PKMu缪子实验：新物理、暗物质探测与成像进展
PKMu: Probing and Knocking with Muons

Qite Li（李奇特）, Zhou Chen（周辰）, Qiang Li（李强）
On behalf of the PKMu collaborators

第十四届全国先进气体探测器研讨会
2026.7.23 广东 惠州

CONTENTS

目录

The PKMu Initiative: Probing and Knocking with Muons

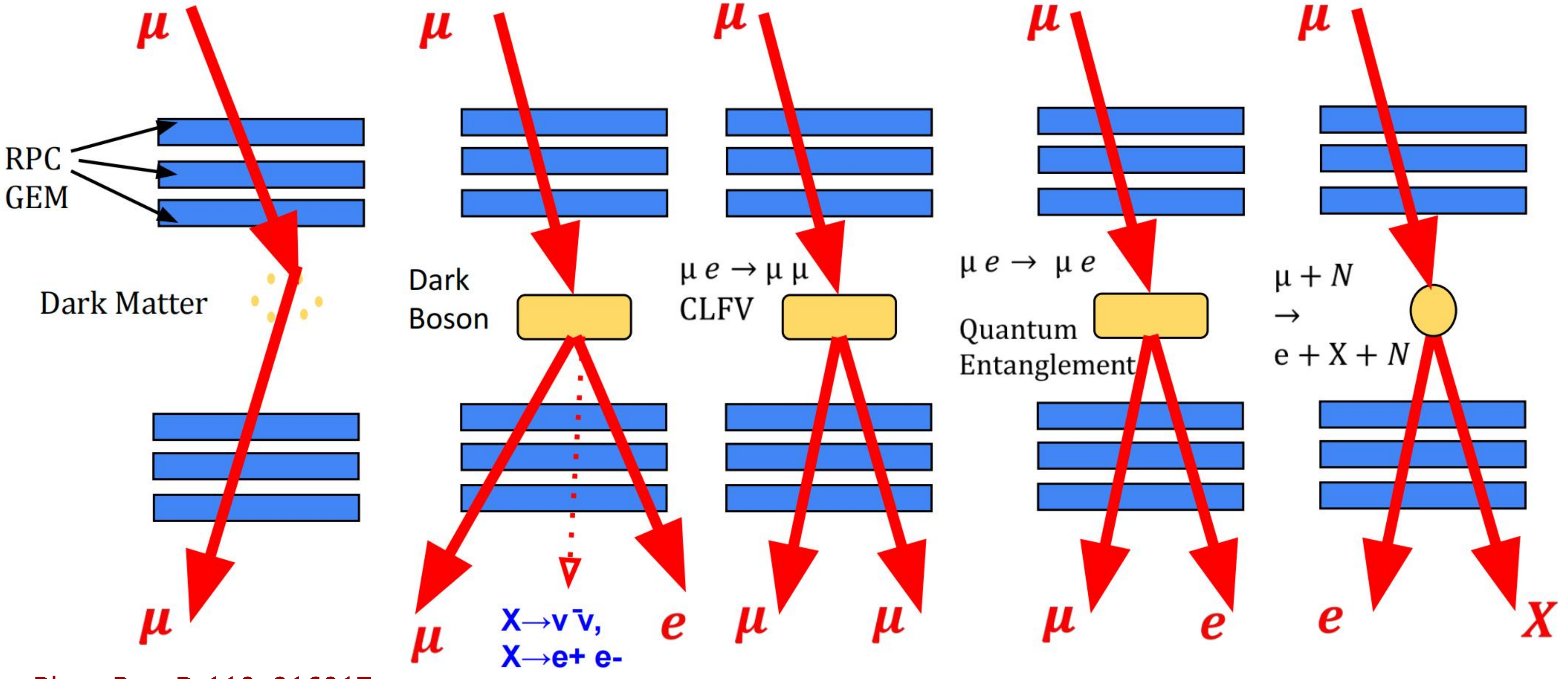
- **Core Goal:** A comprehensive muon-scattering experiment program to explore intresting and new physics.
- **Our Strategy — 创新Innovation, 灵活Agility, and 高影响力High Impact**
  - **Phase I:** Use cosmic-ray muons + self-developed high-precision RPC/GEM detectors
  - **Phase II:** Transition to high-intensity muon beams at Chinese facilities

PKMu Research Landscape:

Innovative and Affordable Muon Scattering Experiment

Mod. Phys. Lett. A 40, 2530008 (2025)

Chin. Sci. Bull. 71, 894 (2026)



Phys. Rev. D 110, 016017

Phys. Rev. Lett. 136, 151001

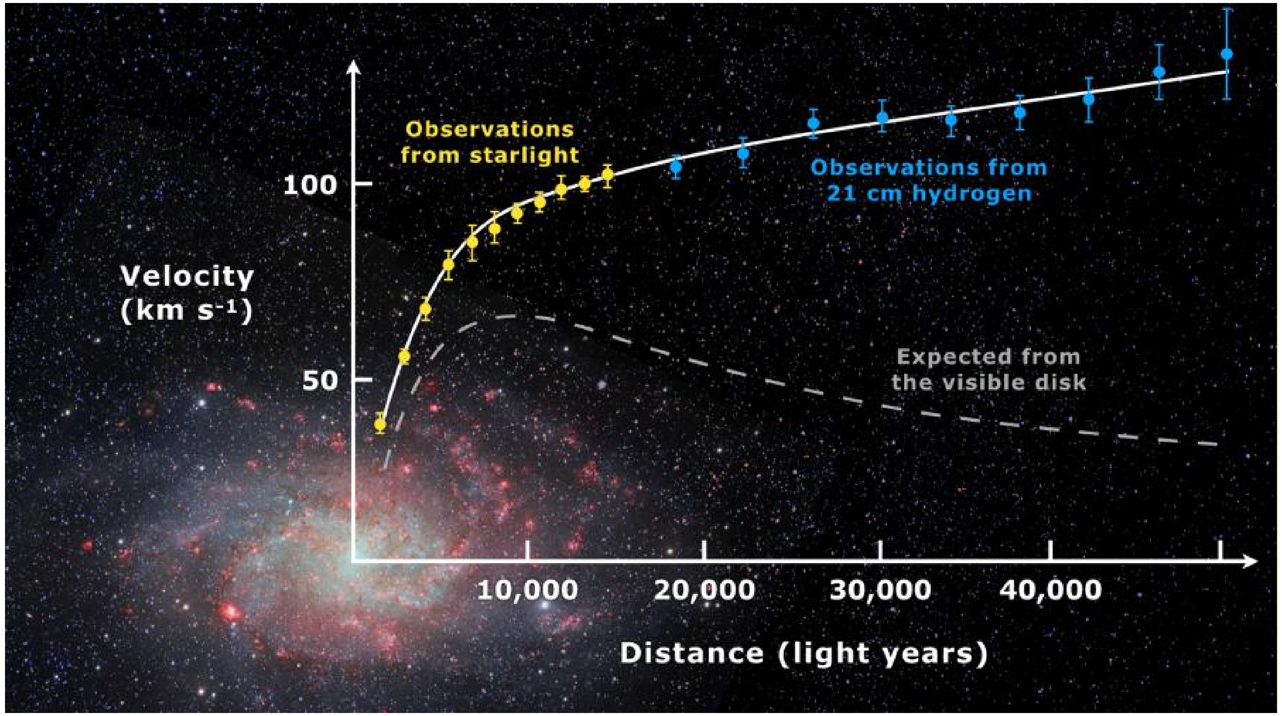
Int. J. Mod. Phys. A 40, 2550164

Phys. Rev. D 113, 072008

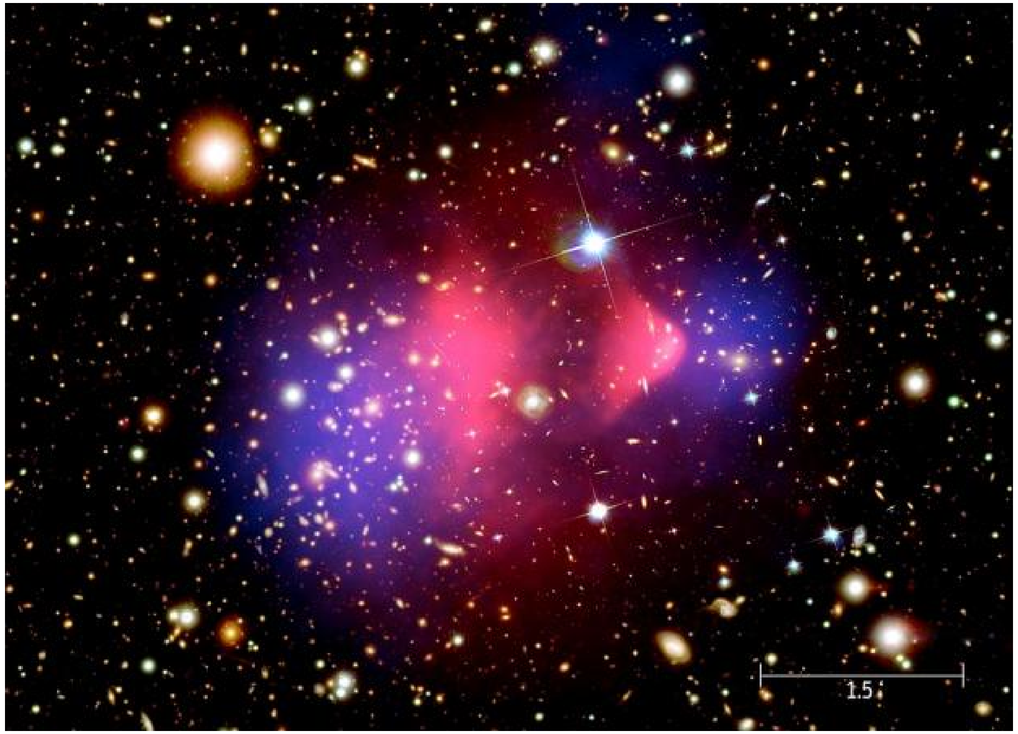
J. Phys. G: Nucl. Part. Phys. 52 075002

Evidence for the Existence of Dark Matter

- Galaxy rotation curve： Observed vs. predicted mismatch.(1933/1970s)
- Bullet Cluster： Dark matter in galaxy collision.
- Normal Matter : Dark Matter : Dark Energy = 5 : 27 : 68



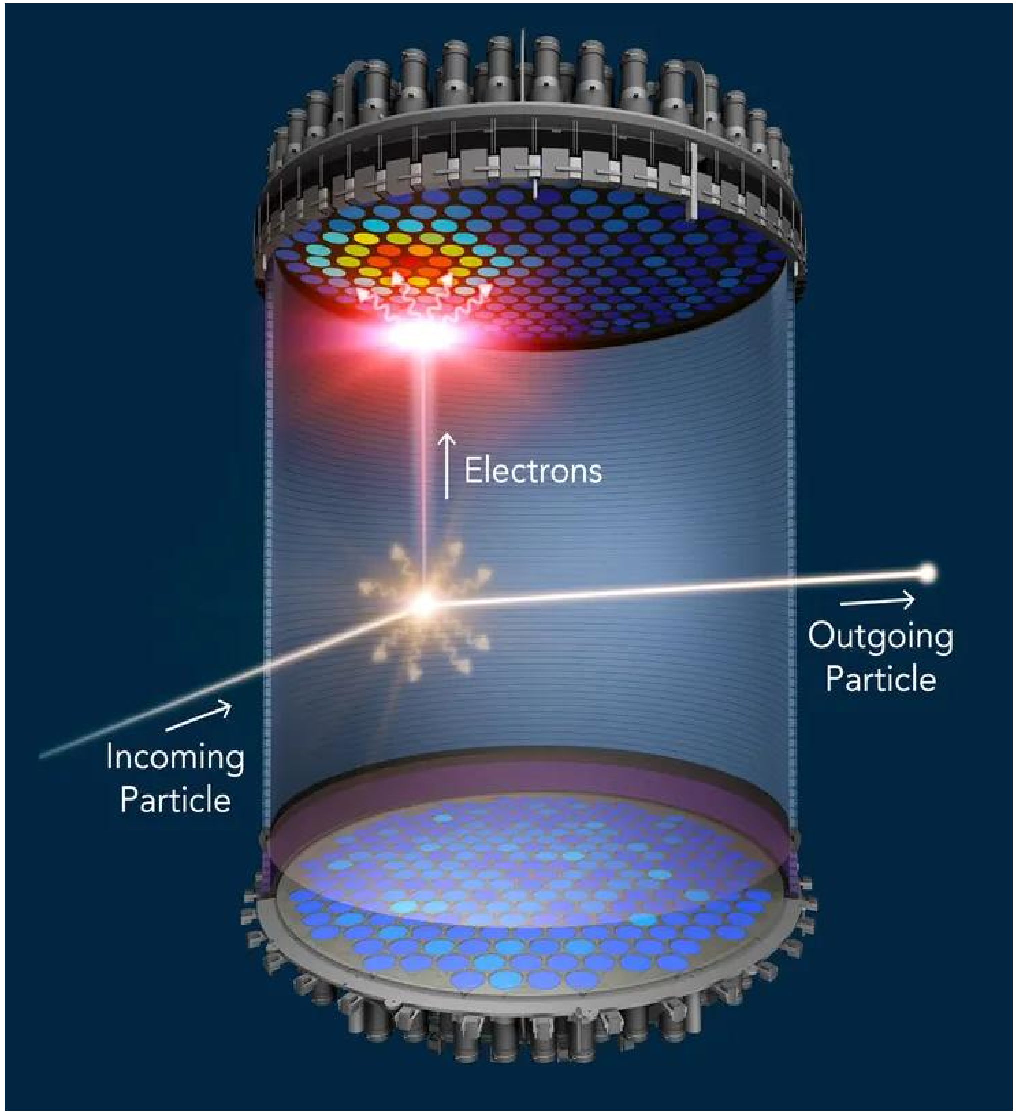
Credit: Mario De Leo. CC BY-SA 4.0.



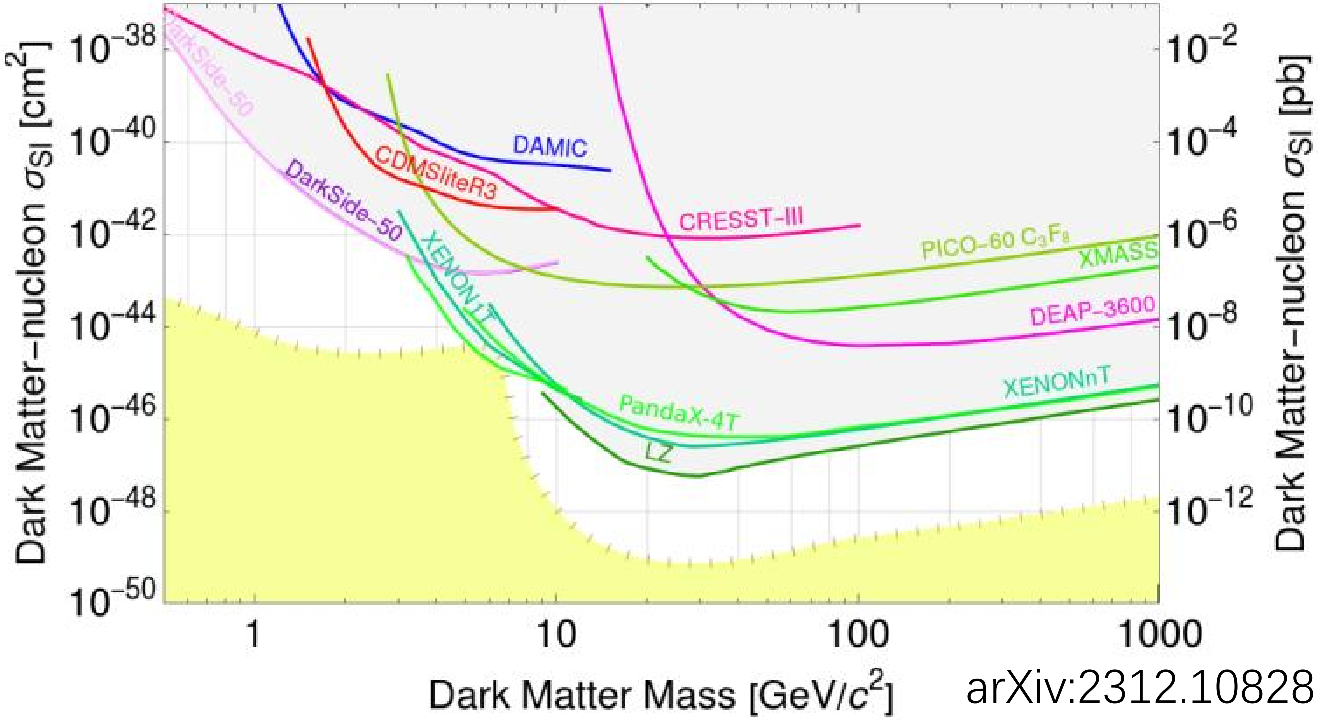
Credit: x-ray: NASA/CXC/CfA/M. Markevitch et al.; optical: NASA/STScI, Magellan/U. Arizona/D. Clowe et al.; lensing map: NASA/STScI ESO WFI, Magellan/U. Arizona/D. Clowe et al.

- Gravitational lensing, microwave background radiation。

Direct Search for Dark Matter (WIMPs)



Credit: LZ Experiment



arXiv:2312.10828

13 December 2024 Nature News:

First sighting of ‘neutrino fog’ sparks excitement

– but is it bad news for dark matter?

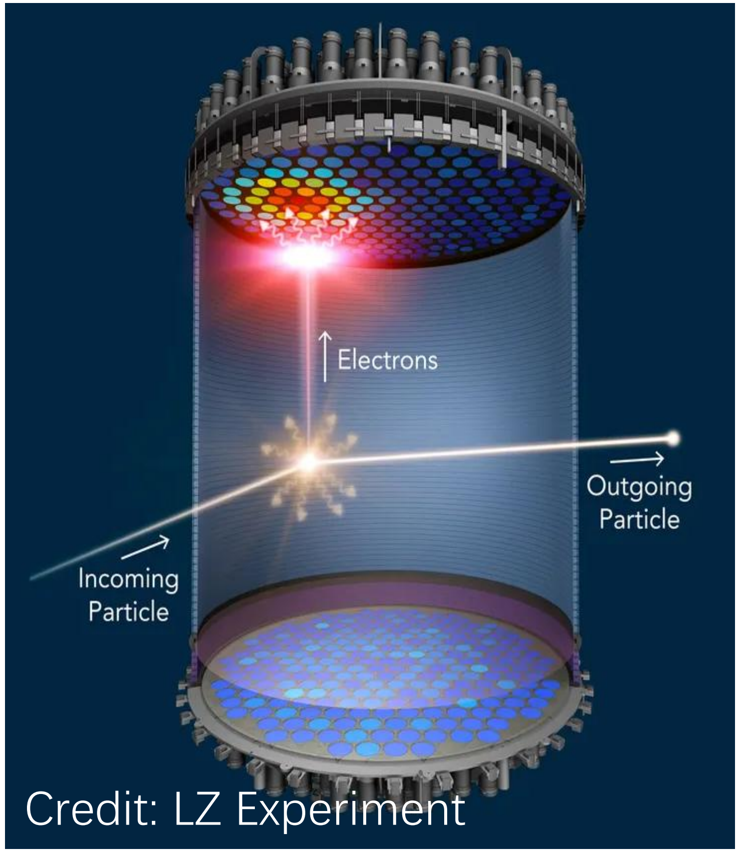
Phys. Rev. Lett. 133, 191001 (2024). && Phys. Rev. Lett. 133, 191002 (2024).

