HIAF和CiADS上缪子源及可能的缪子物理实验

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2025/4/25

Outline

- Introduction of muon source
- Muon sources at HIAF and potential physics
- Muon sources at CiADS and potential physics
- Summary

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- ☐Introduction of muon source
- ☐Muon sources at HIAF and potential physics
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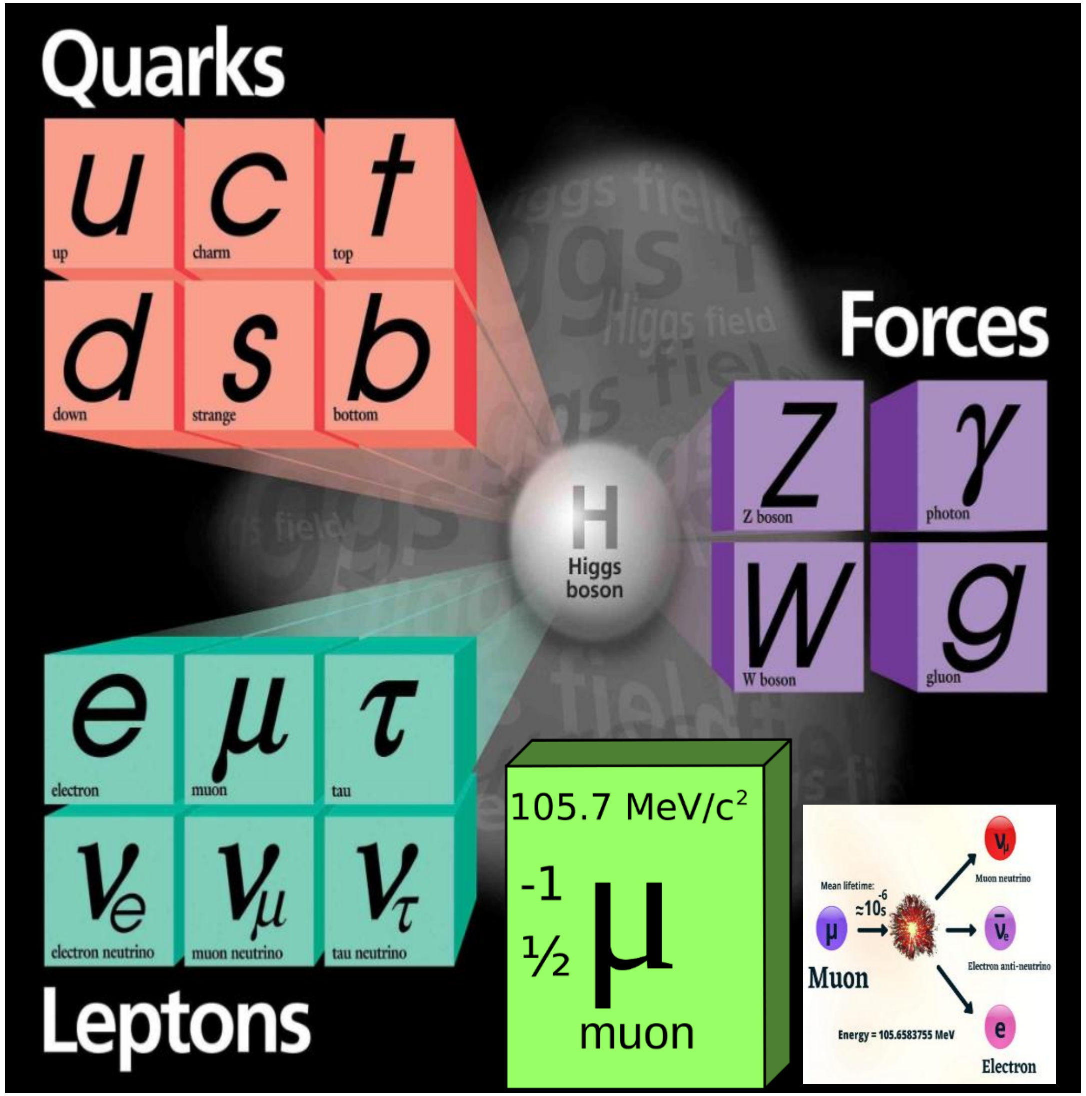
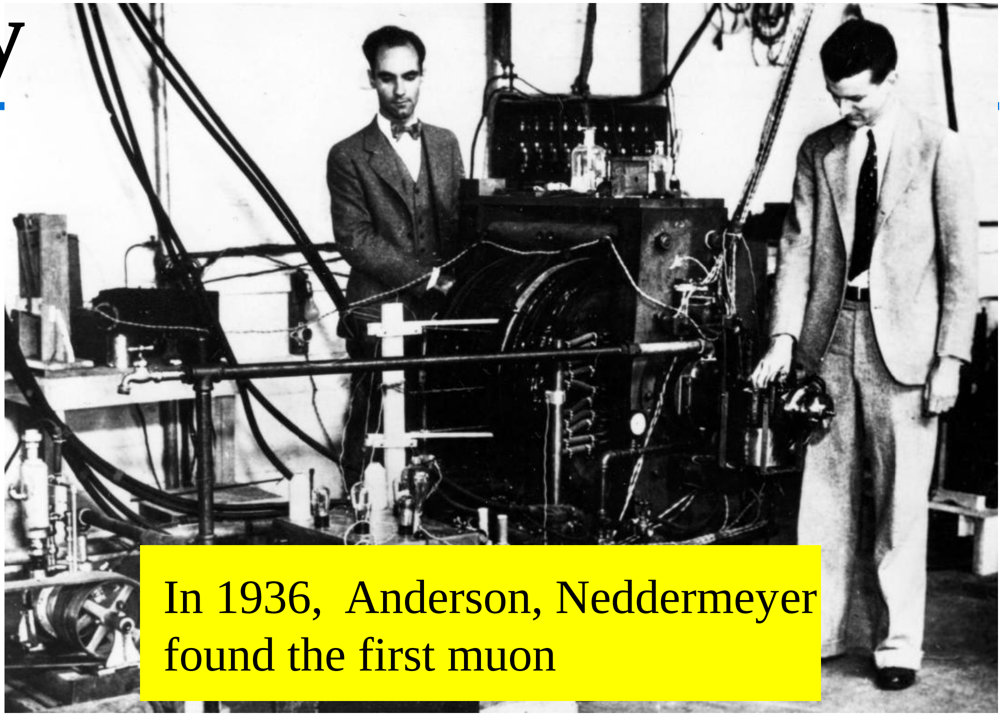
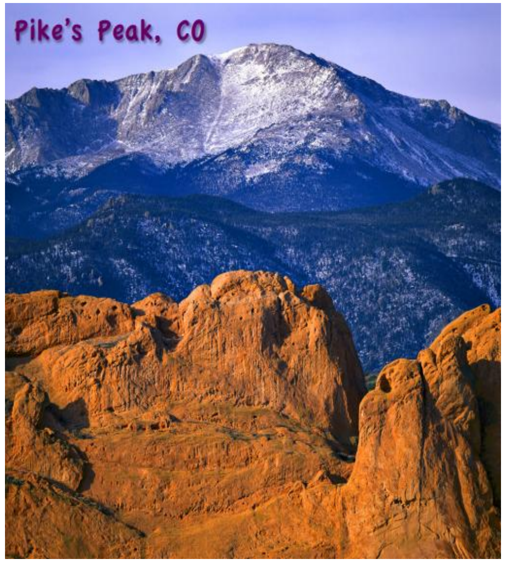
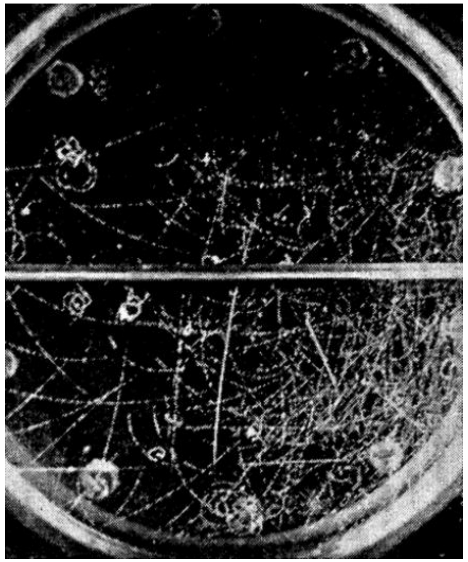
Muon and its discovery





In 1936, Anderson, Neddermeyer found the first muon





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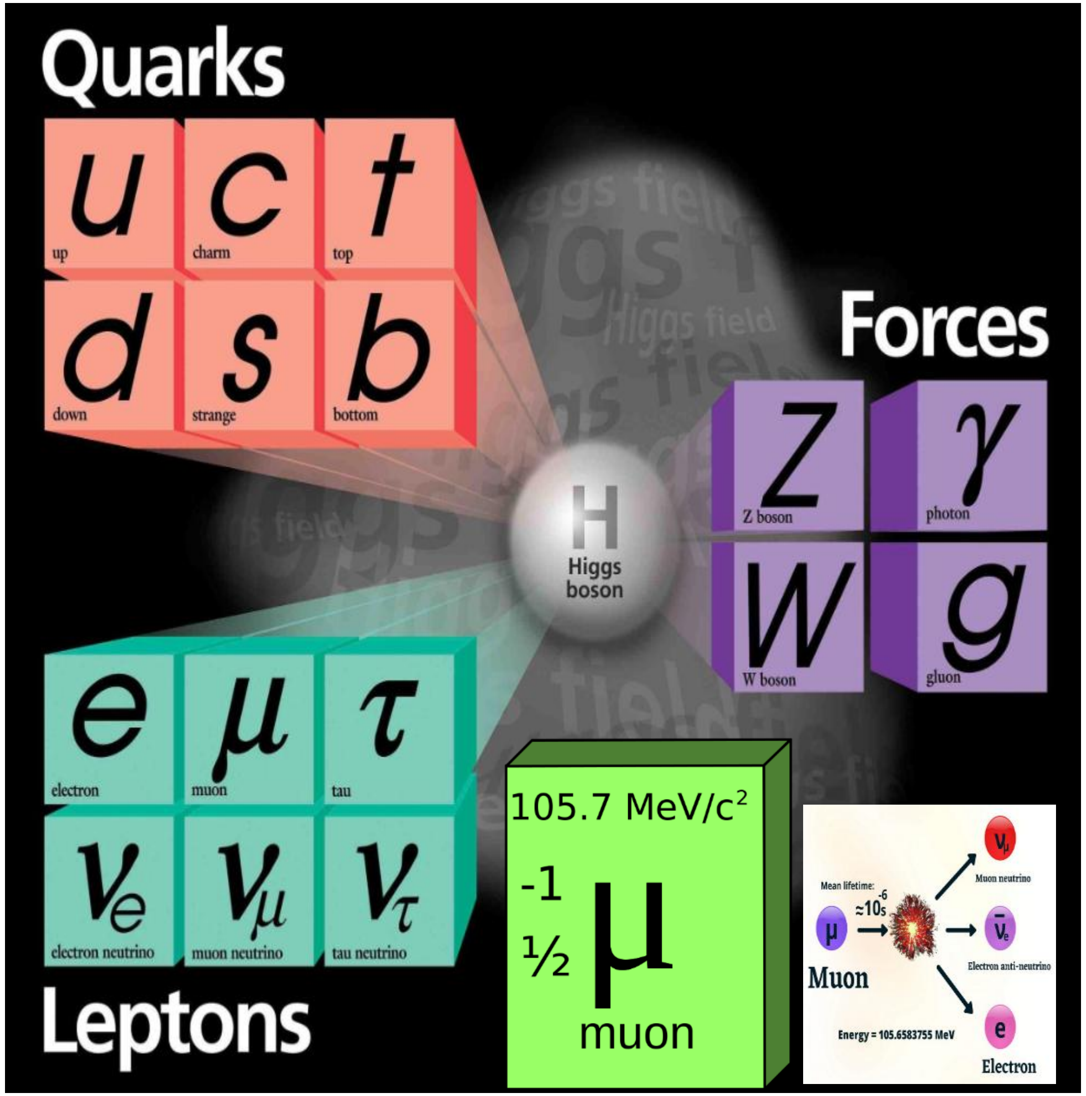
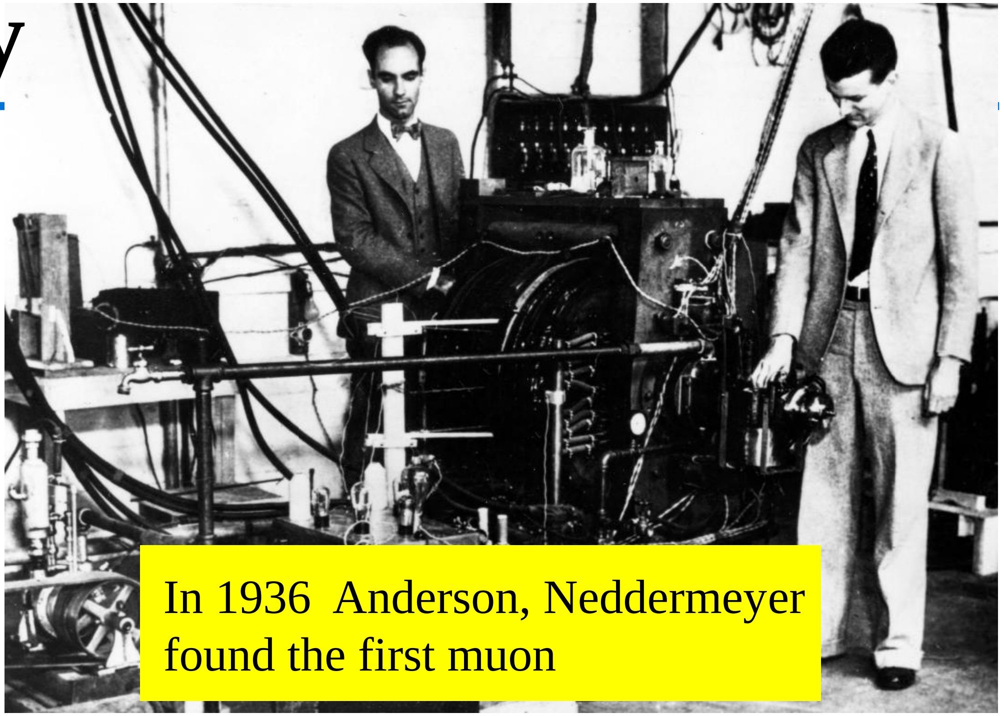
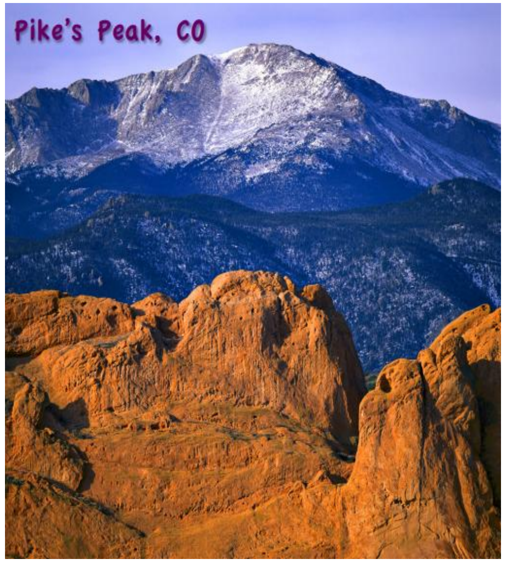
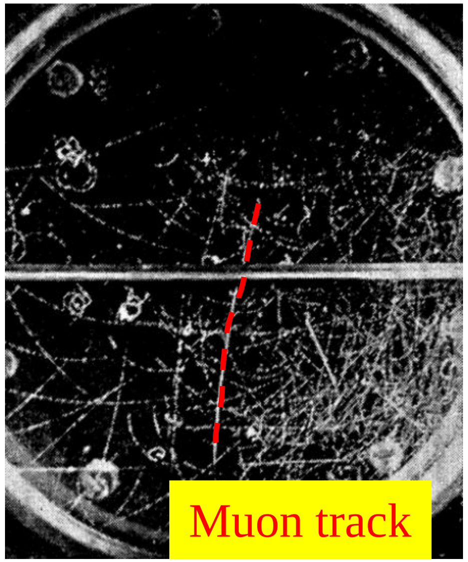




