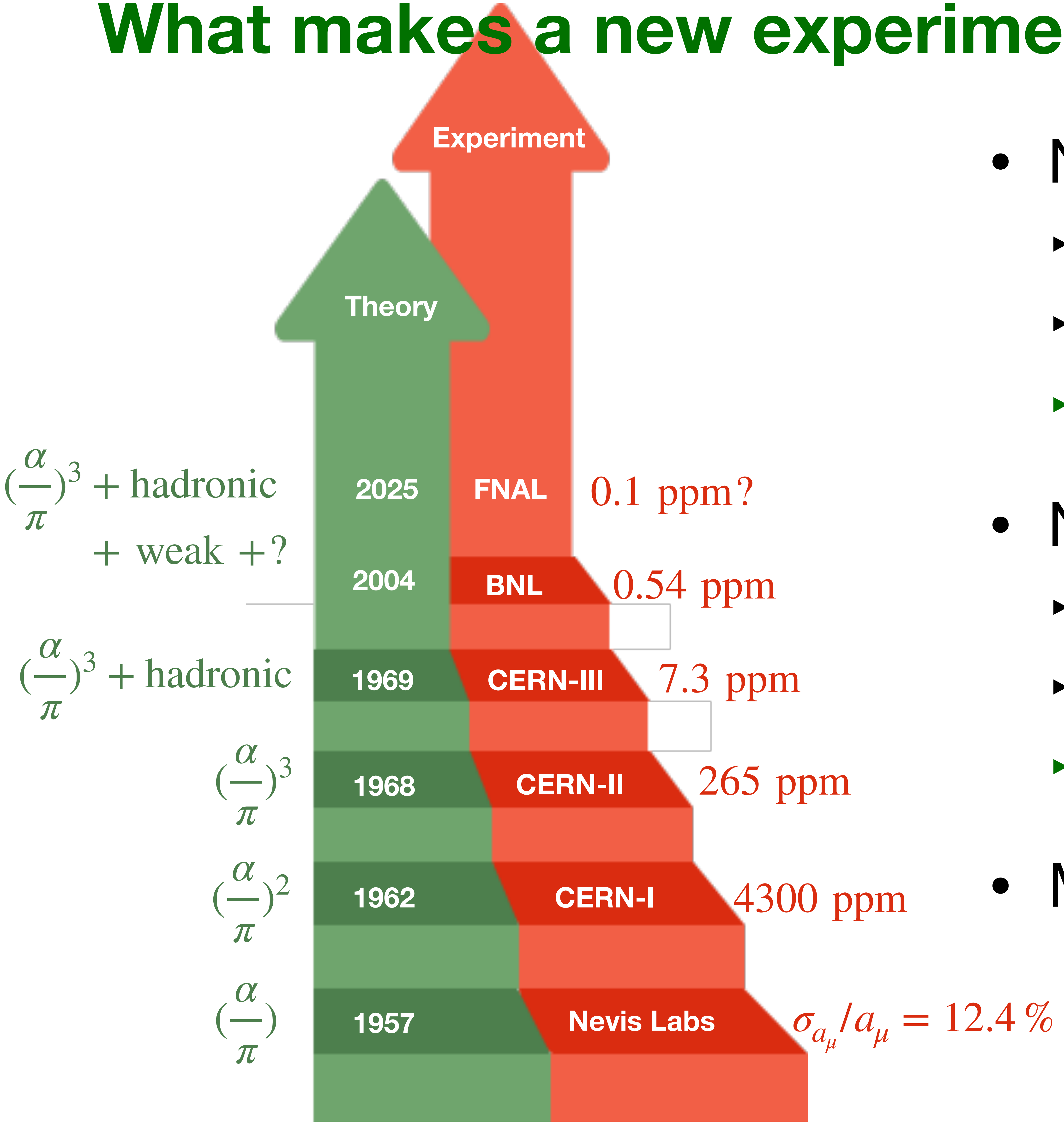

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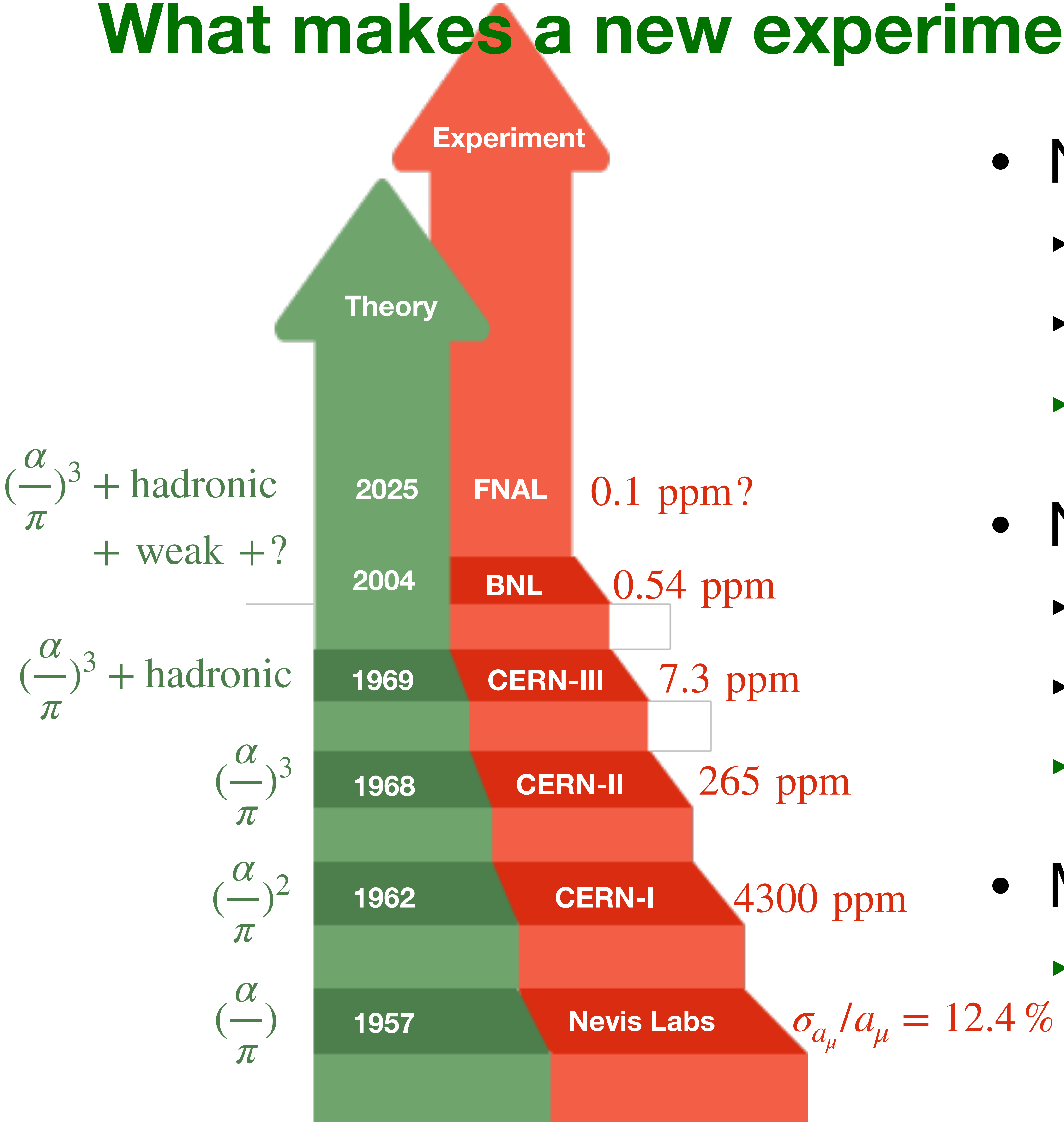

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  - J-PARC: Muon acceleration, 3D spiral injection, …
- More muons increasing the statistics!
  - J-PARC has the highest intensity pulsed muon beam

J-PARC Muon $g-2$/EDM experiment (E34)

Muon cooling

- Surface muon (3.4 MeV, large emittance)

➜ thermal muon (0.2 eV, low emittance)

Muon LINAC

- Muon acceleration to 212 MeV

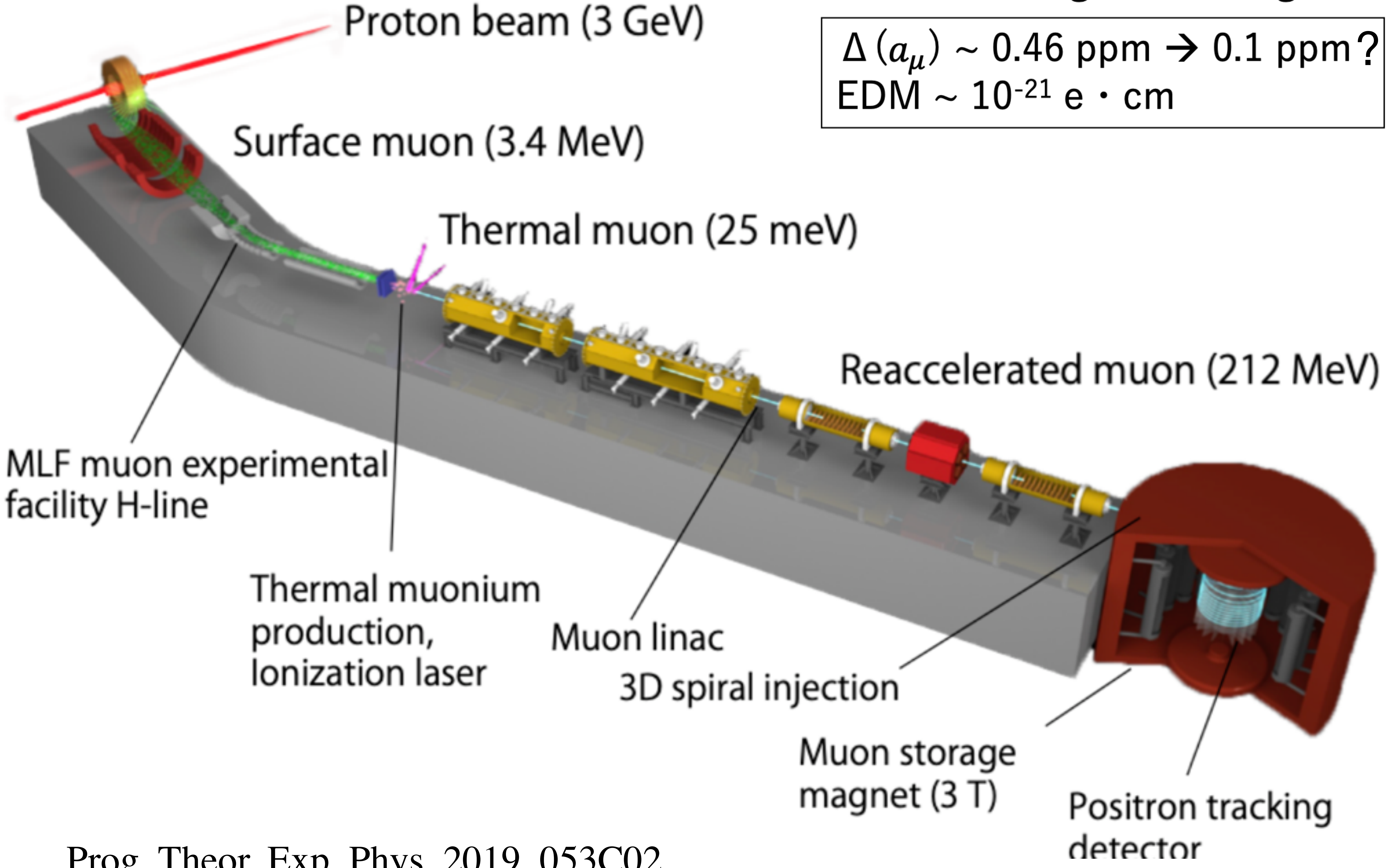
3D spiral injection

- Large kick angle within a few ns
- Good injection efficiency

Storage ring

- Compact storage ring
- Tracking detector

	Initial goal	Final goal
$\Delta(a_\mu)$ ~	0.46 ppm →	0.1 ppm?
EDM ~	10^{-21} e・cm	



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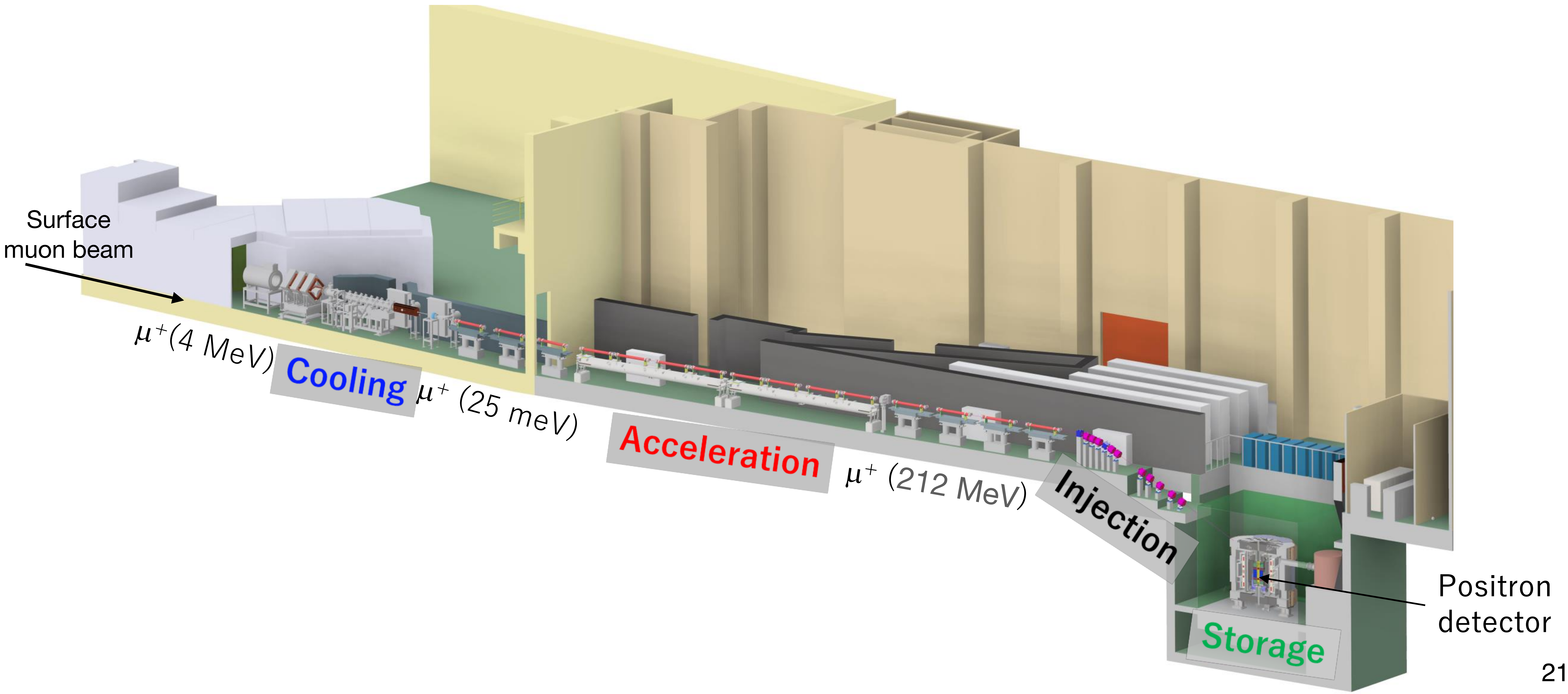
J-PARC Muon $g-2$/EDM experiment (E34)



J-PARC

Japan Proton Accelerator Research Complex

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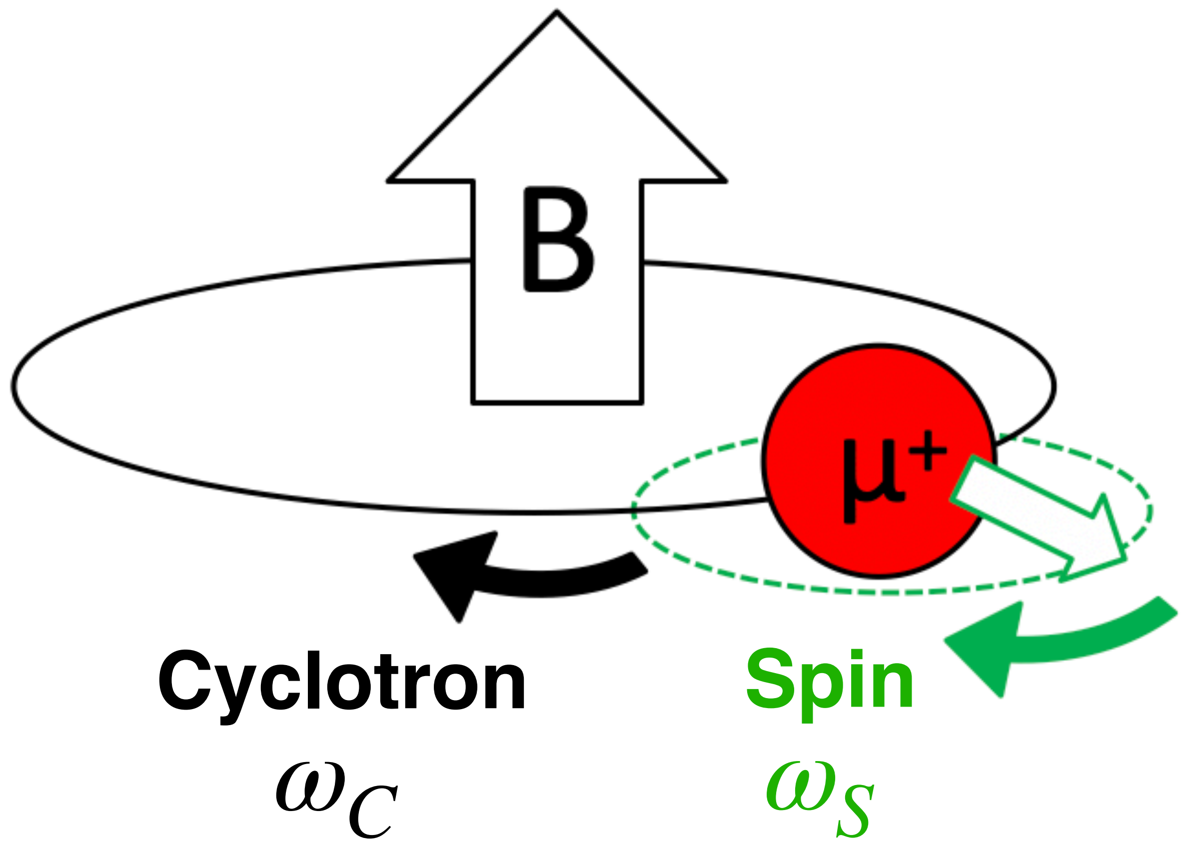
Muon Beam (H-line as of Dec 2023)

Measurement Principle

Muon Precession in the Magnetic Field



$$\vec{\omega} = \vec{\omega_S} - \vec{\omega_C}$$

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

$g-2$ **terms**

EDM term

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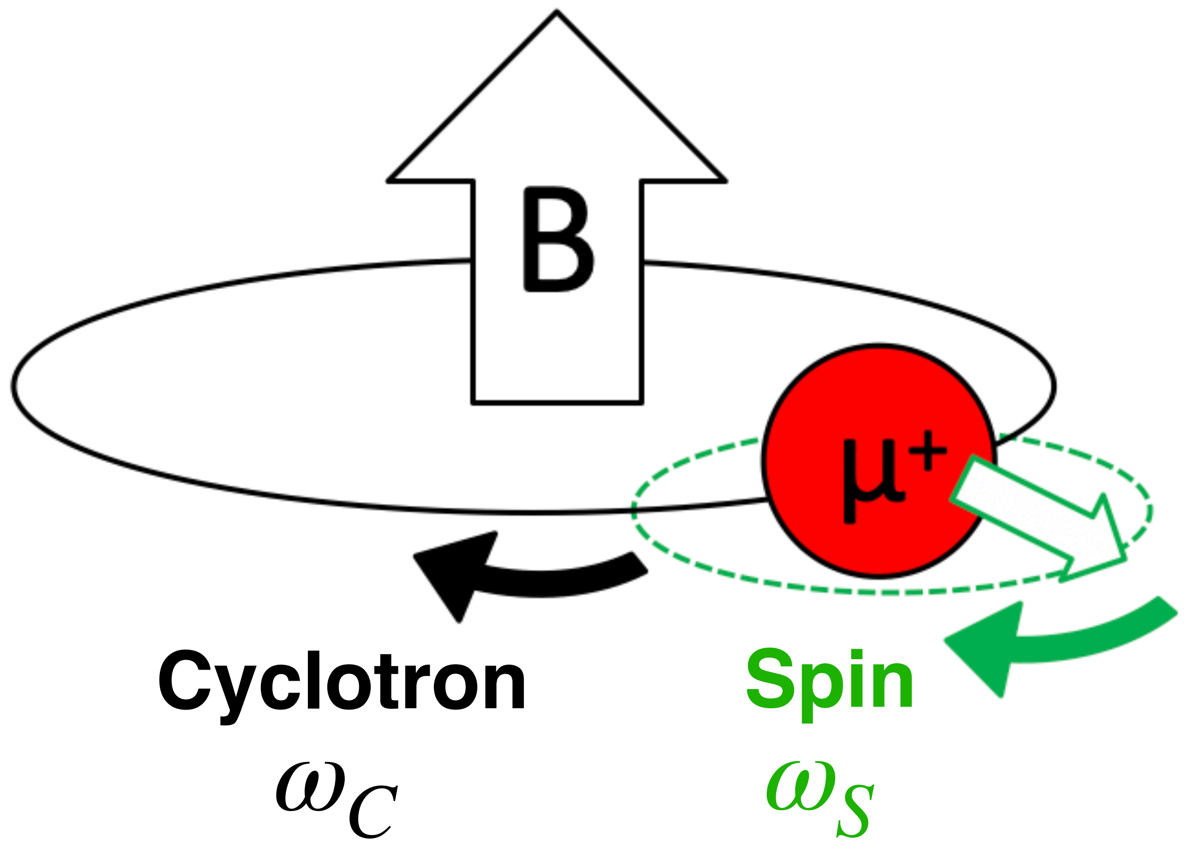

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Magic "γ": $a_\mu = \frac{1}{\gamma^2 - 1}$

BNL E821 approach

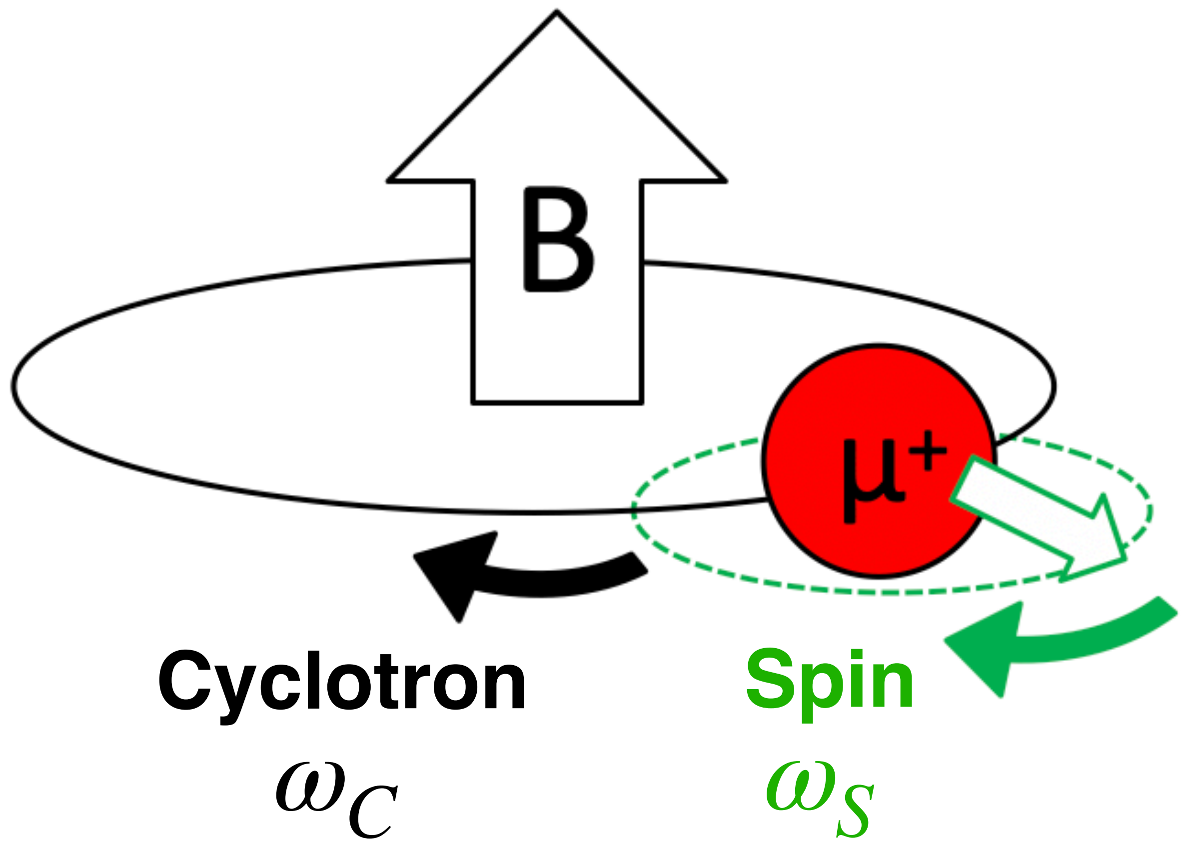
γ=30 (P=3 GeV/c)

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

FNAL E989

Measurement Principle

Muon Precession in the Magnetic Field



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Directly let E = 0

BNL E821 approach
$\gamma=30$ (P=3 GeV/c)

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

FNAL E989

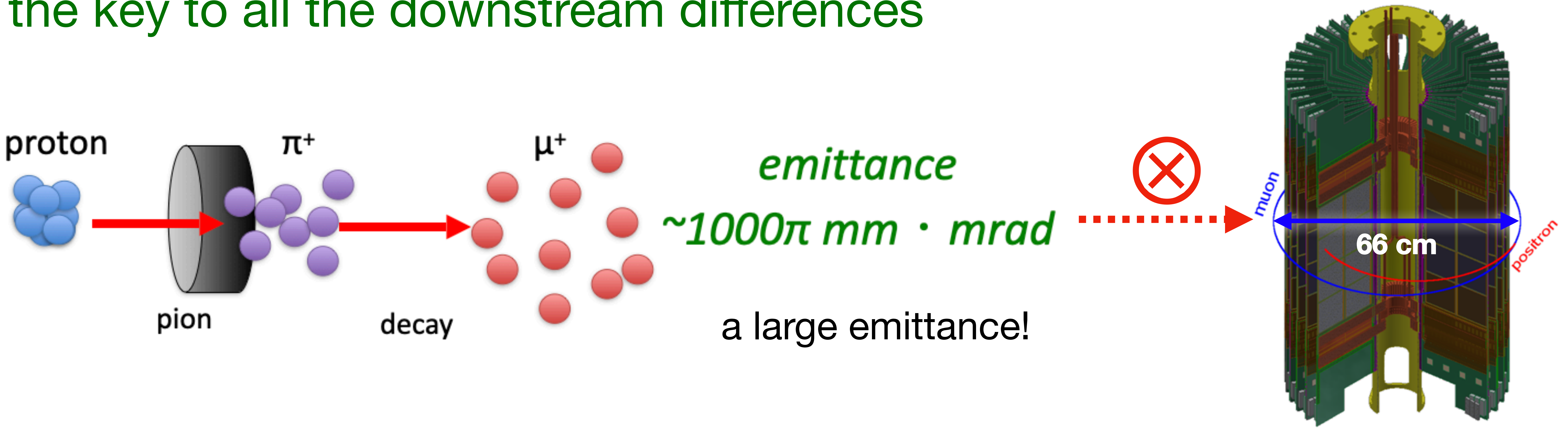
J-PARC approach
E = 0 at any γ

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

J-PARC E34

Muon cooling

the key to all the downstream differences



- The traditional muon beam can not be well-focused without an electric field;

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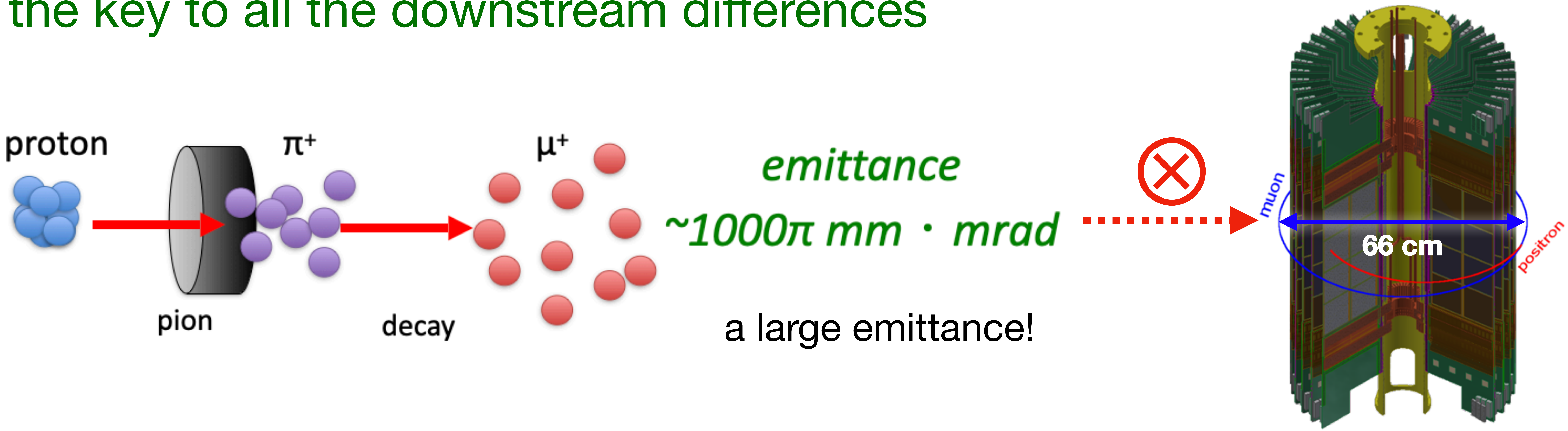

- The traditional muon beam can not be well-focused without an electric field;
- The muon must be compact and non-divergent;
- Typically with a RMS of ~mm → never achieved before.

Muon cooling

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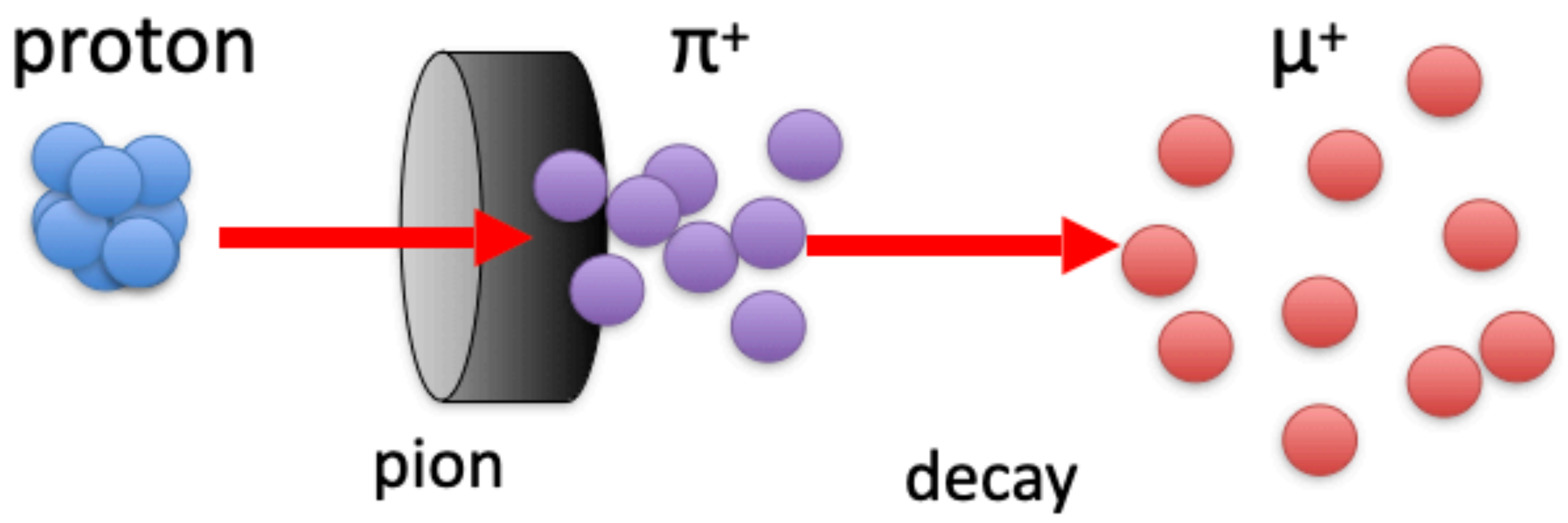
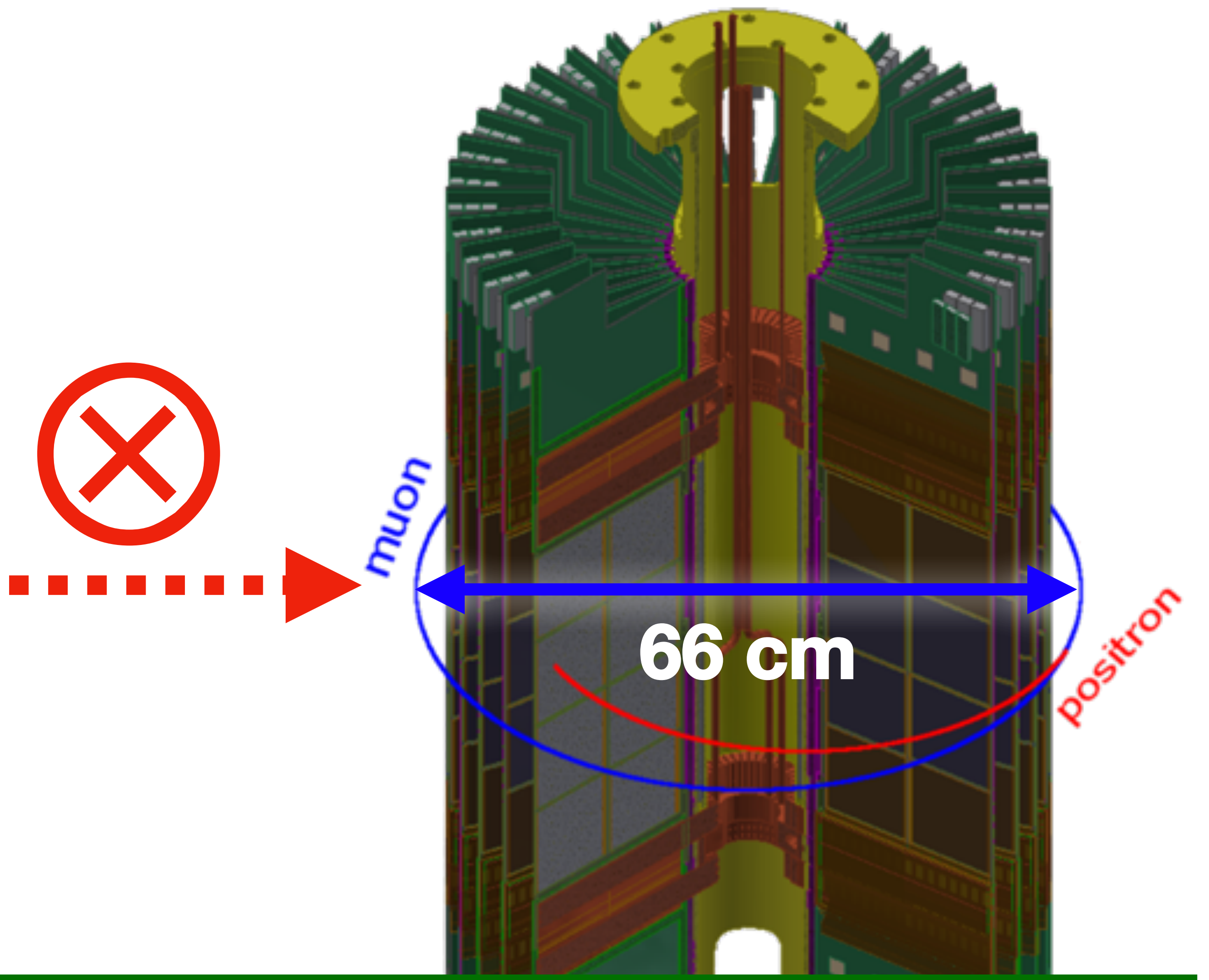


emittance

~1000π mm・mrad



	Fermilab Muon g-2	J-PARC Muon g-2/EDM
Muon momentum	3.09 GeV/c	300 MeV/c
Storage Field	B = 1.45 T	B = 3 T (Solenoidal)
Cyclotron period	149 ns	7.4 ns
Muon orbit diameter	14 m	66 cm
Focusing field	Electric quadrupole	E = 0, very weak magnetic

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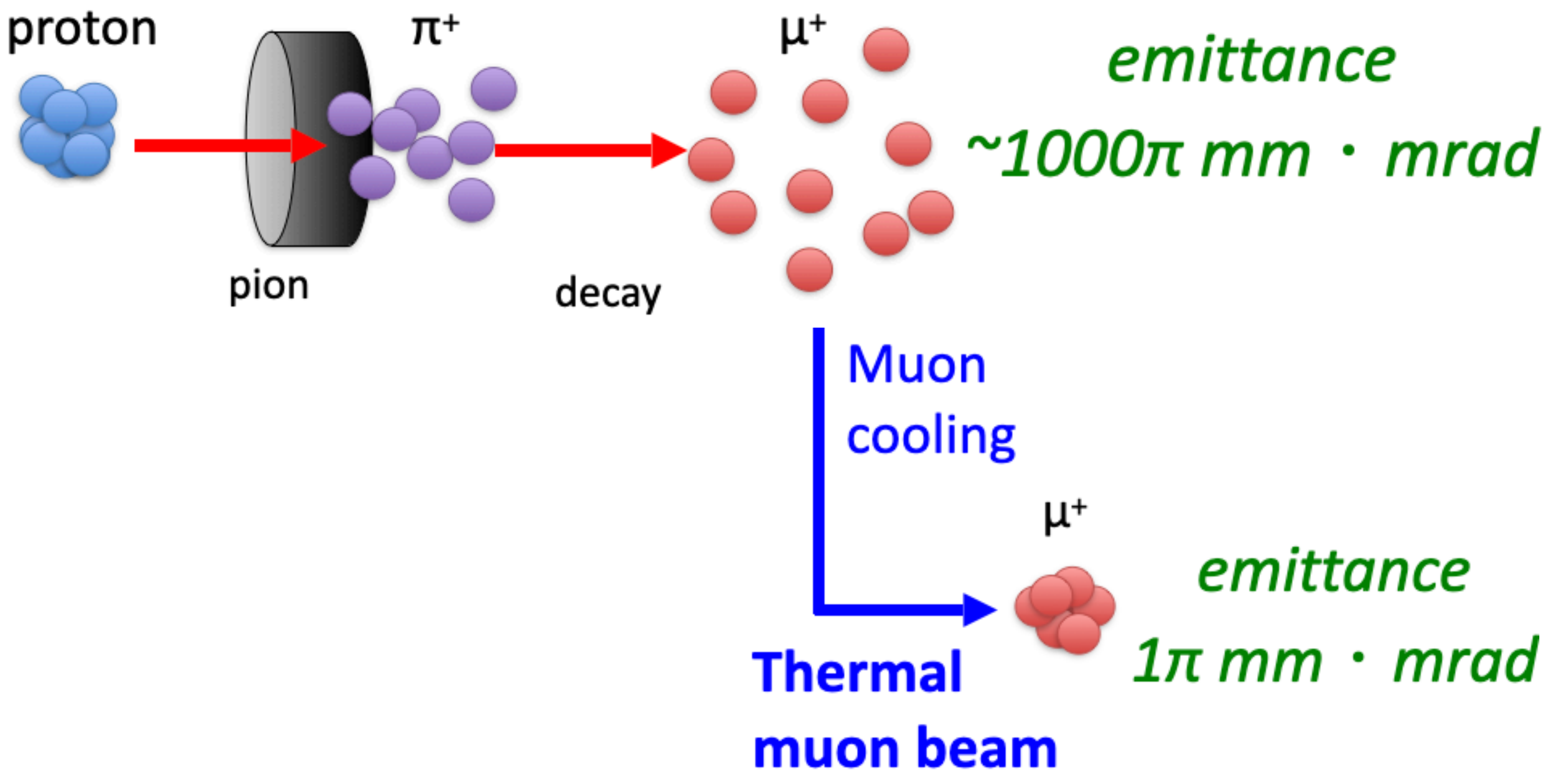

