Probing and Knocking With Muons

Qiang Li

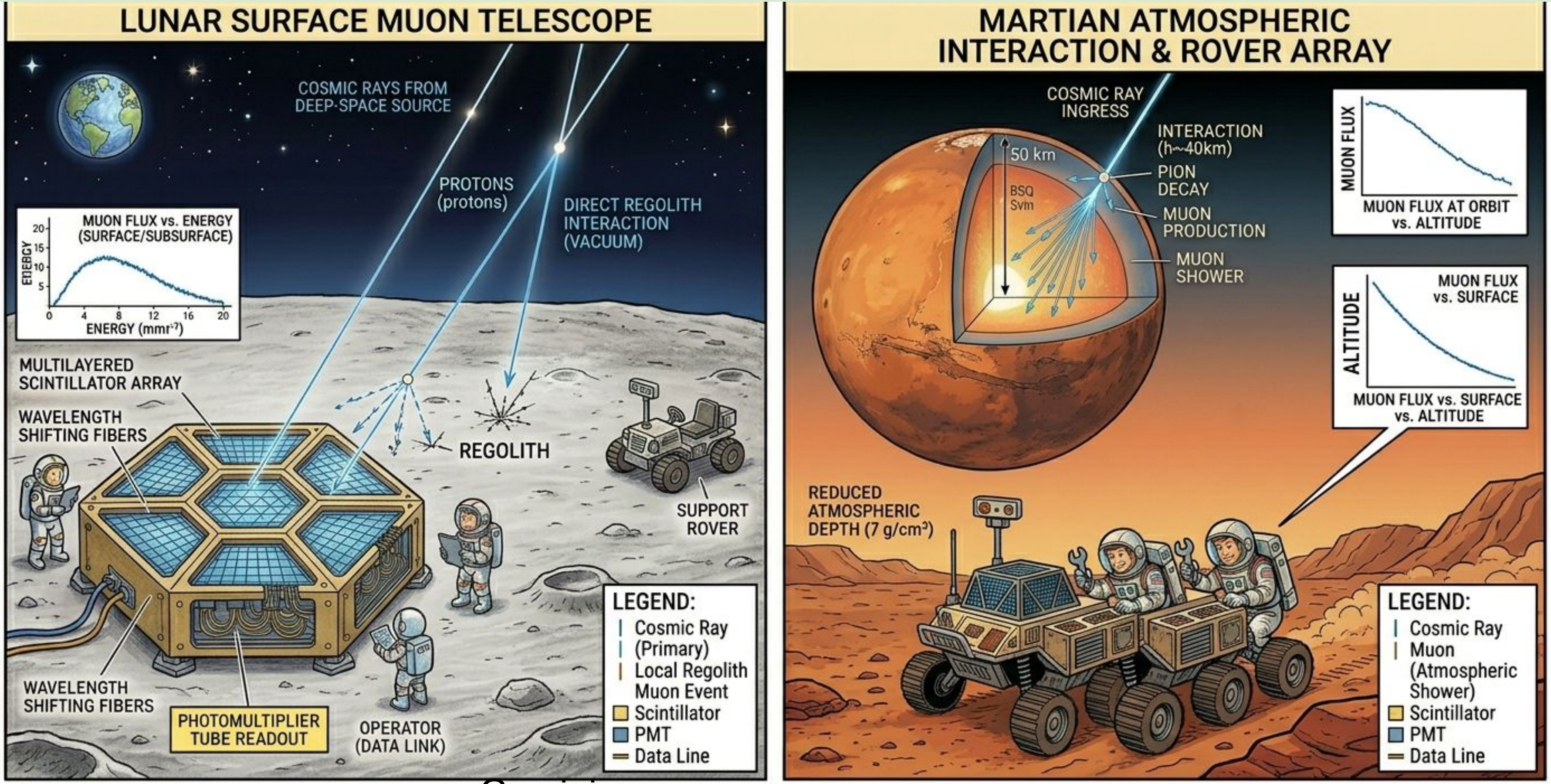
2026/05/16 Nanjing

PKμ

- Core Goal: A comprehensive muon-scattering experiment program to explore precision and new physics.
- Our Strategy — Innovation, Agility, and 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

- **Brief Introduction**
    - Muon Physics, China’s GeV Muon Beam
- A general picture of PKMu
- Muon Tomography
- Exp with Cosmic Muons
- HIAF proposal 1 with Muon beam
- HIAF proposal 2 with Muon beam
- Future and Summary

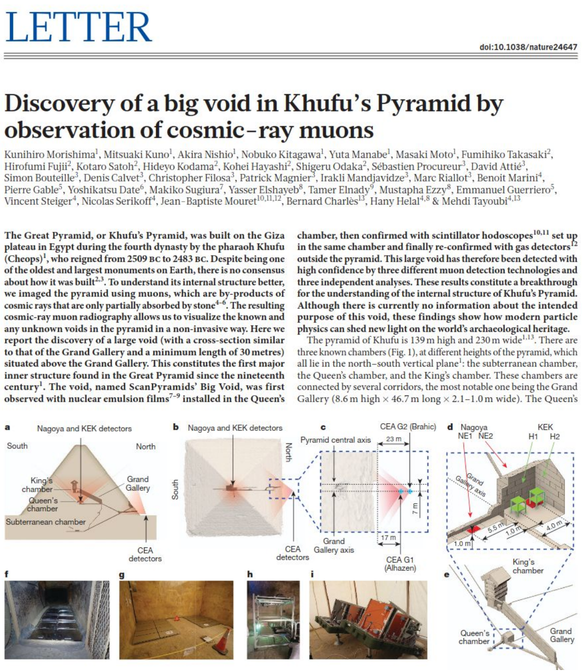
Muons can be everywhere and interesting



Gemini

However, let's focus on our Earth

《Nature》 Muon Tomography



LETTER

doi:10.1038/nature24647

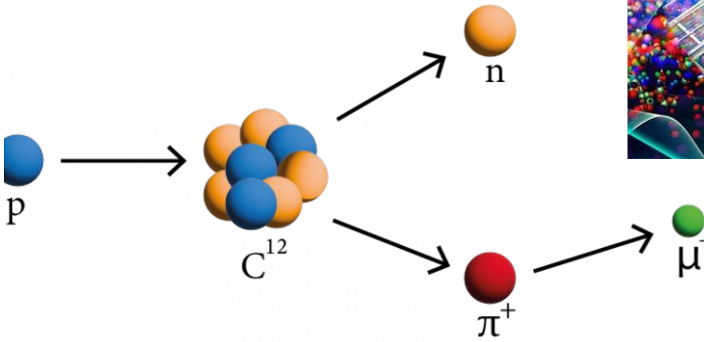
Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima[1], Mitsuaki Kuno[1], Akira Nishio[1], Nobuko Kitagawa[1], Yuta Manabe[1], Masaki Moto[1], Fumihiko Takasaki[2], Hirofumi Fujii[2], Kotaro Satoh[2], Hideyo Kodama[2], Kohei Hayashi[2], Shigeru Odaka[2], Sébastien Procureur[3], David Attié[3], Simon Bouteille[3], Denis Calvet[3], Christopher Filosa[3], Patrick Magnier[3], Irakli Mandjavidze[3], Marc Riallot[3], Benoit Marini[4], Pierre Gable[5], Yoshikatsu Date[6], Makiko Sugiura[7], Yasser Elshayeb[8], Tamer Elnady[9], Mustapha Ezzy[8], Emmanuel Guerriero[5], Vincent Steiger[4], Nicolas Serikoff[4], Jean-Baptiste Mouret[10,11,12], Bernard Charlès[13], Hany Helal[4,8] & Mehdi Tayoubi[4,13]

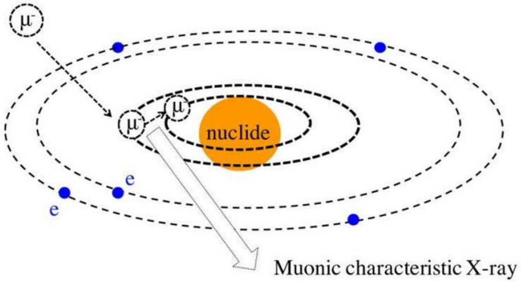
The Great Pyramid, or Khufu's Pyramid, was built on the Giza plateau in Egypt during the fourth dynasty by the pharaoh Khufu (Cheops)[1], who reigned from 2509 BC to 2483 BC. Despite being one of the oldest and largest monuments on Earth, there is no consensus about how it was built[2,3]. To understand its internal structure better, we imaged the pyramid using muons, which are by-products of cosmic rays that are only partially absorbed by stone[4–6]. The resulting cosmic-ray muon radiography allows us to visualize the known and any unknown voids in the pyramid in a non-invasive way. Here we report the discovery of a large void (with a cross-section similar to that of the Grand Gallery and a minimum length of 30 metres) situated above the Grand Gallery. This constitutes the first major inner structure found in the Great Pyramid since the nineteenth century[1]. The void, named ScanPyramids' Big Void, was first observed with nuclear emulsion films[7–9] installed in the Queen's chamber, then confirmed with scintillator hodoscopes[10,11] set up in the same chamber and finally re-confirmed with gas detectors[12] outside the pyramid. This large void has therefore been detected with high confidence by three different muon detection technologies and three independent analyses. These results constitute a breakthrough for the understanding of the internal structure of Khufu's Pyramid. Although there is currently no information about the intended purpose of this void, these findings show how modern particle physics can shed new light on the world's archaeological heritage.

The pyramid of Khufu is 139 m high and 230 m wide[1,13]. There are three known chambers (Fig. 1), at different heights of the pyramid, which all lie in the north–south vertical plane[1]: the subterranean chamber, the Queen's chamber, and the King's chamber. These chambers are connected by several corridors, the most notable one being the Grand Gallery (8.6 m high × 46.7 m long × 2.1–1.0 m wide). The Queen's

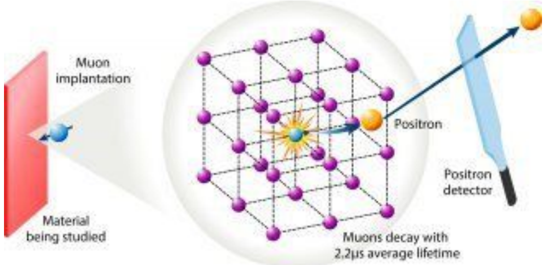
Muon g-2 Experiments



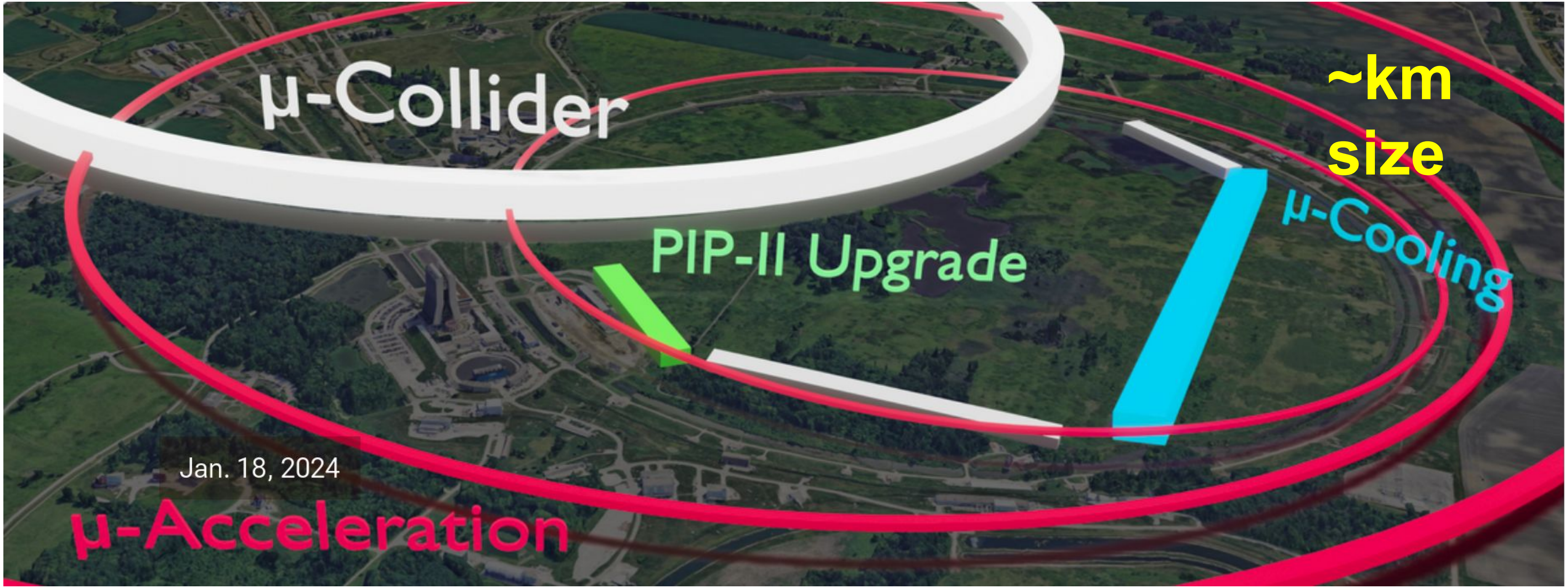
Muonic x-ray spectroscopy



Muon Spin Rotation and Relaxation Spectroscopy

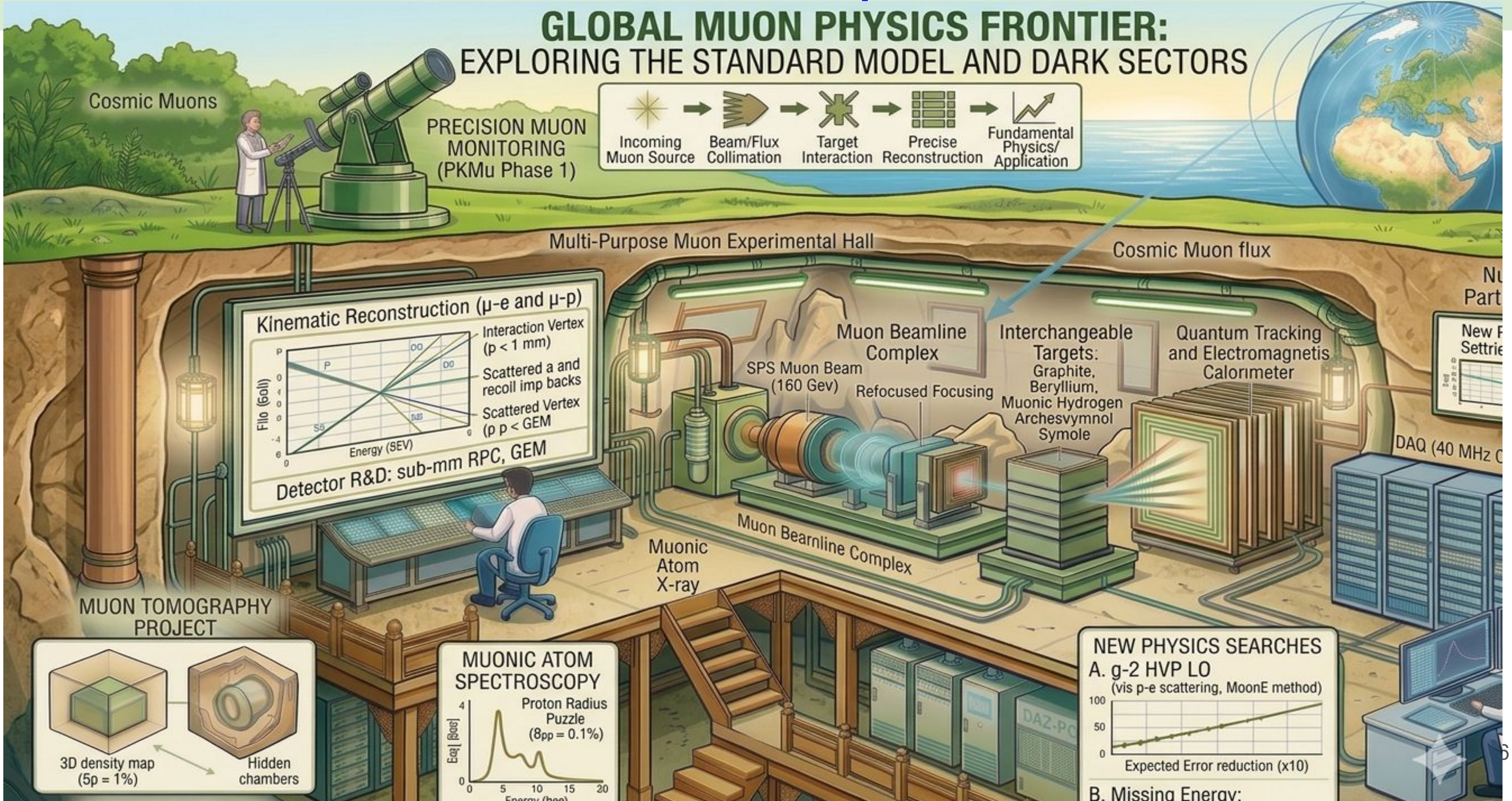


A journey to the TeV future: “Our Muon Shot"



