Muon Physics Programs in China:

A Particle Physics Perspective

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Muon Physics Programs in China

- **Emerging and fast-growing program**
  - **China's muon efforts are transitioning from participation abroad to building domestic initiatives.**
  - **Early milestones in beams, detectors, and analysis show strong momentum. International collaboration and participation is warmly welcomed.**
- **Intensity Frontier: Next-gen particle/muon sources and experiments**
  - **High-Intensity heavy-ion Accelerator Facility (HIAF)**
  - **China-initiative Accelerator-Driven Subcritical system (CiADS)**
  - **China Spallation Neutron Source (CSNS): Muon Station for Science, Technology, and Industry (MELODY), SHINE Muon Source**
- **Broader impact beyond HEP (not covered in this talk)**
  - **Applied science: muon tomography (critical infrastructure, archaeology), non-destructive assay of dense cargo/containers.**
  - **Nuclear & condensed-matter: μSR for magnetic/quantum materials; isotope production and nuclear-structure probes.**
- **Abundant Collaboration Opportunities**

HIAF and CiADS

Two Major National Science and Technology Infrastructure Projects, approved by central government in December 2015.

***Total investment*: ~ 6.8 billion CNY**
***Construction periods*:**

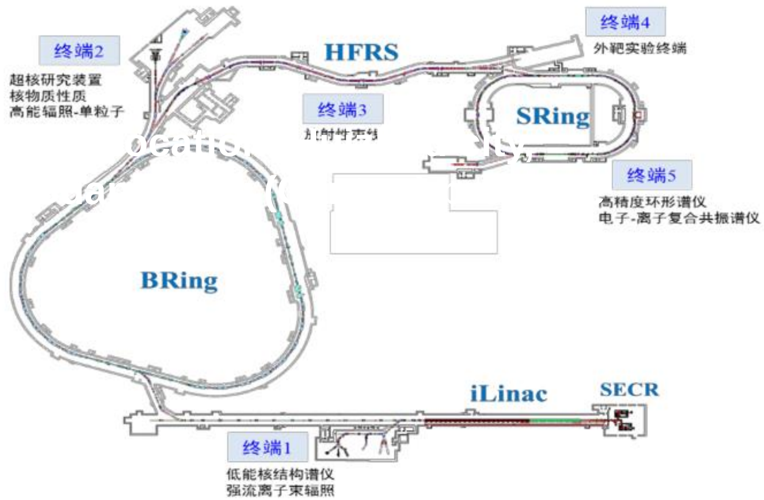
HIAF: Dec. 2018 – Dec. 2025
CiADS: July 2021 – July 2027

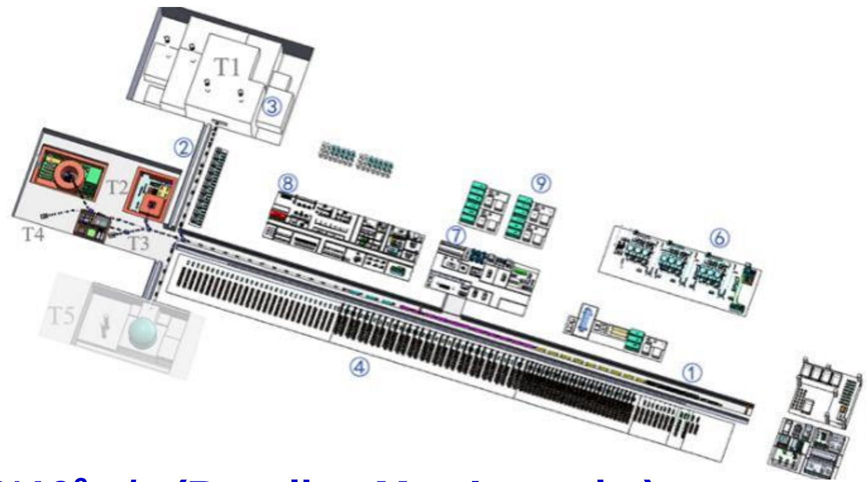
Courtesy Y. He

HIAF and CiADS

High-Intensity heavy-ion Accelerator Facility (HIAF): World's most advanced heavy-ion accelerator with the highest pulsed beam intensity

China-initiative Accelerator-Driven Subcritical system (CiADS): World's first megawatt-level ADS research facility





HIAF beam: 0.5 – 7.5 GeV, 4-8*10^6 μ/s (Baseline Max Intensity)
CiADS beam: 0.5 – 0.6 GeV, 5*10^8 μ/s (Phase-I)

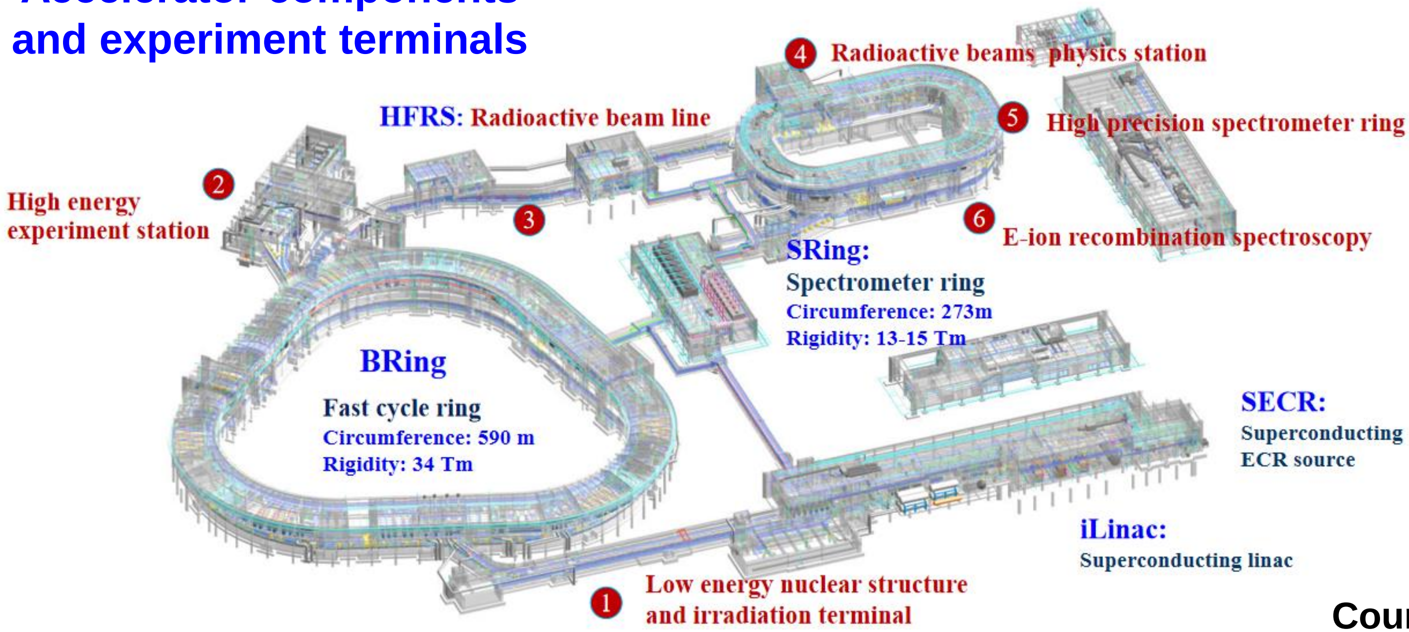
Scientific goals:
1. Nuclear force
2. Origin of heavy elements
3. High-energy/intensity physics
4. Space radiation simulation

Scientific goals:
1. Stable, reliable, and long-term operation of accelerator, spallation target, and reactor systems
2. Foundation for future industrial-scale ADS facility
3. Fundamental physics and applied physics research

Courtesy Y. He

HIAF

Accelerator components and experiment terminals



Courtesy Y. He

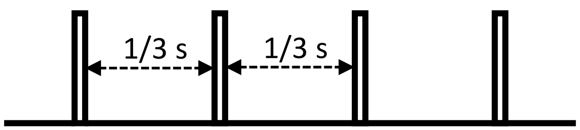
	iLinac	BRing		SRing	
Length / circumference (m)	114	569		277	
Final energy of U (MeV/u)	17 (U^{35+})/150	835 (U^{35+})	9300 (p)	800 (U^{92+})	3500 (p)
Max. magnetic rigidity (Tm)	---	34		15	
Max. beam intensity of U (ppp)	**28 pμA**	**2×10^{11}**	**$(1\text{-}3)\times10^{13}$**	**$(0.5\text{-}1)\times10^{12}$**	**$(1\text{-}3)\times10^{13}$**
Operation mode	CW or pulse	Fast ramping (12T/s, 3Hz)		DC, deceleration	
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)	5 / 5	200/100, 0.5%		40/40, 1.5% (normal mode)	

