北京大學 PEKING UNIVERSITY

PKμ

Phys. Rev. D 110, 016017
IJMPA 38, No. 29n30, 2350154 (2023)

MIP2024-1 , MIP2024-poster
COUSP2024-1 , COUSP2024-2

https://lyazj.github.io/pkmuon-site/

PKMu缪子散射实验的初步进展与展望

PKμ-Probing and Knocking with Muons

Preliminary Progress in Probing Dark Matter with an RPC-based Cosmic Muon Scattering Detection System

李奇特 周辰 李强 PKMUON合作组

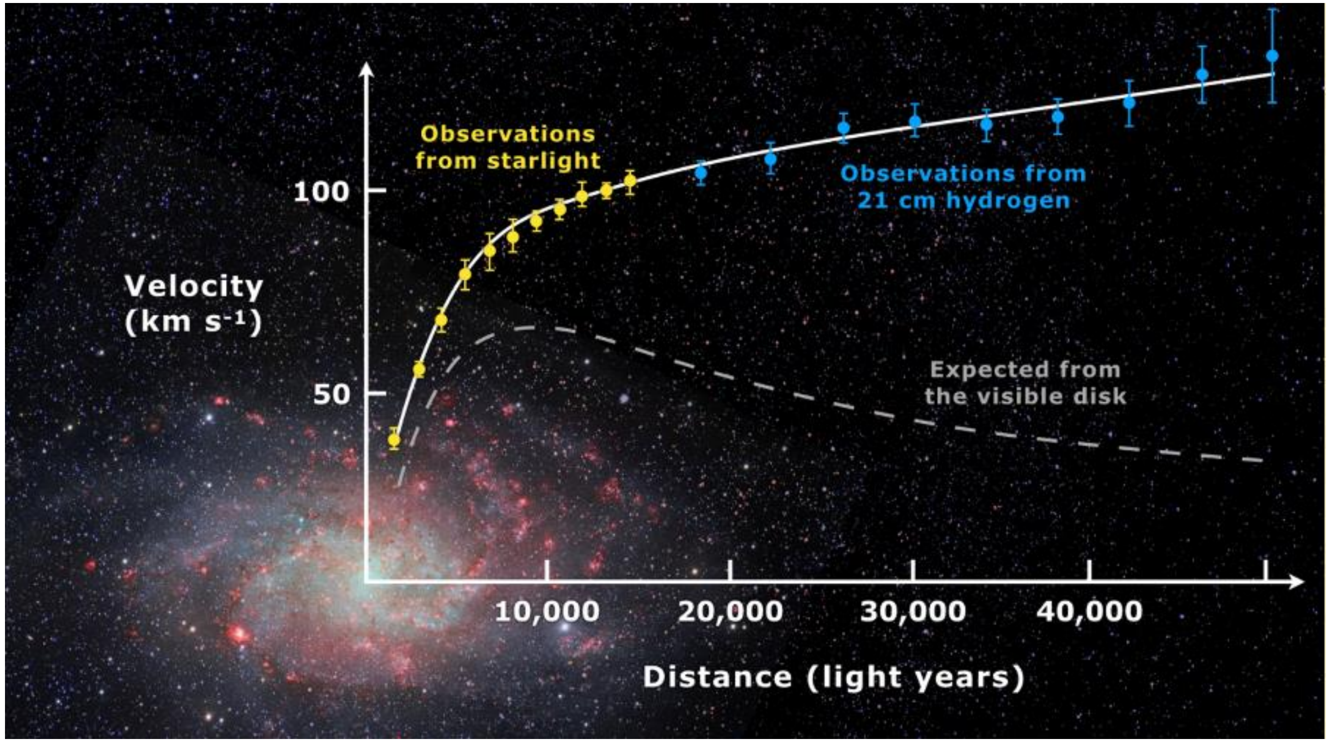
2024.08.26

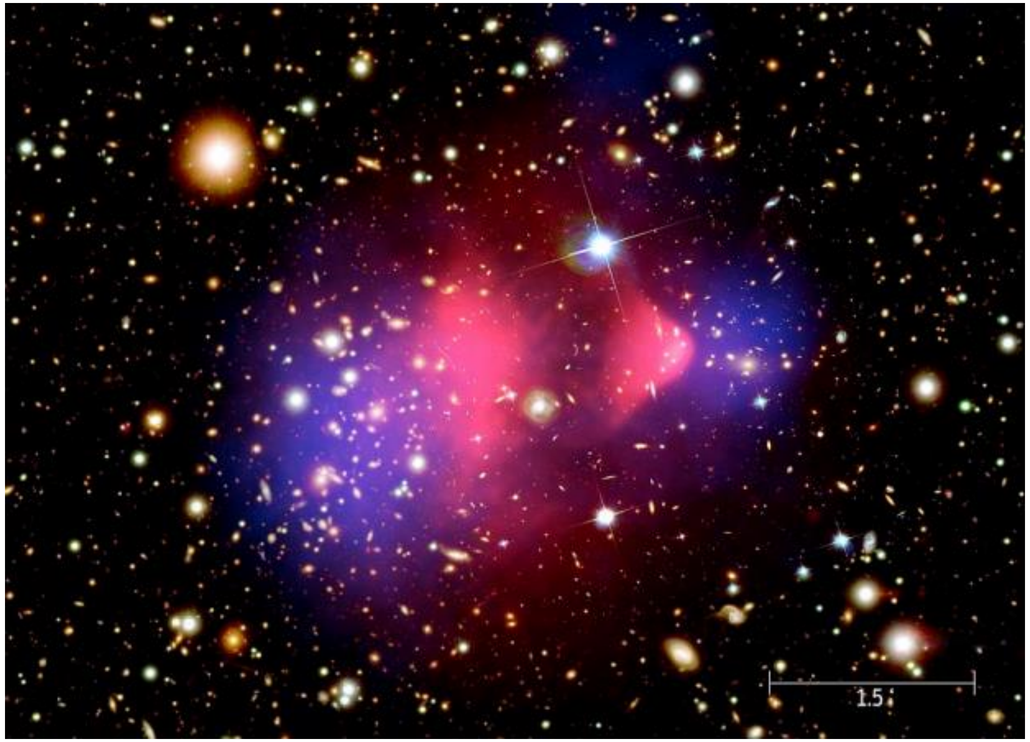
CONTENTS

目录

简介——暗物质存在证据

- 星系旋转曲线(1933/1970s)　　　　子弹星系团



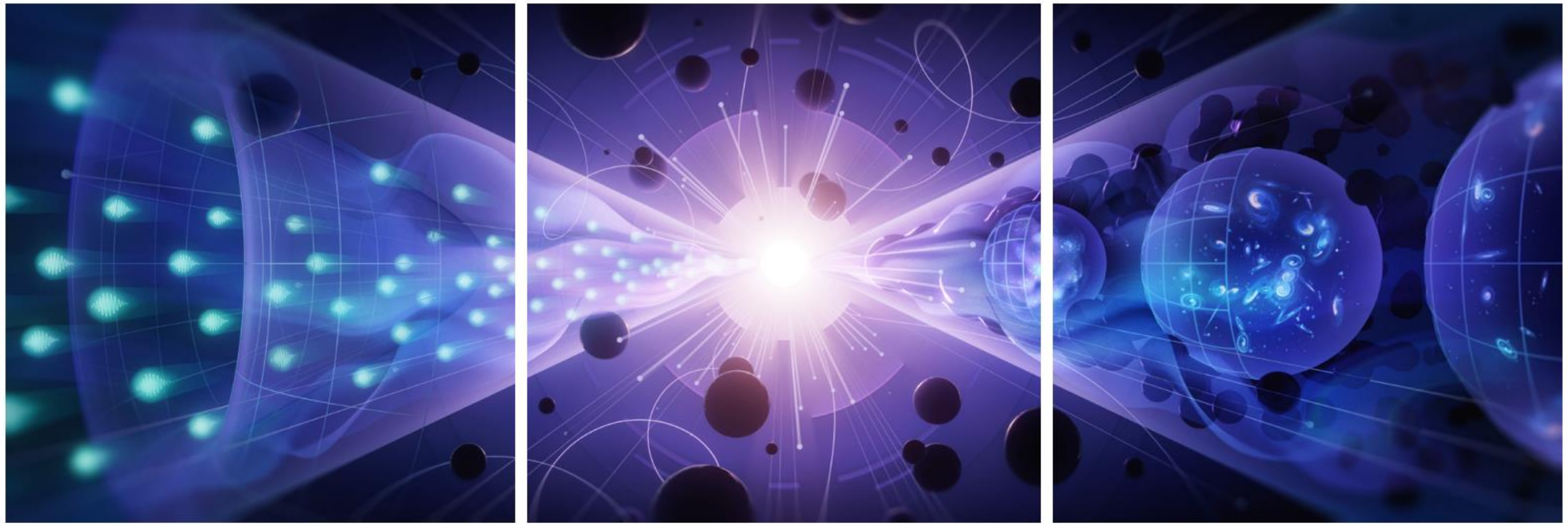


Credit: Mario De Leo. CC BY-SA 4.0.

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.

- 引力透镜、微波背景辐射、大尺度结构形成计算
- 正常物质：暗物质：暗能量　　5:27:68

Report of the 2023 Particle Physics Project Prioritization Panel / USA



Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

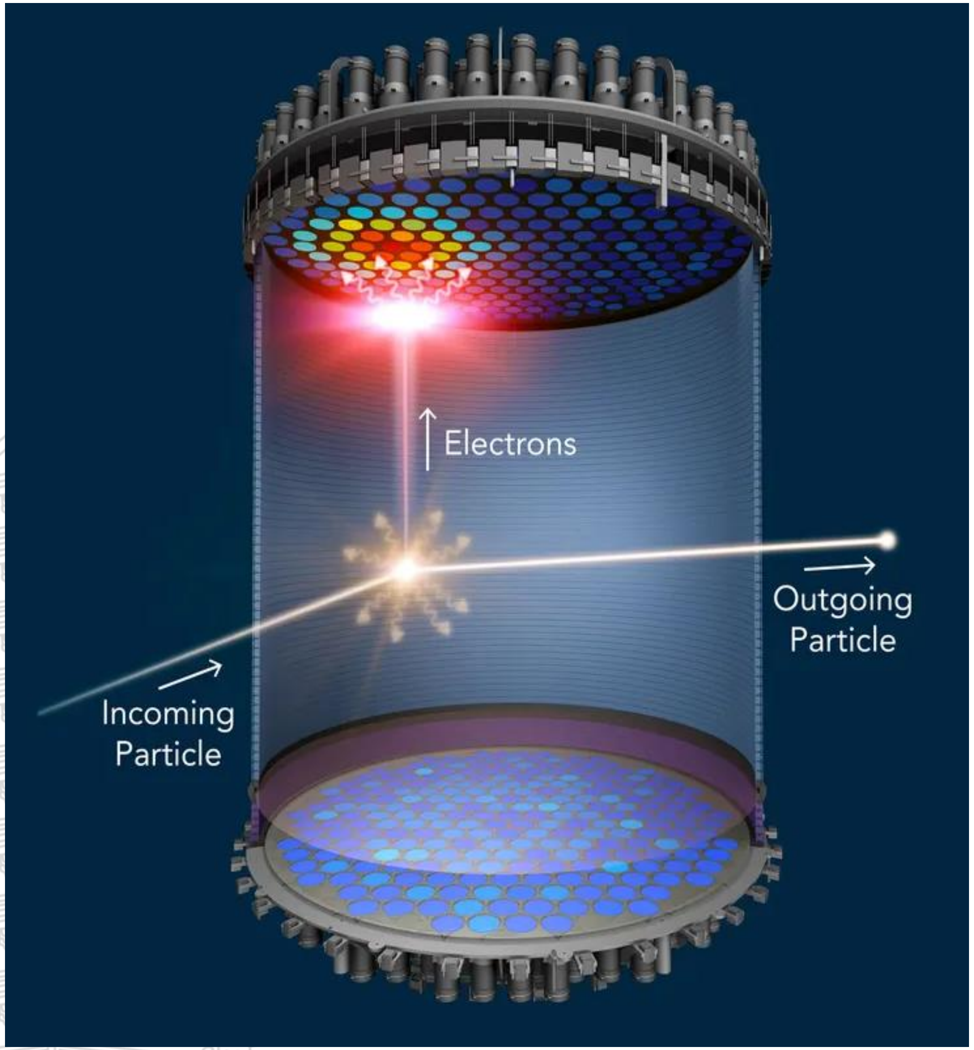
Determine the Nature of Dark Matter. The gravitational evidence for dark matter is overwhelming. We have many ideas for what dark matter could be, with a handful of particularly compelling candidates with viable cosmological histories. The number of strong candidates inspires a multifaceted campaign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