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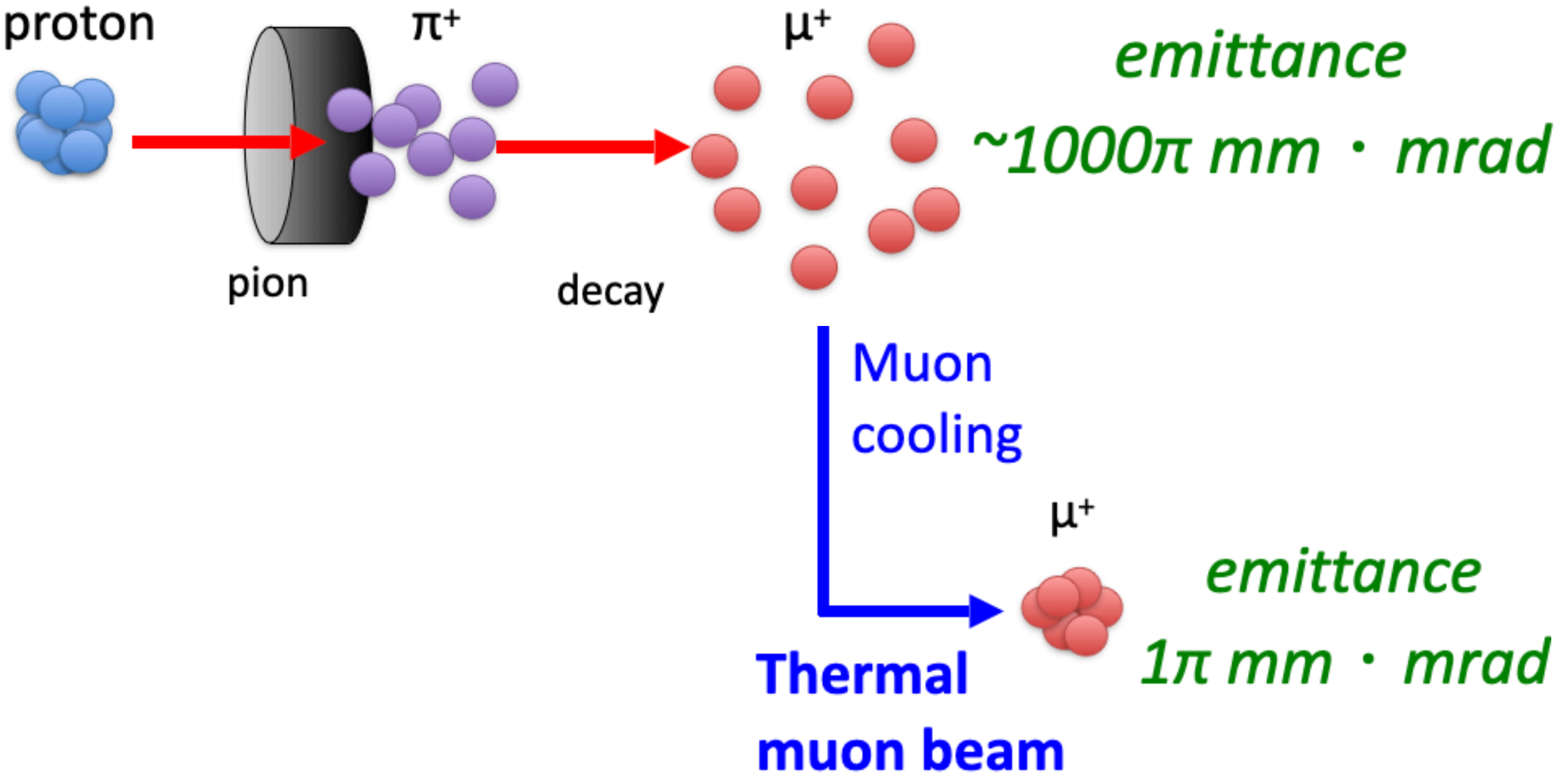
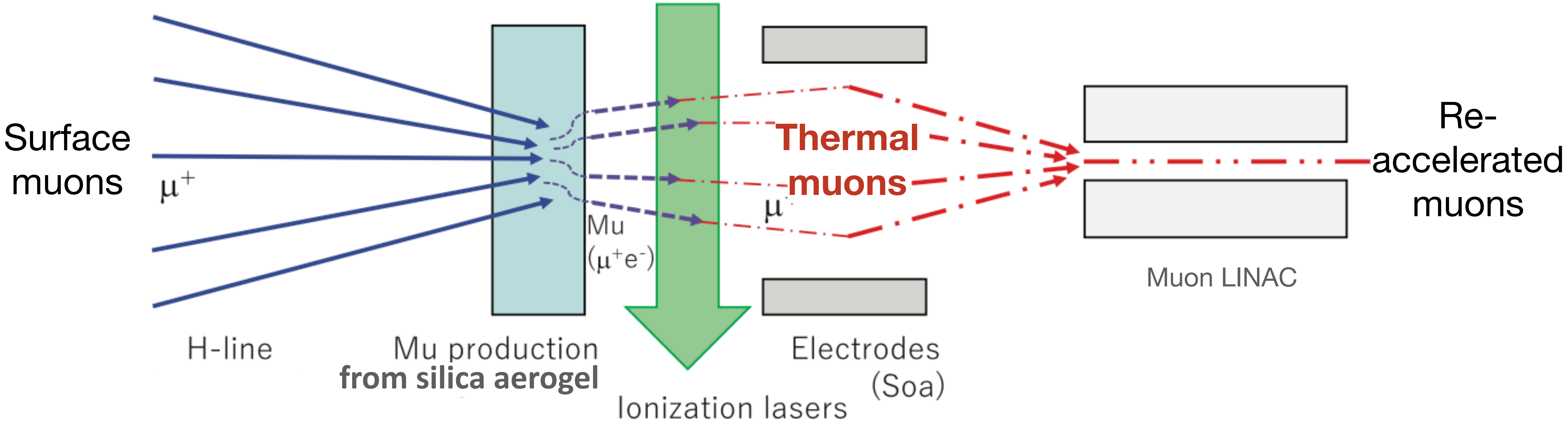


Thermal Muon Source

- Surface muon cooling by laser ionization of muonium (Mu) to thermal muon

Surface muons ⟶ **Thermal muons** ⟶ Re-accelerated muons



Key issues in the thermal muon source

- The thermal muon per injecting surface muon is low (10^{-3}).
- What has been achieved now (10^{-5}) is even lower
- Muonium production and laser efficiency are two key weak points

Table 4. Breakdown of estimated efficiency.

Subsystem	Efficiency	Subsystem	Efficiency
H-line acceptance and transmission	0.16	DAW decay	0.96
Mu emission	0.0034	DLS transmission	1.00
Laser ionization	0.73	DLS decay	0.99
Metal mesh	0.78	Injection transmission	0.85
Initial acceleration transmission and decay	0.72	Injection decay	0.99
RFQ transmission	0.95	Kicker decay	0.93
RFQ decay	0.81	e^+ energy window	0.12
IH transmission	0.99	Detector acceptance of e^+	1.00
IH decay	0.99	Reconstruction efficiency	0.90
DAW transmission	1.00		

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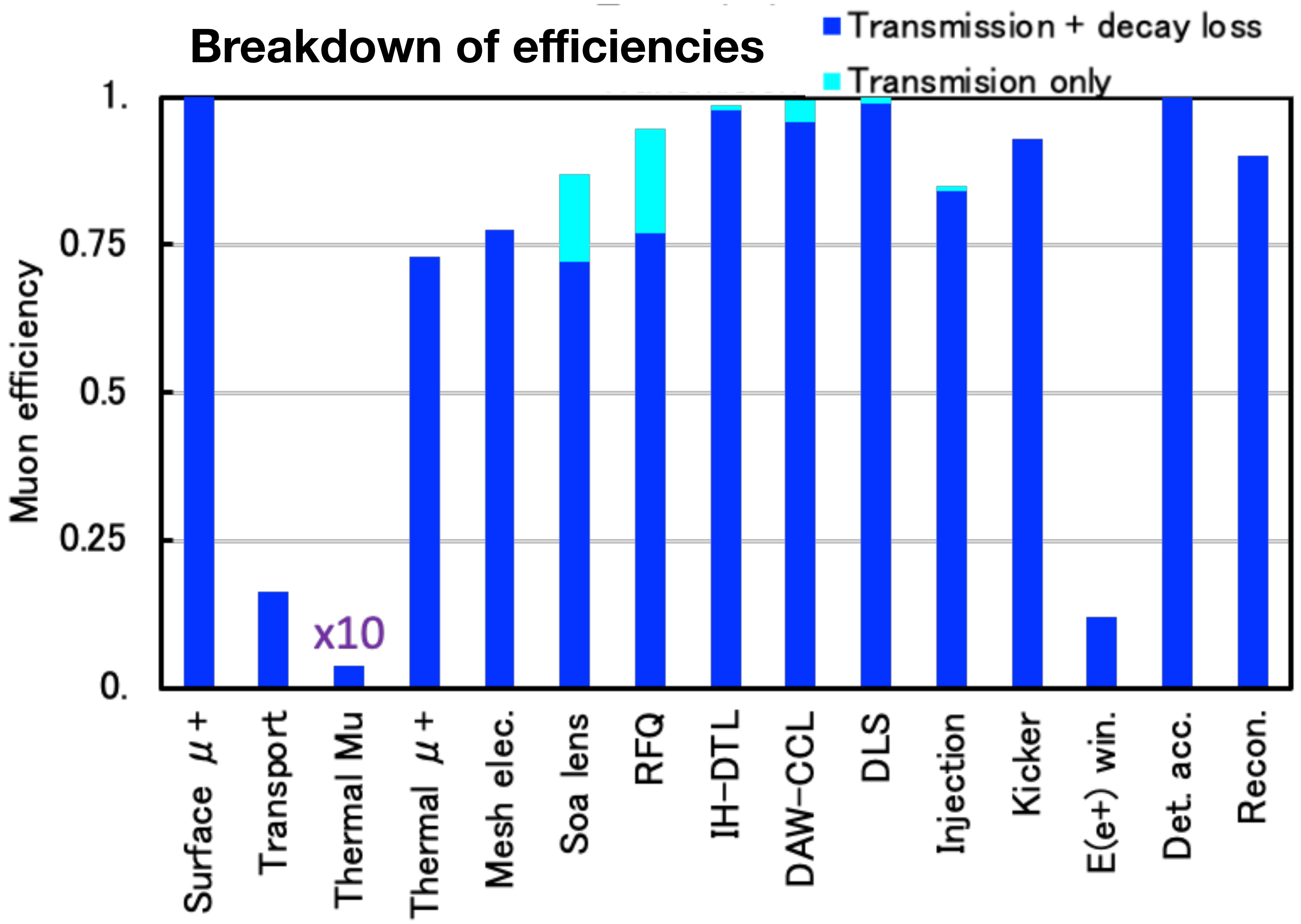

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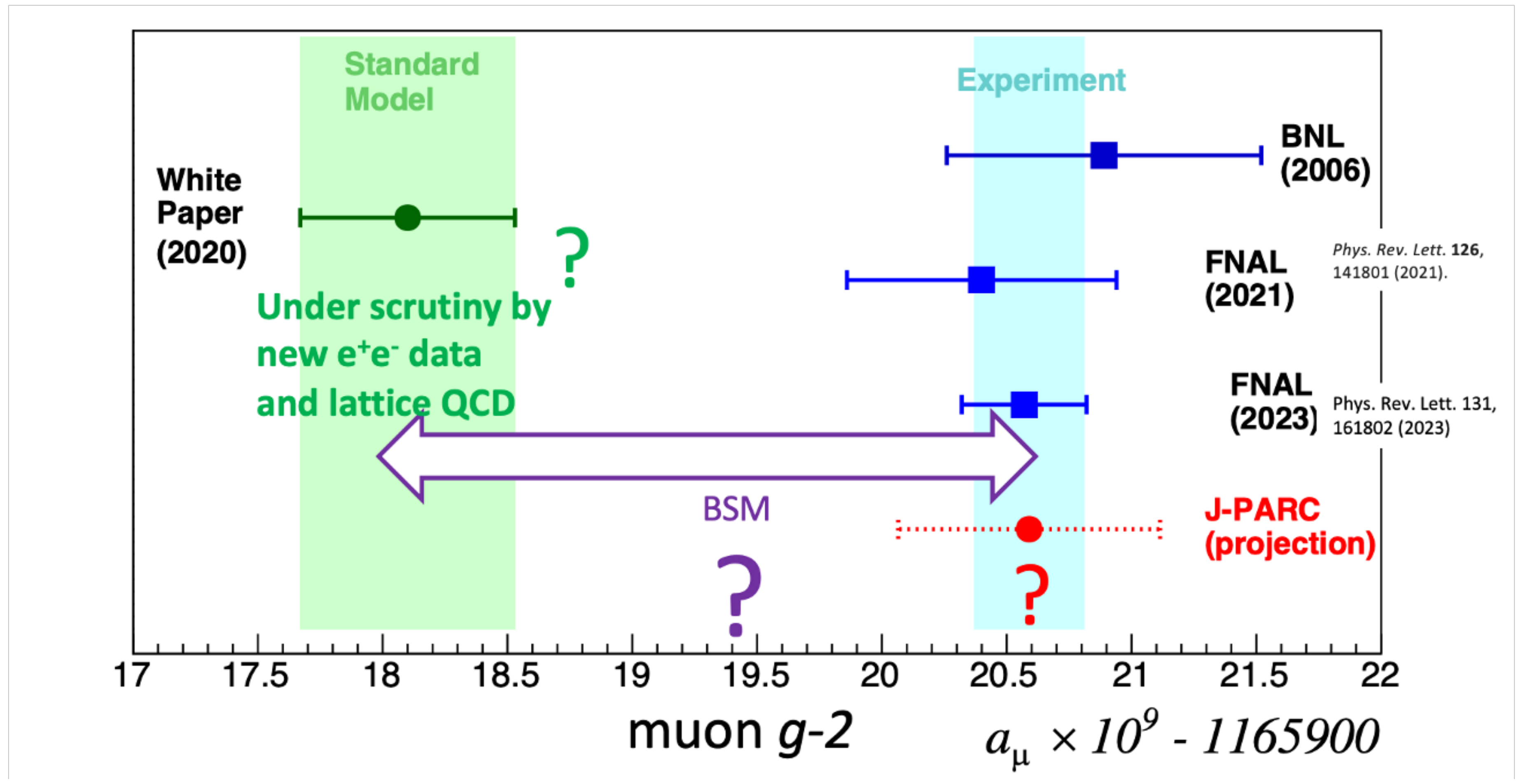
Steps	Efficiency	Intensity [Hz]	E34 TDR intensity [Hz]
Surface muon transport		1.8×10^{6}	3.2×10^{8}
Muon stopping in the aerogel	0.467	8.4×10^{5}	1.35×10^{8}
Muonium formation	0.52	4.3×10^{5}	7.01×10^{7}
Muonium vacuum yield	0.082	3.5×10^{4}	7.21×10^{6}
Laser ionization	1.0×10^{-5}	0.19 (244 nm, 1.5 mJ)	8.24×10^{5} (122 nm, 100 uJ)
Slow muon beam-line transport	0.651	0.12	-
Rate at MCP detector	0.90	0.1	-

Expected Sensitivity

- A TDR muon rate **$3.2\times10^{8}\mu$/sec** at the entrance at 1 MW proton power.
- The expected intensity of stored muon is **1.3×10^{5} μ/sec.** Cumulative efficiency from thermal muon generation to reconstructed positron is 4.0×10^{-4}.
- **2-years data taking** (2×10^{7} seconds, ~230 days) will give a total positron **5.7×10^{11}**, achieving the BNL precision of **0.45 ppm** on a_μ.

Table 5. Summary of statistics and uncertainties.

	Estimation
Total number of muons in the storage magnet	5.2×10^{12}
Total number of reconstructed e^+ in the energy window [200, 275 MeV]	5.7×10^{11}
Effective analyzing power	0.42
Statistical uncertainty on ω_a [ppb]	450
Uncertainties on a_μ [ppb]	450 (stat.)
	$<$ 70 (syst.)
Uncertainties on EDM [10^{-21} e·cm]	1.5 (stat.)
	0.36 (syst.)



Expected Sensitivity

- Systematic uncertainties are estimated to be less than **70 ppb** - smaller than the statistical ones.

Table 6. Estimated systmatic uncertainties on a_μ.

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Diffential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

$\delta a_{\mu\ (syst.)} < 70$ ppb

→ this experiment is **statistically limited**

Expected Sensitivity

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.

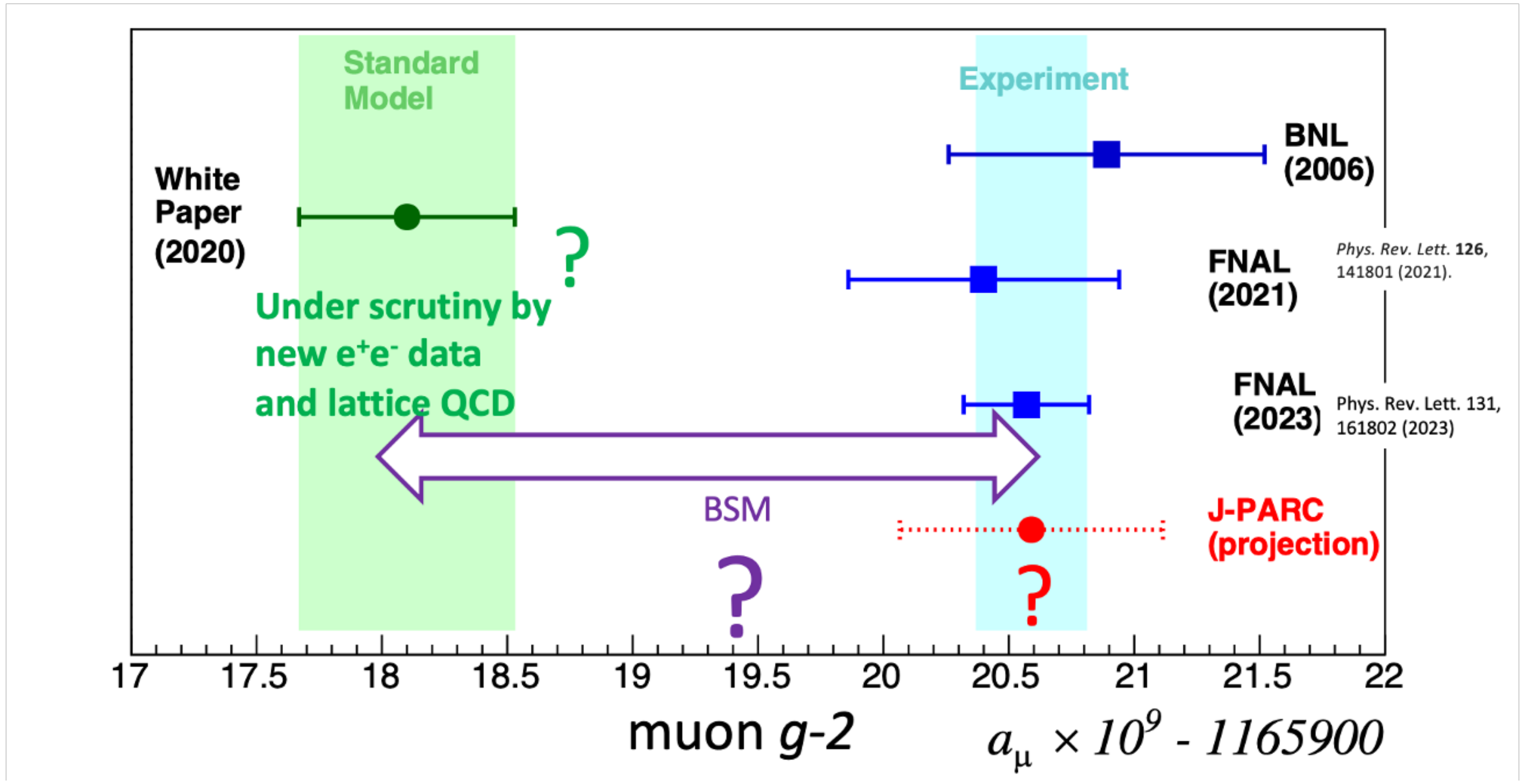
Quantity	Correction terms (ppb)	Uncertainty (ppb)		
ω_a^m (statistical)	⋯	434		
ω_a^m (systematic)	⋯	56	↦ <36	: Pileup, (gain, CBO)
C_e	~~489~~	53	↦ 10	: residual E-fields (no Quads)
C_p	~~180~~	13	↦ 13	: pitch correction
C_{ml}	~~−11~~	5	↦ 2	: differential decay & (muon losses)
C_{pa}	~~−158~~	75	↦ 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		

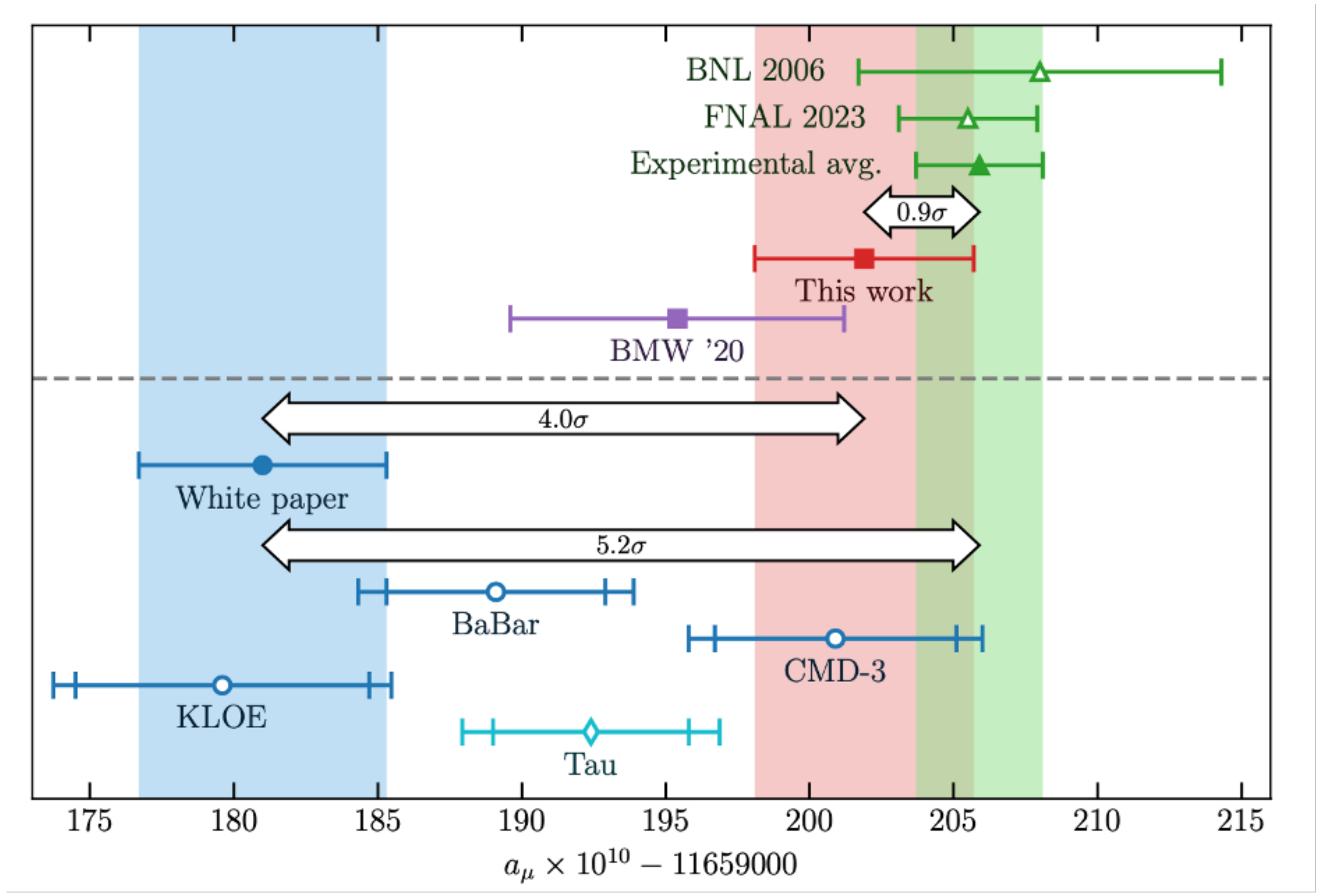
$\delta a_{\mu\,(\text{syst.})} < 70$ ppb

Abe *et al.*, DOI: 10.1093/ptep/ptz030 (2019)
Abi *et al.*, DOI: 10.1103/PhysRevLett.126.141801 (2021)

New ideas

are needed to increase the statistics!

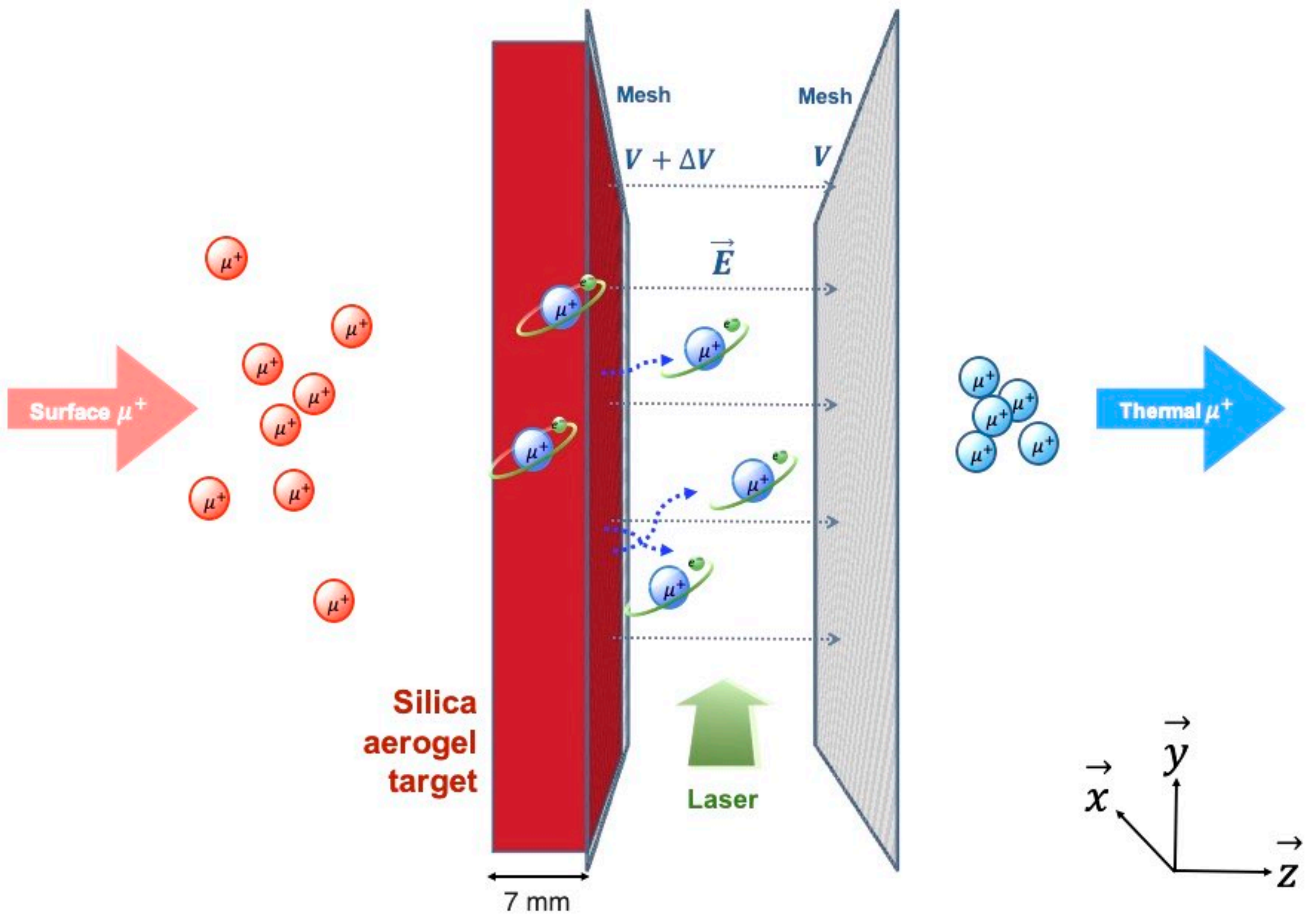


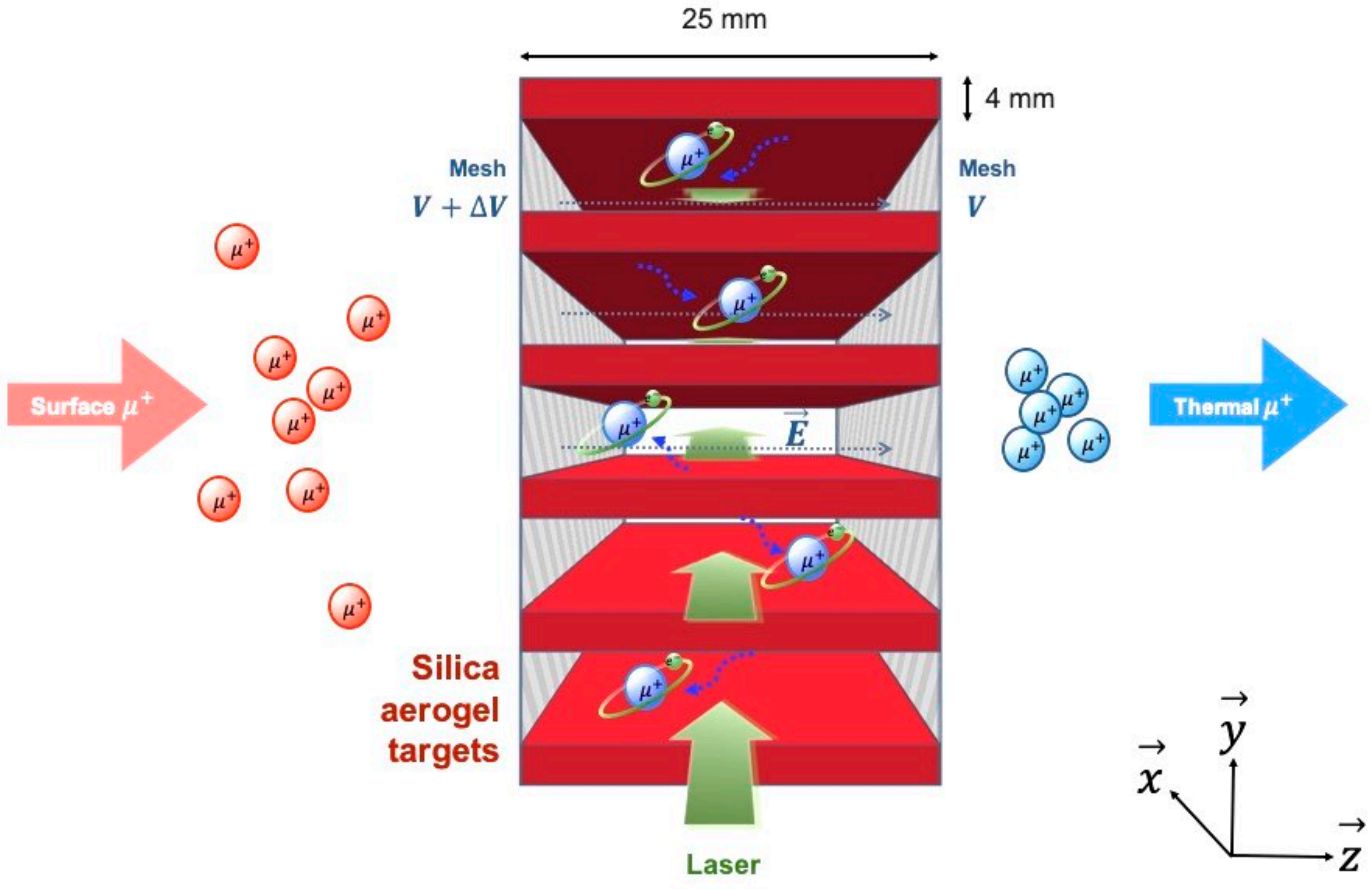


Otherwise, the J-PARC measurement may not be very useful.

New ideas

Multi-layer target for Muonium production





Current design (single-layer)

- **Low Mu emission efficiency (0.0034):**
  - Muon stopping (0.418)
  - Vacuum emission (0.060)
  - Laser spatial constraint (0.269)

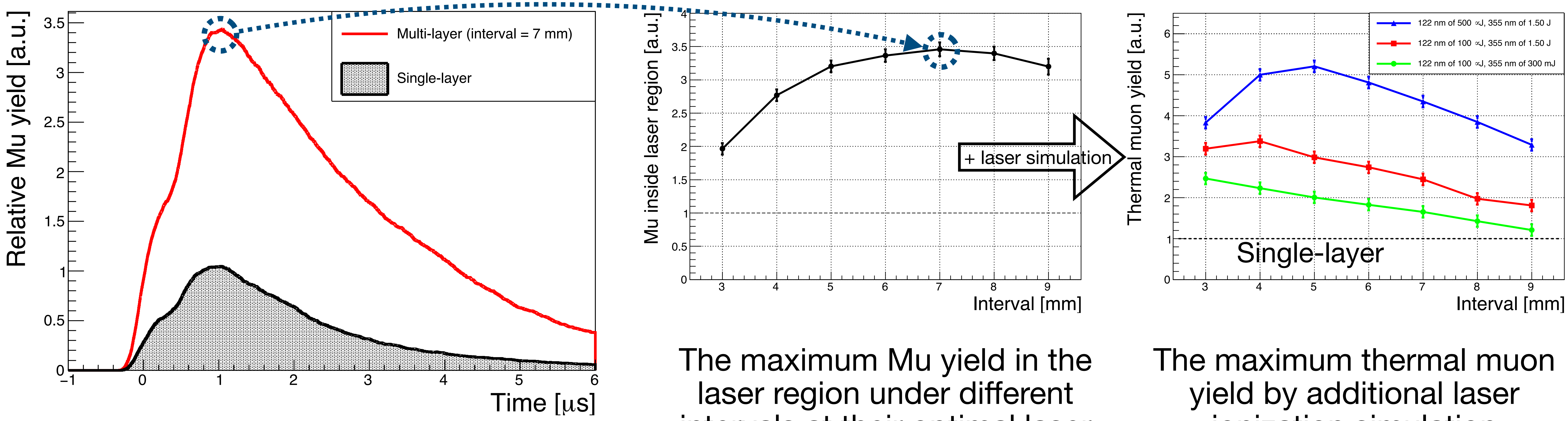
Novel multi-layer target design

- Multi-layer targets stop incident muon
- Mu emits from upper and lower surfaces
- Mu confined between targets

New ideas

Multi-layer target for Muonium production

- It gives about 3.5 times higher yield than our current design (single-layer)



The evolution of Mu into the laser ionization region

The maximum Mu yield in the laser region under different intervals at their optimal laser shooting time.