HIAF

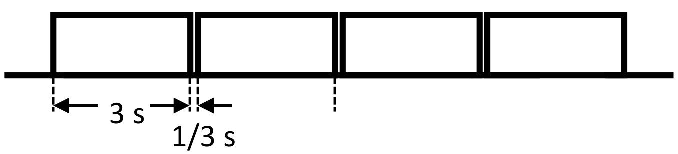
Muon production

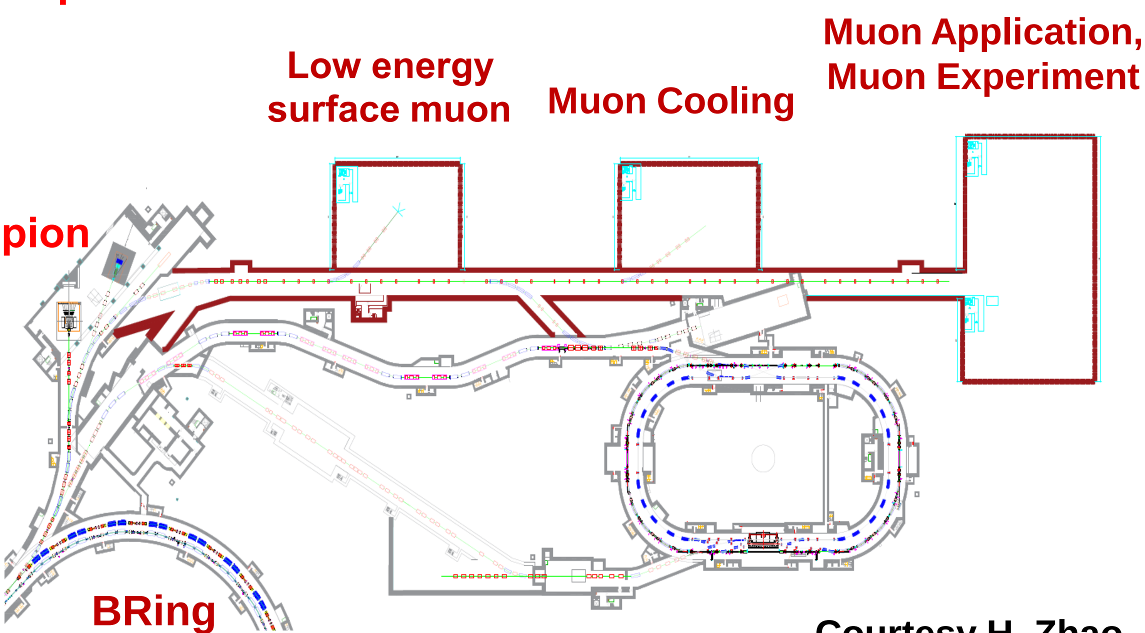
- High-intensity proton/ion to drive the surface/decay muon source
- Fast or slow extraction mode of BRing provides pulse or continuous beam

Fast extraction: High-intensity pulsed pion



Slow extraction: Quasi-continuous pion



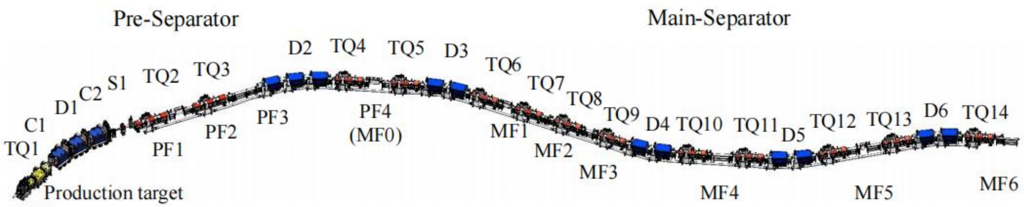


Courtesy H. Zhao

Muon Terminal

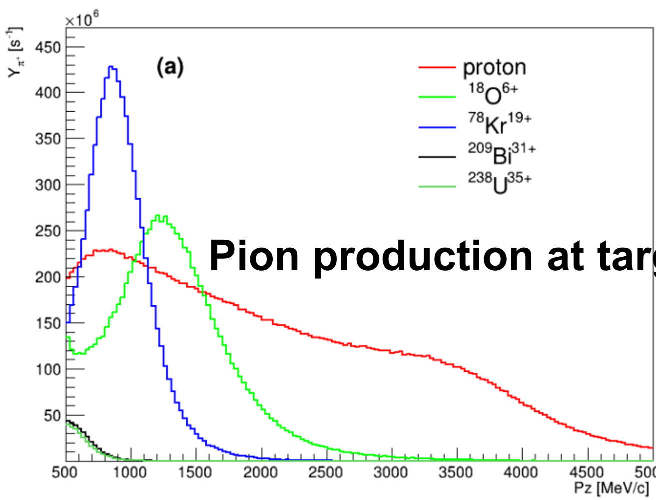
- Decay muon: muon application (tomography) and experiment
- Surface muon: μSR

GeV Muon Beam with HIAF

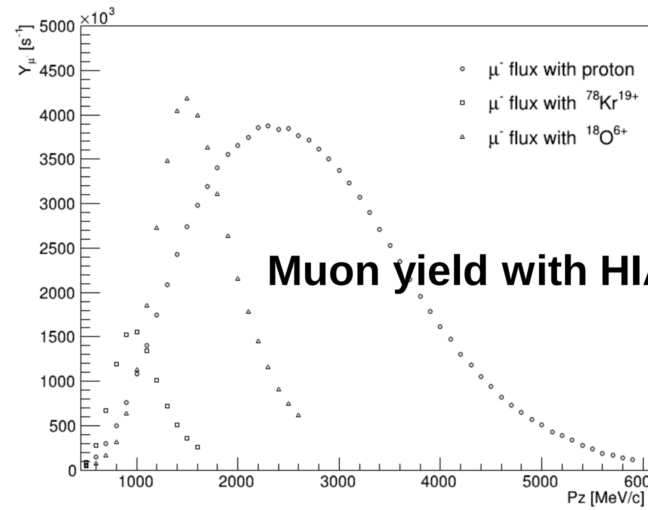


NIM.B 547(2024),165214

Length [m]	Max. angular acceptance [mrad]	Max. momentum acceptance [%]	$B\rho_{max}$ [T·m]
191.38	±30 (X) ±25 (Y)	±2.0	25