National Natural Science Foundation of China

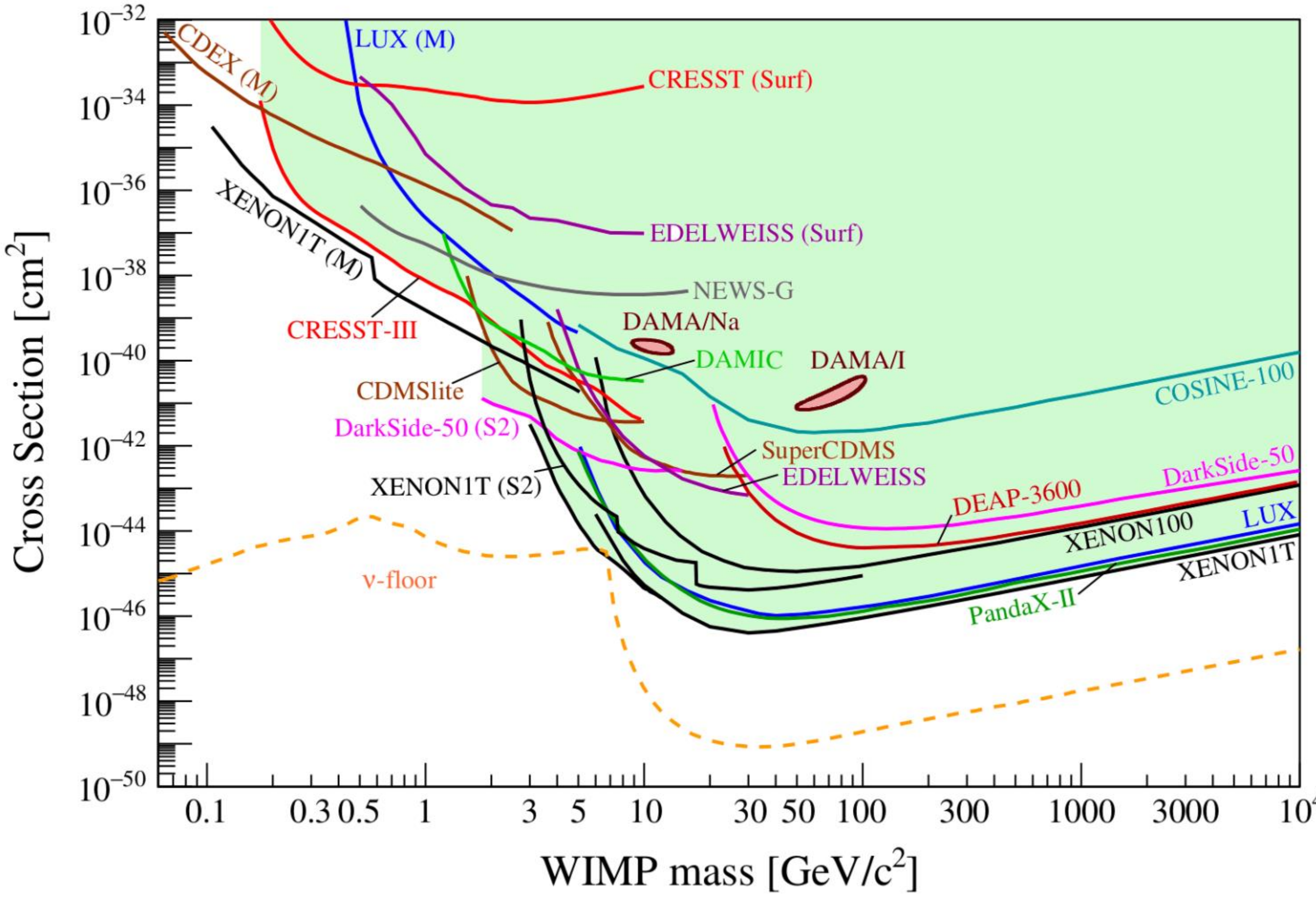
“十四五”优先发展领域（115项）

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。

WIMP 暗物质直接探测实验



Credit: SLAC



APPEC Committee Report arXiv:2104.07634

PKMUON

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

Highlights Recent Accepted Collections Authors Referees Search Press About

Open Access

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

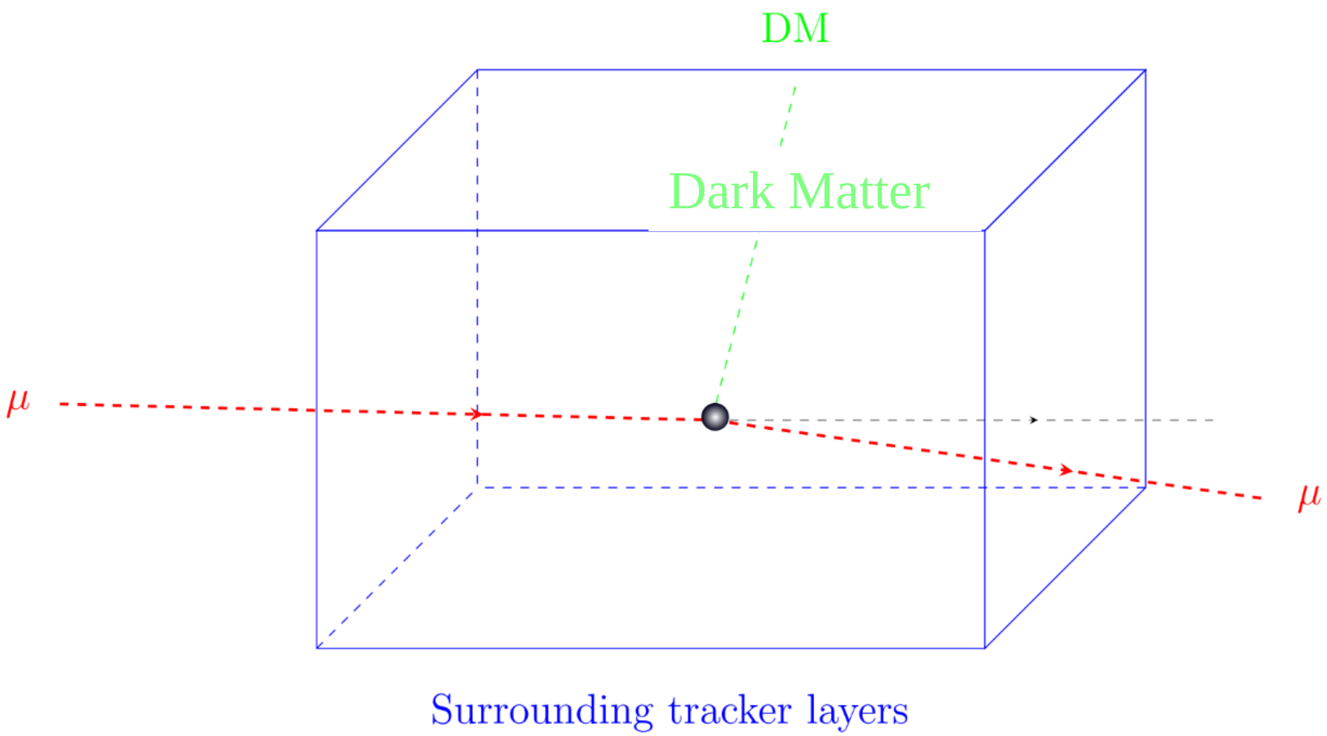
Xudong Yu, Zijian Wang, Cheng-en Liu, Yiqing Feng, Jinning Li, Xinyue Geng, Yimeng Zhang, Leyun Gao, Ruobing Jiang, Youpeng Wu, Chen Zhou, Qite Li, Siguang Wang, Yong Ban, Yajun Mao, and Qiang Li

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

简介——缪子散射探寻暗物质

- 我们希望利用缪子进行暗物质搜索：

1. 缪子与暗物质反应甚少有人研究
2. 缪子是SM第二代轻子
3. 自由缪子寿命较短/宇宙中非常稀少
4. 实验条件：宇宙射线缪子探测成像的经验/中国未来缪子源



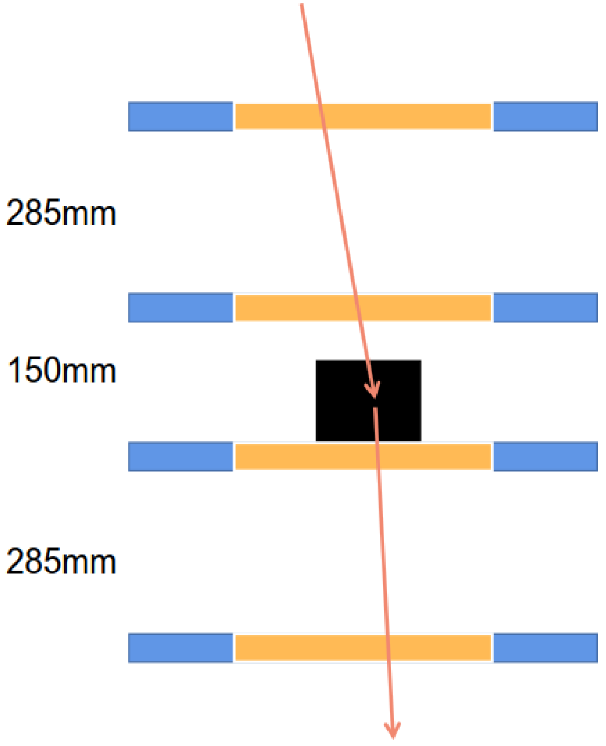
PKMUON：PKU提出的缪子散射成像和暗物质寻找的实验方案

arXiv:2402.13483 arXiv:2303.18117

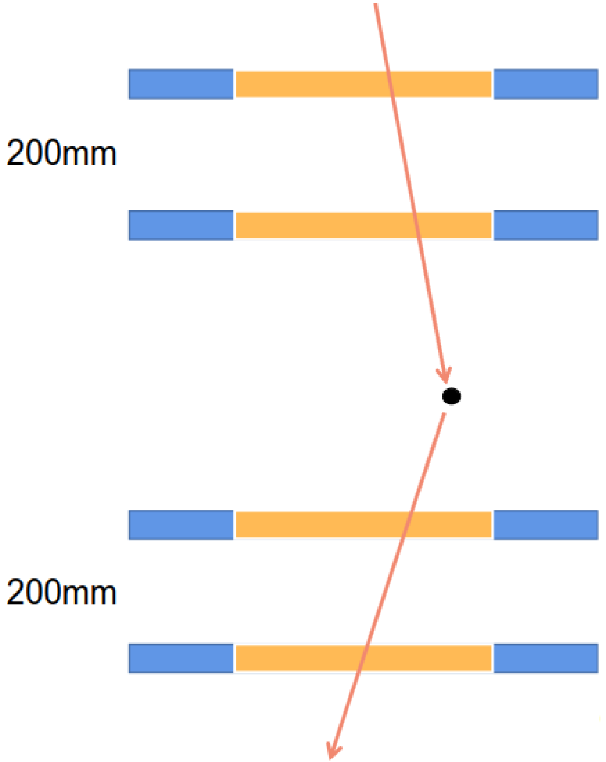
基于 RPC, GEM, AT-TPC, etc.

20cm*20cm 60cm*40cm 完整径迹

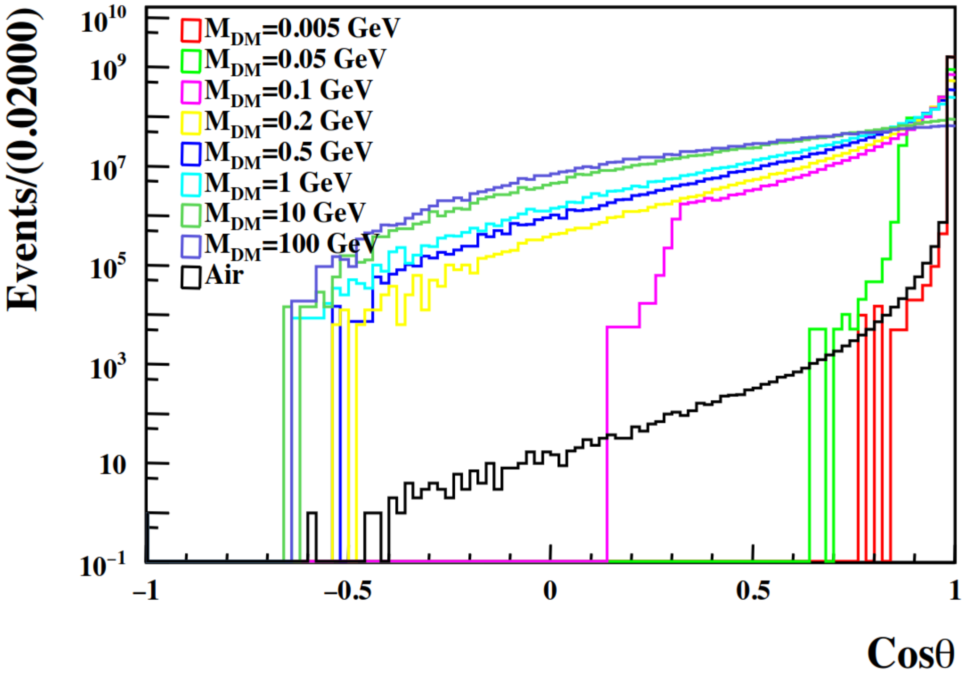
Muon Tomography
缪子成像装置，容易转换成缪子对空间的散射角测量



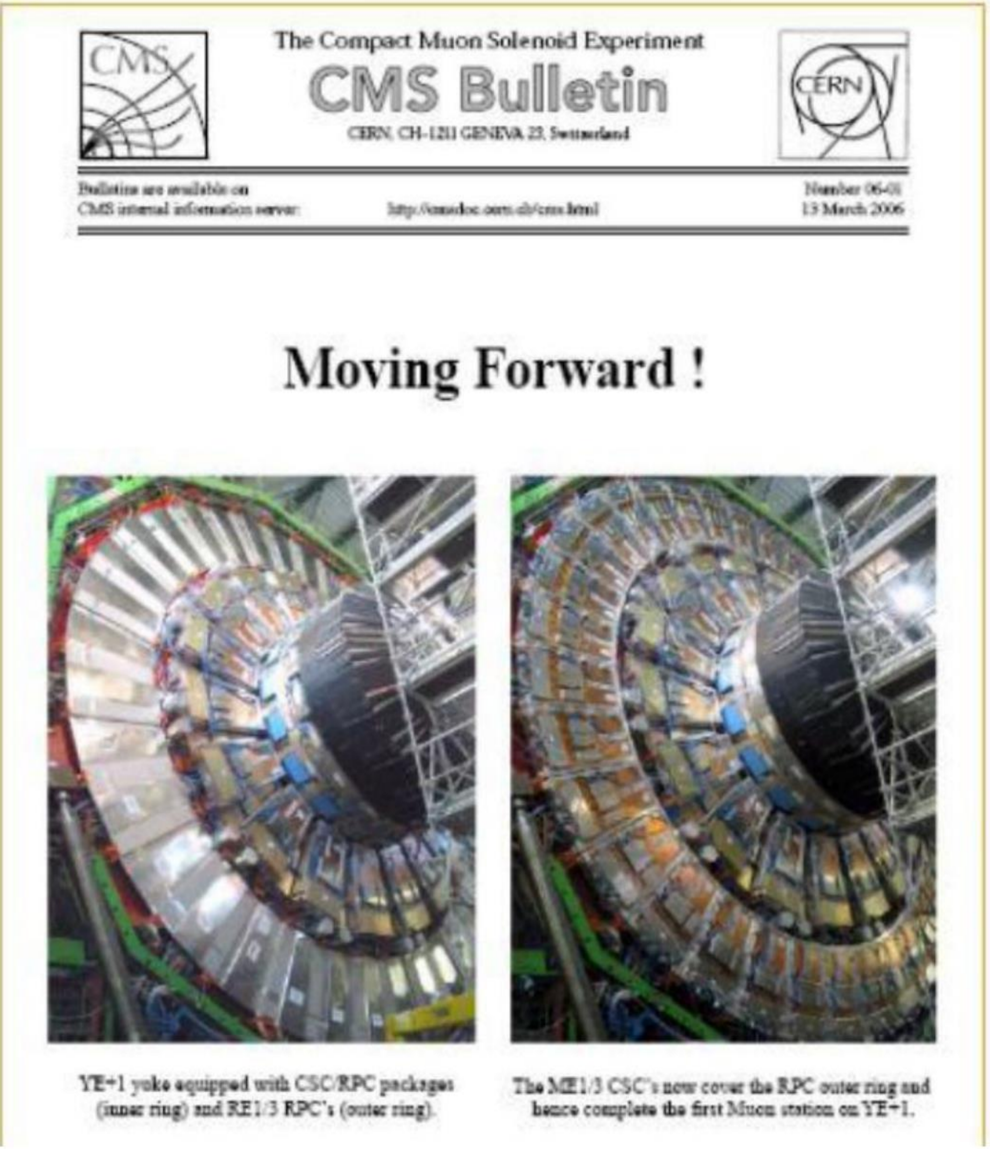
Dark Matter Search 暗物质寻找
(arXiv: 2303.18117 accpted by ITJMPA)



