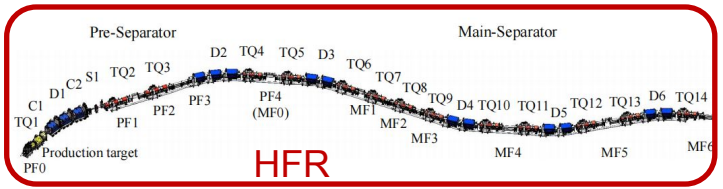
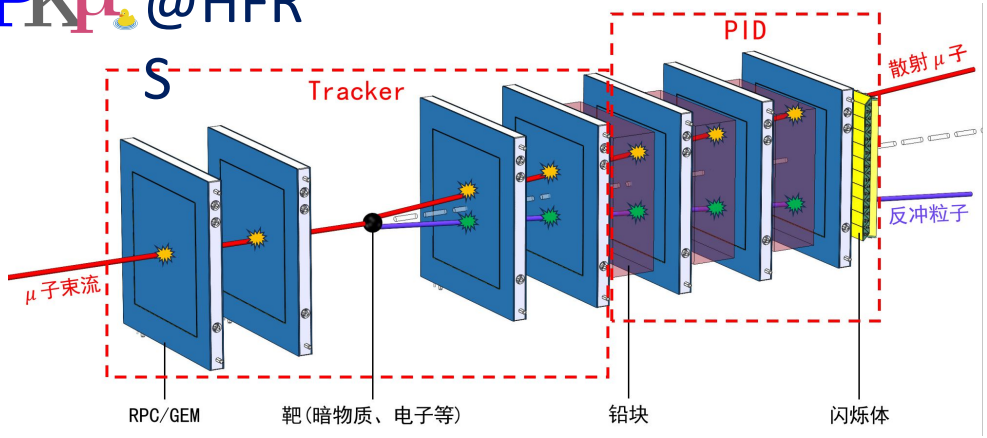
基于HIAF-HFRS装置的缪子散射实验

PKMu(Probing and Knocking with Muons)：由**北京大学**物理学院技术物理系、核物理与核技术全国重点实验室原创提出的的缪子散射实验合作项目，旨在结合缪子散射成像技术与前沿物理研究，通过对缪子散射的测量研究核物理、标准模型和超出标准模型的新物理，如暗物质和暗玻色子探寻、量子纠缠探测、缪子与核散射规律的研究等。

HFRS：**中国科学院近代物理研究所**建设的强流重离子加速器(HIAF)可加速从质子到铀的重离子，可提供高达 10^{11}/s 的高能离子束流。放射性次级束流分离器(HFRS)是 HIAF 上的重要装置，HFRS 束线长 192 米，磁刚度最大 25 Tm，可传输动量高达 7.5 GeV/c 的π/μ粒子。研究表明，基于HIAF-HFRS装置，可获得流强可达 10^6–10^7/s 的GeV能量缪子束流，动量展宽约 4%，束斑直径约 10 cm。



