基于HIAF的单能缪子物理和应用

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- 缪子和缪子源简介

- 基于HIAF的GeV单能缪子束线及其物理和应用

- HIAF进展和总结

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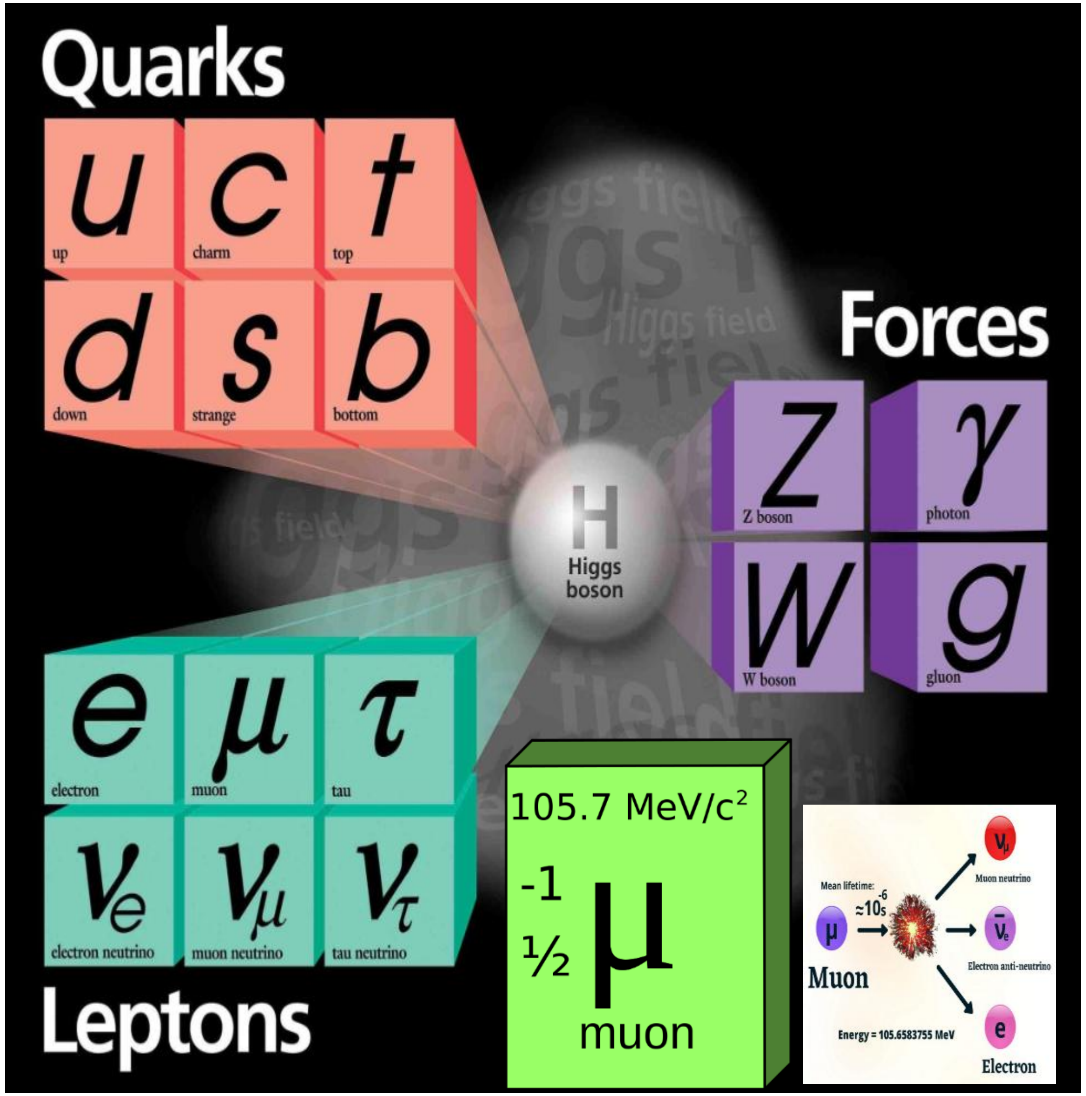
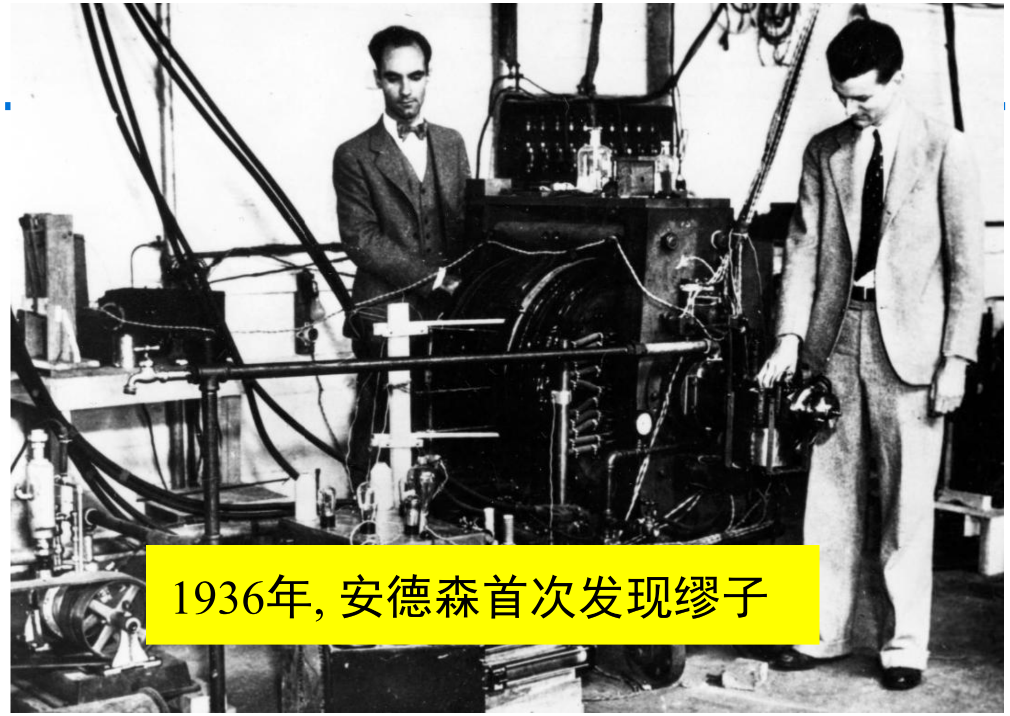
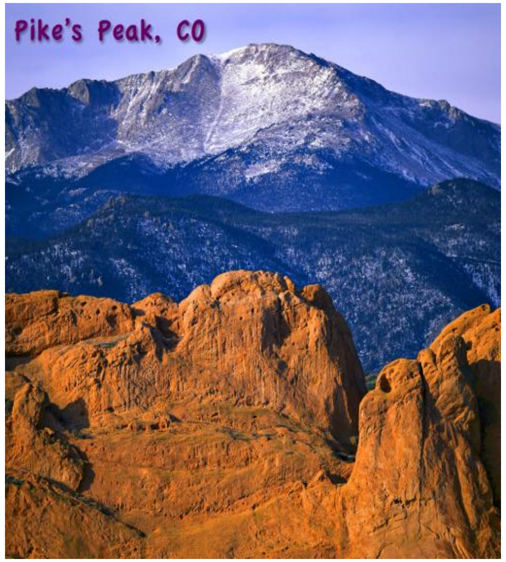
- ☐缪子和缪子源简介
- ☐基于HIAF的GeV单能缪子束线及其物理和应用
- ☐HIAF进展和总结

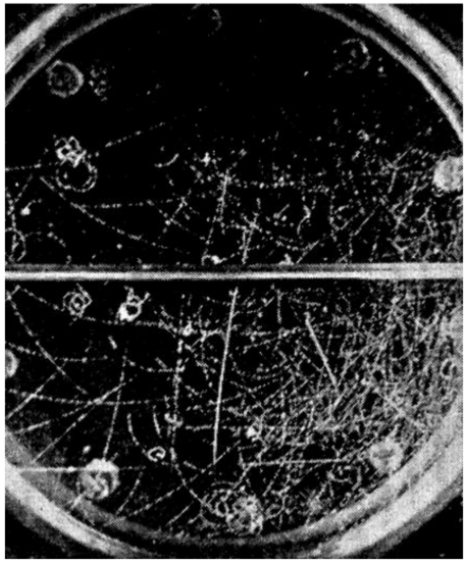
缪子及其发现





1936年, 安德森首次发现缪子





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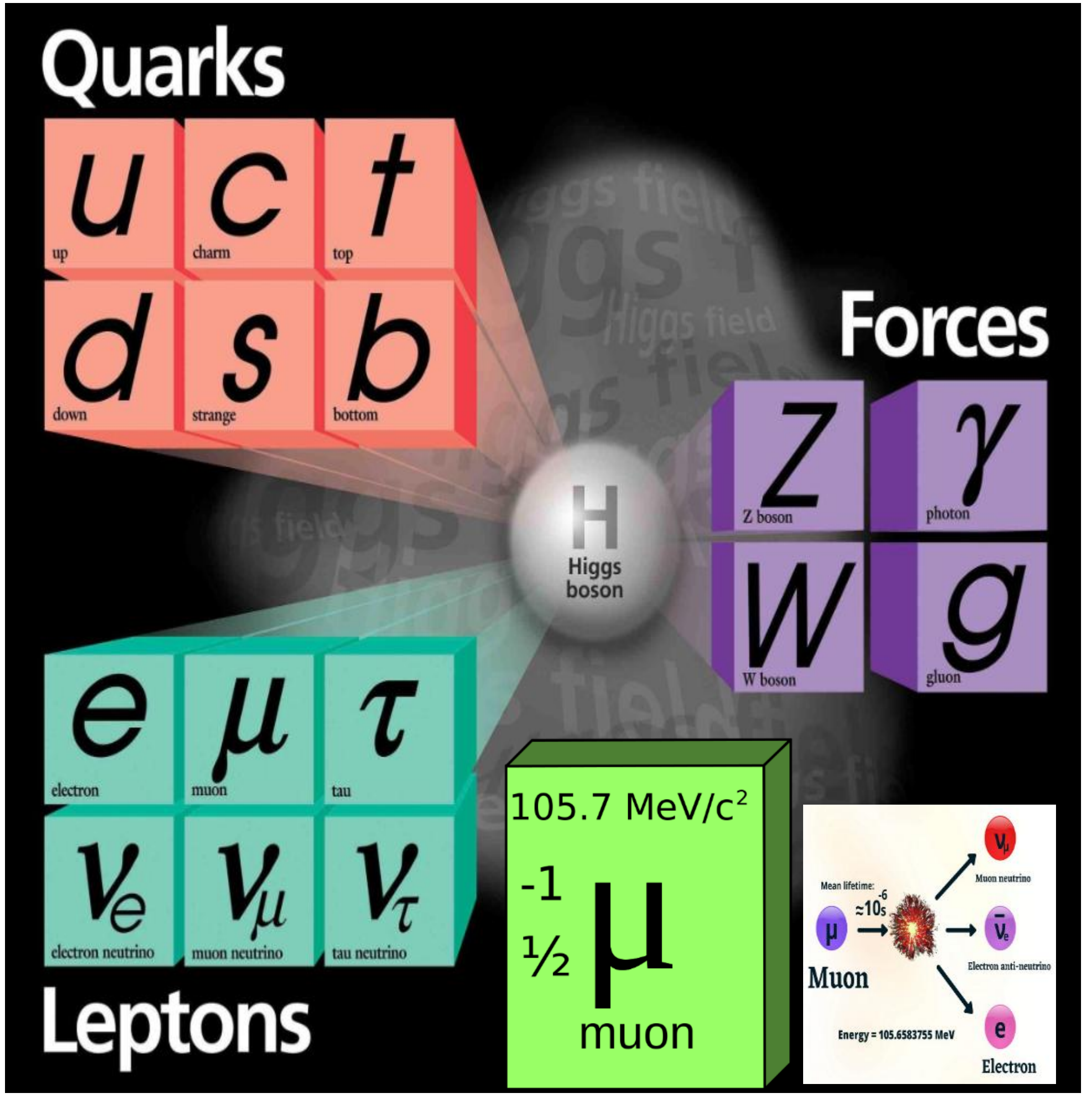

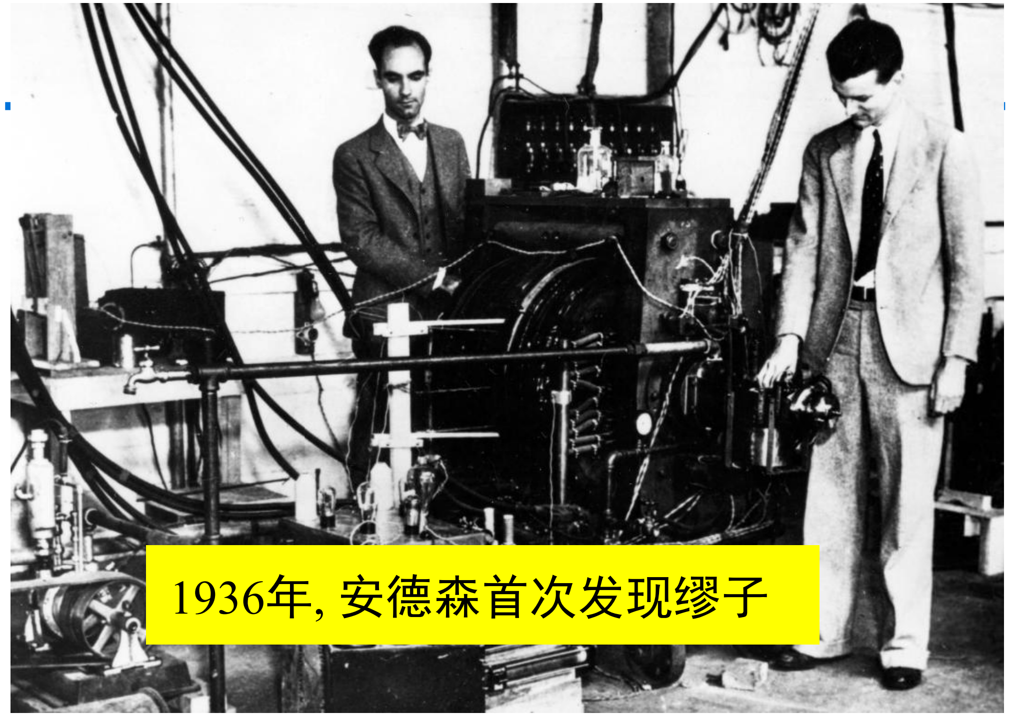

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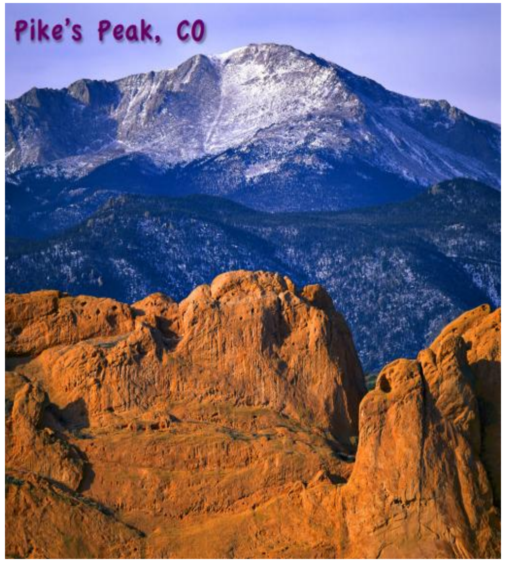
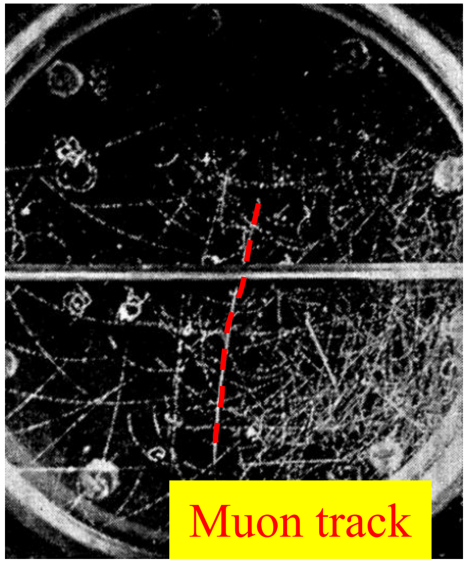
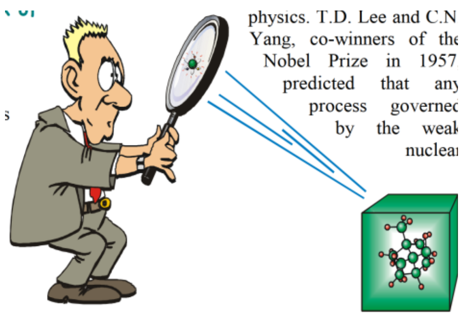


