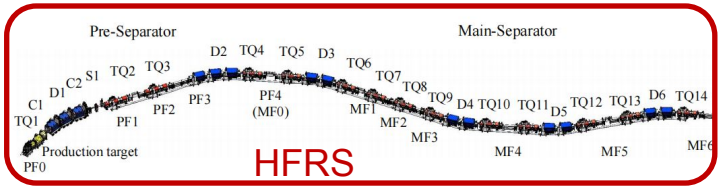
PKMu-HFRS/HIRIBL: Probing and Knocking with a Gev Muon beam at the HIAF HFRS facility

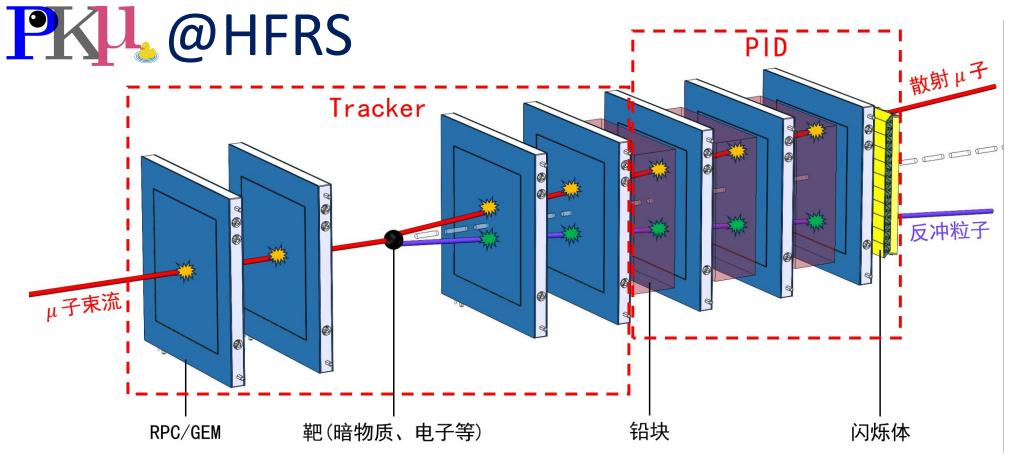
Qiang Li,
for the working group
2025/05/17

International Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP2025)

Muon Scattering Experiment at HIAF-HFRS

PKMu(Probing and Knocking with Muons) Proposed by Peking University together with HIAF-HFRS from Institute of Modern Physics, Chinese Academy of Sciences, China: **using 1-10 GeV Muon to probe new physics beyond the Standard Model**



