The GeV Muon Beam at the HIAF Facility: Opportunities for Muon Physics and Applicaitons

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Outline

- Introduction of muon source
- Muon sources at HIAF
- Physics and Applications Opportunities
- Summary

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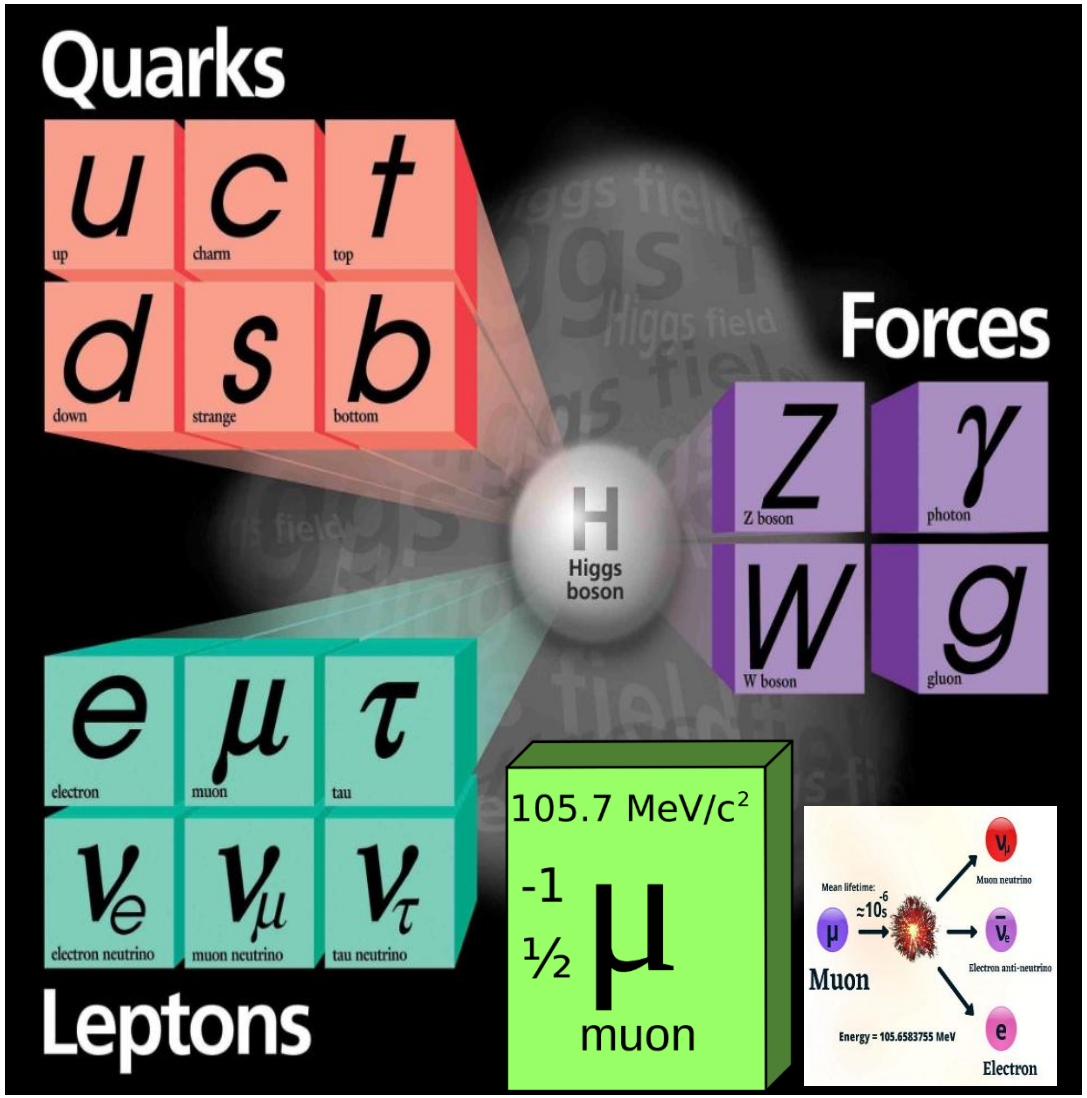
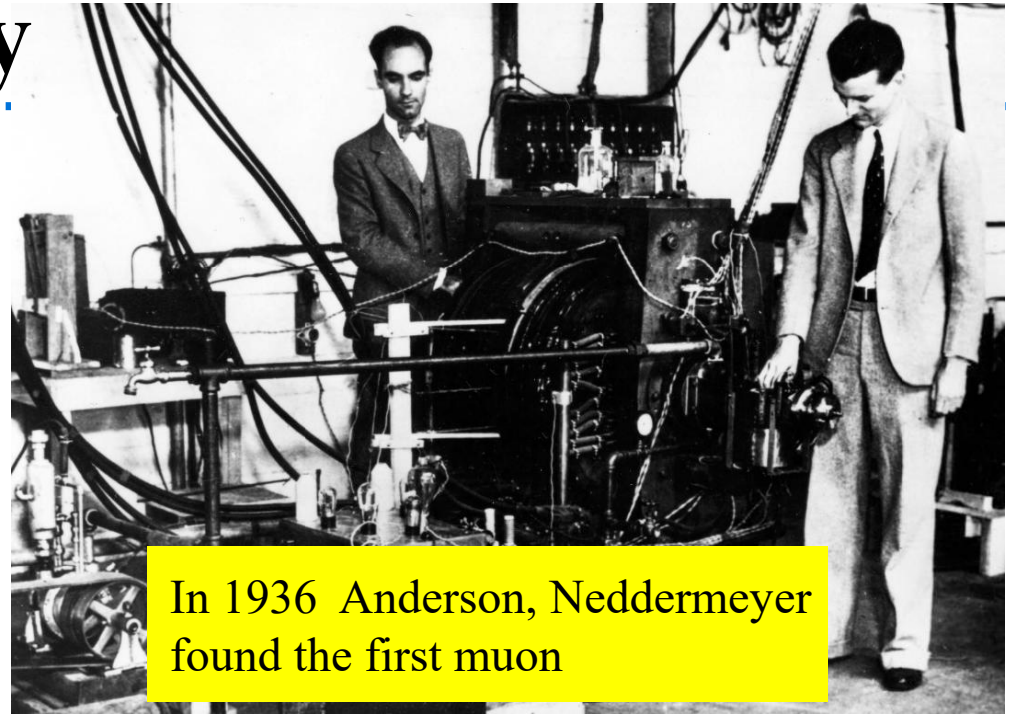
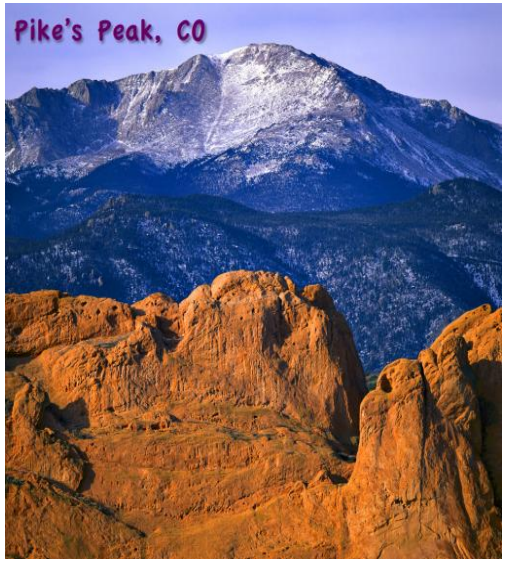
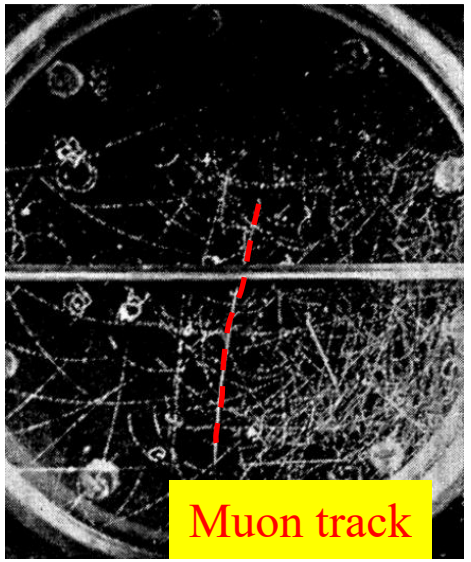
Muon and its discovery





In 1936 Anderson, Neddermeyer found the first muon



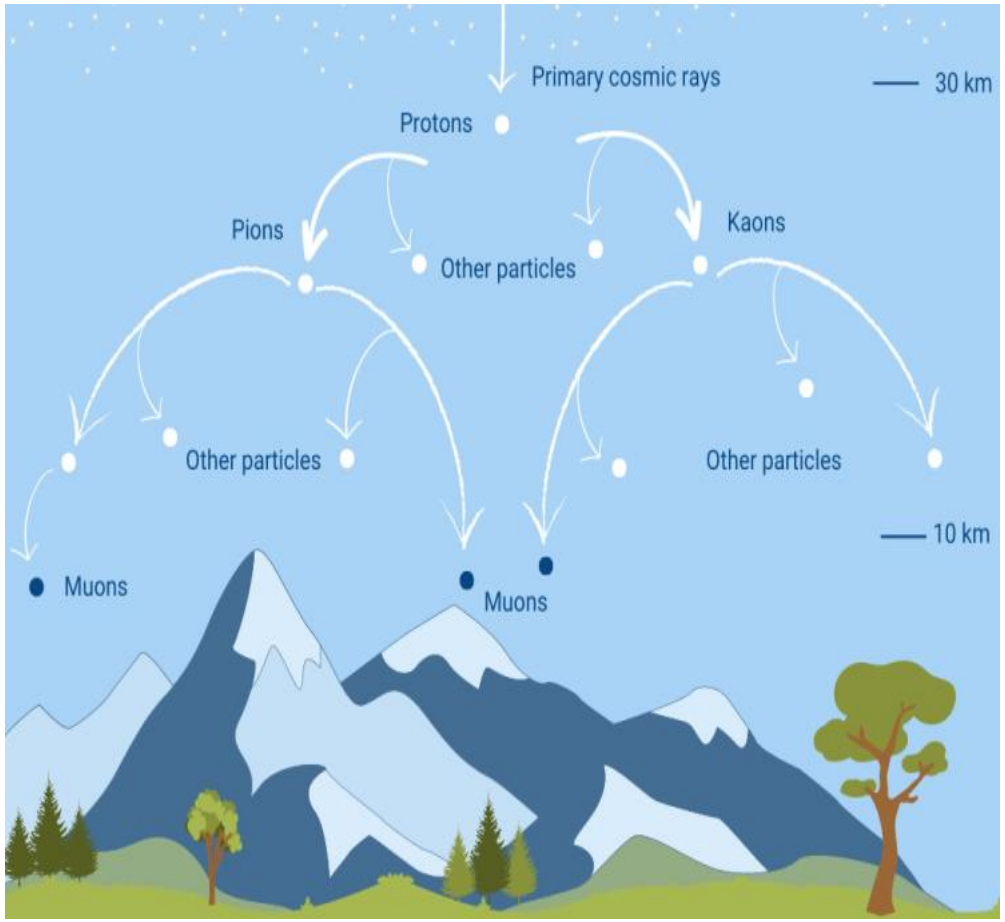


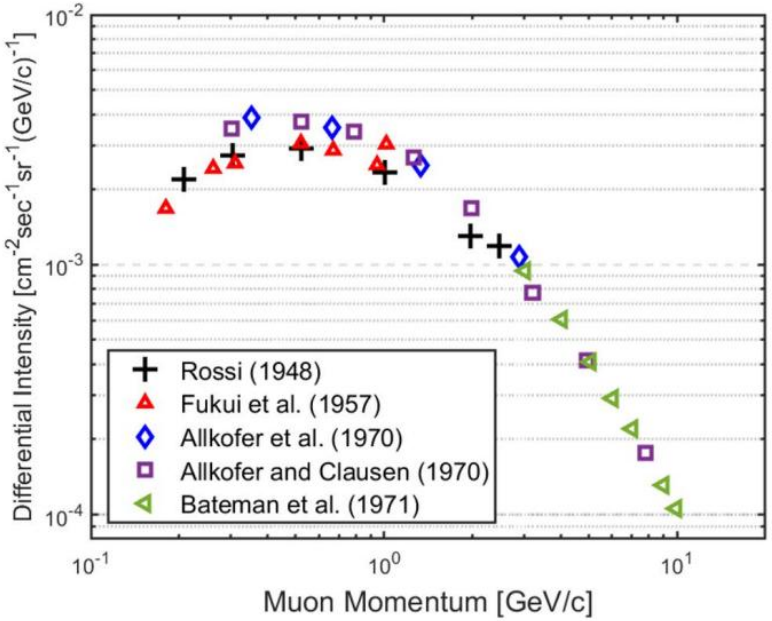
Muon track

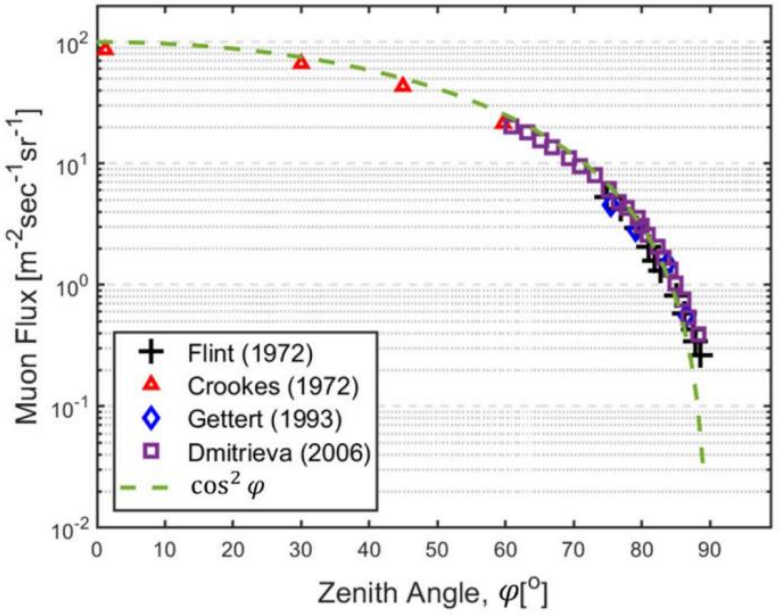
Phys. Rev. 50 (1936) 263

Muon souce

Cosmic ray muon





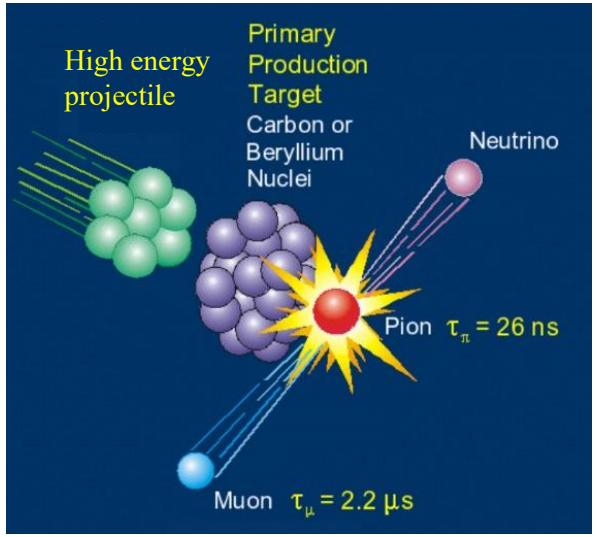


muons at sea leval

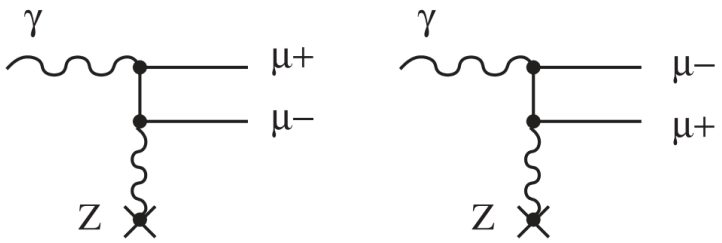
J. Bae, Scientific Reports, 14,6717(2024)