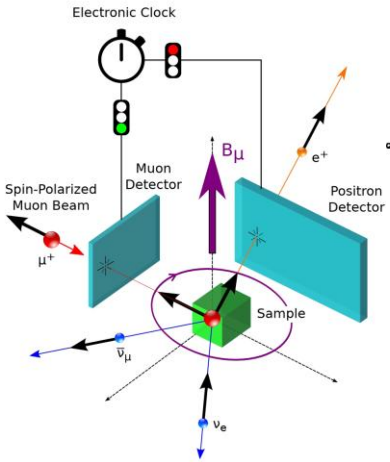


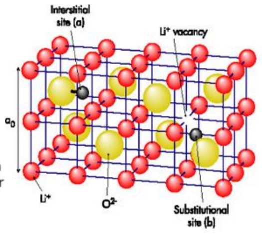
Muon track

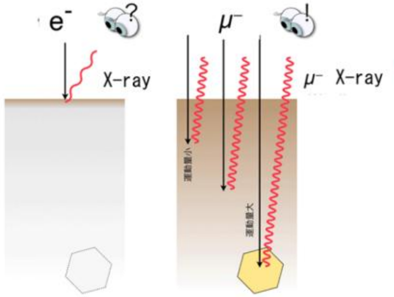
Phys. Rev. 50 (1936) 263

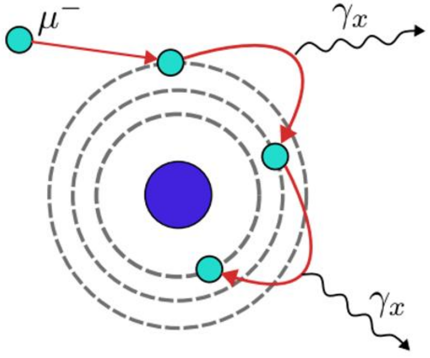
缪子应用广泛





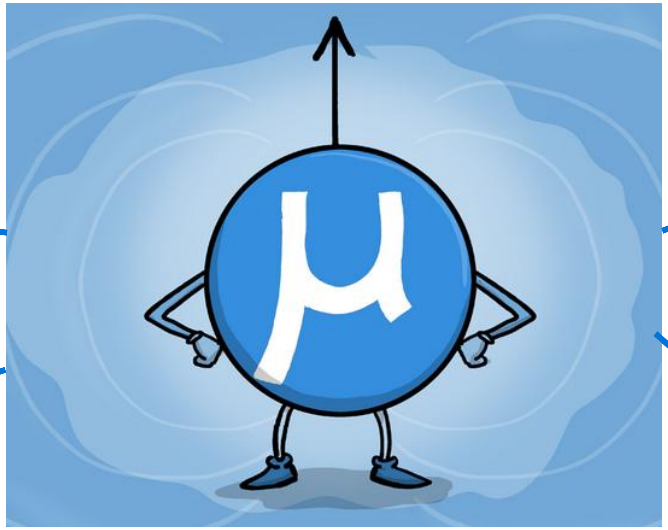






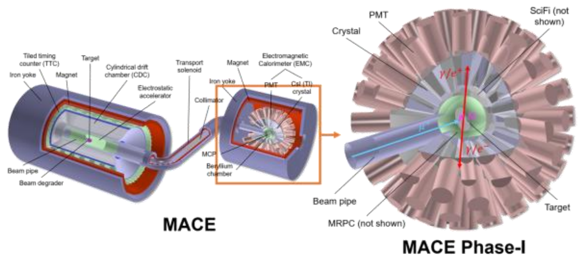
Muon spin rotations

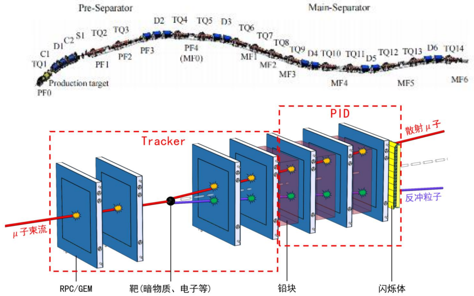
Elemental analysis with muonic X ray

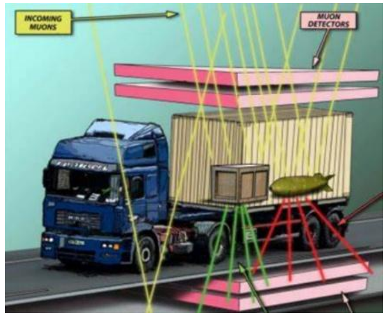


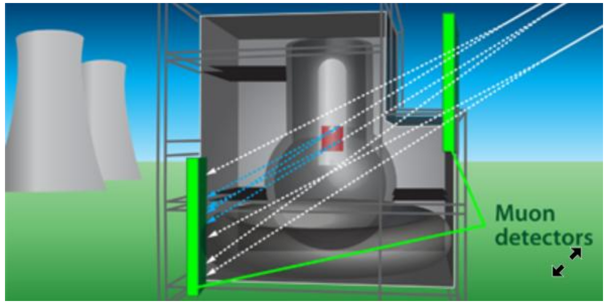
Searching for new physics

Muon tomography

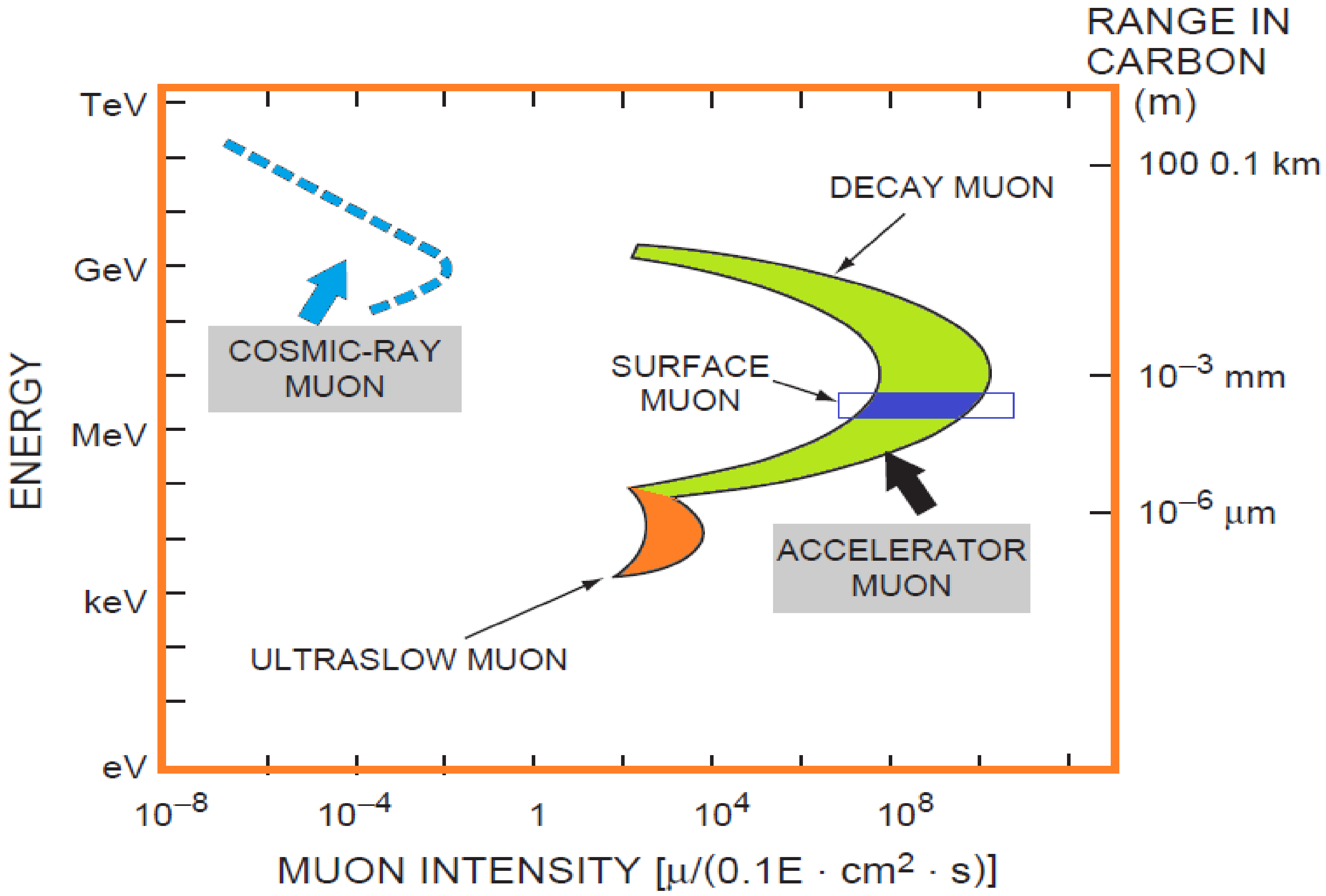








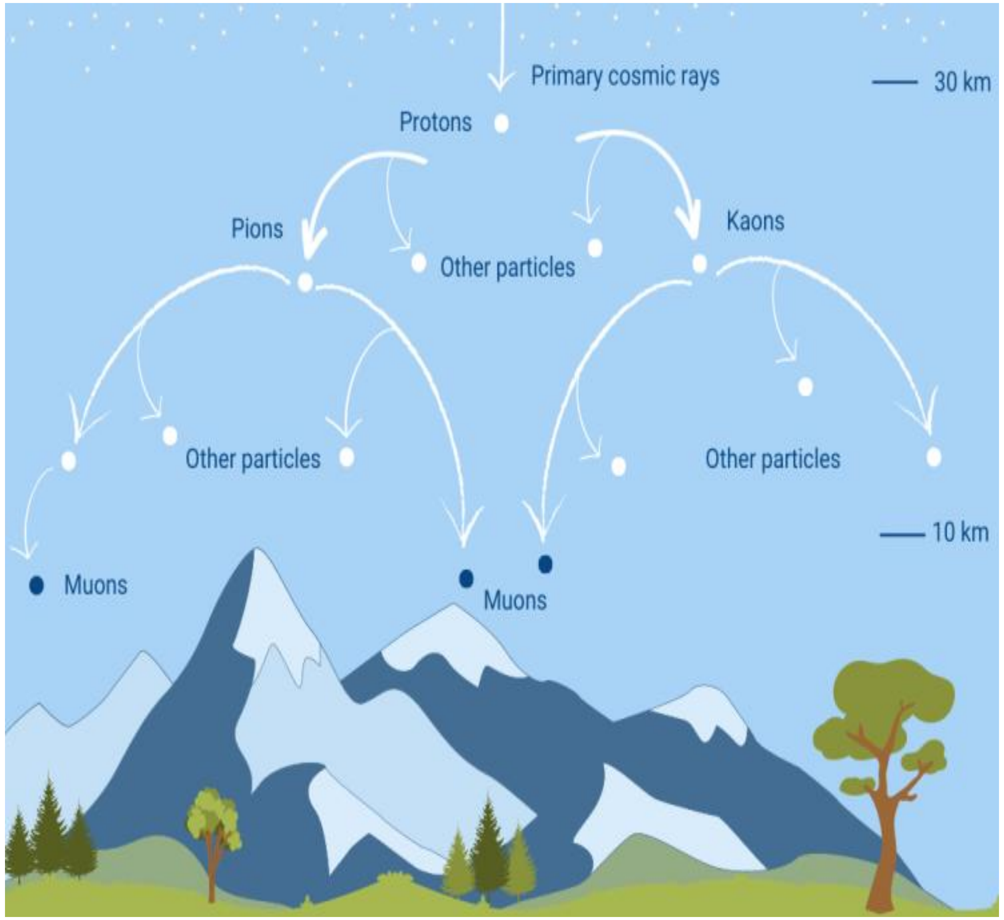
缪子源

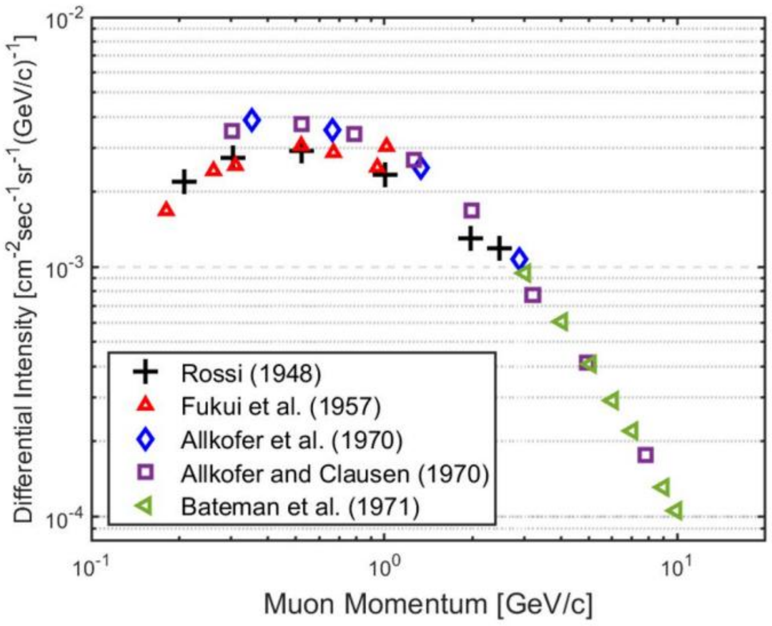


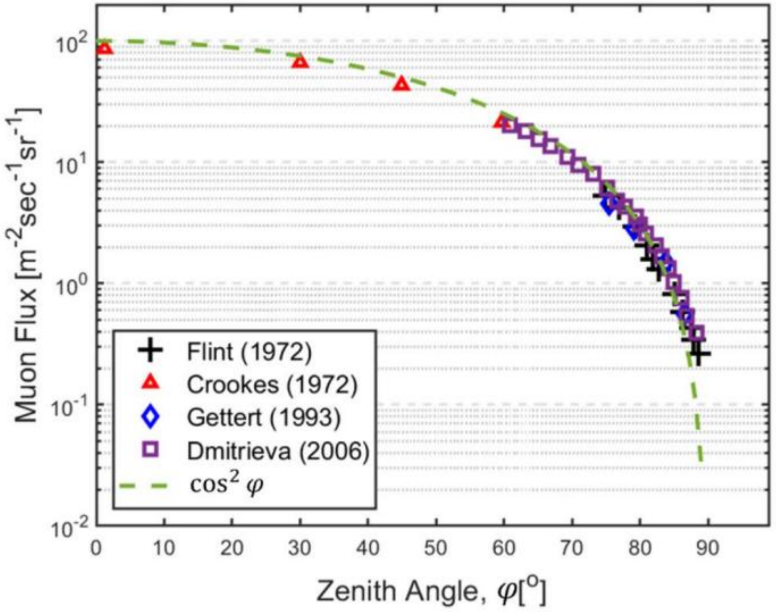
RANGE IN CARBON (m)
TeV
GeV
MeV
keV
eV
ENERGY
100 0.1 km
10^{-3} mm
10^{-6} μm
DECAY MUON
COSMIC-RAY MUON
SURFACE MUON
ACCELERATOR MUON
ULTRASLOW MUON
10^{-8}
10^{-4}
1
10^{4}
10^{8}
MUON INTENSITY [μ/(0.1E · cm^2 · s)]

缪子源

宇宙射线缪子源：





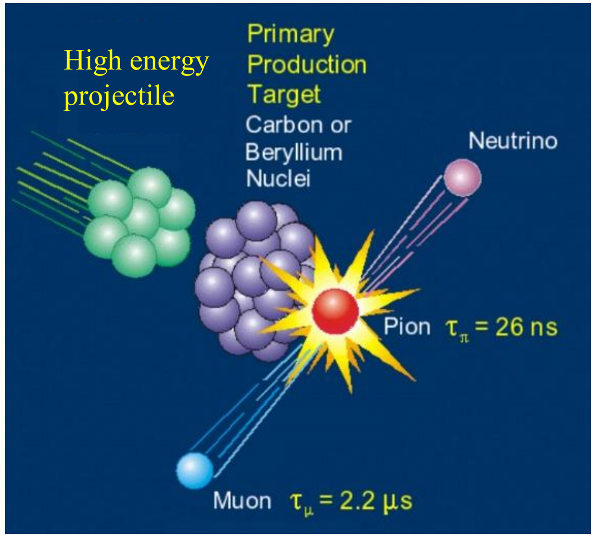


muons at sea leval

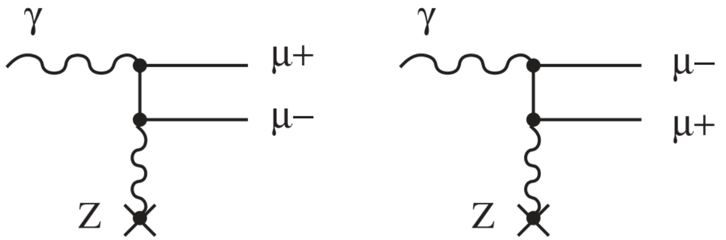
J. Bae, Scientific Reports, 14,6717(2024)