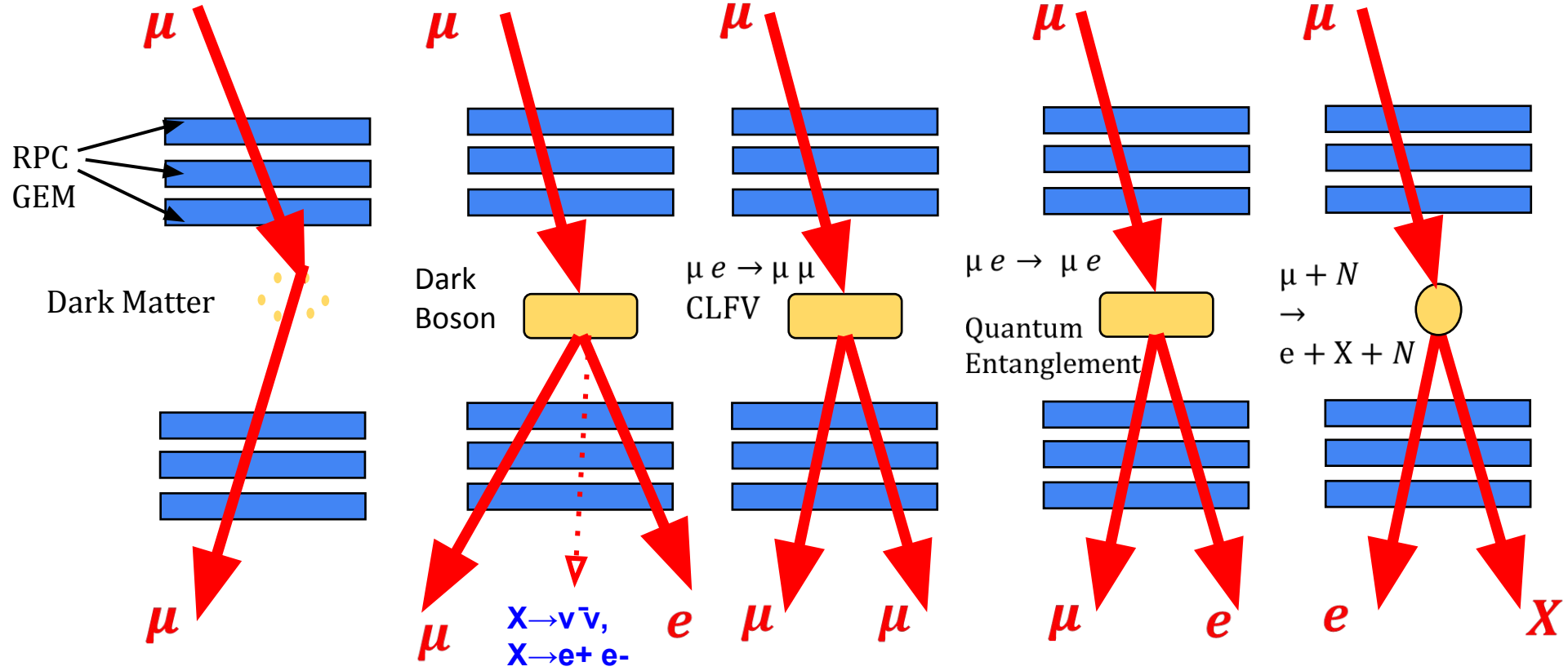


参考文献:[1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

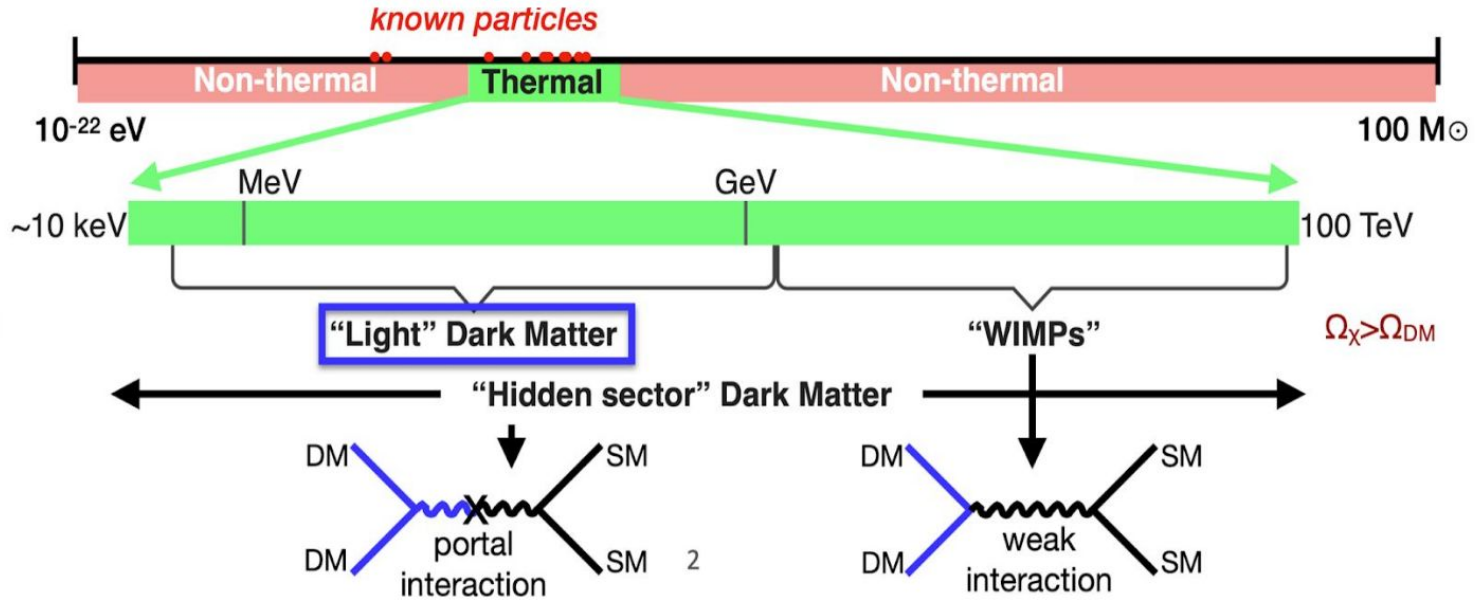
Microscope: multi-purpose platform

→Cosmic μ or μ beam

arXiv:2503.22956 to appear in MPLA



Light Dark Matter → Dark Sector

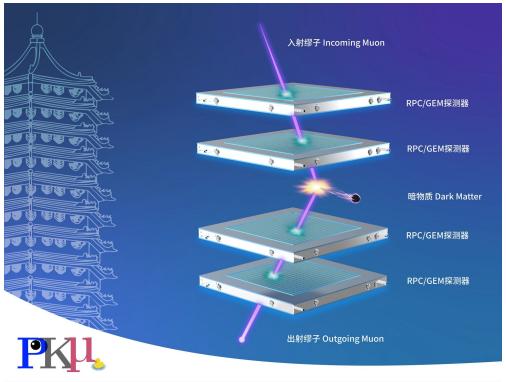


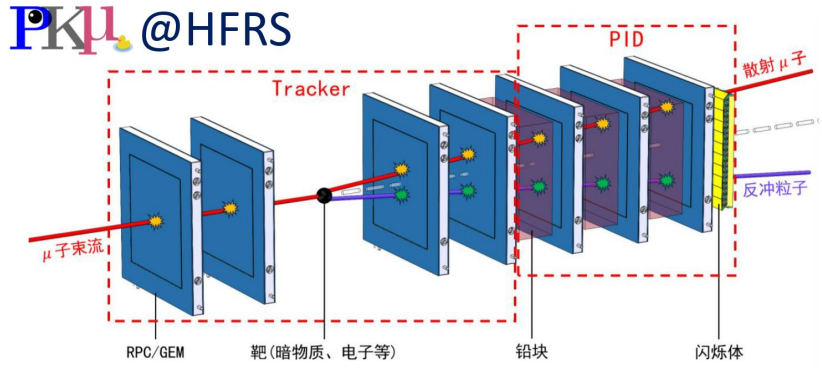
Minimal scenarios with light (sub-GeV) dark matter whose relic density is obtained from thermal freeze-out must include new light mediators. In particular, a very well-motivated case is that of a new "dark" massive vector gauge boson mediator. JHEP03(2018)084 Granada19 LDMX2024

(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(pheno.) μe → μeZ', Z'→νν̄ or Z'→χχ (dark matter)

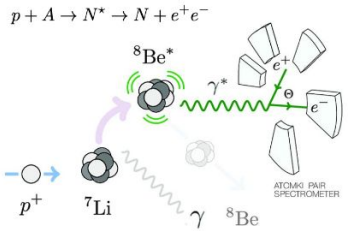




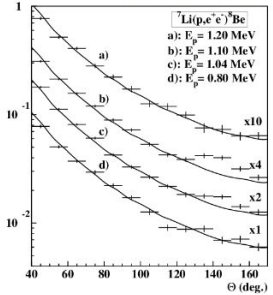
参考文献：[1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

More: X17 Anomaly

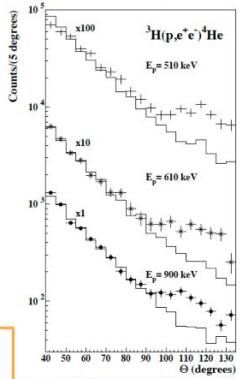
De-excitation of light nuclei via IPC, an anomaly in the decay of ^{8}Be and ^{4}He



PRL 116, 042501 (2016)



Phys. Rev. C 104, 044003 (2021)



CERN COURIER

Rekindled Atomki anomaly merits closer scrutiny

Feb 2020

In ^{12}C [PRC 106, L061601], GDR of ^{8}Be [2308.06473], in ^{8}Be/12C at HUS (Vietnam)

Other efforts ongoing (e-, n beams, etc.)

m_X = (16.98 ± 0.16 ± 0.20) MeV

2

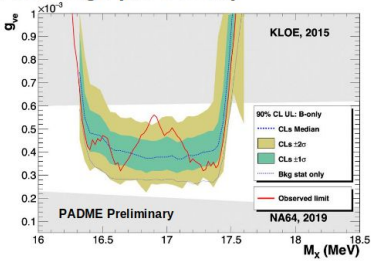
Box opening

Some excess is observed beyond the 2σ local coverage (2.5 σ local)

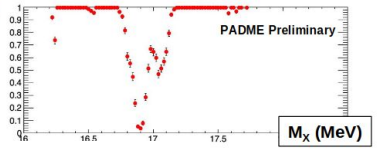
At M_X = 16.90(2) MeV, g_{ve} = 5.6 x 10^{-4}, the global probability dip reaches 3.9$_{-1.1}^{+1.5}$ %, corresponding to (1.77 +- 0.15) σ one-sided (look-elsewhere calculated exactly from the toy pseudo-events)

A second excess is present at larger masses ~ 17.1 MeV, but the absolute probability there is ~ 40%

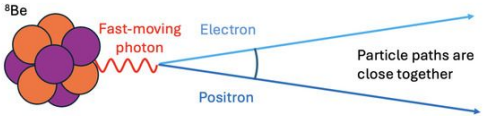
If a 3σ interval is assumed for observation following the estimate M_X = 16.85(4) of PRD 108, 015009 (2023), the p-value dip deepens to 2.2$_{-0.8}^{+1.2}$% corresponding to (2.0+-0.2) σ one-sided