Muon source

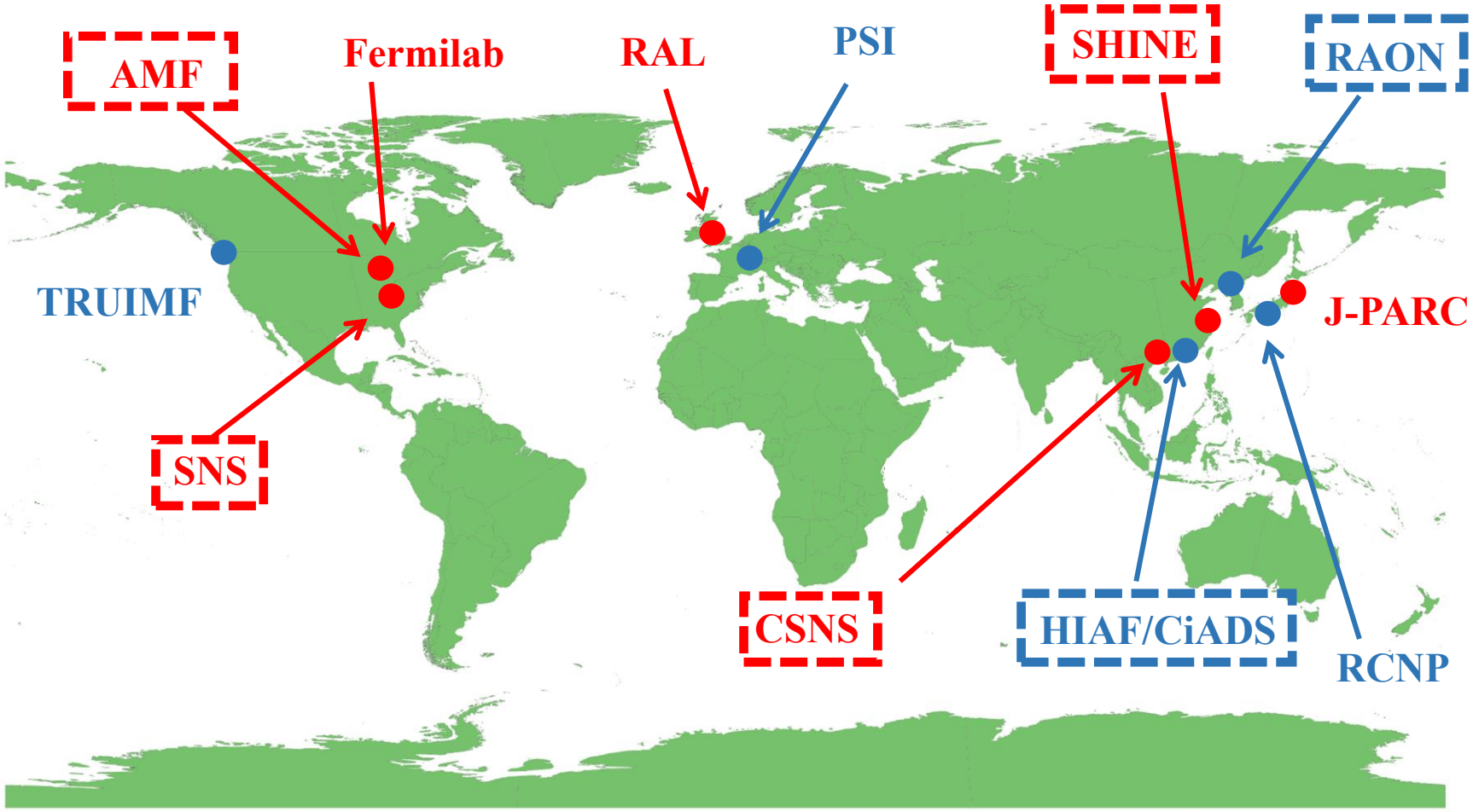
Accelerator based muon



Muon from pion decay

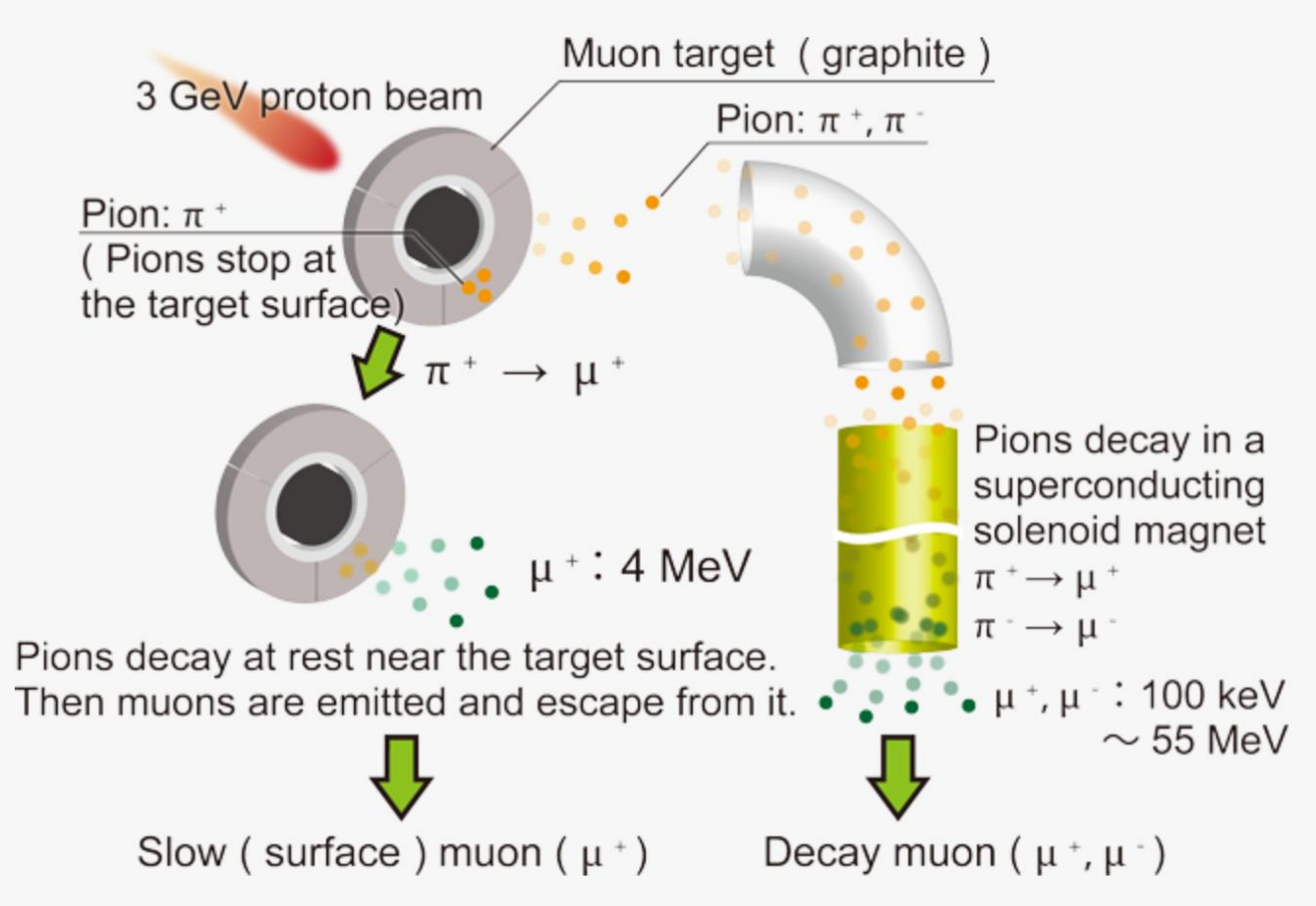


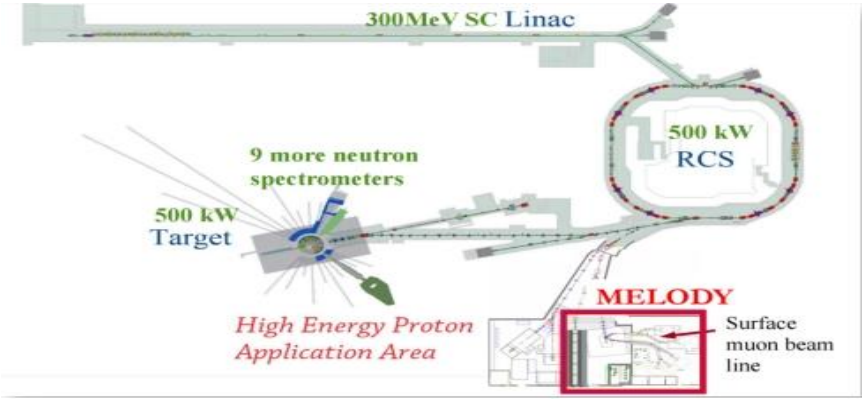
Bethe-Heitler process

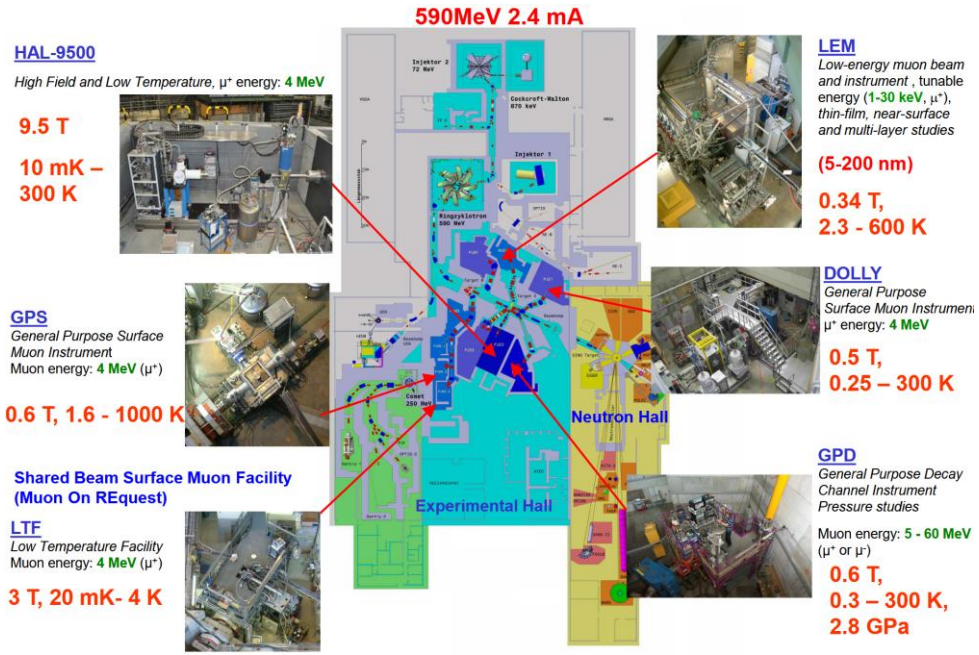


Muon source

Accelerator based muon：
Proton/Ion accelerator







Muon source

Accelerator based muon：
Electron accelerator

Photo-production

$$e^- + Z_1 \rightarrow \gamma + Z_1, \quad \gamma + Z_2 \rightarrow \pi^{\pm} + Z_3 \qquad \sigma_q(E_0)$$

Electro-production

$$e^- + Z_1 \rightarrow (e^-)' + Z_1 + \pi^{\pm} + Z_2 \qquad \sigma_e(E_0)$$

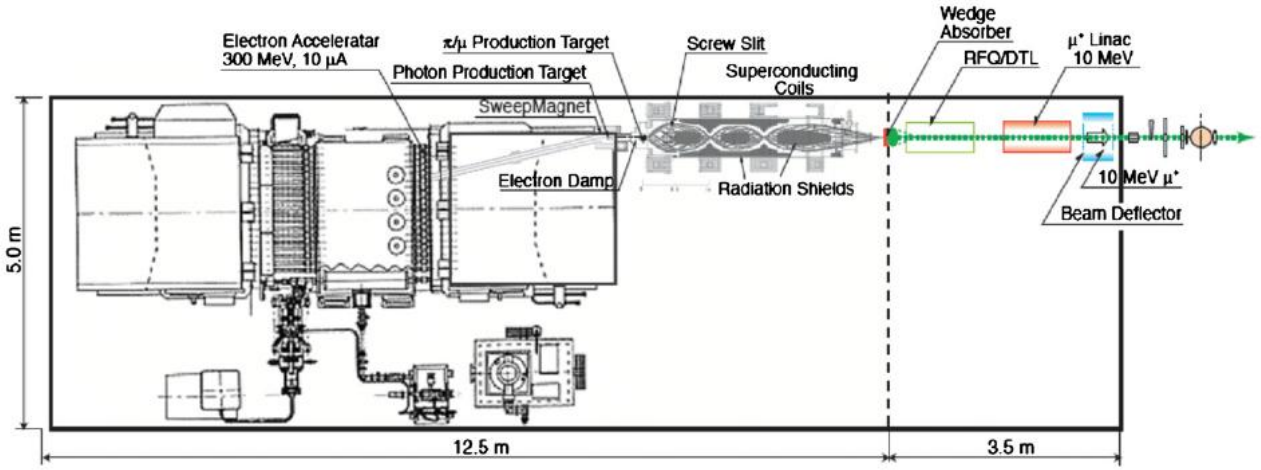
$$\sigma_e(E_0)/\sigma_q(E_0) \approx 0.1$$

muon pair creation

$$\gamma + Z \rightarrow \mu^+\mu^- + \text{anything} \qquad \sigma_{pair}(E_0)$$

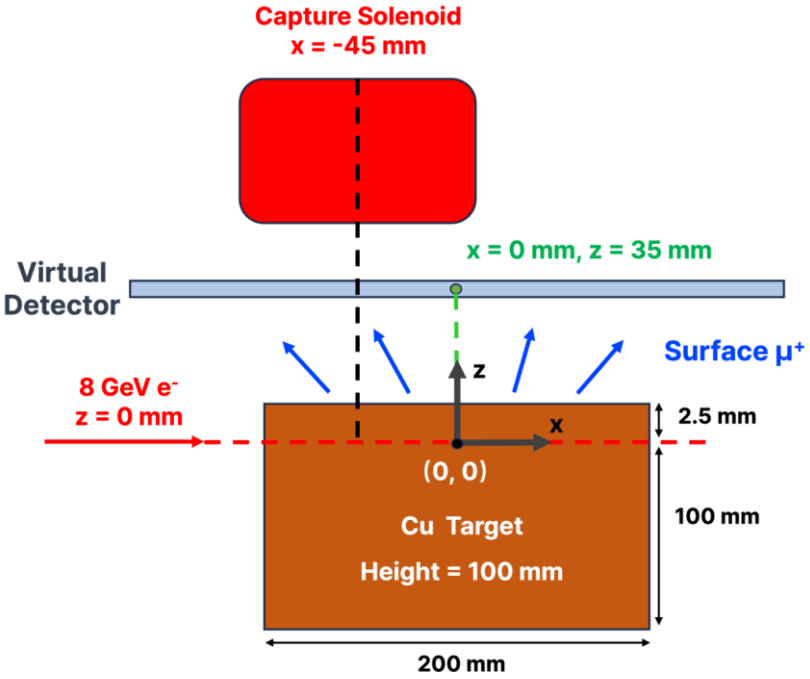
$$\sigma_{pair}(E_0)/\sigma_q \approx 10^{-3}\sim10^{-4}$$

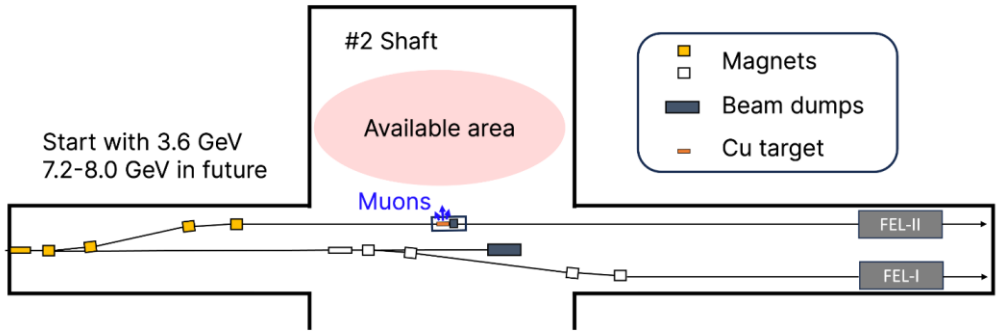
K. Nagamine et al, Physica B 404 (2009) 1020~1023



$$Y(\pi) = (0.63 \times 10^{14}) \times (0.92 \times 10^{-2}) \times (4 \times 10^{-7})/\text{s}$$
$$= 2.3 \times 10^{5}/\text{s}.$$

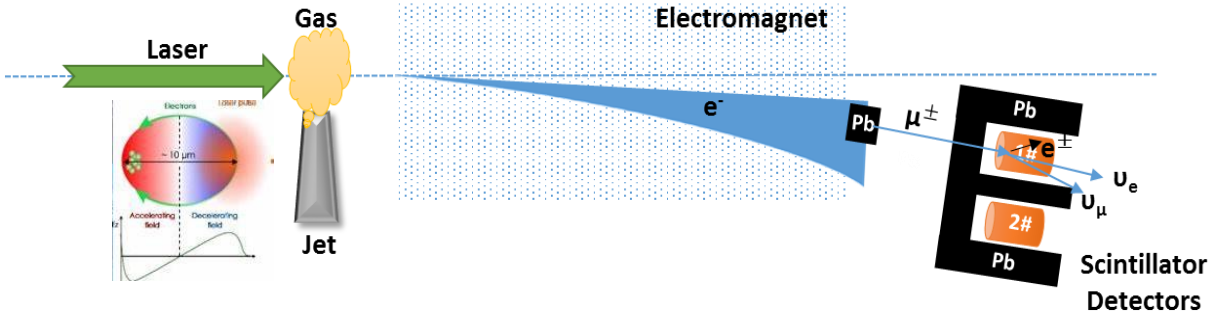
上海交大团队提出利用SHINE的束流产生μ子源

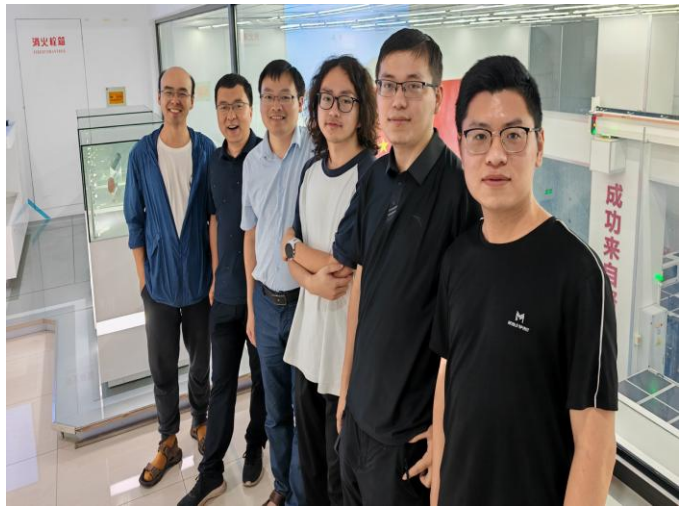




Muon source

Accelerator based muon：
Ultrashort high intensity laser





nature physics

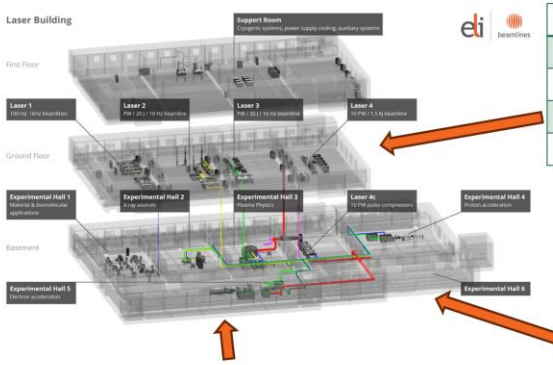
Article https://doi.org/10.1038/s41567-025-02872-2

