PEKING UNIVERSITY

New limits on muon-philic dark matter searches and other recent progresses from PKMu

Leyun Gao (On behalf of the PKMu Collaboration)

The Fifth International Conference on Axion Physics and Experiment (Axion 2026)

2026.8.12 Qingdao, China

The PKMu Initiative: Probing and Knocking with Muons

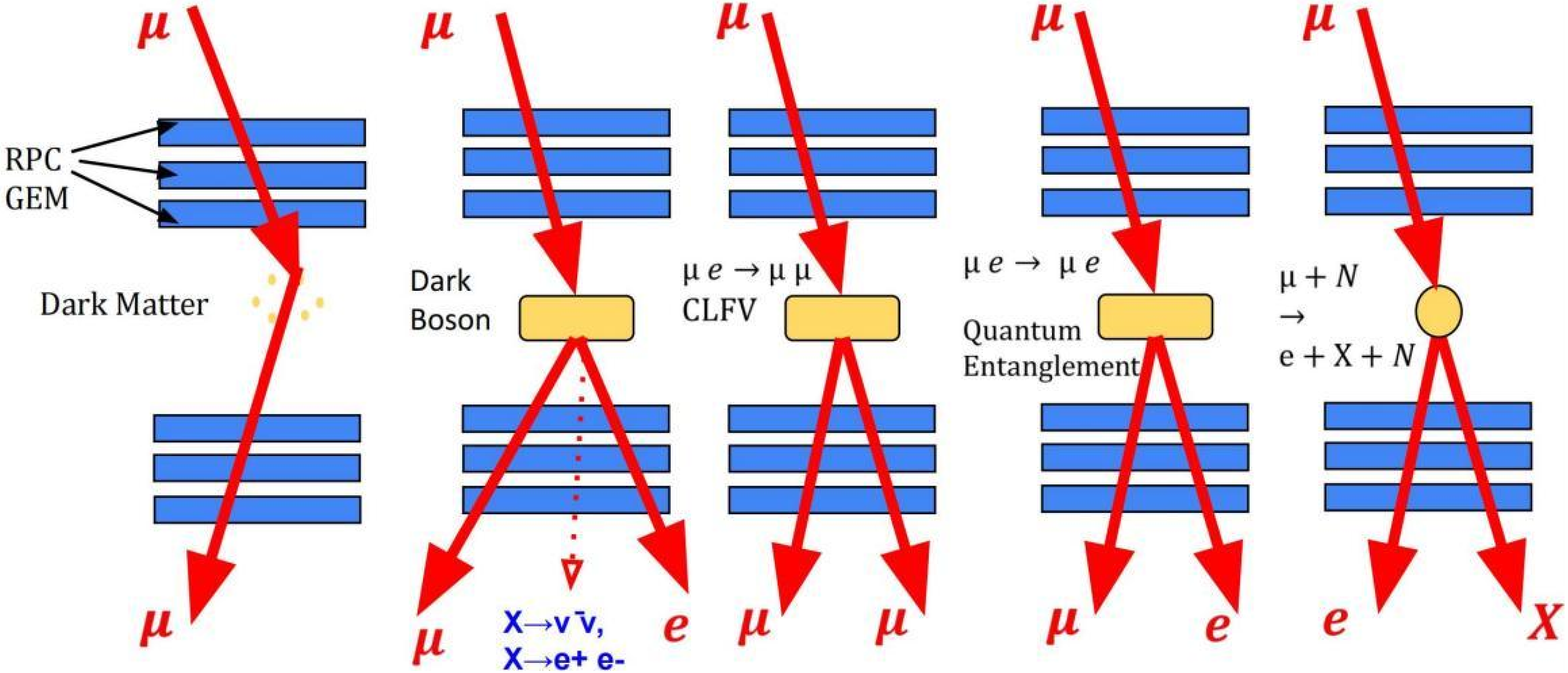
- **Core Goal: A comprehensive muon-scattering experiment program to explore precision and new physics.**
- **Our Strategy — Innovation, Agility, and High Impact**
  - **Phase I: Use cosmic-ray muons + self-developed high-precision RPC/GEM detectors**
  - **Phase II: Transition to high-intensity muon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

PKMu Research Landscape:

Innovative and Economical Muon Scattering Experiment

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

Chin. Sci. Bull. 71, 894 (2026) DOI: 10.1360/CSB-2025-5452



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

Outline

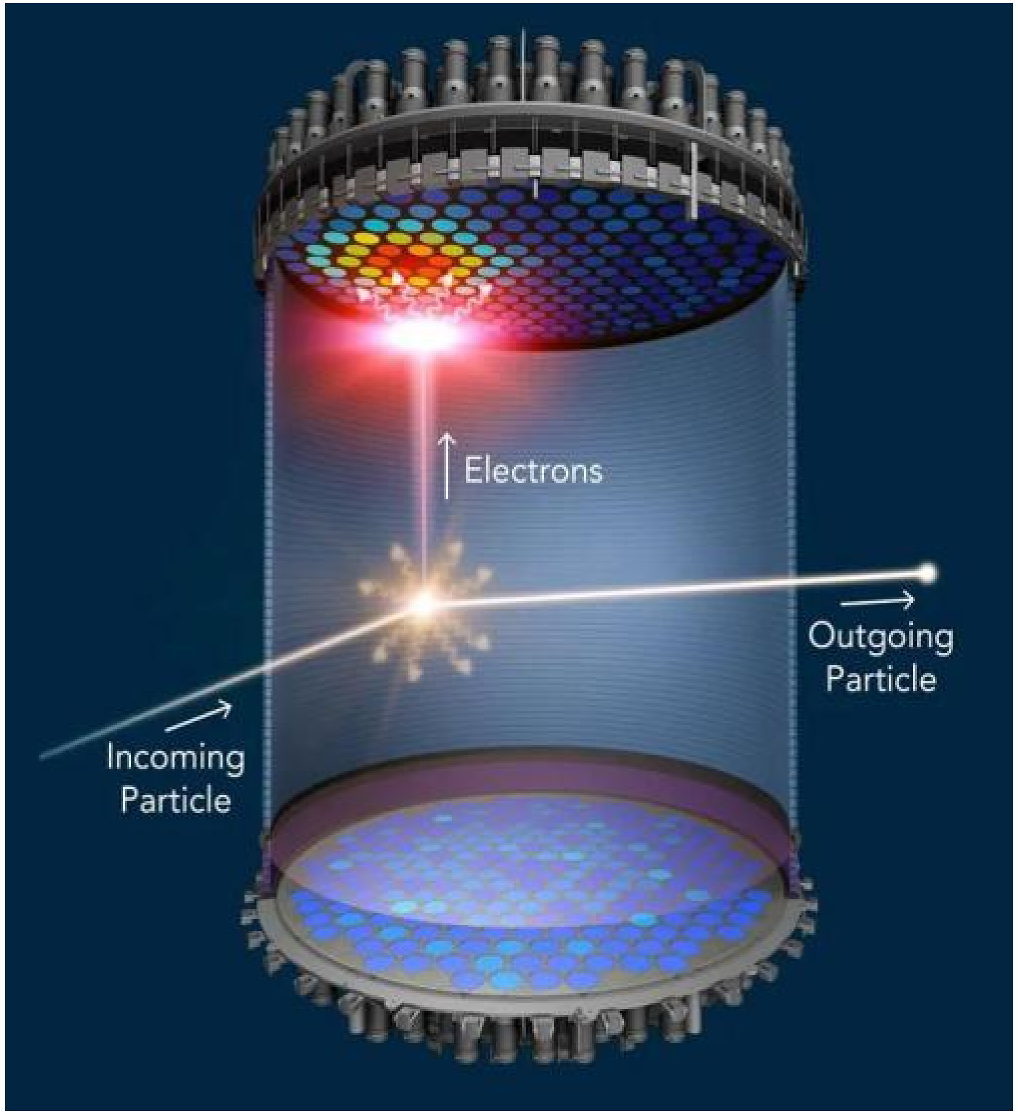
1. Cosmic-ray composition & muon-philic DM limit (recently published in PRL)

2. Searching for LFV scalars & probing atomic binding effects on electrons

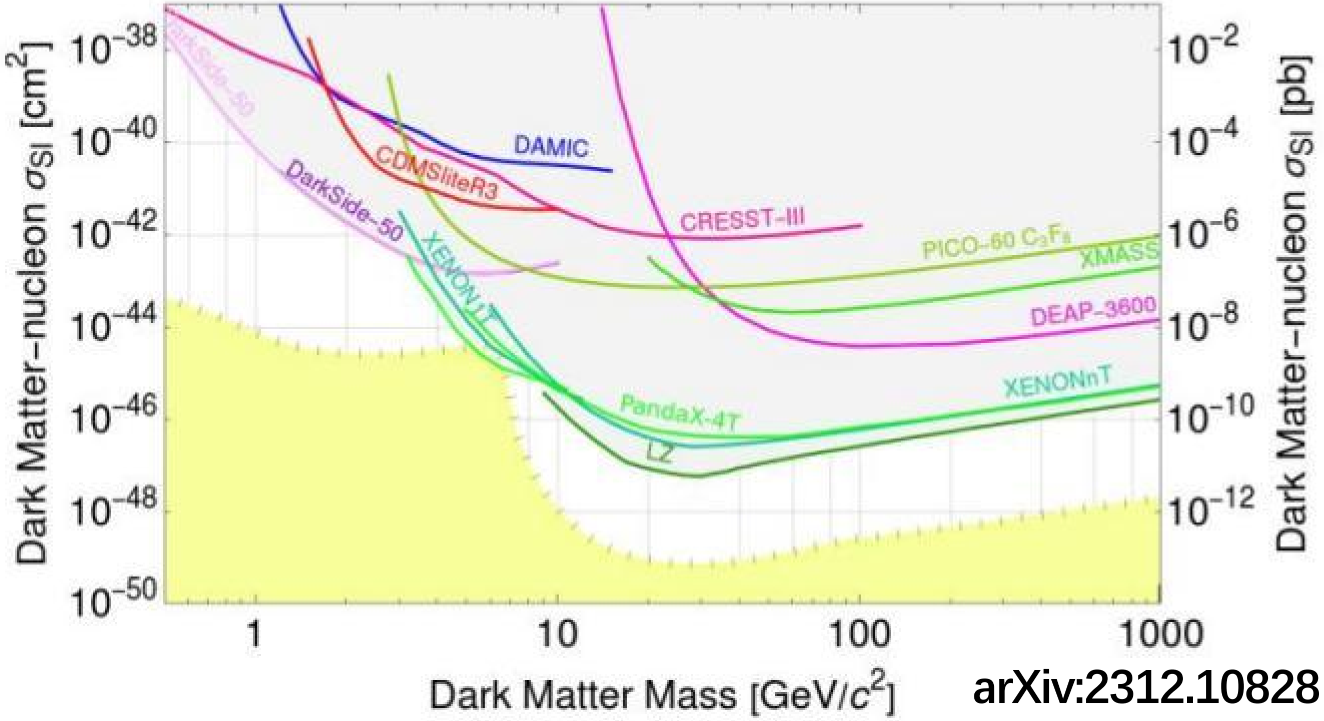
3. The muon Moonshot: Moon subsurface tomography with upward-going muons

4. PKMu@HIAF and future prospects

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?

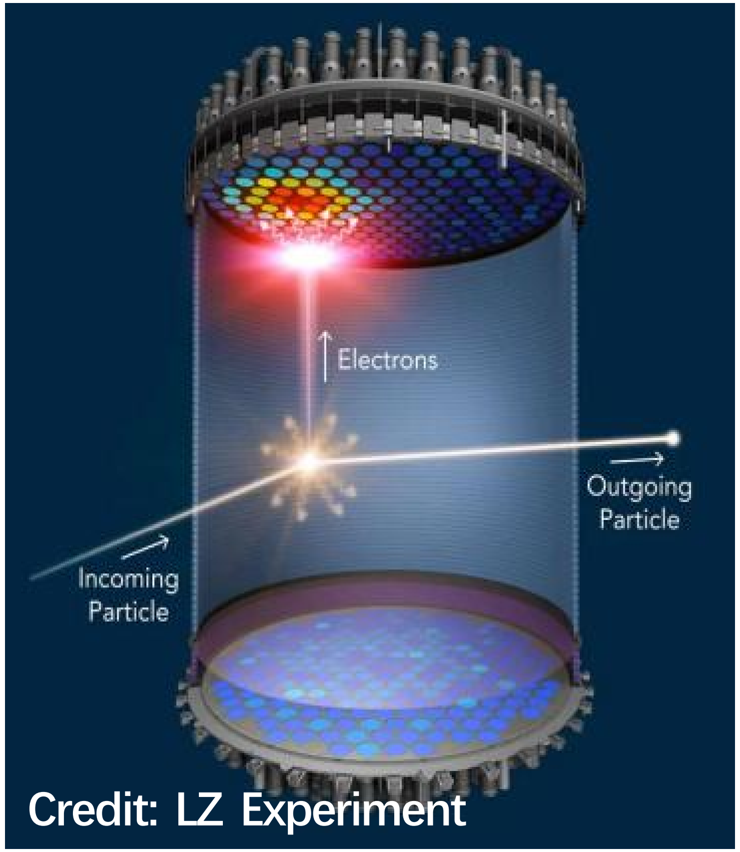
Phys. Rev. Lett. 133, 191001 (2024) & Phys. Rev. Lett. 133, 191002 (2024).

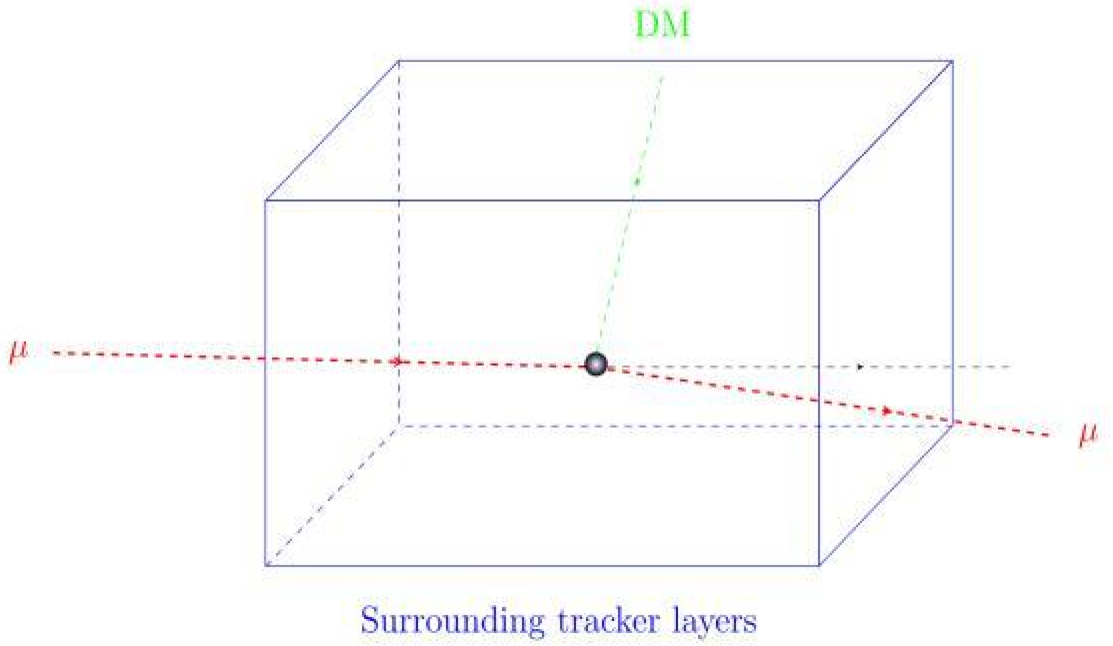
Phys. Rev. Lett. 135, 011802 (2025)

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





Muons may scatter off the DM; Observable: scattering angle

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology
Highlights Recent Accepted Collections Authors Referees Search Press About
Open Access

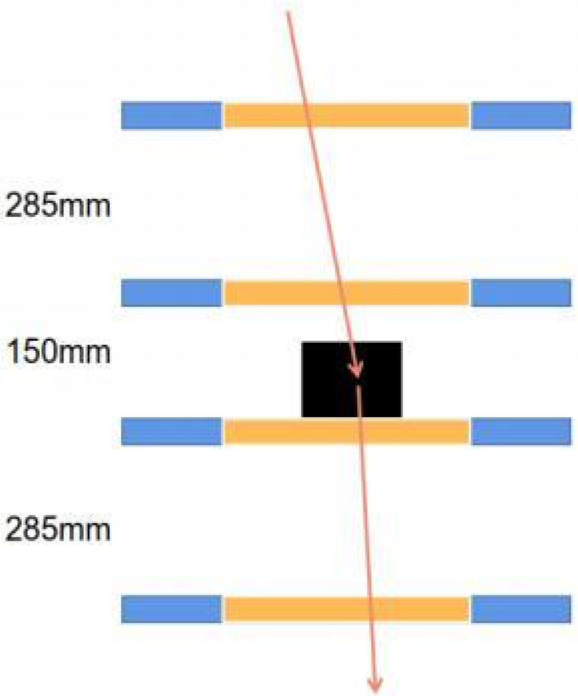
Proposed Peking University muon experiment for muon tomography and dark matter search

Phys. Rev. D 110, 016017(2024)

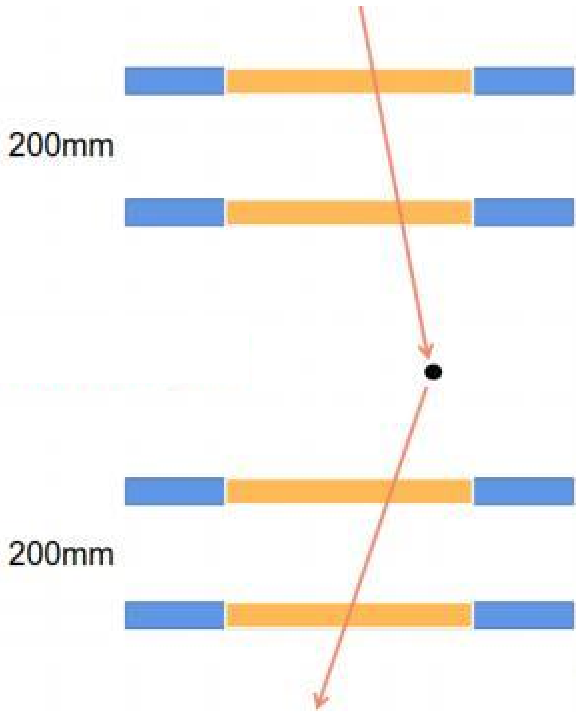
Geant4 simulation results for muon scattering with 1m thick air or DM:

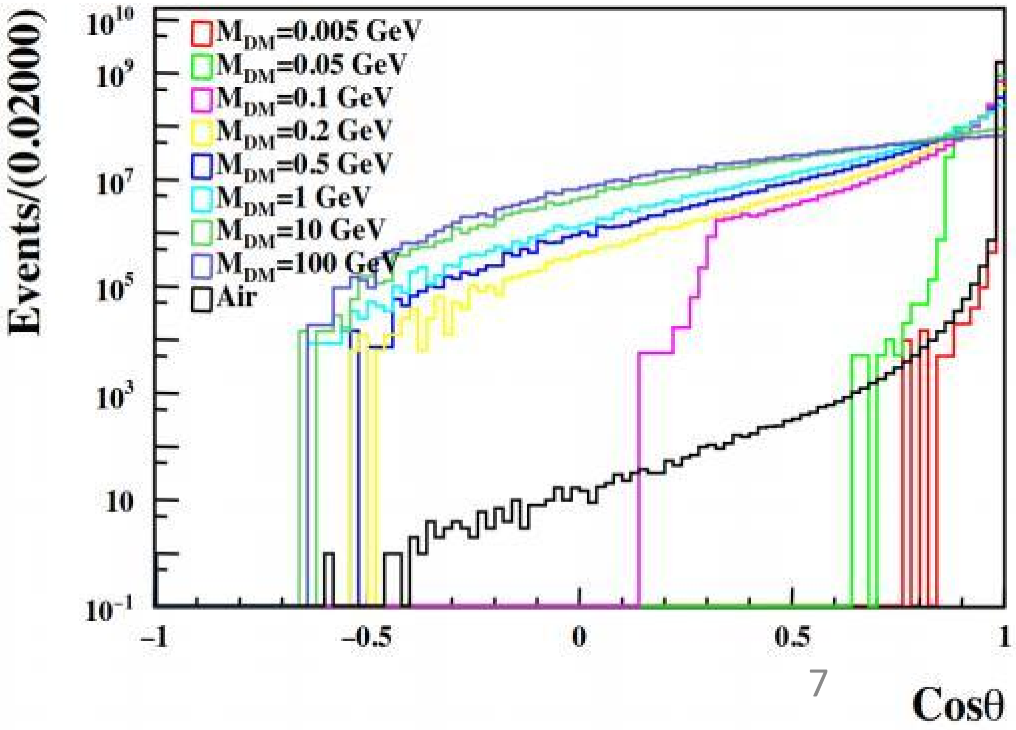
Scattering angle differs a lot!

Muon Tomography: measuring target/interaction properties



Without(?) target: probing dark matter via scattering angle





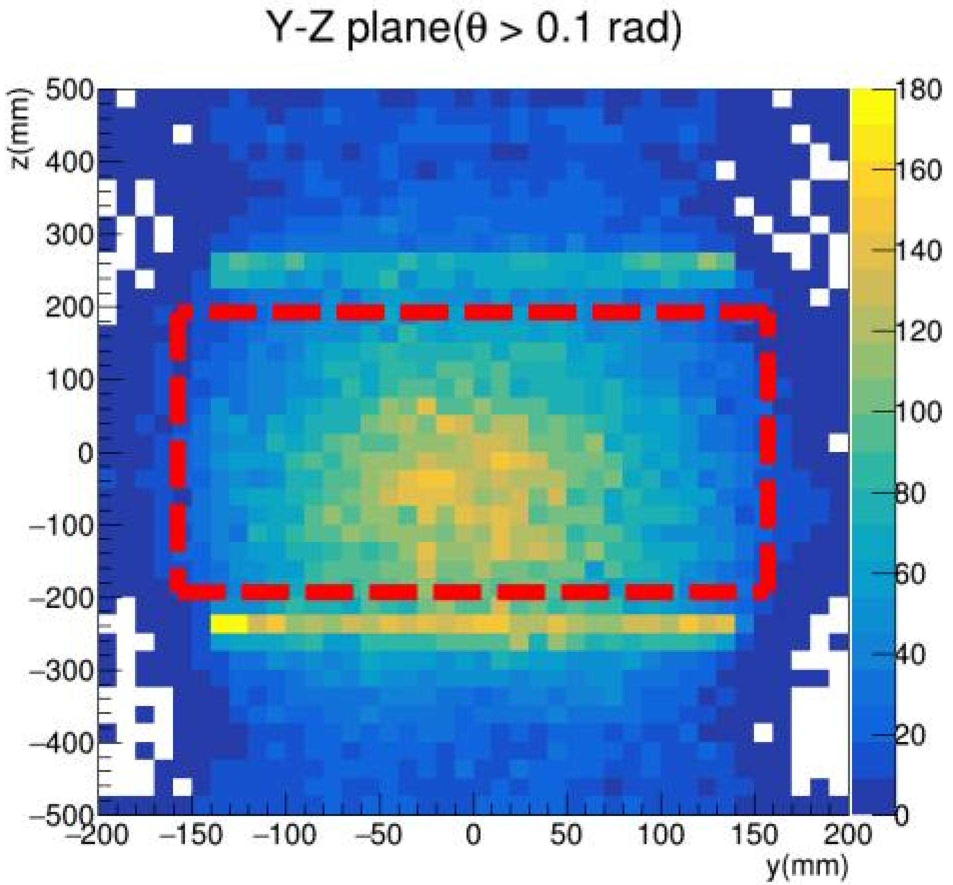
PKMu Cosmic Ray Tomography System (2025)