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 ~ m^2
- 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

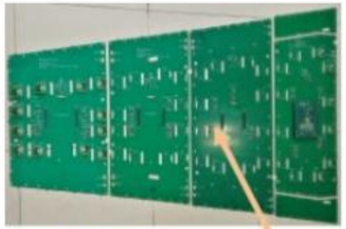
PKU Lab

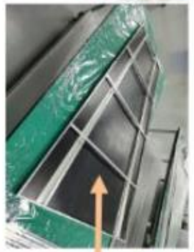
北大基地生产的第一个CMS GEM模块

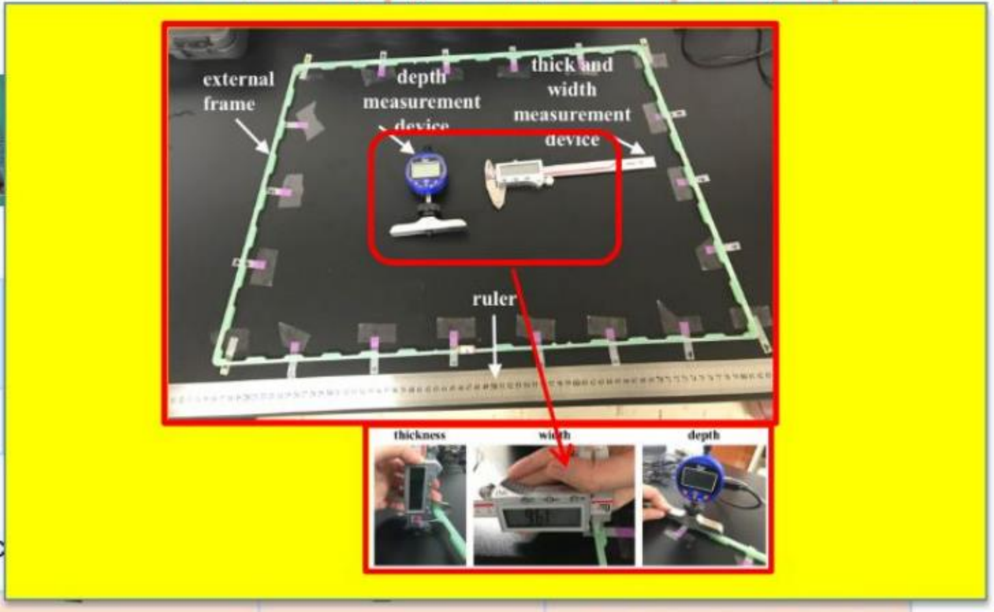
Module Components

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

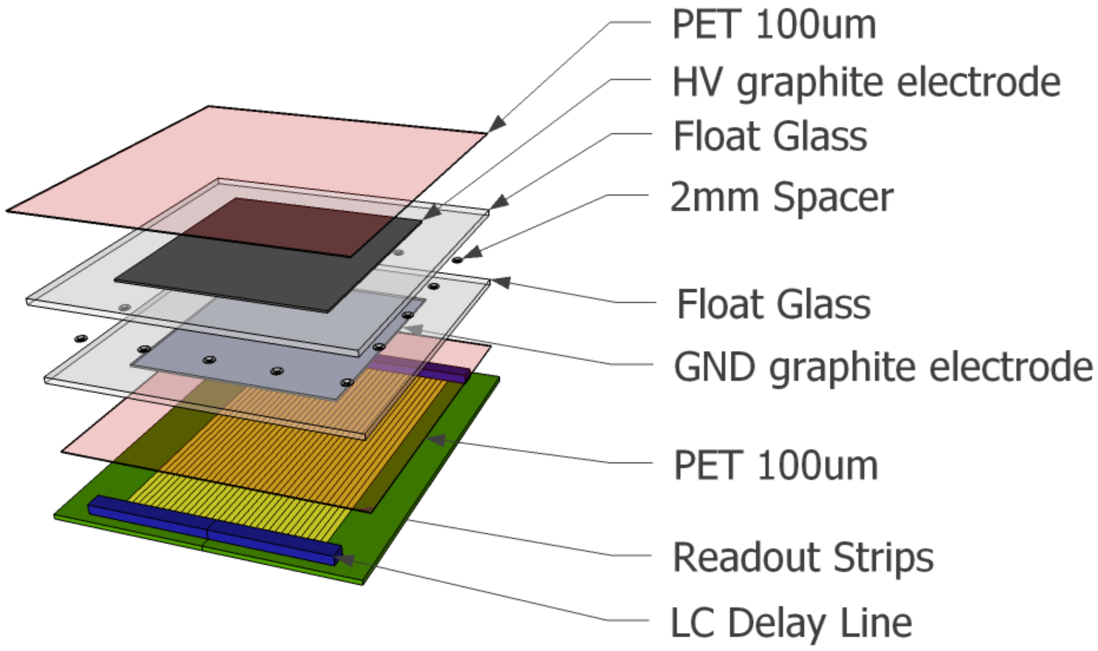
Chamber components

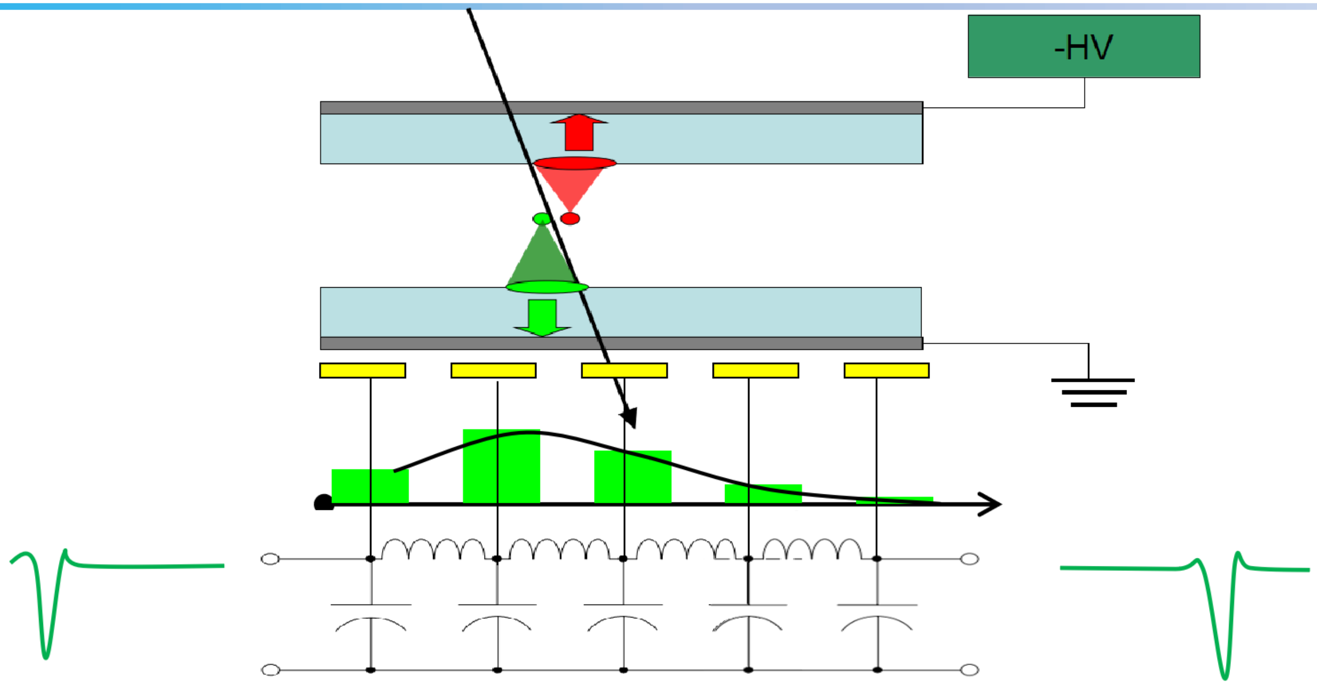
Components	Mechanics	On-detector Fibers	HV filters	Cooling	On-detector Cabling (HV/LV/GND)
% Produced	COMPLETED	COMPLETED	~30%	50% - 100%	COMPLETED

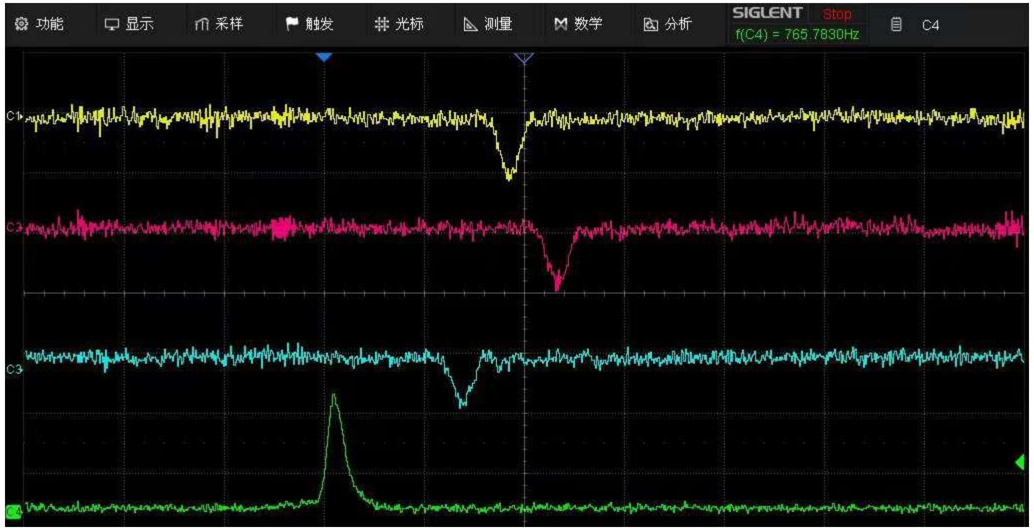
中国组负责生产的GEM部件均已按计划完成并通过CERN检测！

高位置分辨率阻性板气体室（RPC）研发与宇宙射线缪子成像结果

首创大面积玻璃RPC与延迟块读出技术结合
对μ子位置分辨 0.3~0.4 mm (σ)

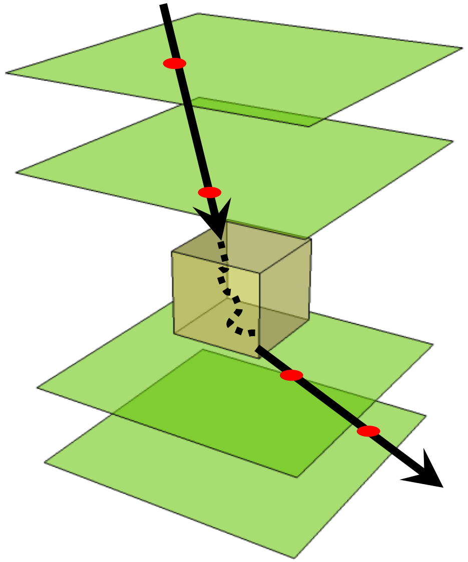


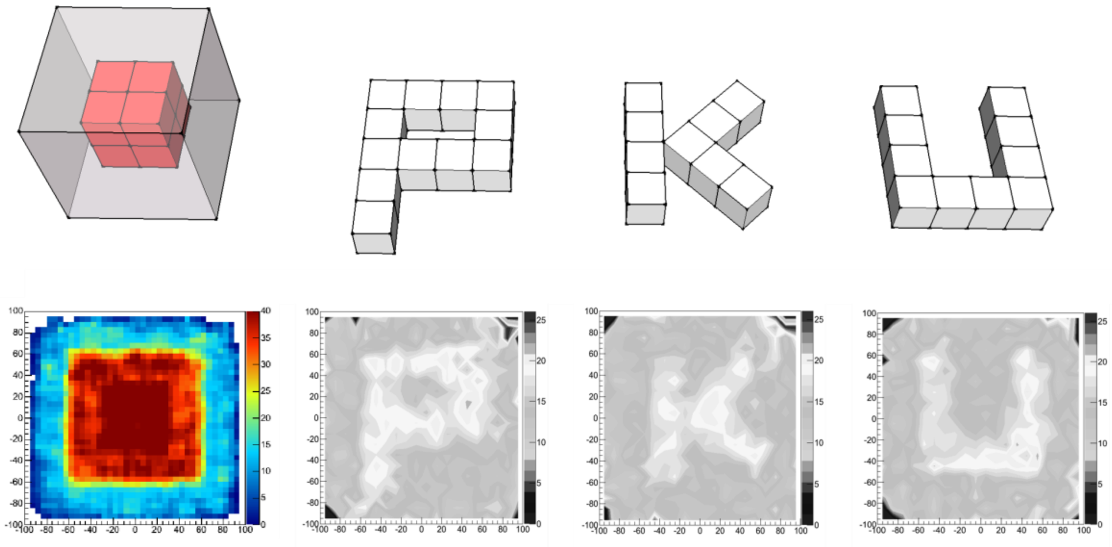




参考文献：

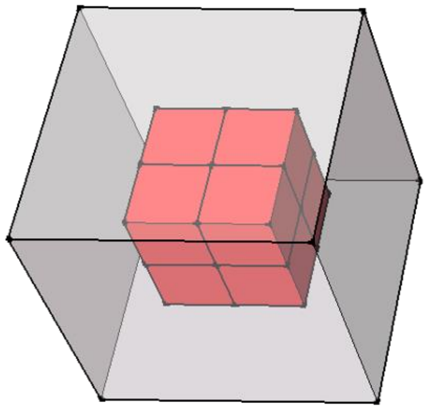
- **Li, Qite**, *et al*. ***NIM-A*** 663.1 (2012): 22-25.
- **Qi-Te, Li,** *et al*. ***Chinese Physics C*** 37 (2013)016002.
- S. Chen, **Q. Li*,** *et al*, ***JINST***: 10 (2014)10022.
- 许金艳,**李奇特***, 等, ***物理实验***, 41(2021)23