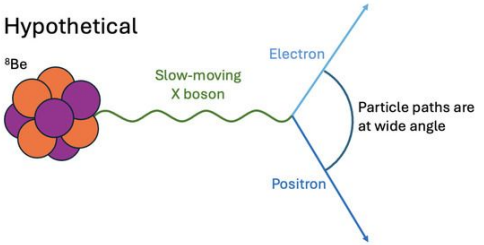
Pvalue



Expected ^{8}Be Transition



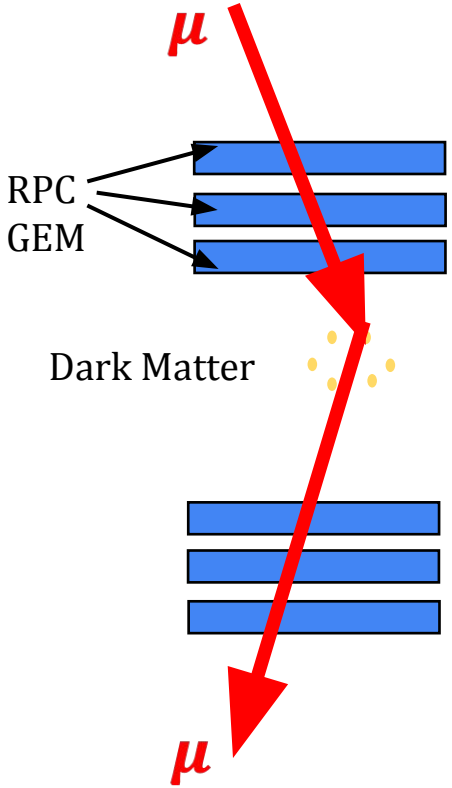
Hypothetical

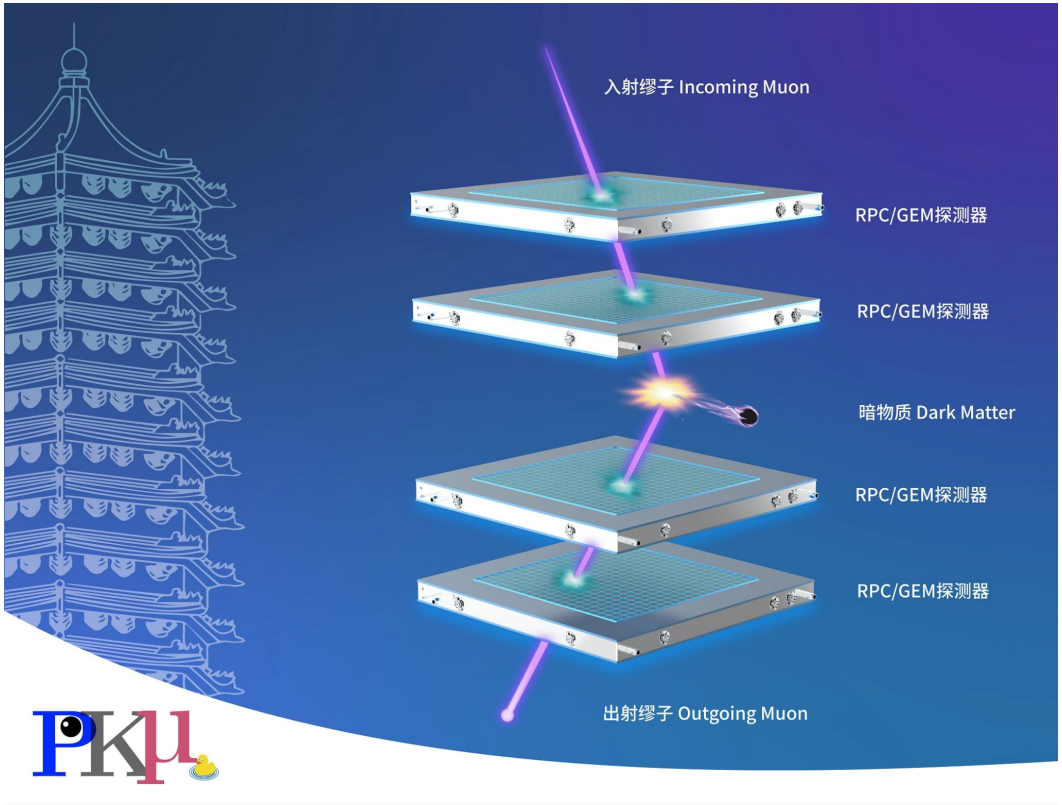


For a 1-10 GeV muon/electron beam scatter off electrons in target,
the C.O.M energy is ~ 10 MeV!

https://agenda.infn.it/event/46739/attachments/134359/201425/padme_RunIII_LNFSeminar.pdf

1) Direct searches for DM

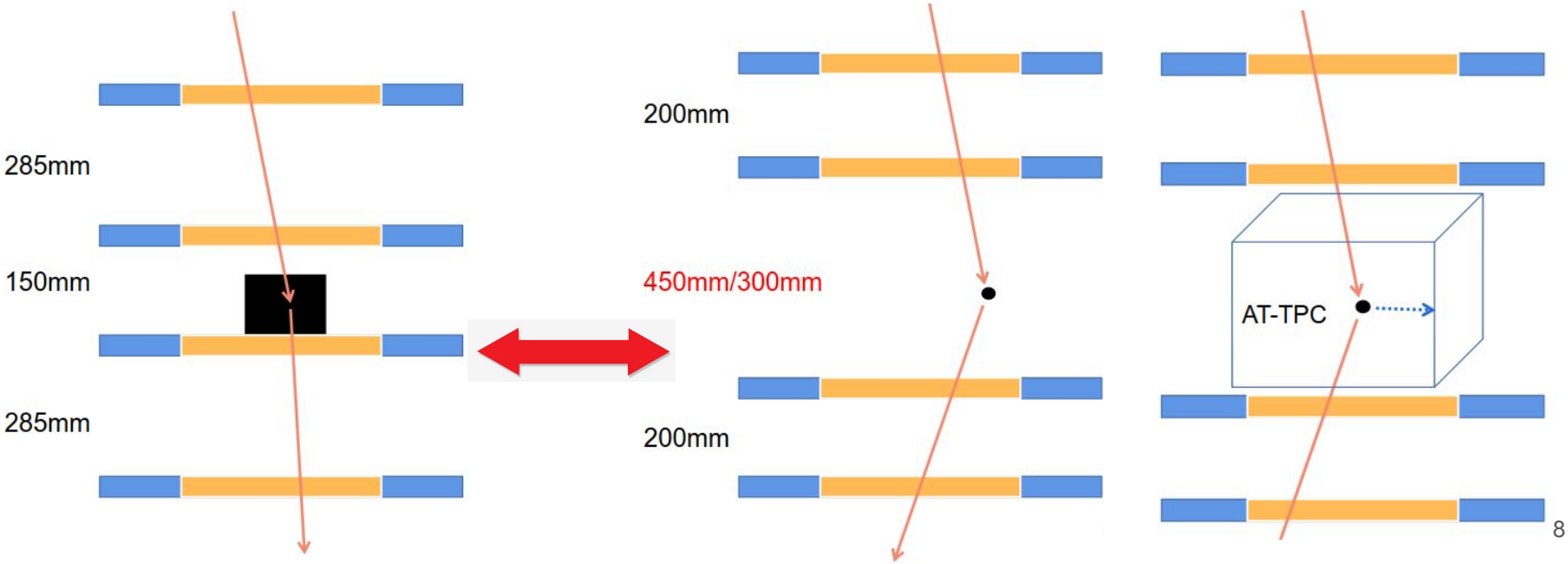




Muon Tomography and Muon-DM scattering

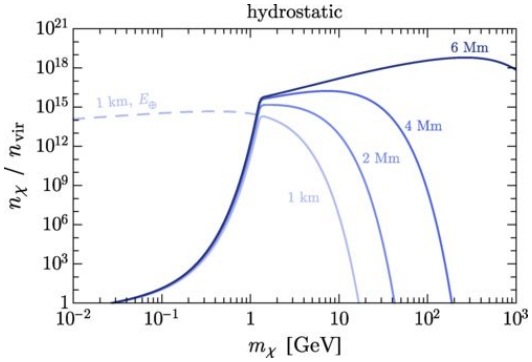
Muon Tomography 缪子成像 ⟷ Dark Matter Search 暗物质寻找

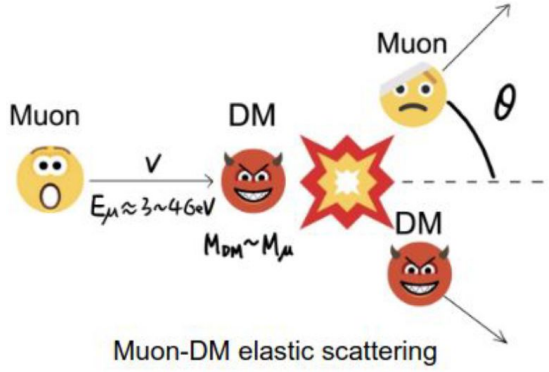
Phys.Rev.D 110 (2024) 1, 016017



Slow Dark matter

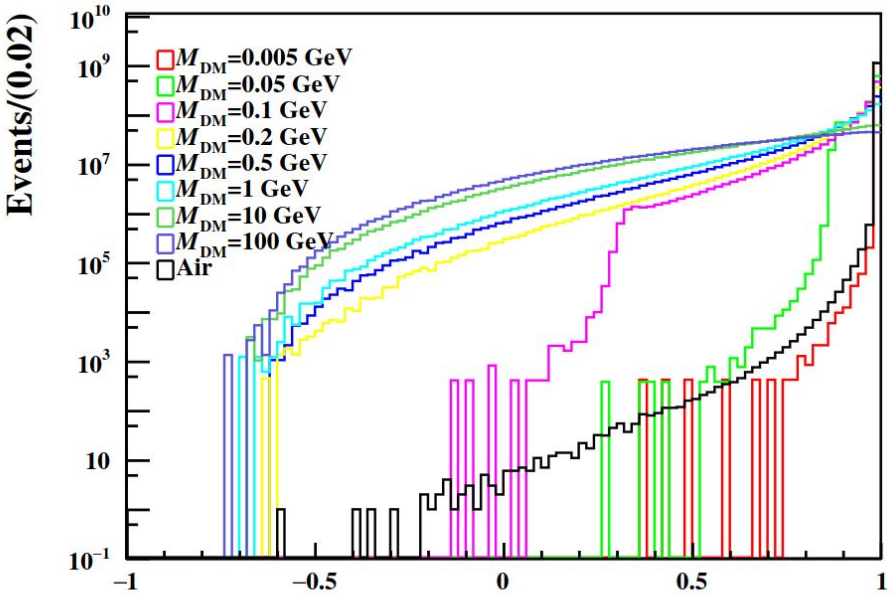
- Earth bounded Dark Matter: terrestrial density of strongly-coupled relics
  PRL. 131 (2023), 011005, PRD 109 (2024), 075027 PRD 103, 115031 (2021)
  - A fraction (fD) of strongly interacting dark matter
  - can be trapped in the Earth, and distributed more uniformly.
  - The density (fE) can be large! **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**



