

CANTON- μ Proposal:

A Next-Generation Muon $g - 2$ Experiment at Sub-0.1 ppm Precision

Ce Zhang

The 4th Liverpool Workshop on Muon Precision Physics
(MPP 2025)



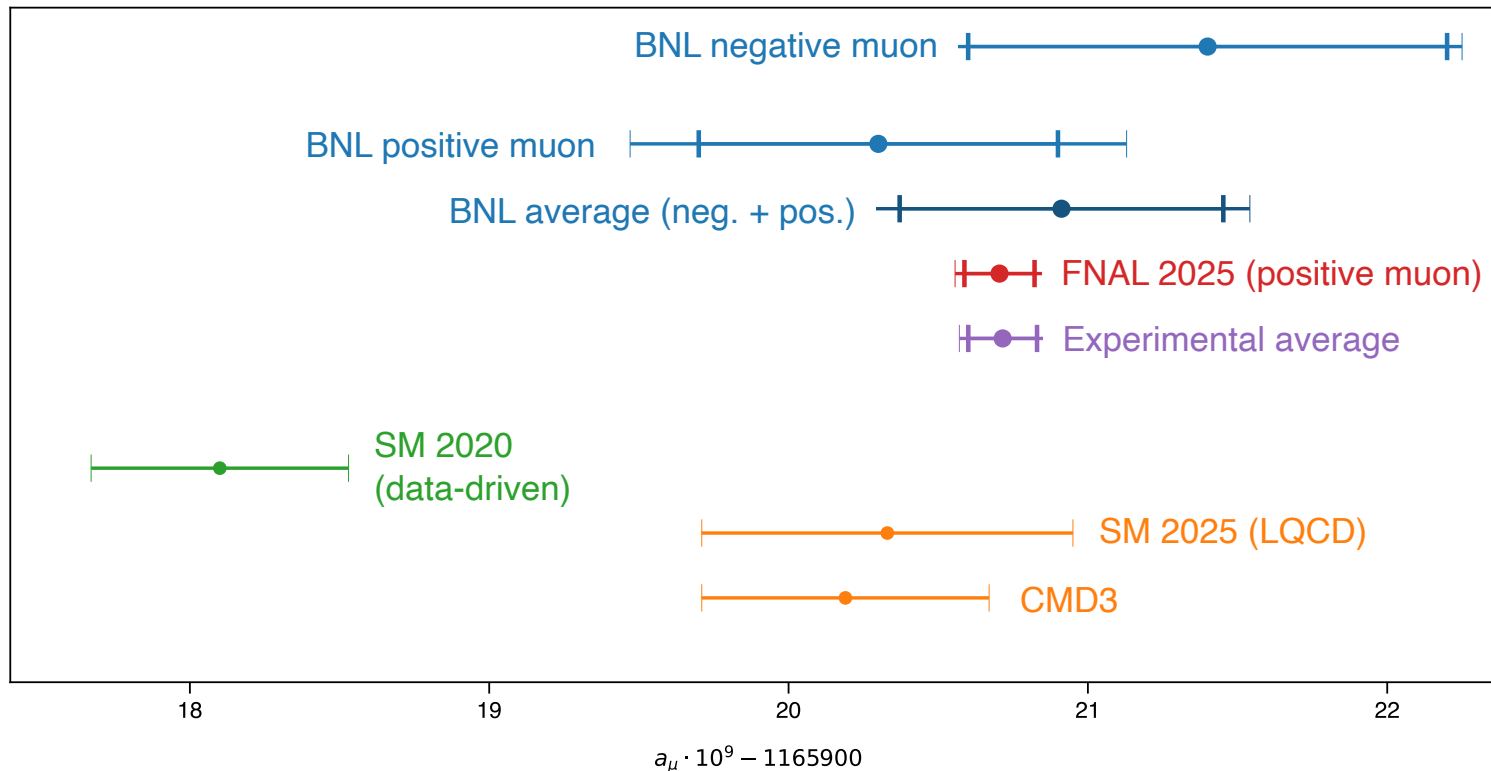
CANTON- μ Proposal:

A Next-Generation Muon $g - 2$ Experiment at Sub-0.1 ppm Precision

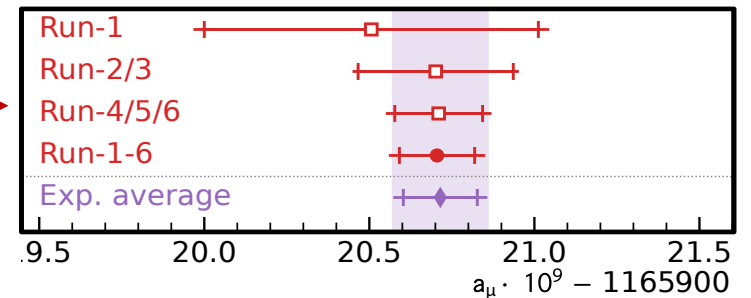
- Muon $g - 2$: status and limitations
- HIAF, and other emerging muon sources in China
- Experimental concepts towards sub-0.1-ppm precision
- Outlook and summary

Muon $g - 2$: status and limitations

- The theory remains unsettled — different approaches give inconsistent results that still need to be understood.



FNAL Results

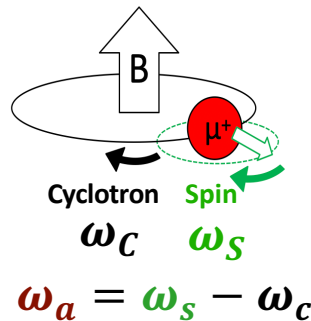
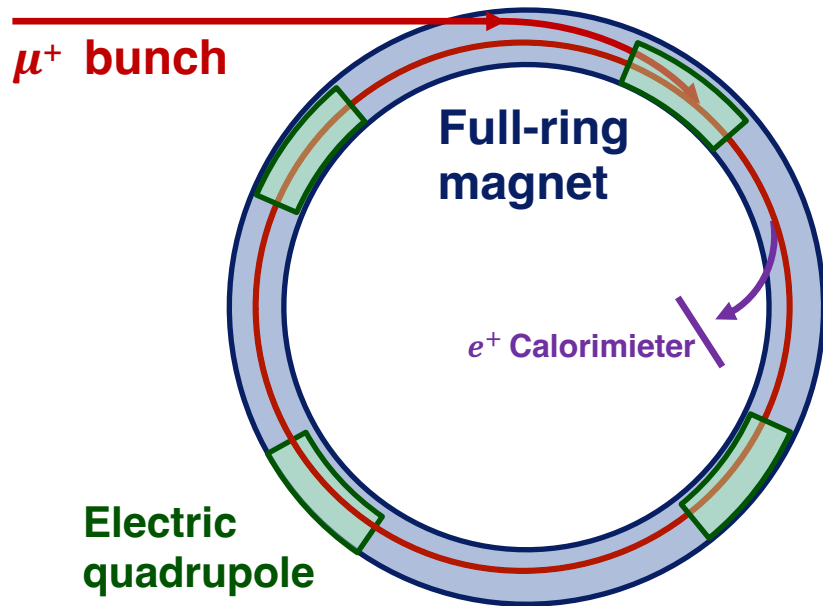


- The Fermilab results agree well;
- The current exp world average is dominantly driven by this *single* experiment.

Experimental limitations

1) Single experimental method

- The method has remained unchanged since CERN-III (1979).
- Muons at *magic momentum* (3.1 GeV/c) are injected into a uniform B-field, with (a) calorimeters detecting positrons and (b) NMR probes calibrating the field.



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

Muon at 3.1 GeV/c, $\gamma = 30$

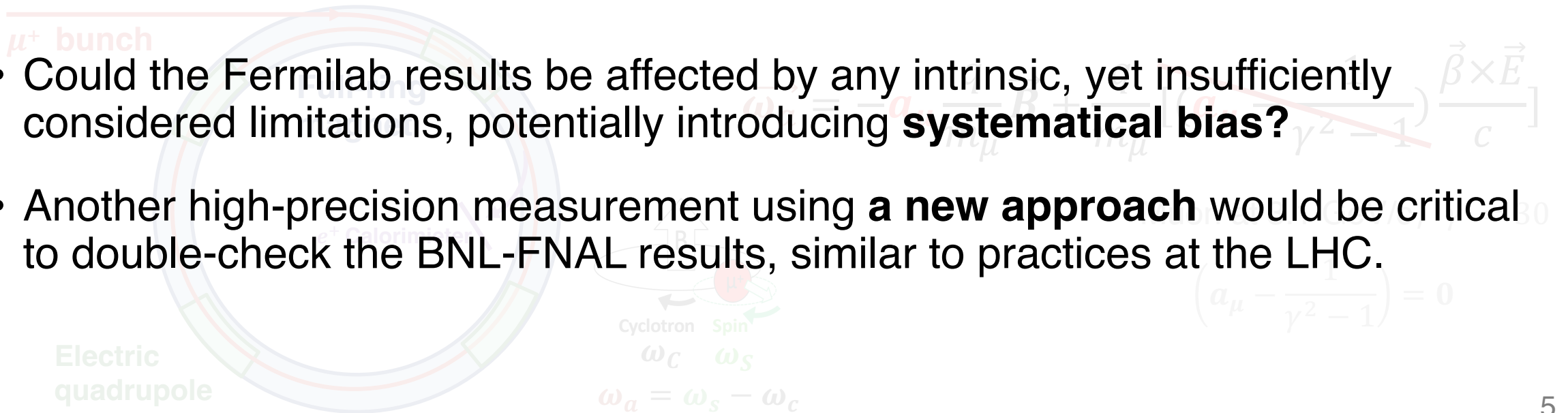
$$\left(a_\mu - \frac{1}{\gamma^2 - 1} \right) = 0$$

Experimental limitations

1) Single experimental method

- The method has remained unchanged since CERN-III (1979).
- Muons at *magic momentum* (3.1 GeV/c) are injected into a uniform B-field, with (a) calorimeters detecting positrons and (b) NMR probes calibrating the field.

- Could the Fermilab results be affected by any intrinsic, yet insufficiently considered limitations, potentially introducing **systematical bias**?
- Another high-precision measurement using **a new approach** would be critical to double-check the BNL-FNAL results, similar to practices at the LHC.



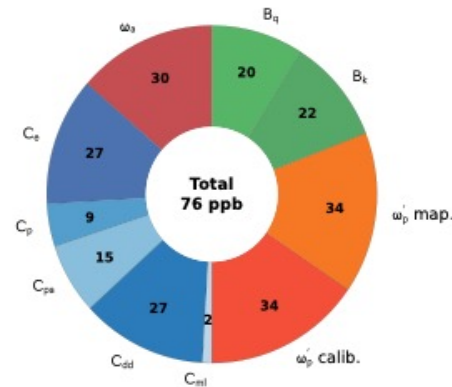
Experimental limitations

1) Single experimental method

- Also, this approach had essentially hit the limit — the systematic and statistical uncertainties are roughly comparable. The systematics errors are distributed almost uniformly.

Run-4/5/6

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	114
ω_a^m (systematic)	...	30
C_e Electric Field	347	27
C_p Pitch	175	9
C_{pa} Phase Acceptance	-33	15
C_{dd} Differential Decay	26	27
C_{ml} Muon Loss	0	2
$\langle \omega_p' \times M \rangle$ (mapping, tracking)	...	34
$\langle \omega_p' \times M \rangle$ (calibration)	...	34
B_k Transient Kicker	-37	22
B_q Transient ESQ	-21	20
μ_p' / μ_B	...	4
m_μ / m_e	...	22
Total systematic for $\mathcal{R}_\mu'$	...	76
Total for a_μ	572	139



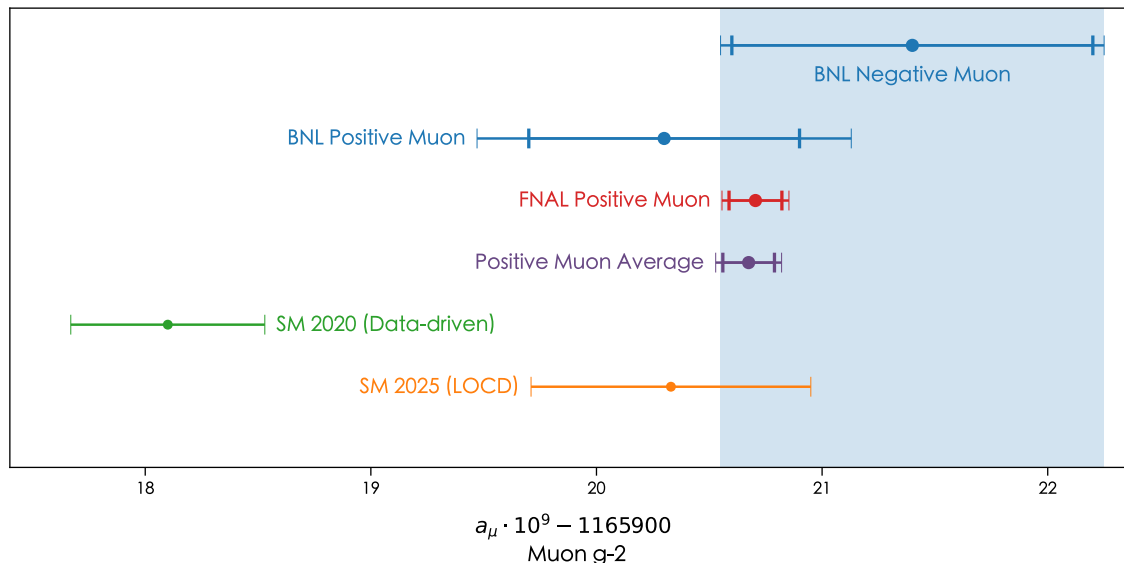
- Systematics are “evenly” distributed:
 - No dominant source
 - Further improving would require to reduce in many categories

$\frac{\omega_a}{\omega_p'}$	Stat. Uncertainty (ppb)	Syst. Uncertainty (ppb)	Total Uncertainty (ppb)
Run-1-6	98	78	127
	TDR goal 100 ppb ✓	TDR goal: 100 ppb ✓	TDR goal: 140 ppb ✓

Experimental limitations

2) No precise result for negative muons

- The Fermilab experiment measured the *positive* muon (μ^+) with a precision of **0.14 ppm** (2025);
- The most recent measurement of the *negative* muon (μ^-) still dates back to the BNL result (2004), with a precision of **0.7 ppm** — about five times worse.



- Notably, theoretical differences are being investigated and potentially converging. Theory is expected to reach a higher precision in the next few years
- $\mu^- g - 2$ will be the least precise and most outdated results by then.

New Physics with $(g - 2)_{\mu^-}$

1) CPT and Lorentz-violation test

- In the Standard Model, μ^+ and μ^- $g-2$ should be the same. A difference would be direct evidence of CPT violation.
- A precise μ^- $g-2$ alongside μ^+ would greatly improve sensitivity to new physics and tightens constraints on many models.

PRL **100**, 091602 (2008)

PHYSICAL REVIEW LETTERS

week ending
7 MARCH 2008

Search for Lorentz and CPT Violation Effects in Muon Spin Precession

G. W. Bennett,² B. Bousquet,¹⁰ H. N. Brown,² G. Bunce,² R. M. Carey,¹ P. Cushman,¹⁰ G. T. Danby,² P. T. Debevec,⁸ M. Deile,¹³ H. Deng,¹³ W. Deninger,⁸ S. K. Dhawan,¹³ V. P. Druzhinin,³ L. Duong,¹⁰ E. Efstathiadis,¹ F. J. M. Farley,¹³ G. V. Fedotovitch,³ S. Giron,¹⁰ F. E. Gray,⁸ D. Grigoriev,³ M. Grosse-Perdekamp,¹³ A. Grossmann,⁷ M. F. Hare,¹ D. W. Hertzog,⁸ X. Huang,¹ V. W. Hughes,^{13,*} M. Iwasaki,¹² K. Jungmann,^{6,7} D. Kawall,¹³ M. Kawamura,¹² B. I. Khazin,³ J. Kindem,¹⁰ F. Krienen,¹ I. Kronkvist,¹⁰ A. Lam,¹ R. Larsen,² Y. Y. Lee,² I. Logashenko,^{1,3} R. McNabb,^{8,10} W. Meng,² J. Mi,² J. P. Miller,¹ Y. Mizumachi,^{9,11} W. M. Morse,² D. Nikas,² C. J. G. Onderwater,^{6,8} Y. Orlov,⁴ C. S. Özben,^{2,8} J. M. Paley,¹ Q. Peng,¹ C. C. Polly,⁸ J. Pretz,¹³ R. Prigl,² G. zu Putlitz,⁷ T. Qian,¹⁰ S. I. Redin,^{3,13} O. Rind,¹ B. L. Roberts,¹ N. Ryskulov,³ S. Sedykh,⁸ Y. K. Semertzidis,² P. Shagin,¹⁰ Yu. M. Shatunov,³ E. P. Sichtermann,¹³ E. Solodov,³ M. Sossong,⁸ A. Steinmetz,¹³ L. R. Sulak,¹ C. Timmermans,¹⁰ A. Trofimov,¹ D. Urner,⁸ P. von Walter,⁷ D. Warburton,² D. Winn,⁵ A. Yamamoto,⁹ and D. Zimmerman¹⁰

(Muon $g - 2$ Collaboration)

In 2008, BNL set stringent limits on the parameters of CPT-violating Standard-Model Extension (SME):

$$\Delta\omega_a \equiv \langle\omega_a^{\mu^+}\rangle - \langle\omega_a^{\mu^-}\rangle = \frac{4b_Z}{\gamma} \cos\chi$$

$$b_Z = -(1.0 \pm 1.1) \times 10^{-23} \text{ GeV}$$

b_Z is a parameter characterizing the potential for CPT-odd (CPT-violating) effects.

New Physics with $(g - 2)_{\mu^-}$

1) CPT and Lorentz-violation test

- In the Standard Model, μ^+ and μ^- $g-2$ should be the same. A difference would be direct evidence of CPT violation.
- A precise μ^- $g-2$ alongside μ^+ would greatly improves sensitivity to new physics and tightens constraints on many models.