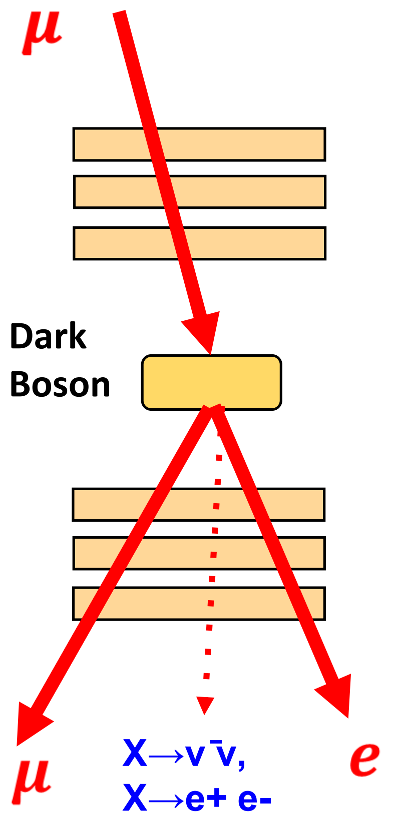
Pion production at target

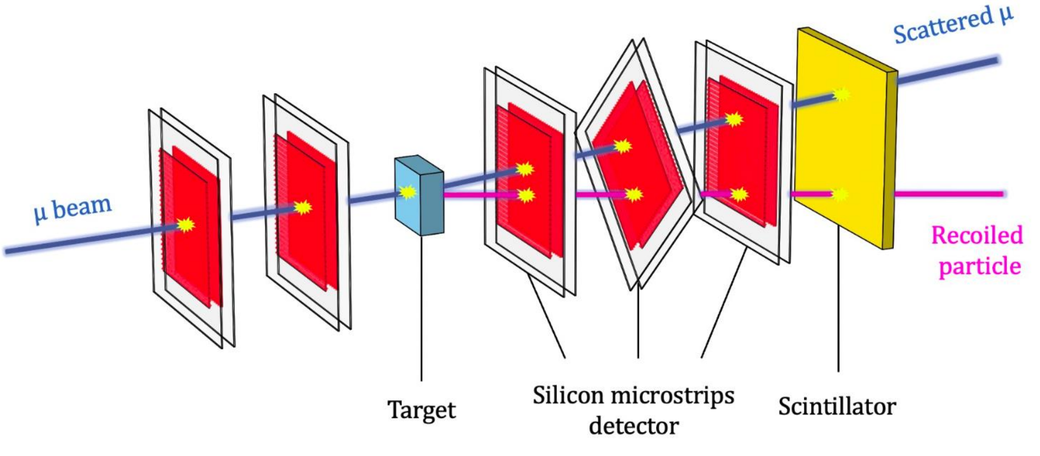


Muon yield with HIAF

- **High-rigidity Radioactive Ion Beam Line (HIRIBL): world's longest and highest rigidity beamline**
- **HIRIBL is long enough for GeV energy pion/muon production, decay and transportation**
- **Intensity of muon with momentum of 3 GeV can reach $4*10^6$/s**

Searching for New Physics with HIAF



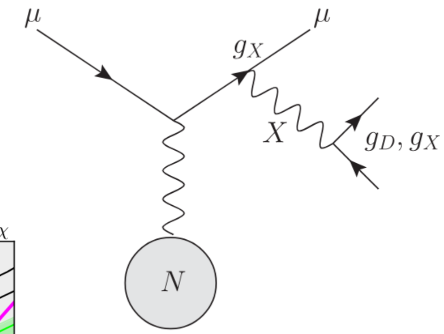


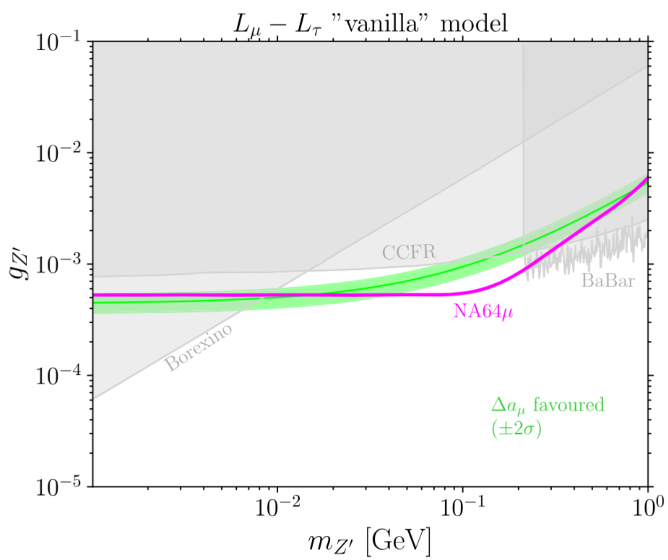
PKMu Experiment:
GeV Muon beam complementary to higher energy experiments like NA64 and MUonE

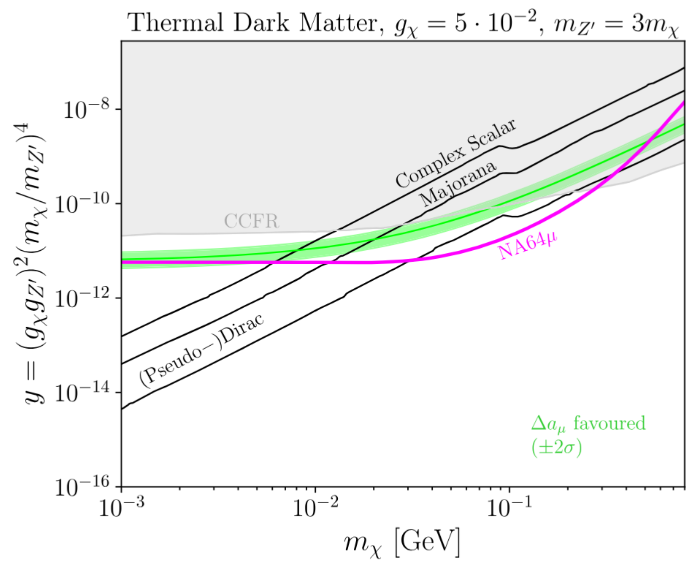
NA64 Results

$$\mathcal{L} \supset -\frac{1}{4} F'_{\alpha\beta} F^{\alpha\beta\prime} + \frac{m_{Z'}^2}{2} Z'_\alpha Z^{\alpha\prime} - g_{Z'} Z'_\alpha J^\alpha_{\mu-\tau},$$