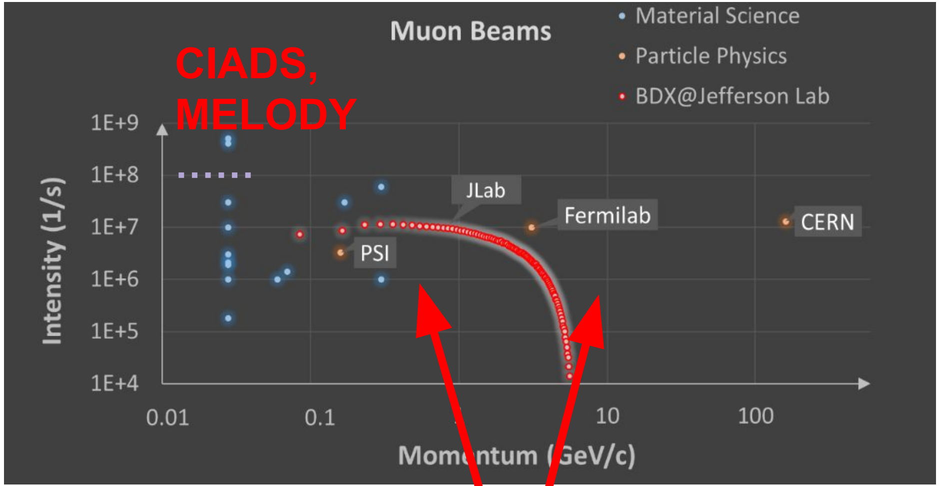
https://www.physics.utoronto.ca/news-and-events/events/colloquium/talk-on-jan-18-2024/

However, let's focus on the present, 1-100 GeV



Muon Scattering Worldwide

- **150 GeV Muon Beam @CERN: AMBER, MUonE, NA64**
  - **Nuclear Properties,**
  - **New Physics Searches**
- **US JLab has a similar plan**
- **Many Possible Muon beams to appear in China soon**



PRAB 28 (2025) 053401

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

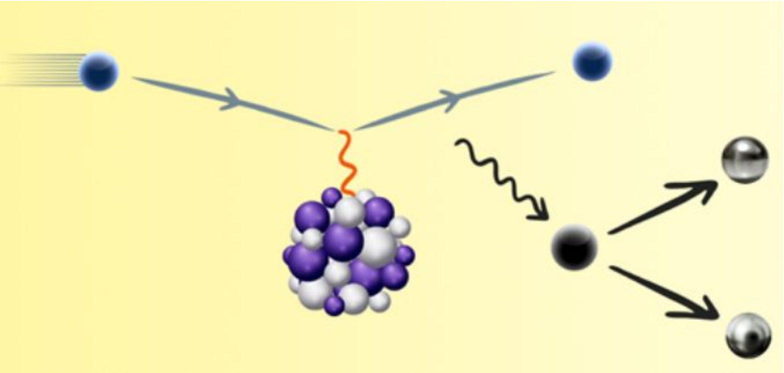
Yu Xu,[1,2] Xueheng Zhang,[1,2,3] Yuhong Yu,[1,2,3] Pei Yu,[1,2] Li Deng,[1,2] Jiajia Zhai,[1,2] Liangwen Chen,[1,2,3,*] He Zhao,[1,2,3] Lina Sheng,[1,2,3] Guodong Shen,[1,2,3] Ziwen Pan,[4] Qite Li,[5] Chen Zhou,[5] Qiang Li,[5] Lei Yang,[1,2,3] and Zhiyu Sun[1,2,3,†]

HIAF可以利用HIRIBL束线产生缪子束流

- **动量范围：500MeV/c – 7.5GeV/c**
- **缪子产额：$10^6 - 10^7\ \mu/s$**
- **束斑大小：半径约30 mm**

Upgraded HIAF (HIAF-U) can reach 20+ GeV with 100 more intense muon beam

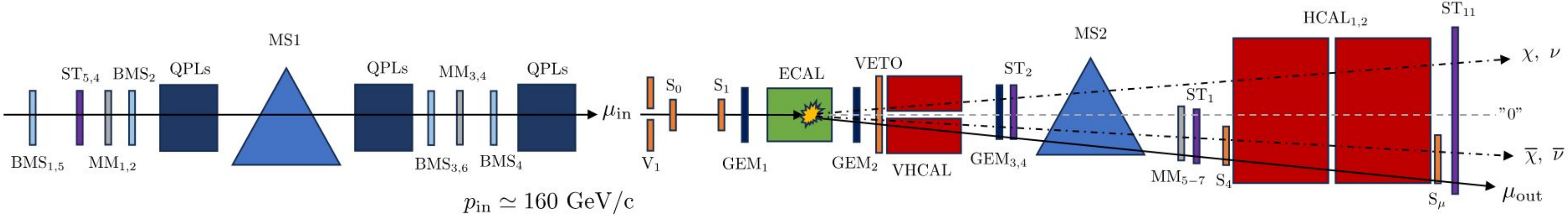
PRL132, 211803 (2024) Search for Dark Sectors at NA64μ



Careful Accounting Could Reveal the Dark Sector

May 21, 2024 • *Physics* 17, s54

An experiment at CERN seeks signs of dark matter by looking for missing energy and momentum in the debris of particle collisions.



百米长度，多种探测器，磁场测量缪子动量，电磁量能器作为靶，后端HCAL作veto

FIG. 2. Schematic illustration of the NA64μ setup and of a signal event topology. Well-defined incoming muons with momentum $p_{\rm in} \simeq 160$ GeV$/c$ are reconstructed in the first magnet spectrometer and tagged by a set of scintillator counters before arriving at the active target (ECAL). In the collision of muons with the target nuclei the bremsstrahlunglike reaction and subsequent invisible decay, $\mu N \to \mu N(Z' \to \text{invisible})$ is produced. The resulting scattered muon with momentum $p_{\rm out} \leq 80$ GeV$/c$ is measured in the second spectrometer (MS2).

Muon Source In China

https://indico.itp.ac.cn/event/384/contributions/2338/attachments/1435/2311/Liangwen_CHEN_muon_sources_at_HIAF-0425.pdf

MELODY@CSNS pulsed, ~2028

Muon@ SHINE high-repetition-rate, 2030

Muon@ SULF compact muon source

HIAF-HIRIBL GeV energy muon

MuST@CiADS continuous, ~2029

HIAF: GeV Muon beam in 2026?

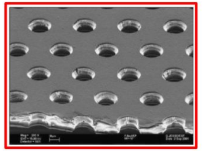
https://indico.itp.ac.cn/event/384/contributions/2338/attachments/1435/2311/Liangwen_CHEN_muon_sources_at_HIAF-0425.pdf

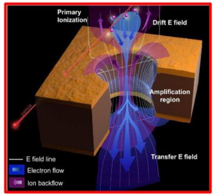
- Brief Introduction
    - Muon Physics, China's GeV Muon Beam
- **A general picture of PKMu**
- Muon Tomography
- Exp with Cosmic Muons
- HIAF proposal 1 with Muon beam
- HIAF proposal 2 with Muon beam
- Future and Summary

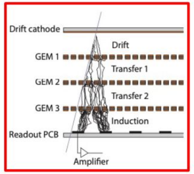
PeKing Univ. Muon group (PKMu)

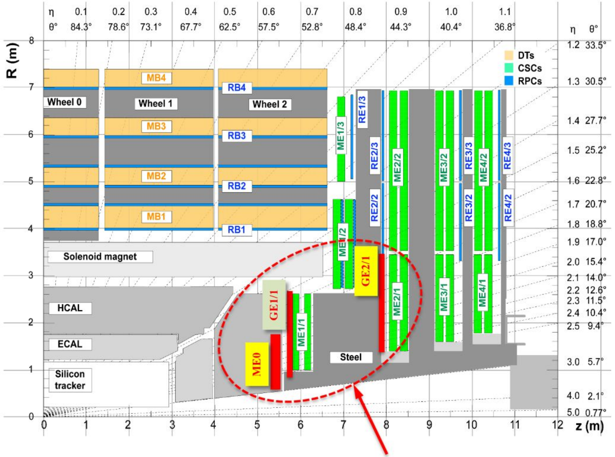
- ➔ **CMS Muon Trigger RPC**: assembled and tested at PKU at around 2002
- ➔ **RPC R&D for nuclear physics**
- ➔ **CMS GEM** upgrade program

北大基地生产的第一个CMS GEM模块









CMS端盖缪子探测器 GEM升级

北京大学、清华大学、中山大学、北京航空航天大学

Combination of glass RPC & Delay-line Readout


Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

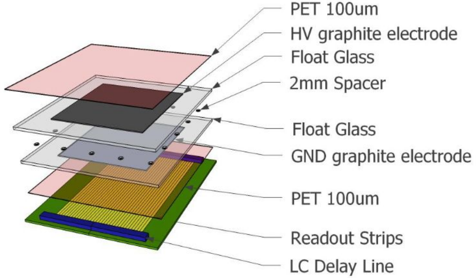
journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Study of spatial resolution properties of a glass RPC

Qite Li, Yanlin Ye *, Chao Wen, Wei Ji, Yushou Song, Rongrong Ma, Chen Zhou, Yucheng Ge, Hongtao Liu

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China



Reference:

- 许金艳,**李奇特***, 等, ***物理实验*** 41(2021)23
- **Qi-Te, Li,** et al. ***Chinese Physics C*** 37 (2013)016002.
- S. Chen, **Q. Li***, et al, ***JINST***: 10 (2014)10022.

90% R134a+9% i-C_4H_{10}+1% SF_6 50ml/Min

PKMu (R&D) MUonE (ongoing)

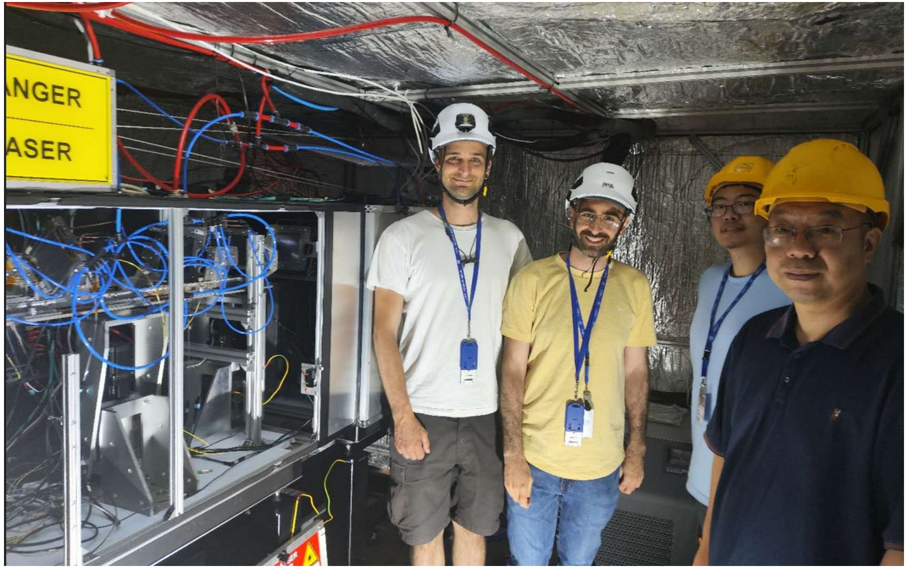
PKMu: Muon on target experiment proposed by PKU for multi-purpose including cosmic ray, dark boson, and **quantum entanglement**.