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

Shanghai Superintense Ultrafast Laser Facility (SULF)

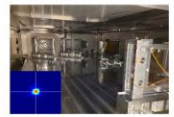
eli

ELI Beamlines for muons

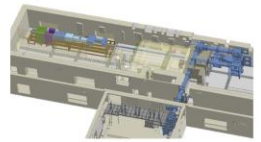


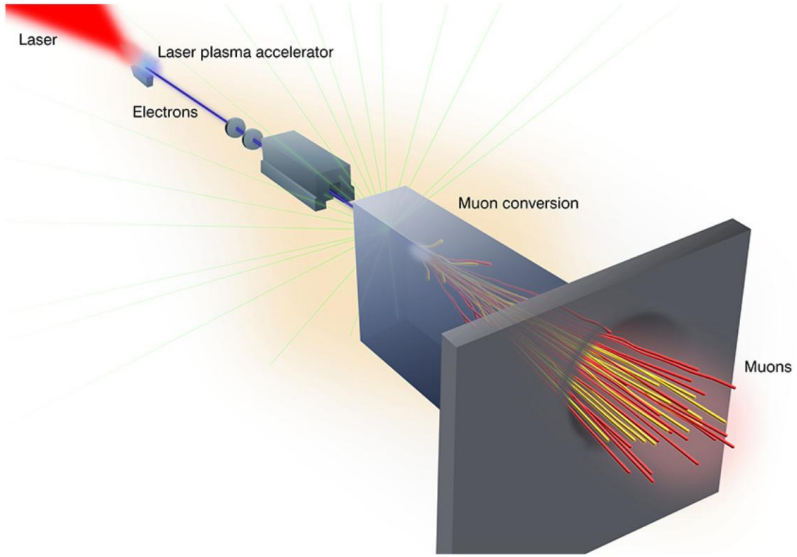
L1-Allegra	L2-Duha	L3-HAPLS	L4-Aton
OPCPA	OPCPA	Ti:Sa	Nd:Glass
100 mJ	2 J	30 J	1.5 kJ
15 fs	25 fs	30 fs	150 fs
1 kHz	20 Hz	10 Hz	0.01 Hz

ELBA Beamline (L3-HAPLS)



Future Beamline (L4-Aton)





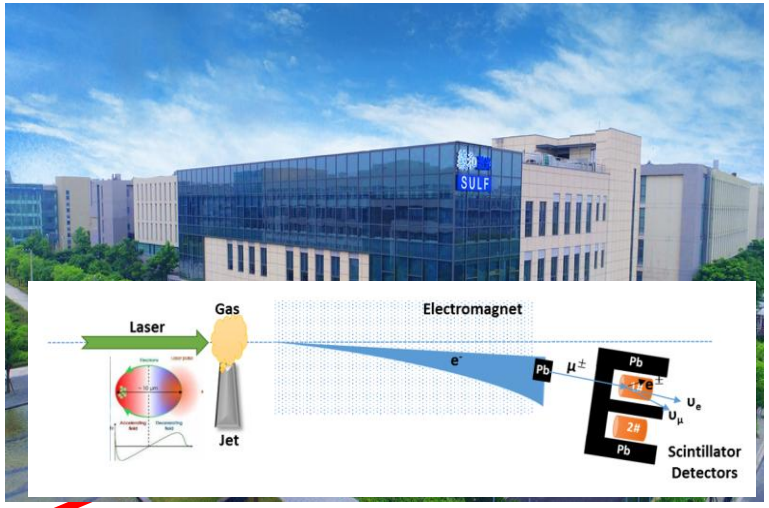
Berkeley Lab Laser Accelerator (BELLA)

Muon sources in China

MELODY@CSNS pulsed，~2028

Muon@ SHINE high-repetition-rate，2030

Muon@ SULF compact muon source

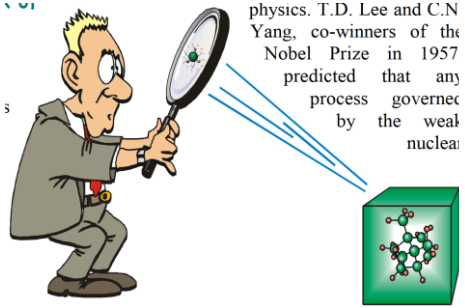


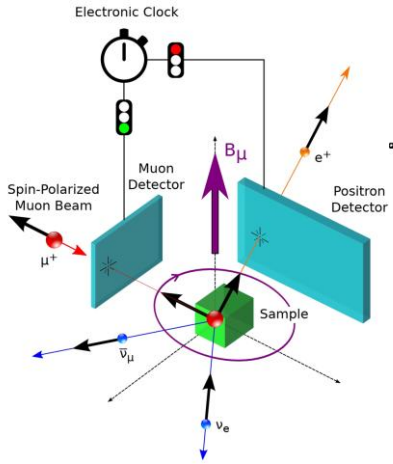
HIAF-HIRIBL

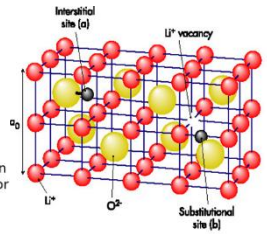
GeV energy muon

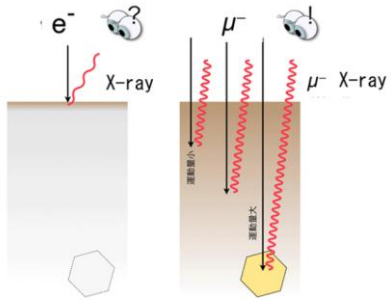
MuST@CiADS continuous，~2029

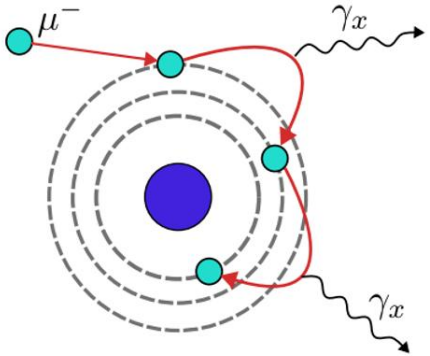
Broad applications of muon source facility

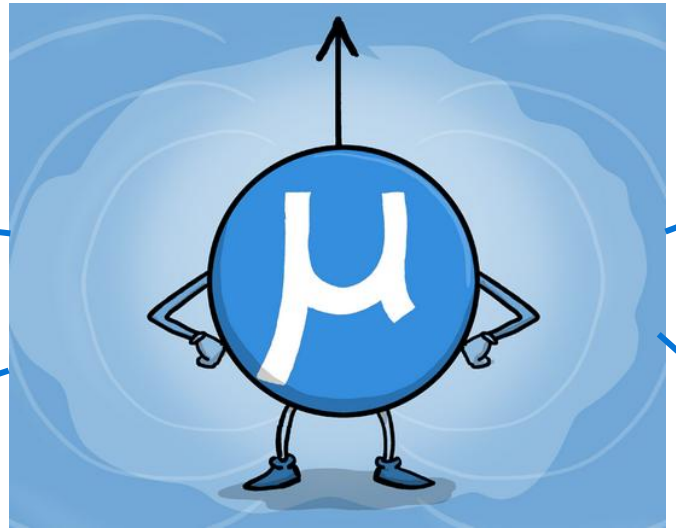










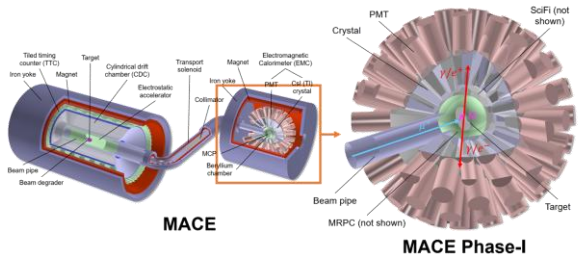


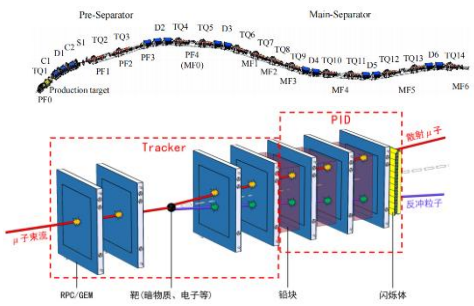
Muon spin rotations

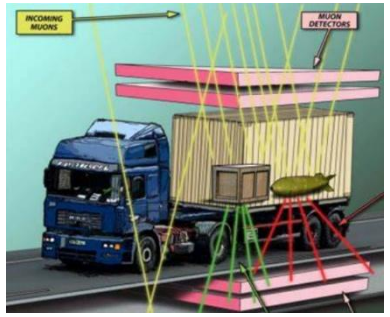
Searching for new physics

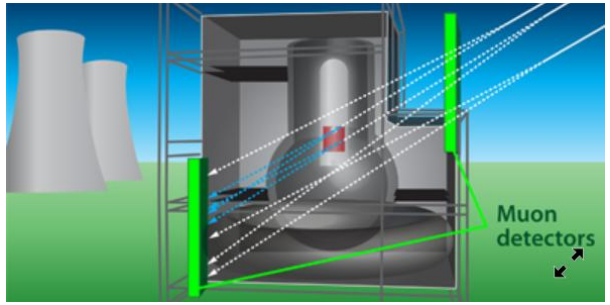
Elemental analysis with muonic X ray

Muon tomography









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- Introduction of muon source
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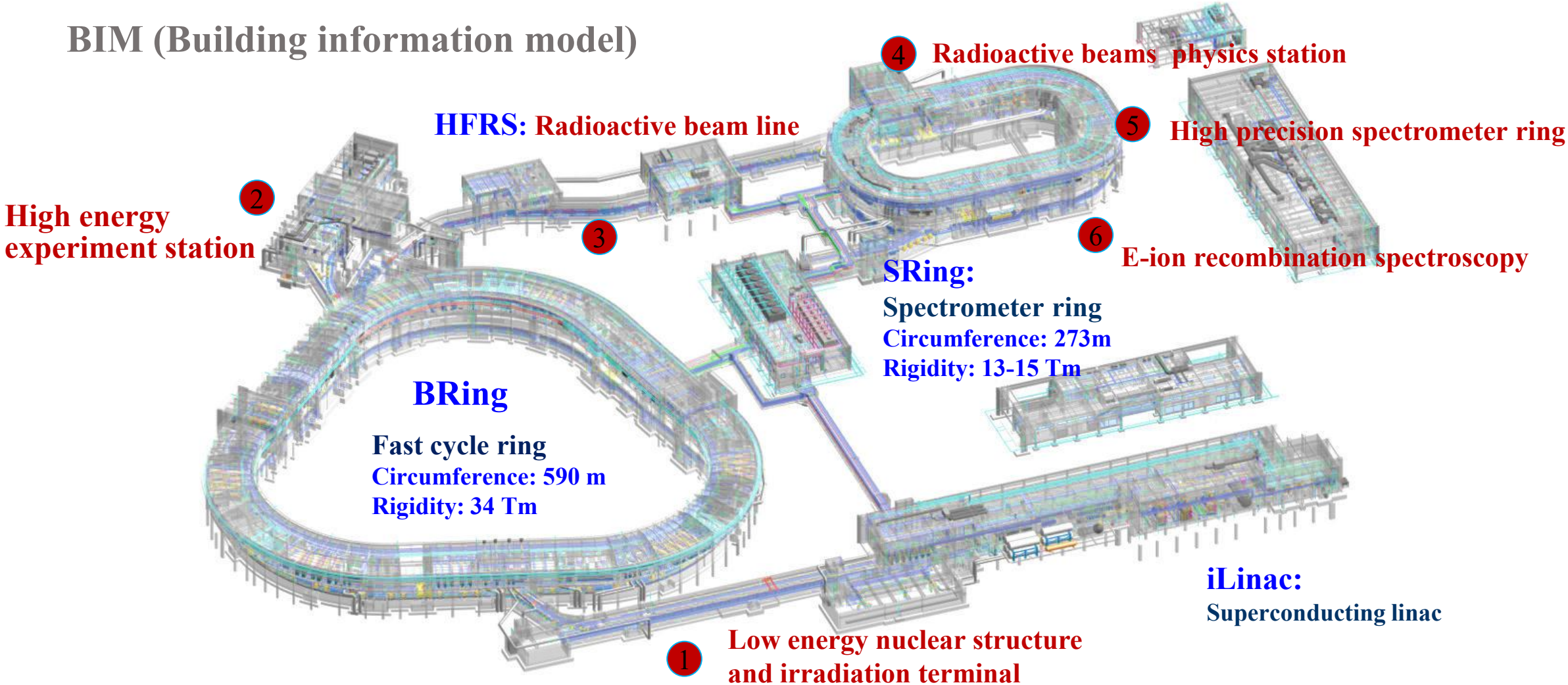
HIAF Facility

- **Experiment terminals**

BIM (Building information model)



HIAF Facility

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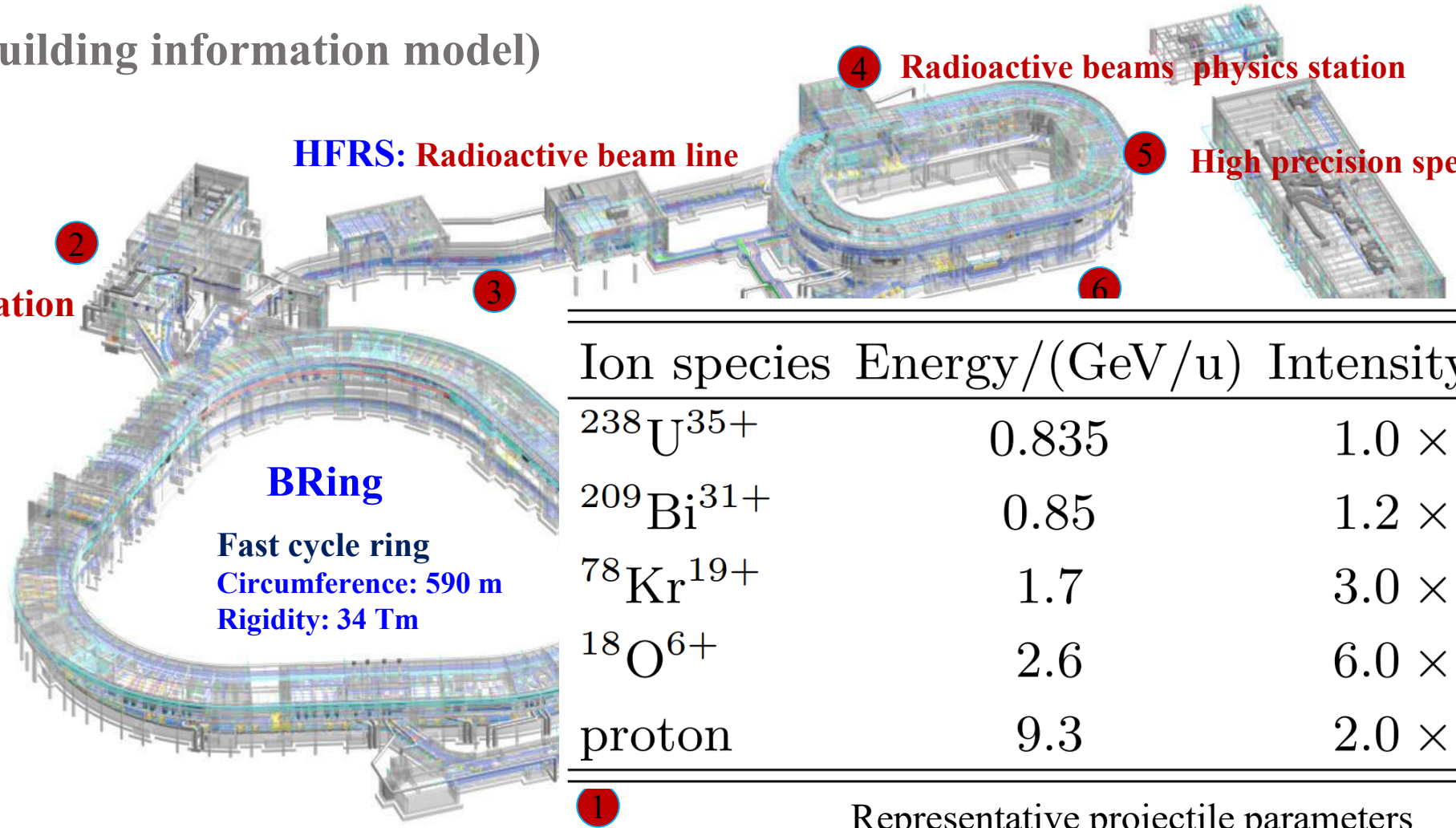
BIM (Building information model)