• SME Lagrangian:

$$\mathcal{L}' = -a_\kappa \bar{\psi} \gamma^\kappa \psi - \underbrace{(b_\kappa)}_{\text{CPT-odd}} \bar{\psi} \gamma_5 \gamma^\kappa \psi - \frac{1}{2} H_{\kappa\lambda} \bar{\psi} \sigma^{\kappa\lambda} \psi + \frac{1}{2} i c_{\kappa\lambda} \bar{\psi} \gamma^\kappa \overleftrightarrow{D}^\lambda \psi + \frac{1}{2} i d_{\kappa\lambda} \bar{\psi} \gamma_5 \gamma^\kappa \overleftrightarrow{D}^\lambda \psi$$

- All terms violate Lorentz invariance
- a_κ , b_κ are CPT-odd; others are CPT-even

CPT- and Lorentz-Violation Tests with Muon $g - 2$

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University, MS 38677, USA

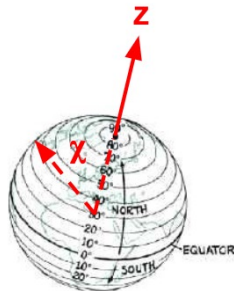


Table D21. Muon sector, $d = 3$

Combination	Result	System	Ref.
$ \text{Re } H_{011}^{\text{NR}(0B)} , \text{Im } H_{011}^{\text{NR}(0B)} , \text{Re } g_{011}^{\text{NR}(0B)} , \text{Im } g_{011}^{\text{NR}(0B)} $	$< 2 \times 10^{-22}$ GeV	Muonium spectroscopy	[20]*
$ \text{Re } H_{011}^{\text{NR}(1B)} , \text{Im } H_{011}^{\text{NR}(1B)} , \text{Re } g_{011}^{\text{NR}(1B)} , \text{Im } g_{011}^{\text{NR}(1B)} $	$< 7 \times 10^{-23}$ GeV	"	[20]*
b^T/m_μ	$(7.3 \pm 5.0) \times 10^{-7}$	Muon decay	[184]*
b_Z	$-(1.0 \pm 1.1) \times 10^{-23}$ GeV	BNL, $g_\mu - 2$	[185]
$\sqrt{(\tilde{b}_X^{\mu+})^2 + (\tilde{b}_Y^{\mu+})^2}$	$< 1.4 \times 10^{-24}$ GeV	"	[185]
$\sqrt{(\tilde{b}_X^{\mu-})^2 + (\tilde{b}_Y^{\mu-})^2}$	$< 2.6 \times 10^{-24}$ GeV	"	[185]
$\sqrt{(\tilde{b}_X)^2 + (\tilde{b}_Y)^2}$	$< 2 \times 10^{-23}$ GeV	Muonium spectroscopy	[186]
$b_Z - 1.19(m_\mu d_{Z0} + H_{XY})$	$(-1.4 \pm 1.0) \times 10^{-22}$ GeV	BNL, CERN $g_\mu - 2$ data	[187]
b_Z	$(-2.3 \pm 1.4) \times 10^{-22}$ GeV	CERN $g_\mu - 2$ data	[187], [188]*
$ \text{Re } H_{011}^{(3)(0B)} , \text{Im } H_{011}^{(3)(0B)} $	$< 5 \times 10^{-23}$ GeV	"	[20]*
$\tilde{H}_{011}^{(3)}$	$(-1.6 \pm 1.7) \times 10^{-22}$ GeV	BNL, CERN $g_\mu - 2$ data	[20]*
$ \text{Re } \tilde{H}_{011}^{(3)} , \text{Im } \tilde{H}_{011}^{(3)} $	$< 2.0 \times 10^{-24}$ GeV	BNL, $g_\mu - 2$	[20]*
$m_\mu d_{Z0} + H_{XY}$	$(1.8 \pm 6.0) \times 10^{-23}$ GeV	"	[185]

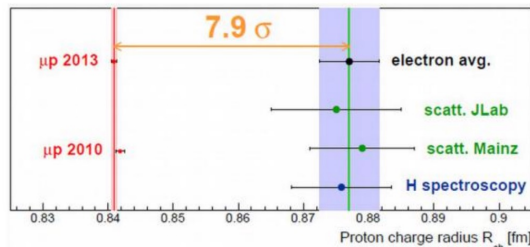
New Physics with $(g - 2)_{\mu^-}$

2) Connection to atomic physics

- Negative muons can form muonic atoms (e.g., muonic hydrogen & helium).
- The negative muon $g-2$ can be connected with muon spectroscopy exps, providing insights into higher-order QED and nuclear structure effects.

Proton charge radius

- Back to 2013, a lot of interest on the proton charge radius
- The Proton Radius Puzzle
 - Test theoretical understanding of proton
 - Related to the QCD



μp 2013: Antognini *et al.*,
Science **339**, 417 (2013)
JLab: Zhan *et al.*, PLB
705, 59-64 (2011)
Mainz: Bernauer *et al.*,
PRL **105**, 242001 (2010)
 μp 2010: Pohl *et al.*,
Nature **466**, 213 (2010)

TABLE I. Contributions to the muonic hydrogen Lamb shift. The proton radius is taken from [20]. The various contributions are discussed in the text.

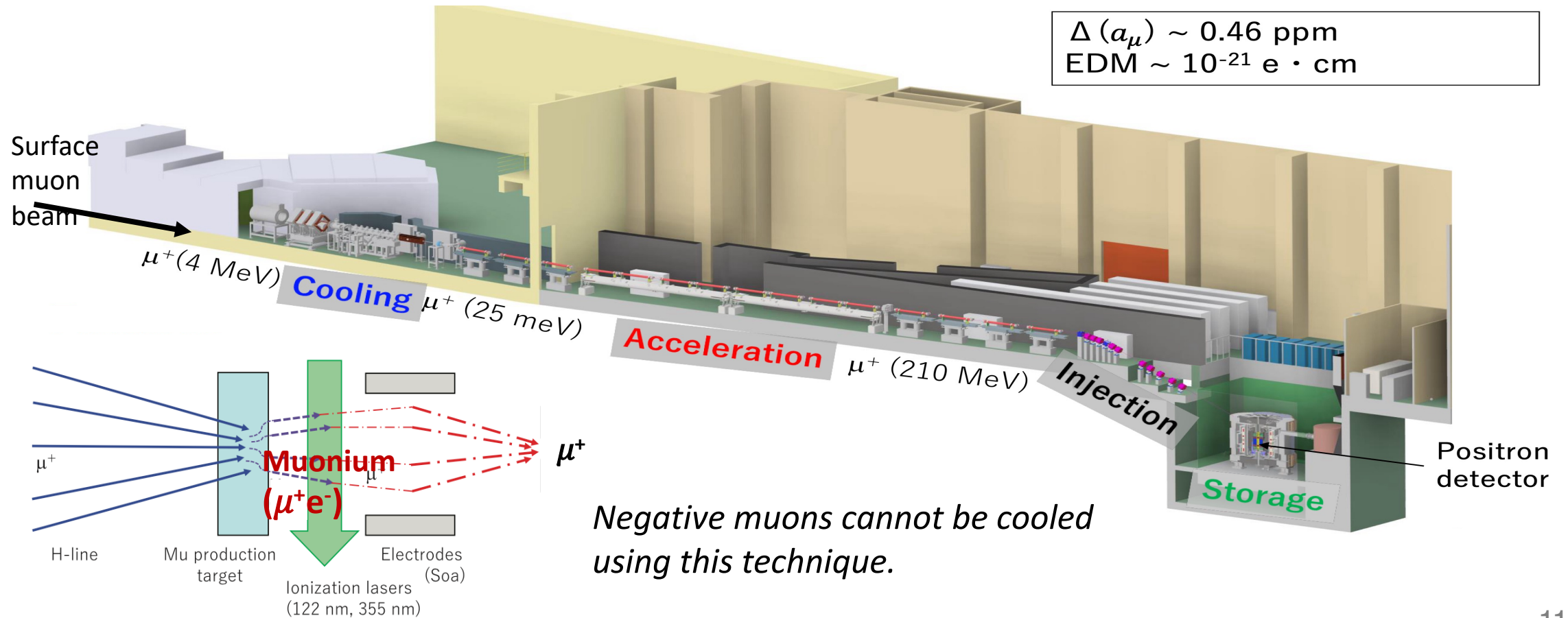
Contribution	Value (meV)	Uncertainty (meV)
Uehling	205.0282	
Källén-Sabry	1.5081	
Wichmann-Kroll	-0.00103	
Virt. Delbrueck	0.00135	0.00015
Mixed μ -e VP	0.00007	
Hadronic VP	0.011	0.002

Phys. Rev. A **71**, 032508:

HVP could be updated with negative muon $g-2$

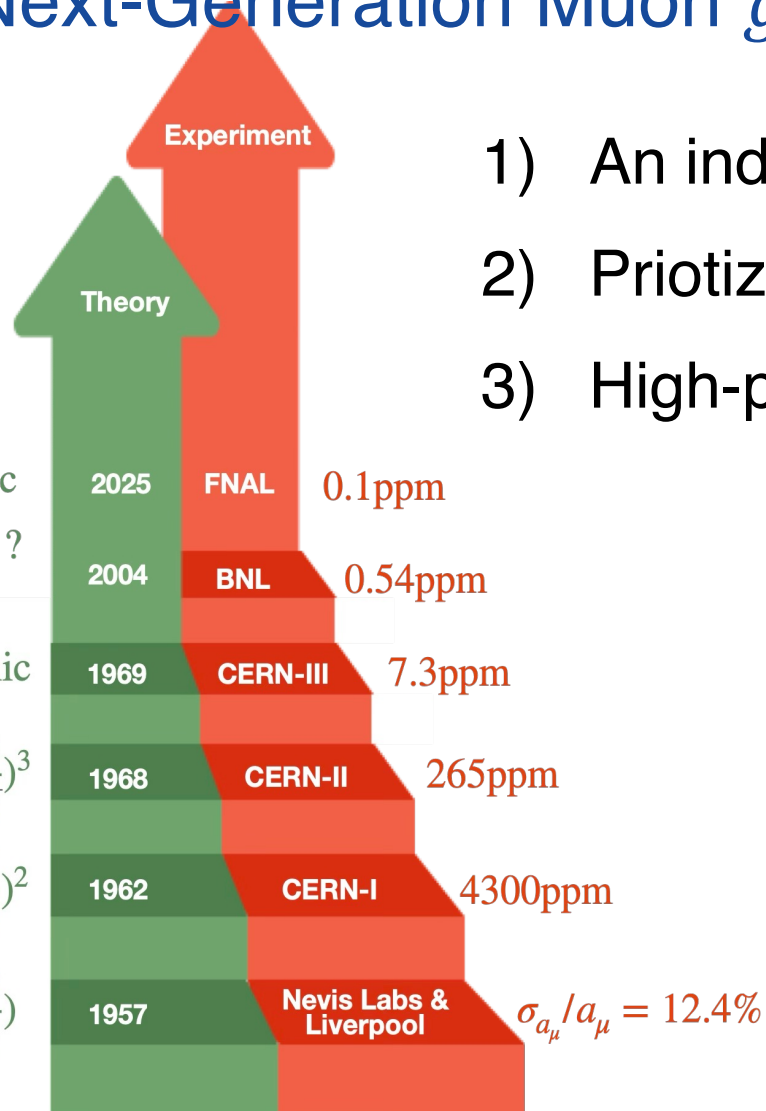
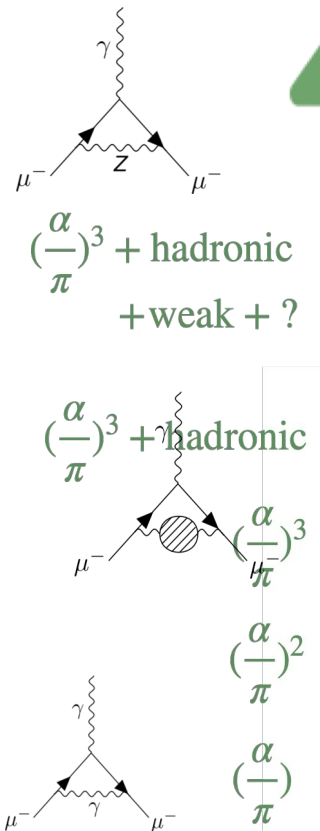
The g-2 experiment at J-PARC

Featuring *positive* muon cooling



Other possibilities

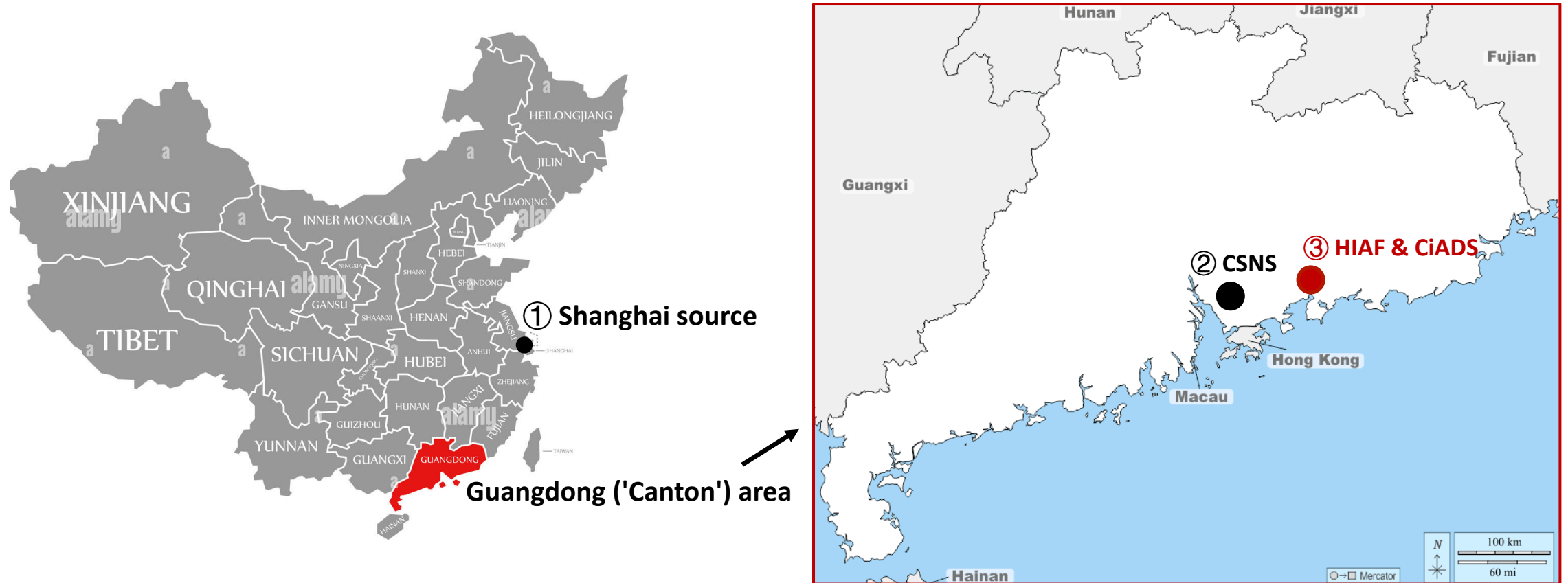
for Next-Generation Muon $g-2$ measurements



- 1) An independent new method;
- 2) Prioritizing $g-2$ of negative μ , if feasible;
- 3) High-precision, matching or surpassing FNAL (0.1 ppm).

→ Prerequisite: a high-intensity muon source

A glimpse of muon sources in China



Check out my backup slides for source ① and ②

Muon sources in China

③ HIAF and CiADS

- Two neighbourhood facilities managed by **Institute of Modern Physics (IMP)** of the Chinese Academy of Sciences



- Mainly focused on heavy-ion science and technology, based on the Heavy Ion Research Facility in Lanzhou (HIRFL);
- Also covers nuclear physics, atomic and molecular physics, material radiation effects, radiation biology, particle accelerator technology...

Muon sources in China

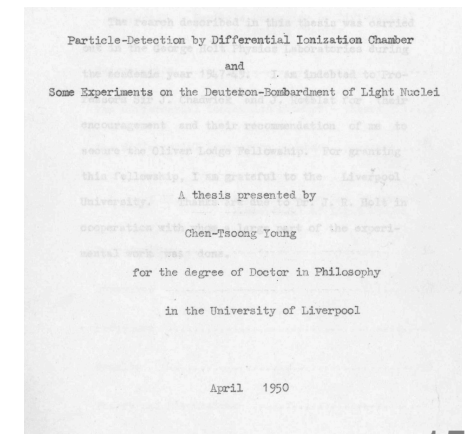
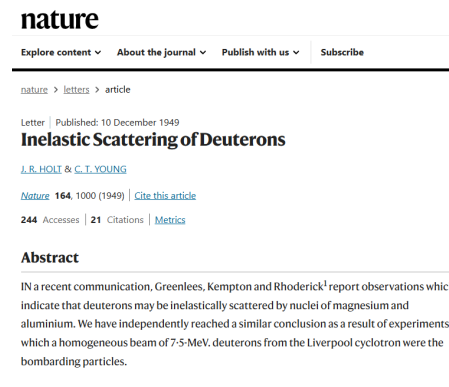
③ HIAF and CiADS

- Two neighbourhood facilities managed by **Institute of Modern Physics (IMP)** of the Chinese Academy of Sciences

- The institute was founded by a physicist **Young, Chen-Tsoong** who carried out PhD research in Liverpool (1947-49) in the George Holt Physics Laboratories and worked with J. Chadwick, J. Rotblat and J. R. Holt.