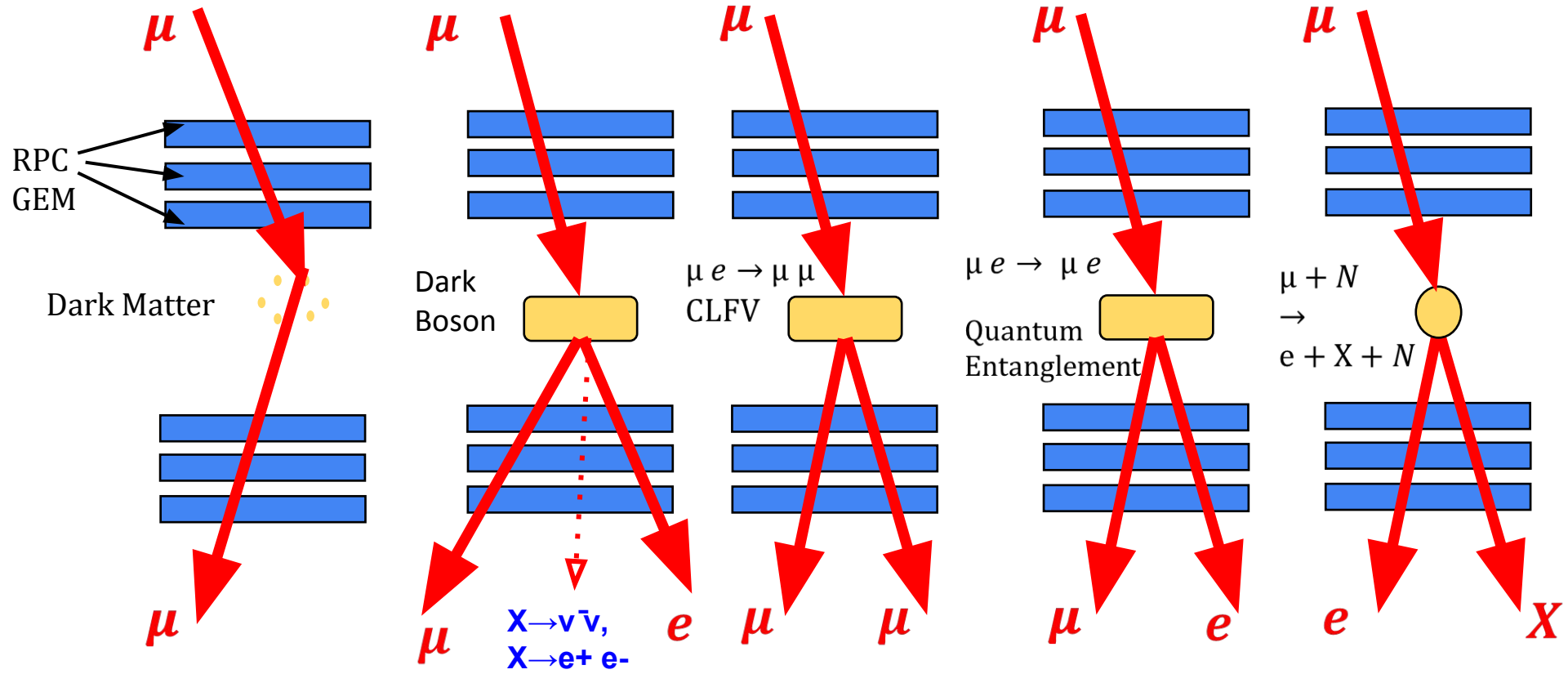
PKμ@HFRS



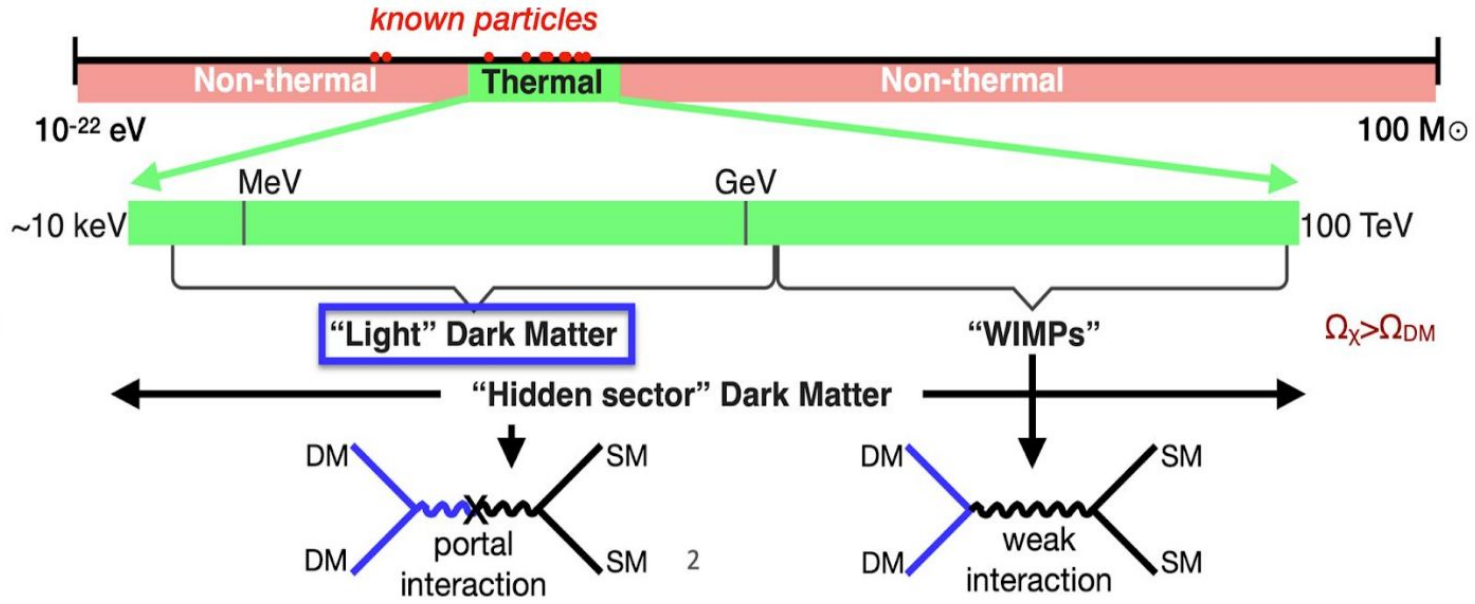
参考文献：[1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

Microscope: multi-purpose platform

→Cosmic μ or μ beam



Light Dark Matter → Dark Sector

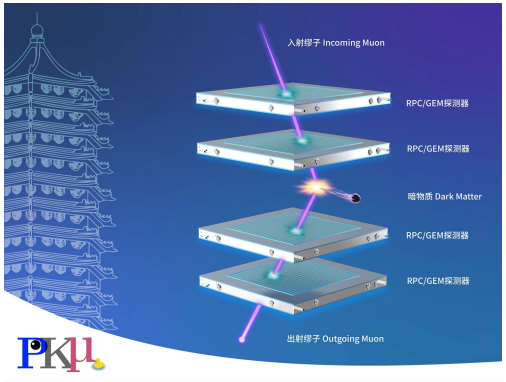


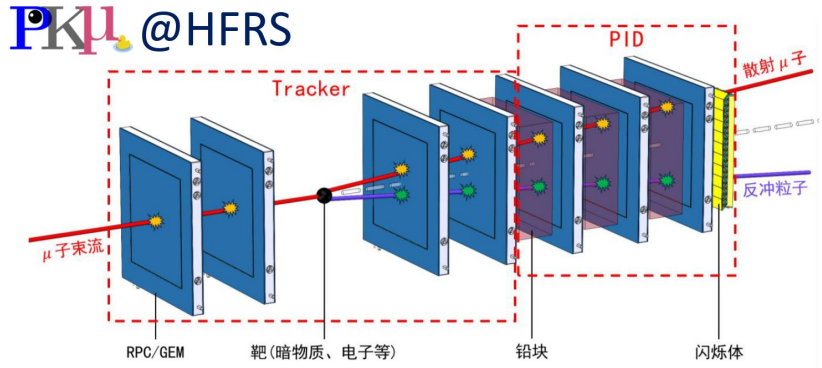
Minimal scenarios with light (sub-GeV) dark matter whose relic density is obtained from thermal freeze-out must include new light mediators. In particular, a very well-motivated case is that of a new "dark" massive vector gauge boson mediator. JHEP03(2018)084 Granada19 LDMX2024

(获得热遗留下来的轻(次GeV)暗物质的最低限度情景必须包含新的轻媒介粒子。特别是，一个非常有动机的情况是存在一种新的'暗"质量矢量规范玻色子作为媒介粒子。)

Muon Philic Dark Sector

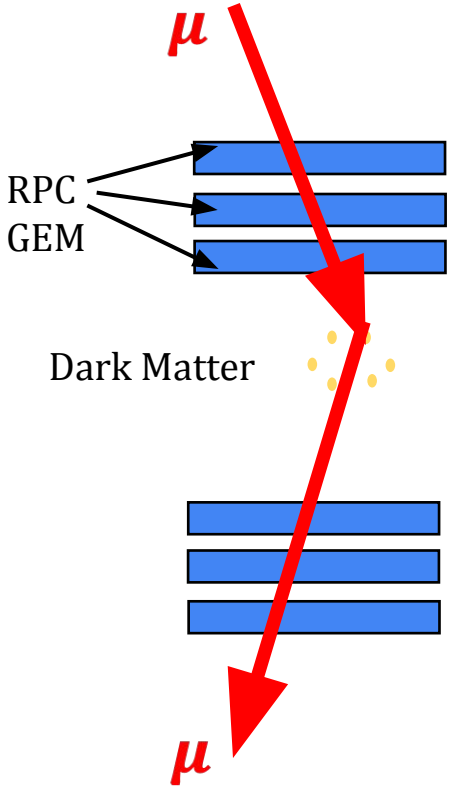
- Muon Philic Dark Matter may be possible or even necessary!
  - $L\mu - L\tau$ gauged model (Z', χ) quite popular recently
  - 1) Direct searches for DM
    - See the PKMu proposal: *Phys.Rev.D* 110 (2024) 1, 016017
  - 2) On target experiments for Dark Boson: (see also cosmology constraints)
    - LDMX,DarkShine; eN → eNZ', Z'→νν̄ or Z'→χχ (dark matter)
    - NA64μ, MMM μN → μNZ', Z'→νν̄ or Z'→χχ (dark matter)
    - MuonE μe → μeZ', Z'→νν̄ or Z'→χχ (dark matter)