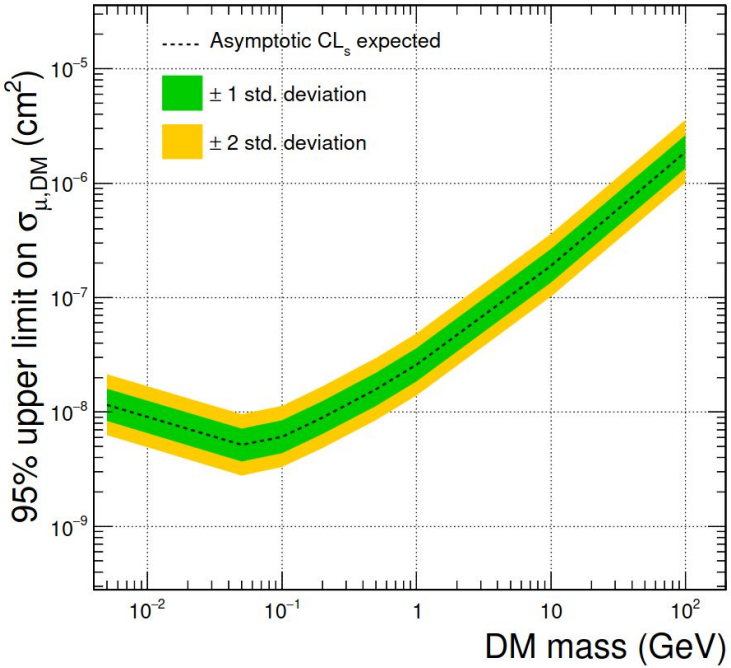


Different from XENON/PandaX:
Relativistic muon hit quasi-static DM

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

PKMuon Collaboration

PKMuon Collaboration

3 followers · China · https://lyazj.github.io/pkmuon-site/ · seeson@pku.edu.cn

Overview | Repositories 10 | Projects | Packages | People 2

Pinned

PKMUON_G4sim Public
Forked from yuxdPKU/PKMUON_G4sim
Geant4-based simulation of PKMUON
C++

geomu Public
Forked from lyazj/geomu
Geographic Muon Simulation
C++

pkmuon-site-src Public
Forked from lyazj/pkmuon-site-src
source code of PKMUON site
Stylus

root-easy-debug Public
Forked from lyazj/root-easy-debug
Debug CERN ROOT macros in an extremely easy way
C

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

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

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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.

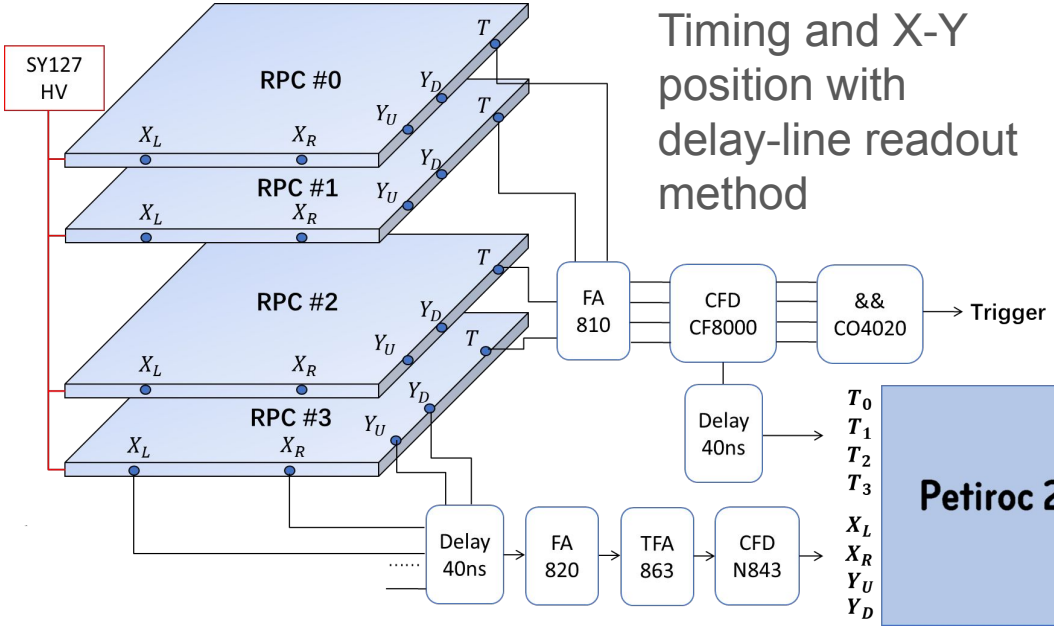
DOI: 10.1103/PhysRevD.110.016017

Current Box Exp. Status

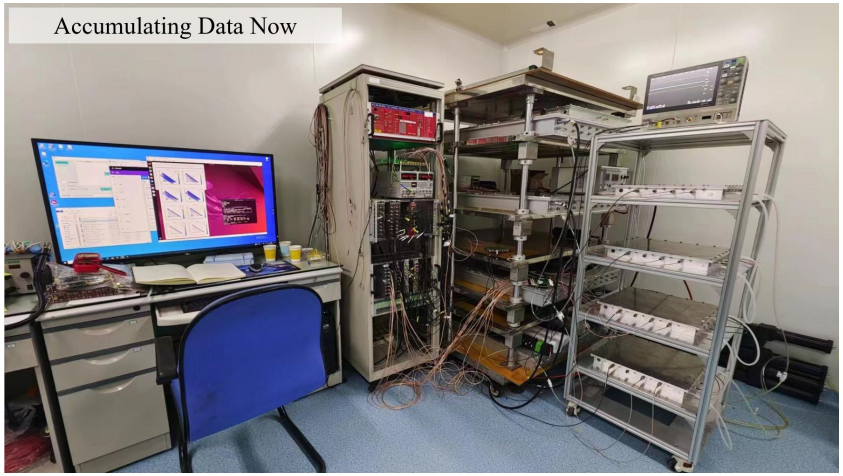
recent report from Cheng-en Liu and Qite Li

