PEKING UNIVERSITY

Probing and Knocking with Muons for Dark Matter and others

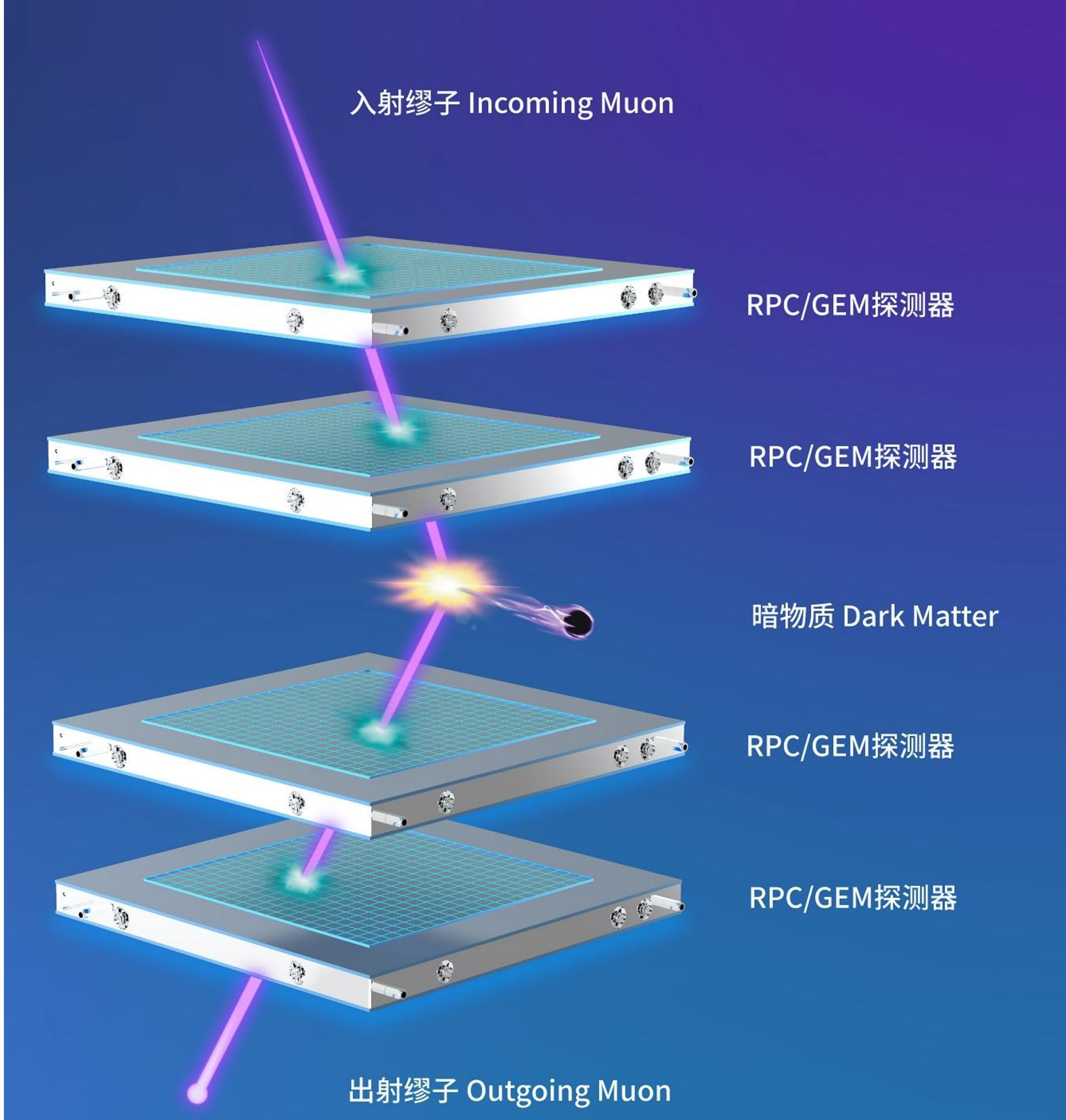
李奇特 Qite Li liqt@pku.edu.cn
李强 Qiang Li qliphy0@pku.edu.cn
周辰 Zhou Chen czhouphy@pku.edu.cn

On behalf of the PKMu collaborators

Ref:

[1] Phys. Rev. D 110, 016017 PKMu for DM
[2] arXiv: 2407.05831 PKMu for CLFV

SPCS 2024, Shanghai
2024.11.14



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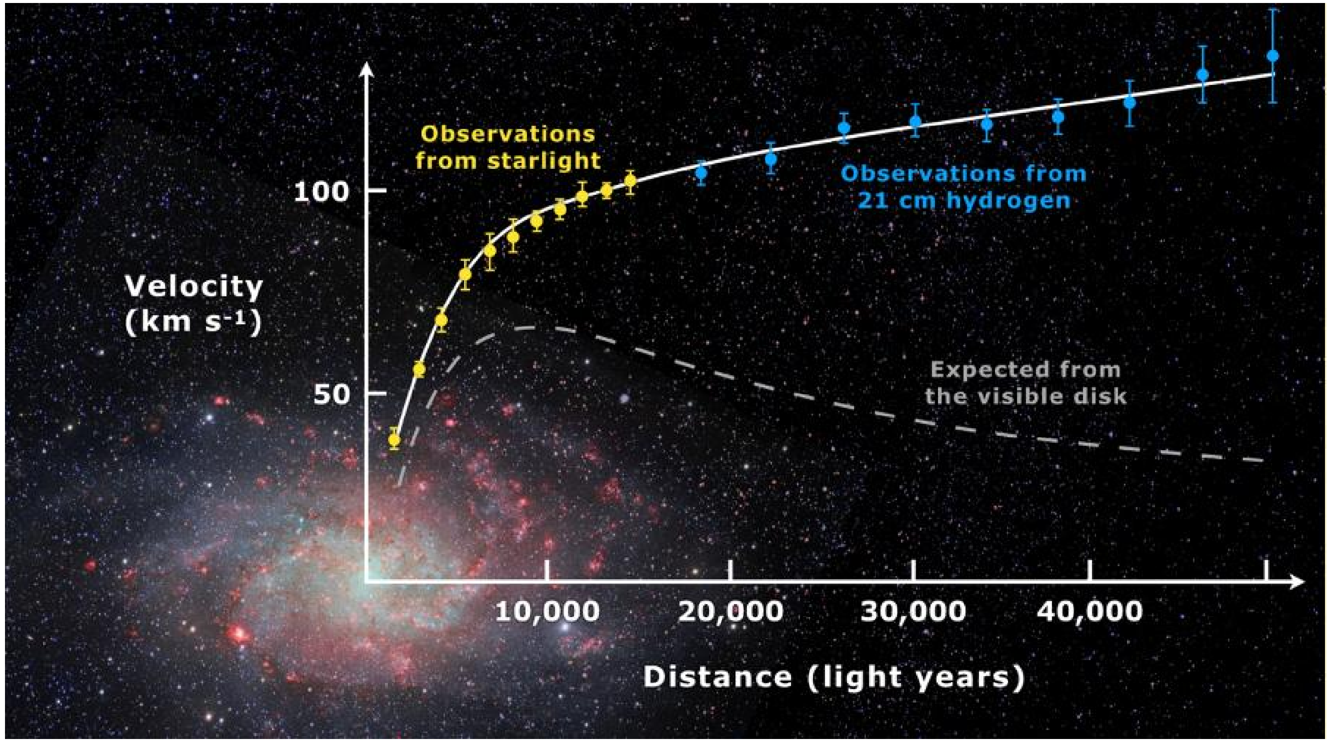
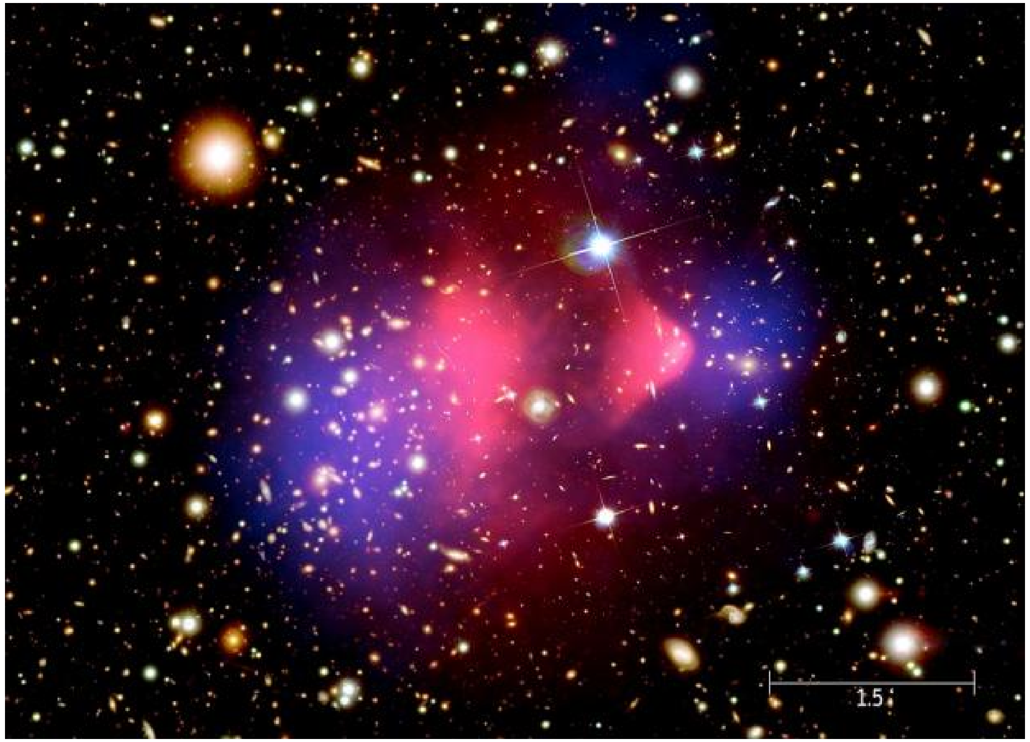
Evidence for the existence of dark matter

- Galaxy rotation curves (1933/1970s)



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

Bullet Cluster



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

- Gravitational lensing, microwave background radiation
- Normal matter:dark matter:dark energy = 5:27:68

Report of the 2023 Particle Physics Project Prioritization Panel / USA

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

Determine the Nature of Dark Matter. The gravitational evidence for dark matter is overwhelming. We have many ideas for what dark matter could be, with a handful of particularly compelling candidates with viable cosmological histories. The number of strong candidates inspires a multifaceted campaign to determine the nature of dark matter, leveraging underground facilities, quantum sensors, telescopes, and accelerator-based probes.

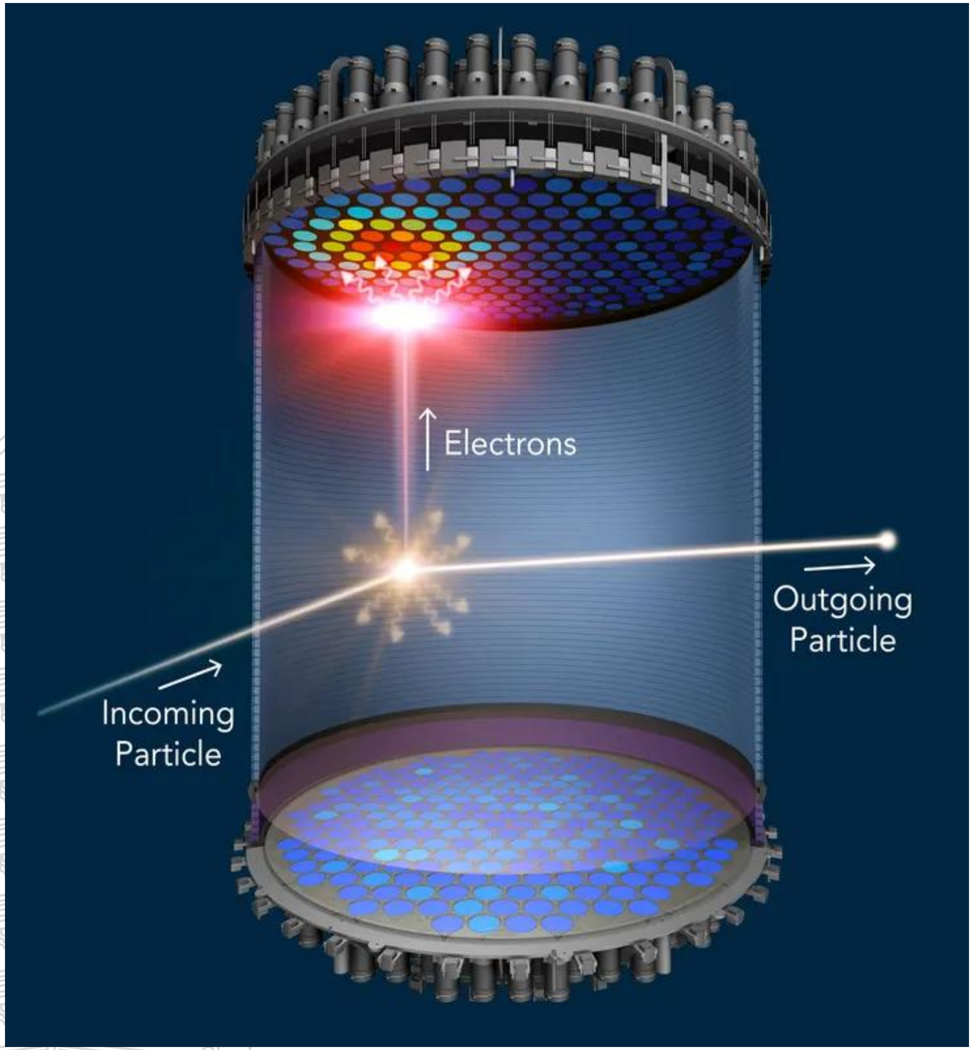
National Natural Science Foundation of China