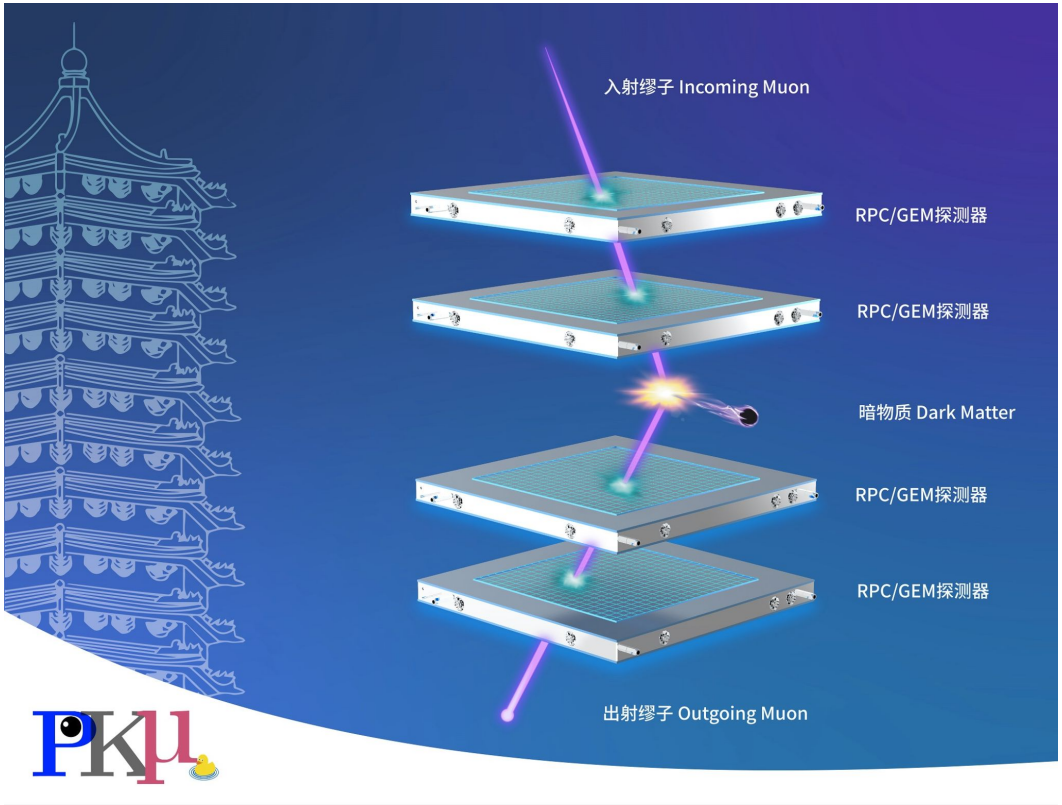




参考文献：[1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

1) Direct searches for DM

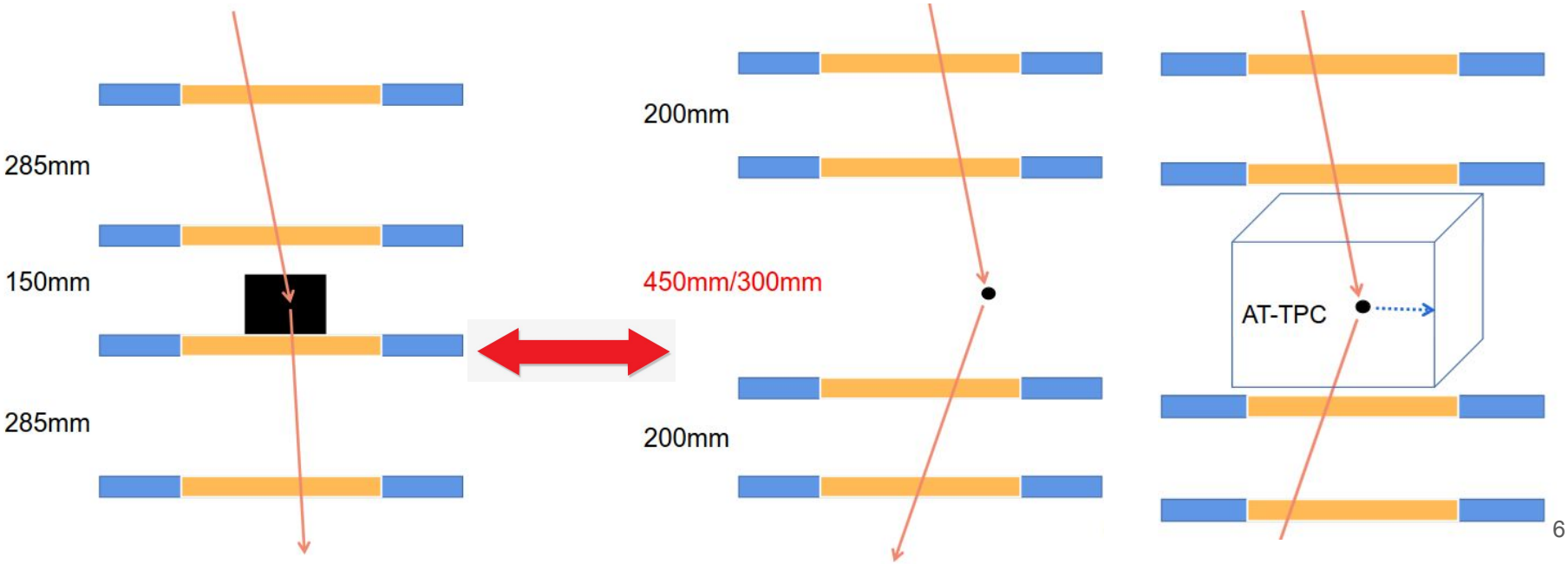




Muon Tomography and Muon-DM scattering

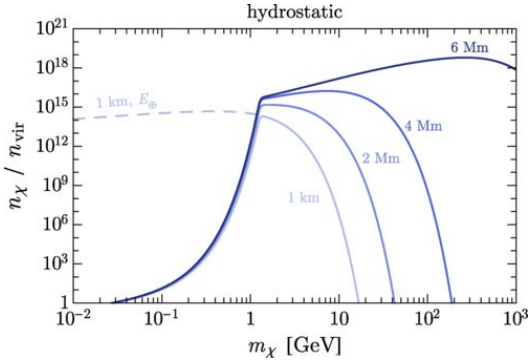
Muon Tomography 缪子成像 ⟷ Dark Matter Search 暗物质寻找