Phys. Rev. Lett. 135, 011802 (2025)

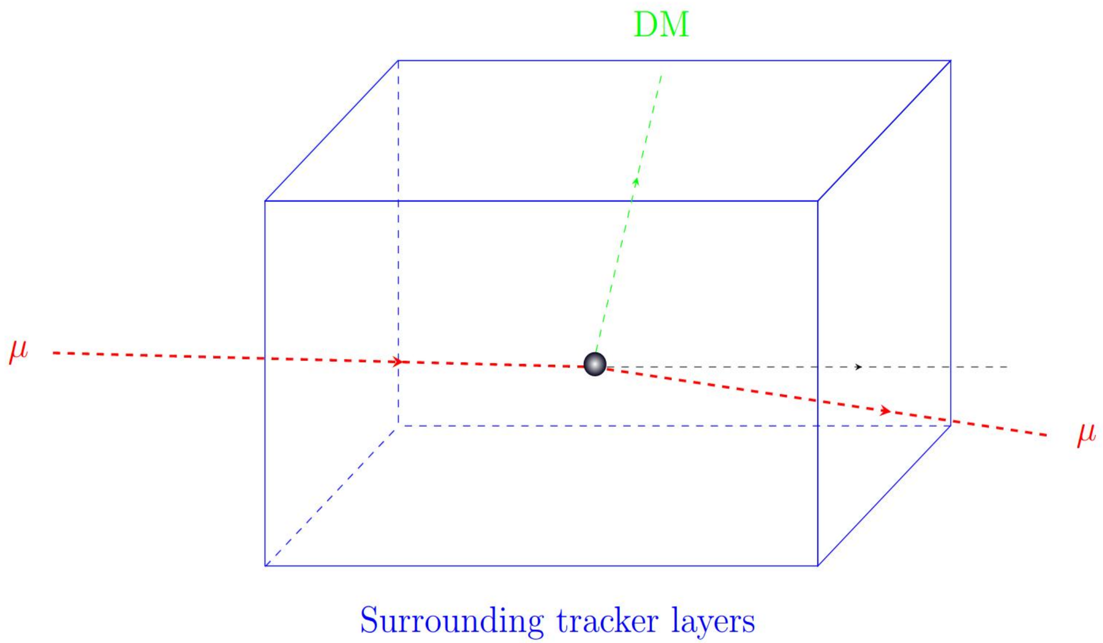
Using Muons to Probe Dark Matter

Muon-dark matter interactions remain understudied. Muons are second-generation leptons in the Standard Model. Free muons are short-lived/rare in the universe.

1. **Passive Waiting to Active Knocking:** Enhanced sensitivity to light-mass dark matter
2. **Cosmic Muon from Background to SIGNAL:** Complementary approaches



Credit: LZ Experiment



If DM scatters muons, the observable is the deflection angle

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Phys. Rev. D 110, 016017(2024)

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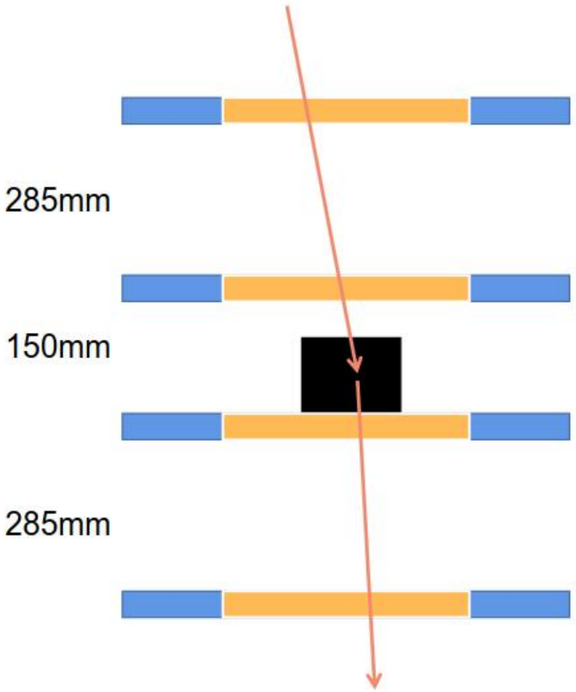
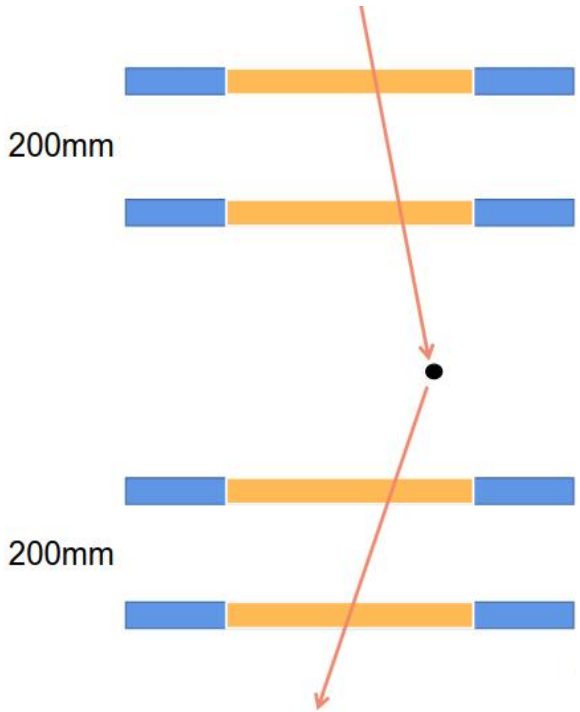
Proposed Peking University muon experiment for muon tomography and dark matter search

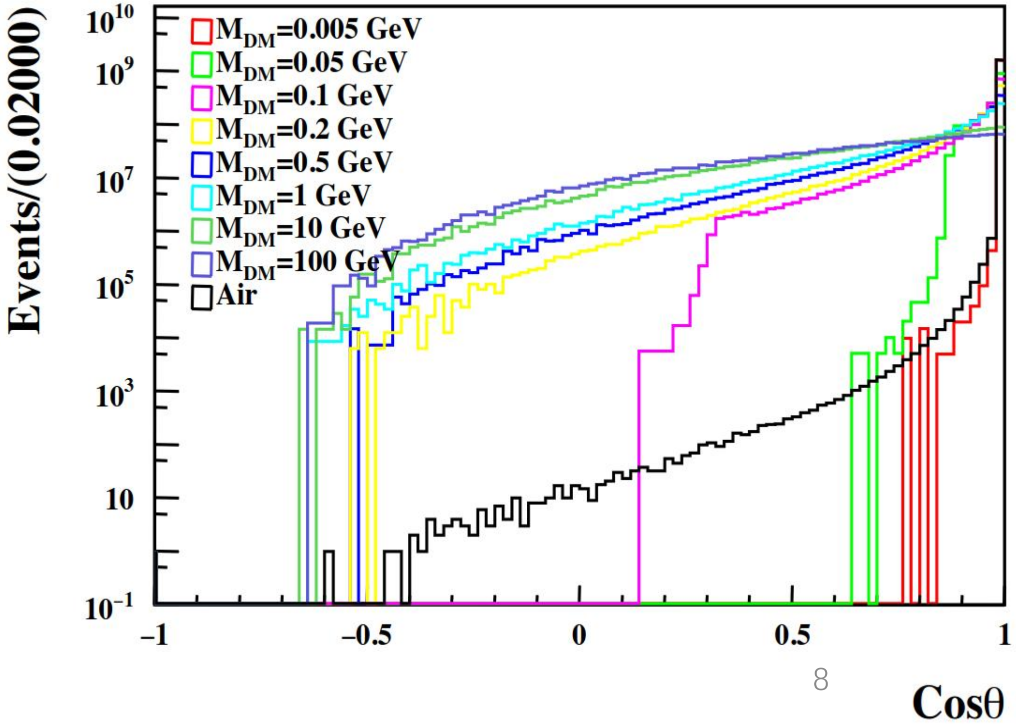
缪子穿过1m厚度空气及不同质量暗物质的散射角模拟结果
Geant4 simulation results for muon scattering with 1m thick air or DM

Muon Tomography 缪子散射成像
测量样品散射角



Dark Matter Search暗物质寻找
测量缪子暗物质散射角

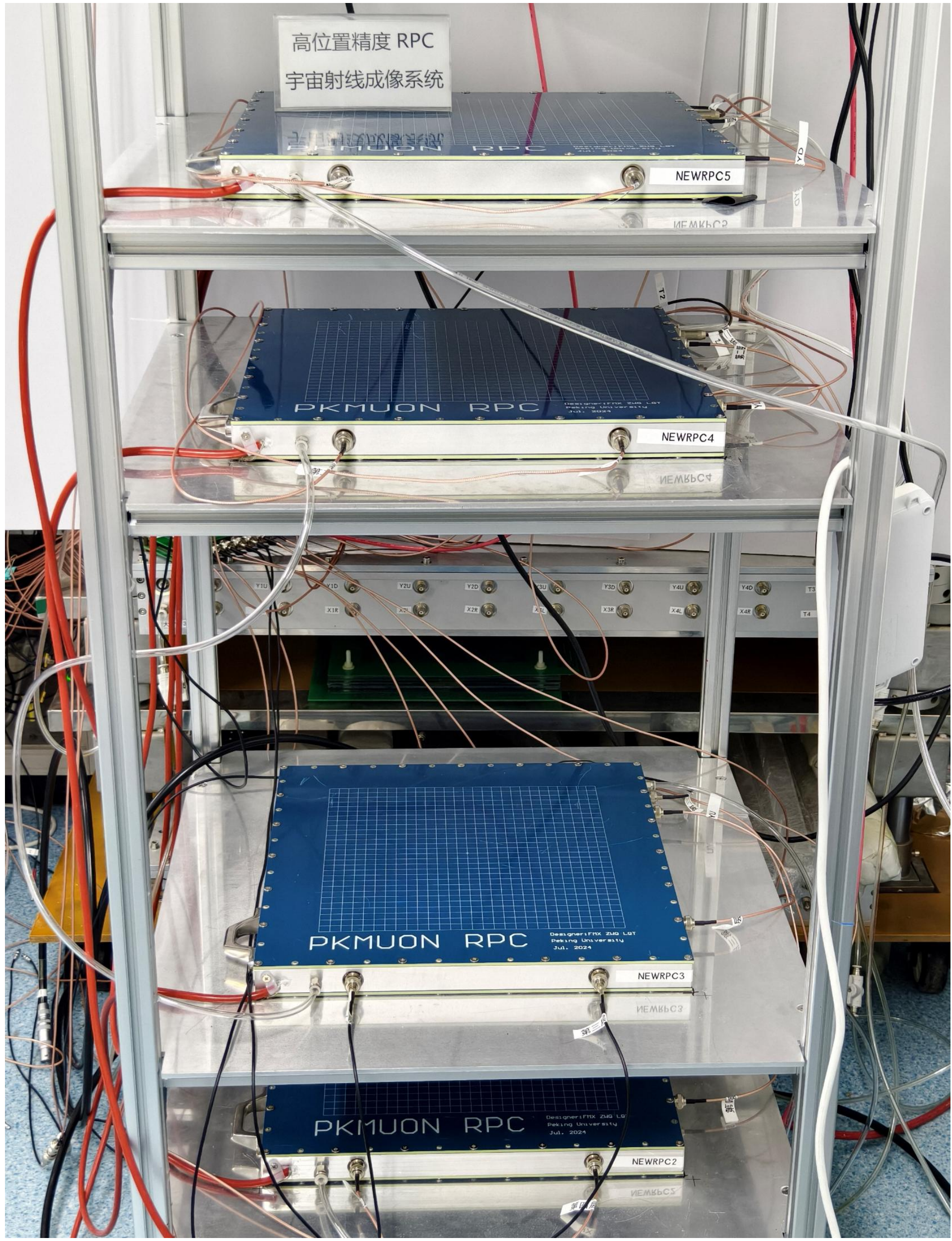




PKMu Cosmic Ray Tomography System(2025)

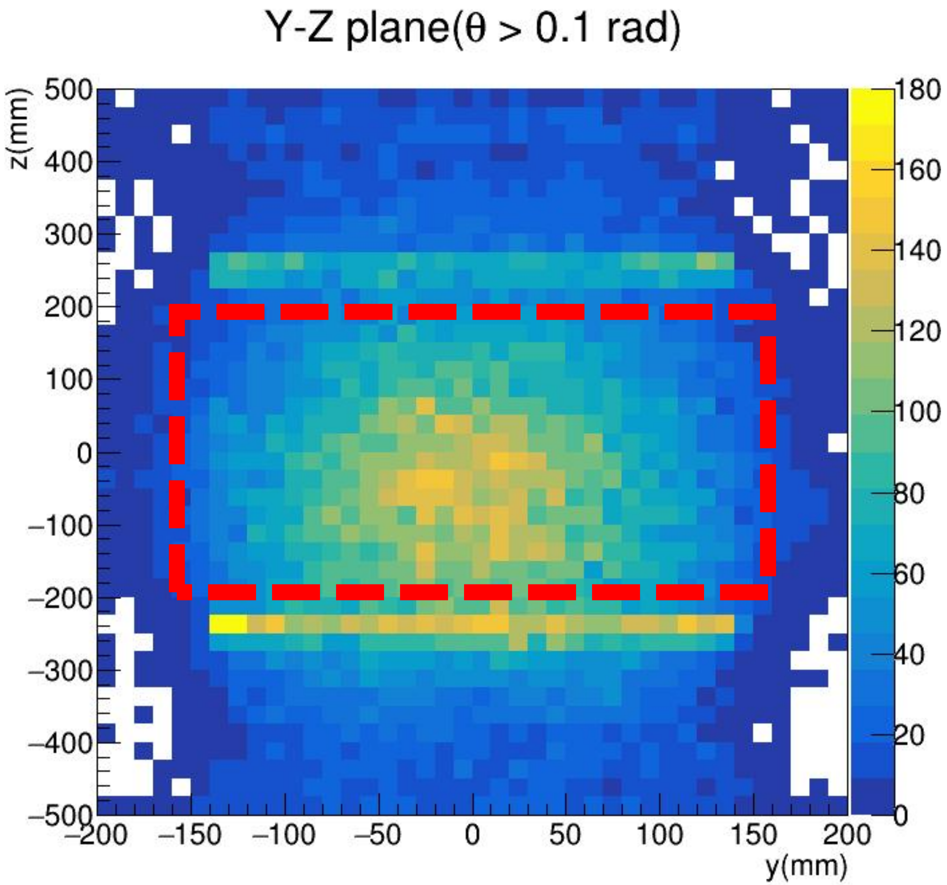
- 4 layers of glass RPC with LC delay-line readout
  - Active area 28×28 cm^2
  - vertical spacing 20–50–20 cm
  - Single RPC spatial resolution $\sigma \approx$ 0.5-0.7 mm

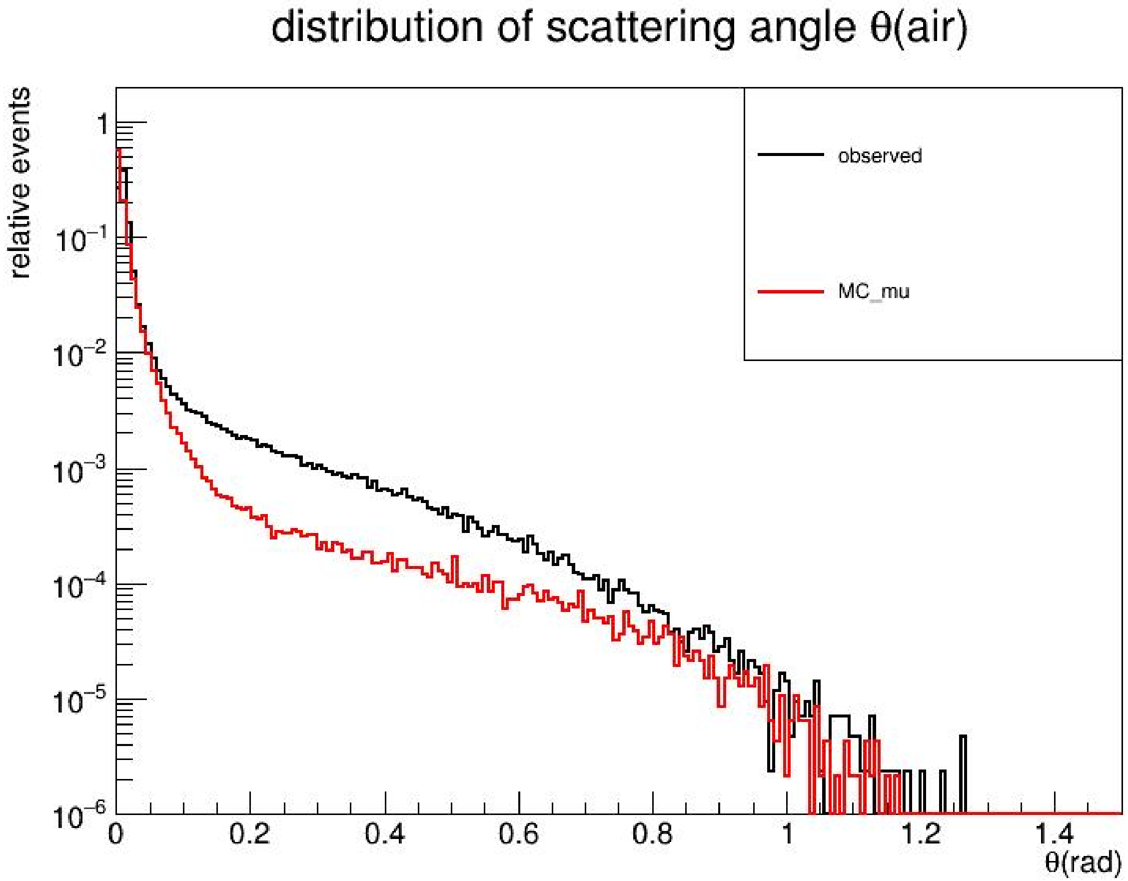
- 63-day continuous physics run: 1.18 million effective events recorded



Scattering Angle Distribution in ROI Area

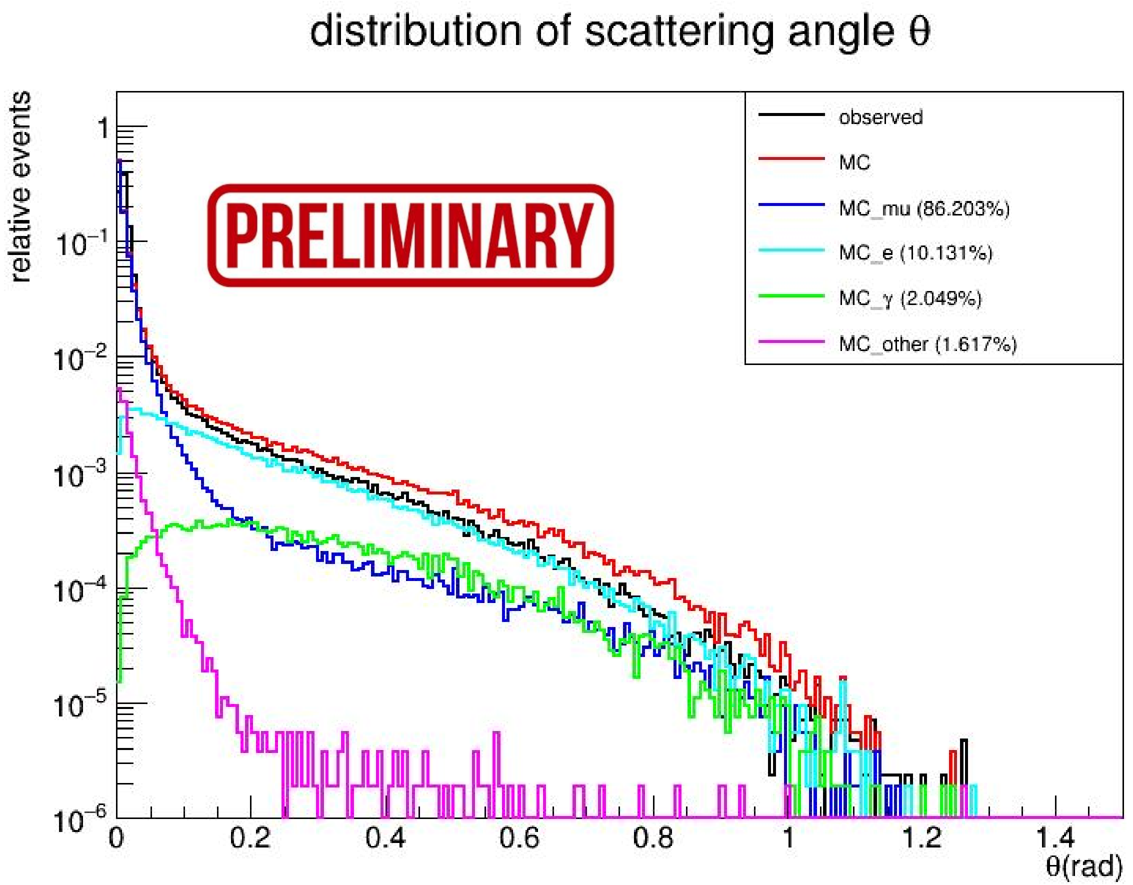
- Analyzed angular distribution within detector’s sensitive volume (-200 mm<z<200 mm)
- Large-angle scattering events persist after selection





Simulation of Cosmic Rays at Sea Level(All-Particle Composition)

- Simulated particle components at sea level: μ, e, γ, p, n, π
- Small-angle scattering dominated by muons
- Large-angle scattering primarily from electrons and photons
- Possible discrepancies between measured particle composition and simulation results.