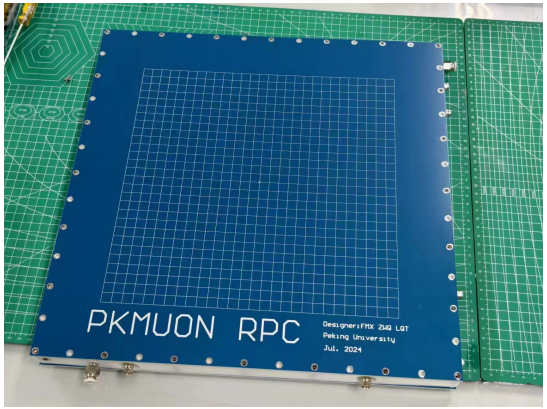
4-station 20cm*20cm RPC for the moment

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



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



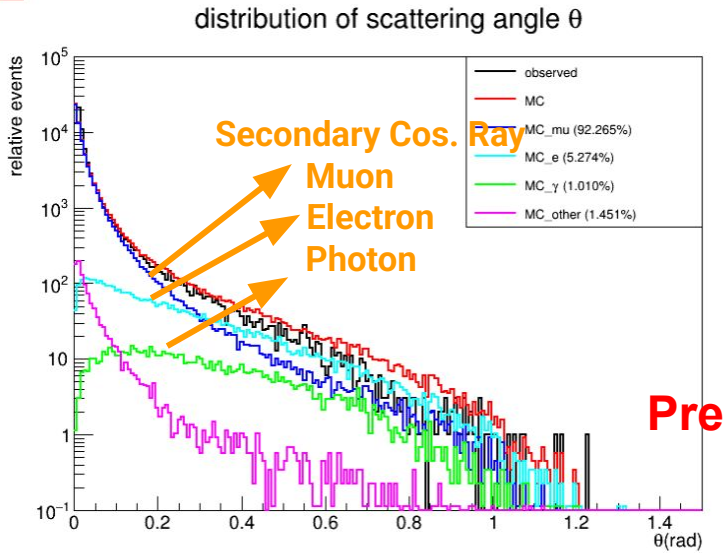


Byproduct: cosmic ray measurements

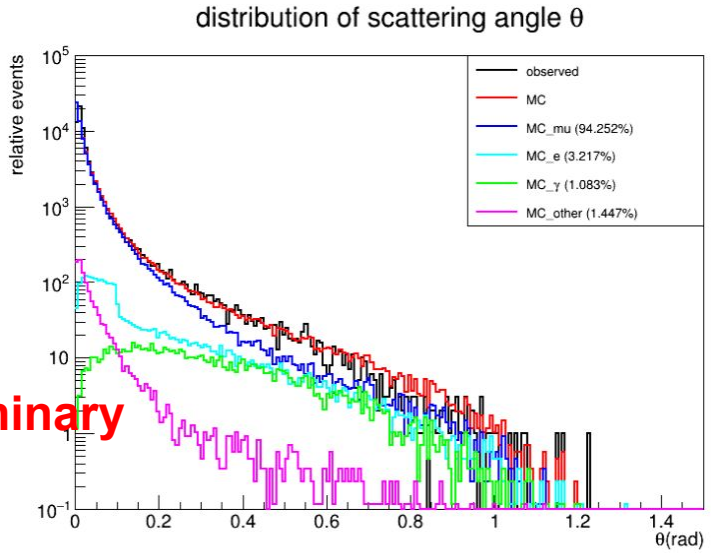
缪子、电子、光子 在大散射角度区域 有很好的区分度

⇨ 地面宇宙次级射线新型测量手段

铅块数据对比

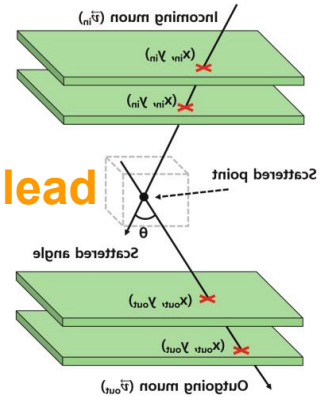


无调整



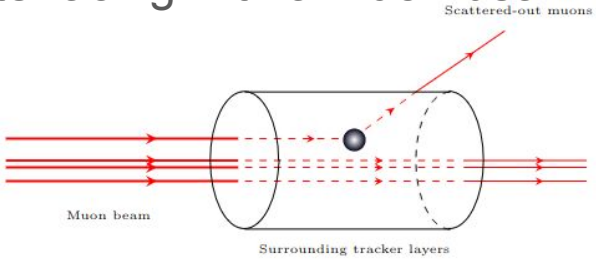
联合拟合后

Preliminary



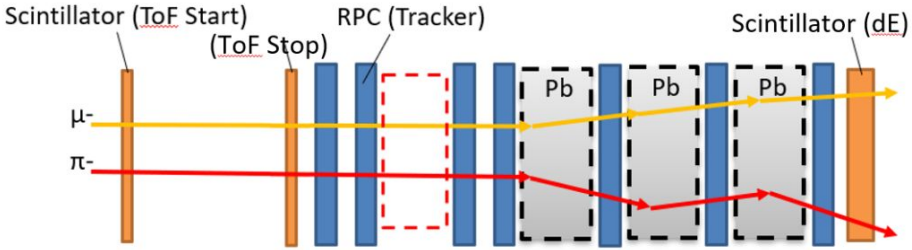
Current Beam Exp. Status

Interfacing with a muon beam at e.g. HIAF



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

More detectors such as LGAD, Si Strip in plan to be integrated.



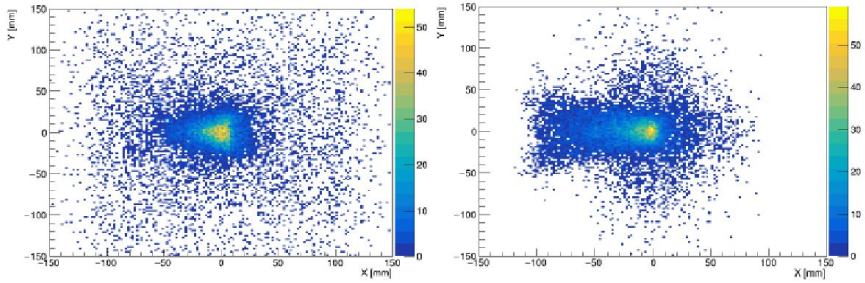


图 6.9: 左：1GeV 缪子束流束斑轮廓。右：3GeV 的缪子束流的束斑轮廓

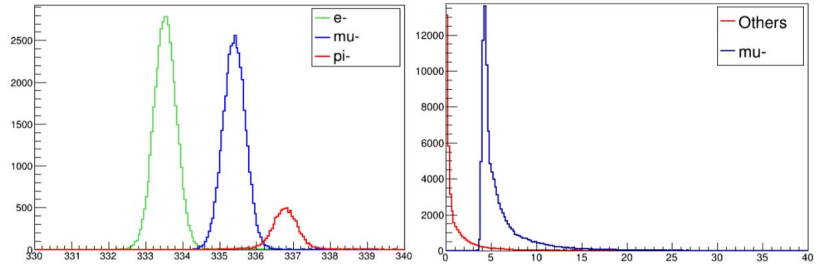
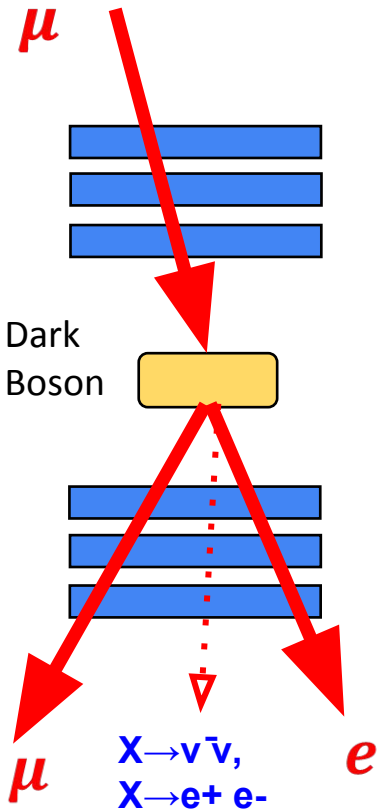
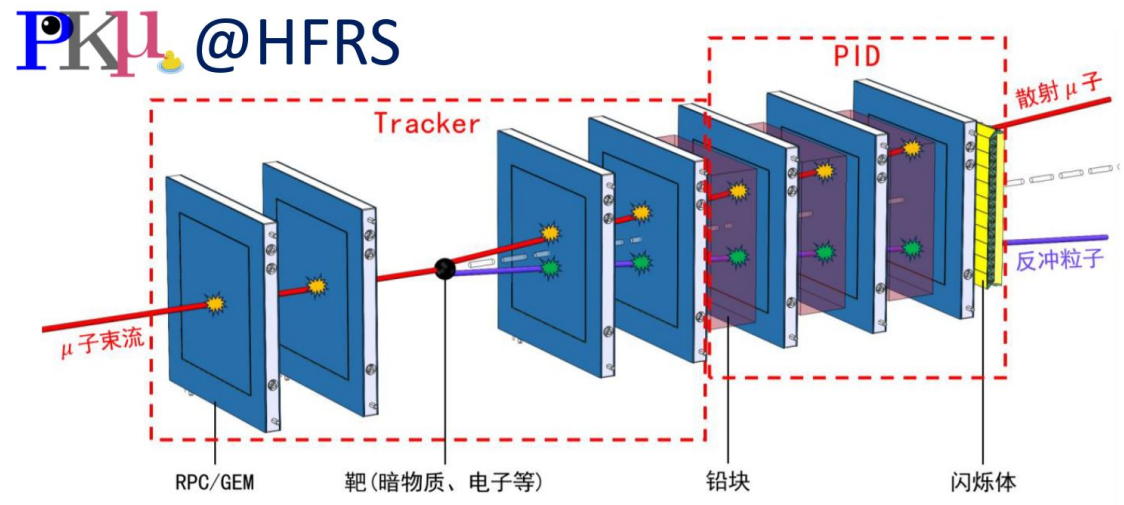