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

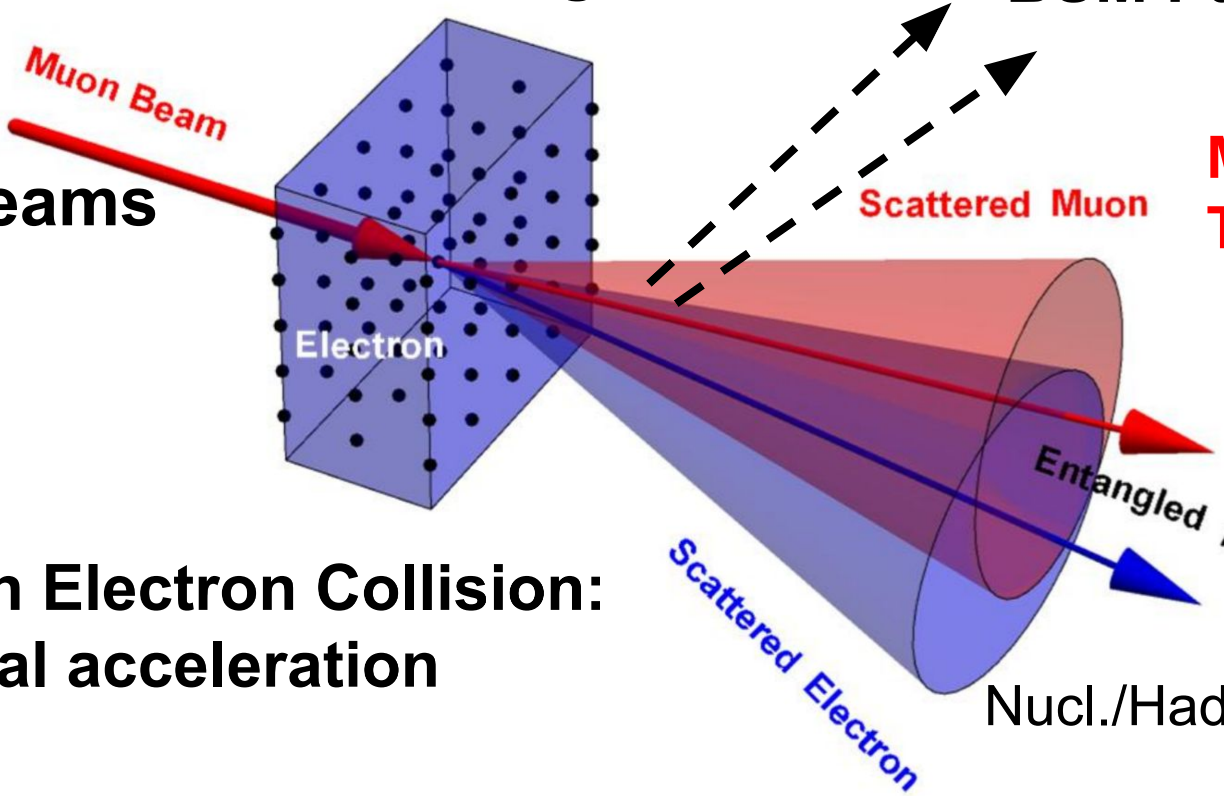


GeV Muon Scattering

Cosmic
or
Muon beams

Surrounding DM

BSM Particles



Muon Tomography

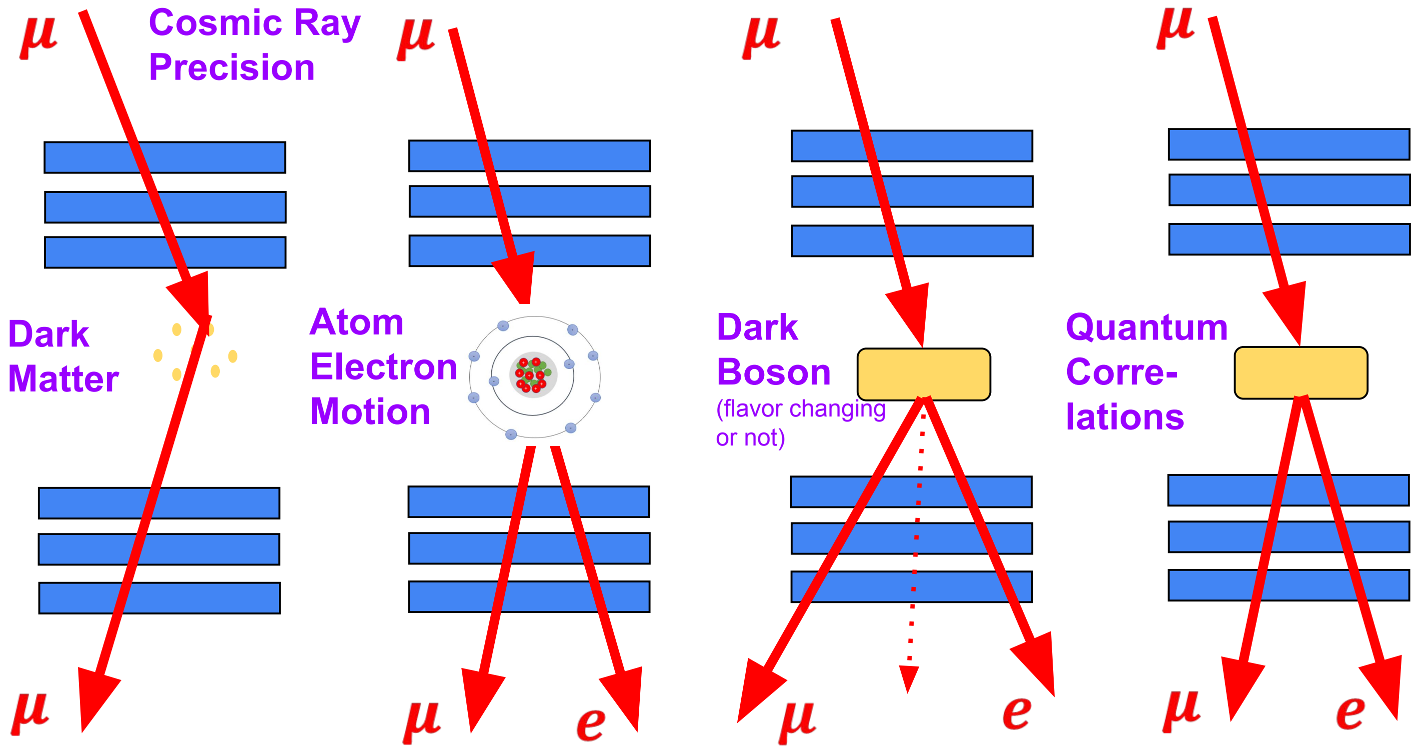
Quantum Entanglement

Muon Electron Collision: orbital acceleration

Nucl./Hadron Physics

Rich Physics via Probing and Knocking with Muons

Cosmic muons (Local lab) or muon beams (HIAF, CERN…)



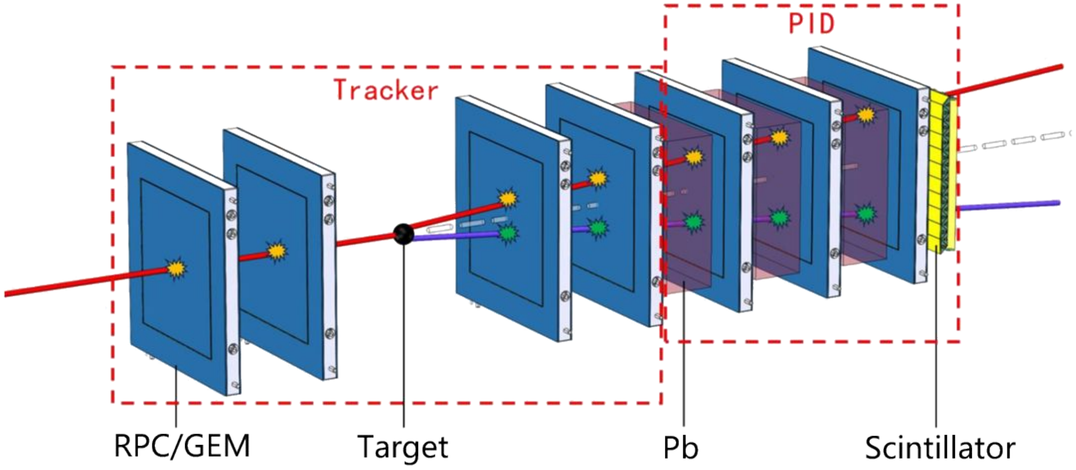
Detector Legos

Tracking: RPC, GEM, SStrip, LGAD

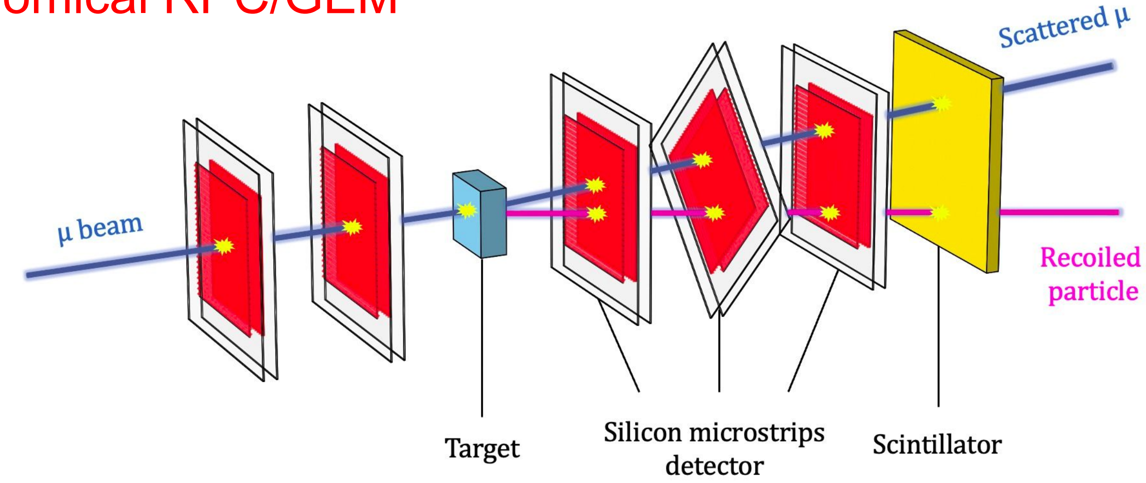
PID, veto: Scintillator Absorber

Readouts: delay line, 2D, multi-leptons

arXiv: 2507.23458; arXiv:2507.03914, PRD 110, 016017 (2024); JPG52 (2025) 075002; PRD 111, 116018 (2025), arXiv:2507.23458, MPLA 40 (2025) 24, 2530008



Economical RPC/GEM



Mimicking one-station MUonE

Flexibility, multi-purpose

Detector Legos

Tracking:
RPC, GEM, SStrip, LGAD

PID, veto:
Scintillator
Absorber

Readouts:
delay line, 2D, multi-leptons

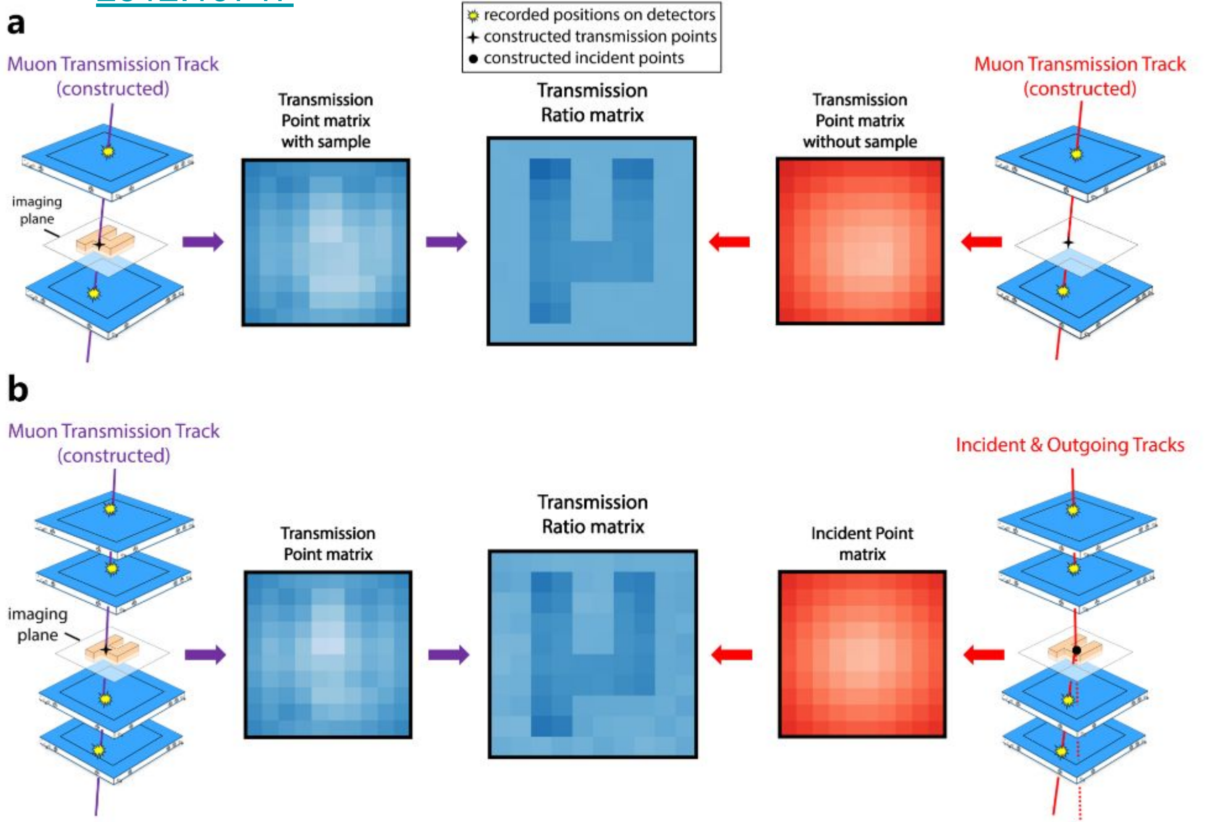
- Brief Introduction
  - Muon Physics, China’s GeV Muon Beam
- A general picture of PKMu
- **Muon Tomography**
- Exp with Cosmic Muons
- HIAF proposal 1 with Muon beam
- HIAF proposal 2 with Muon beam
- Future and Summary

PμMA: Millimeter-Resolution cosmic muon Imaging

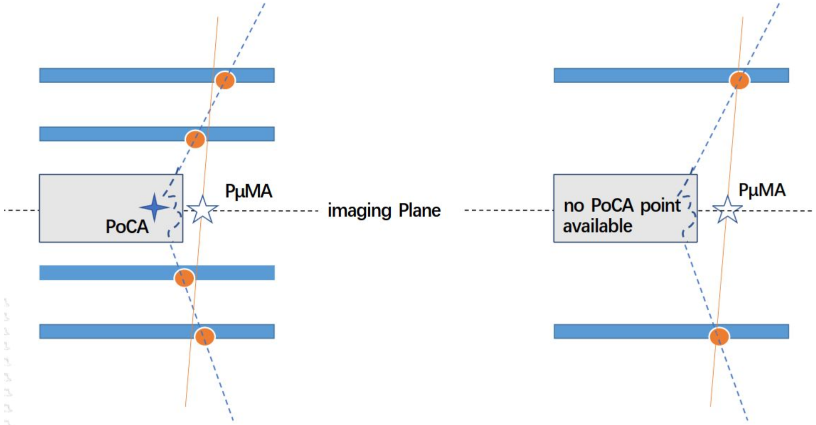
2512.19747

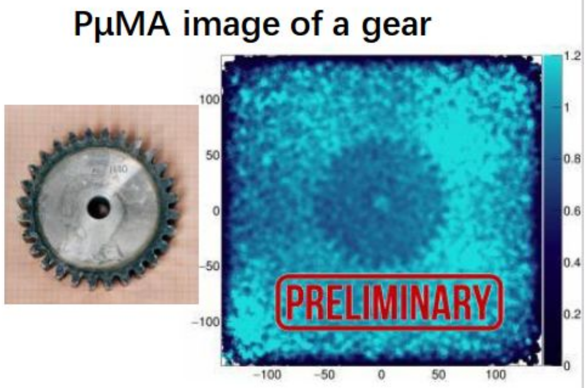
Projection-shifted Muon Transmission Tomography:

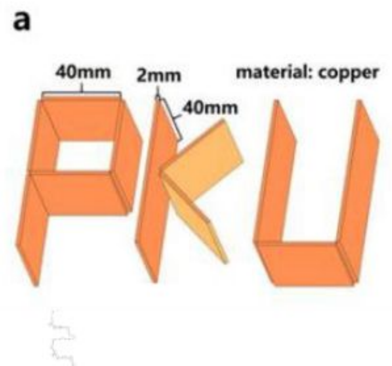
- reconstructs tracks by **linking** upstream and downstream hits,
- projecting scattering induced deflection as **a measurable shift on an imaging plane**,
- enables millimeter scale resolution requiring **only two detectors**.