1912.4 – 1987.12

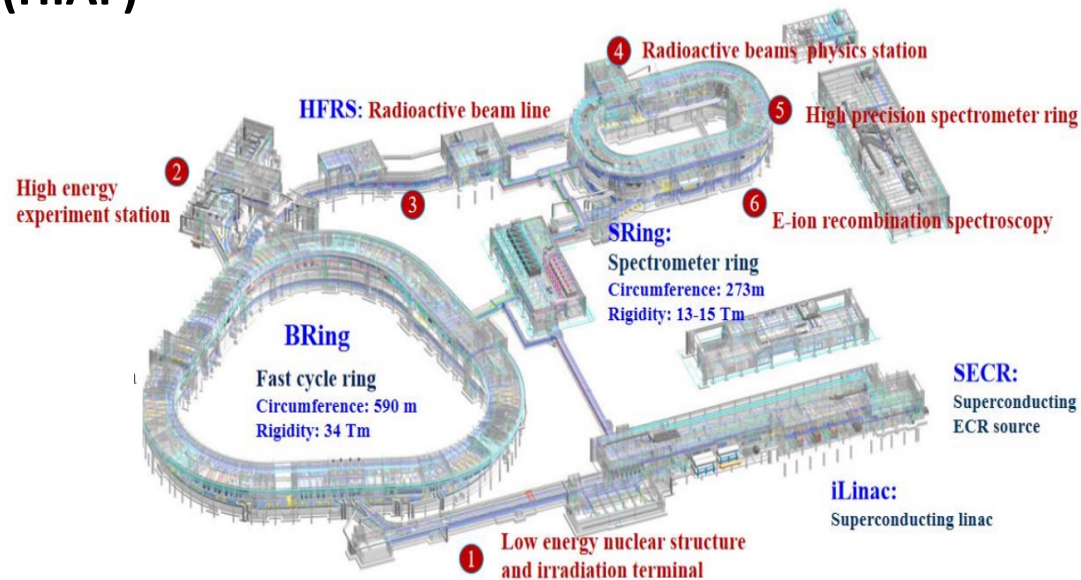


Muon sources in China

③ HIAF and CiADS

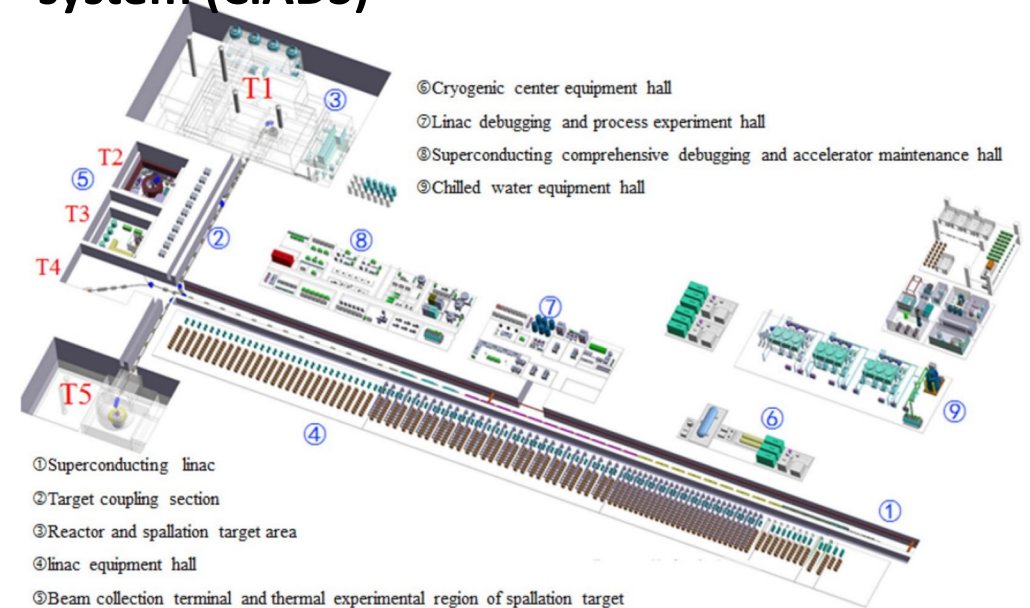
- Two neighbourhood facilities managed by **Institute of Modern Physics (IMP)**

High-Intensity heavy-ion Accelerator Facility (HIAF)



<https://english.imp.cas.cn/research/facilities/HIAF/>

China-initiative Accelerator-Driven Subcritical system (CiADS)



<https://english.imp.cas.cn/research/facilities/CiADS/>

Muon sources in China

③ HIAF and CiADS

- Two neighbourhood facilities managed by **Institute of Modern Physics (IMP)**

High-Intensity heavy-ion Accelerator Facility (HIAF)

- Heavy-ion acceleration and nuclear physics: nuclear structure, nuclear astrophysics, and high-energy-density matter;
- High-current ion sources, superconducting linacs, and large storage rings;
- Comparable to GSI/FAIR in capability;
- Planning a **high-energy muon (1-20 GeV)**.

China-initiative Accelerator-Driven Subcritical system (CiADS)

- Nuclear energy and waste transmutation;
- To demonstrate the Accelerator-Driven System (ADS) concept for sustainable nuclear energy and minimal radioactive waste;
- High-power proton linear accelerator coupled to a subcritical lead-bismuth reactor;
- Planning a **low-energy muon** (e.g. surface muon beam).

Muon sources in China

③ HIAF and CiADS



CiADS



CiADS



LINAC

Subcritical reactor

Experimental hall
(including muon beam line), expected ~2028

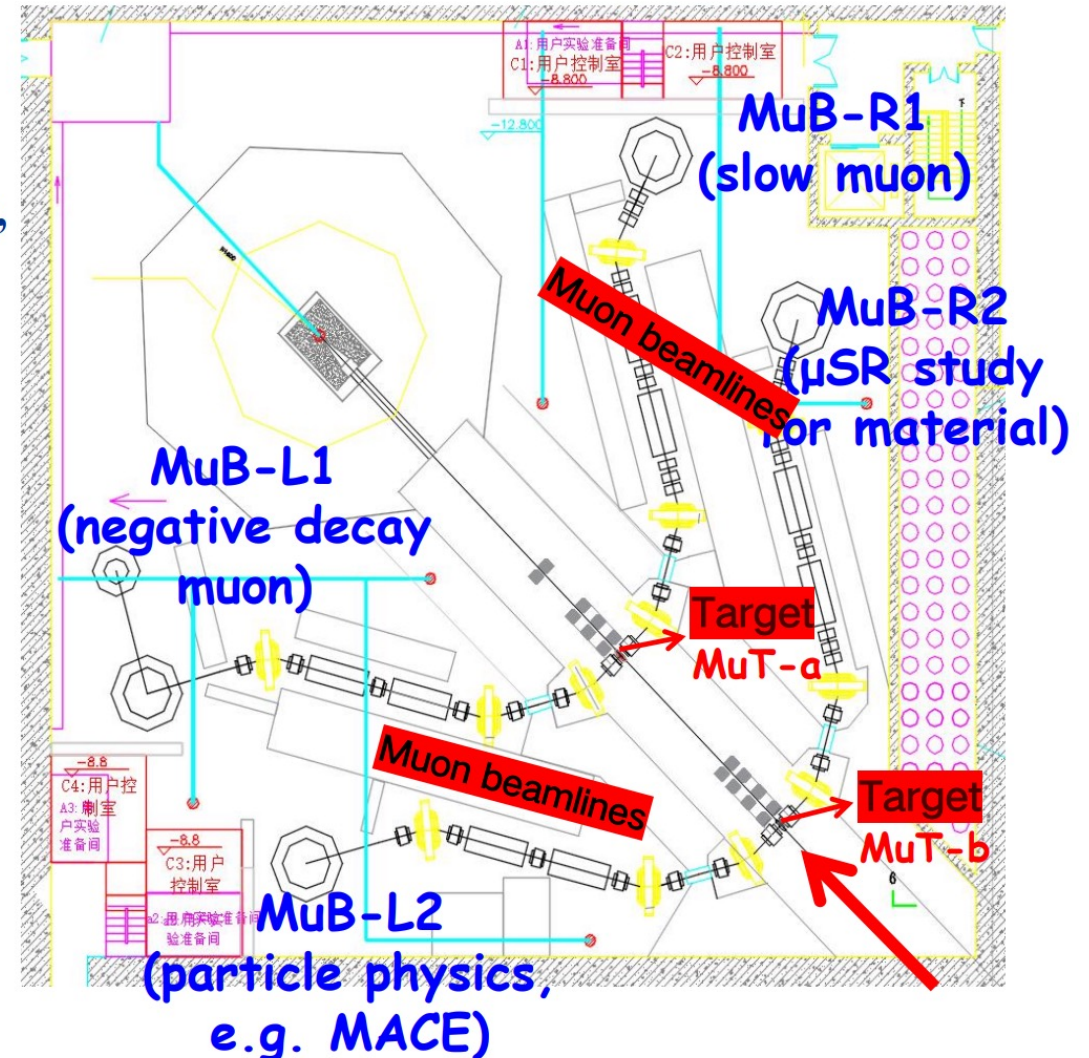


The plan of CiADS muon source (MuST)



- ❑ Muon terminal area: $\sim 800 \text{ m}^2$
- ❑ Construction plan of 2 phases
 - Phase I (2025–2028): one target station (0.5 mA, 600 MeV, CW wave & time-structured beam), two muon beamlines
 - Phase II (2029–2032): Add one additional target station and two beamlines, power upgradable to 3 MW
- ❑ Current design parameters

Beam power	Target	Focusing method	Muon intensity (μ^+/s)
1st phase 300 kW	Graphite rotating target	Solenoid + quadrupole	$> 5\text{E}7$
		Full solenoid	$> 5\text{E}8$
2nd phase 3 MW	Liquid lithium target	Solenoid + quadrupole	$> 1\text{E}9$
		Full solenoid	$> 1\text{E}10$

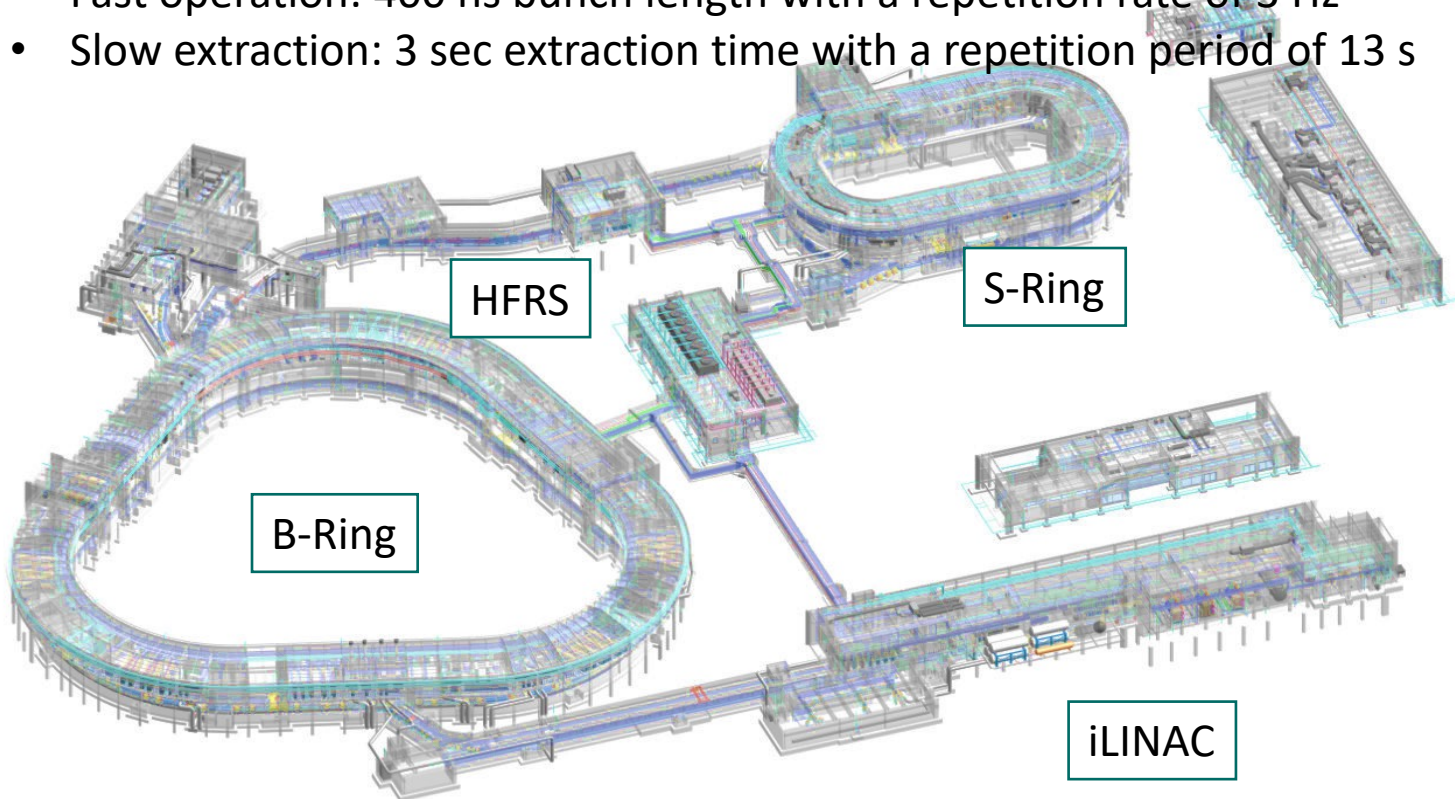


HIAF

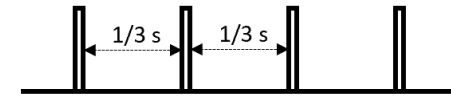
High Intensity heavy-ion Accelerator Facility

Two modes:

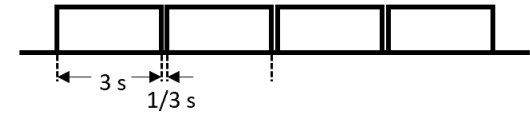
- Fast operation: 400 ns bunch length with a repetition rate of 3 Hz
- Slow extraction: 3 sec extraction time with a repetition period of 13 s



Fast extraction: High-intensity pulsed p/ion

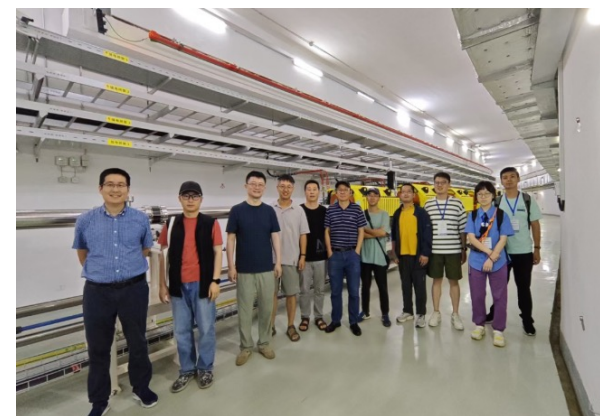


Slow extraction: Quasi-continuous p/ion



	34Tm, 3Hz	
Ions	Particle per pulse (ppp)	Energy(Ge V/u)
$^{238}\text{U}^{35+}$	1.0×10^{11}	0.84
$^{209}\text{Bi}^{27+}$	1.2×10^{11}	0.85
$^{78}\text{Kr}^{19+}$	3.0×10^{11}	1.7
$^{18}\text{O}^{6+}$	6.0×10^{11}	2.6
Proton	2.0×10^{12}	9.3

HIAF



HIAF

First beam commissioning achieved on 28th October



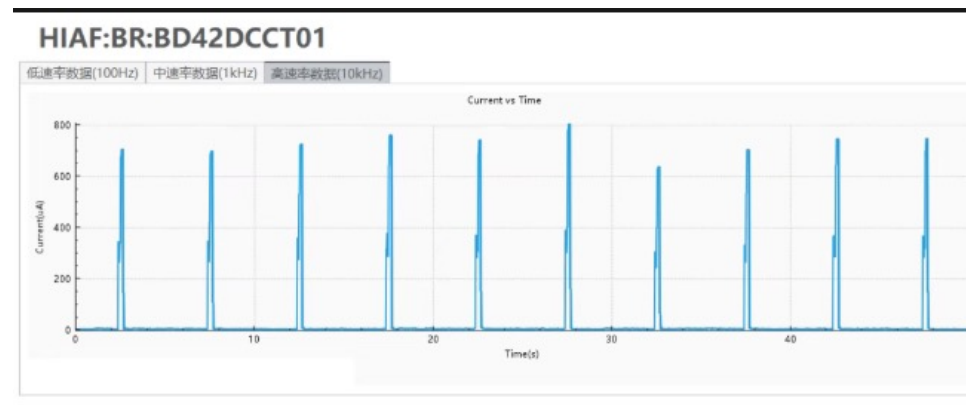
Home / News / Highlights

31 Oct, 2025

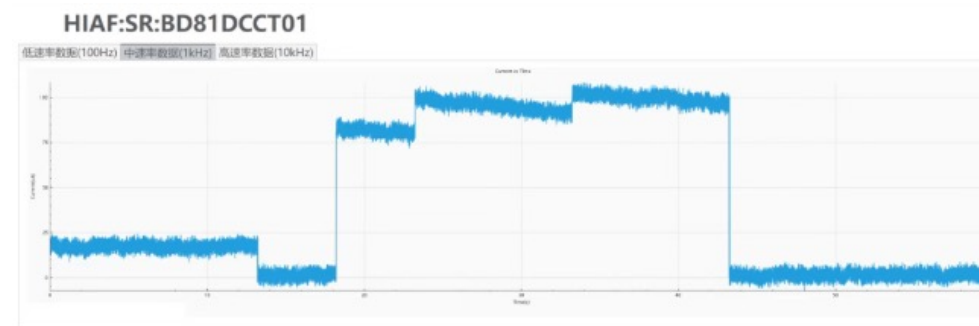
China's High-Intensity Heavy-Ion Accelerator Facility Completes Beam Commissioning