$$-g_\chi Z'_\alpha J^\alpha_\chi,$$

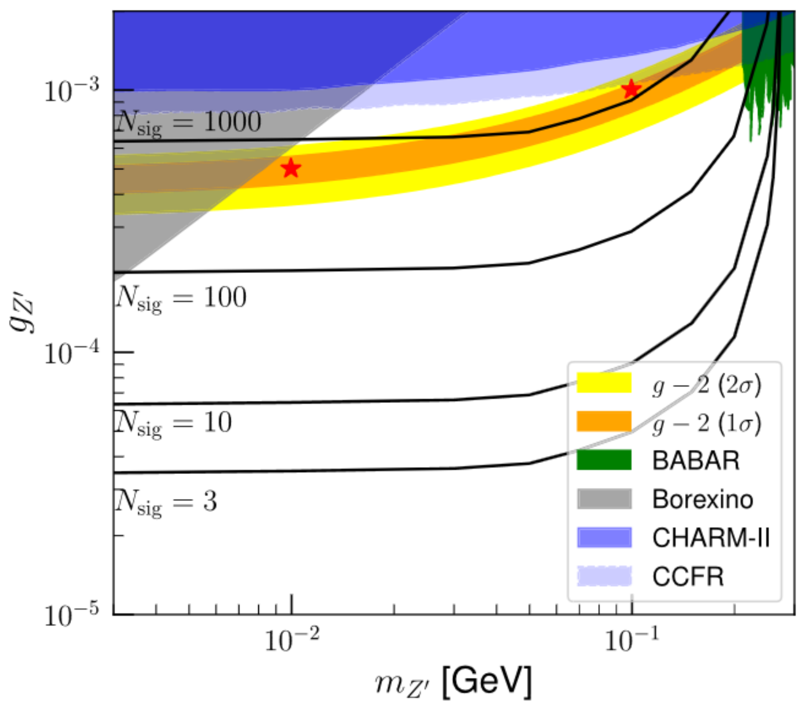


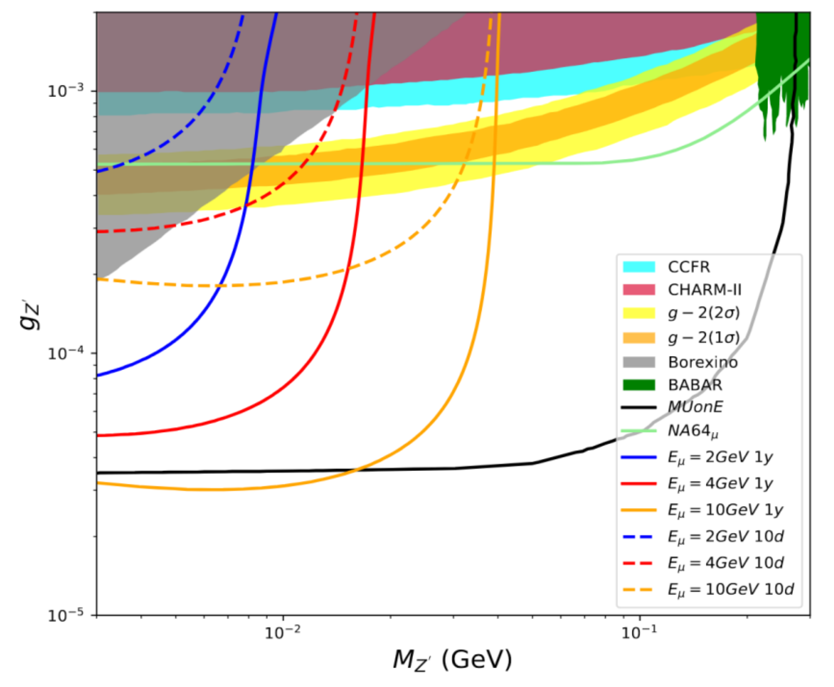




Phys. Rev. Lett. 132, 211803

Dark Boson Z' Search with HIAF





PKMu simulation result

MuonE: Phys.Rev.D 106 (2022) 5, L051702

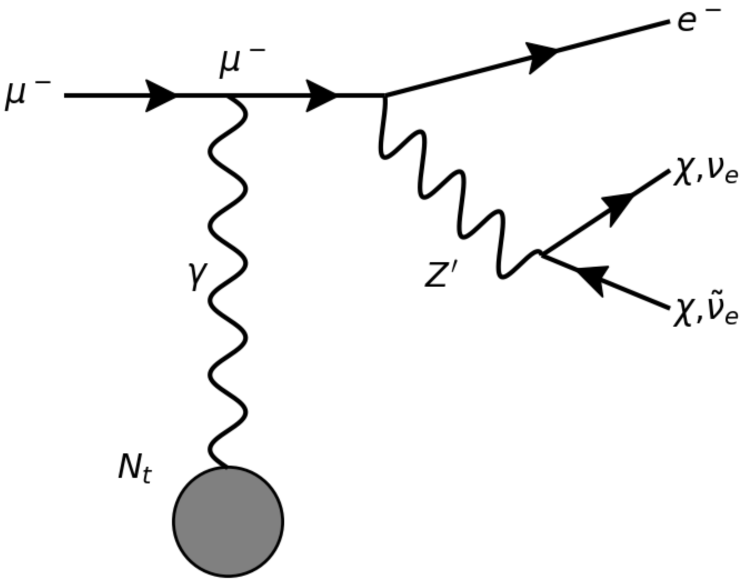
PKMu: More sensitive to dark boson at MeV region

Courtesy Q. LI

Flavor Changing Z' Search with HIAF

DREAMuS: Dark matter REsearch with Advanced Muon Source

- **Dark matter (χ) from a heavy, flavor-violating Z′**
- **3 GeV muon interaction with 350 μm tungsten target**



Flavor Changing Z' Search with HIAF

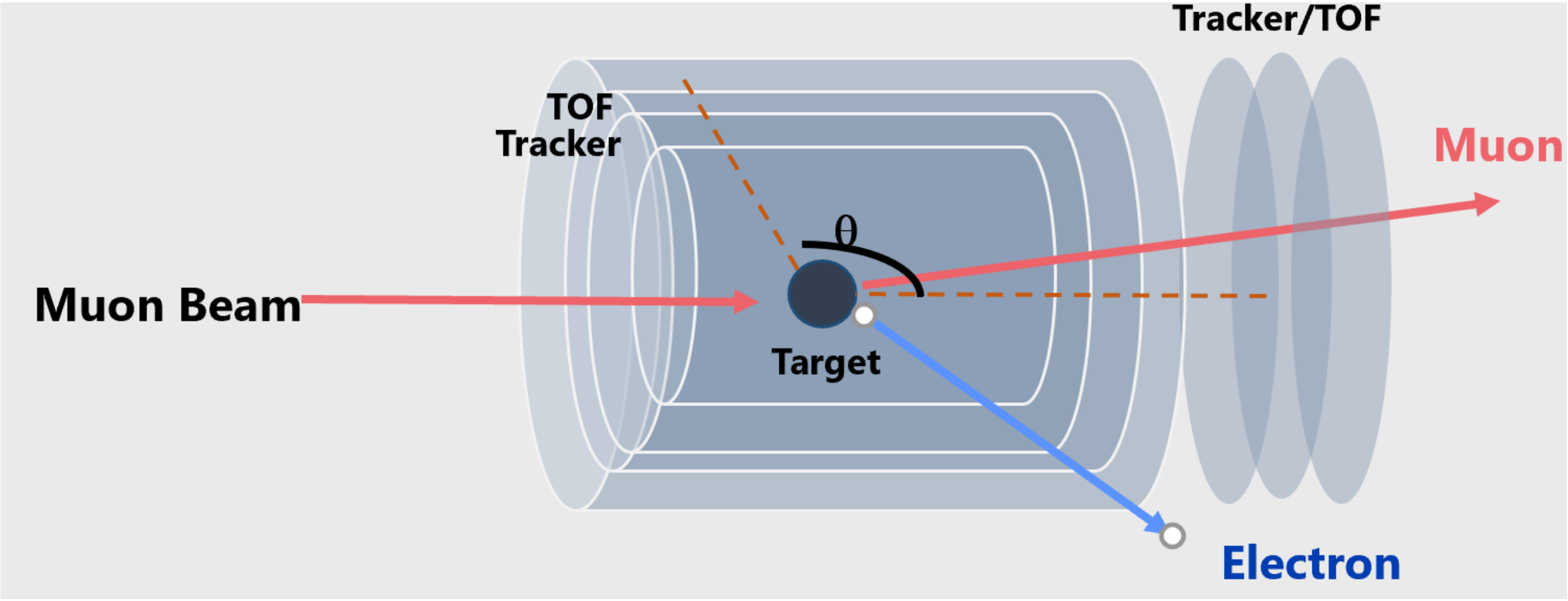
Particle (veto) detector
- Muon veto : TOF > 11 ns
  - Remove muon beam remnant
- Proton veto : TOF < 14 ns

Single track with Tracker/TOF
- Number of track = 1
- Tracking efficiency: 99%

Geometry acceptance:
- Electron θ acceptance: $|\theta| < 120°$

Electron p_T selection:
- pT > 20 MeV

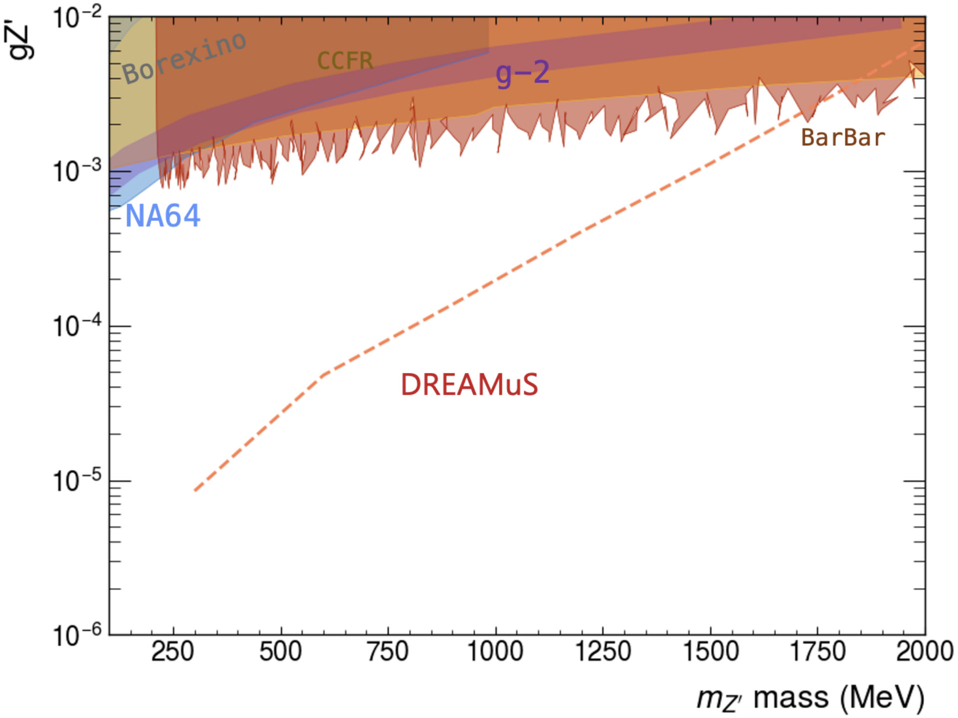
Electron θ selection:
- $|\theta| > 0.75$ radian (43 °)