缪子源

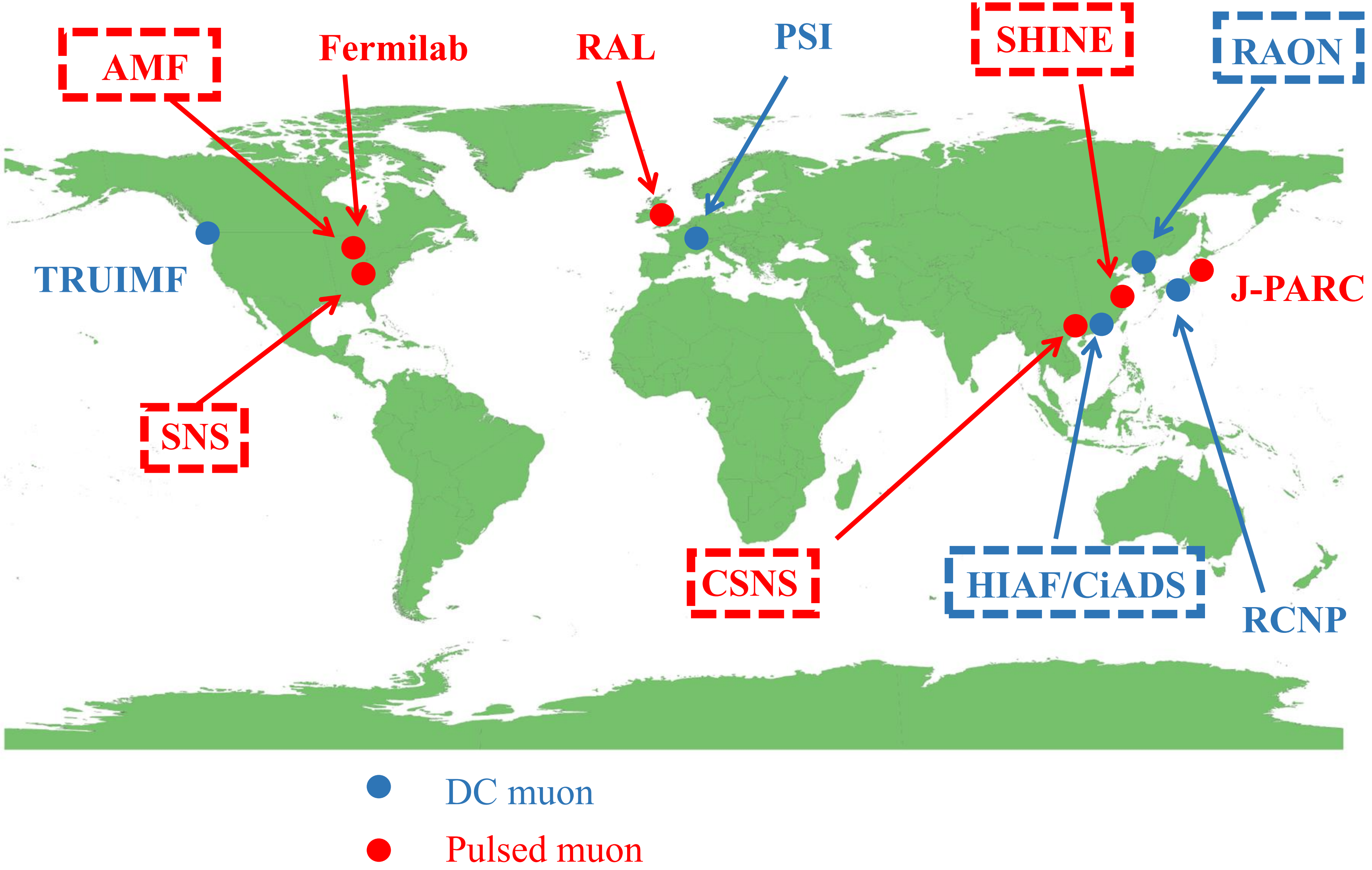
加速器缪子源：



Muon from pion decay

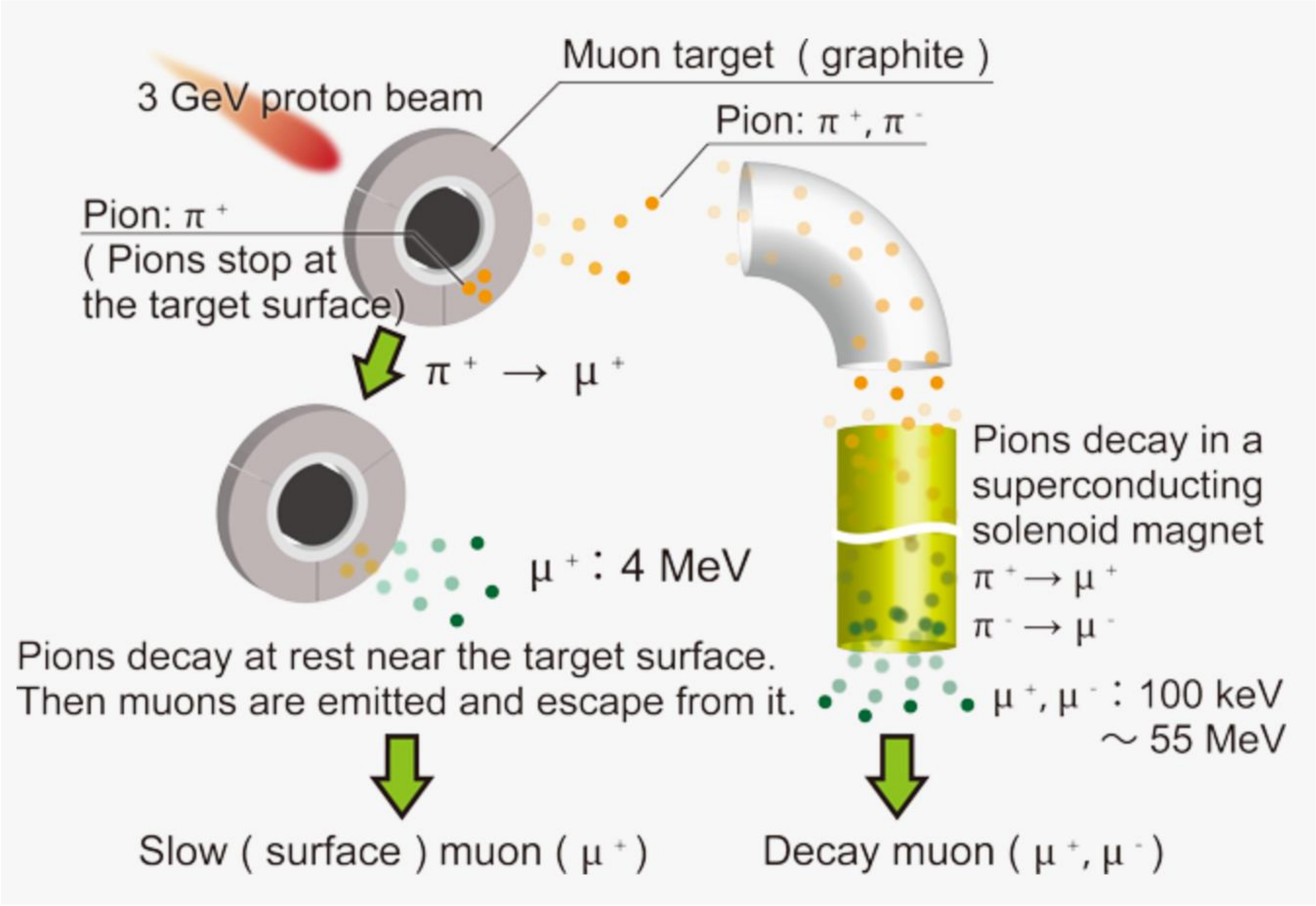


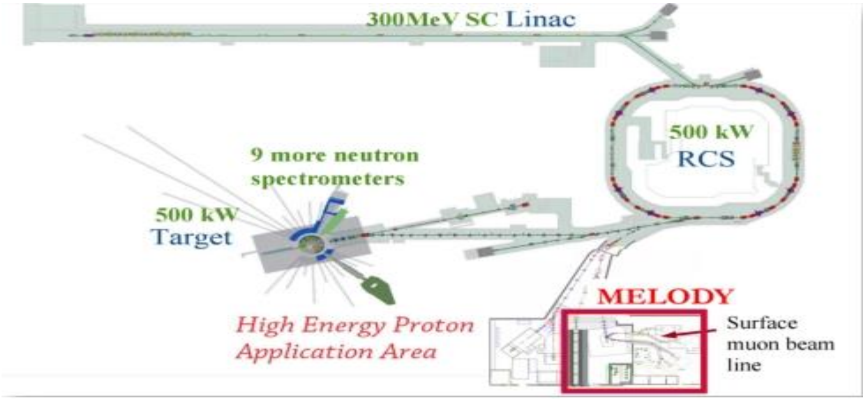
Bethe-Heitler process

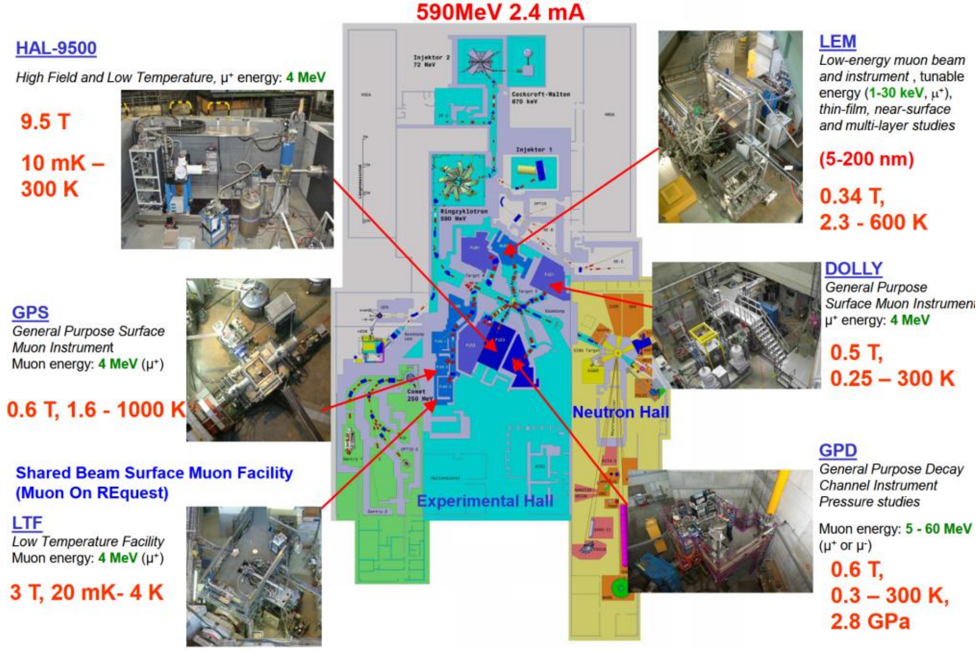


缪子源

加速器缪子源：质子加速器







缪子源

加速器缪子源：电子加速器

上海交大团队提出利用SHINE的束流产生μ子源

Photo-production

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

Electro-production

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

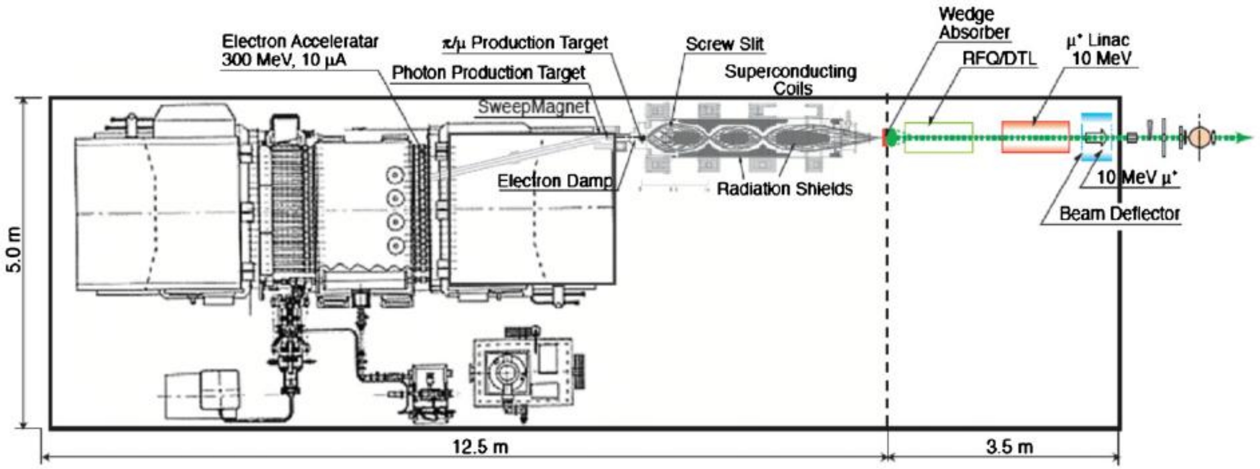
$$\sigma_e(E_0)/\sigma_q(E_0) \approx 0.1$$

muon pair creation

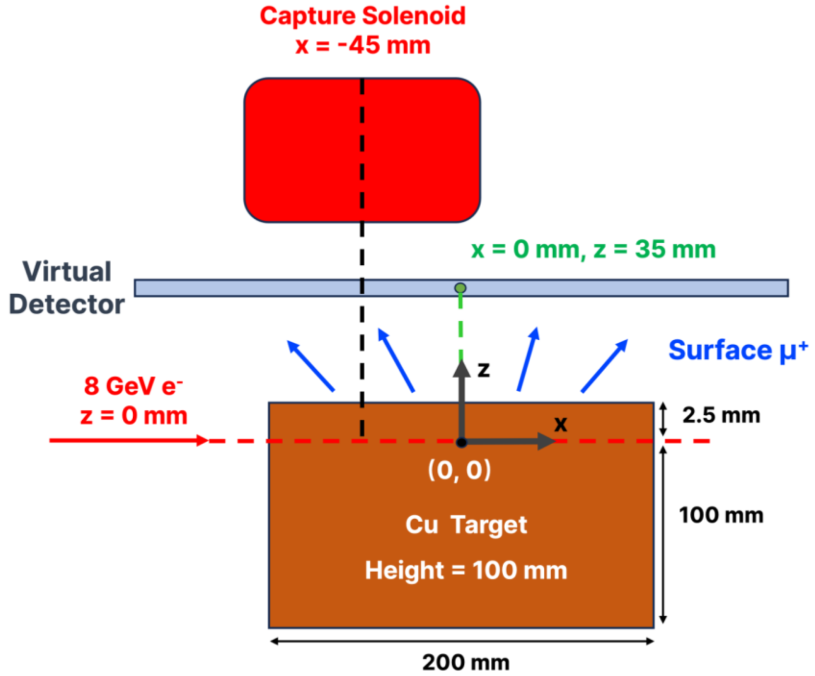
$$\gamma + Z \to \mu^+\mu^- + \text{anything} \qquad \sigma_{pair}(E_0)$$

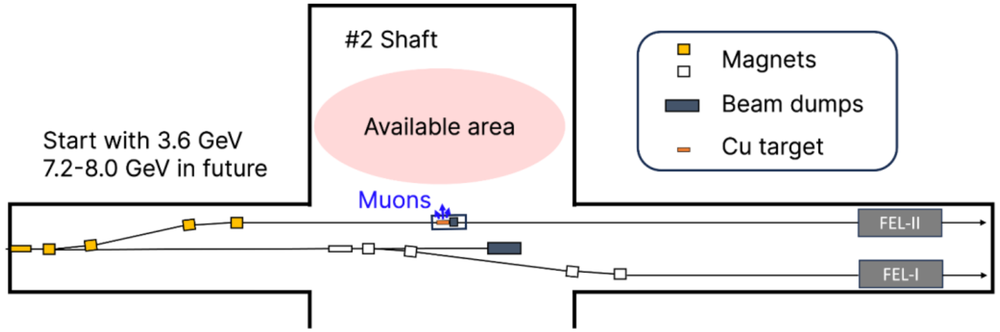
$$\sigma_{pair}(E_0)/\sigma_q \approx 10^{-3}\sim10^{-4}$$