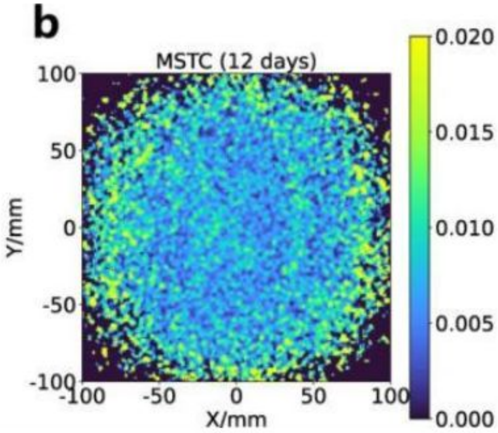


PμMA: Millimeter-Resolution cosmic muon Imaging

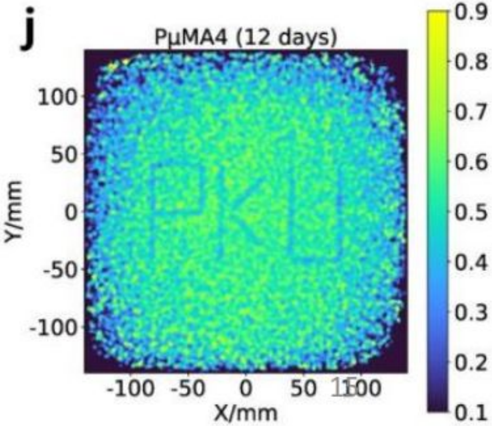








PμMA



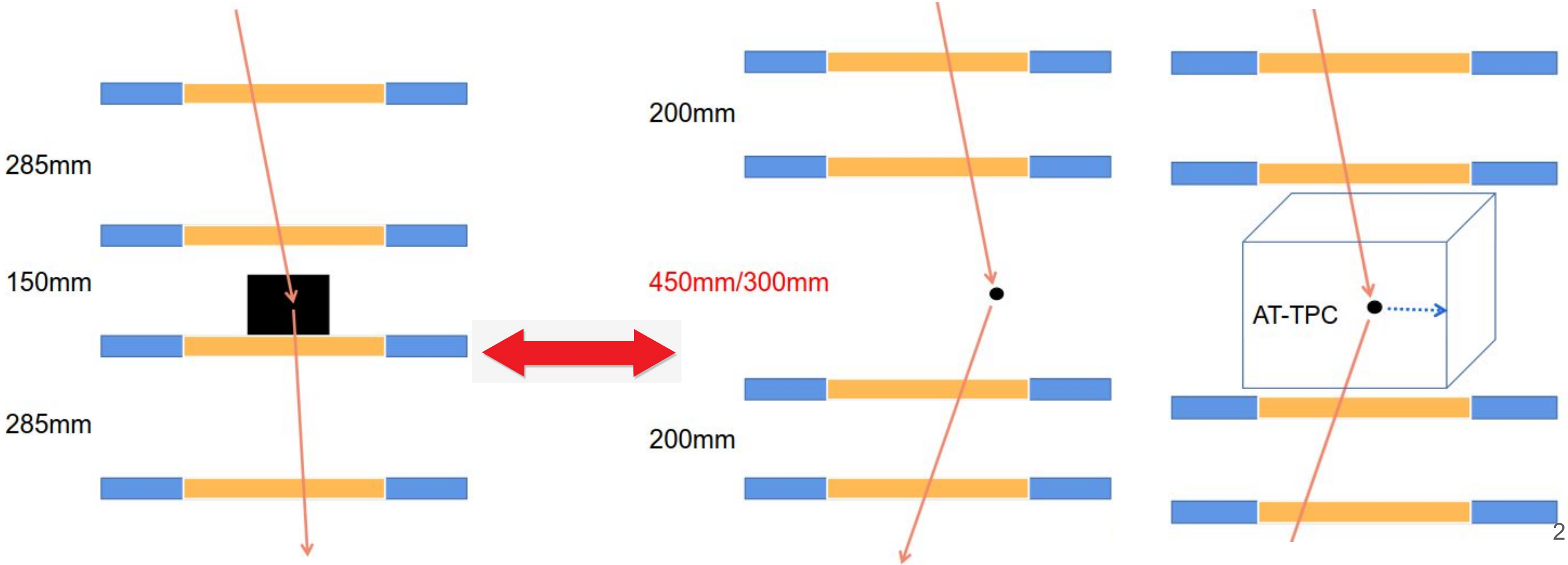
- Brief Introduction
  - Muon Physics, China’s GeV Muon Beam
- A general picture of PKMu
- Muon Tomography
- Exp with Cosmic Muons
- HIAF proposal 1 with Muon beam
- HIAF proposal 2 with Muon beam
- Future and Summary

Muon Tomography and Muon-Philic DM Search

Muon Tomography
缪子成像

Dark Matter Search
暗物质寻找

[Phys.Rev.D 110 (2024) 1, 016017]()

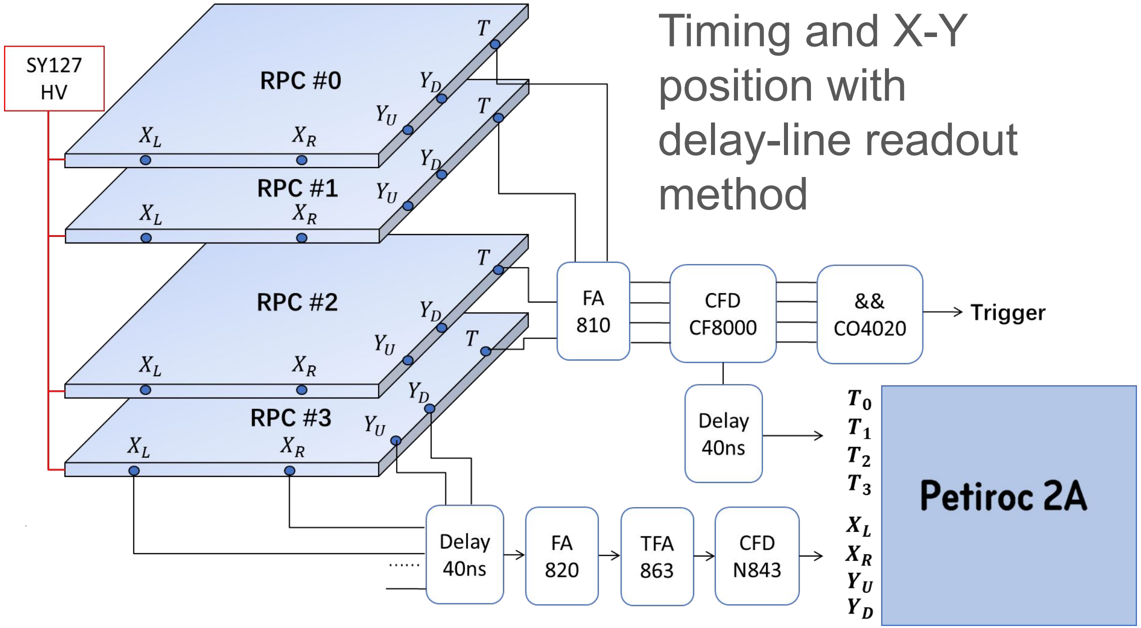


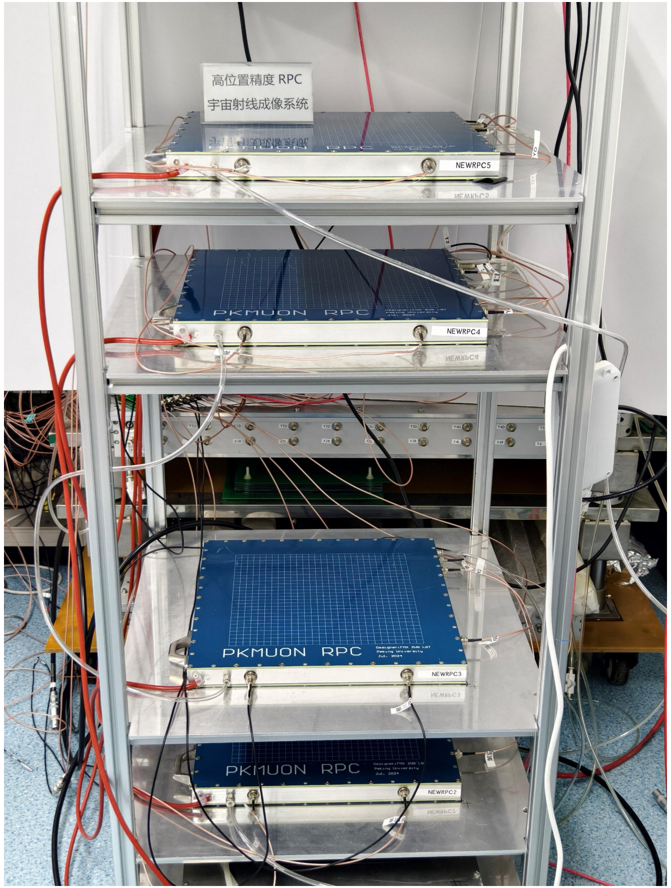
A small lab exp costing ~50000 RMB

PRL136 (2026) 15, 151001

4-station 28 cm*28 cm RPC for the moment
A spatial Resolution of 0.7 mm
Petiroc 2A is a 32-channel front-end ASIC

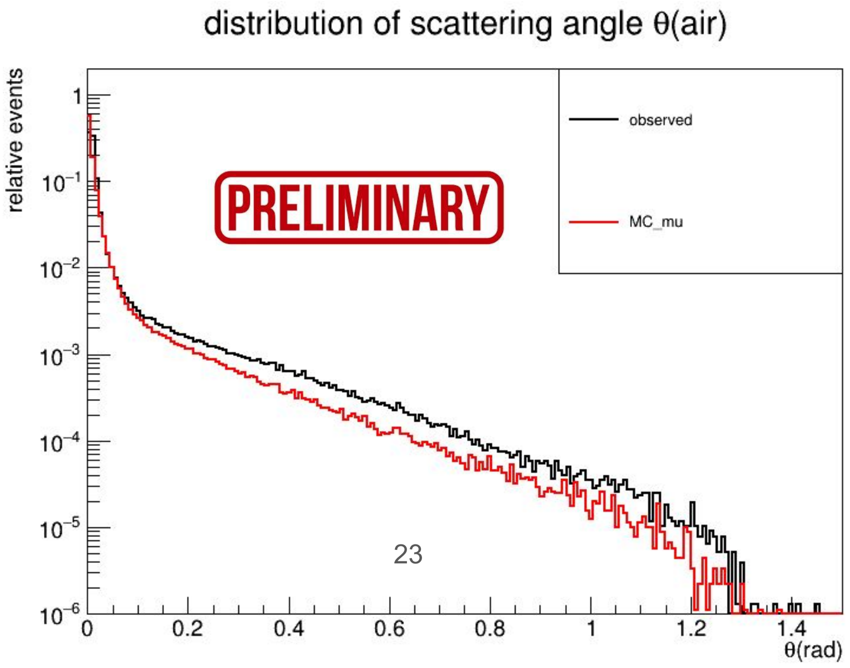
Timing and X-Y position with delay-line readout method





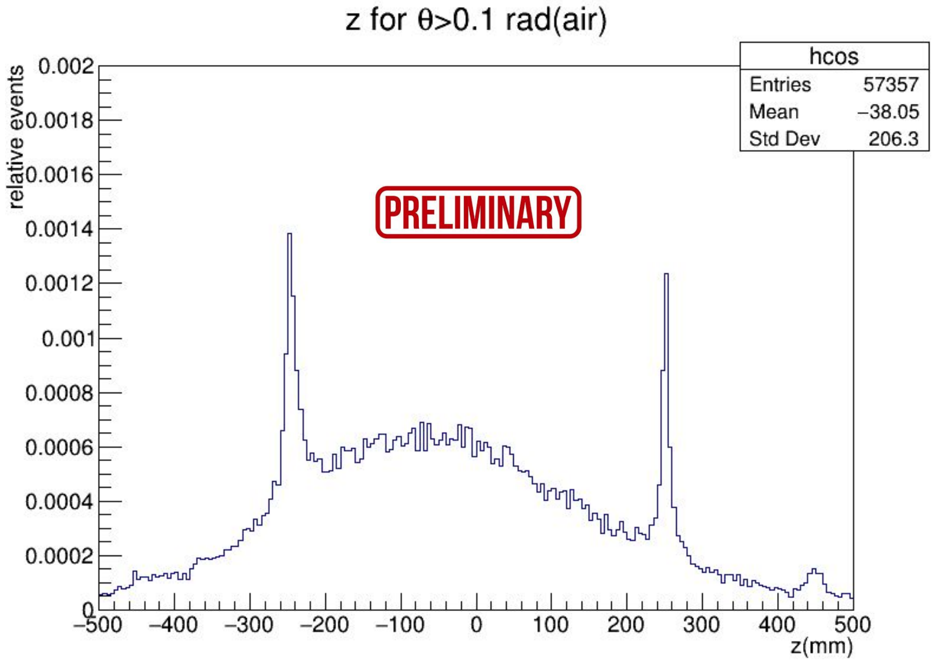
Initial Comparison Between Experiment and Simulation

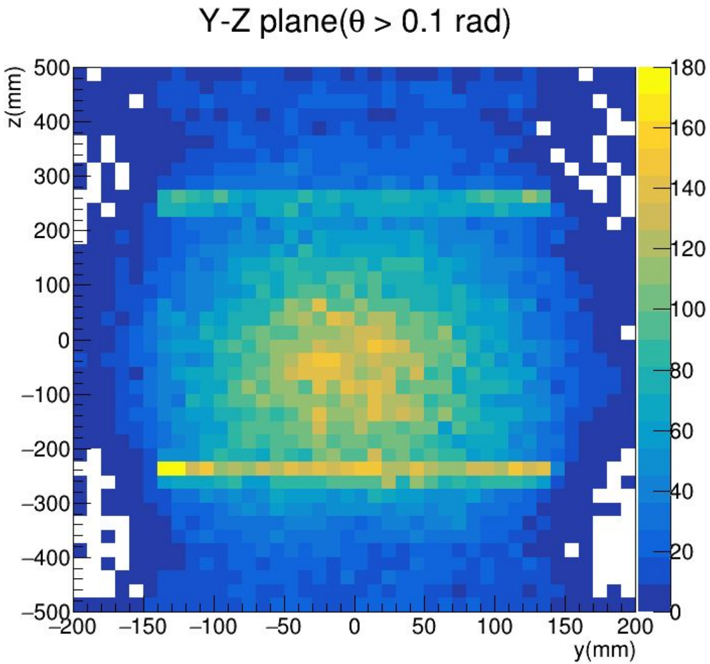
- Simulated the scattering angle distribution of cosmic-ray muons
- Significant discrepancy observed between experimental results and simulations at large scattering angles.
- What is the origin of these large-angle scattering events?



Spatial Distribution of Large-Angle Scattering Events

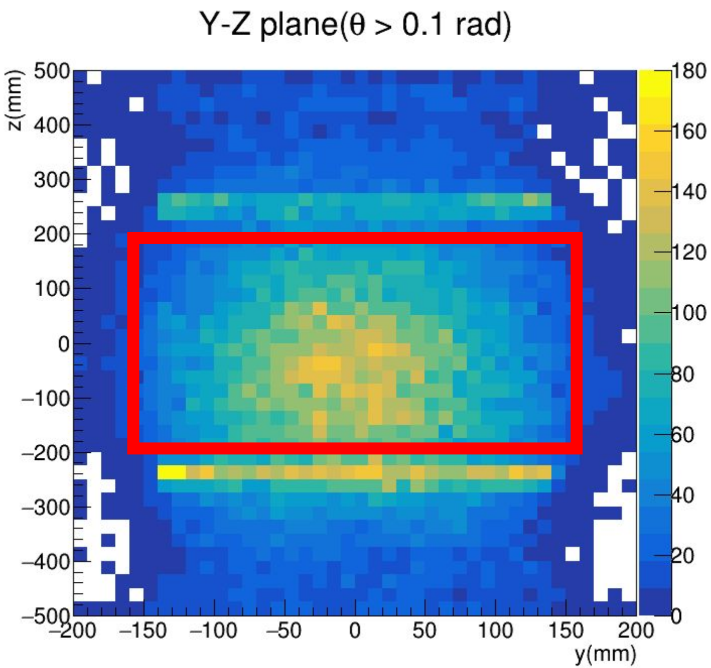
- Analyzed height(z-coordinate) distribution of large-angle scattering vertices
- Multiple events clustered at RPC detector positions