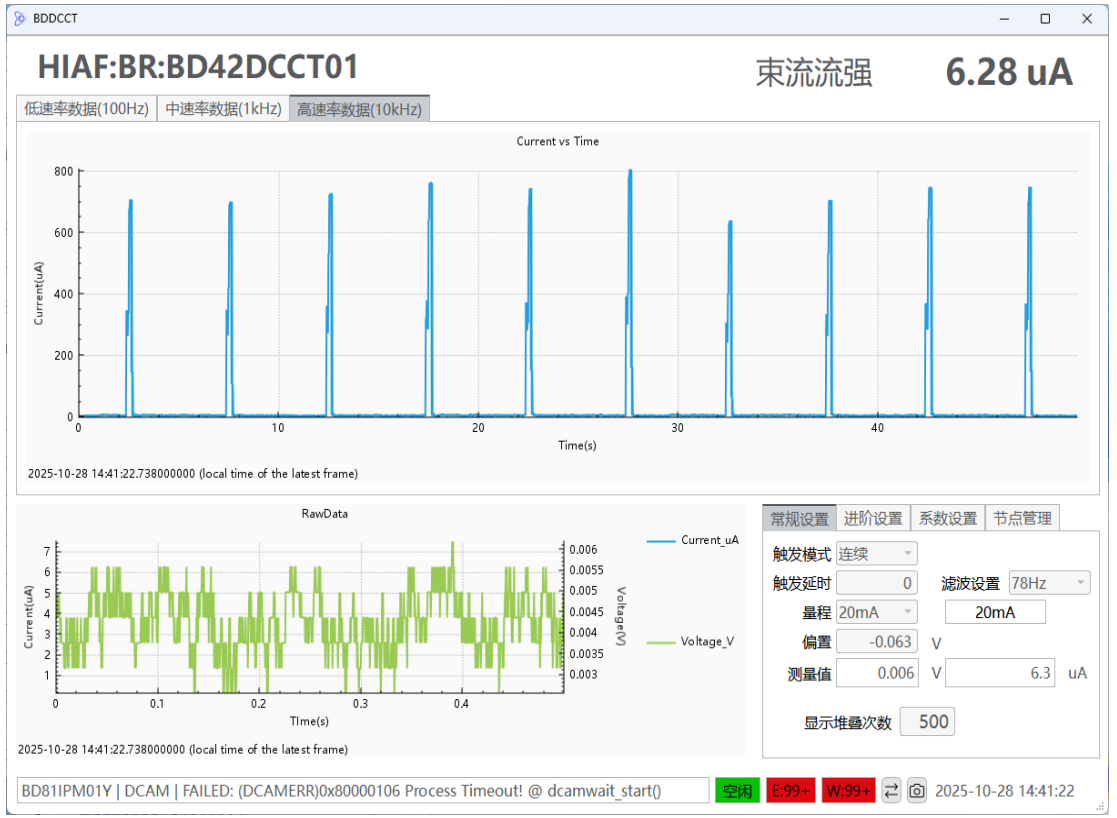


Ion species	Energy/(GeV/u)	Intensity/(ppp)
$^{238}U^{35+}$	0.835	1.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{18}O^{6+}$	2.6	6.0×10^{11}
proton	9.3	2.0×10^{12}

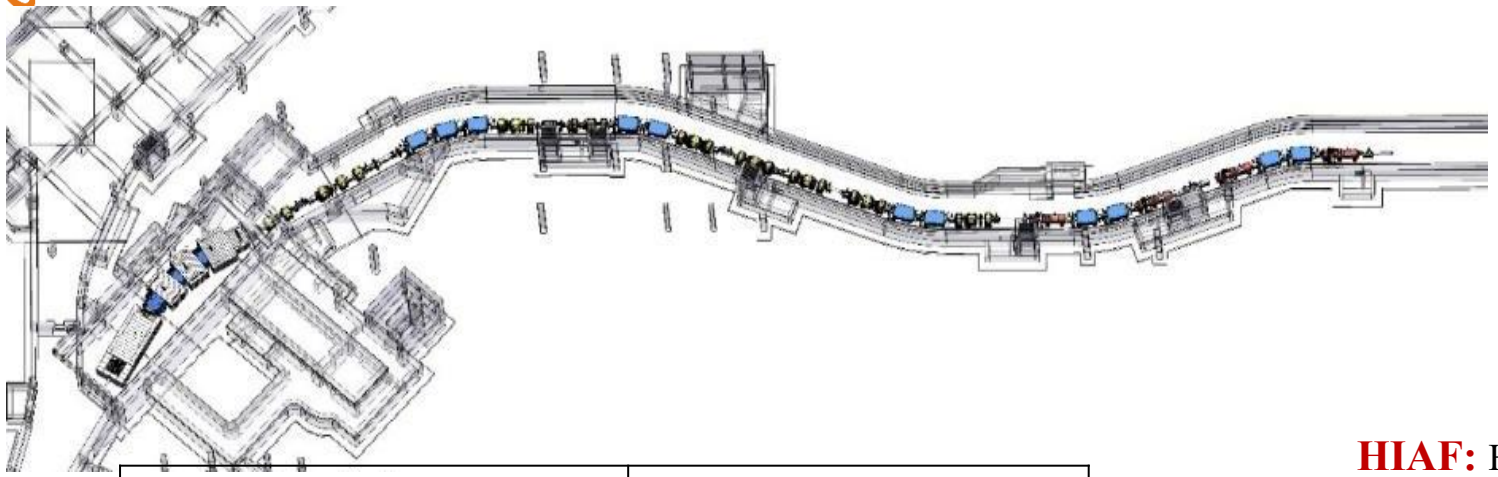
1 Representative projectile parameters

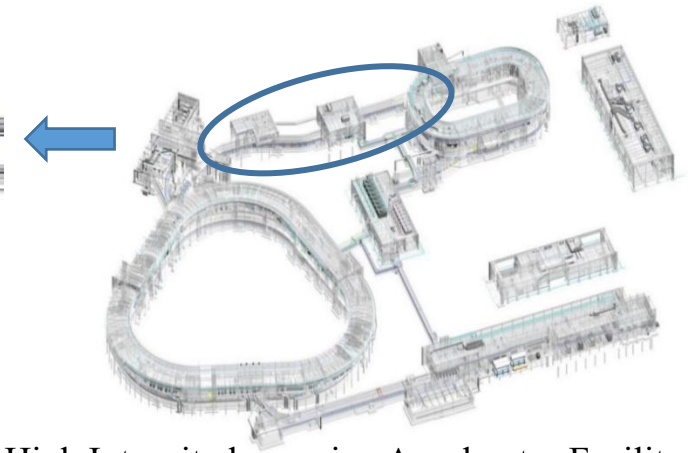
Heavy-ion Accelerator Fires Up

HIAF generated its first beam on 27 October



HIRIBL(HFRS)@HIAF





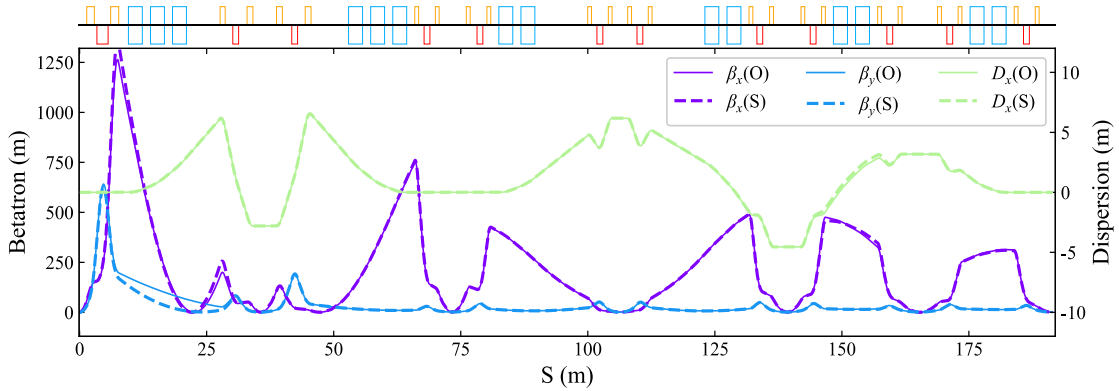
HIAF: High Intensity heavy-ion Accelerator Facility
The project was proposed and constructed by IMP, CAS. The total budget is 3.0 billion CNY

Max. magnetic rigidity	**25Tm (II stage)** **15Tm (I stage)**
Angular acceptance	**H: ±30 mrad** **V: ±25 mrad**
Momentum acceptance	**±2.0%**
Ion-optical mode	**Achromatic mode,** **Dispersive mode**
Beam size at target	**Slow ext.: ±1/±1.5** **Fast ext.: ±4/±6**
First order Momentum resolution (x=±1mm)	**Pre: 850** **Main: 700 / 1100**

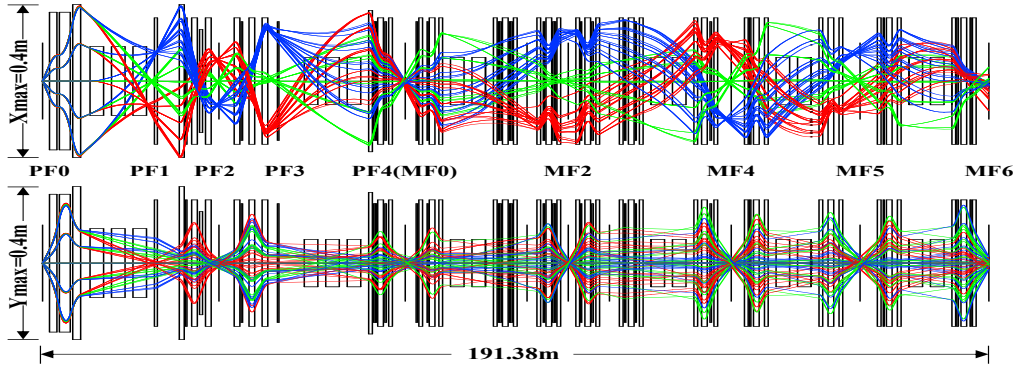
- **High-performance next-generation secondary beam separator**
- **Production, separation, purification, and transport of short-lived exotic nuclei**
- **Unique beam optics to realize both high-efficiency separator and high-precision spectrometer**

HIRIBL@HIAF

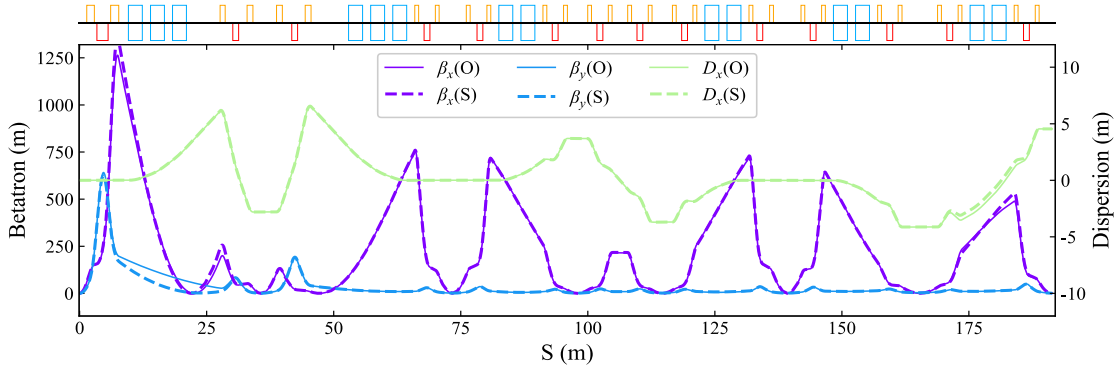
- Using the magnets measurement data, dividing the magnet into segments to optimize the beam optics again, which can normalize the longitudinal magnetic field, take into account edge and overlapping fields
- The Twiss parameters of the sliced model at each focal plane are identical to those of the original model



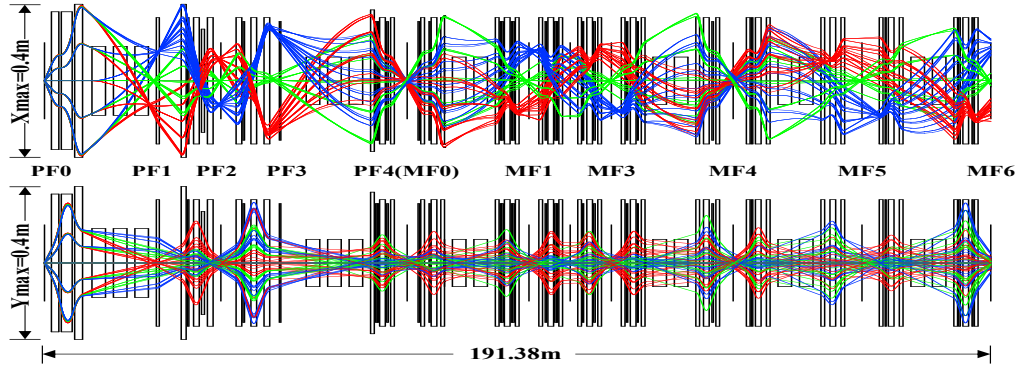
Beam optics of achromatic mode in slow-extraction in first order



Envelope of achromatic mode in slow-extraction in third order



Beam optics of dispersive mode in slow-extraction in first order

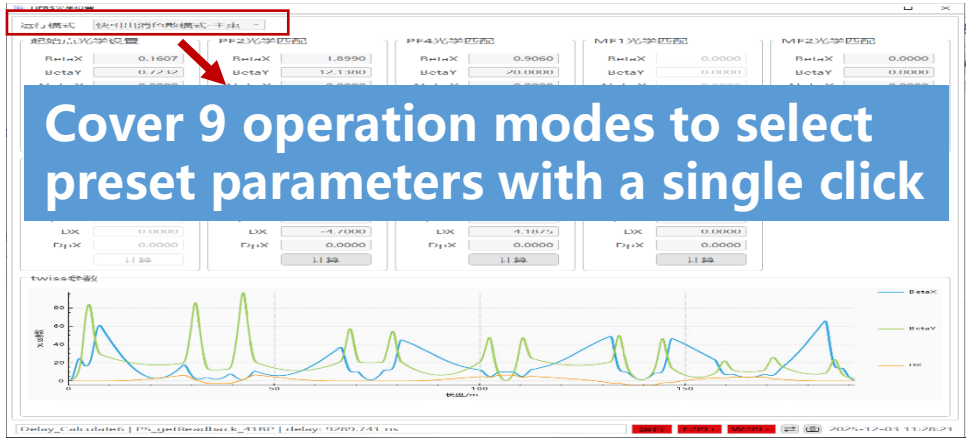


Envelope of dispersive mode in slow-extraction in third order

Credit: Lina Sheng

Installation and integration test of HIRIBL

- Equipment installation started May 2024, and all of 555 sets were on-site installation at Dec. 2024
- Integration test, integrating optical design into physical control, and performing digital burn-in in 2025

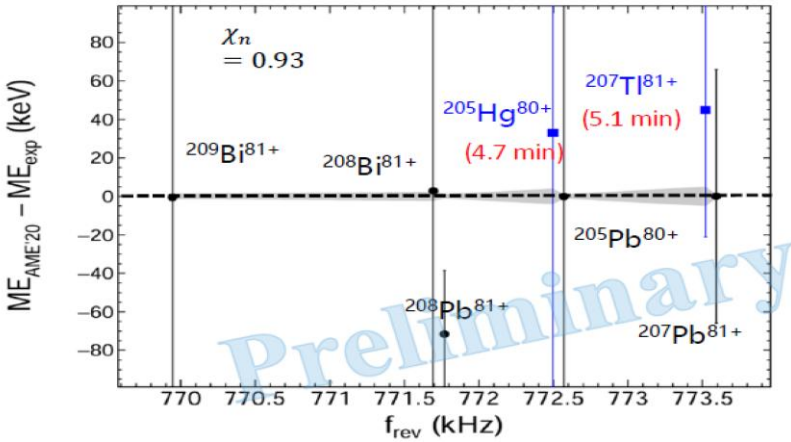


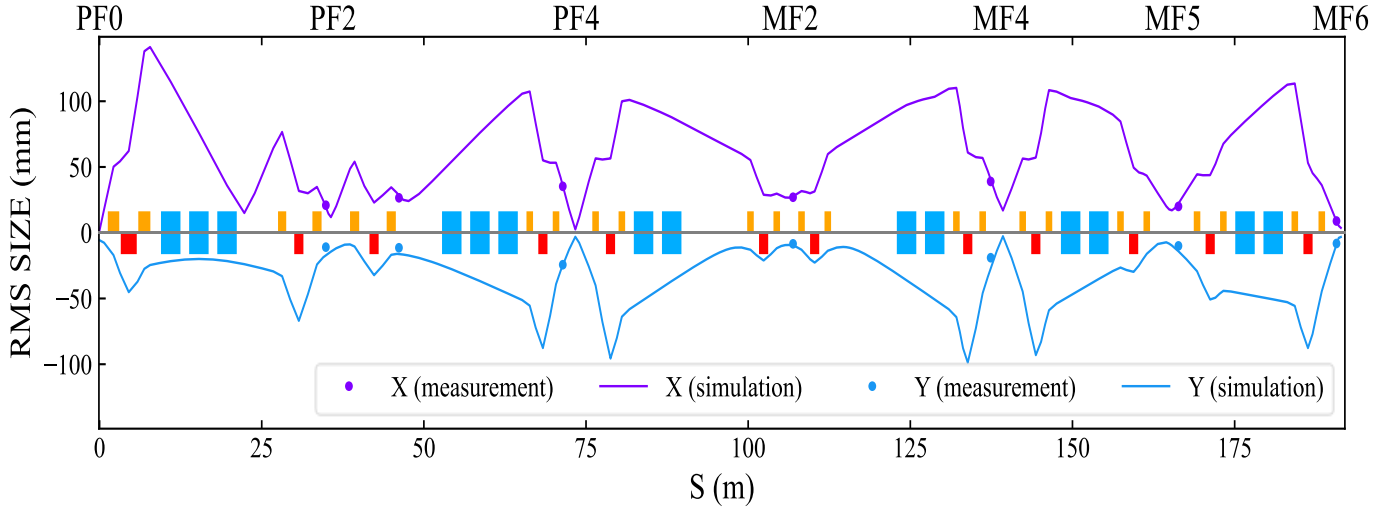
Oct. 2025, the beam commissioning succeeded under theoretical parameters

Beam commissioning and experiment of HIRIBL

High-precision mass measurement experiments at SRing is succeeded with the fast-extraction achromatic mode beam optics. The transmission efficiency of the interested RIB ^{205}Hg exceeds 90%.