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



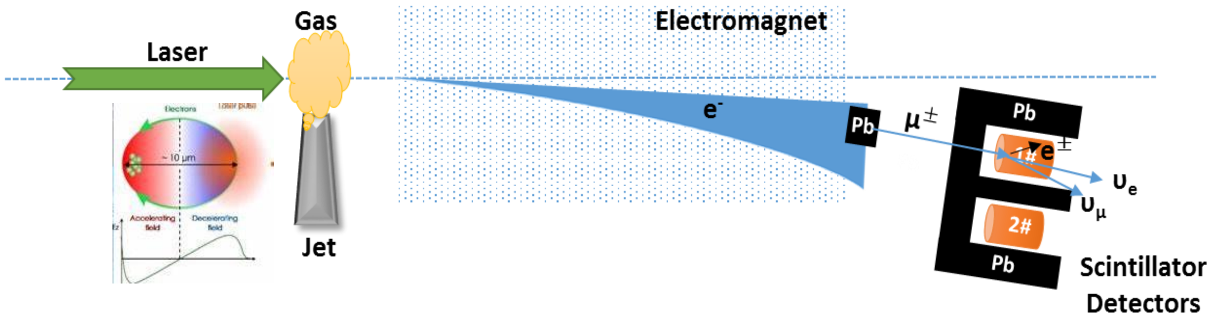
$$Y(\pi) = (0.63 \times 10^{14}) \times (0.92 \times 10^{-2}) \times (4 \times 10^{-7})/\text{s}$$
$$= 2.3 \times 10^5/\text{s}.$$





缪子源

激光缪子源



nature physics

Article

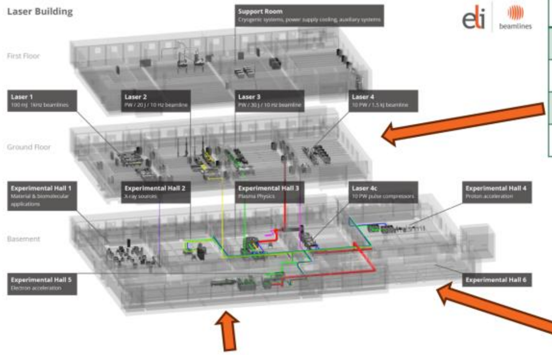
https://doi.org/10.1038/s41567-025-02872-2

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

上海羲和激光

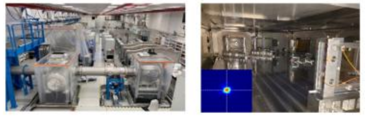
eli

ELI Beamlines for muons

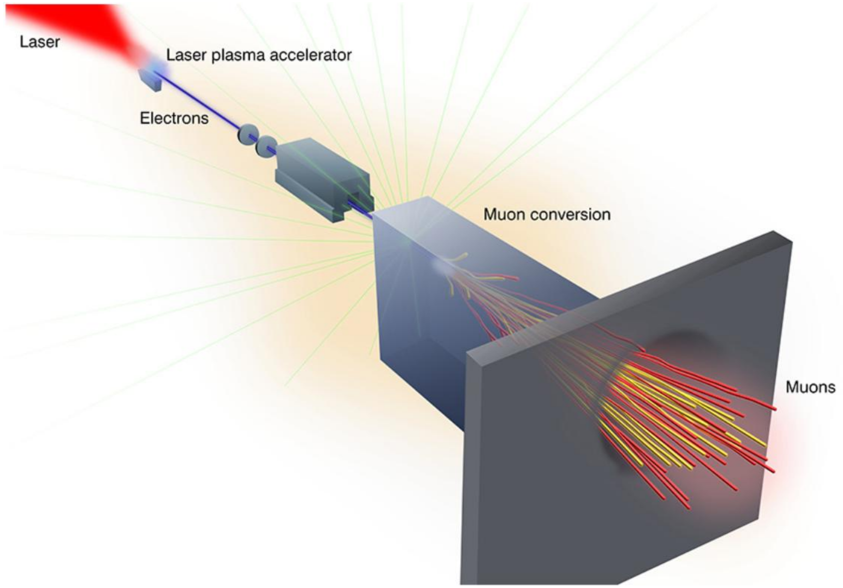


L1-Allegra	L2-Duha	L3-HAPLS	L4-Aton
OPCPA	OPCPA	Ti:Sa	Nd:Glass
100 mJ	2 J	30 J	1.5 kJ
15 fs	25 fs	30 fs	150 fs
1 kHz	20 Hz	10 Hz	0.01 Hz

ELBA Beamline (L3-HAPLS)



Future Beamline (L4-Aton)



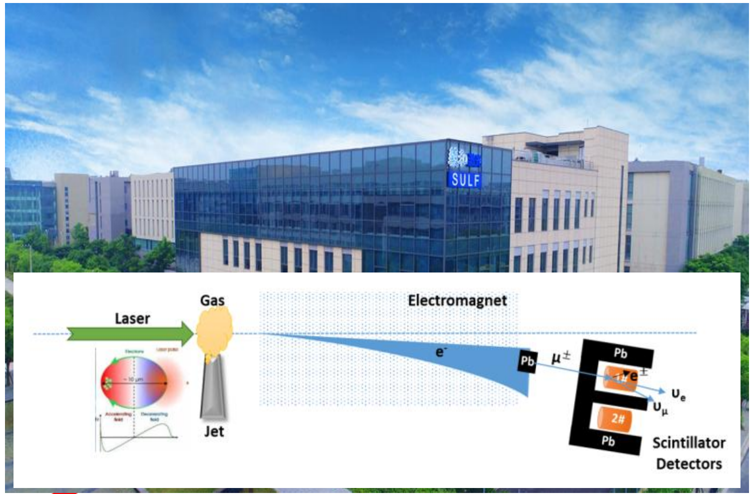
Berkeley Lab Laser Accelerator (BELLA)

蓬勃发展的中国缪子源

MELODY@CSNS 脉冲型缪子源

SHINE Muon Source 高重频脉冲型缪子源

Muon Source@ SULF 台式激光缪子源



HIAF-HIRIBL
GeV单能缪子源

MuST@CiADS 连续型缪子源

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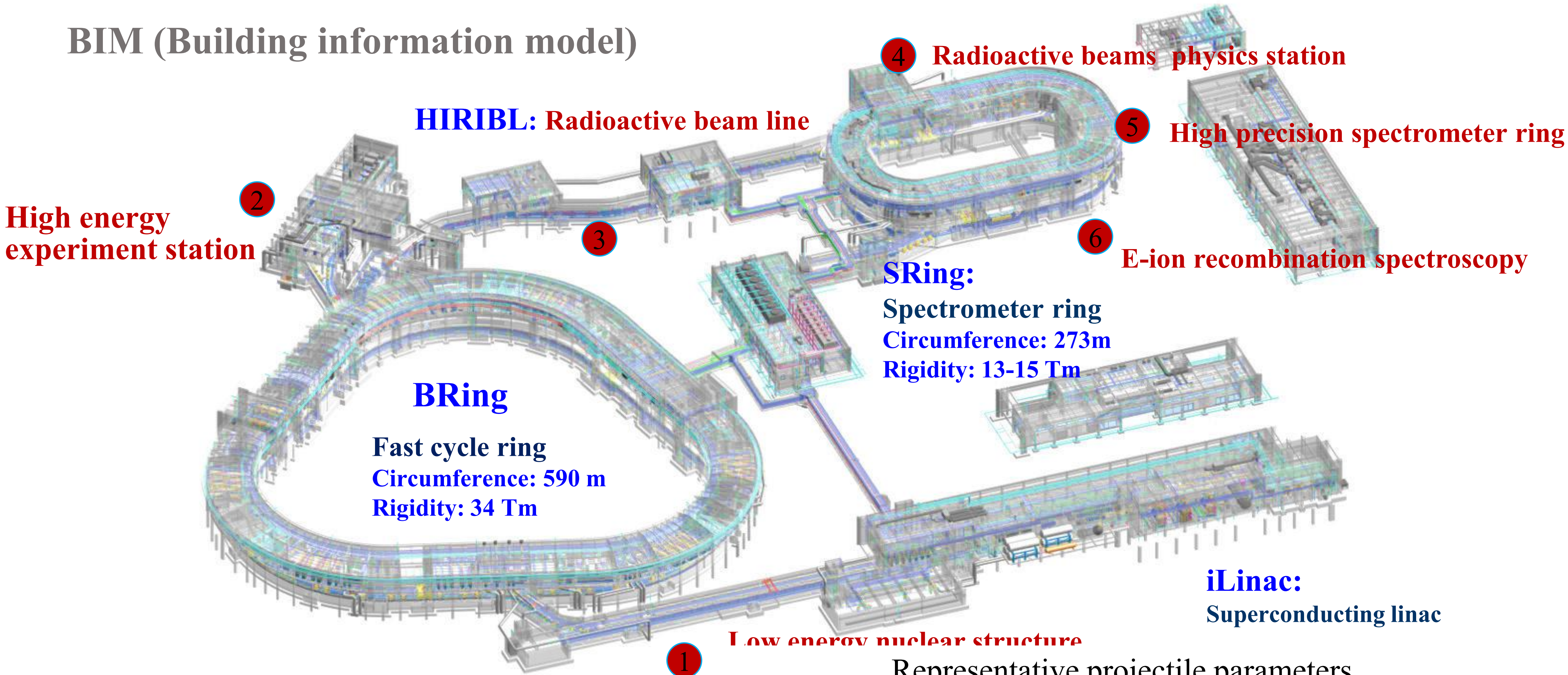
- HIAF进展和总结

HIAF装置

- 实验终端

BIM (Building information model)



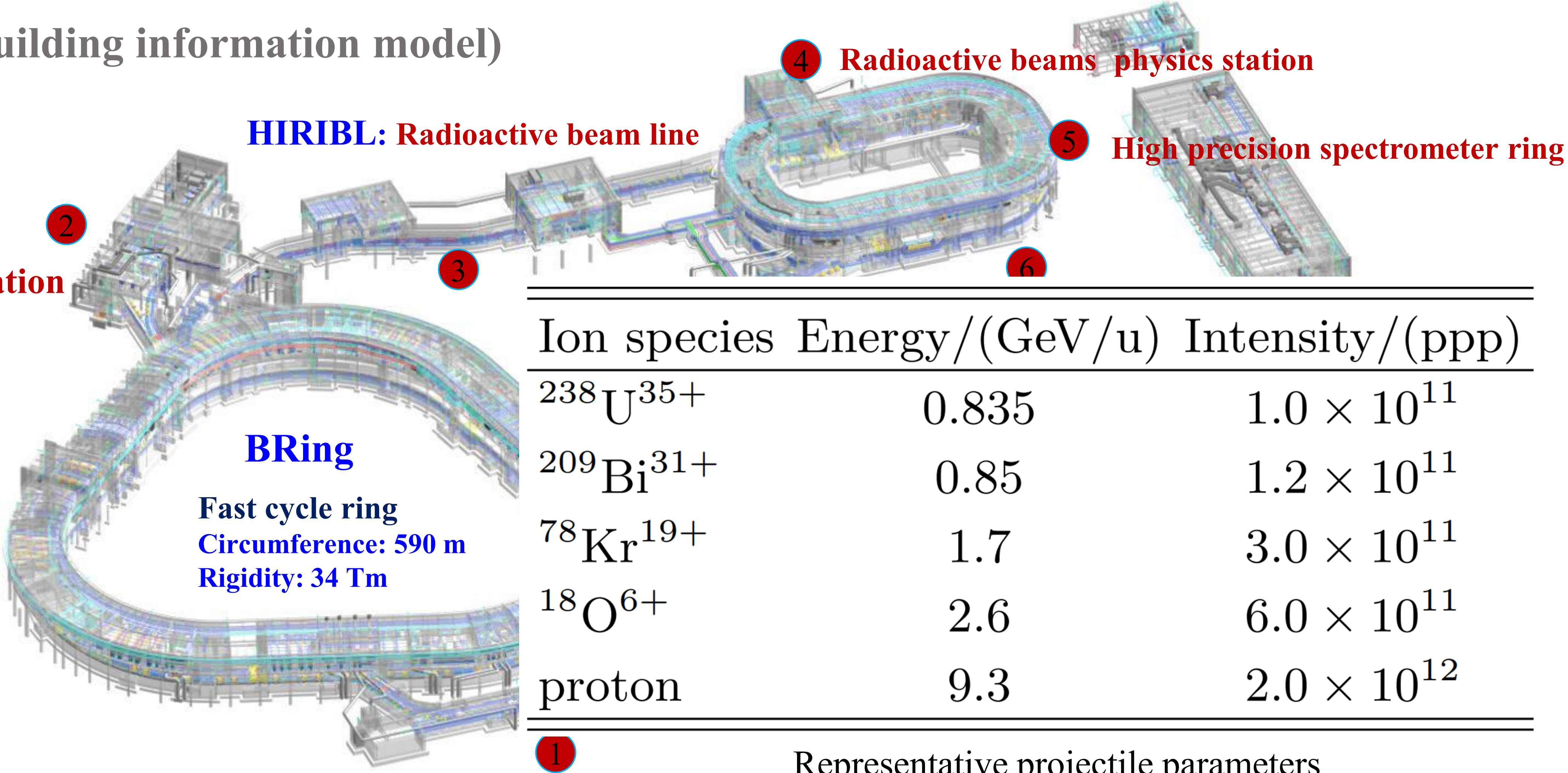
Low energy nuclear structure

Representative projectile parameters

HIAF装置

- **实验终端**

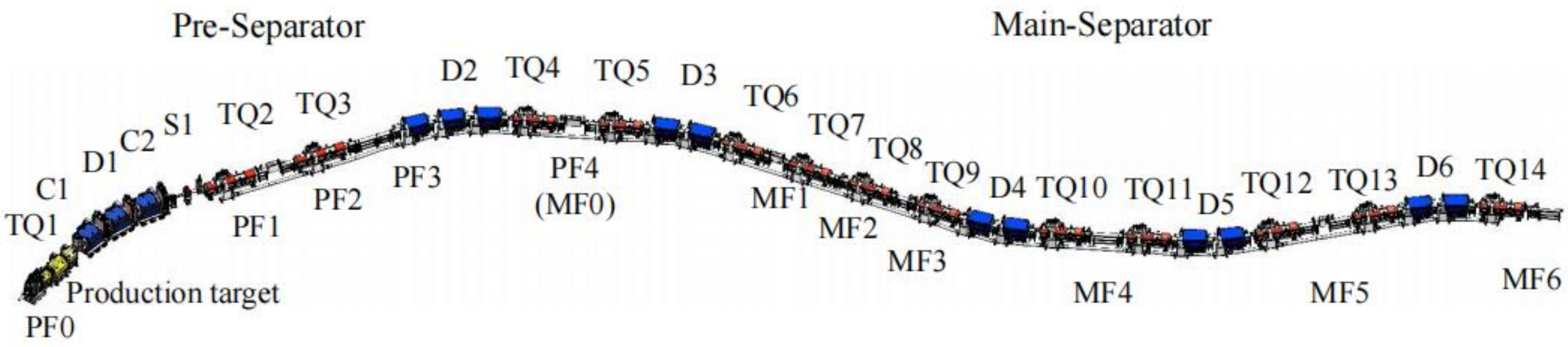
BIM (Building information model)



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

HIRIBL束线



	Length (m)	Beam size at target (mm)	Angular acceptance(mrad)	Momentum acceptance (%)	Resolving power	Max. Bρ (Tm)
HIRIBL 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