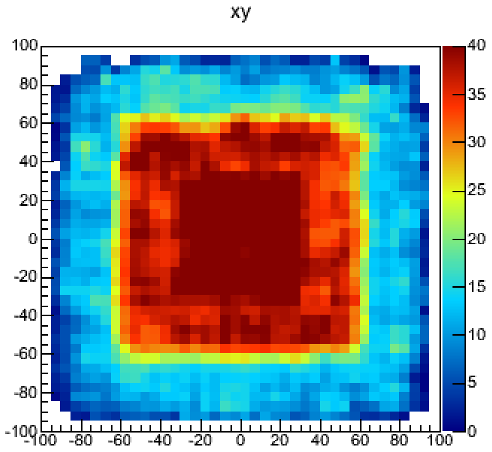


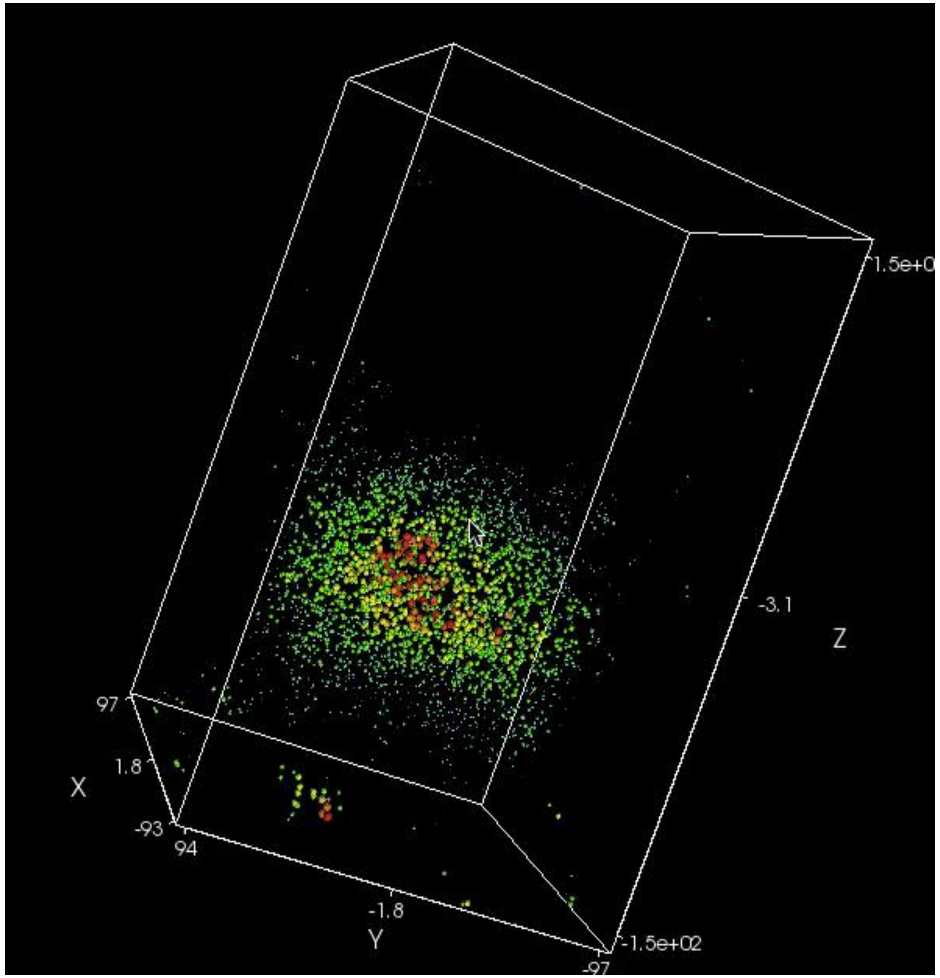


- 用这种高位置分辨率RPC搭建宇宙射线缪子成像系统探测宇宙射线缪子入射与出射径迹矢量，可测量到非常小的散射偏转角<5mrad (0.3°)，重建灵敏区内物质分布信息
- 右图是北京大学缪子成像原型机对包裹在12*12*12cm^{3}铁壳中的6*6*6cm^{3}方形铅块，以及用3*3*3cm^{3}铁块组成的PKU字母的成像结果

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



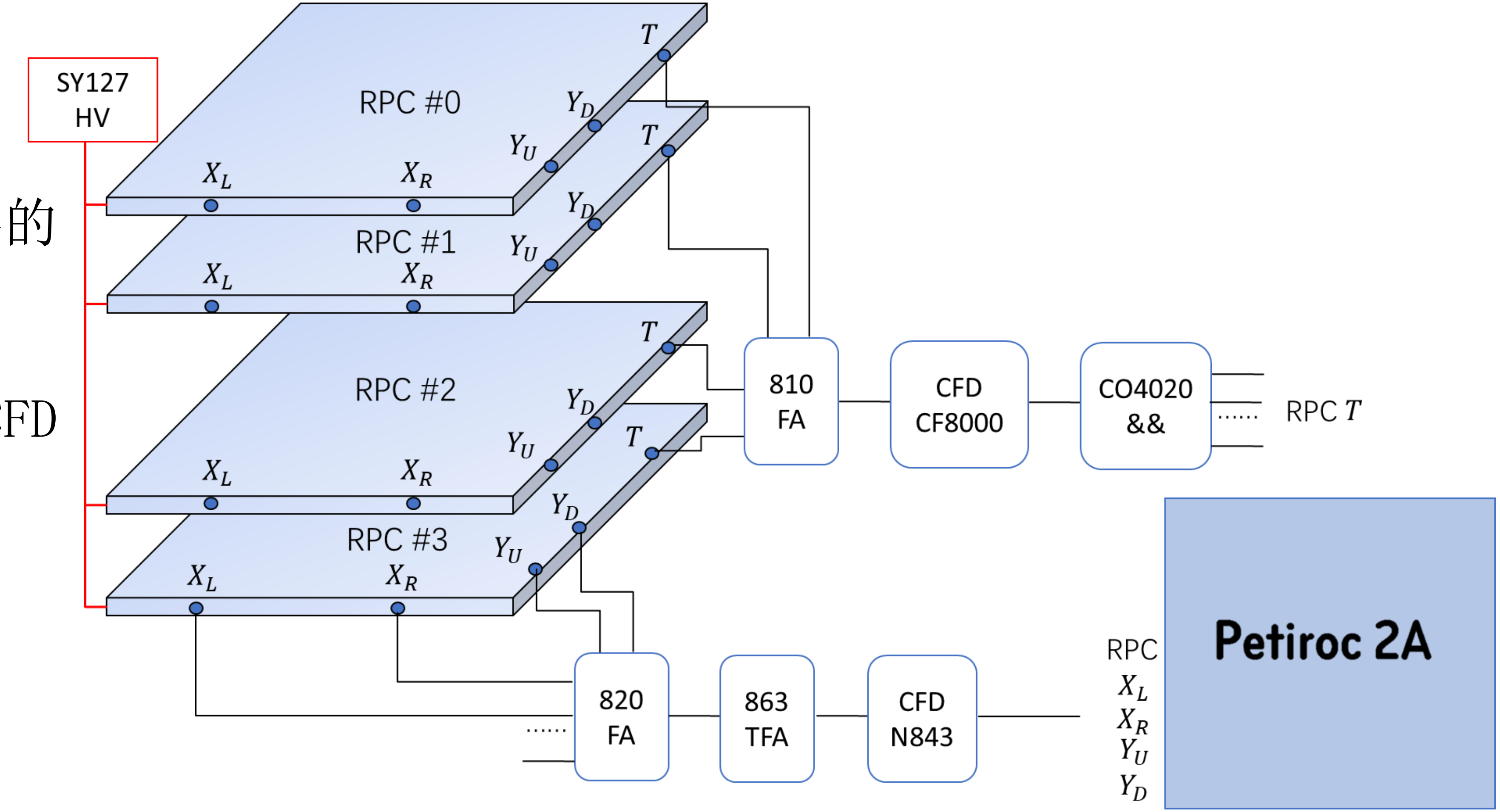




· Liu C M , Wen Q G , Zhang Z Y , et al. Study of muon tomographic imaging for high-Z material detection with a Micromegas-based tracking system[J]. 2020.

暗物质探测系统——4RPCs设置

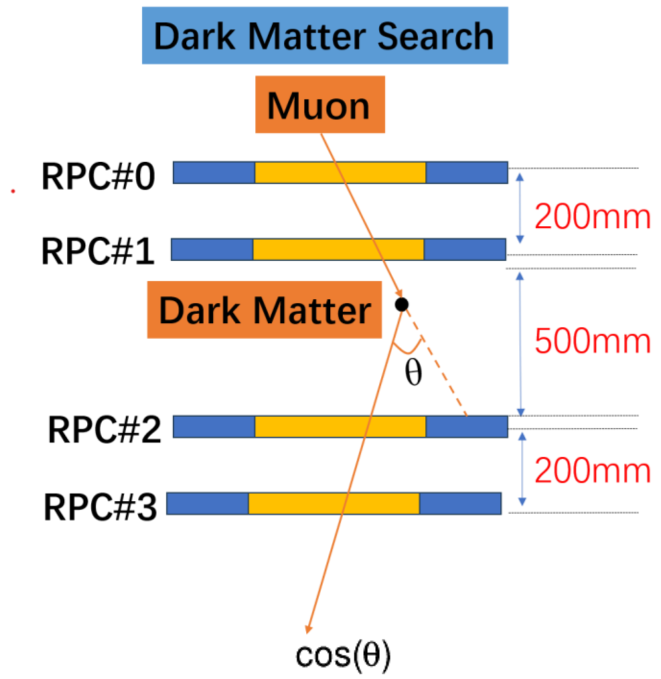
- 间隔20cm-50cm-20cm
- Petiroc是由中科大提供的基于ASIC的获取系统
- 4个T信号经过放大器、CFD和符合插件通入Petiroc
- 剩余位置路通过放大器、CFD通入Petiroc

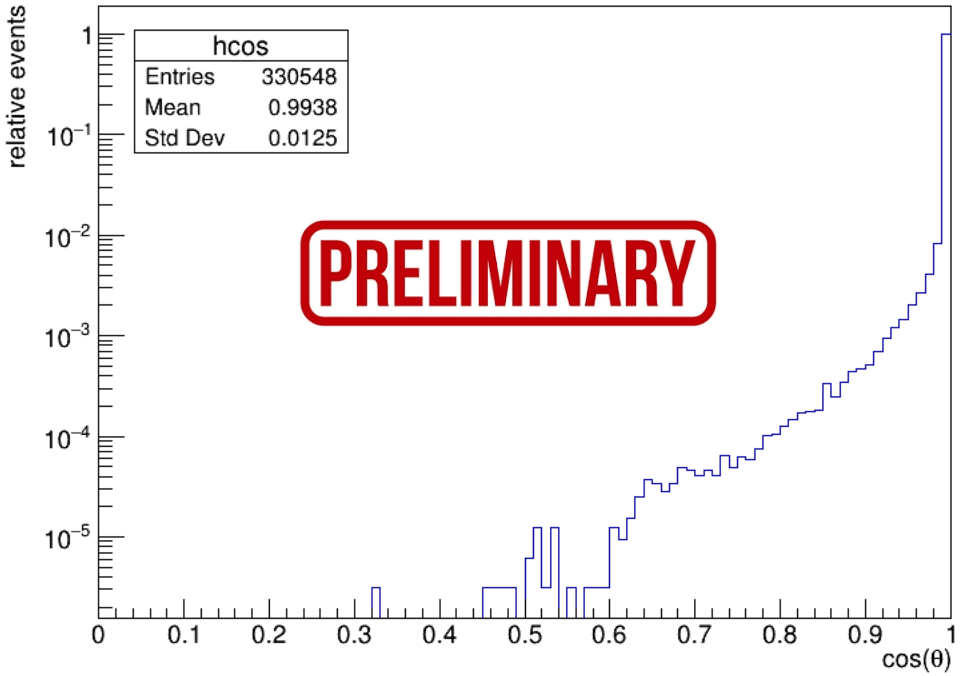


Accumulating Data Now

长期测试

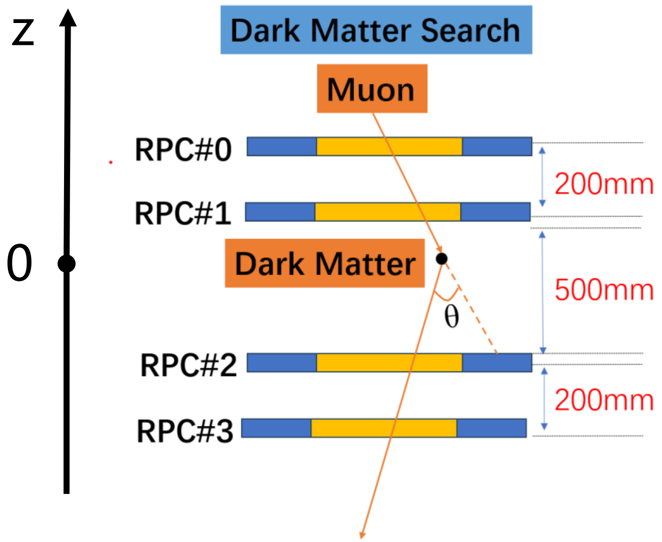
- 2024年1月开始，测量了3个月的宇宙线缪子在空间中的散射。
- 灵敏体积为50cm*20cm*20cm。
- 有效事件330548，平均散射角0.0252rad
- 定义θ>0.2rad为大角度散射事件，则占比为1.6%。