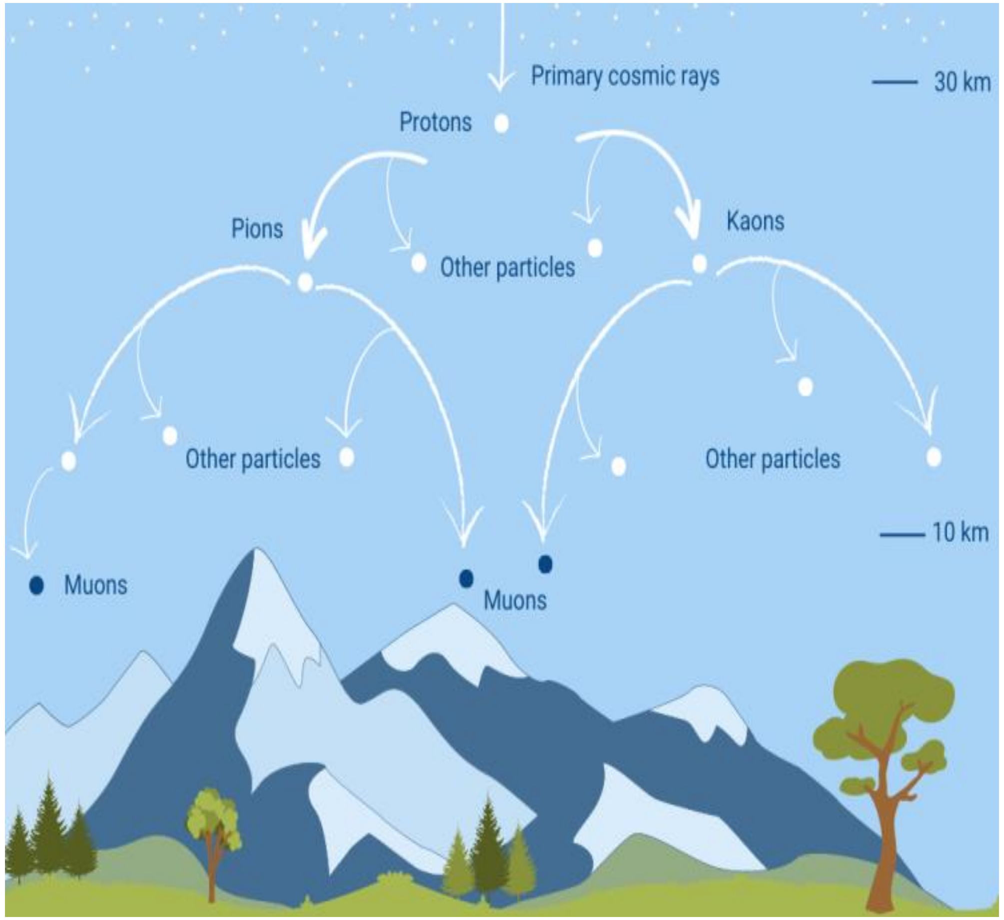


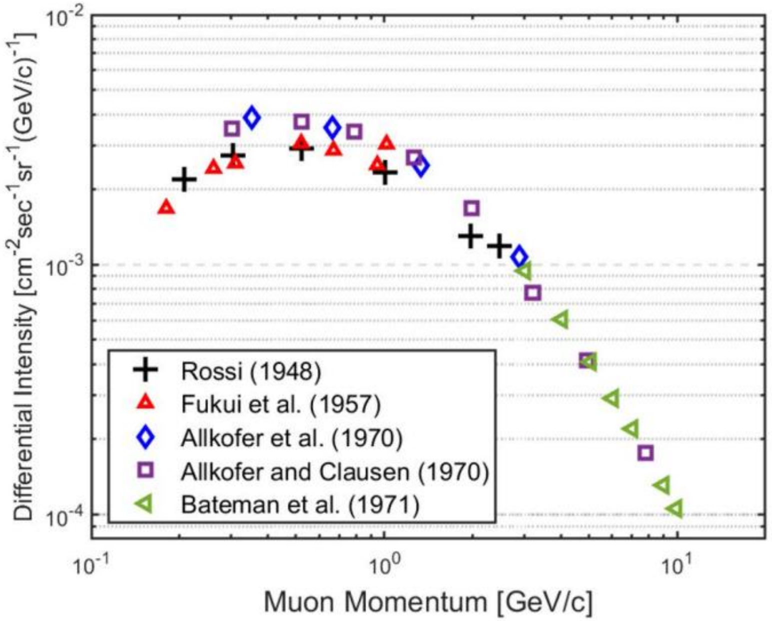


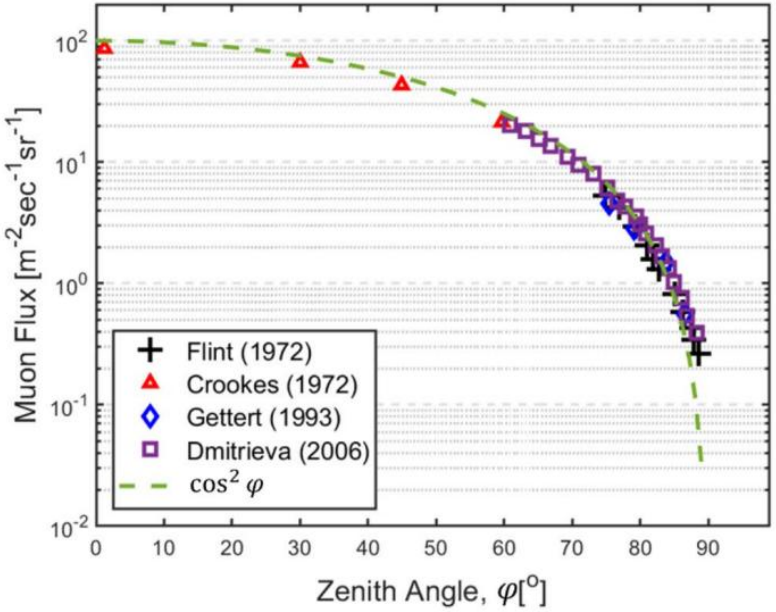
Phys. Rev. 50 (1936) 263

Muon souce

Cosmic ray muon:





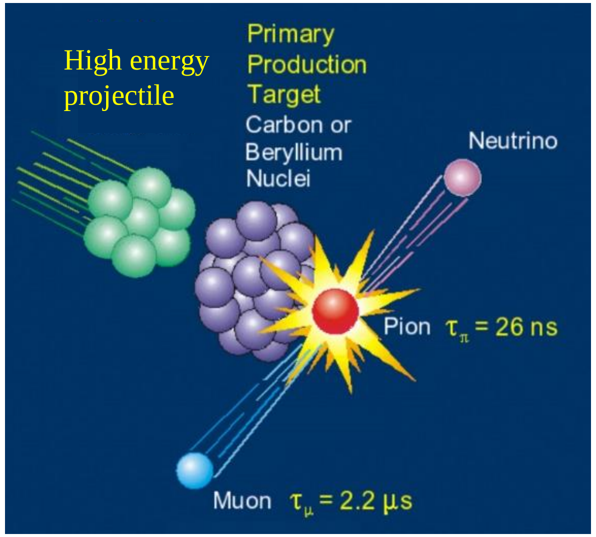


muons at sea leval

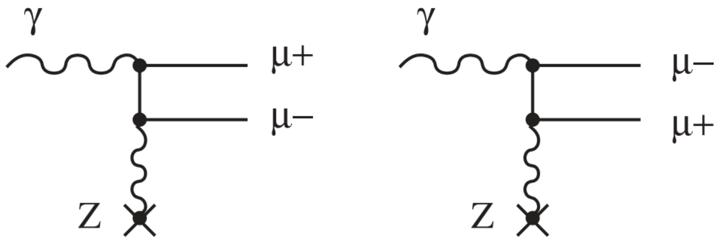
J. Bae, Scientific Reports, 14,6717(2024)

Muon source

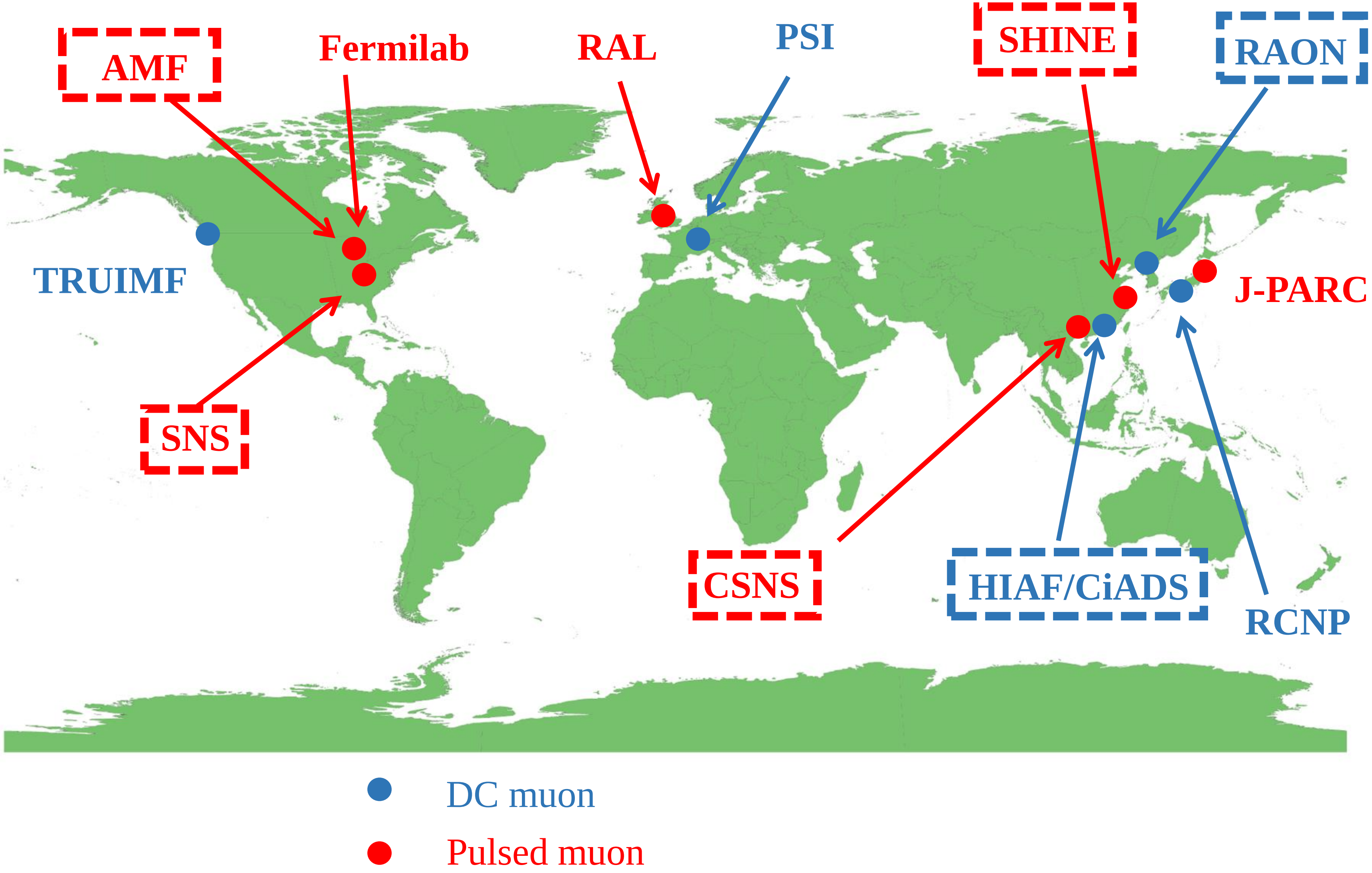
Accelerator generation:



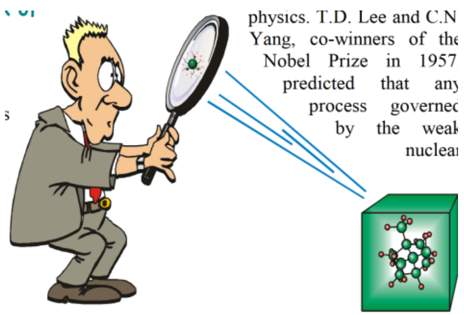
Muon from pion decay

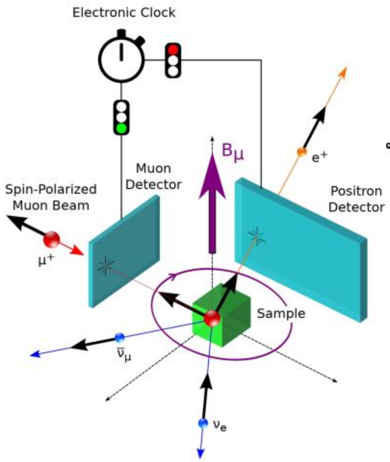


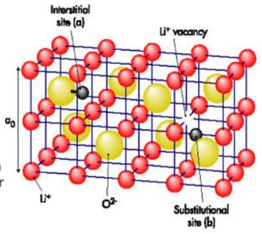
Bethe-Heitler process

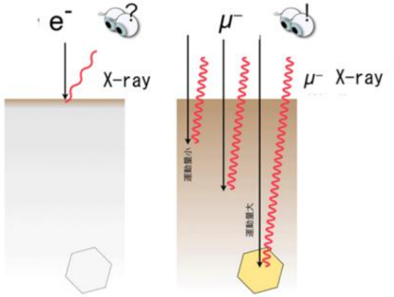


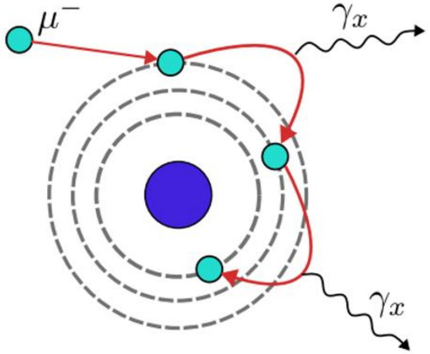
Broad applications of muon source facility



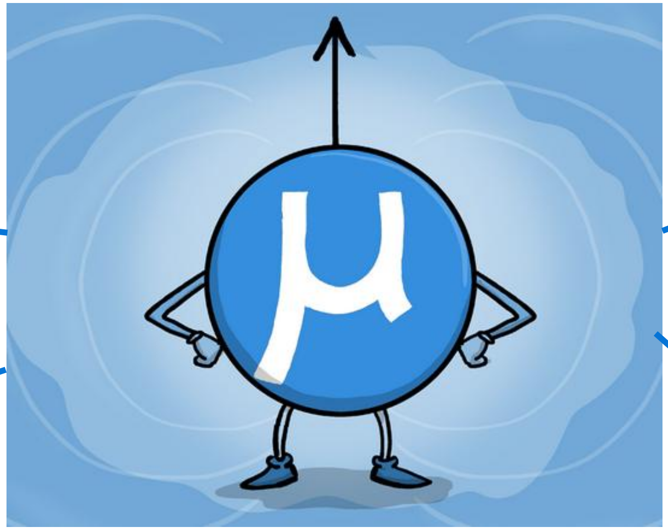








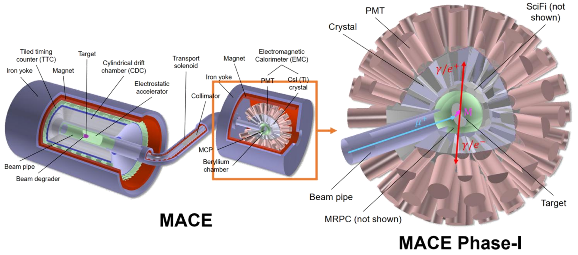
Muon spin rotations

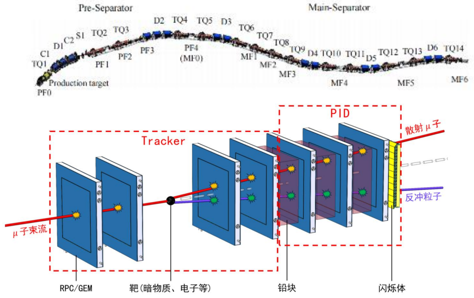


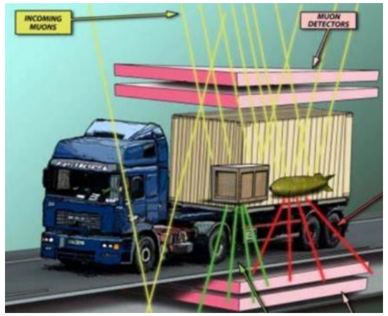
Elemental analysis with muonic X ray

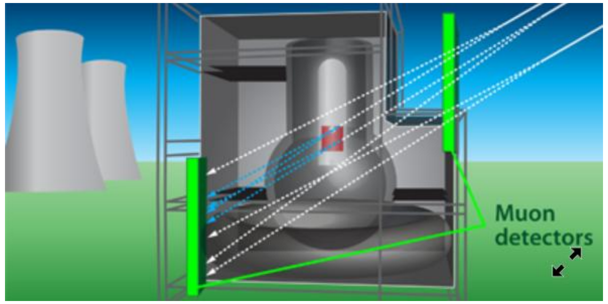
Searching for new physics

Muon tomography









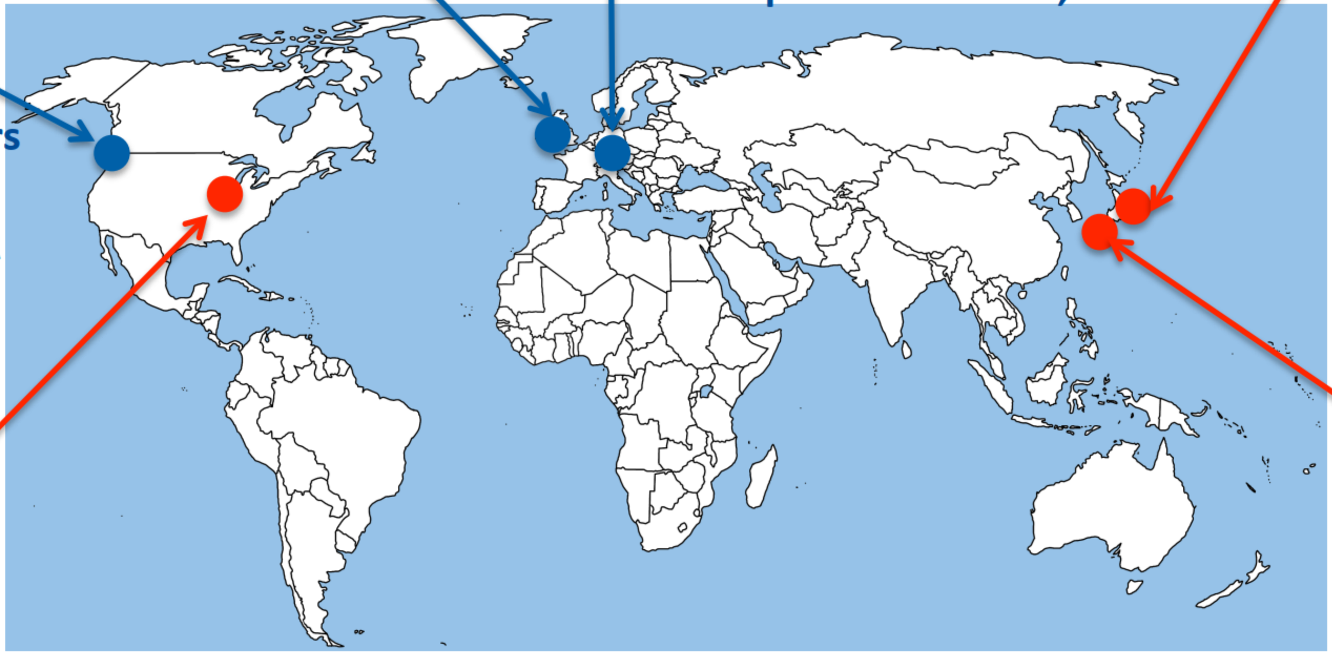
Global precision muon physics experiments