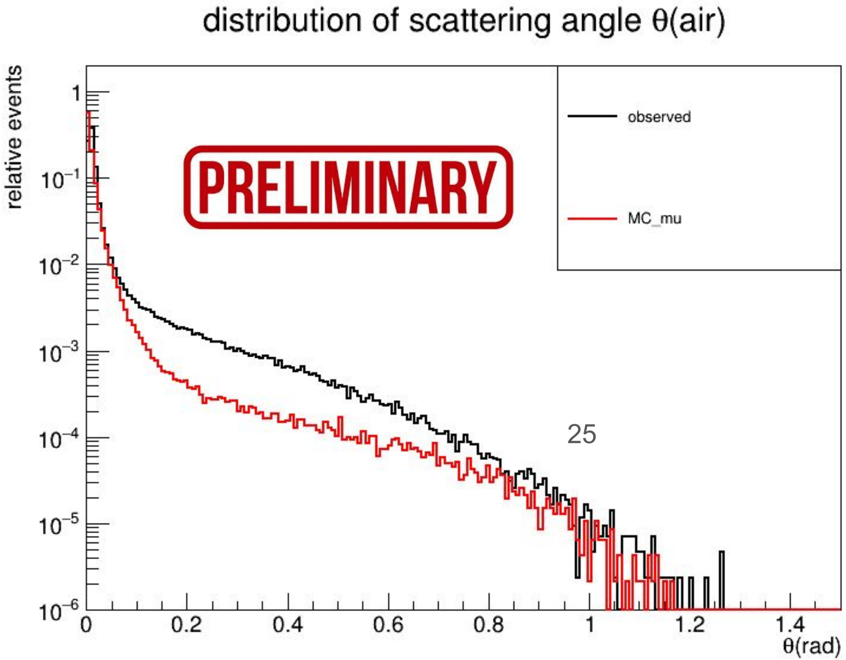




Scattering Angle Distribution in ROI Area

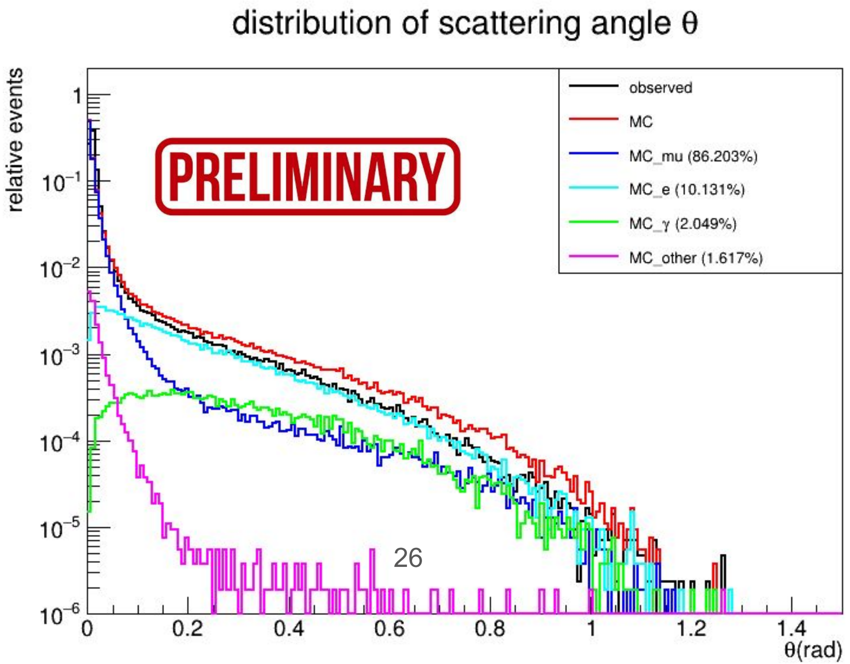
- Analyzed angular distribution within detector’s sensitive volume (-200 mm<z<200 mm)
- Large-angle scattering events persist after selection





Simulation of CRs at Sea-level (All-Particle Composition)

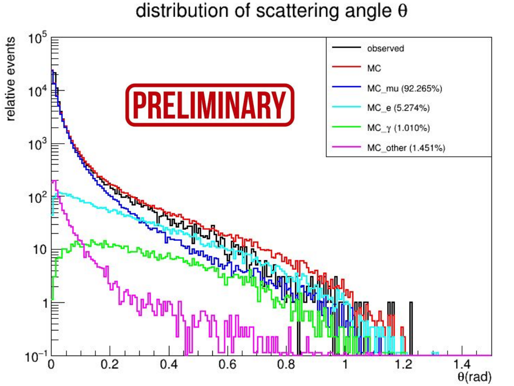
- Simulated particle components at sea level： μ, e, γ, p, n, π
- Small-angle scattering dominated by muons
- Large-angle scattering primarily from electrons and photons
- Possible discrepancies between measured particle composition and simulation results.

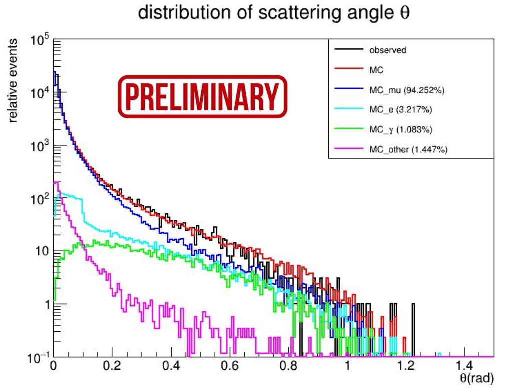


Air data

Joint-Fitting Method(0.1-1.5 rad)

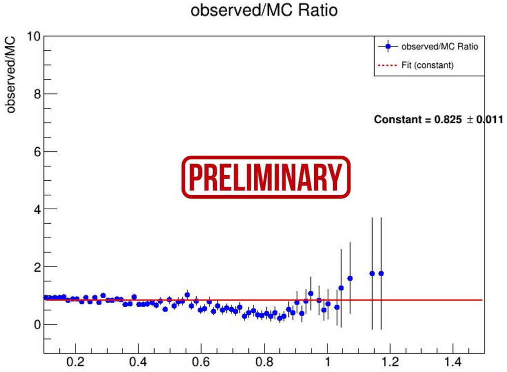
- Performed combined fitting of lead block data using Roofit
- Simultaneously fitted all particle component distributions to experimental measurements
- Validation showed excellent agreement
- Successfully applied the same methodology to air data: scaling factor of e=0.610±0.158 (fitted ratio/unfitted ratio)

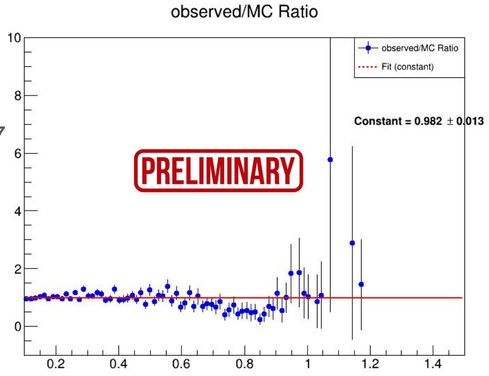




Unfitted

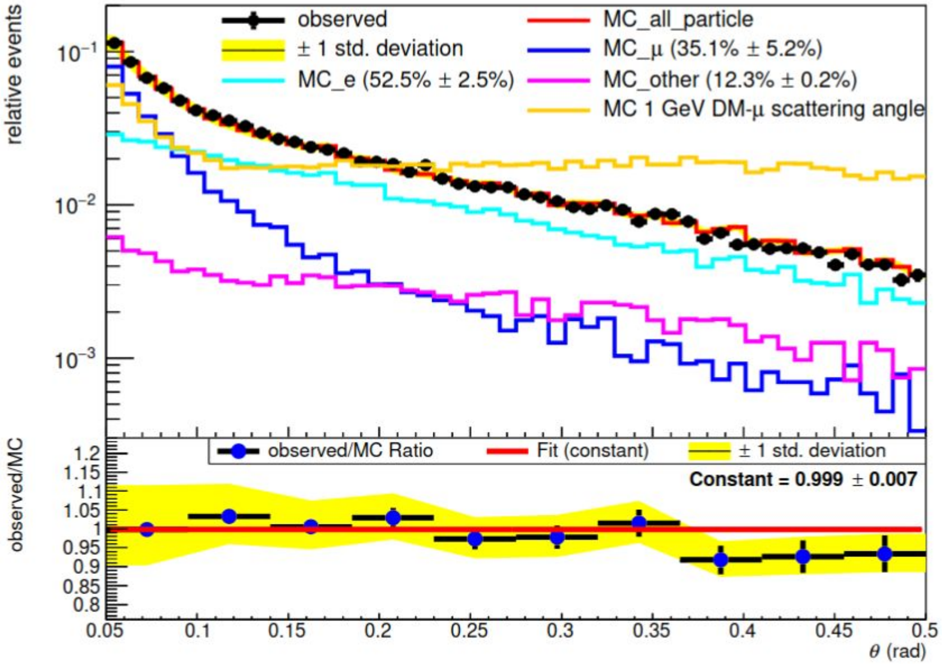
Fitted

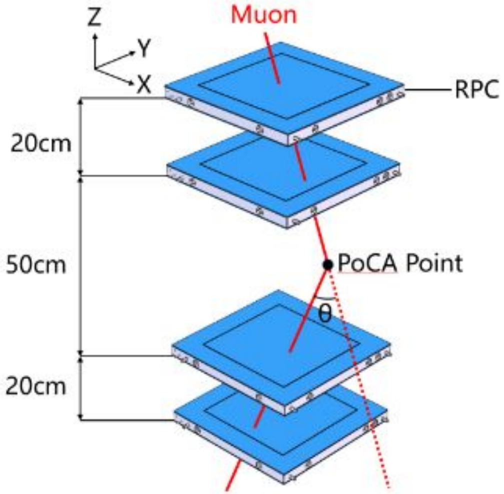




Precision Measurement of Secondary Cosmic Rays

During a **63-day** campaign from February 12, 2025, **1.18 million** cosmic ray scattering events were recorded and analyzed. **The scattering angle observable is sensitive to the cosmic ray component fractions!**





Muon Philic DM Search

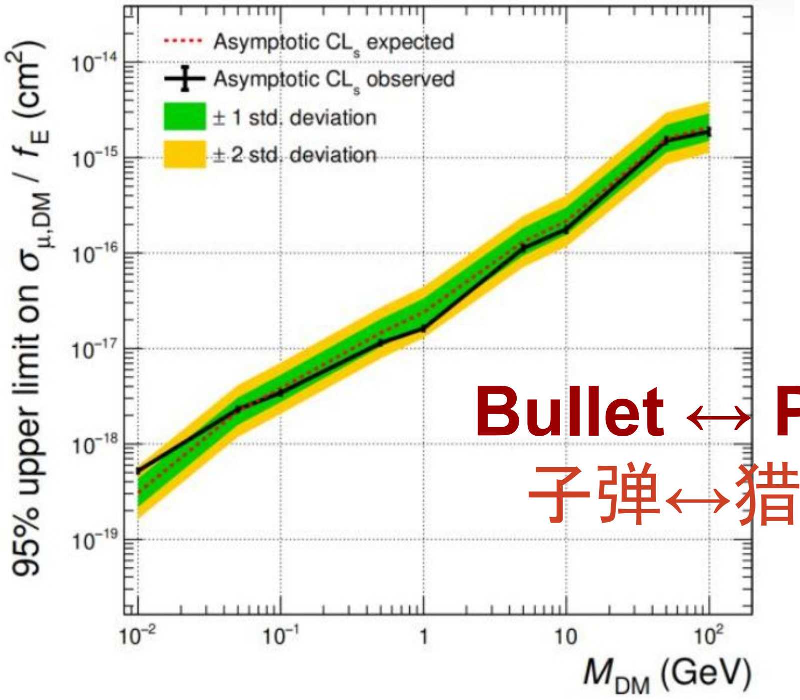
PKMu cosmic ray DM search

- 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 m3 detector + 1 year exposure + full angular range → 4–5 orders of magnitude improvement



Bullet ↔ Prey

子弹↔猎物

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.

11

Int.J.Mod.Phys.A 38 (2023) 29n30, 2350154

Phys.Rev.D 110 (2024) 1, 016017

PHYSICAL REVIEW D **110,** 016017 (2024)

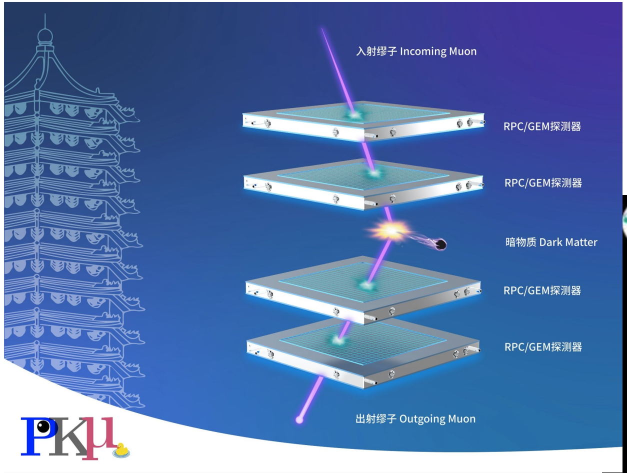
Proposed Peking University muon experiment for muon tomography and dark matter search

Xudong Yu,* Zijian Wang, Cheng-en Liu, Yiqing Feng, Jinning Li, Xinyue Geng, Yimeng Zhang, Leyun Gao, Ruobing Jiang, Youpeng Wu, Chen Zhou,† Qite Li,‡ Siguang Wang, Yong Ban, Yajun Mao, and Qiang Li§

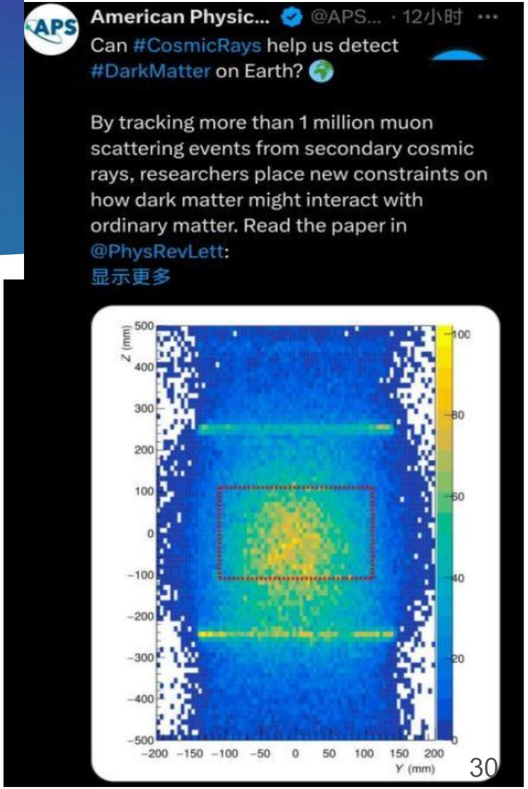
State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing, 100871, China

(Received 23 March 2024; accepted 24 June 2024; published 19 July 2024)

Phys.Rev.Lett. 136 (2026) 15, 151001



APS promotion



PHYSICAL REVIEW LETTERS **136,** 151001 (2026)

Probing Cosmic Ray Composition and Muonphilic Dark Matter via Muon Tomography

Cheng-en Liu, Rongfeng Zhang, Zijian Wang, Andrew Michael Levin, Leyun Gao, Jinning Li, Minxiao Fan, Youpeng Wu, Zibo Qin, Yong Ban, Zaihong Yang, Qite Li,* Chen Zhou,† and Qiang Li‡

(PKMu Collaboration)

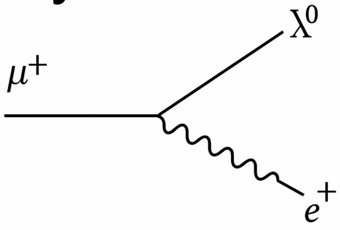
State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China

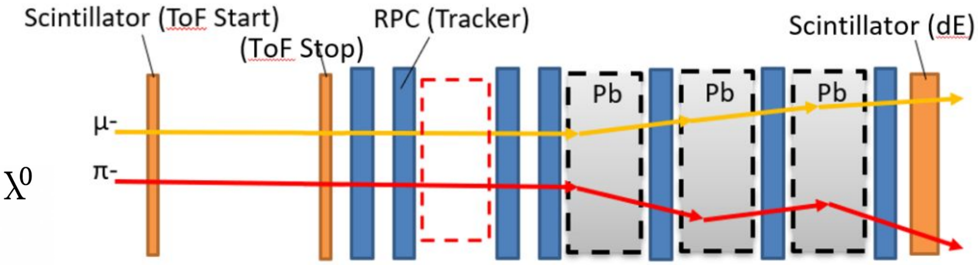
(Received 21 August 2025; revised 27 November 2025; accepted 27 February 2026; published 14 April 2026)

- Brief Introduction
  - Muon Physics, China's GeV Muon Beam
- A general picture of PKMu
- Muon Tomography
- Exp with Cosmic Muons
- HIAF proposal 1 with Muon beam
- HIAF proposal 2 with Muon beam
- Future and Summary

PKMu@HIAF-HIRIBL: exp-v0 (1-10 days) ?