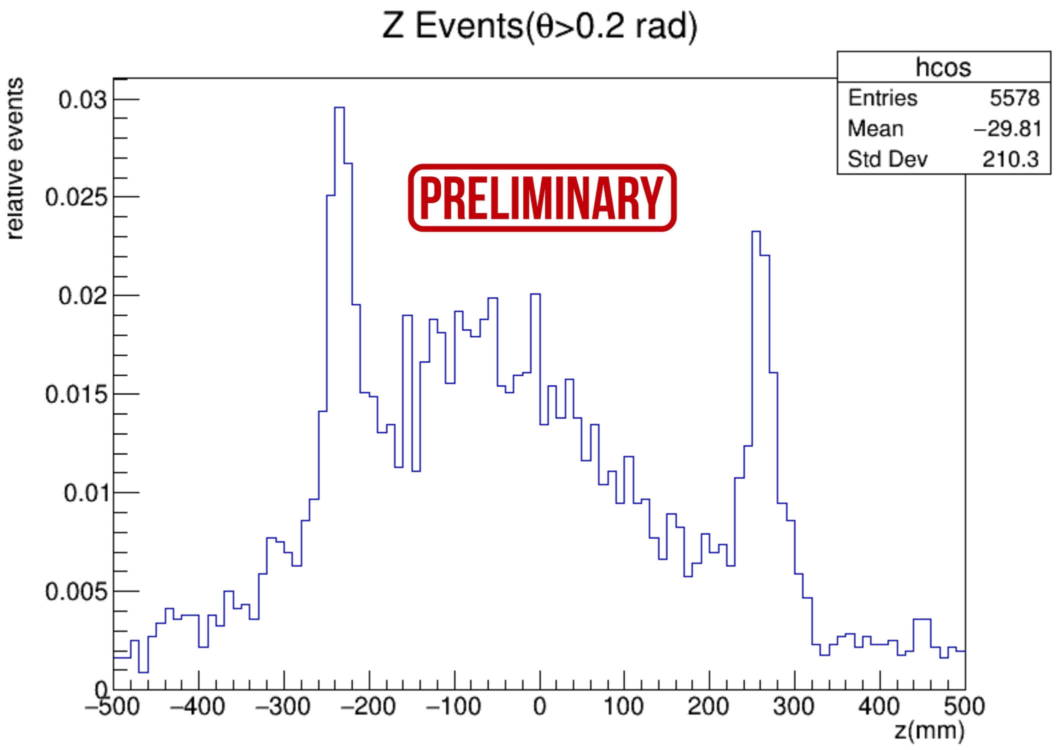


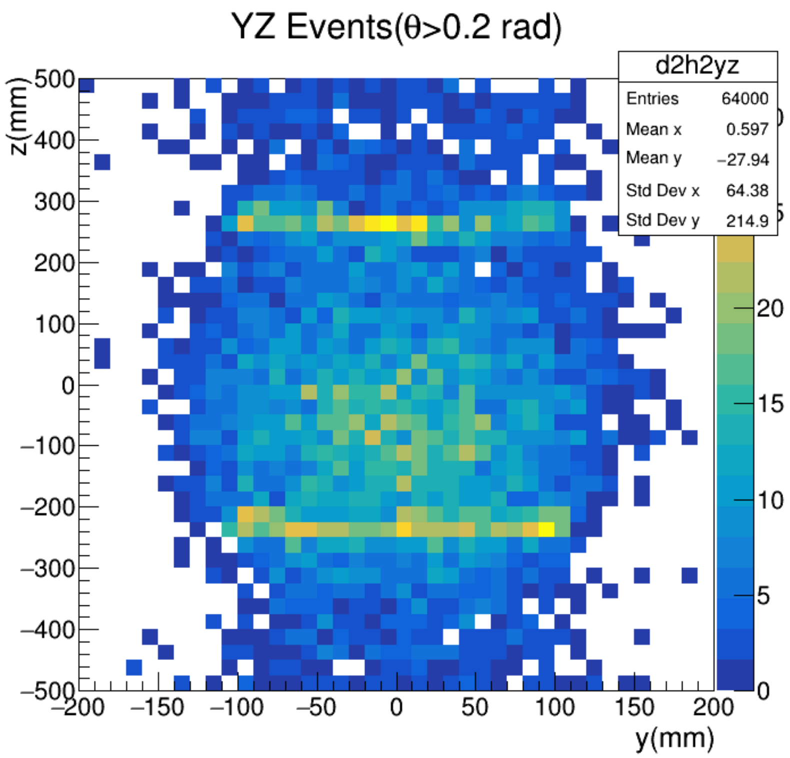


长期测试

- 观察大角度散射事件的散射点高度z
- 许多事件分布在RPC位置

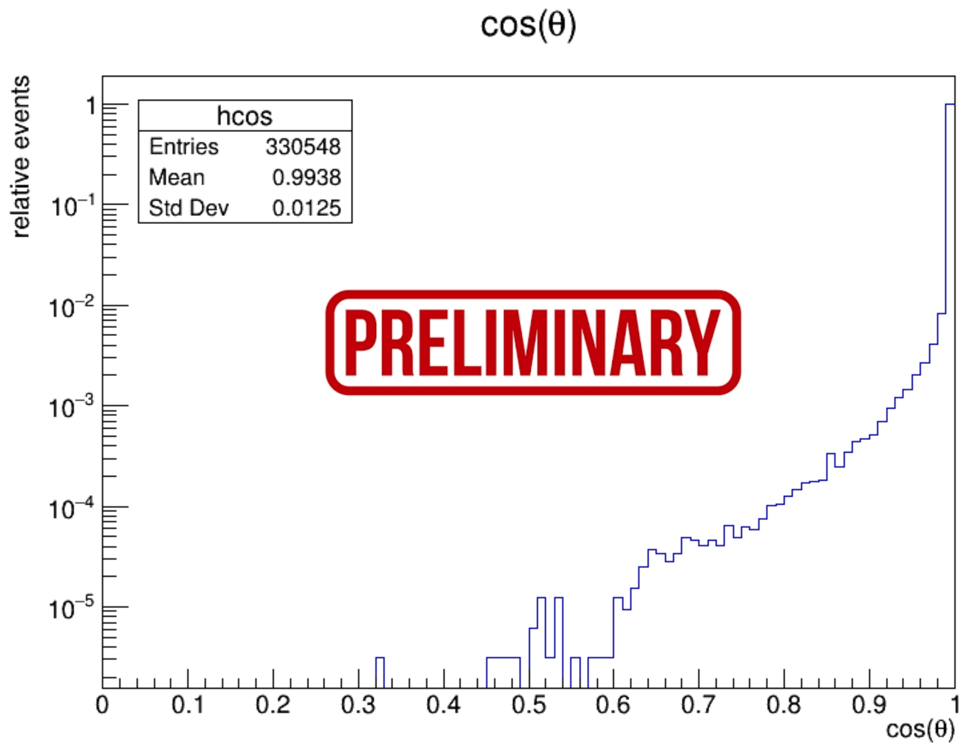


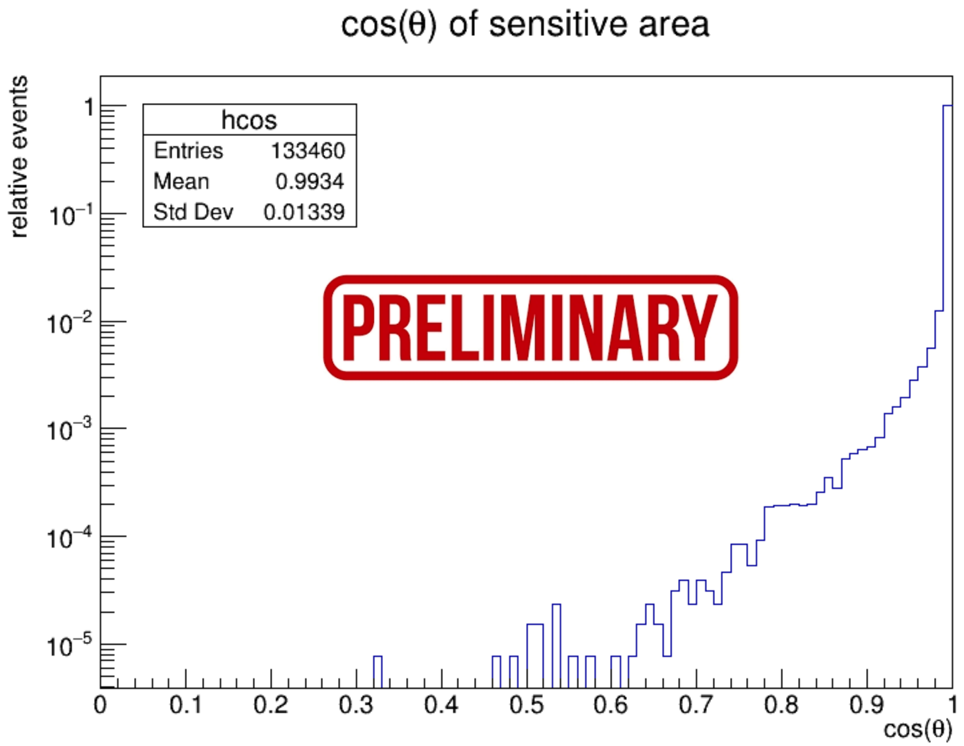




长期测试

- 观察灵敏区范围内的散射角分布，仍存在大角度事件
- 有效事件133460， θ>0.2rad事件2999，占比2.247%
- 平均散射角0.0315rad

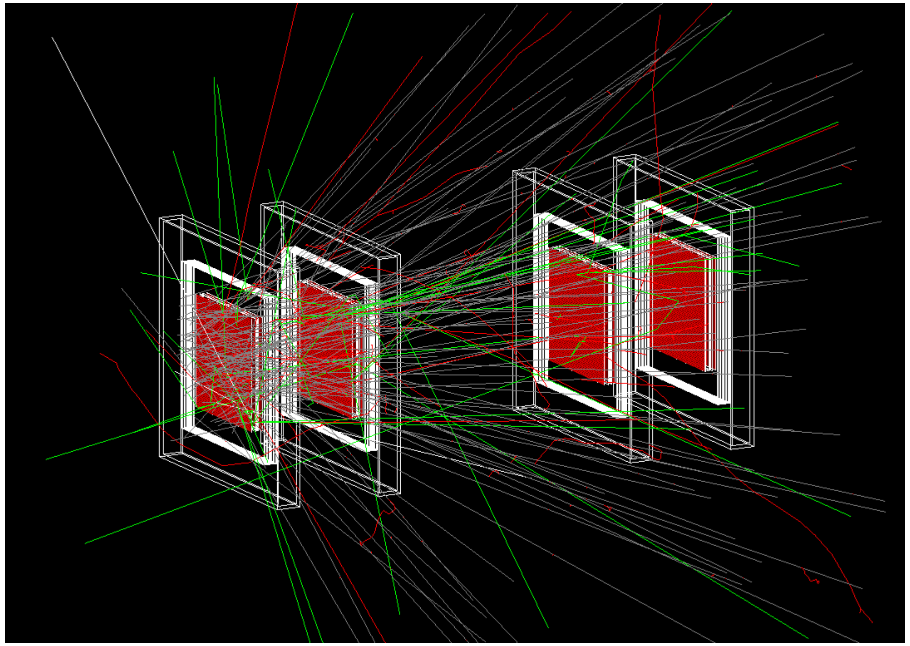


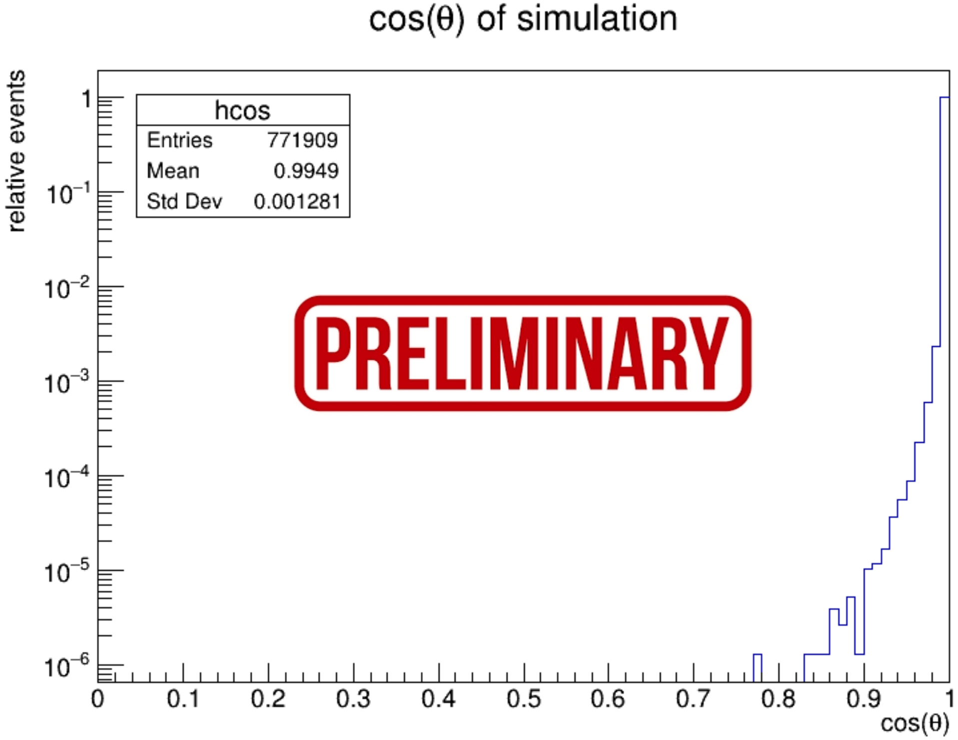


长期测试——物理模拟（王子健）

- 利用GEANT4 构建了相同尺寸、材料以及间隔距离设置的缪子散射探测系统，模拟了该系统在空间中宇宙线缪子散射的散射角分布。

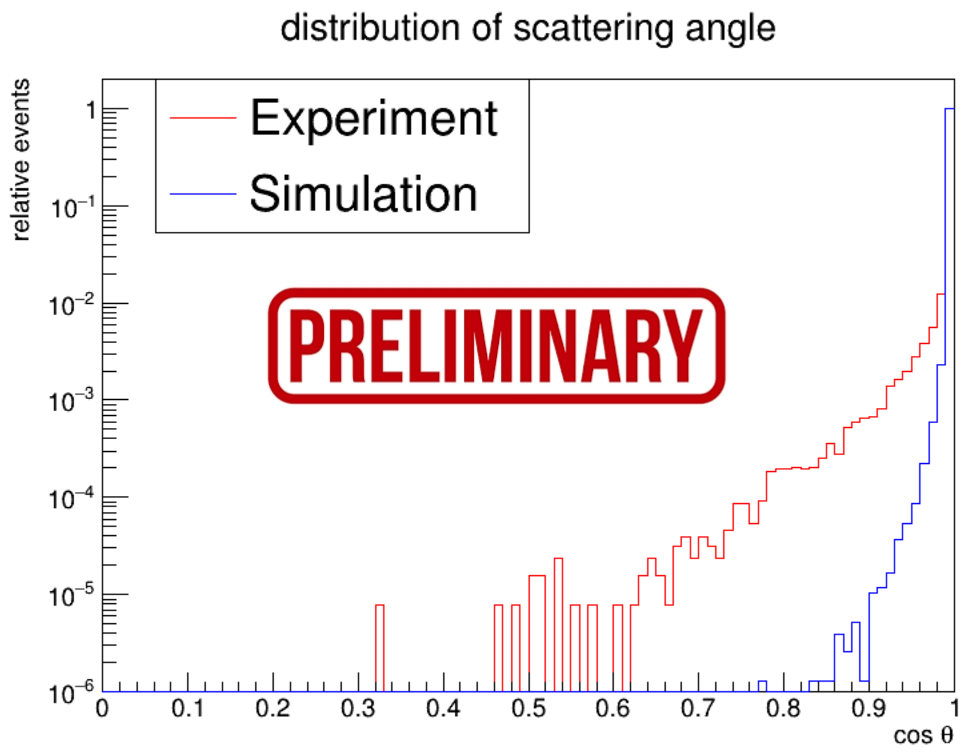
- 模拟位置分辨为0.57mm，模拟粒子为10^8个
- 有效事件771909，θ>0.2rad事件822，占比0.106%
- 平均散射角0.0145rad