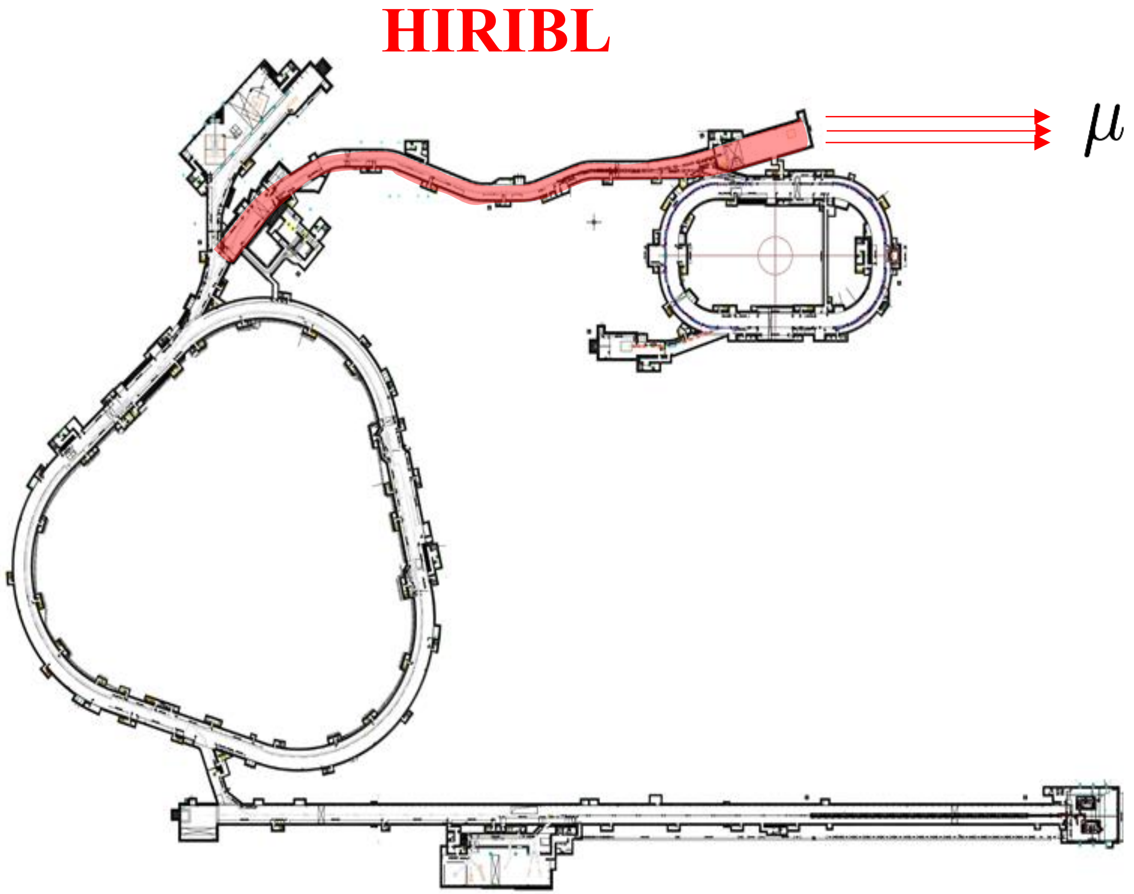
HFRS and Radioactive beamlines around the world

HIRIBL一条性能先进的弹核碎裂型次级束流装置

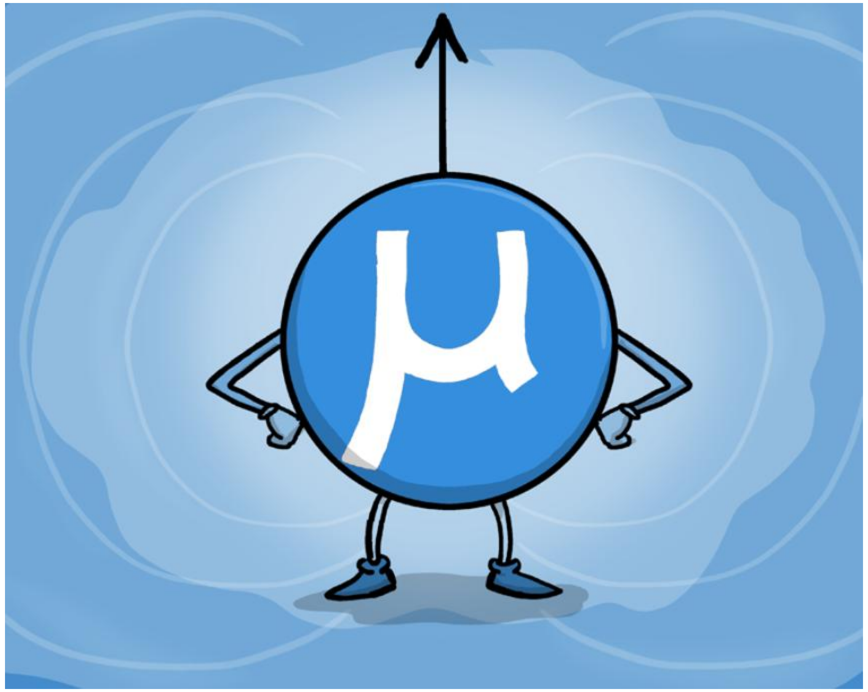
HIRIBL束线

HIRIBL束线

HIAF装置的缪子束线



How many muon
can we order?



HIAF装置的缪子束线

HIRIBL

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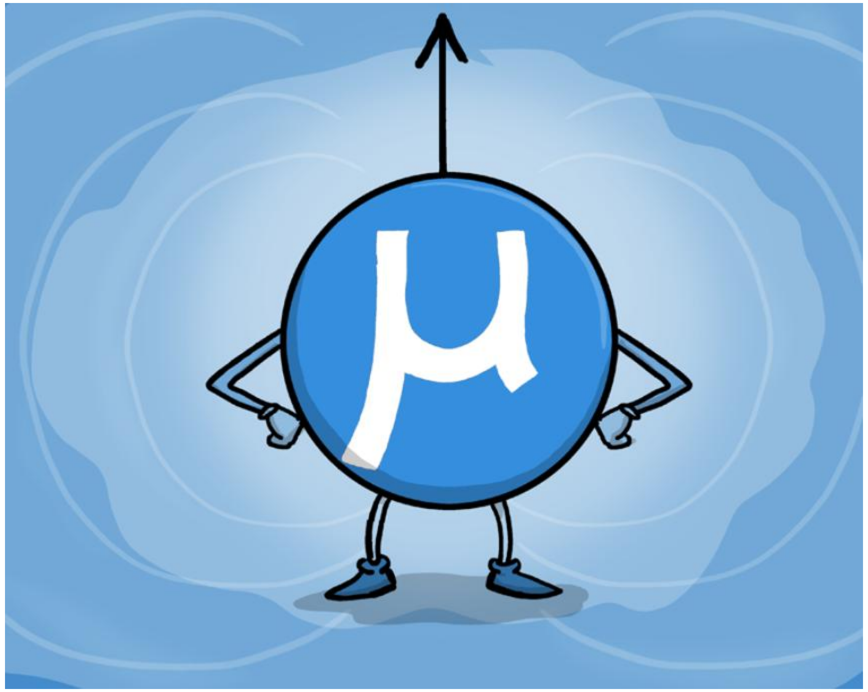
$^{18}O^{6+}$	2.6	6.0×10^{11}
Proton	9.3	2.0×10^{12}

Parameters	Value
Length (m)	192
rms of beam spot at the target (mm)	$\sigma_x = 0.4$, $\sigma_y = 0.6$
Maximum magnetic rigidity (Tm)	25
Maximum angular acceptance (mrad)	$x' = \pm 30$, $y' = \pm 25$
Maximum momentum acceptance	$\pm 2\%$

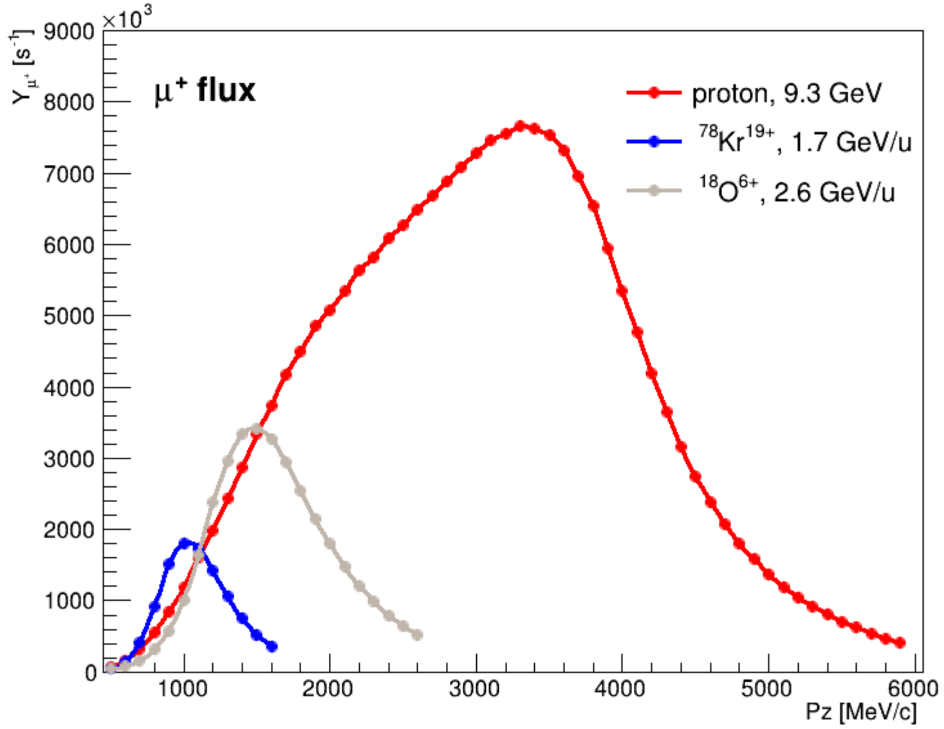
How many muon can we order?

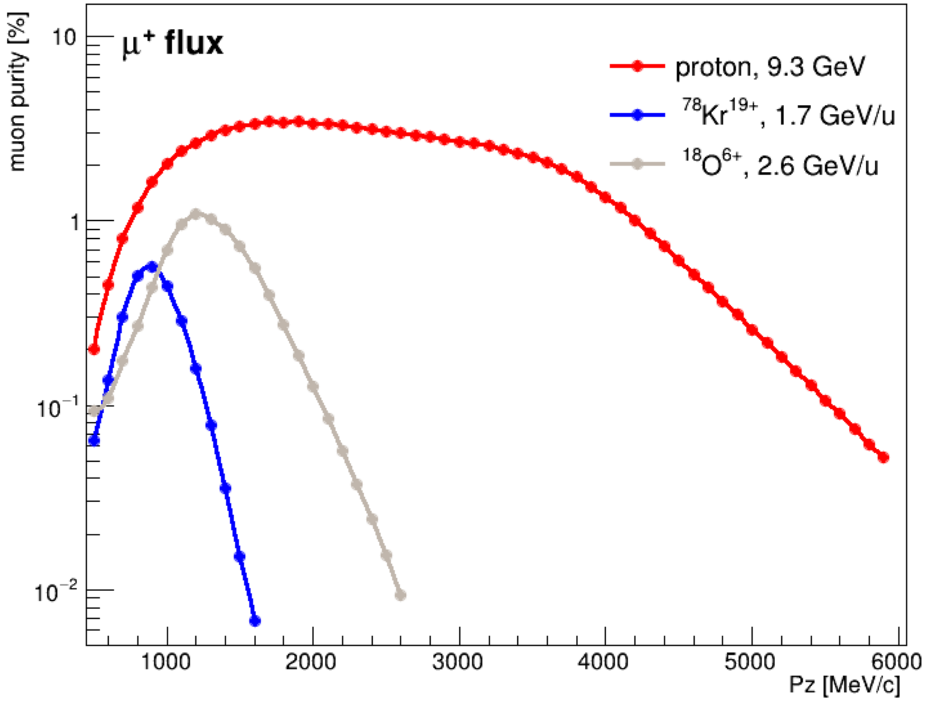


HIAF装置的缪子束线

- 缪子产额
- 缪子纯度

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%





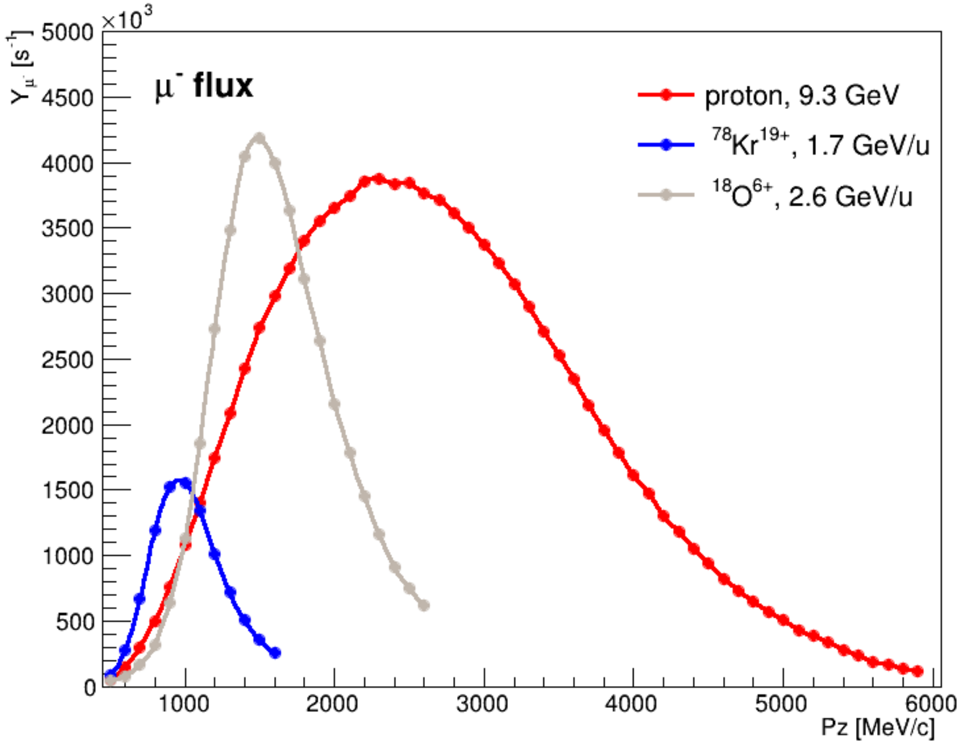
HIAF装置上几种典型主束所产生μ子产额及相应纯度

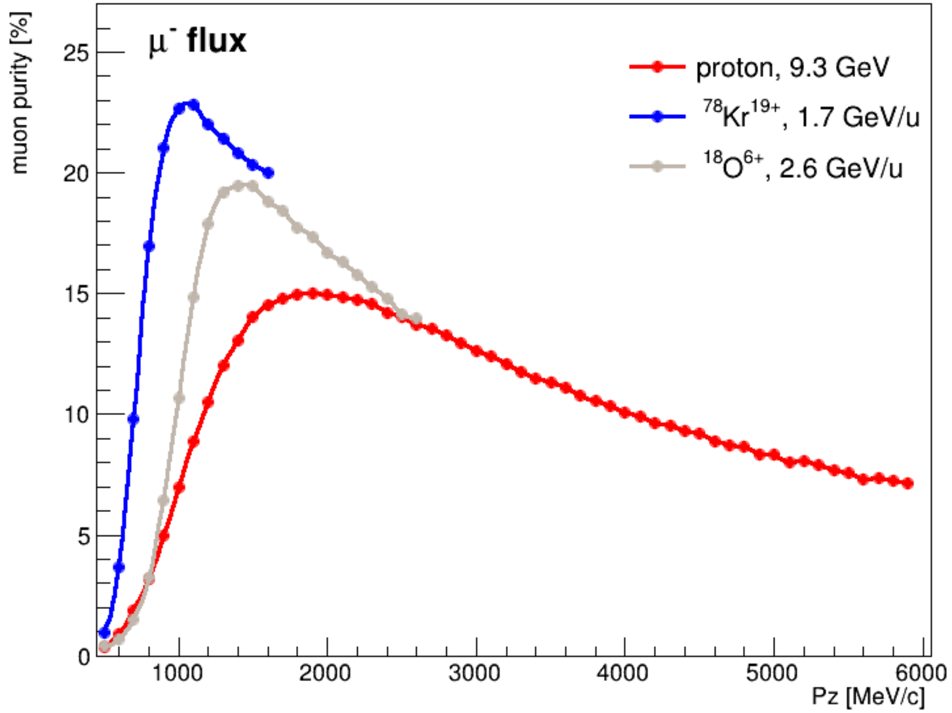
Phys. Rev. Accel. Beams **28**, 053401 (**2025**)