1. Beam properties
2. Muon Tomography
3. mu > e X0
   Esp:
   mX0~105 MeV

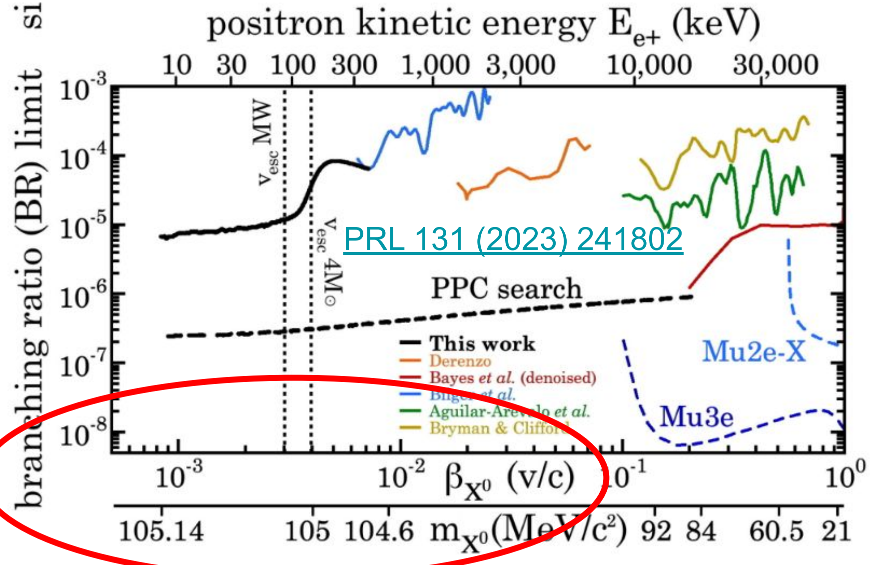




Millimeter-Resolution Cosmic-Ray Imaging via Projection-Shifted Muon Transmission Tomography

[2512.19747](https://arxiv.org/abs/2512.19747)

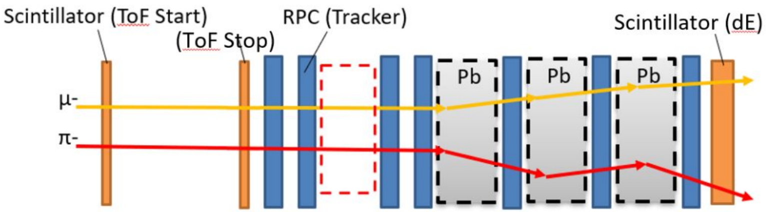
Zibo Qin[1], Rongfeng Zhang[1], Pei Yu[2], Cheng-en Liu[1], Liangwen Chen[2], Feng Zhang[3], Zaihong Yang[1], Qite Li[1*], Qiang Li[1*]



PRL 131 (2023) 241802

Detectors Requirement (PID)

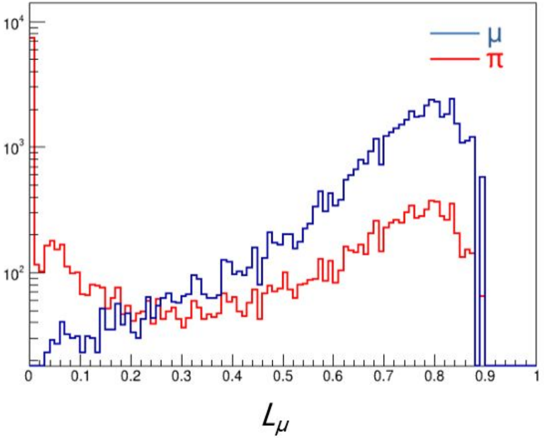
[Jinning Li@MIP2025]



A prototype detection system@HIRIBL for muon beam condition monitoring, detector testing, and preliminary experiments (scattering, tomography)

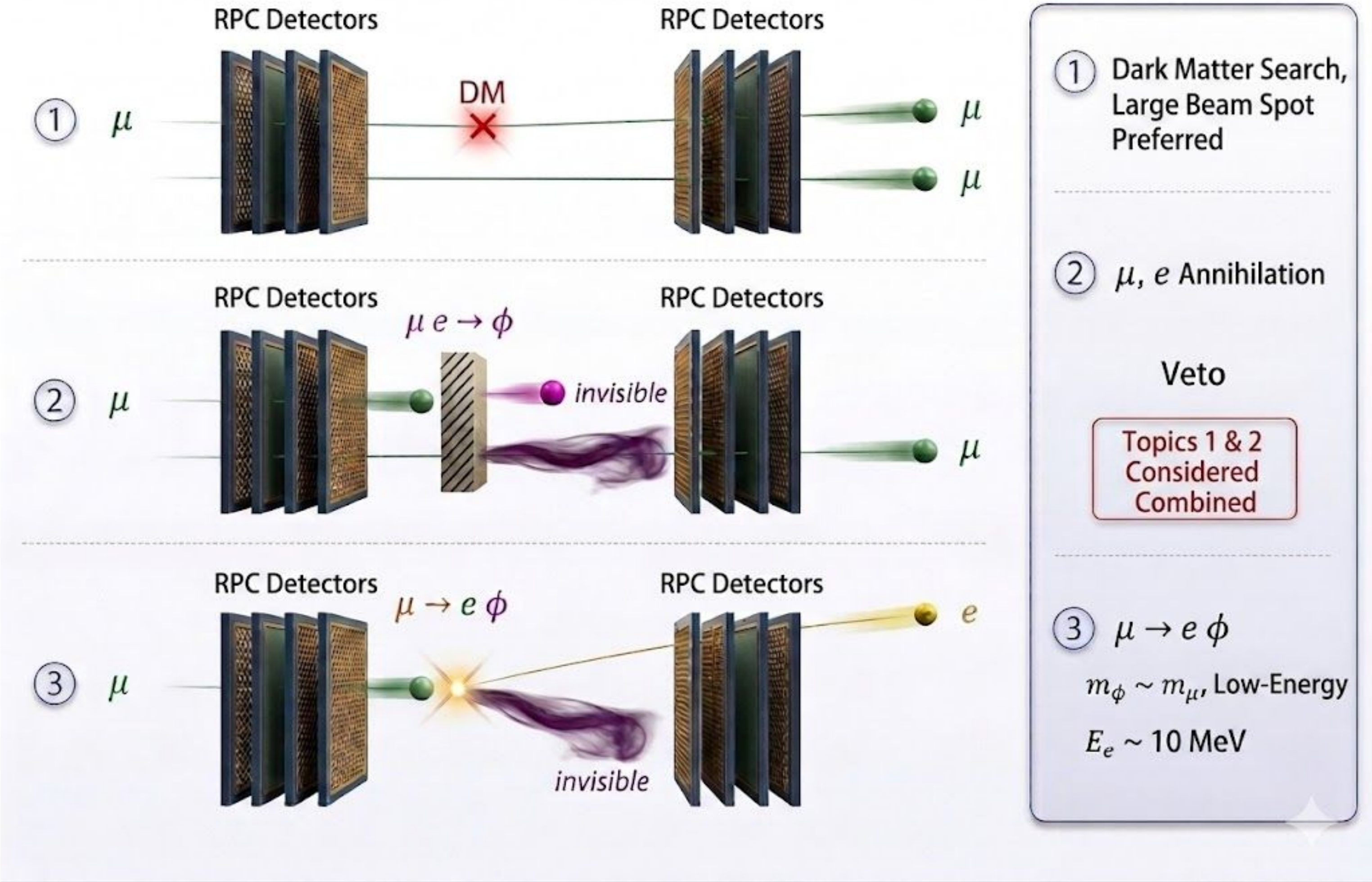
- Beam profile and divergence
- Beam particle identification
  - Mass difference: ToF, dE
    - Different physical processes: dE

10cm-thick Pb
Plastic scintillators



3 GeV/c muons and pions (simplified simulation: 4% momentum spread; equal numbers of muons and pions)

PID based on the product of likelihoods of 3 variables:
(ToF / energy deposition / square residual of linear track)
Over 70% muon\pion efficiency in this preliminary version.
Upgrade: detailed simulation, delicate detectors (ECal/RICH…)


RPC Detectors
RPC Detectors
1 μ
DM
μ
μ
RPC Detectors
RPC Detectors
2 μ
$\mu e \to \phi$
invisible
μ
RPC Detectors
RPC Detectors
3 μ
$\mu \to e\,\phi$
e
invisible
1 Dark Matter Search, Large Beam Spot Preferred
2 μ, e Annihilation
Veto
Topics 1 & 2 Considered Combined
3 $\mu \to e\,\phi$
$m_\phi \sim m_\mu$, Low-Energy
$E_e \sim 10$ MeV

μe→Φ resonant production

Method 1: rest electron

$$\sigma_{\rm rest}(E_B) = ZA\frac{1}{\sqrt{2\pi}\sigma_E}\exp\left[-\frac{(E_B-E_{\rm res})^2}{2\sigma_E^2}\right].$$

Method 2: Compton profile

$$\rho(k) = -\frac{1}{2\pi k}\frac{dJ}{dk}.$$

$$|\mathcal{M}|^2 = 2g_\phi^2\left(P_A\cdot P_B - m_A m_B\right),$$

$$\sigma(E_B) = \int_{k_{\min}}^{k_{\max}} dk\,\frac{|\mathcal{M}|^2\,k\,n(k)}{16\pi p_B^2 E_A}.$$

Method 3: Spinor Solver

$$U_{E\kappa m}(\mathbf{k}) = \frac{4\pi}{k}\begin{pmatrix} g_{E\kappa}(k)\mathcal{Y}_{\kappa m}(\hat{k}) \\ -f_{E\kappa}(k)\mathcal{Y}_{-\kappa m}(\hat{k})\end{pmatrix}.\quad |\mathcal{M}|^2 = 2g_\phi^2\left(P_A\cdot P_B - m_A m_B\right),$$

$$n(k) = \sum_{\text{shells}}\sum_m\sum_a U_a^\dagger(\mathbf{k})U_a(\mathbf{k}).$$

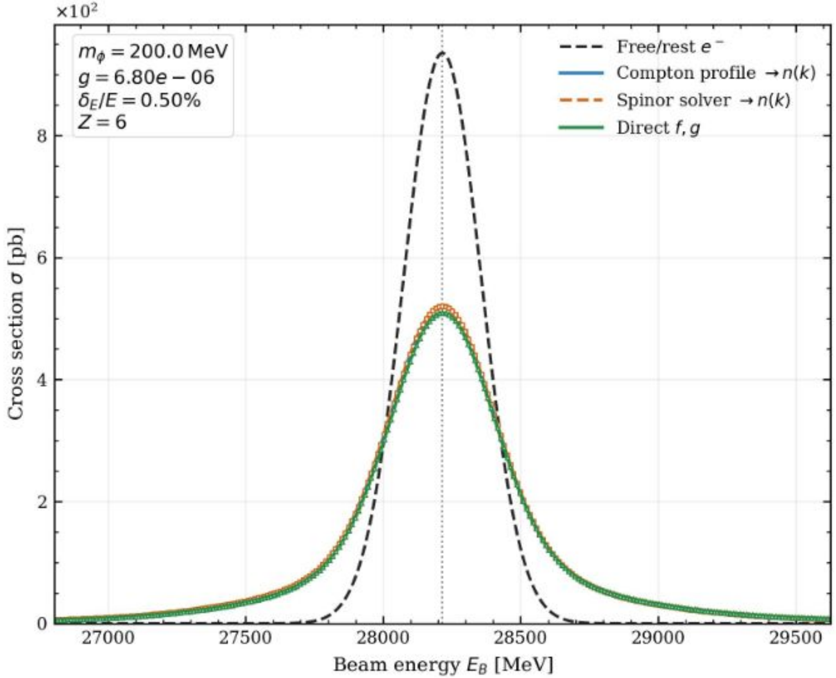
$$\sigma(E_B) = \int_{k_{\min}}^{k_{\max}} dk\,\frac{|\mathcal{M}|^2\,k\,n(k)}{16\pi p_B^2 E_A}.$$

Method 4: direct *f,g*

$$|\mathcal{M}|^2_{n\kappa j} = \frac{2w_{n\kappa j}\pi^2 g_\phi^2}{k^2}\left[(E_B-m_B)g_{n\kappa}^2(k) - 2g_{n\kappa}(k)f_{n\kappa}(k)p_B x_0 + (E_B+m_B)f_{n\kappa}^2(k)\right].$$

$$|\mathcal{M}|^2_{\rm direct} = \sum_{n\kappa j}|\mathcal{M}|^2_{n\kappa j}.$$

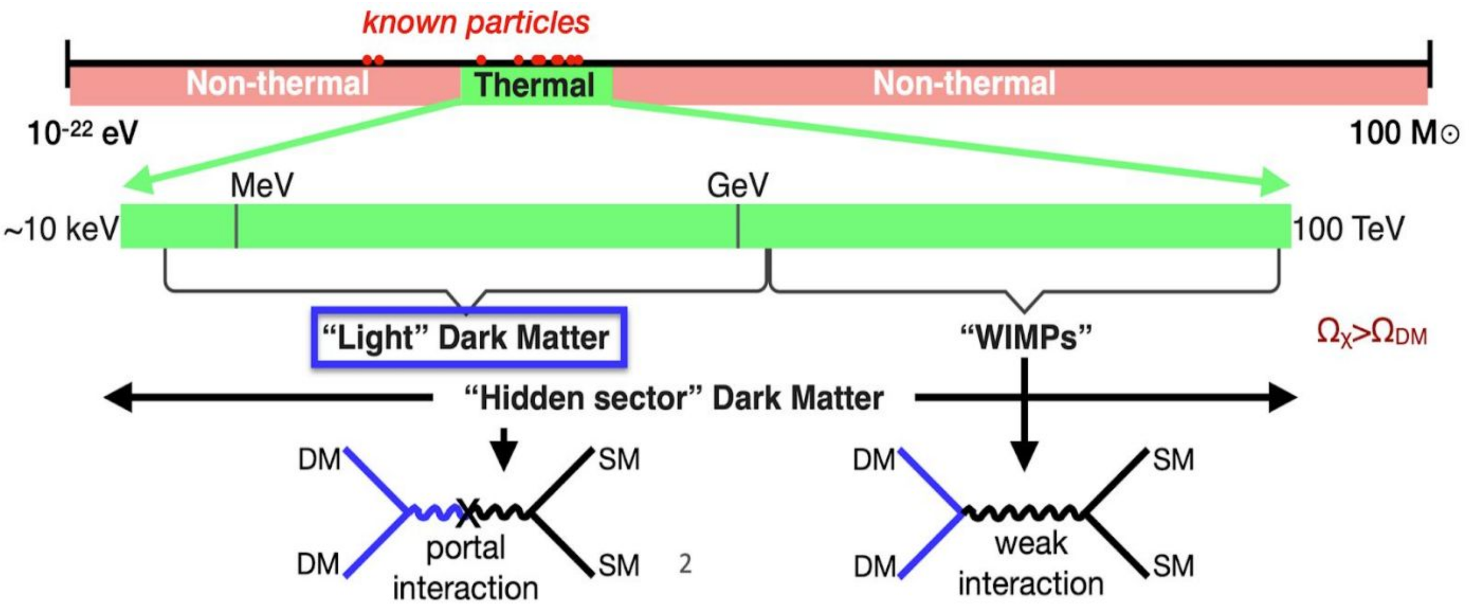
$$\sigma_{f,g}(E_B) = \int_{k_{\min}}^{k_{\max}} dk\,\frac{k\,|\mathcal{M}|^2_{\rm direct}}{16\pi p_B^2 E_A}.$$



$$\mathcal{U}_{E\kappa m}(\mathbf{p}) = \frac{4\pi}{p}(-i)^l\begin{bmatrix} g_{E\kappa}(p) \\ f_{E\kappa}(p)(\sigma\cdot\hat{\mathbf{p}})\end{bmatrix}\mathcal{Y}_{+\kappa m}(\hat{\mathbf{p}})$$