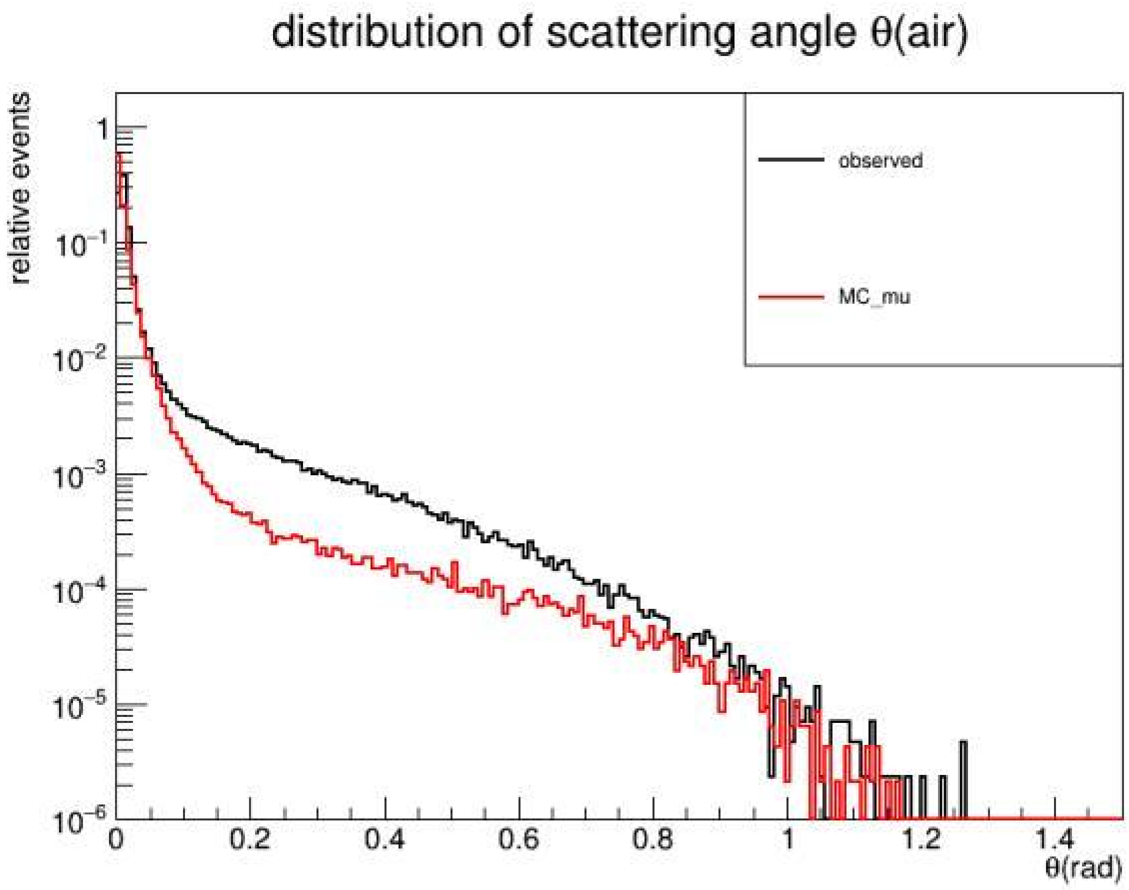
- **4 layers of glass RPC** with LC delay-line readout
  - Active area **28 × 28 cm²**
  - vertical spacing 20–50–20 cm
  - Single RPC spatial resolution **σ ≈ 0.5-0.7 mm**

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

Scattering Angle Distribution in ROI Area

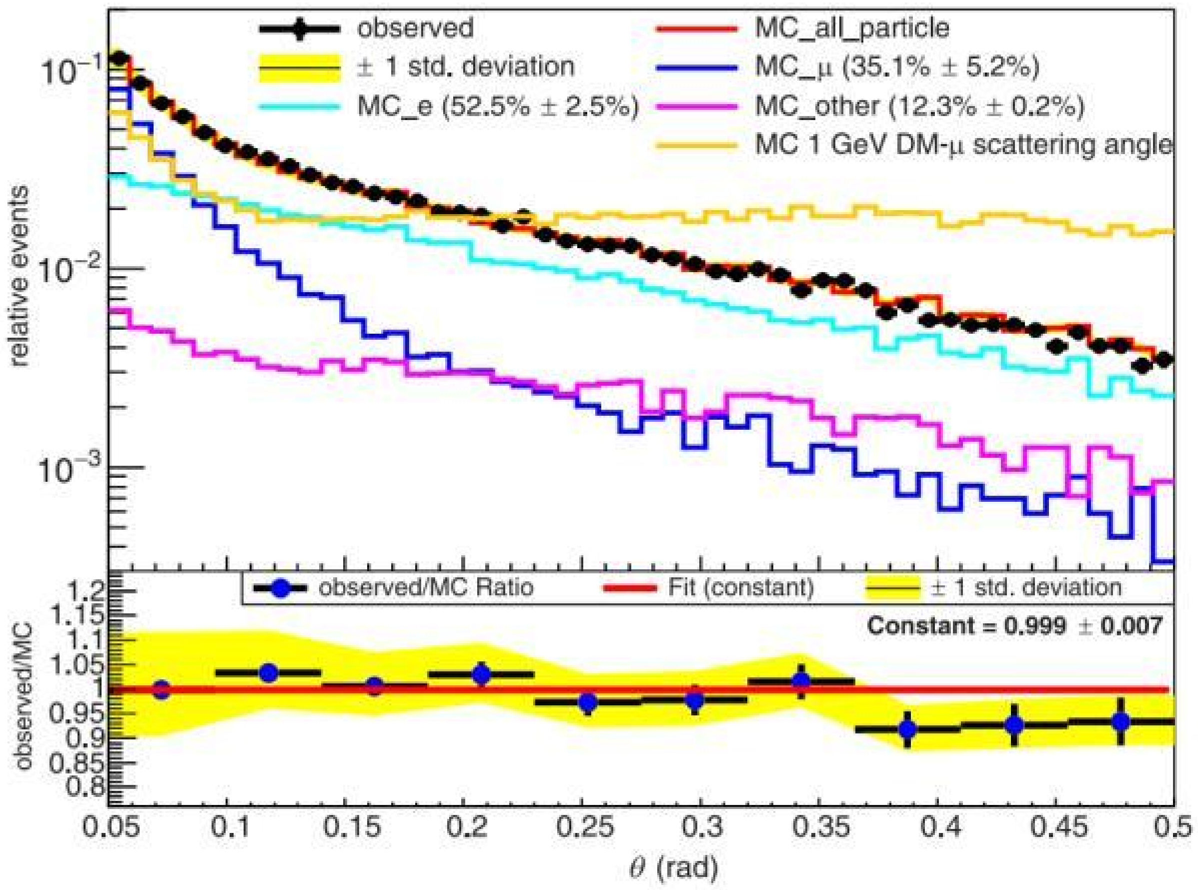
- **Analyzed angular distribution within detector 's sensitive volume (-200 mm < z < 200 mm)**
- **Large-angle scattering events persist after selection**





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.**



PKMu cosmic ray DM search

- **At the 95% confidence level, the limit reaches 1.62 × 10^{-17} cm² 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**

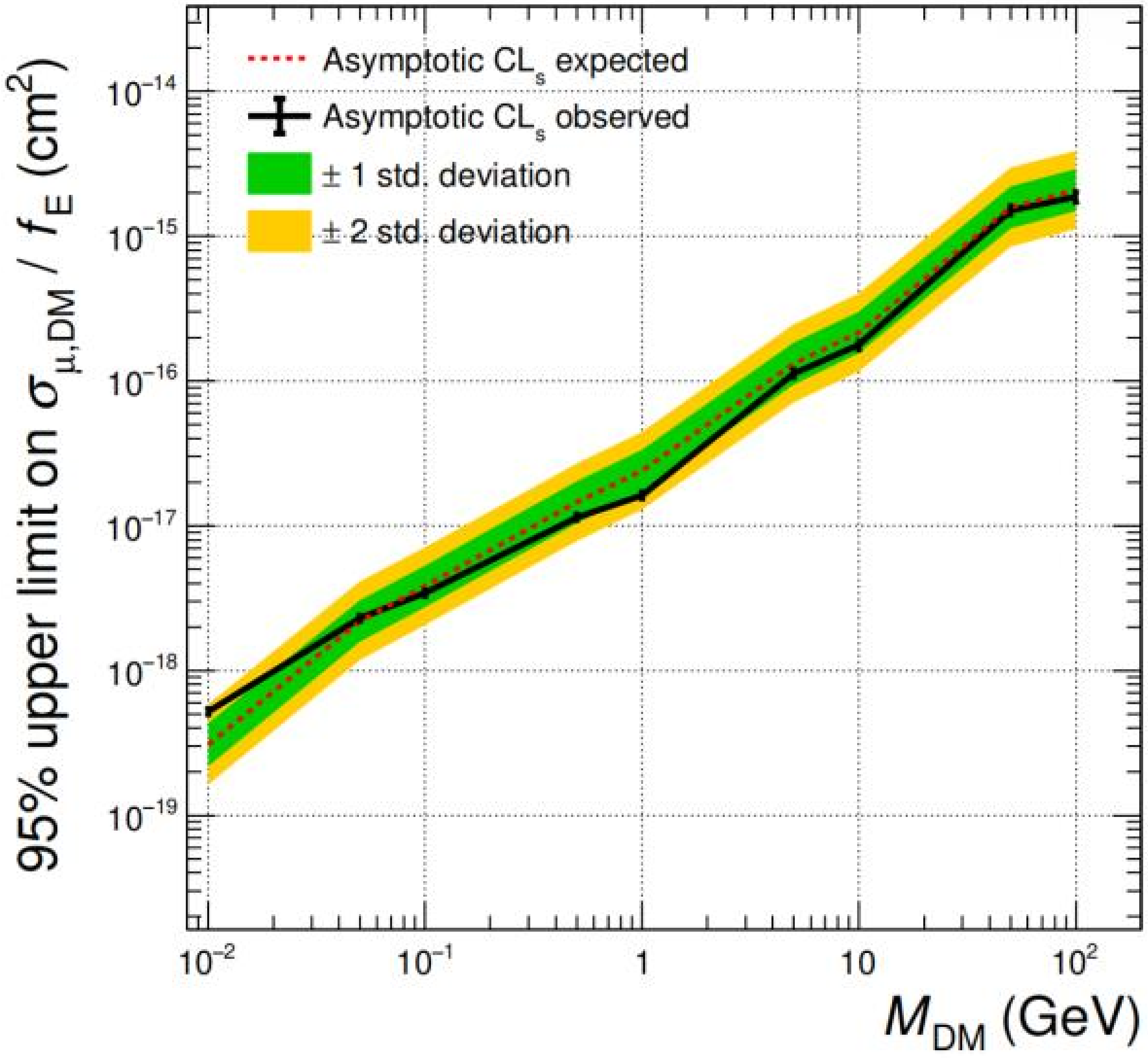
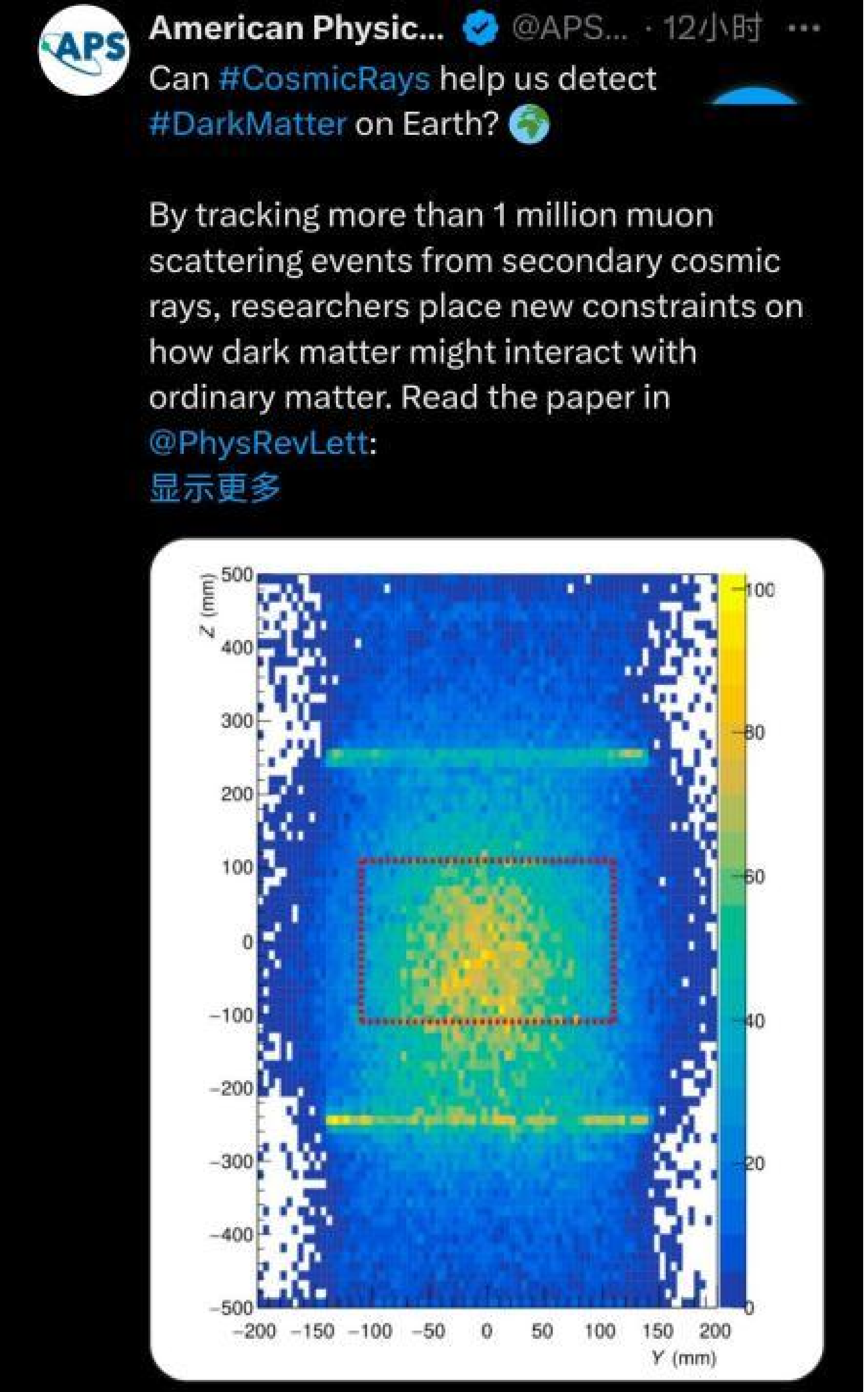


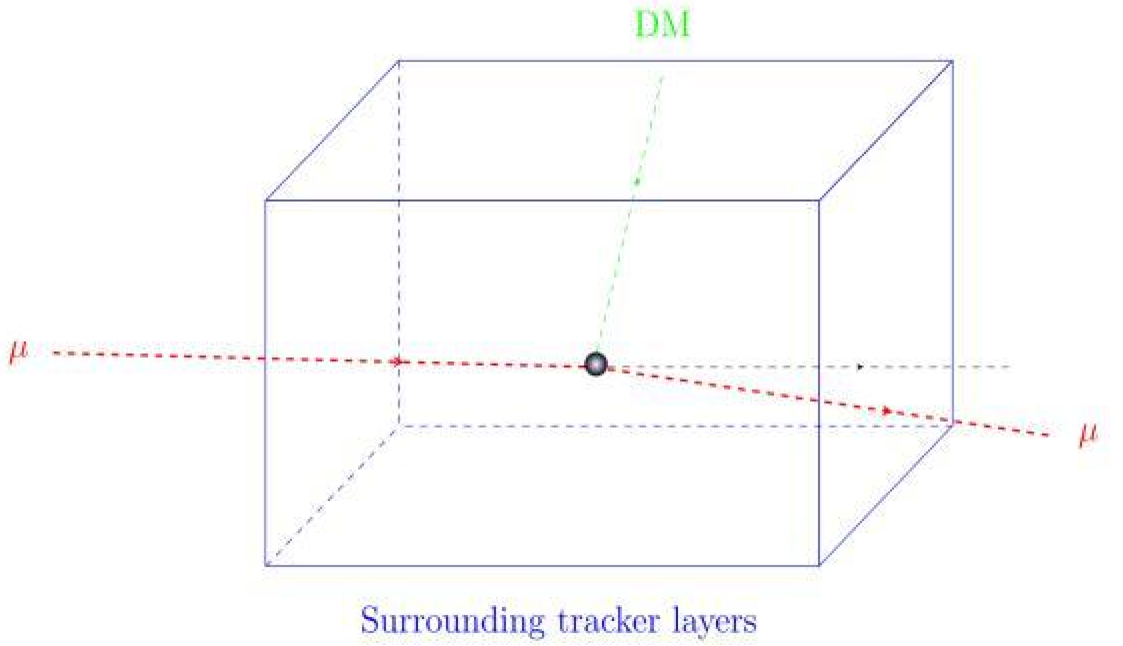
FIG. 4: Expected and observed 95% CL upper limits on the DM-muon interaction cross section versus M_{DM}. he green and yellow bands represent the 1σ and 2σ regions, respectively.



<- APS promotion

Phys. Rev. Lett. 136, 151001 *Summary*

- ✅ *Precision sea-level electron fraction (~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*



Muons may scatter off the DM; Observable: scattering angle

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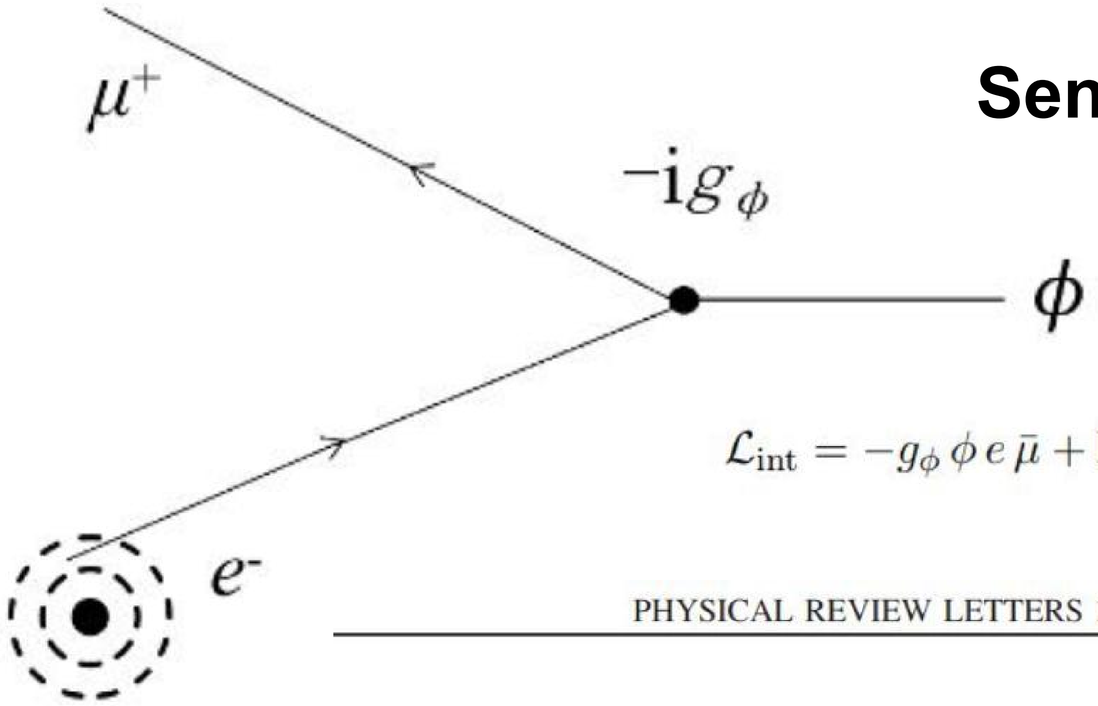
Atomic $\mu e \to \Phi$: motivations

Resonance enhancement

Simple final states

Sensitive to CLFV



$$\mathcal{L}_{\rm int} = -g_\phi\, \phi\, e\, \bar{\mu} + \text{h.c.}, \qquad \mathcal{L}_{\rm dark} = -g_D\, \phi\, \bar{\chi}\, \chi$$

Sensitive to atomic binding effects

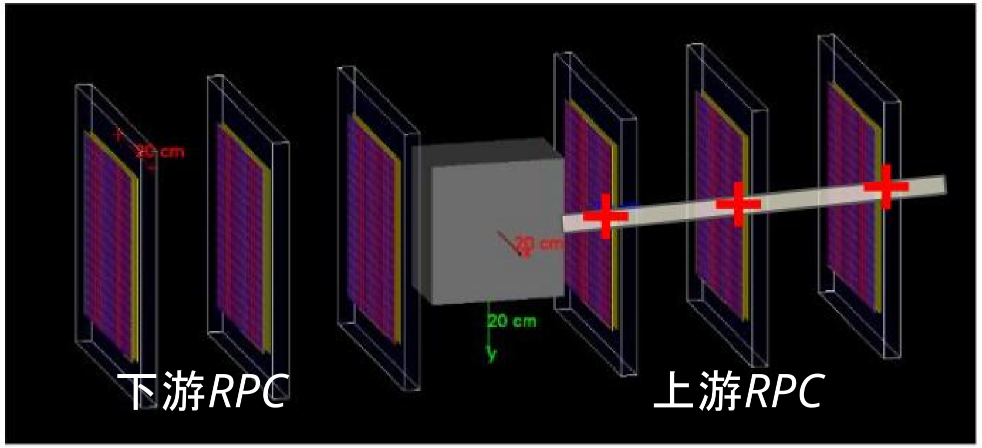
PHYSICAL REVIEW LETTERS **134,** 061802 (2025)

Atoms as Electron Accelerators for Measuring the Cross Section of $e^+e^- \to$ Hadrons

Fernando Arias-Aragón,[1,*] Luc Darmé,[2,†] Giovanni Grilli di Cortona,[3,‡] and Enrico Nardi[1,4,§]

https://arxiv.org/abs/2607.18669

Atomic $\mu e \to \Phi$: prospects

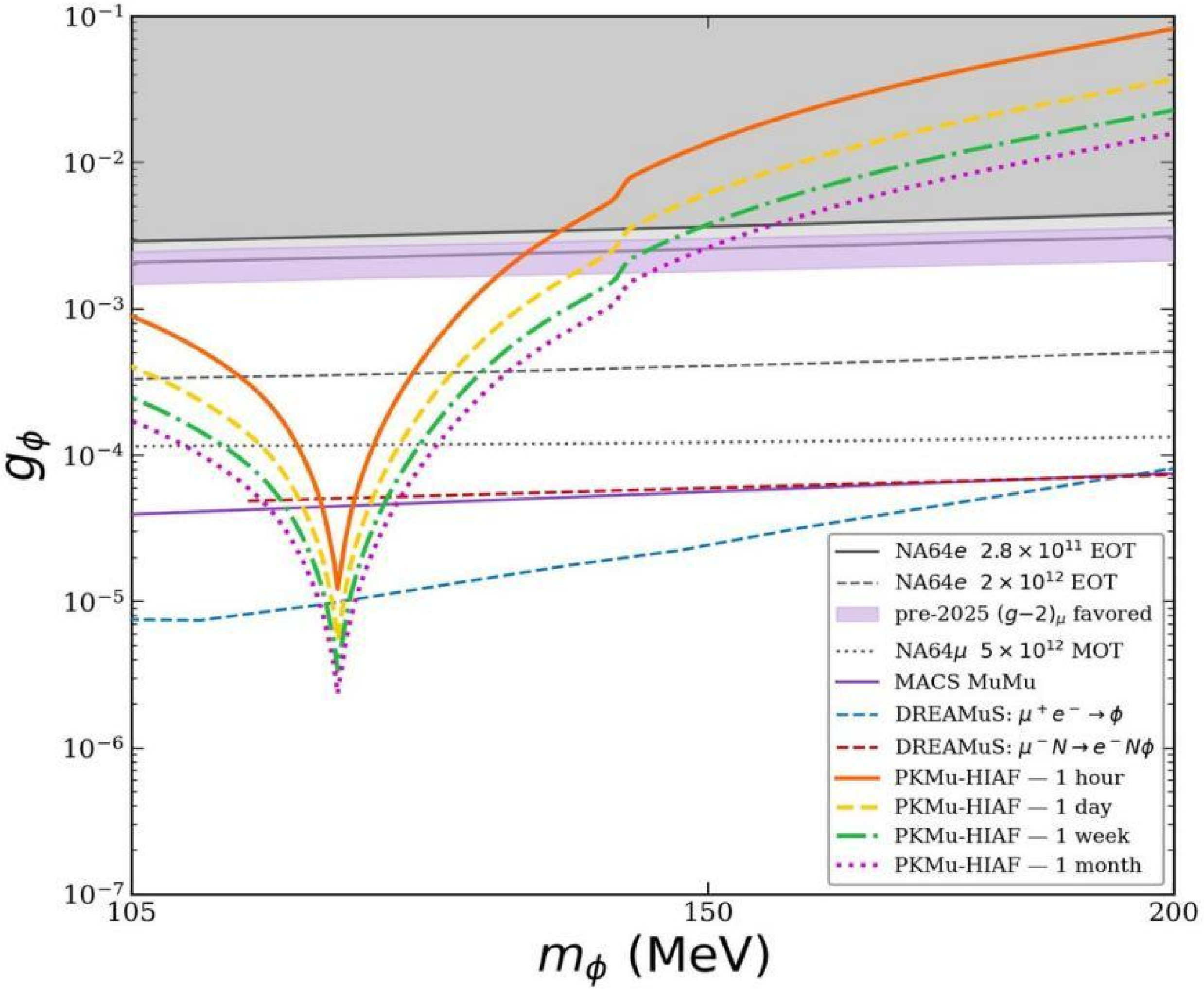


Cut 1. upstream tagging
Cut 2. downstream veto
Cut 3. beam spot r < 3 cm
Cut 4. target pointing