Simulation of Cosmic Rays at Sea Level(All-Particle Composition)

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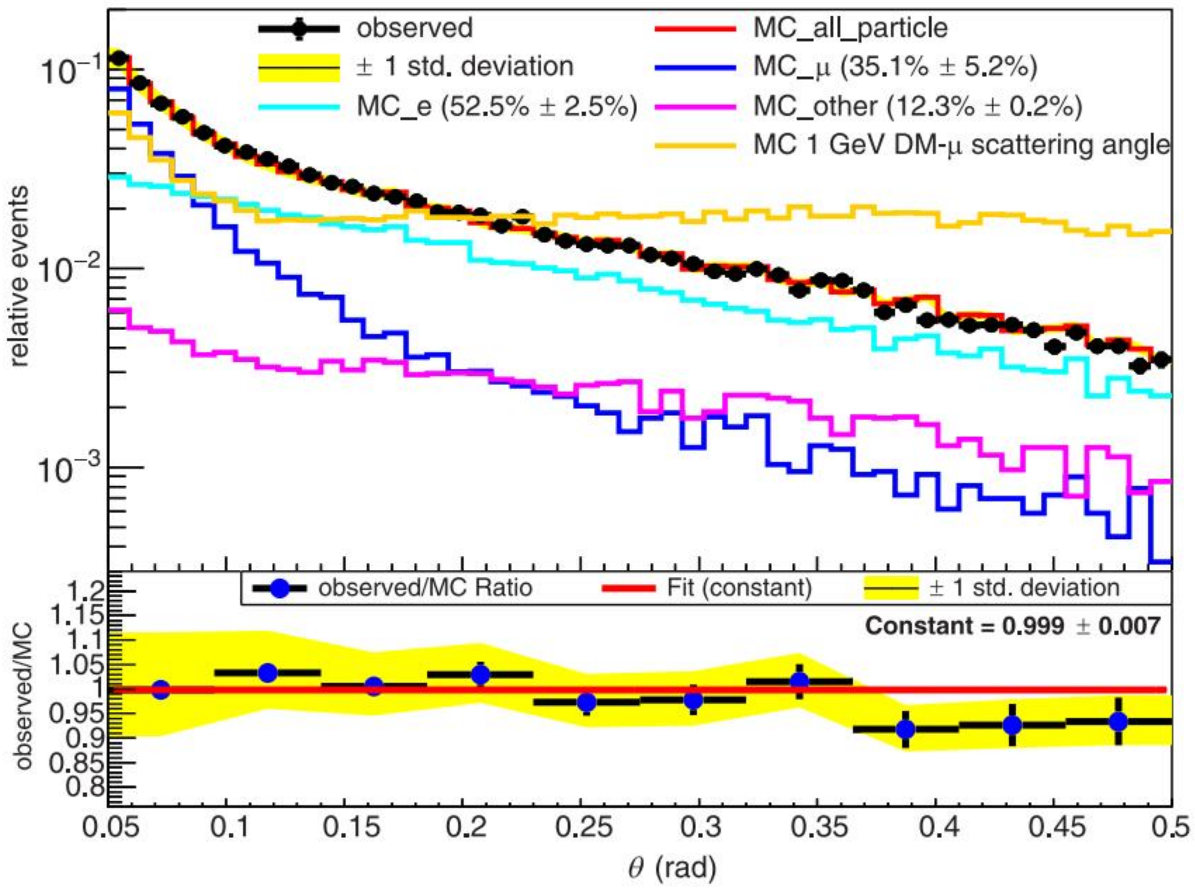


PKMu cosmic ray DM search

- At the 95% confidence level, the limit reaches 1.62×10^{-17} cm^2
- for 1 GeV slow DM, demonstrating sensitivity limit to light muon-coupled slow DM.
- the first limit from direct muon-DM scattering measurement.
- New DM search method
- Projection: 1 m^3 detector + 1 year exposure + full angular range → 4–5 orders of magnitude improvement

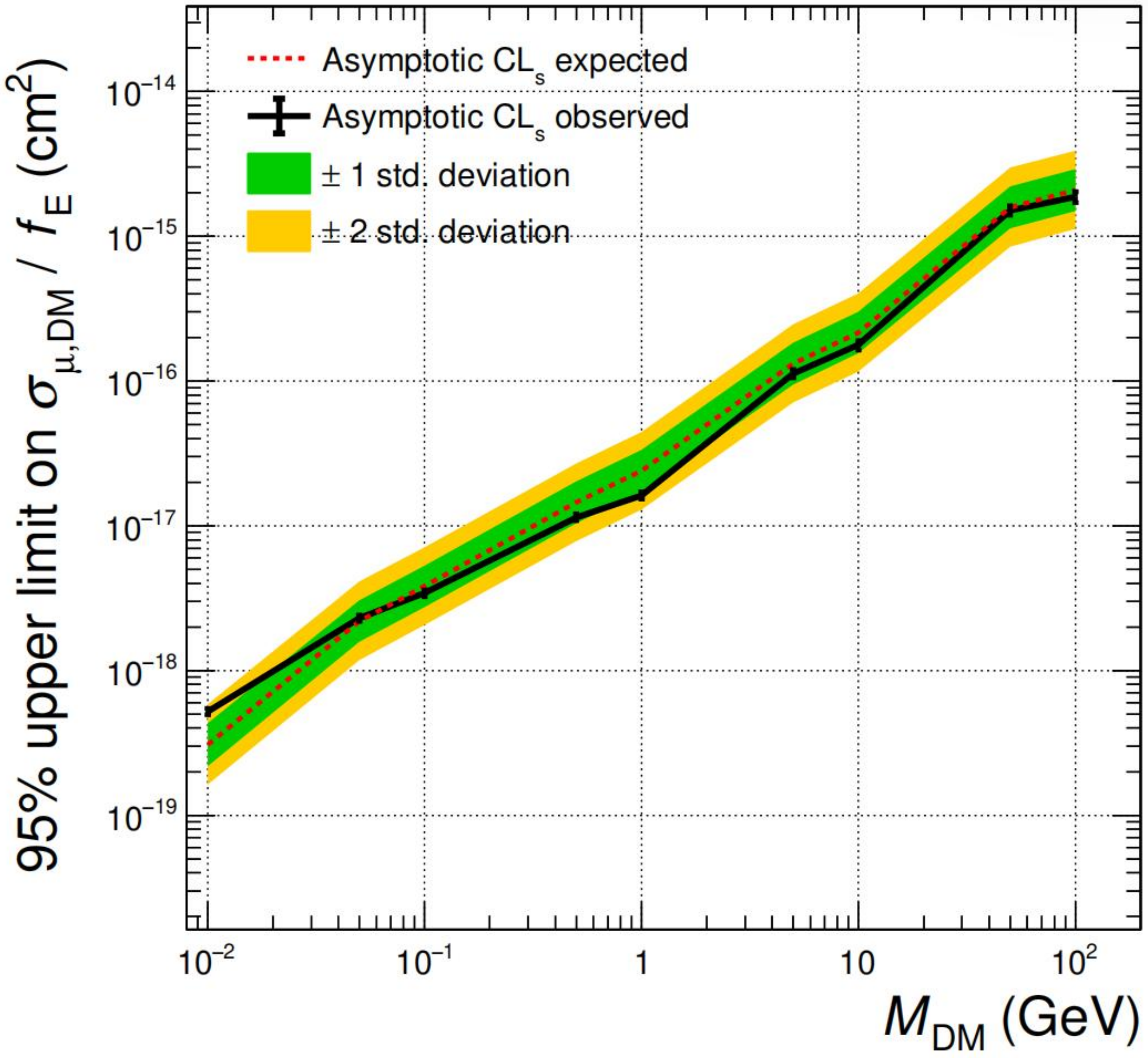


FIG. 4: Expected and observed 95% CL upper limits on the DM-muon interaction cross section versus M_{DM}. he green and yellow bands represent the 1σ and 2σ regions, respectively.

Phys. Rev. Lett. 136, 151001 Take-Home Message

- ☑ Precision sea-level electron fraction (Δ~2%)
- ☑ First direct cosmic-ray muon-DM scattering limit (1.6×10^{-17} cm² @ 1 GeV)
- ☑ Deep understanding of secondary backgrounds
- ☑ Cosmic Muon from Background to SIGNAL
- **→Cheng-en Liu’ s Poster**

★ ★ ★ ★ ★ APS promotion★ ★ ★ ★ ★

北京大学研究人员筛选百万个宇宙线散射事件，在地球搜寻暗物质 | APS期刊重点内容

原创 APS APSPhysics 2026年4月24日 11:59

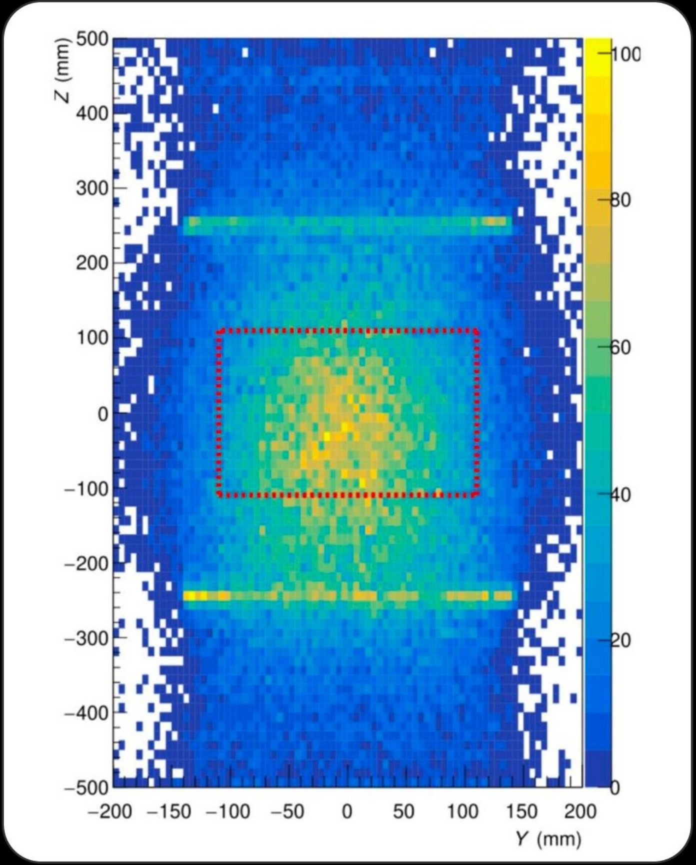
北京 2人

American Physic... @APS... · 12小时

Can #CosmicRays help us detect #DarkMatter on Earth? 🌍

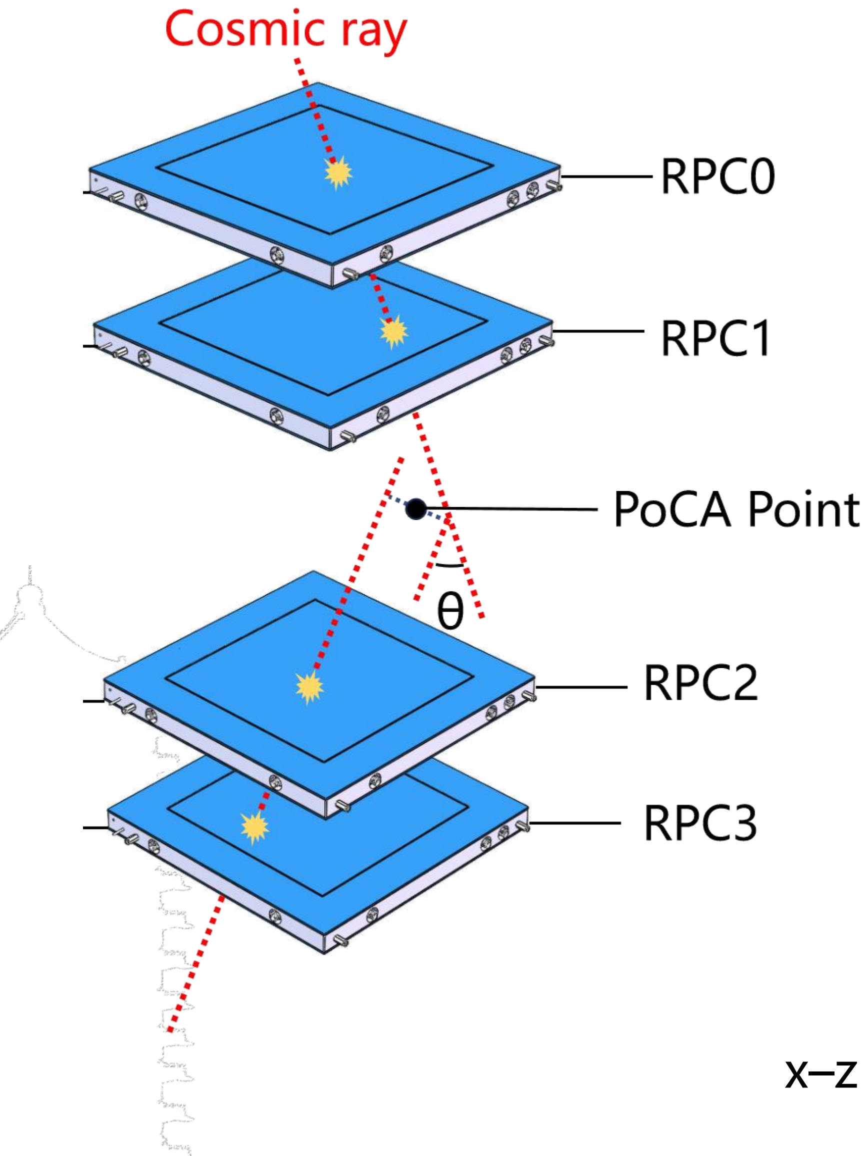
By tracking more than 1 million muon scattering events from secondary cosmic rays, researchers place new constraints on how dark matter might interact with ordinary matter. Read the paper in @PhysRevLett:

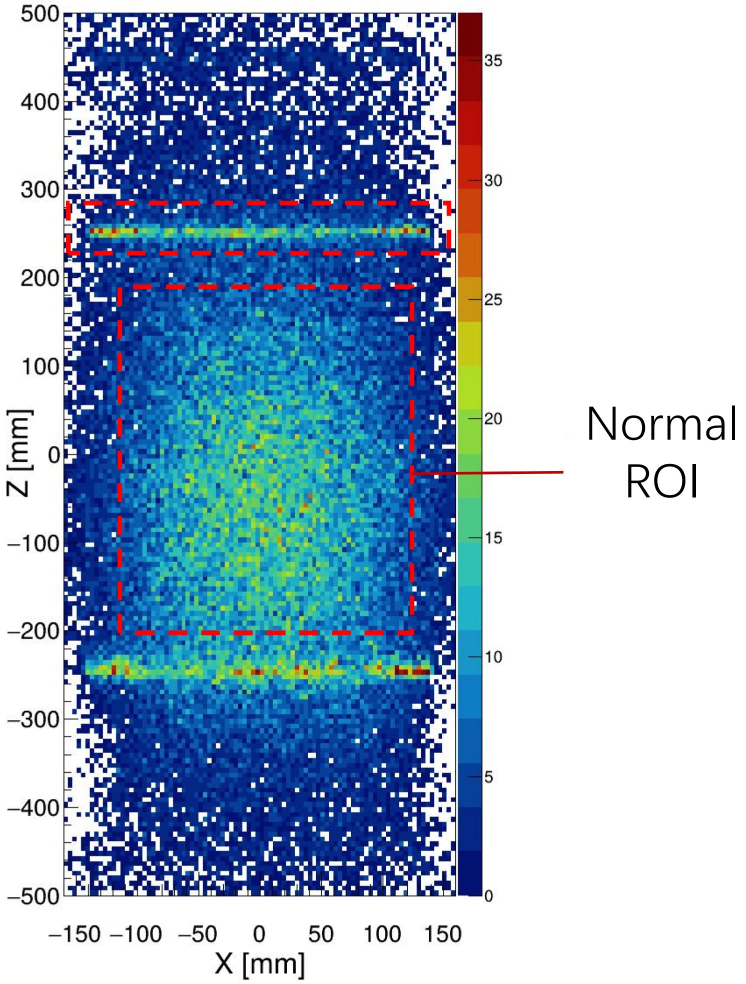
显示更多



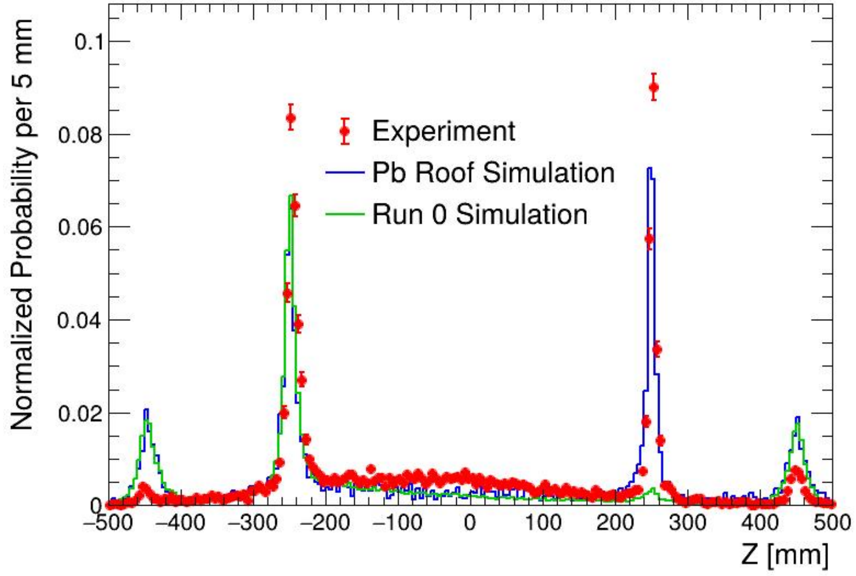
"Noise" Becomes Signal: Secondary Particle Signatures in Muography

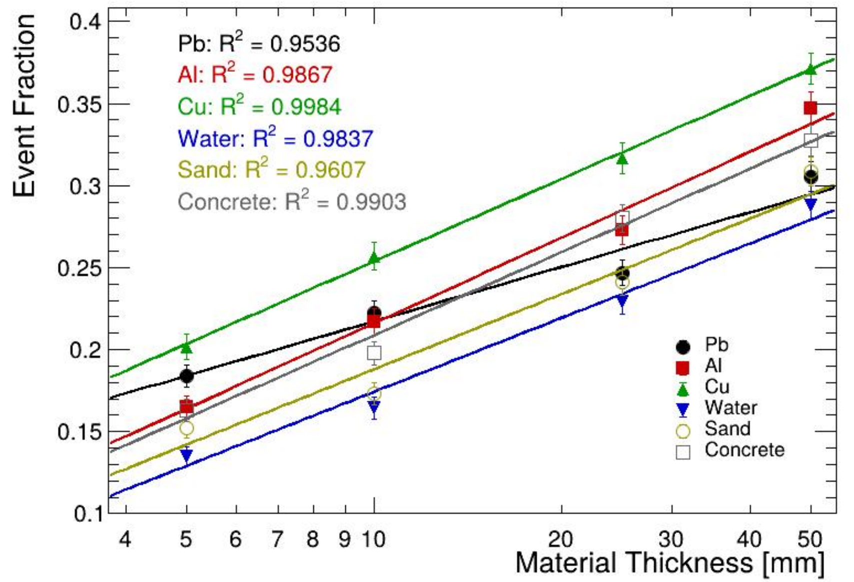
J. Appl. Phys. 139, 014903 (2026) **张荣峰本科生科研**