HIAF装置的缪子束线

- 缪子产额
- 缪子纯度

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%



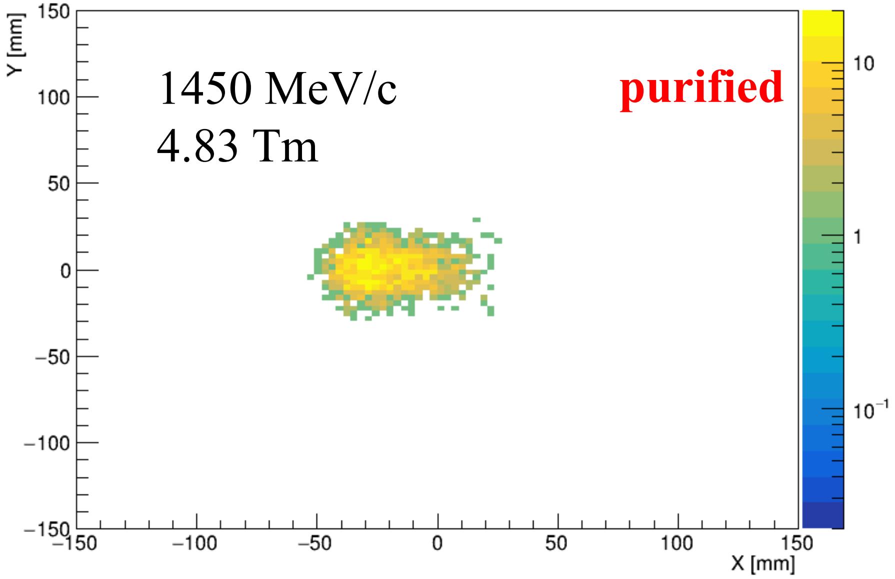


HIAF装置上几种典型主束所产生μ子产额及相应纯度

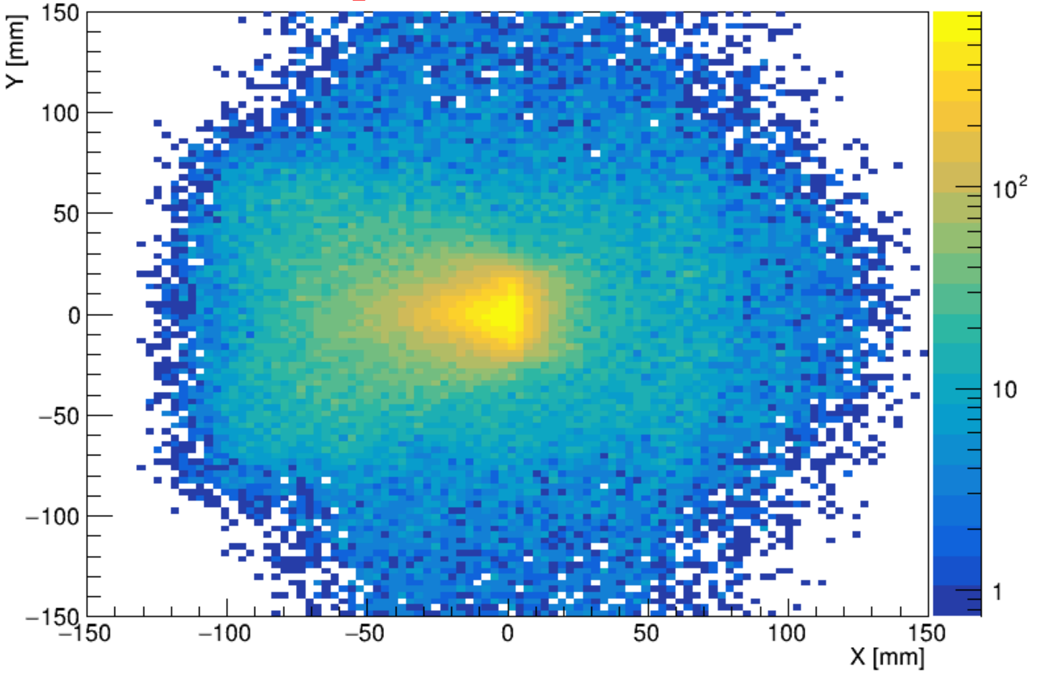
Phys. Rev. Accel. Beams **28**, 053401 (**2025**)

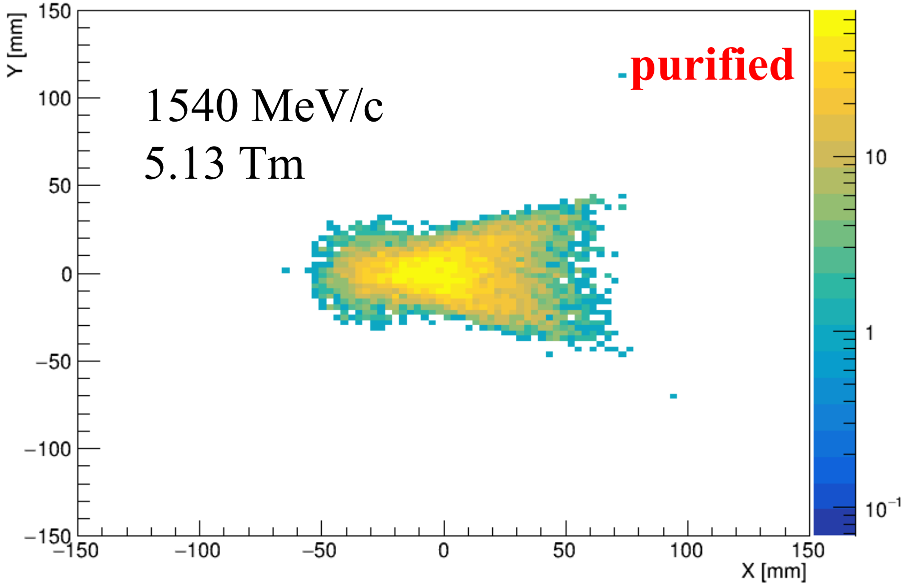
HIAF装置的缪子束线

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

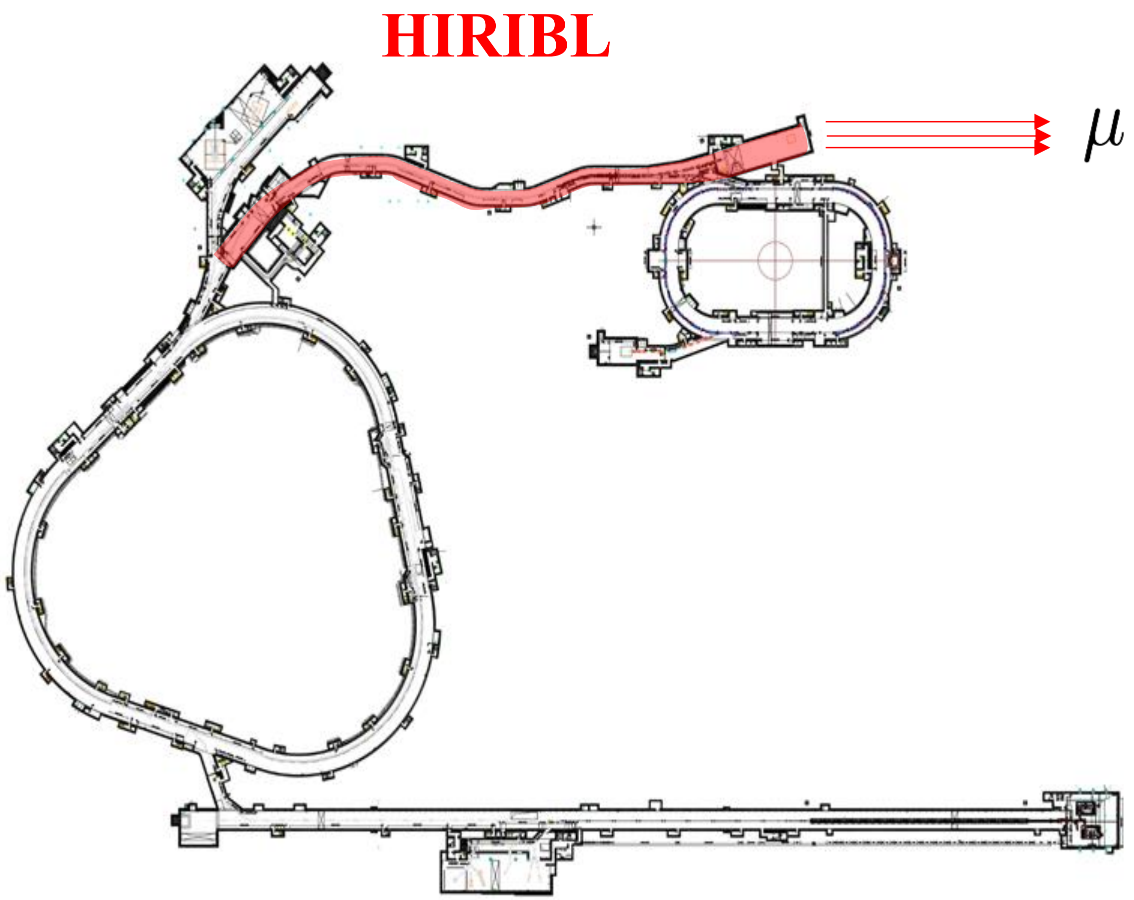


unpurified





HIAF装置的缪子束线

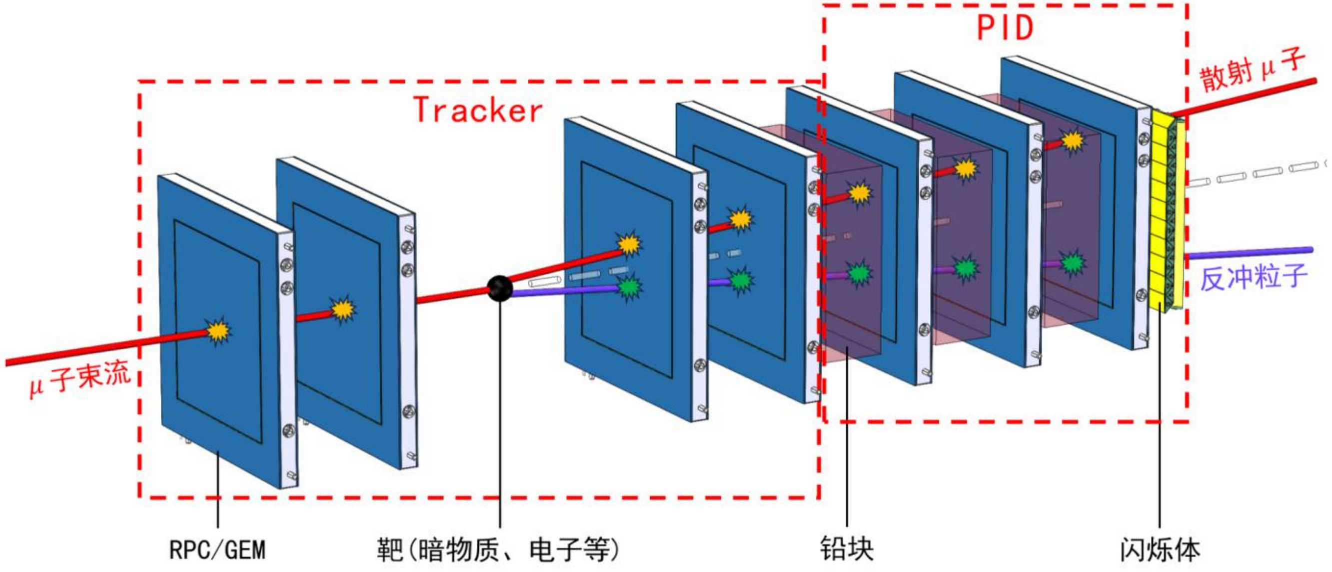


What can we do with these muons?

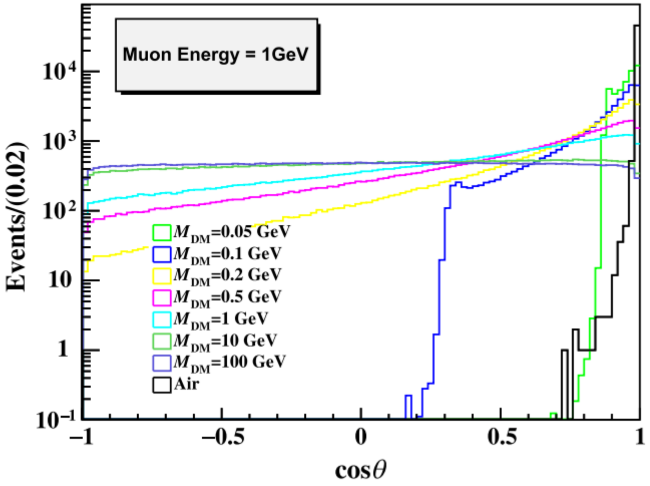
基于GeV单能缪子束的物理和应用

Probing and Knocking with Muons

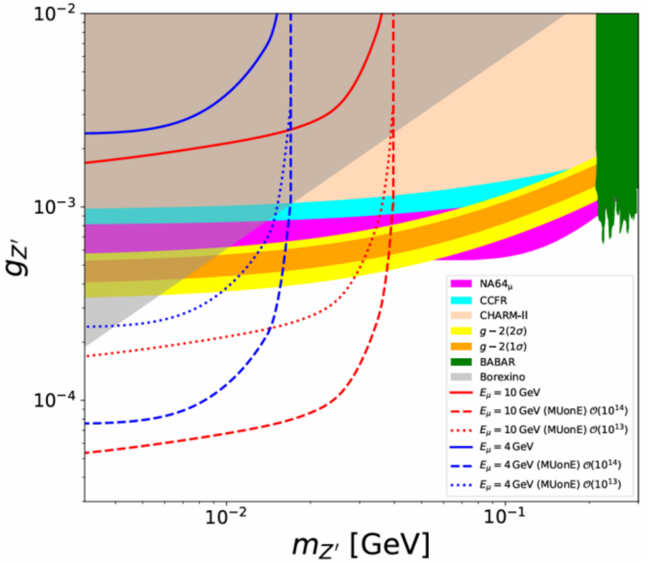
- One of the highest intensity (4e6/s) GeV energy muon around world
- Direct searches for DM
- Searching dark boson



PKμ@HIRIBL



Searching for Muon Philic Dark Sector



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

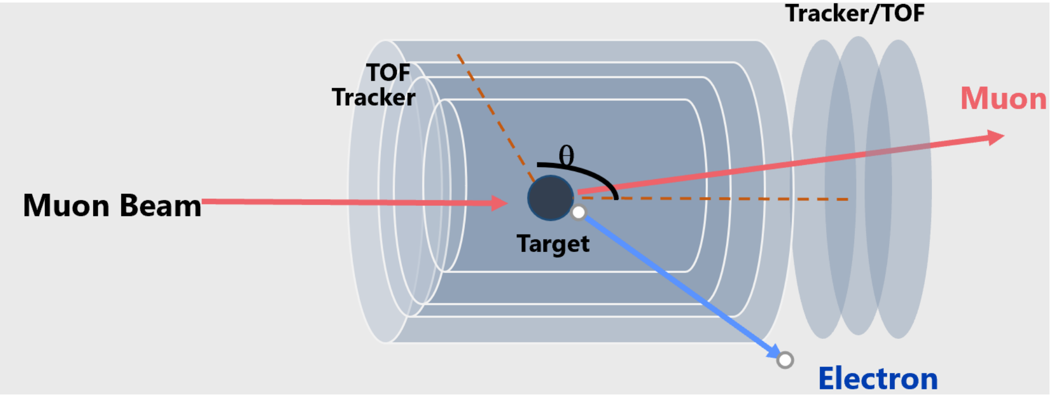
Credit: Prof. Qiang Li

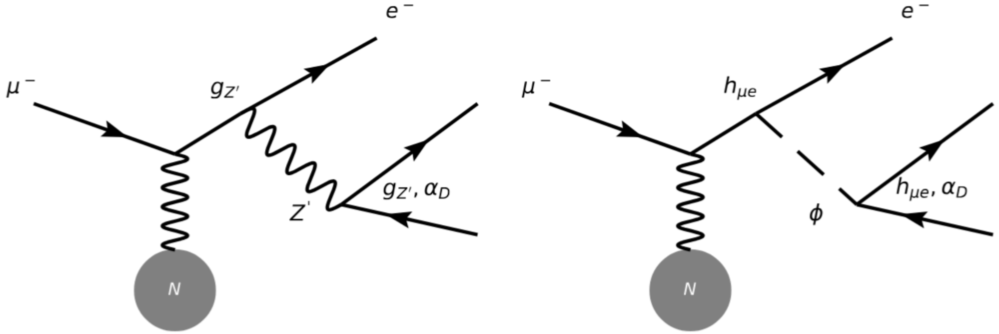
Phys. Rev. D 110, 016017
arXiv:2410.20323
arXiv:2411.12518
arXiv:2511.08950