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

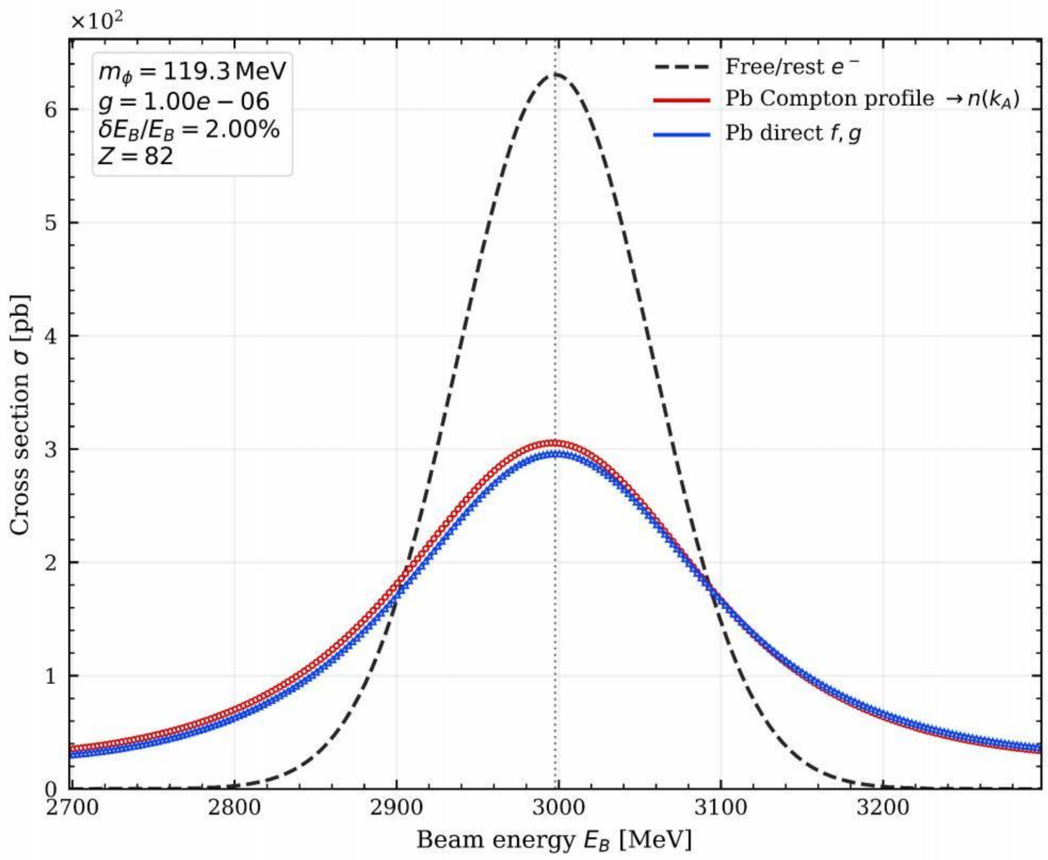
https://arxiv.org/abs/2607.18669



Atomic $\mu e \rightarrow \Phi$: prospects

Resonance peak broden by:
(1) Energy spread
(2) Binding effects

Two methods cross validated:
(1) Compton profile
(2) Wave function



Sensitive to:
(1) m(Φ)
(2) Material

Generalization:
(1) X-e collider with enhanced c.m.e
(2) Material profiler
(3) Syst. in precision

https://arxiv.org/abs/2607.18669

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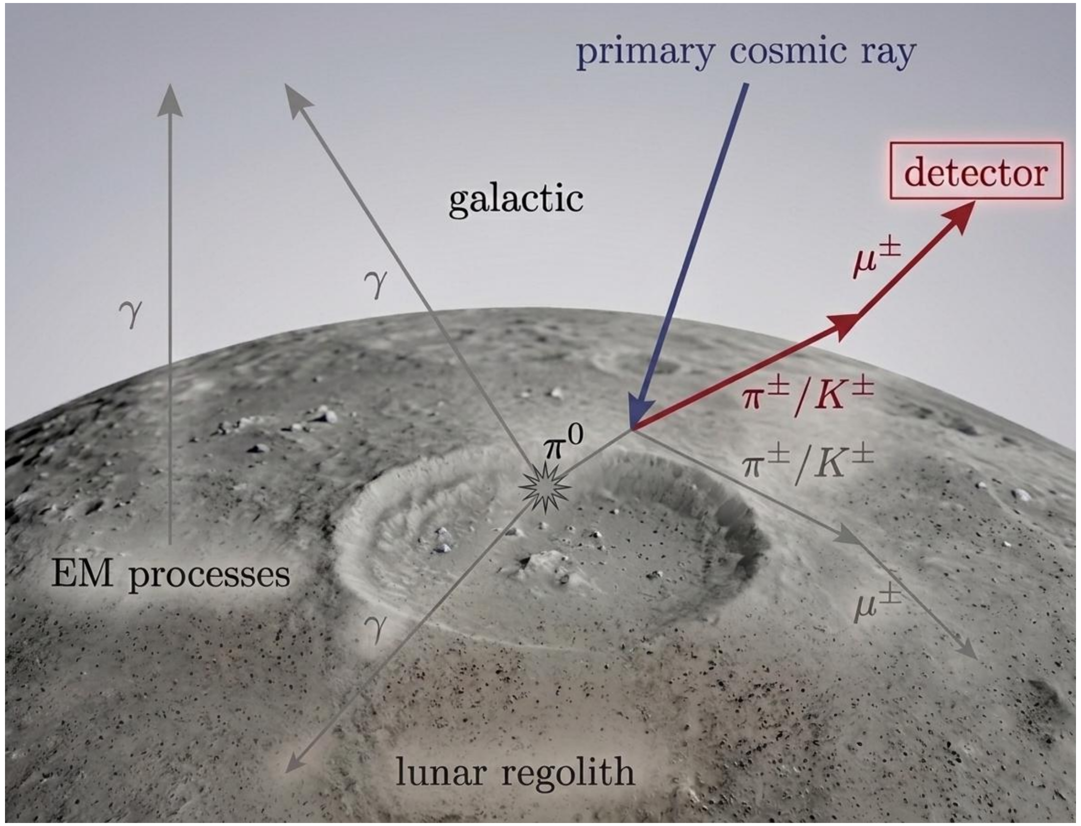
Muon Moonshot: motivation

Moon surface:
(1) Solid regolith
(2) No atmosphere
(3) Similar galactic environment

Muon tomography:
(1) Non-invasive
(2) Vast muons in CR
(3) Well established on Earth



Upward-going muons remain under-explorerd!

(1) Near-surface:
- Displaced pion decay
- Microscopic view

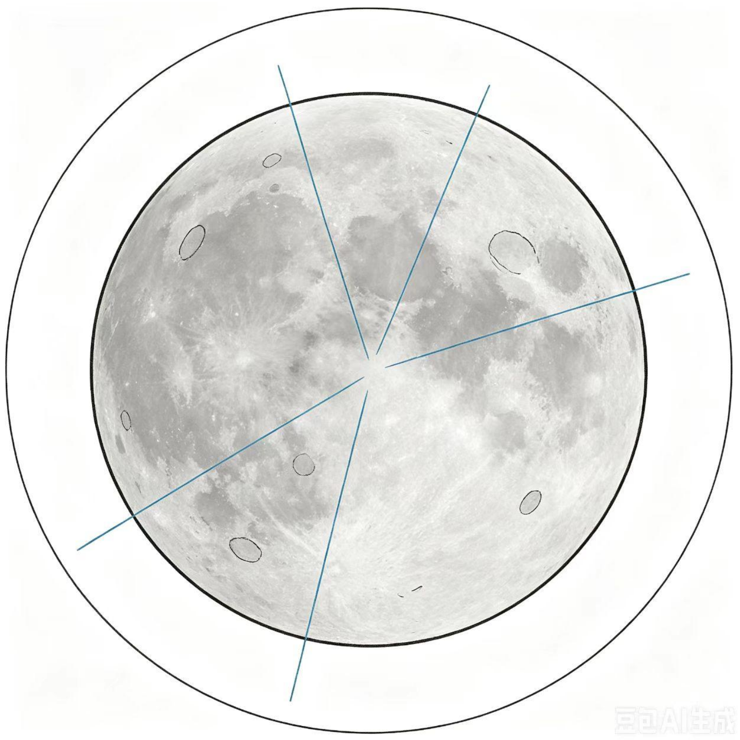
(2) Higher altitude:
- Displaced muon decay
- Macroscopic view

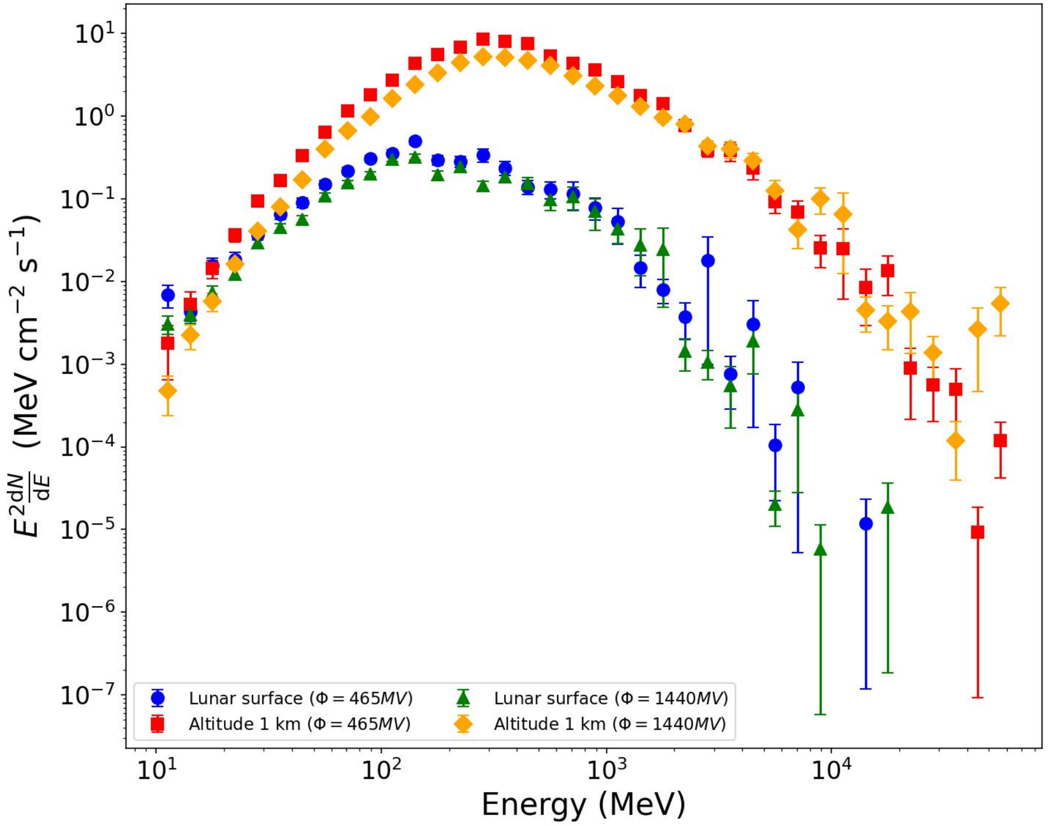
https://arxiv.org/abs/2607.10403

Muon Moonshot: FLUKA simulation

Three-layer ideal model, with no detector effects (proof of concept)

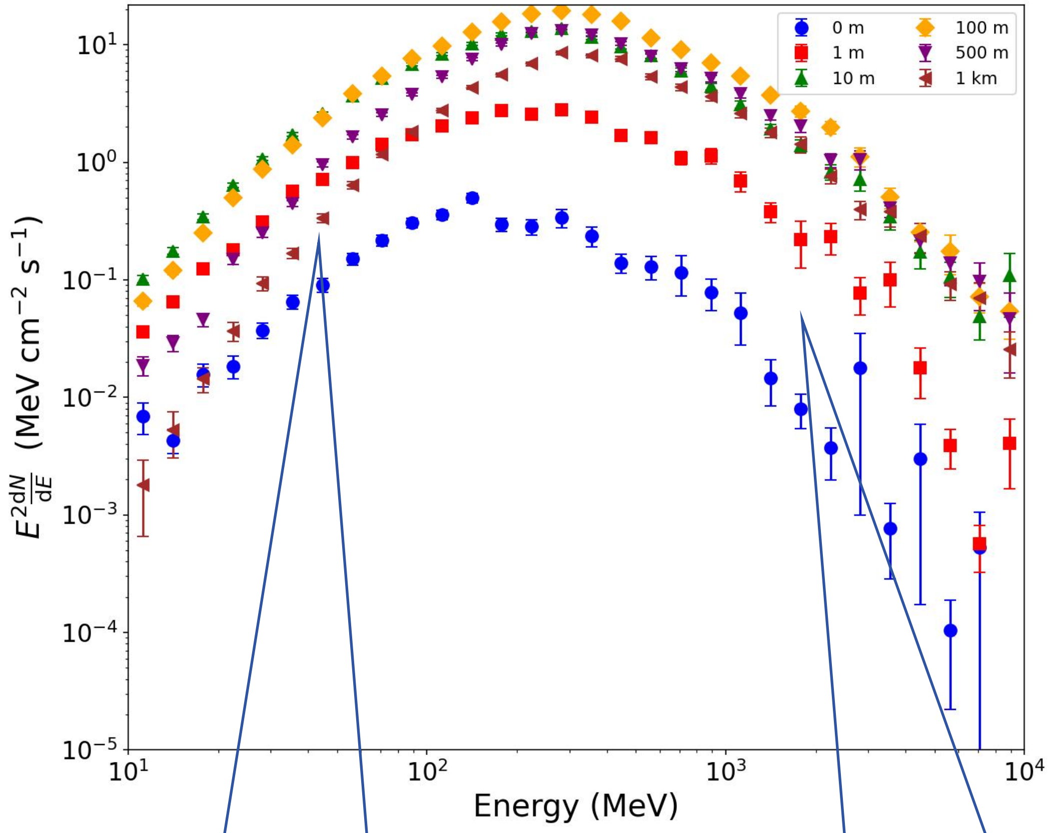
Solar modulation min/max considered

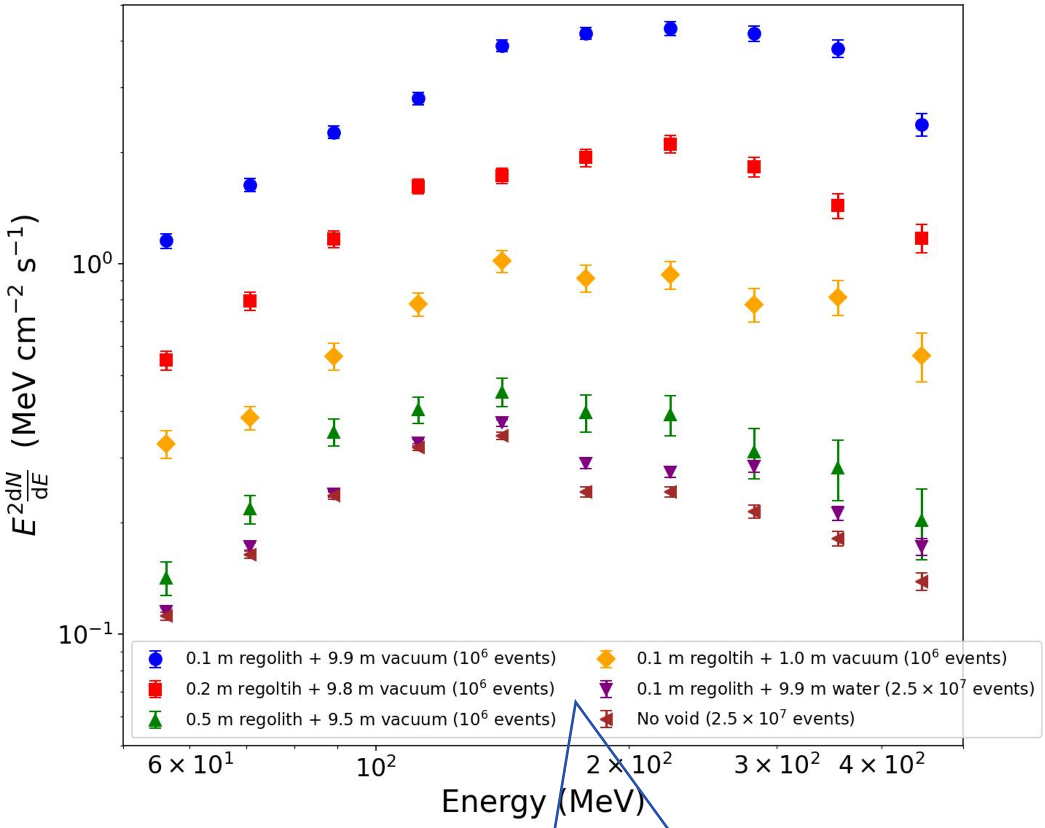




https://arxiv.org/abs/2607.10403

Muon Moonshot: tomography potential



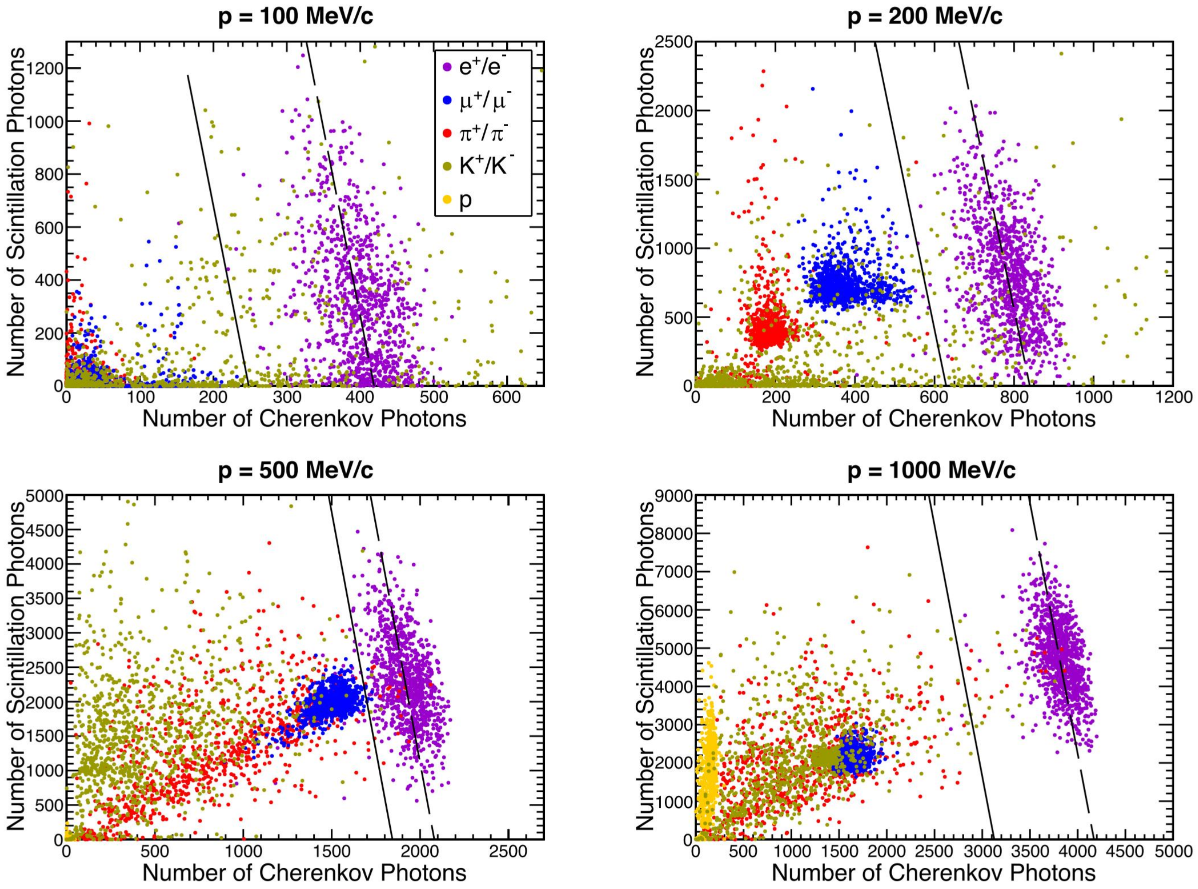


high altitude
muon decay controlling

low altitude
pion decay controlling

Allows ~0.5 m of cover
Requires ~1 m cavity

Muon Moonshot: PID system



Requirements:

(1) Muon/pion PID at O(100 MeV)

(2) Limited spatial dimensions

Proposed solution with IMP:

- Dual readout

- Tunable sensitive momentum range with different materials

- Compact, suitable for deep-space experiments, with demonstrated prior experience

[Chen et al. Nucl. Sci. Tech. 37 (2026) 8, 156](#)

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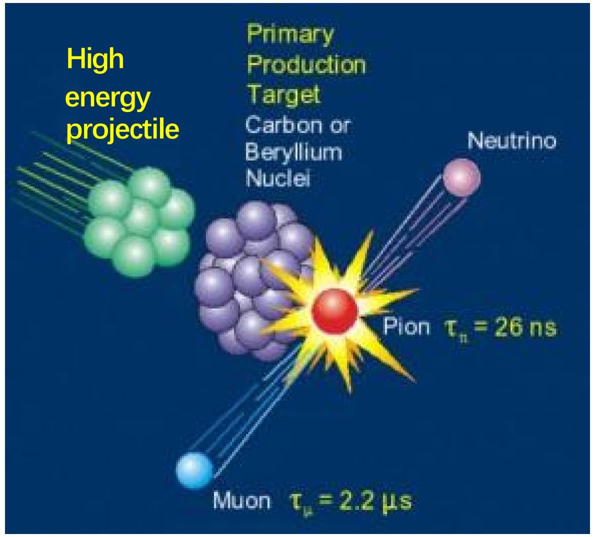
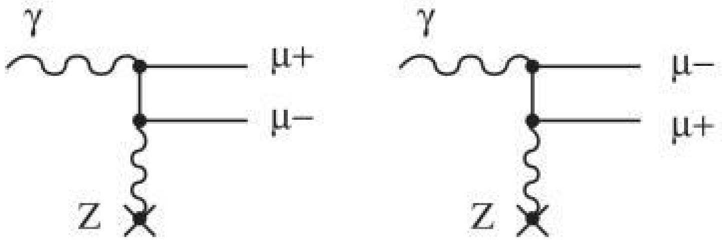
Muon Beam world wide

From IMP, China

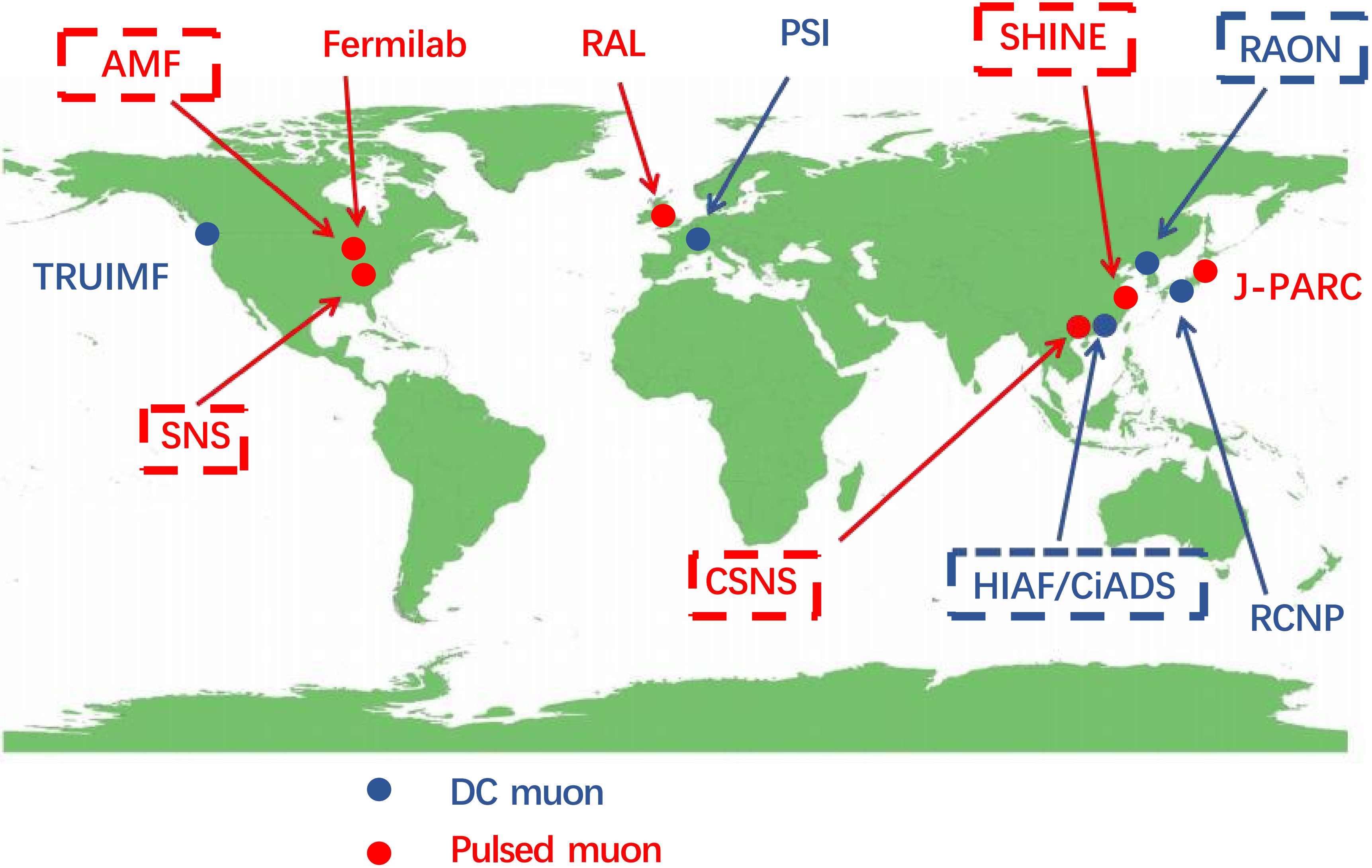
Accelerator generation:



Muon from pion decay



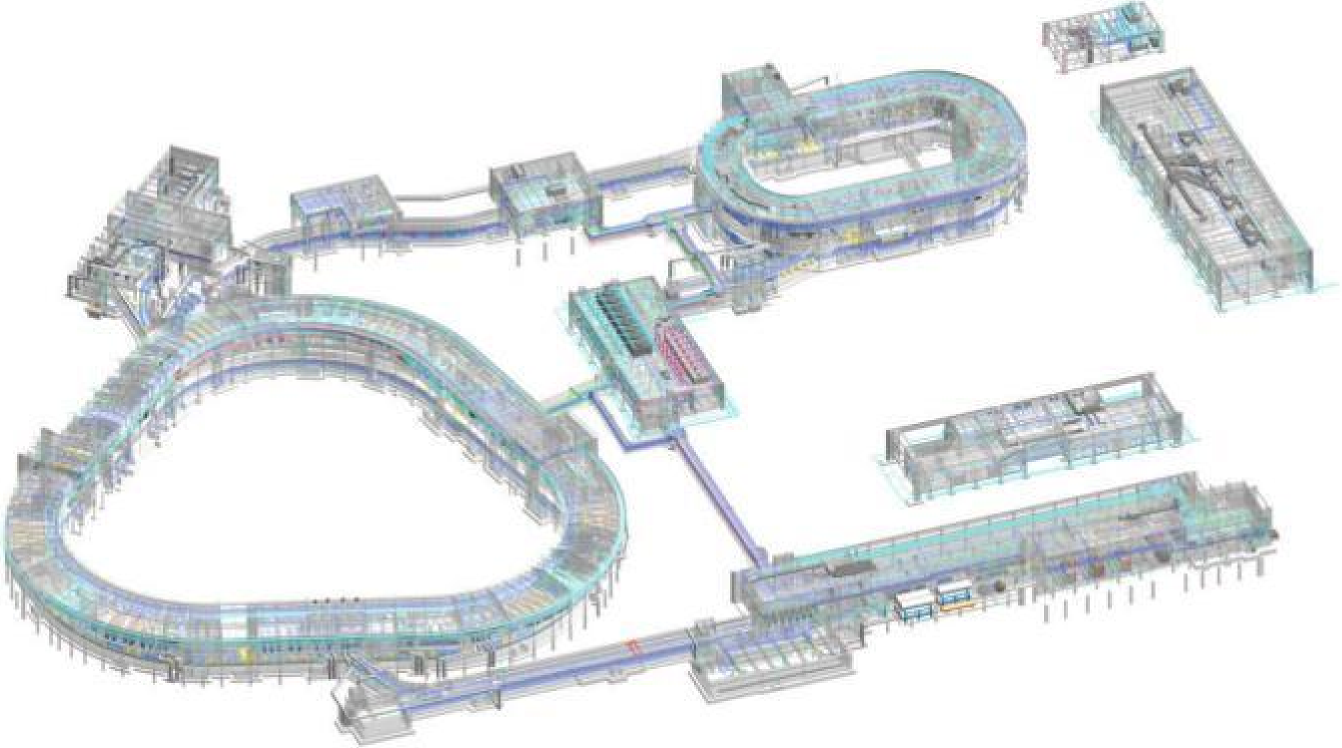
Bethe-Heitler process



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

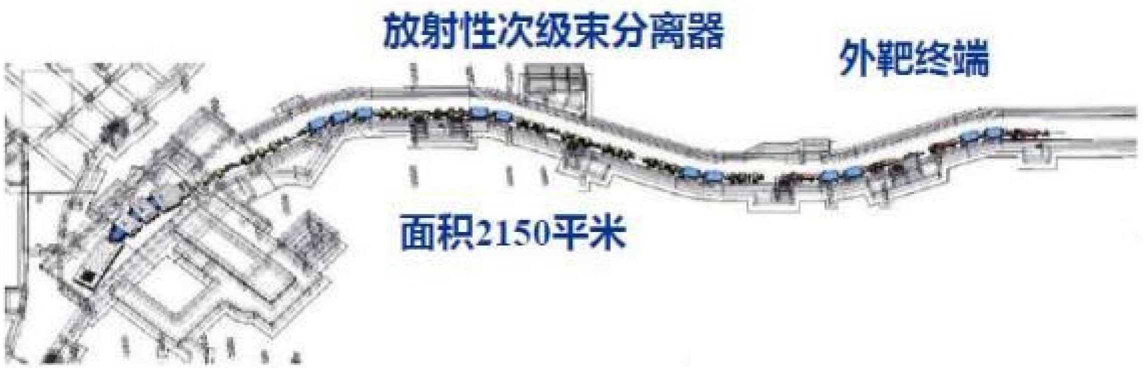
Feasibility study of the GeV-energy muon source based on the High Intensity Heavy-Ion Accelerator Facility

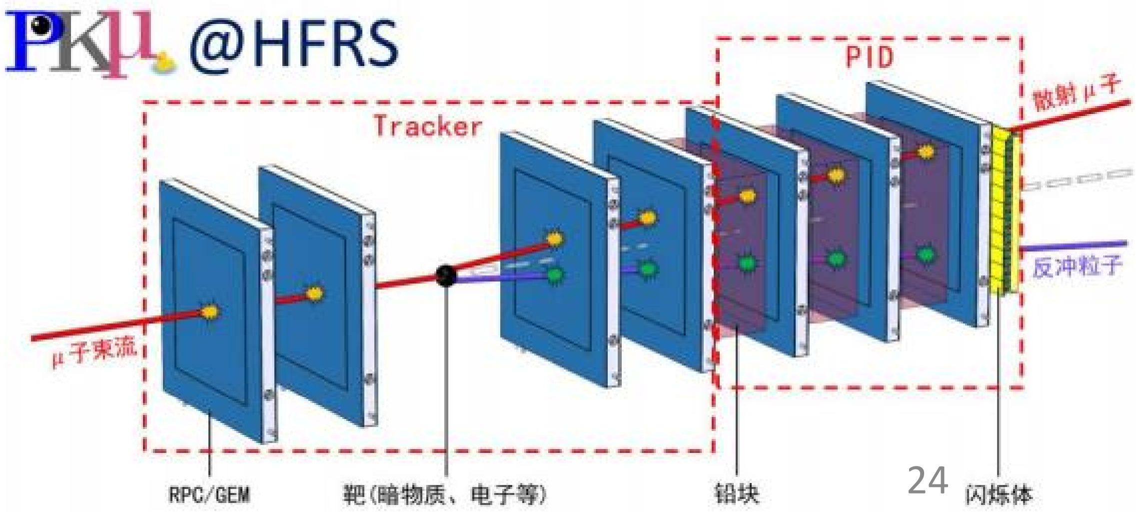
Yu Xu,[1,2] Xueheng Zhang,[1,2,3] Yuhong Yu,[1,2,3] Pei Yu,[1,2] Li Deng,[1,2] Jiajia Zhai,[1,2] Liangwen Chen,[1,2,3,*] He Zhao,[1,2,3] Lina Sheng,[1,2,3] Guodong Shen,[1,2,3] Ziwen Pan,[4] Qite Li,[5] Chen Zhou,[5] Qiang Li,[5] Lei Yang,[1,2,3] and Zhiyu Sun[1,2,3,†]



HIRIBL (High-Rigidity Radioactive Ion Beam Line) can be tuned to serve:

- **O(GeV) muons at ~10^6/s, up to ~99% purity**
- **Energy spread at ~2%**
- **Polarization tunable**





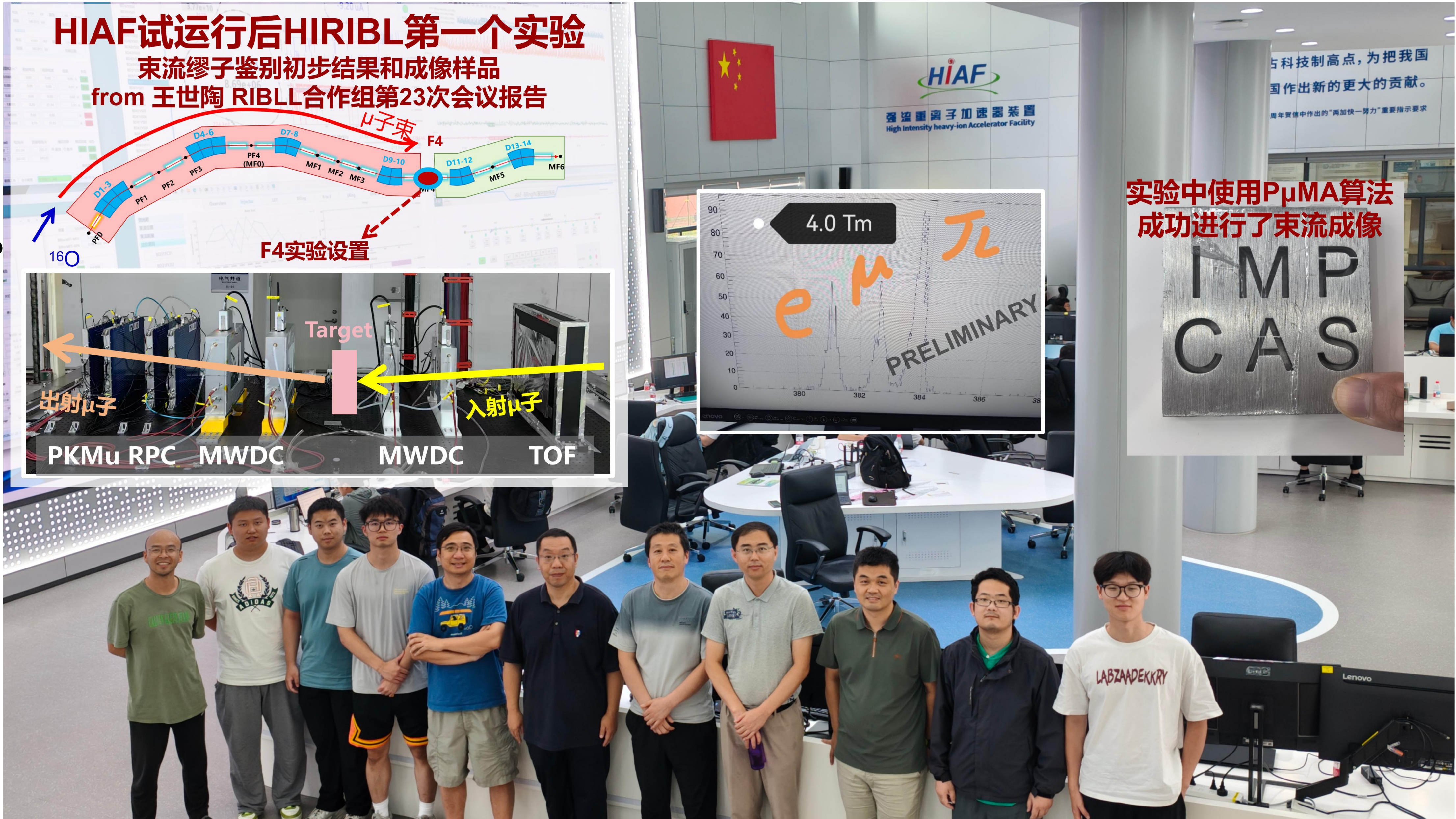
First commissioning run in July 2026

- O(10^4) muons collected

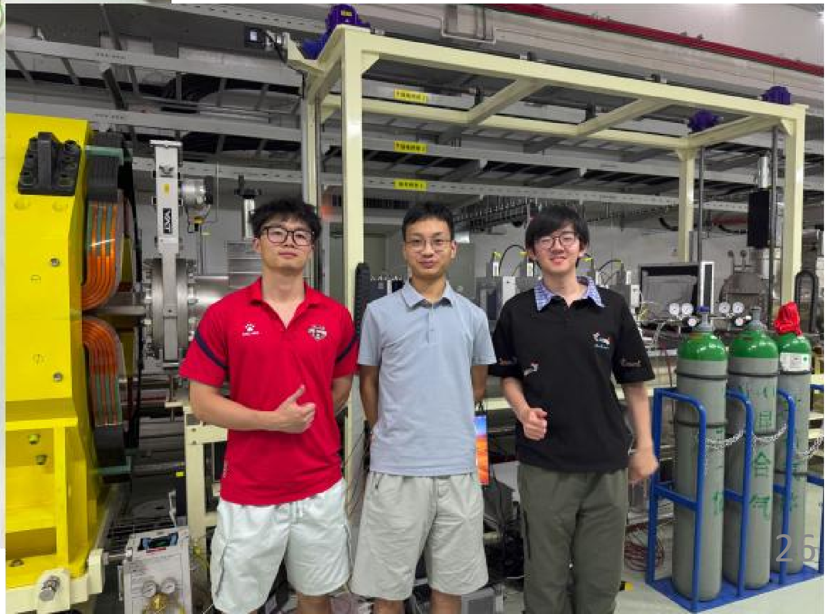
- PID results show excellent muon ID at 4 Tm

- The pattern IMP is clearly reconstructed by the PμMA algorithm

- Simple yet efficient combinations of RPCs, DCs, and TOF detectors show great potential for future muon spectrometer experiments



PKMu members collaborate closely at HIAF



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**
- **Future beam program: Dark bosons, CLFV, atomic binding effects, quantum entanglement**
- **Driven by innovation, open for collaboration**
- **Promising future muon spectrometer experiments collaborated with HIAF-HIRIBL**

Reference:

[1] Phys. Rev. Lett. 136, 151001 (2026) Cosmic muon-DM search experiment
[2] Chin. Sci. Bull. 71, 894 (2026) PKMu Introduction
[3] Phys. Rev. D 110, 016017 (2024) Muon Tomography for DM
[4] Phys. Rev. D 113, 072008 (2026) Light Dark Sectors
[5] J. Appl. Phys. 139, 014903 (2026) Secondary Particle Signatures in Muograpny
[6] Phys. Rev. Accel. Beams, 28, 053401(2025) HIAF Muon Beam
[7] Mod. Phys. Lett. A 40, 2530008 (2025) PKMu Overview
[8] J. Phys. G: Nucl. Part. Phys. 52 075002 (2025) for QE
[9] Int. J. Mod. Phys. A 40, 2550164 (2025) for CLFV
[10] arXiv:2512.19747 PμMA [11] arXiv:2607.18669 CLFV
[12] arXiv:2606.20180 NAMT [13] arXiv: 2607.10403 Moonshot

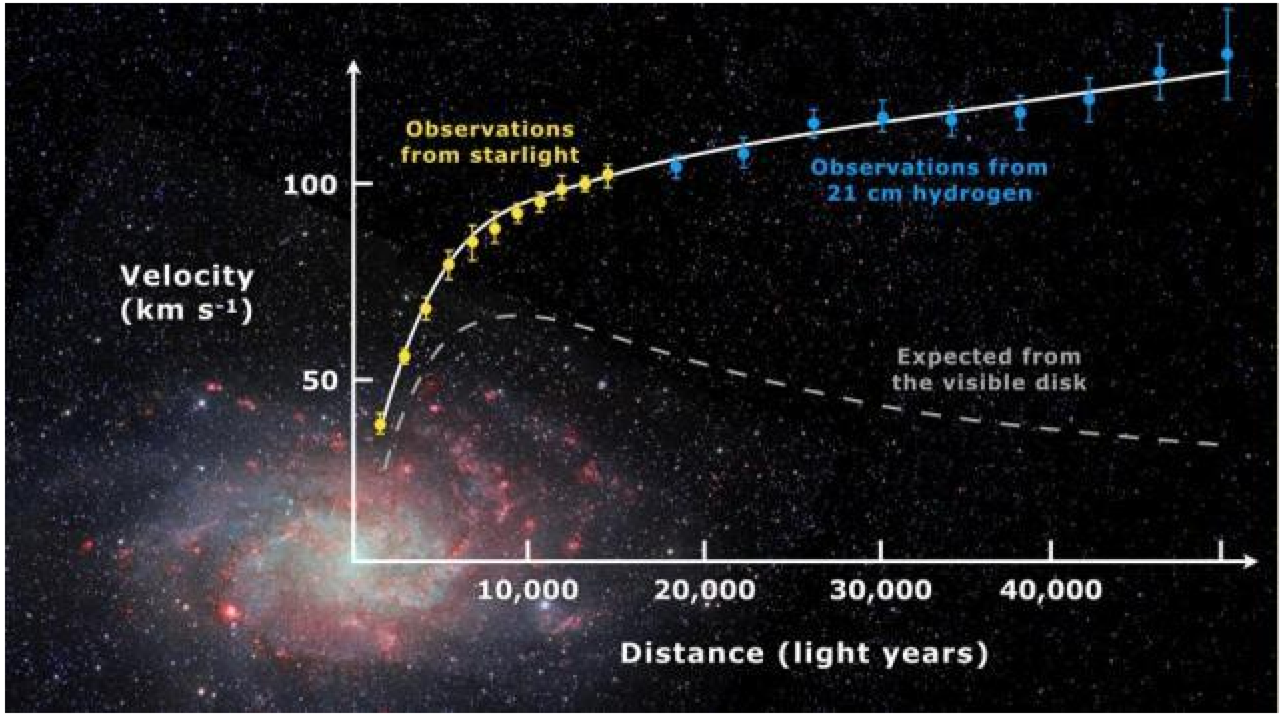
Special Thanks

Group Photo of PKMu Team

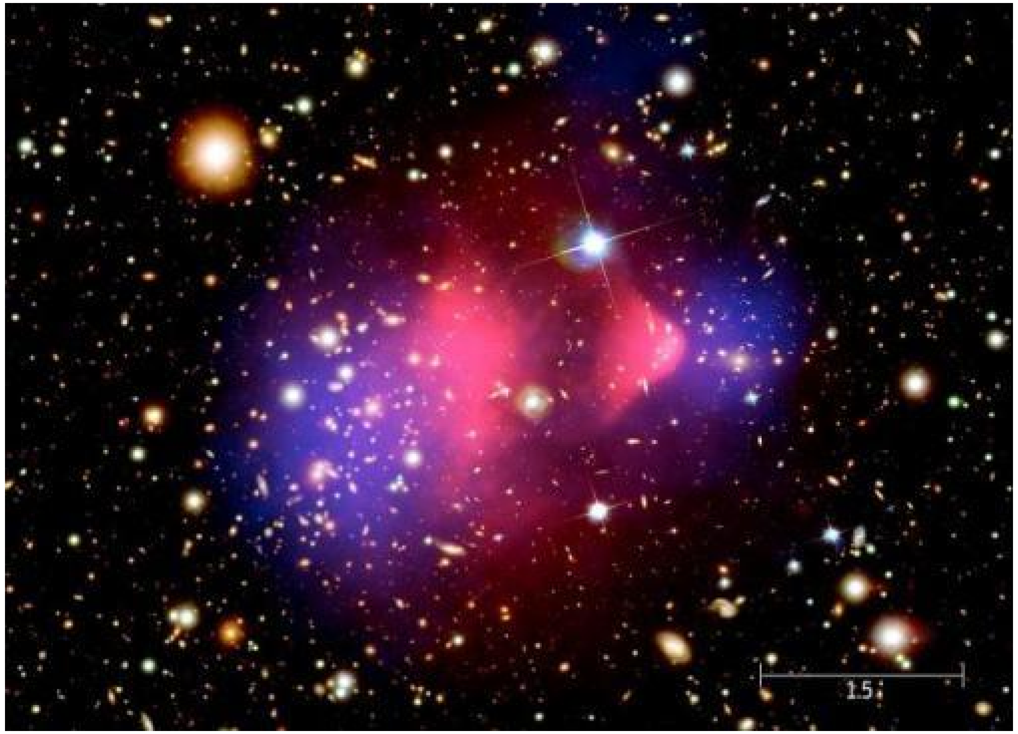
backup

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.

Other evidences: Gravitational lensing, microwave background radiation.

PKU RPC R&D History


The Compact Muon Solenoid Experiment

CMS Bulletin

CERN, CH-1211 GENEVA 23, Switzerland

Bulletins are available on CMS internal information server: http://cmsdoc.cern.ch/cms.html

Number 06-01
13 March 2006

Moving Forward !

YE+1 yoke equipped with CSC/RPC packages (inner ring) and RE1/3 RPC's (outer ring).

The ME1/3 CSC's now cover the RPC outer ring and hence complete the first Muon station on YE+1.

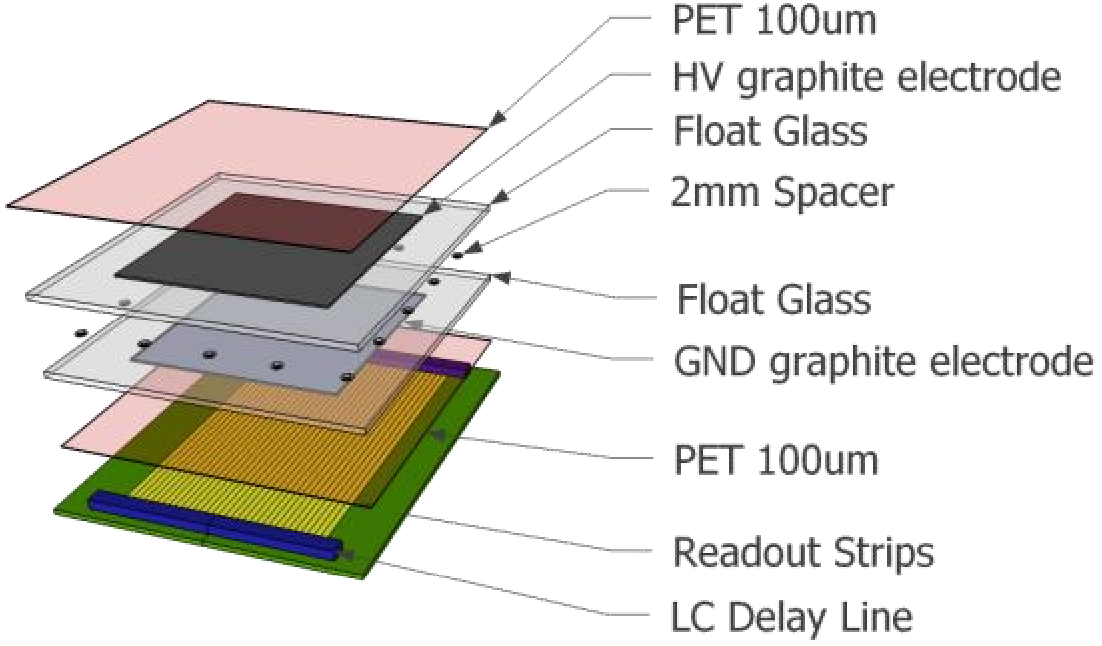
- Resistive Plate Chamber
  - R. Santonico(in 1980s)

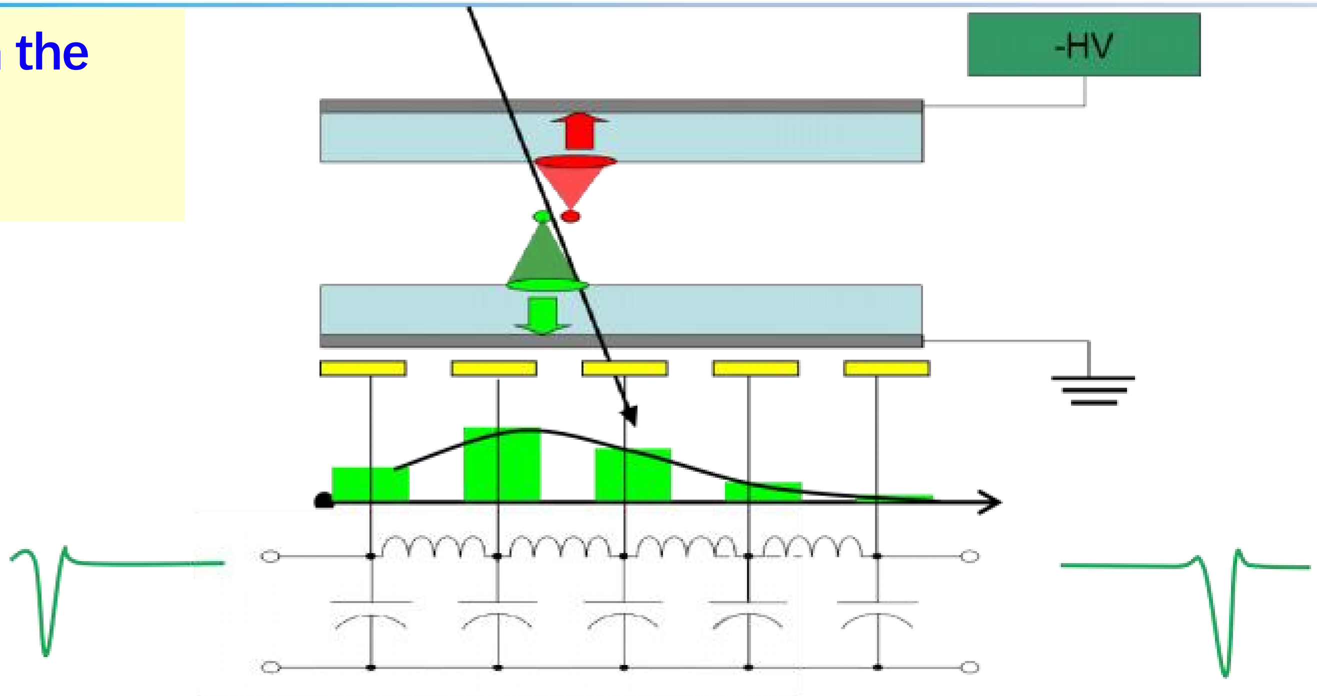
- Large Area ~ m^2
- Good Time Solution~1ns
- Acceptable Spatial Resolution
  - ~3mm ~1cm