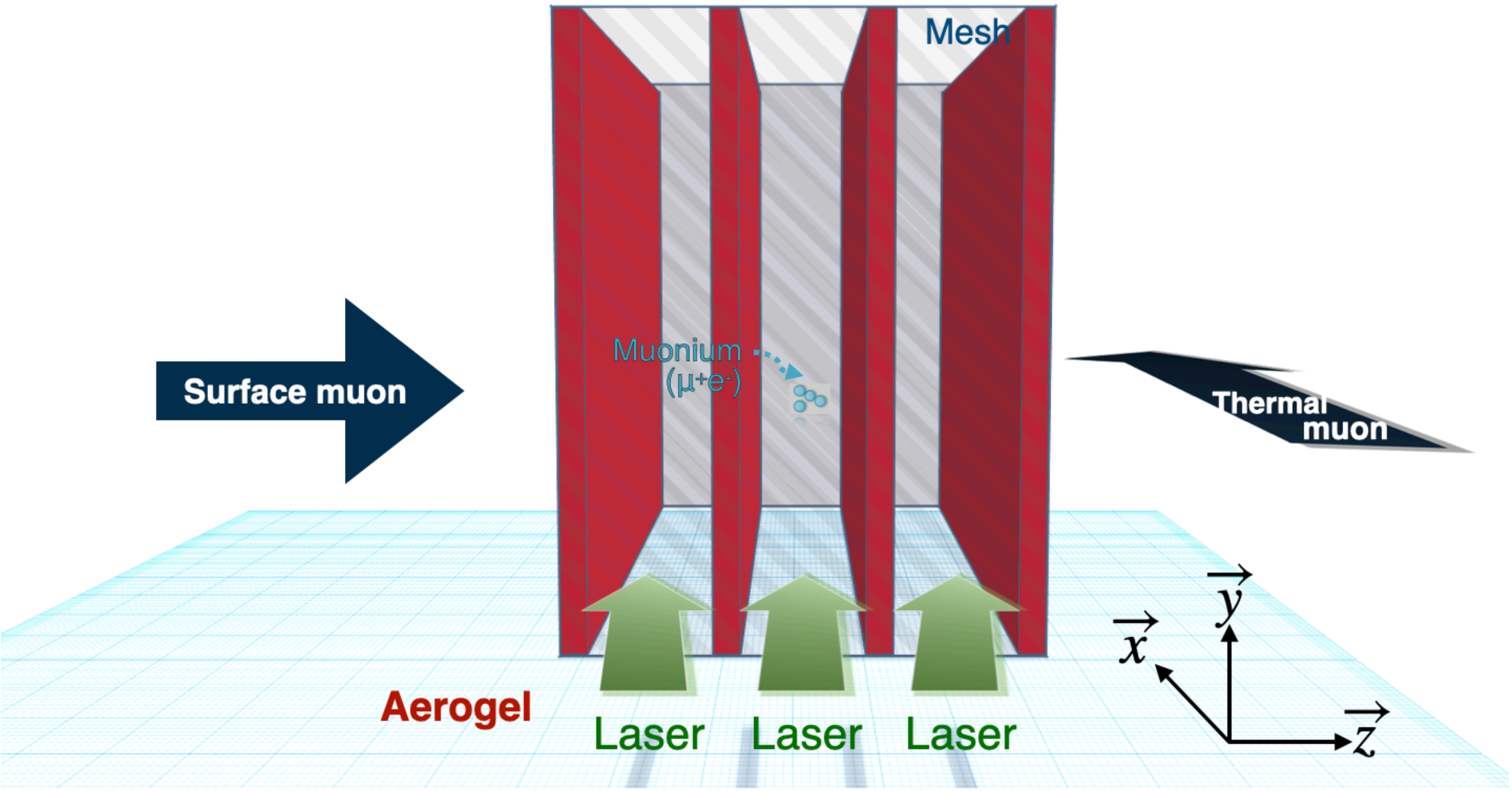
The maximum thermal muon yield by additional laser ionization simulation

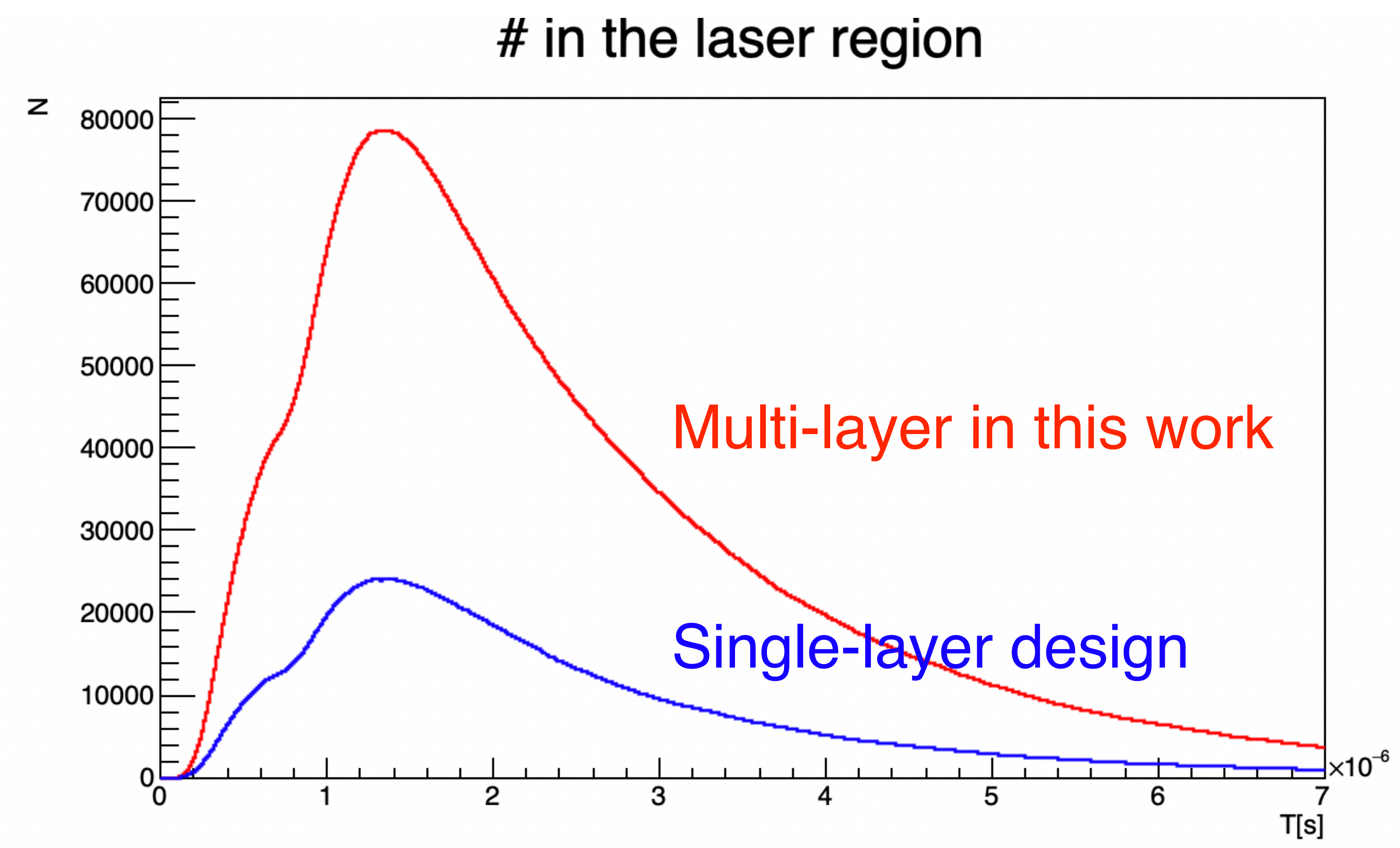
C. Zhang et al., NIMA. 1042, 167443 (2022).

New ideas

Multi-layer target for Muonium production

- Another version uses multi-layers facing the incident beam, resulting in a higher yield;
- The extraction is turned 90 degrees, making construction more challenging.





Simulation predicted even higher yields
(4 times if 4 layers → 8 times at max)

More new ideas

and potential collaboration in Liverpool

- Can we have more innovative ideas to enhance the muon statistics?

The statistical precision of the anomalous spin precession angular frequency ω_a is determined as

$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P} \sqrt{\frac{2}{NA^2}}$$

More new ideas

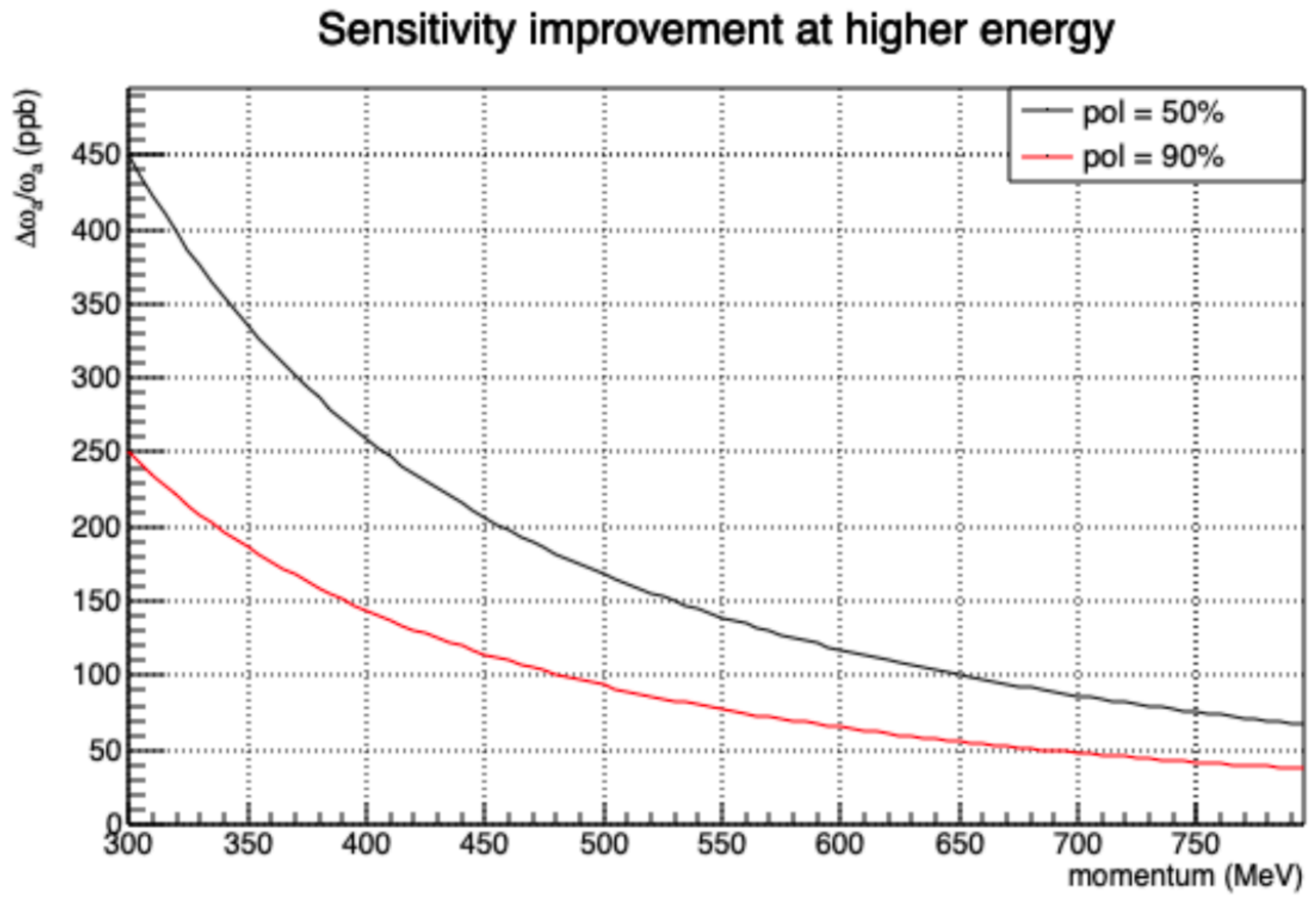
and potential collaboration in Liverpool

- Can we have more innovative ideas to enhance the muon statistics?

The statistical precision of the anomalous spin precession angular frequency ω_a is determined as

$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P}\sqrt{\frac{2}{NA^2}}$$

1. Higher momentum (γ):
   - Muon acceleration (300 MeV → 600 MeV)
   - with a higher B field (3T → 6T)
2. Improve the polarization (P): 50% → 75%+?



- For more details, see the next talk by Graziano.

Summary

- Muon g-2 is a precision battle between experiments and theory.
- Muon g-2 experiments are a battle between stat and syst uncertainties.

Summary

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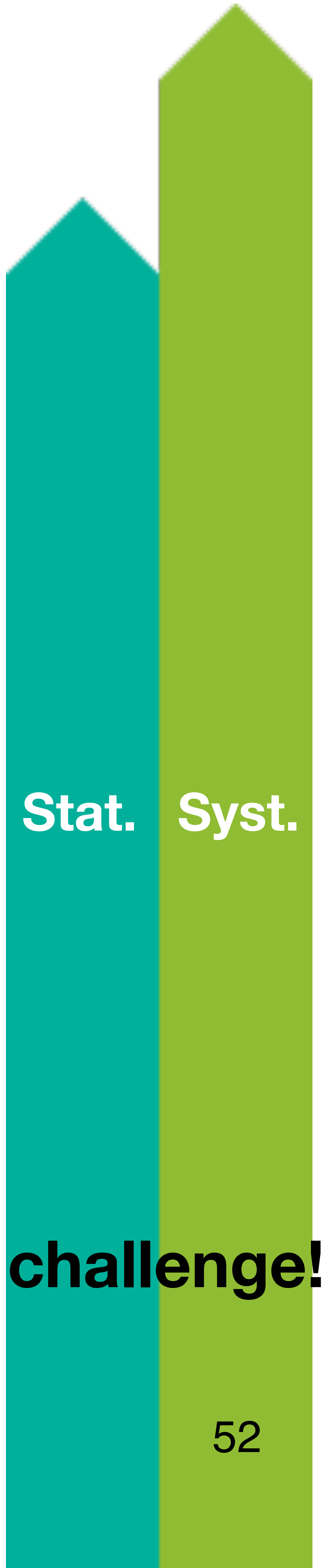
- Fermilab Muon g-2 is over:
    - The storage ring method has reached its systematic limit;
    - Not very useful to continue collecting data to increase statistics.

Summary

- Muon g-2 is a precision battle between experiments and theory.
- Muon g-2 experiments are a battle between stat and syst uncertainties.
- Fermilab Muon g-2 is over:
  - The storage ring method has reached its systematic limit;
  - Not very useful to continue collecting data to increase statistics.
- J-PARC Muon g-2 holds great potential:
  - New technologies offer very low systematic uncertainties;
  - It currently suffers from **low statistics: new ideas are needed to address this challenge!**



Backup

The CERN muon g-2 experiments (1960-1979)

F. Farley, E. Picasso The Muon (g–2) Experiments at CERN
Ann. Rev. Nucl. Part. Sci. 29 (1979) 243-282

The history of the muon $(g-2)$ experiments

B. Lee Roberts* SciPost Phys. Proc. 1, 032 (2019)

Review

The 47 years of muon $g-2$

F.J.M. Farley[a,*], Y.K. Semertzidis[b]

[a]Yale University, New Haven, CT 06520, USA
[b]Brookhaven National Laboratory, Upton, NY 11973, USA

Received 30 October 2003

Fig. 10. The first experimental magnet in which muons were stored at CERN for up to 30 turns. Left to right: Georges Charpak, Francis Farley, Bruno Nicolai, Hans Sens, Antonio Zichichi, Carl York and Richard Garwin.

They measure a_μ since the measure the spin relative to the momentum

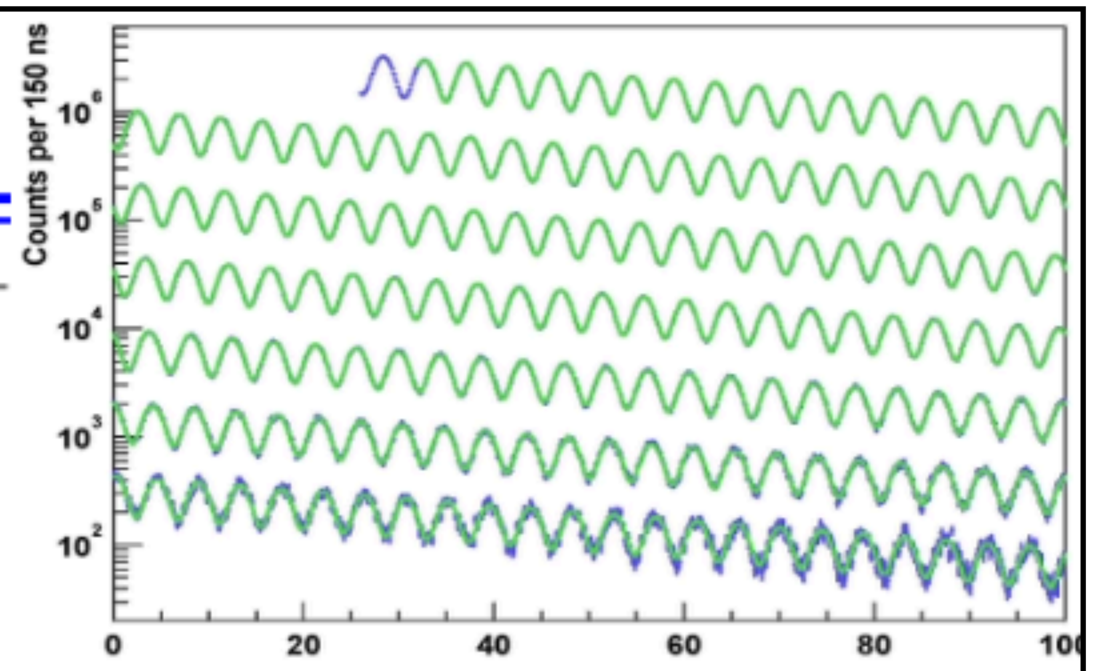
$$\vec{\omega}_a = \omega_S - \omega_C = -\frac{Qe}{m} a_\mu \vec{B}$$

$a_\mu = (g_\mu - 2)/2 \sim g_\mu/1000$

23

E821, 1984-2001

$3.6 \times 10^9\ e^-$



(2006)

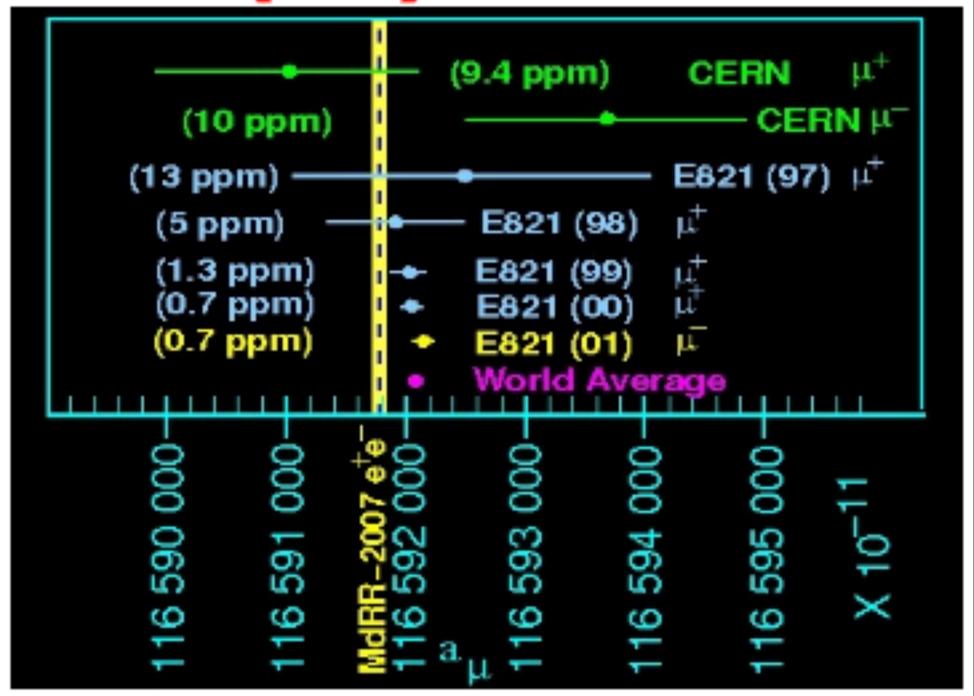
$a_\mu(\text{expt}) = 0.00116592089(63)$ **(0.54 ppm)**

$a_\mu(\text{theory}) = 0.00116591820(73)$

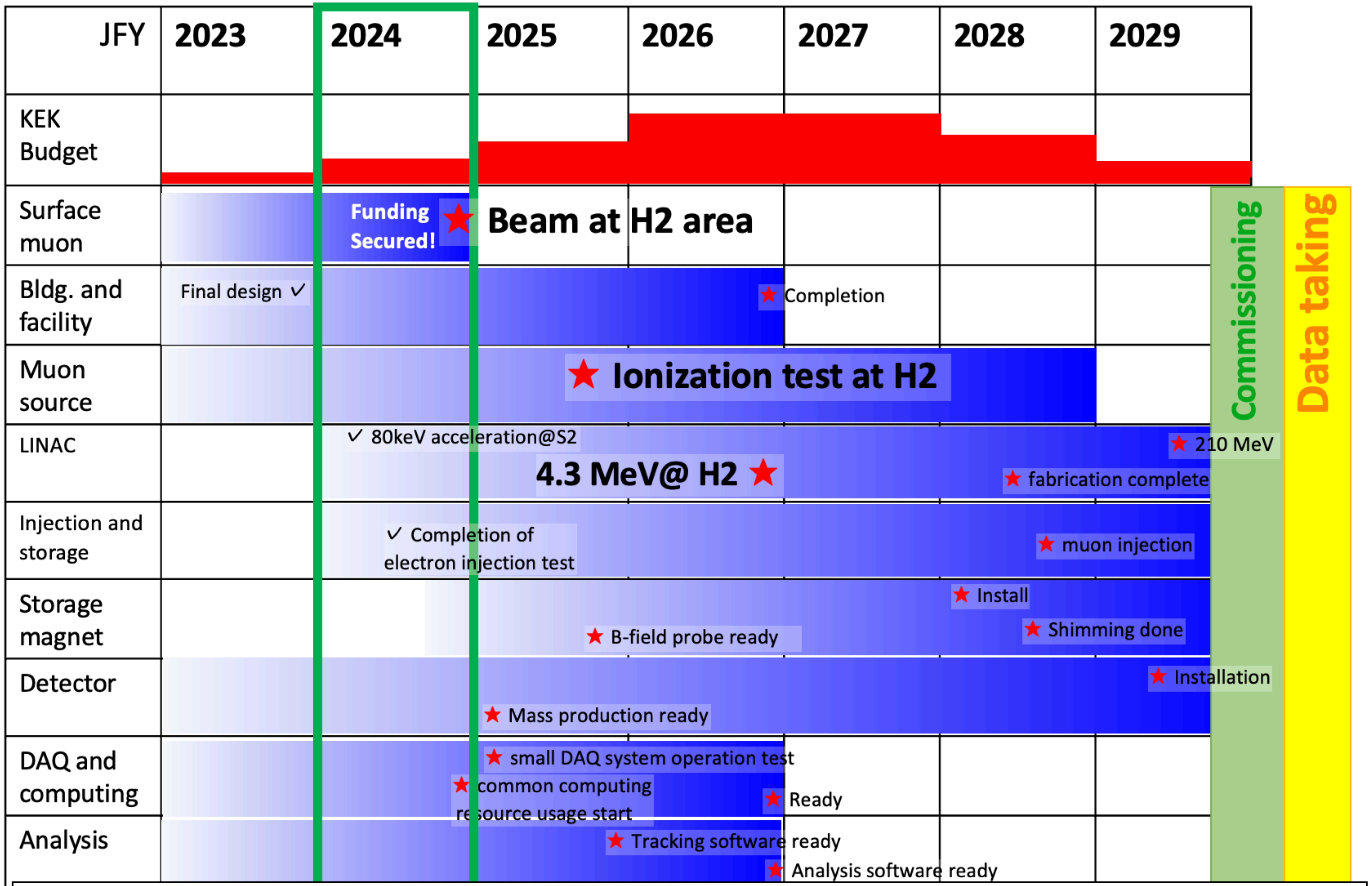
(HMNT 03)

$$a_\mu^{BNL} - a_\mu^{SM} = (279 \pm 76)\times 10^{-11}\ (3.7\sigma)$$

~3 "standard deviations" with SM
→ Hint of new physics?



Schedule and milestones (need revisions) **16**



We formed an adhoc team to reconsider the design and planning of the experimental bldg.

Towards the Ultimate Muon Anomaly Test

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

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

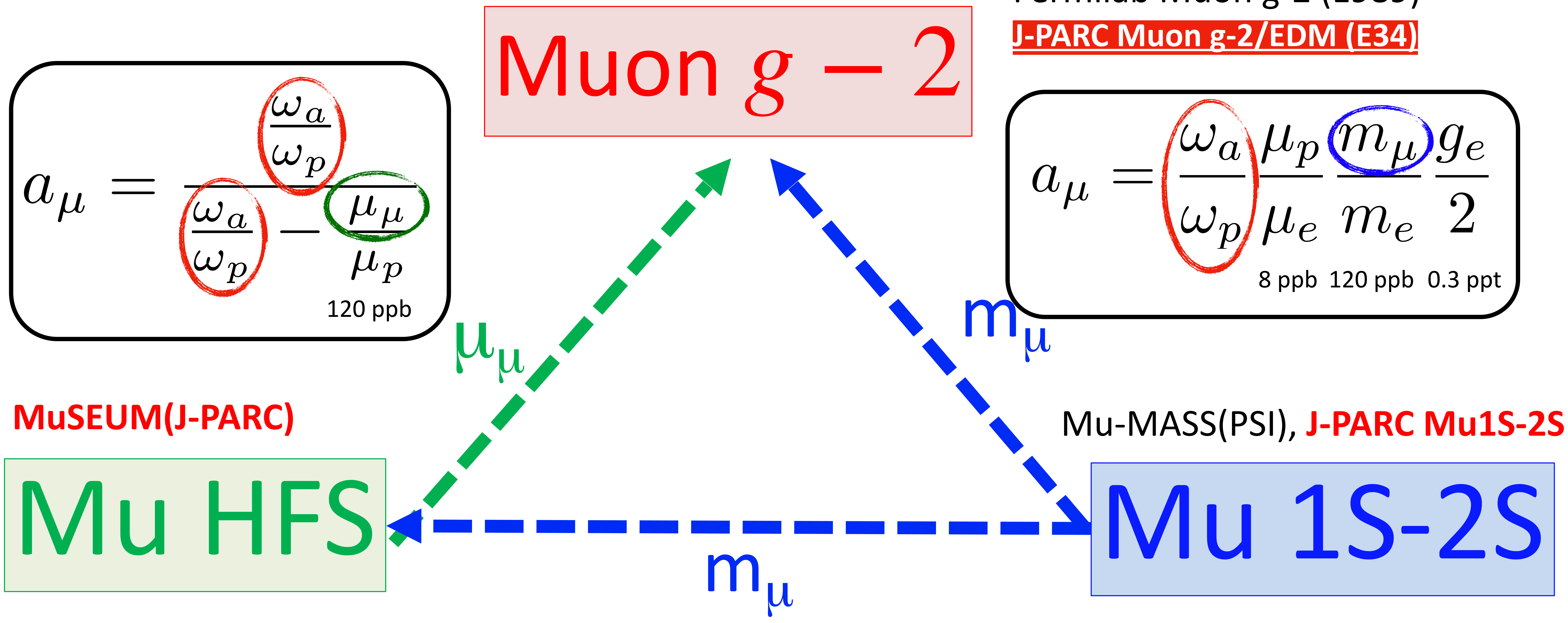
120 ppb

Fermilab Muon g-2 (E989)

J-PARC Muon g-2/EDM (E34)

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

8 ppb 120 ppb 0.3 ppt



MuSEUM(J-PARC)

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

Mu-MASS(PSI), **J-PARC Mu1S-2S exp.**

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

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

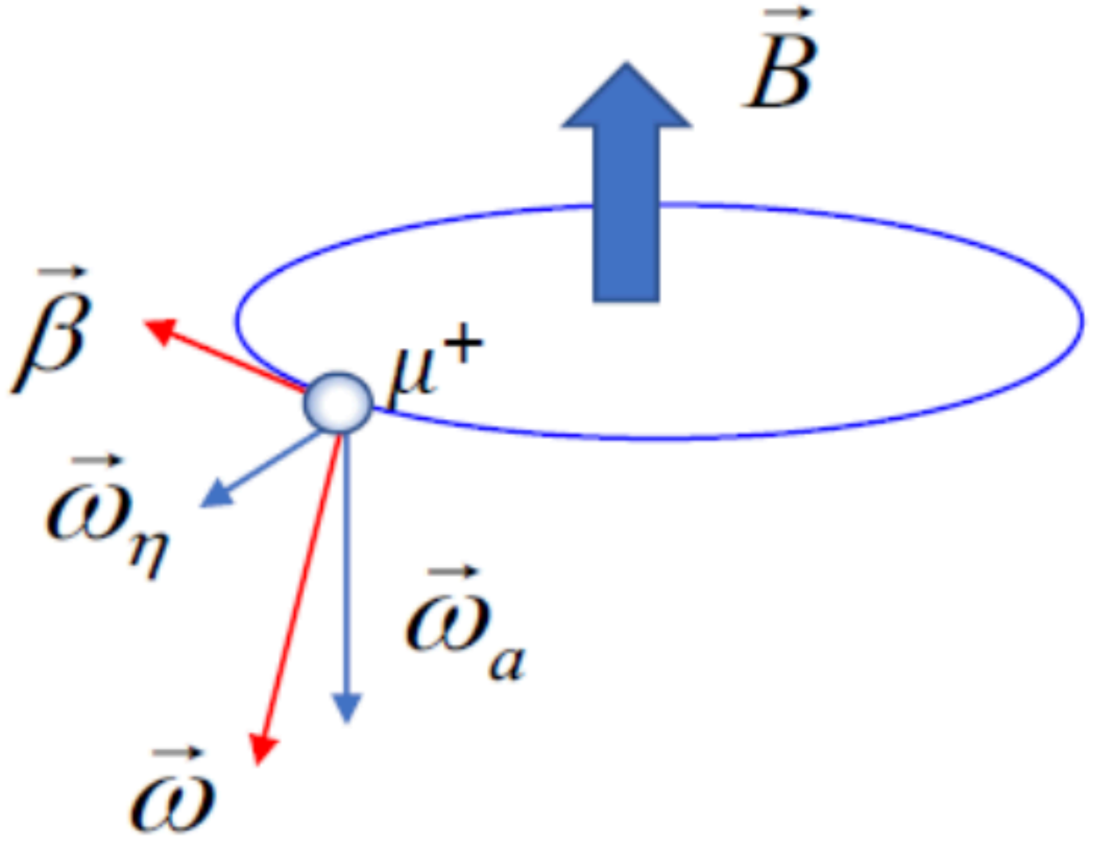
Precision Comparison

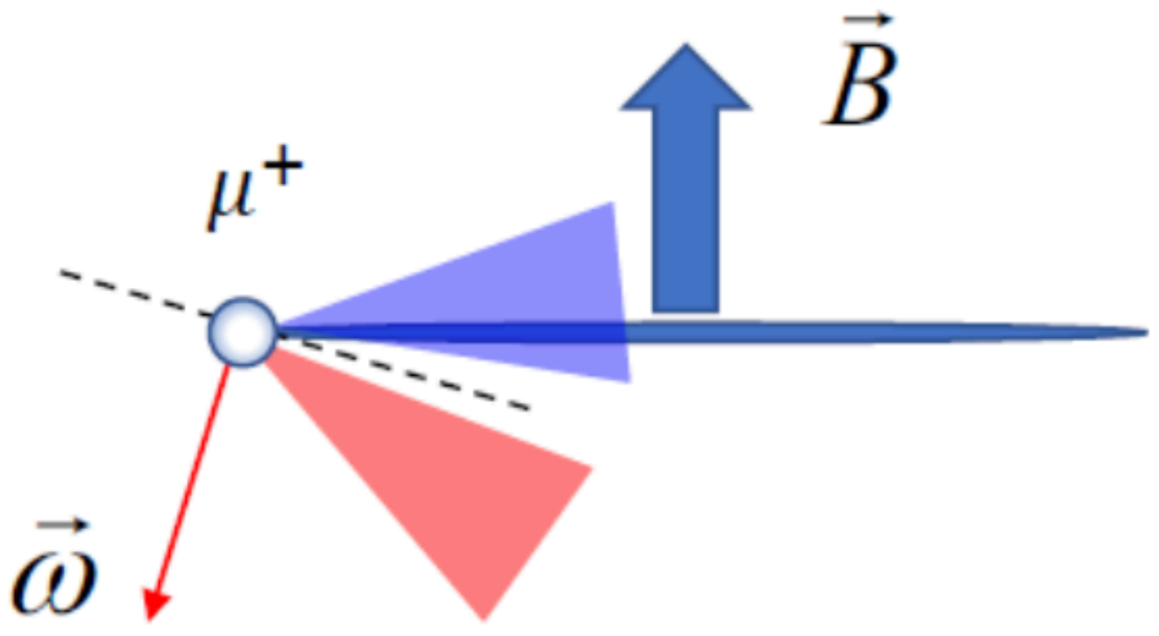
J-PARC E34

	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-1)
(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

EDM Measurement

- EDM measurement relies on the tilt of muon precession to the mid plane.





- No E-field simplifies the measurement for J-PARC.

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

FNAL E989

(at magic γ)

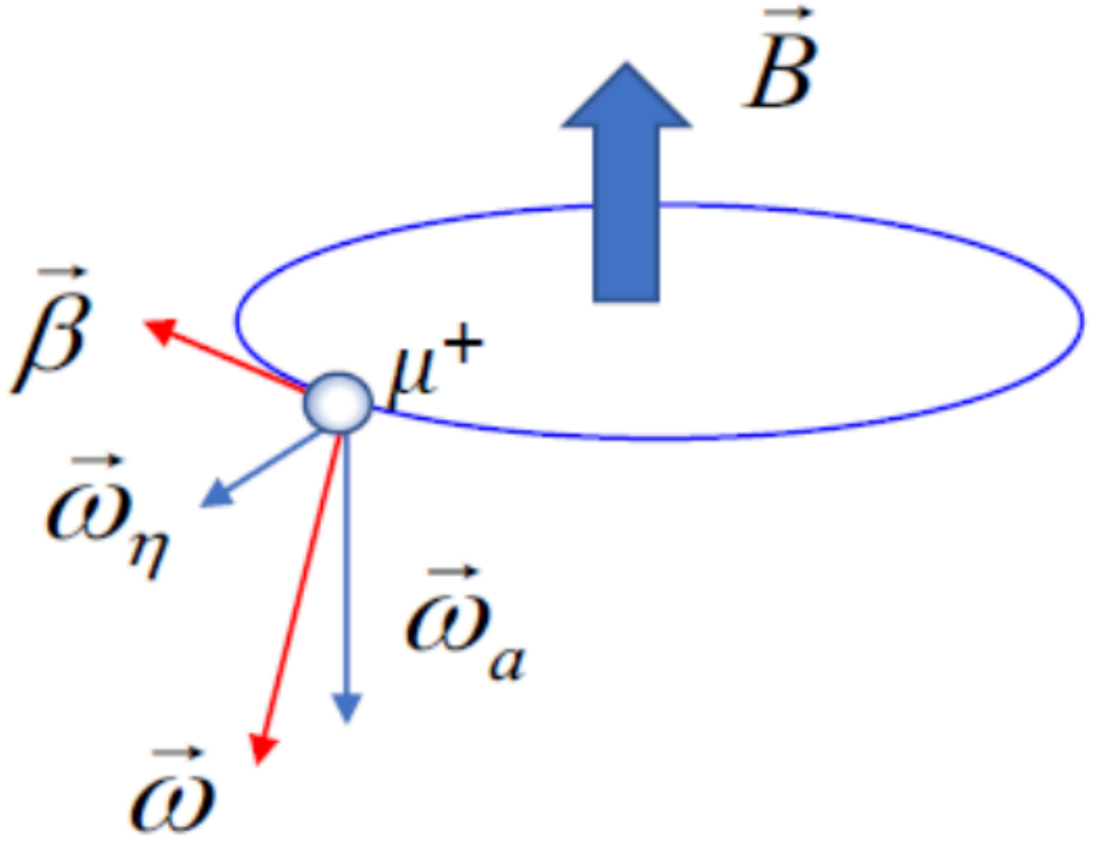
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

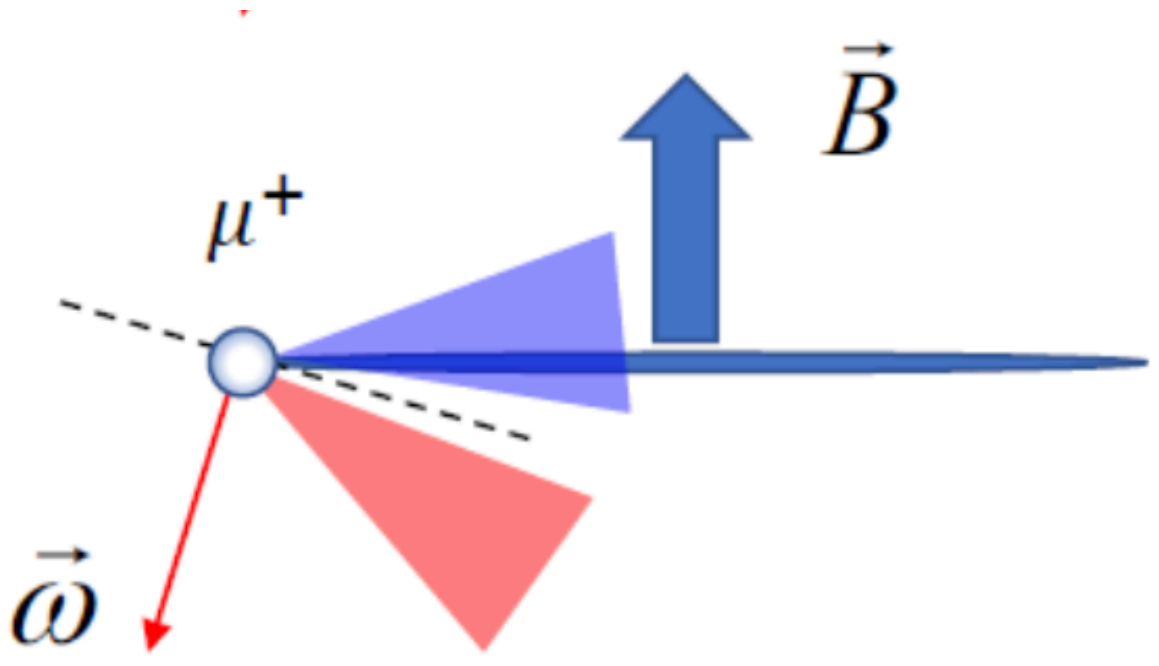
J-PARC E34

(E = 0 at any γ)