- Primary beam: $^{209}Bi^{31+}$ with 633.86 MeV/u
- Primary intensity: 31 mA (3E+10 ppp)
- Fast-extraction period: 3s
- Primary target: graphite with 10 mm
- Al degrader: 4mm with uniform thickness

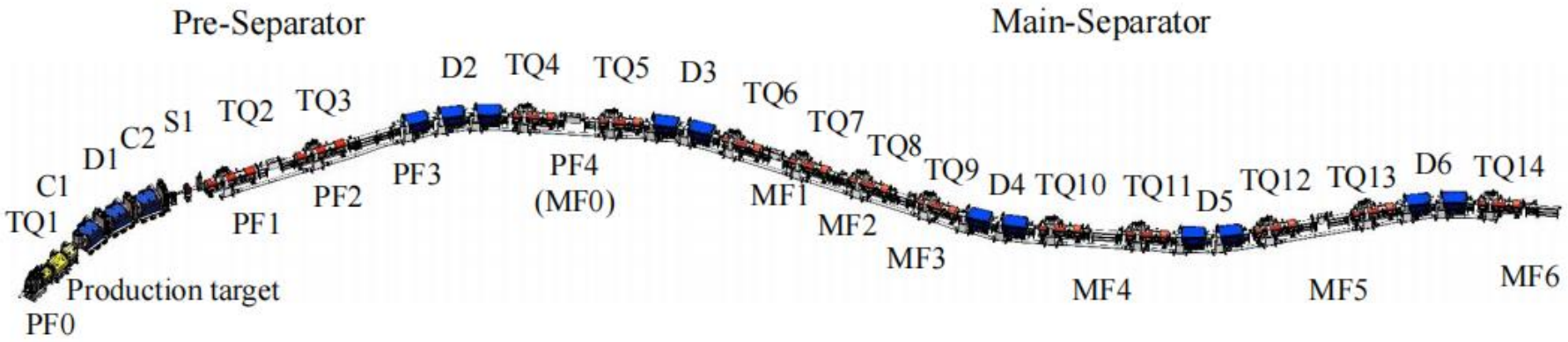




Comparison of theoretical and measured beam envelope of $^{209}Bi^{31+}$

Transport efficiency of $^{209}Bi^{31+}$ is about 98%

HIRIBL

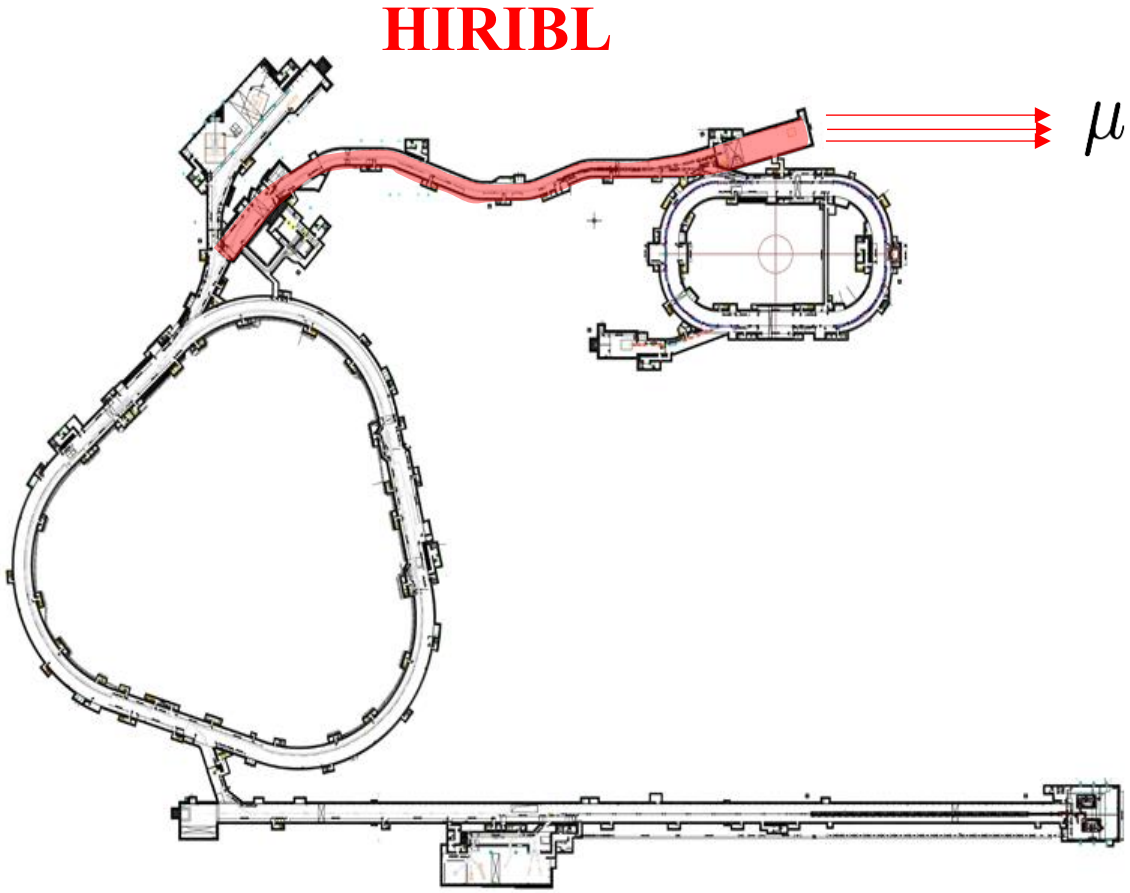


	Length (m)	Beam size at target (mm)	Angular acceptance(mrad)	Momentum acceptance (%)	Resolving power	Max. Bρ (Tm)
HIRIBL(HFRS) NIM.B 547(2024),165214	191.38	±1/±1.5	±30 (X); ±25 (Y)	±2.0	850/1100 (ΔX=±1mm)	25
SuperFRS NIM.B 204(2003),71	182.2	±1/±2	±40 (X); ±20 (Y)	±2.5	750/1500 (ΔX=±1mm)	20
BigRIPS Prog.Theor.EXP.Phys.2012,03C003	78.2	±0.5/±0.5	±40 (X); ±50 (Y)	±3	1260/3420 (ΔX=±0.5mm)	9.5
ARIS NIM.B 317(2013), 349	86.8	±0.5/±0.5	±40 (X); ±40 (Y)	±5	1720/3000 (ΔX=±0.5mm)	8

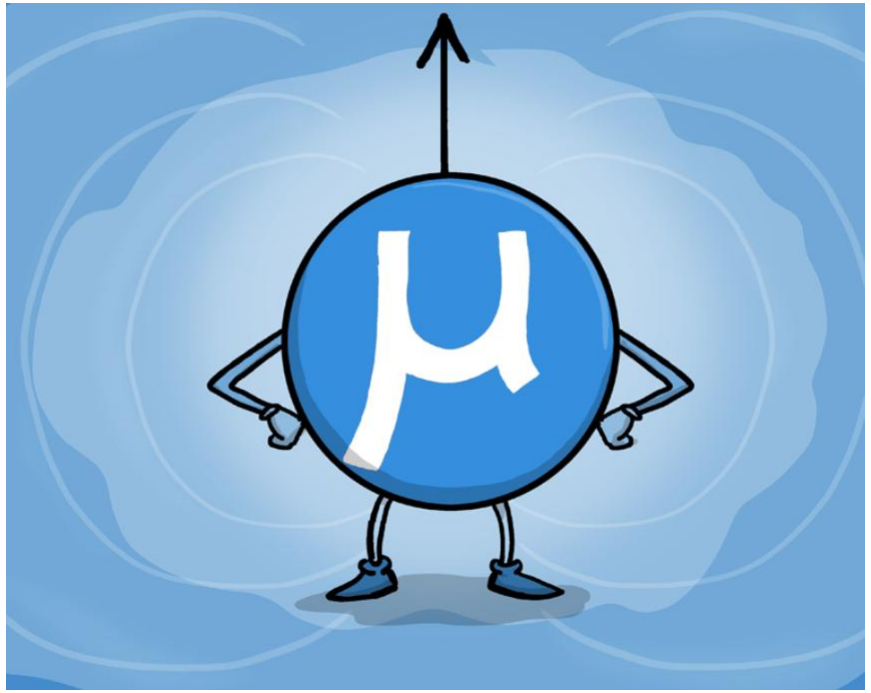
HFRS and Radioactive beamlines around the world

HIRIBL is capable of producing muons with GeV energies

Muon source at HIAF

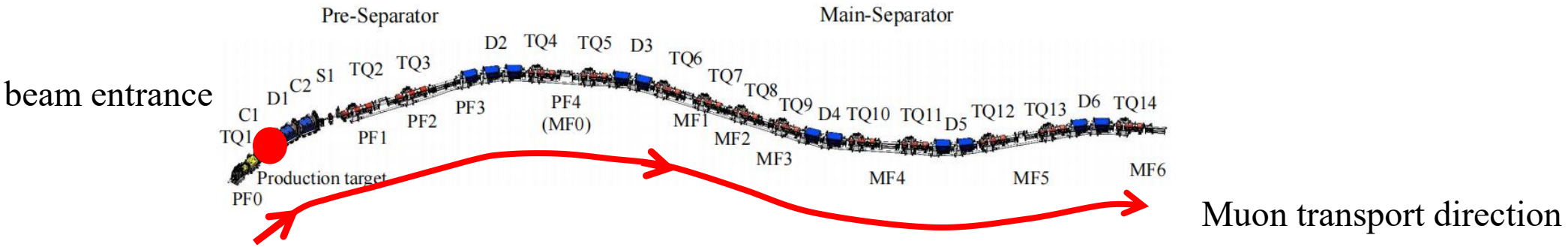


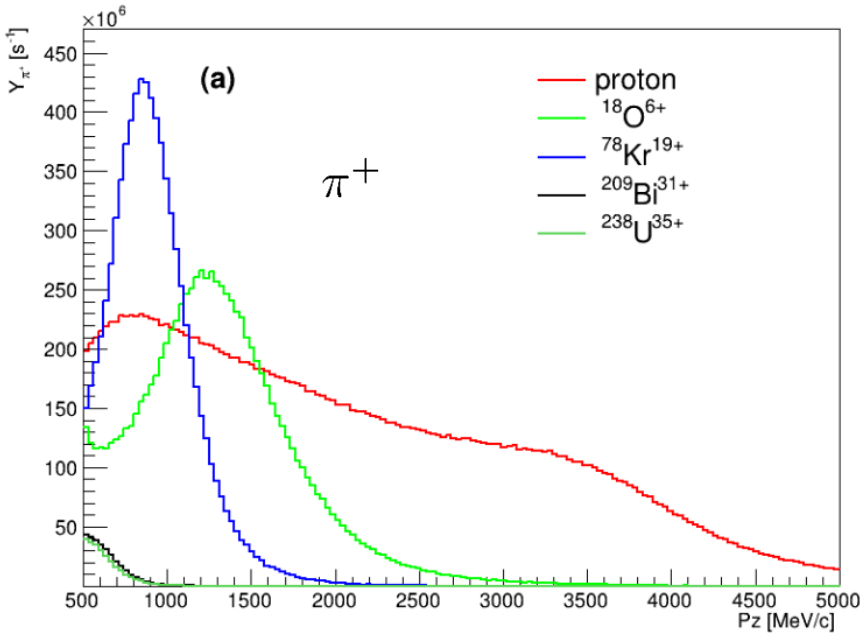
How many muon can we order?

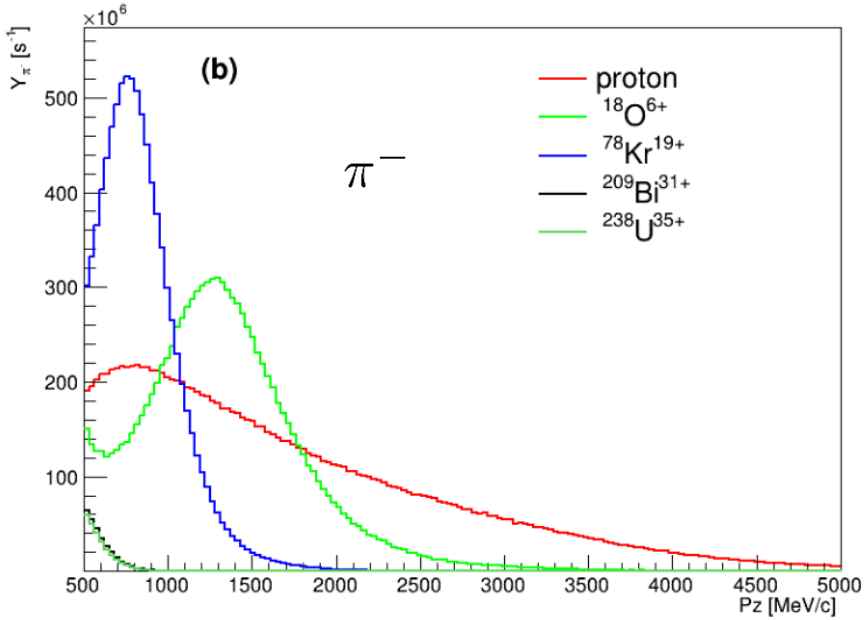


Muon source at HIAF

- Pion production at the beam entrance



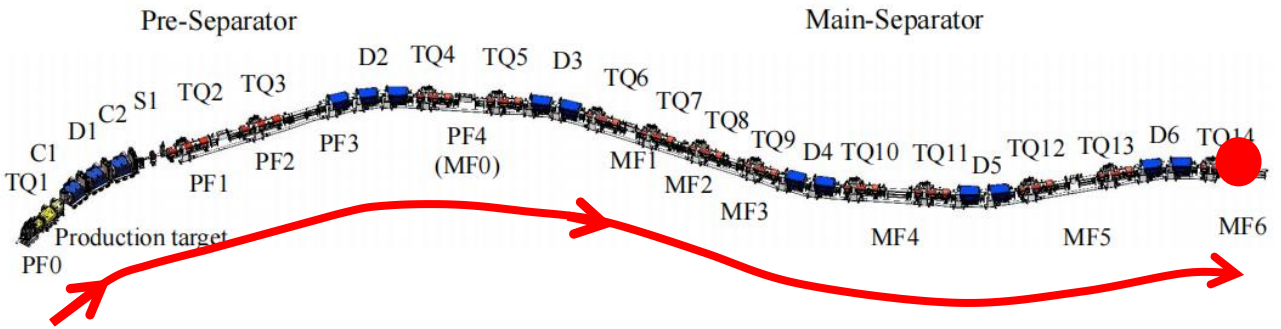


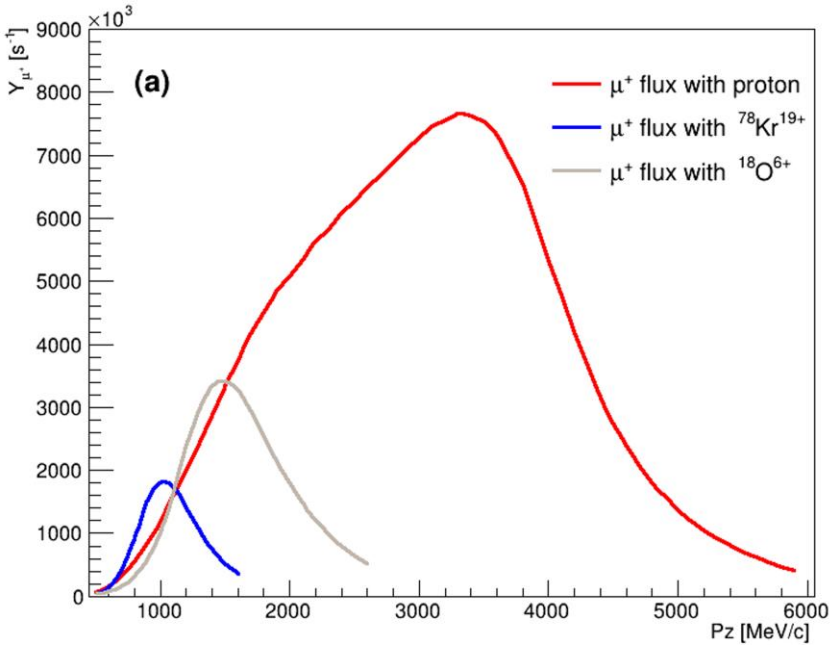


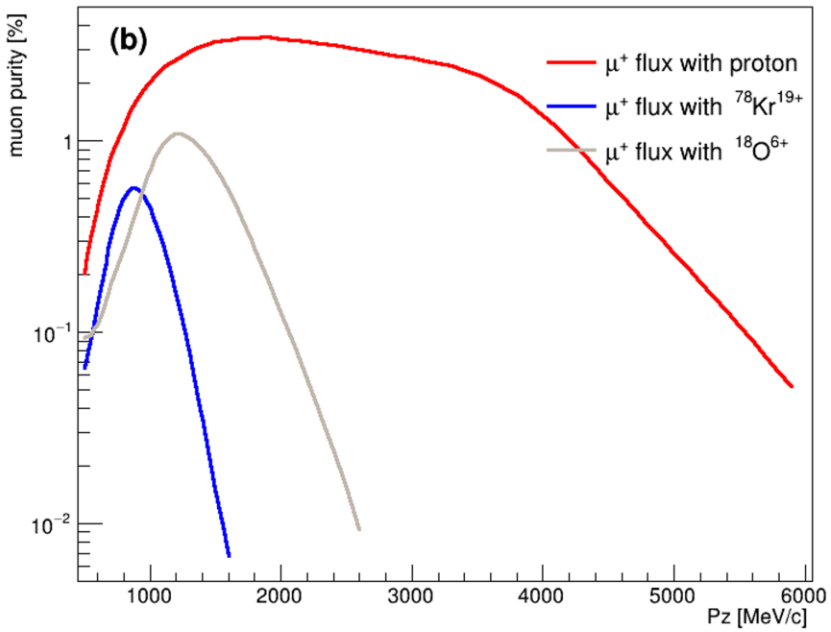
Phys. Rev. Accel. Beams 28, 053401 (2025)