国家自然科学基金
"十四五" 发展规划

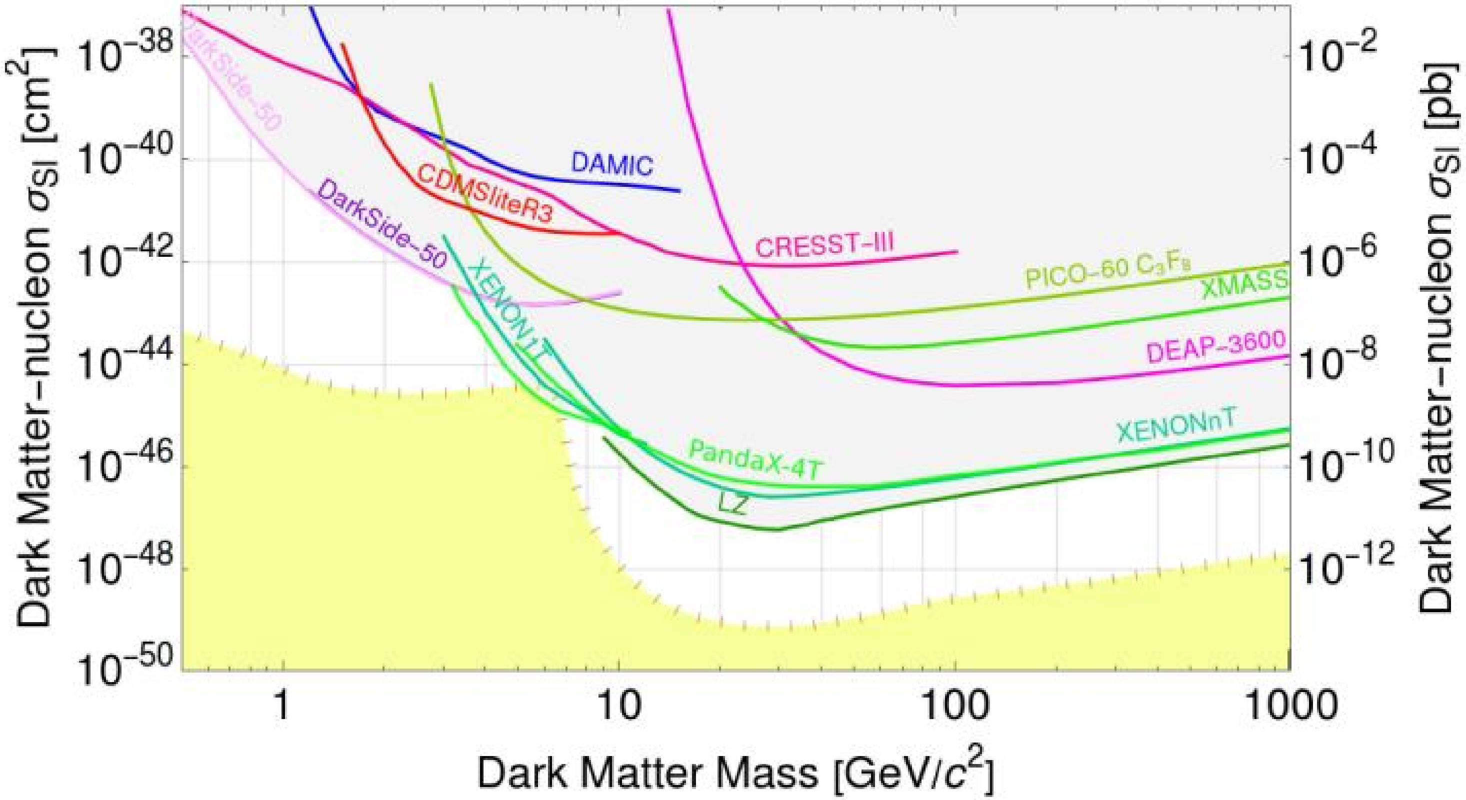
“十四五”优先发展领域（115项）

7.暗物质、暗能量以及星系巡天研究
围绕宇宙的起源和演化前沿科学问题，重点研究暗物质和暗能量的本质，宇宙网络中的星系形成与演化，超大质量黑洞的起源与演化。

Direct detection experiment of WIMP dark matter



Credit: SLAC



arXiv:2312.10828

PKMu

Probing and Knocking with Muons

arXiv:2303.18117 [hep-ph] accpted by International Journal of Modern Physics A

arXiv:2402.13483 [hep-ex] accpted by Phys. Rev. D 110, 016017

PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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Open Access

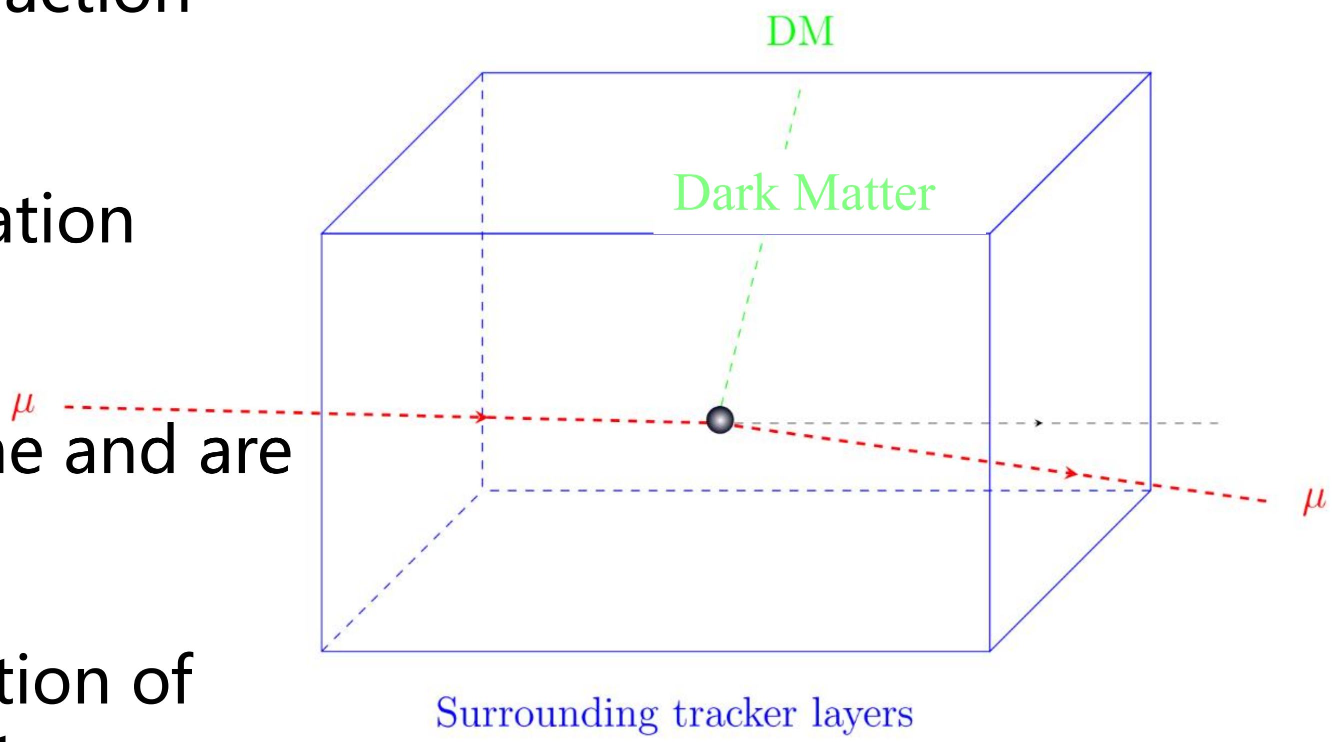
Proposed Peking University muon experiment for muon tomography and dark matter search

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

Phys. Rev. D **110**, 016017 – Published 19 July 2024

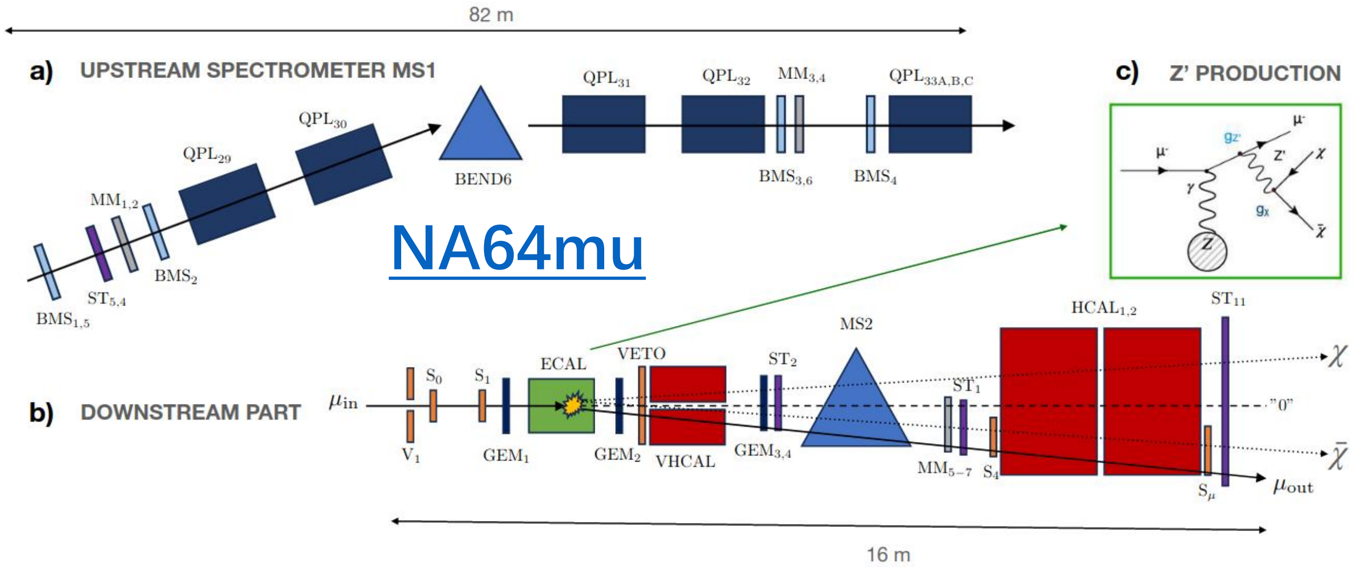
Why we consider using muons to detect dark matter

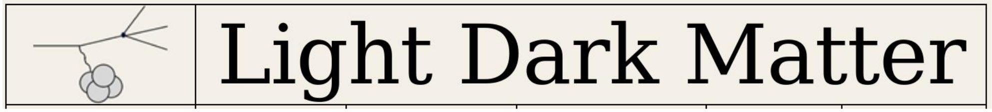
- 1. Few groups have studied the reaction between muons and dark matter.
- 2. The muon is the second-generation lepton of the Standard Model.
- 3. Free muons have a short lifetime and are very rare in the universe.
- 4. Experimental conditions: Detection of cosmic ray muons experience /Future muon sources in China.



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…”





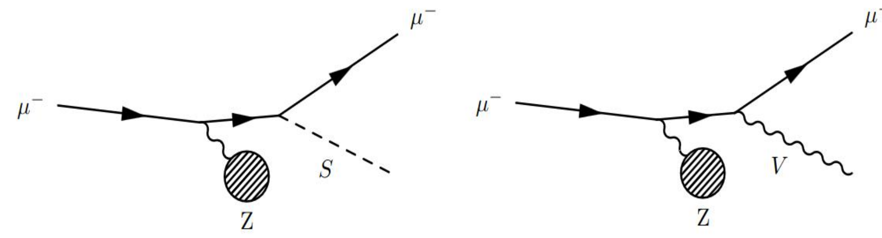
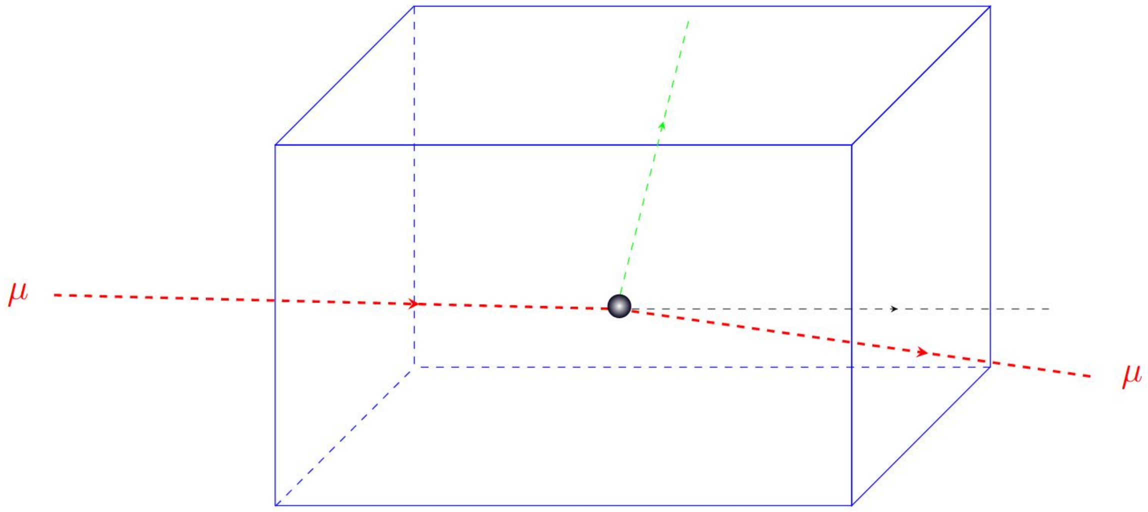


Figure 1. Dark bremsstrahlung signal process for simplified models with invisibly decaying scalar (*left*) and vector (*right*) forces that couple predominantly to muons. In both cases, a relativistic muon beam is incident on a fixed target and scatters coherently off a nucleus to produce the new particle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