RIKEN-RAL
Materials – muSR
Techniques – LE beams

PSI
Lifetime – Fermi constant (MuLan, FAST)
Muon Capture – (Mucap, MuSun, AlCap)
Proton Radius – (mp/d Lamb Shift, CREMA, MuSE)
CLFV - (MEG, mu3e)
Materials – muSR
Techniques – LE Beams, HI beams

TRIUMF
Decay Parameters - TWIST
Materials - muSR

JPARC
Muon g-2 (E34)
CLFV – COMET, DeeMee
Muonium Spectroscopy - MUSEUM



RCNP
HI Beams Facility – MUSIC

Fermilab
Muon g-2 (E989)
Muon eDM (E989)
CLFV – mu2e

Theoretical work also very widespread

Past Present Future

Courtesy:
B. Kiburg@NuFact 2015

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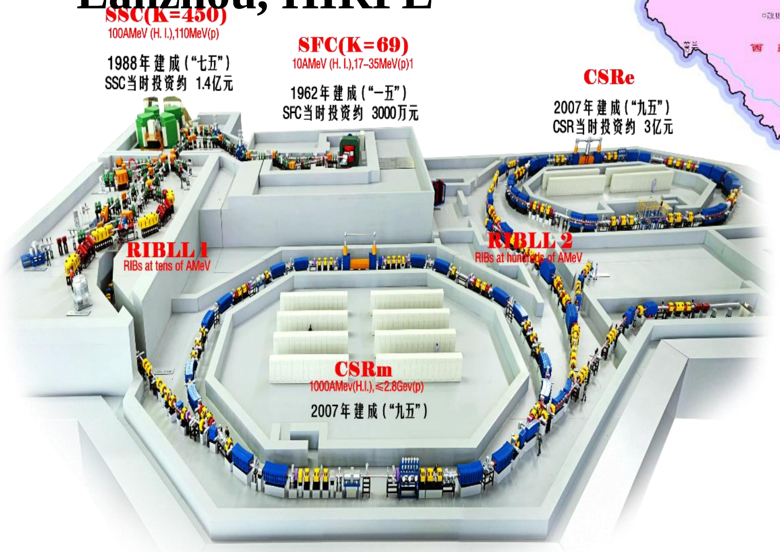
Institute of Modern Physics

Lanzhou Campus

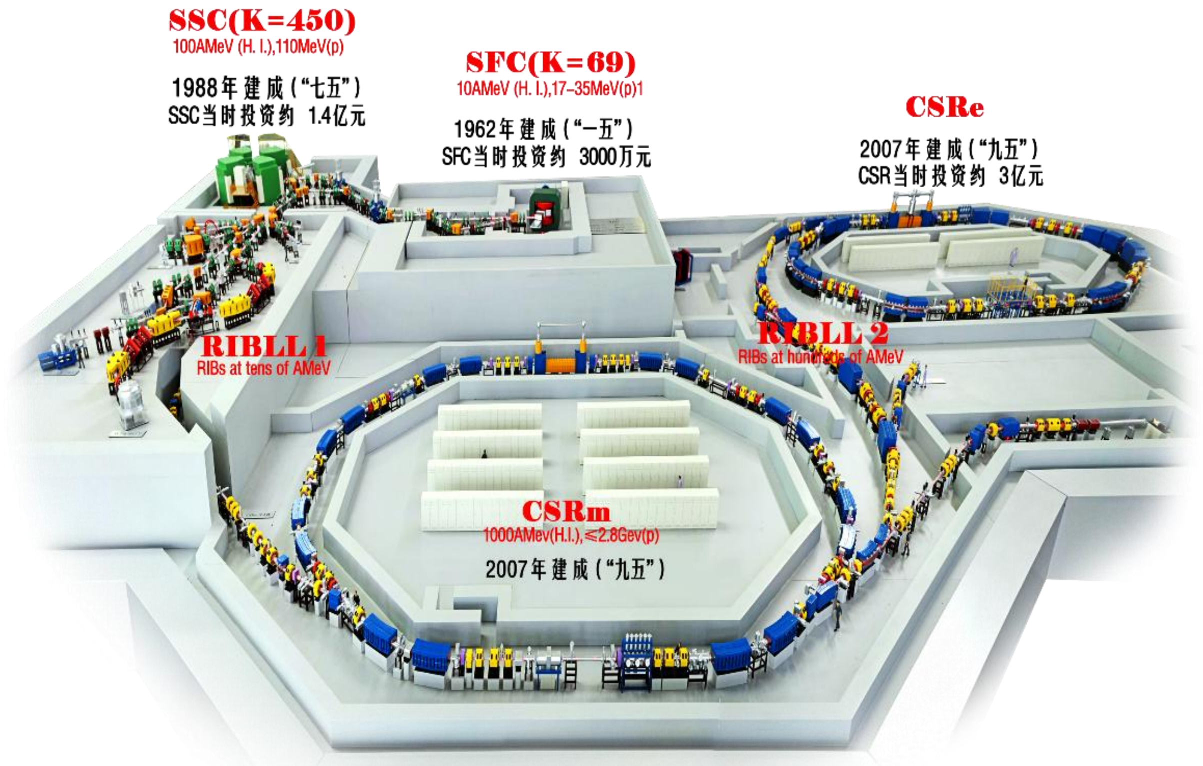
Heavy Ion Facility in Lanzhou, HIRFL



Huizhou Campus

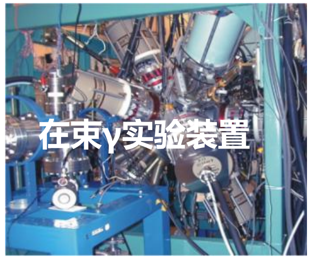
Heavy-Ion Research Facility at Lanzhou（HIRFL）

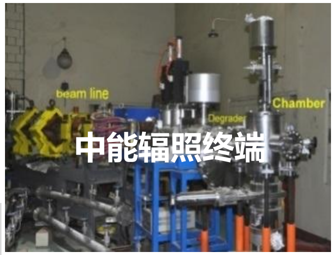
Lanzhou Campus



HIRFL is the highest energy heavy ion accelerator in China

Heavy-Ion Research Facility at Lanzhou（HIRFL）





- 20 experimental terminals
- nuclear physics, atomic physics, materials science, life sciences
- More than 200 users and over 150 experiments annually

Huizhou Campus

总部区

装置区

The under-construction HIAF and CiADS accelerator complex

Location: Huizhou city, Guangdong province

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

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

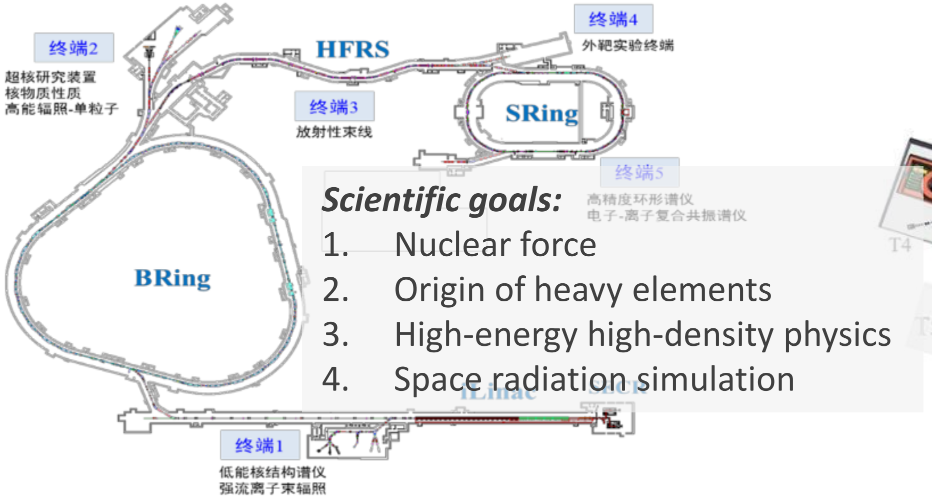
Two Major National Science and Technology Infrastructure Projects, approved by central government in December 2015.

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

***Construction periods*:**

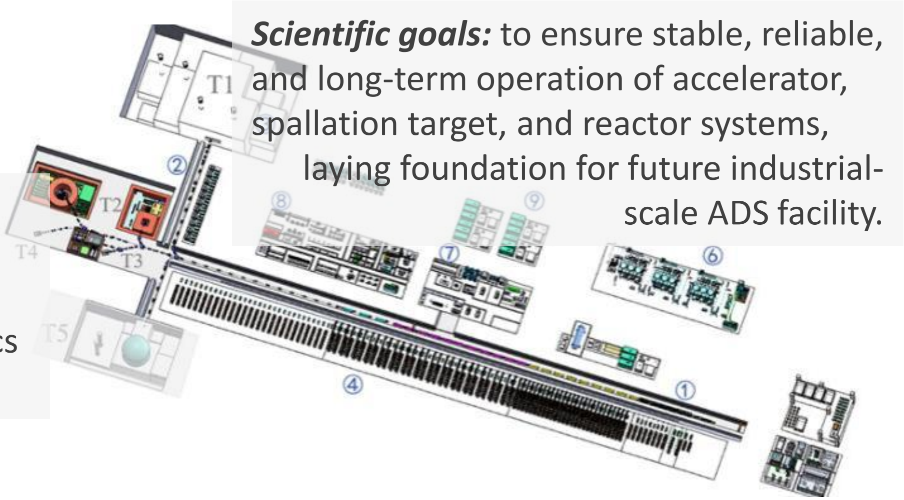
HIAF: Dec. 2018 – Dec. 2025

CiADS: July 2021 – July 2027



Scientific goals:

1. Nuclear force
2. Origin of heavy elements
3. High-energy high-density physics
4. Space radiation simulation



Scientific goals: to ensure stable, reliable, and long-term operation of accelerator, spallation target, and reactor systems, laying foundation for future industrial-scale ADS facility.

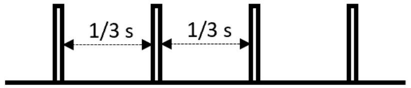
HIAF Facility

- **To explore the limit of nuclear existence**
- **To study exotic nuclear structure**
- **Understand the origin of the elements**
- **To study the properties of High Energy and Density Matter**

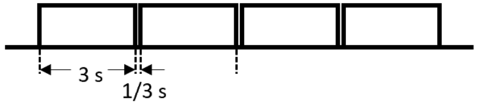
……

Courtesy He Zhao

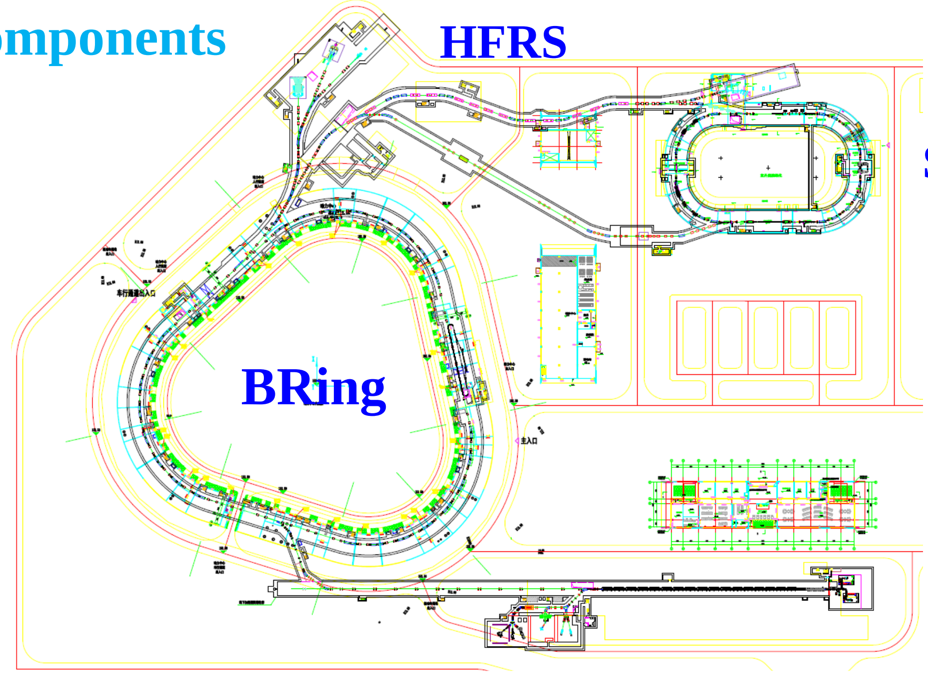
Fast extraction: High-intensity pulsed p/ion



Slow extraction: Quasi-continuous p/ion



Accelerator components

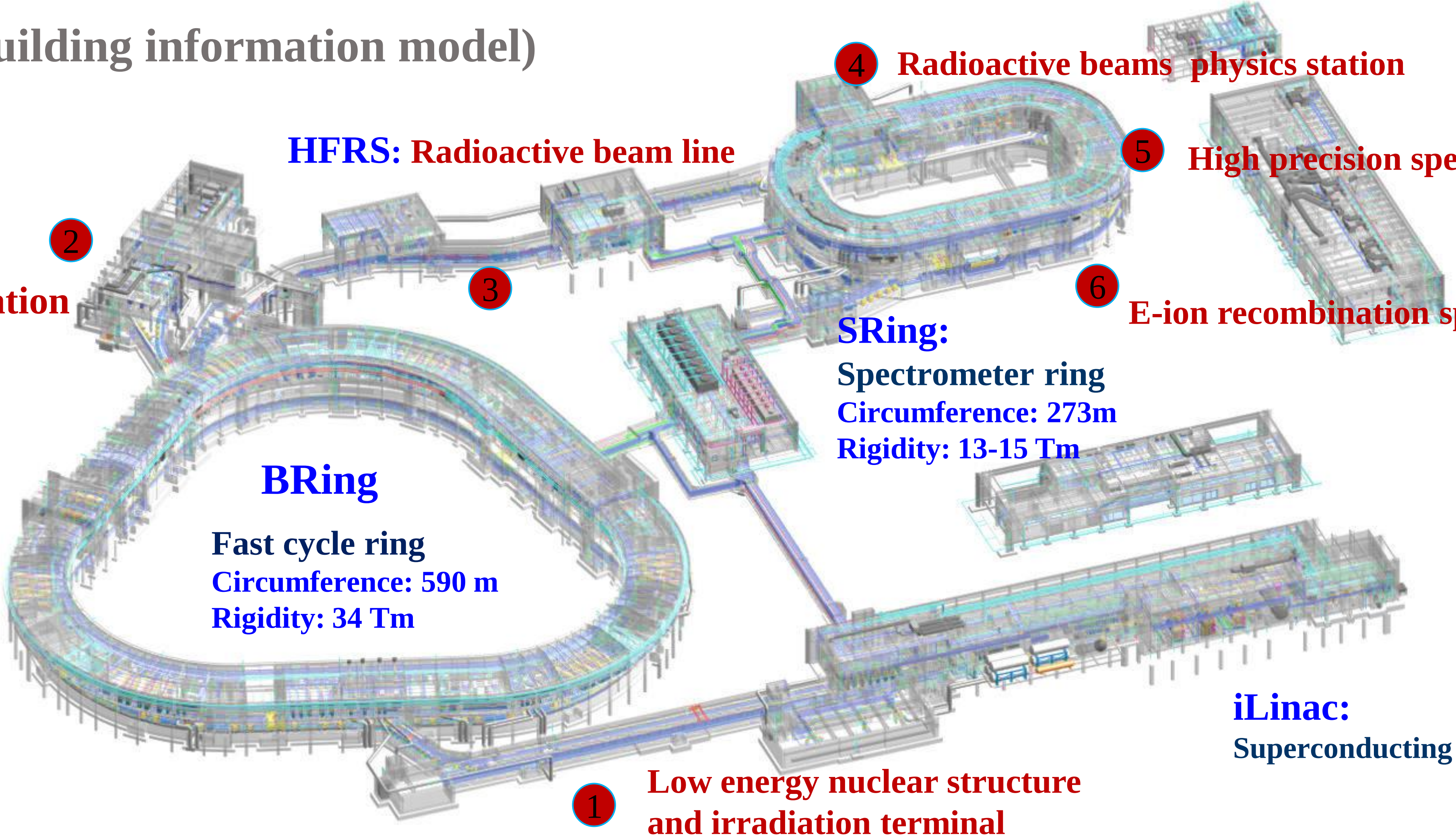


	iLinac	BRing		SRing	
Length / circumference (m)	114	569		277	
Final energy of U (MeV/u)	17 (U^{35+})/150	835 (U^{35+})	9300 (p)	800 (U^{92+})	3500 (p)
Max. magnetic rigidity (Tm)	---	34		15	
Max. beam intensity of U (ppp)	**28 pμA**	**2×10^{11}**	**$(1\text{-}3)\times10^{13}$**	**$(0.5\text{-}1)\times10^{12}$**	**$(1\text{-}3)\times10^{13}$**
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 Facility