https://english.imp.cas.cn/news/highlights/202510/t20251031_1095238.html



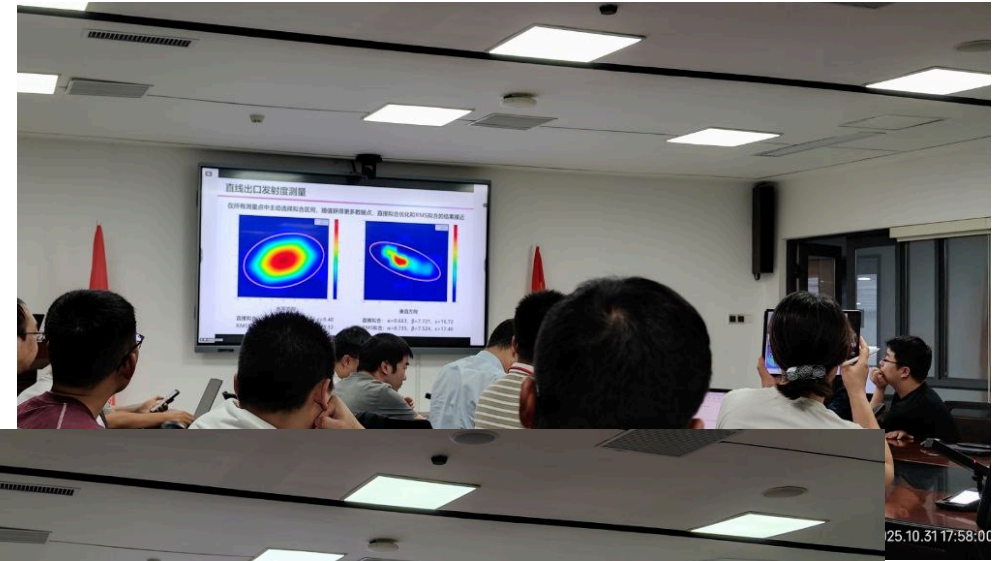
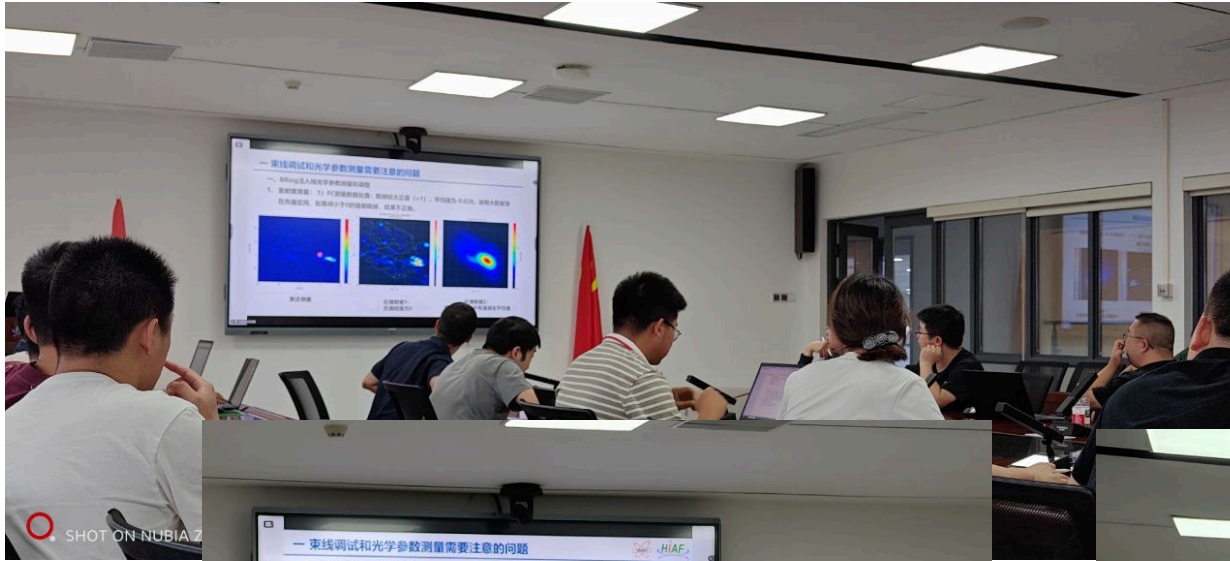
the first signal ^{18}O at B-ring



the first signal ^{18}O at S-ring

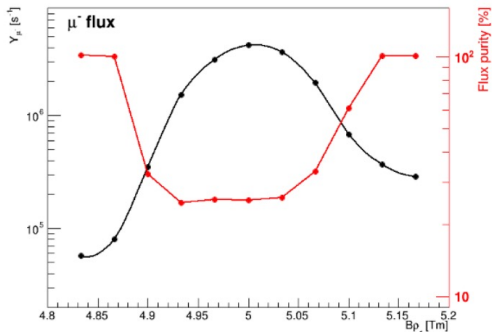
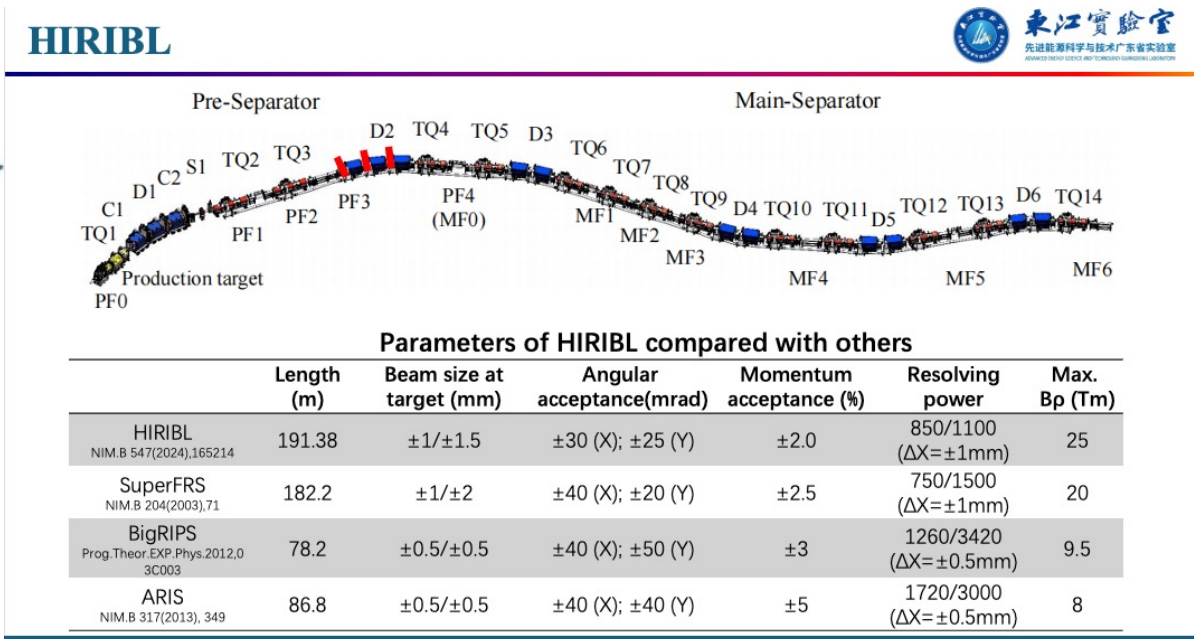
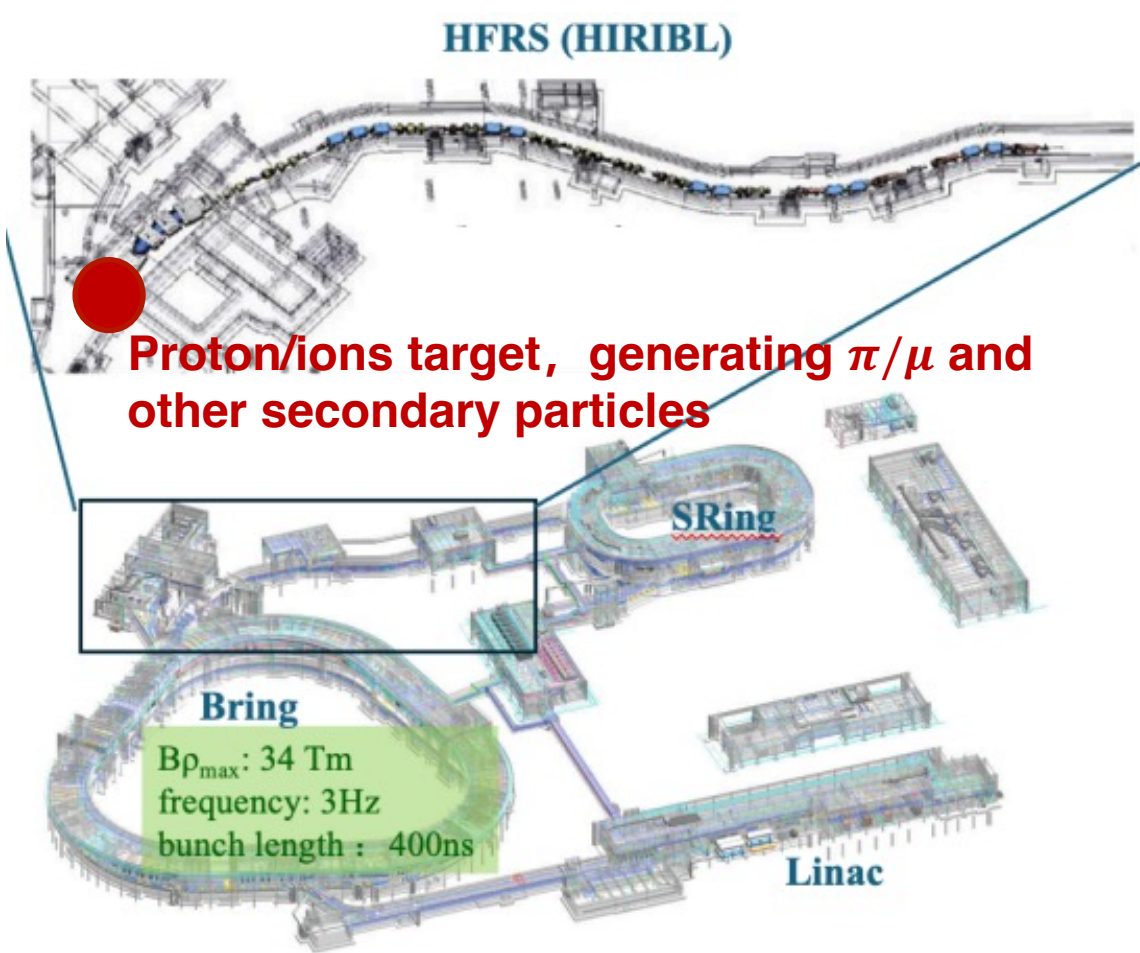
HIAF

Discussions on the first beam commissioning result



HFRS (HIRIBL)

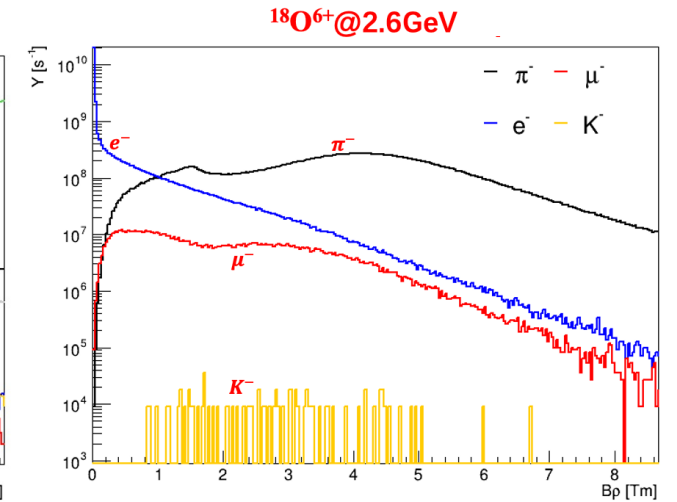
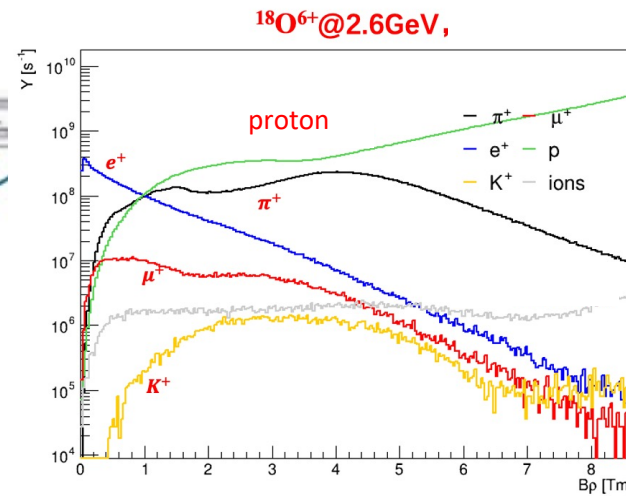
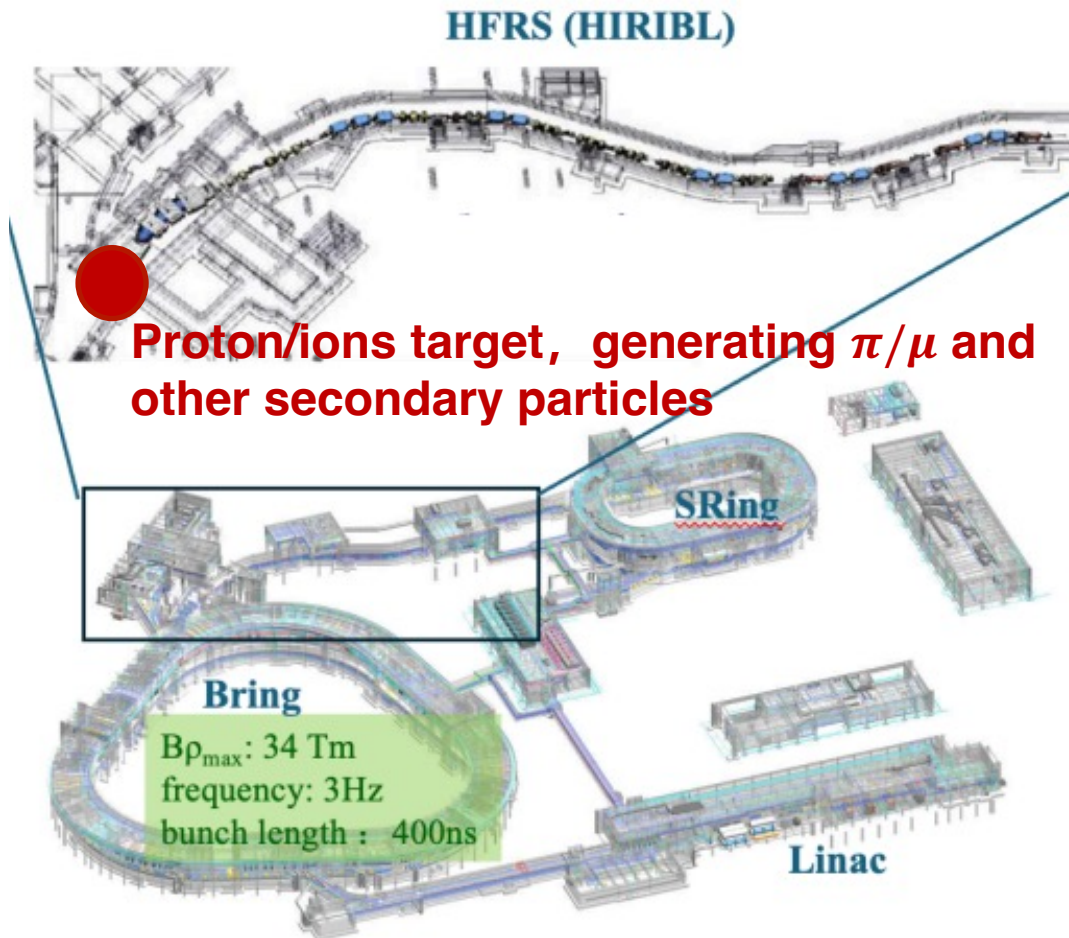
The world's longest and highest magnetic rigidity radioactive beam-line



Yu Xu @ [MIP2025](#)

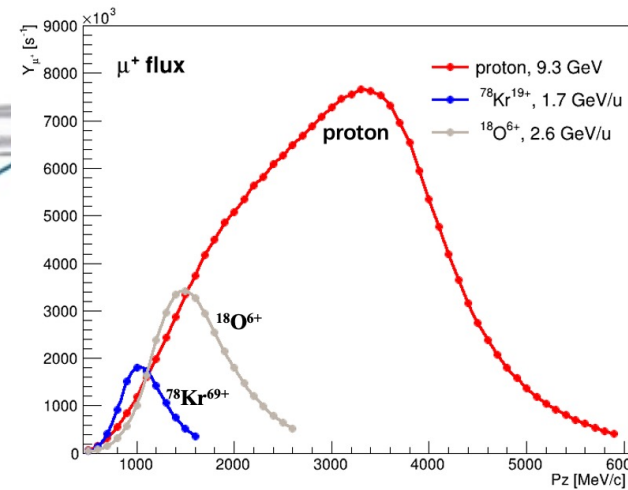
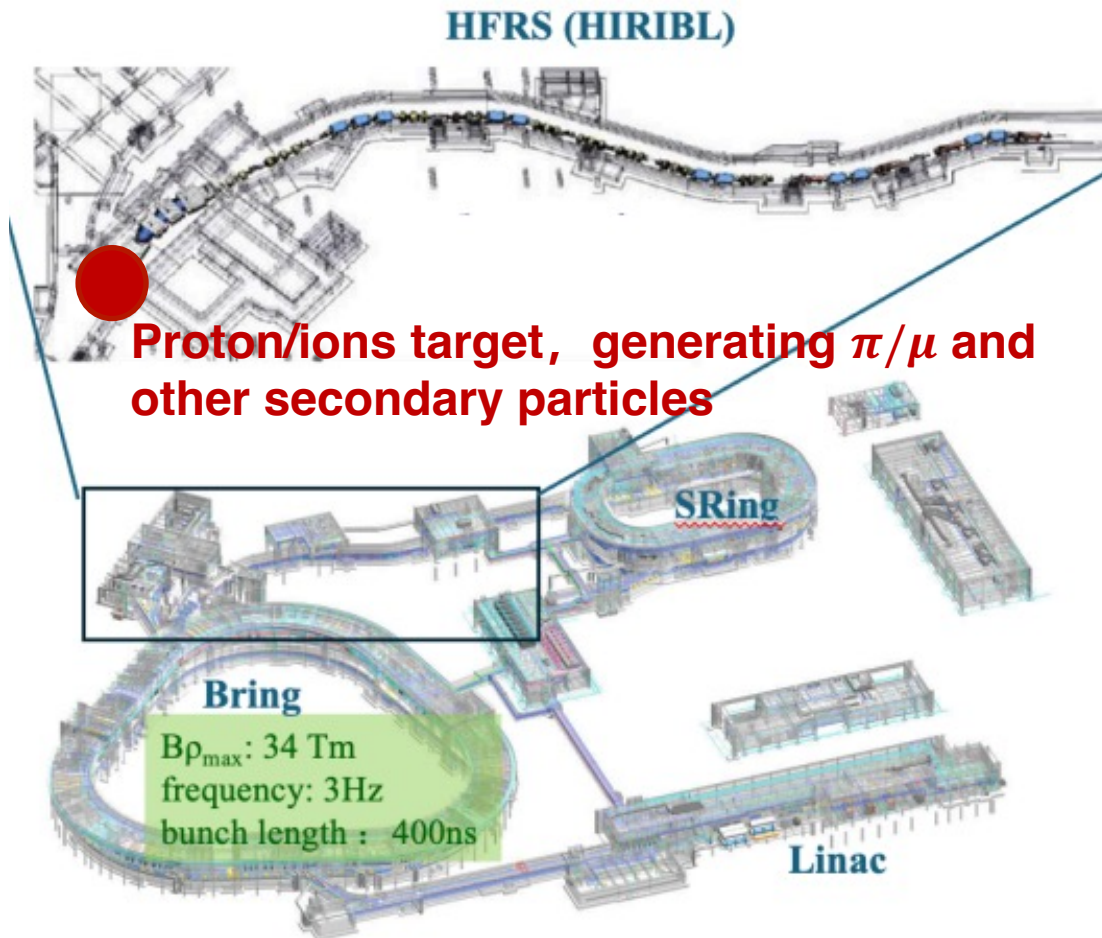
HFRS (HIRIBL)