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

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

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

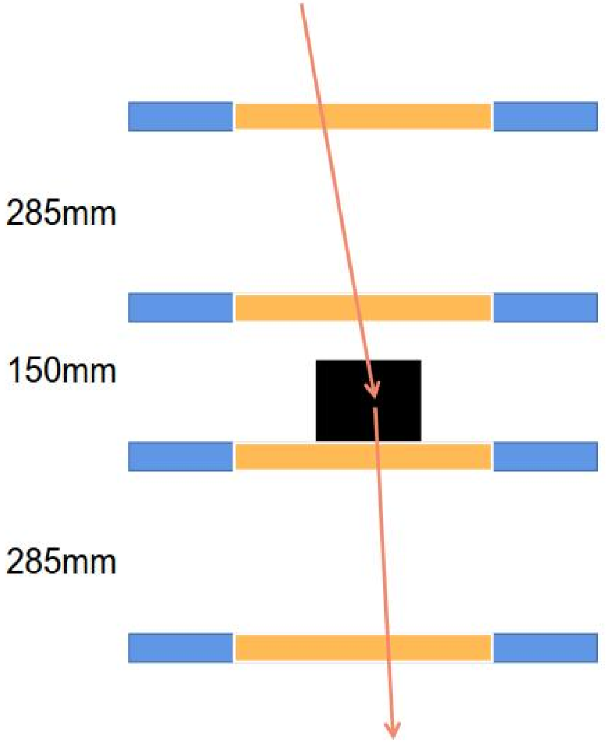
One year

PKμ-Probing and Knocking with Muons

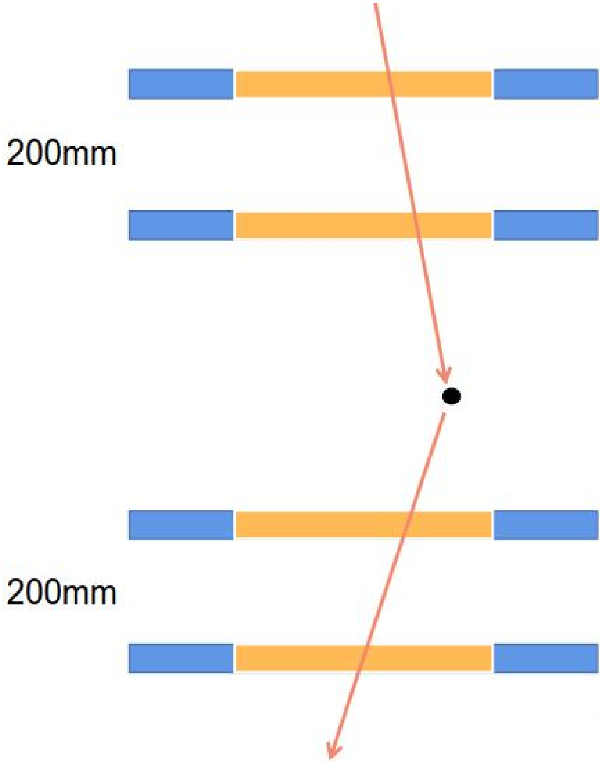
Phys. Rev. D 110, 016017

基于 RPC, 20cm*20cm GEM, 60cm*40cm AT-TPC, etc. 完整径迹

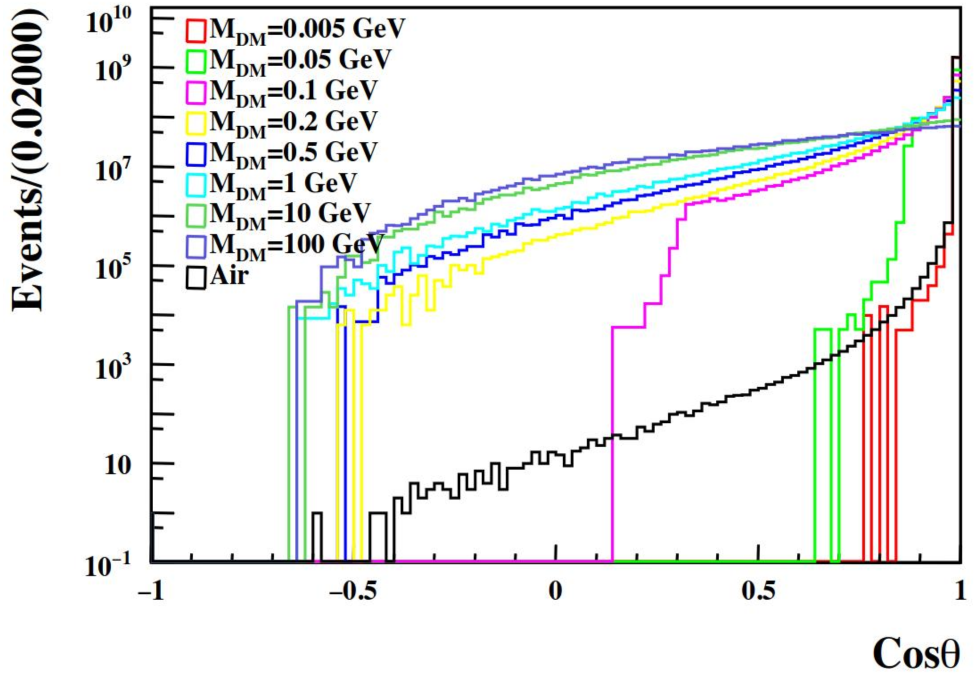
Muon Tomography
缪子成像装置，容易转换成缪子对空间的散射角测量



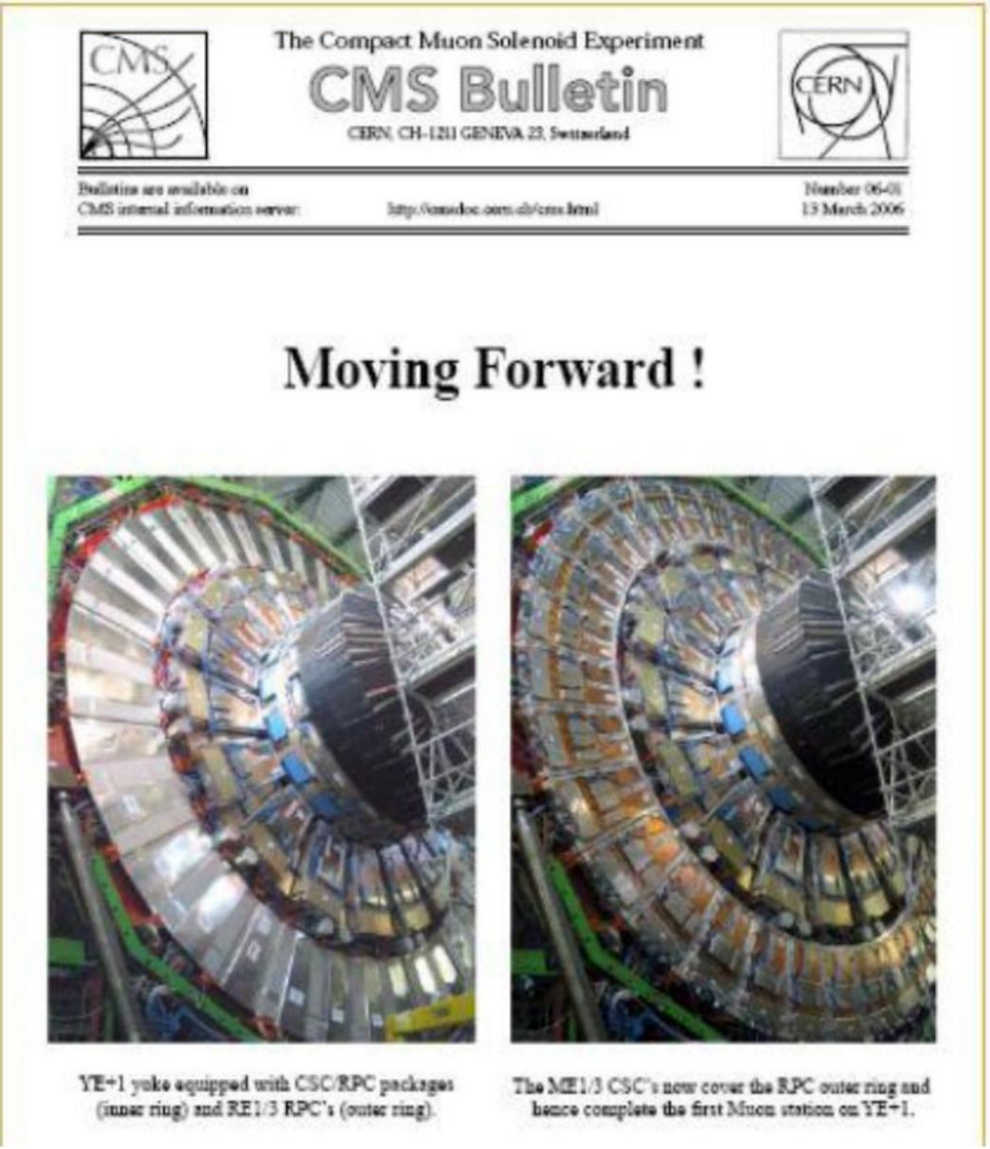
Dark Matter Search 暗物质寻找
(arXiv: 2303.18117 accpted by ITJMPA)



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



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 ~ m²
- Good Time Solution~1ns
- Acceptable Spatial Resolution
  – ~3mm ~1cm

CMS Muon Trigger RPCs

Assembled and tested by PKU (~2002)

GE2/1 GEM：探测器部件生产进展

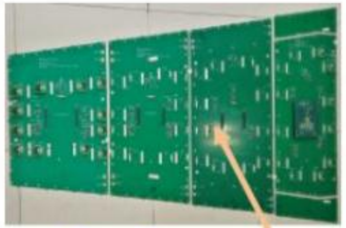
PKU Lab

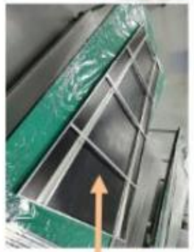
北大基地生产的第一个CMS GEM模块

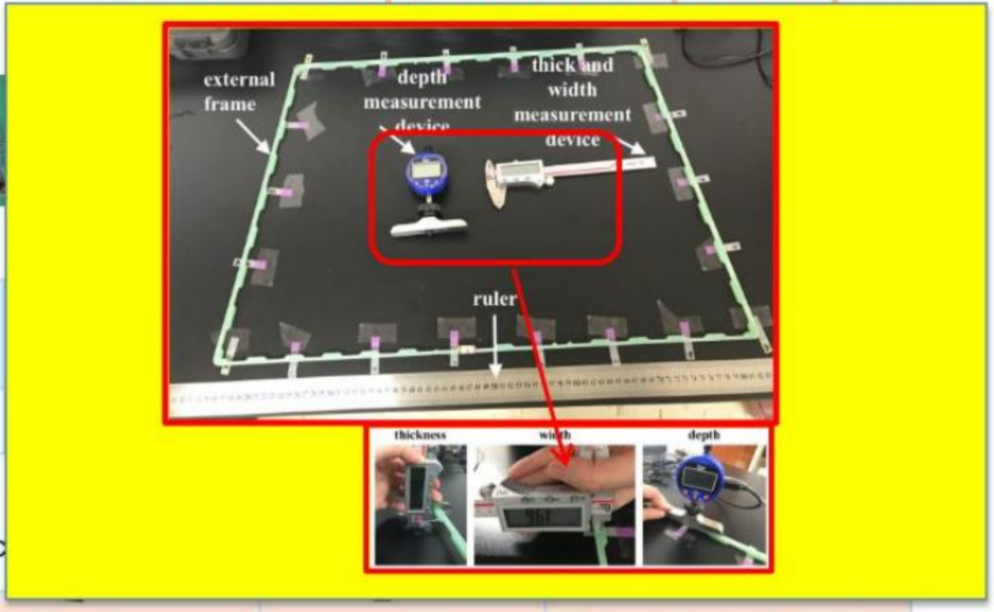
Module Components

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 %	27.6 %

(> 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

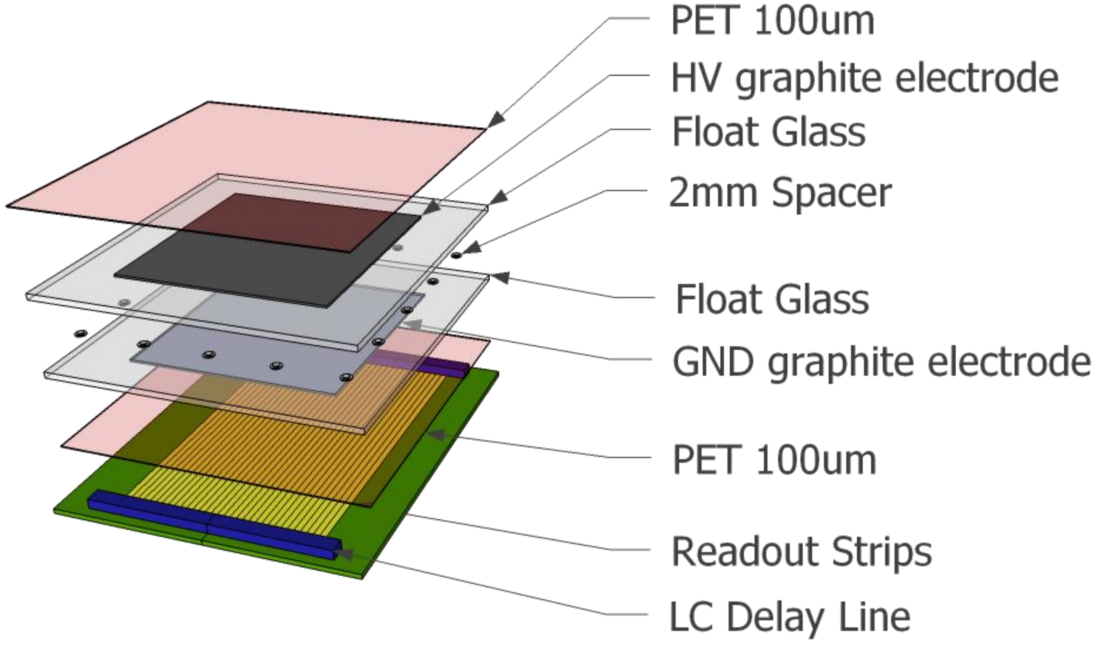
Chamber components

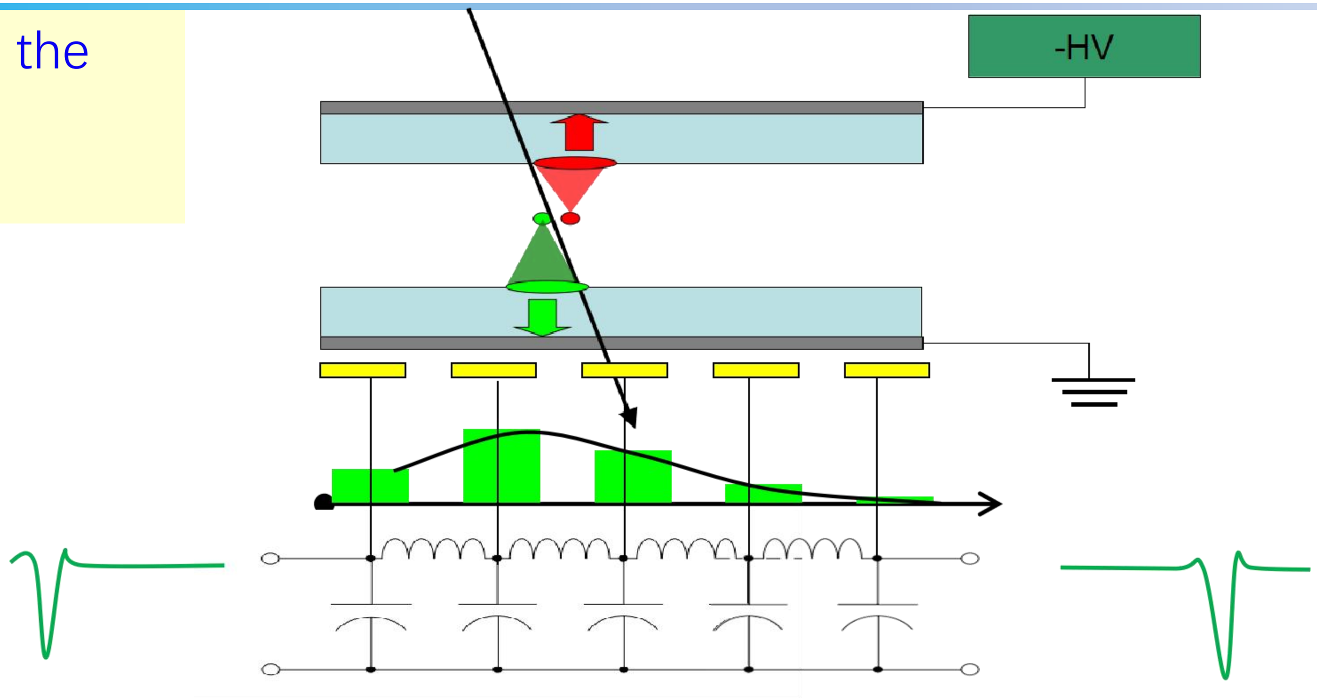
Components	Mechanics	On-detector Fibers	HV filters	Cooling	On-detector Cabling (HV/LV/GND)
% Produced	COMPLETED	COMPLETED	~30%	50% - 100%	COMPLETED