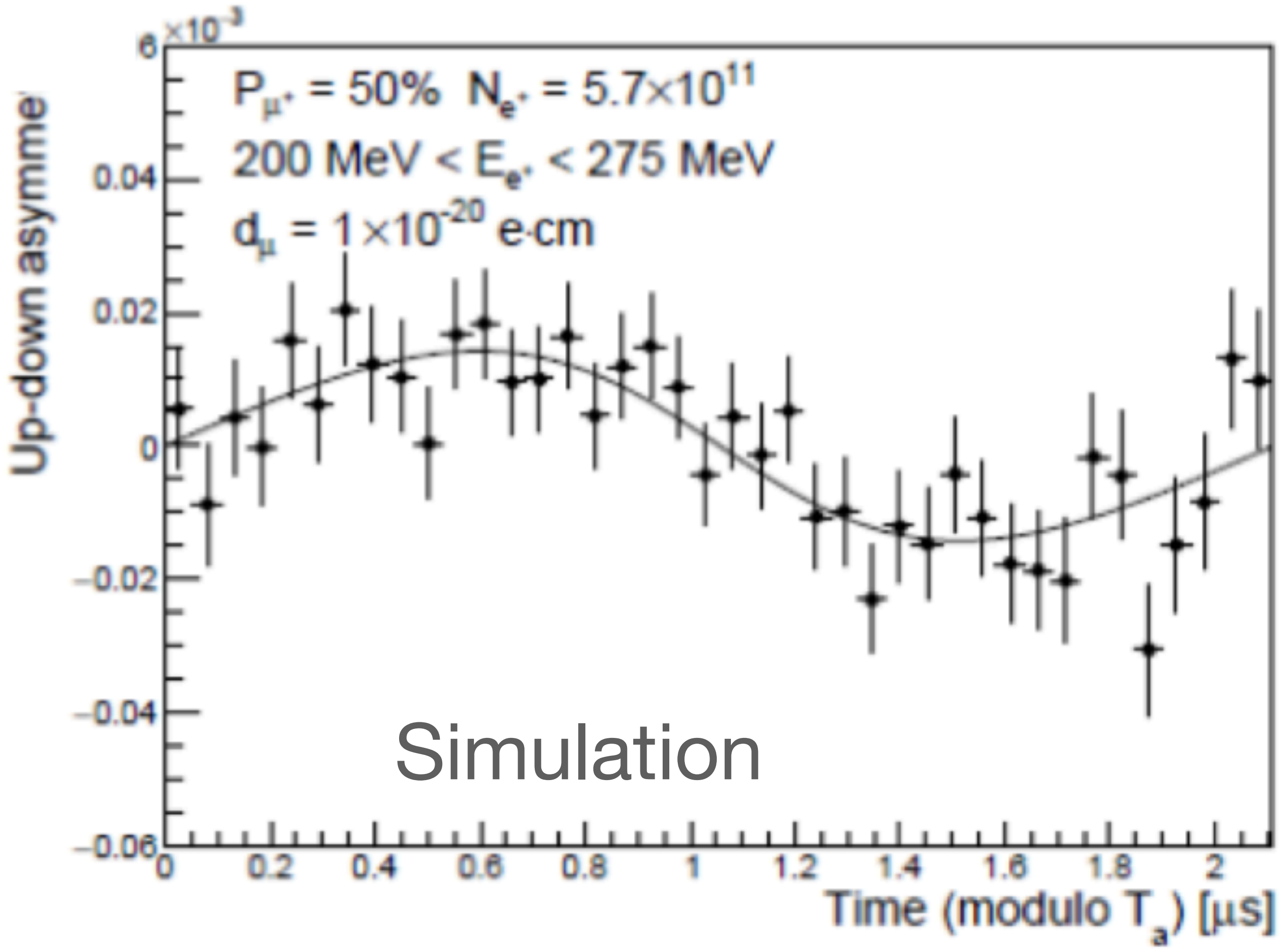
EDM Measurement

- EDM measurement relies on the tilt of muon precession to the mid plane



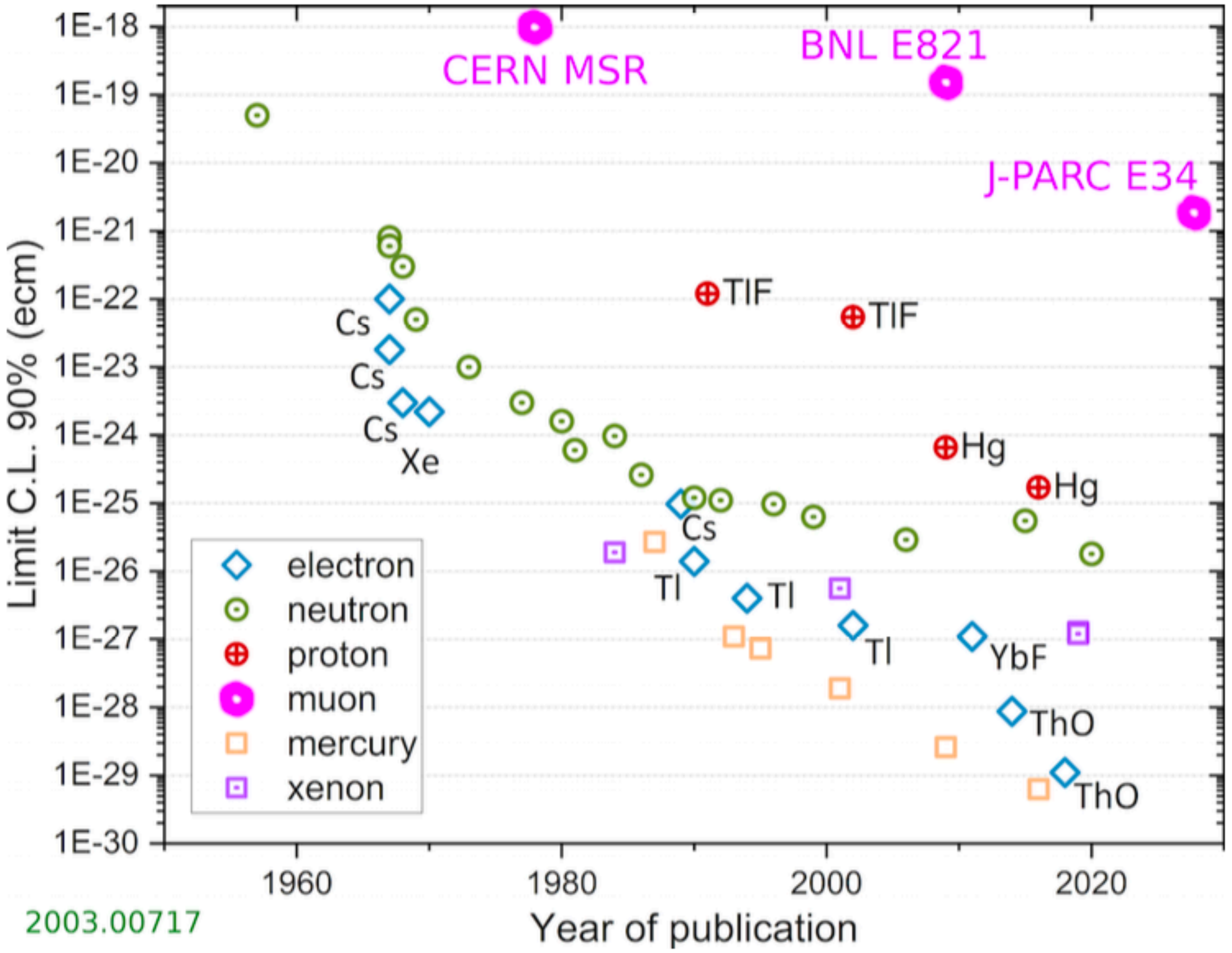


- Observed in up-down asymmetry
- $\omega_\eta/\omega_a \sim(\eta\beta/2a_\mu)$
- Good detector alignment precision is essential
- aim at 10^{-21} e cm sensitivity (10^{-5} rad)
- 1 μm detector alignment measurement is developed



EDM Measurement

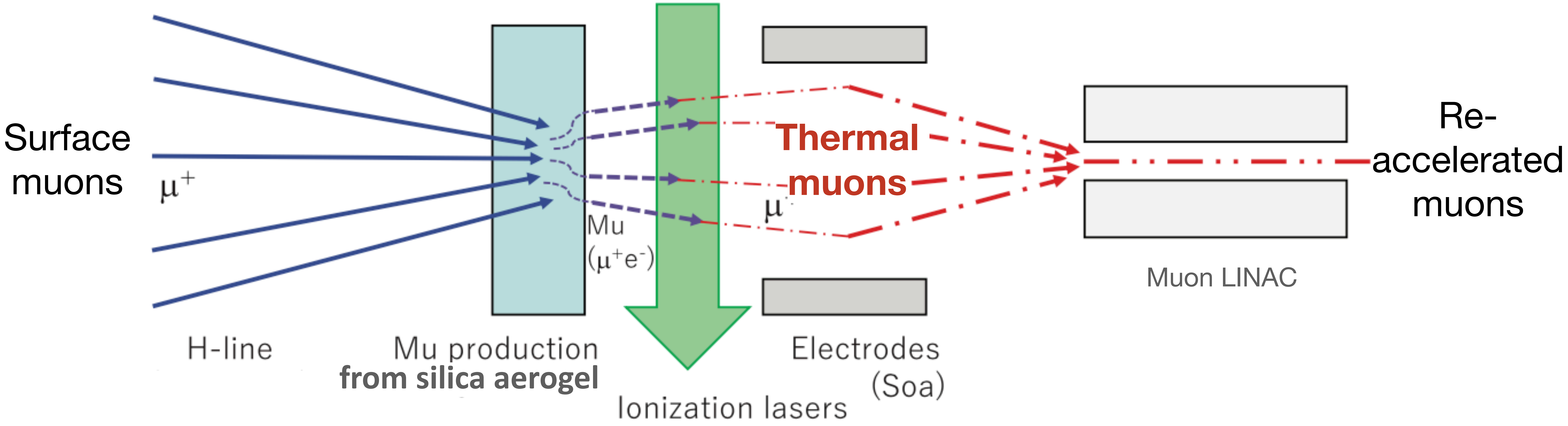
- The muon EDM SM expectation is ~ 2×10^{-38} e cm
- The current experimental limit is 1.8×10^{-19} e cm by the BNL E821.



Thermal Muon Source

- Surface muon cooling by laser ionization of muonium (Mu) to thermal muon

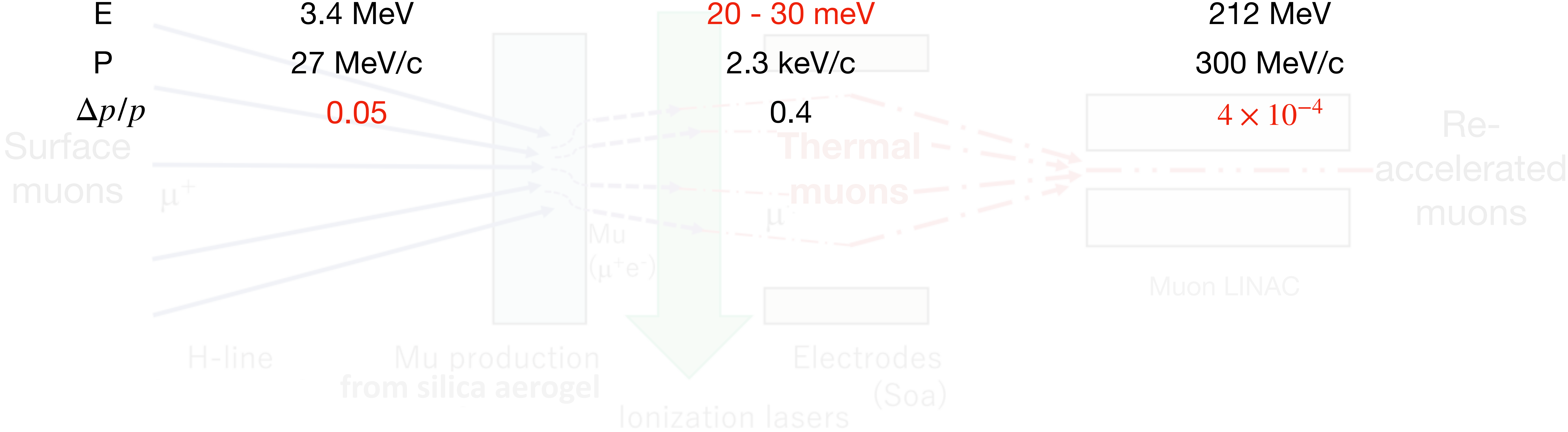
Surface muons ⟶ **Thermal muons** ⟶ Re-accelerated muons



Thermal Muon Source

- Surface muon cooling by laser ionization of muonium (Mu) to thermal muon

	Surface muons →	**Thermal muons** →	Re-accelerated muons
E	3.4 MeV	20 - 30 meV	212 MeV
P	27 MeV/c	2.3 keV/c	300 MeV/c
$\Delta p/p$	0.05	0.4	4×10^{-4}



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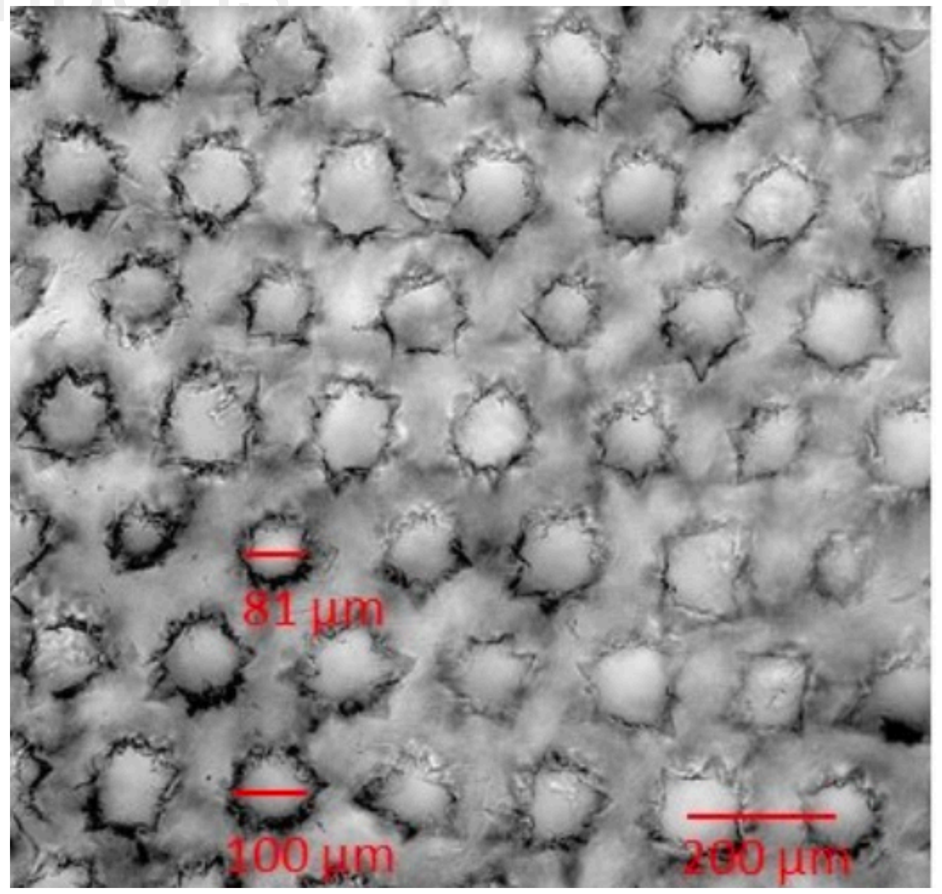
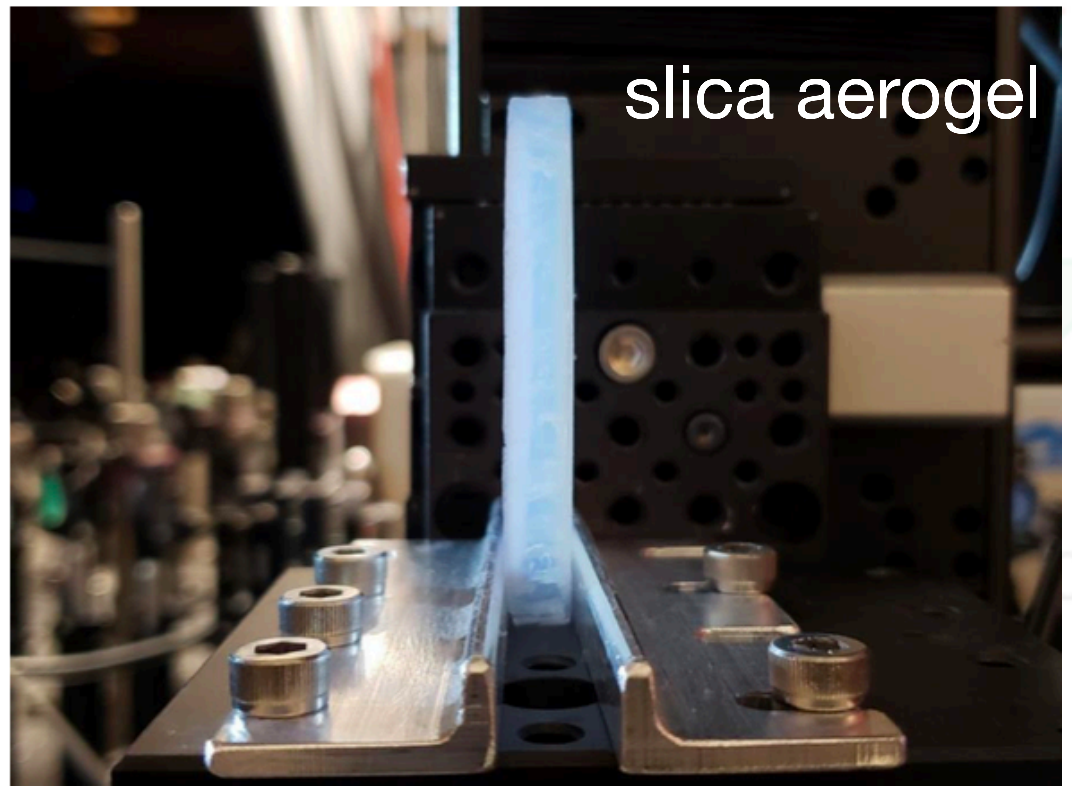
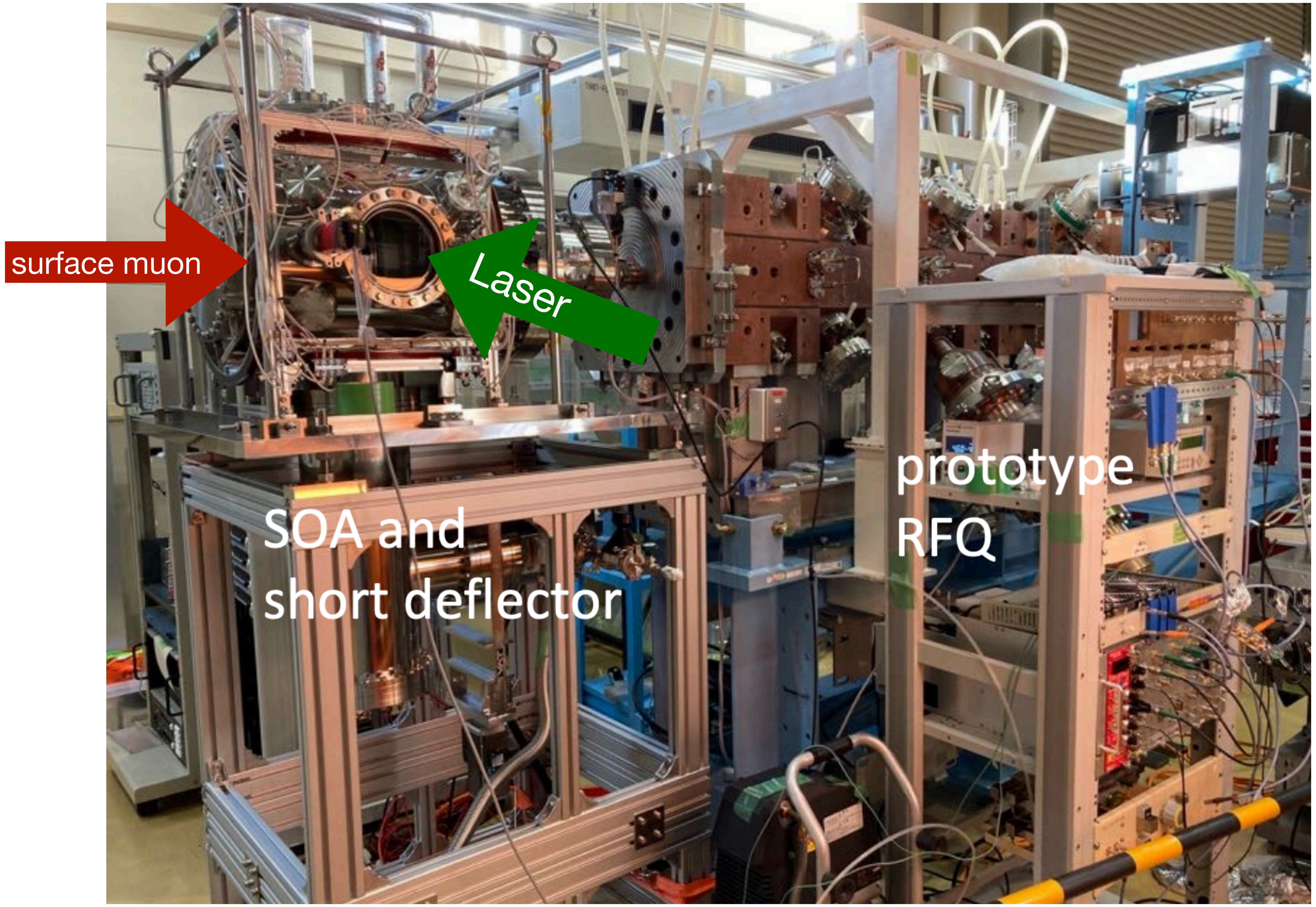




2013	● Muonium emission from silica aerogel [PTEP 103C0
2014	● Laser-ablation on aerogel surface [PTEP 091C01 (2014)]
2020	● Study of muonium emission from laser-ablated silica aerogel [PTEP 123C01 (2020)]

Thermal Muon Source



- Two laser options are under development:

122 nm laser

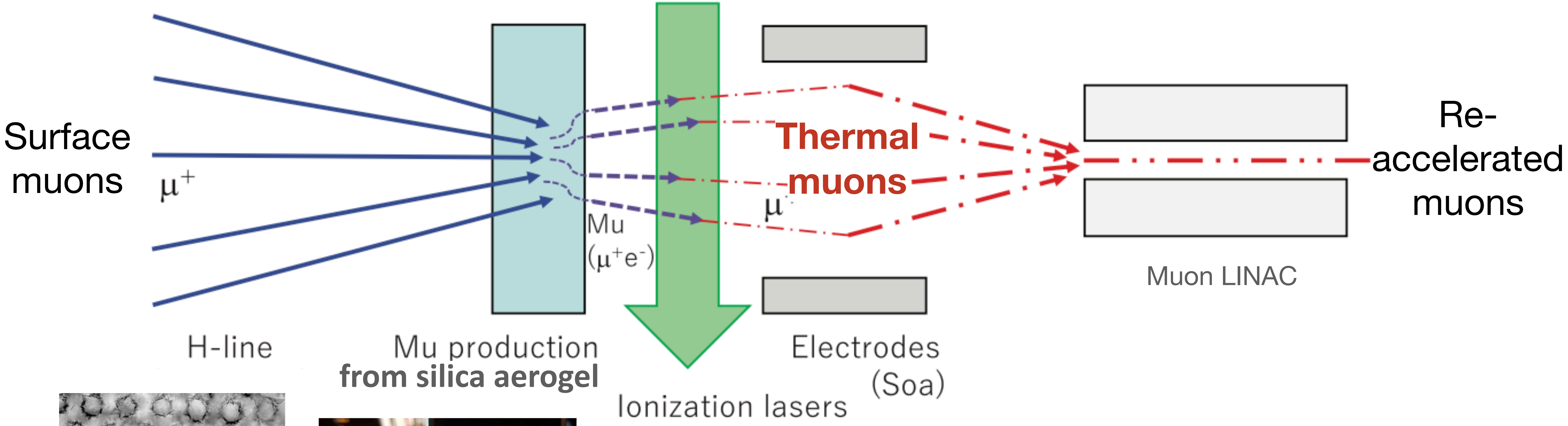
- Challenging
- High efficiency (73% efficiency at 100 μJ, now only 5 to 10 μJ achieved)

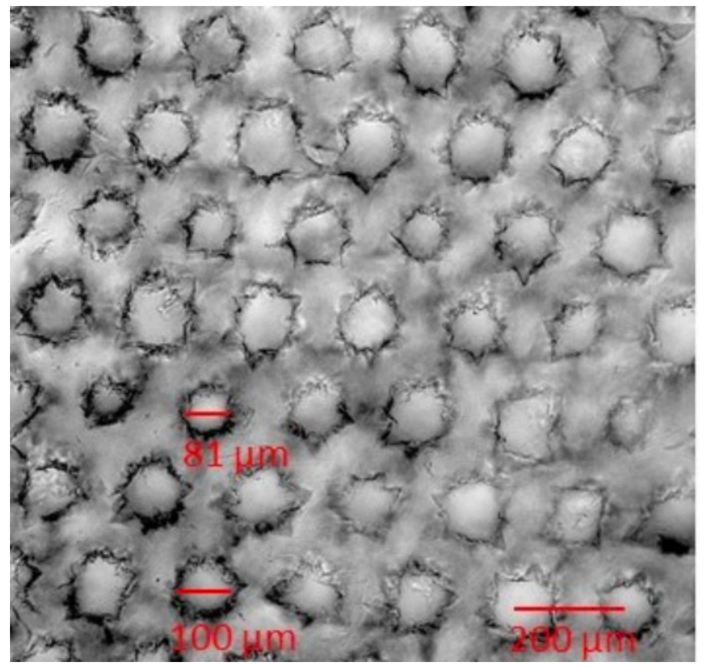
244 nm laser

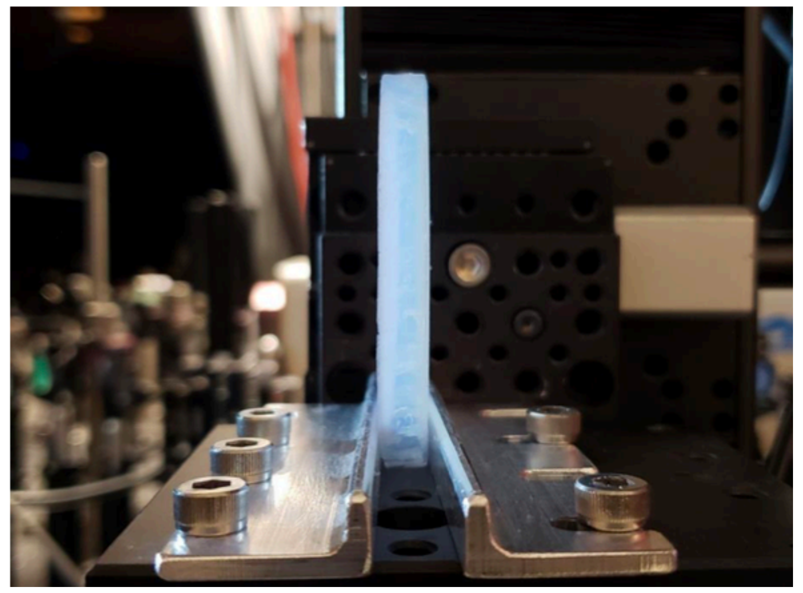
- Easier for development
- Being used since 2021
- Efficiency under estimation (lower than 122 nm)

Thermal Muon Source

- Surface muon cooling by <u>laser ionization of muonium (Mu)</u> to thermal muon







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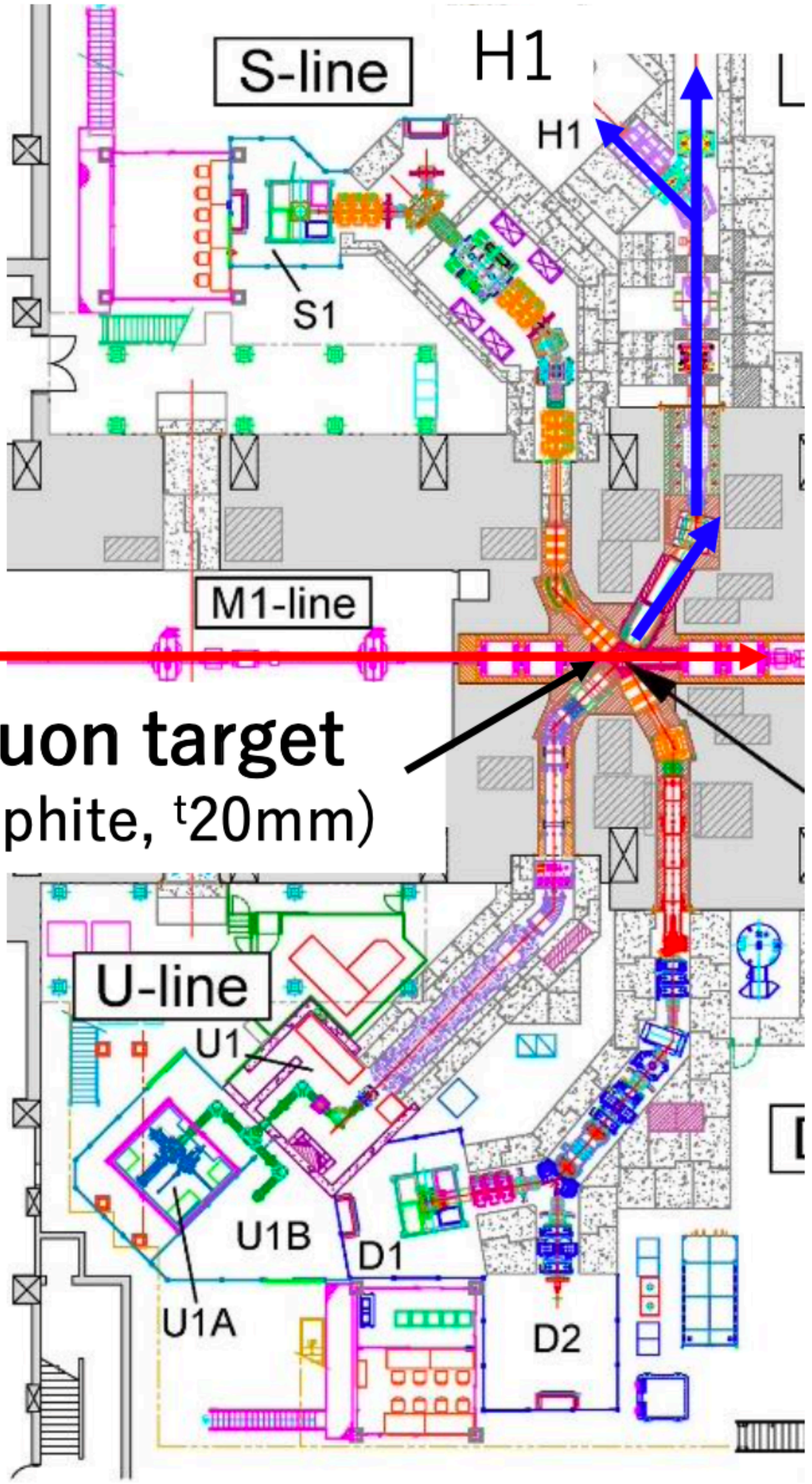
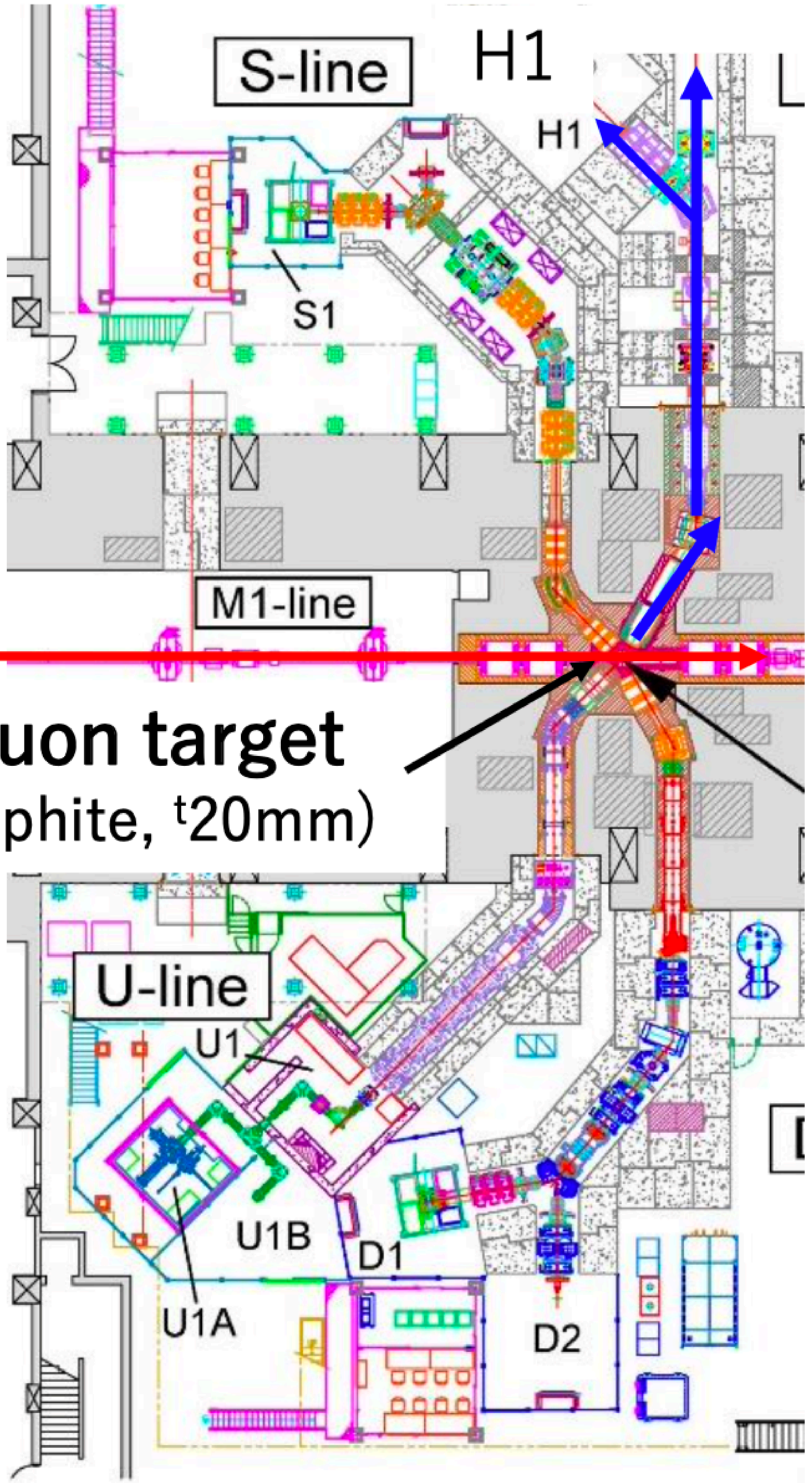
Muon Source at J-PARC MLF