The world's longest and highest magnetic rigidity radioactive beam-line



HFRS (HIRIBL)

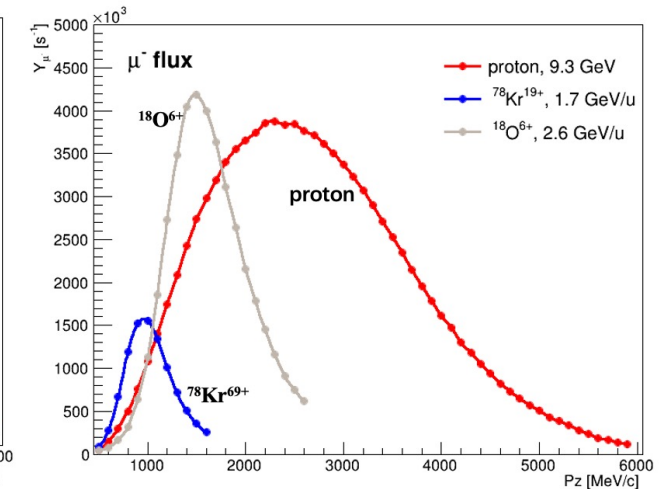
The world's longest and highest magnetic rigidity radioactive beam-line



positive muon

- Maximum μ^+ flux: $8.2 \times 10^6/\text{s}$
 - projectile : proton
 - P_z : 3.5 GeV/c

w/ purification: $2.4 \times 10^5/\text{s}$



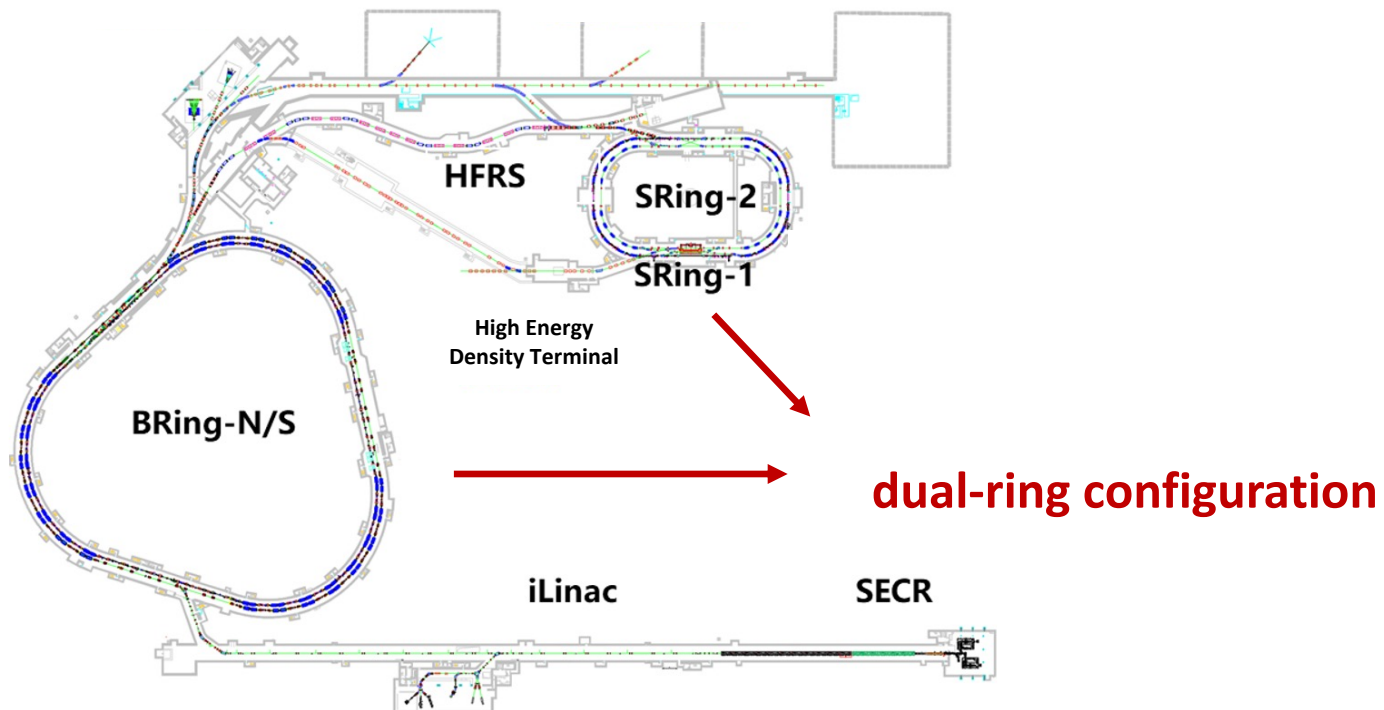
negative muon

- Maximum μ^- flux: $4.2 \times 10^6/\text{s}$
 - projectile: $^{18}\text{O}^{6+}$
 - P_z : 1.5 GeV/c

w/ purification: $3.7 \times 10^5/\text{s}$

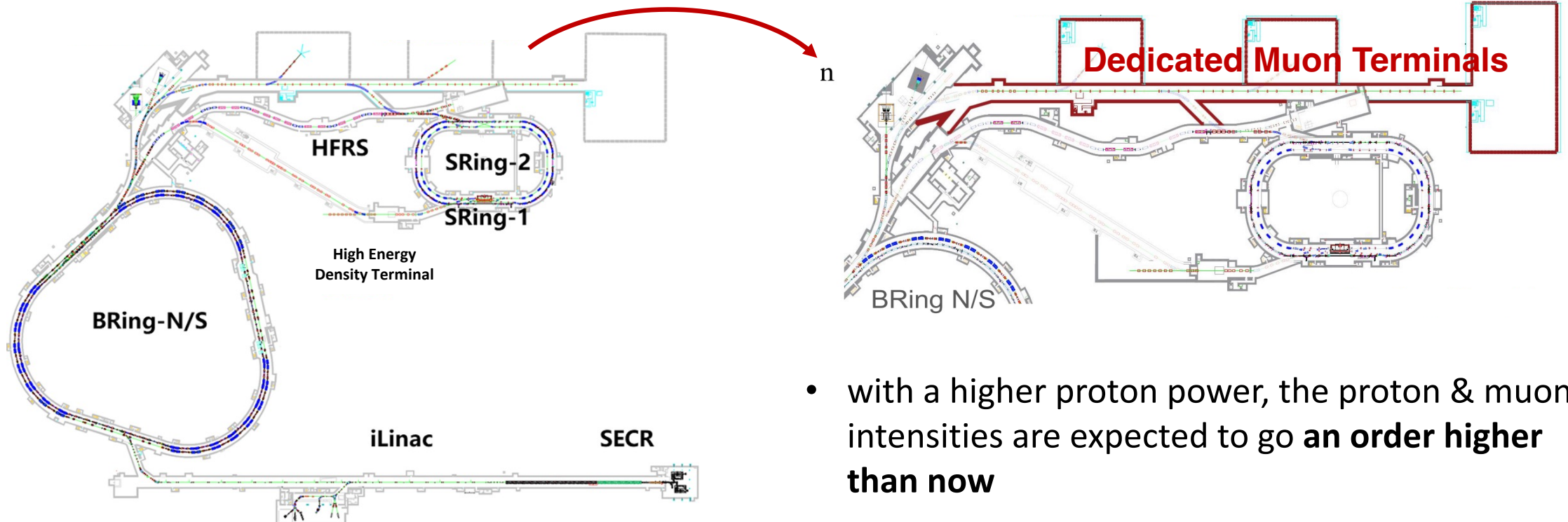
HIAF-U

- An upgrade planned for the second phase of HIAF, aims to increase the proton energy from 9 to **25 GeV**, with a dedicated muon beamline in the design.



HIAF-U

- An upgrade planned for the second phase of HIAF, aims to increase the proton energy from 9 to **25 GeV**, with a dedicated muon beamline in the design.



- with a higher proton power, the proton & muon intensities are expected to go **an order higher than now**

Muon beams comparison

The only (?) facility worldwide *planning* a GeV-scale high-intensity pulsed μ^-

TABLE I. Comparison of muon beam parameters at Fermilab and HIAF

	Fermilab	HIAF	HIAF-U
Proton Intensity (/s)	6.8×10^{13}	5×10^{13}	4×10^{14}
Proton energy (GeV/u)	8.0	9.1	25
Repetition frequency (Hz)	15	3	10
Proton bunch time width (ns)	100	100-400 (TBD)	TBD
Muon intensity [/s]	5×10^6	$\approx 4 \times 10^6$	$\approx 4 \times 10^7$ (?)
Muon energy (for $g - 2$)	3.1 GeV/c	2 - 4 GeV/c	10 - 20 GeV/c
Muon momentum spread (%)	2%	2%-3%	TBD

→ Currently intensity at HIAF is comparable to FNAL, while HIAF-U would very likely surpass it.

Muon beam for $g - 2$

① Higher energy (higher γ)

- The statistical precision of ω_a :

$$\frac{\Delta\omega_a}{\omega_a} \propto \frac{1}{\gamma B P \sqrt{N}}$$

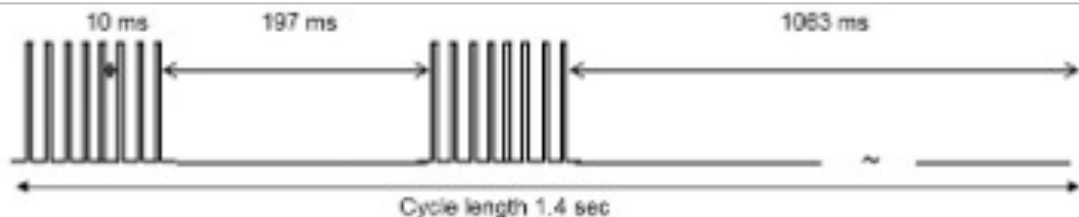
	FNAL	J-PARC	HIAF	HIAF-U
γ	30	3	20 – 40 (2-4 GeV)	150 (15 GeV)
B	1.5 T	3 T	3 T or higher	6 – 15 T?
P	100%	50%	100%	100%
N required to achieve the same precision in $\Delta\omega_a/\omega_a$	N	100 N	$N/4$	$N/500$

Muon beam for $g - 2$

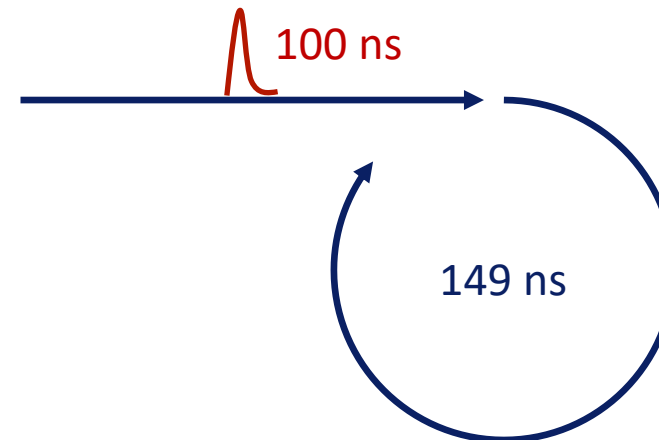
② Time structure

- High-intensity pulsed muons evenly spaced in time, maximize the number of bunches (high-repetition rate; 3Hz is not very good)
- Each bunch should be as short in duration width as possible
 - The injection must be completed before the bunch finishes one full turn in the ring;
 - bunch time < cyclotron period $\rightarrow$ at Fermilab this condition is $100 \text{ ns} < 149 \text{ ns}$.

11 Hz operation with 1 ms data-taking



FNAL: duty cycle is ~1%, bunch width 100 ns



Muon beam for $g - 2$

② Time structure

- High-intensity pulsed muons evenly spaced in time, maximize the number of bunches (high-repetition rate; 3Hz is not very good)
- Each bunch should be as short in duration width as possible
 - The injection must be completed before the bunch finishes one full turn in the ring;
 - bunch time < cyclotron period $\rightarrow$ at Fermilab this condition is 100 ns < 149 ns.
 - This subsequently determines the acceptable B field:

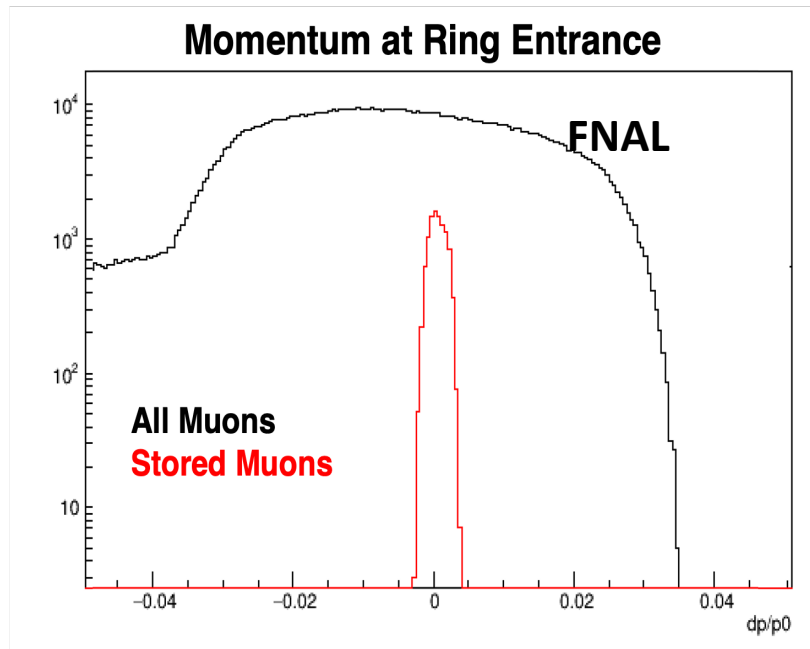
$$T = \frac{2\pi\gamma m_\mu}{qB}$$

$\gamma \sim 30$ (3GeV) and $B \sim 3\text{T} \rightarrow T = 70 \text{ ns}$
a very challenging condition

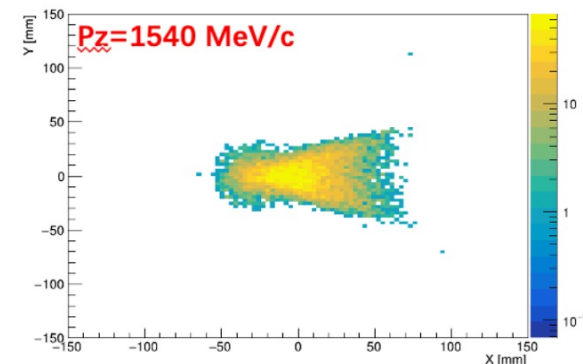
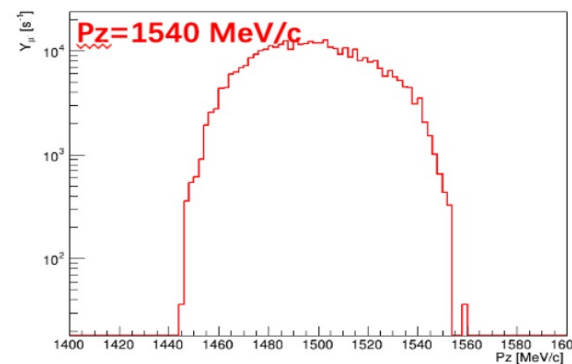
Muon beam for $g - 2$

③ Momentum spread

- For FNAL g-2, The momentum acceptance is narrow ('magic momentum'), making the injection efficiency is roughly 2-3%.



Currently, simulation at HIAF shows a **similar momentum spread** → We'd expect a similar injection efficiency but there's room for improvement (next slides).



CANTON- μ Proposal

Creative Anomalous magnetic moment Observation with Negative-muon

- We propose using HIAF's muon beam for muon g-2 measurement, featuring an independent approach that prioritizes negative muons and targets a final precision surpassing FNAL's 0.13 ppm.