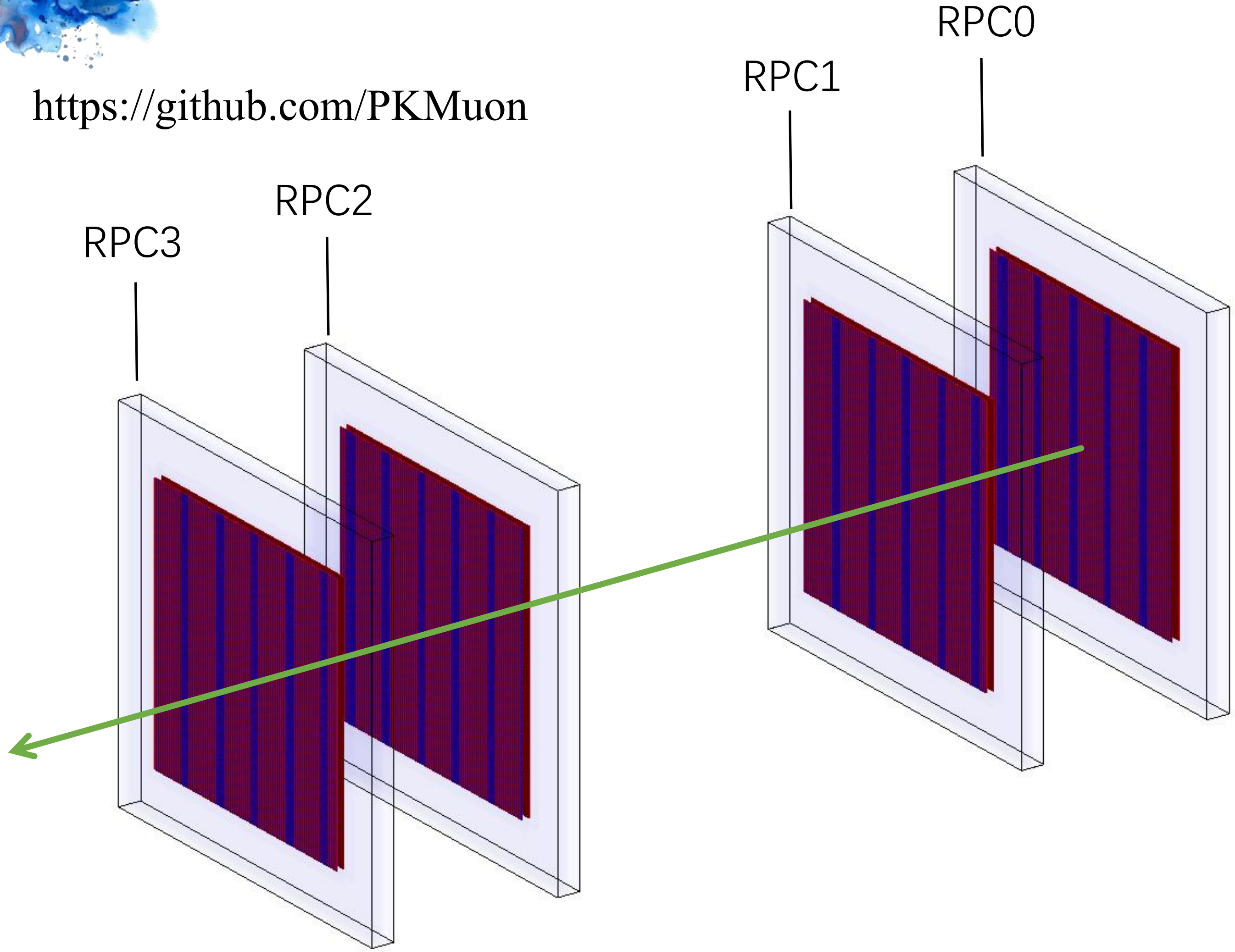
x–z distribution of PoCA points

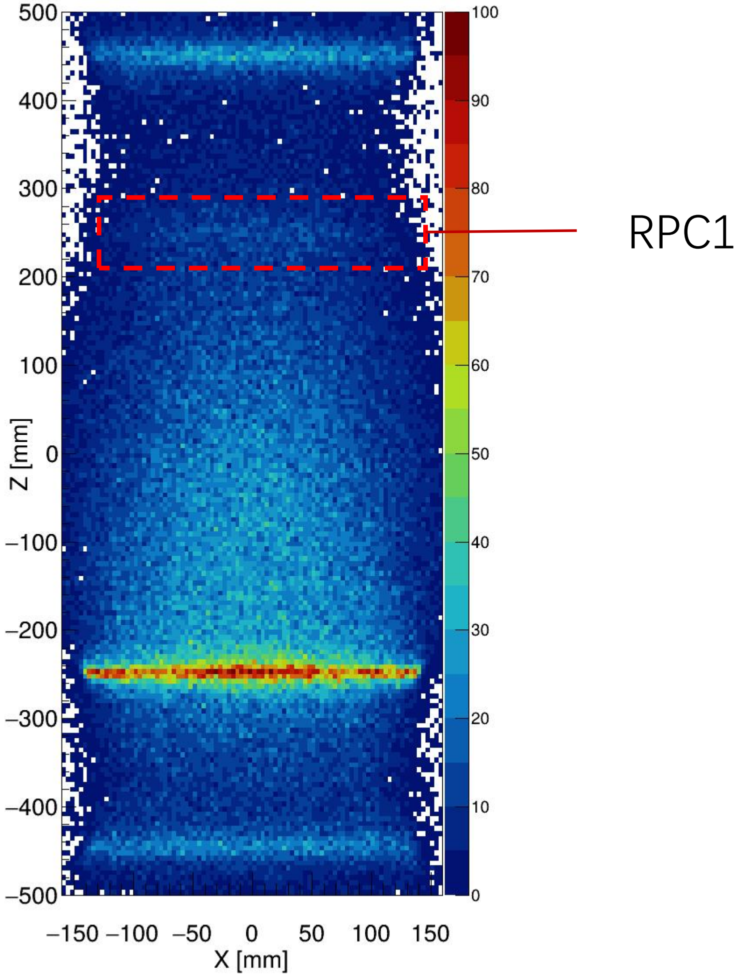




Geant4 Simulation version 1

https://github.com/PKMuon

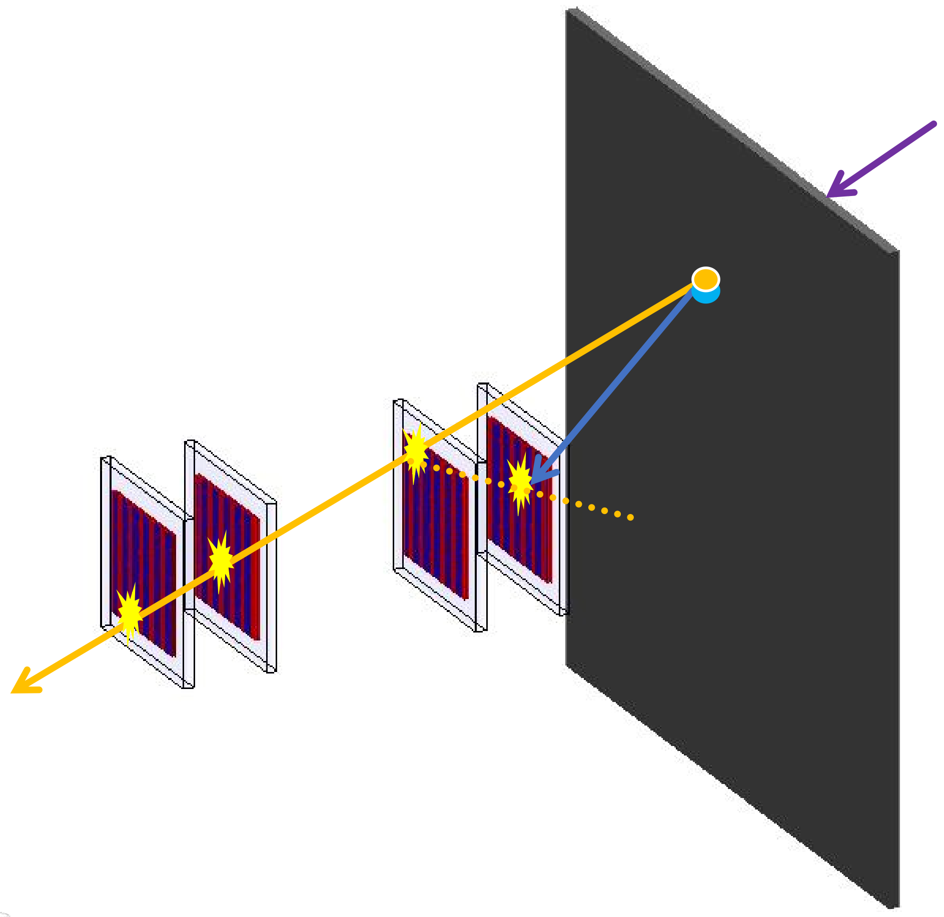


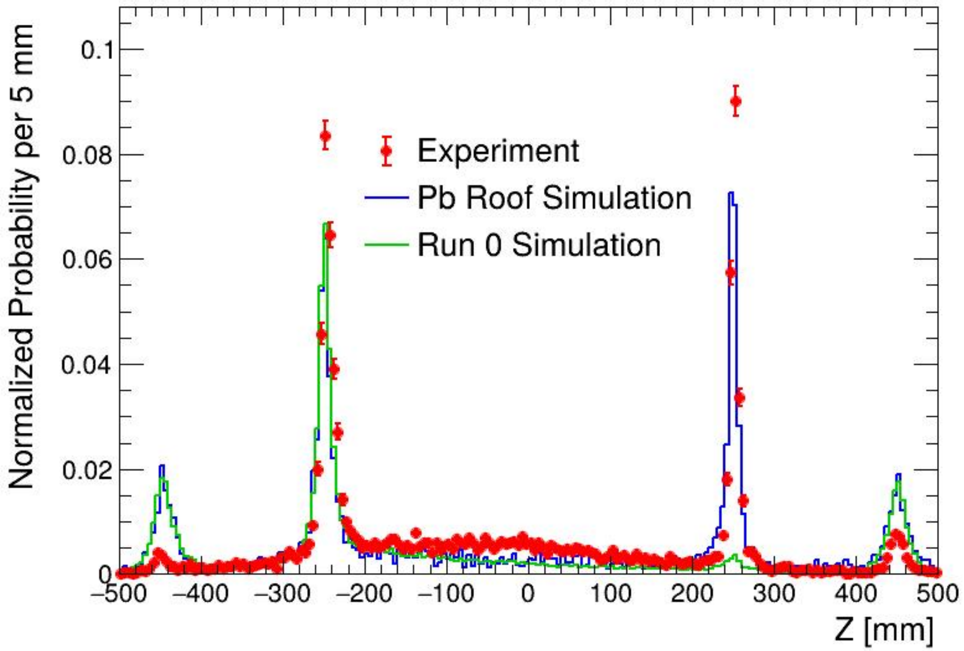


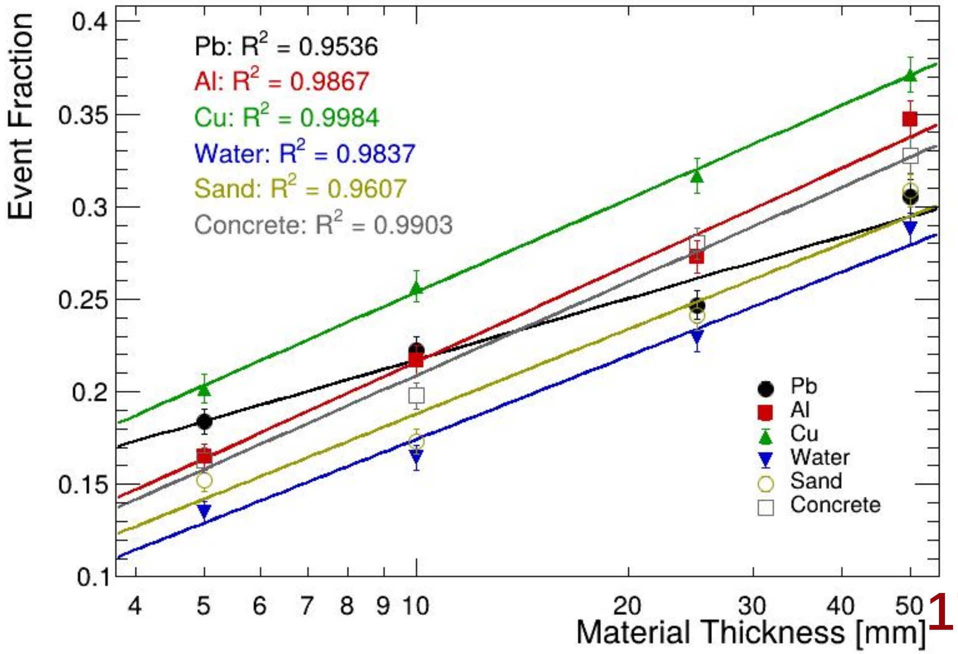
Simulation run0: Cosmic rays generated by CRY, with particles produced immediately above the top of RPC0
CRY: https://doi.org/10.1109/nssmic.2007.4437209

x–z distribution of PoCA points simulating air scattering

J. Appl. Phys. 139, 014903 (2026)

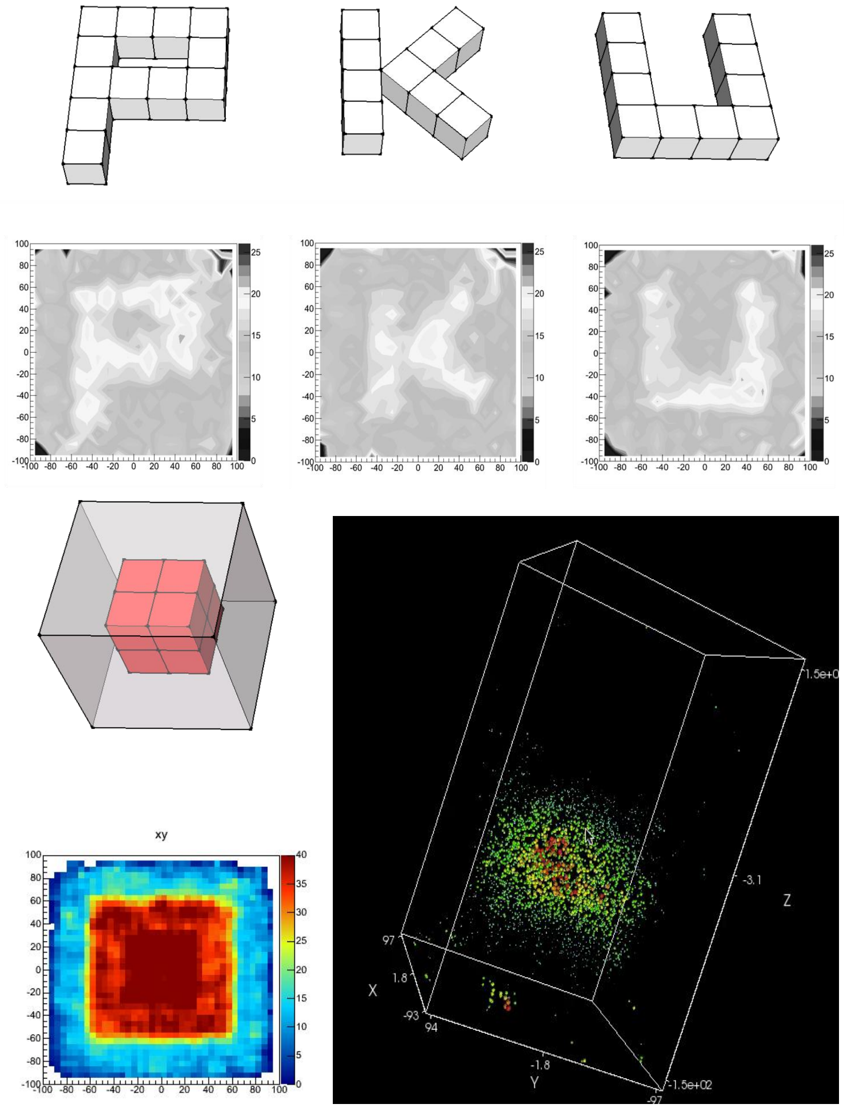


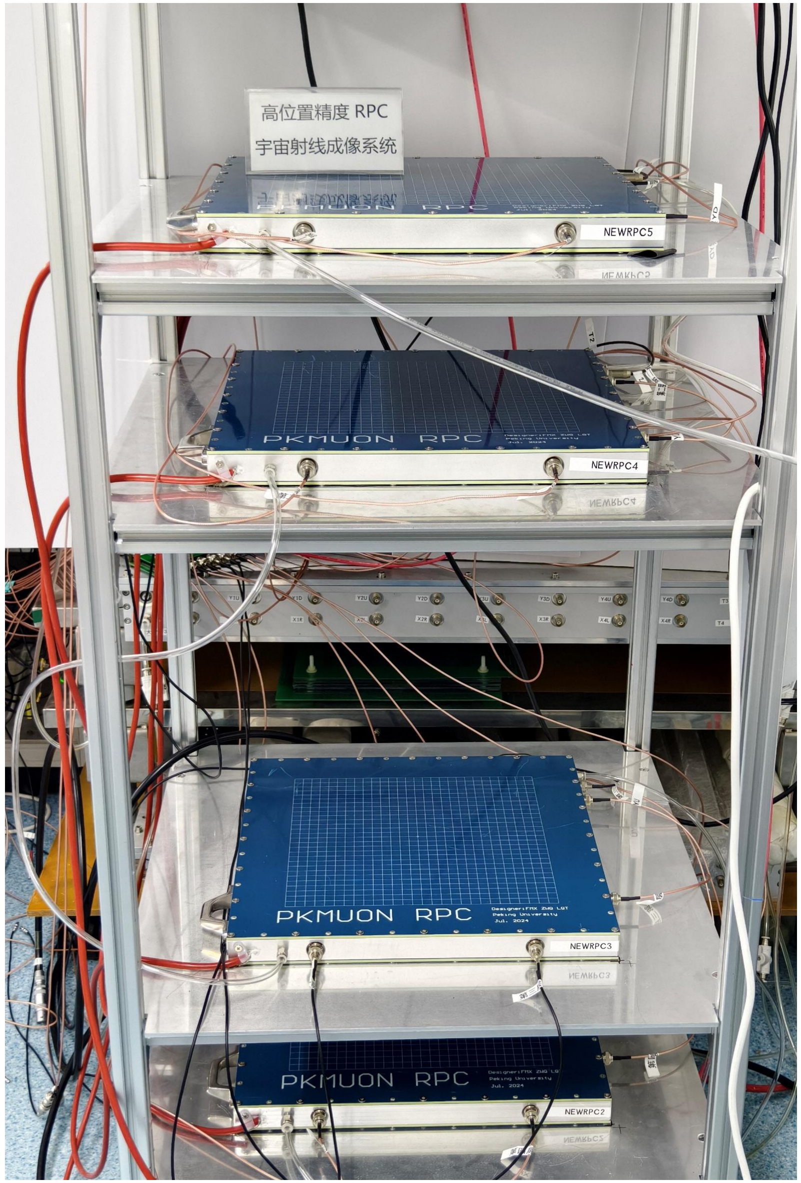




simulation run1:A large-area material simulating the roof effect is placed above the detection system, with particles generated at the top of this "roof."