图 6.13: 缪子散射探测系统信号与背景响应模拟：成像系统前飞行时间谱（左）；末端闪烁体能量损失谱（右）

2) On target experiments for Dark Boson



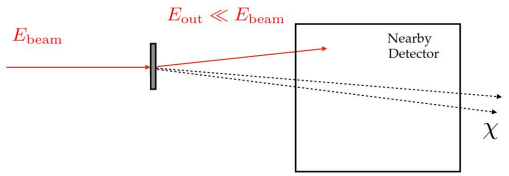


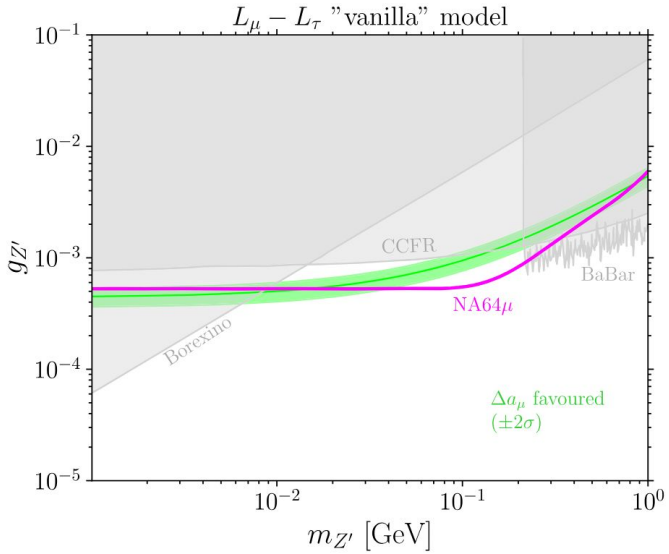
参考文献: [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

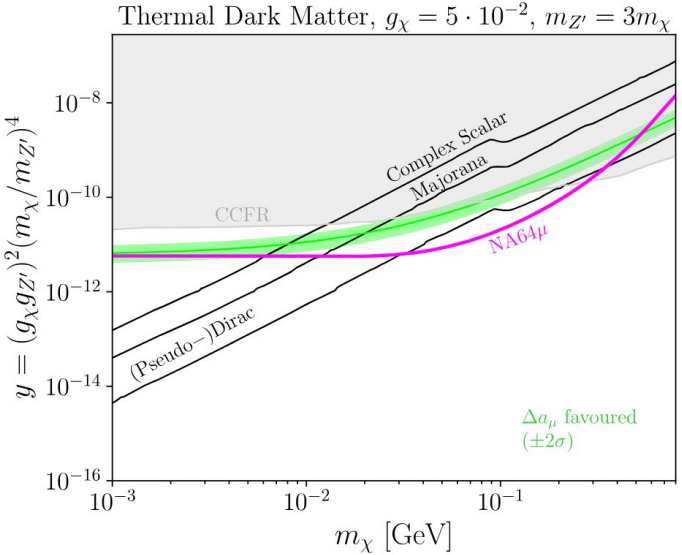
NA64μ recent results

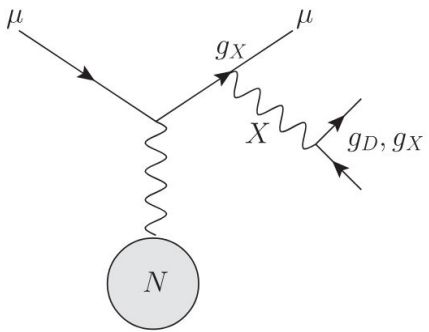
$$\mathcal{L} \supset -\frac{1}{4} F'_{\alpha\beta} F^{\alpha\beta\prime} + \frac{m_{Z'}^2}{2} Z'_\alpha Z^{\alpha\prime} - g_{Z'} Z'_\alpha J^\alpha_{\mu-\tau},$$