3 GeV proton from RCS

2×10^{15} /s @1MW



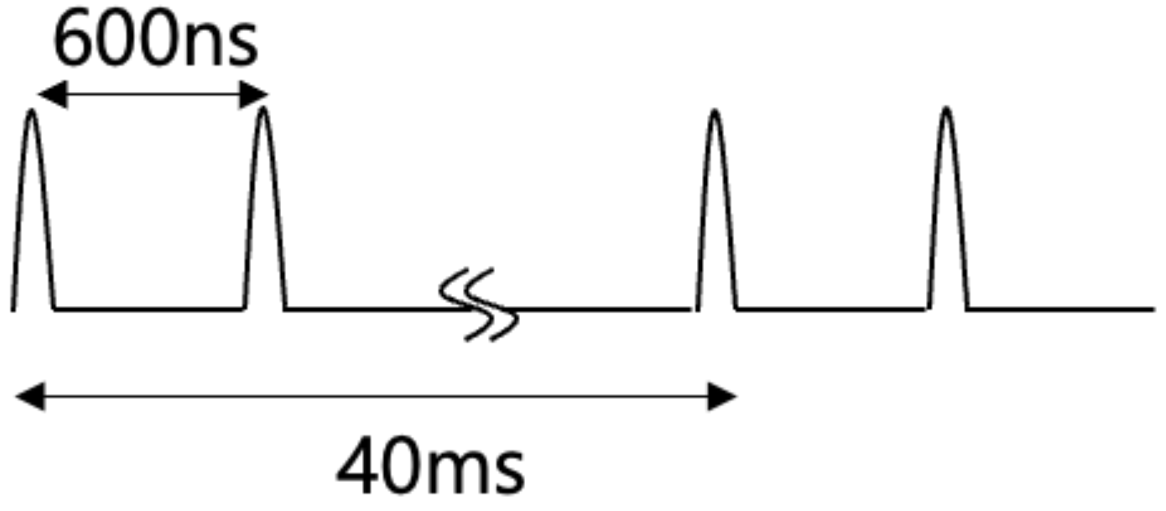
Muon Source at J-PARC MLF



3 GeV proton from RCS

2×10^{15} /s @1MW

Repetition rate 25 Hz, double bunches
Tandem target: 5% for μ, 95% for n



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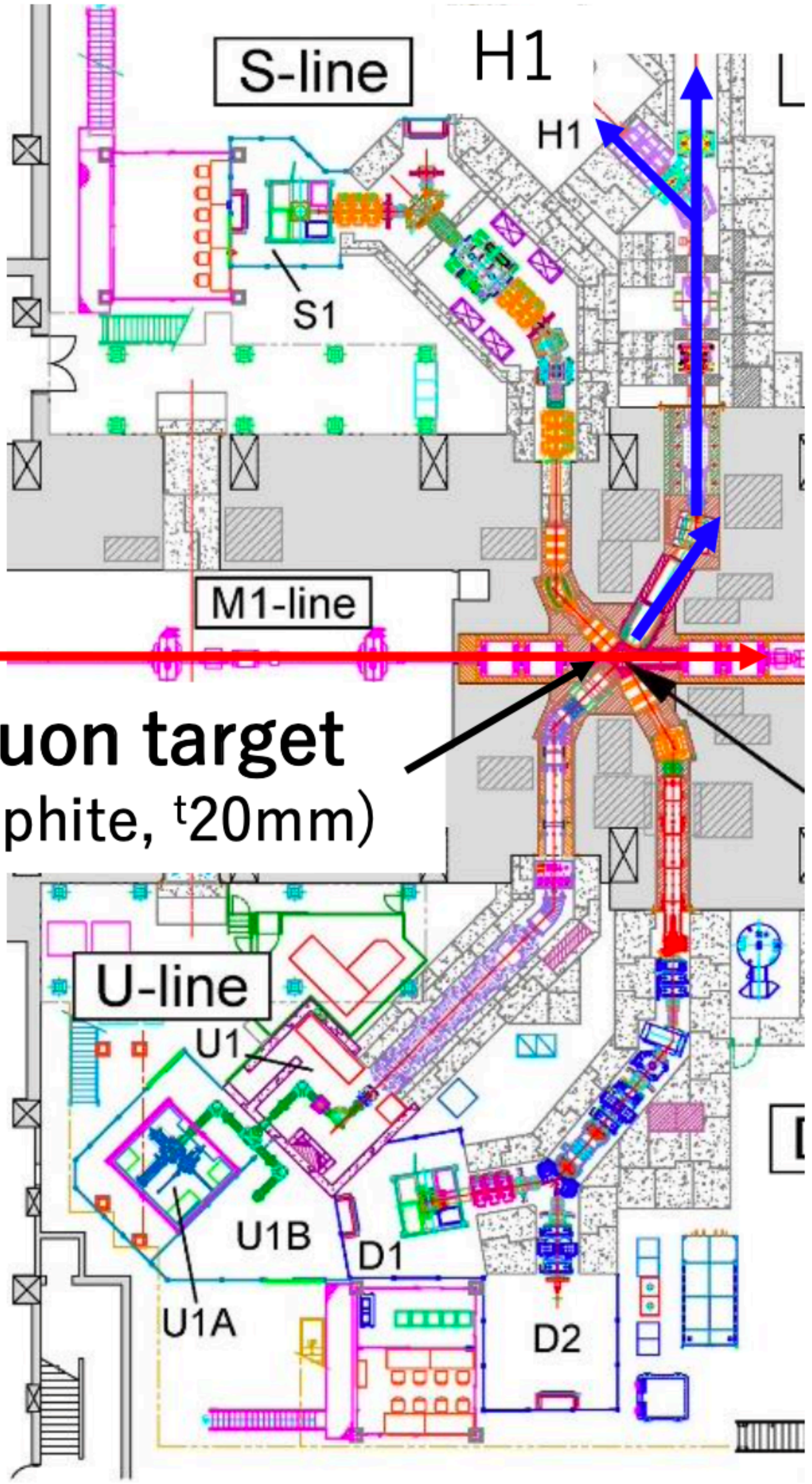
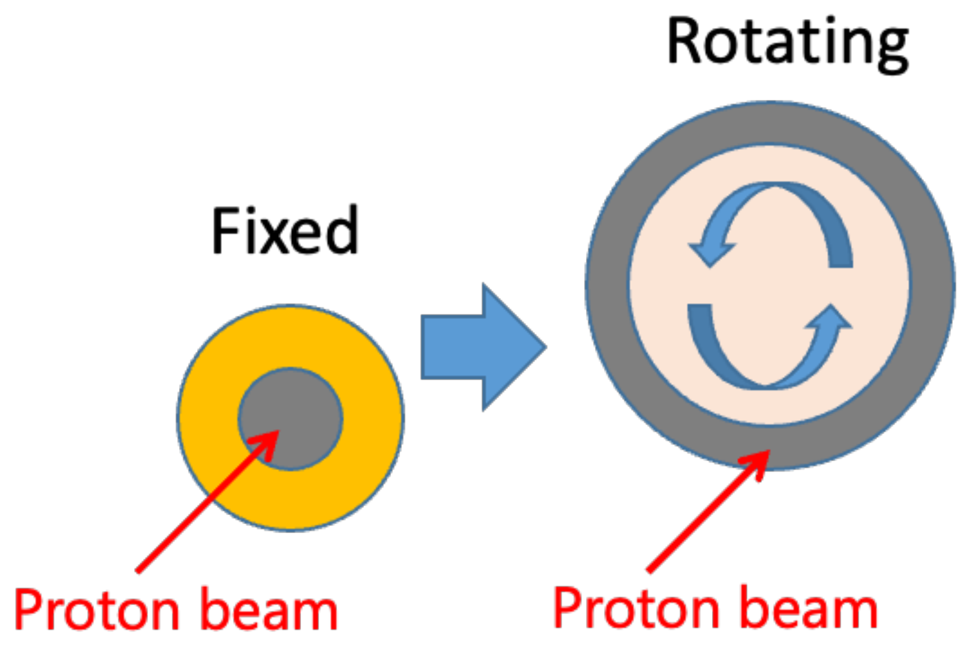
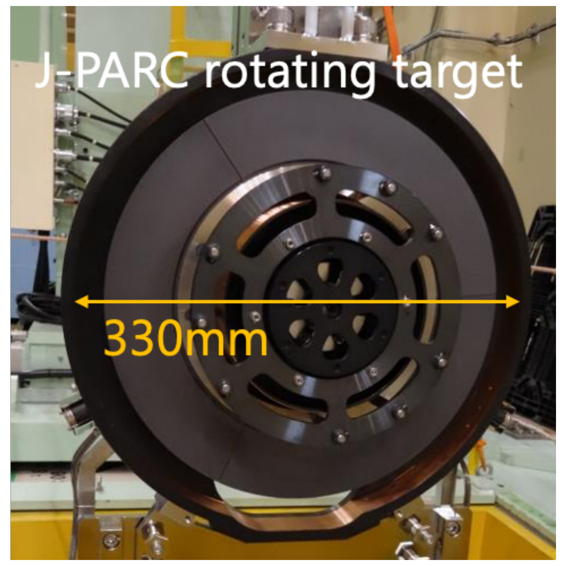
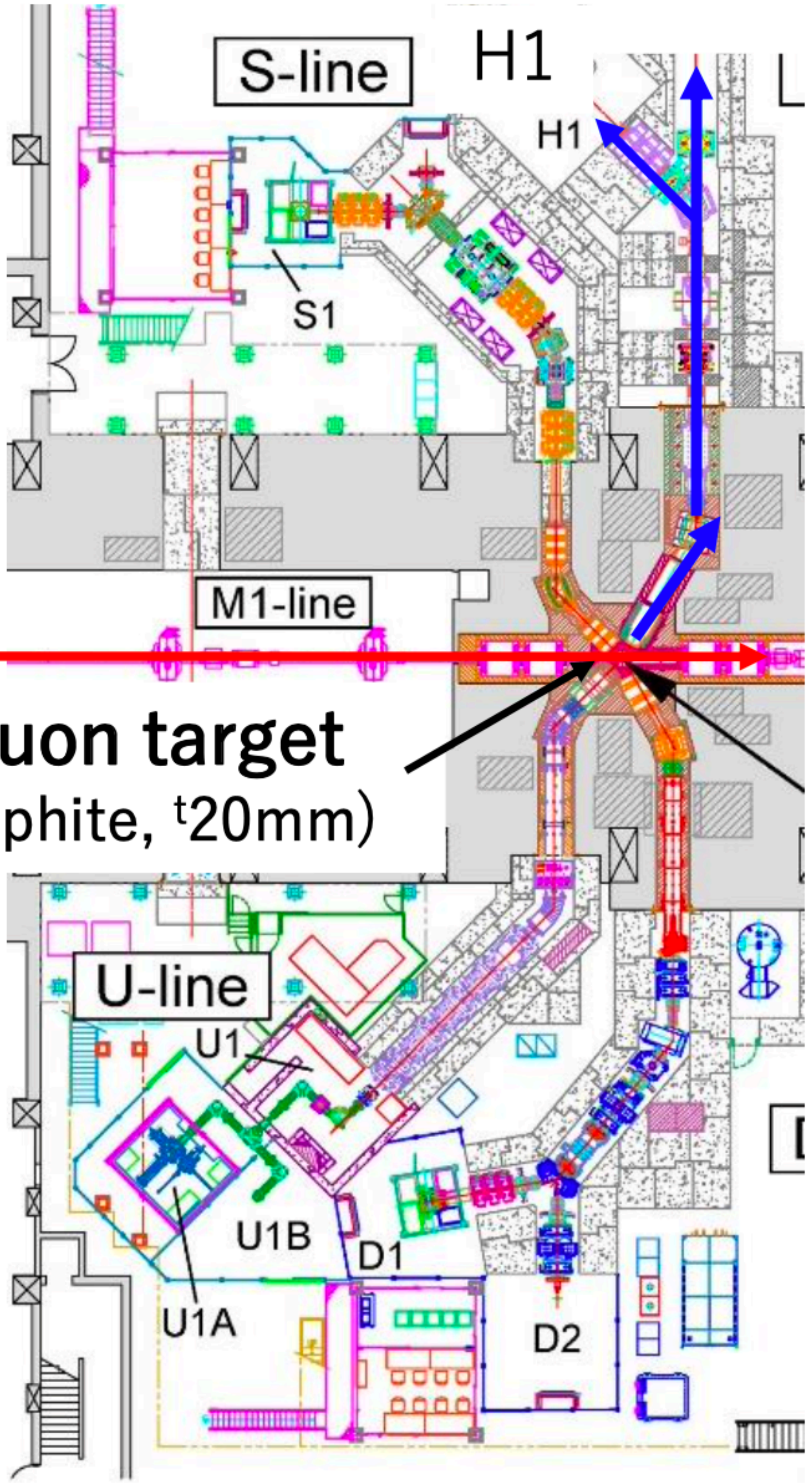






Muon Source at J-PARC MLF

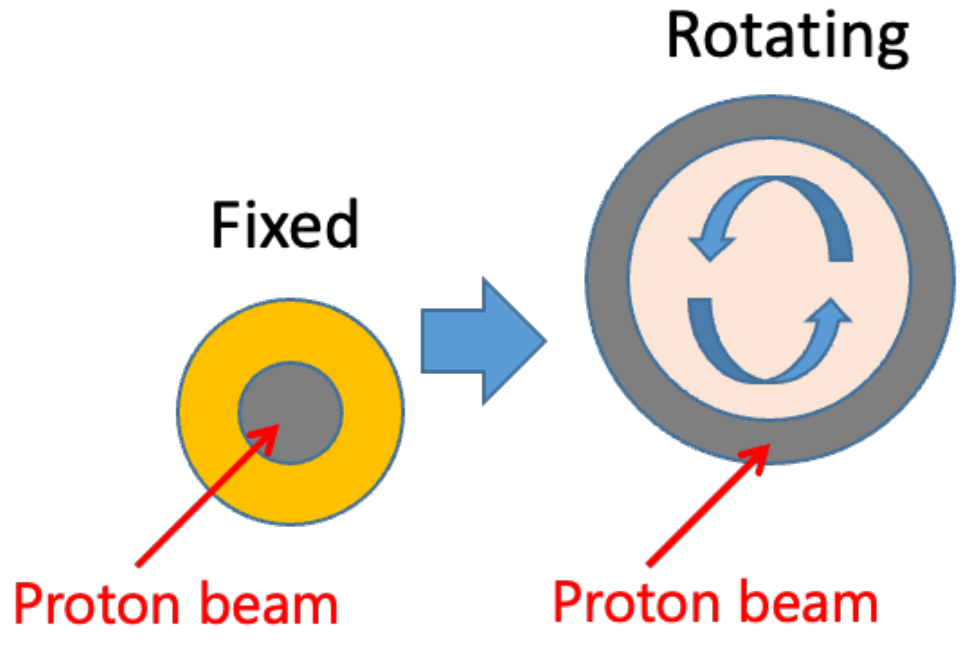
S line
- surface μ⁺
- S1 for μSR
- S2 for Mu 1S-2S
- S3/S4 are planned

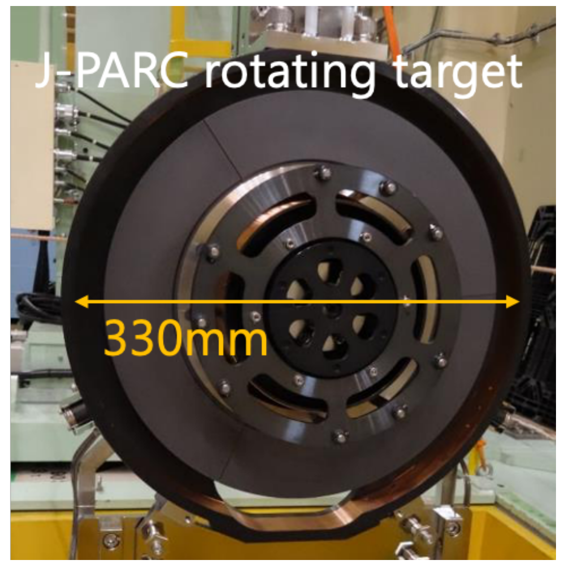


Muon target
(graphite, ᵗ20mm)

3 GeV proton from RCS

2×10^{15} /s @1MW





H line
- **surface μ⁺ (>10⁸ μ⁺/s)**, cloud μ⁺/μ⁻, e⁻
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- H2 for g-2/EDM & TμM

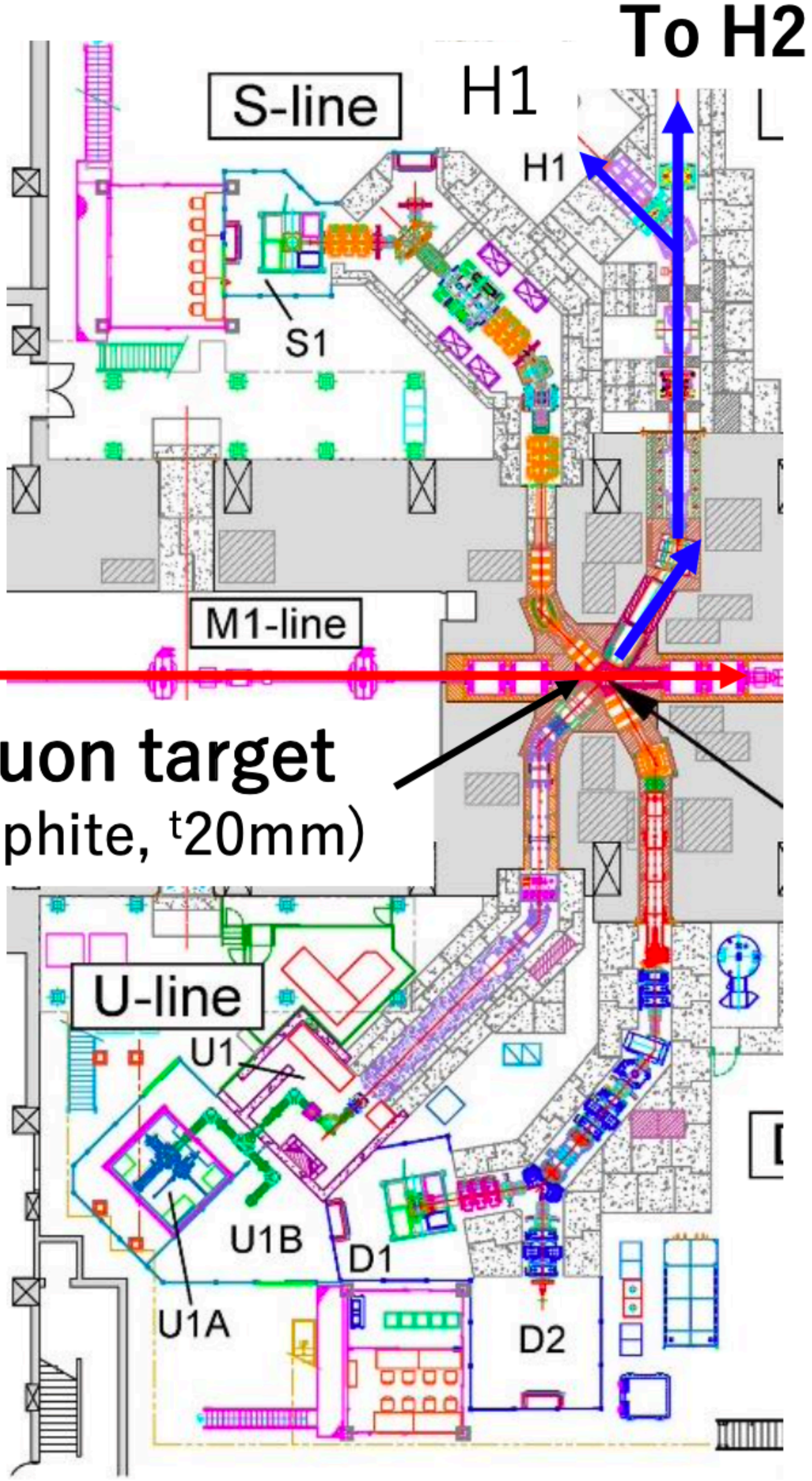
Under construction

Muon Source at J-PARC MLF

S-line
- surface μ^+
- dedicated to μSR
- S1 area is available
- S2 is under construction
- S3/S4 are planned

3 GeV proton from RCS

2×10^{15} /s @1MW

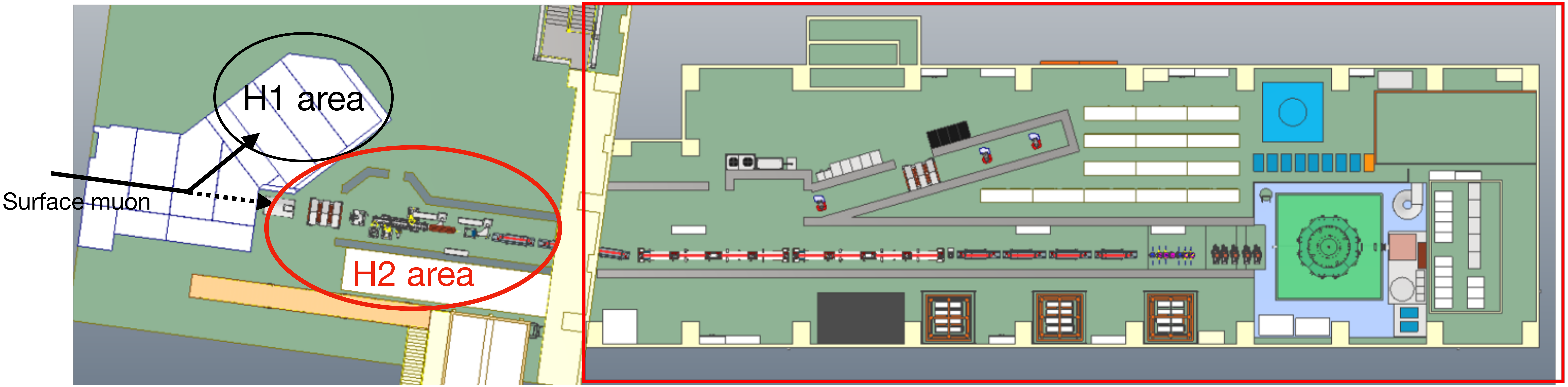


H-line
- **surface μ^+ (>10^8 μ^+/s),** decay μ^+/μ^-, e^-
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- **H2** for g-2/EDM & transmission muon microscopy
- under construction

U-line
- ultra slow μ^+
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning

D-line
- decay μ^+/μ^-, surface μ^+
- D1 area for μSR
- D2 for variety of science

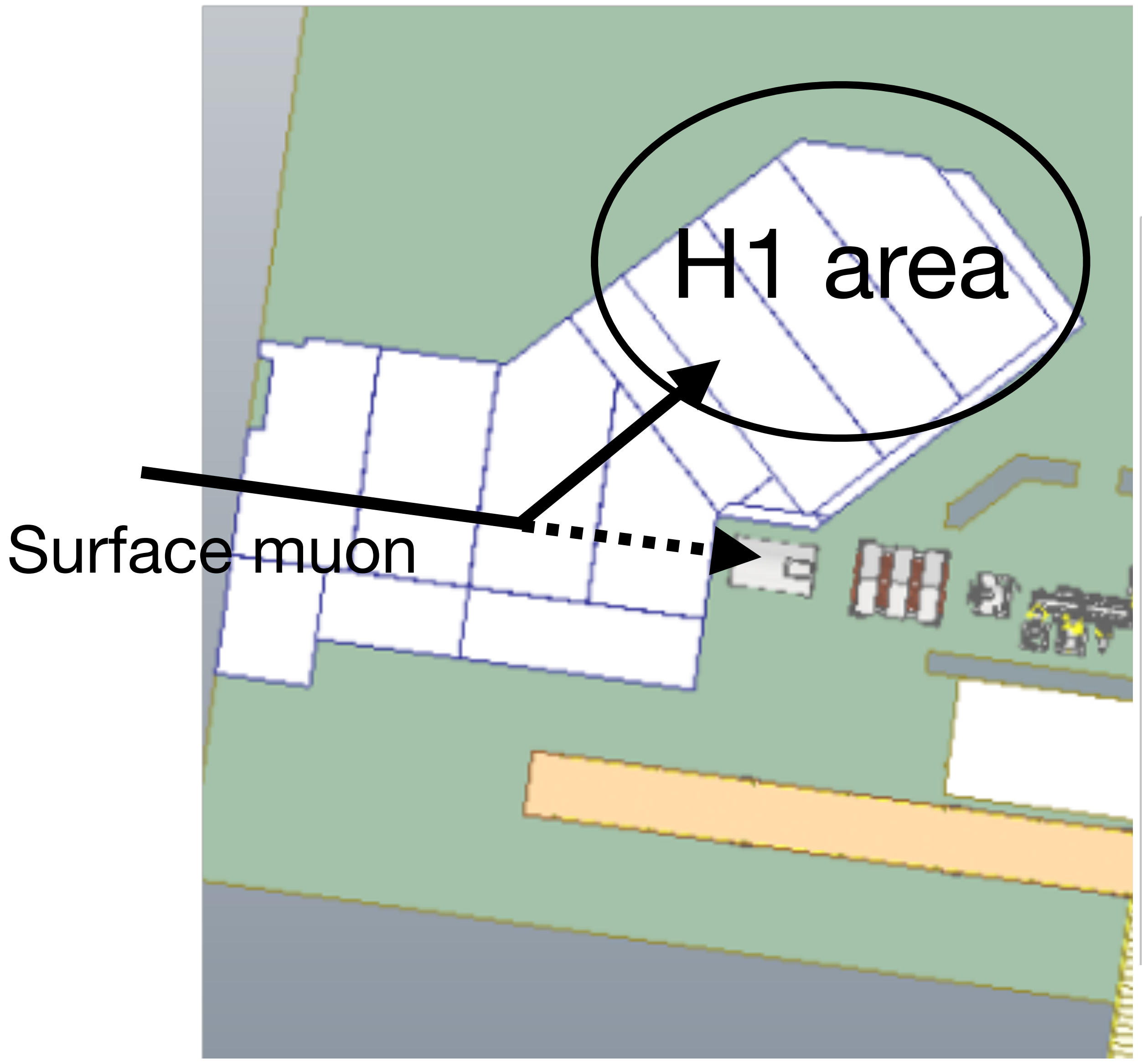
H-line Construction



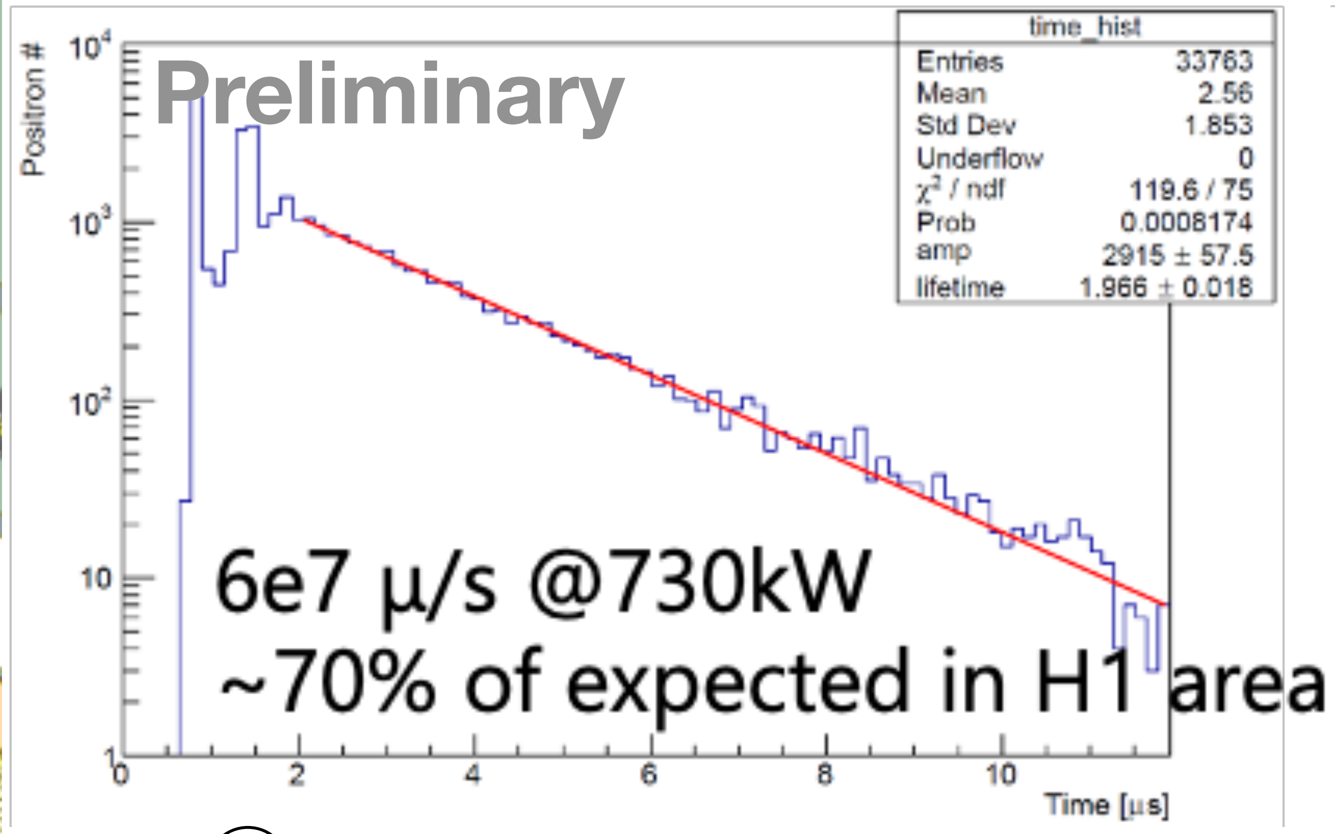
Extension building for muon LINAC, kicker and storage ring

- Beam commissioning is ongoing at the **H1 area.**
- Construction of the **H2 area** is in progress.
- **The extension building** design is ready to start construction in 2023.

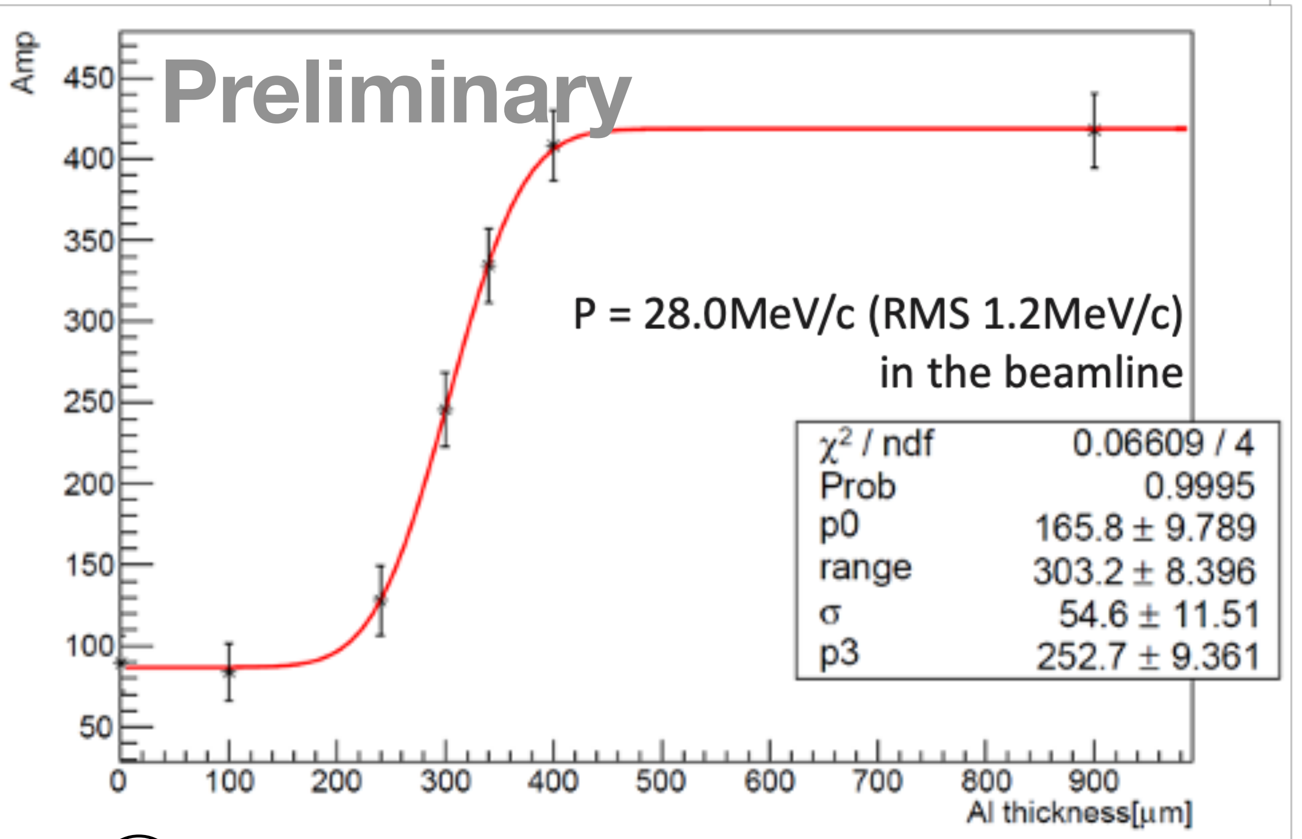
H-line Construction



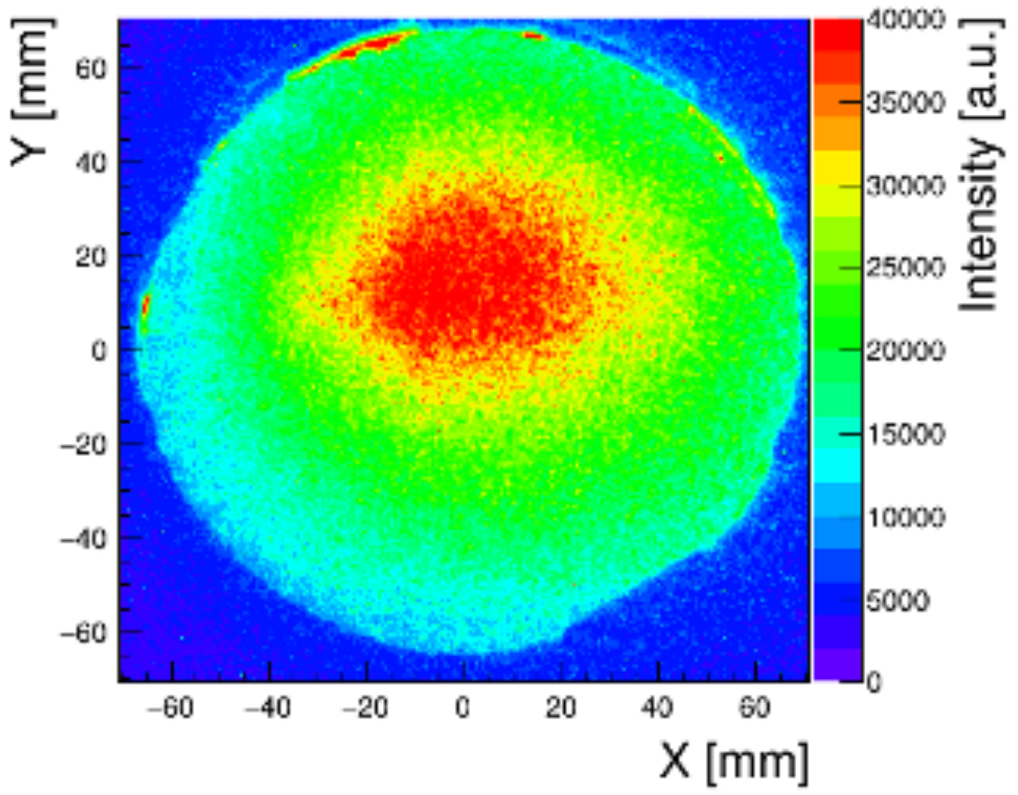
- The first beam was delivered to the **H1 area** on Jan. 15th, 2022



① Beam intensity measurement



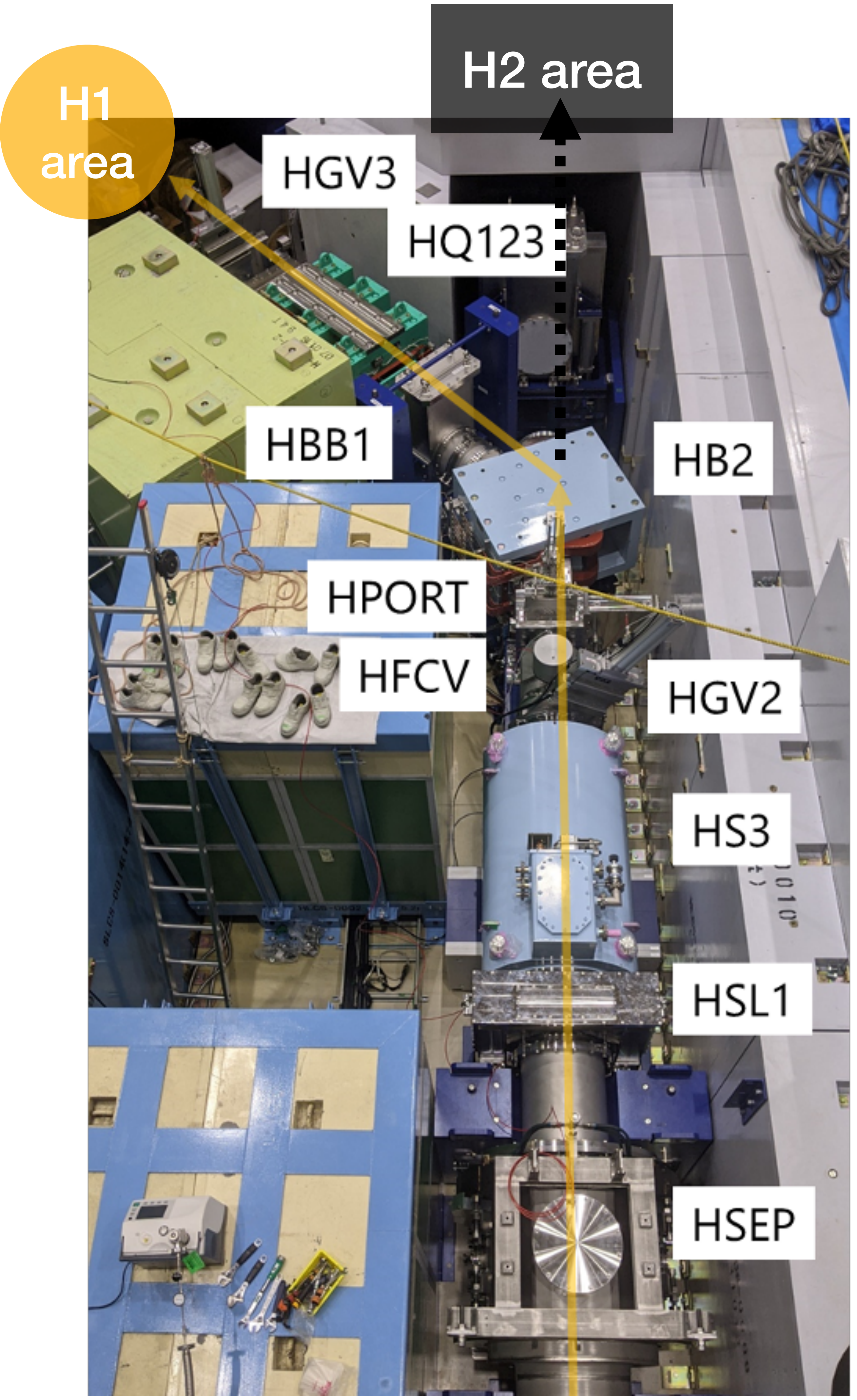
② Momentum estimation

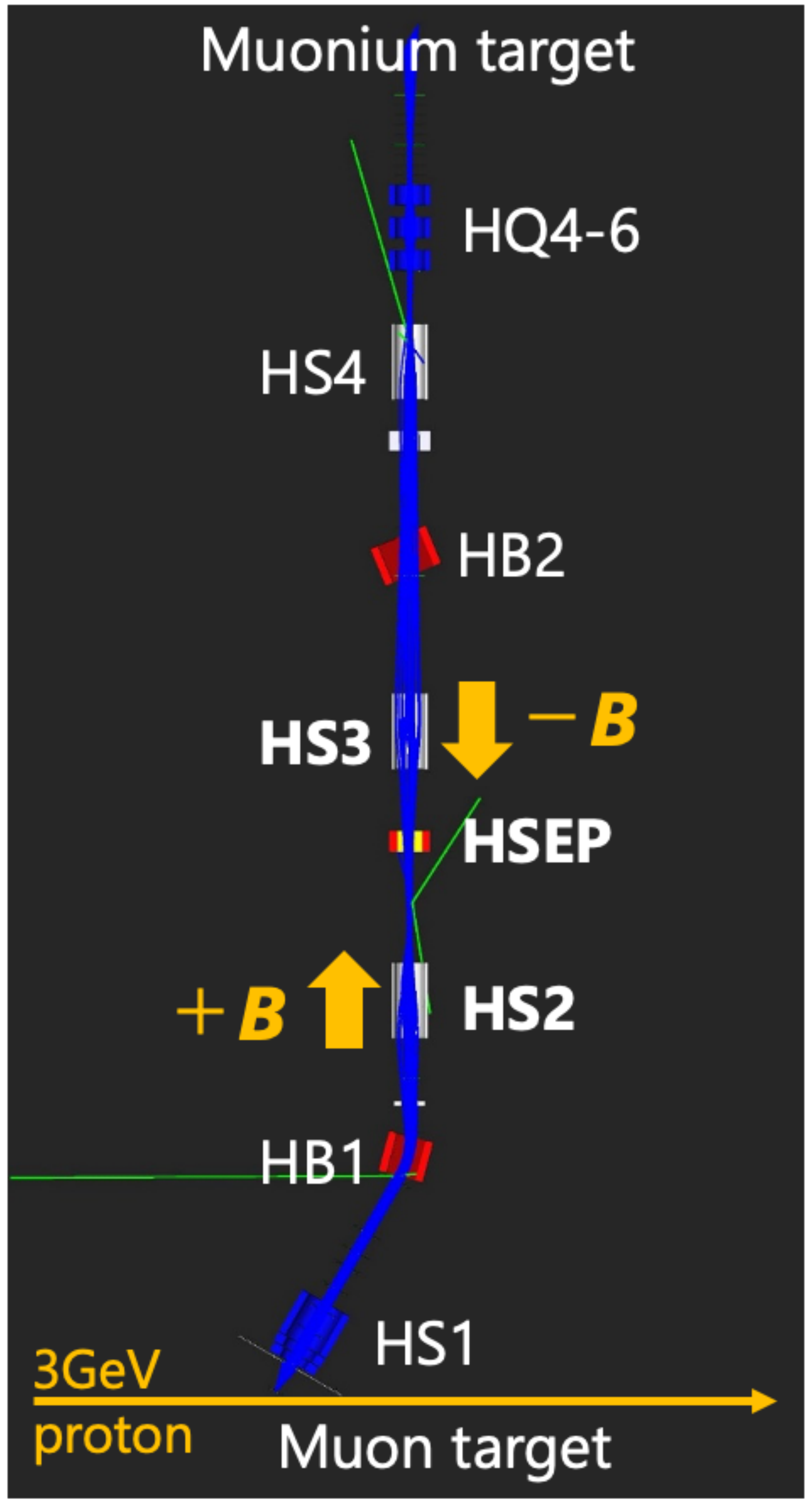


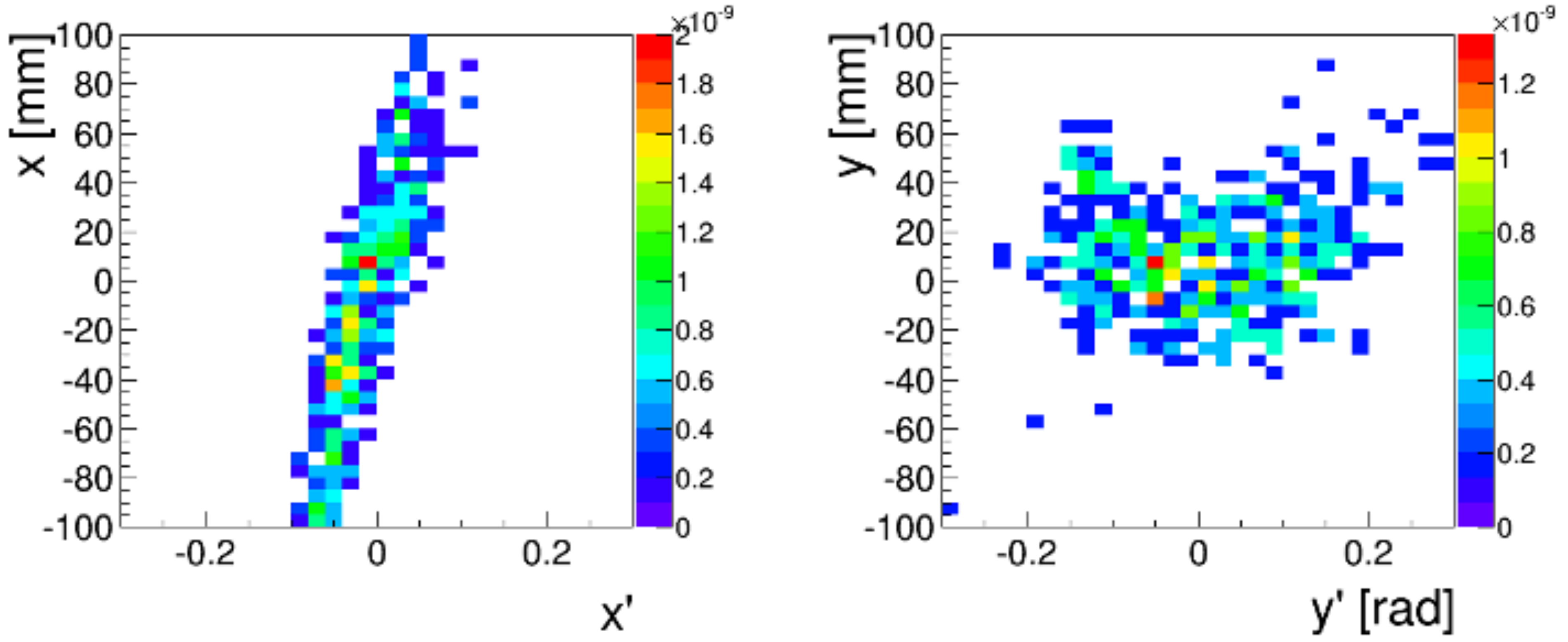
③ Beam profile measurement

- Beam commissioning is ongoing at the **H1 area.**
- Construction of the **H2 area** is in progress.
- **The extension building** design is ready to start construction in 2023.