Muon source at HIAF

- Muon yield and the corresponding purity



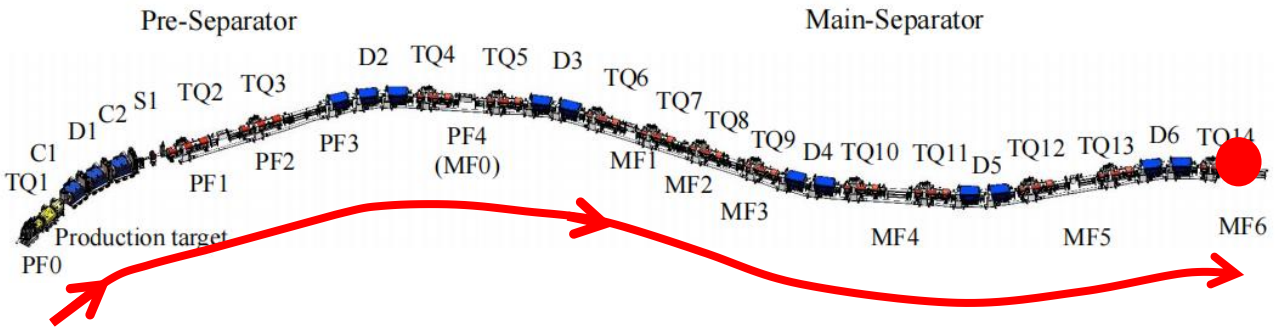




Phys. Rev. Accel. Beams 28, 053401 (2025)

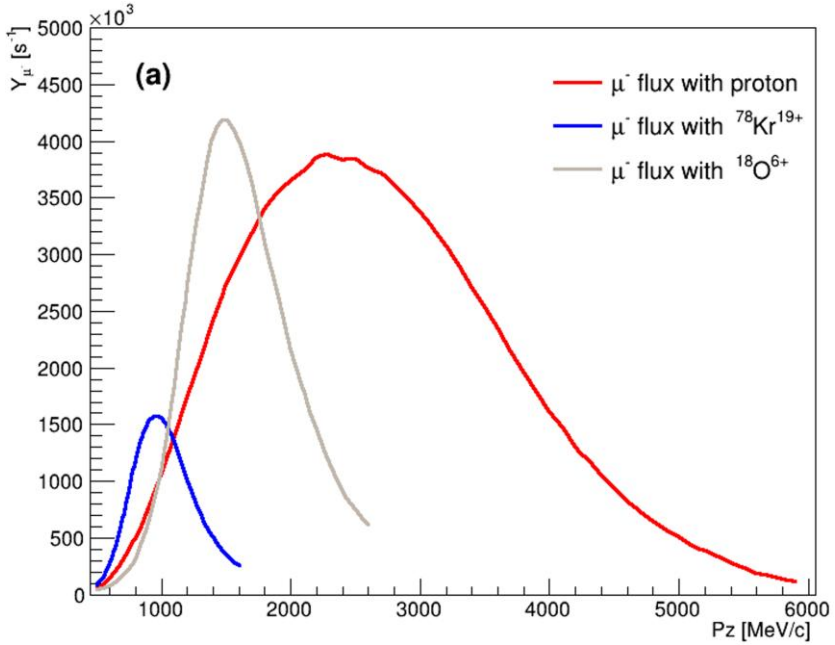
Muon source at HIAF

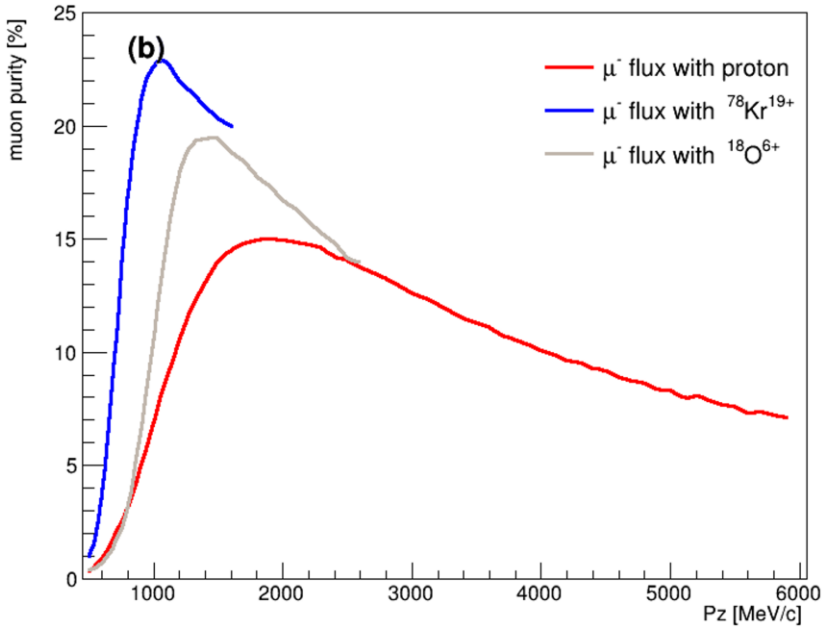
- Muon yield and the corresponding purity



Exit of the beam

Muon transport direction

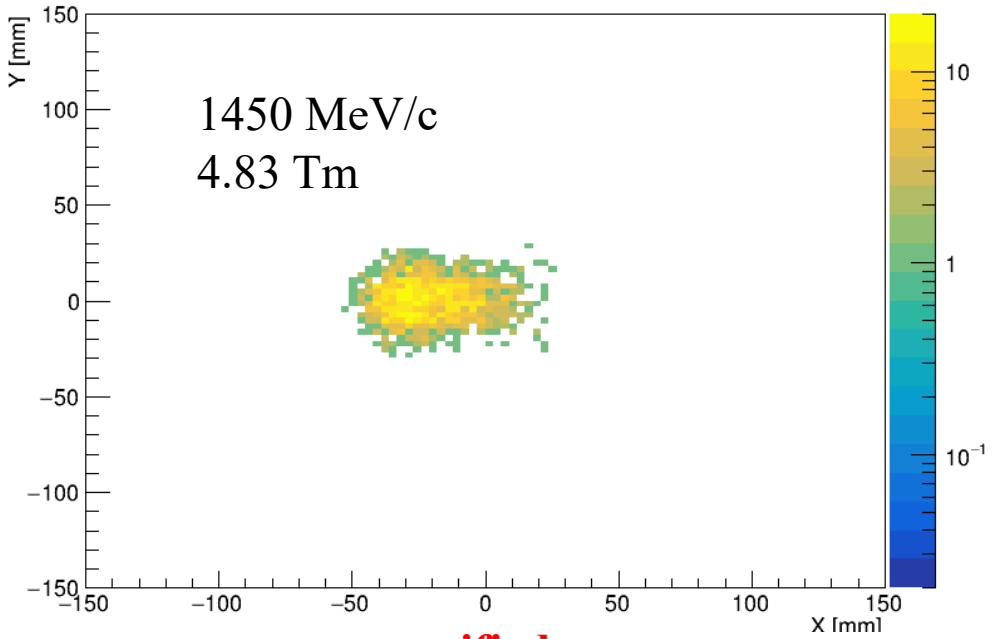




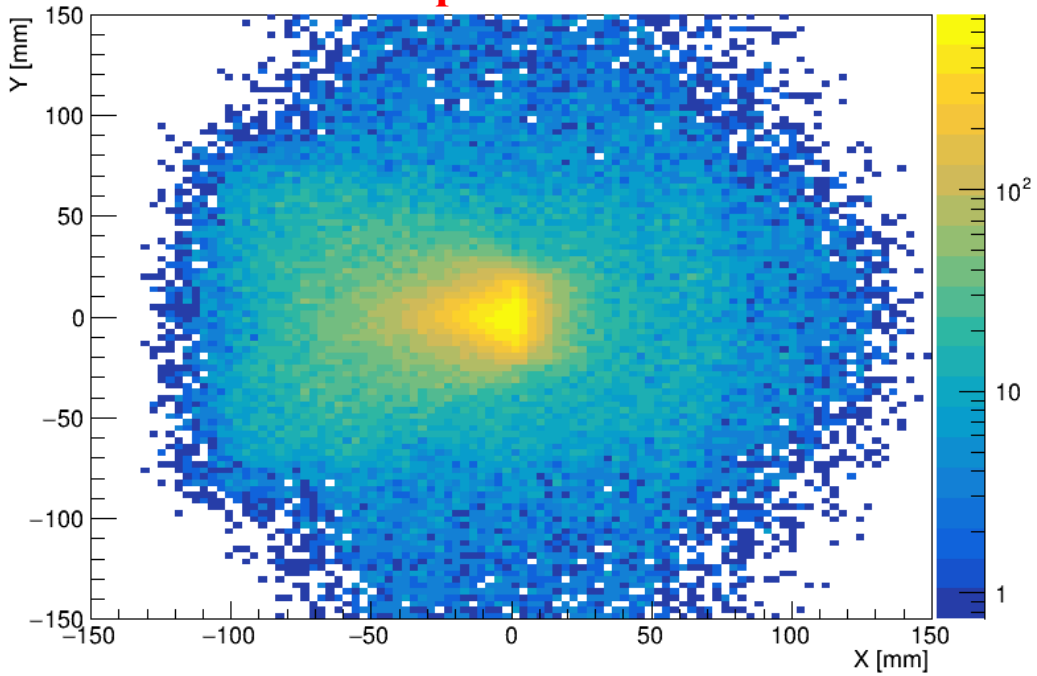
Phys. Rev. Accel. Beams 28, 053401 (2025)

Muon source at HIAF

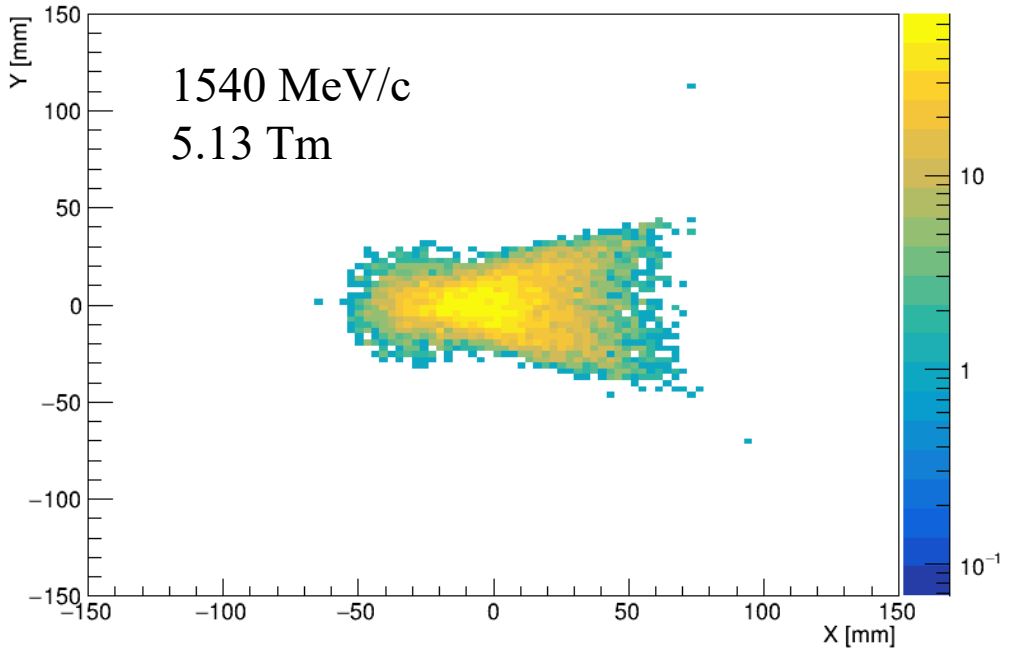
- Projectile $^{18}O^{6+}$
- muon momenta 1.5 GeV/c (Beam line Magnetic rigidity 5 Tm)



unpurified



purified

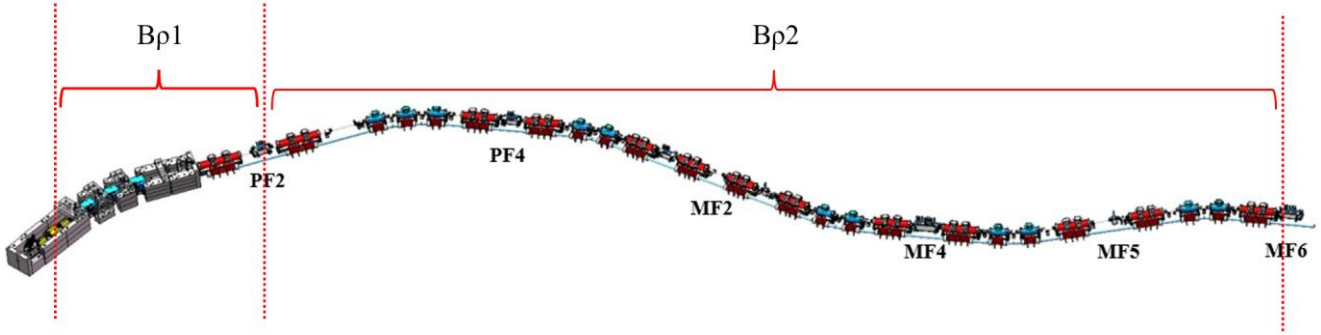


Polarized muon source

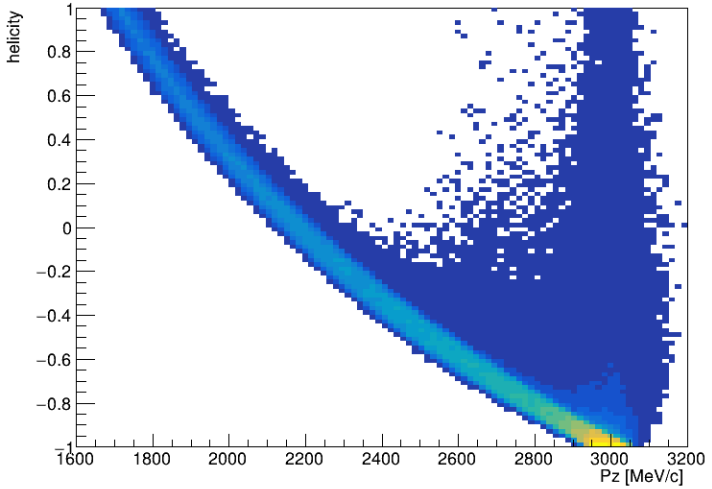
- **By collecting muons from the forward and backward decays of pions, polarized muons can be delivered**