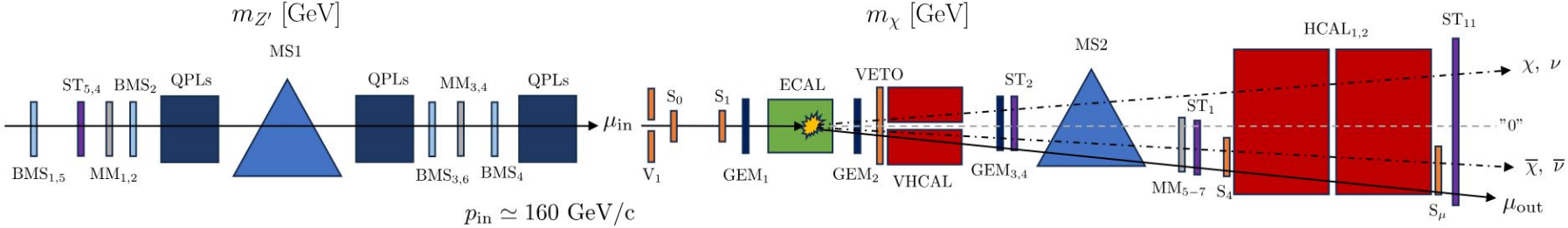
$$-g_\chi Z'_\alpha J^\alpha_\chi,$$





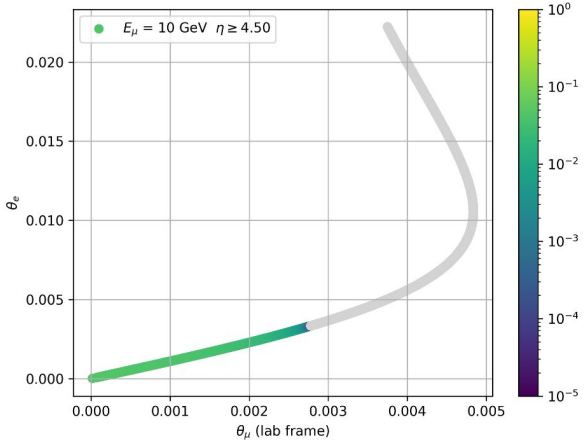






Z' and X at PKMu@HFRS

- **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."*

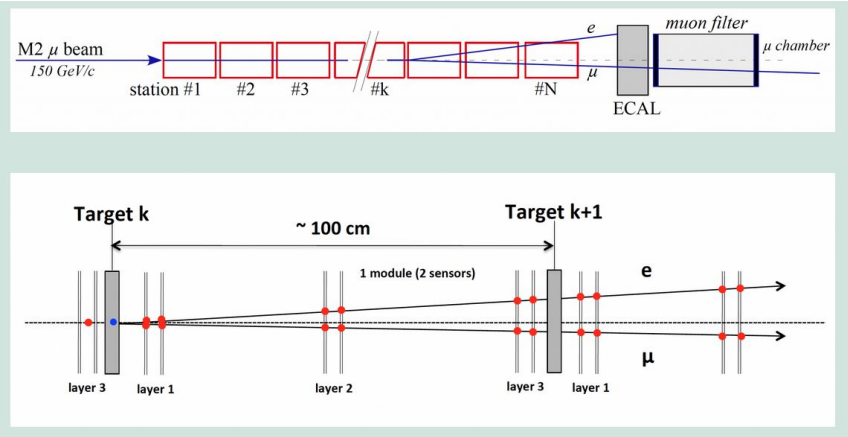


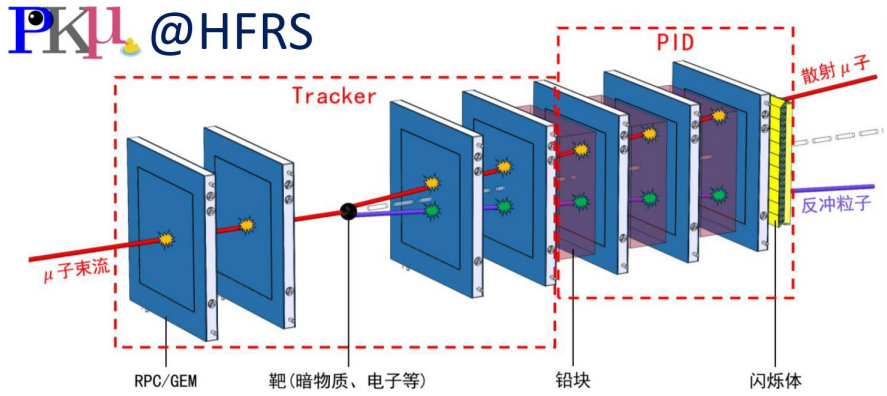
arXiv:2411.12518

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

PKU joined MUonE recently, and will also perform BSM searches there

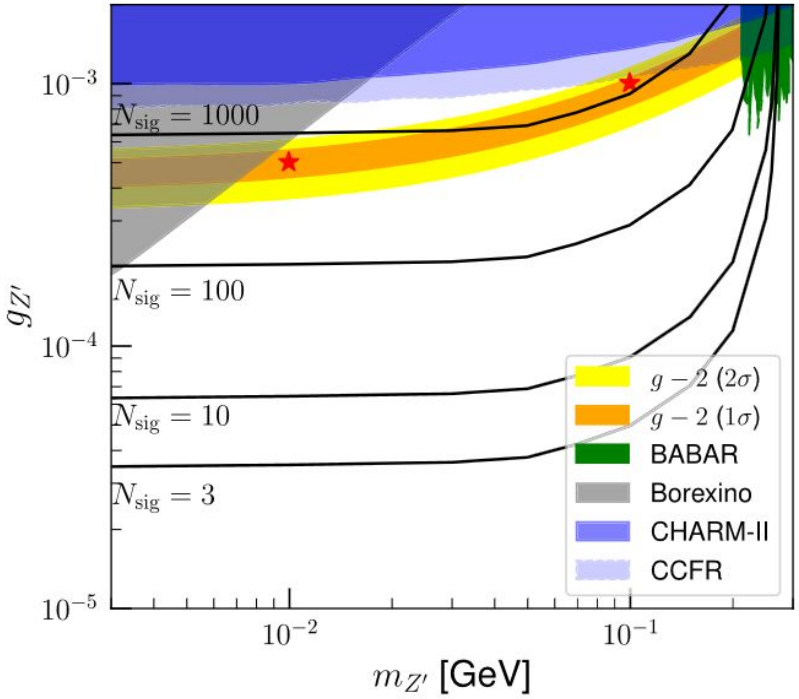


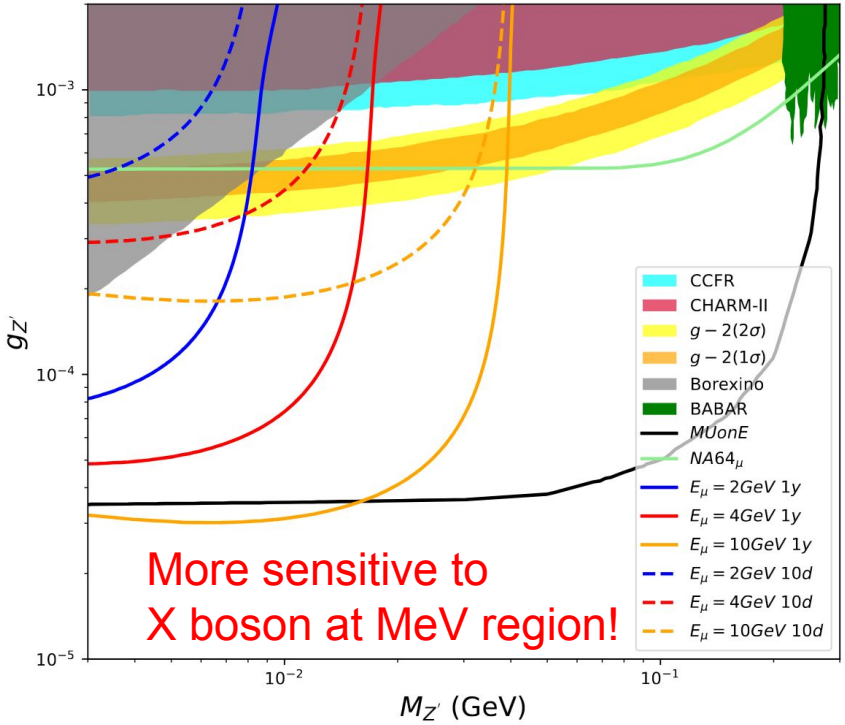


参考文献: [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

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





Phys.Rev.D 106 (2022) 5, L051702

Preliminary results

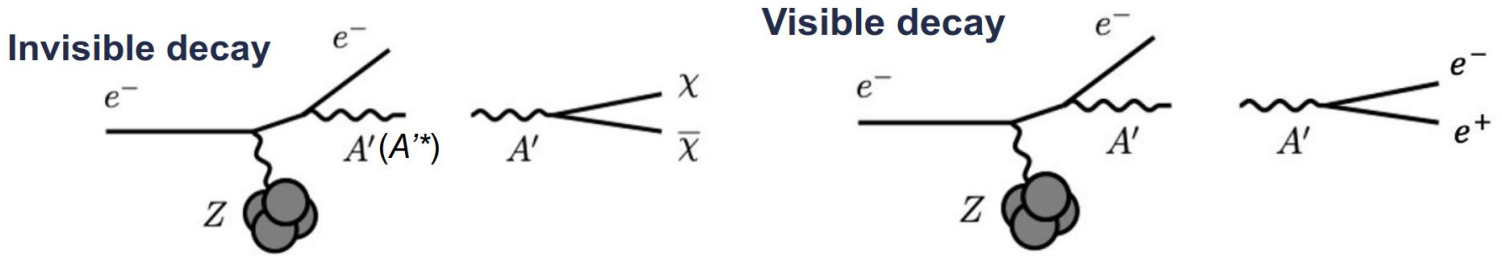
Our roadmap to detect Dark Sector

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

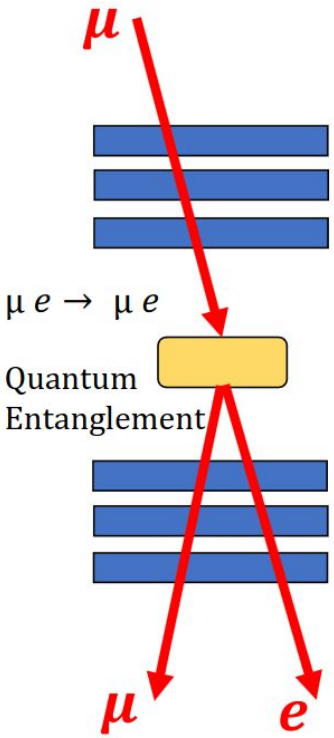
Using RPC+GEM to measure angular direction; Scintillator and absorber for PID

- 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**

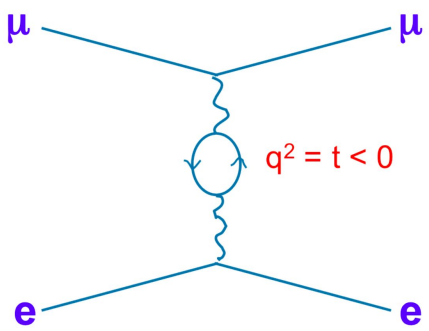
先只通过角度测量来进行探测(very small coupling->very long flying distance, thus ~invisible)，进而再利用能量测量信息(量能器)