H-line Surface Muon Optics



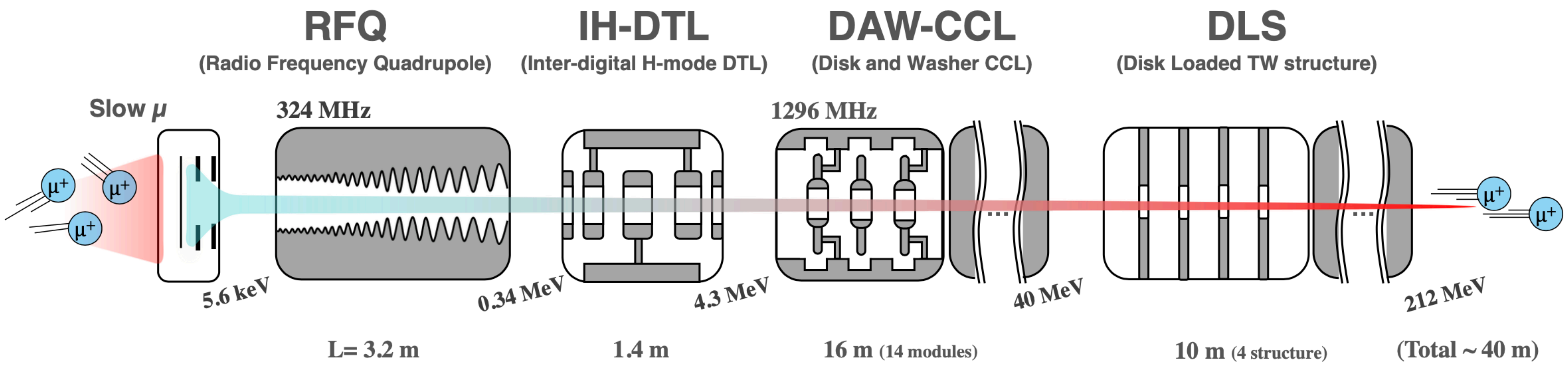




Simulated beam profile at H2 area entrance

- The beam-line consist of solenoids ("HS"), bending magnets ("HB"), DC separator ("HSEP"), quadruples ("HQ"), etc.
- Beam-line optics was tuned to deliver 1.6×10⁸ surface μ/s at the muonium production target under a 1MW proton beam power.

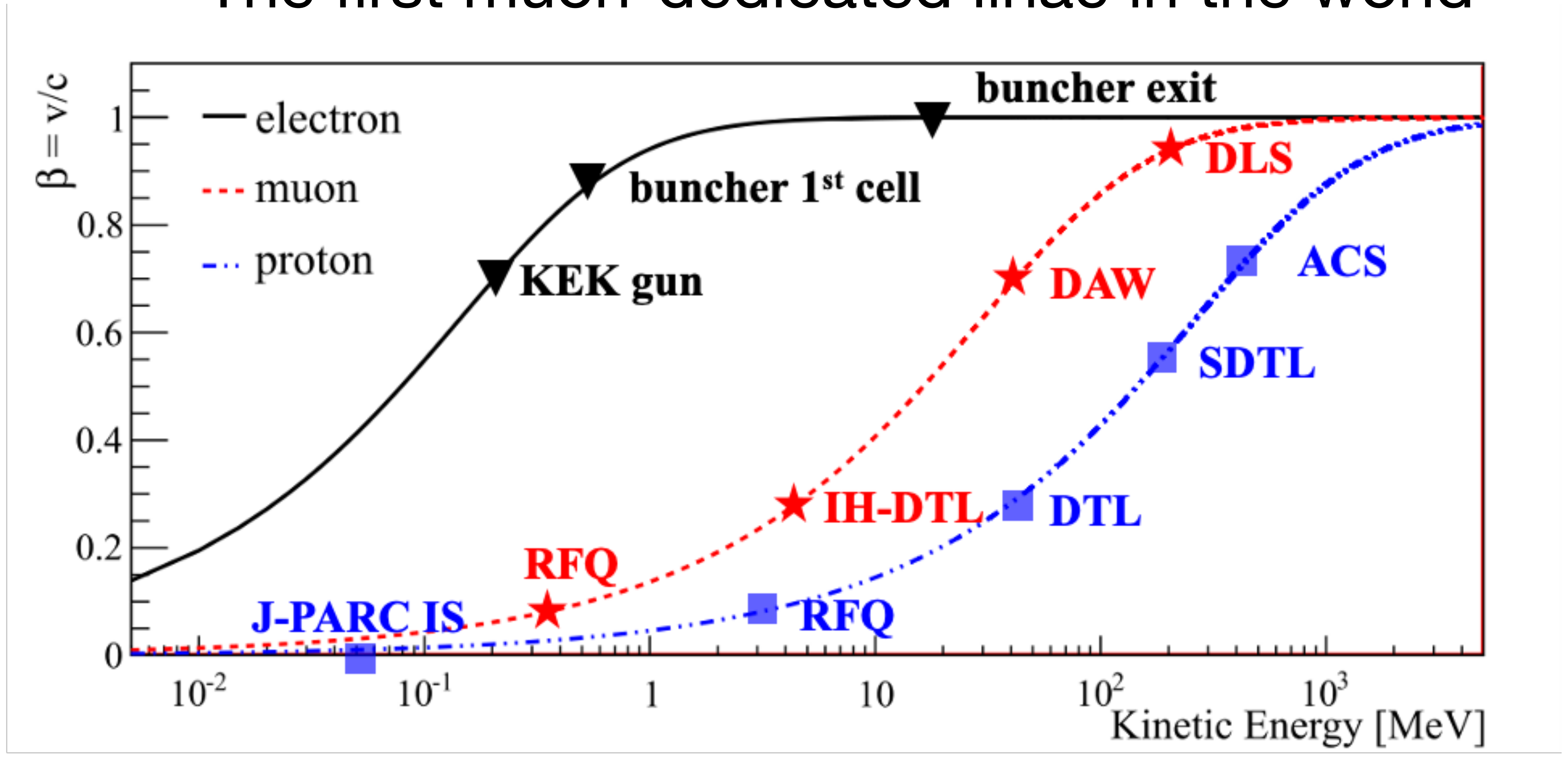
Muon Acceleration



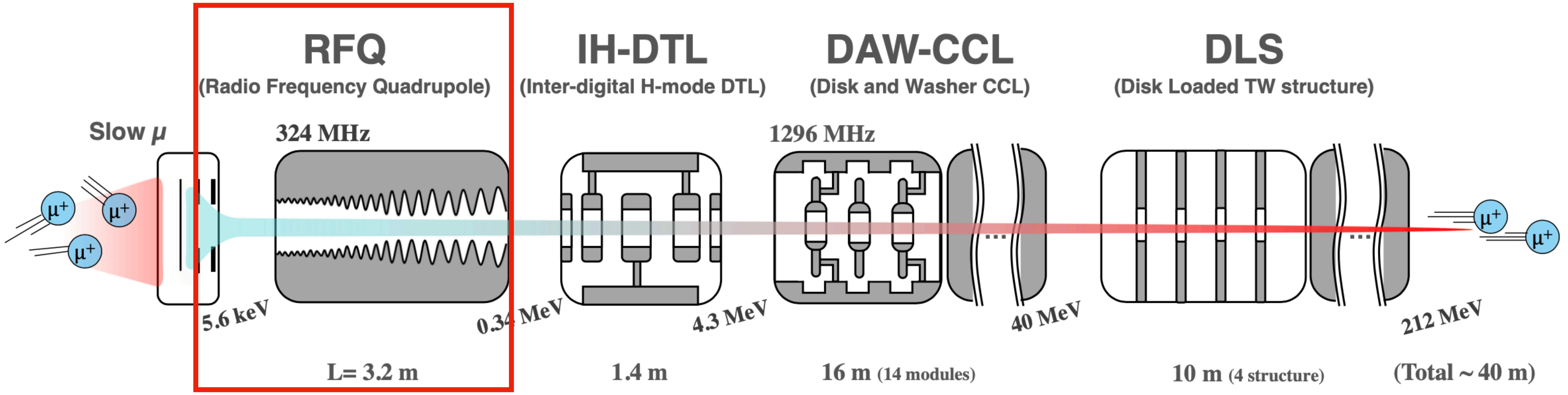
Muon LINAC parameters

Frequency (2-stage)	324MHz, 1296MHz
Intensity	1×10^6 /s
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	1.5 π mm mrad
Momentum spread	0.1 %

- The first muon-dedicated linac in the world



Muon Acceleration



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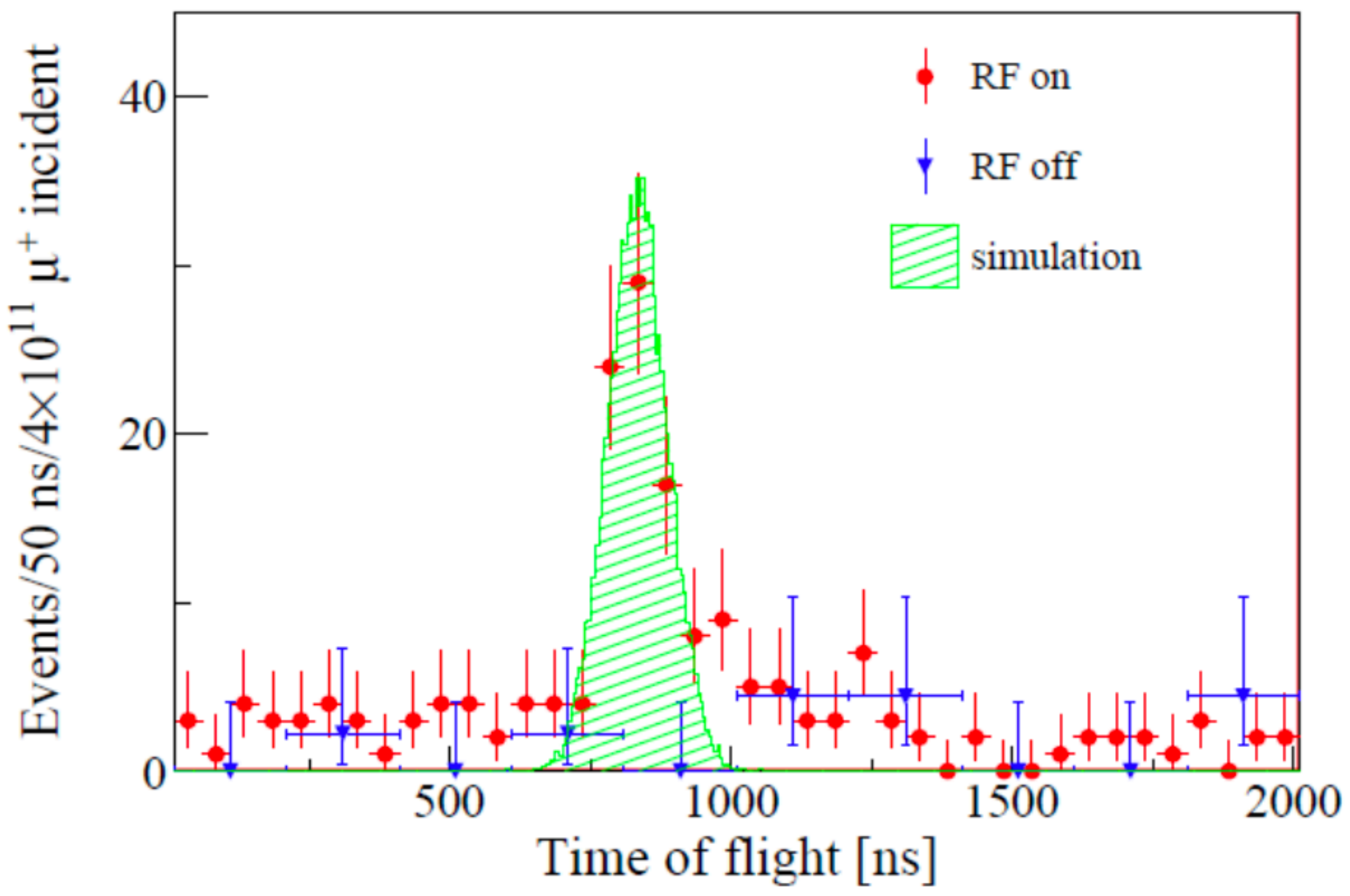
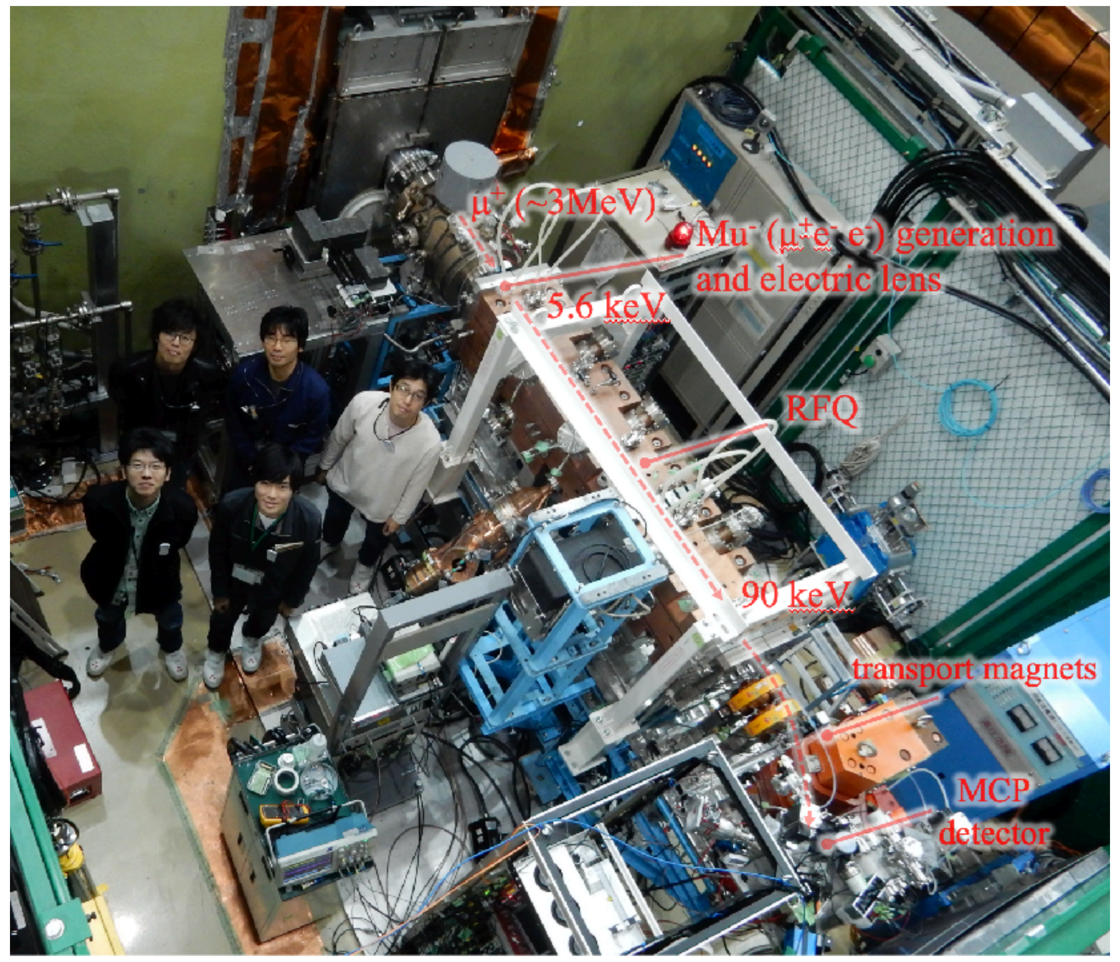
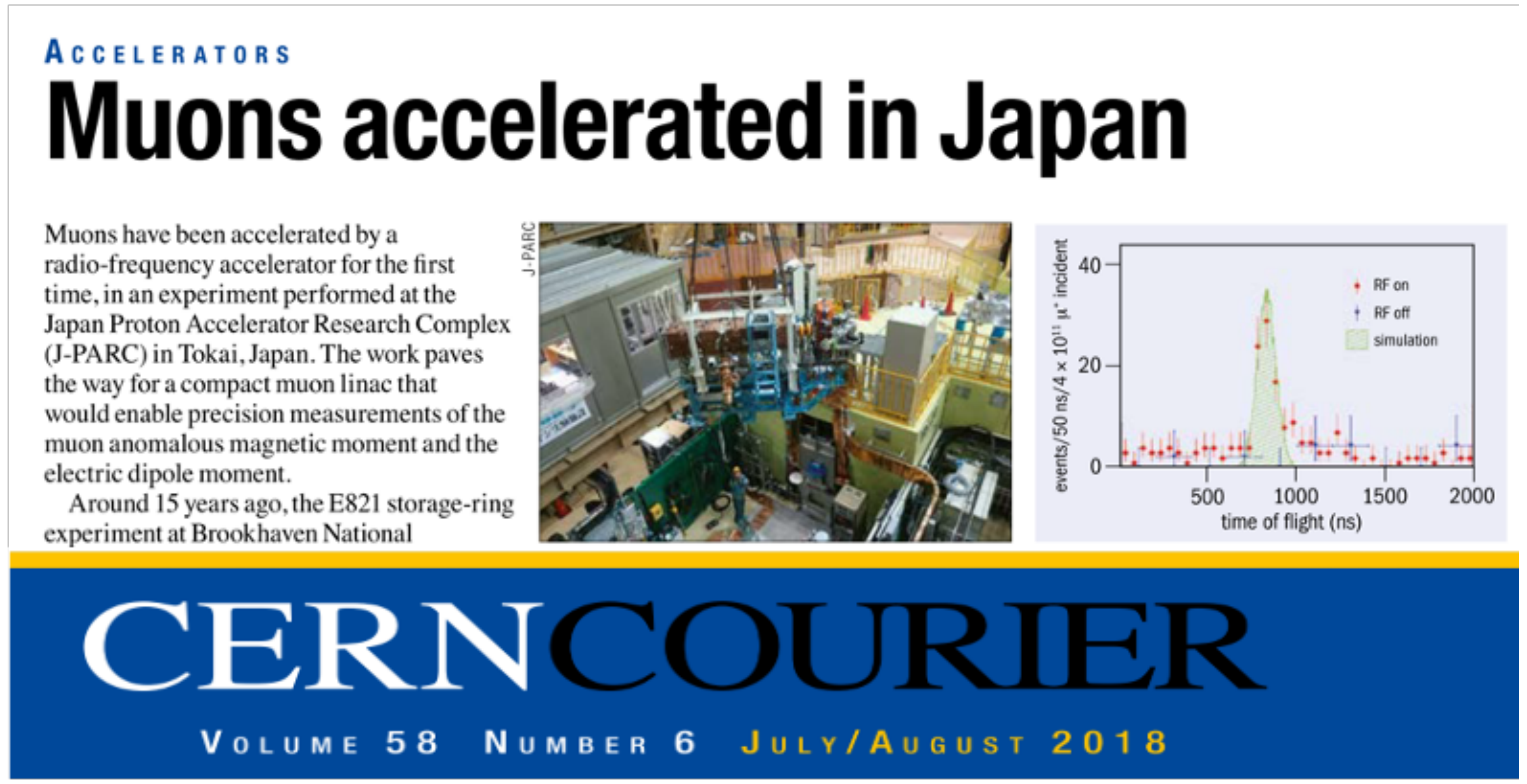
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	1.5 π mm mrad
Momentum spread	0.1 %

- **First muon acceleration using RF linac!**

Phys. Rev. Accel. Beams 21, 050101 (2018)







ACCELERATORS

Muons accelerated in Japan

Muons have been accelerated by a radio-frequency accelerator for the first time, in an experiment performed at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan. The work paves the way for a compact muon linac that would enable precision measurements of the muon anomalous magnetic moment and the electric dipole moment.

Around 15 years ago, the E821 storage-ring experiment at Brookhaven National

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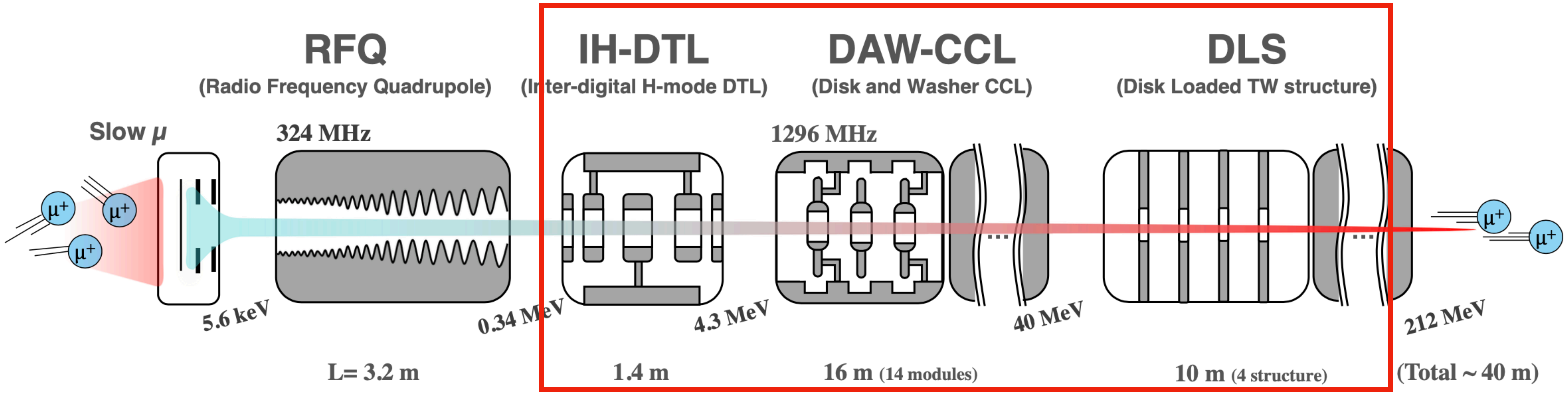
VOLUME 58 NUMBER 6 JULY/AUGUST 2018

Muon Acceleration



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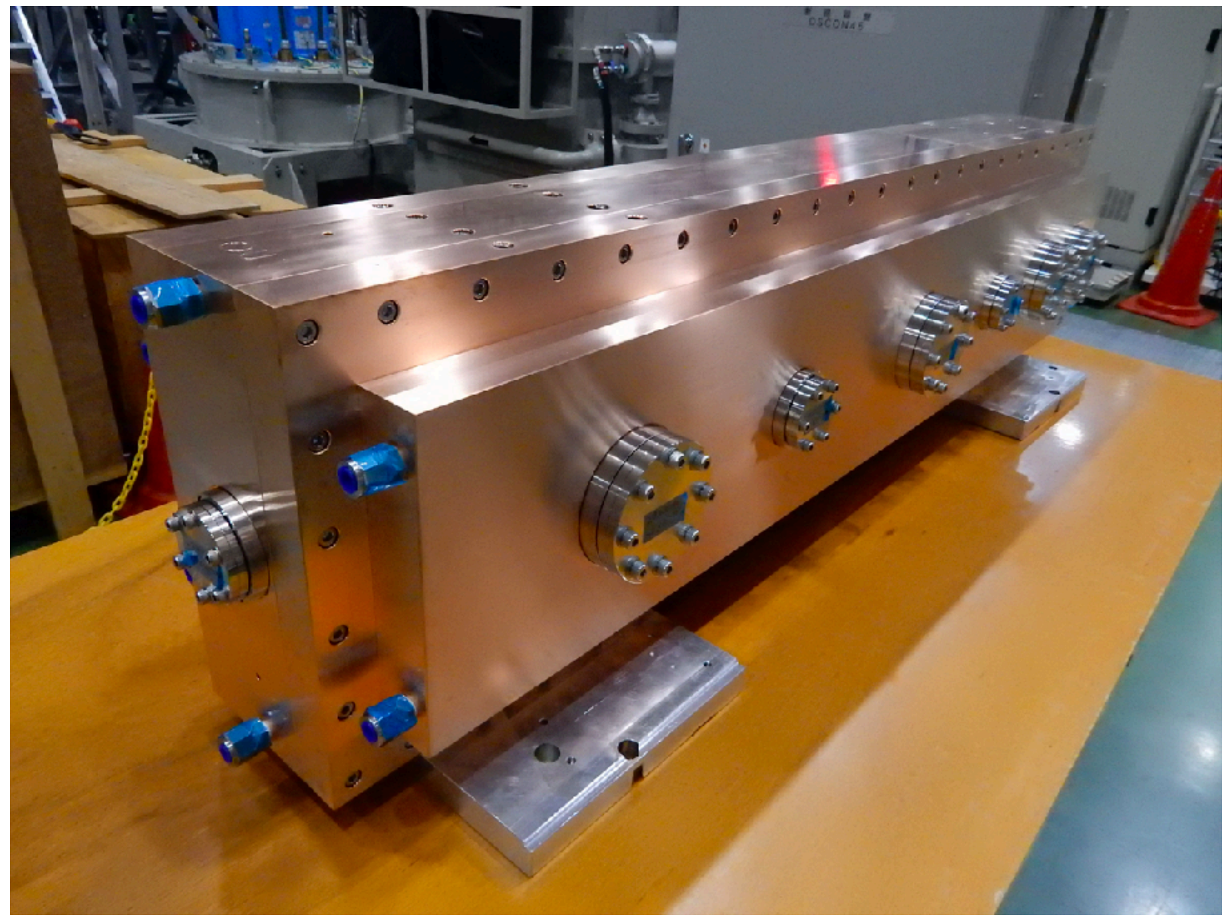
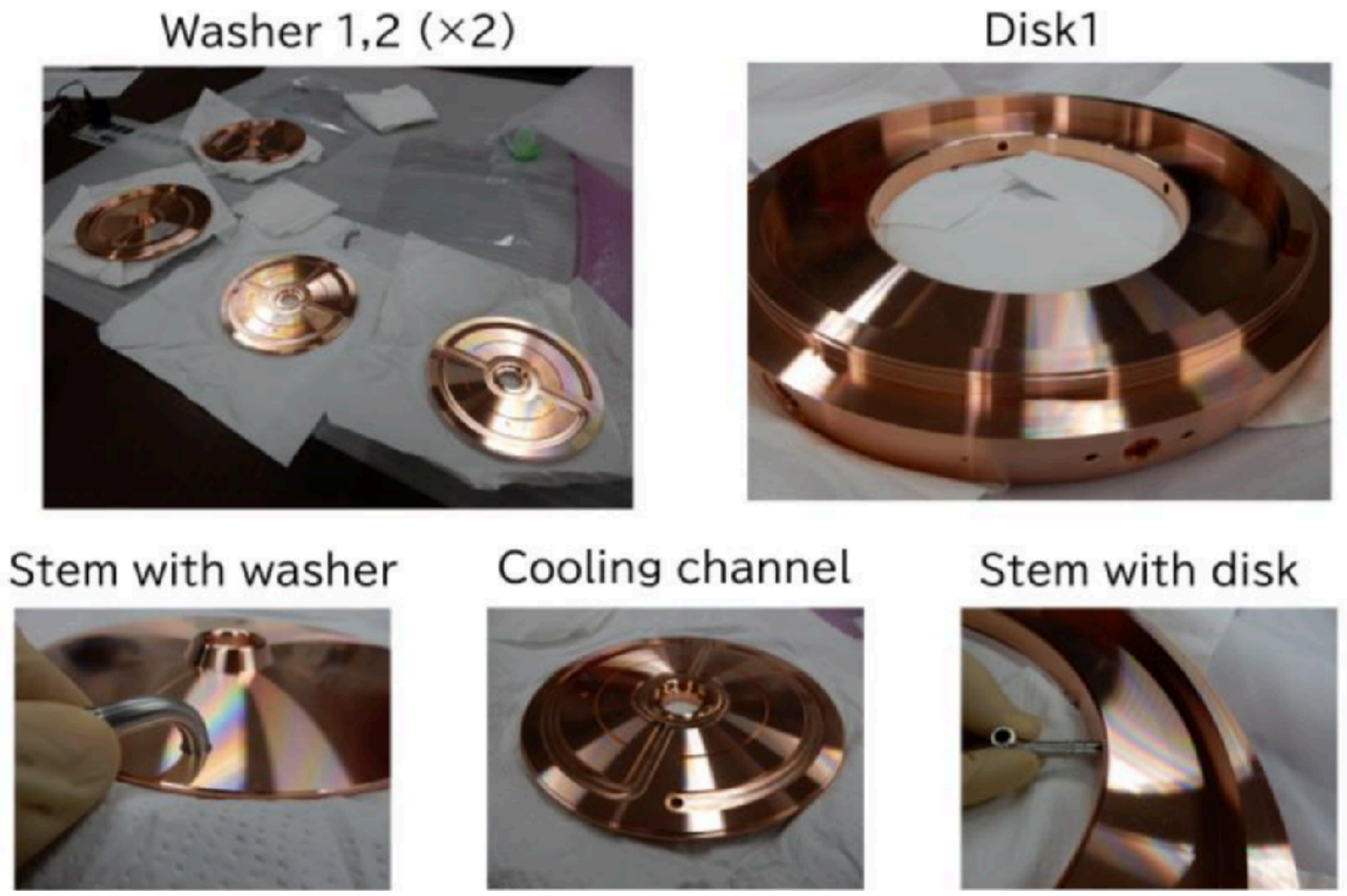
Momentum spread	0.1 %

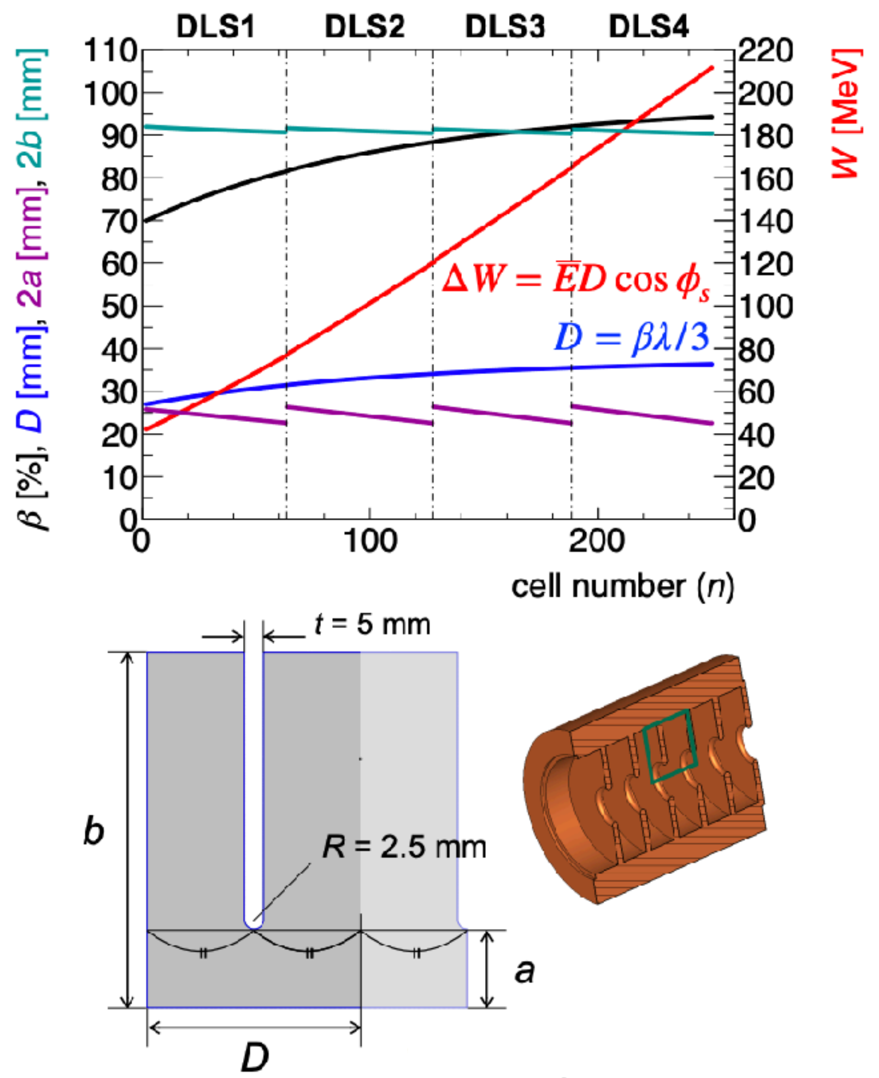
- Completed fabrication of the real IH-DTL
- Fabricating the 1st DAW tank & proto-DLS.