长期测试——散射角分布

- 实验结果cosθ最小可达0.4以下，模拟结果最小不小于0.75。
- 在θ>0.2rad处，实验结果的占比为2.247%，而模拟结果为0.106%。
- 大角度散射事件的实验结果约为模拟结果的21.102倍

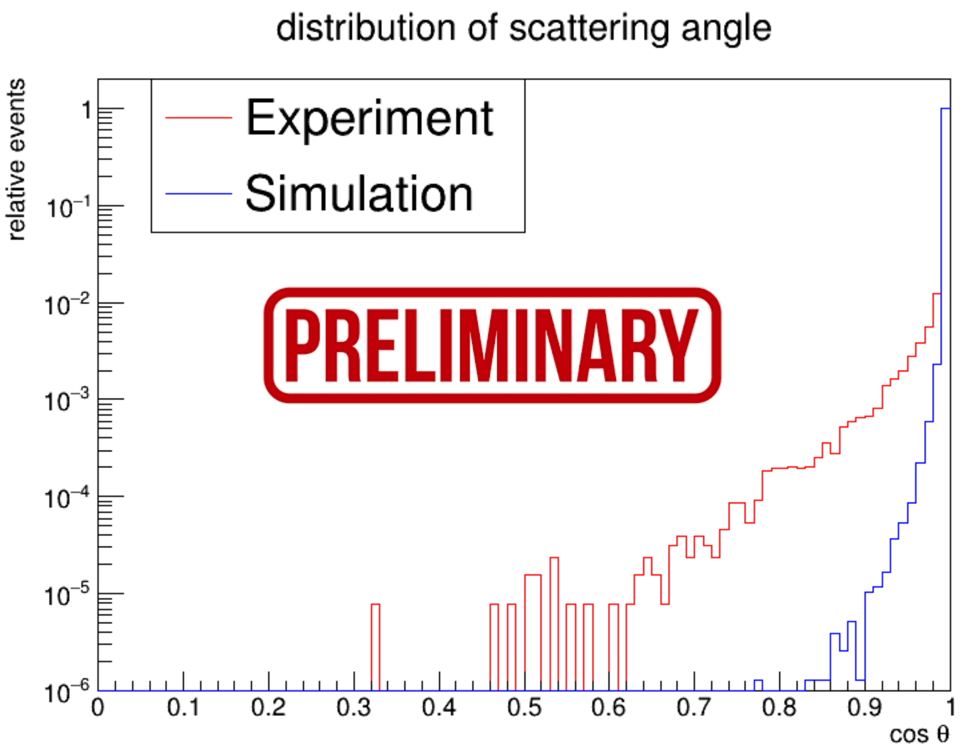


长期测试——散射角分布

- **实验结果与模拟结果存在差异的原因**：

1. 缪子多重散射事件
2. 低能缪子的影响
3. 宇宙射线中缪子之外的成分影响
4. 可能存在多个缪子或其他粒子进入探测系统的事件
5. GEANT4模拟用的物理过程可能和现实中对μ子大角度散射模拟有所偏差

对缪子在材料和空间中的散射可能需要有进一步的理解



RPC测试总结

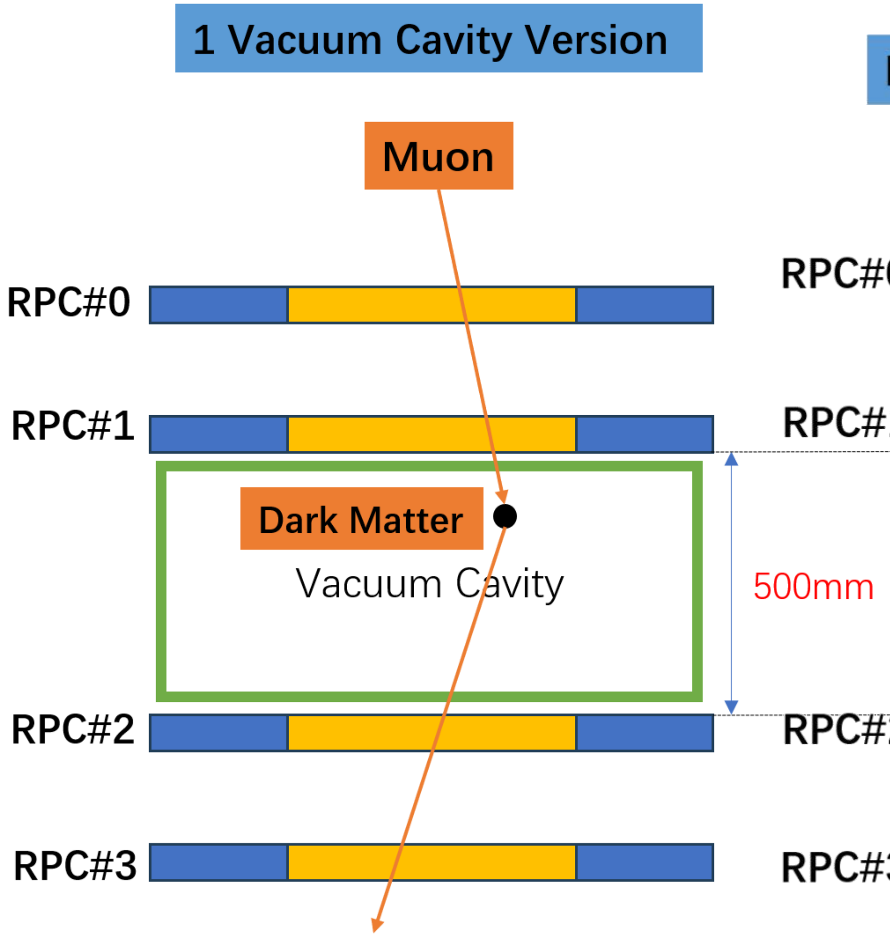
- 我们使用延迟线玻璃RPC搭建了缪子散射成像系统，对20cm*20cm*50cm灵敏体积内宇宙线缪子散射进行了3个月的测试。
- 在GEANT4中构建了相同尺寸、材料以及间隔距离设置的缪子散射探测系统，模拟了该系统在空气中宇宙线缪子散射的散射角分布。
- 对比实验结果与模拟结果，发现实验测得的大角度散射事件占比远高于模拟结果，

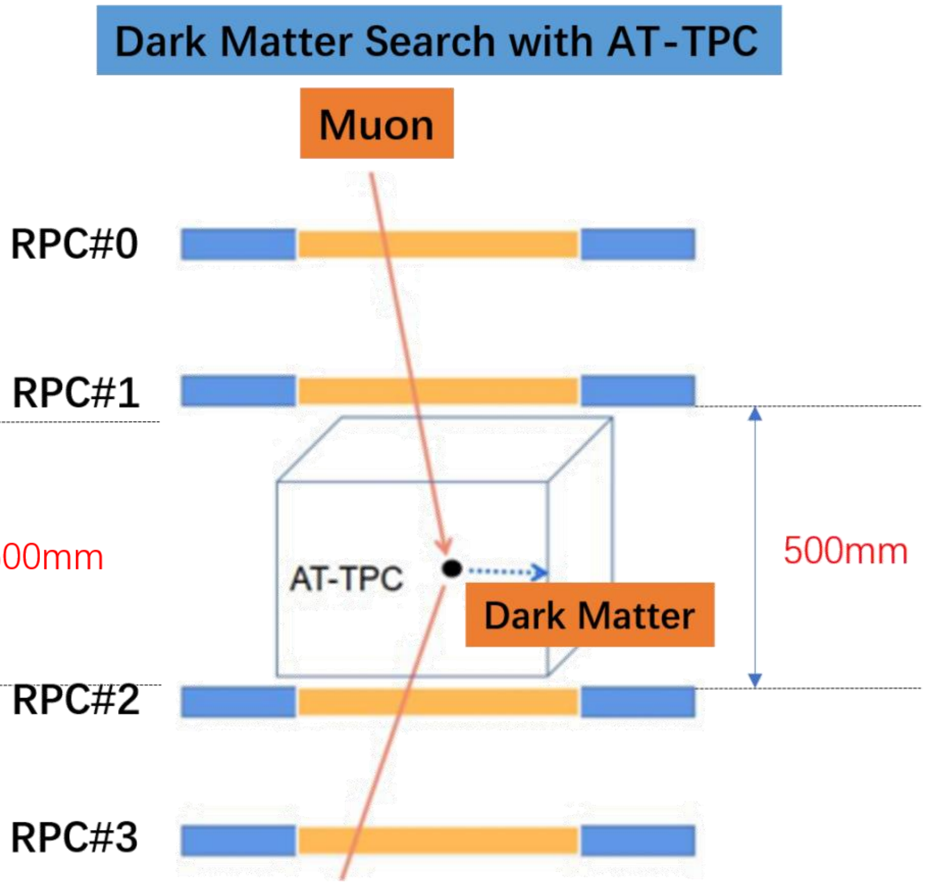
这预示着缪子在空间和材料中的散射过程还有需要进一步理解的地方。我们将进一步优化实验和模拟，研究缪子的散射物理过程。