PKMu成像方面创新工作---超越传统缪子散射成像的成像法





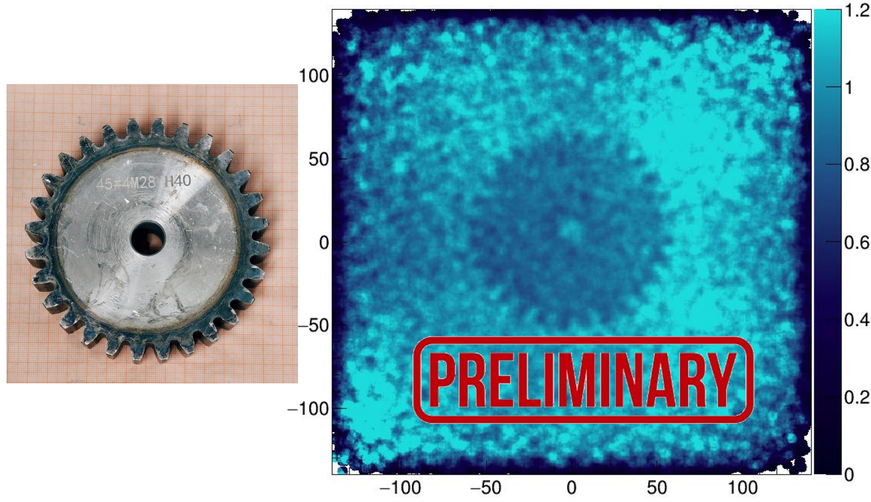
PμMA: 超高精度缪子成像 arXiv:2512.19747 （秦梓博本科生科研工作）

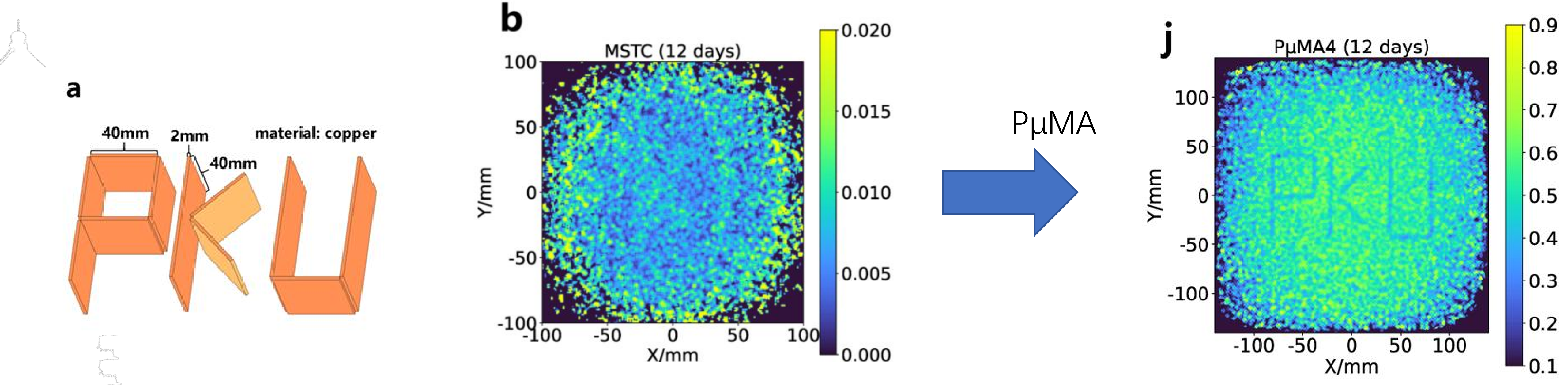
Problem: PoCA-based MST has poor spatial resolution for mm-scale object

Projection-shifted MUon transMission tomogrAghy (PμMA)

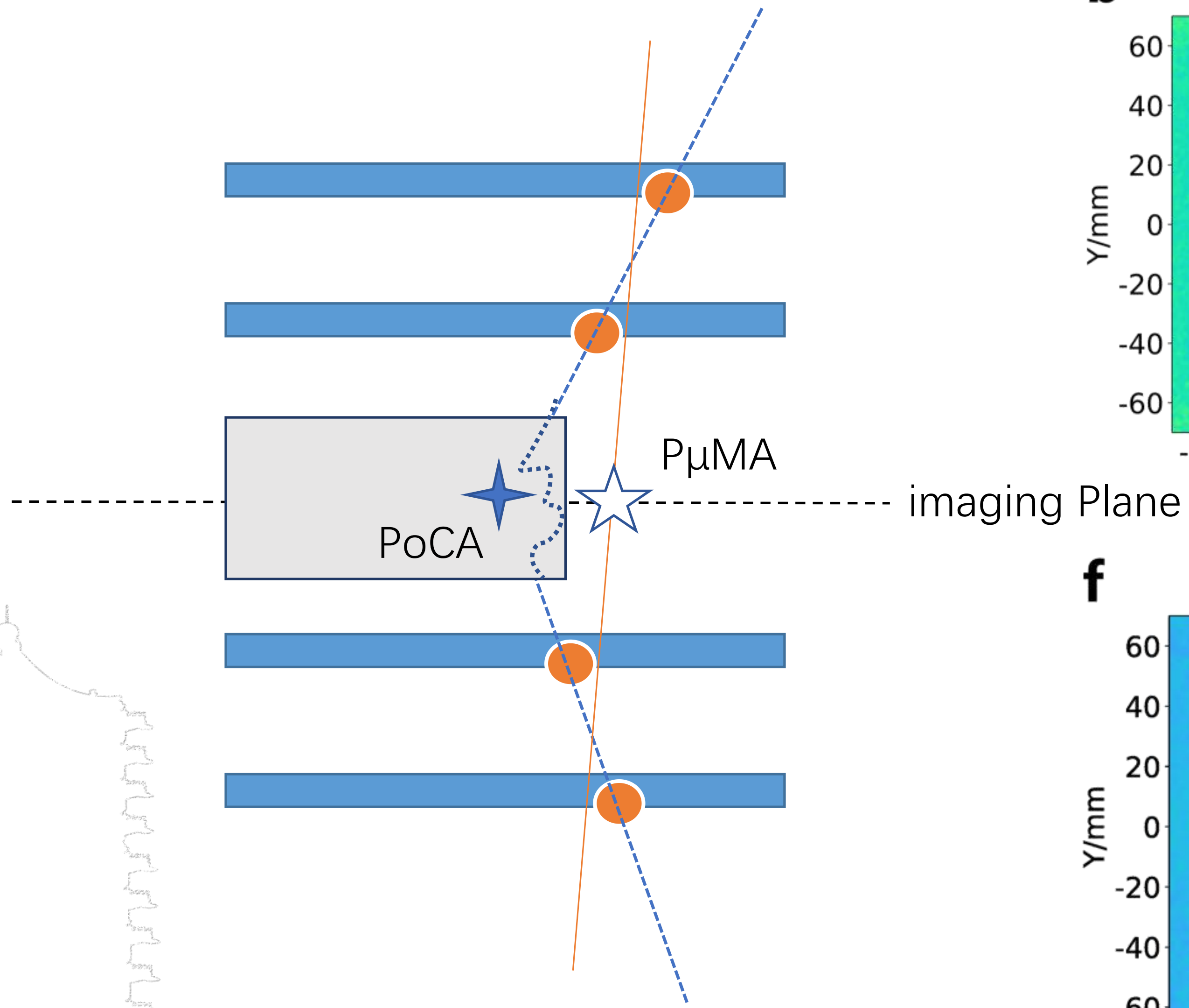
Unlike conventional approaches that rely on scattering-angle measurements to locate scattering points, PμMA constructs transmission tracks by connecting hit positions in upstream and downstream detectors. The material-induced angular deflection is then projected as a detectable shift in an imaging plane. This approach **allows millimeter-resolution cosmic-ray imaging with as few as two detectors**

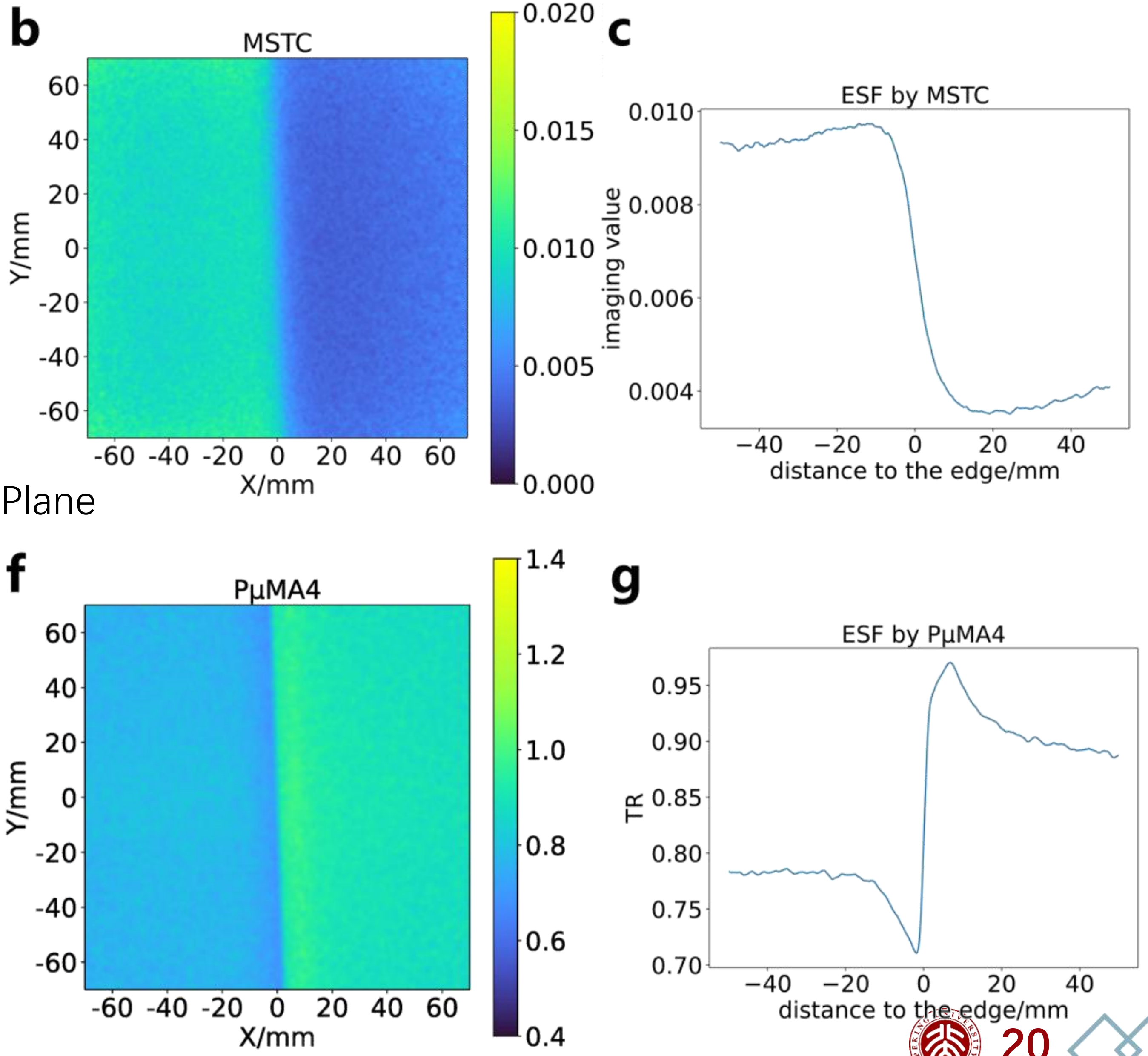
PμMA image of a gear



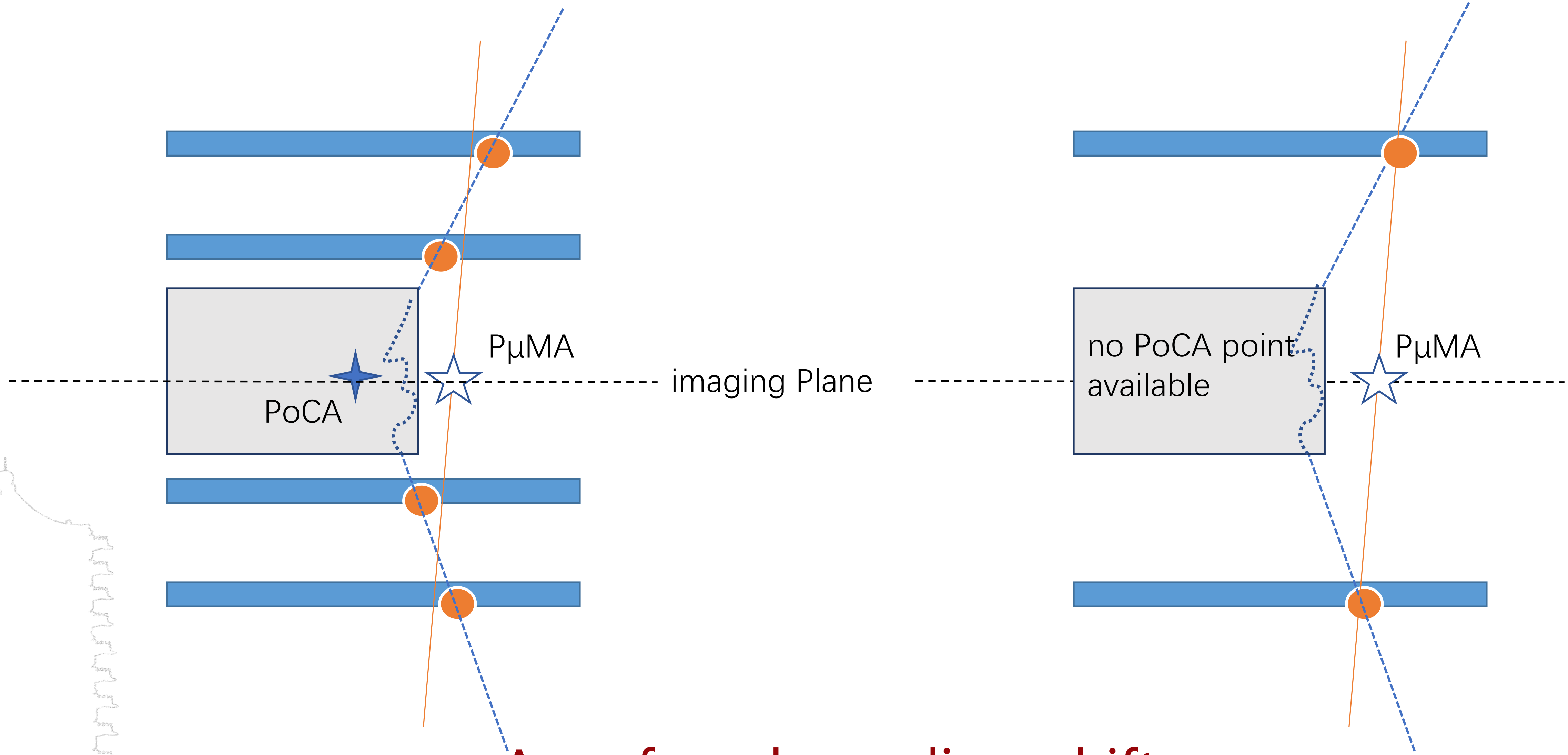


PμMA方法可形成清晰的边缘，宇宙射线实测边缘~mm，模拟平行纯束流可达55μm



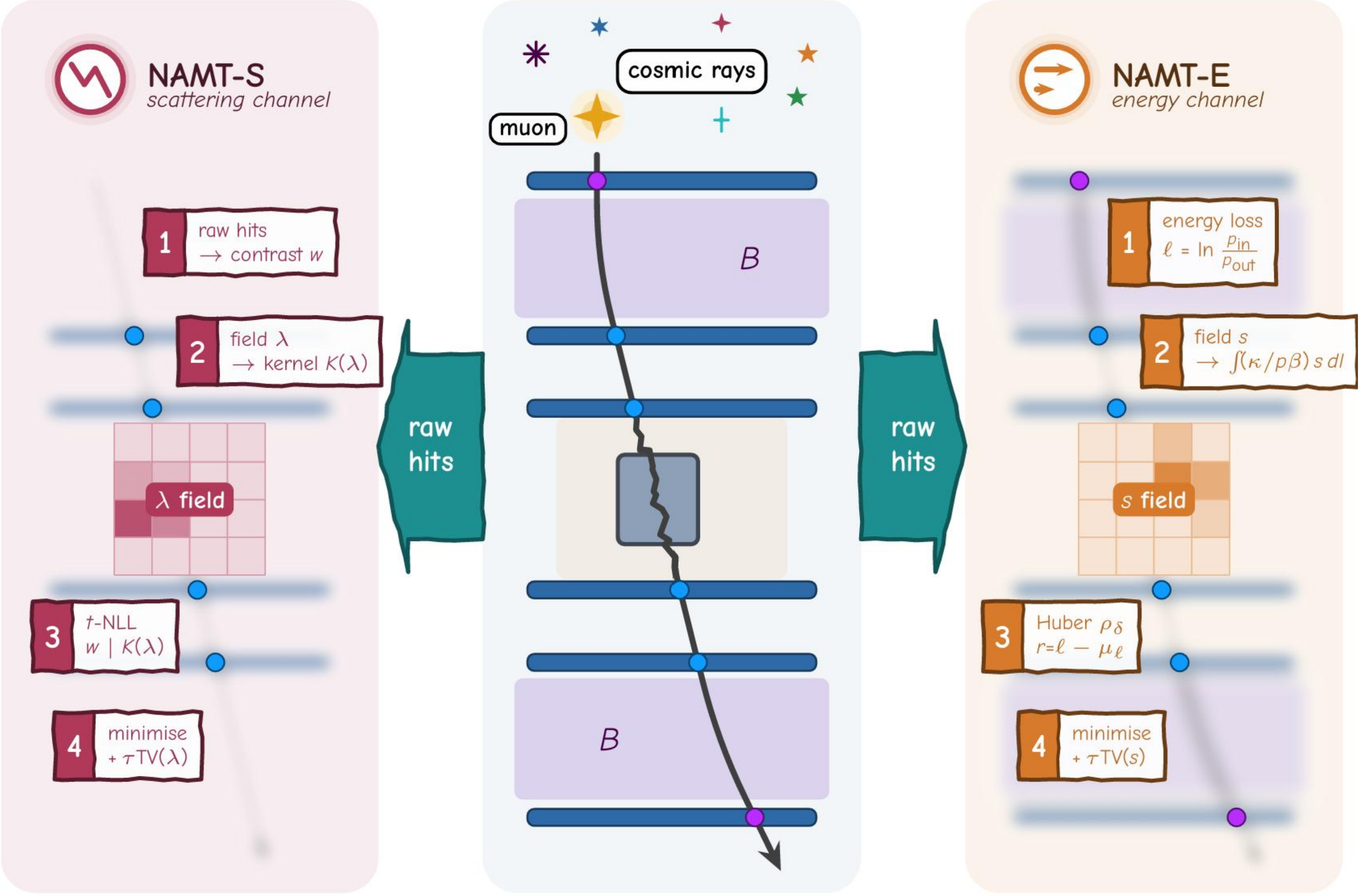


PμMA可完全不测散射角，只用两个探测器就能成像



A profound paradigm shift:
give muon tomography back to the muon.