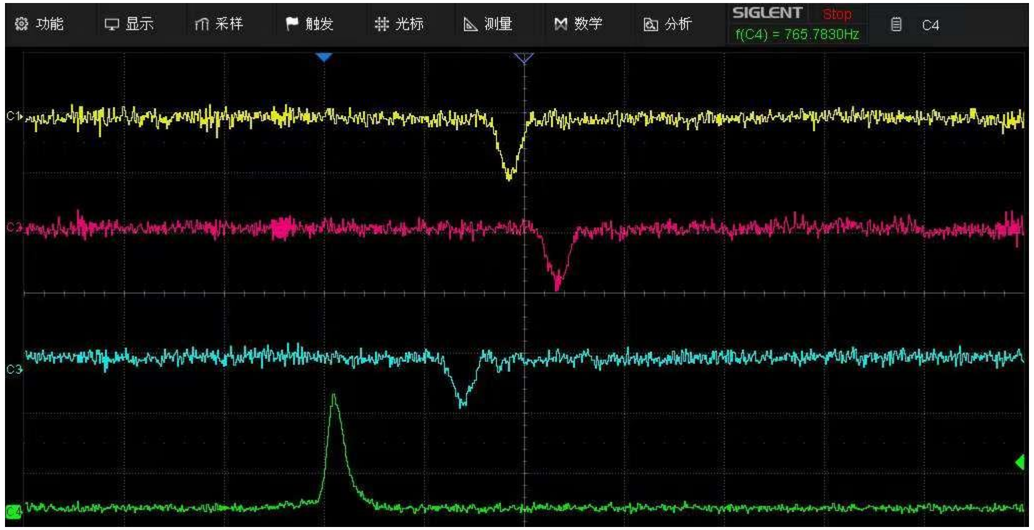
中国组负责生产的GEM部件均已按计划完成并通过CERN检测！

High resolution RPC R&D (2012~2013)

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

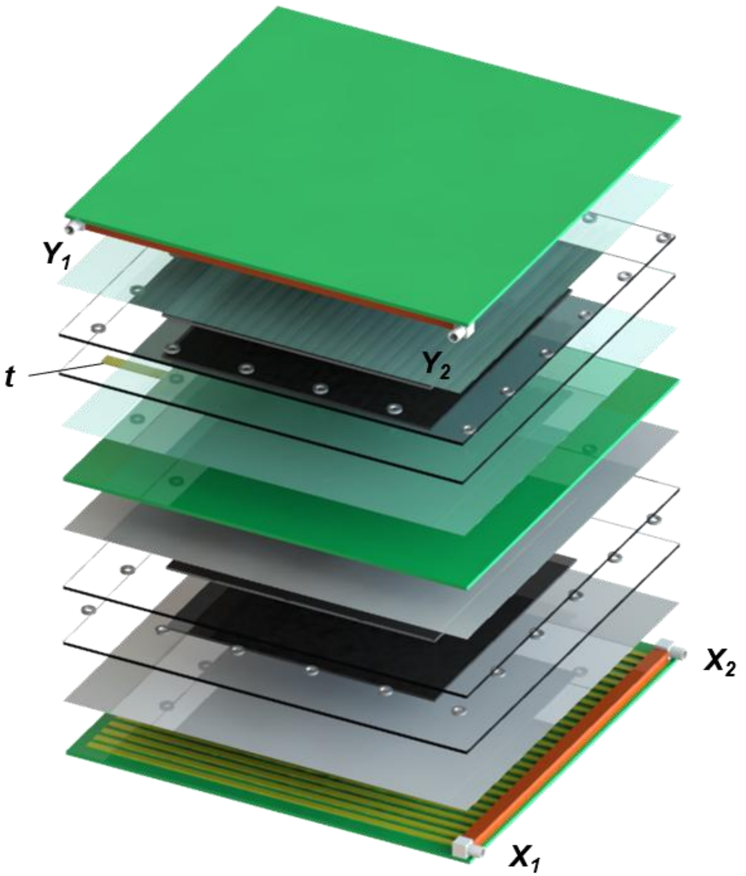
3D Imaging Test(2013~2014)

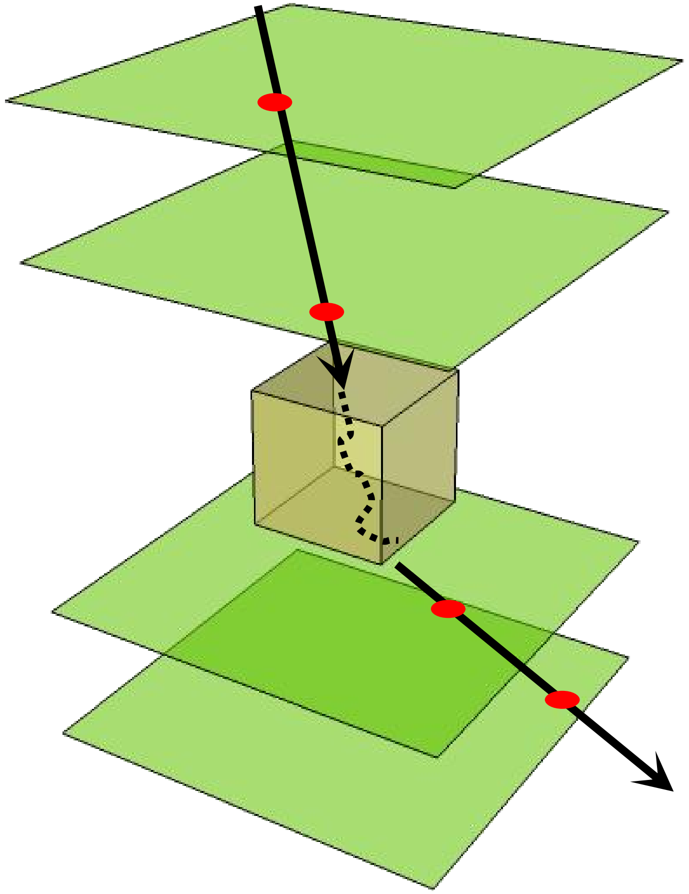
4 X-Y readout RPC Boxs, distance 285mm

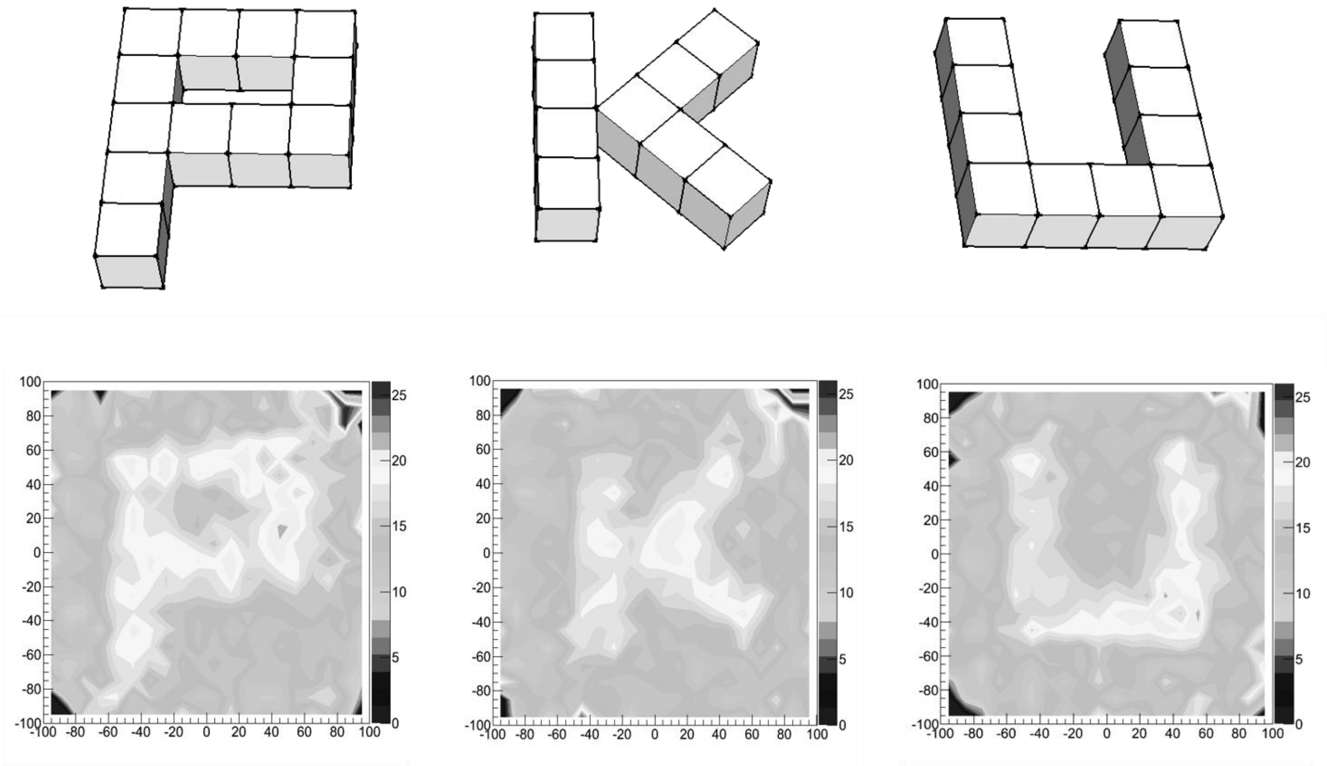
Active area 203mm*203mm

PKU prototype muon tomography System

Using only 20 TDC channels



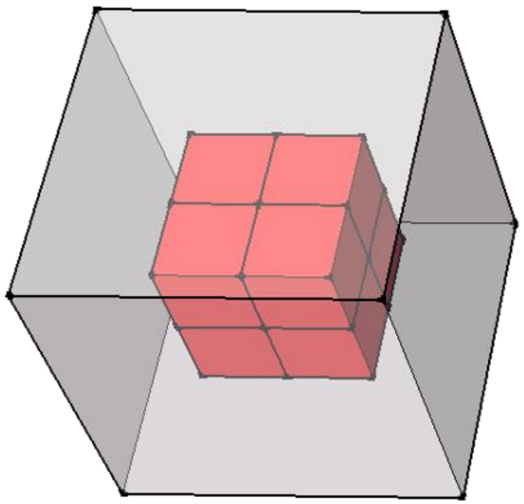


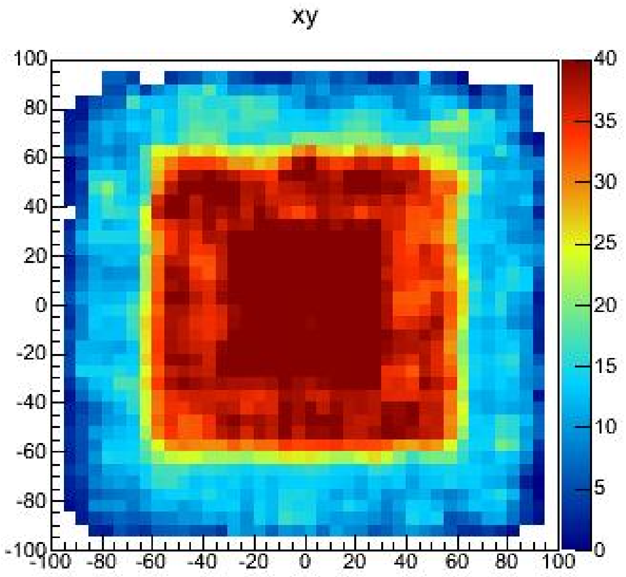


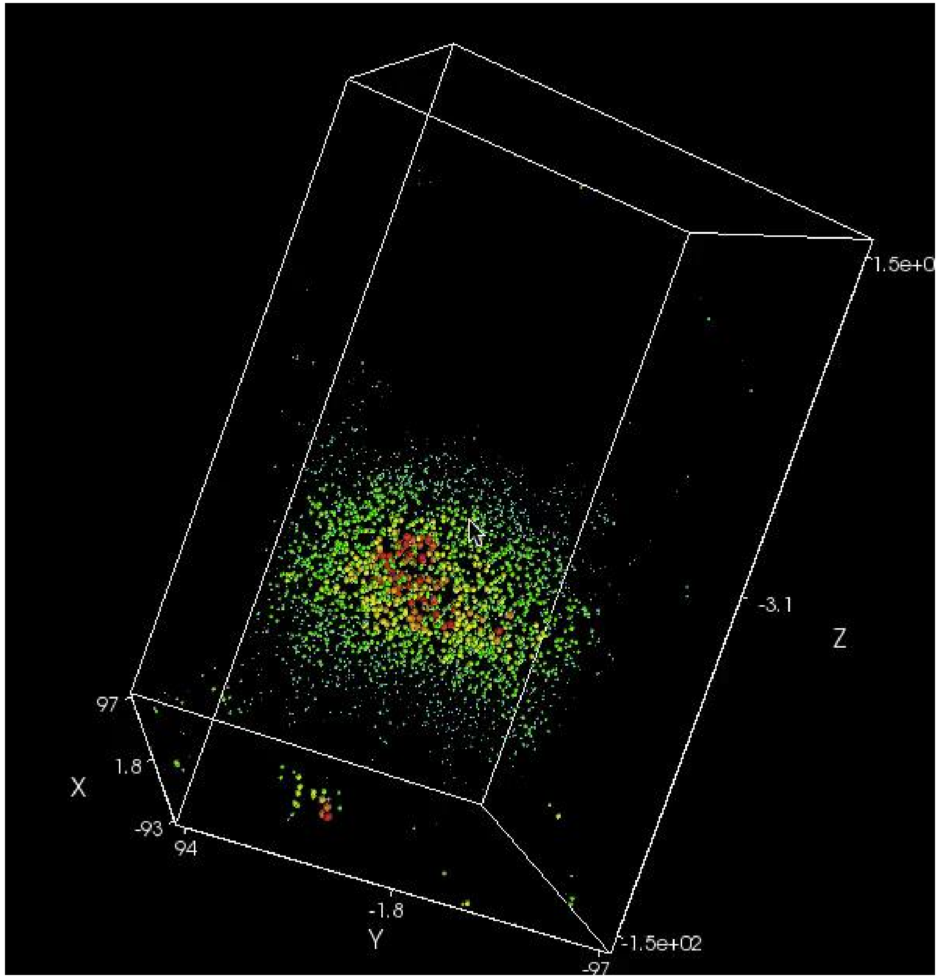
P K U
some 3*3*3cm^3
Fe blocks

- Using this RPC with high position resolution to build a cosmic ray muon imaging system to detect the incident and outgoing trajectory vectors of cosmic ray muons can measure a very small scattering deflection angle of <5 mrad (0.3°) and reconstruct the material distribution information in the sensitive area.