未来计划

1. 将探测系统升级为真空腔模式，排除空气干扰

2. 使用AT-TPC排除多重散射的影响，定位反应点

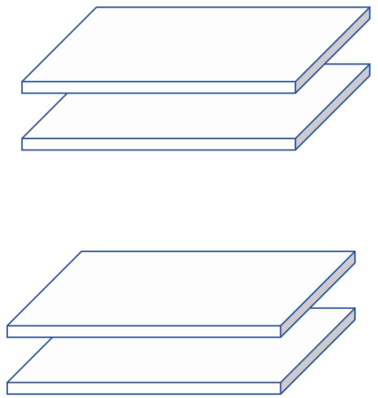


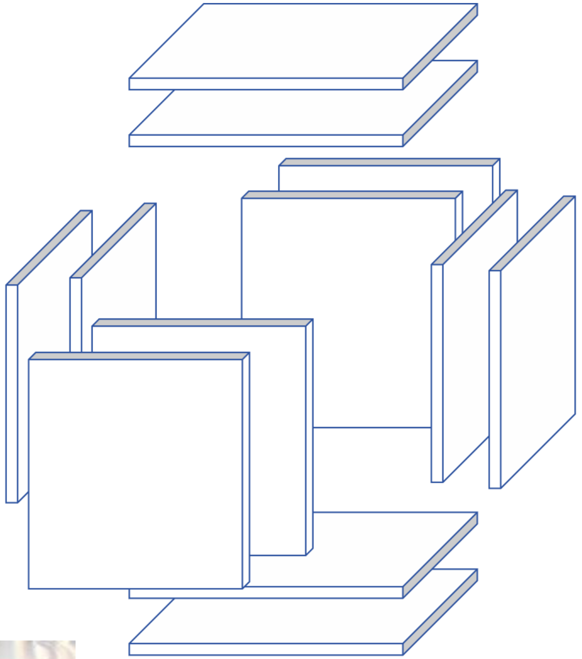


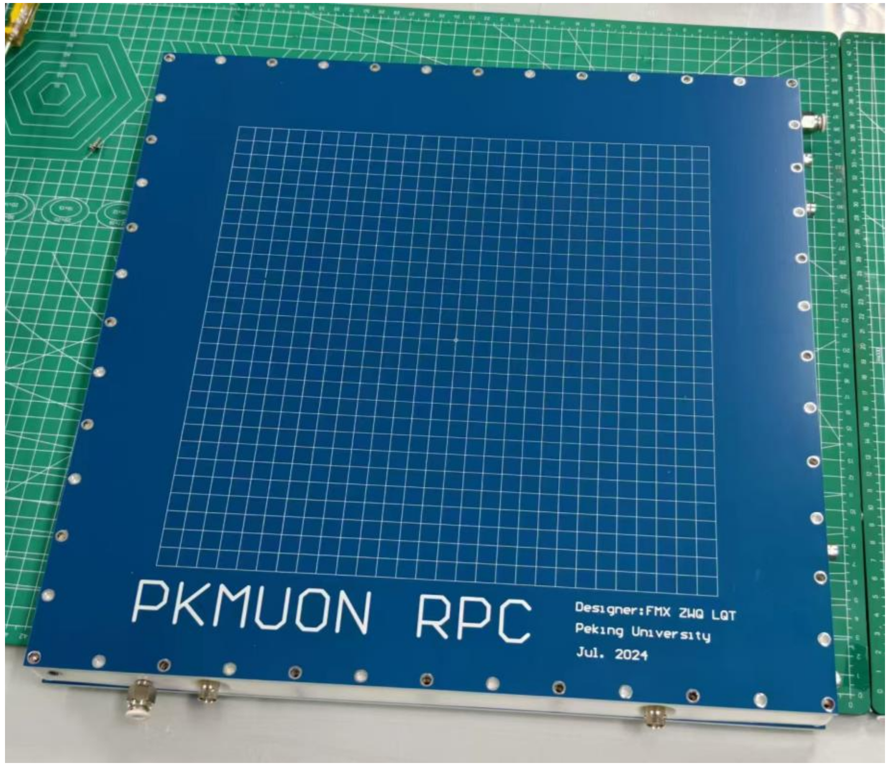
未来计划

3、增加侧面探测器，提高缪子在大角度散射的接受度

4、平方米至百平方米量级的缪子散射测量站研发

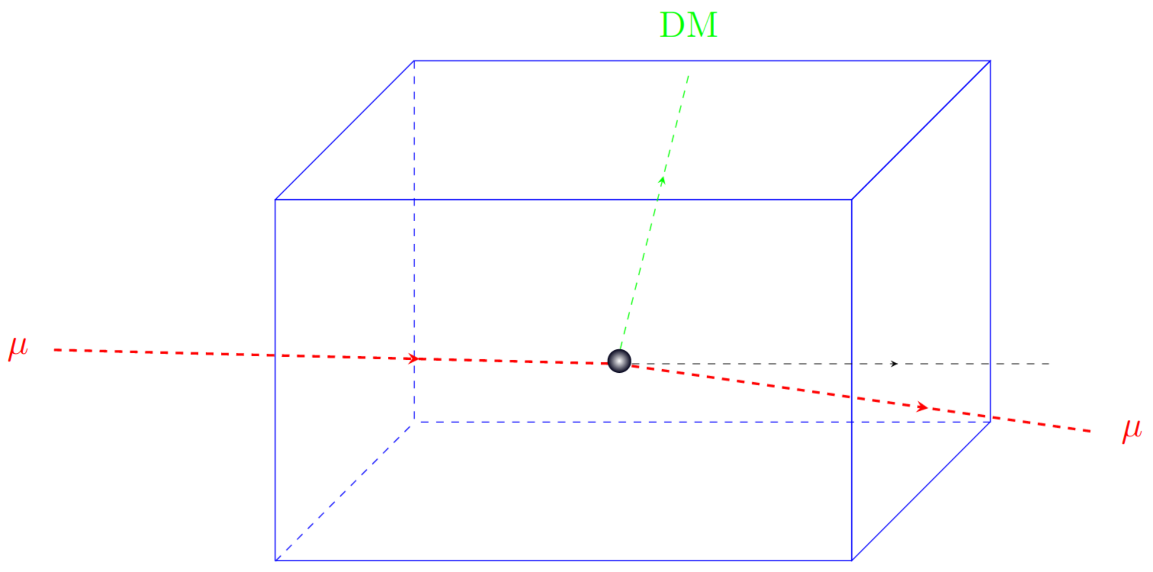






- **Phase I:**
  - Muon Tomography using RPC/GEM
  - Probing dark with Cosmic Muons
- **Phase II:**
  - PKMu + Chinese Muon beams (CSNS, HIAF)
- **Phase III:**
  - Muon On Target using Chinese Muon beams
    - Invisible $\mu + N \rightarrow \mu$ + dark
    - Visible $\mu + N \rightarrow \mu$ + di-leptons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

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:

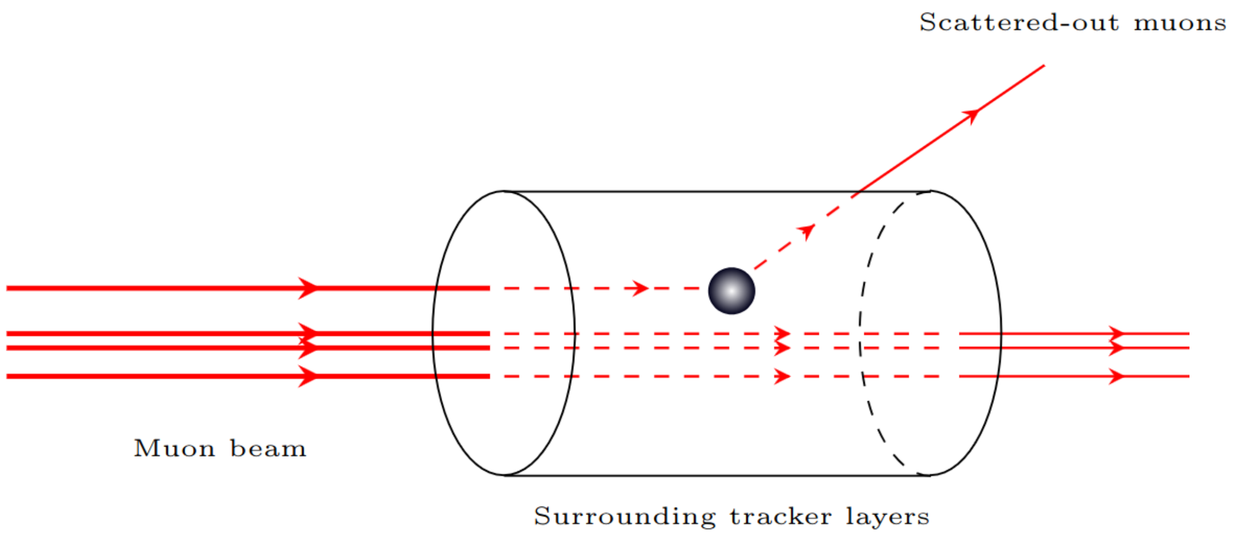
$$\boxed{\rho V/\mathrm{M_D} \times \sigma_D \times F_\mu,}$$

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 $\sim 1/60$/s/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



The estimated rate per second:

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

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

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

One year

Notice the surrounding area is around 100 cubic centimeters.

Melody, CIADS, HIAF Chinese Muon beams

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

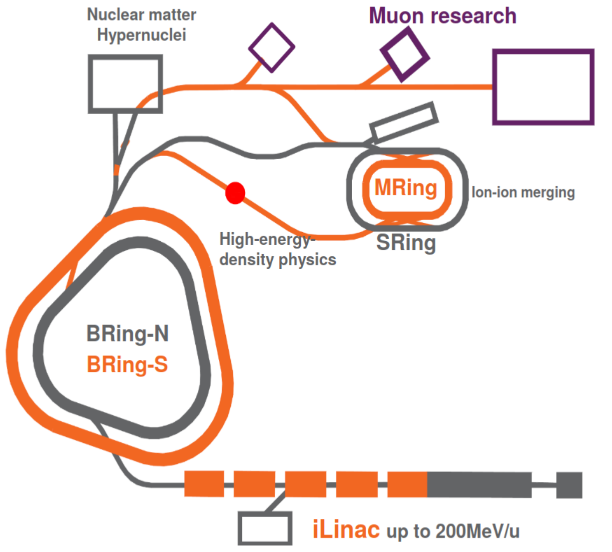
	Surface Muon	Negative Muon	Decay Muon
Proton Power (kW)	20	Up to 100	Up to 100
Pulse width (ns)	130 to 10	500	130 to 10
Muon intensity (/s)	$10^5 \sim 10^6$	Up to $5*10^6$	Up to $5*10^6$
Polarization (%)	>95	>95	50~95
Positron (%)	<1%	NA	<1%
Repetition (Hz)	1	Up to 5	Up to 5
Teminals	2	1~2	2
Muon Momentum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

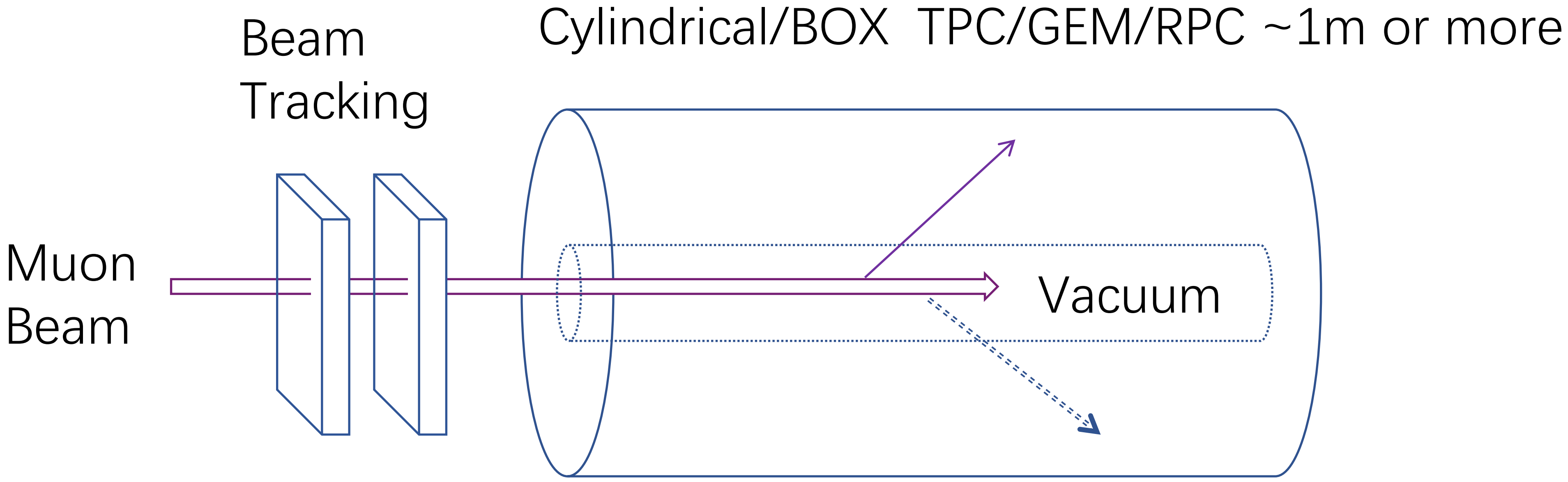
- **BRing-N**: 34Tm, 569m, 3Hz
- **SRing**: 17(25)Tm, 270.5m, accumulation/compression
- **BRing-S**: 86Tm, 3Hz, superconducting
- **MRing**: 45Tm, superconducting, beam merging

	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, ~1GeV

Muon Beam-DM Detectors requirement



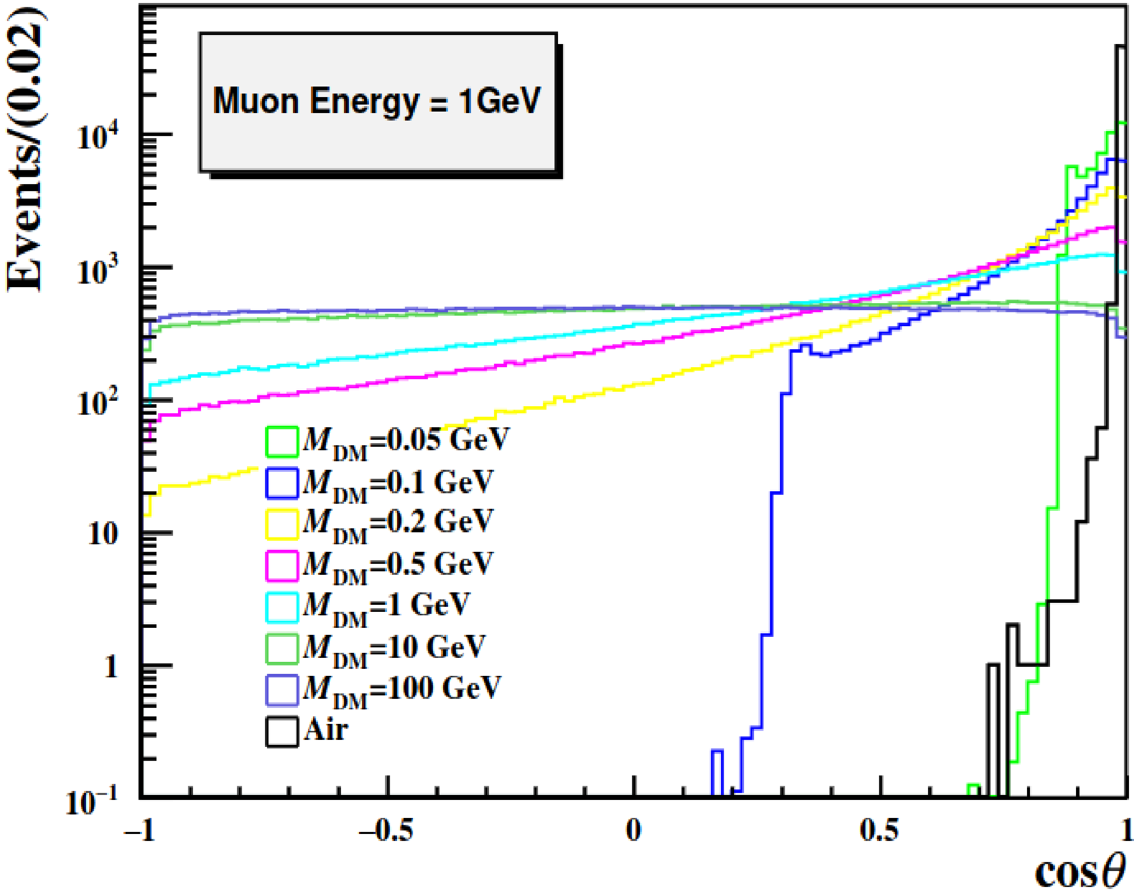
PID: muon / electron / ect.

Muon DM Beam experiment: Geant4 Simulation

If the scattering angle is large enough, muons may hit the surrounding detector.

$M_{DM} \backslash E^{\mu}_{kin}$	100 MeV (%)	1 GeV (%)	10 GeV (%)
0.05 GeV	84.29 ± 0.04	74.85 ± 0.04	45.93 ± 0.05
0.1 GeV	91.74 ± 0.03	83.07 ± 0.04	58.17 ± 0.05
0.2 GeV	94.35 ± 0.02	88.16 ± 0.03	68.37 ± 0.05
0.5 GeV	95.17 ± 0.02	92.16 ± 0.03	78.91 ± 0.04
1 GeV	95.34 ± 0.02	93.88 ± 0.02	84.68 ± 0.04
10 GeV	95.35 ± 0.02	95.36 ± 0.02	94.06 ± 0.02
100 GeV	95.43 ± 0.02	95.37 ± 0.02	95.37 ± 0.02

TABLE II. Signal detection efficiency under different assumptions of DM mass and muon beam energies.