Real IH-DTL

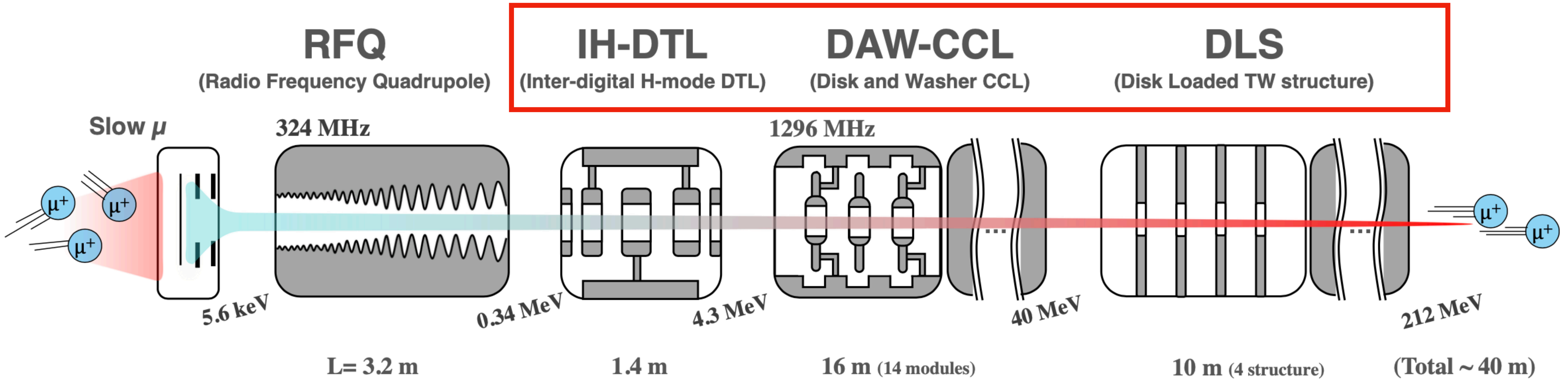


Real DAW in production



proto-DLS soon

Muon Acceleration



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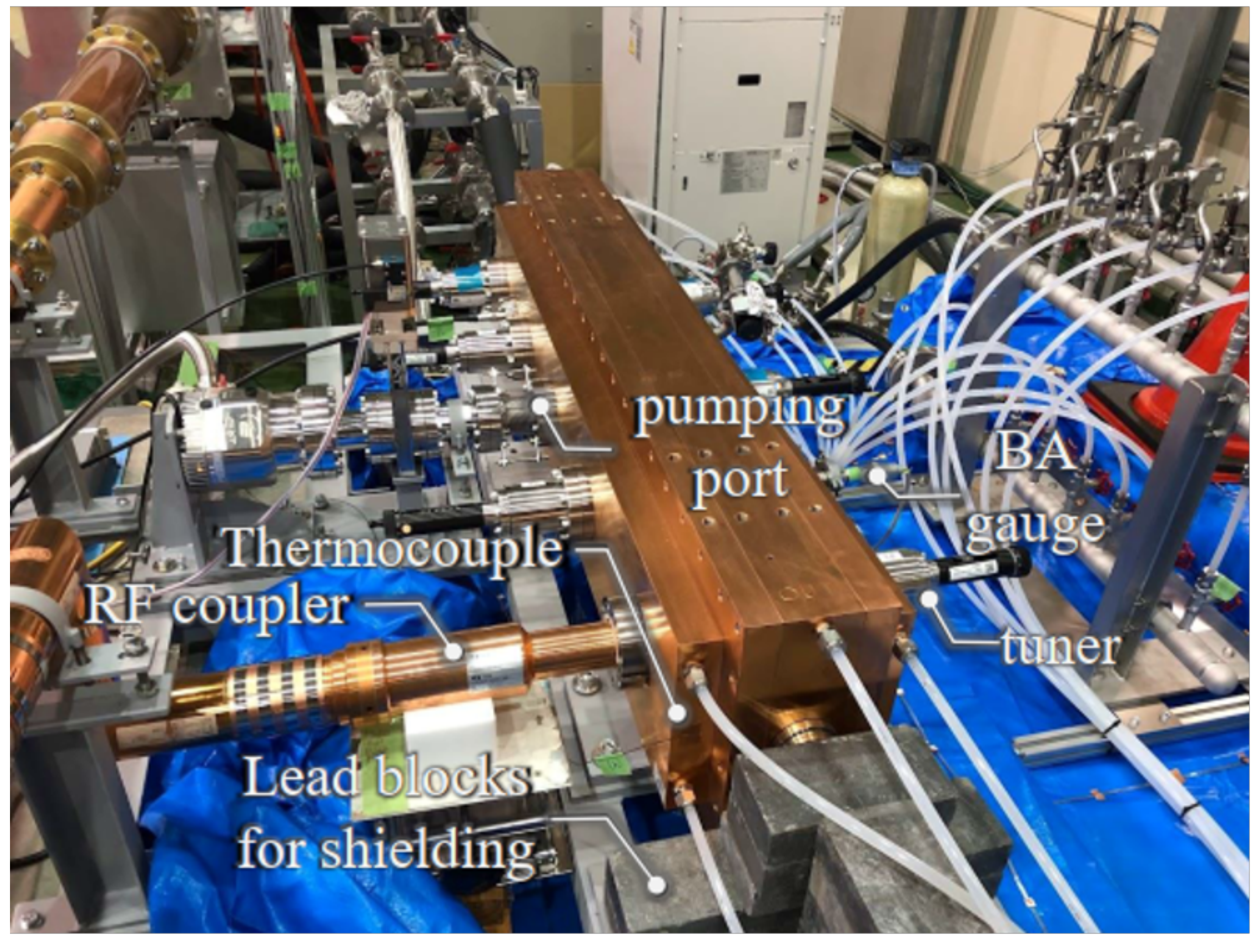
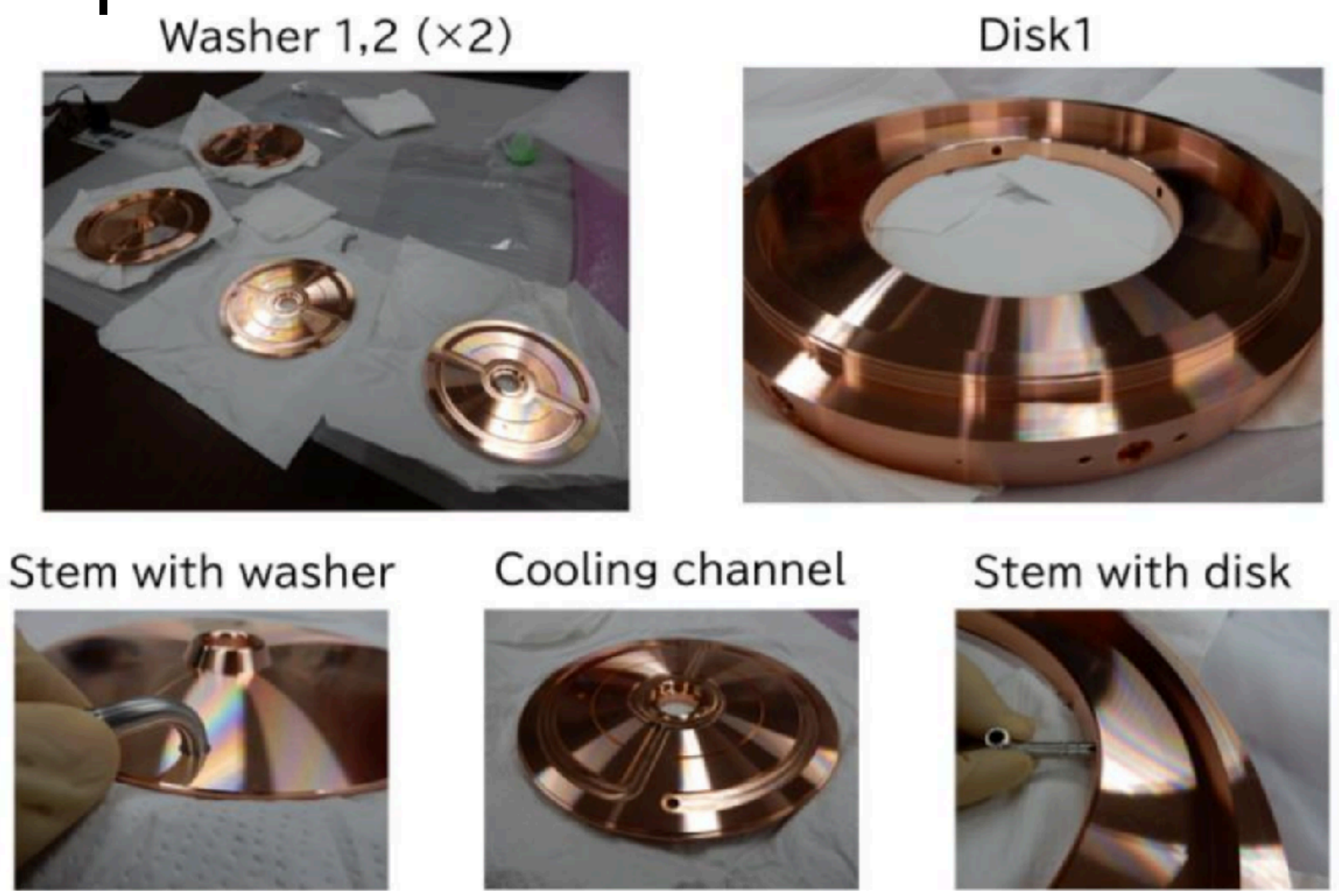
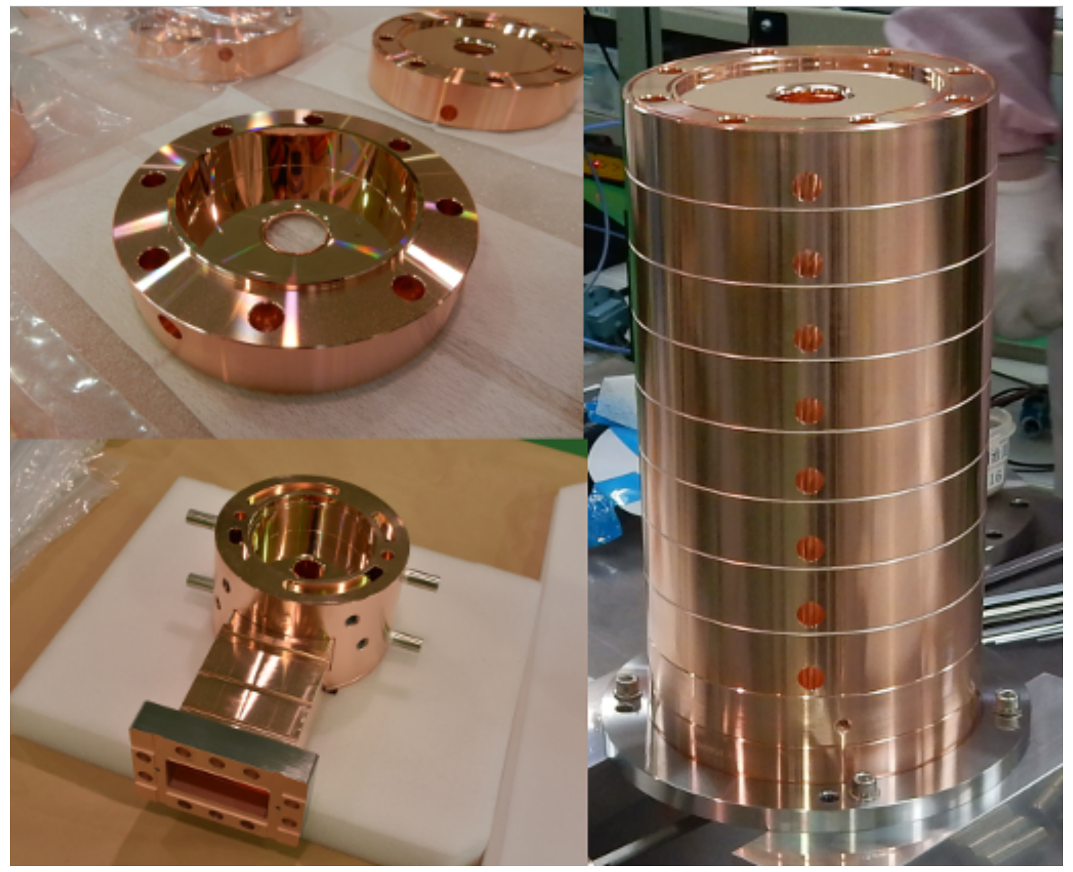
- Fabrication of the real IH-DTL completed
- Fabricating the 1st DAW tank & proton-DLS.



Real IH-DTL with high-power test



DAW ready for production

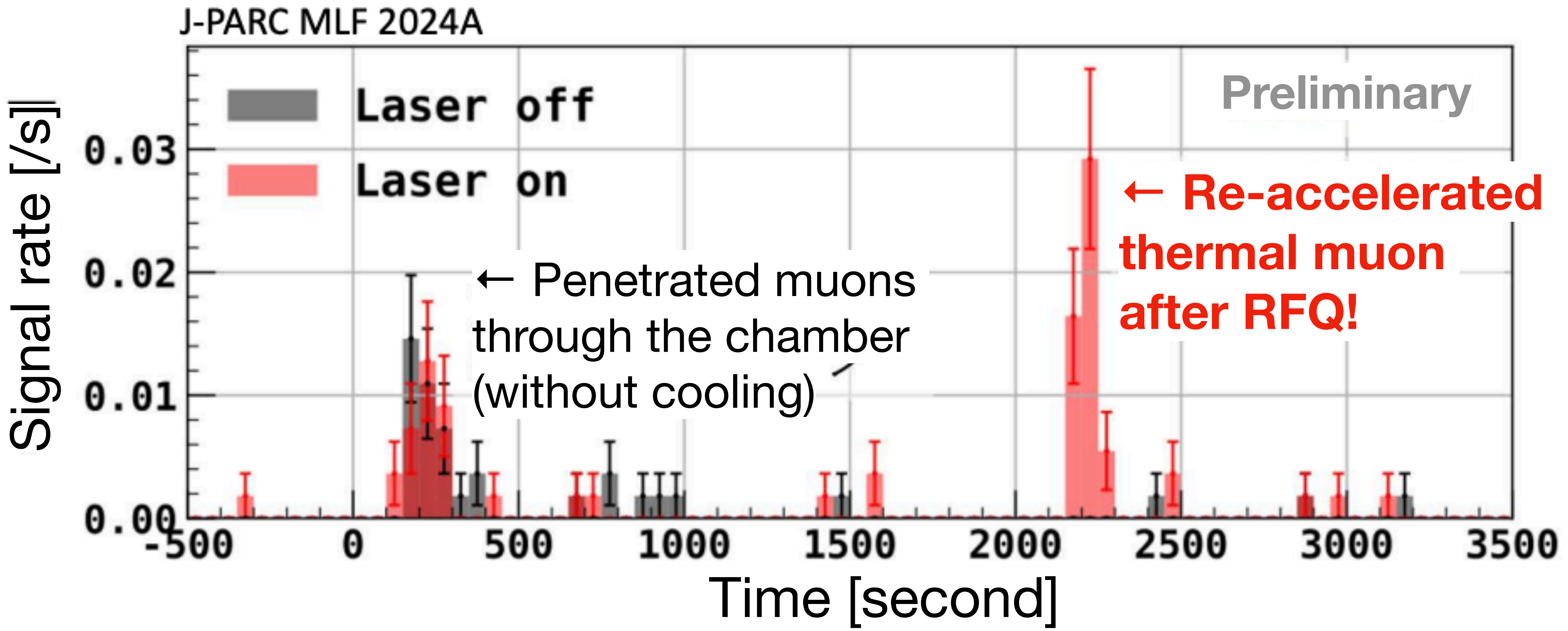


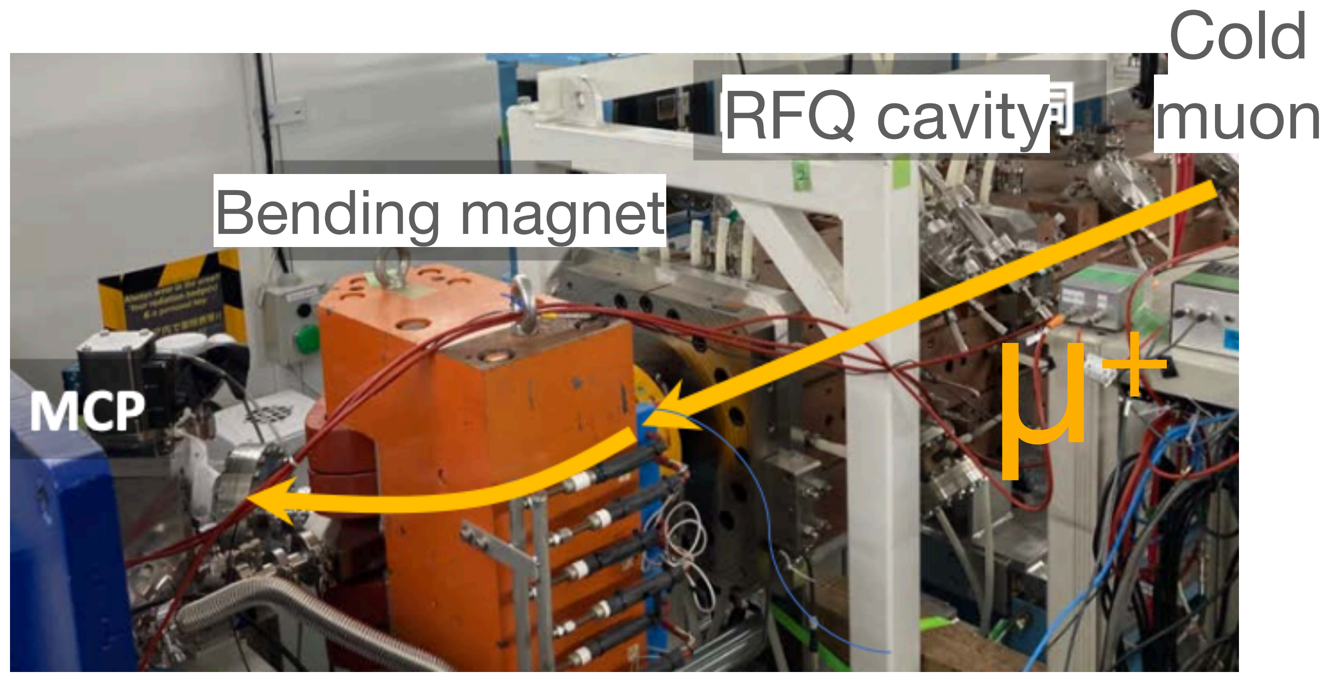
DLS prototype
(ready for production soon)

Muon Acceleration

The latest exciting result on April 2024

- The first-ever positive thermal muon RF re-acceleration to 90 keV was demonstrated at the J-PARC MLF S2 area on April 2024.





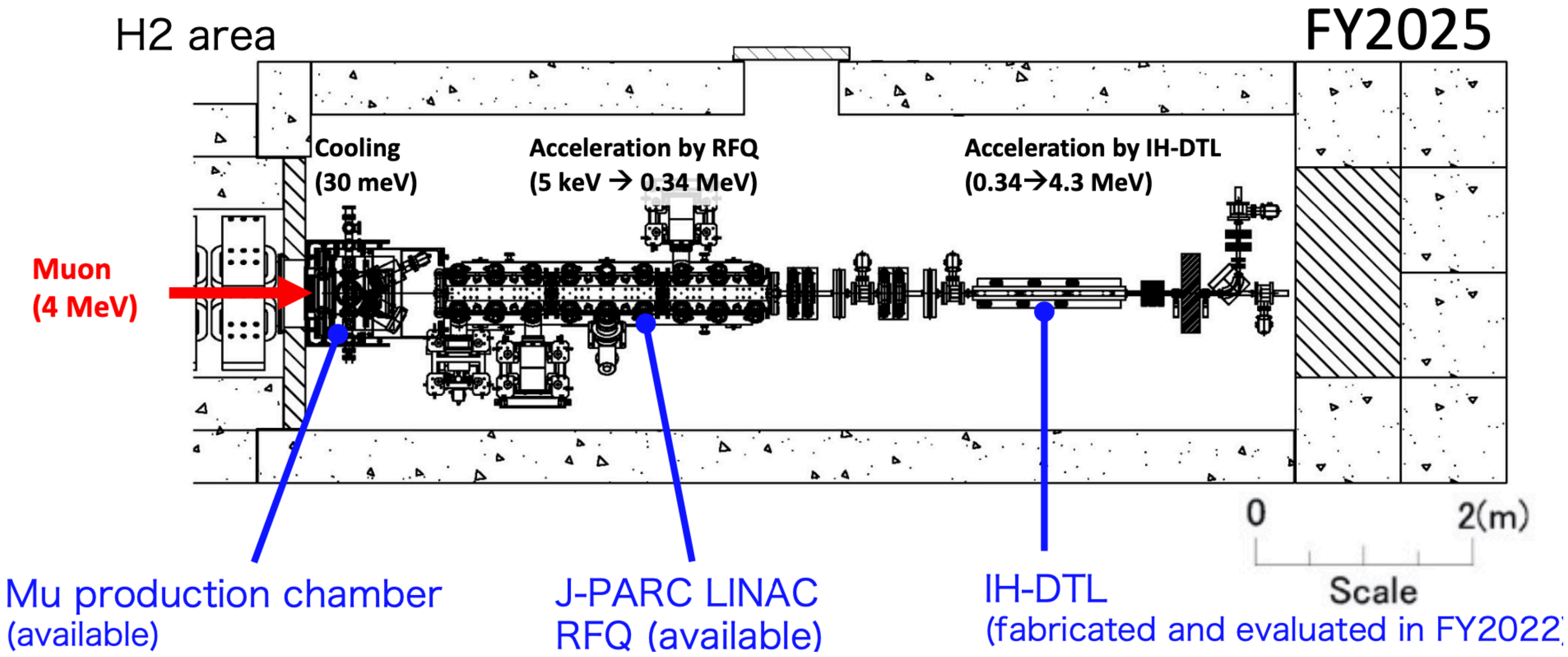
A big milestone for the experiment

Press release in English: https://j-parc.jp/c/en/press-release/2024/05/23001341.html

Muon Acceleration

Next milestone: acceleration to 4 MeV

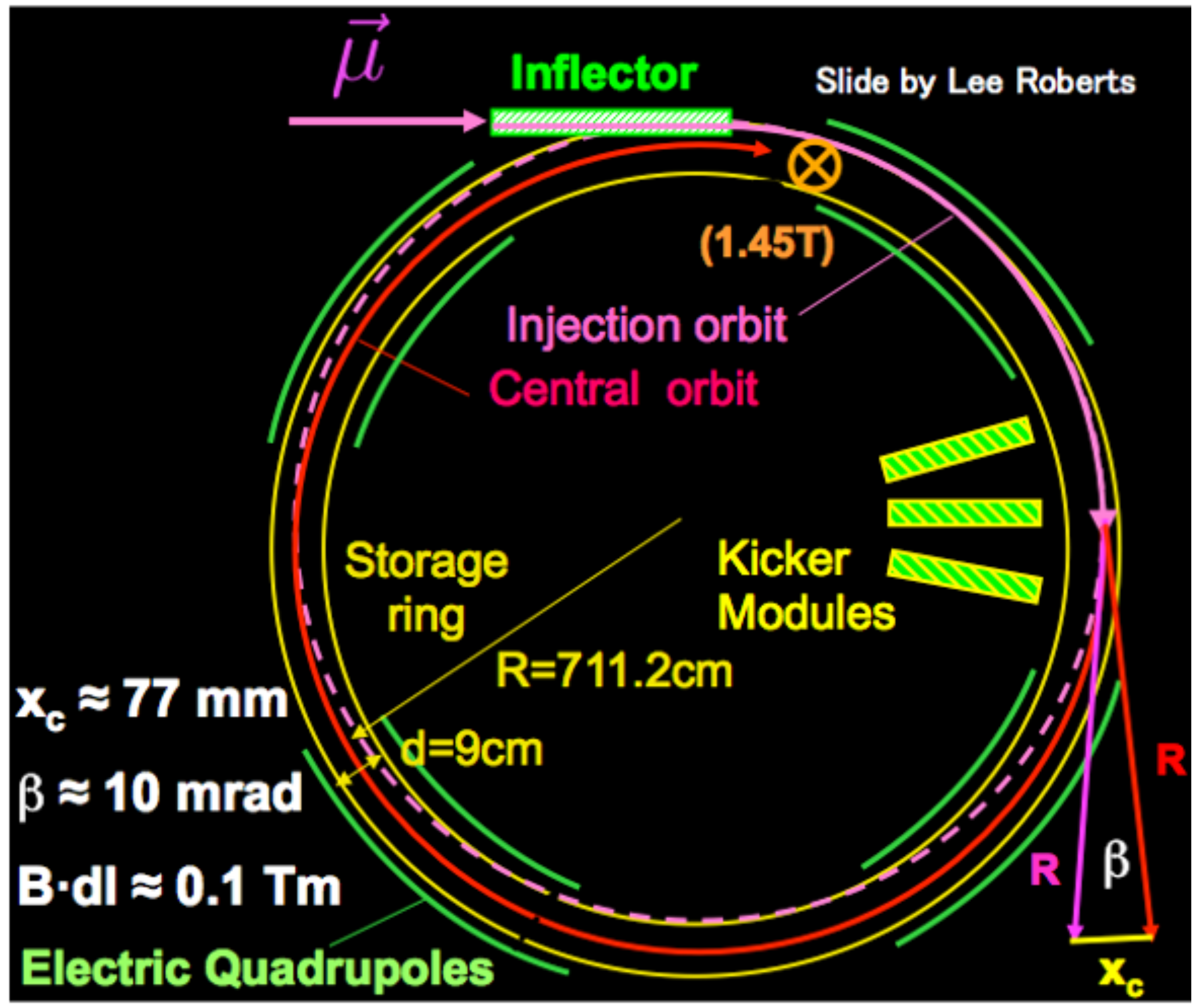
- the next step is to add IH-DTL to do further acceleration to 4 MeV at H2 area (the final experimental site)



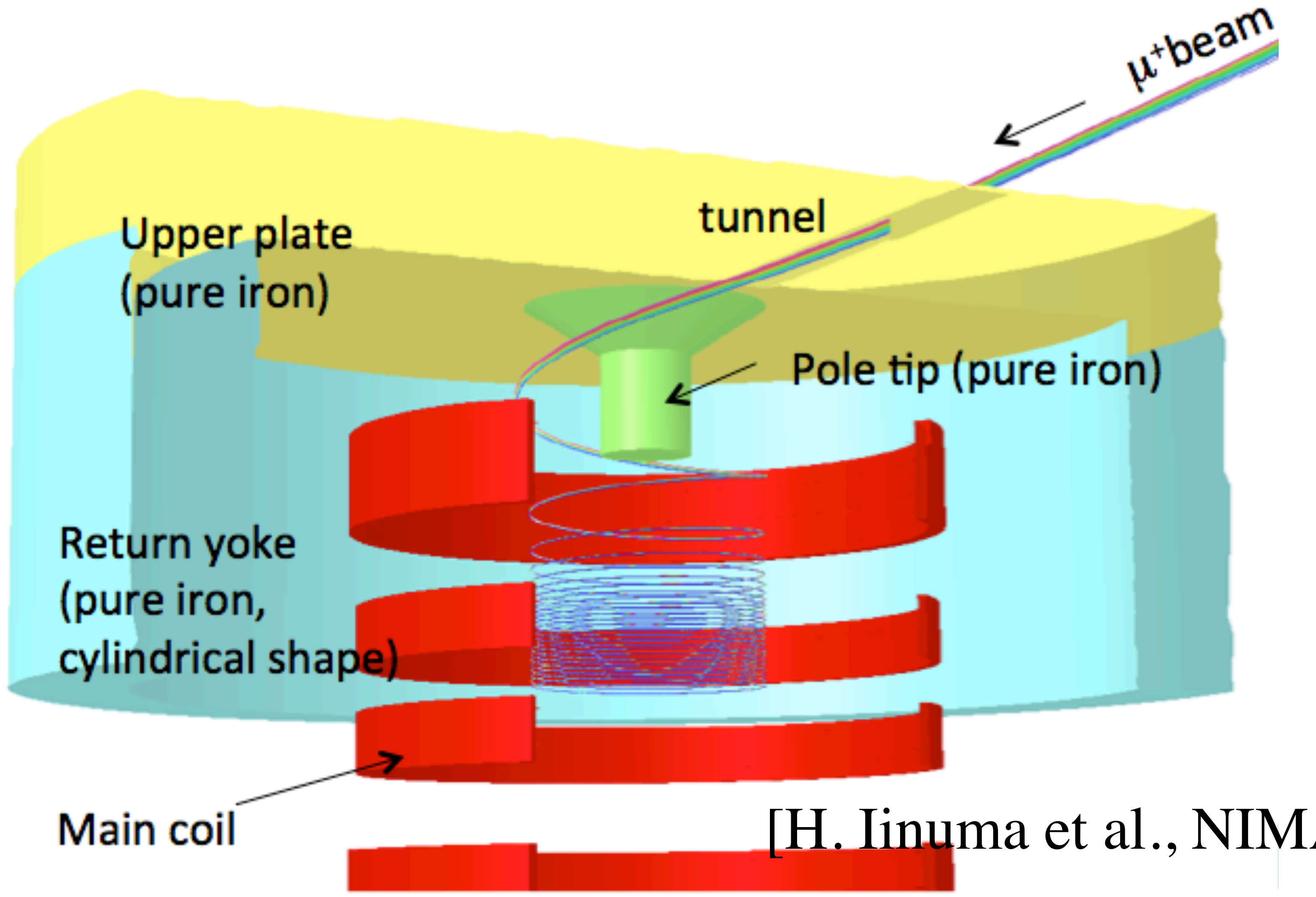
3D Spiral Injection

Why to inject the beam 3D spirally?

- The 3D spiral injection scheme has been invented for **small muon orbit**



[PRD73, 072003, 2006]



[H. Iinuma et al., NIMA 832, 51, 2016]

Conventional 2D injection @BNL and FNAL

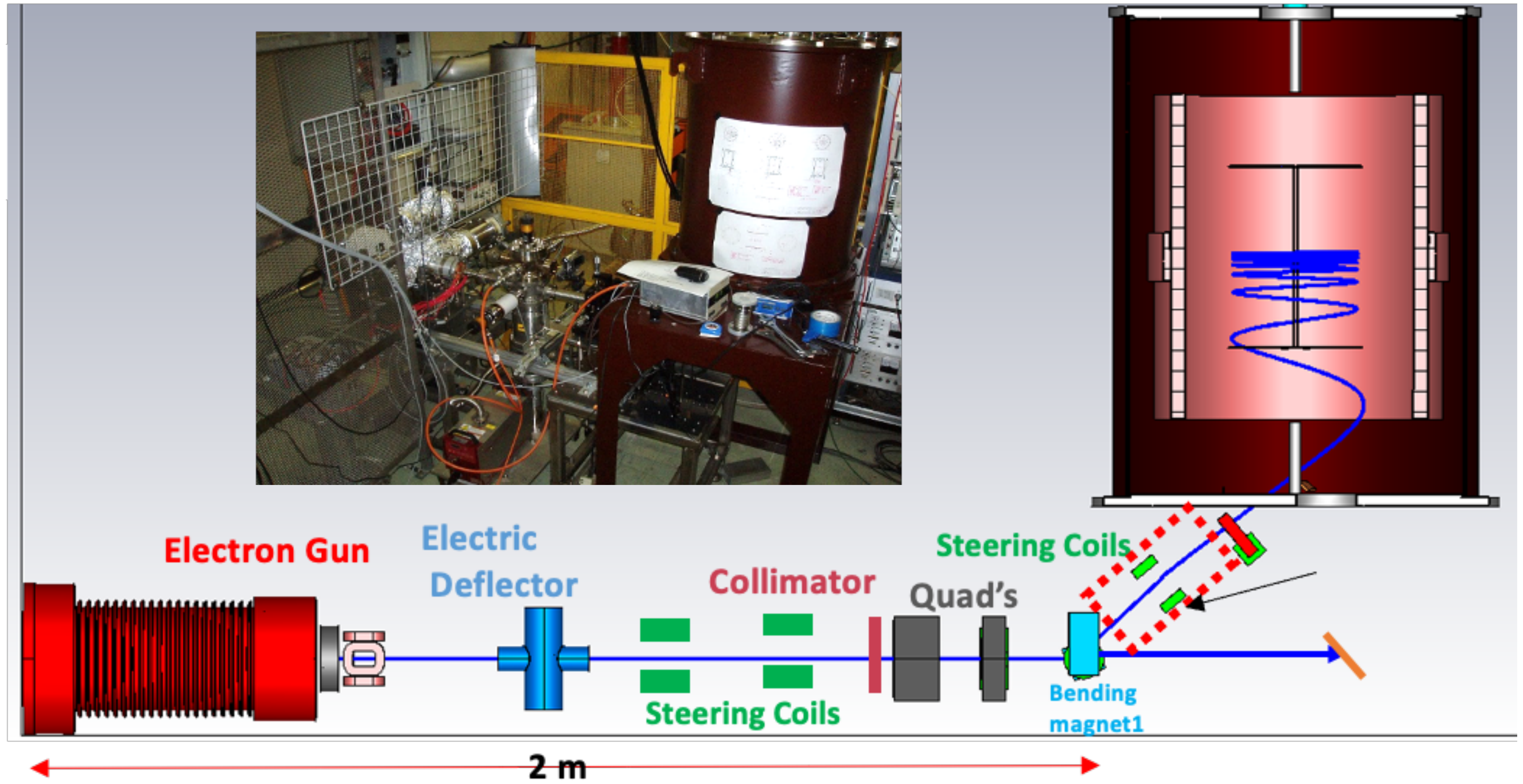
- Inflector + horizontal kicker
- Efficiency ~3-5%

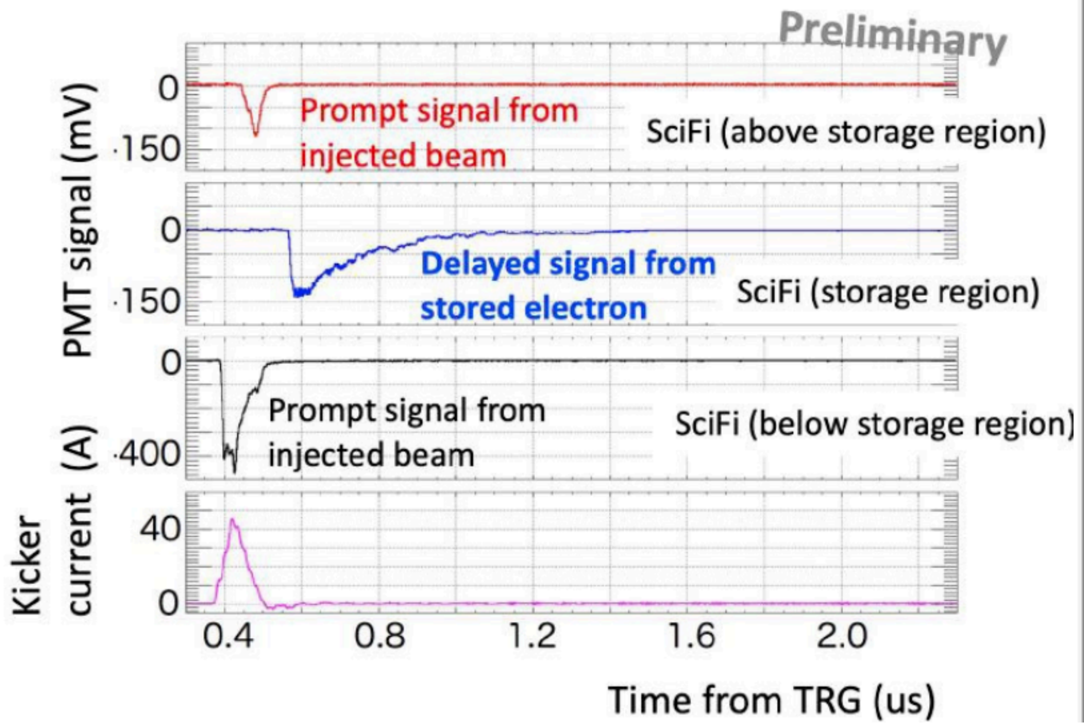
Novel injection @J-PARC

- 3D spiral injection + vertical kicker
- Efficiency > 80%
- to be adopted for the EDM @ PSI too

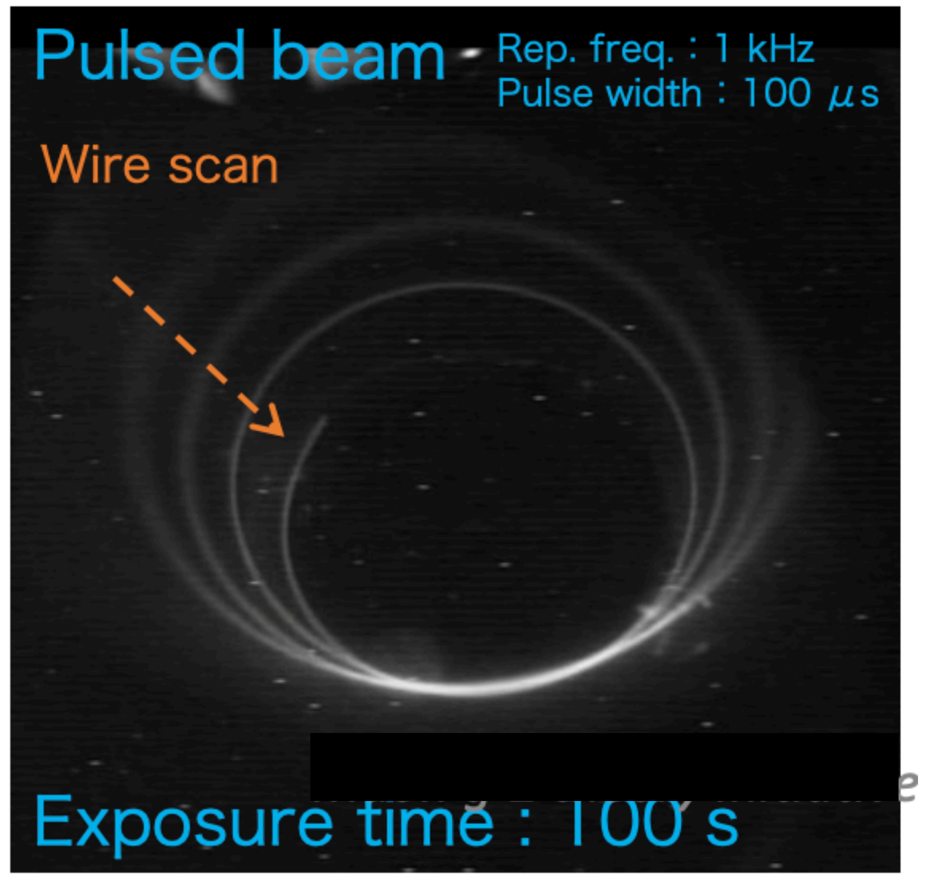
3D Spiral Injection

- Prototypes of the kicker were fabricated, and the 3D injection scheme is validated using a low momentum pulsed electron beam at KEK
- Simulation is still ongoing before finalising the design





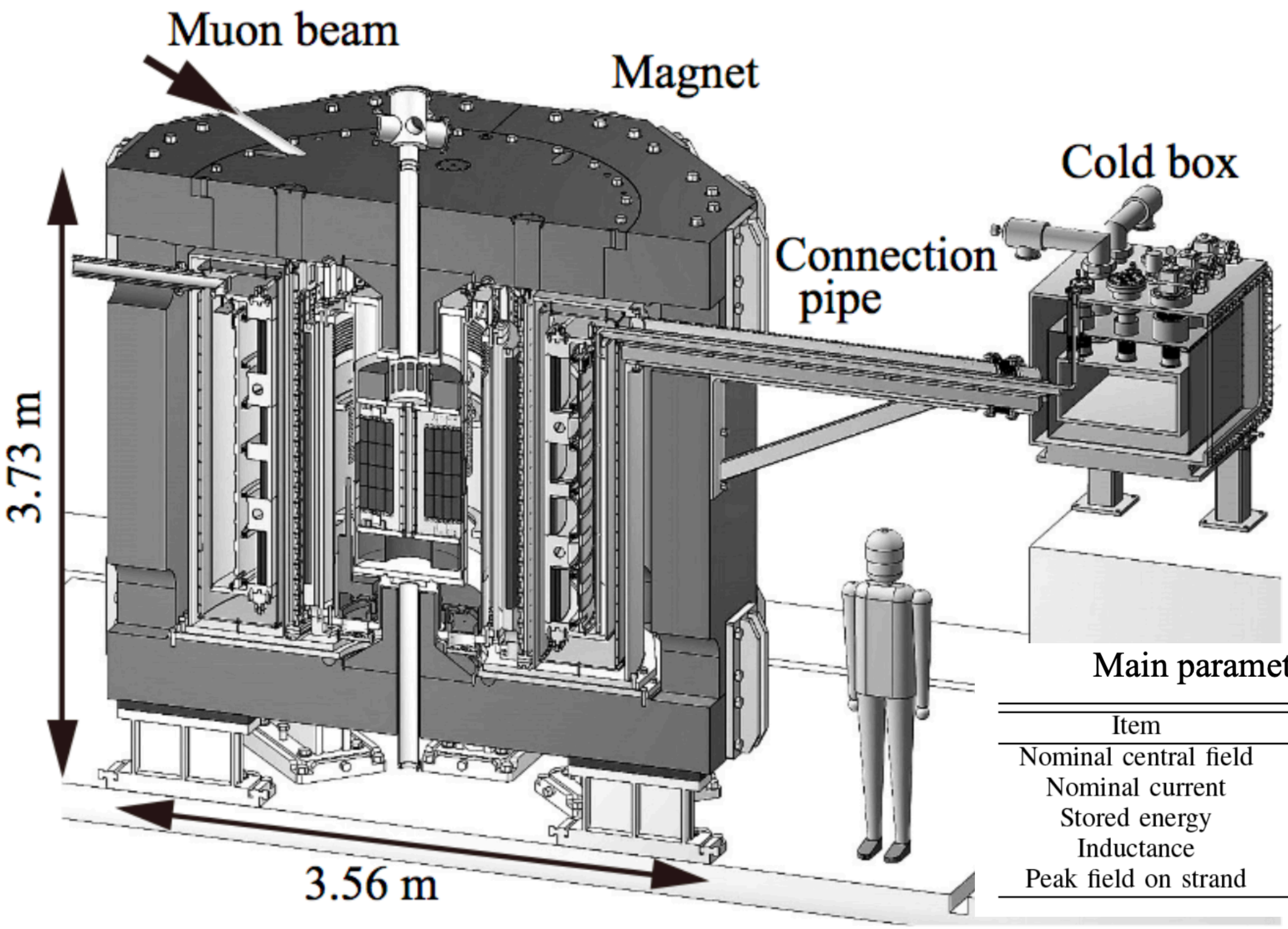
- First signal from stored electron beam was successfully observed