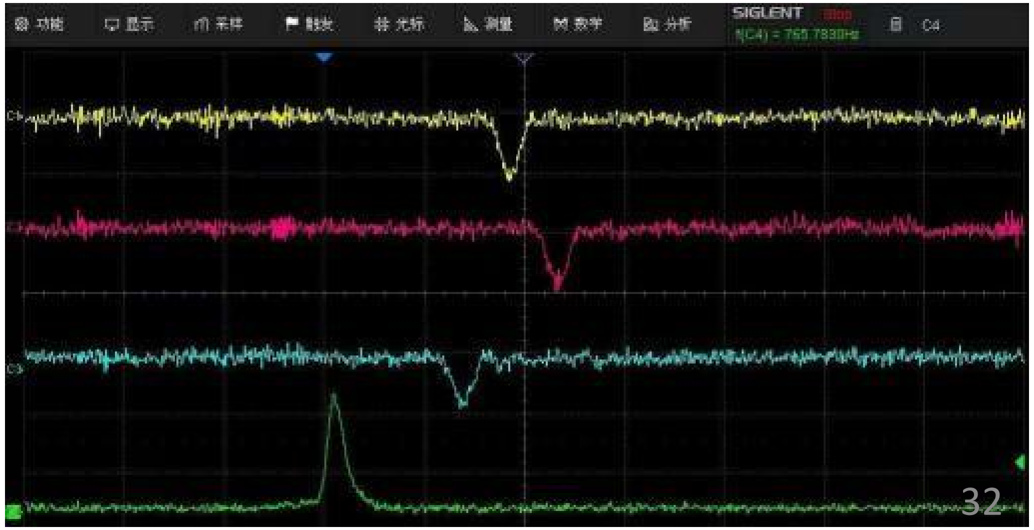
CMS Muon Trigger RPCs
Assembled and tested by PKU (~2002)

High resolution RPC R&D（2012~2013） Li Qite and Ye Yanlin， *et al.*

Innovatively combine the large-area glass RPC with the delay-line readout technology. 2 TDC/1 dim
Spatial resolution of muons. 0.3~0.4 mm (σ)





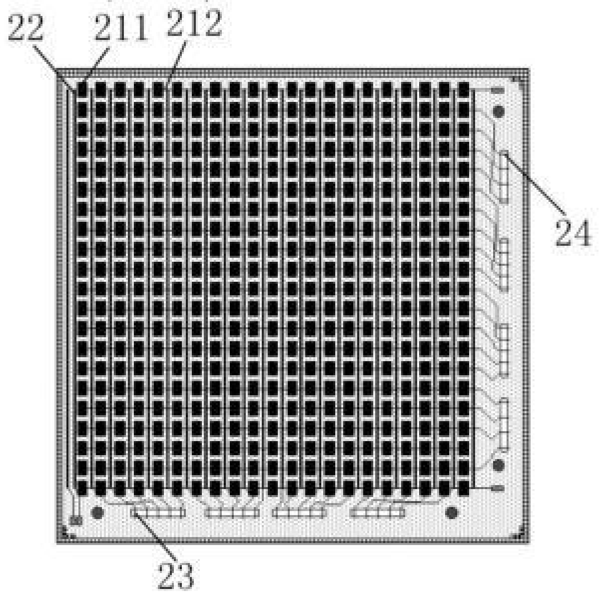


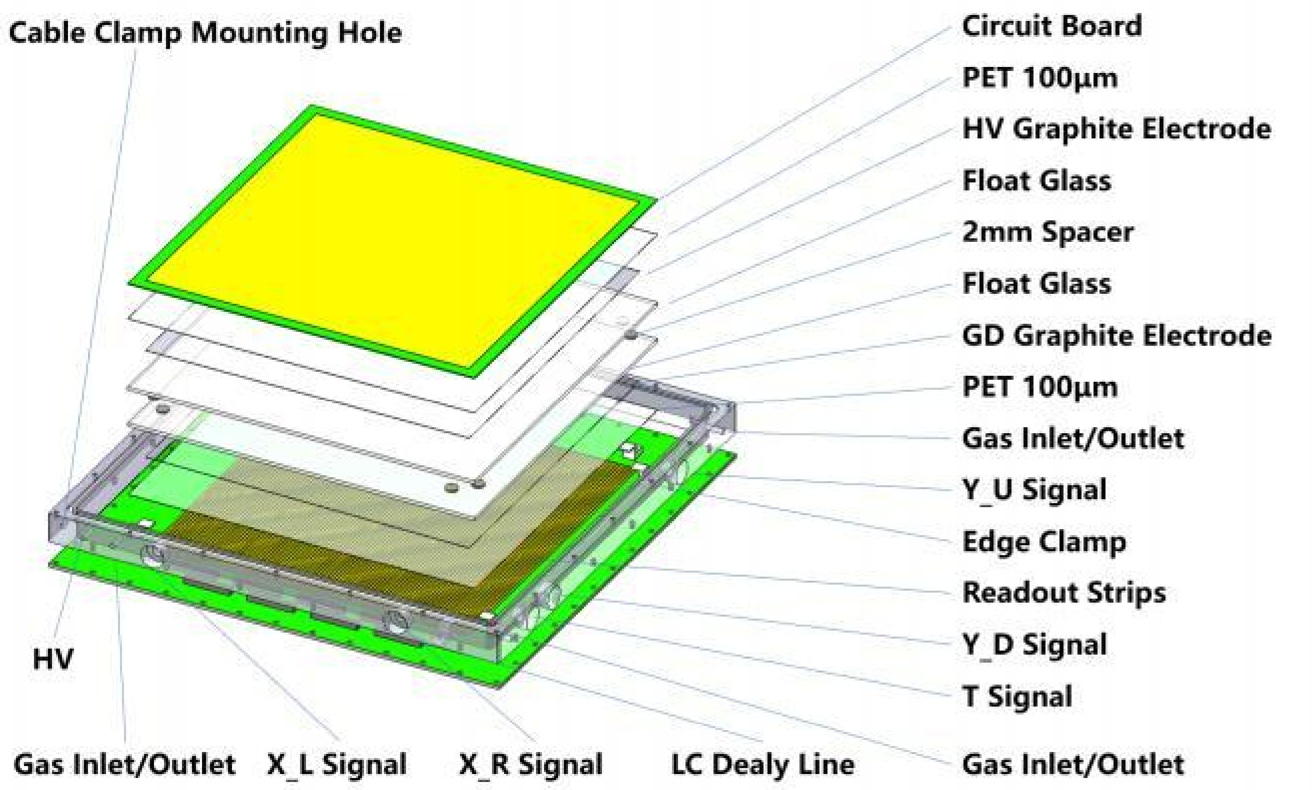
Ref：

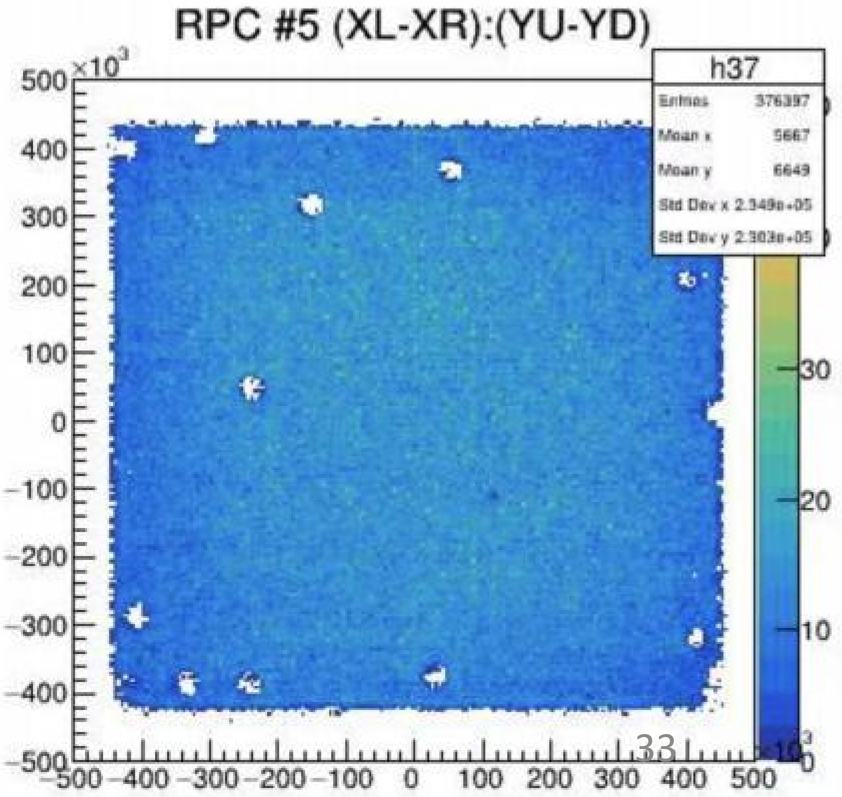
- Li, Qite, *et al.* *NIMA* 663.1 (2012): 22-25.
- Qi-Te, Li, *et al.* *Chinese Physics C* 37 (2013)016002.
- S. Chen, Q. Li*, *et al*, *JINST*: 10 (2014)10022.
- 许金艳,李奇特*, 等, *物理实验*, 41(2021)23

2D RPC Readout Strip Design（2024）

- **Enables 2D position readout from a single RPC layer.**
- **Reduced detector material, simplified detector structure**
- **Simple and elegant position reconstruction**
- **National Invention Patent Granted: ZL 2025 1 1044987.1**







GE2/1 GEM：探测器部件生产进展

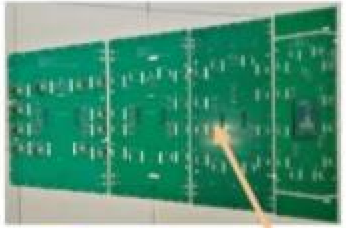
PKU Lab

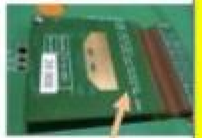
北大基地生产的第一个CMS GEM模块

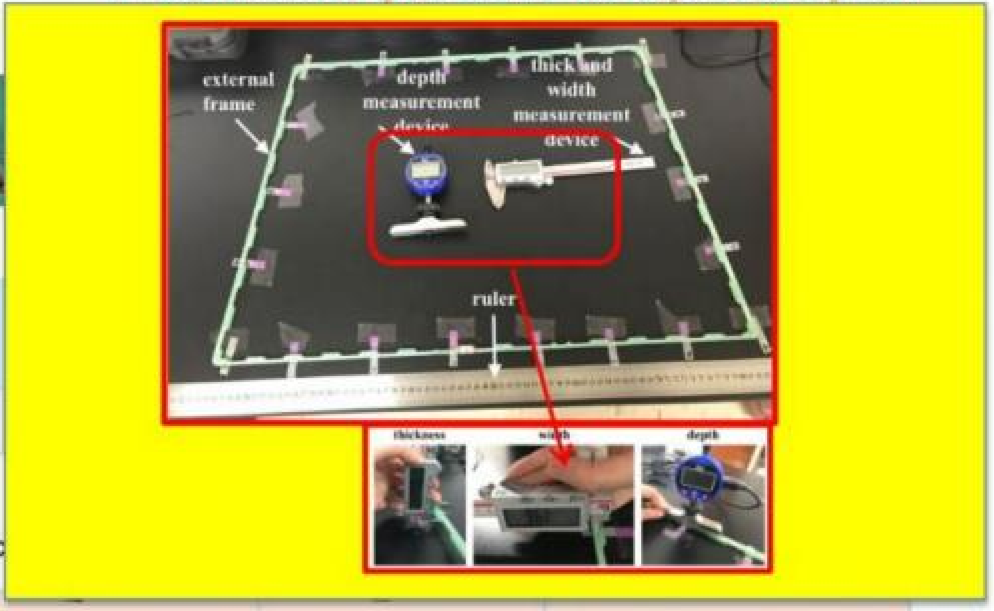
Module Components

Components	GEM Foils	External Frames	Internal Frames	O-rings	Drift PCB	RO PCB	T-nuts	Pull-outs
% Produced	82%	COMPLETED	COMPLETED	COMPLETED	27% - 41%	27% - 41%	42.4 %	27.5 %

(> 50% expected by Aug. 2023) (> 50% expected by Sep.2023)







On-detector electronics

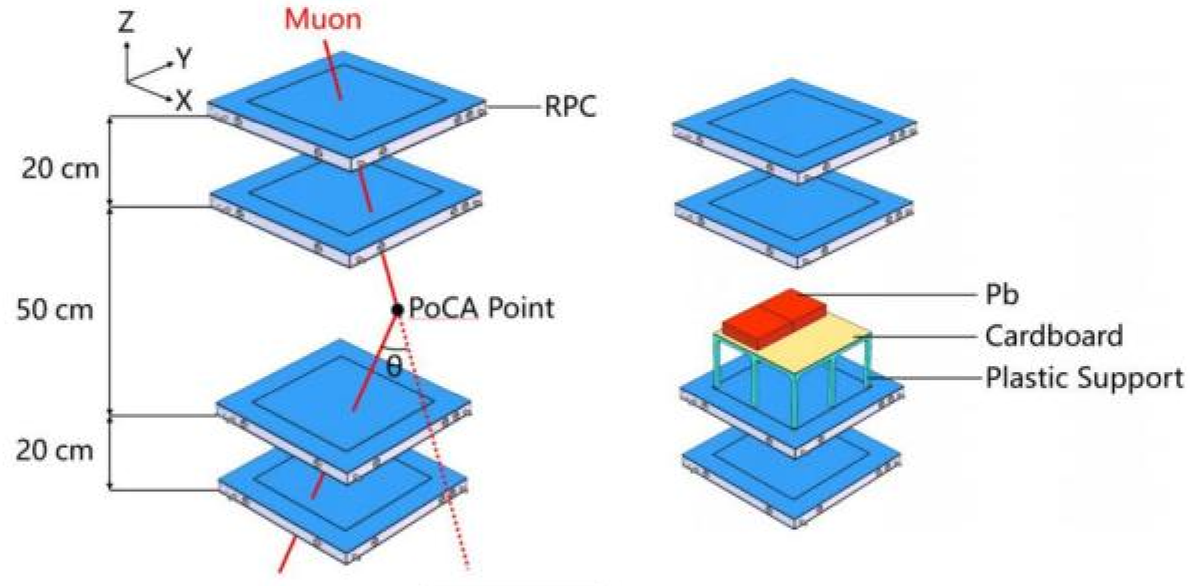
Components	GEB	OH	VFAT (Plug-in Card)
% Produced	COMPLETED	COMPLETED	60.2 %

In progress
(>50% expec

Chamber components

Components	Mechanics	On-detector Fibers	HV filters	Cooling	On-detector Cabling (HV/LV/GND)
% Produced	COMPLETED	COMPLETED	~30%	50% - 100%	COMPLETED

中国组负责生产的GEM部件均已按计划完成并通过CERN检测！



(a) (b)

FIG. 1. Experimental configurations. (a) Physics Run: four vertically aligned glass RPCs (28×28 cm^2) with spacings of 20, 50, and 20 cm; the muon scattering angle θ is defined. (b) Control Run: two lead blocks ($12 \times 12 \times 3$ cm^3) placed 150 mm above the third RPC, centered at the origin ($X \in [-120, 0]$ mm, $Y \in [-120, 120]$ mm).

Using the same simulation framework described earlier, the configuration of the Control Run, as shown in Fig. 1(b), is replicated to obtain simulated cosmic-ray data under identical detector conditions. This setup enables a clear division of the scattering region into a lead block zone, defined by scattering coordinates $X \in$ (-110 mm, -50 mm), and an air zone, defined by $X \in$ (50 mm, 110 mm). Applying the same fitting method, it is found that in the lead block region, muons account for $(96.6 \pm 0.2)\%$ and electrons for $(0.7 \pm 0.2)\%$. In the air region, the muon and electron fractions are $(32.3 \pm 1.4)\%$ and $(54.6 \pm 1.4)\%$, respectively. The low electron fraction in the lead block region is expected, as electrons are less penetrating than muons and cannot traverse the lead to reach the downstream RPC layers. The same fitting method is applied to a Physics Run, with results shown in Fig. 3.

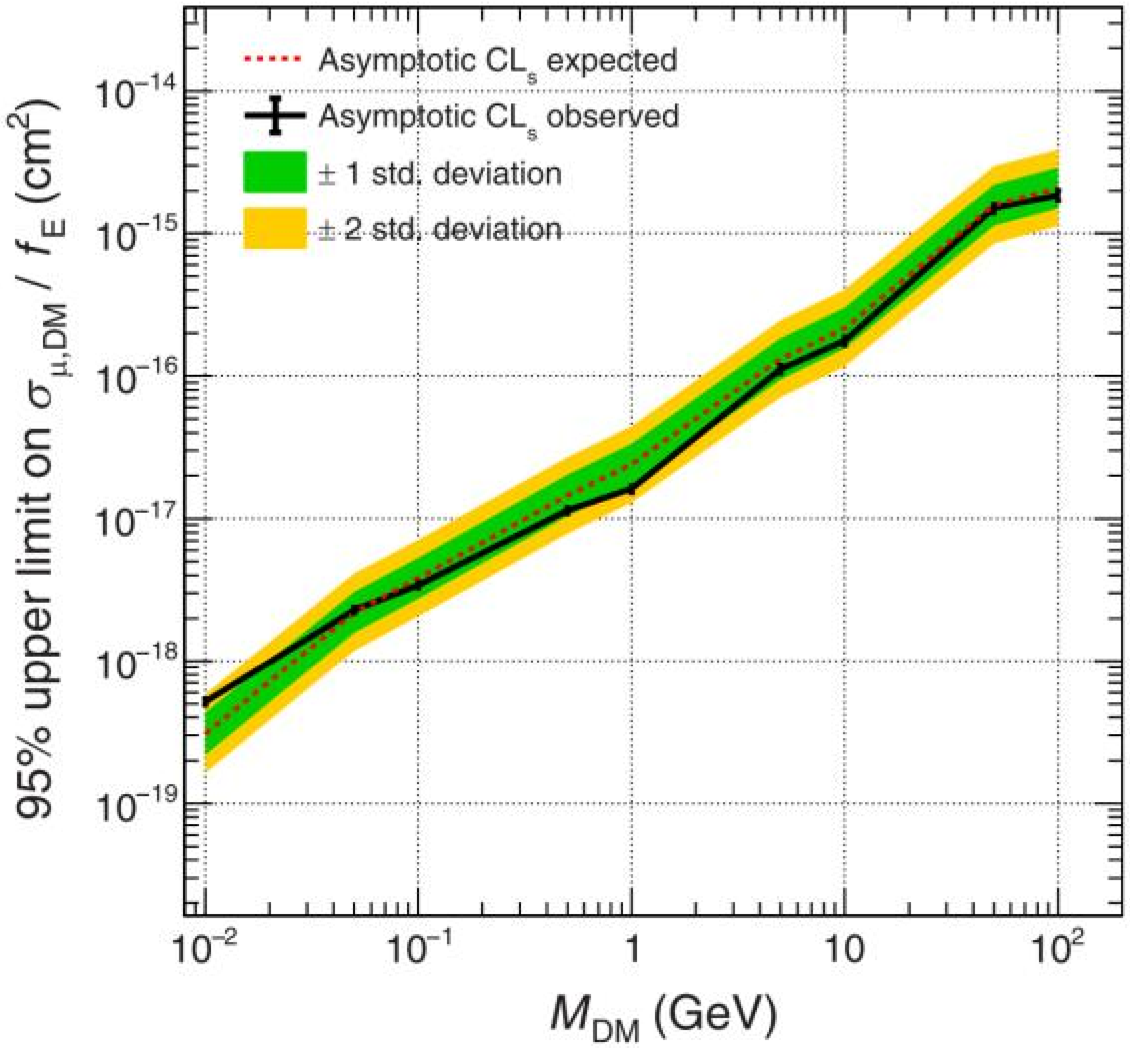


FIG. 4. Expected and observed 95% CL upper limits on the DM-muon interaction cross section versus M_{DM}, assuming a local DM density enhancement factor of 10^{15} arising from Earth-bound thermalized component. The green and yellow bands represent the 1σ and 2σ regions, respectively.

Equation (2) follows from the above considerations.

$$dN/dt = \rho V / M_{\mathrm{DM}} \times \sigma_{\mu,\mathrm{DM}} \times F_{\mu} \times \epsilon_1 \times \Omega_a \times \epsilon_2. \quad (2)$$

However, if a strongly interacting dark matter component is captured and thermalized within Earth, its local surface density can be enormously enhanced for DM with a mass of 1 GeV, the density may increase by a factor of 10^{15} [26,27]. To account for this possibility, an enhancement factor $f_E = 10^{15}$ is introduced, such that $D_{\mathrm{E}} = f_E \rho / D_{\mathrm{DM}}$, where D_{E} denotes the number density of the exotic slow DM under investigation, and D_{DM} is the M_{DM} in unit GeV.

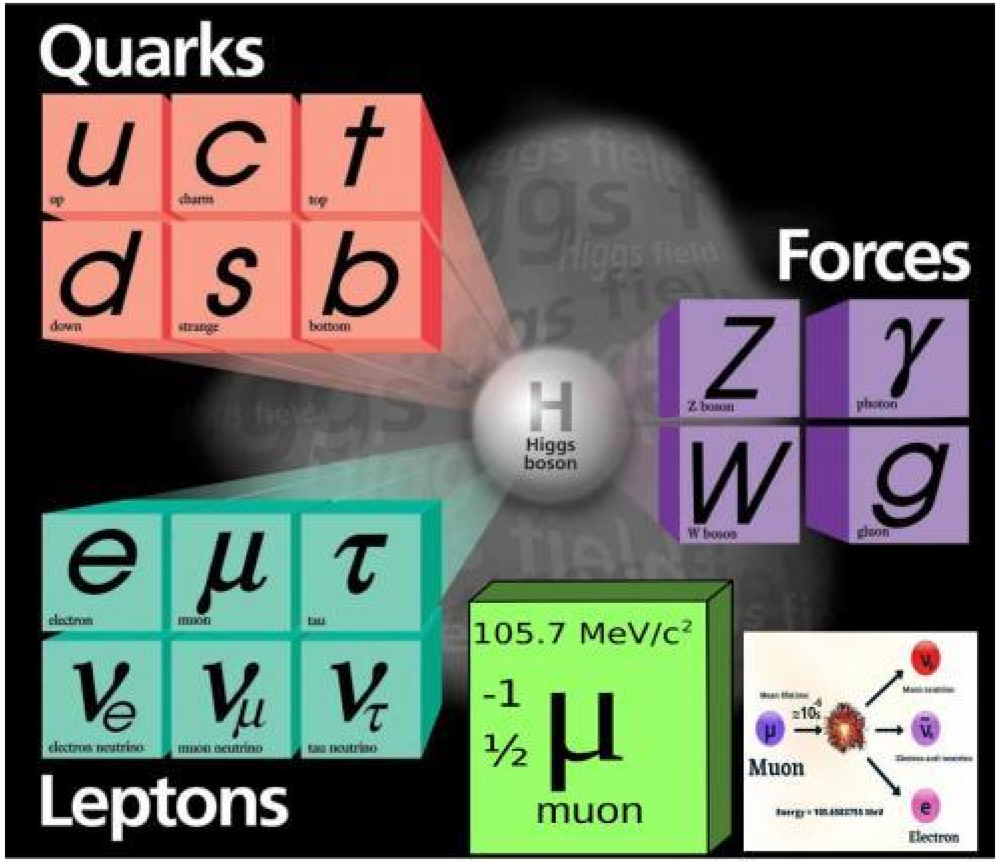
[26] D. McKeen, D. E. Morrissey, M. Pospelov, H. Ramani, and A. Ray, Phys. Rev. Lett. **131**, 011005 (2023).

[27] A. Berlin, H. Liu, M. Pospelov, and H. Ramani, Phys. Rev. D **109**, 075027 (2024).