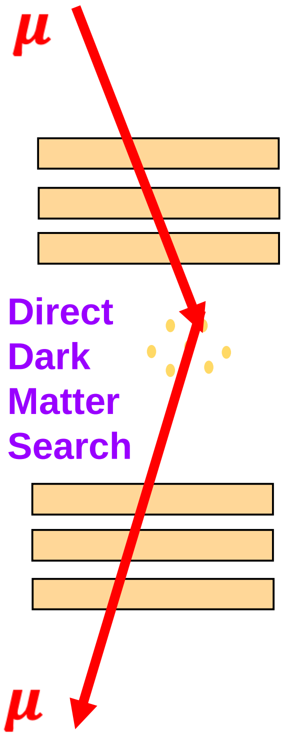
Flavor Changing Z' Search Sensitivity with HIAF

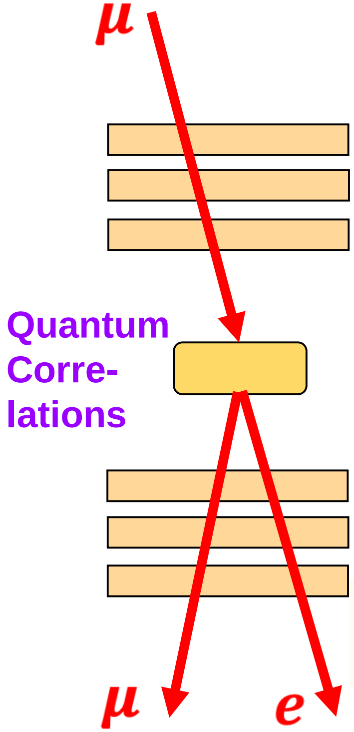
Stringent limit on flavor violating Z' model

- **$6*10^{12}$ MOT with background free assumption,** $m_{Z'} = 3m_\chi$
- **90% C.L. limit on $g_{Z'}$: ~10^{-5}**
- **In comparison with $L_\mu - L_\tau$ "vanila" model**



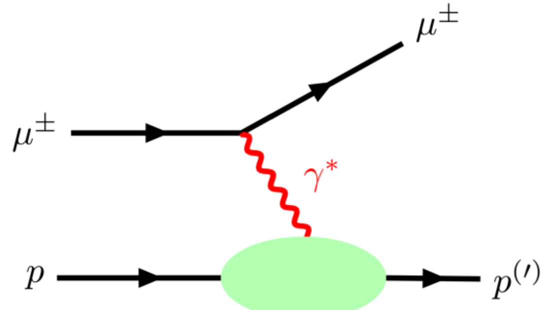
Other Physics Potentials with HIAF

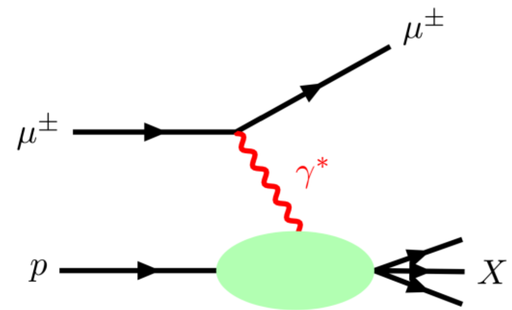


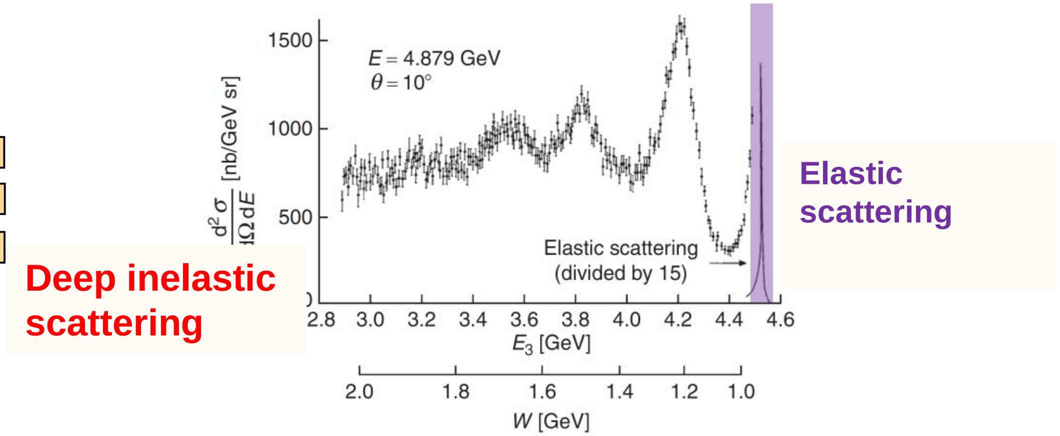


PRD 110 (2024) 1, 016017

arXiv:2502.07597





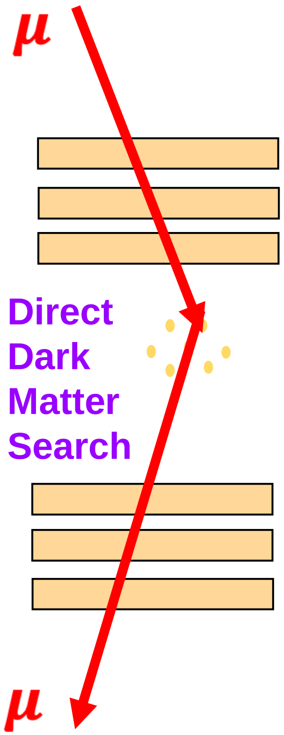


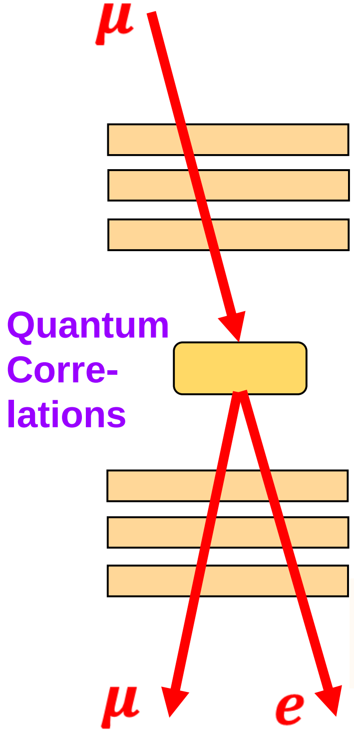
Proton charge radius

Proton Structure

LUNE: Low-energy mUon-Nucleon scattering Experiment

Other Physics Potentials with HIAF





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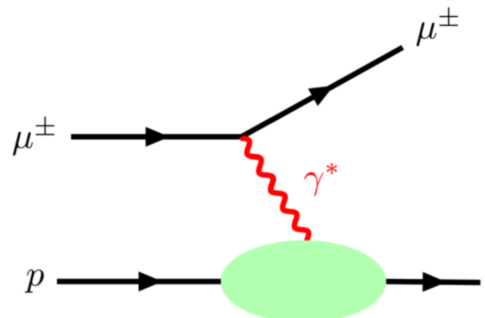
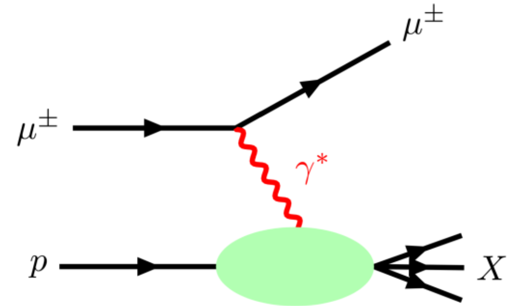
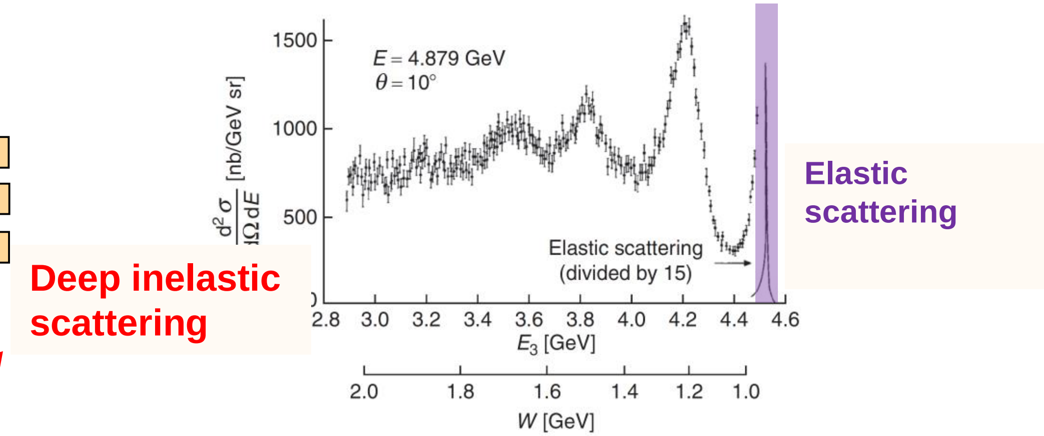