- Experiment terminals

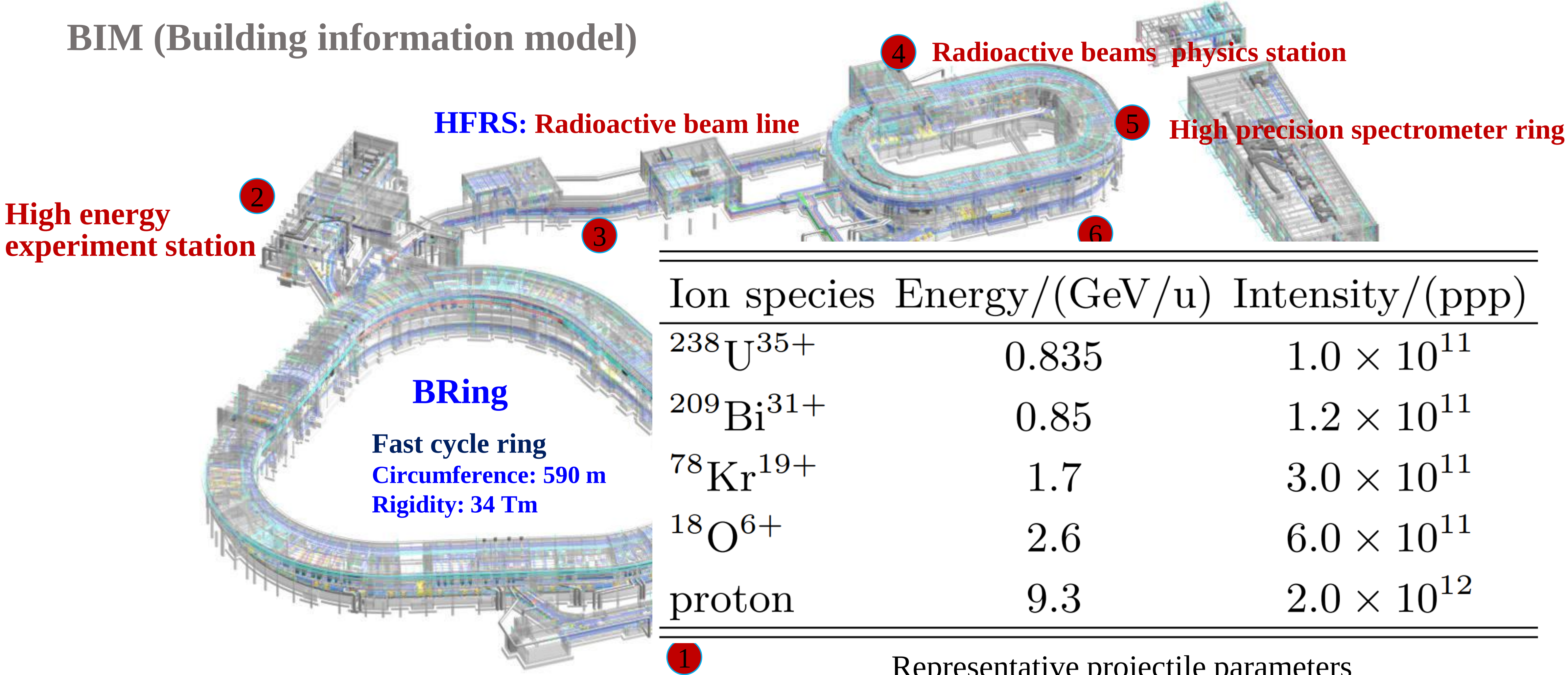
BIM (Building information model)



HIAF Facility

- **Experiment terminals**

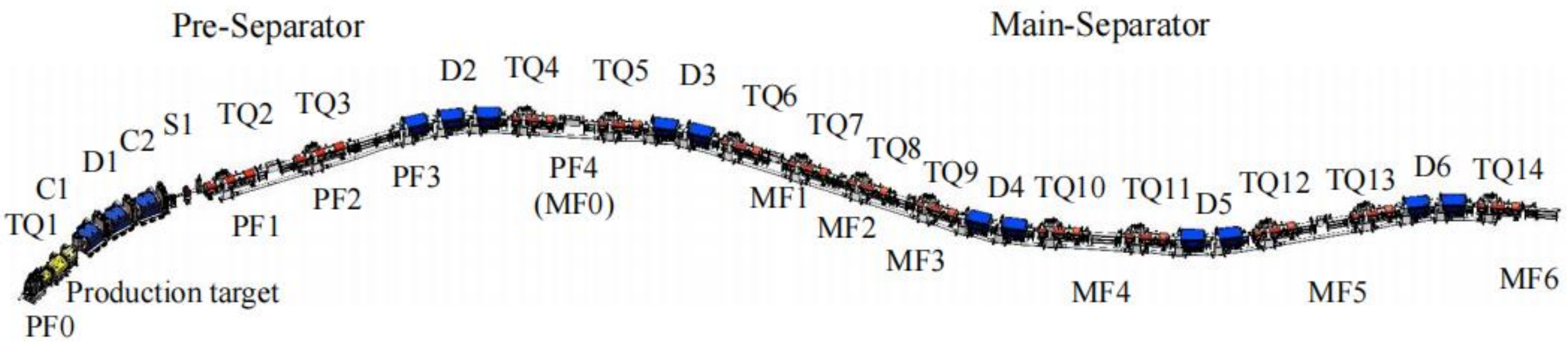
BIM (Building information model)



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}

Representative projectile parameters

HFRS(High Energy Fragment Separator)



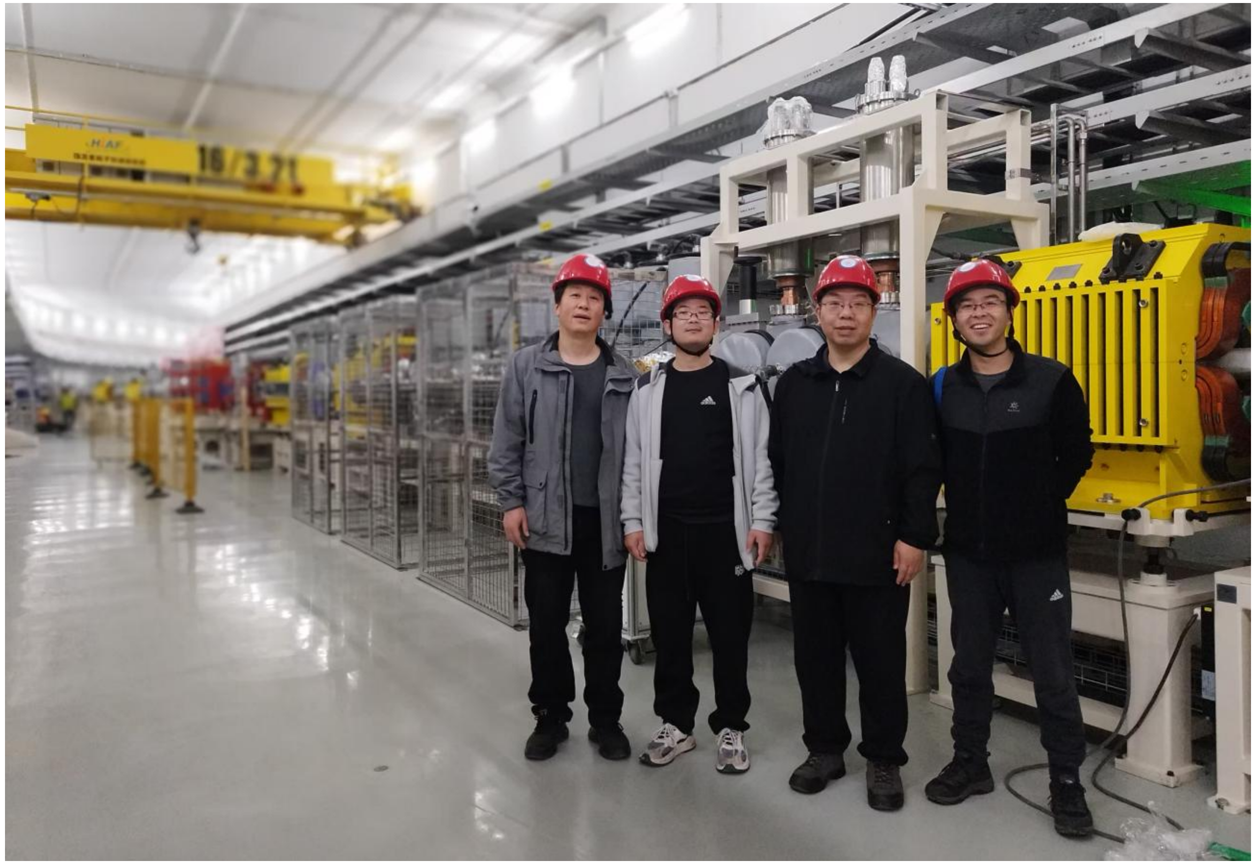
	Length (m)	Beam size at target (mm)	Angular acceptance(mrad)	Momentum acceptance (%)	Resolving power	Max. Bρ (Tm)
HFRS NIM.B 547(2024),165214	191.38	±1/±1.5	±30 (X); ±25 (Y)	±2.0	850/1100 (ΔX=±1mm)	25
SuperFRS NIM.B 204(2003),71	182.2	±1/±2	±40 (X); ±20 (Y)	±2.5	750/1500 (ΔX=±1mm)	20
BigRIPS Prog.Theor.EXP.Phys.2012,03C003	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

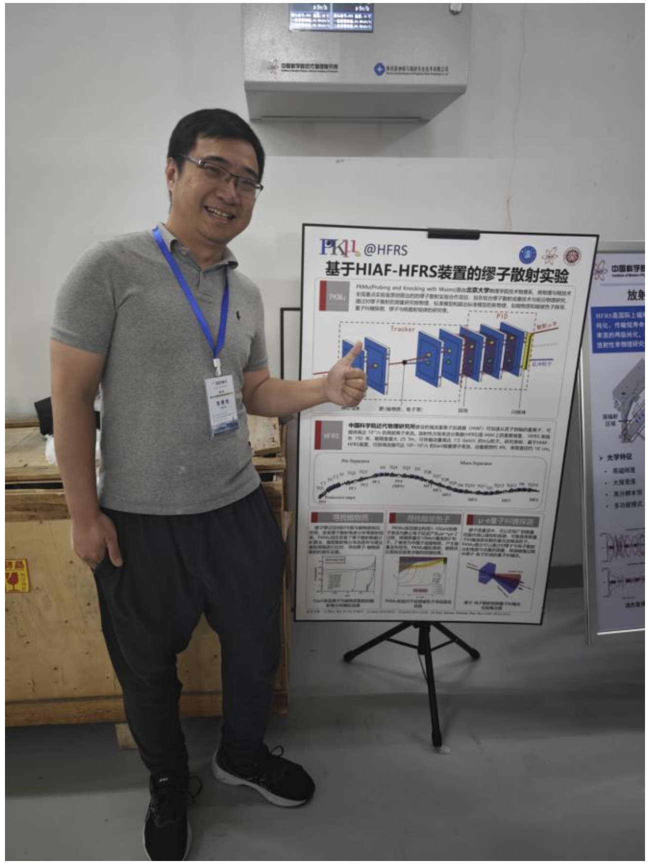
HFRS and Radioactive beamlines around the world

HFRS—条性能先进的弹核碎裂型次级束流装置

HFRS(High Energy Fragment Separator)

HFRS(High Energy Fragment Separator)

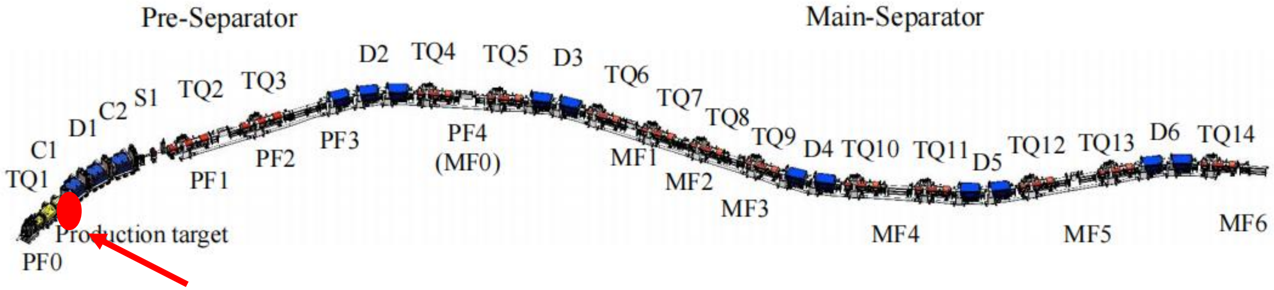




Muon source at HIAF

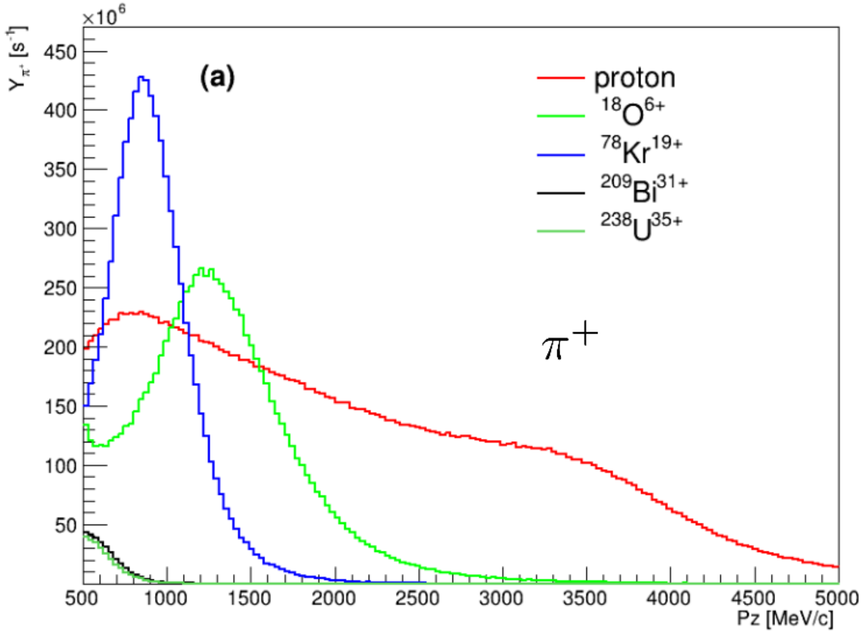
- Pion decay length

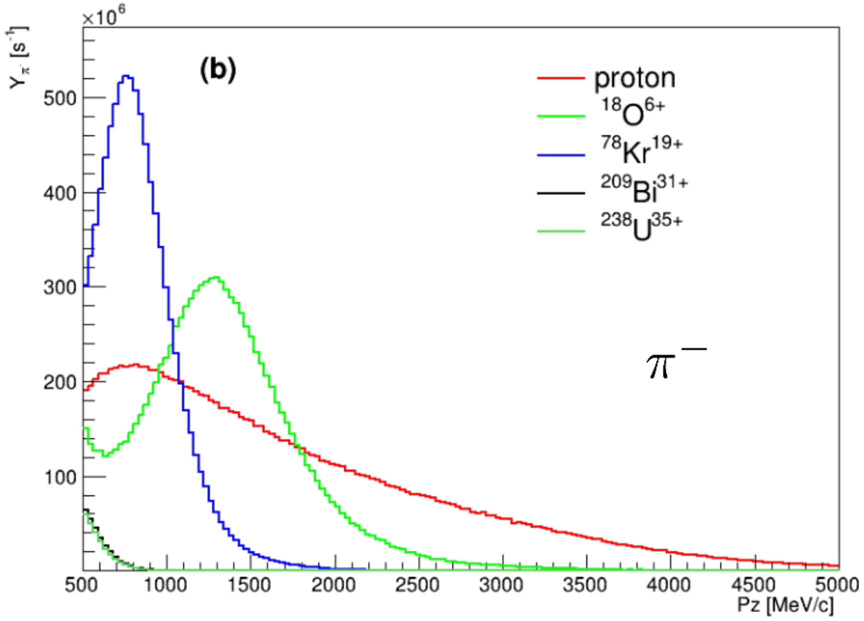
$$\lambda_\pi = v\gamma\tau_\pi = \frac{c \cdot \tau_\pi\,[2.6 \cdot 10^{-8}\ \mathrm{s}]}{m_\pi\,[139.6\ \mathrm{MeV/c^2}]}\, p_\pi\,[\mathrm{MeV/c}] \simeq 0.055\,\frac{p_\pi}{\mathrm{MeV/c}}\,[\mathrm{m}]$$