- Visualisation of 3D spiral geometry with a CCD camera

Storage Magnet

- **3 Tesla** MRI-type superconducting solenoid magnet is under design

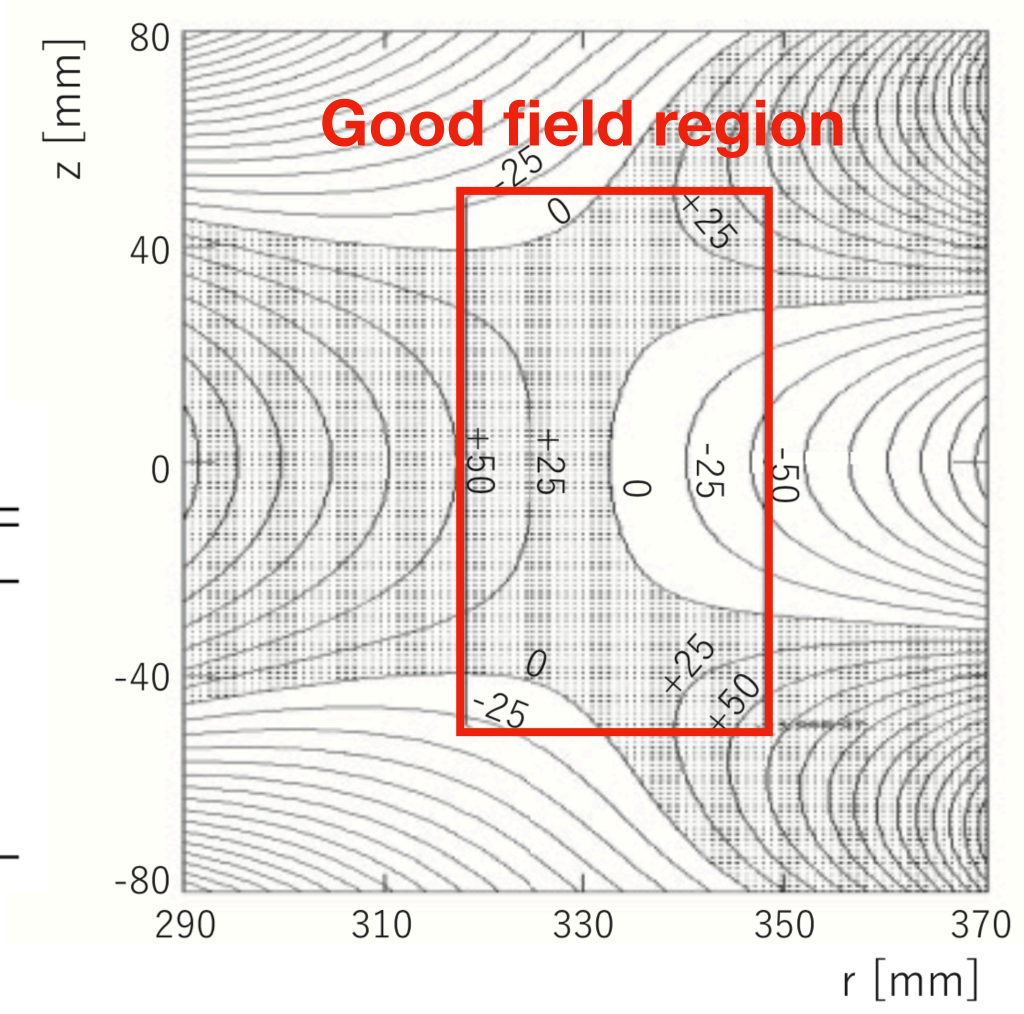


Main parameters

Item	Unit	Value
Nominal central field	T	3.0
Nominal current	A	417.5
Stored energy	MJ	14.6
Inductance	H	166.9
Peak field on strand	T	5.4

M. Abe et. al., NIM A 890, 51 (2018)

- ❖ Muon storage region:
  - ➢ radius : 33.3±1.5 cm
  - ➢ height : ±5 cm
  - ➢ Field strength : 3T
  - ➢ Uniformity : 0.1 ppm (Azimuthal integral)
- ❖ Injection region :
  - ➢ Smooth field for beam injection
- ❖ Weak focus field: -5e-4 T/m of Br at maximum



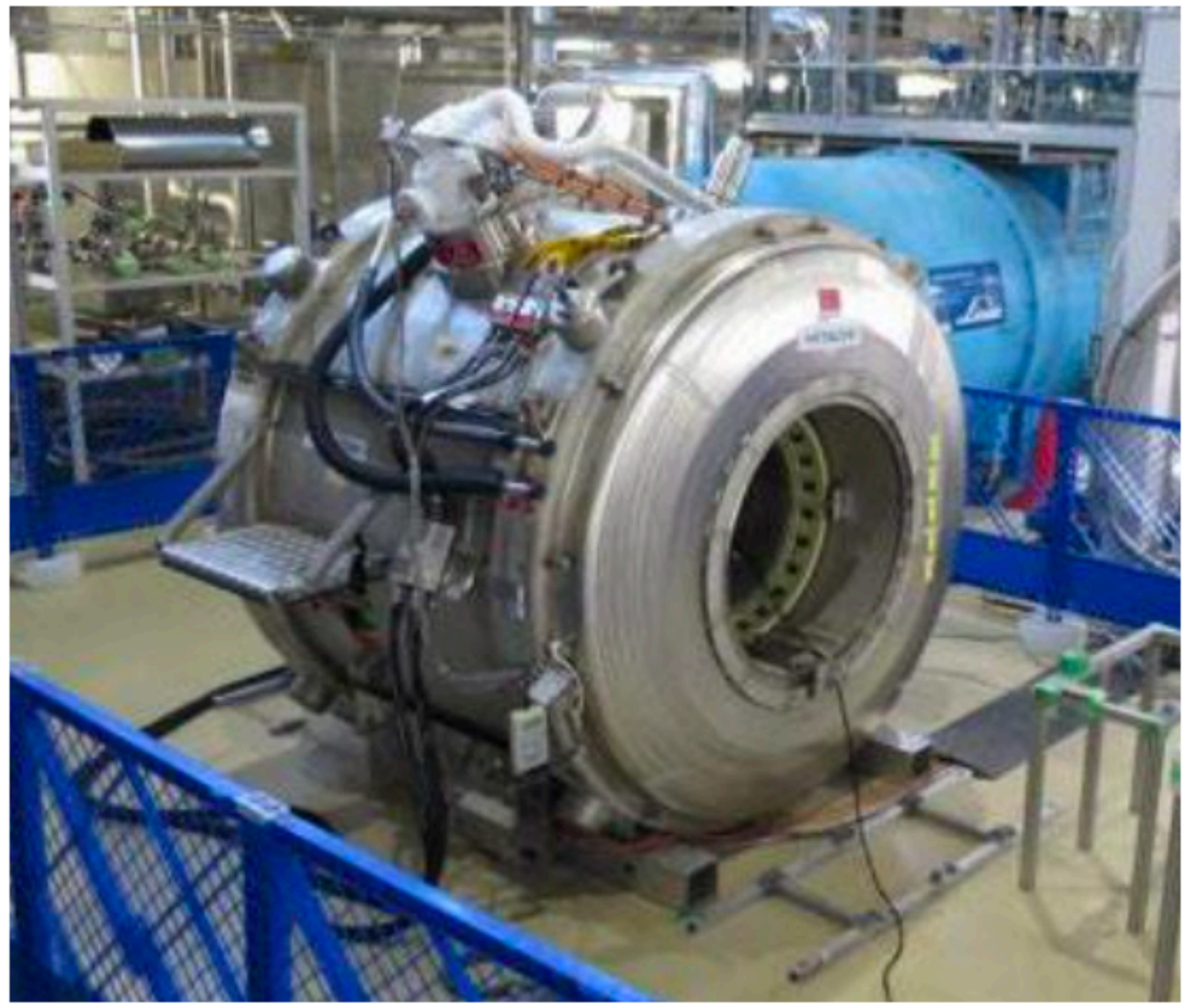
Average magnetic field uniformity is better than 0.1 ppm

25 ppb/line

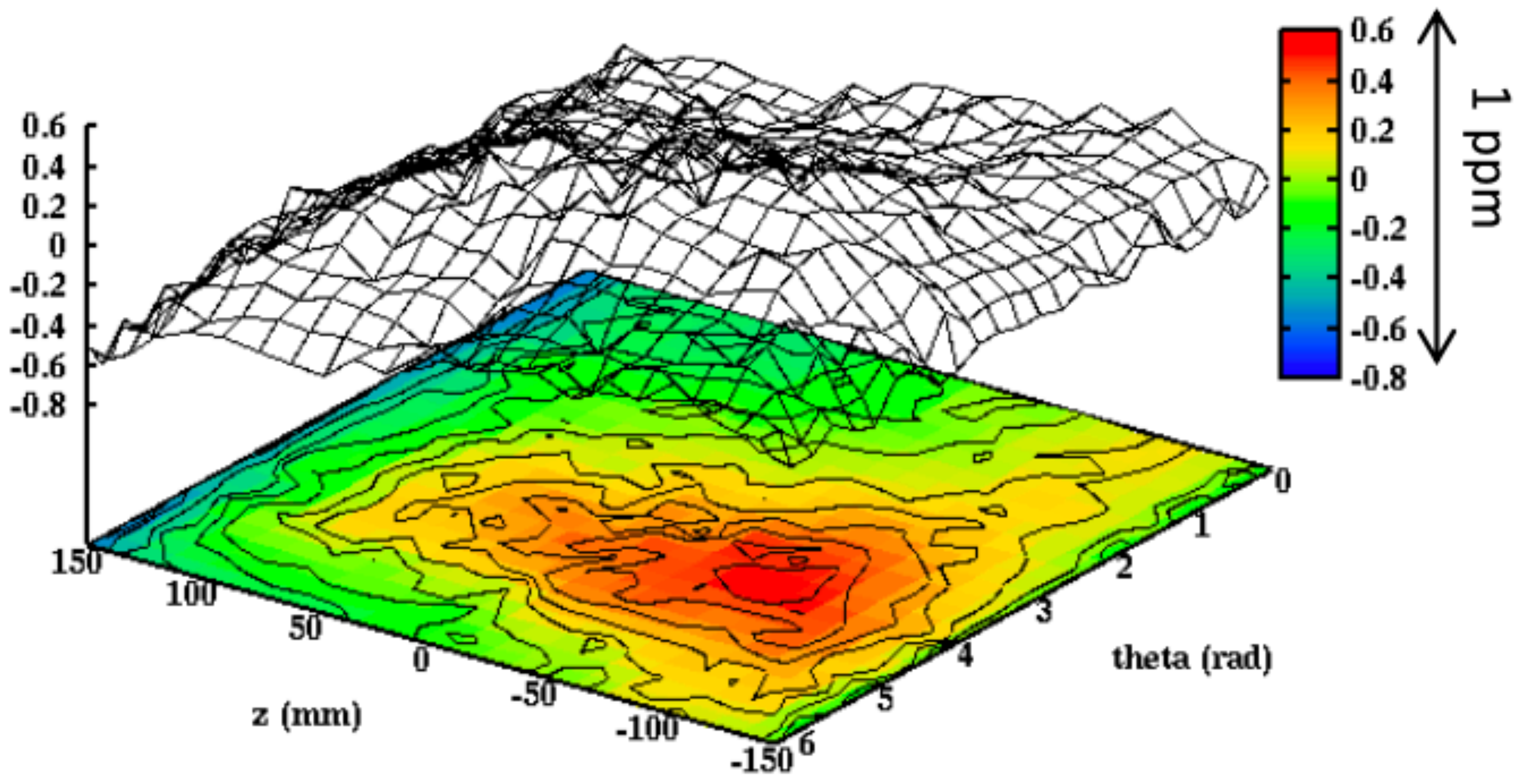
Storage Magnet

Magnetic Field Calibration

- Local uniformity of 1 ppm was demonstrated by the MUSEUM experiment magnet at **1.2 T**; further tests will be carried out at **3 T.**
- In the **cross-calibration of FNAL and J-PARC** field probes at ANL, ~7 ppb agreement was obtained with 15 ppb uncertainties.



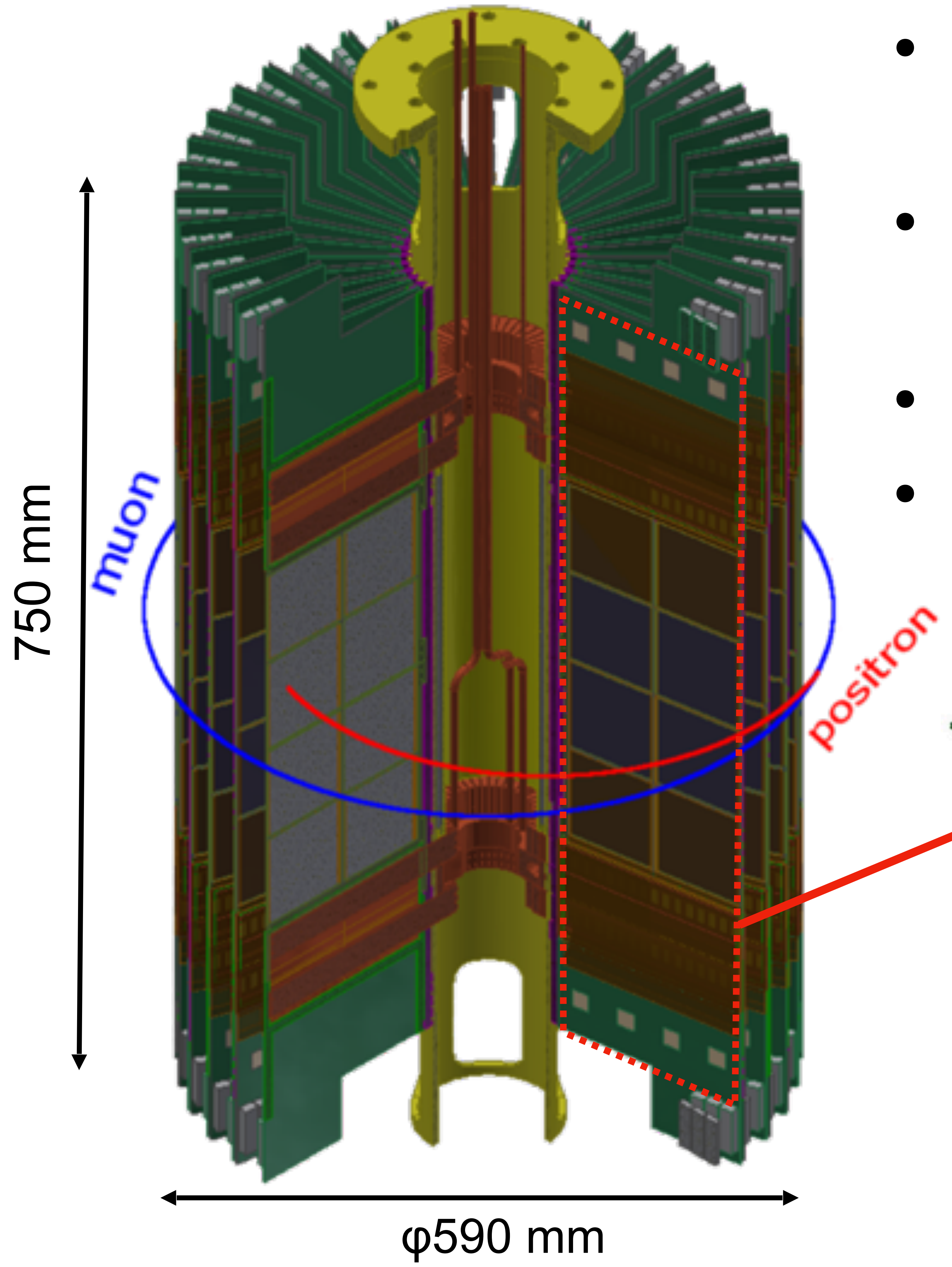
MRI magnet for MuSEUM experiment



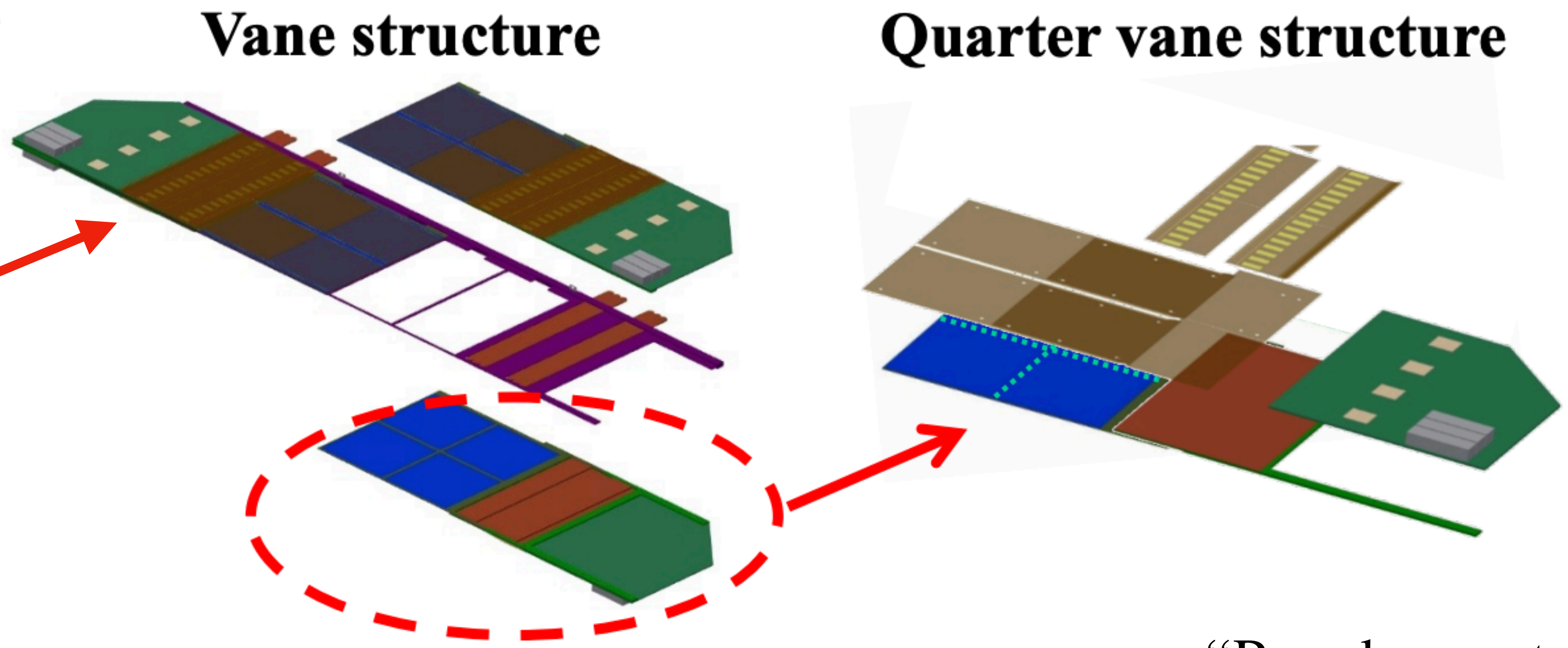
Magnetic field after shimming

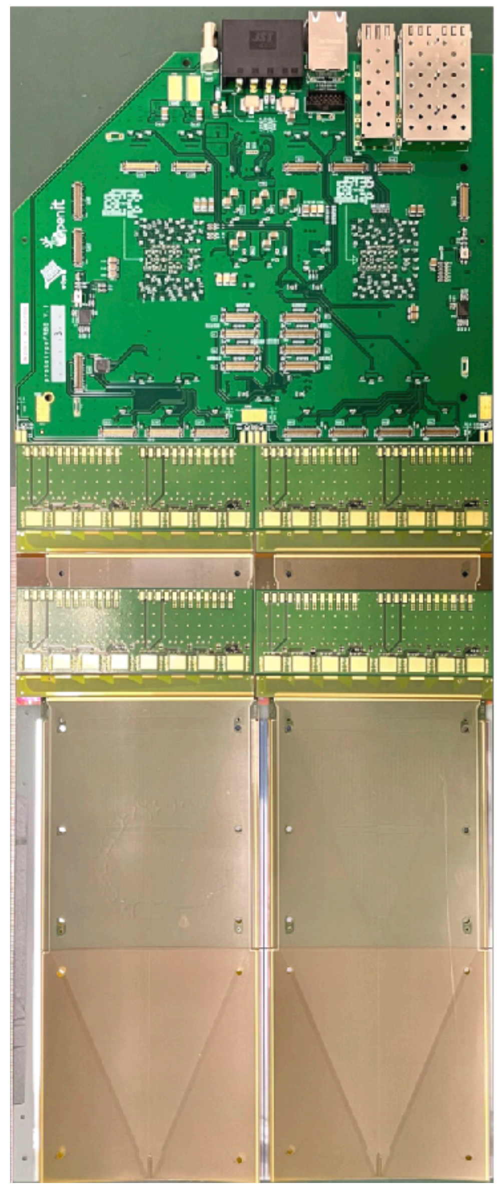
Cross calibration at ANL in January 2019

Positron Tracking Detector



- Positrons tracks are reconstructed from hits in radially arranged detector modules (Vane).
- Consists of **40** radial rectangle modules. A quarter vane consists of **4 silicon sensors + 32 readouts ASICs.**
- Mass production is ongoing.
- Operation test in a high magnetic field in 2023.

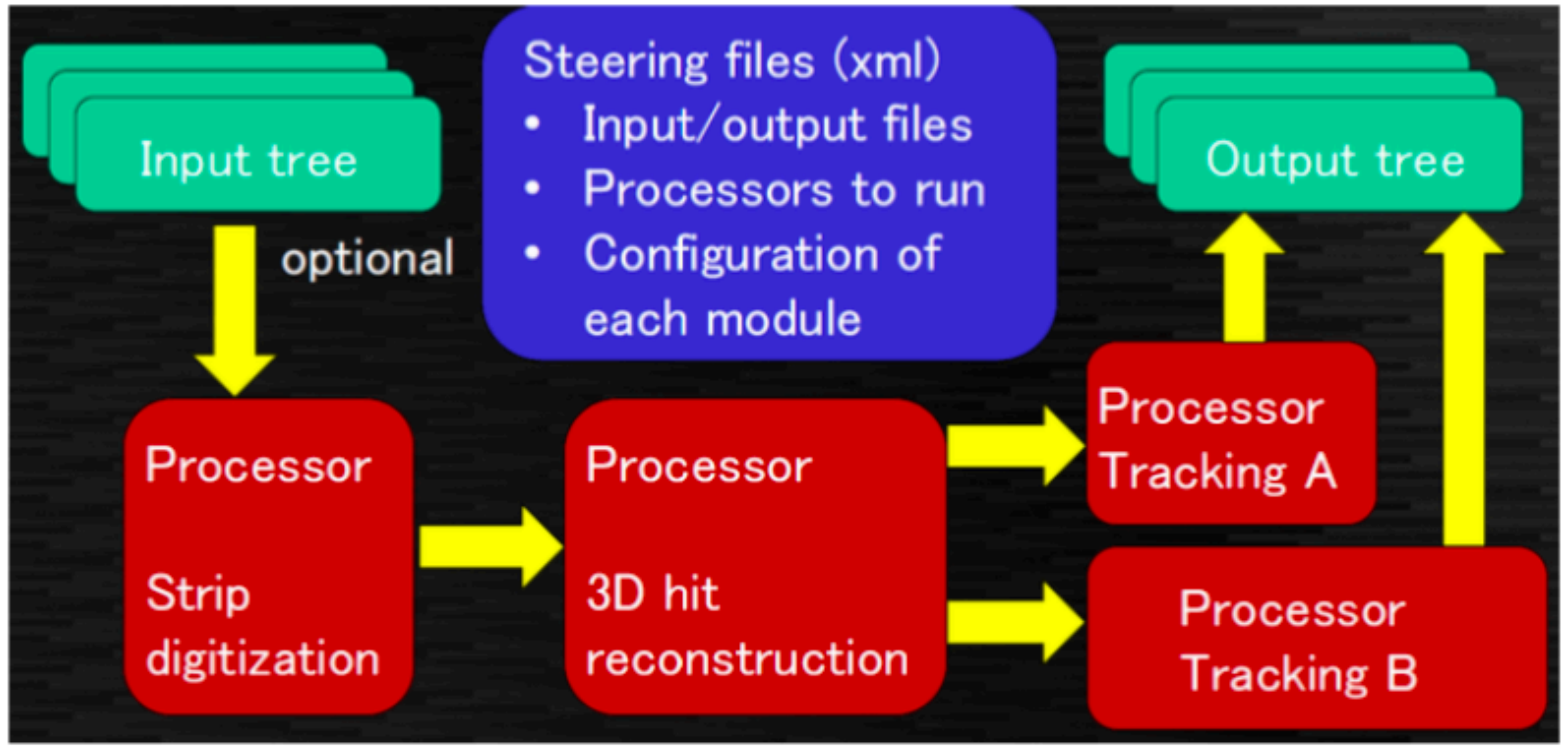




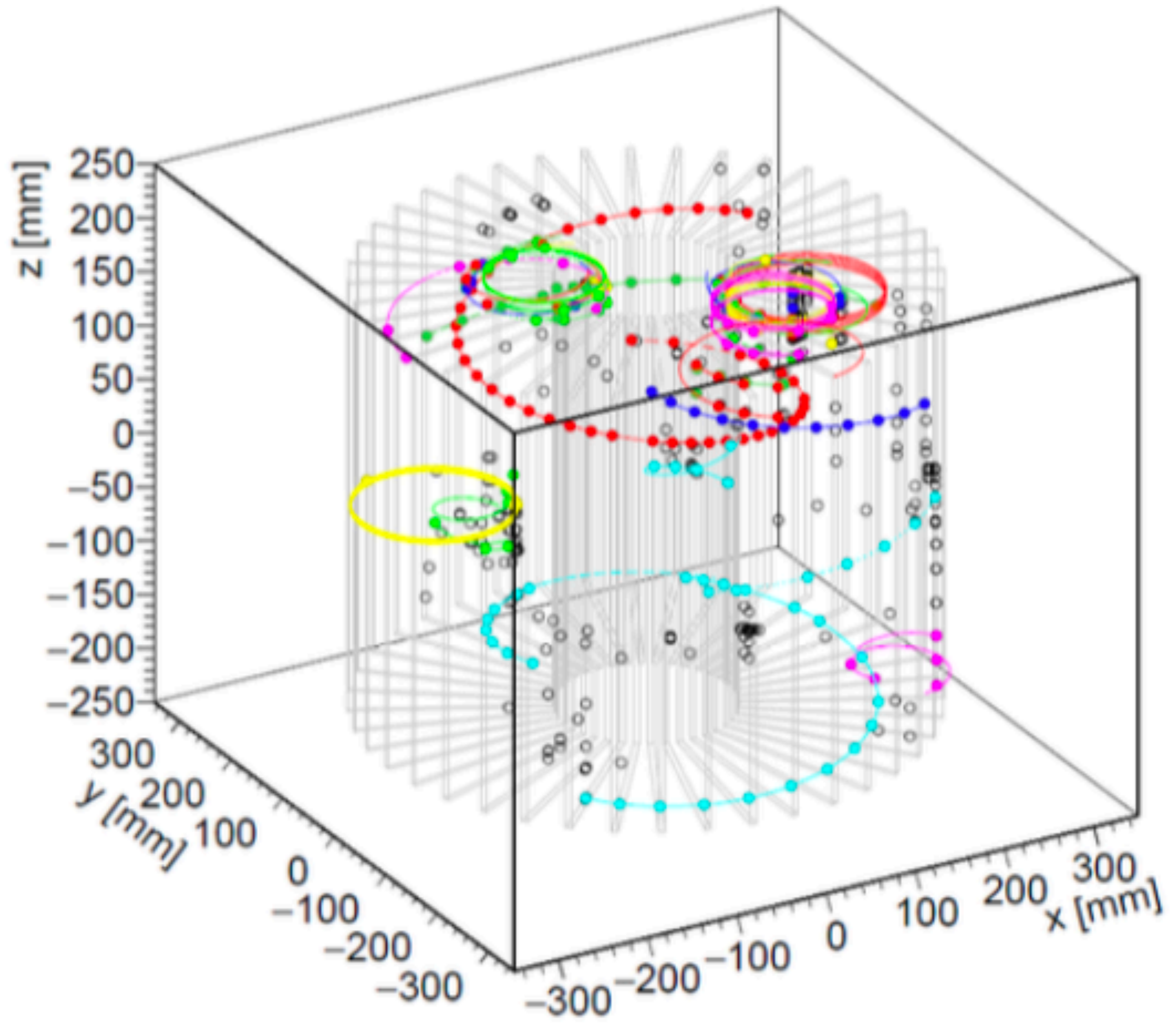
"Pseudo-quarter vane"

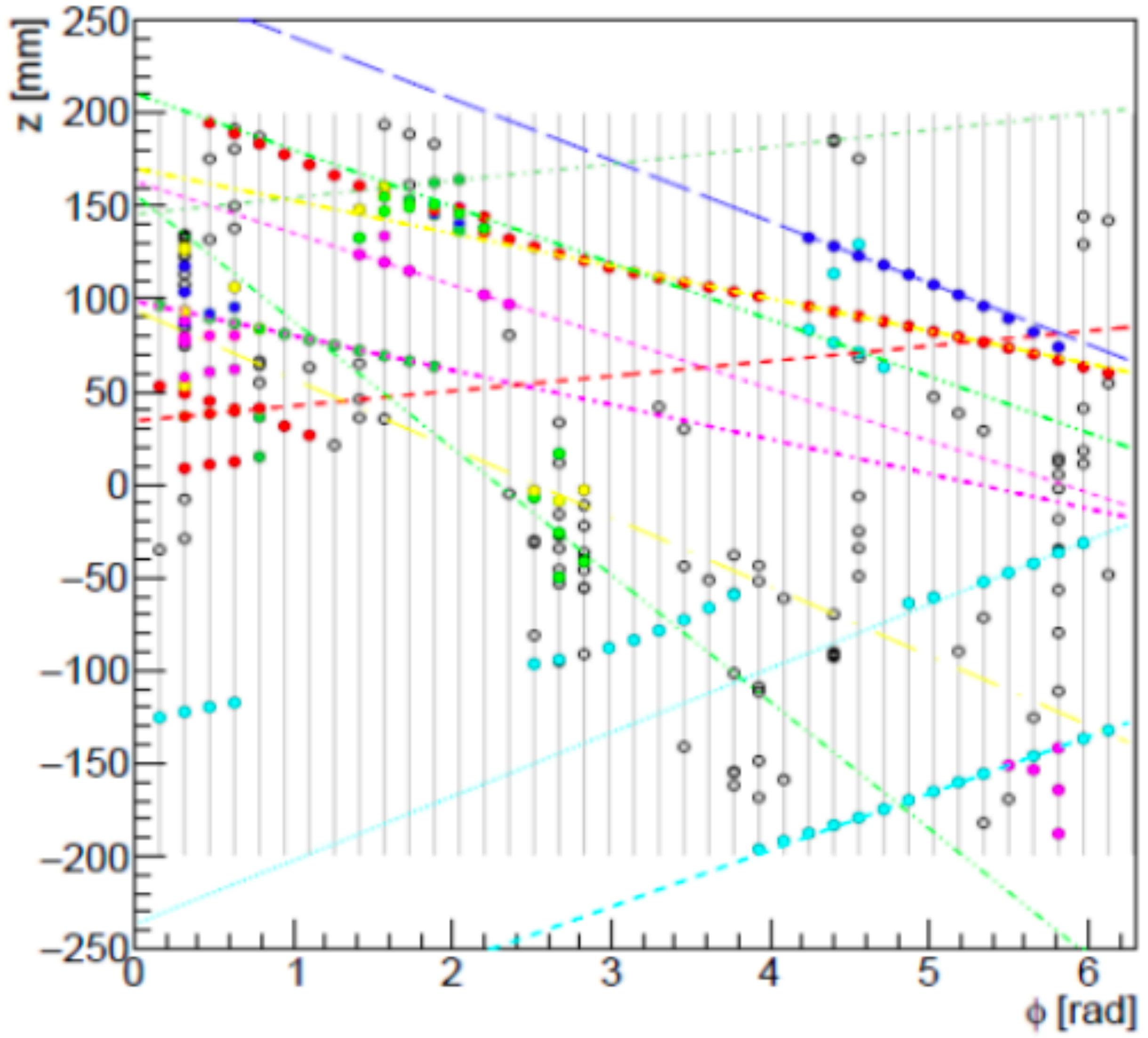
Software Development

- To manage detector simulation and track reconstruction, a new software framework was developed (named “g2esoft”).
- A reconstruction algorithm in high track density is being implemented. Application of Graph Neural Networks (GNN), etc., is ongoing.



Concept of g2esoft



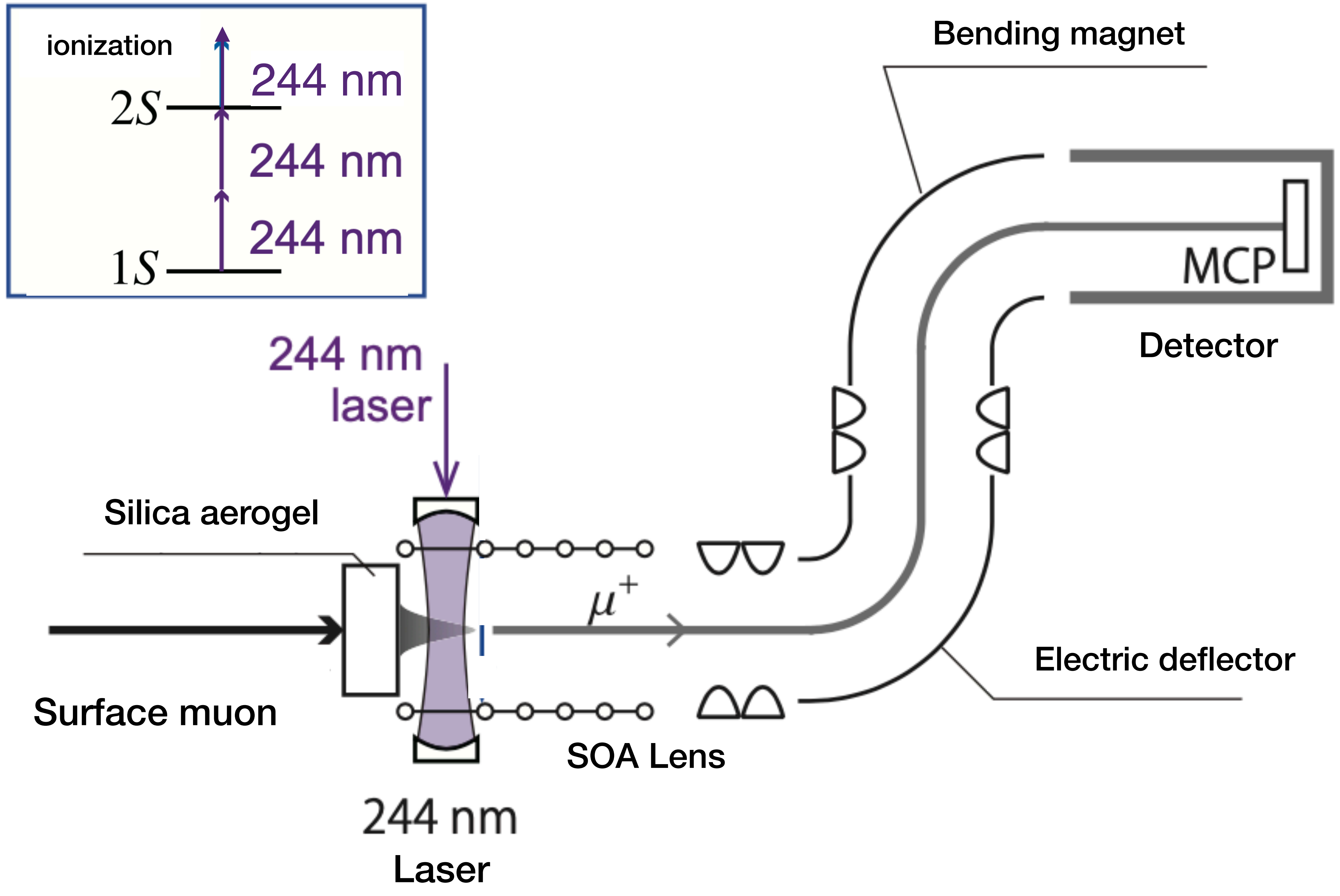


Simulated positron hits and reconstructed tracks with 25 positrons

Thermal Muon Source

Muonium (Mu) Laser Ionization Test

- The quick demonstration of thermal muon generation via laser ionization of muonium from silica aerogel at the J-PARC MLF S2 area



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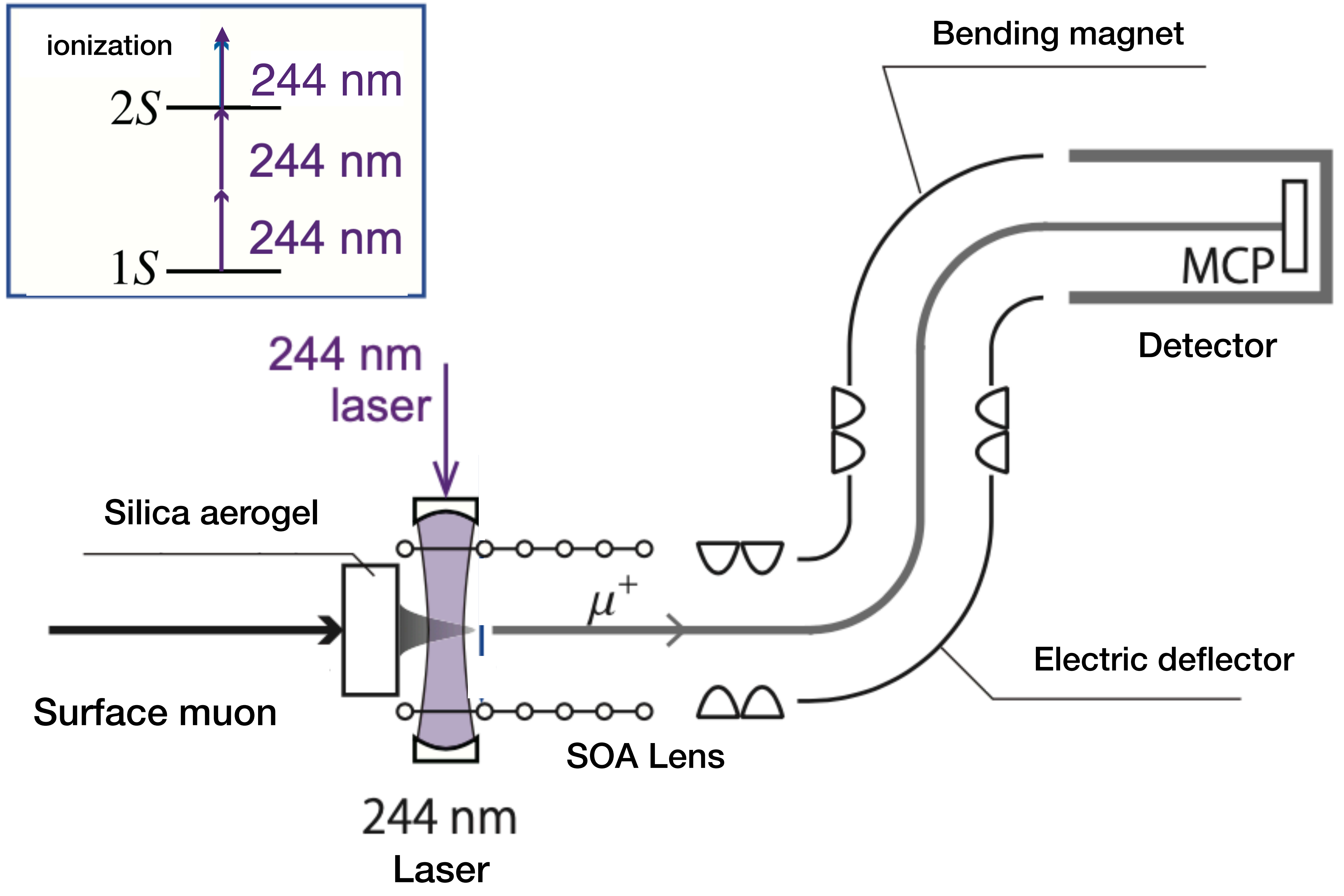

$$\Delta\nu_{1S2S} \simeq \frac{3\alpha^2}{8h} m_e c^2 (1 + \frac{m_e}{m_\mu})^{-1}$$

- With the 244 nm laser, It is also a direct measurement of Mu 1S-2S interval → **determination of muon mass**

  (Similar to Mu-MASS at PSI)

- **Final goal:**
  - Muon mass: 1 ppb
  - (1S-2S: 10 kHz, 4 ppt)

Thermal Muon Source

Muonium (Mu) Laser Ionization Test

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