- Brief Introduction
  - Muon Physics, China’s GeV Muon Beam
- A general picture of PKMu
- Muon Tomography
- Exp with Cosmic Muons
- HIAF proposal 1 with Muon beam
- HIAF proposal 2 with Muon beam
- Future and Summary

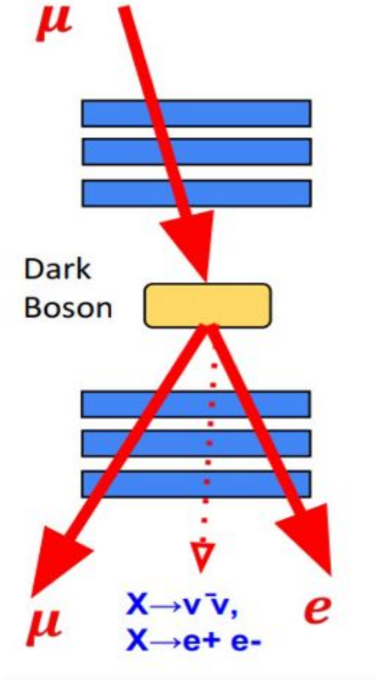
Light Dark Matter → larger Dark Sector

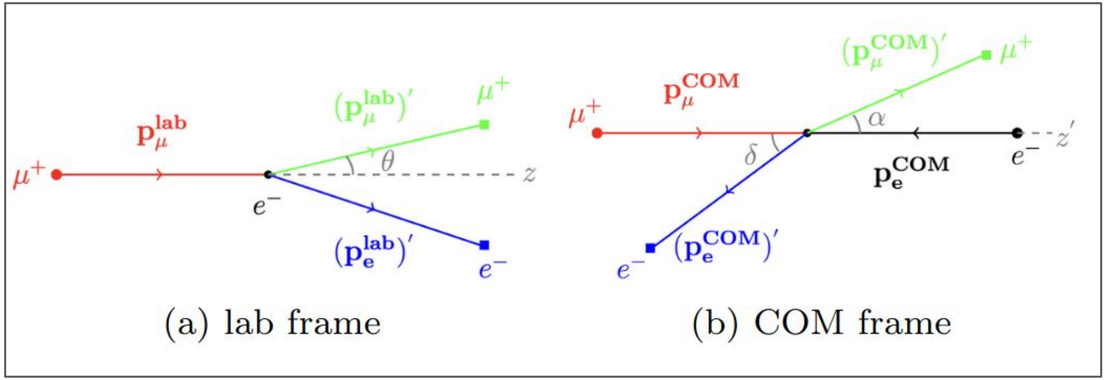


In the context of light-mass (sub-GeV) dark matter minimal models that obtain their relic density through the freeze-out mechanism, it is necessary to introduce a new light mediator. In particular, the scenario of introducing a new "dark" massive vector gauge boson as the mediator is very well-motivated theoretically. JHEP03(2018)084 Granada19 LDMX2024

Searching for Dark Boson at HIAF (>months)

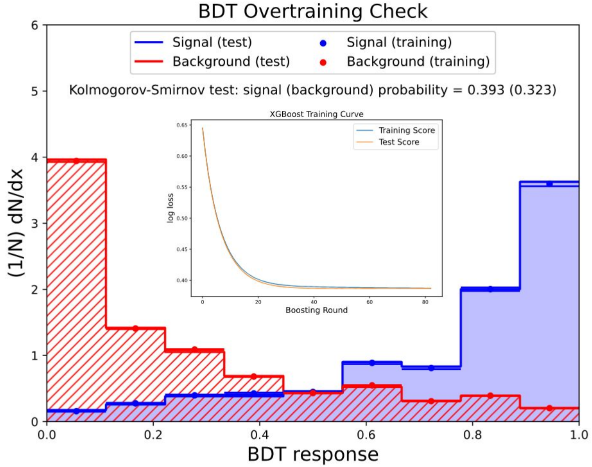
PRD 113 (2026) 7, 072008



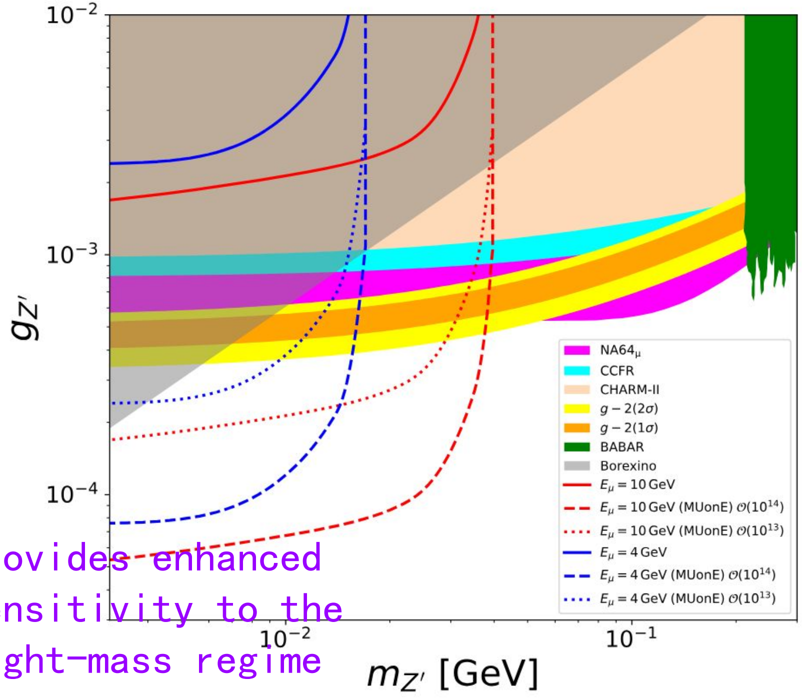


Using the 1–10 GeV muon beam at HIAF to study the minimal L_mu - L_tau model, via mu e →mu e Z', where Z' decay invisibly.

Compared to NA64/MUonE, the lower center-of-mass energy allows for higher detection sensitivity to light-mass Z', particularly in 10 MeV mass region.



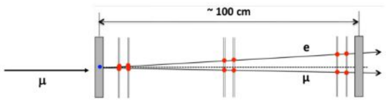
μe→μeZ′ (>months)

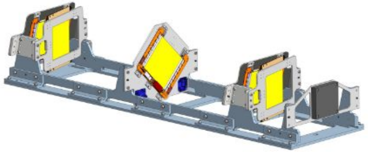


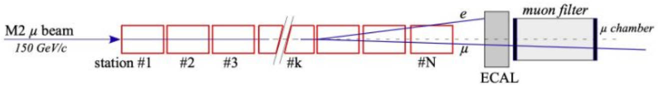
Provides enhanced sensitivity to the light-mass regime

https:// arxiv.org/abs/2307.02404
https://arxiv.org/abs/2109.10093
https://doi.org/10.1016/0370-2693(90)90146-W
https://doi.org/10.1103/PhysRevLett.66.3117
https://arxiv.org/abs/1606.03501
https://doi.org/10.1103/PhysRevLett.107.141302

- ➔ **100 mass points** analyzed for each beam energy (**4 GeV & 10 GeV**).
- ➔ For each point, Optimal BDT threshold chosen to maximize signal significance; final event selection applied.
- ➔ 95% C.L. upper limits on $g_{Z'}$ derived using the likelihood test statistic : $Z = 2(\mu s + b\log(b/(\mu s + b))) \sim \chi^2(1)$
- ➔ A multi-station telescope setup, such as the 40-station **MUonE** experiment with 10 cm lead targets replacing graphite, could greatly enhance signal yield and achieve unprecedented sensitivity to the Z' coupling around $\mathbf{m_{Z'} \sim 10\ MeV}$, surpassing current experimental results.
- ➔ With a conservative estimate of 10^{13} MOT per year, the MUonE-based search would still provide world-leading constraints on the light Z′ dark boson.







Horizontal 10 TeV CR

ref

$$\Phi_T(E_0,\theta) = A_T \times 0.14 E_0^{-\gamma}\left(\frac{1}{1+1.1\hat{E}_0\cos\theta^*/115}+\frac{0.054}{1+1.1\hat{E}_0\cos\theta^*/810}+r_c\right)$$

水平方向，cos~0，能量压低效应小

无需百吨强磁铁

小型实验：验证 mu-e散射作为能量比例尺

大型实验：100 TeV 大气缪子？

Phys. Rev. D 29 (1984) 1

PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOLUME 29, NUMBER 1 1 JANUARY 1984

Cosmic-ray muon spectrum up to 20 TeV at 89° zenith angle

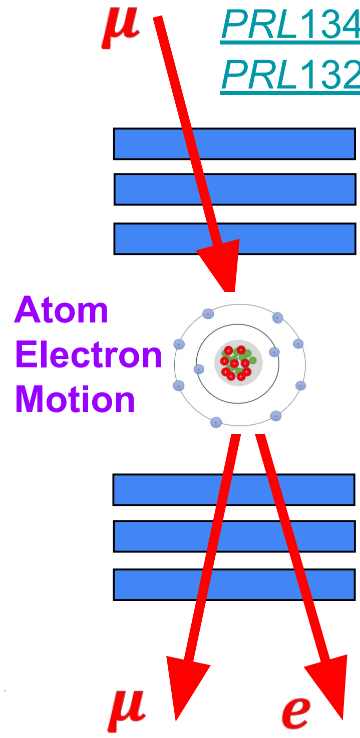
S. Matsuno, F. Kajino, Y. Kawashima, T. Kitamura, K. Mitsui, Y. Muraki, Y. Ohashi, A. Okada, and T. Suda

Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan

- Brief Introduction
    - Muon Physics, China’s GeV Muon Beam
- A general picture of PKMu
- Muon Tomography
- Exp with Cosmic Muons
- HIAF proposal 1 with Muon beam
- HIAF proposal 2 with Muon beam
- Future and Summary

GeV scale Muon-Electron Collider

arXiv:2504.00100, *PRL*134(2025)6, 061802, *PRL*132(2024)26, 261801



- Heisenberg Uncertainty Principle → Electron localization near the nucleus → High momentum.
- In high-Z targets, atomic electrons reach relativistic momenta (O(10) MeV).
- **C.O.M. Energy Elevation:** A 10 GeV Muon beam hitting these "moving" electrons can reach a effective C.O.M. energy of ~GeV.

Muon, Thorium229, X-ray

Unlocking the Thorium-229 Frontier: From Nuclear Clocks to Fundamental Physics

April 24, 2026
Huizhou
Asia/Shanghai timezone

Enter your search term

https://indico.ihep.ac.cn/event/29103

- Overview
- Timetable
- Contribution List
- Registration
- Participant List

这是MIP2026的卫星会议。 住宿和相关要求请浏览MIP主页 https://indico.itp.ac.cn/event/384/

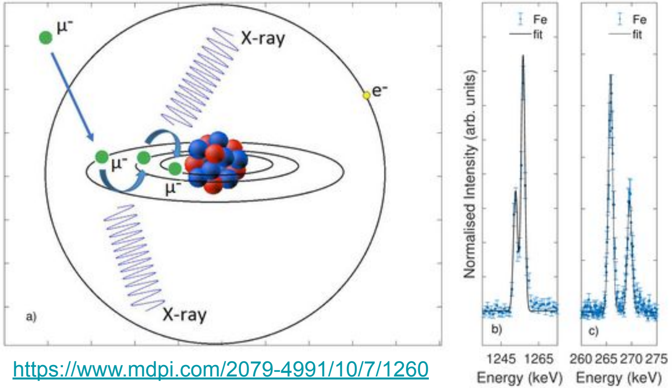
线上： https://meeting.tencent.com/dm/8XkxmQesL5yd #腾讯会议：667-578-864 会议密码：1234

线下： 朝云厅 中海希尔顿酒店(*广东省惠州市惠城区市民乐园西路7号中海广场*)

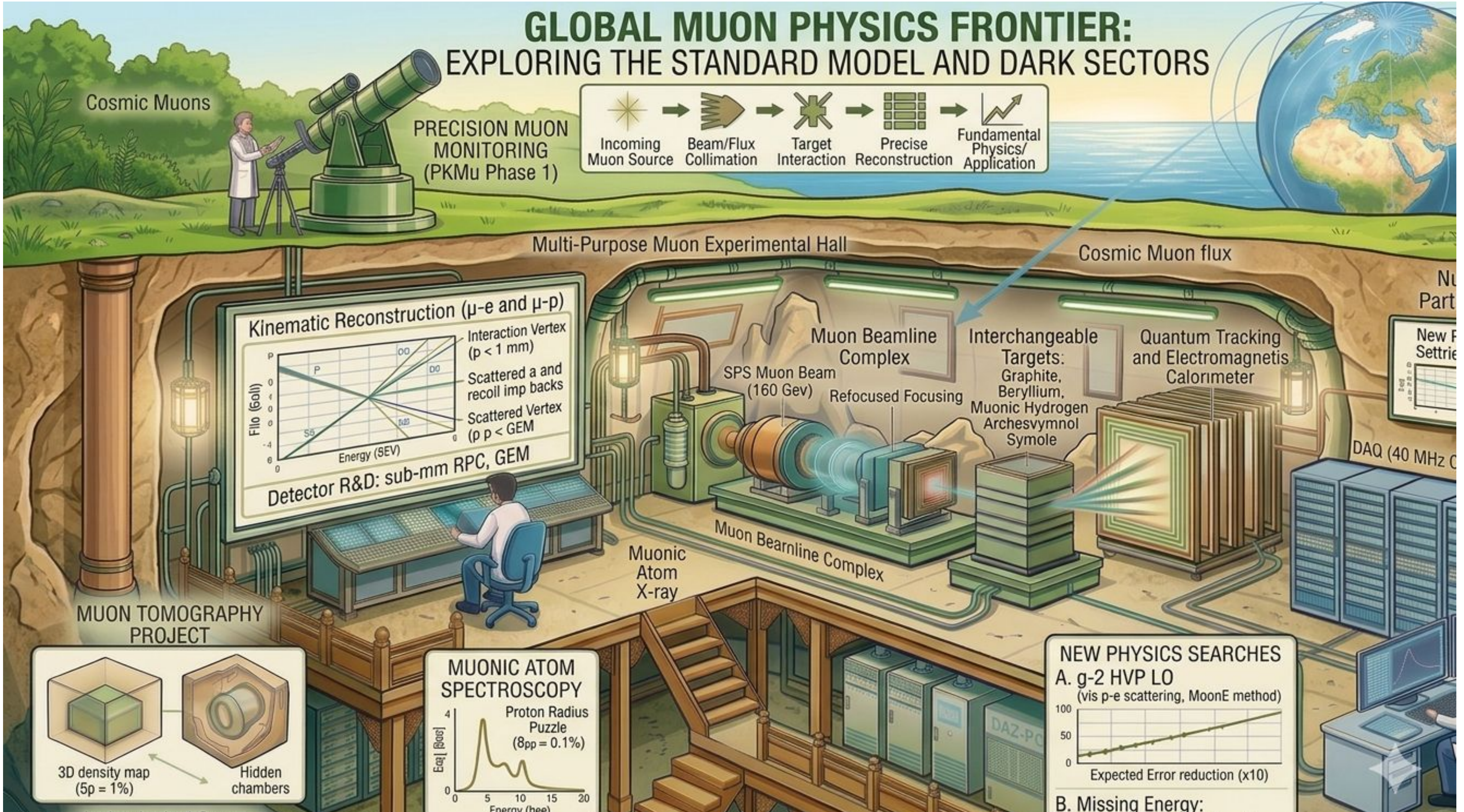
This is a satellite meeting for MIP2026 (https://indico.itp.ac.cn/event/384/) to be held at IMP, Huizhou, from April 25 to 27, aiming for informal discussions and fruitful collaborations.