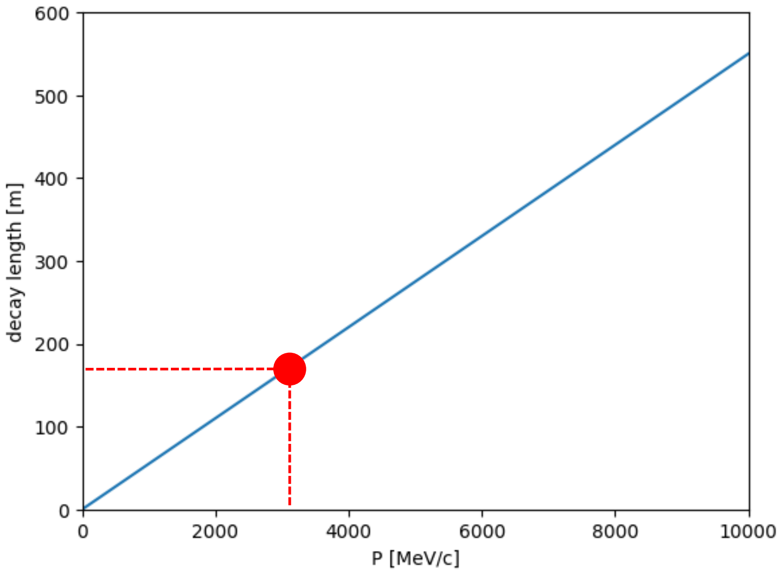


Beam entrance

- Pion production at the beam entrance





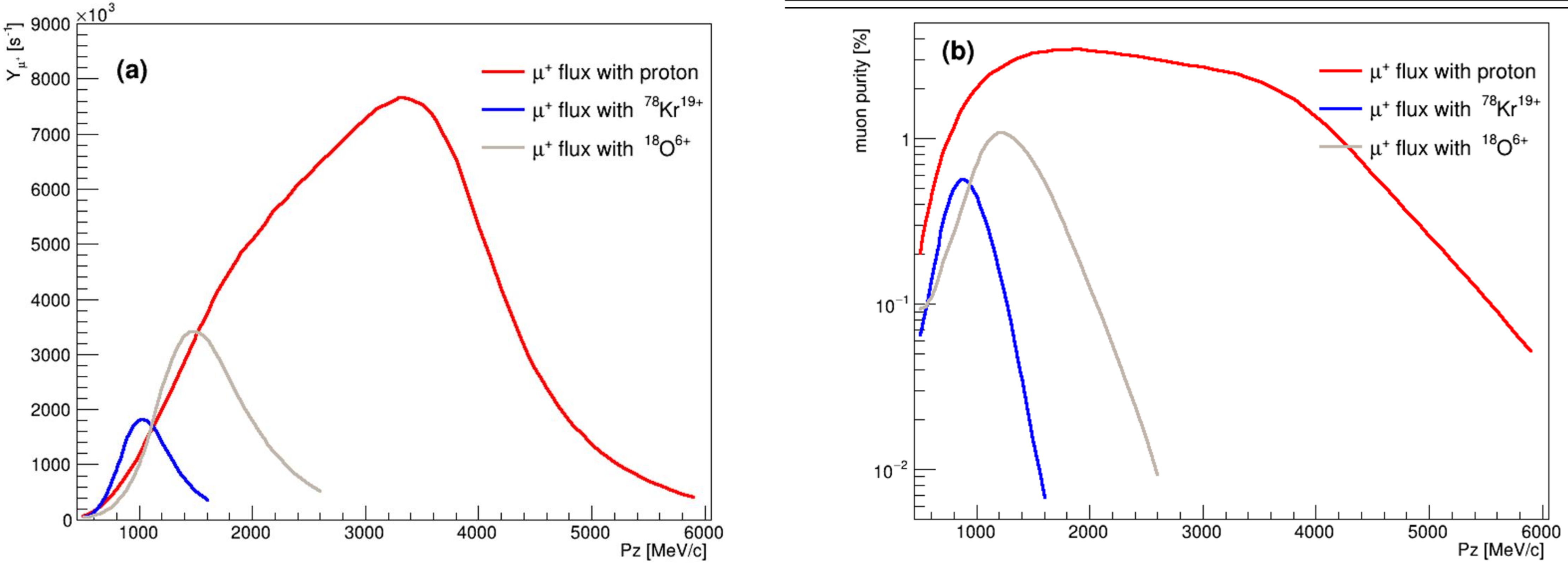


arxiv:2502.20915

Muon source at HIAF

- Muon production
- Muon purity

μ^+ beam	proton	$^{18}O^{6+}$	$^{78}Kr^{19+}$
momentum [GeV/c]	3.5	1.5	1.0
flux intensity [μ^+/s]	8.2×10^6	3.5×10^6	1.8×10^6
muon purity	2.0%	0.80%	0.60%

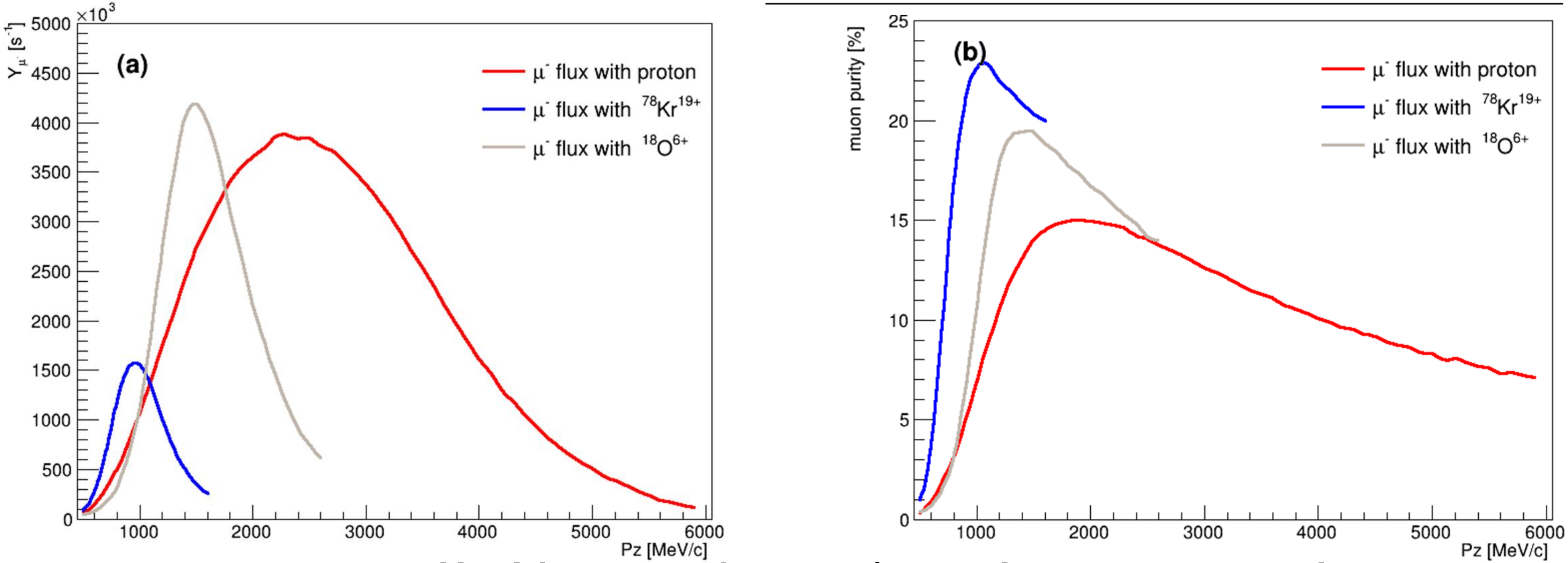


Muon yield and the corresponding purity for several representative projectiles

Muon source at HIAF

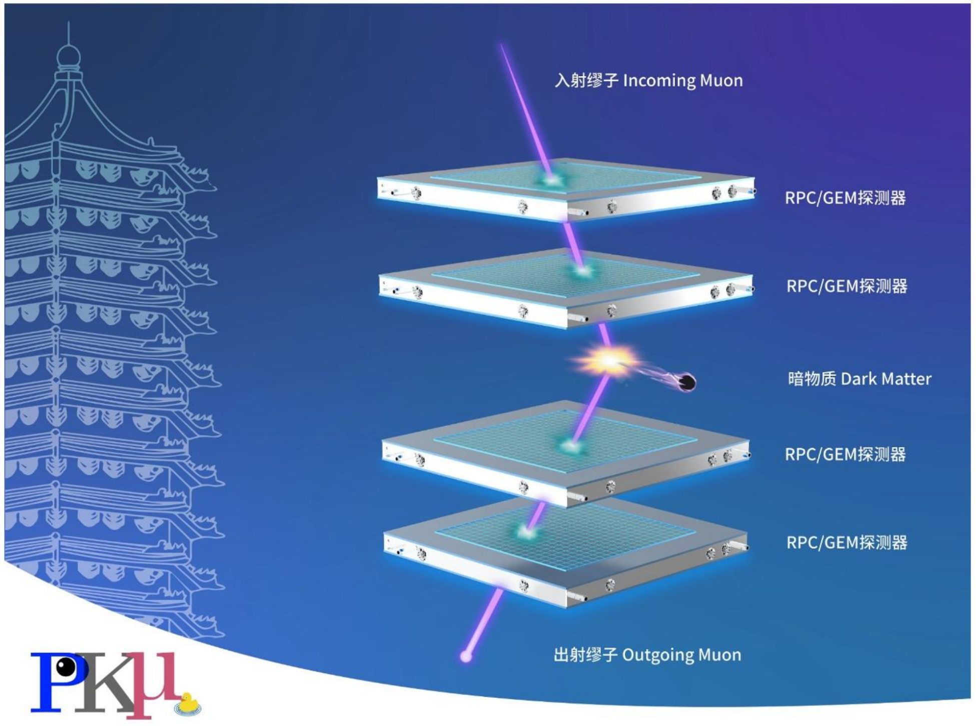
- Muon production
- Muon purity

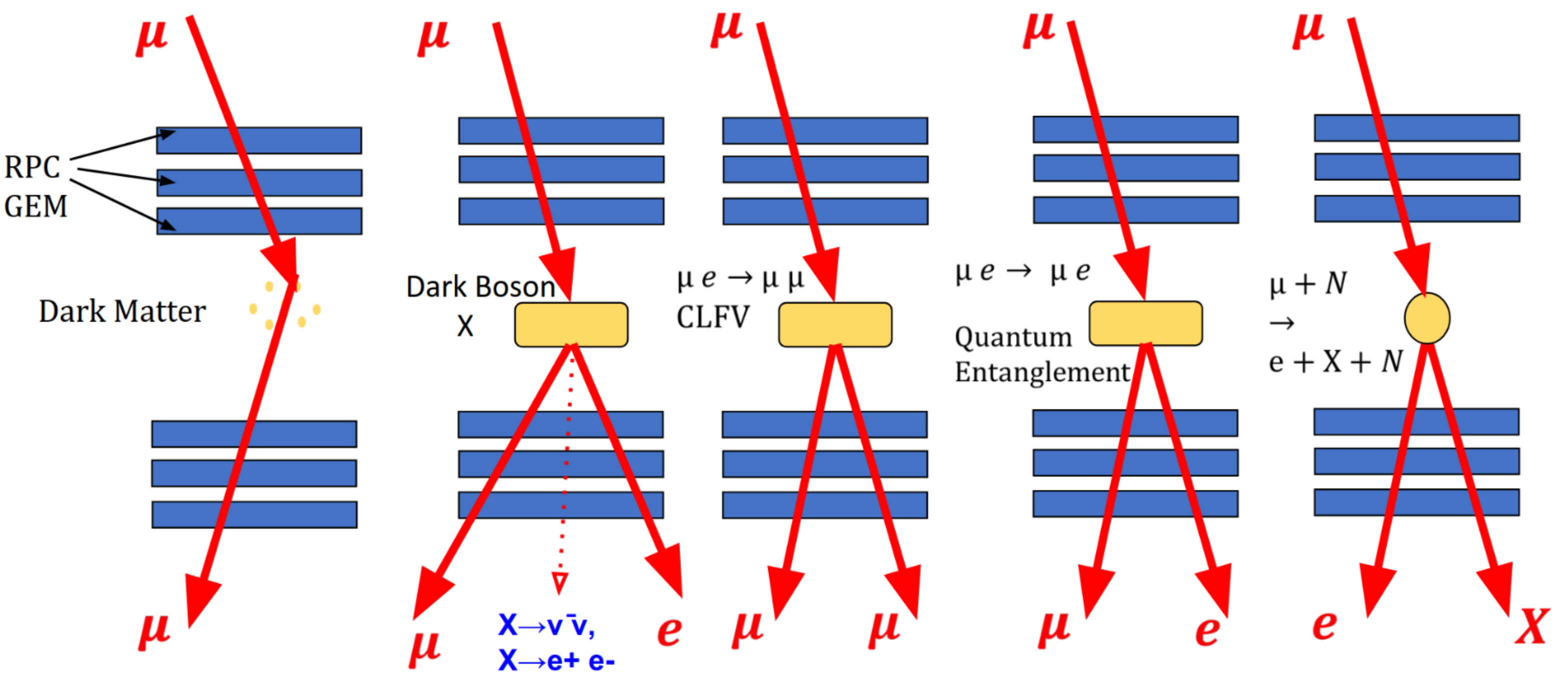
μ^- beam	proton	$^{18}O^{6+}$	$^{78}Kr^{19+}$
momentum [GeV/c]	2.3	1.5	1.0
flux intensity [μ^-/s]	3.8×10^6	4.2×10^6	1.6×10^6
muon purity	13%	20%	23%



Muon yield and the corresponding purity for several representative projectiles

Probing and Knocking with Muons



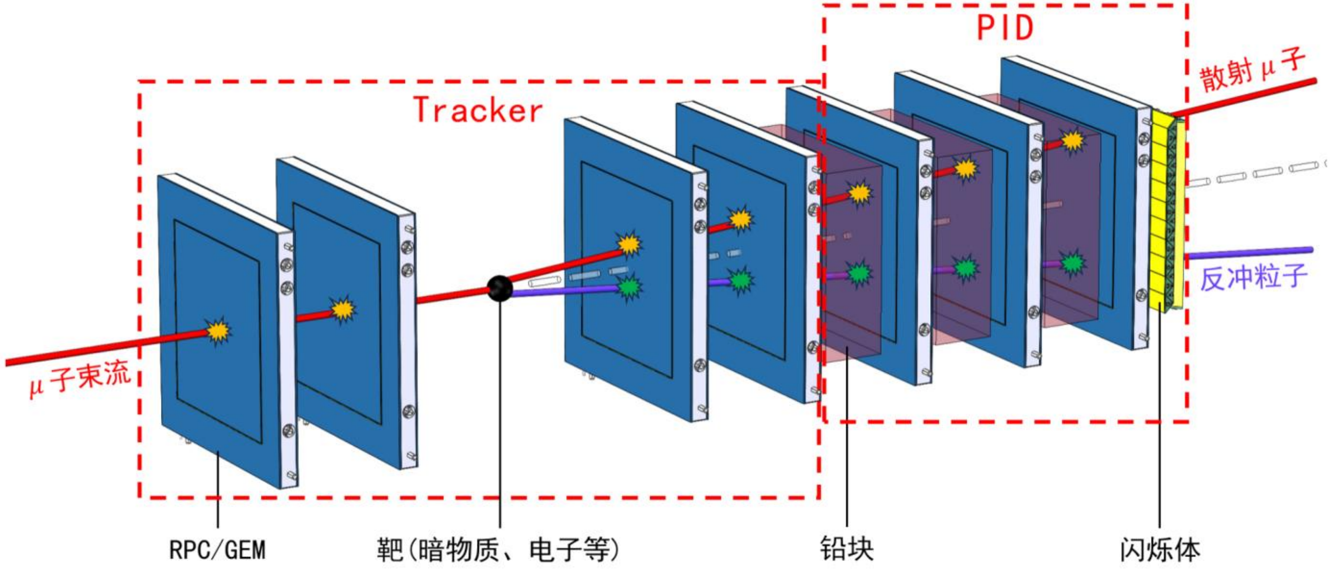


arXiv:2503.22956

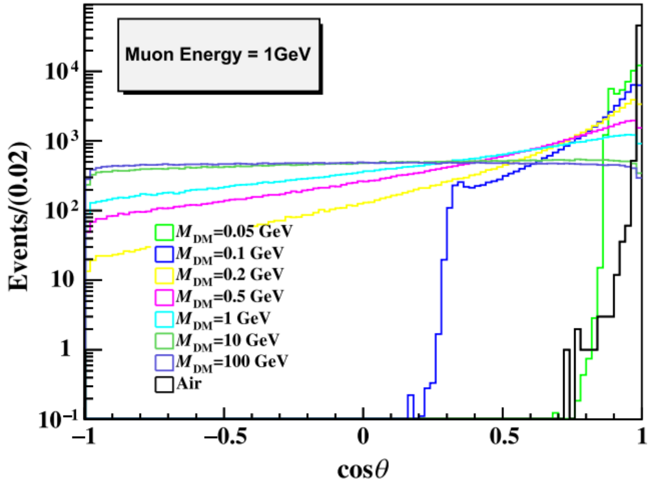
Potential muon experiments with muon @HIAF

- A first high energy muon scattering experiment in China?