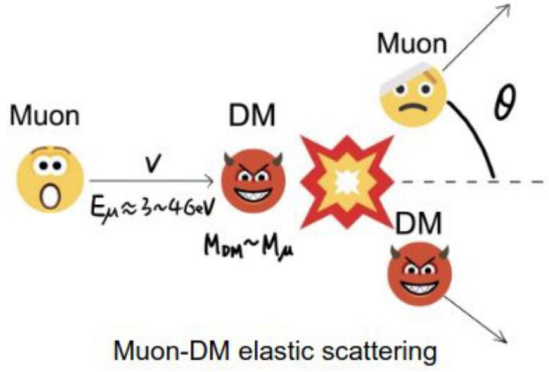
Phys.Rev.D 110 (2024) 1, 016017



Slow Dark matter

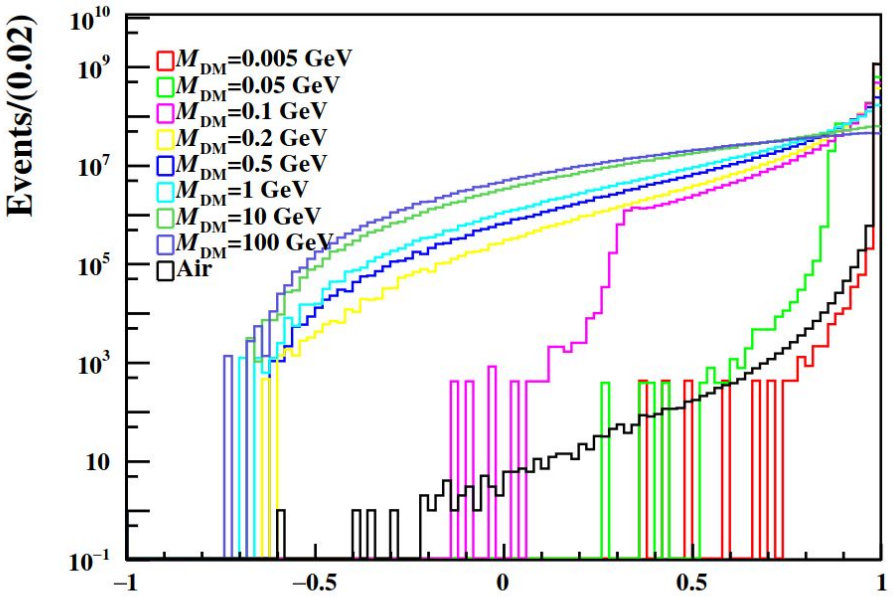
- Earth bounded Dark Matter: terrestrial density of strongly-coupled relics
  PRL. 131 (2023), 011005, PRD 109 (2024), 075027 PRD 103, 115031 (2021)
  - A fraction (fD) of strongly interacting dark matter
  - can be trapped in the Earth, and distributed more uniformly.
  - The density (fE) can be large! **fE=fD×nD** ~ fD*10^15/cm^3
- Alternative detection techniques needed
  - to detect such a large density of slowly moving DM
  - Superconducting Cloud Chamber (for Milli-charged Particle though)
- **For slow or frozen DM, no proposal yet!**
  - → **limits on both cross section and fE=fD×nD**

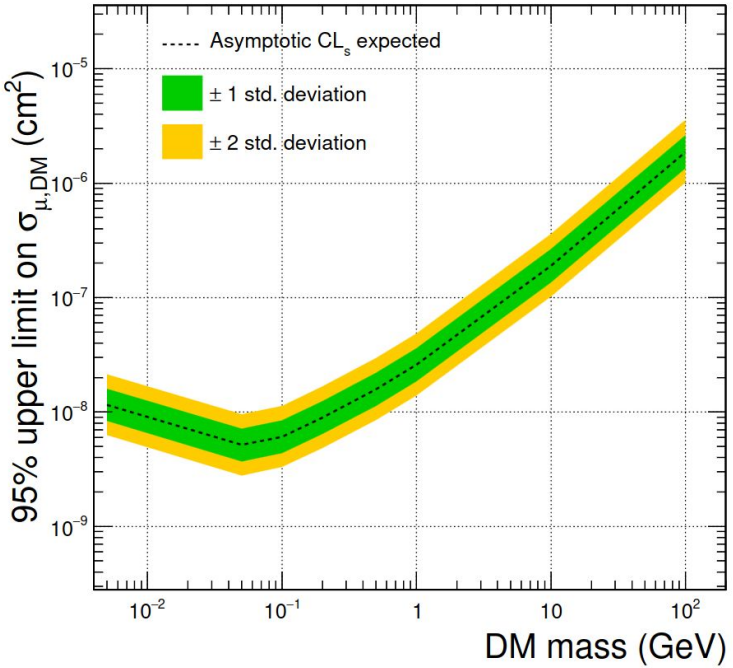




Different from XENON/PandaX:
Relativistic muon hit quasi-static DM

Muon DM Box experiment: expected results

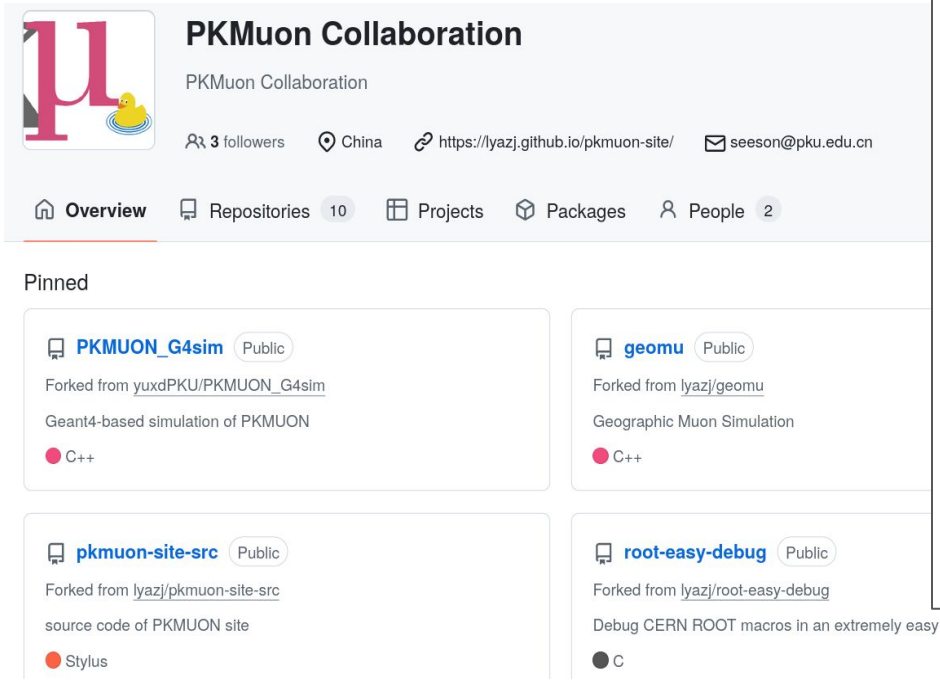


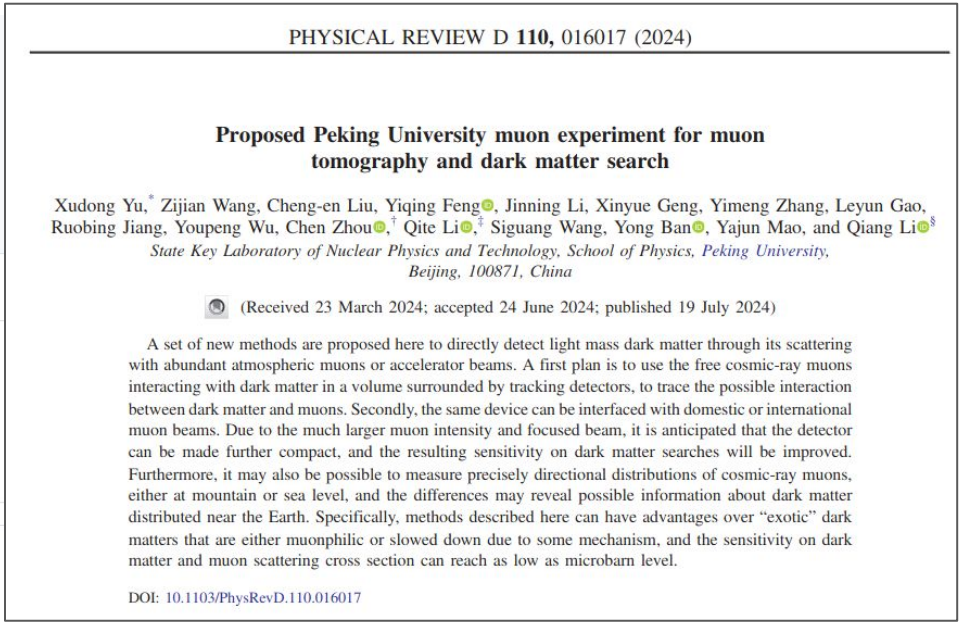


- "Asimov" data is used
- Binned maximum likelihood fits
- UL determined by CLs method
- Only take statistical uncertainty into consideration