Projectile：proton 9.3GeV

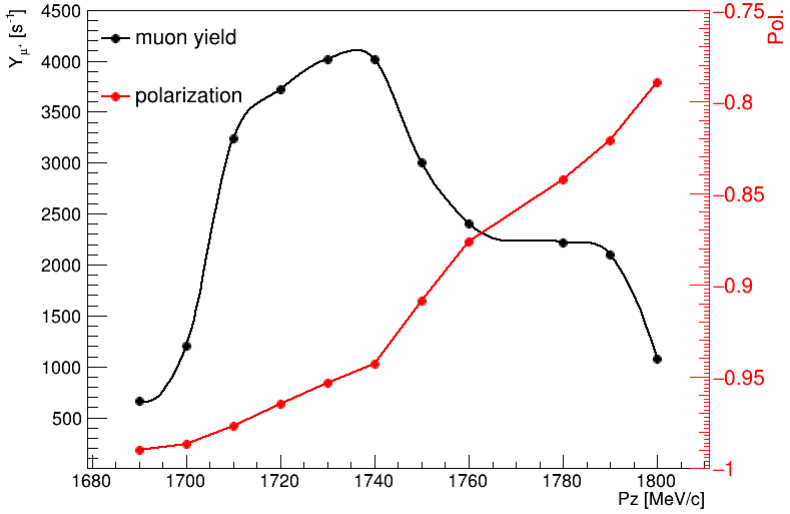
Ridigity of the first part： pion 3GeV/c



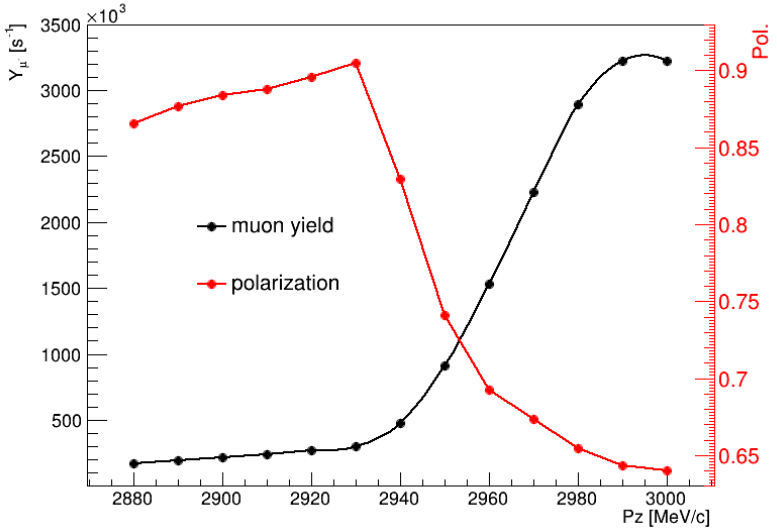
helicity−momentum distribution



Muons from backward decays of pions

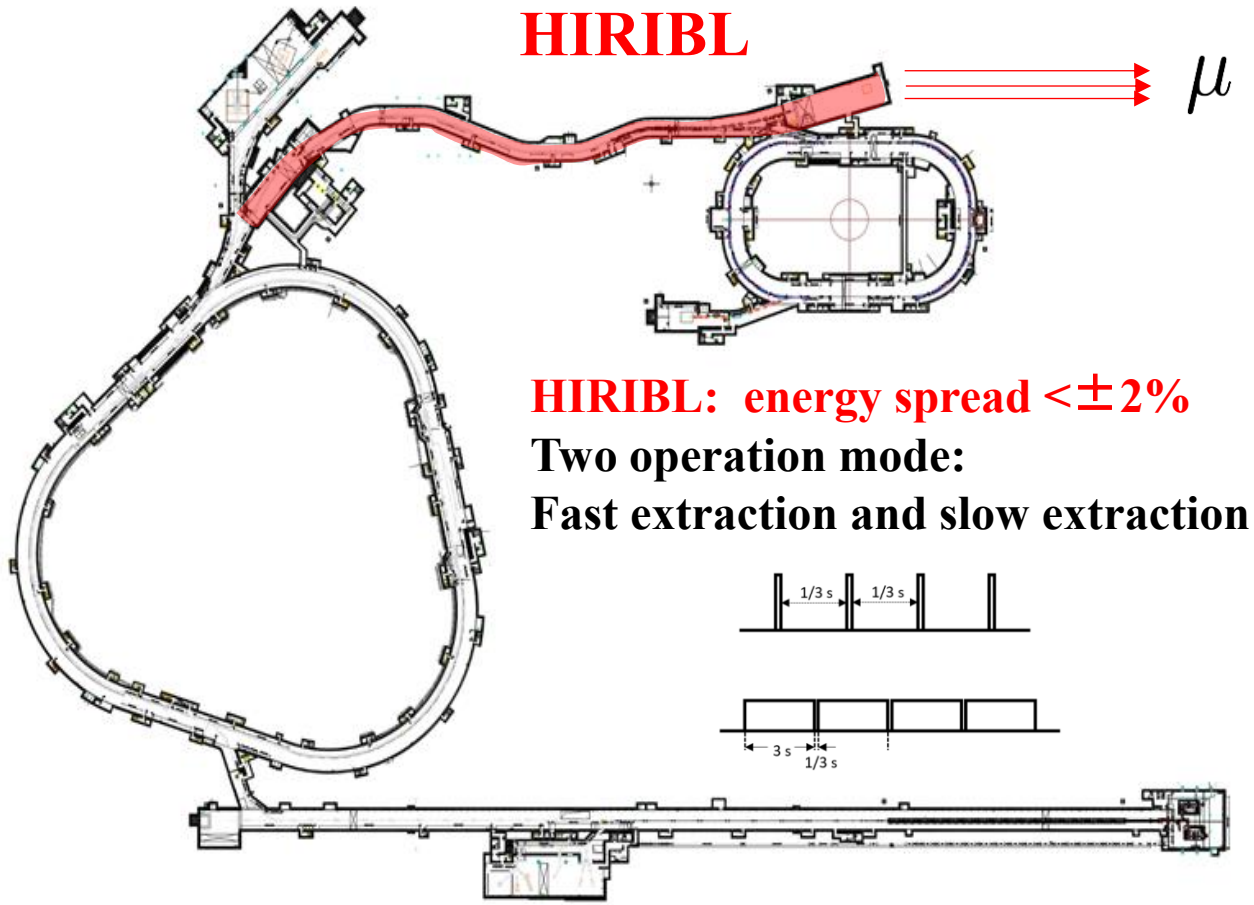


Muons from forward decays of pions



Muon source at HIAF

- **HIAF is capable of delivering high-energy muon beam with a narrow energy spread**
- **Polarized muon can also be obtained**



Muon beam@HIAF-HIRIBL

Projectile	Muon	
	Intensity (μ^+/s)	Momentum (GeV/c)
$^{78}Kr^{19+}$	1.8×10^6	1.0
$^{18}O^{6+}$	3.5×10^6	1.5
Proton	8.2×10^6	3.5

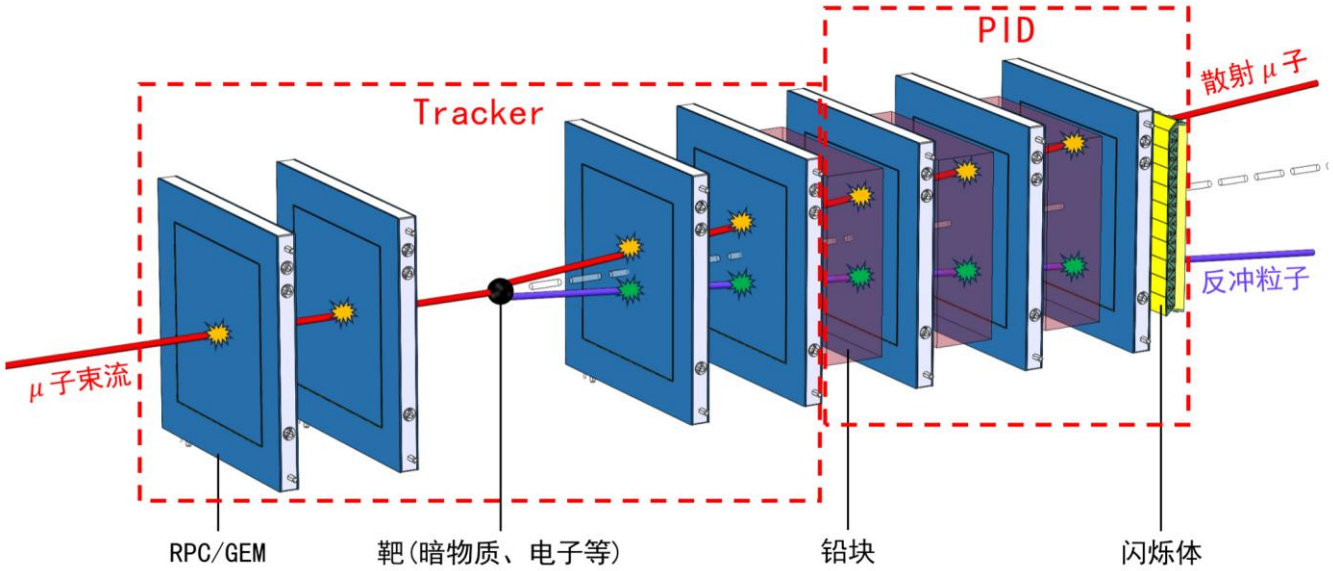
Outline

- Introduction of muon source
- Muon sources at HIAF
- Physics and Applications Opportunities
- Summary

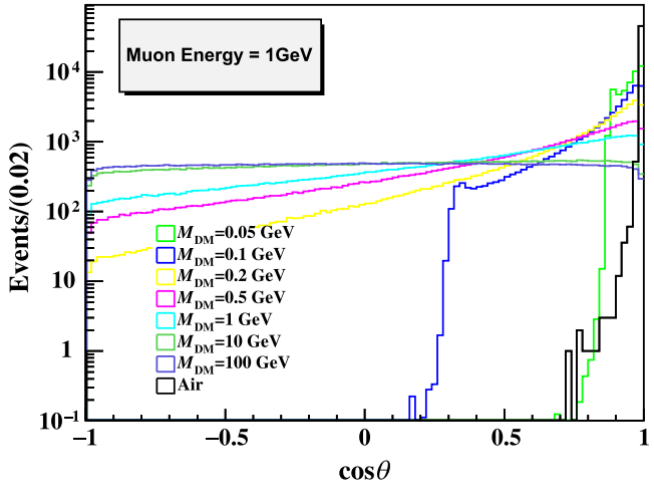
Potential muon experiments with muon @HIAF

Probing and Knocking with Muons

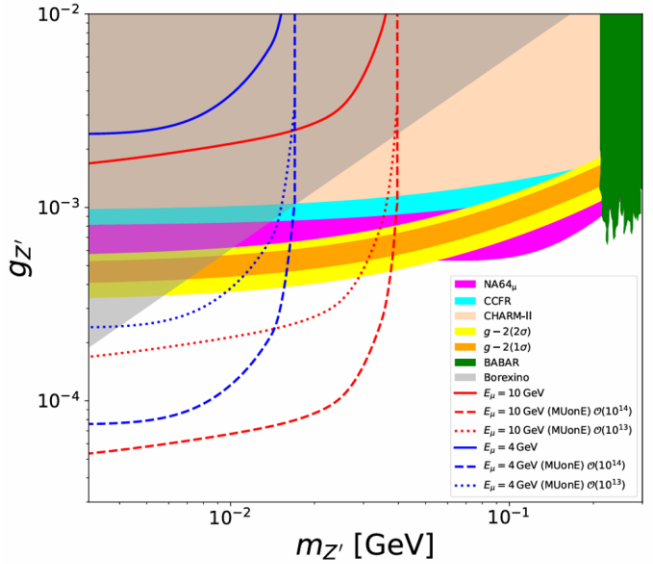
- One of the highest intensity (4e6/s) GeV energy muon around world
- Direct searches for DM
- Searching dark boson



PKμ@HIRIBL



Searching for Muon Philic Dark Sector



Could be more sensitive to X boson at 1-10 MeV region!

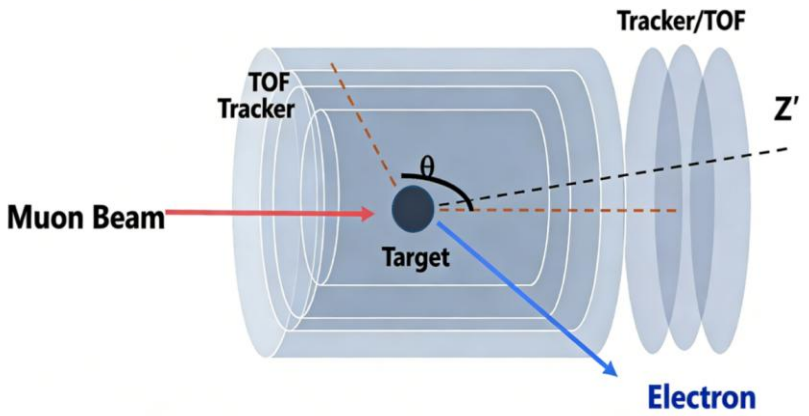
Credit: Prof. Qite Li
Prof. Chen Zhou
Prof. Qiang Li

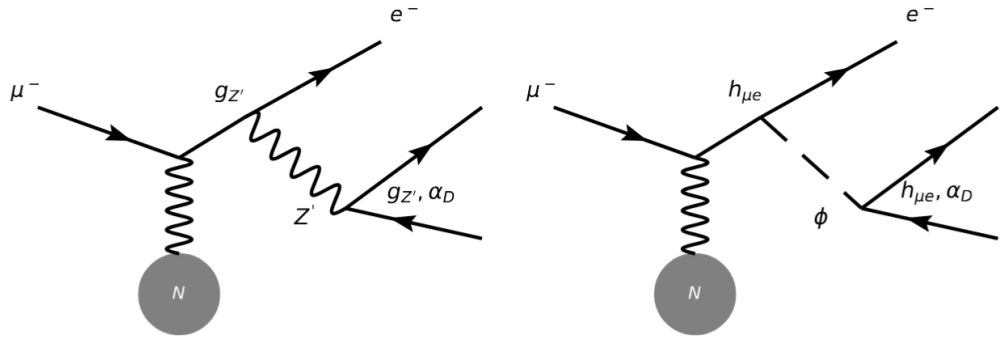
Phys. Rev. D 110, 016017
J.Phys.G 52 (2025) 7, 075002
Phys.Rev.D 113 (2026) 7, 072008
Int.J.Mod.Phys.A 40 (2025) 35, 2550164

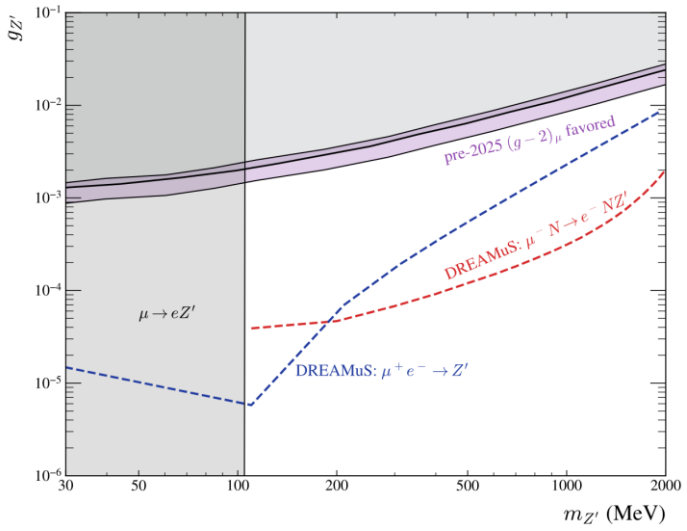
Potential muon experiments with muon @HIAF

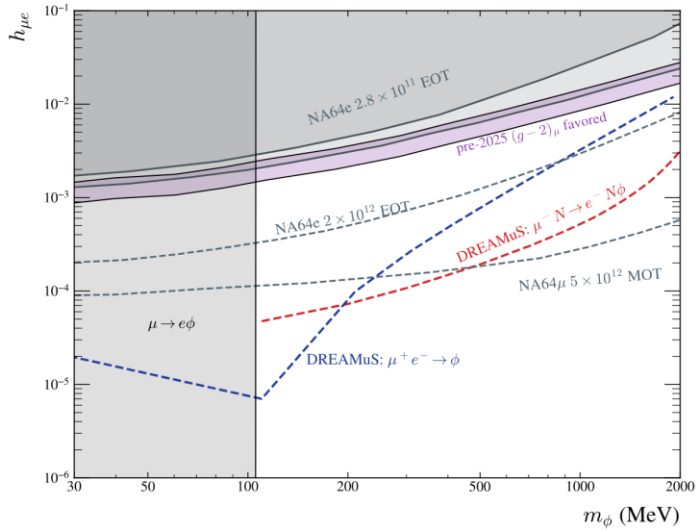
DREAMuS: Dark matter REsearch with Advanced Muon Source

- Dark matter (χ) from a flavor-violating Z′ or ϕ scalar particle
- 3 GeV muon interaction with 22cm lead target









Best limit on flavor violating scalar ϕ model in the low mass region

- 90% C.L. limit on $g_{Z'}$: ~ 10^{-4} - 10^{-5}
- 90% C.L. limit on $h_{\mu e}$: ~ 10^{-4} - 10^{-5}