Using Muons to Detect Dark Matter

- **Why Muon Scattering?**

1. **Muon-dark matter interactions remain understudied.**
2. **Muons are second-generation leptons in the Standard Model.**
3. **Free muons are short-lived/rare in the universe.**
4. **Enhanced sensitivity to light-mass dark matter**
5. **Complementary to traditional DM detection approaches----Muon from background to SIGNAL**
6. **Experimental Advantages:**
   - ➢ **Expertise in cosmic-ray muon detection/tomography.**
   - ➢ **Future muon sources in China(MELODY, HIAF, CiADS, SHINE)**

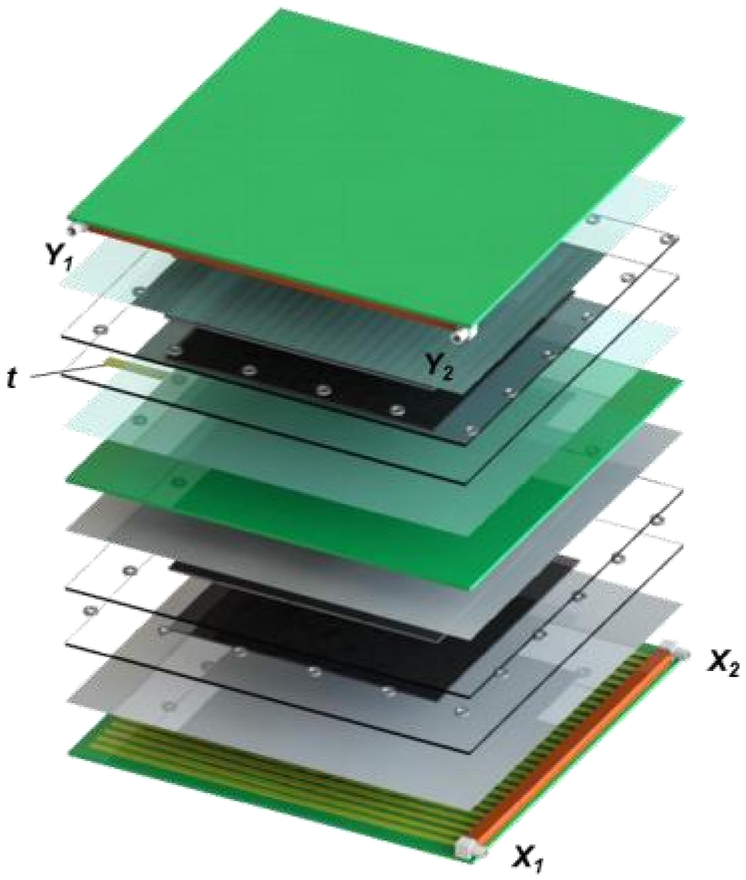


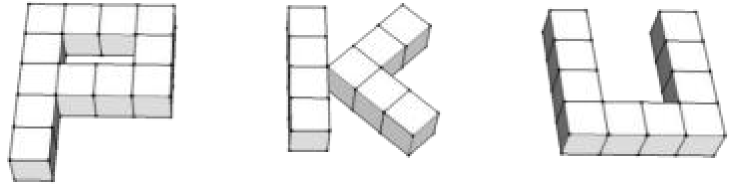
3D Imaging Test(2013~2014)

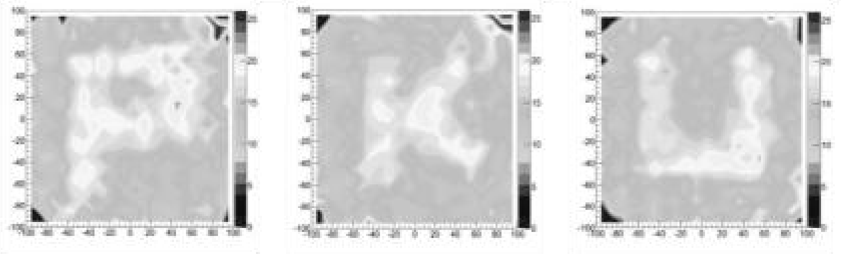
4 X-Y readout RPC Boxs, distance 285mm

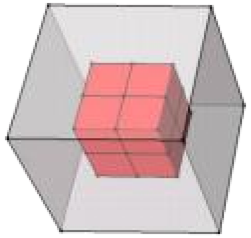
Active area 203mm*203mm

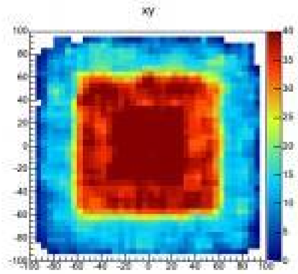
Using only 20 TDC channels

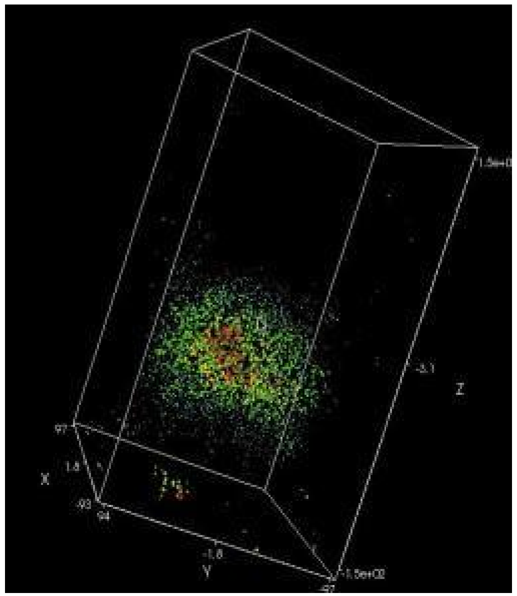






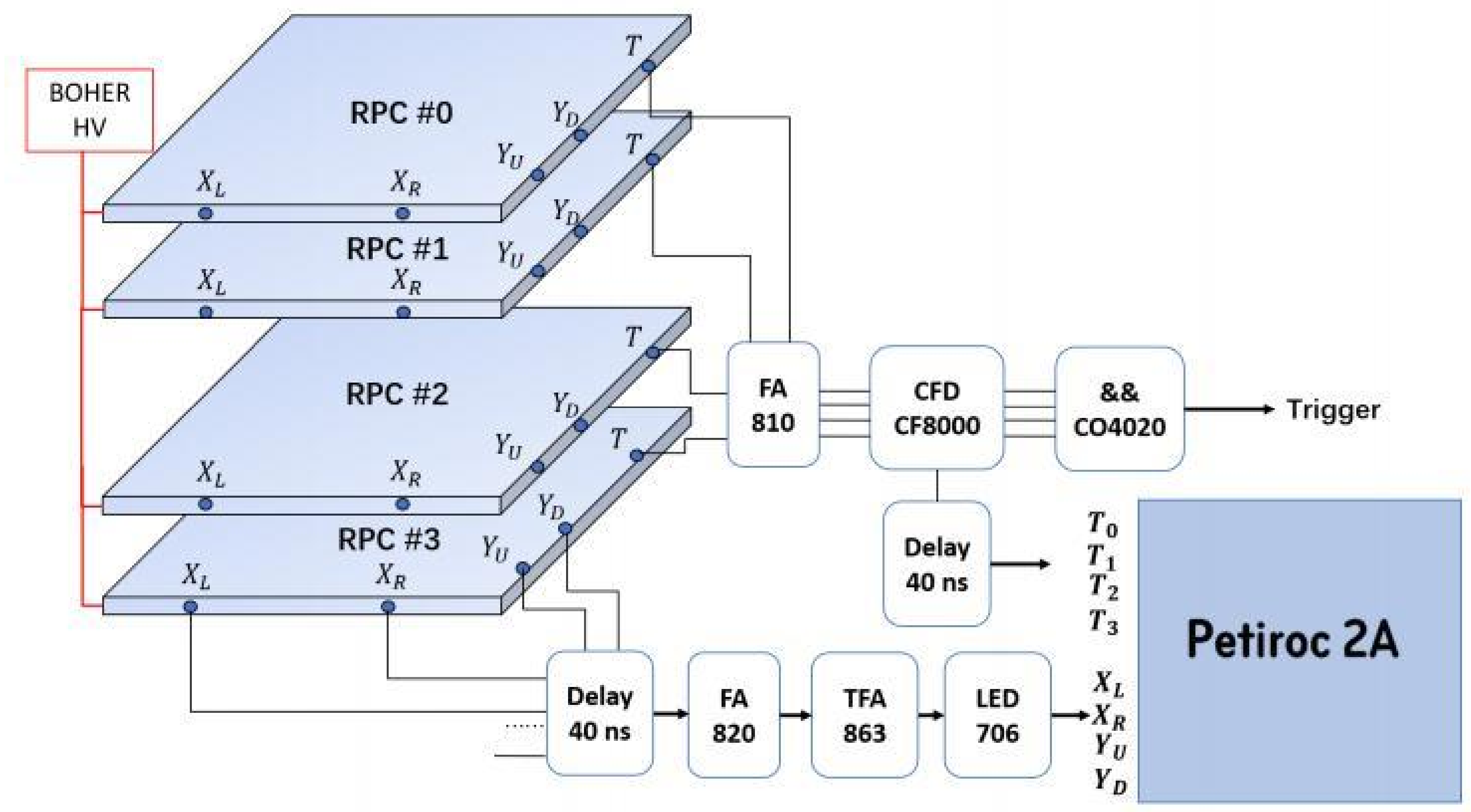






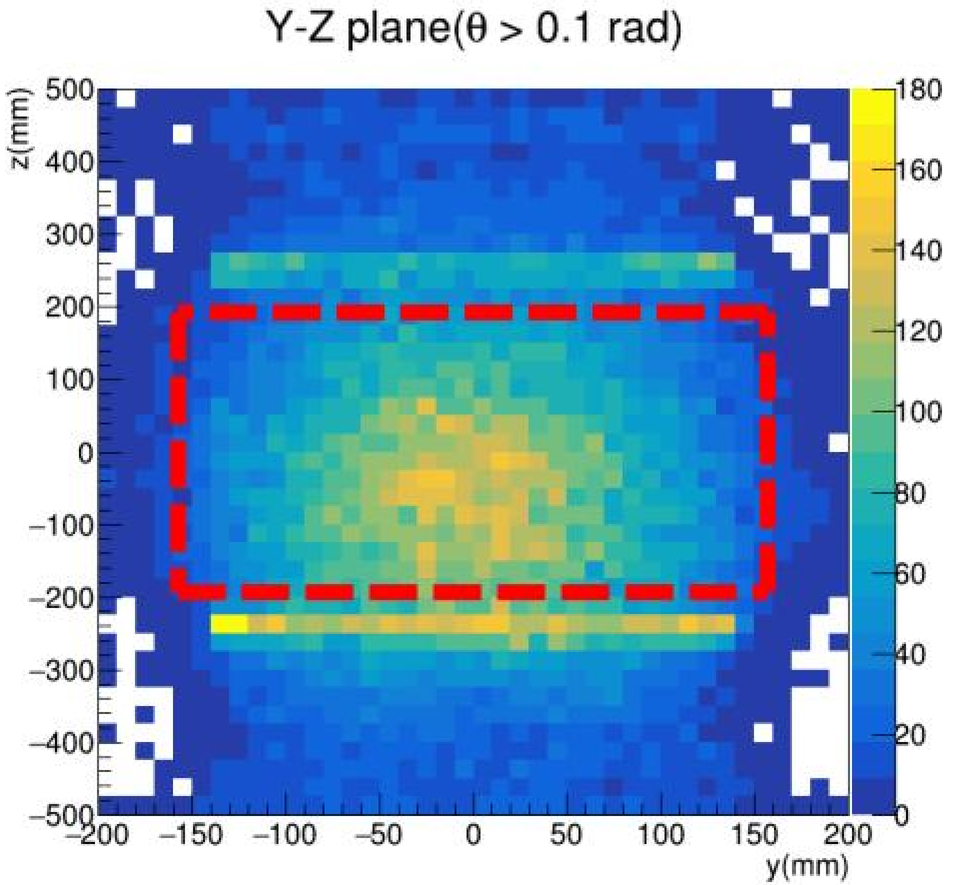
4RPCs Muon Tomography System(2025)

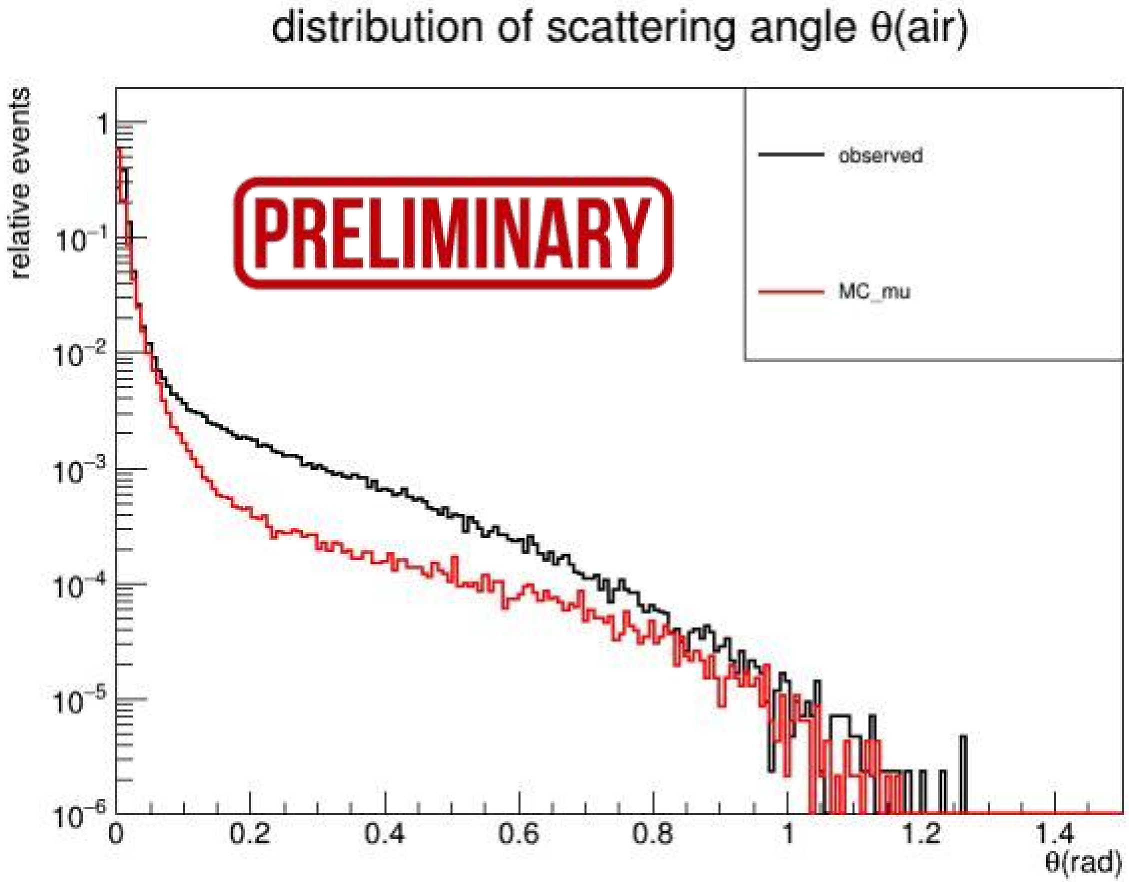
- RPC 280mm ×280mm 20cm-50cm-20cm
- Petiroc 2A ASIC DAQ by USTC
- Air: 63days 1.18M events



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





Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP 2024)

19 Apr 2024, 02:00 → 22 Apr 2024, 12:20 Asia/Shanghai

Peking University

Chen Zhou (Peking University (CN)), Qiang Li (Peking University (CN)), Qite Li (Peking University)

MIP2024

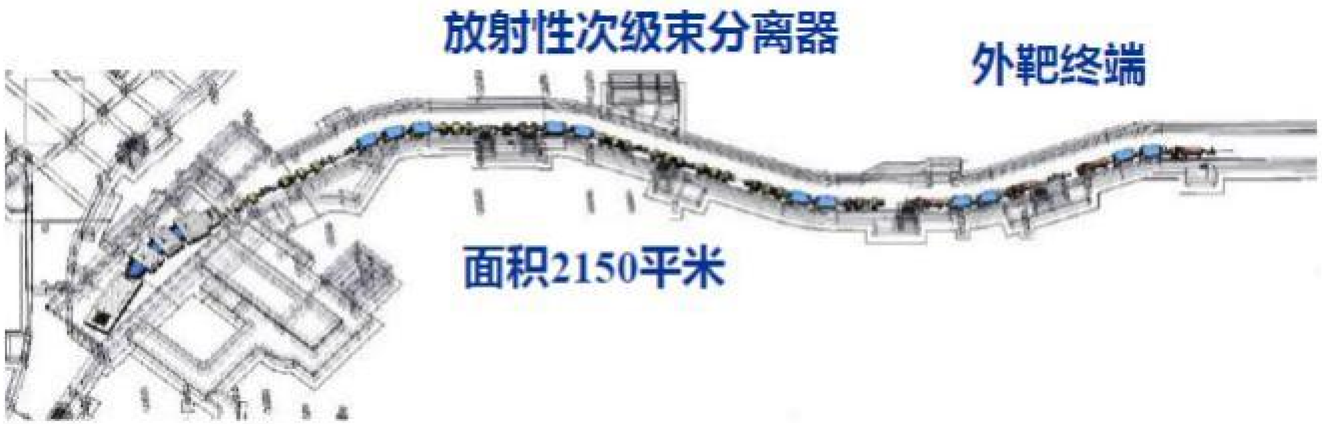
Several possible Chinese Muon beams in the near future:
Melody,
CIADS, HIAF

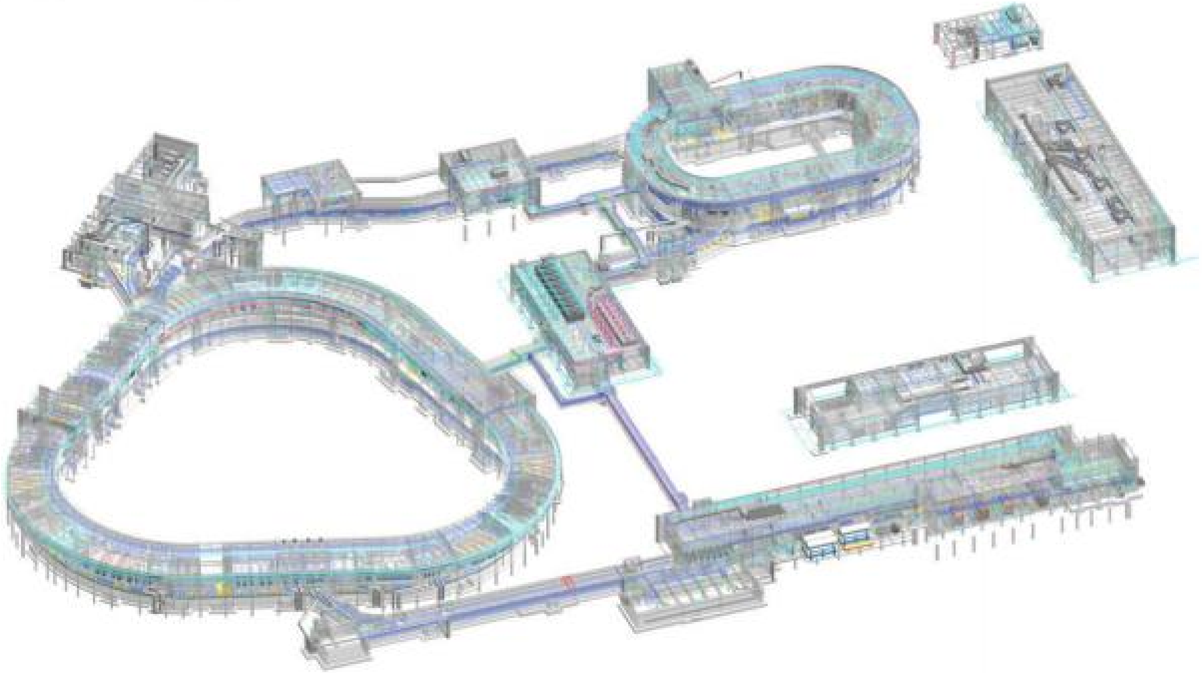
High-rigidity Radioactive Ion Beam Line (HIRIBL)

From Xu Yu

- The radioactive beamline with the highest magnetic rigidity: 25 T·m

- Designed for cutting-edge nuclear physics research with radioactive beams, it can:
- Separate and purify exotic particles produced in projectile fragmentation and fission reactions;
- Separate and purify pions generated in projectile-induced reactions, as well as muons originating from their decays.



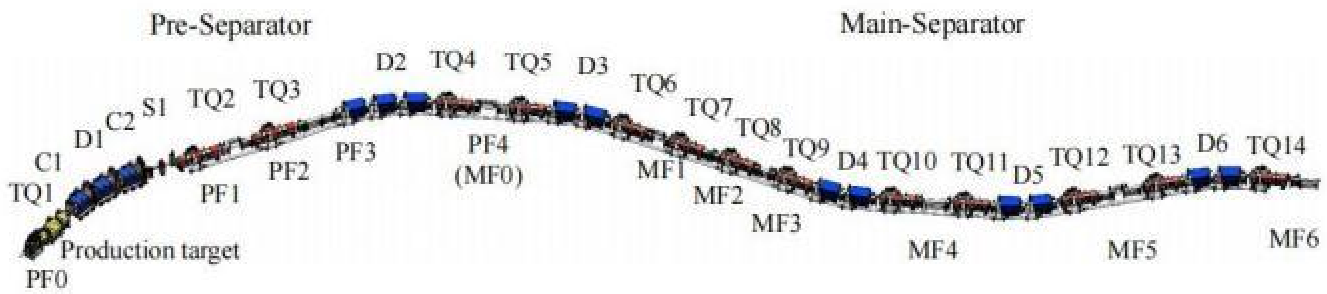


Muon Beam on HIAF HIRIBL

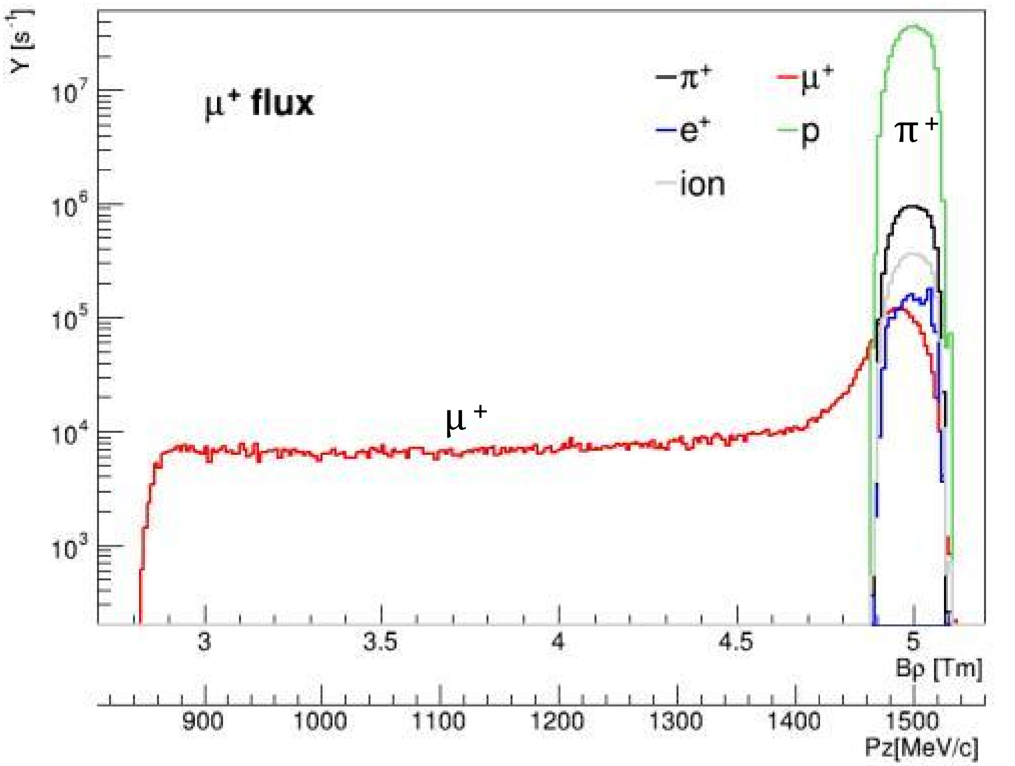
from Xu Yu

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

- Beamline magnetic rigidity setting: 5 T·m, corresponding to a particle momentum of 1500 MeV/c.
- The muon beam composition is complex:
  - The μ^- beam contains π^-, μ^-, e^-, etc.
  - The μ+ beam additionally contains protons (constituting over 90% of the beam) as well as some heavy ions.
- Particle momenta:
  - The momentum distribution of contaminant particles such as electrons and protons is 1500 ± 2% MeV/c.
  - The muon momentum spectrum exhibits a long tail originating from pion decays during beam transport.
  - The momentum difference between muons and contaminant particles can be exploited to obtain a purified muon beam.