NAMT-扰动感知缪子成像 arXiv:2606.20180 **赵志政本科毕业论文工作**



Nuisance-Aware Muon Tomography

- 第 1、2 层 hit

用来确定入射直线和入射方向

- 第 3、4 层 hit

与无散射预测点比较，得到残差。

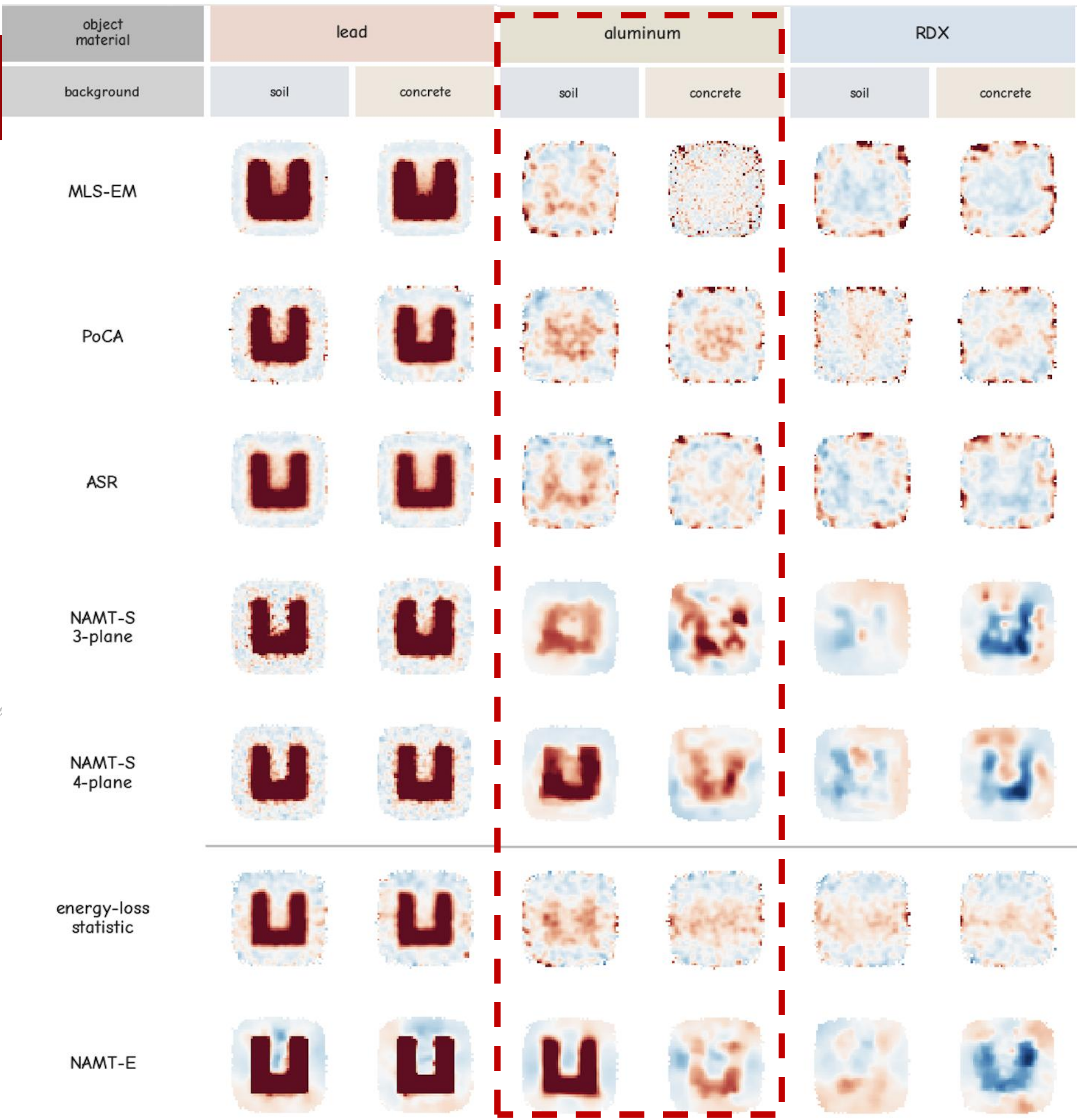
由残差和空场标定数学统计扰动不同求解反演材料场，使用深度学习反向传播中的自动微分 + GPU加速

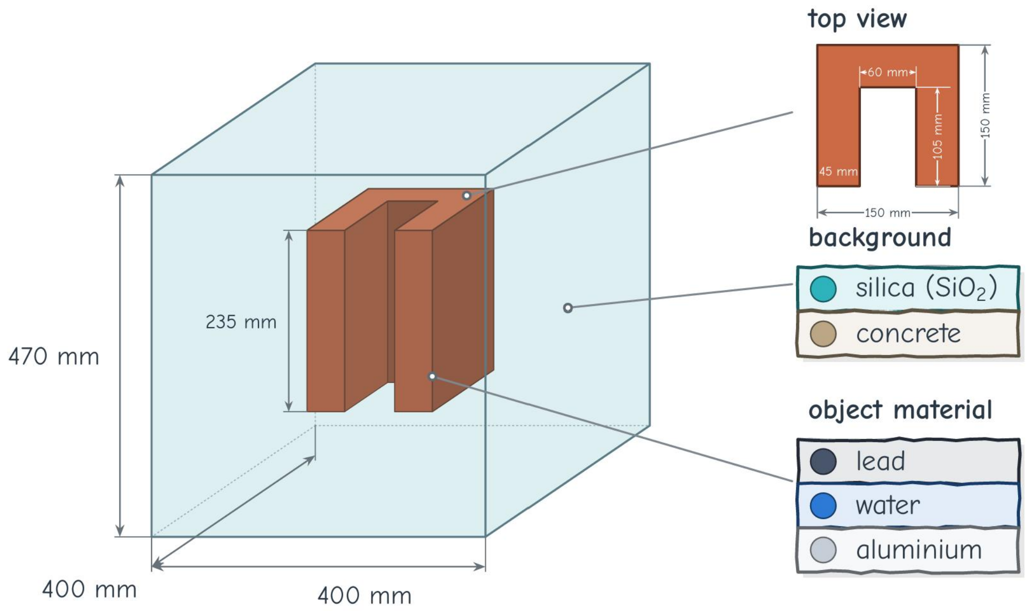
NAMT-S散射通道

用 muon 在下游探测板上的位置偏移重建材料散射场

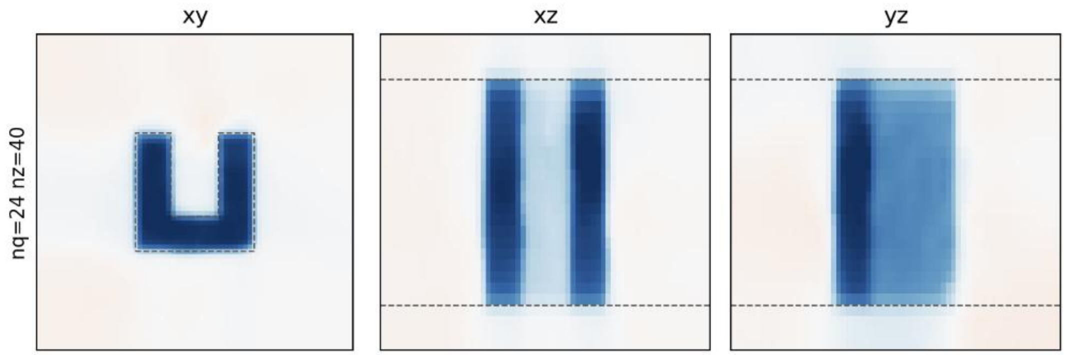
NAMT-E能损通道

如果可以测量能量，能损版本用同样的路径积分思想重建阻止本领场





NAMT-E water/SiO2 with nq=24 quadrature (sharper depth edges)

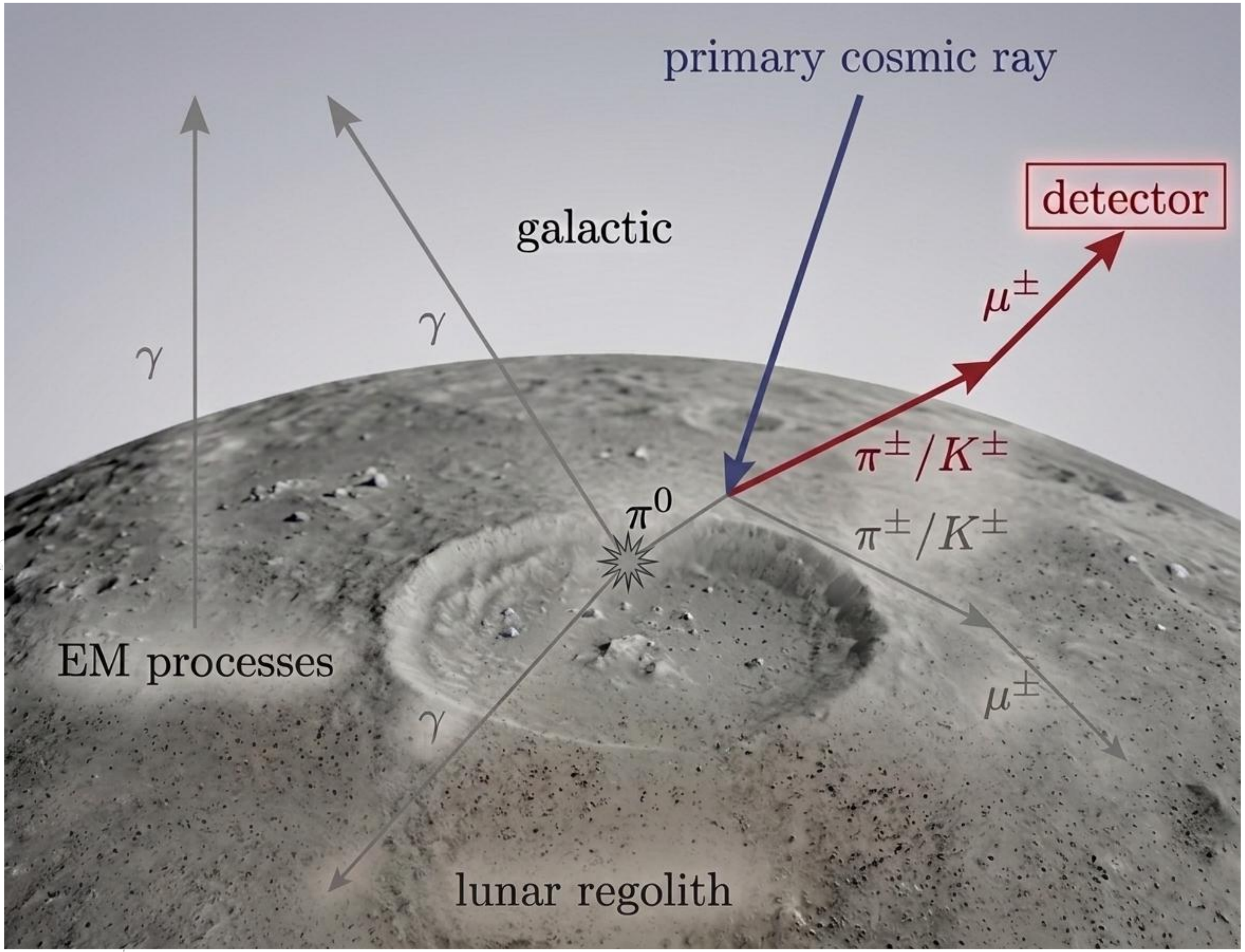


超灵敏：铝与混凝土密度差仅 0.02 g/cm³，成功区分

高稳健：探测器分辨率劣化到3mm的时仍稳定成像

“空白扫描+干扰感知+深度学习方法求解”框架非常创新

月球上的缪子成像 arXiv: 2607.10403 胡子墨(本科生)、高乐耘（博士生）



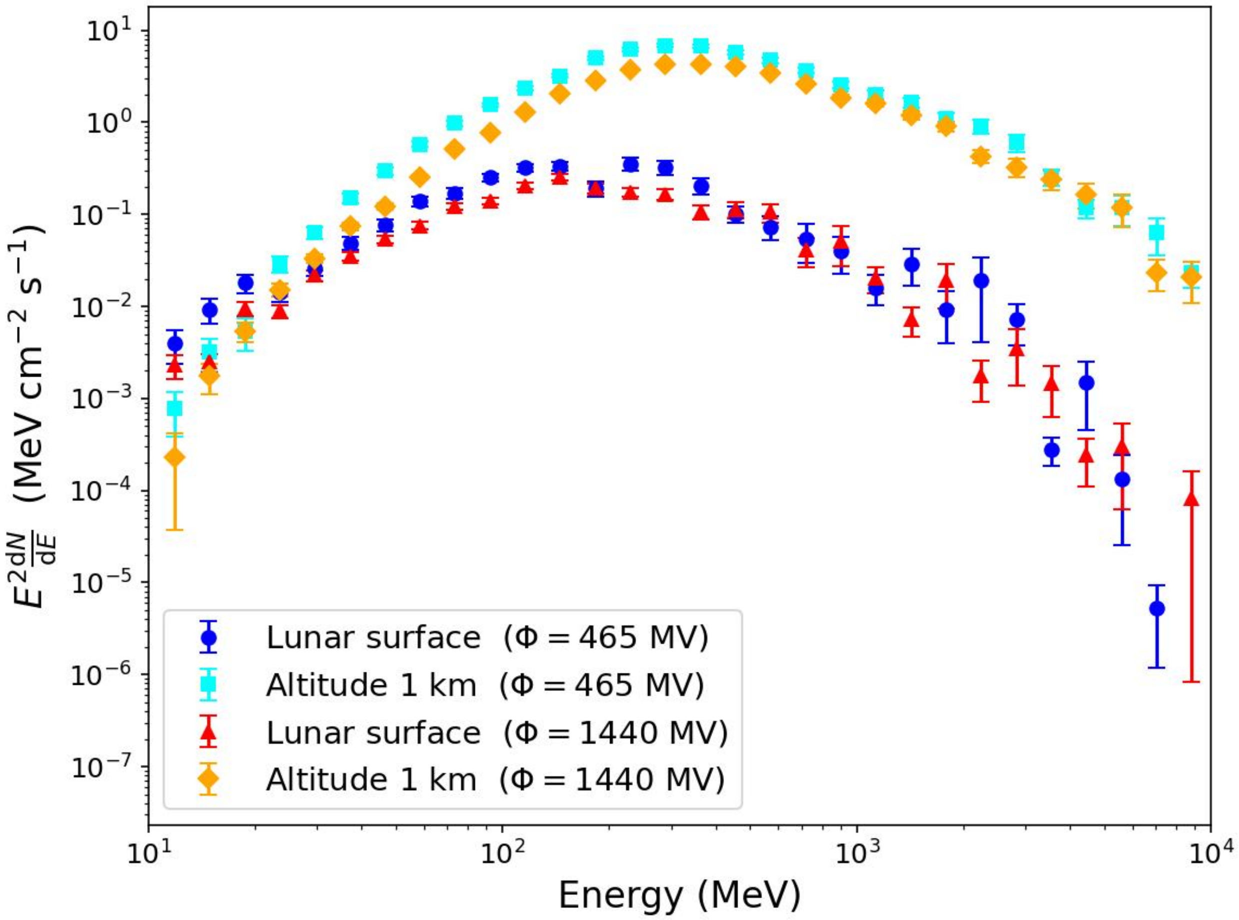
Primary galactic rays strike regolith and produce secondaries
secondary mesons: pions kaons

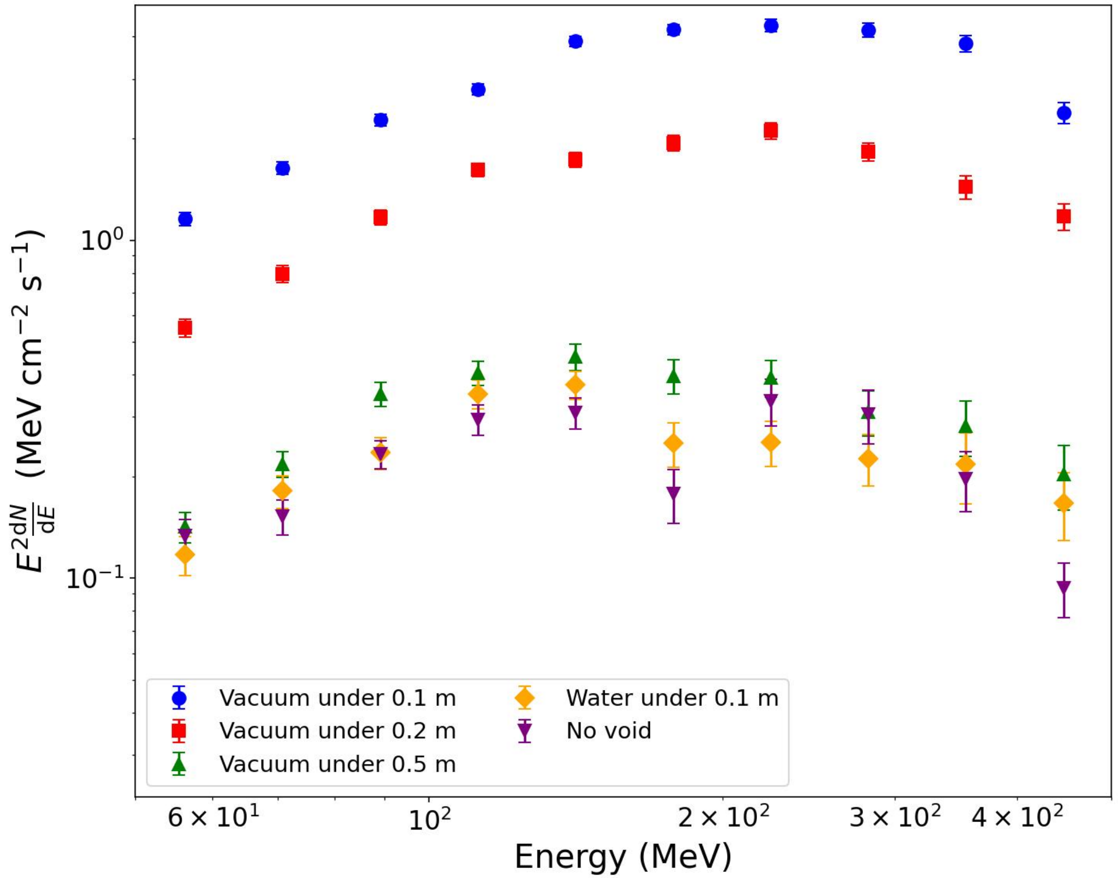
Muon comes mostly from $\pi^\pm \rightarrow \mu^\pm + \nu_\mu$ (channel near 100%)
$\pi^\pm$ has $c\tau$=7.8 m

Primary CR penetration ~0.1 m to 1 m, which corresponds to pion generation depth

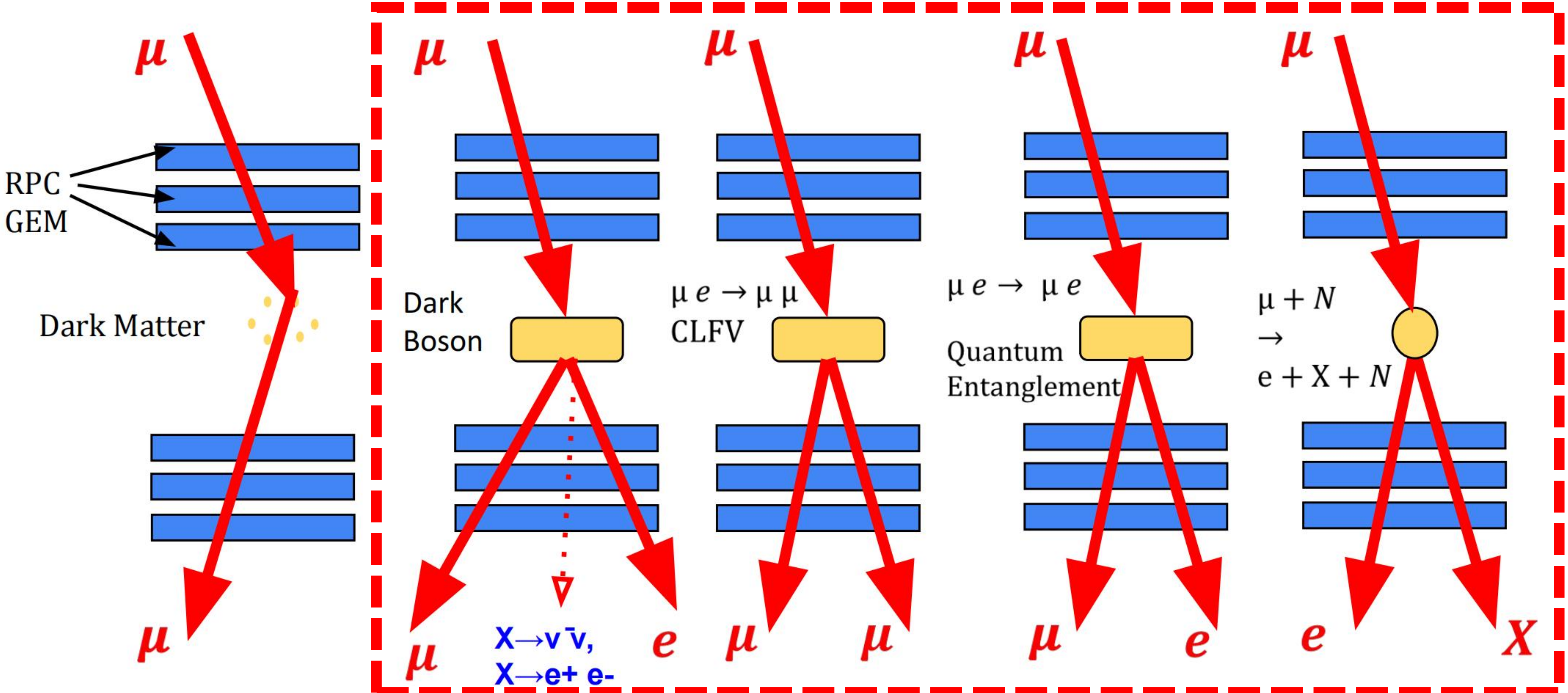
Therefore most charged pions come out of the surface undecayed
These pions subsequently decay into muons, vastly increasing muon flux at a height