Concept A

Co-magnetometer

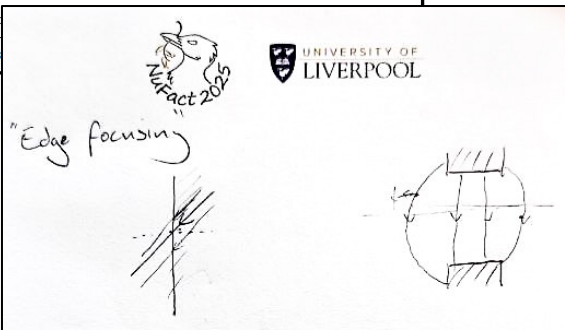
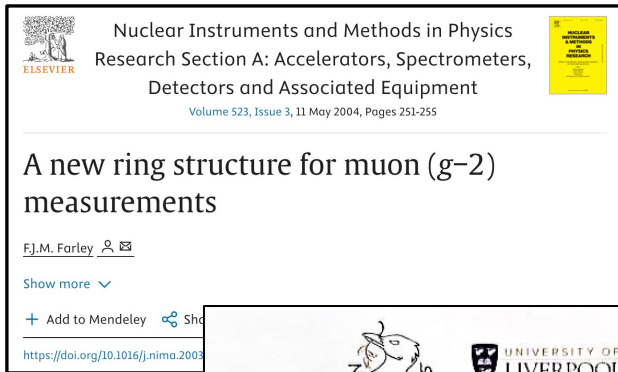
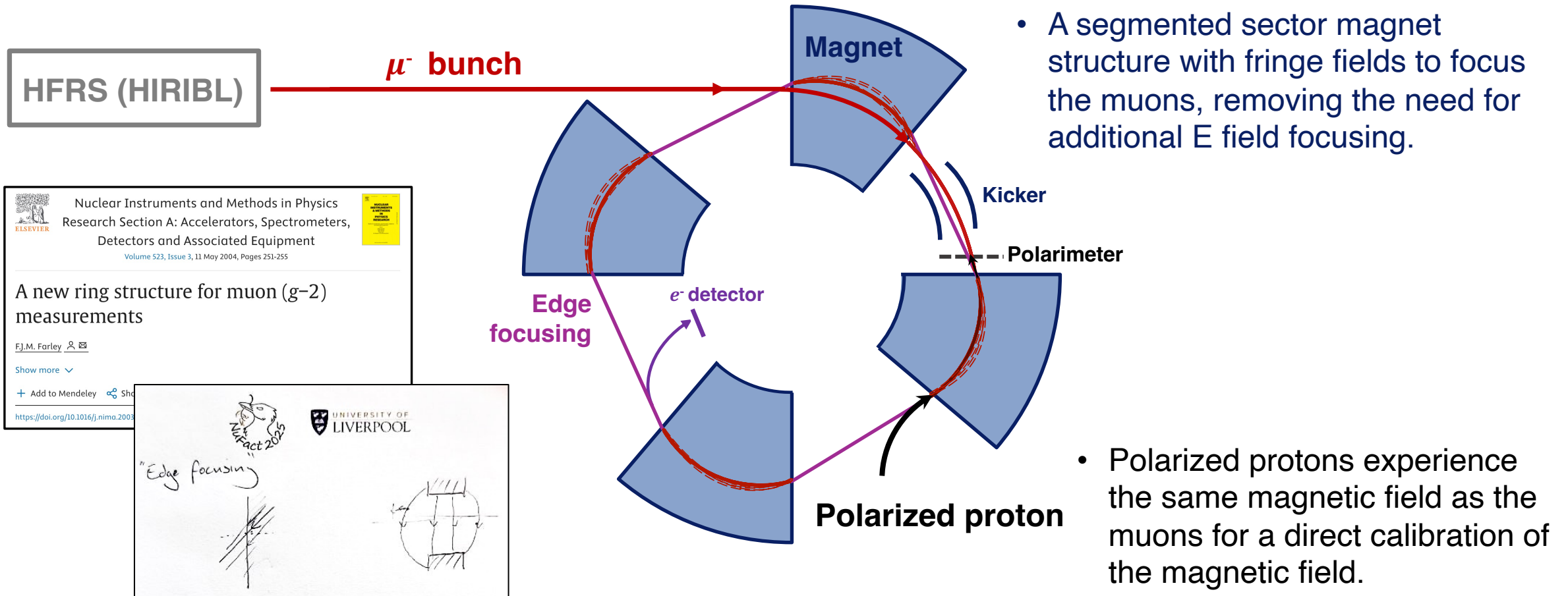
- a sector magnet design, eliminating E-field and a flexible muon momentum
- a polarized proton to directly calibrate the B field, a muon-proton “co-magnetometer”

Concept B

Weak hybrid focusing

- Combining electric and magnetic quadrupole focusing provides a more flexible longitudinal focusing scheme
- Also suppresses E-field corrections and CBO etc, while allowing a flexible momentum

Concept A – Comagnetometer

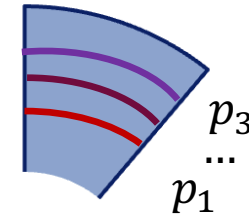


courtesy: Chris Rogers

Concept A – Comagnetometer

Details

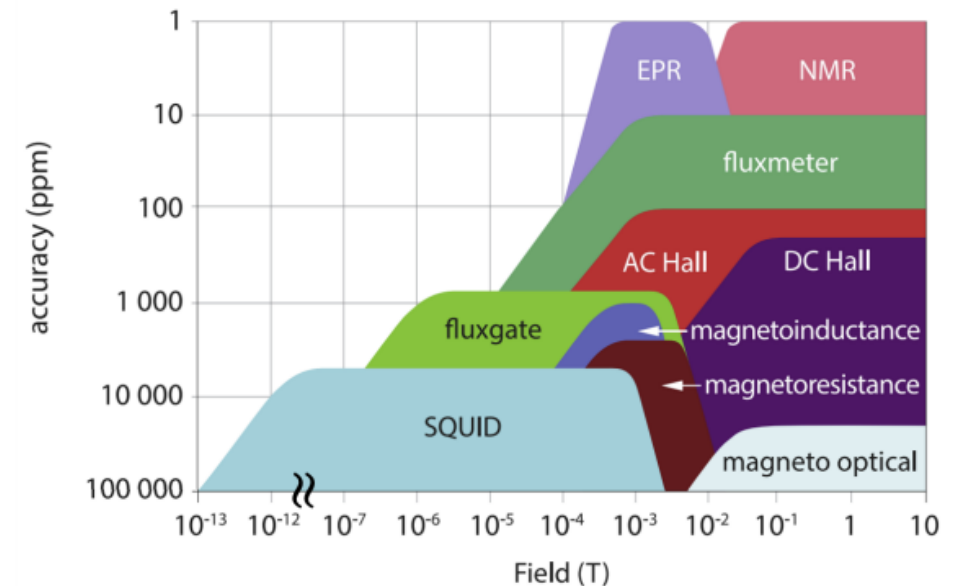
- A 3 - 6 T B-field $\rightarrow$ radii of about 7 m - 3 m
 - Small volume easier for field uniformity $\rightarrow$ a reduced systematics;
 - Challenging due to the limit of upstream bunch width;
- A strict momentum acceptance is relaxed
 - Muons of different momenta experience exactly the same spin evolution after one full turn in the magnetic field;
 - The injection efficiency could be greatly improved from FNAL's 2-3%
- No inflector needed $\rightarrow$ only need to design kicker(s)



Concept A – Comagnetometer

B-field calibration systematics

- Forseenably, one big challenge is the segment magnets – its fabrication and the related field calibration (with polarized protons)
- First thing – demonstrate it really works!
- **Polarized protons:** essentially a denser form of the NMR probe.
 - Fringe fields with large gradients confined to limited regions where NMR fails;
 - The proton approach could be combined with conventional methods — EPR probes or machine-learning-based fitting — to further improve the precision.



Courtesy Bingzhi Li

Concept A – Comagnetometer

Other sytematics

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	114
ω_a^m (systematic)	...	30
C_e Electric Field	347	27
C_p Pitch	175	9
C_{pa} Phase Acceptance	-33	15
C_{dd} Differential Decay	26	27
C_{ml} Muon Loss	0	2
$\langle \omega_p' \times M \rangle$ (mapping, tracking)	...	34
$\langle \omega_p' \times M \rangle$ (calibration)	...	34
B_k Transient Kicker	-37	22
B_q Transient ESQ	-21	20
μ_p'/μ_B	...	4
m_μ/m_e	...	22
Total systematic for $\mathcal{R}'_\mu$	...	76
Total for a_μ	572	139

- Removing the E-field would improve the systematics for both ω_a and ω_p
 - For both it stands as one of the largest uncertainty sources
- New systematics at B-field (protons, calibration etc)
 - Remove the dominant part currently and distribute the new systematic effects to the magnetic field part, which has more 'buffer' in the systematics chart

Concept A – Comagnetometer

Phase-II: upgrade with 10-20 GeV muon

- With a higher muon energy (and subsequently a higher B-field), the statistical sensitivity won't be a problem at all:
 - A 15 GeV muon with 15 T B-field $\rightarrow$ N/500;
 - A systematics-limited, and truly next generation g-2 experiment: driving advances in theory and techs.
- Being free from statistical limits opens a new window:
 - Pencil beam with a direct collimator: a better systematics related to beam dynamics – CBO, field mapping etc.
 - clock/counter-clock wise measurements
- Others: a dedicated muon beam-line with a delivery ring?

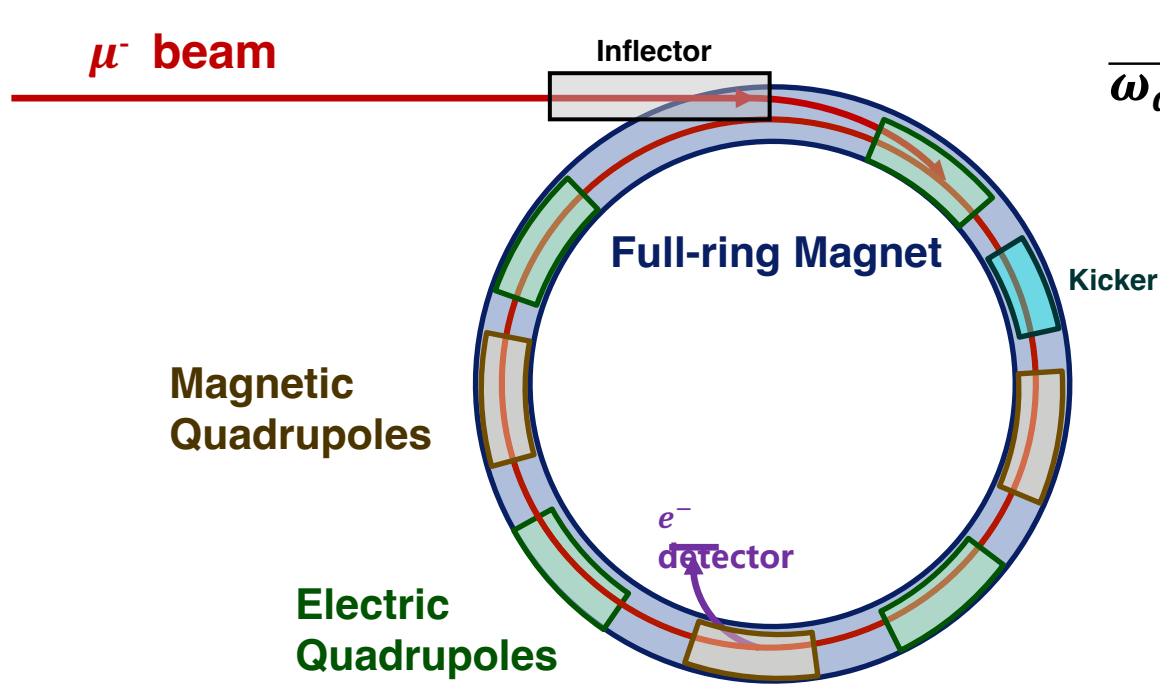


Comparisons

Facilities	CERN/BNL/FNAL	J-PARC	HIAF (HIAF-U)
Muon momentum	3.1 GeV/c	300 MeV/c	Flexible 2-4 GeV (HIAF) 10-20 GeV (HIAF-U)
Magnet	Full-ring magnet	Full-ring magnet	Sector magnet
Storage	B-field & E-field	B-field	Edge B-field focusing w/o E-field
Field calibration	NMR calibration	NMR calibration	Calibration via polarized proton and other methods
Data taking	650 days (FNAL)	> 300 days (expected)	100-200 days
Precision	μ^+ : 0.14 ppm (FNAL) μ^- : 0.7 ppm (BNL)	μ^+ : 0.46 ppm $\rightarrow$ ~0.1ppm	μ^-/μ^+ : 0.1 ppm $\rightarrow$ 0.05 ppm

Concept B – Hybrid weak focusing

- A hybrid focusing system with E-quadrupoles and B-quadrupoles, using higher-order B fields to compensate for higher-order E-fields:



$$\vec{\omega}_a = -\mathbf{a}_\mu \frac{q}{m_\mu} (\vec{B}_0 + \dots) + \frac{q}{m_\mu} \left[\left(\mathbf{a}_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]$$

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25**, 024001 (2022)

Analytical estimations of the chromaticity and corrections to the spin precession frequency in weak focusing magnetic storage rings

On Kim^{1,*} and Yannis K. Semertzidis^{1,2}

¹Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea

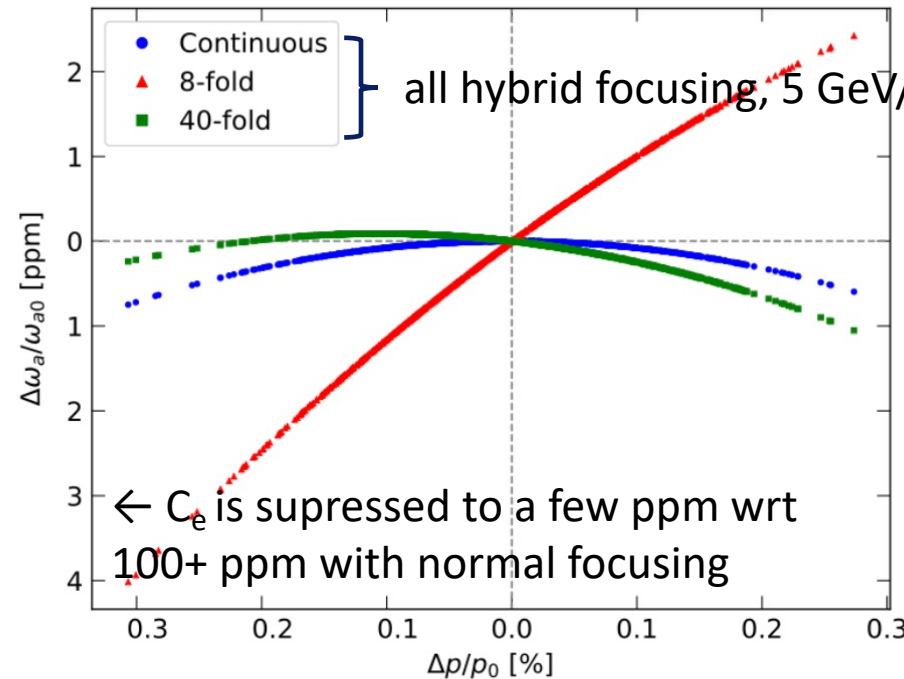
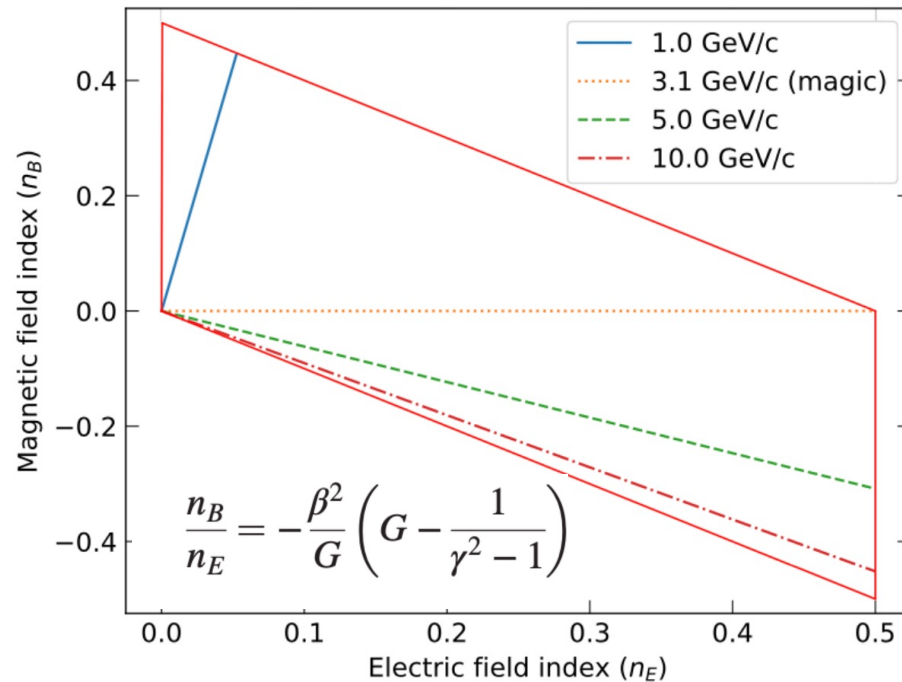
²Department of Physics, Korea Advanced Institute for Science and Technology, Daejeon 34141, Republic of Korea



(Received 18 October 2021; accepted 8 February 2022; published 18 February 2022)

Concept B – Hybrid weak focusing

Details

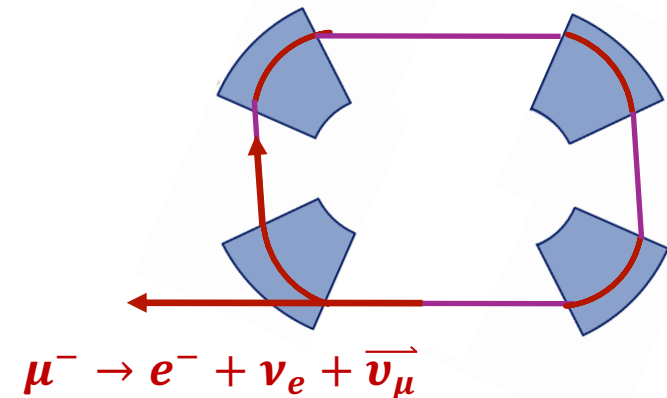
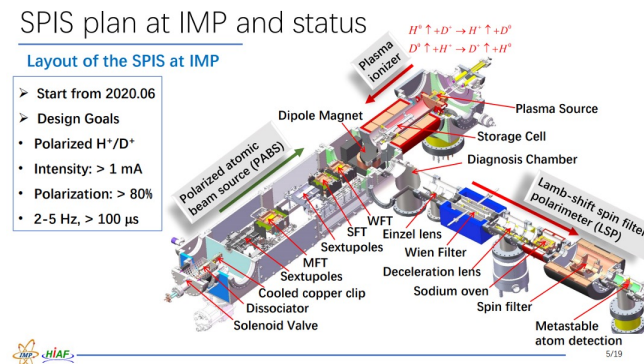


Now all are analytic - will need to demonstrate it works with a more realistic beam dynamics

- In principle it's straightforward to recycle the magnet from FNAL
- If Concept A turns to be too challenging, one could start with a more traditional version here.

Comments and feedbacks

- The biggest 'showstopper' I've received so far is still the question about the physics motivation. *Case closed* - this is the external perception of g-2.
- Some physics & technical connections
 - Polarized protons: synergy with the Electron-ion collider in China (EicC)
 - Proton EDM?
 - Neutrino factory?
 - ...