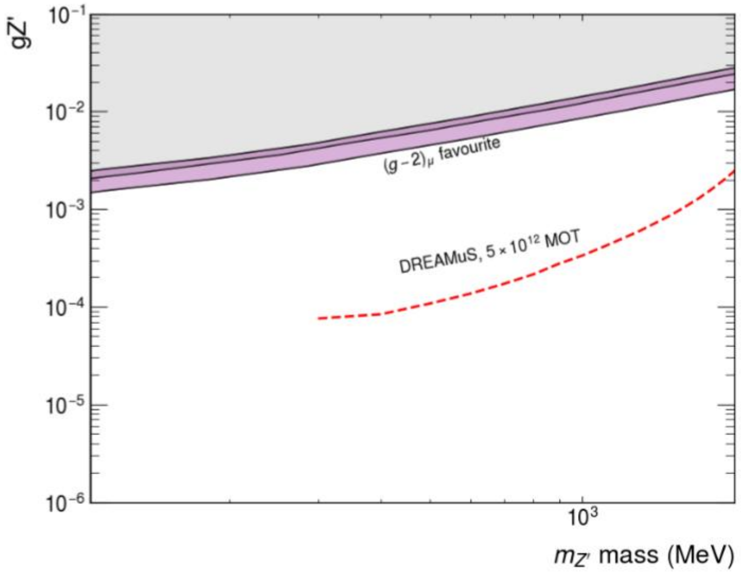
基于GeV单能缪子束的物理和应用

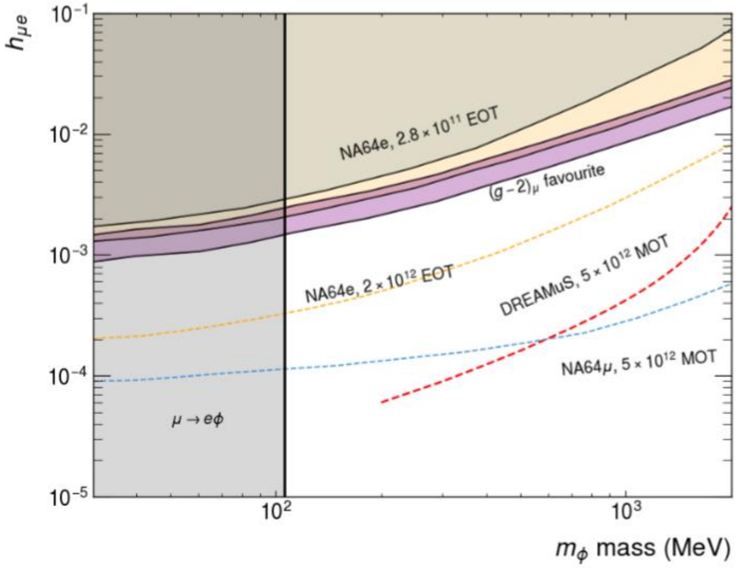
DREAMuS: Dark matter REsearch with Advanced Muon Source

- 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}

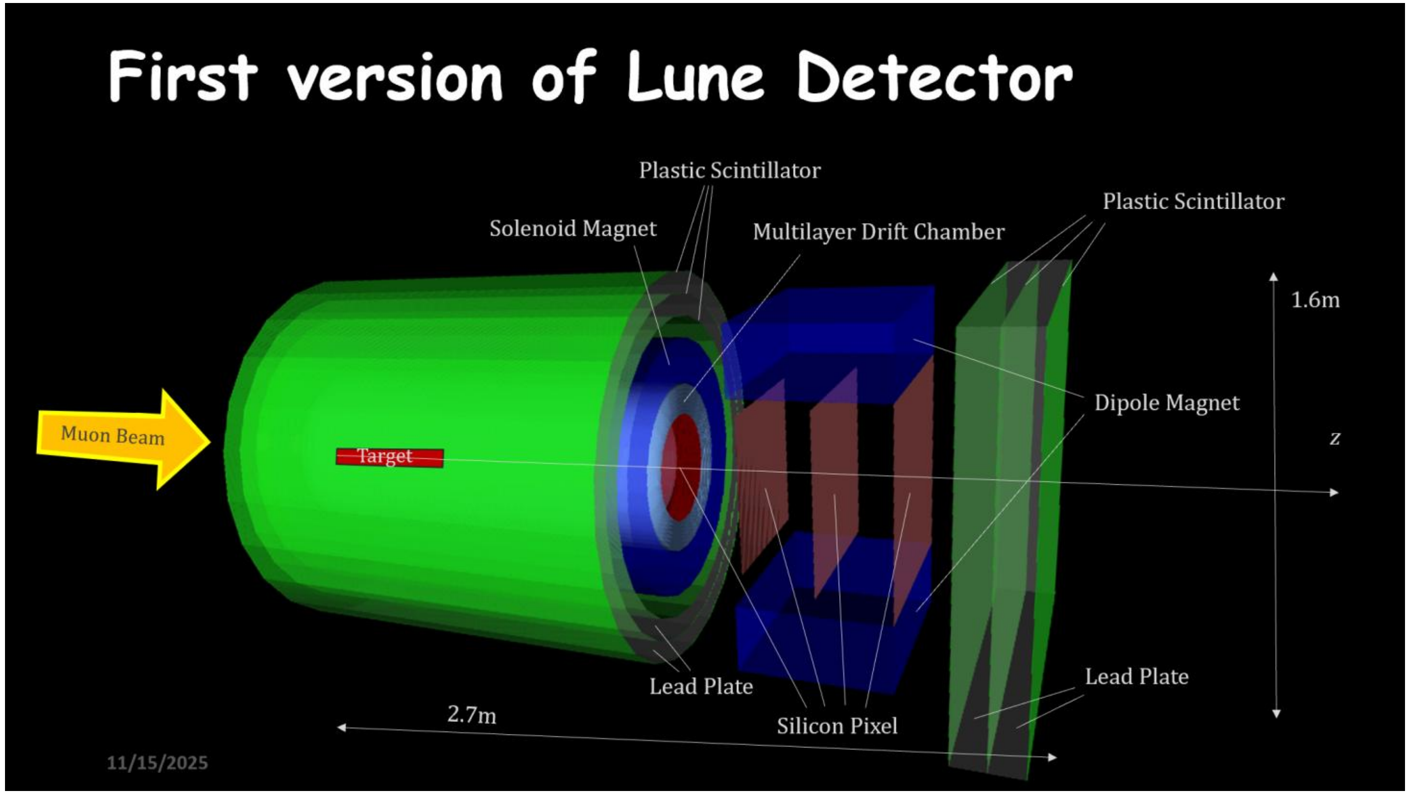
Credit: Prof. Liang Li

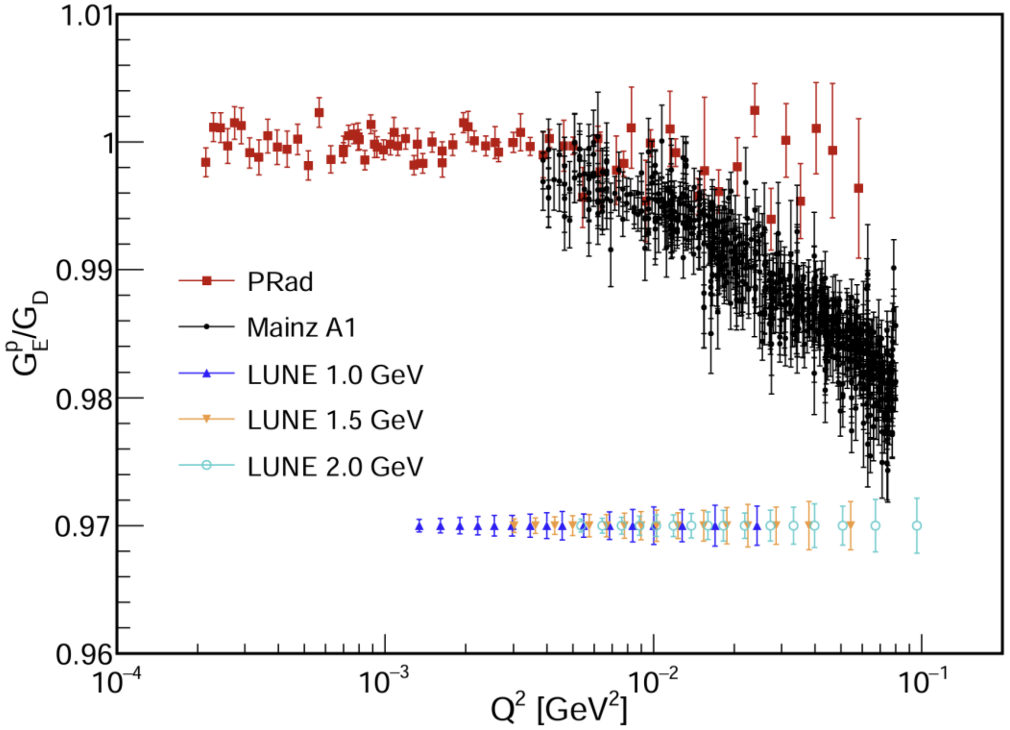
基于GeV单能缪子束的物理和应用

LUNE :Low-energy mUon-Nucleon scattering Experiment

Assuming 20 cm LH2 target
15 days @ 1.0 GeV
30 days @ 1.5 GeV
60 days @ 2.0 GeV

Stat. uncertainty on proton radius:
~ 0.0022 fm (~0.3%)
Compared to 1% (Amber), 0.5% (MUSE)





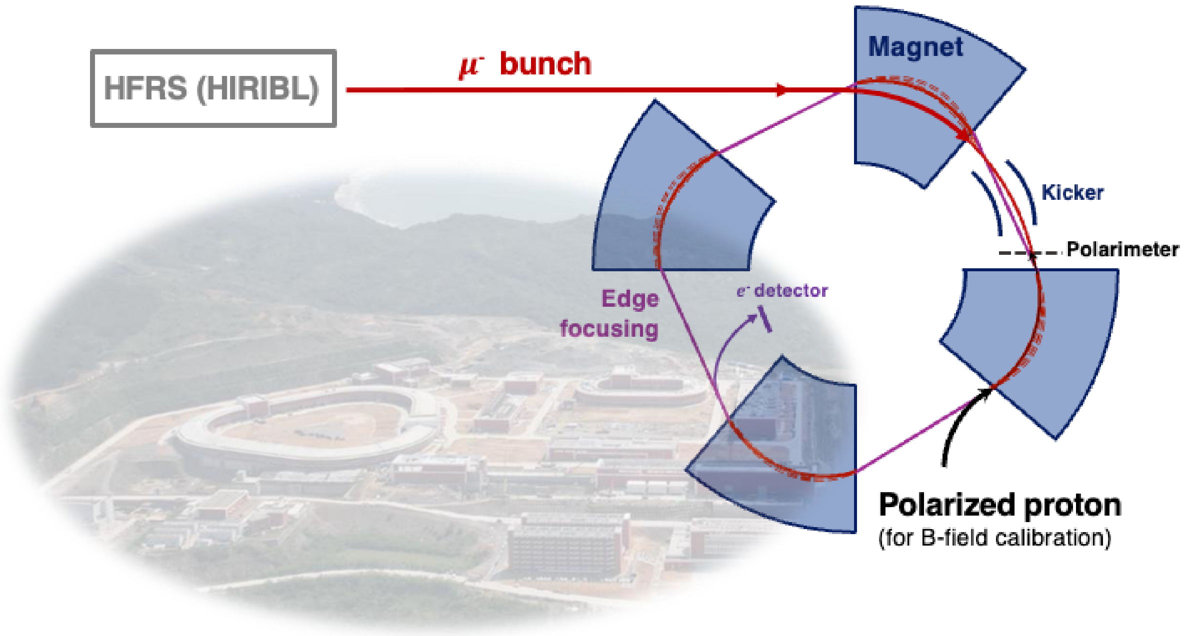
Credit: Prof. Hang Yin

基于GeV单能缪子束的物理和应用

CANTON-μ : Creative Anomalous magNetic momenT Observation with Negative-muon

We propose a new muon g-2 experiment using HIAF's unique GeV-scale, high intensity muon:

- It prioritizes *negative* muons, offering both precision SM measurement and probe to New Physics.
- The precision aims at 0.05 ppm, surpassing Fermilab's 0.14 ppm - a truly **next-generation experiment**.



Facilities	CERN / BNL / FNAL	J-PARC	HIAF
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
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 → ~0.1ppm	μ^-/μ^+: 0.1 ppm → 0.05 ppm

More details: see Ce Zhang's talk @ PKU seminar (Chinese) / MPP2025 workshop (English); the paper will be released on arXiv soon.

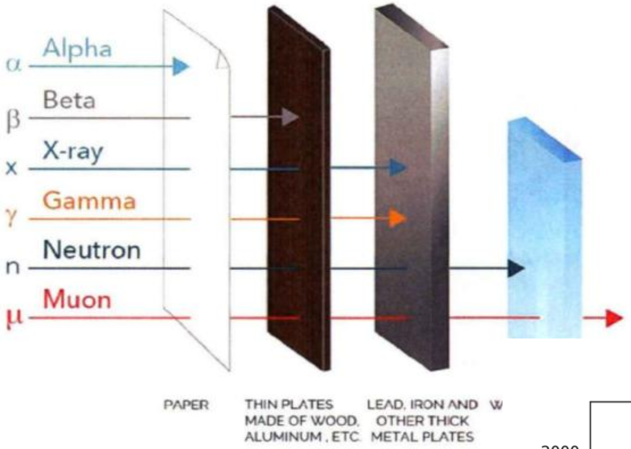
Credit: Dr. Cedric Zhang

基于GeV单能缪子束的物理和应用

- 缪子成像对重核、高密物质灵敏，可对物质内部结构无损成像
- 加速器缪子成像物质分辨等能力显著强于宇宙射线缪子成像

缪子成像显著优势

- 穿透力更强
- 对高密度高Z材料敏感
- 清洁安全、无损伤
- 无需防护

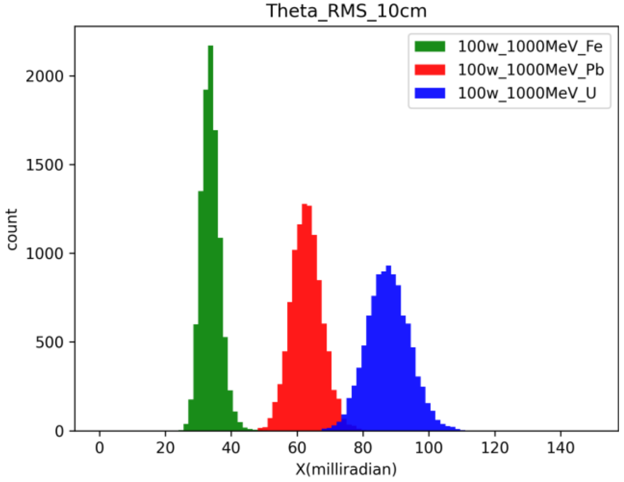


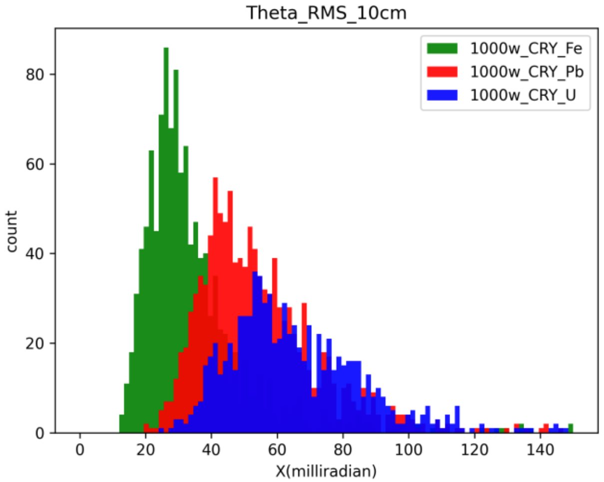
加速器缪子源

- 高能量，能量单一性强
- 高通量，方向单一
- 能量可调

特点	宇宙线缪子	加速器缪子源
通量	$0.02/cm^2/s$	**$>10^4/cm^2/s$**
能量分布	范围宽	**单色、自主可调**
方向	随机、不稳定	**稳定可控**
优劣势	易获取、精度差	**精度高、效率高**