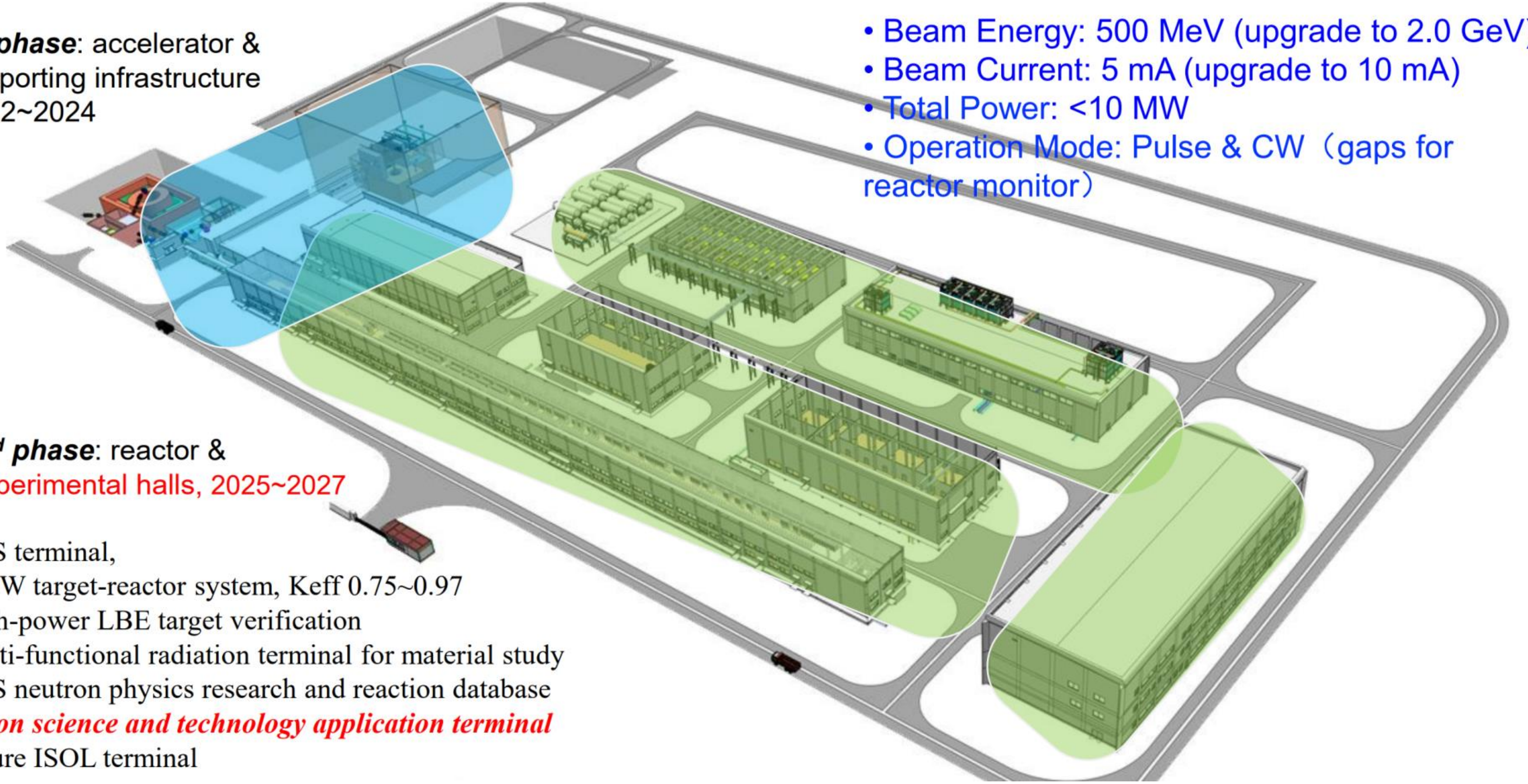


Proton charge radius

Proton Structure

LUNE: Low-energy mUon-Nucleon scattering Experiment

CiADS Design



1st phase: accelerator & supporting infrastructure 2022~2024

- Beam Energy: 500 MeV (upgrade to 2.0 GeV)
- Beam Current: 5 mA (upgrade to 10 mA)
- Total Power: <10 MW
- Operation Mode: Pulse & CW（gaps for reactor monitor）

2nd phase: reactor & experimental halls, 2025~2027

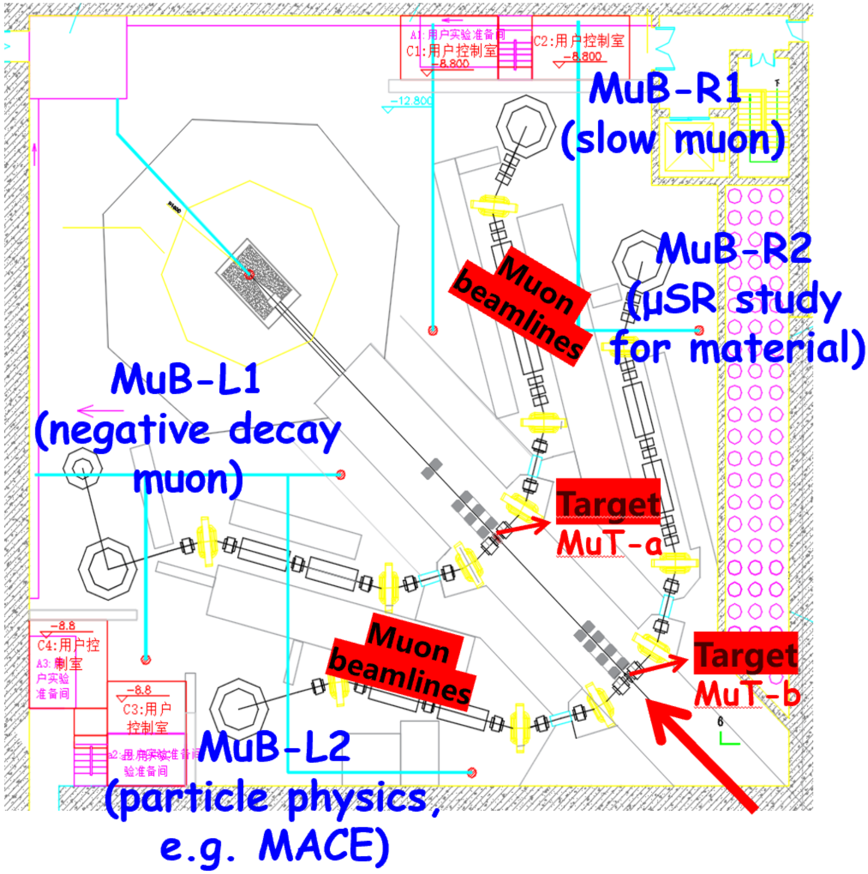
- T1: ADS terminal,
  10MW target-reactor system, Keff 0.75~0.97
- T2: High-power LBE target verification
- T3: Multi-functional radiation terminal for material study
- T4: ADS neutron physics research and reaction database
- ***T5: Muon science and technology application terminal***
- T6: Future ISOL terminal

Courtesy R. Wang

CiADS Muon Source: MuST

- **Muon terminal area: ~800 m²**
- **Construction plan of 2 phases**
  - **Phase I (2025–2028): one target station (0.5 mA, 600 MeV, CW wave & time-structed beam), two muon beamlines**
  - Phase II (2029–2032): Add one additional target station and two beamlines, power upgradable to 3 MW
- **Current design parameters**