Imaging Results of a 6*6*6cm^3 Square Lead Block Wrapped in a 12*12*12cm^3 Iron Shell



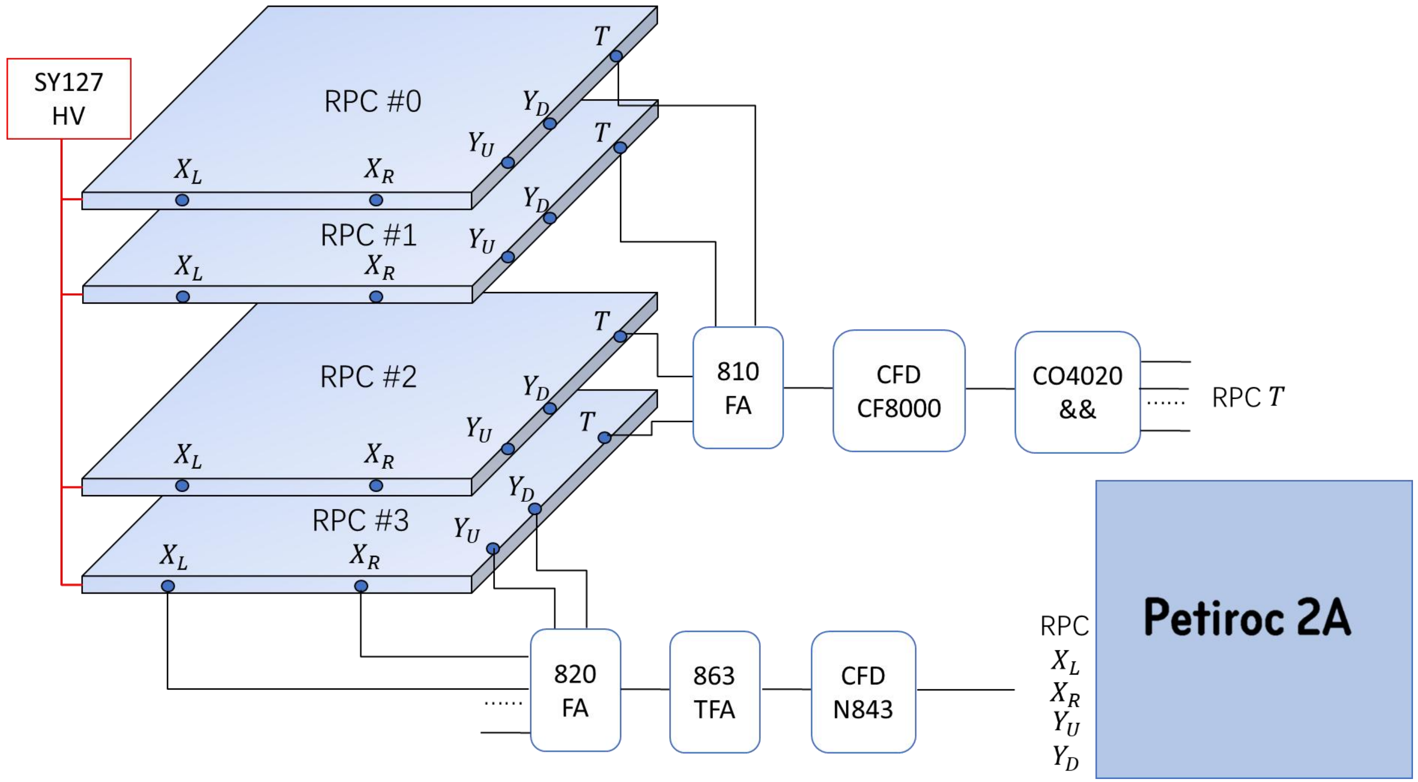




· Liu C M , Wen Q G , Zhang Z Y , et al. Study of muon tomographic imaging for high-Z material detection with a Micromegas-based tracking system[J]. 2020.

4RPCs Muon tomography for Dark Matter search (2023 - 2024)

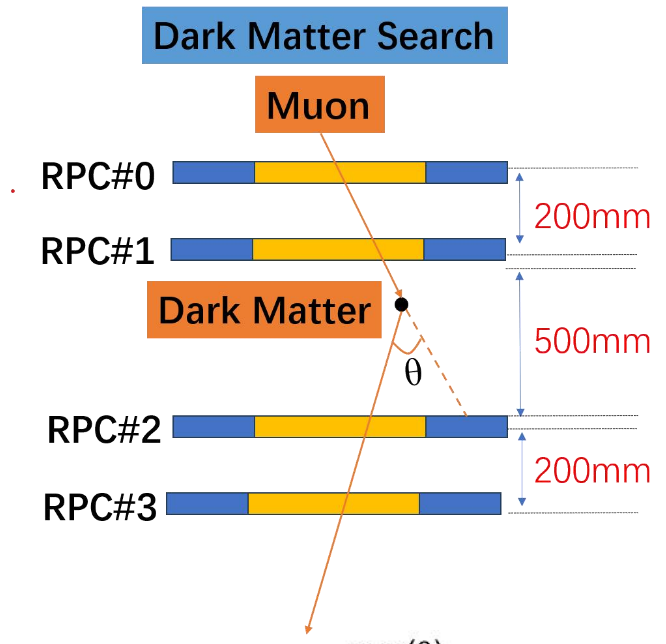
- 20cm-50cm-20cm
- Petiroc 2A ASIC DAQ by USTC

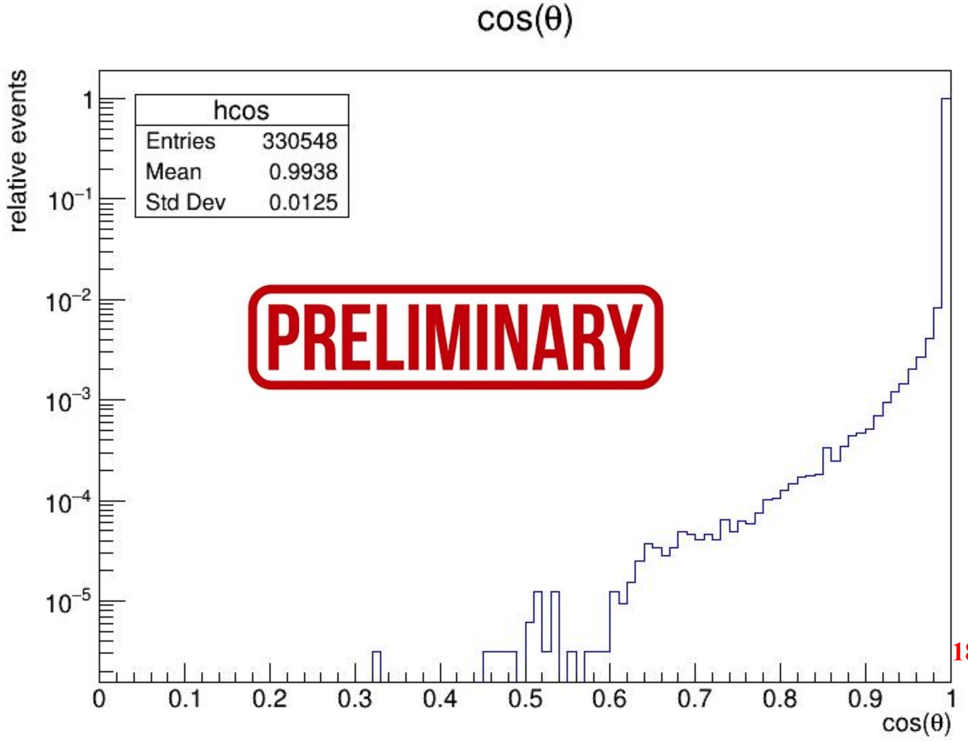


Run1 Muon Scattering data

- Jan. 2024 - May. 2024
- data accumulated 92 days in air
- sensitive volume
  - 50x20x20 cm^3