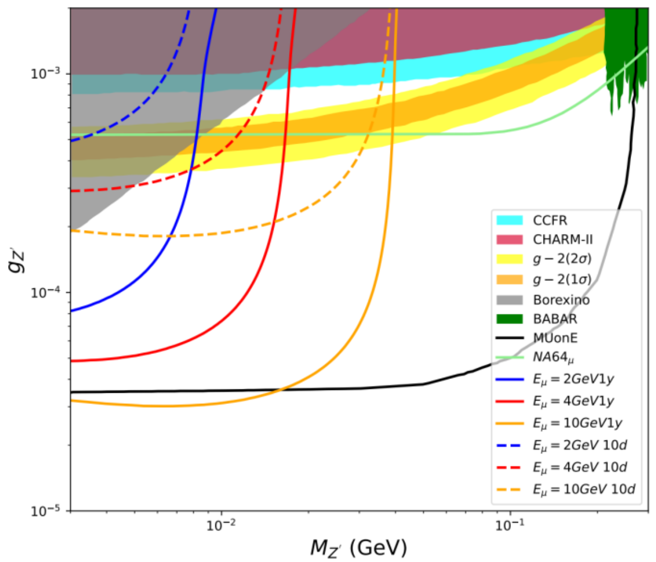
  - One of the highest intensity (4e6/s) GeV energy muon around world
  - Direct searches for DM
  - Searching dark boson



PKμ@HFRS



Searching for Muon Philic Dark Sector



Could be more sensitive to X boson at 1-10 MeV region!
（to appear soon on arXiv）

Phys. Rev. D 110, 016017 arXiv:2410.20323 arXiv:2411.12518

Potential muon experiments with muon @HIAF

- 暗物质、暗玻色子
- 量子纠缠
- 质子半径
- 大 x 区域 Parton distribution function
- ……

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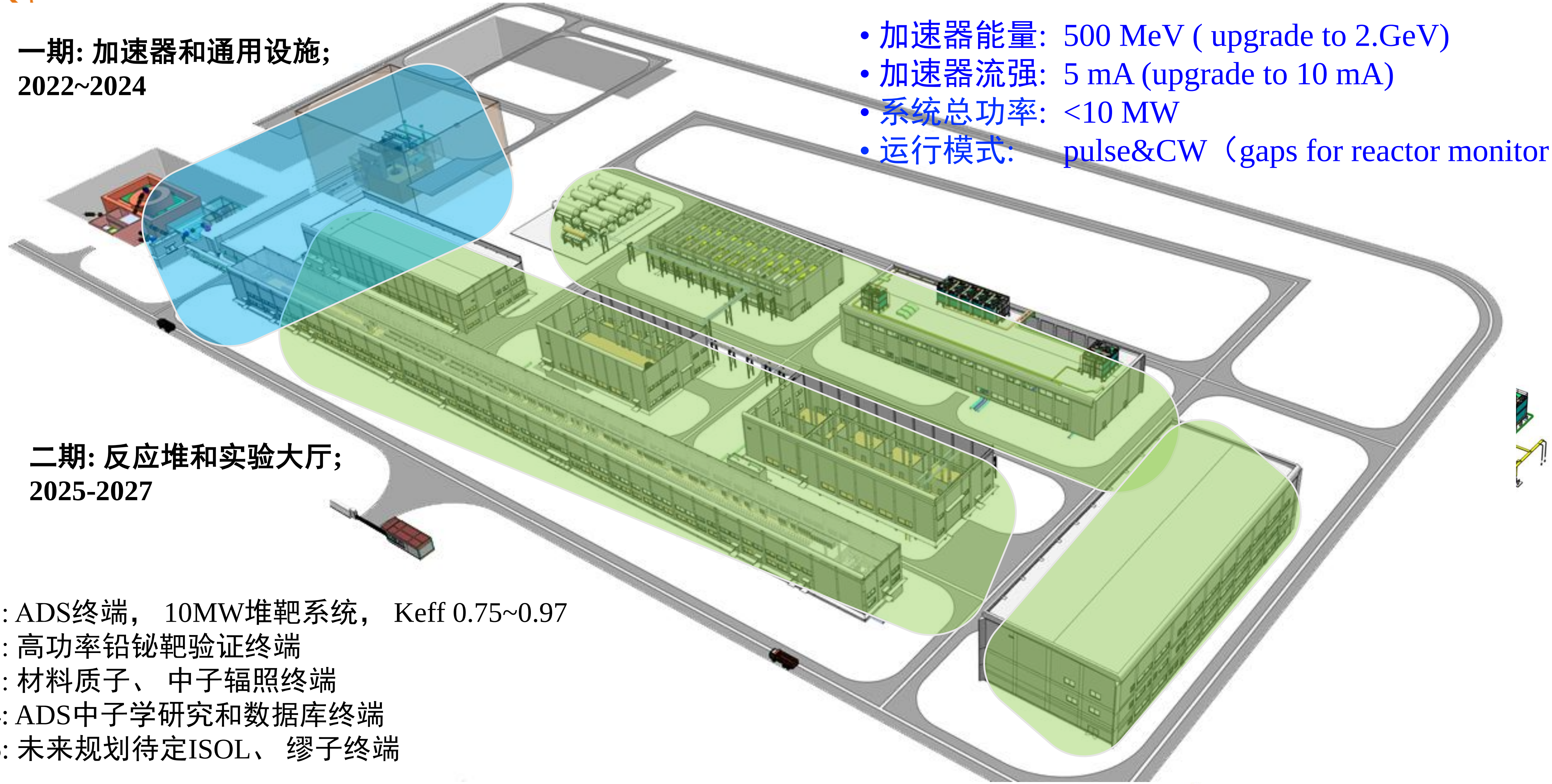
CiADS Facility



一期: 加速器和通用设施;
2022~2024

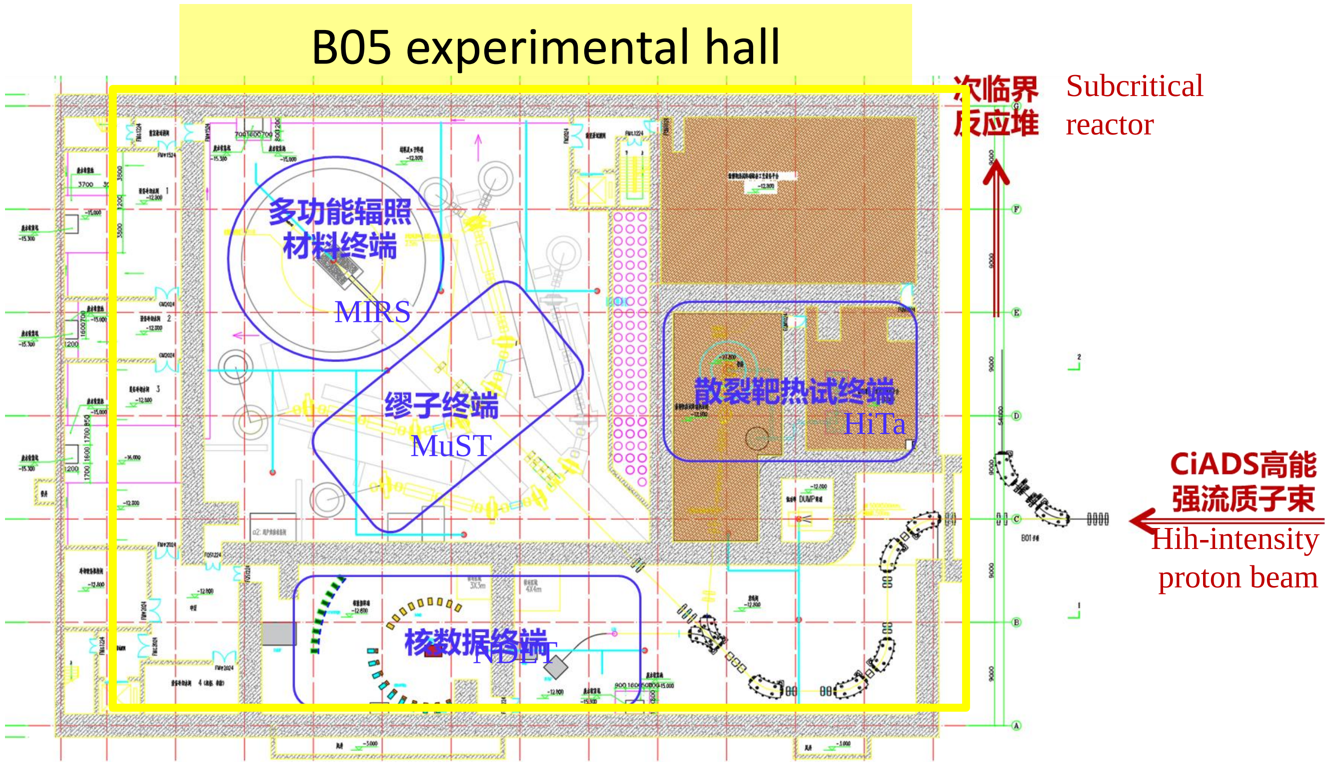
二期: 反应堆和实验大厅;
2025-2027

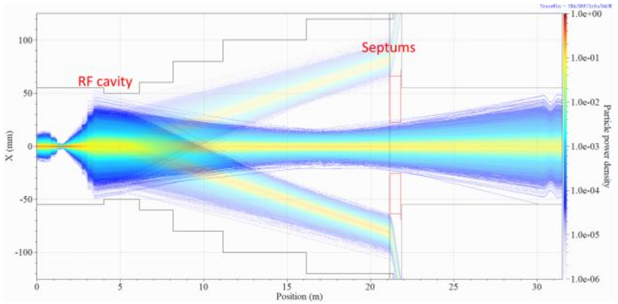
- 加速器能量: 500 MeV (upgrade to 2.GeV)
- 加速器流强: 5 mA (upgrade to 10 mA)
- 系统总功率: <10 MW
- 运行模式: pulse&CW（gaps for reactor monitor）

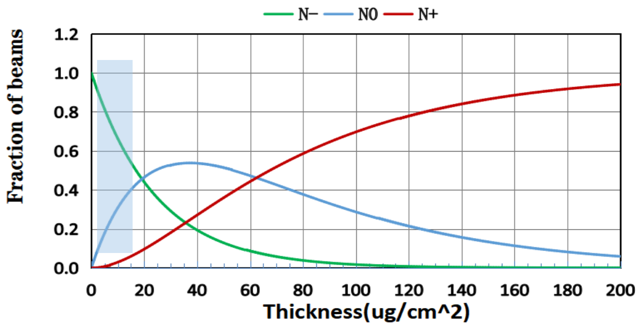
- T1: ADS终端， 10MW堆靶系统， Keff 0.75~0.97
- T2: 高功率铅铋靶验证终端
- T3: 材料质子、 中子辐照终端
- T4: ADS中子学研究和数据库终端
- T5: 未来规划待定ISOL、 缪子终端

CiADS Facility

- CiADS reactor
  - A research facility with 3 months of annual operation
- Terminals at B05 experimental hall
  - High-power target testing terminal (HiTa)
  - Nuclear data experiment terminal (NDET)
  - *Muon Science and Technology application terminal (MuST)*
  - Multifunctional Material Irradiation Terminal (MIRS)
- Beam supply modes
  - CiADS Reactor: ~3 months
  - Terminals at B05 Hall : 8–9 months (single or multi-terminal operation)
- Beam-splitting methods
  - RF + Beam-cutting magnet: ISOL vs B05
  - Stripper foil + Bidirectional dipole magnet: HiTa vs NDET vs MuST+MIRS



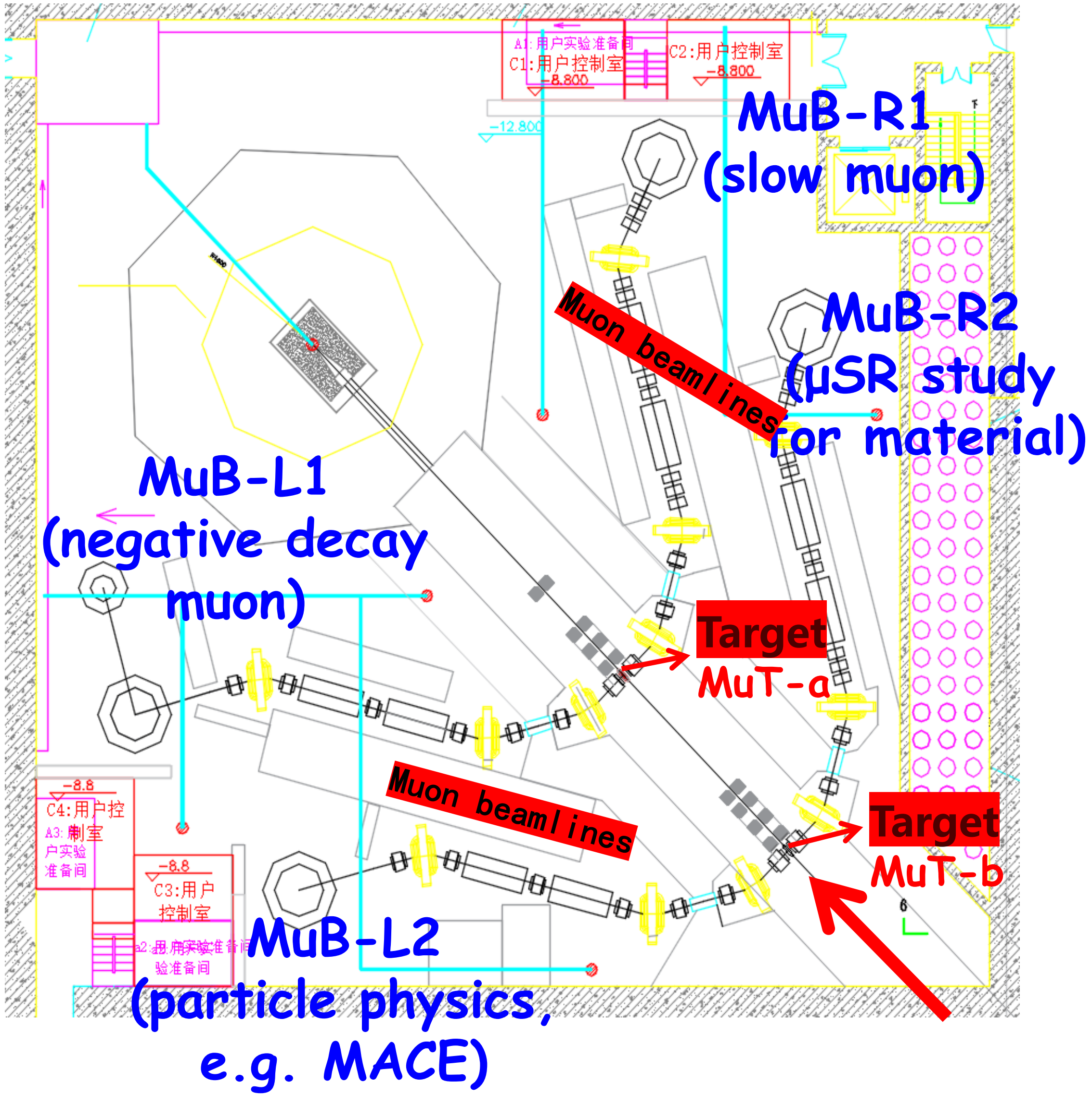




The plan of CiADS muon source (MuST)