束流成分@MF6



GE2/1 GEM：探测器部件生产进展

PKU Lab

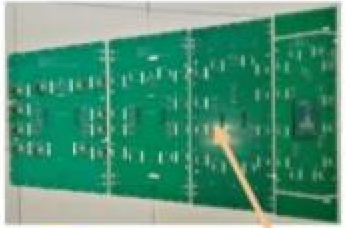
北大基地生产的第一个CMS GEM模块

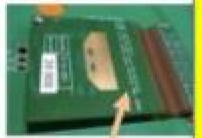
北大基地GEM测试设备

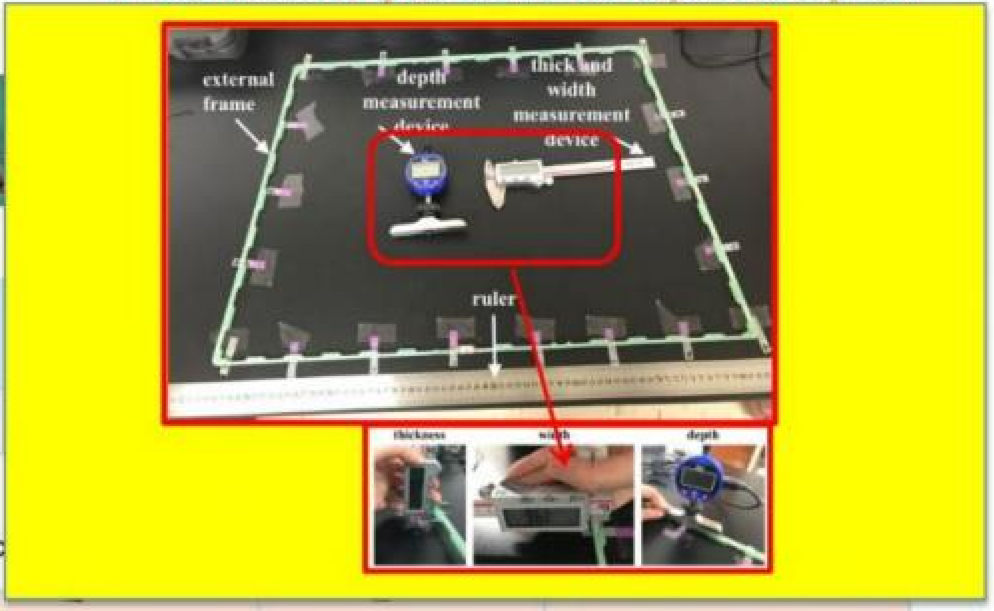
Module Components

Components	GEM Foils	External Frames	Internal Frames	O-rings	Drift PCB	RO PCB	T-nuts	Pull-outs
% Produced	82%	COMPLETED	COMPLETED	COMPLETED	27% - 41%	27% - 41%	42.4 %	27.5 %

(> 50% expected by Aug. 2023) (> 50% expected by Sep.2023)







On-detector electronics

Components	GEB	OH	VFAT (Plug-in Card)
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In progress
(>50% expec

Chamber components

Components	Mechanics	On-detector Fibers	HV filters	Cooling	On-detector Cabling (HV/LV/GND)
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中国组负责生产的GEM部件均已按计划完成并通过CERN检测！

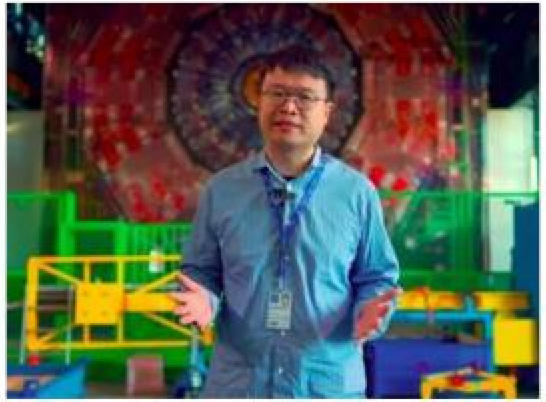
PKU HEP-CMS Group

7 faculties: Yong Ban, Ya-Jun Mao, Qiang Li, Da-Yong Wang, Si-Guang Wang, Chen Zhou, Xiaohu Sun

2 engineers: Qite Li, Z.H.Xue

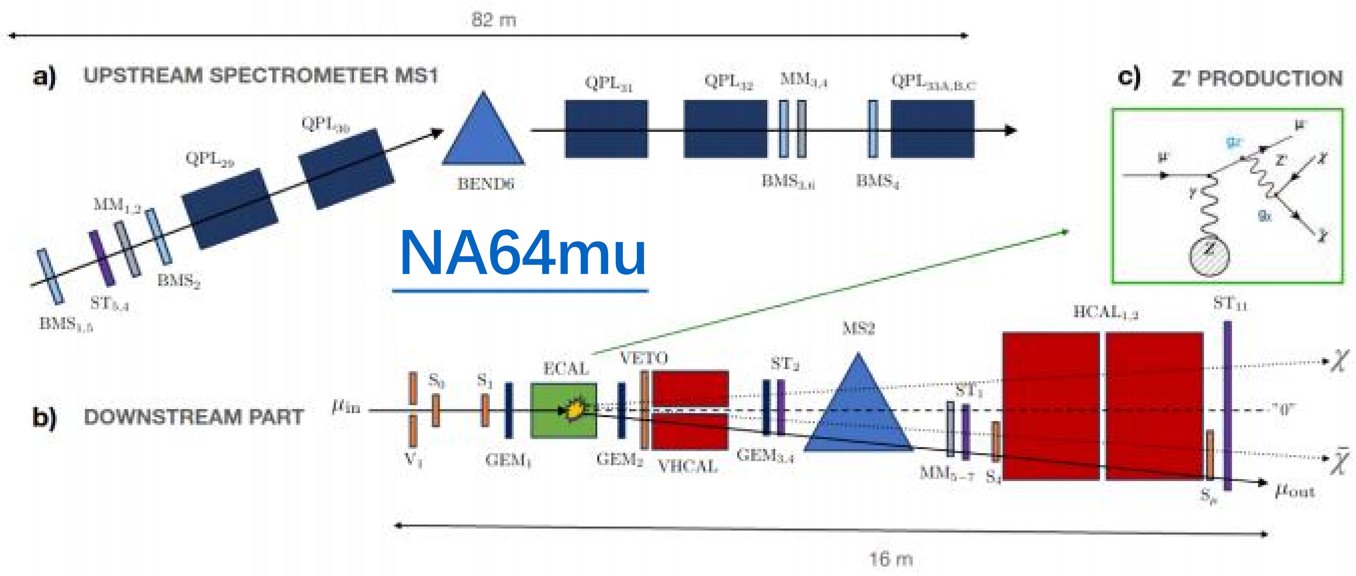
5 postdocs: Andrew Levin, Antonios Agapitos, Zhiyuan Li, Qianying Guo, …

30 students
+ One large theo. group focusing on QCD and TeV Physics
In CMS since 1996, Stable support from Government
RPC and GEM ; VBS; B→Kμμ; Boosted Jet



Prelude: NA64, DarkShine, LDMX, MMM

- Muon Philic Dark Matter may be possible or necessary! (arXiv: 1804.03144)
- Some Electron/Muons on Target Experiments
  - DarkShine is ~ LDMX based on Shanghai Synchrotron Radiation Facility
  - MMM (M3) is a US proposed muon-LDMX experiment
    - Intrigued by a proposal based on CERN NA64
    - “a lower-energy, e.g. 15 GeV, muon beam allows for greater muon track curvature and, therefore, a more compact experimental design_”



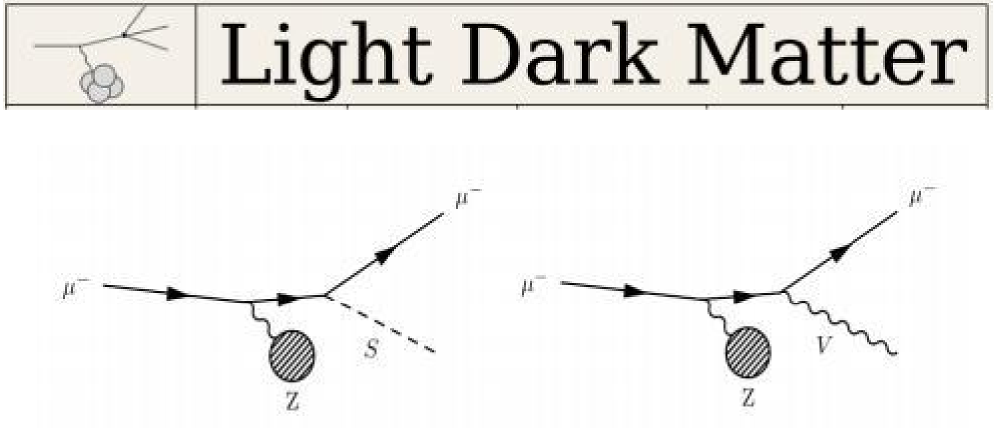
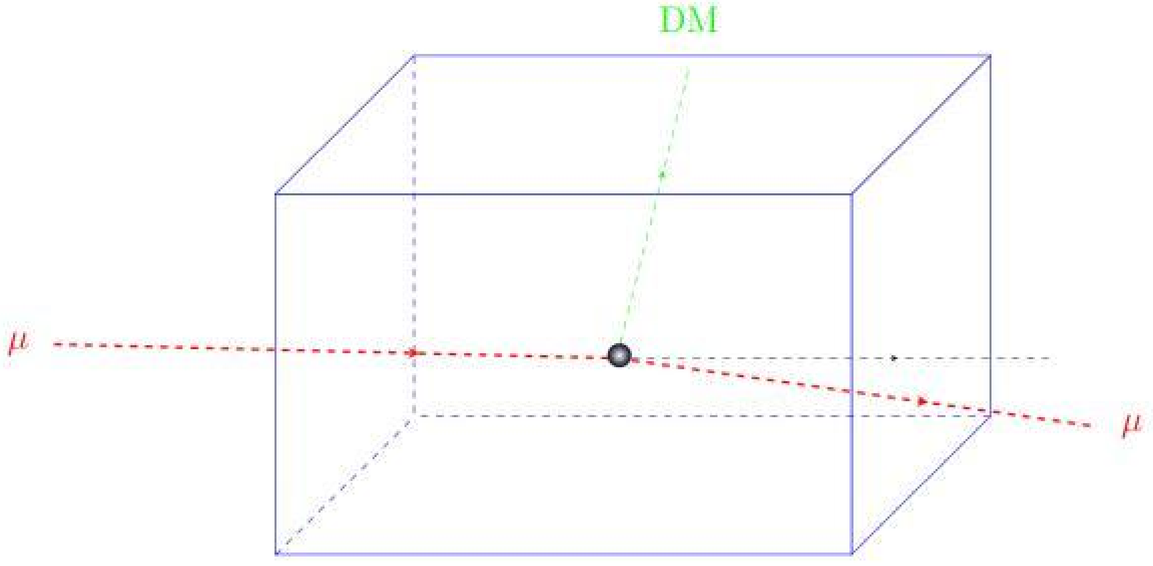


Figure 1. Dark bremsstrahlung signal process for simplified models with invisibly decaying scalar (*left*) and vector (*right*) forces that couple predominantly to muons. In both cases, a relativistic muon beam is incident on a fixed target and scatters coherently off a nucleus to produce the new particle as initial- or final-state radiation.

Phase I: Muon Tomography for Muon-DM scattering



Notice for high speed muons, it is appropriate to treat DM as frozen in the detector volume (V), and the estimated rate per second could be:

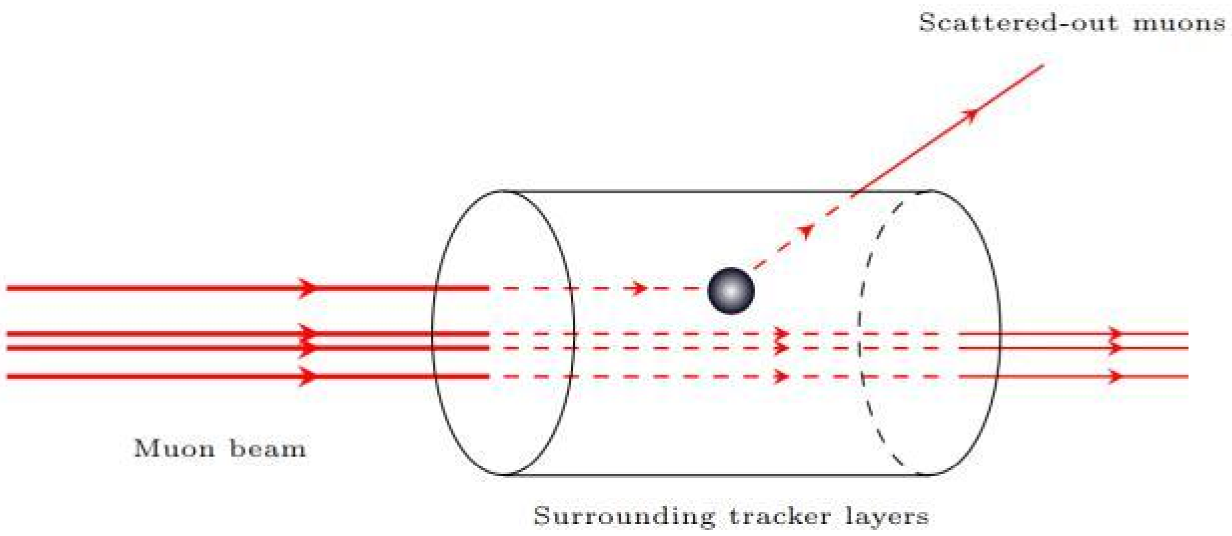
$$\rho V/\mathrm{M_D} \times \sigma_D \times F_\mu,$$

The local density of DM is at the order of $\rho \sim 0.3$ GeV/cm^3 and with a typical velocity of $v = 300$ km/s. While F_μ is the muon flux $\sim 1/60/\mathrm{s}/\mathrm{cm}^2$ at the sea level. For Dark Matter mass $M_D \sim 0.1$ GeV, and detector box volume as $V \sim 1\,\mathrm{m}^3$. Thus the sensitivity on Dark Matter Muon scattering cross section for 1 year run will be around

$$\boxed{\sigma_D \sim 10^{-12}\mathrm{cm}^2}$$

One year

Phase II: Muon Beam scattered with DM



For $M_D = 0.03\,\mathrm{GeV}$, $L = 1\,\mathrm{m}$, and $N_\mu \sim 10^6/\mathrm{s}$ (e.g., CSNS Melody design), and one year 10^7s.

$$N = 10^{13} \times \sigma_D \times 100/\mathrm{cm}^2,$$

Thus the sensitivity on Dark Matter Muon scattering cross section for 1 year run will be around

The estimated rate per second:

$$dN/dt = N_\mu \times \sigma_D \times L \times \rho/\mathrm{M_D},$$

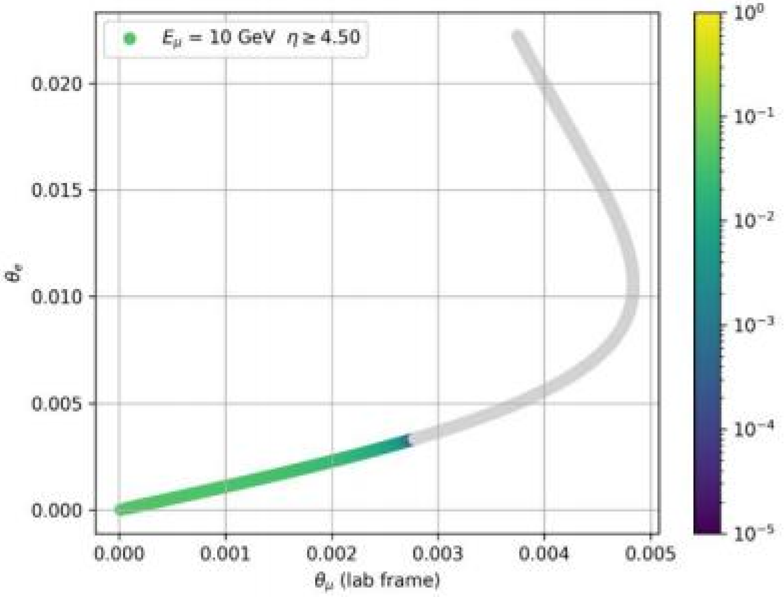
$$\boxed{\sigma_D \sim 10^{-15}\mathrm{cm}^2}$$

One year

Notice the surrounding area is around 100 cubic centimeters.

Z’ and X at PKMu@HFRS

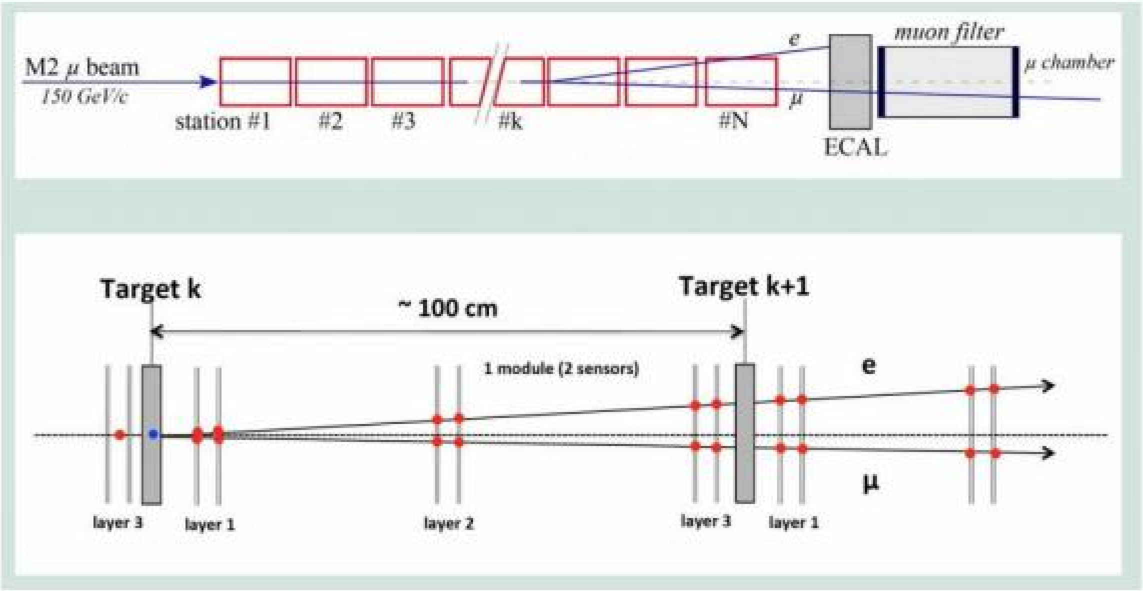
- **1-10 GeV muon scattered on electrons in target:**
  - C.O.M energy is around 10 MeV!
  - Sensitive to $L\mu - L\tau$ Z’ boson at around 1-100 MeV:
    - $\mu e \rightarrow \mu e Z'$, $Z' \rightarrow \nu\bar{\nu}$
  - Also matches the mass range for ATOMKI X17 MeV anomaly
    - $\mu e \rightarrow \mu e X$, $X \rightarrow \nu\bar{\nu}$, $e^+ e^-$;
    - Search for pseudoscalar bosons decaying into e+e− pairs in the NA64 experiment at the CERN SPS: <u>*PRD* 104 (2021) 11, L111102</u> $e\text{-}N \rightarrow e\text{-}N + a$, $a \rightarrow e^+ e^-$
    - See also tensor and scalar options in <u>arXiv:2501.05507</u>
      - *“the measurements from the two experiments (ATOMKI and MEGII) remain compatible within 2σ” and “A CP-even scalar could serve as potential solution to the anomalies observed in the Helium and Carbon data and that will become relevant in case the null result from the MEG-II search in Beryllium transitions will be confirmed.”*

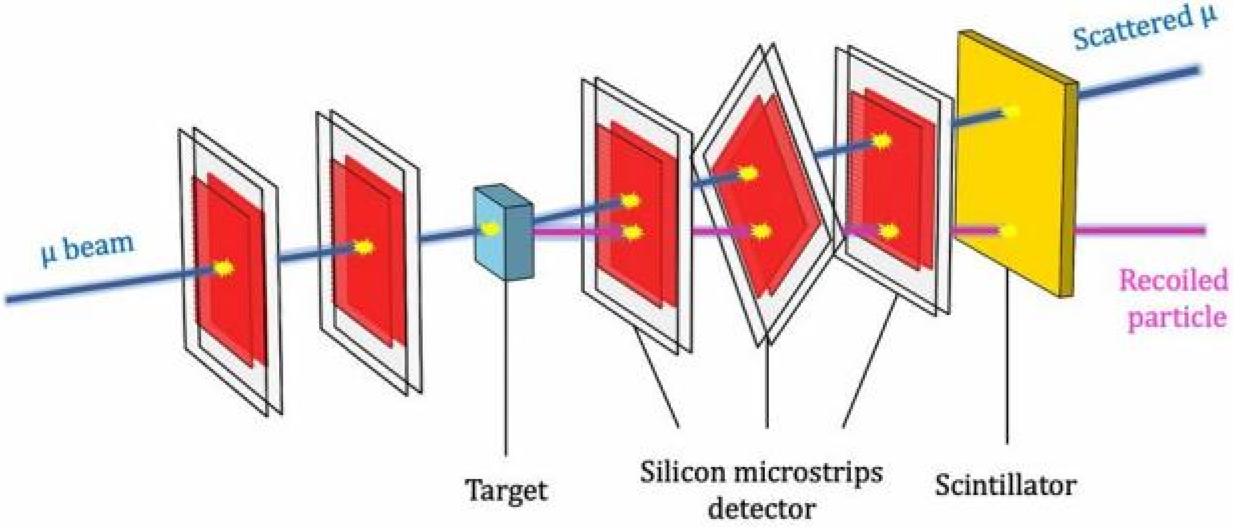


arXiv:2411.12518

PKMu@HFRS vs. MuonE

- Muon Beam energy: 150 GeV vs. 1-10 GeV
- C.O.M energy for PKMu@HFRS is around 10 MeV
  - suitable for low mass searches
- Detector Can be more compact

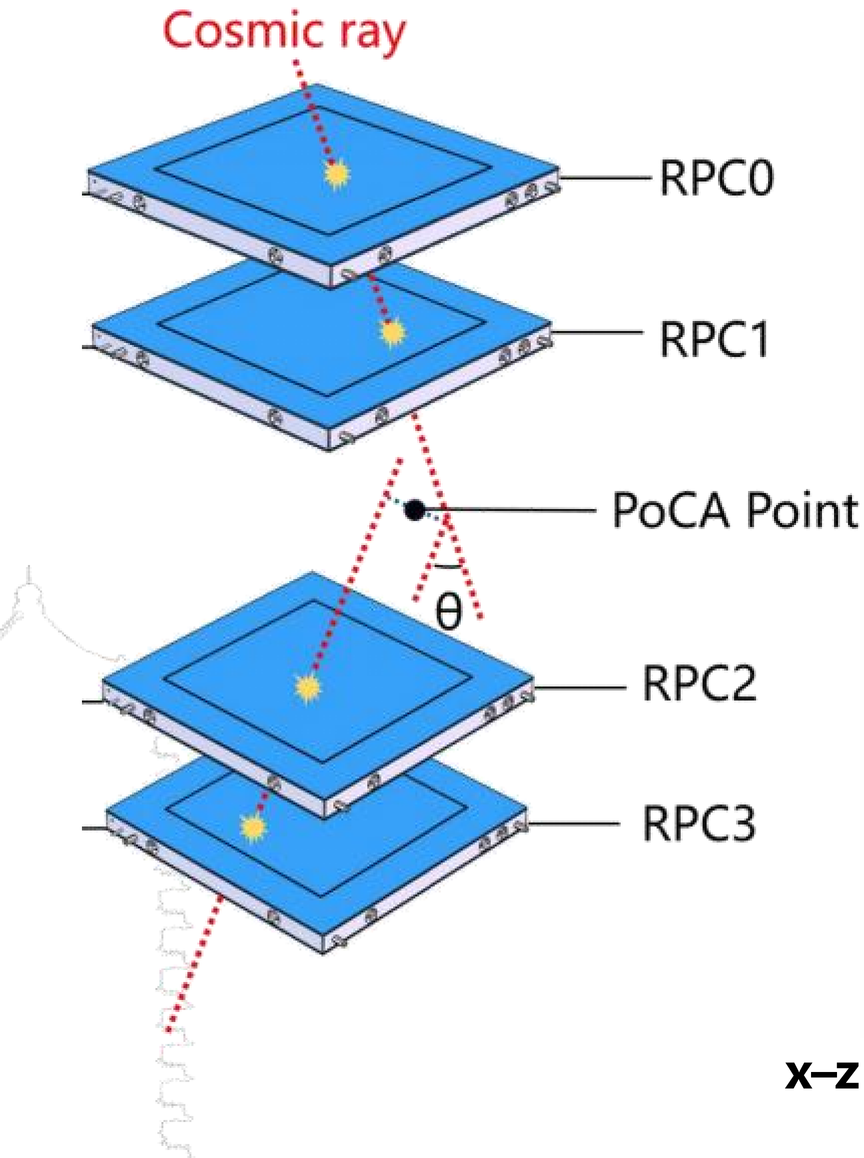


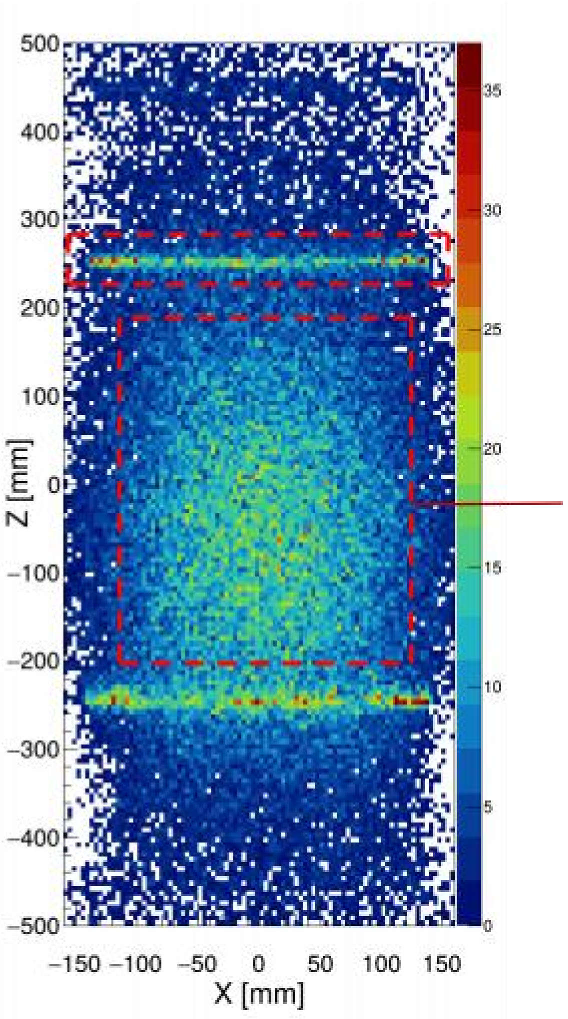


NA64 has limited angle acceptance (the beam energy is high as 150GeV), that may be the reason it is not sensitive to Mx>16 MeV