轨道探测器，探测大面积深层空洞
月表探测器，探测浅层结构





PKMu The Next Phase
From Cosmic Rays to Accelerator Beams



Phys. Rev. D 110, 016017

Phys. Rev. Lett. 136, 151001

Int. J. Mod. Phys. A 40, 2550164

Phys. Rev. D 113, 072008

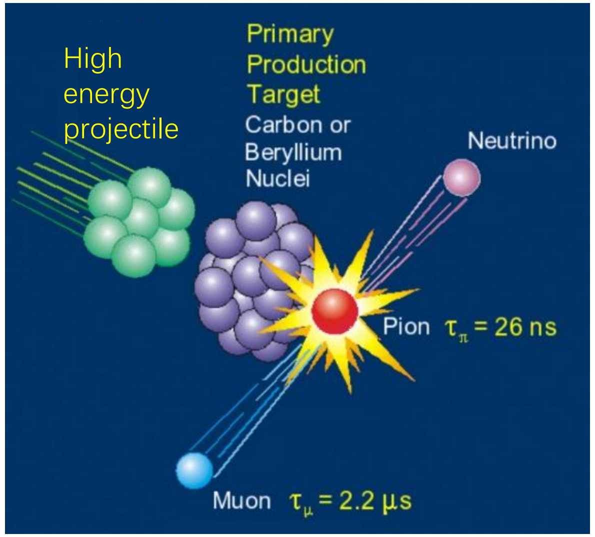
J. Phys. G: Nucl. Part. Phys. 52 075002

Muon Beam world wide

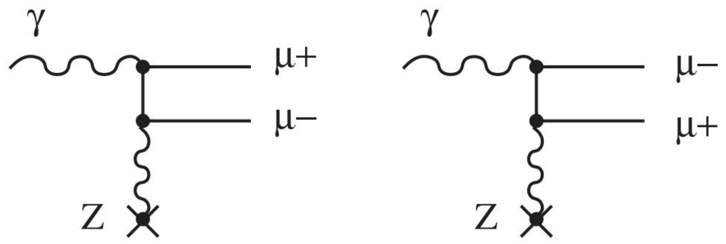
From Xu Yu / Liangwen Chen

東江實驗室
先进能源科学与技术广东省实验室
ADVANCED ENERGY SCIENCE AND TECHNOLOGY GUANGDONG LABORATORY

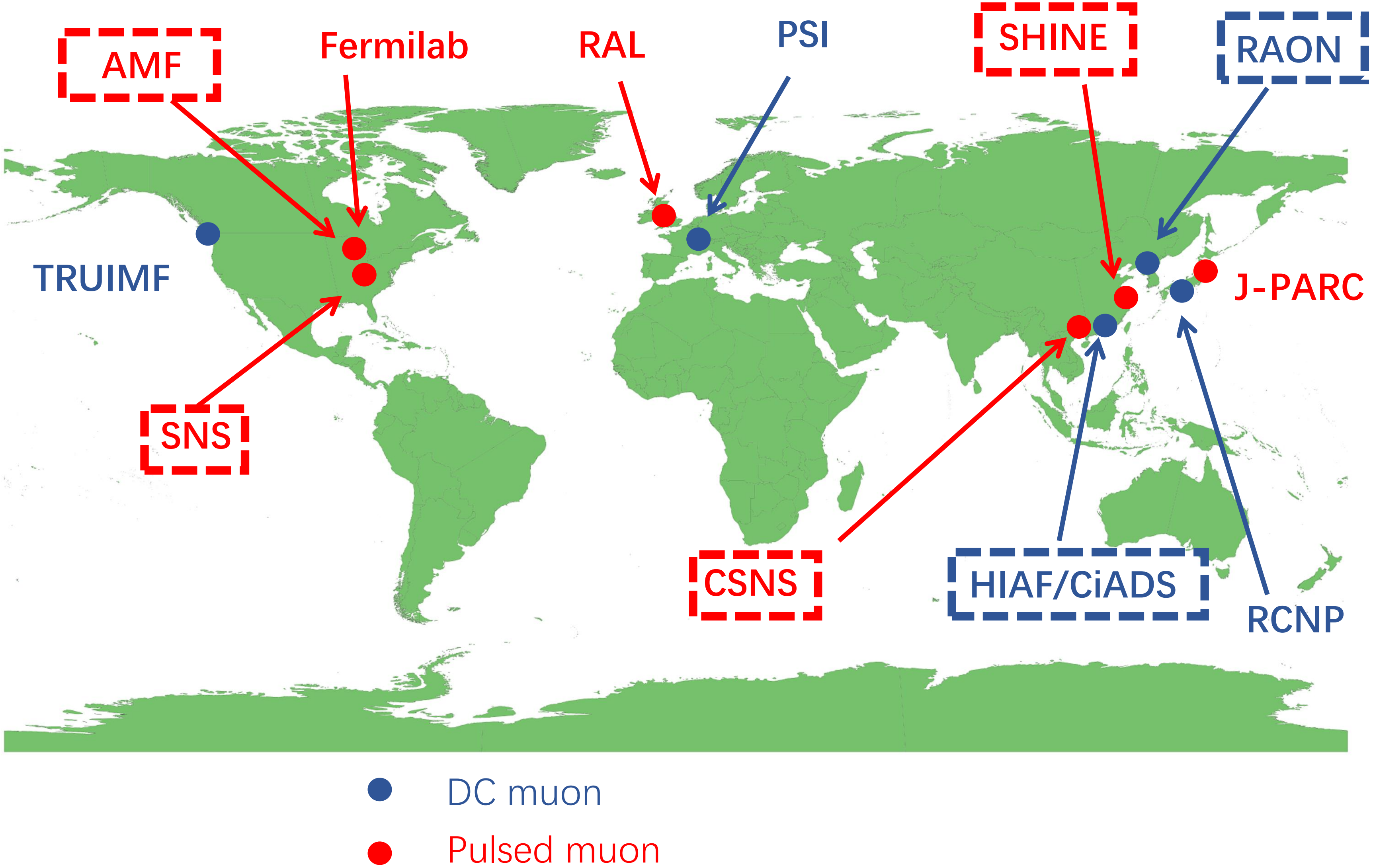
Accelerator generation:

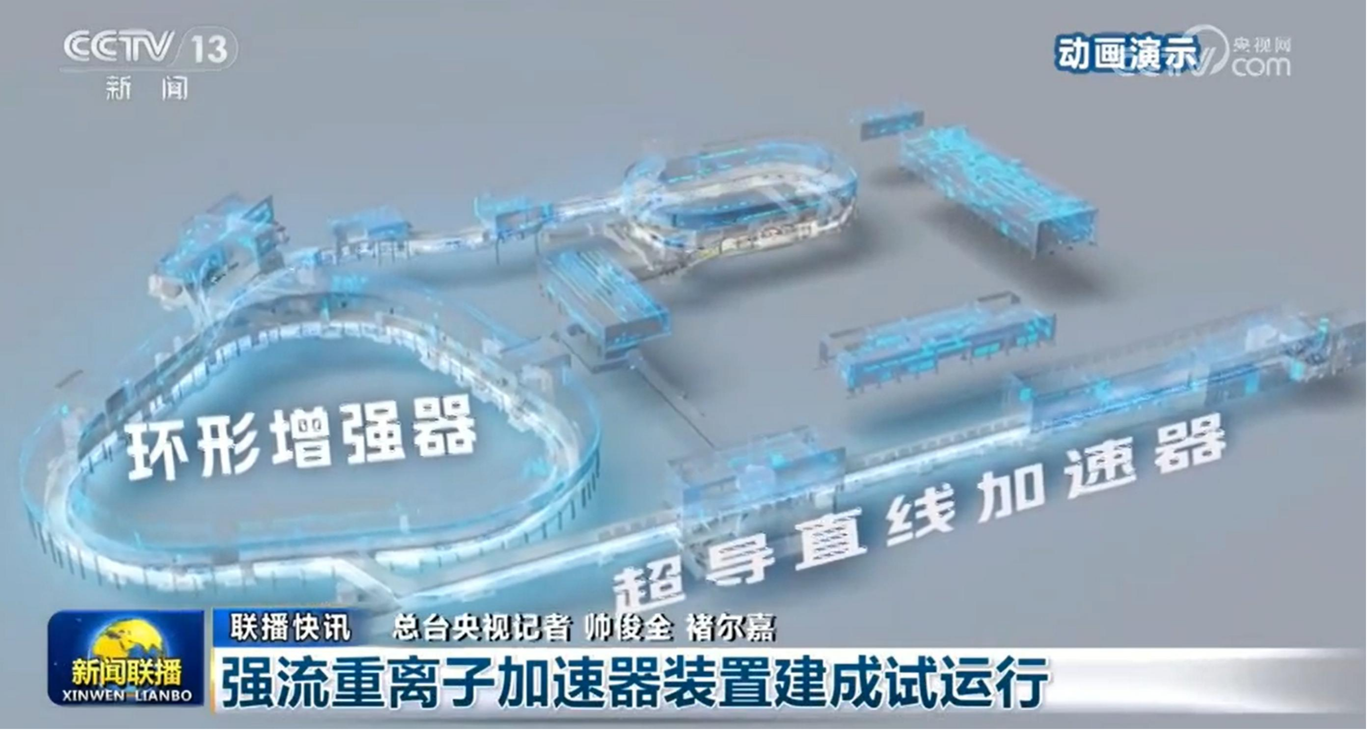


Muon from pion decay

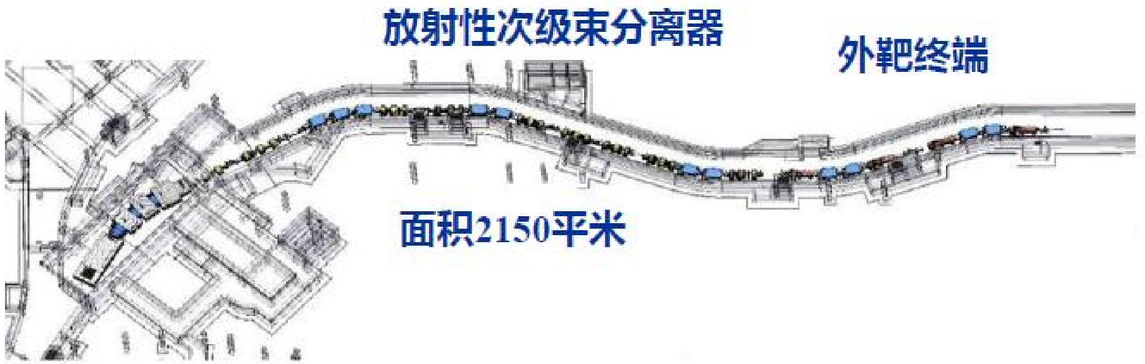


Bethe-Heitler process





7月21日，位于广东省惠州市的国家重大科技基础设施建设项目——强流重离子加速器装置（HIAF）通过了由中国科学院科技基础能力局主持的工艺验收，标志着该装置完成所有工程建设内容，进入试运行阶段，开始投入科学研究。



PHYSICAL REVIEW ACCELERATORS AND BEAMS **28,** 053401 (2025)

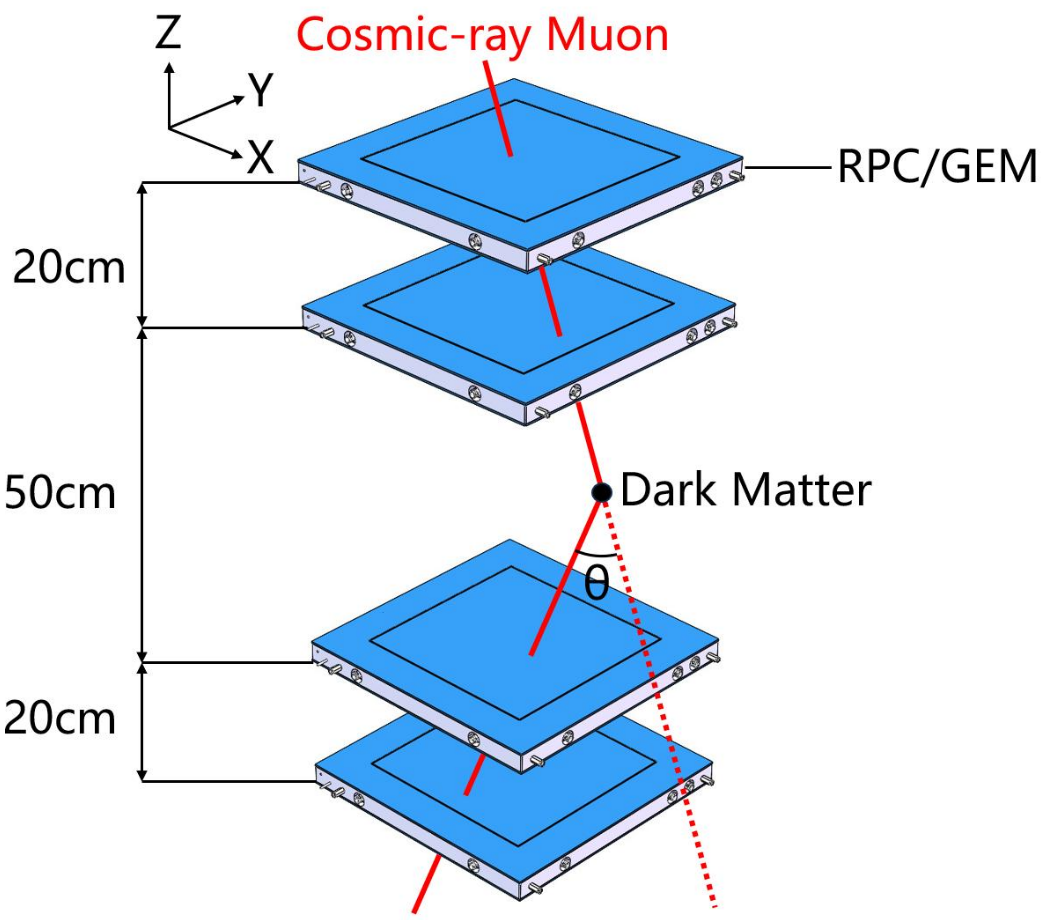
Feasibility study of the GeV-energy muon source based on the High Intensity Heavy-Ion Accelerator Facility

Yu Xu,[1,2] Xueheng Zhang,[1,2,3] Yuhong Yu,[1,2,3] Pei Yu,[1,2] Li Deng,[1,2] Jiajia Zhai,[1,2] Liangwen Chen,[1,2,3,*] He Zhao,[1,2,3] Lina Sheng,[1,2,3] Guodong Shen,[1,2,3] Ziwen Pan,[4] Qite Li,[5] Chen Zhou,[5] Qiang Li,[5] Lei Yang,[1,2,3] and Zhiyu Sun[1,2,3,†]

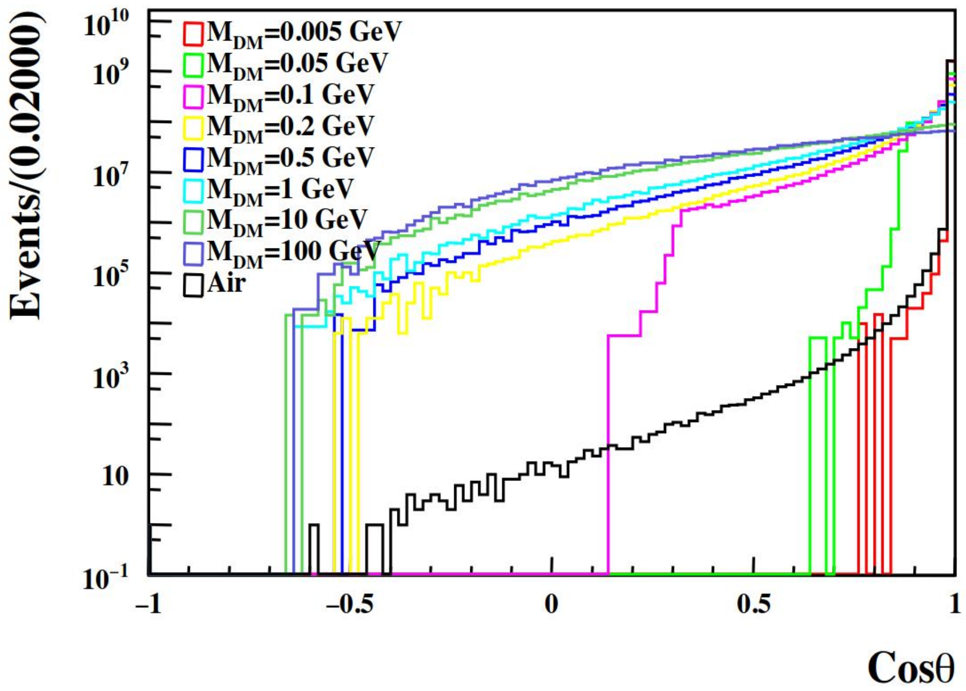
PKMu Proposed by Peking University together with HIAF-HIRIBL from Institute of Modern Physics, Chinese Academy of Sciences, China:

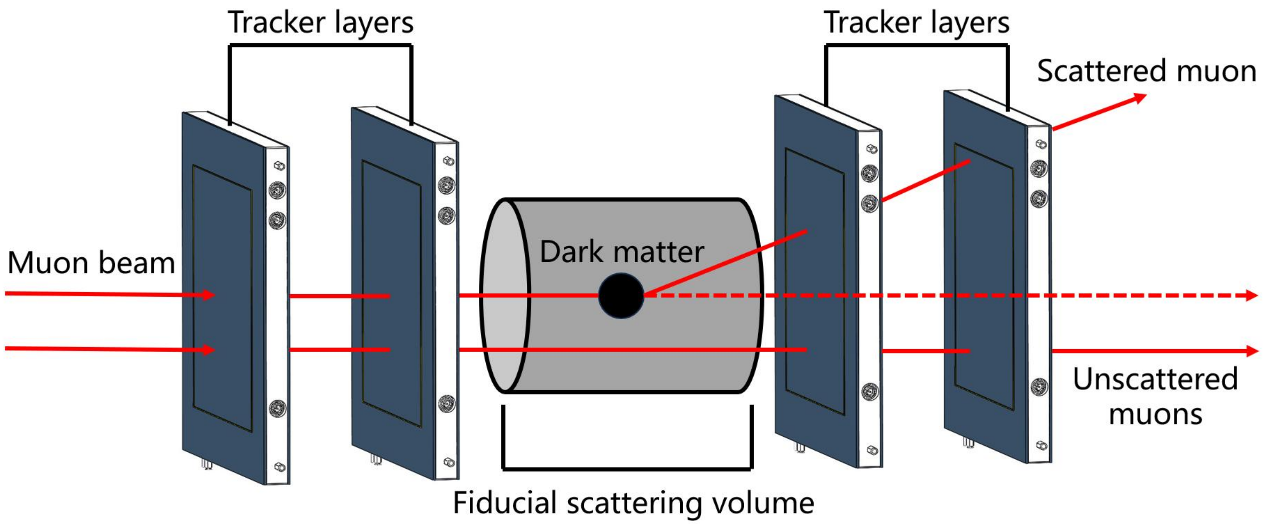
using ~ GeV Muon to probe new physics beyond the Standard Model