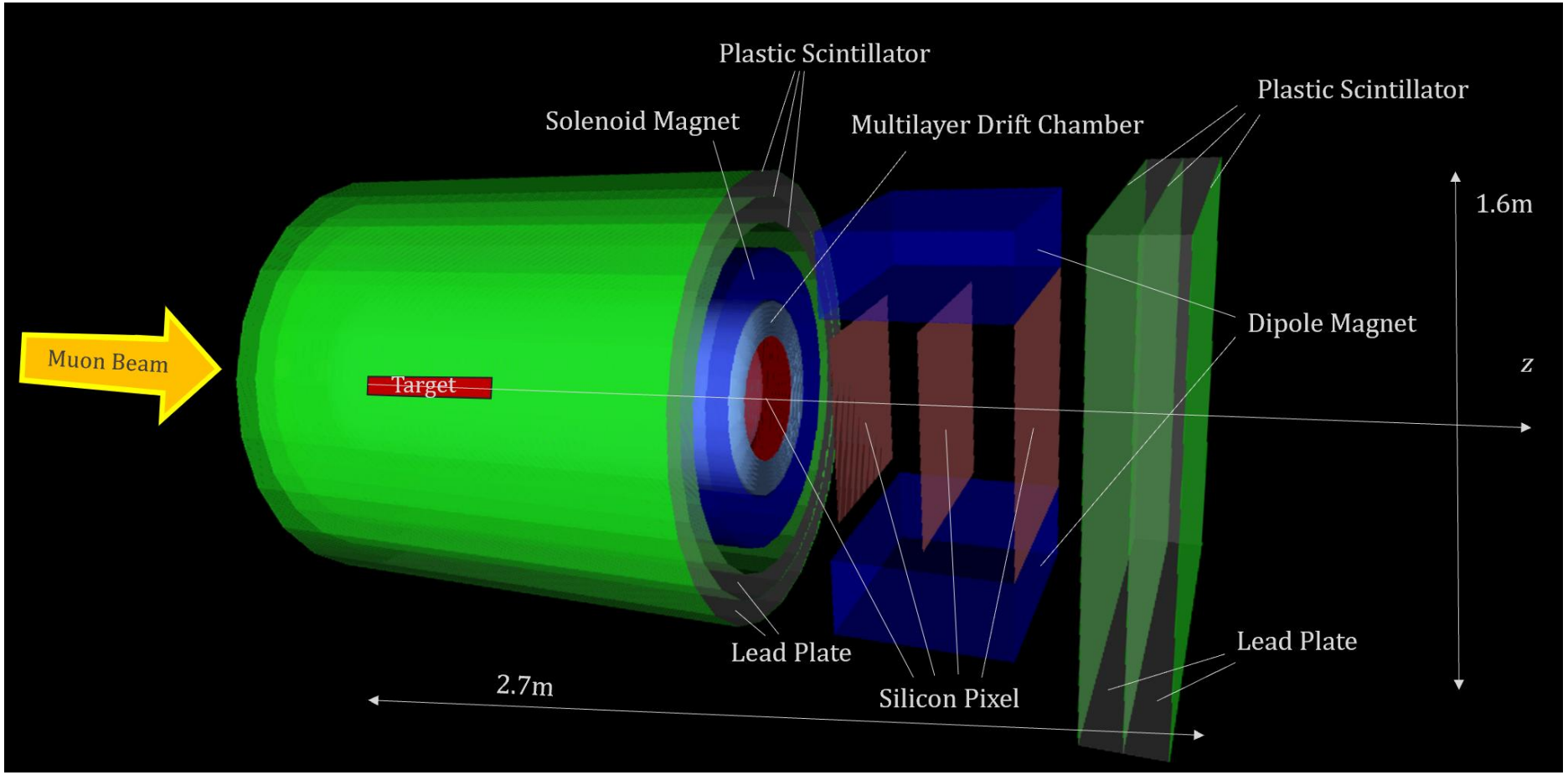
Credit: Prof. Liang Li

arXiv: 2604.10257

Potential muon experiments with muon @HIAF

LUNE :Low-energy mUon-Nucleon scattering Experiment

Phase-I: demonstration phase (< 10 M CNY)
Phase-II: full operation phase



Analyses	Impacts
Proton charge radius	★★★★★
Two photon exchange	★★★★
Proton Form factors	★★★★
Resonances	★★★
DIS	★★★★★
Semi inclusive DIS	★★★★★
DVCS	★★★★
NP (Dark matter)	★★★★
Neutron charge distri.	★★★★★
Short range corr./EMC	★★★★★
Coulomb Distortion	★★★★★

Credit: Prof. Hang Yin

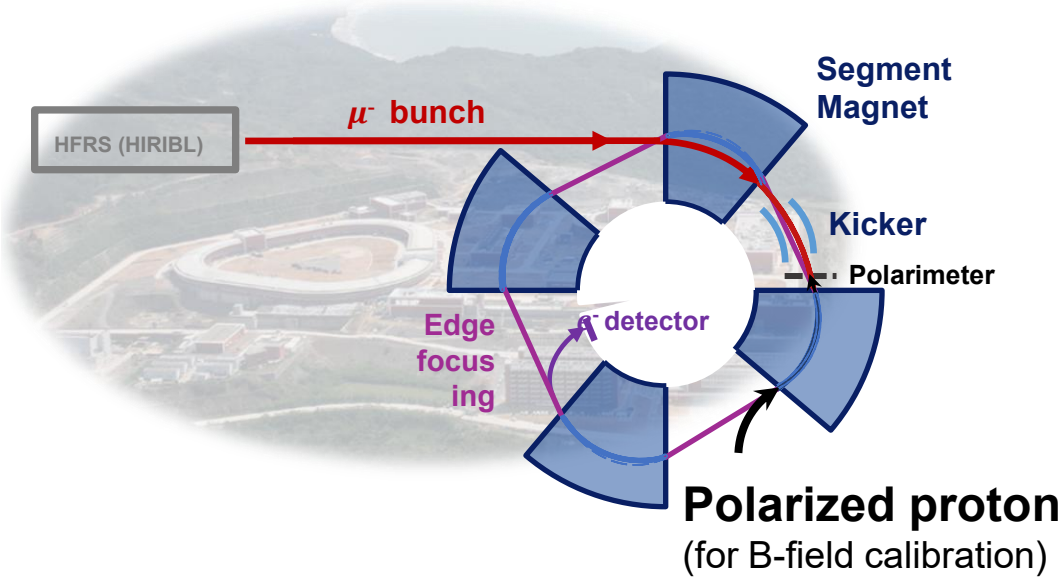
Potential muon experiments with muon @HIAF

CANTON-μ : Coherent Anomalous magNetic momenT ObservatioN with muon

- A next-generation muon g−2 experiment targeting sub-0.1 ppm precision — the first proposal to surpass the Fermilab record (0.13 ppm)
- By prioritizing *negative* muons, it offers both precision SM test and probe to unique CPT symmetry sensitivity.

	CERN/BNL/FNAL g-2	J-PARC g-2	HIAF g-2 (CANTON-μ)
Muon momentum	3.1 GeV/c	300 MeV/c	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
Precision	μ^+: 0.14 ppm (FNAL) μ^-: 0.7 ppm (BNL)	μ^+: 0.46 ppm → 0.1ppm (?)	μ^-/μ^+: 0.1 ppm → **0.05 ppm**

arXiv: 2512.11486

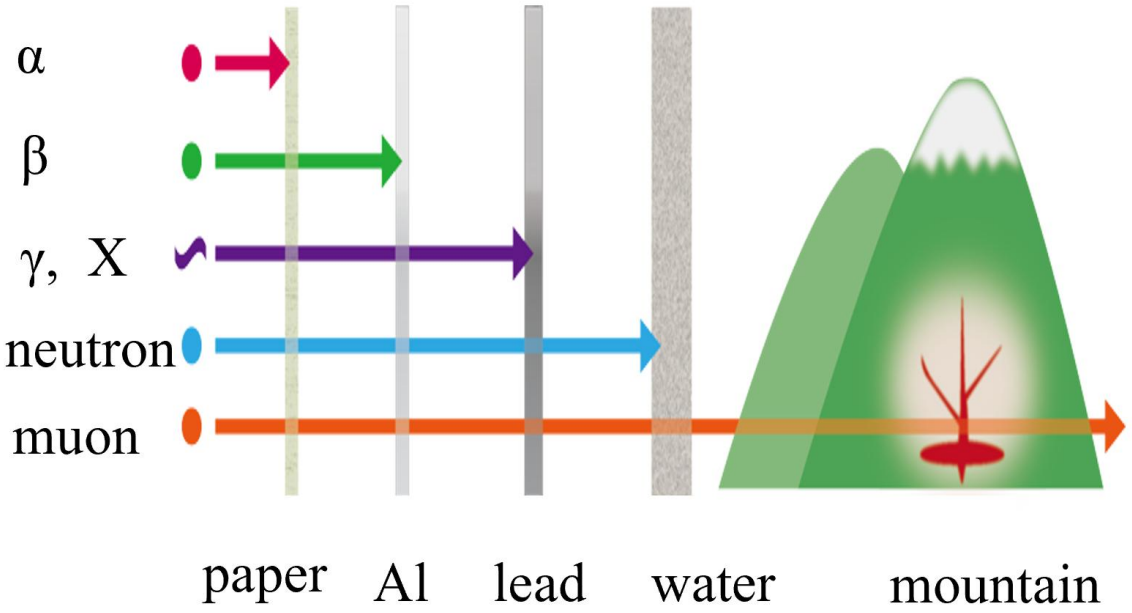


Credit: Dr. Ce Zhang

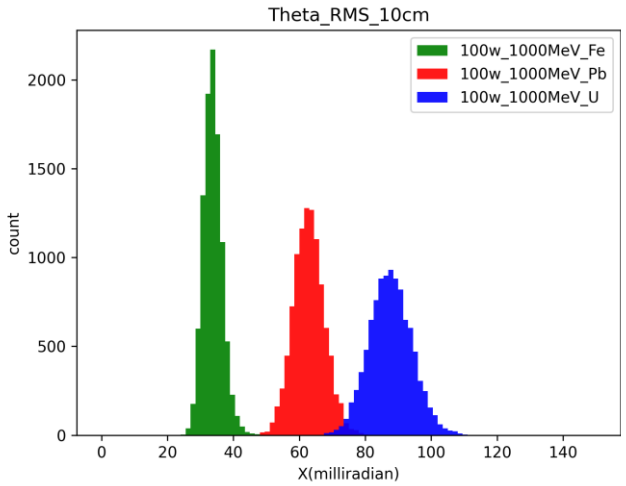
Muon tomography @HIAF

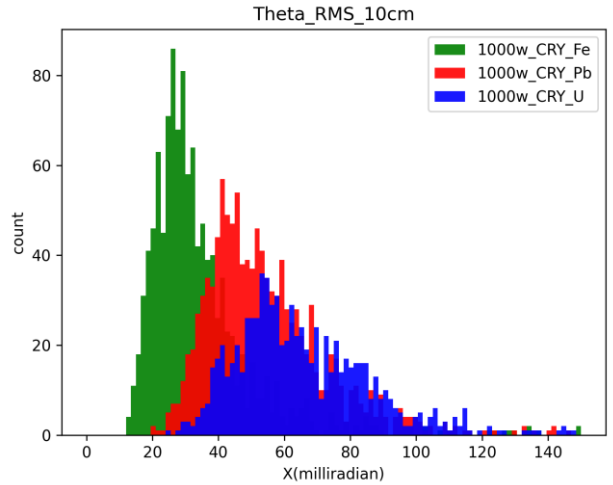
- Muon tomography enables non-destructive imaging of the internal structure of large objects
- Accelerator-based muon imaging offers significantly superior material discrimination capability compared to cosmic-ray muon imaging

	Cosmic ray muon	Accelerator based muon
Intensity	0.02/cm²/s	**>10⁴/cm²/s**
Energy spread	High	**Low**
Direction	Random	**Controllable**



Accelerator based muon V.S. Cosmic ray muon

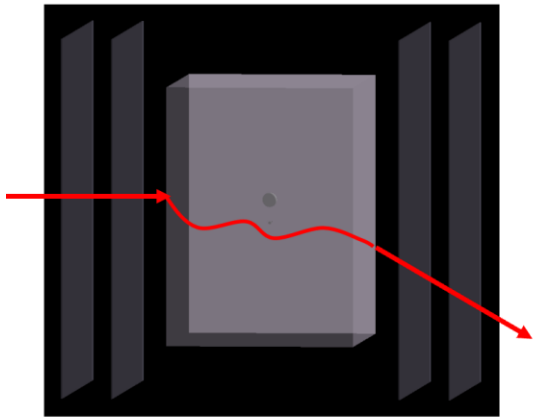


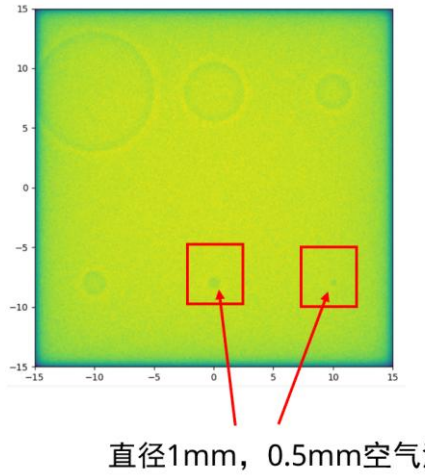


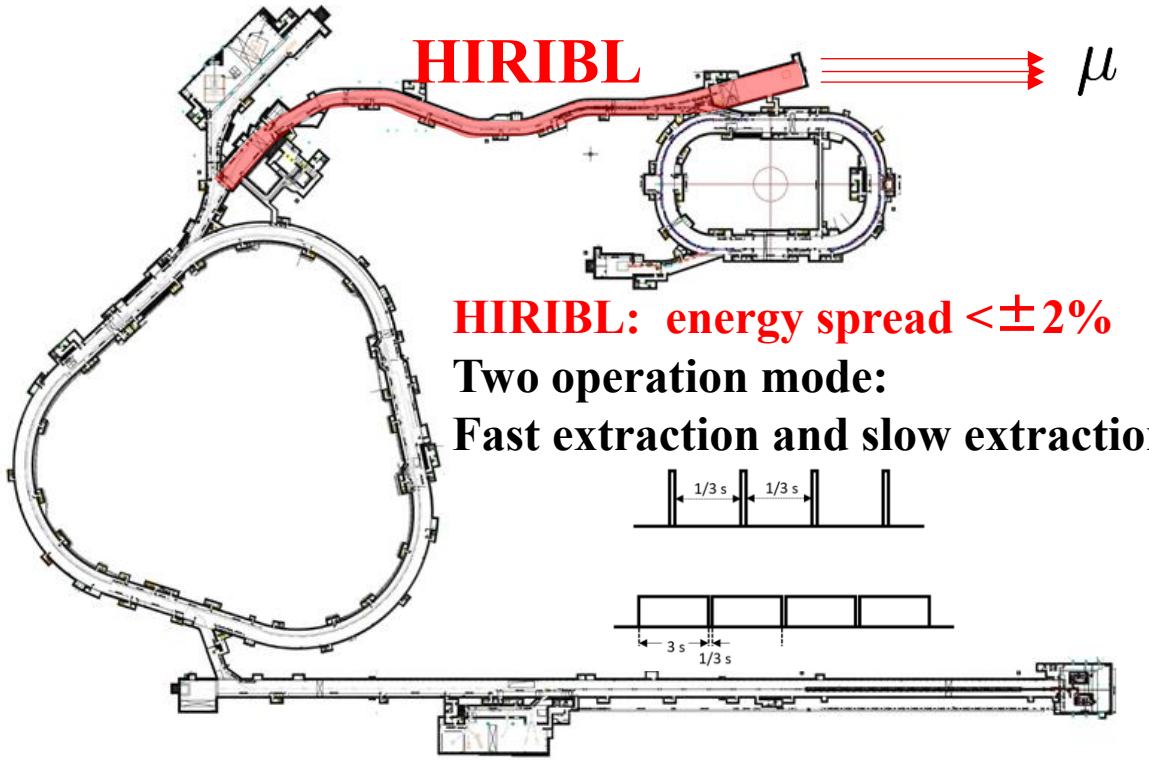
Muon tomography @HIAF

Accelerator-based muon tomography

- resolve sub-millimeter-sized bubbles within a 13-centimeter-thick titanium block
- identify centimeter-length cracks within a meter-scale water tank



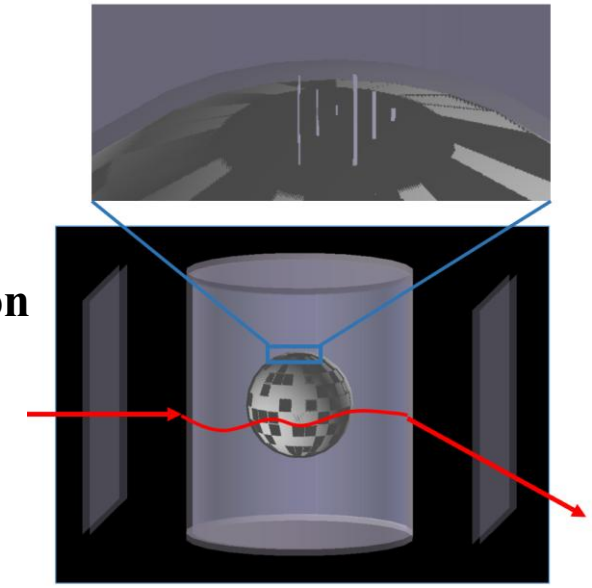


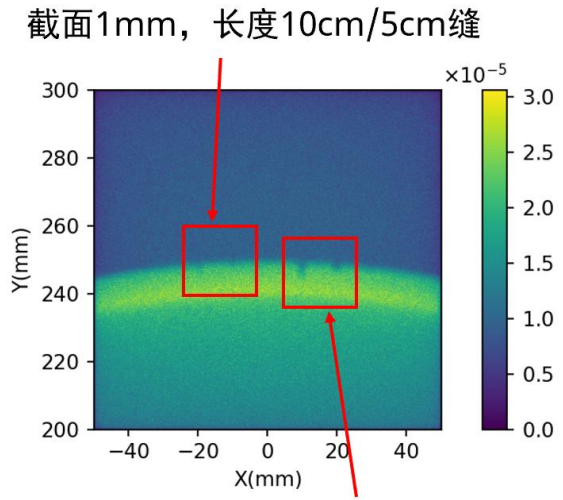


HIRIBL: energy spread <±2%

Two operation mode:

Fast extraction and slow extraction





Outline

- Introduction of muon source
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- The HIAF is operating and could deliver GeV energy muons.
- GeV energy muon beams at HIAF offers new opportunities for muon physics and muon tomography.
- Collaborations are welcome.

Thank you for your attention!


强电桥架 2
信号桥架 1
Welcome collaborations !