We are pleased to announce a half-day interdisciplinary workshop dedicated to the remarkable isotope Thorium-229, whose unique low-energy nuclear transition opens unprecedented opportunities across multiple fields of physics. This focused event will bring together experts and researchers working on laser spectroscopy, nuclear structure, muonic atoms, and particle physics to explore the full scientific potential of this extraordinary system.

The workshop aims to provide a comprehensive overview of the current status and future prospects of Thorium-229 research. Topics will include precision laser control of the nuclear isomeric transition, advances toward a nuclear optical clock, theoretical and experimental insights into nuclear properties, and the role of muonic atom spectroscopy in probing nuclear structure. In addition, discussions will address implications for fundamental symmetries, searches for new physics, and connections to particle and astroparticle physics.



https://www.mdpi.com/2079-4991/10/7/1260


GLOBAL MUON PHYSICS FRONTIER:
EXPLORING THE STANDARD MODEL AND DARK SECTORS
Cosmic Muons
PRECISION MUON MONITORING (PKMu Phase 1)
Incoming Muon Source
Beam/Flux Collimation
Target Interaction
Precise Reconstruction
Fundamental Physics/ Application
Multi-Purpose Muon Experimental Hall
Cosmic Muon flux
Kinematic Reconstruction (μ-e and μ-p)
Interaction Vertex (p < 1 mm)
Scattered a and recoil imp backs
Scattered Vertex (p p < GEM
Energy (SEV)
Detector R&D: sub-mm RPC, GEM
Muon Beamline Complex
SPS Muon Beam (160 Gev)
Refocused Focusing
Interchangeable Targets: Graphite, Beryllium, Muonic Hydrogen Archesvymnol Symole
Quantum Tracking and Electromagnetis Calorimeter
DAQ (40 MHz C
Muonic Atom X-ray
Muon Bearnline Complex
MUON TOMOGRAPHY PROJECT
3D density map (5ρ = 1%)
Hidden chambers
MUONIC ATOM SPECTROSCOPY
Proton Radius Puzzle (8pp = 0.1%)
Energy (hee)
DAZ-PC
NEW PHYSICS SEARCHES
A. g-2 HVP LO
(vis p-e scattering, MoonE method)
Expected Error reduction (x10)
B. Missing Energy:

附录

arXiv:1911.01498

欧洲核子研究中心高能缪子实验

~160GeV高能缪子束线

CERN: The European Organization for Nuclear Research

Studies for New Experiments at the CERN M2 Beamline within "Physics Beyond Colliders": AMBER/COMPASS++, NA64μ, MuonE

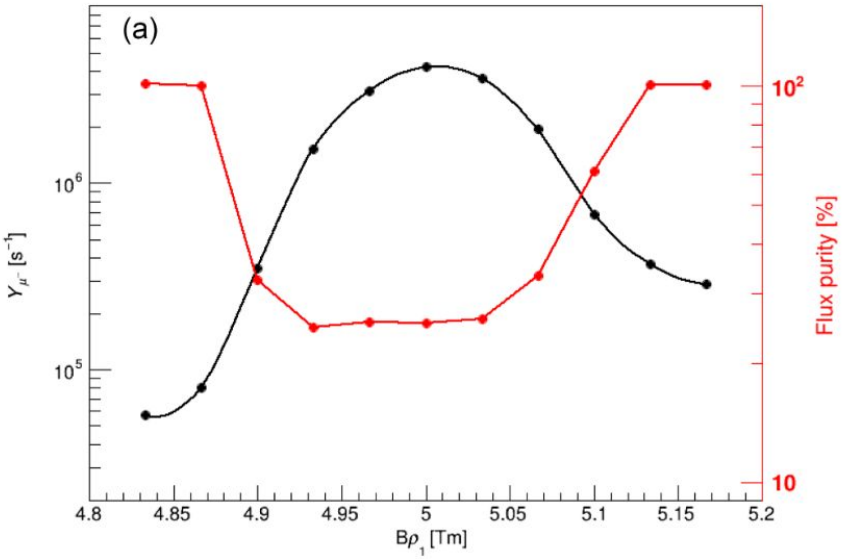
与质子、核子、电子散射

Johannes Bernhard,[1,a)] Dipanwita Banerjee,[1,2] Eva Montbarbon,[1] Markus Brugger,[1] Nikolaos Charitonidis,[1] Serhii Cholak,[1] Gian Luigi D'Alessandro,[1,3] Lau Gatignon,[1] Alexander Gerbershagen,[1] Bastien Rae,[1] Marcel Rosenthal,[1] Maarten van Dijk,[1] and Benjamin Moritz Veit[1,4]

HIAF-HIRIBL高能缪子束流

TABLE IV. The maximum muon flux intensities with proton, $^{18}O^{6+}$, and $^{78}Kr^{19+}$ projectiles, and the corresponding muon beam momenta and purities.

	Proton	$^{18}O^{6+}$	$^{78}Kr^{19+}$
μ^+ beam			
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%
μ^- beam			
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%



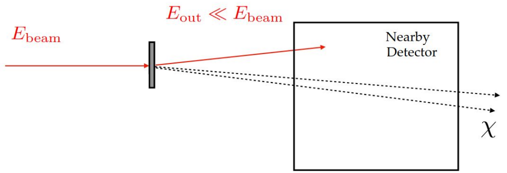
PID among muon, pion and electron are important for muon beam experiment.

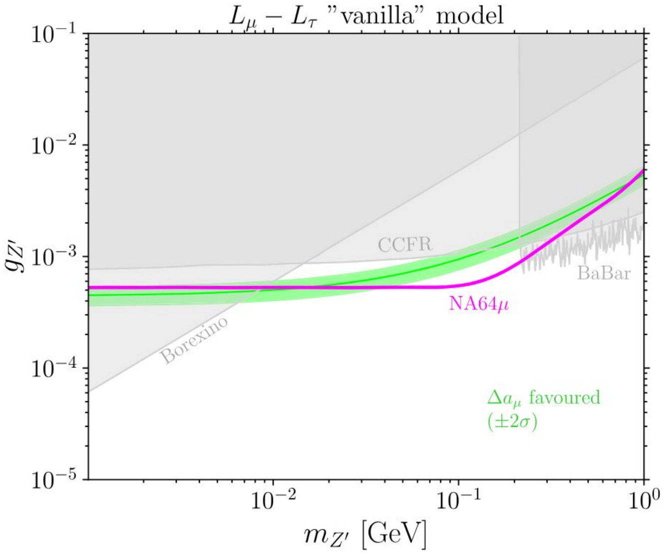
Phys.Rev.Accel.Beams 28 (2025) 5, 053401

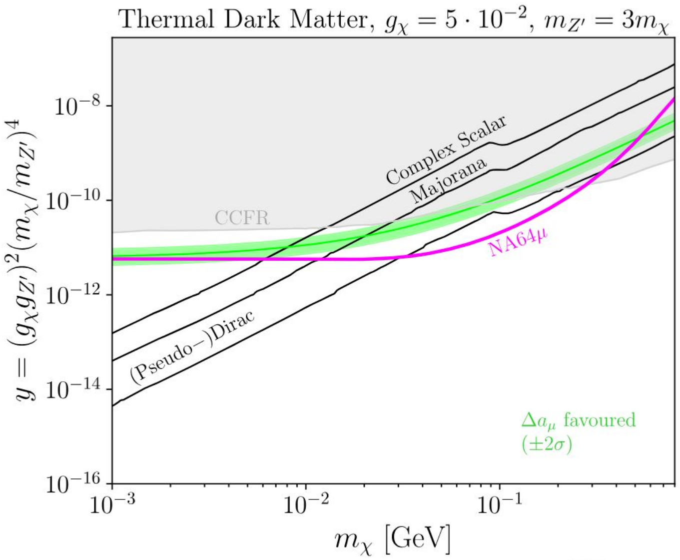
CERN NA64 μ 的实验结果

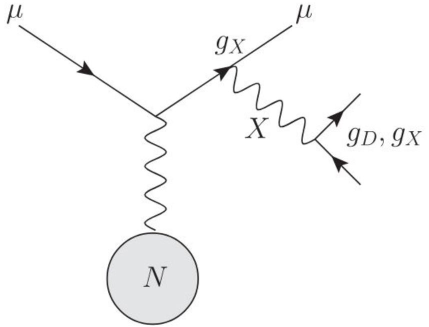
$$\mathcal{L} \supset -\frac{1}{4}F'_{\alpha\beta}F^{\alpha\beta\prime} + \frac{m_{Z'}^2}{2}Z'_\alpha Z^{\alpha\prime} - g_{Z'}Z'_\alpha J^\alpha_{\mu-\tau},$$

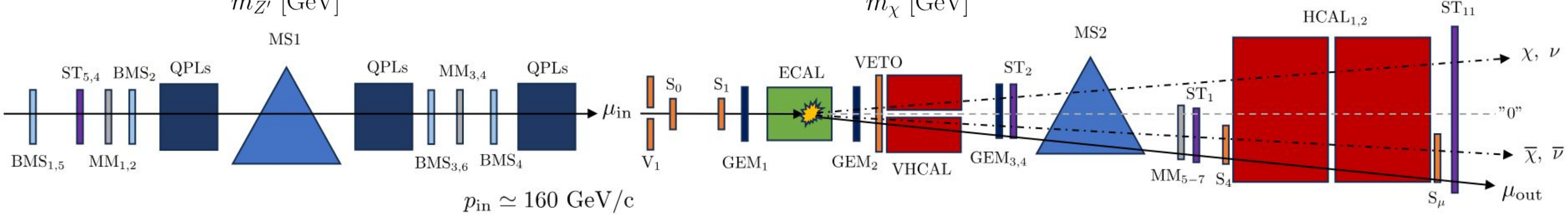
$$-g_\chi Z'_\alpha J^\alpha_\chi,$$











amber talk

缪子与质子散射：AMBER测量质子半径等

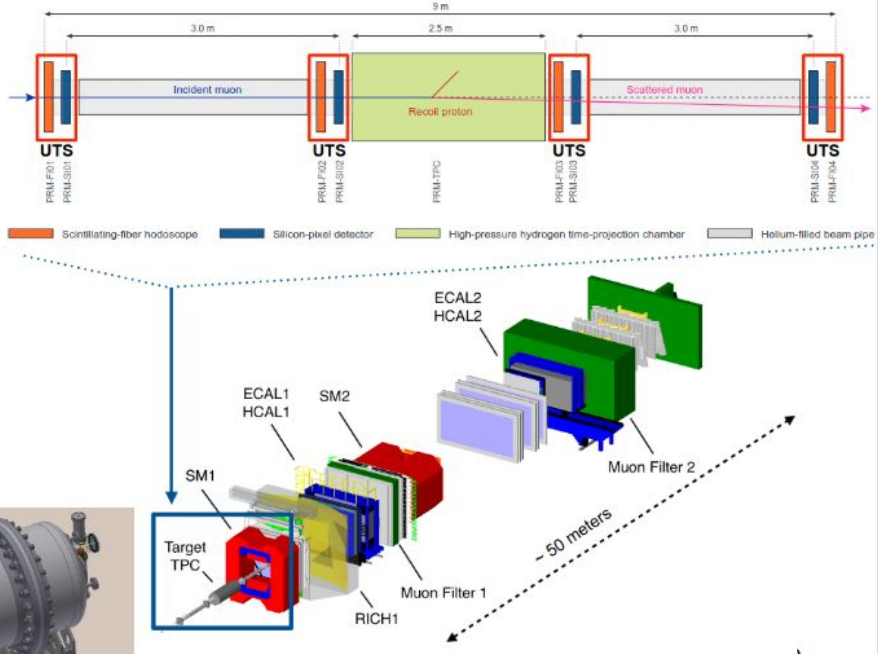
Apparatus for Meson and Baryon Experimental Research

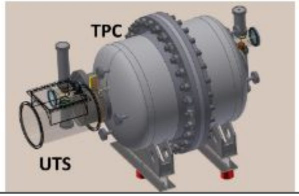
100 GeV muon beam, 2 x 10^6 μ/s

Time Projection Chamber (TPC) filled with hydrogen (up to 20 bar): **active target**

Recoil proton measured at TPC, incoming and scattered muons detected in the Unified Tracking Stations (UTS)

Small scattering angle (100 μrad):
$Q^2_{min} = 10^{-3}$ $(GeV/c)^2$



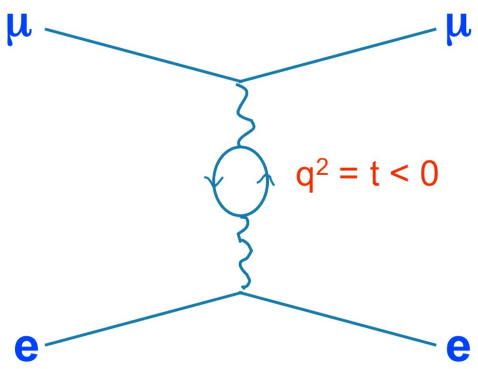


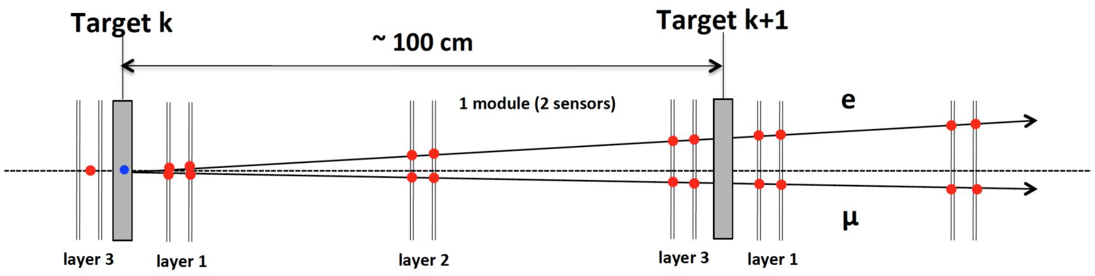
AMBER 是 CERN SPS 固定靶实验计划中的新一代强子物理实验。主要束流：高能 π、K、p 以及 μ 子束流（动量最高可达 ~190 GeV/c）

继承并升级了COMPASS的成熟探测器系统(磁谱仪、跟踪、PID 等)

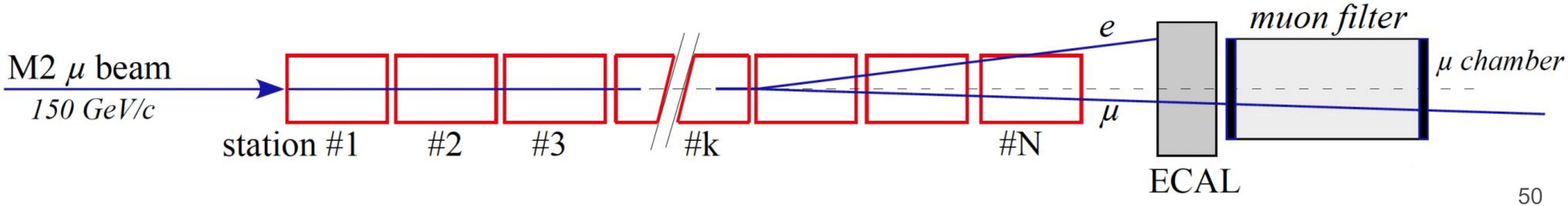
缪子与电子散射：MUonE 精密测量SM

https://web.infn.it/MUonE/





轻靶，无磁场，良好的径迹探测器，电磁量能器及末端缪子探测器提供PID。模块化，每模块约1米长。



JHEP 09 (2018) 153

缪子与核散射：MMM 寻找新物理