- 330548 valid events
- mean scaterring angle 0.0252 rad
- 1.6% θ>0.2rad

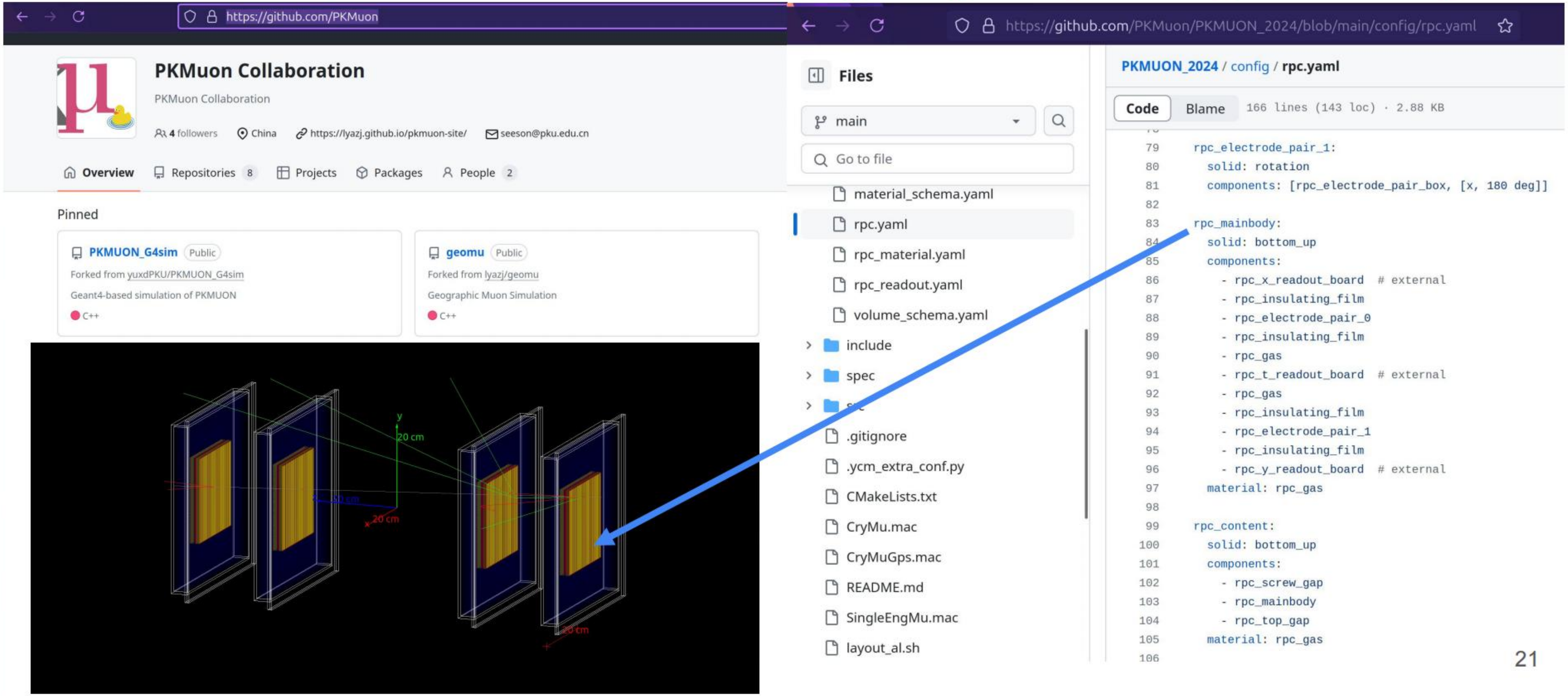




Growing PKMuon Software Framework

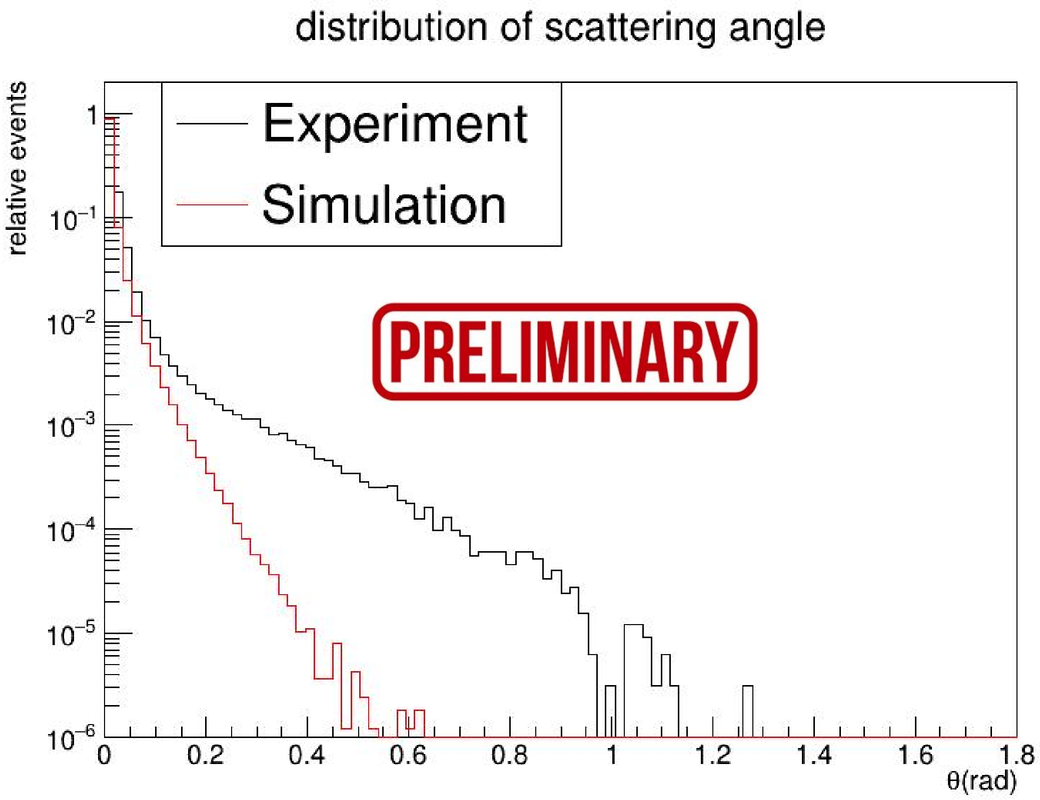
Collaborate on GitHub

Organize geometry modularly and extensibly



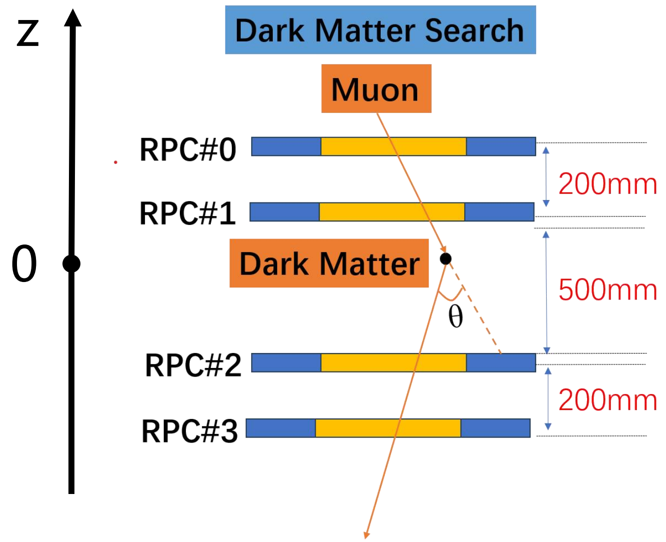
Run1——Preliminary comparison between experiment and simulation

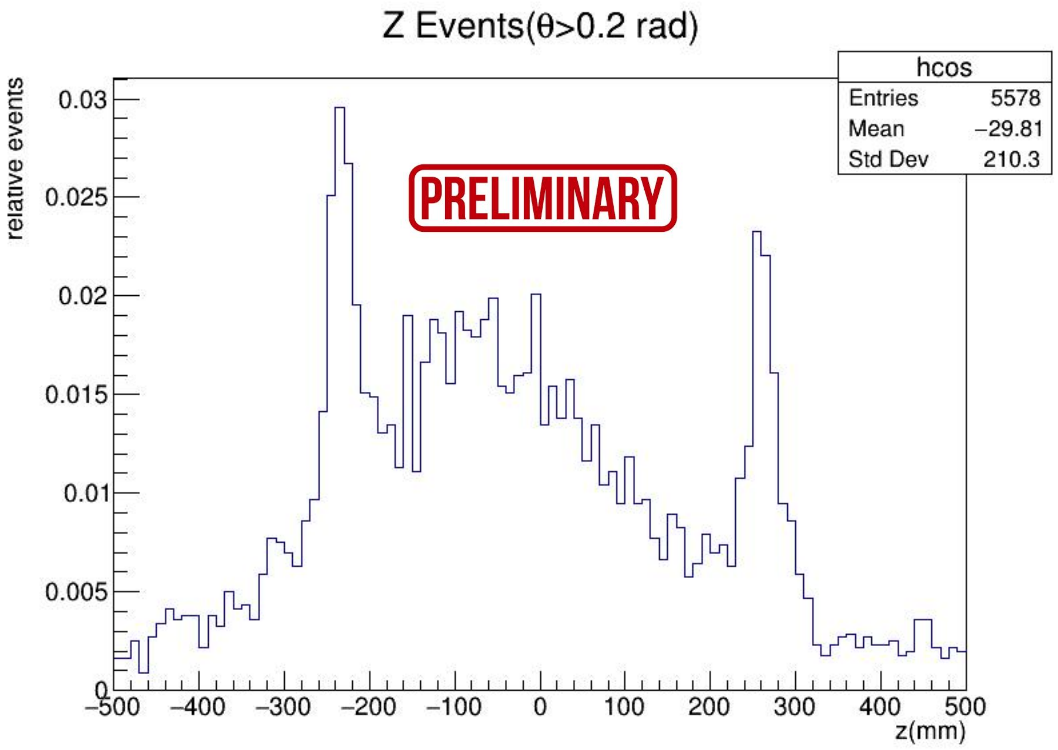
- Simulated the scattering angle distribution of cosmic ray muons.
- The experimental results differ significantly from the simulated muon scattering results at large scattering angles.
- Where do large-angle scatterings come from?