In the exotic DM scenario as mentioned previously, the limit can approach μb

Current Software and Simulation Status





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)

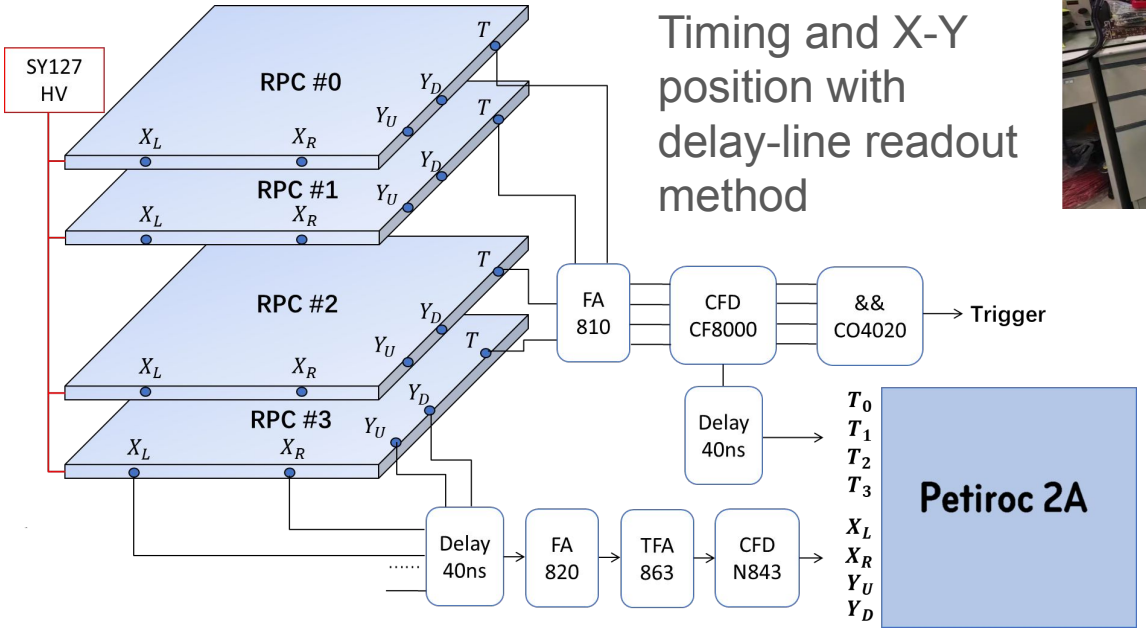
A set of new methods are proposed here to directly detect light mass dark matter through its scattering with abundant atmospheric muons or accelerator beams. A first plan is to use the free cosmic-ray muons interacting with dark matter in a volume surrounded by tracking detectors, to trace the possible interaction between dark matter and muons. Secondly, the same device can be interfaced with domestic or international muon beams. Due to the much larger muon intensity and focused beam, it is anticipated that the detector can be made further compact, and the resulting sensitivity on dark matter searches will be improved. Furthermore, it may also be possible to measure precisely directional distributions of cosmic-ray muons, either at mountain or sea level, and the differences may reveal possible information about dark matter distributed near the Earth. Specifically, methods described here can have advantages over "exotic" dark matters that are either muonphilic or slowed down due to some mechanism, and the sensitivity on dark matter and muon scattering cross section can reach as low as microbarn level.