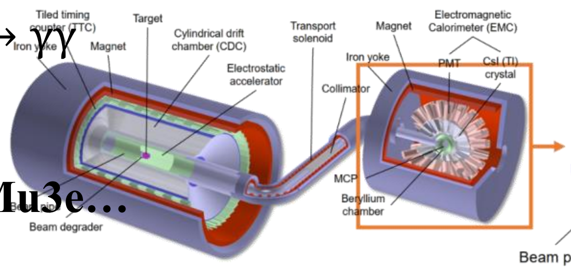
Beam power	Target	Focusing method	Muon intensity (μ^+/s)
1st phase 300 kW	Graphite rotating target	Solenoid + quadrupole	> 5E7
		Full solenoid	> 5E8
2nd phase 3 MW	Liquid lithium target	Solenoid + quadrupole	> 1E9
		Full solenoid	> 1E10



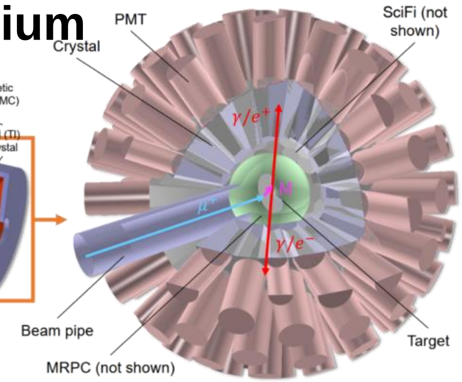
Courtesy Y. He

CiADS Physics Potential

- **High-precision tests of rare processes of muon and muonium**
  - ✓ $(\mu^+e^-) \rightarrow \mu^-e^+$, $(\mu^+e^-) \rightarrow e^+e^-$, $(\mu^+e^-) \rightarrow \gamma\gamma$
  - ✓ $(\mu^+e^-) \rightarrow$ invisible
  - ✓ **Experiments like Mu2e, COMET, MEG, Mu3e…**



MACE



MACE Phase-I

  - ✓ **MACE: Muonium-to-Antimuonium Conversion Experiment**

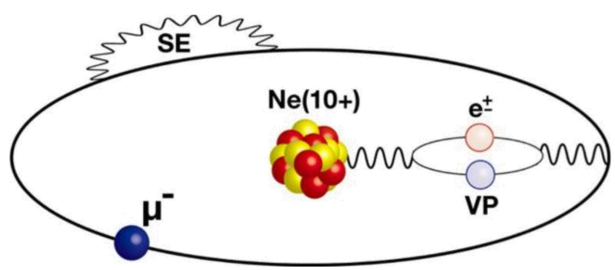
Searching for charged lepton flavor violation,

new physics beyond the standard model, CPT test

Courtesy J. Tang

- **High-precision X-ray measurement of muonic atom**

Muon orbits with
a much smaller
distance to charge center

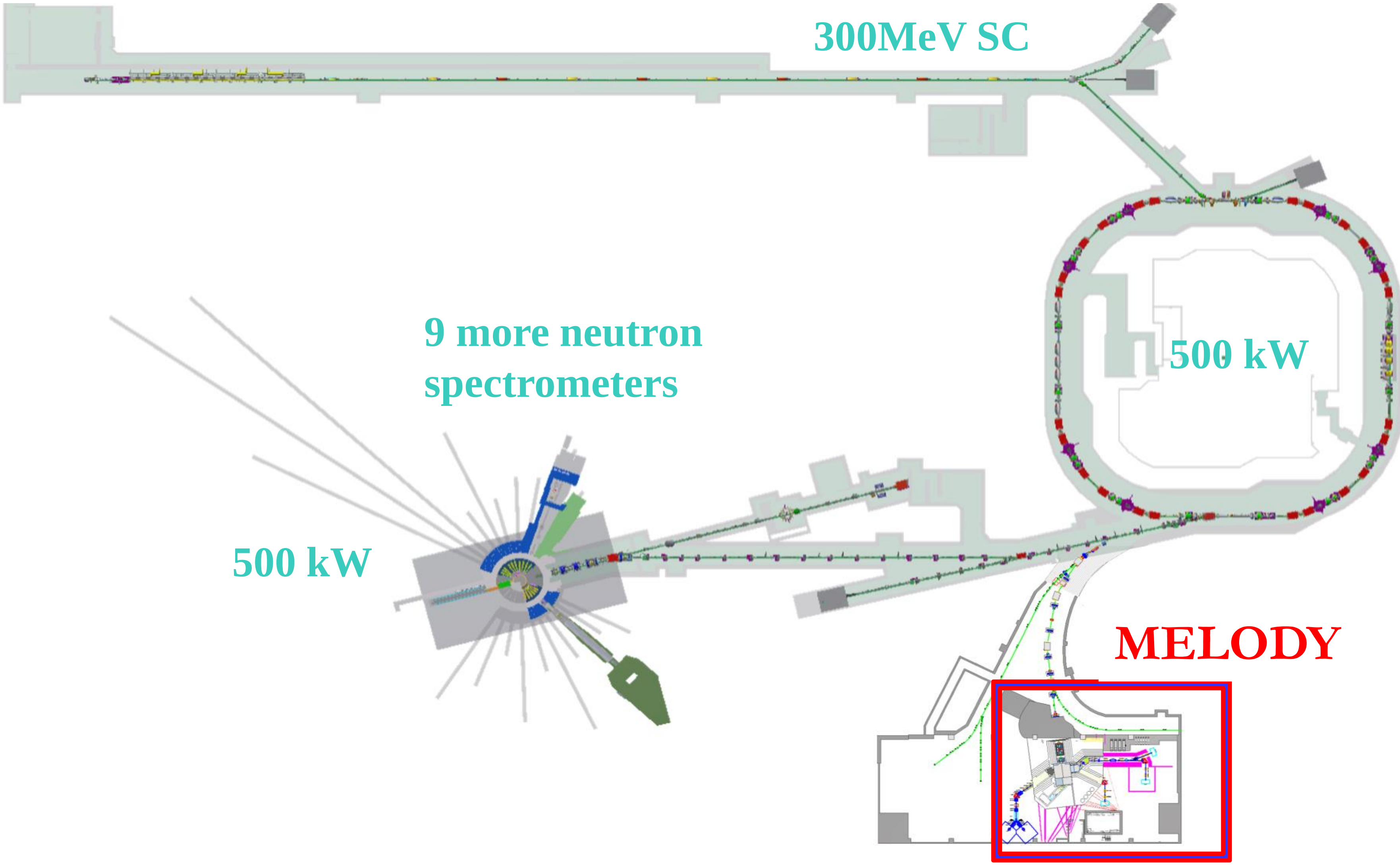


Precision test of strong filed QED, and looking for the fifth interaction in muonic atom!

China Spallation Neutron Source

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

China Spallation Neutron Source II



Courtesy Y. Bao

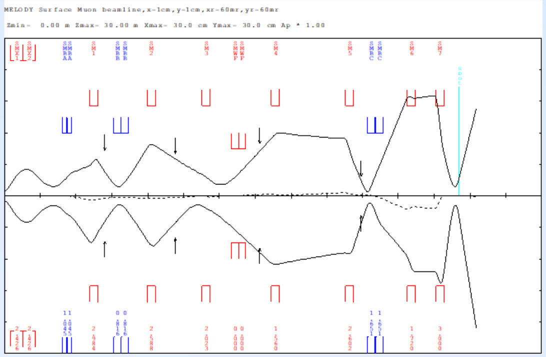
MELODY: Muon station for sciEnce technoLOgy and inDustrY

◆ Design parameters

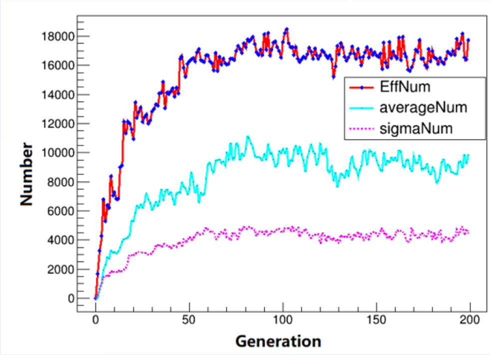
1. Momentum: 28 MeV/c, Polarizability: >95%
2. Intensity: $>10^5$ μ/s, Positron background: <1%

◆ Optical design by Transport

1. **Fully focusing solenoids,** 3 dipole bending magnet.
2. SMWF, SMK, 5 collimators
3. Deflection angle: SMBA @34, SMBB @40.9, SMBC @90, Kicker @8, Septum @15