- **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**

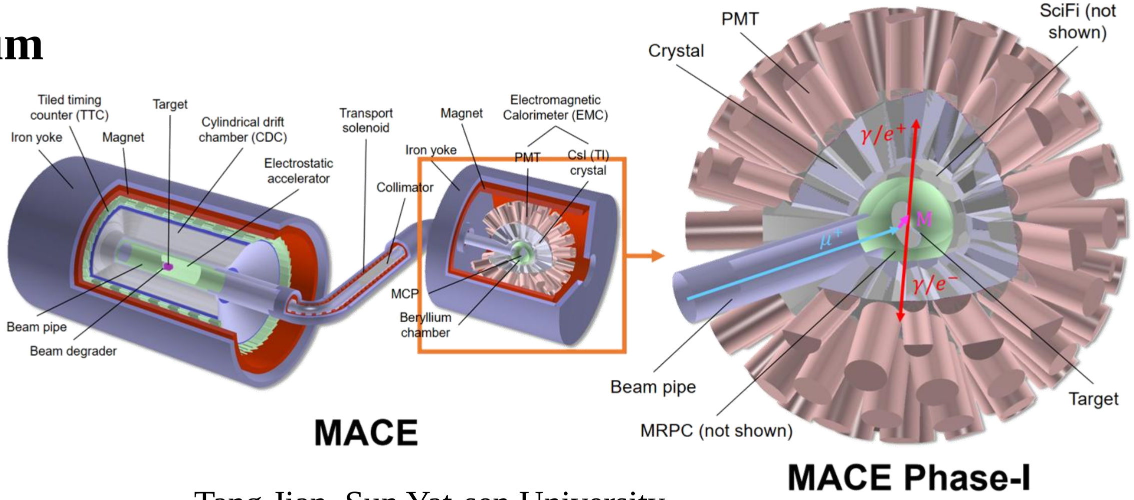
Beam power	Target	Focusing method	Muon intensity (μ^+/s)
1st phase 300 kW	Graphite rotating target	Solenoid + quadrupole	> 5E7
		Full solenoid	> 5E8
2nd phase 3 MW	Liquid lithium target	Solenoid + quadrupole	> 1E9
		Full solenoid	> 1E10



Potential muon experiments at MuST

- **High-precision tests of rare processes of muon and muonium**

✓ ***Searching for charged lepton flavor violation, new physics beyond the standard model, CPT test***



Tang Jian, Sun Yat-sen University

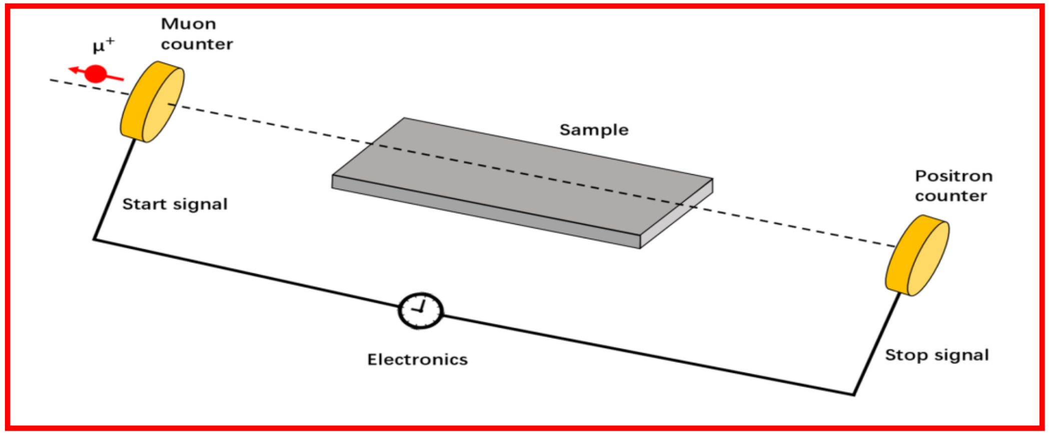
- **High-precision measurement of muon spin rotation**

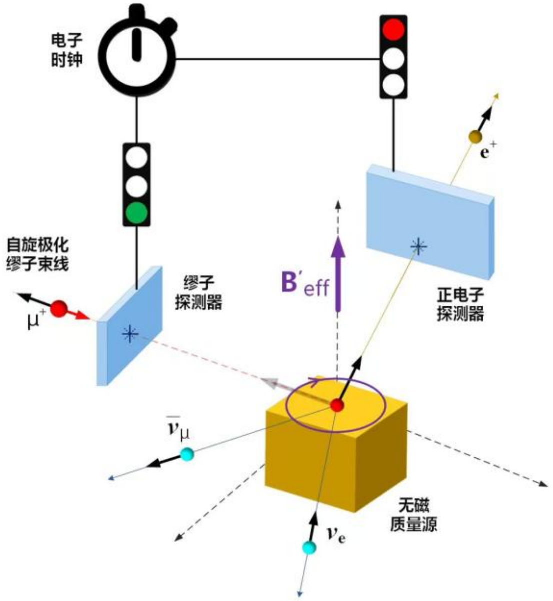
***Searching for NEW spin-dependent interaction at long range** (mediated by light axion-like particle or light boson)*

eg.:

$$V_{SP}(r) = \frac{\hbar^2 g_S g_P}{8\pi m}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)\frac{\exp(-r/\lambda)}{r}\vec{\sigma}\cdot\hat{r}$$

$$V_{VA}(r) = \frac{\hbar g_V g_A}{2\pi}\frac{\exp(-r/\lambda)}{r}\vec{\sigma}\cdot\vec{v}$$



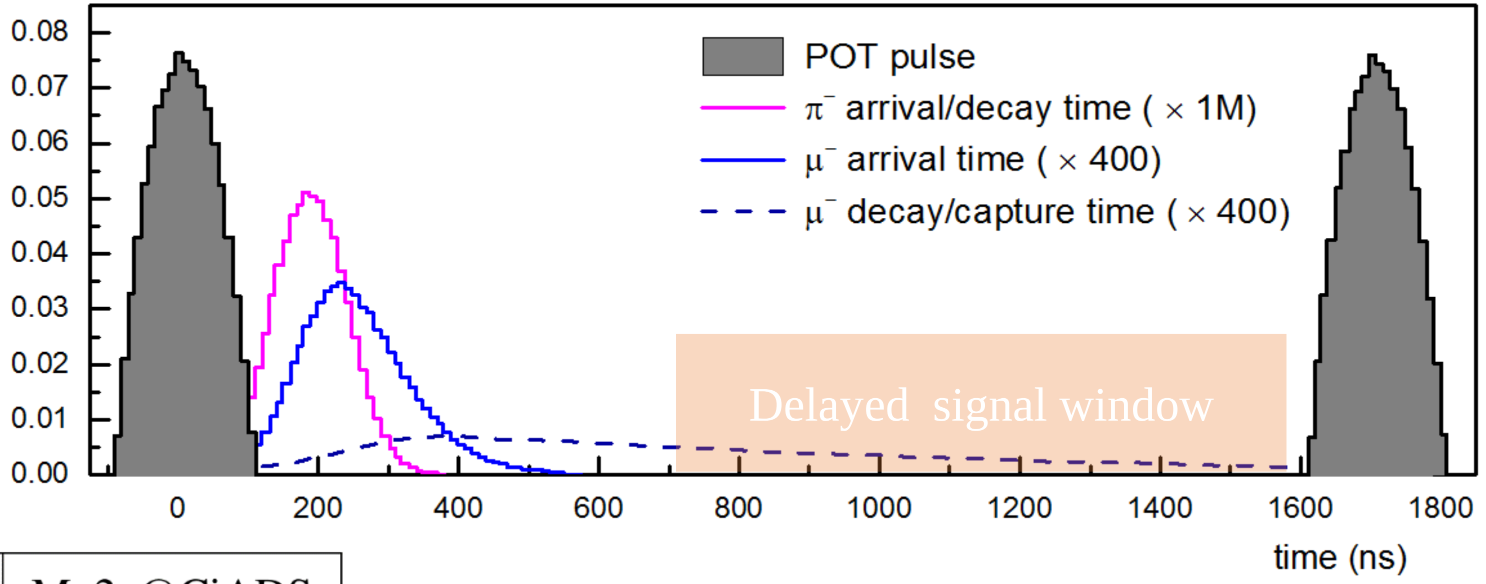


Yan Haiyang, Ningbo University

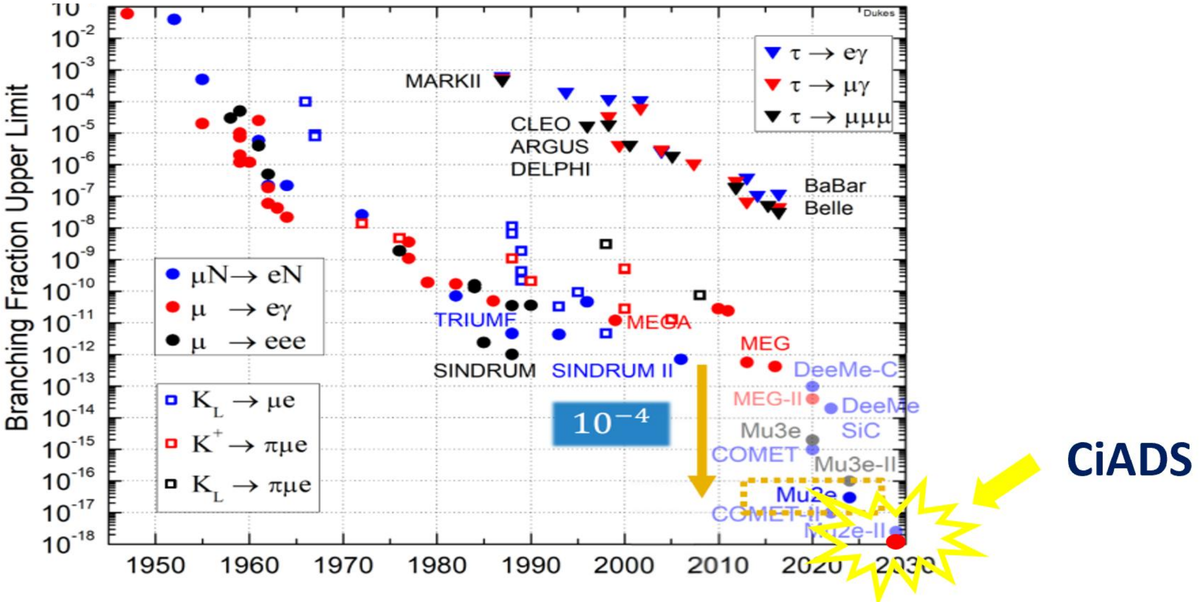
Potential mu e conversion experiment at CiADS

The time structure of the beam can be realized in CiADS

对Mu2e, 每个脉冲的POT约为3×10^{7}
对CiADS, 每个脉冲的POT可达7×10^{9}

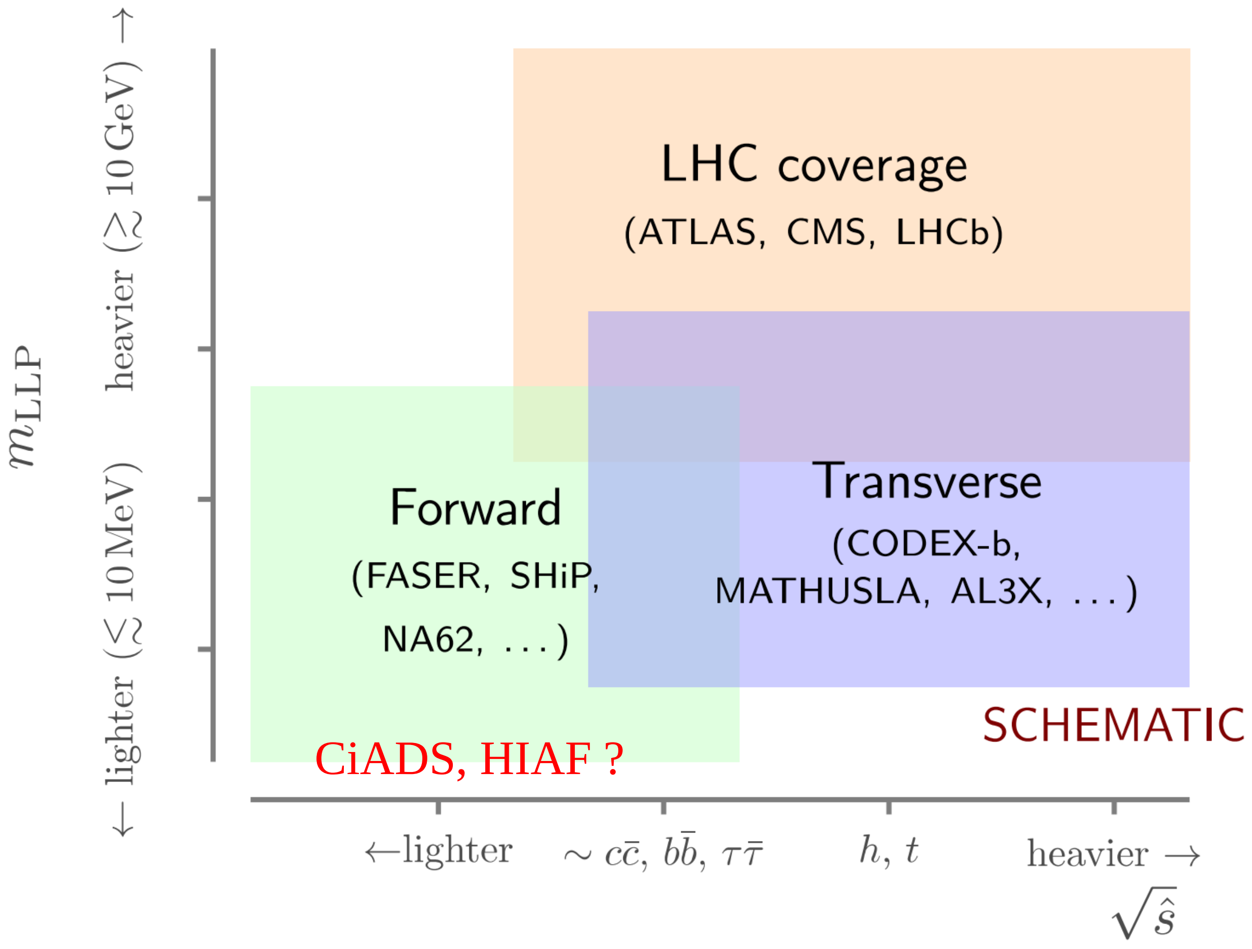


Parameters	Mu2e-II	Mu2e@CiADS
Proton kinetic energy	800 MeV	1000 MeV
Proton on target per second	8×10^{14}	4×10^{15}
Stopped muon per proton	9×10^{-5}	$\sim1\times10^{-4}$
Muon capture efficiency	0.609	0.609
Geometrical acceptance	0.04	0.04
Single event sensitivity	3×10^{-18}	$\sim7\times10^{-19}$



SES ~ 10^{-19} even more during 2030-2040

Exploring the lifetime frontier at CiADS



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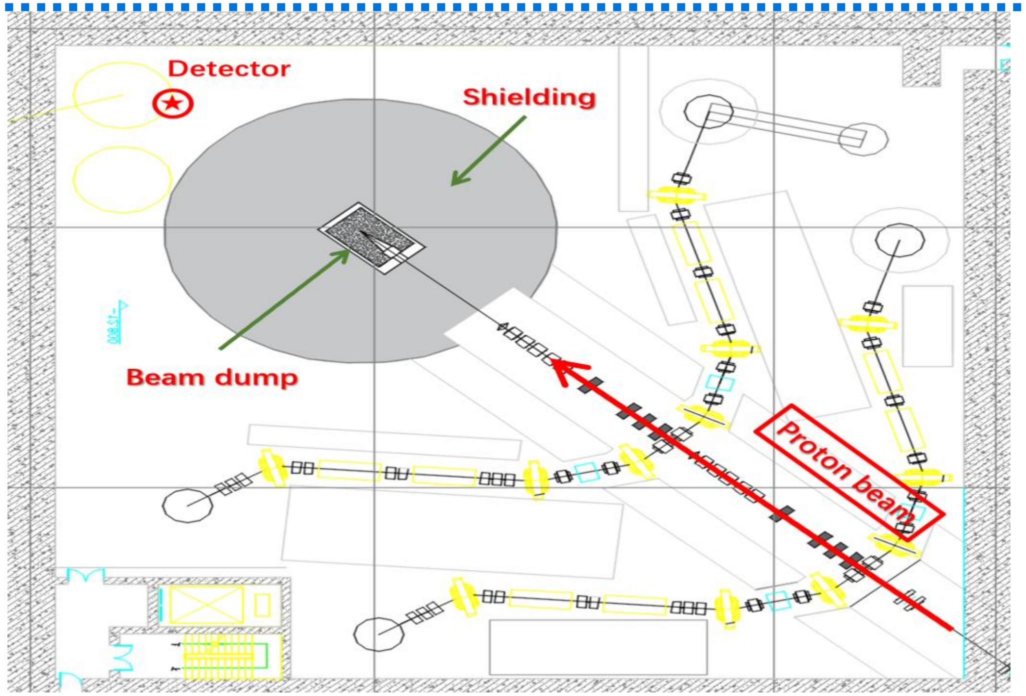