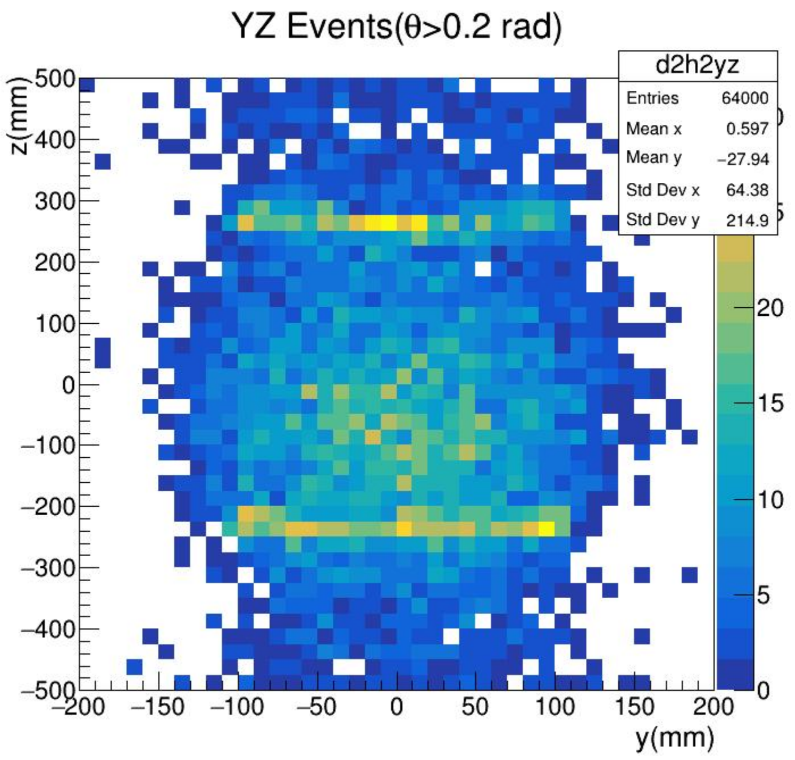


Run1 Muon Scattering data

Large Muon Scattering points on RPC and sensitive area

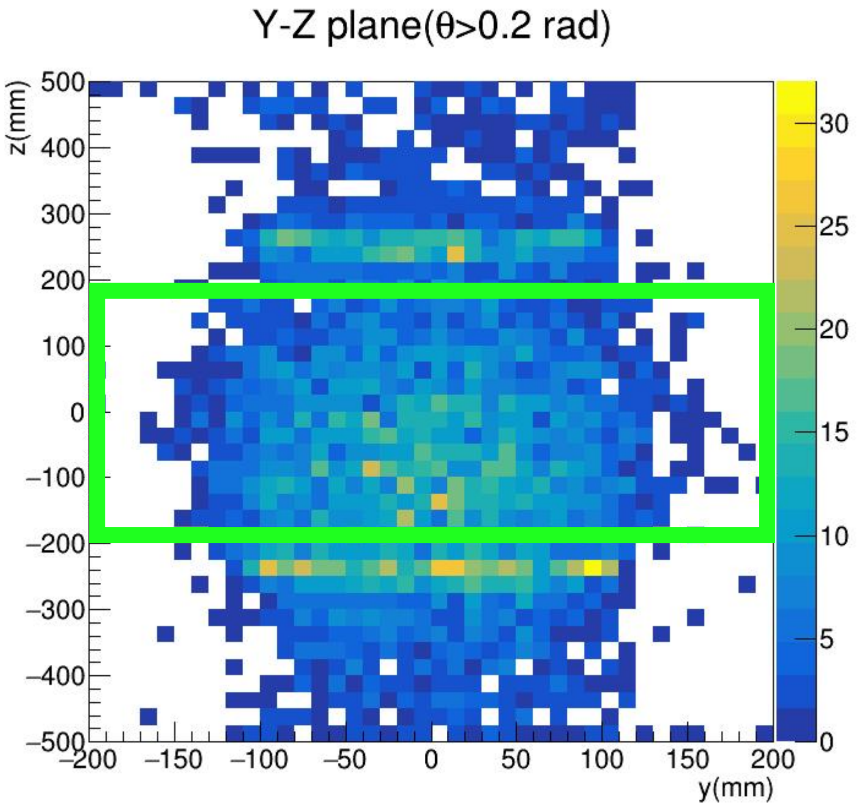


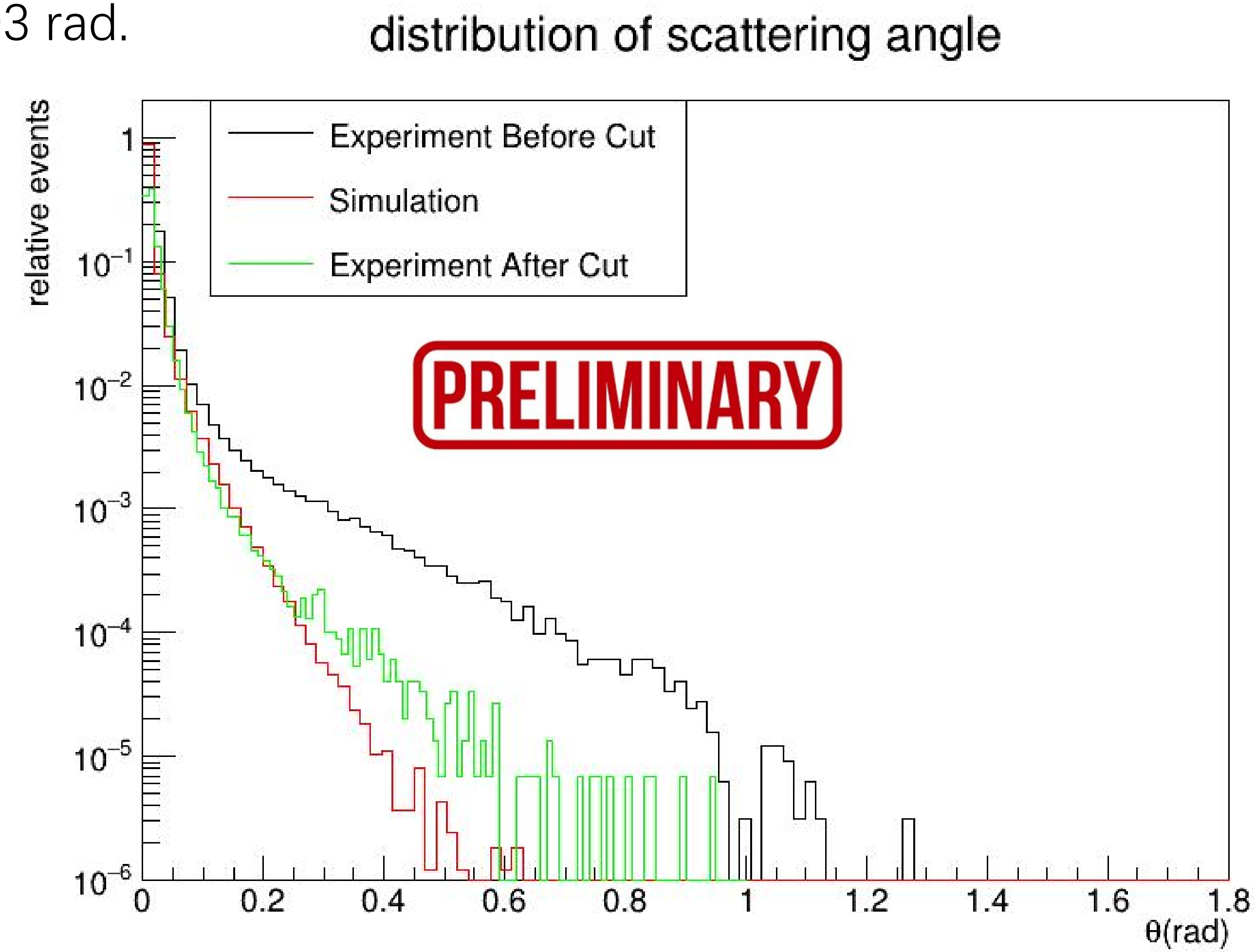




Run1——Scattering angles within the ROI

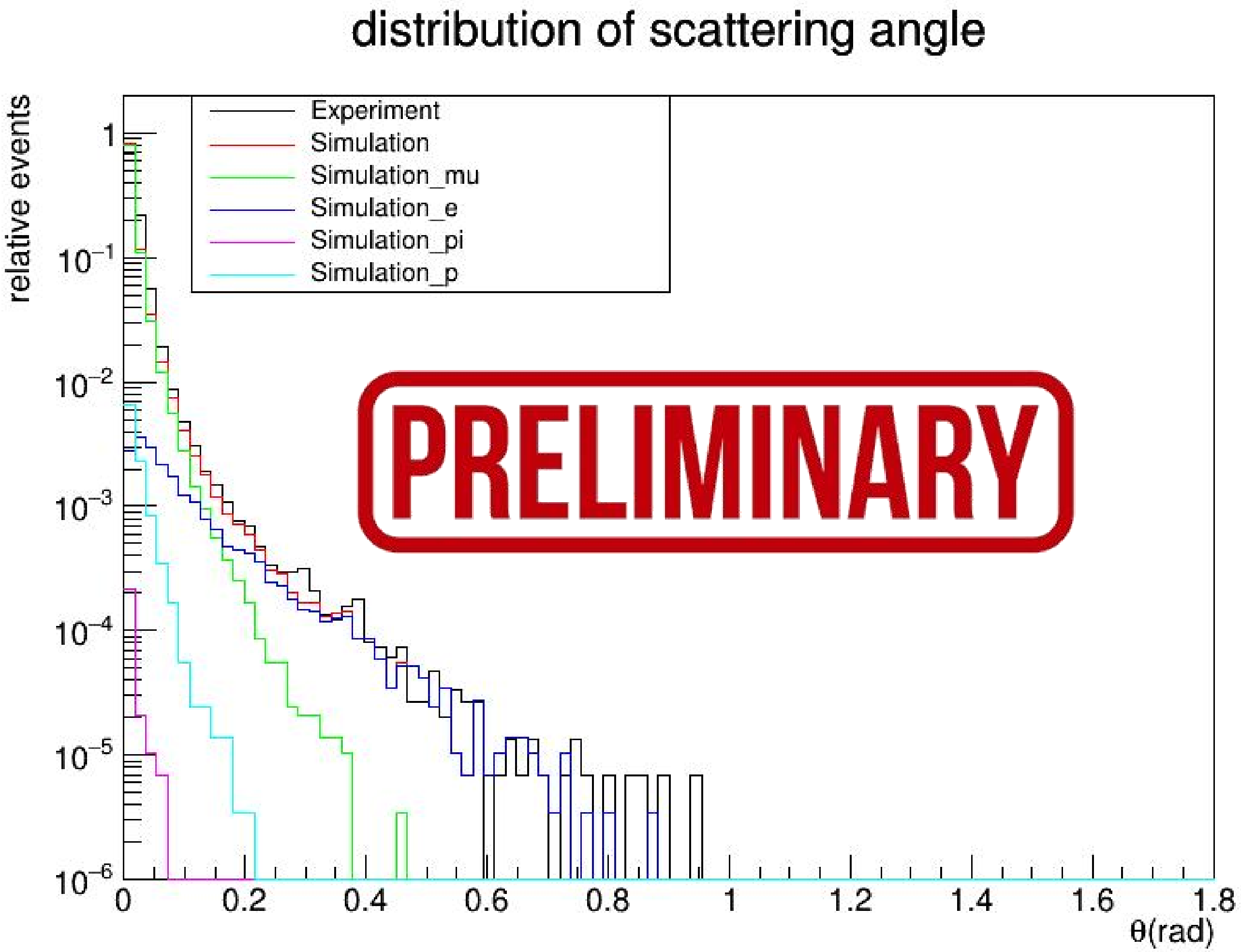
- there are still events at large angles.
- 147,251 valid events
- $\theta > 0.2$ rad accounting for 0.37%.
- The average scattering angle is 0.0193 rad.





Run1——Detailed simulation

- Simulation of the composition of secondary cosmic ray particles at sea level: μ, e, π, p
- The small angle is mainly for muons, and the large angle is mainly for high-energy electron
- partially understand the source of large-angle scattering
- To improve the detection limit of muon search for dark matter, it is necessary to exclude background events of high-energy electrons



RUN1 summary

- We have proposed a novel method for searching for dark matter using muon scattering.

- We conducted a 3-month test of muon scattering using a RPC-based muon scattering imaging system and obtained the scattering angle distribution.

- Using GEANT4, we constructed a muon scattering detection system with the same dimensions, materials, and spacing settings, and simulated the scattering angle distribution of cosmic ray scattering in air for this system.

- The experimental results showed a significantly higher number of events at large scattering angles than expected from the muon scattering simulation. Even after filtering events within the ROI, there were still excesses.

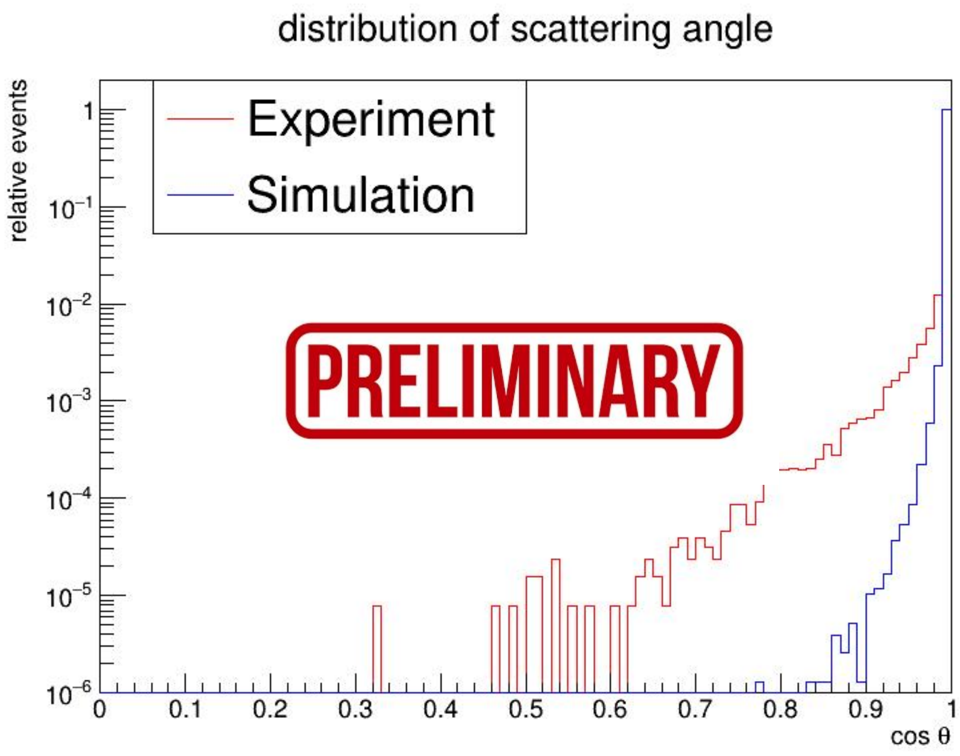
- Further analysis revealed that small-angle scatterings were mostly muons, while large-angle scatterings were mostly electrons.

- The data is still under analysis, and the results will be published soon. Please stay tuned.

- **Possible Reasons for the differences between experimental results and simulation results:**

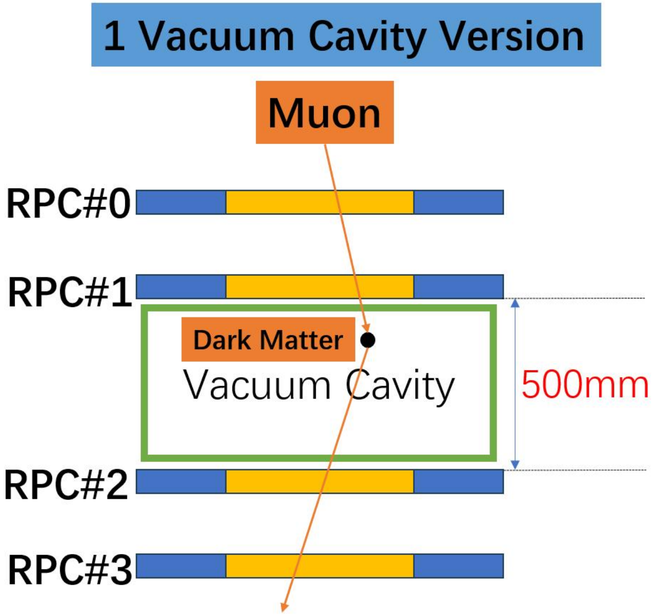
- Muon multiple scattering events
- Influence of low-energy muons
- Influence of components other than muons in cosmic rays
- There may be events where multiple muons or other particles enter the detection system
- The physical processes used in GEANT4 simulation may deviate from the simulation of large-angle scattering of muons in reality

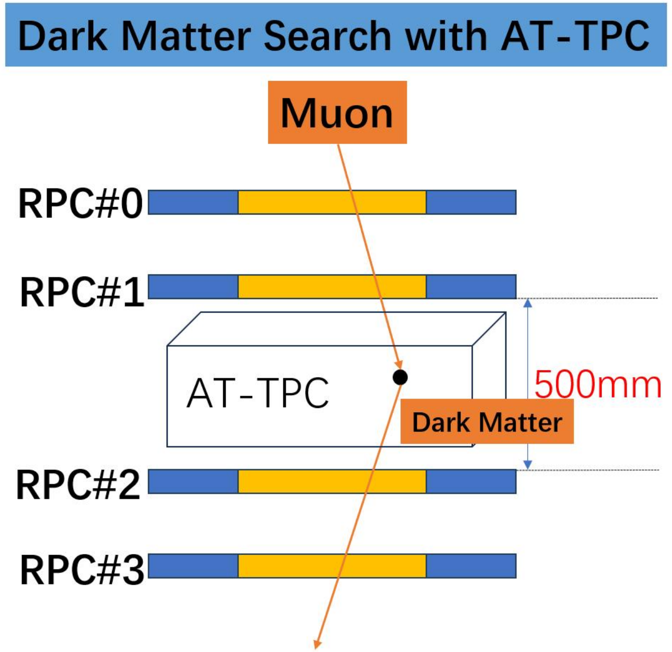
- A further understanding of the scattering of muons in materials and space may be needed.

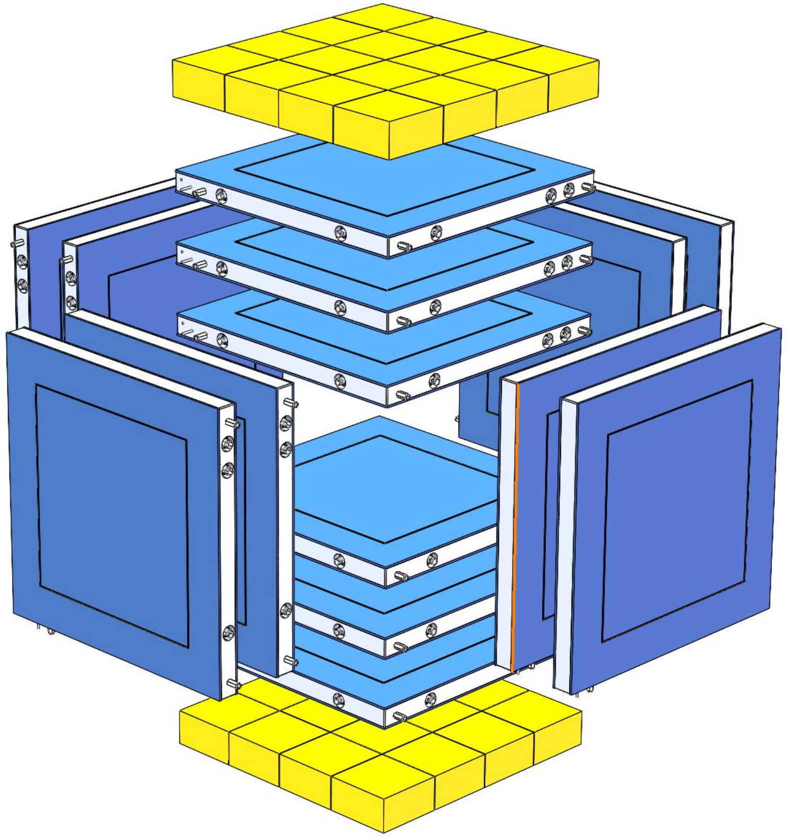


Future experiments

1. Upgrade the detection system to vacuum chamber mode to eliminate air interference.
2. Use AT-TPC to eliminate the influence of multiple scattering and locate the reaction point.
3. Large angle acceptance
4. PID