提议束流实验1：缪子束探寻暗物质



宇宙线实验: 利用宇宙线缪子散射探寻暗物质
(63天观测，已完成)

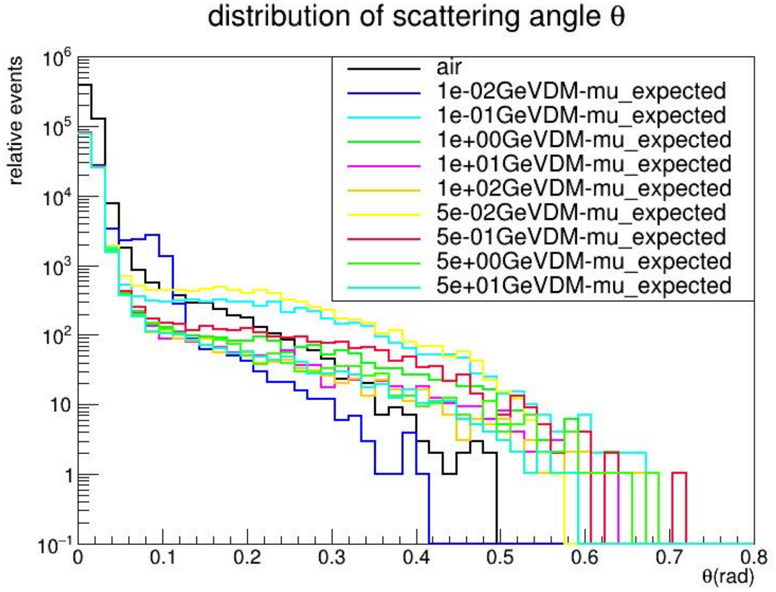




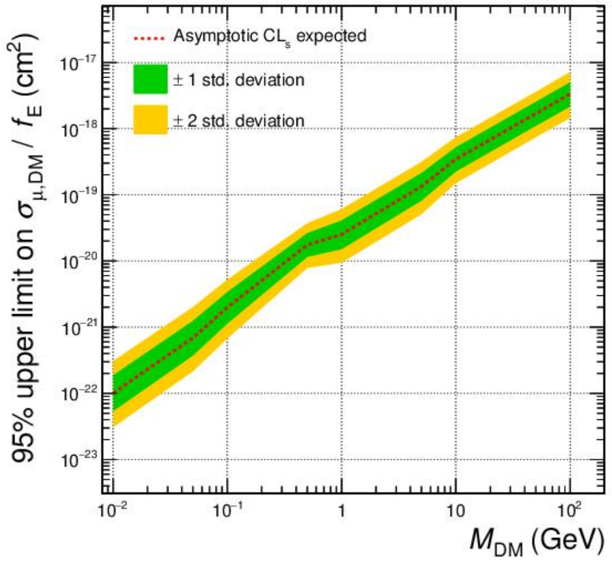
束流实验: 利用束流缪子散射探寻暗物质

对束流缪子暗物质实验模拟结果

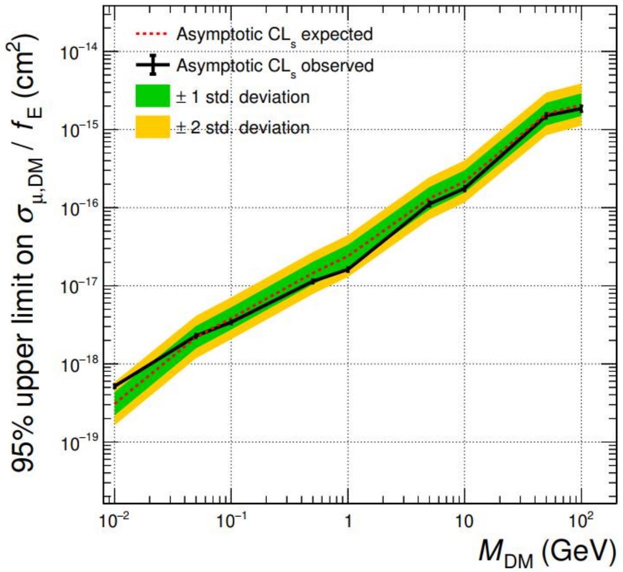
1. 在HIAF束流缪子模拟中，在10^5/s流强，1 GeV能量缪子，仅需11s运行时长即可优于宇宙线探测2个月结果，对于1 GeV暗物质，反应截面上限约为10^{-18} cm²
2. 束流能量1.15 GeV运行1天时间，对于1 GeV暗物质，95%置信区间下散射截面上限约2.54×10^{-20} cm²
3. 模拟研究发现散射截面上限主要受统计量影响，受束流能量与束斑大小的影响较小，**可利用其他缪子打靶实验的本底数据进行分析**



束流缪子与不同质量暗物质反应的散射角分布



HIAF模拟24小时
2.54×10^{-20} cm²



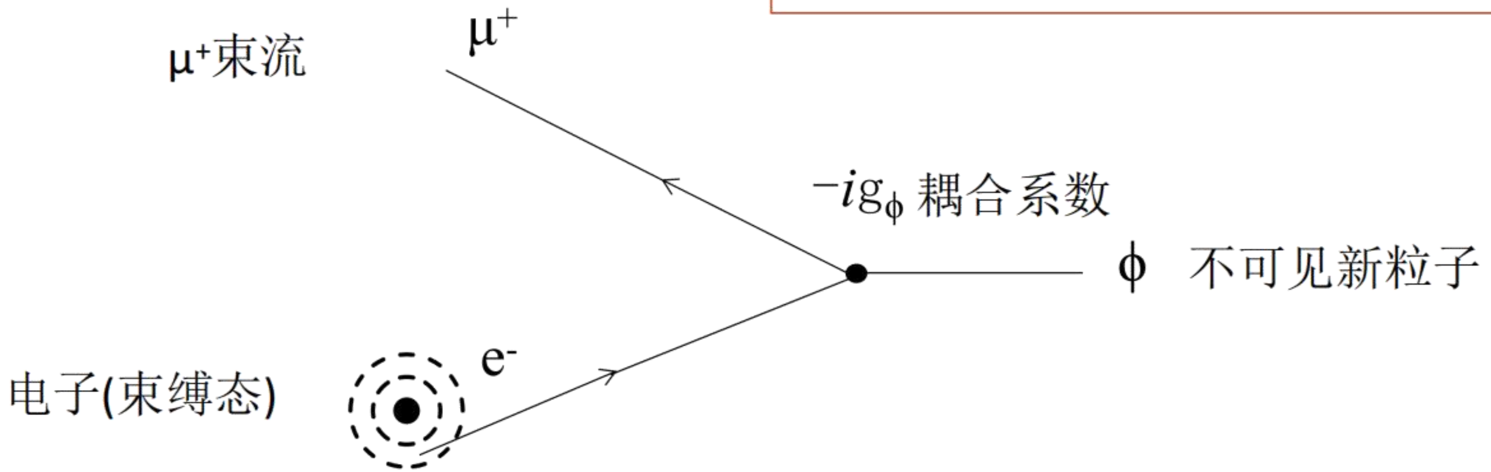
宇宙线实验2个月
1.61×10^{-17} cm²

提议束流实验2：μe湮灭+带电轻子味道破坏（CLFV）

$\mu^+ e^- \rightarrow \phi$

$$\mathcal{L}_{\text{int}} = -\phi\left(y_{e\mu}\,\bar{e}\,\mu + y_{\mu e}\,\bar{\mu}\,e\right) + \text{h.c.}$$

arXiv:2607.18669



- 通常的高能物理计算假设电子自由且静止。但对于湮灭过程，共振质量附近电子的**动量分布会显著影响反应截面，**我们采用**束缚态狄拉克旋量**处理靶电子:

电子动量

$$\mathcal{U}_{E\kappa m} = \frac{4\pi}{k_A}(-i)^l \begin{bmatrix} g_{E\kappa}\,\mathcal{Y}_{+\kappa m}\left(\hat{\mathbf{k}}_{\mathbf{A}}\right) \\ -f_{E\kappa}\,\mathcal{Y}_{-\kappa m}\left(\hat{\mathbf{k}}_{\mathbf{A}}\right) \end{bmatrix}$$

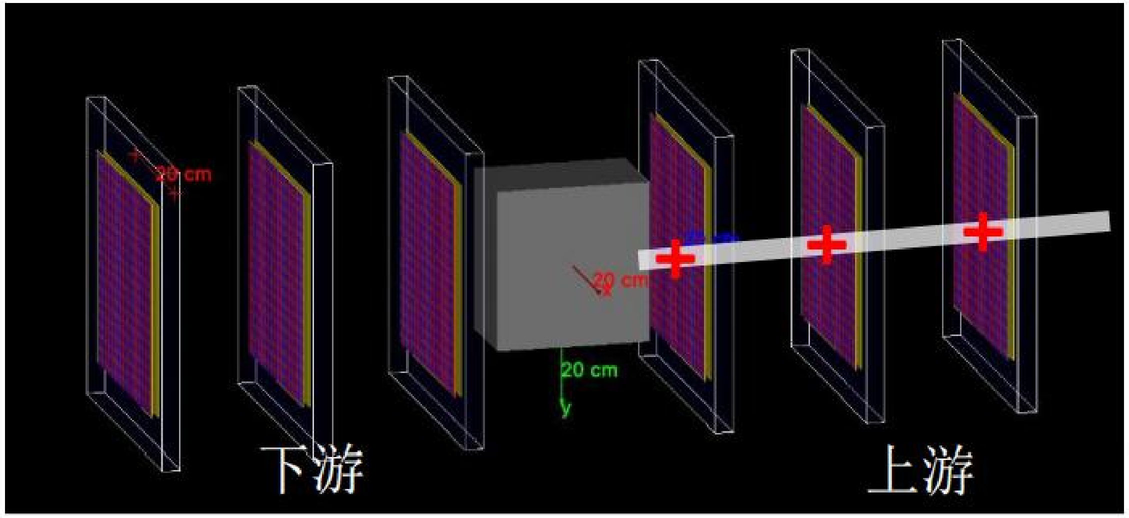
归一化

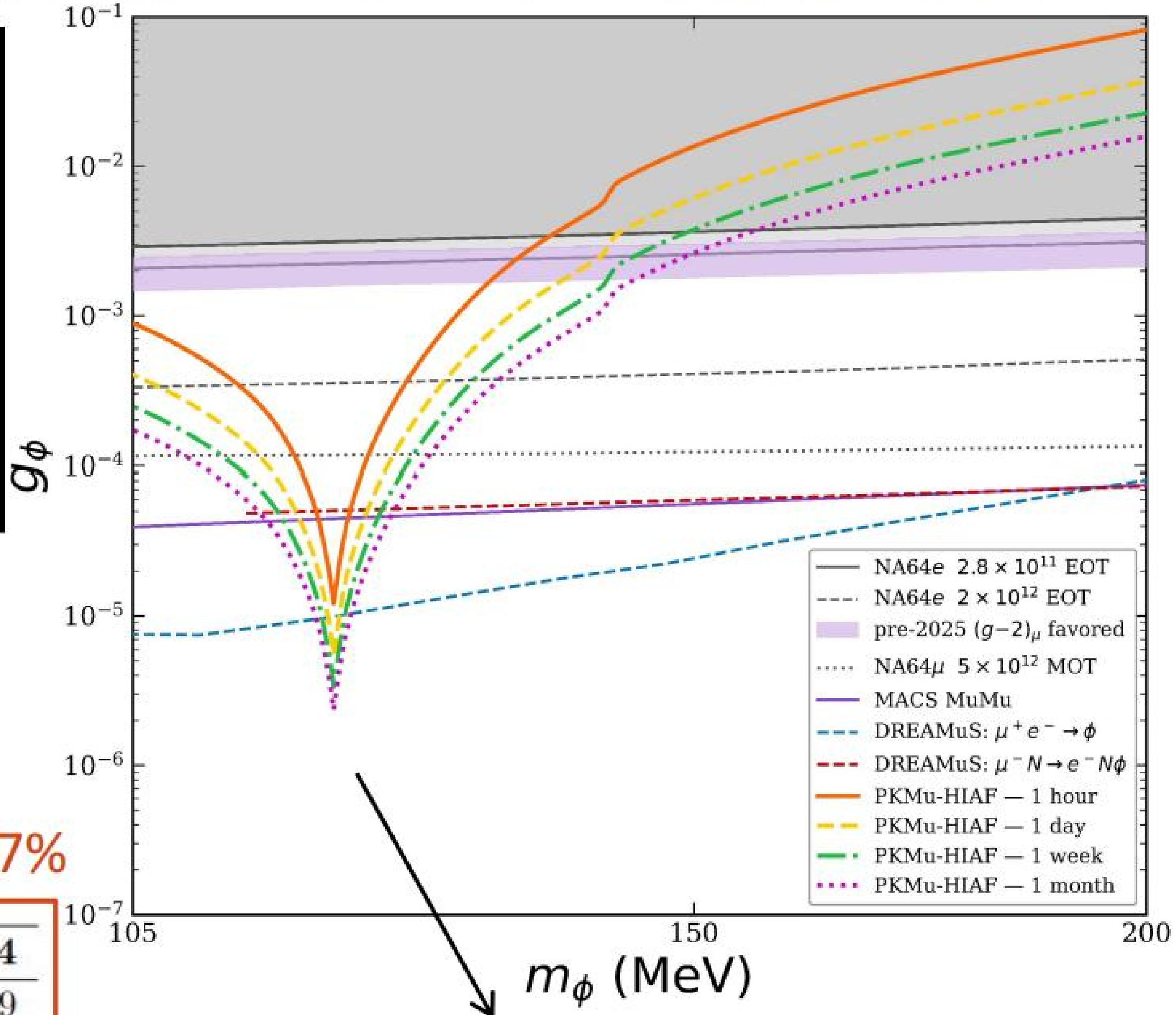
$$\frac{1}{(2\pi)^3}\sum_m \int \mathcal{U}^\dagger_{E\kappa m}\,\mathcal{U}_{E\kappa m}\,d^3k_A = 2E_A$$

径向分量：f,g函数，由Roothan-Hartree-Fock (RHF) 程序数值解出

角向分量：旋量球谐函数

- 24小时 (6.5×10^{10} MOT) 就可以在共振质量附近得到目前国际最优结果。
- 后续可以通过改变束流能量对共振质量做扫描，获得更大质量范围的优势结果。





筛选 1. 上游符合
筛选 2. 下游否决
筛选 3. 束斑半径 r0<30mm
筛选 4. 靶点指向

≈ 20.7%

Table 1. Cutflow summary for signal and background events.

Process	Generated	Cut 1	Cut 2	Cut 3	Cut 4
Signal	221,983	221,983	219,061	46,108	45,969
Background	24,769,782	24,764,801	2,211	395	387

- 99.999%

我们的结果

PKMu (R&D) MUonE (ongoing)

PKMu: Muon on target experiment proposed by PKU for multi-purpose including cosmic ray, dark boson, and **quantum entanglement**.

HIRIBL: **1-10GeV 10^6-10^7/s muon** beam line from the HIAF facility from the imp, cas, China.

MUonE: a Muon Electron scattering exp at CERN exploiting a **150-160 GeV 10^7-10^8/s** beam, aims at an independent and precise determination of the leading hadronic contribution to the muon g-2.

HIAF, Hui Zhou

MUonE CERN


高亮度和高精度前沿缪子物理研讨会
MIP2024 北京大学 2024年4月19日-22日


PKμ.@HFRS
PKMu-HFRS Workshop
Probing and Knocking with a GeV Muon beam at the HIAF-HFRS facility
Apr 25, 2025 W206, School of Physics, PKU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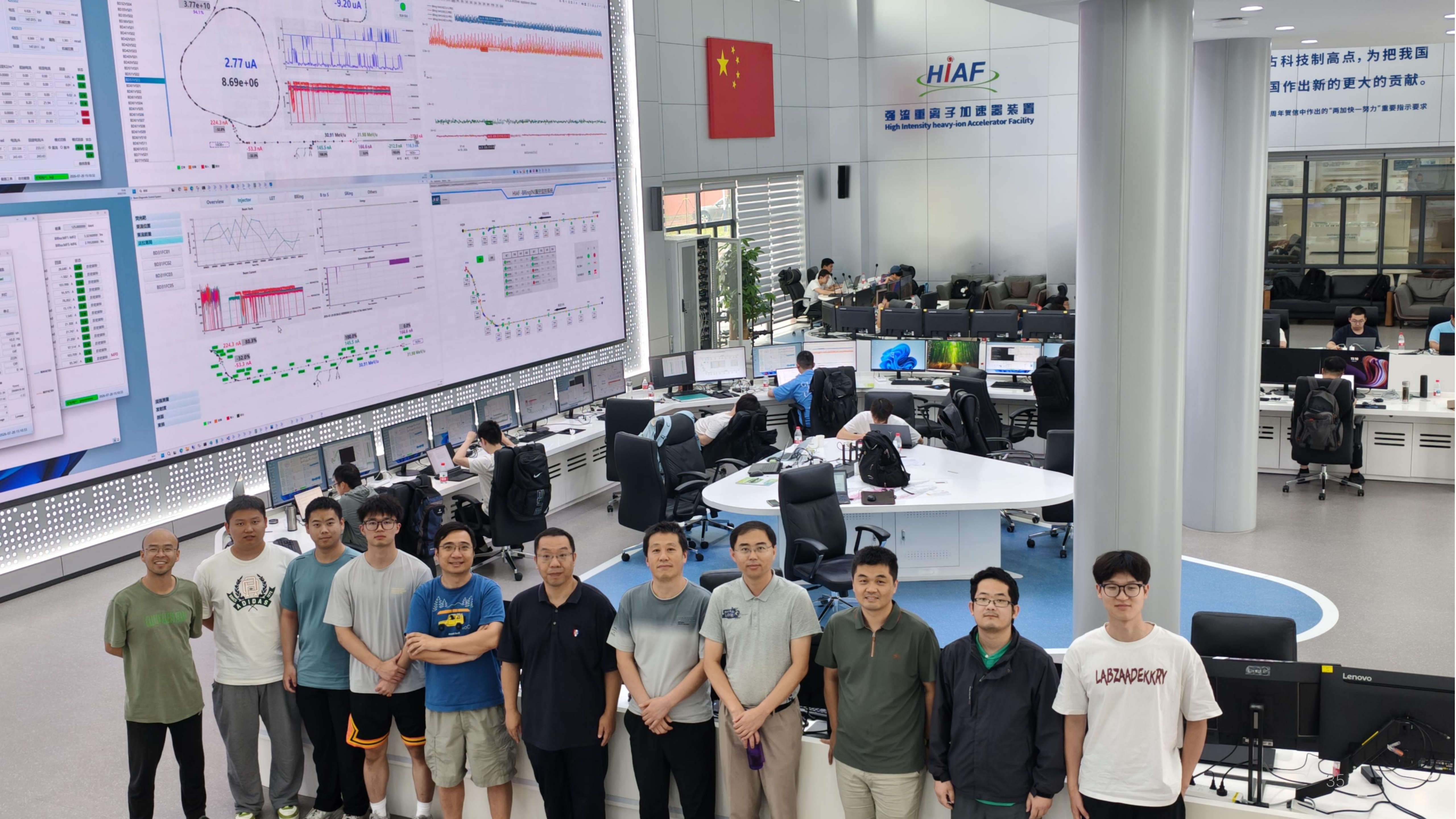
HIAF
强流重离子加速器装置
High Intensity heavy-ion Accelerator Facility
2.77 uA
8.69e+06
Lenovo

PKMu: Probing and Knocking with Muons

- A comprehensive muon scattering program from Peking University
- PRL 2026: First direct cosmic-ray muon-DM scattering limit + precision cosmic-ray composition. Technologies outcomes: Sub-mm RPC(2D readout), PμMA, secondary-particle imaging, NAMT
- Future beam program: Dark Matter Dark bosons, CLFV, quantum entanglement...
- **用相对小和灵活的装置可以结合非常好的物理创新，快速探索有趣的和重要的科学前沿**

Ref:

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[12] arXiv:2606.20180 NAMT
[13] arXiv: 2607.10403 Moonshot

Special Thanks
特别致谢

李奇特 Qite Li liqt@pku.edu.cn

Group Photo of PKMu Team