More: Muon Electron Scattering



- MuonE exploits 160 GeV Muon beam to measure muon electron scattering, and a precise determination of the leading hadronic contribution to the muon g-2.
- **Muon electron scattering at lower energy (~GeV)** may be interesting to SM test itself, and Quantum entanglement probe PRD 107, 116007 (2023):



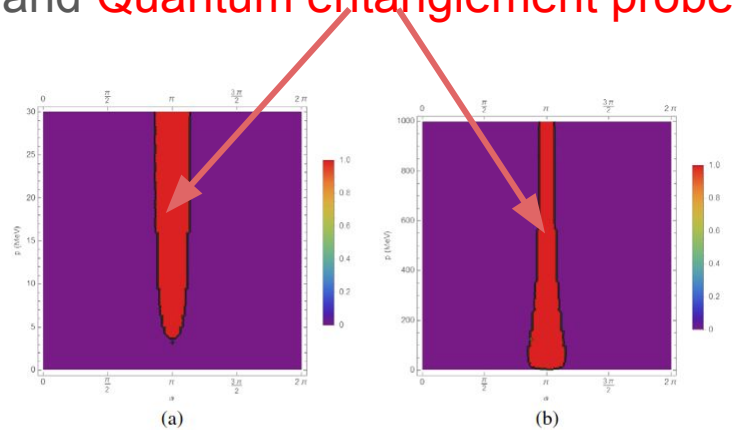
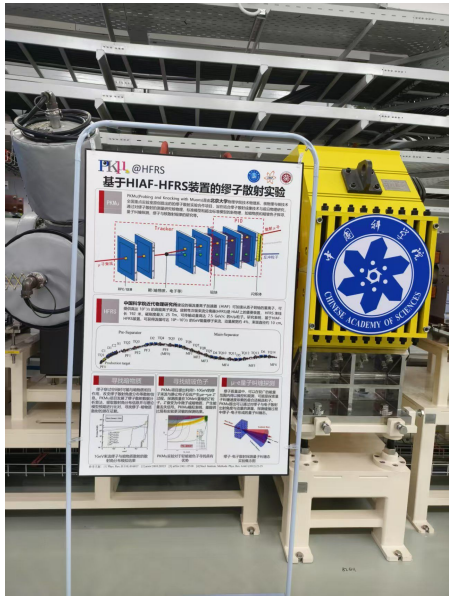


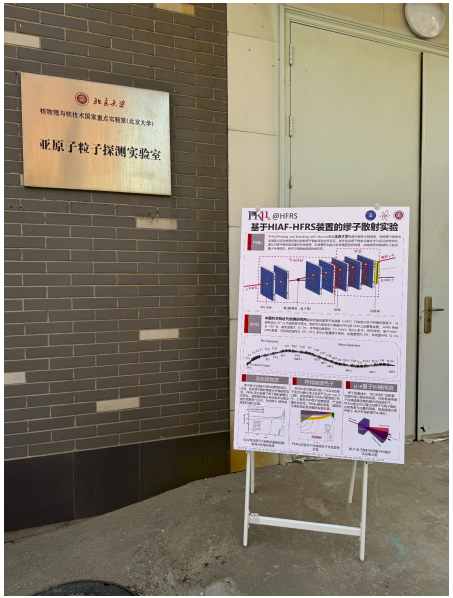
FIG. 15. The red regions correspond to the values of p and θ for which the final state is entangled at low—< 30 MeV—(a) and high—< 1 GeV—(b) energies.

arXiv:2502.07597

arXiv:2411.12518

PKMu@HFRS Lab/Collaboration

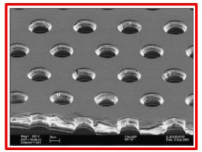


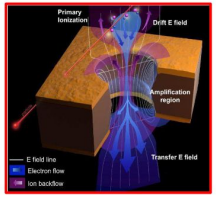


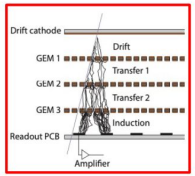
PKU Muon Detector Development

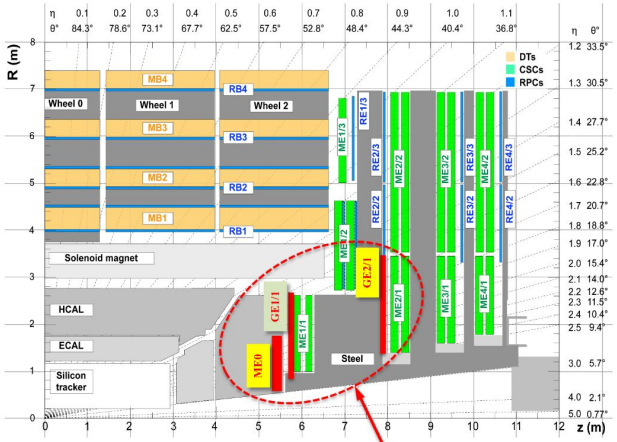
- ➔ CMS Muon Trigger RPC: assembled and tested at PKU at around 2002
- ➔ RPC R&D for nuclear physics
- ➔ CMS GEM upgrade program

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

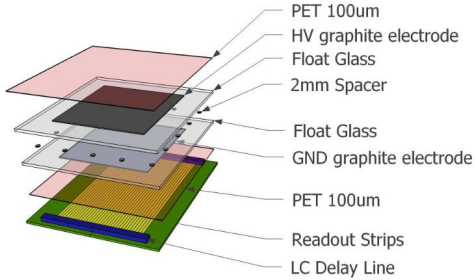
Combination of glass RPC & Delay-line Readout

Nuclear Instruments and Methods in Physics Research A

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

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



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- 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

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

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

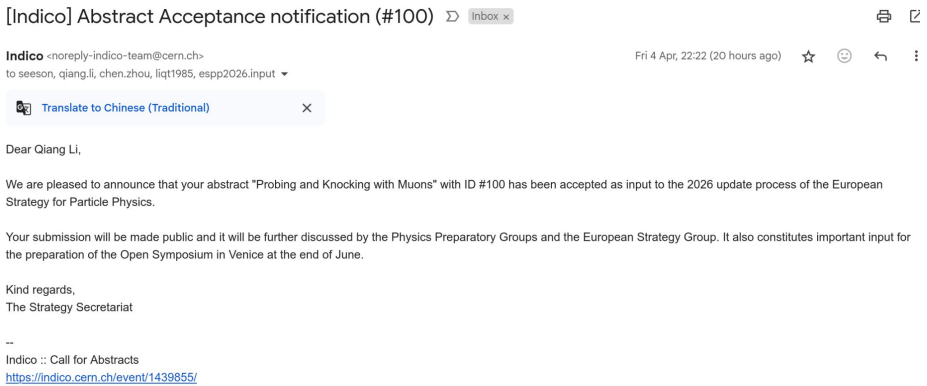
Peking University

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

[Input to the European Strategy for Particle Physics 2026]



[Indico] Abstract Acceptance notification (#100) Inbox ×

Indico <noreply-indico-team@cern.ch> Fri 4 Apr, 22:22 (20 hours ago)

to seeson, qiang.li, chen.zhou, liqt1985, espp2026.input

Translate to Chinese (Traditional)

Dear Qiang Li,

We are pleased to announce that your abstract "Probing and Knocking with Muons" with ID #100 has been accepted as input to the 2026 update process of the European Strategy for Particle Physics.

Your submission will be made public and it will be further discussed by the Physics Preparatory Groups and the European Strategy Group. It also constitutes important input for the preparation of the Open Symposium in Venice at the end of June.

Kind regards,
The Strategy Secretariat

--
Indico :: Call for Abstracts
https://indico.cern.ch/event/1439855/

More from our collaborators:

1. Leyun Gao
   a. Software, CLFV, Quantum
2. Zijian Wang
   a. Dark Z boson
3. Cheng-en Liu
   a. Dark Matter
4. Jinning Li
   a. Interfacing with beam

We look forward to one of the first GeV muon beam and muon scattering experiment in China!

https://github.com/PKMuon