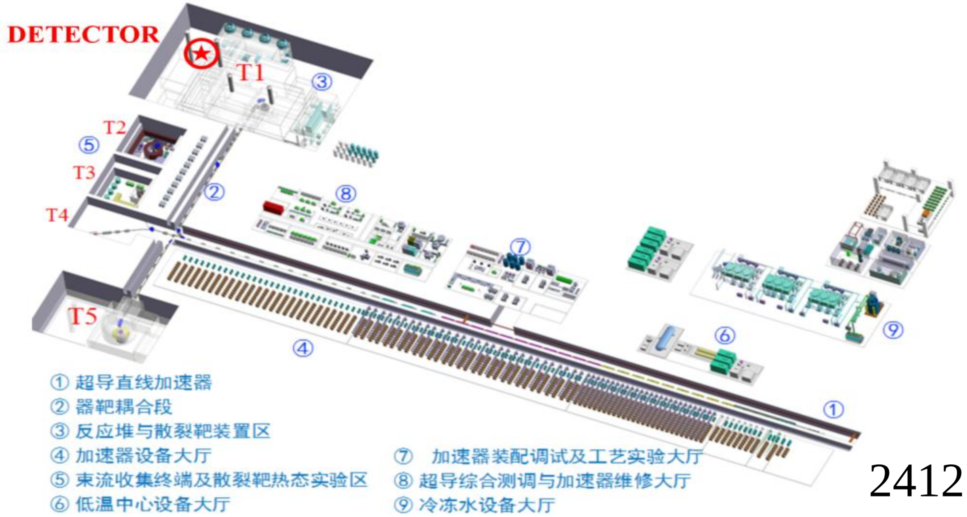

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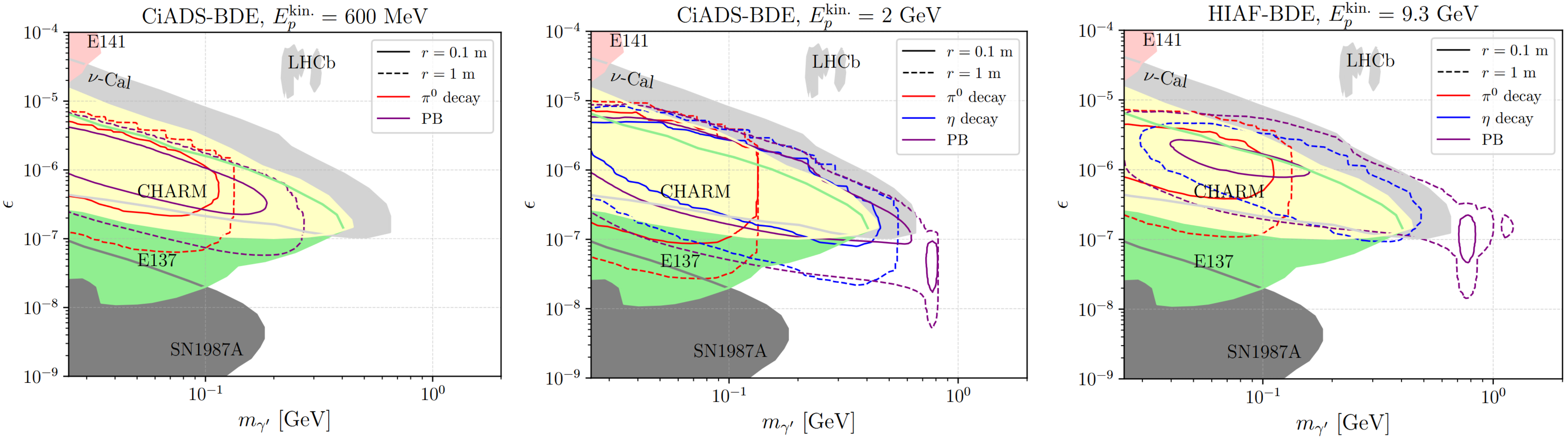
Exploring the lifetime frontier at CiADS

Facility	Proton Energy @ Current	Duty factor	POT per year
CiADS	500/600 MeV @ 0.5 mA	75%	6.6×10^{22}
	500/600 MeV @ 5 mA	75%	6.6×10^{23}
	2 GeV @ 5 mA	75%	6.6×10^{23}
HIAF	9.3 GeV @ 0.024 mA	8.3%	3.9×10^{20}



Outline

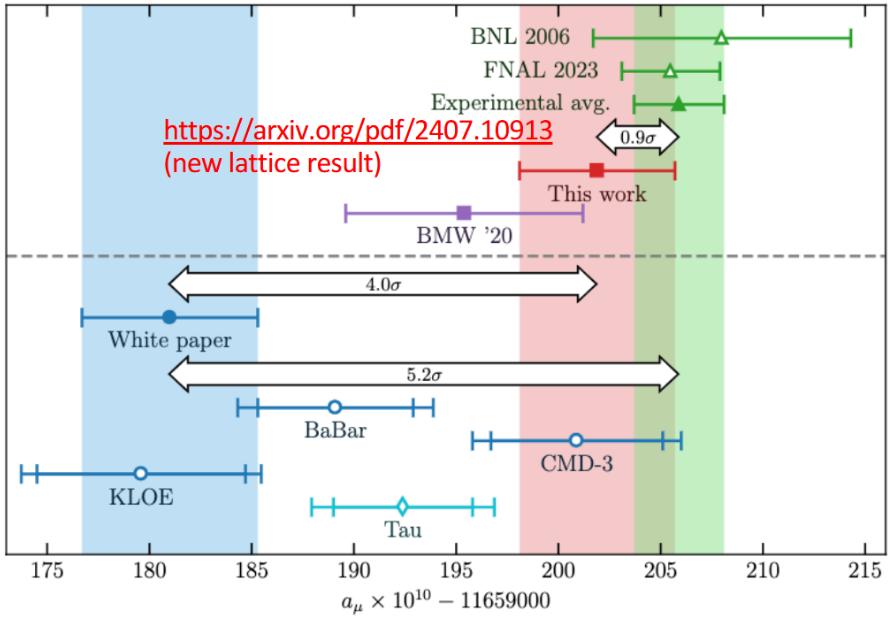
- Introduction of muon source
- Muon sources at HIAF and CiADS
- Potential particle physics experiments at HIAF and CiADS
- Summary

Summary

Muons as Probes for New Physics

- Muons have been an invaluable probe of the Standard Model.
- Precision muon searches and searches for muon/electron flavor transitions are indirect probes of new physics:

Muon g-2 anomaly



Courtesy: S. C. Middleton @NuFact 2025

In general:

- *Do not decay hadronically → clean, well-understood backgrounds.*
- *Lifetime ~2.2 μs → can be stored efficiently before decay, decay easy to measure.*

Plus:

- *Mass scaling could mean 10^4 enhancement in coupling to BSM over electrons.*

Can create high-intensity, clean, background-free, experimental environment to probe new physics.

Many experimental searches looking for new physics in the muon sector or ways to elucidate the apparent g-2 discrepancy will come online this decade…..

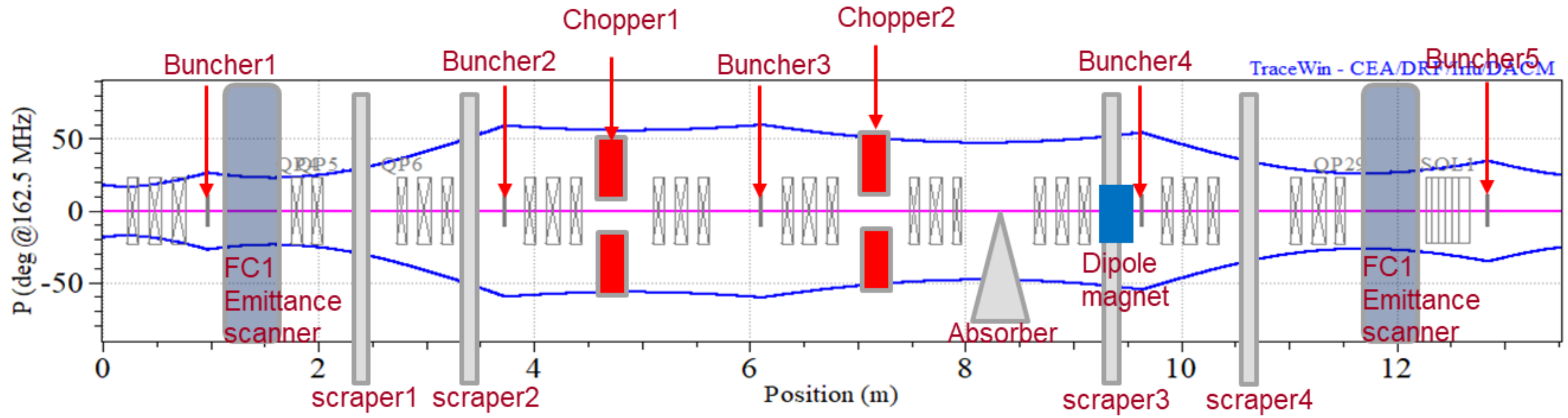
…. the 2020's are proving to be a very exciting time for muon physics!

- The CiADS will operate in 2027 and demonstrate the full fuel-recycle strategy in 2030.
- The HIAF will operate by the end of 2025 to start the frontier research on HED physics, QED, QCD, and so on.
- Muon sources at CiADS and HIAF are the future terminal under discussion and plan to construct. Welcome the ideas of experiments and applications.

Thank you for your attention!

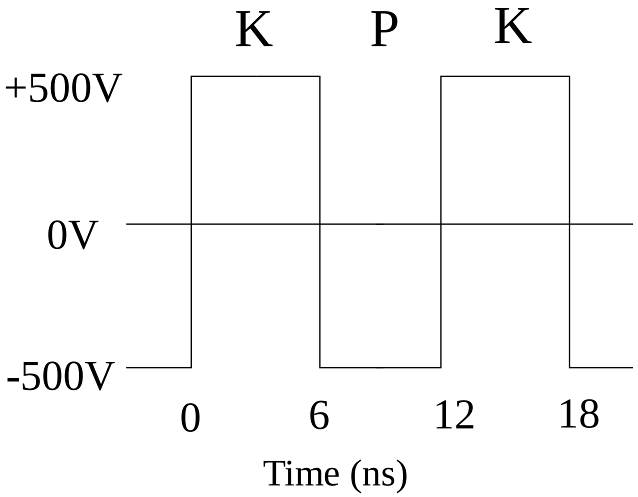
Kick and pick for the beam time structure

•

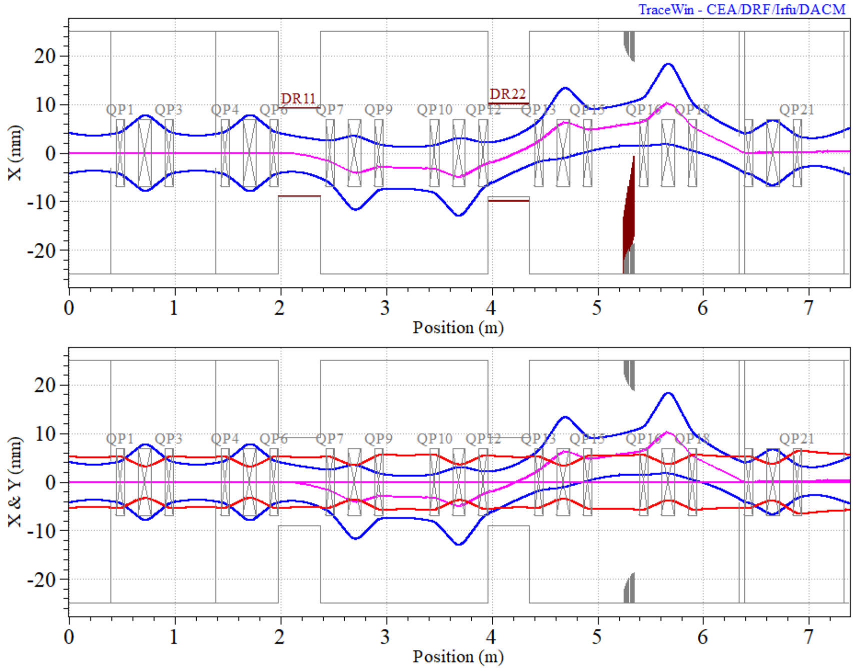


MEBT layout

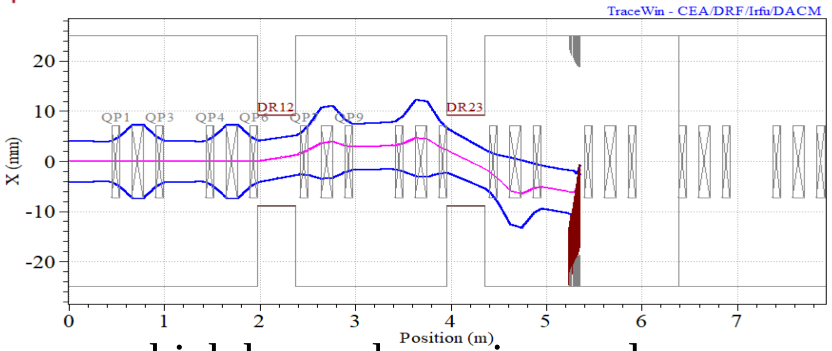
Credits:陈伟龙



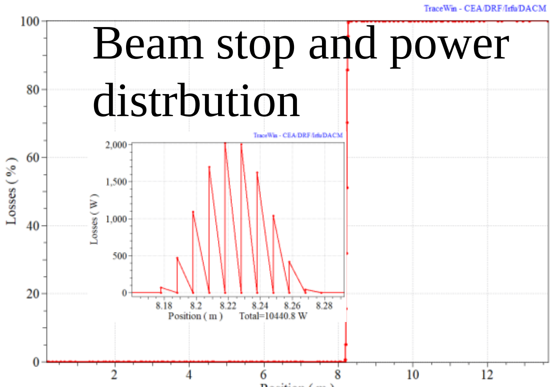
Ideal Voltage between the electrode
(K: kicked P: picked)



Pick beam dynamic envelop

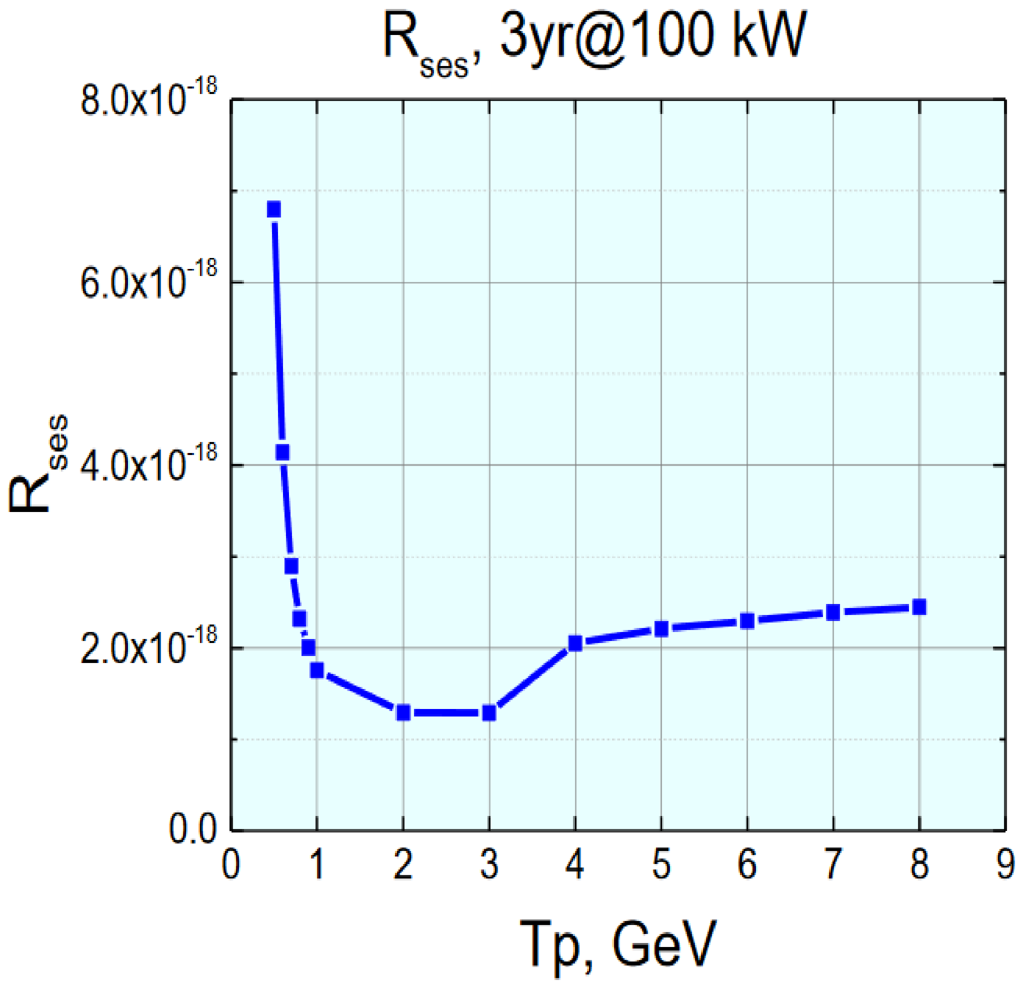


kick beam dynamic envelop



Beam stop and power distrbution

Sensitivity of Muon electron conversion



D. Glenzinski, et al. 1612.08931,1307.1168


强电桥架 2

2021年1月


2021年1月


2025年3月