DOI: 10.1103/PhysRevD.110.016017

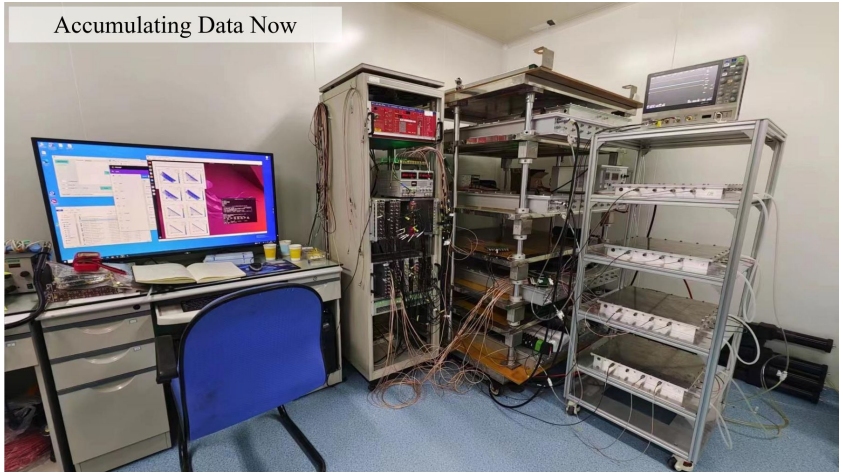
Current Box Exp. Status

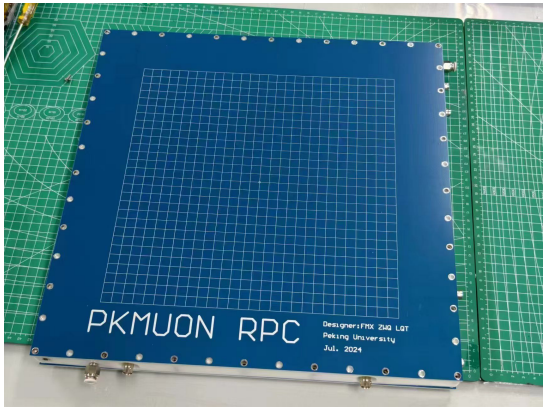
4-station 20cm*20cm RPC for the moment

Petiroc 2A is a 32-channel front-end ASIC

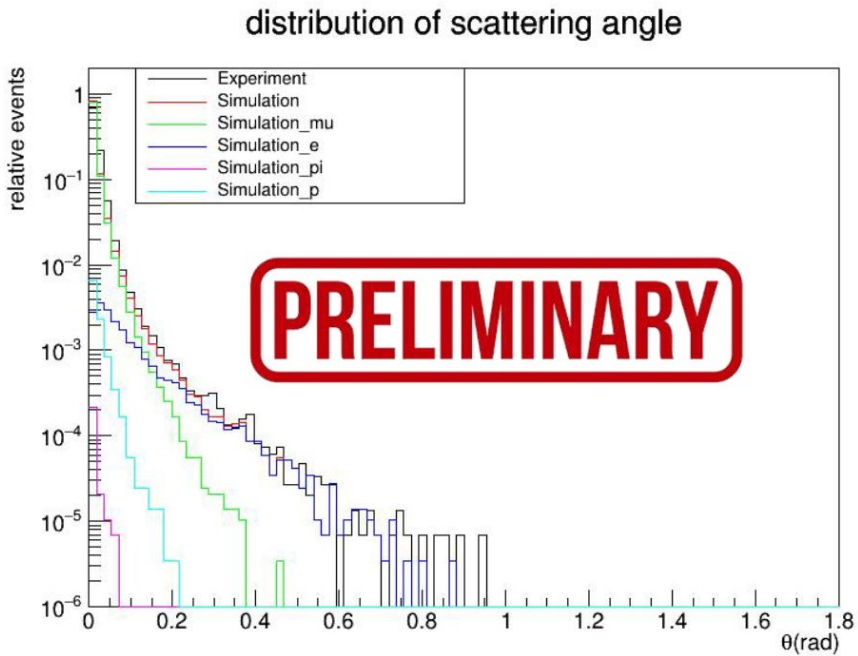


Timing and X-Y position with delay-line readout method





- 3+ months data taking since Jan. 2024
- 有效事件147251，θ>0.2rad事件占比0.37%
- 平均散射角0.0193rad
- 对海平面上次级宇宙线粒子成分进行模拟：μ, e, pi, p
- 小角度主要为缪子，大角度主要为高能电子（物理过程检查中）
- 部分理解了大角度散射的来源
- 为改善缪子探寻暗物质的探测下限，需进行对高能电子的本底事件排除

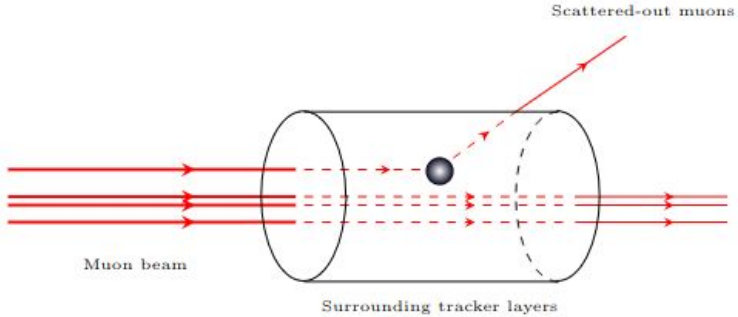


Stay Tuned!

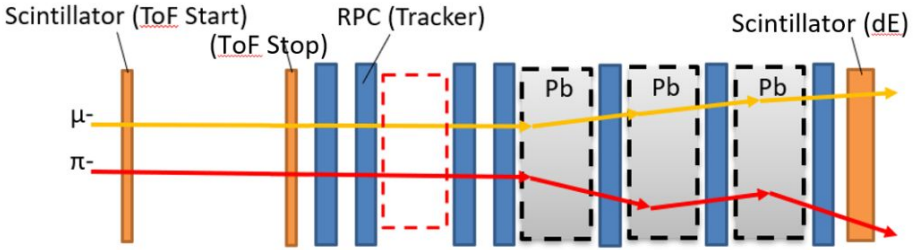
More results in a recent report from Cheng-en Liu and Qite Li

Current Beam Exp. Status

Interfacing with a muon beam at e.g. HIAF



Cylindrical GEM (CGEM) detector structure for BESIII inner tracker system upgrade



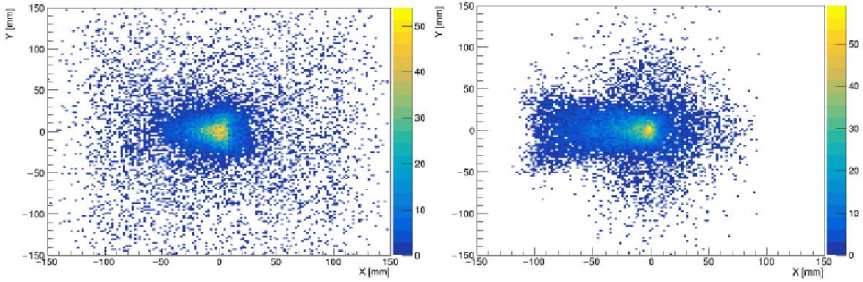


图 6.9: 左：1GeV 缪子束流束斑轮廓。右：3GeV 的缪子束流的束斑轮廓

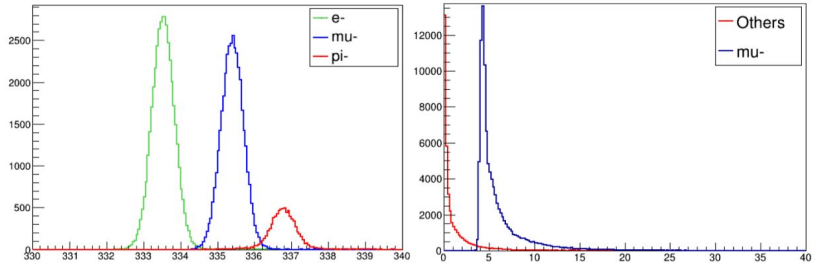
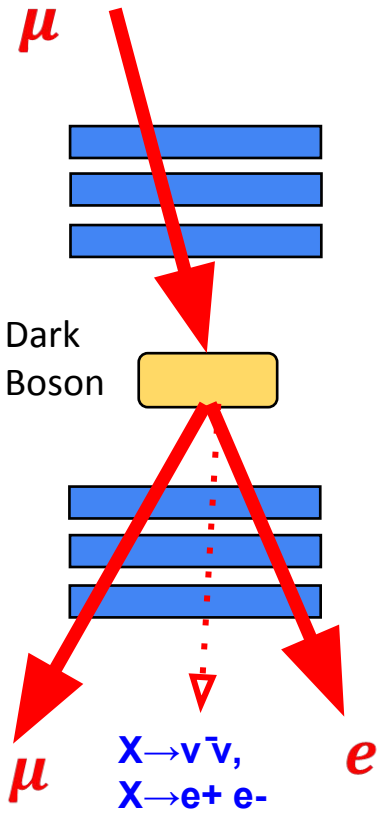
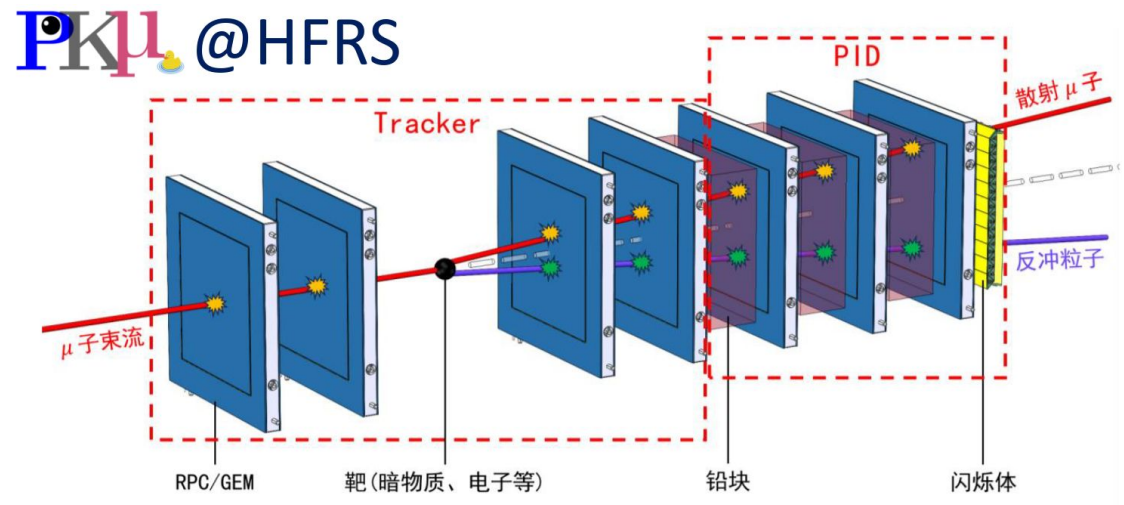