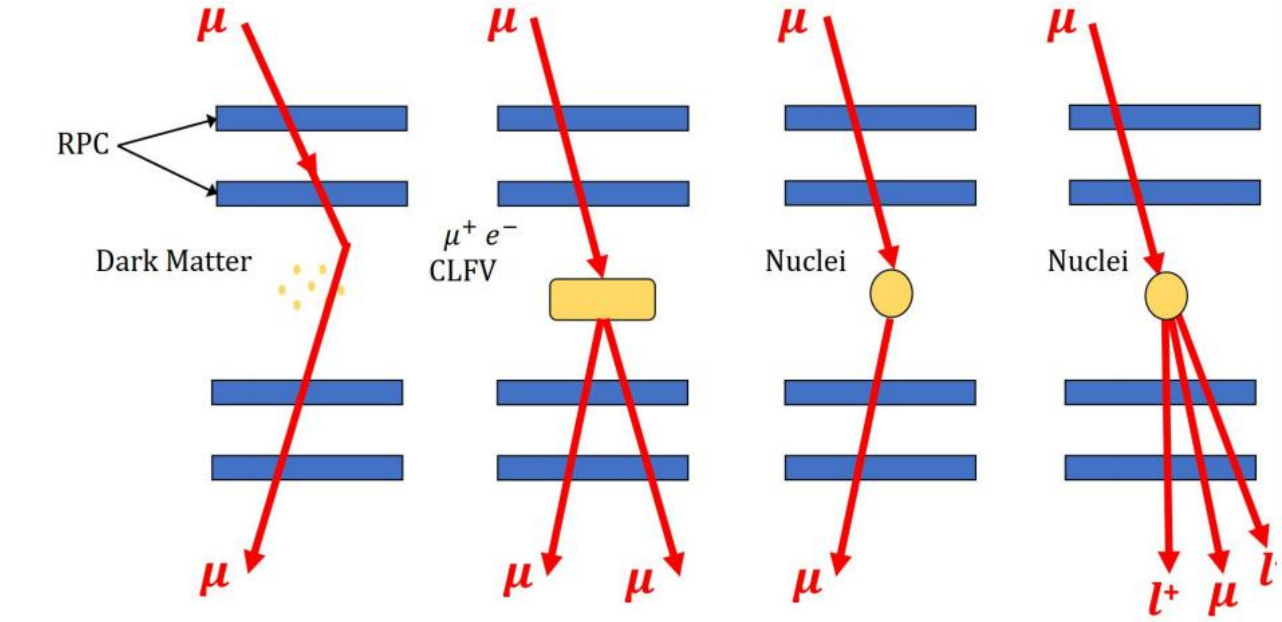


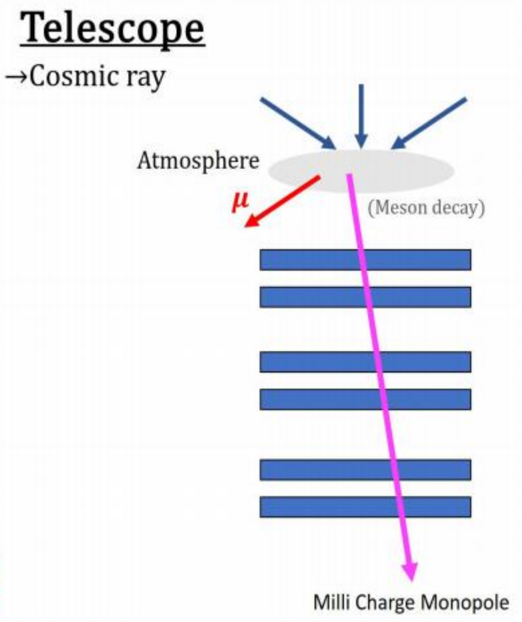


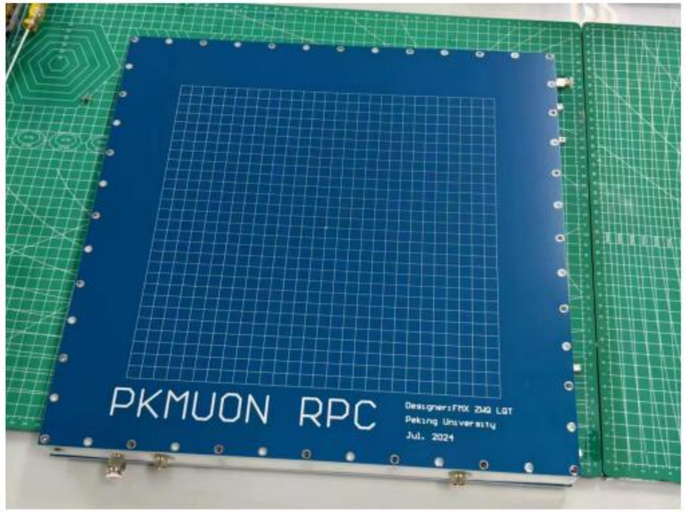
Future

Interfacing Cosmic Muon or Muon beam

→Cosmic μ or μ beam







More physics program:
CLFV, Muon-Nuclei scattering …

Larger area
RPC or GEM
being produced

CLFV arXiv: 2407.05831

Highlights, byproducts

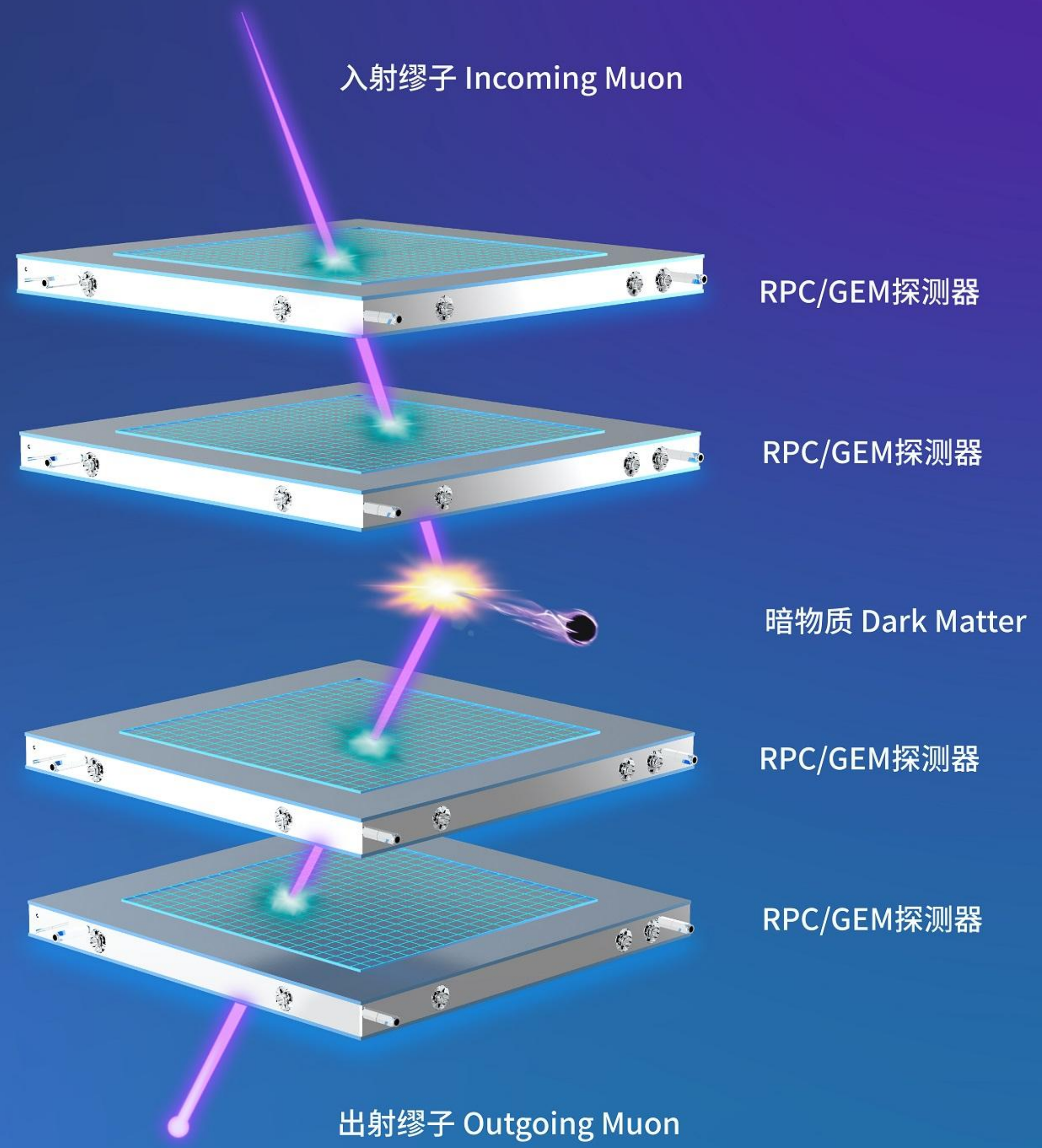
- Muon dark matter detection step by step
- Full scale Detector R & D & Applications
  - TPC / AT-TPC protential use on cosmic ray μ or μ beam dark matter scattering measurement
- Muon tomography applications
  - Cosmic muon manipulation
- HEP Muon experiment with Chinese Muon beam
  - More possibilities with Muon on target
- A route towards Muon collisions
  - Can also extend to neutrino experiment using muon decay

THANKS

Ref:

PKMu for DM
[1] Phys. Rev. D 110, 016017

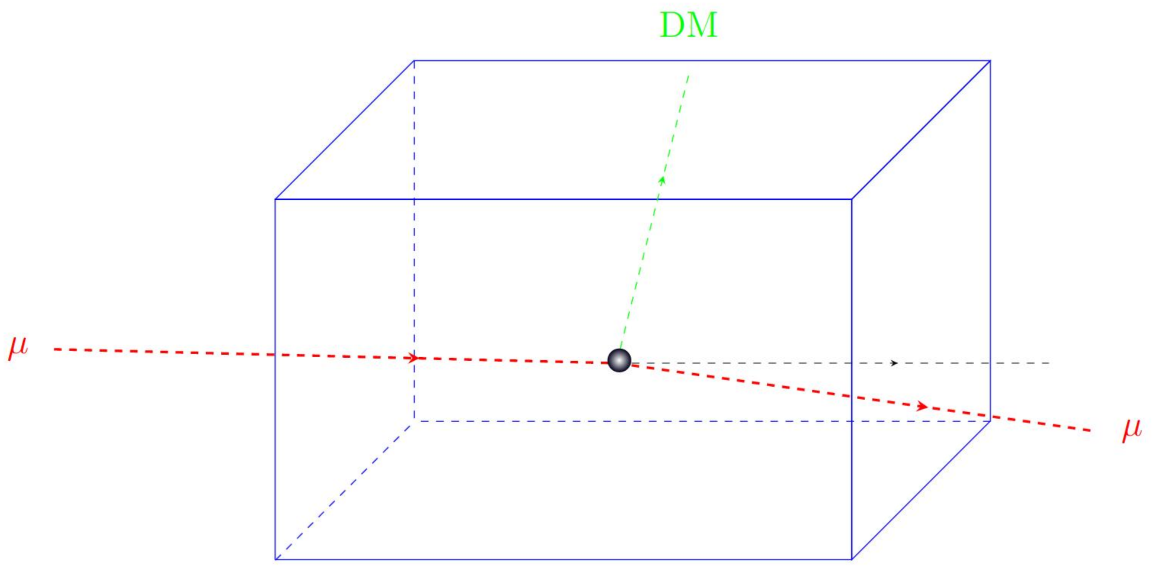
PKMu for CLFV
[2] arXiv: 2407.05831



Backup

- **Phase I:**
  - Muon Tomography using RPC/GEM
  - Probing dark with Cosmic Muons
- **Phase II:**
  - PKMu + Chinese Muon beams (CSNS, HIAF)
- **Phase III:**
  - Muon On Target using Chinese Muon beams
    - Invisible $\mu + N \to \mu + \text{dark}$
    - Visible $\mu + N \to \mu + \text{di-leptons}$
    - Muon Electron Threshold Scan: CLFV Z’, LFV DM
    - Others: trident, laser-assisted decay

Phase I: Muon Tomography for Muon-DM scattering



Surrounding tracker layers

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:

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

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

Melody, CIADS, HIAF Chinese Muon beams

Melody @CSNS: approved and the first Chinese Muon beam will be built in 5 years.

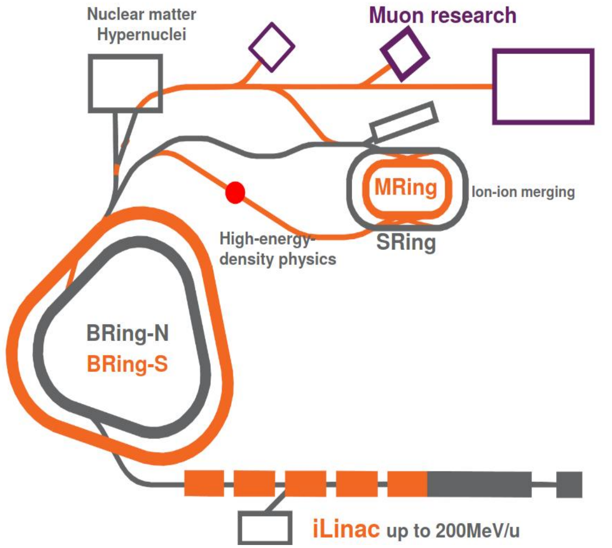
	Surface Muon	Negative Muon	Decay Muon
Proton Power （kW）	20	Up to 100	Up to 100
Pulse width (ns)	130 to 10	500	130 to 10
Muon intensity （/s）	$10^5 \sim 10^6$	Up to $5*10^6$	Up to $5*10^6$
Polarization （%）	>95	>95	50~95
Positron （%）	<1%	NA	<1%
Repetition （Hz）	1	Up to 5	Up to 5
Terminals	2	1~2	2
Muon Momentum（MeV/c）	30	30	Up to 120
Full Beam Spot（mm）	10 ~ 30	10 ~ 30	10~30

HIAF & HIAF-U

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences
HIAF

- **BRing-N**: 34Tm, 569m, 3Hz
- **SRing**: 17(25)Tm, 270.5m, accumulation/compression
- **BRing-S**: 86Tm, 3Hz, superconducting
- **MRing**: 45Tm, superconducting, beam merging

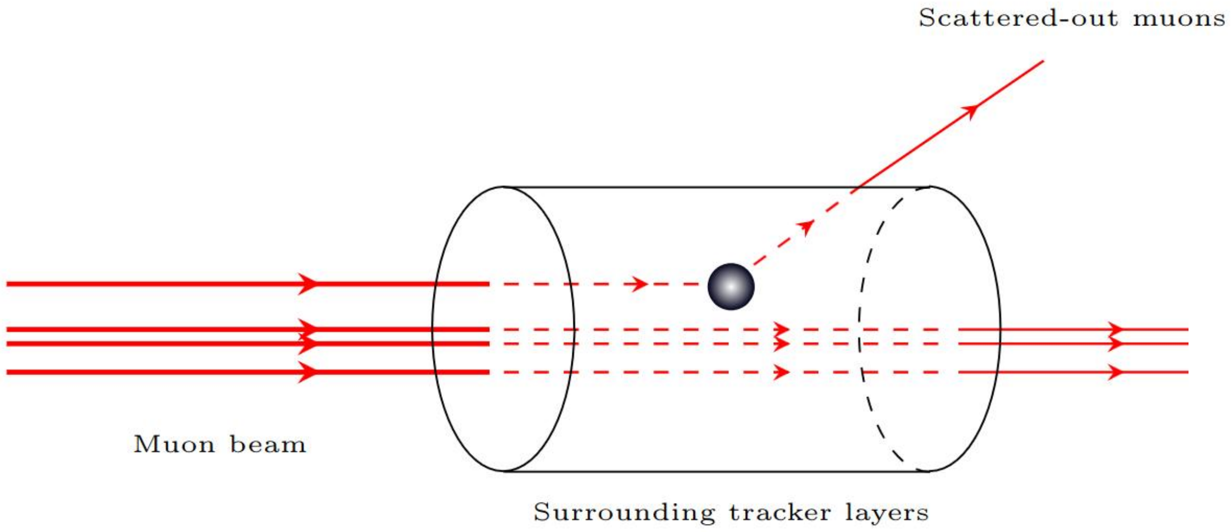
	Particle (GeV/u)		Intensity (ppp)	Est. time
FAIR	2.7	$^{238}U^{28+}$	5×10^{11}	2025
NICA	4.5	$^{197}Au^{32+}$	4×10^{9}	2022
FNAL	8.0	p	6.8×10^{13}	2028
	3.0	$^{238}U^{35+}$	2×10^{12}	
HIAF-U	9.1	$^{238}U^{92+}$	1×10^{12}	2032
	25	p	4×10^{14}	



~30 MeV, ~100 MeV (2028)

~1GeV (2026)

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 $10^7\mathrm{s}$.

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

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.