加速器缪子 V.S. **宇宙射线缪子**



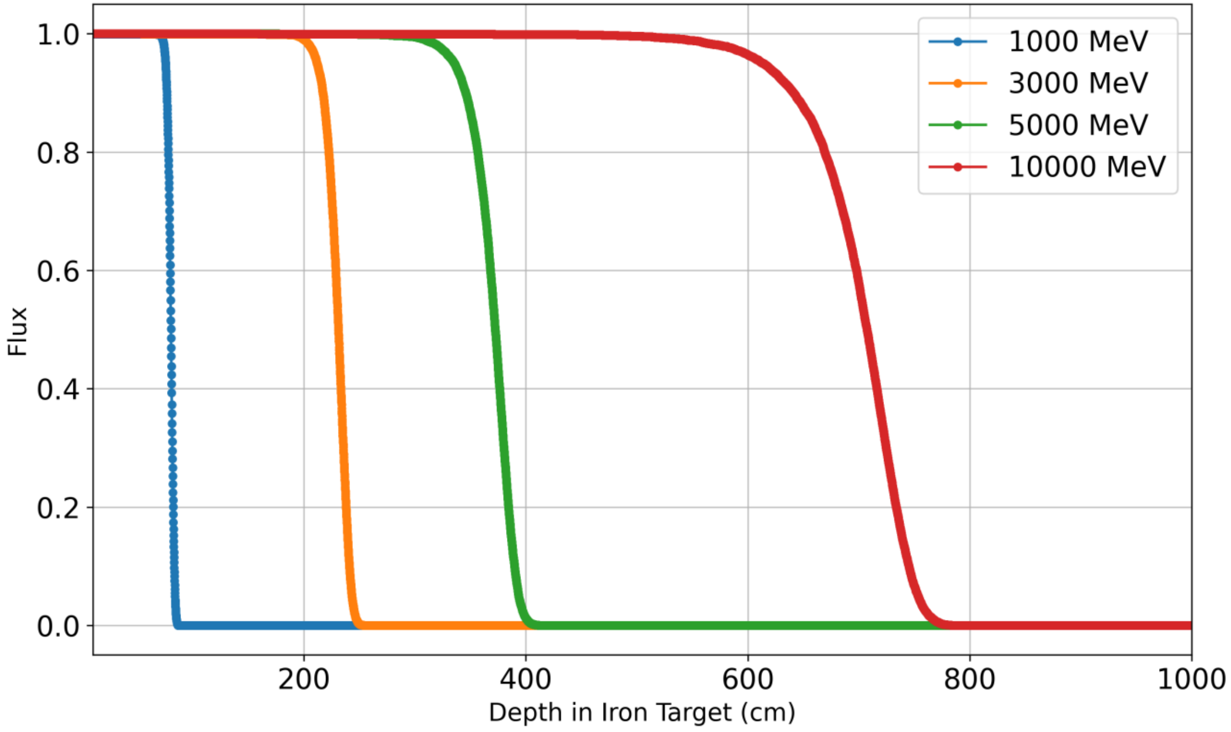


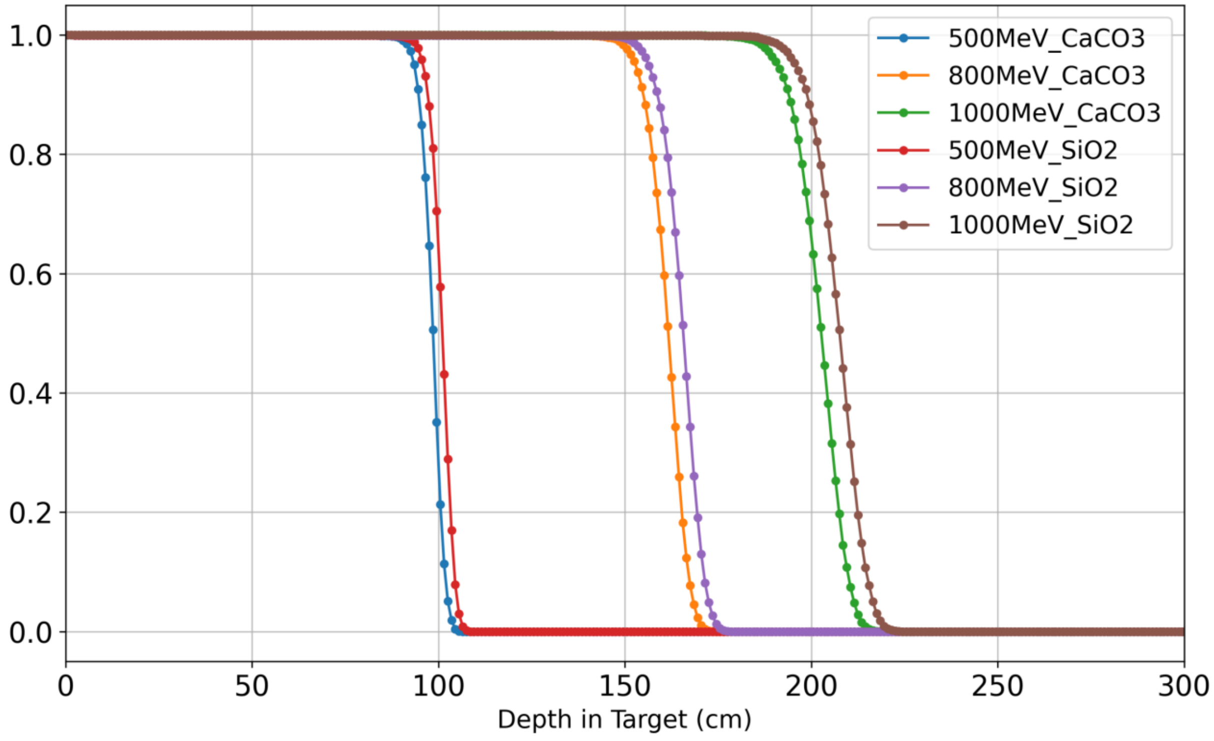
加速器单能缪子成像有很强的物质分辨能力

基于GeV单能缪子束的物理和应用

缪子的射程

1GeV能量的缪子可以穿透1m左右的铁



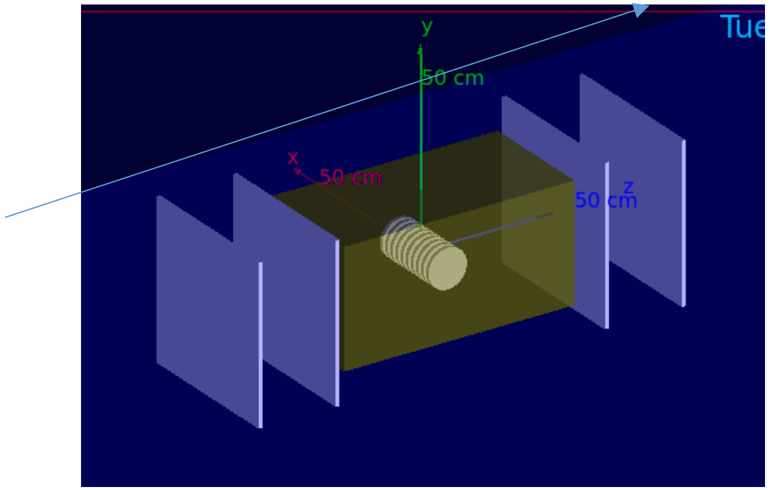


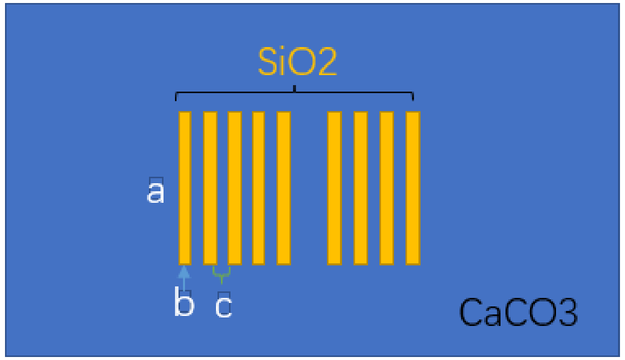
不同能量缪子在铁中的射程

不同能量缪子在SiO2中的射程

基于GeV单能缪子束的物理和应用

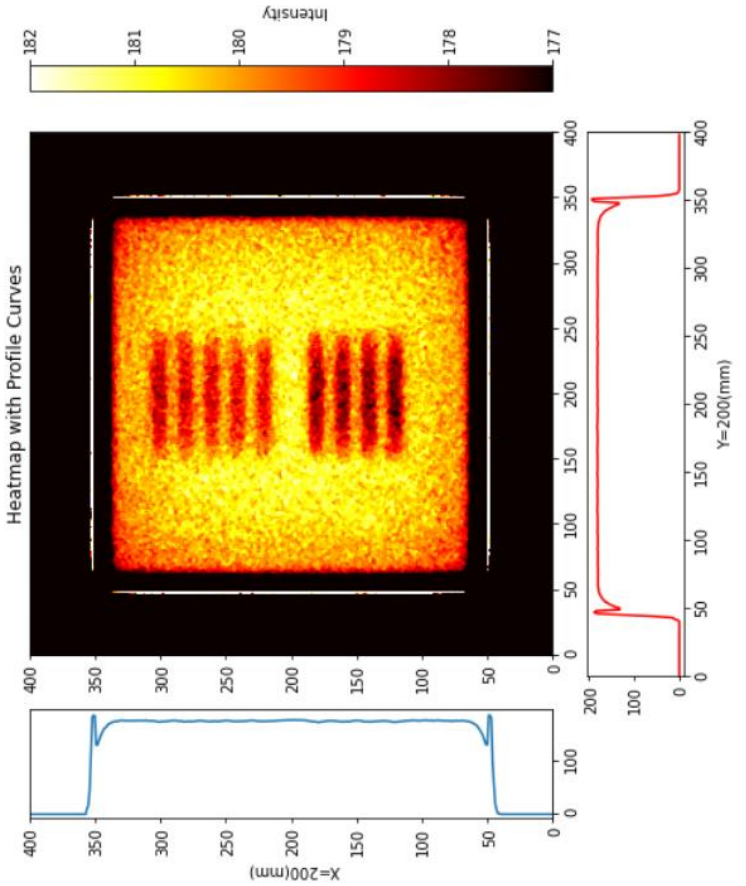
加速器缪子成像的密度分辨率





a=10cm，b=1cm，c=1cm

被CaCO3材料包裹的SiO2材料



- CaCO3的尺寸为：30cm×30cm×60cm
- SiO2的为直径10cm，厚度1cm的圆盘
- 束流缪子的能量为：1GeV

二氧化硅实际的密度为2.65g/cm^3

碳酸钙的实际密度为2.71g/cm^3

- 1GeV的缪子，~6e6/cm^{2}的通量下，可以区分CaCO3包裹体内密度差异0.1g/cm^{3}的SiO2

目录

HIAF总体进展

土建完工，配套全部投入运行，工艺设备安装全部完成，核心关键设备通过工艺测试验收，束流全线贯通

HIAF总体进展

装置占地440亩，建筑面积5.8万平米，包括2.0公里地下隧道与10个地上单体建筑；已通过建安工程专项验收

一号测试大厅

二号测试大厅

制冷中心

综合测试大厅

直线设备楼

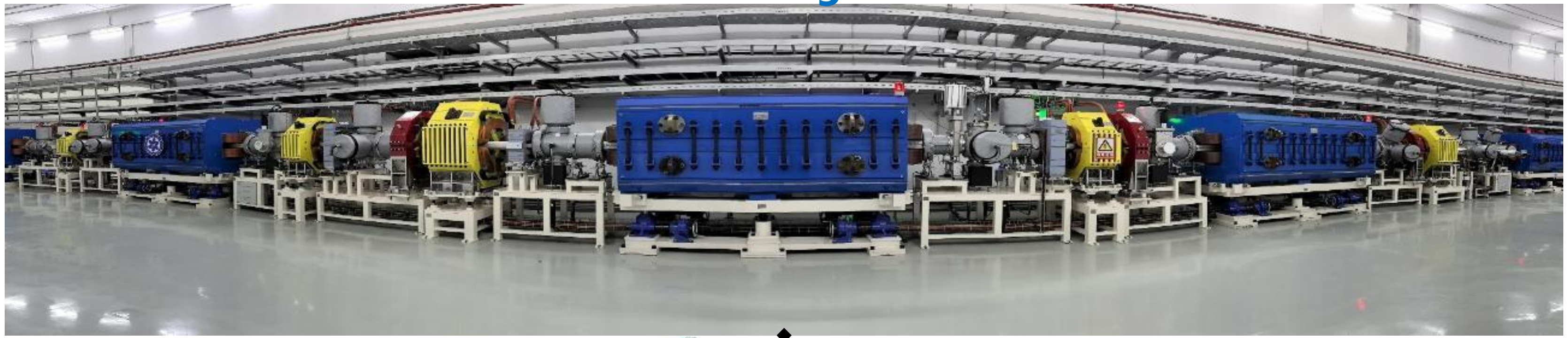
中央控制楼

HIAF总体进展

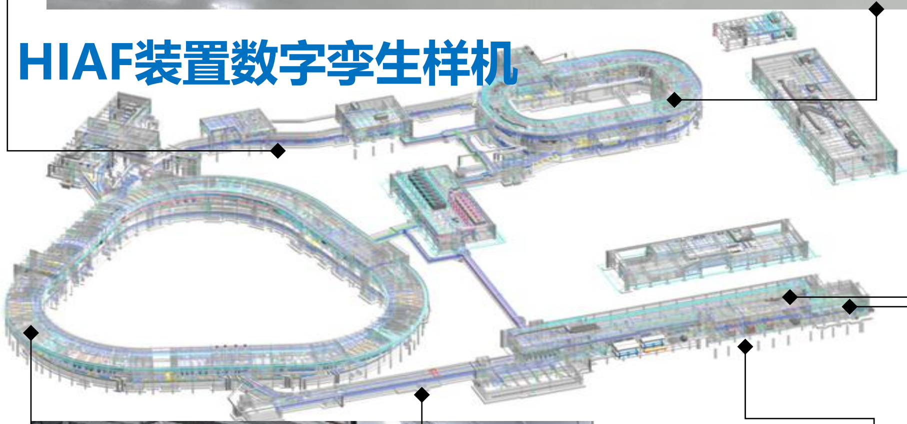
加速器工艺设备安装全部完成，真空全线贯通，设备联调联测全部完成

HIRIBL

SRing

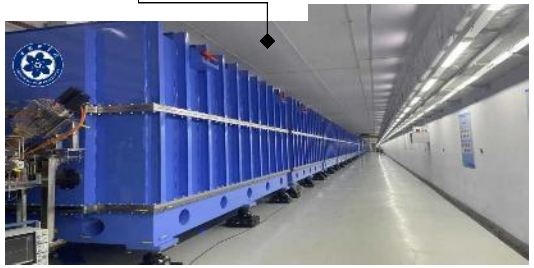


HIAF装置数字孪生样机

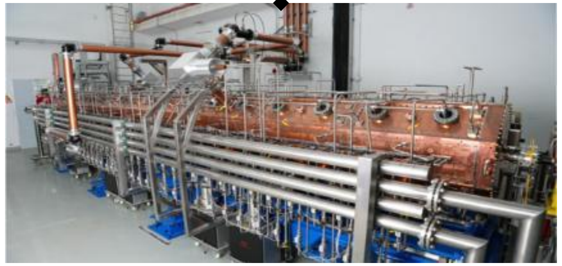


BRing

Bring injector



SC LINAC



LINAC

HIAF总体进展：首次束流调试

HIAF束流调试一次成功，10.27 成功出束，10.28 全线贯通，为后续指标调试和项目验收奠定了坚实基础

《科学》杂志报道强流重离子加速器装置调试成功

Heavy-ion accelerator fires up

An accelerator that will produce the world's most intense pulses of heavy ions generated its first beam on 28 October. When fully operational, China's High Intensity heavy-ion Accelerator Facility (HIAF), nestled among the mountains of southern Guangdong province, will send pulses of exotic, short-lived ions into fixed targets or into a storage ring to support research on the properties of atomic nuclei and how stars forge heavy elements, as well as material sciences and biomedicine. The research center, which joins the ranks of similar facilities worldwide, represents a $420 million investment by the Chinese Academy of Sciences's Institute of Modern Physics. Institute officials say HIAF will be open to foreign researchers. —Dennis Normile

- 国内缪子源发展蓬勃
- HIAF装置已经束流全线贯通，HIRIBL次级束线具备产生GeV能量单能缪子的能力
- HIAF可以为缪子源、缪子物理和应用的发展提供新的机遇。

Thank you for your attention!


Welcome collaborations !