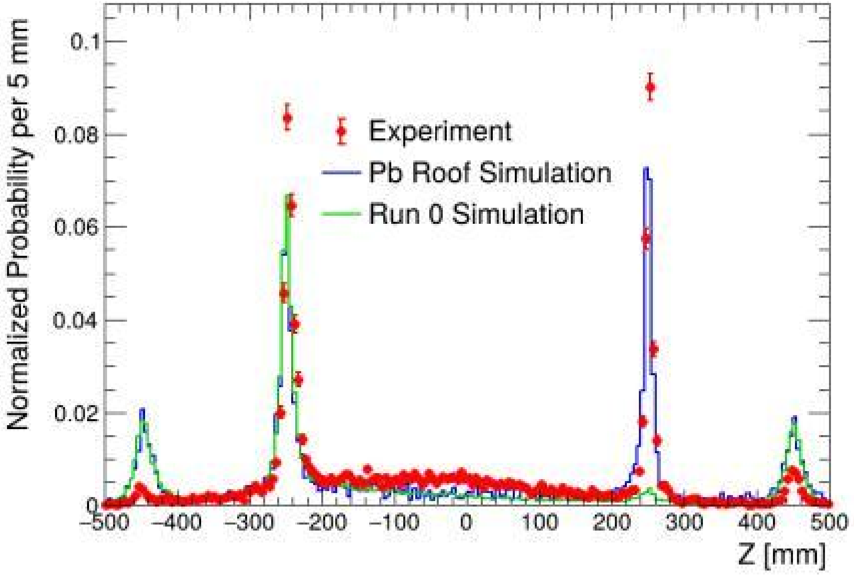
Noise Becomes Signal: Secondary Particle Signatures in Muography

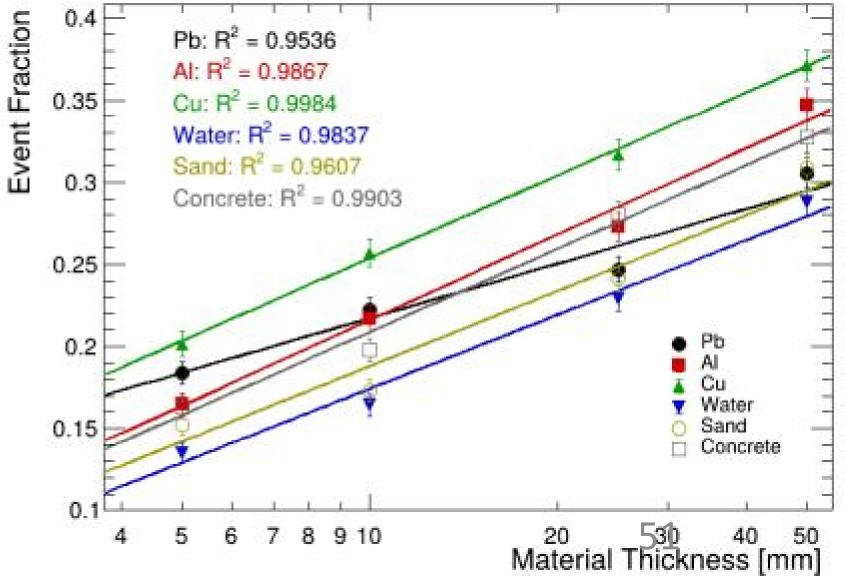
J. Appl. Phys. 139, 014903 (2026)





x–z distribution of PoCA points





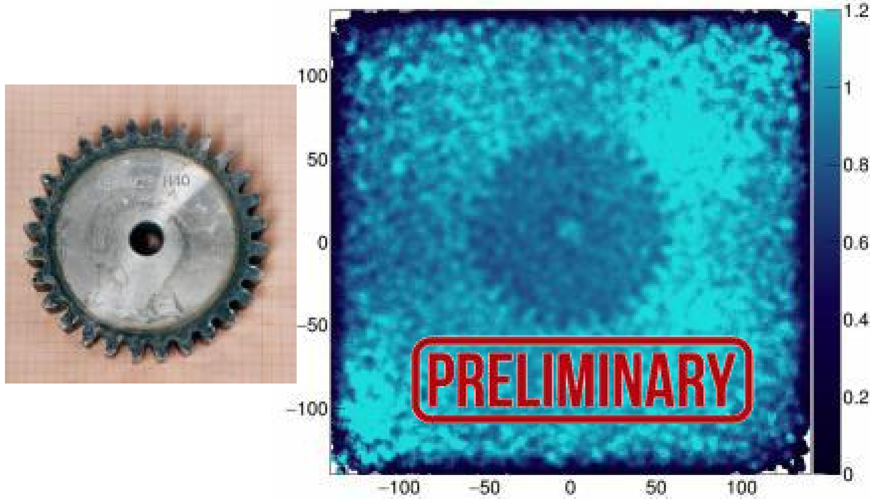
PμMA: Millimeter-Resolution cosmic muon Imaging

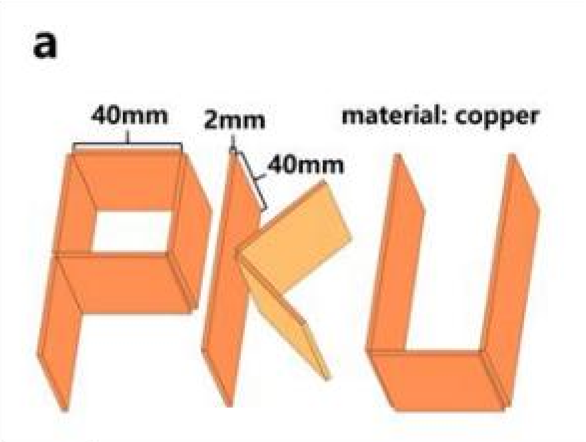
arXiv:2512.19747 (2026)

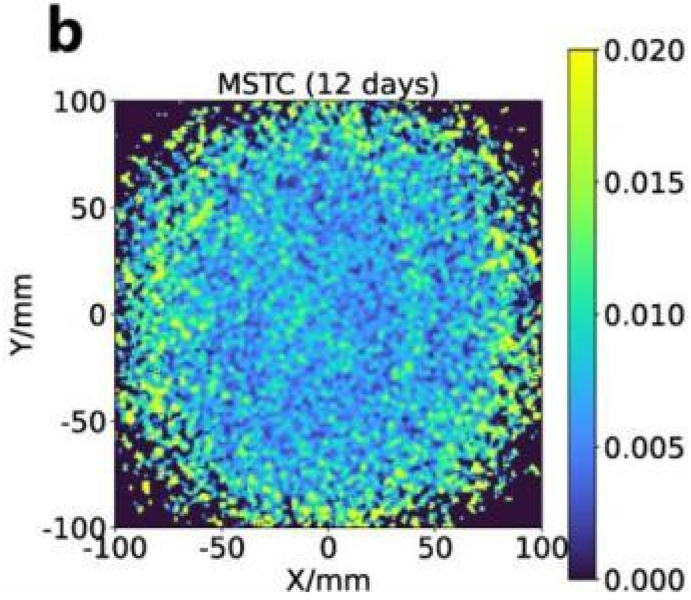
Problem: PoCA-based MST has limited spatial resolution for millimeter-scale objects.

Solution: Projection-shifted Muon Transmission Tomography (PμMA) reconstructs tracks by linking upstream and downstream hits, projecting scattering-induced deflection as a measurable shift on an imaging plane. This enables millimeter-scale resolution using only two detectors.

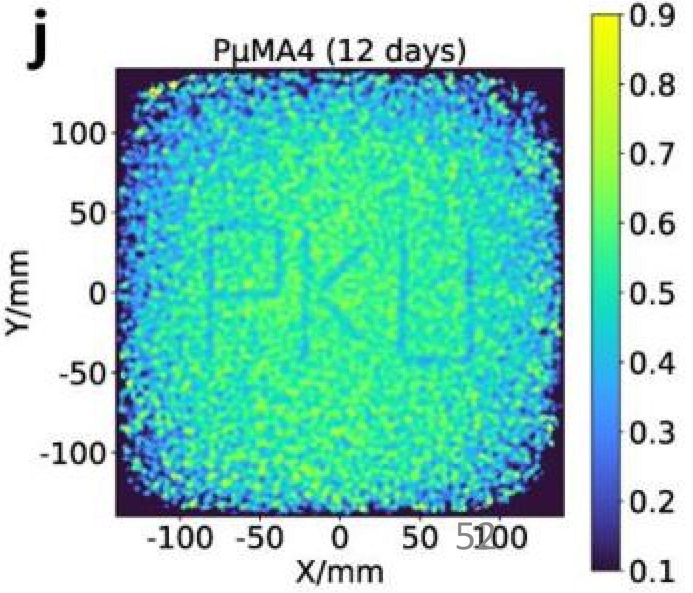
PμMA image of a gear

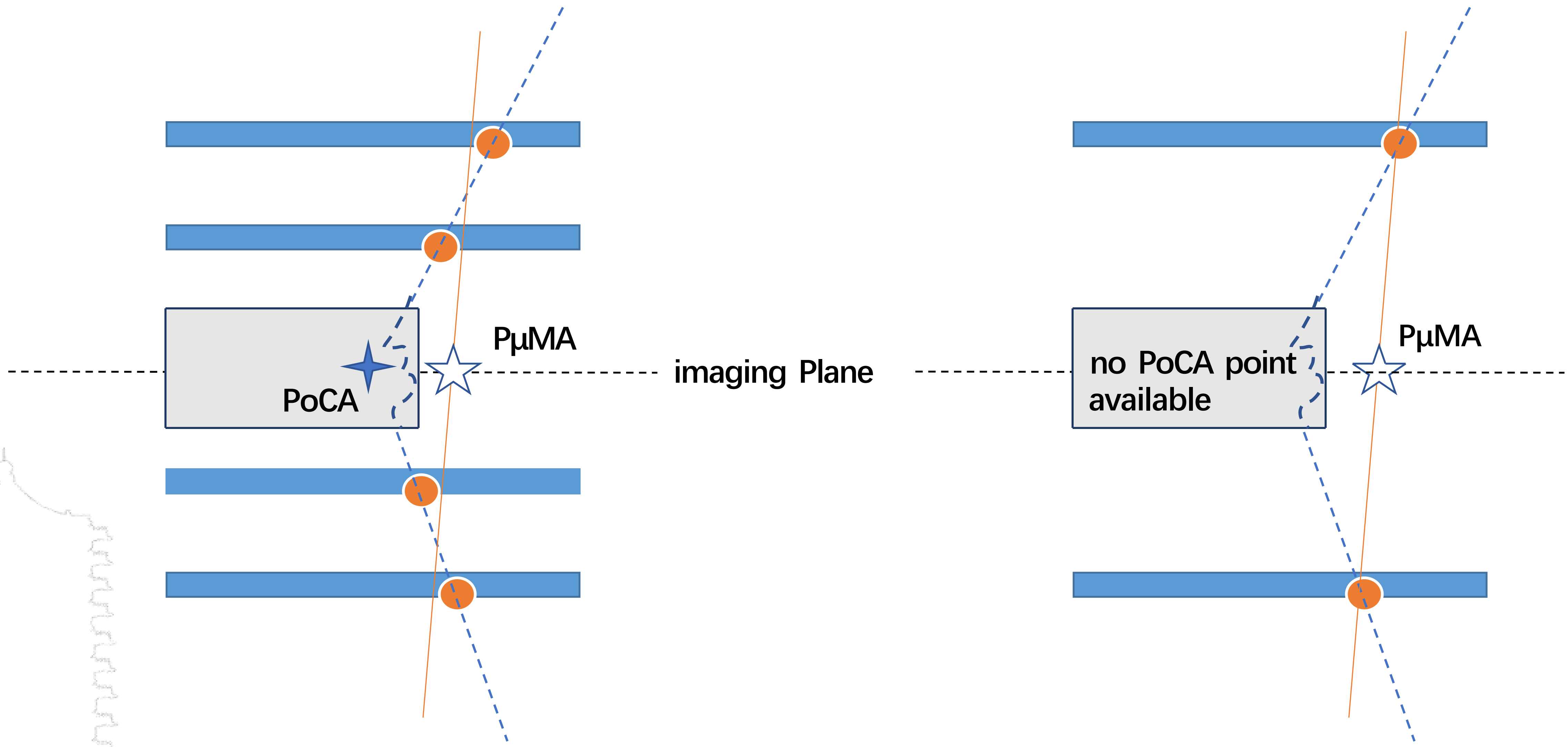


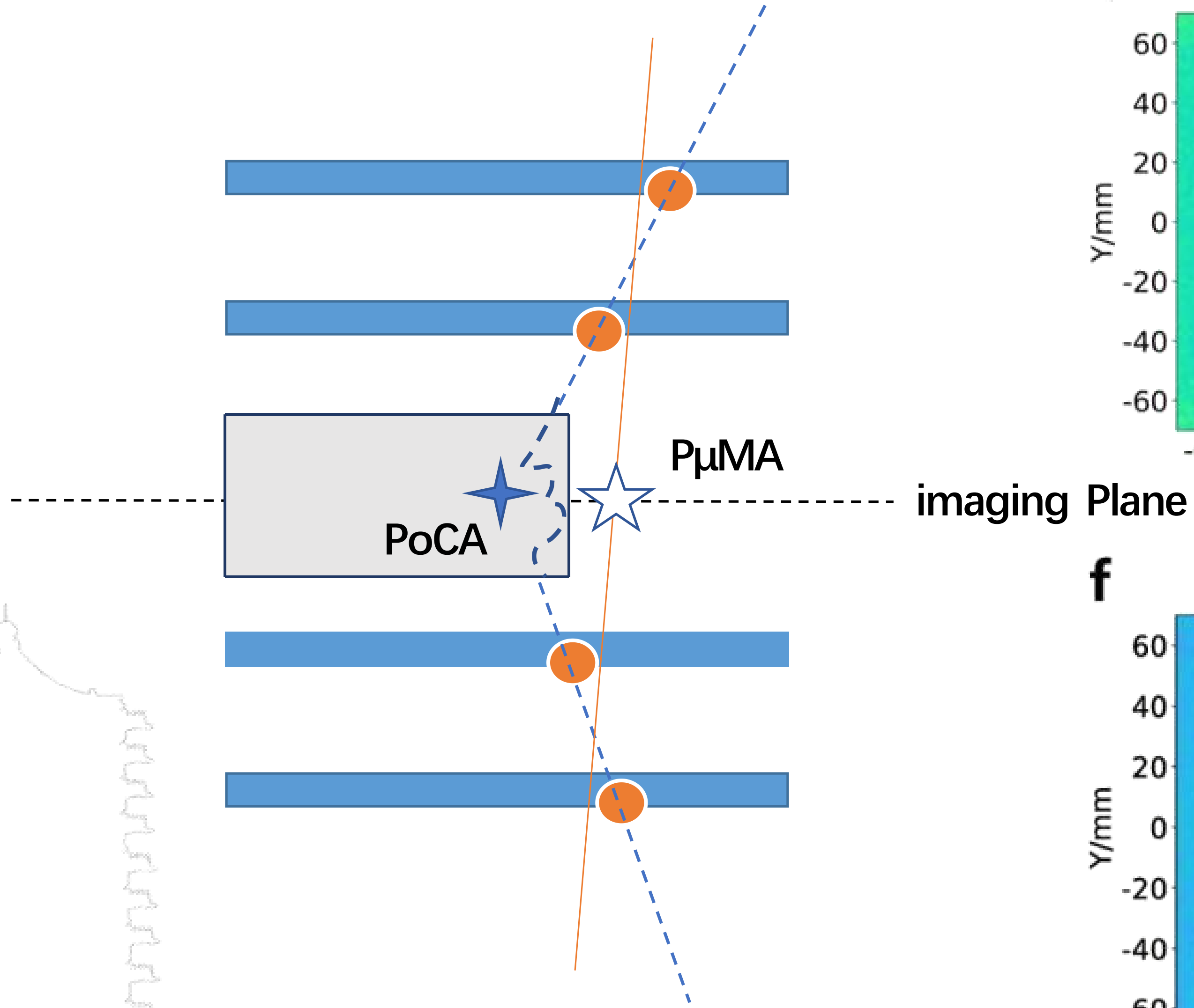




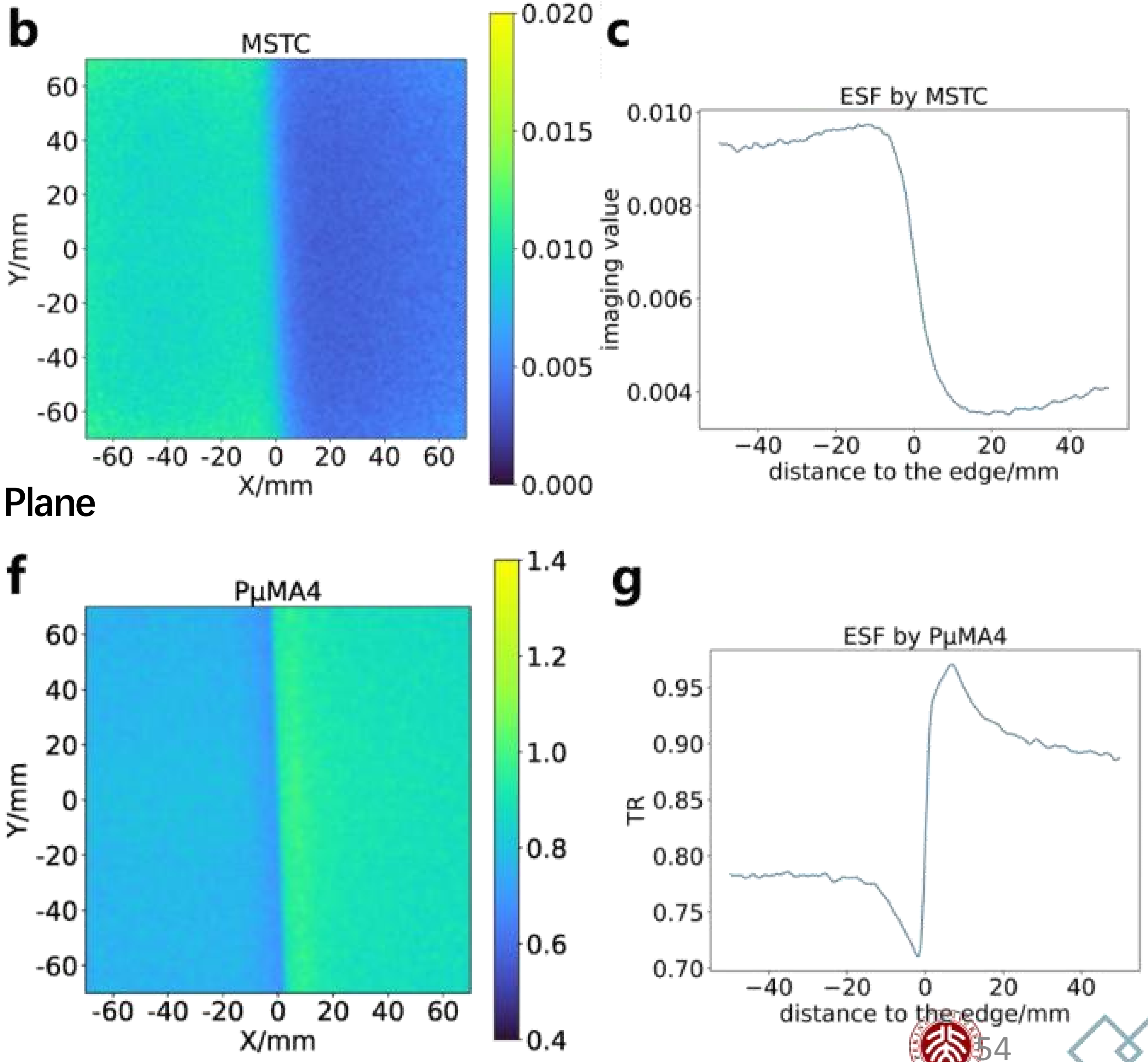
PμMA




PμMA
PoCA
imaging Plane
PμMA
no PoCA point available



PμMA
PoCA
imaging Plane



b
MSTC
Y/mm
X/mm
c
ESF by MSTC
imaging value
distance to the edge/mm
f
PμMA4
Y/mm
X/mm
g
ESF by PμMA4
TR
distance to the edge/mm

A 4 GeV muon-beam scattering experiment is well suited to probe a Z′ with mass ~10 MeV, as predicted in models such as Lμ−Lτ and X17. The multi-station detector geometry of MUonE further enhances sensitivity to these signals.

PHYSICAL REVIEW D **113,** 072008 (2026)

Search for light dark sectors with GeV muon beams

Zijian Wang,* Leyun Gao, Zhuo Chen, Cheng-en Liu, Jinning Li, Qite Li, Chen Zhou, and Qiang Li
School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, 100871, China

Yu Xu, Xueheng Zhang, Liangwen Chen, and Zhiyu Sun
Institute of Modern Physics, Chinese Academy of Science, Lanzhou, 730000, China and University of Chinese Academy of Sciences, Beijing, 100049, China

Ce Zhang†
University of Liverpool, Liverpool, L69 7ZX, United Kingdom

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Sub-GeV light dark matter often requires new light mediators, such as a dark Z boson in the $L_\mu - L_\tau$ gauge theory. We study the search potential for such a Z' boson via the process $\mu e^- \to \mu e^- X$, with X decaying invisibly, in a muon on-target experiment using a high-intensity 1–10 GeV muon beam from facilities such as HIAF-HIRIBL. Events are identified by the scattered muon and electron from the target using the silicon strip detectors in a single-station telescope system. Backgrounds are suppressed through a trained boosted decision tree classifier, and activity in downstream subdetectors remains low. We find that this approach can probe a Z' in the 10 MeV mass range with improved sensitivity.

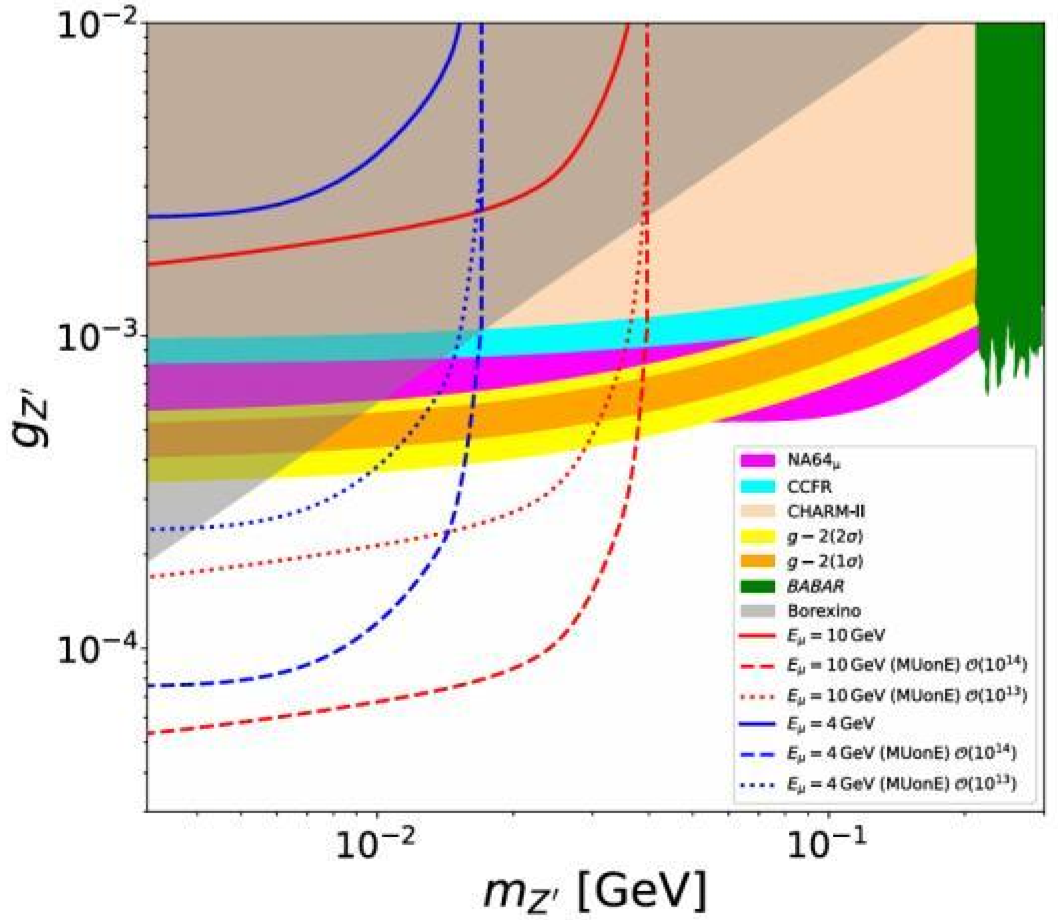

FIG. 7. Upper limits on the coupling $g_{Z'}$ as a function of the Z' mass $m_{Z'}$. The solid red and blue lines represent the limits obtained for muon beam energies of 10 and 4 GeV, respectively, using the HIAF setup, assuming one year of data taking. The shaded regions in light brown, light blue, purple, green, and gray are excluded by CHARM-II [32], CCFR [33], NA64$_\mu$ [13], *BABAR* [34], and Borexino [35], respectively. The orange and yellow bands show the regions favored by the muon $g-2$ anomaly at the 1σ and 2σ levels, respectively [36–44].