图 6.13: 缪子散射探测系统信号与背景响应模拟：成像系统前飞行时间谱（左）；末端闪烁体能量损失谱（右）

2) On target experiments for Dark Boson



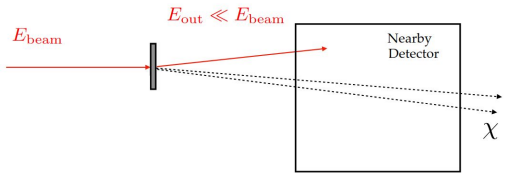


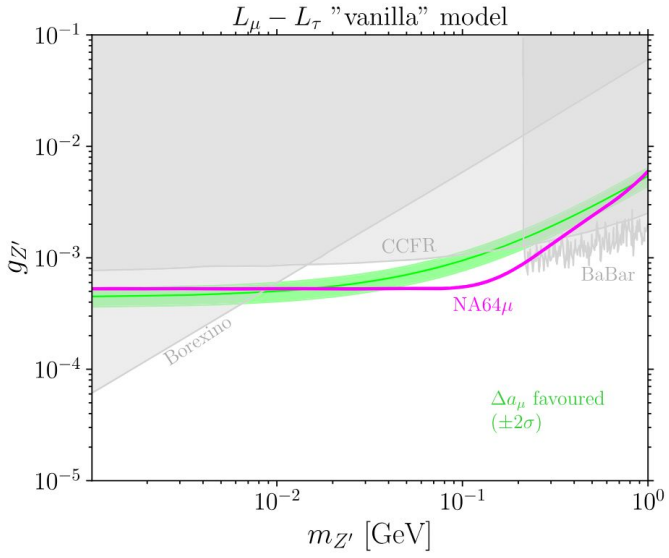
参考文献: [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

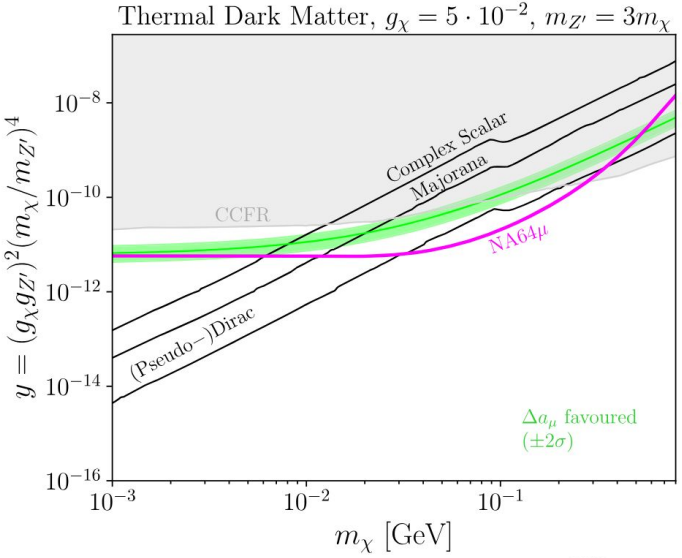
NA64μ recent results

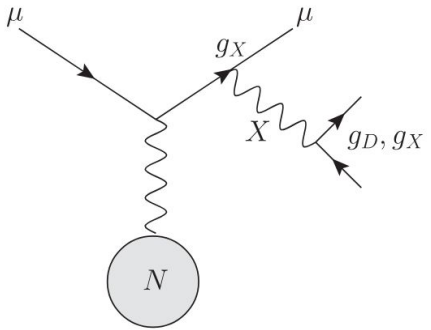
$$\mathcal{L} \supset -\frac{1}{4} F'_{\alpha\beta} F^{\alpha\beta\prime} + \frac{m_{Z'}^2}{2} Z'_\alpha Z^{\alpha\prime} - g_{Z'} Z'_\alpha J^\alpha_{\mu-\tau},$$