Outlook

- Draft proposal to arXiv soon;
- More detailed feasibility studies: the storage ring design, beam dynamics simulation, new systematics estimation, ...
- More possibilities on physics & technical connections;
- Long-term vision (still a bit of a dream at this stage!): CDR, TDR, ...
 - The decision would also depend on the progress from the theory side

Summary

- We propose a new muon g-2 experiment, CANTON- μ , at China's HIAF, whose muon beams perfectly meet the needs for g-2 — a GeV-scale, high-intensity pulsed muons.
 - The new experimental concept goes beyond the magic momentum constraint, enabling higher statistical precision and largely removing E-field systematics:
 - Phase I: 2–4 GeV muons — aiming at 0.1 ppm precision (comparable to FNAL);
 - Phase II: 10–20 GeV muons — aiming at 0.05 ppm precision, 3x better than FNAL.
- making it truly **a next-generation muon g-2 experiment.**

Summary

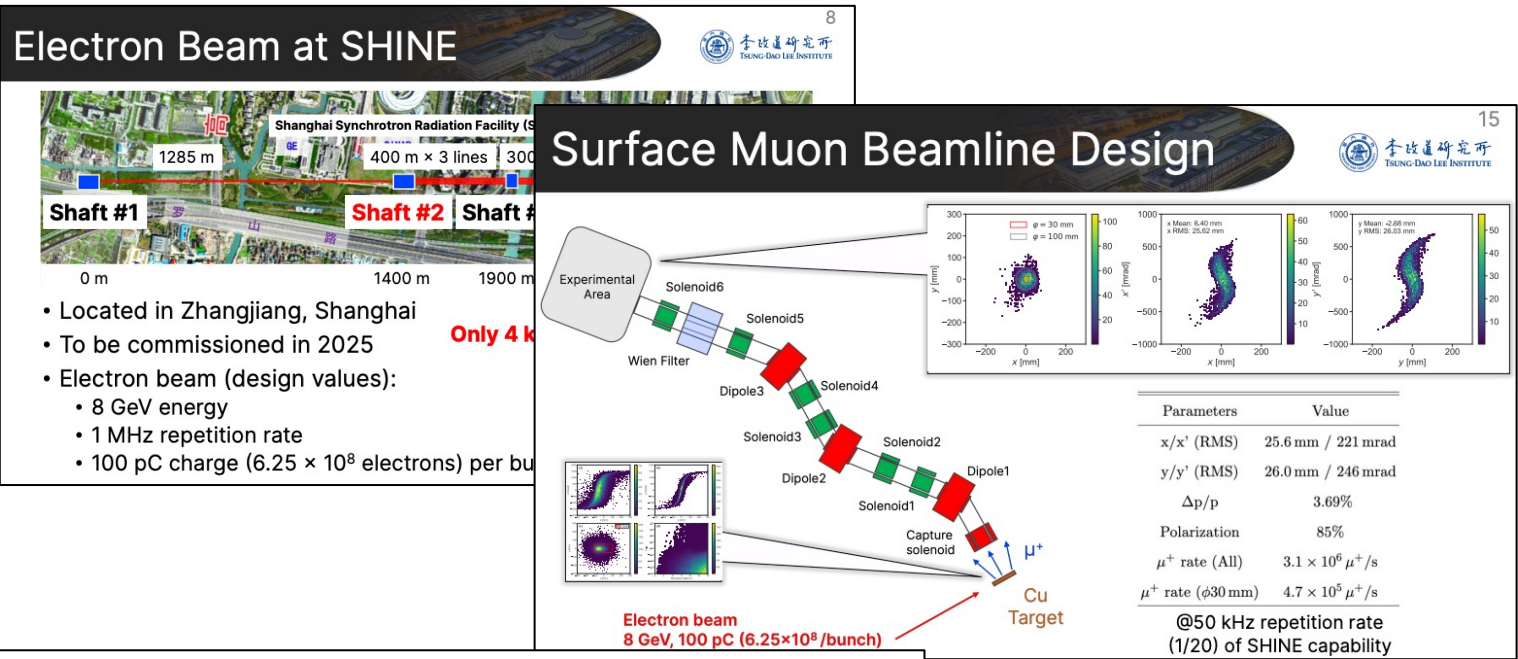
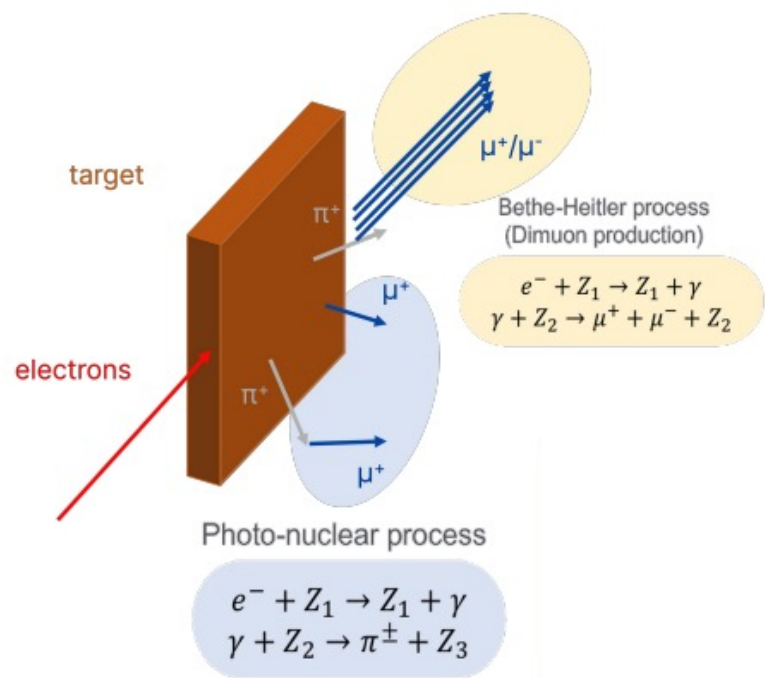
- The whole thing still at a very early stage - many feasibility studies to be done.
- The facility is under commissioning - muons are expected within 2–3 years.
- We hope to make muon g-2 the flagship experiment at HIAF — it's a long-term journey, any support and ideas along the way would be greatly appreciated.
- Good synergies with new initiatives at PSI/BNL/... as seen in this workshop!
- **Thanks!**

Backup

Muon sources in China

① Shanghai source

- Electron as a potential driver for muon sources
- Feature: high-repetition rate pulsed beam



Yusuke Takeuchi, Kim Siang Khaw @ MIP2025

Muon sources in China

① Shanghai source

- Electron as a potential driver for muon sources – more efforts:

nature physics

Article

<https://doi.org/10.1038/s41567-025-02872-2>

Proof-of-principle demonstration of muon production with an ultrashort high-intensity laser

Received: 7 September 2024

Accepted: 10 March 2025

Published online: 6 May 2025

Check for updates

Feng Zhang^{1,11}, Li Deng^{2,3,11}, Yanjie Ge^{4,5,11}, Jiaxing Wen¹, Bo Cui¹, Ke Feng⁴, Hao Wang⁴, Chen Wu^{6,7}, Ziwen Pan⁸, Hongjie Liu¹, Zhigang Deng¹, Zongxin Zhang⁴, Liangwen Chen^{2,3,9}, Duo Yan^{2,3,9}, Lianqiang Shan¹, Zongqiang Yuan¹, Chao Tian¹, Jiayi Qian⁴, Jiacheng Zhu⁴, Yi Xu⁴, Yuhong Yu^{2,3,9}, Xueheng Zhang^{2,3,9}, Lei Yang^{2,3,9}, Weimin Zhou¹, Yuqiu Gu¹, Wentao Wang⁴, Yuxin Leng⁴, Zhiyu Sun^{2,3,9} & Ruxin Li^{4,5,10}

Zhang, F., Deng, L., Ge, Y. *et al.* Proof-of-principle demonstration of muon production with an ultrashort high-intensity laser. *Nat. Phys.* **21**, 1050–1056 (2025).
<https://doi.org/10.1038/s41567-025-02872-2>

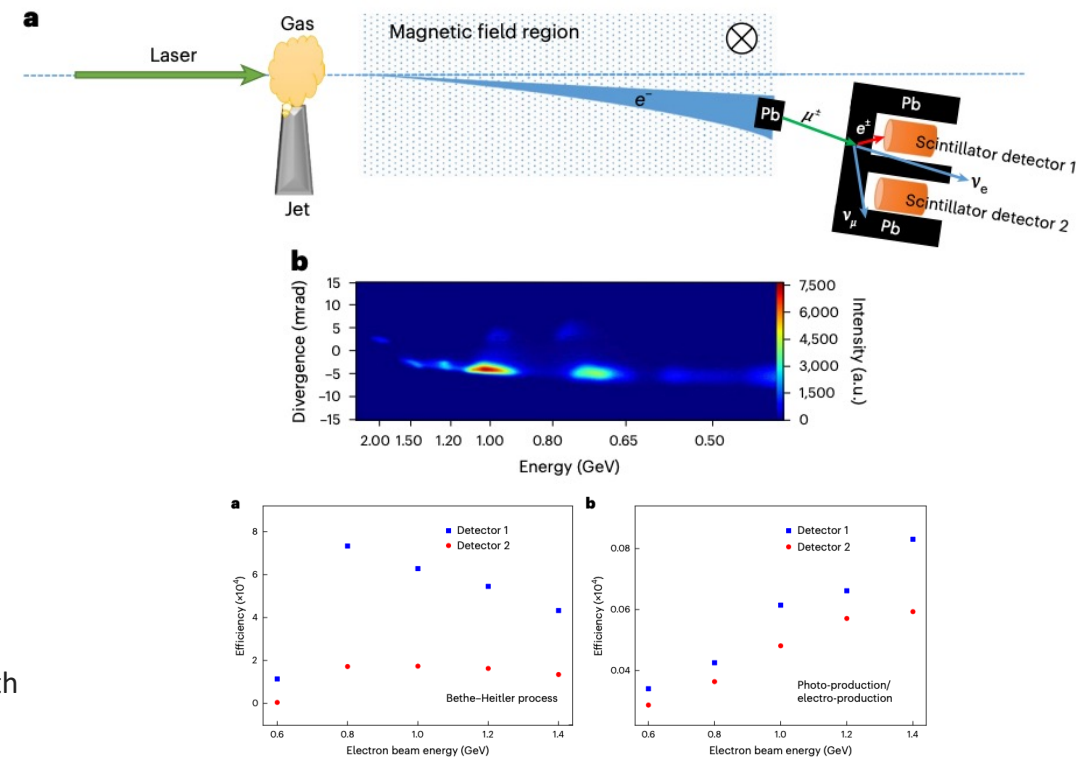
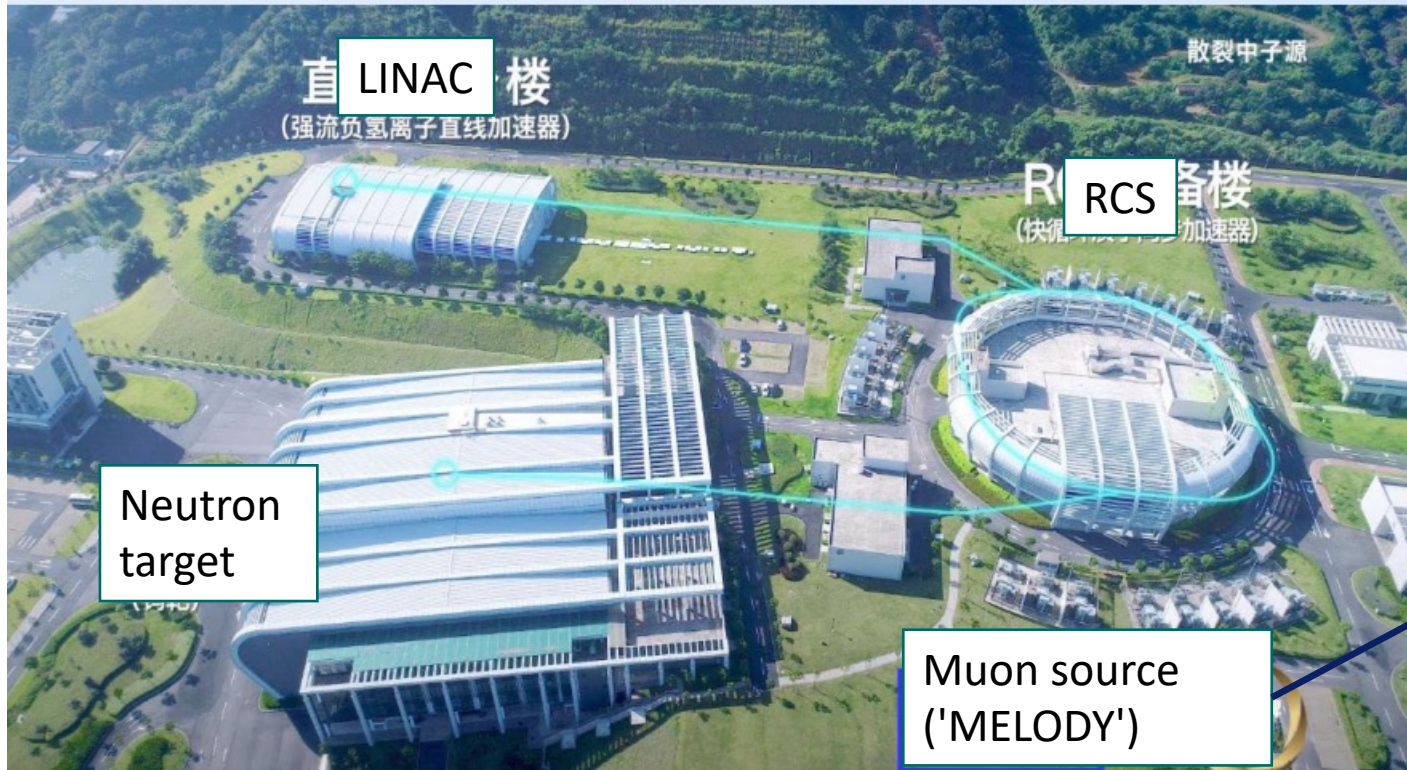


Fig. 6 | Detection efficiencies of muons in the experiment setting. a, The Bethe–Heitler process. **b,** Photo-production or electro-production. The uncertainties of detection efficiencies mainly arose from standard deviation, which was smaller than the marker size in the figure.

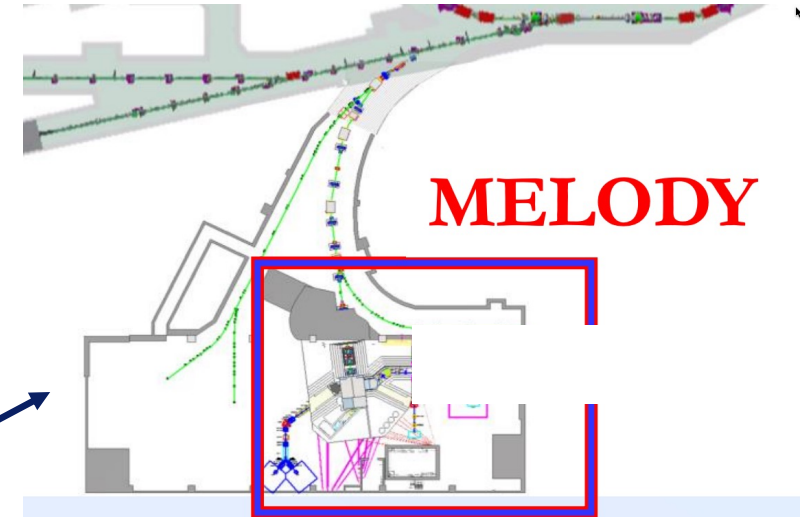
Muon sources in China

② CSNS (The China Spallation Neutron Source)



Accelerator: 170kW 25Hz 1.6GeV proton beam
Neutron Spectrometers: 9 built and 2 under construction

A facility managed by IHEP



Yu Bao, ECJ [workshop @ Shanghai](#)

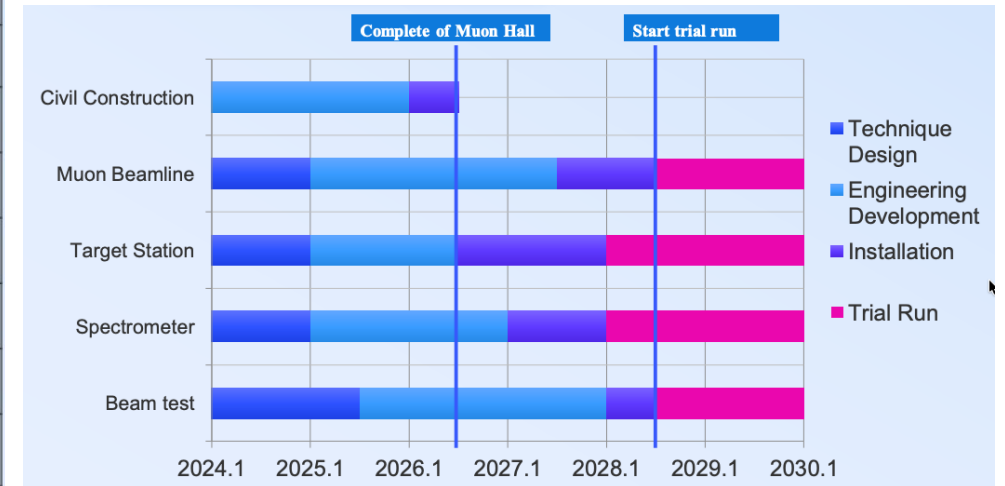
Muon sources in China

② CSNS (The China Spallation Neutron Source)

Design Parameters

Proton driver	Power	Repetition	Energy	Time Structure	σ_x	σ_y
	20 kW	1 Hz	1.6 GeV	120ns/409ns	3.1 mm	8.5 mm
Muon beam	Surface Muon (SMBT)		Negative Muon (NMBT)		Decay Muon (DMBT)	
Momentum	28 MeV/c		28 MeV/c		20~120 MeV/c	
dp/p	6%		13%		8% @ 120 MeV/c	
Beam spot	$\Phi 10\text{mm}-\Phi 100\text{mm}$		$\Phi 100\text{mm}$		$\Phi 30\text{mm}$	
Intensity	$10^5-10^7 \mu^+/s$		$4 \times 10^5 \mu^+/s$		$4 \times 10^6 \mu^+/s$	
Polarization	> 95%		~ 20 %		> 70%	
Pulse width	130 ns (SP) ~ 520ns (DP)		520 ns		130 ns (SP) ~ 520ns (DP)	
Spectrometer	Segments	Asymmetry	Count Rate	FOM: A ² *R	Temperature	LF/TF
	1584/3024*	~0.3	38/76* MEv/h	2.9/5.8*	2K ~ 300K	5000 G/ 400 G

Yu Bao, ECJ [workshop @ Shanghai](#)