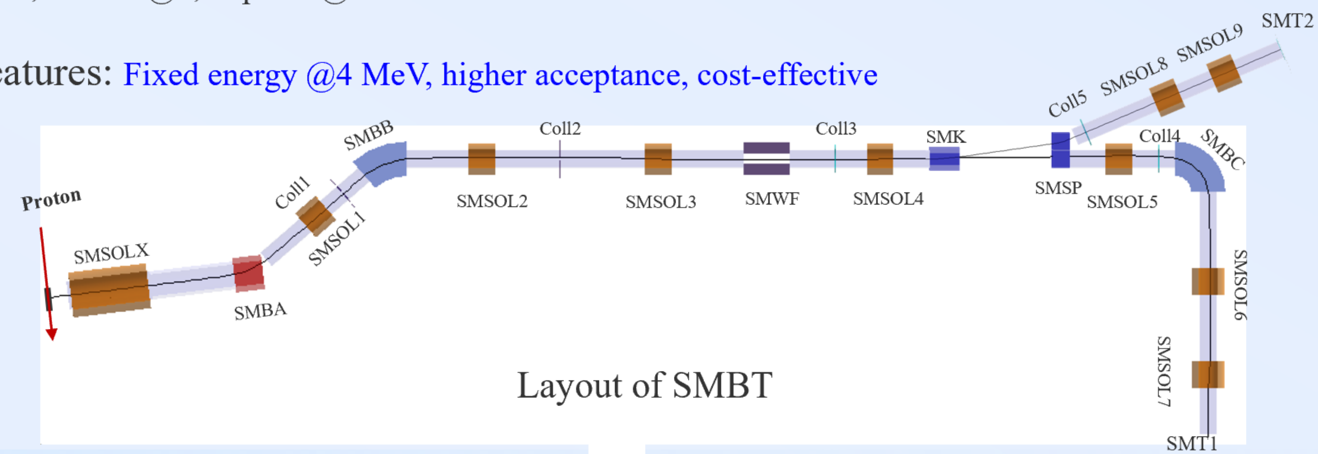


optical design



AI optimization

◆ Features: Fixed energy @4 MeV, higher acceptance, cost-effective



Layout of SMBT

2 terminals:

SMT1 for muSR

SMT2 for R&D

Courtesy Y. Bao

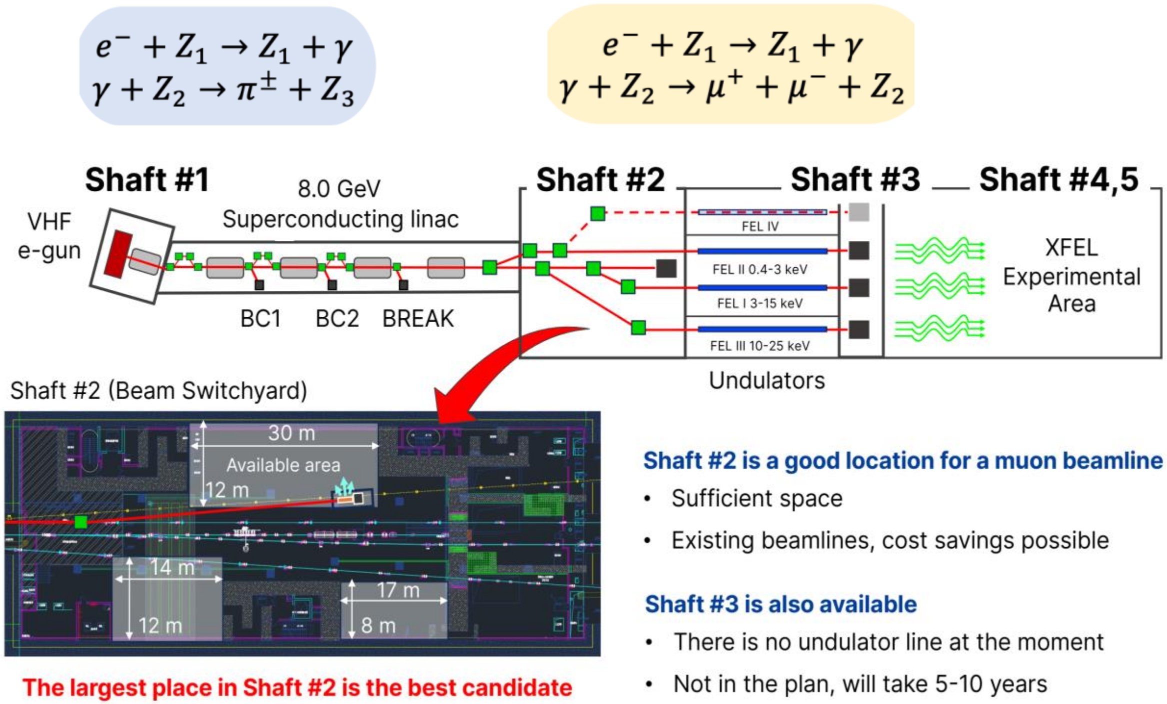
Muon Source at SHINE

SHINE is high-repetition X-FEL facility under construction at Shanghai (2019-2027)

- **Electron beam: 8 GeV, 1 MHz, 100 pC per bunch**
- **Possible to drive a muon facility**

Muon facility

- **Available space (underground)**
- **Shared beam time, 50 kHz**
- **2.5*10^7 μ+/s (surface μ), 500 μ/bunch, for μSR applications**
- **Under design and testing**

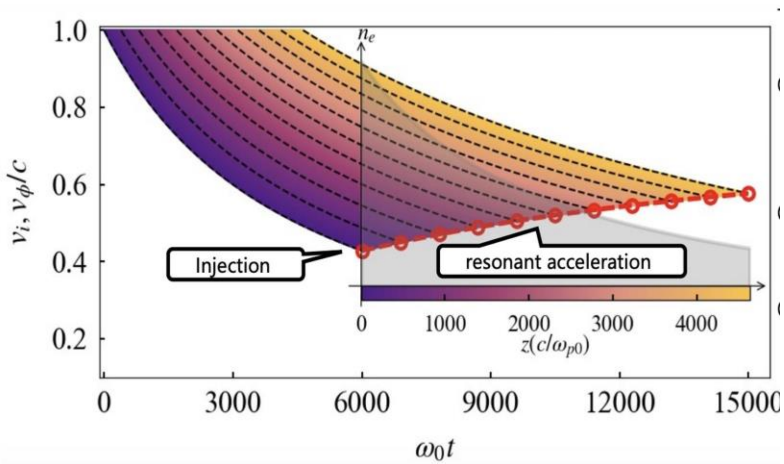


Courtesy J.Y. Tang, K.S. Khaw

Laser-driven Muon Sources

Several groups in China studying laser-driven muon sources and muon acceleration by laser-plasma wake-field

- **Experiment at SULF (10PW/1PW-0.1Hz): conversion eff. 0.01μ/e**
- **TeV muon acceleration driven by laser plasma at PKU (slowing down plasma wave)**



Shanghai Super-intense Ultrafast Laser Facility (SULF)

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Article | Published: 06 May 2025

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

Feng Zhang, Li Deng, Yanjie Ge, Jiaxing Wen, Bo Cui, Ke Feng, Hao Wang, Chen Wu, Ziwen Pan, Hongjie Liu, Zhigang Deng, Zongxin Zhang, Liangwen Chen, Duo Yan, Lianqiang Shan, Zongqiang Yuan, Chao Tian, Jiayi Qian, Jiacheng Zhu, Yi Xu, Yuhong Yu, Xueheng Zhang, Lei Yang, Weimin Zhou, ... Ruxin Li + Show authors

Nature Physics **21**, 1050–1056 (2025) | Cite this article

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Courtesy J.Y. Tang

Conclusion and Outlook

- Young and accelerating muon physics program in China
  - Several muon facilities under construction: HIAF, CiADS, MELODAY, SHINE etc.
- Wide participation in international experiments and projects (not covered in this talk)
  - Fermilab g-2, J-PARC g-2/EDM, COMET, Mu2e, MUonE, IMCC etc.
- High leverage for international collaboration.
  - Detector R&D, manpower and resources, data and computing strategy
  - Joint efforts are hightly encouraged
- Unique particle physics potential with HIAF/CiADS muon source
  - HIAF will operate by end of 2025, CiADS by end of 2027