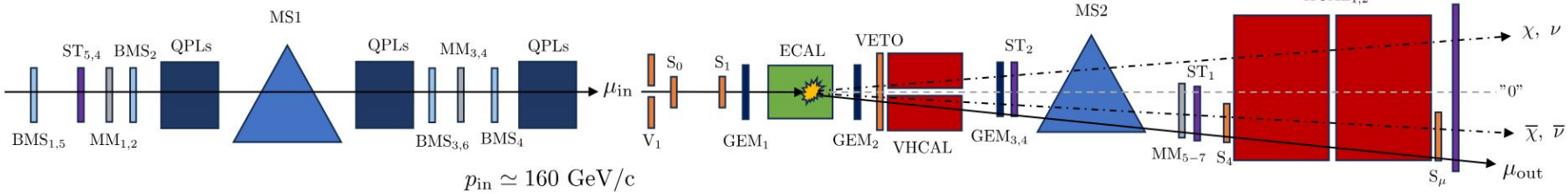
$$-g_\chi Z'_\alpha J^\alpha_\chi,$$





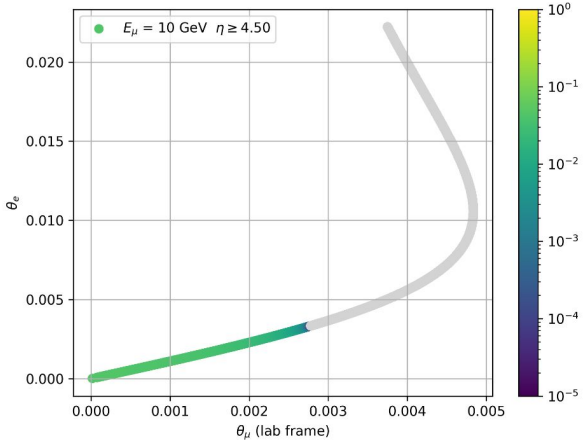






Z' and X at PKMu@HFRS

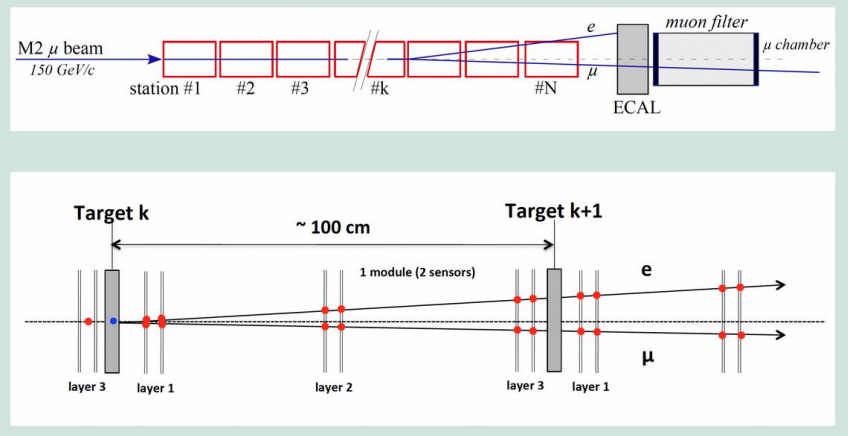
- **1-10 GeV muon scattered on electrons in target:**
  - C.O.M energy is around 10 MeV!
  - Sensitive to $L\mu - L\tau$ Z' boson at around 1-100 MeV:
    - μe → μeZ', Z'→ν ν̄
  - Also matches the mass range for ATOMKI X17 MeV anomaly
    - μe → μeX, X→ ν ν̄, e+ e-;
    - Search for pseudoscalar bosons decaying into e+e− pairs in the NA64 experiment at the CERN SPS: *PRD* 104 (2021) 11, L111102 e-N→e-N + a, a → e+ e-
    - See also tensor and scalar options in arXiv:2501.05507
      - *"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."*

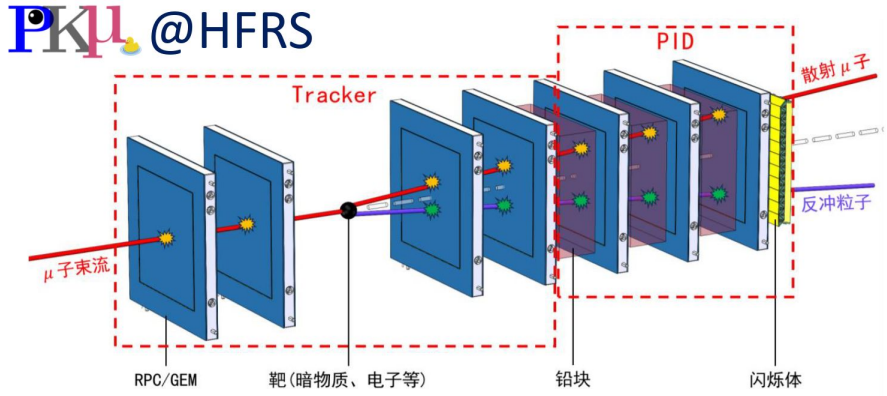


arXiv:2411.12518

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

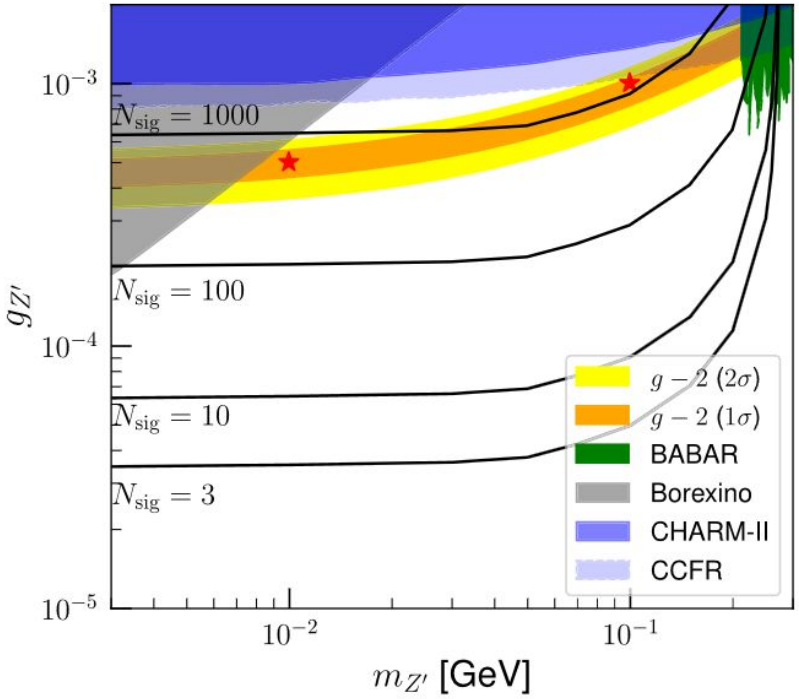


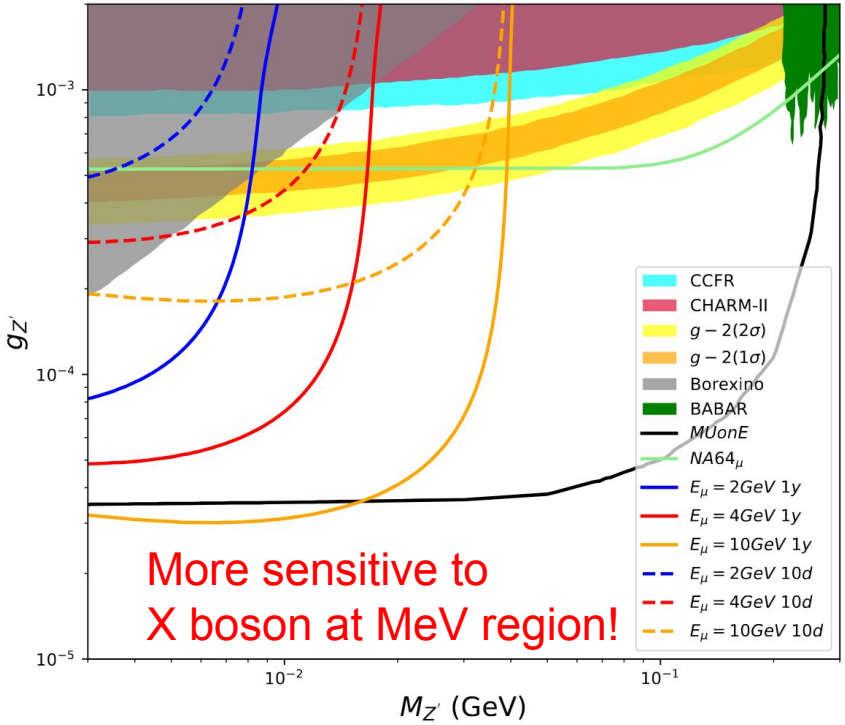


参考文献: [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

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

PKMu@HFRS vs. MuonE





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Preliminary results

Our roadmap to detect Dark Sector

A compact detector for muon scattering with target electrons or nuclei:

Using RPC+GEM to measure angular direction; Scintillator and absorber for PID

- μe → μeZ', Z'→ν ν̄ final state leptons with wide scattered angle
- μe → μeX,
  - X→ ν ν̄ final state leptons with wide scattered angle
  - X→ e+ e- **electron energy measurement**
- ee → eeX,
  - X→ ν ν̄ final state leptons with wide scattered angle
  - X→e+ e- **electron energy measurement**

先只通过角度测量来进行探测(very small coupling->very long flying distance, thus ~invisible), 进而再利用能量测量信息(量能器)