HIAF and CiADS



HIAF and CiADS



HIAF

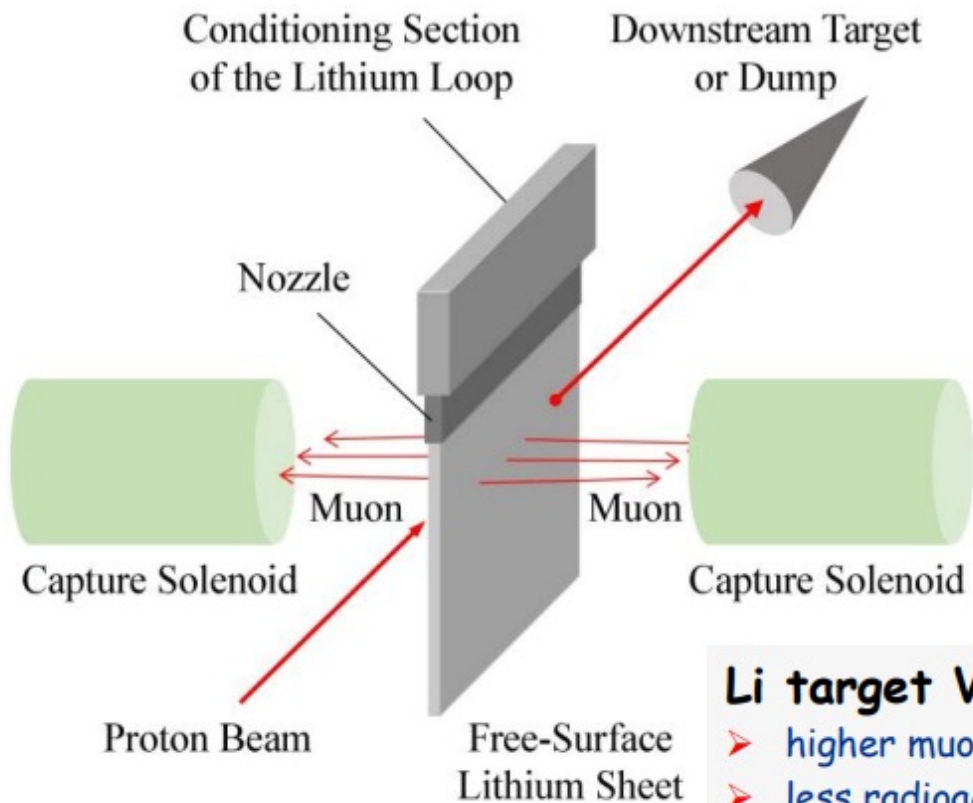
CIADS



CiADS



Concept of lithium jet target



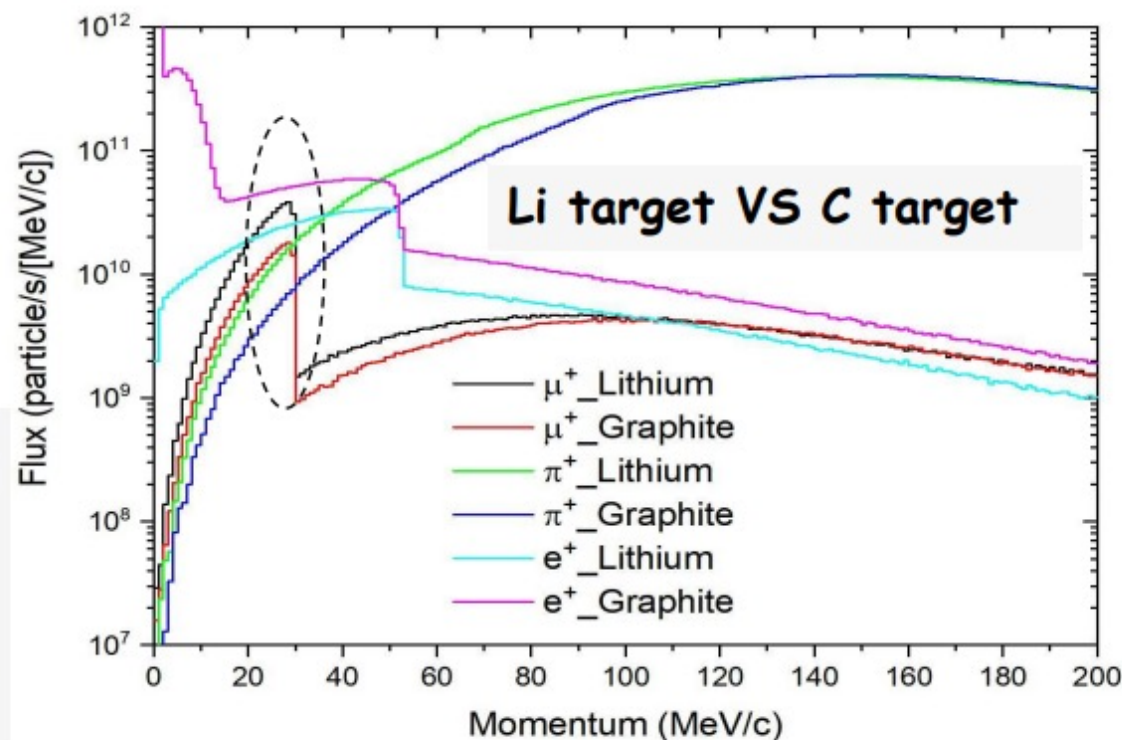
H.-J Cai et al, PRAB 27, 023703, 2024

Li target VS C target

- higher muon rate
- less radioactive nuclide and positrons background
- supporting higher beam power, free of irradiation damage

Design parameters:

- 3MW proton beam on target: 600MeV & 5mA
- Muon rate from target of $\sim 10^{11} \mu^+/\text{s}$



Muon beam comparison

Facility	Status
BNL	No muon beam available post BNL g-2
FNAL	No muon beam post g-2, now focusing on mu2e and neutrino
CERN	Muon beams at 150+GeV, focusing on target experiments (NA64, MUonE)
J-PARC	Low-energy muon beam; no plan for muon beam at main ring
PSI	Low-energy muon beam;
ISIS	Low-energy muon beam;

HIAF's GeV-scale, high-intensity pulsed μ^- beam — perhaps the only one in the next 20 years (?)

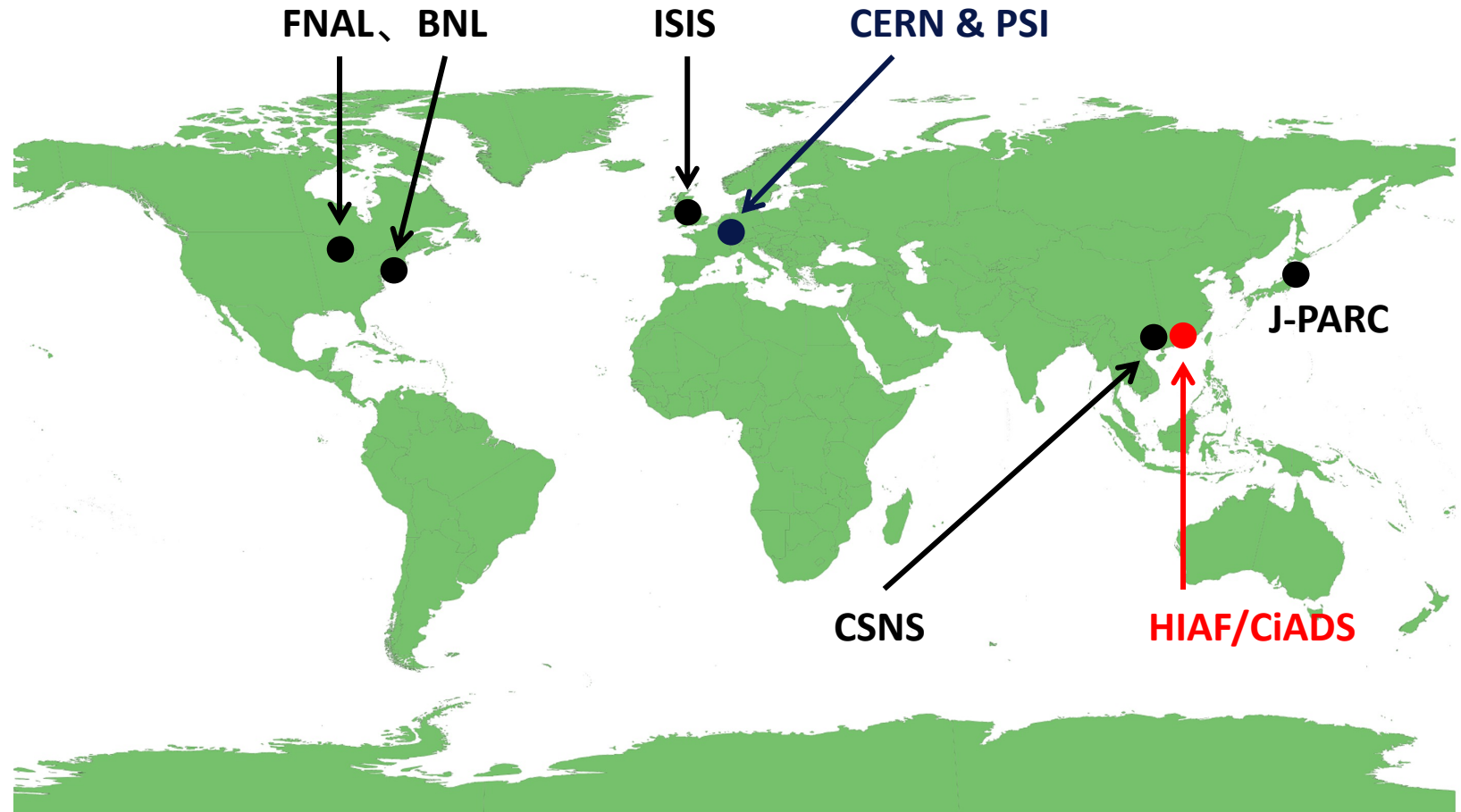
Proton accelerator based muon source

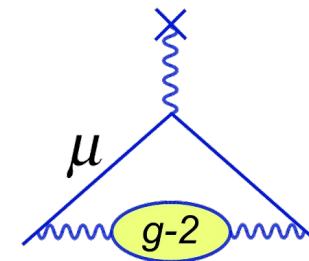
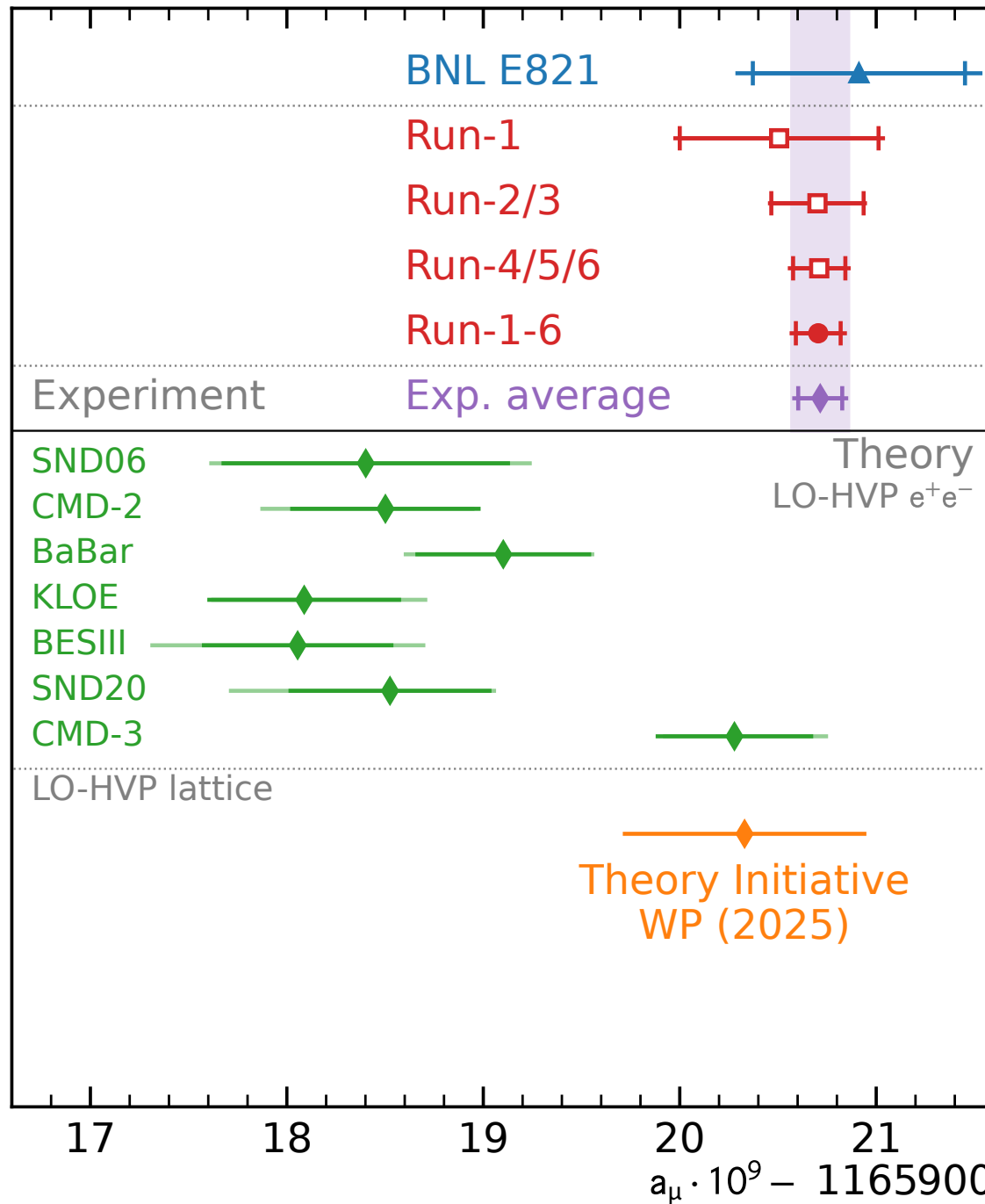
Low energy O(MeV)

ISIS
PSI
J-PARC
CSNS
CiADS

High energy O(GeV+)

FNAL
BNL
CERN
HIAF





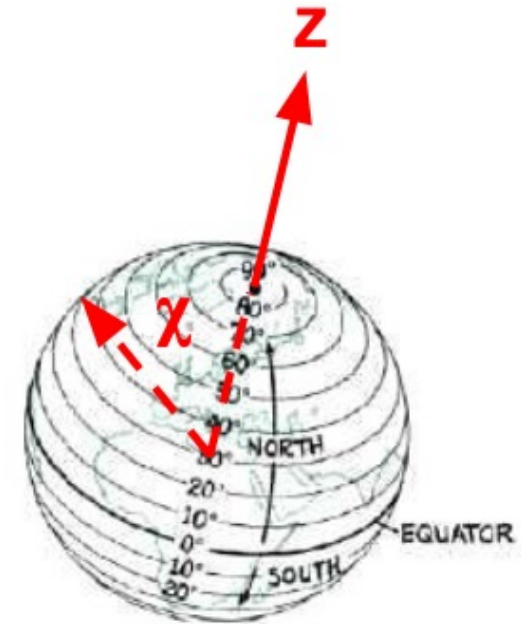
CPTLV: SME and Muon g-2



- SME Lagrangian:

$$\mathcal{L}' = -a_\kappa \bar{\psi} \gamma^\kappa \psi - \underbrace{b_\kappa}_{\text{circled}} \bar{\psi} \gamma_5 \gamma^\kappa \psi - \frac{1}{2} H_{\kappa\lambda} \bar{\psi} \sigma^{\kappa\lambda} \psi \\ + \frac{1}{2} i c_{\kappa\lambda} \bar{\psi} \gamma^\kappa \overleftrightarrow{D}^\lambda \psi + \frac{1}{2} i d_{\kappa\lambda} \bar{\psi} \gamma_5 \gamma^\kappa \overleftrightarrow{D}^\lambda \psi$$

- All terms violate Lorentz invariance
- a_κ, b_κ are CPT-odd; others are CPT-even
- Predicts two CPT/Lorentz Violating signatures for muon g-2:
 - Gomes, Kostelecky, Vargas, Phys.Rev.D90:076009,2014
 - **Sidereal (or annual) variation in ω_a**
 - **Difference in ω_a between μ^+ / μ^-**
 - Use frame where Z is the orientation of the earth's axis relative to the fixed, distant stars, and χ is the colatitude (earth's precession negligible in our case)



SME Muon Sector Current Limits (Kostelecký et.al.)



Table D21. Muon sector, $d = 3$

Combination	Result	System	Ref.
$ \text{Re } H_{011}^{\text{NR}(0B)} , \text{Im } H_{011}^{\text{NR}(0B)} , \text{Re } g_{011}^{\text{NR}(0B)} , \text{Im } g_{011}^{\text{NR}(0B)} $	$< 2 \times 10^{-22} \text{ GeV}$	Muonium spectroscopy	[20]*
$ \text{Re } H_{011}^{\text{NR}(1B)} , \text{Im } H_{011}^{\text{NR}(1B)} , \text{Re } g_{011}^{\text{NR}(1B)} , \text{Im } g_{011}^{\text{NR}(1B)} $	$< 7 \times 10^{-23} \text{ GeV}$	"	[20]*
b^T/m_μ	$(7.3 \pm 5.0) \times 10^{-7}$	Muon decay	[184]*
b_Z	$-(1.0 \pm 1.1) \times 10^{-23} \text{ GeV}$	BNL $g_\mu - 2$	[185]
$\sqrt{(\check{b}_X^{\mu+})^2 + (\check{b}_Y^{\mu+})^2}$	$< 1.4 \times 10^{-24} \text{ GeV}$	"	[185]
$\sqrt{(\check{b}_X^{\mu-})^2 + (\check{b}_Y^{\mu-})^2}$	$< 2.6 \times 10^{-24} \text{ GeV}$	"	[185]
$\sqrt{(\tilde{b}_X)^2 + (\tilde{b}_Y)^2}$	$< 2 \times 10^{-23} \text{ GeV}$	Muonium spectroscopy	[186]
$b_Z - 1.19(m_\mu d_{Z0} + H_{XY})$	$(-1.4 \pm 1.0) \times 10^{-22} \text{ GeV}$	BNL, CERN $g_\mu - 2$ data	[187]
b_Z	$(-2.3 \pm 1.4) \times 10^{-22} \text{ GeV}$	CERN $g_\mu - 2$ data	[187], [188]*
$ \text{Re } H_{011}^{(3)(0B)} , \text{Im } H_{011}^{(3)(0B)} $	$< 5 \times 10^{-23} \text{ GeV}$	"	[20]*
$\check{H}_{010}^{(3)}$	$(-1.6 \pm 1.7) \times 10^{-22} \text{ GeV}$	BNL, CERN $g_\mu - 2$ data	[20]*
$ \text{Re } \check{H}_{011}^{(3)} , \text{Im } \check{H}_{011}^{(3)} $	$< 2.0 \times 10^{-24} \text{ GeV}$	BNL $g_\mu - 2$	[20]*
$m_\mu d_{Z0} + H_{XY}$	$(1.8 \pm 6.0) \times 10^{-23} \text{ GeV}$	"	[185]