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

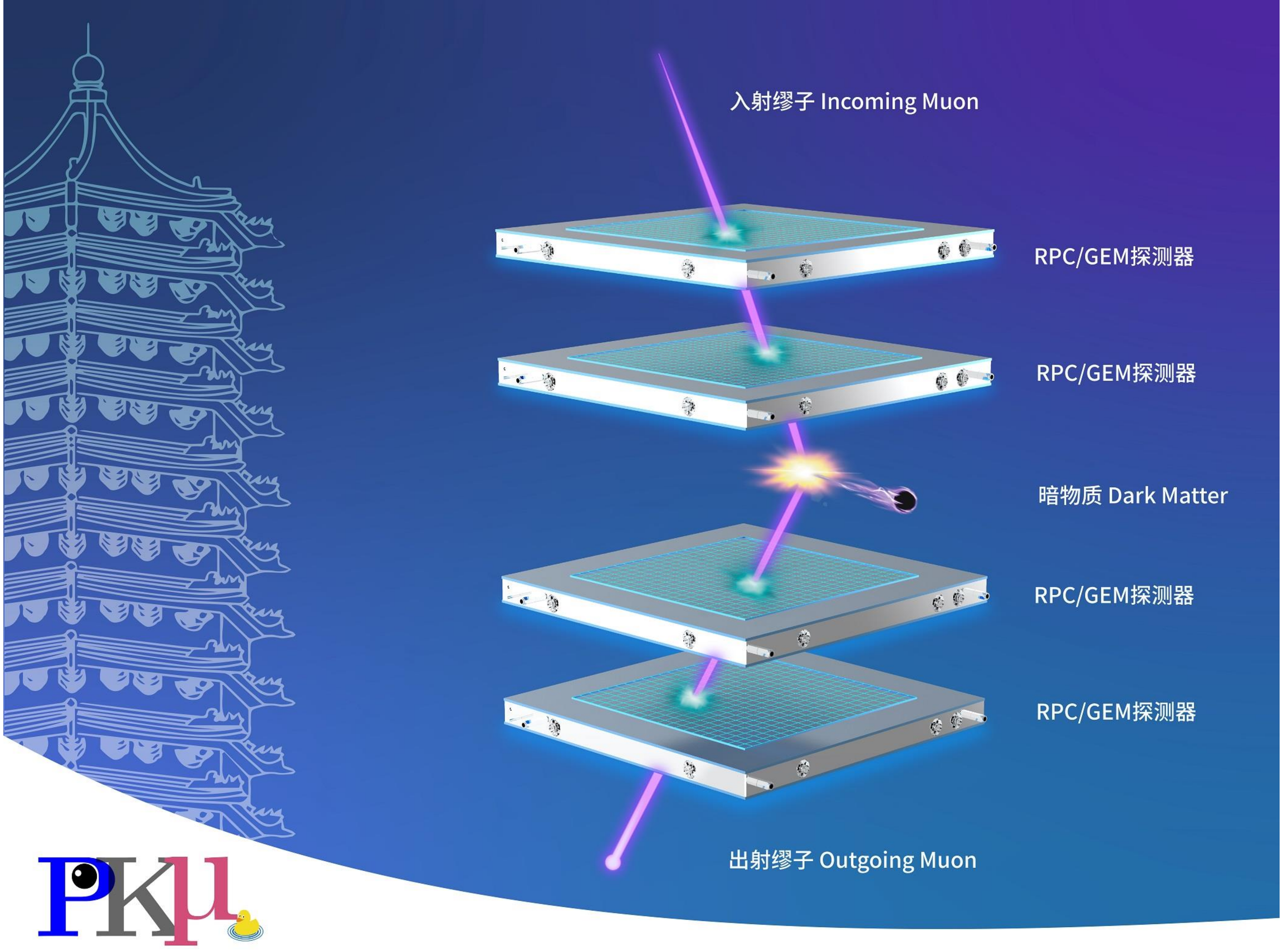
Phys. Rev. D 110, 016017
IJMPA 38, No. 29n30, 2350154 (2023)

MIP2024-1 , MIP2024-poster
COUSP2024-1 , COUSP2024-2

https://lyazj.github.io/pkmuon-site/

2024-8-26

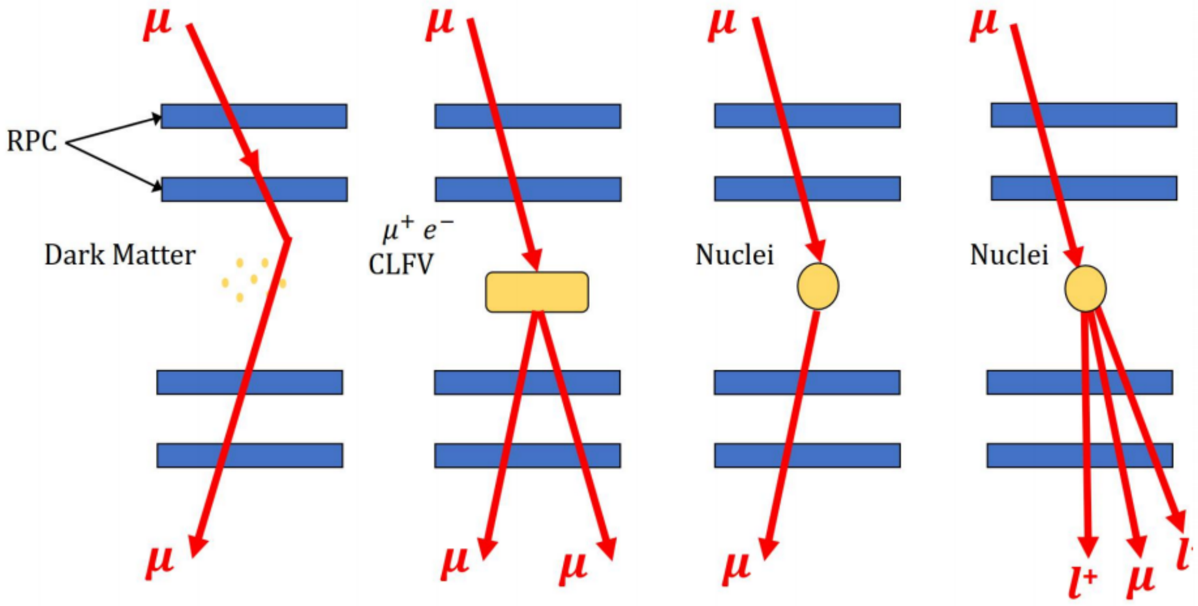
Backup

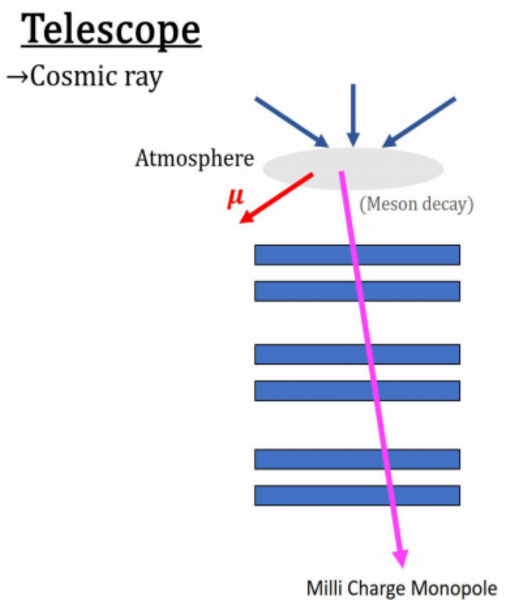

入射缪子 Incoming Muon
RPC/GEM探测器
RPC/GEM探测器
暗物质 Dark Matter
RPC/GEM探测器
RPC/GEM探测器
出射缪子 Outgoing Muon
PKμ

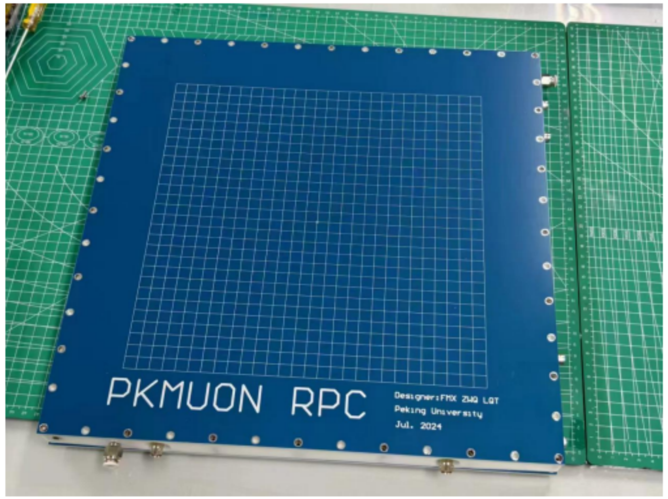
Future

Interfacing Cosmic Muon or Muon beam

→Cosmic μ or μ beam





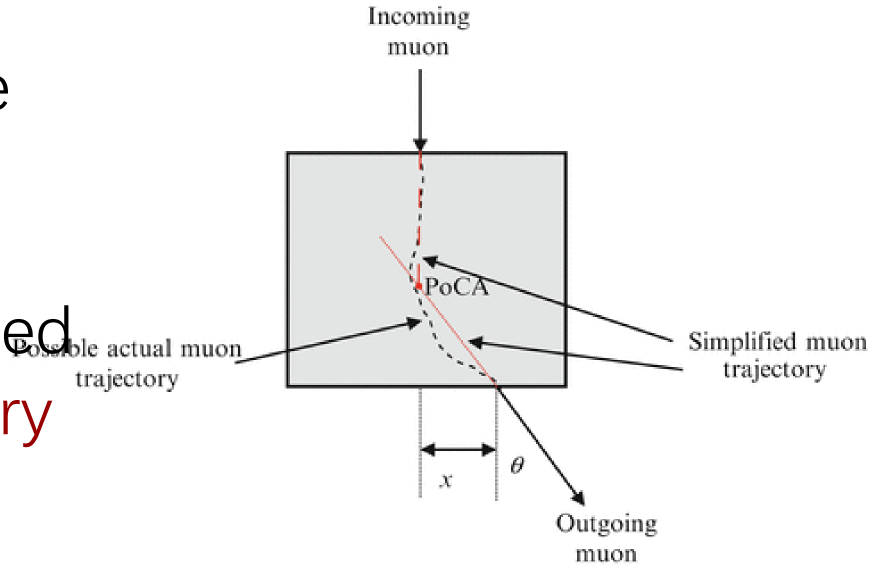


More physics program:
CLFV, Muon-Nuclei scattering …

Larger area
RPC or GEM
being produced

Prelude-1: Muon Tomography

- **Cosmic-ray muons** can be exploited as tool to probe the interior of large scale objects: Muographers2023.
- Rich applications on e.g., Meteorology, Archeology
- Muon Tomography Algorithms being further developed
- Precision measurement of cosmic muons still necessary (direction, momentum, altitudes⋯)



Journal of Cosmology and Astroparticle Physics

Seasonal variation of the underground cosmic muon flux observed at Daya Bay

F.P. An[1], A.B. Balantekin[2], H.R. Band[3], M. Bishai[4], S. Blyth[5,6], D. Cao[7], G.F. Cao[8], J. Cao[8], Y.L. Chan[9], J.F. Chang[8] + Show full author list

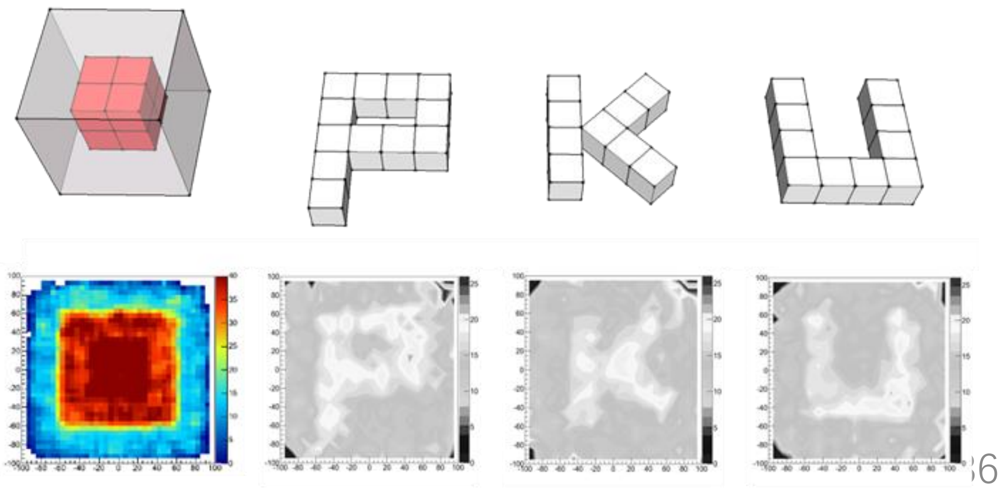
Published 2 January 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2018, January 2018

Citation F.P. An *et al* JCAP01(2018)001

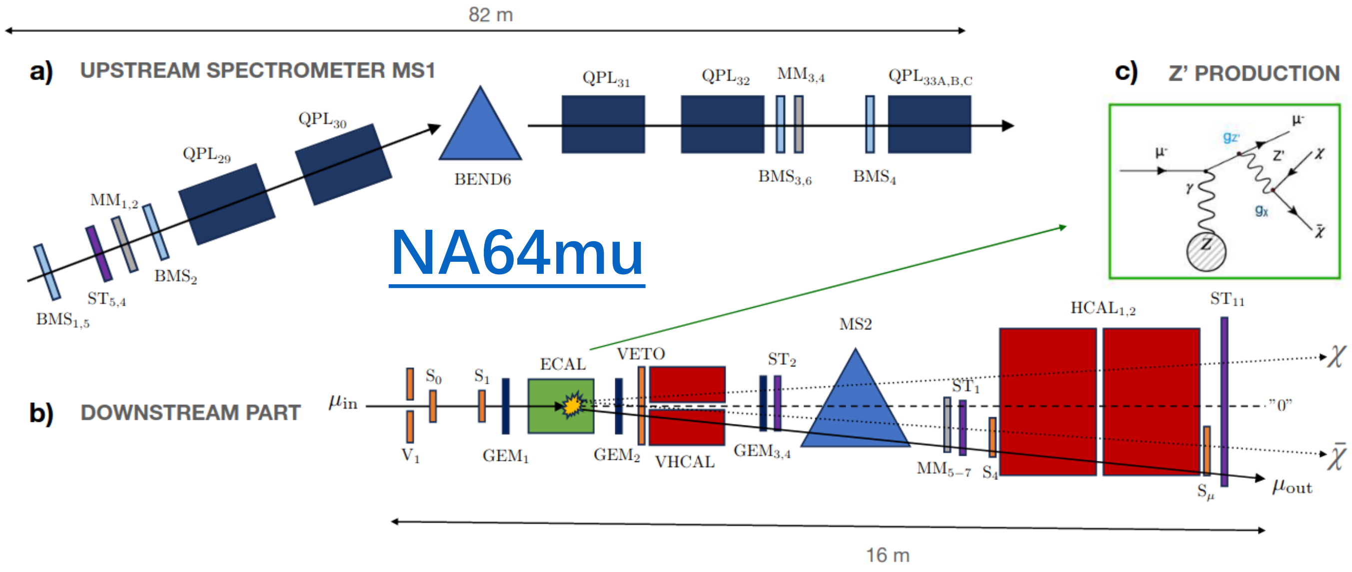
DOI 10.1088/1475-7516/2018/01/001

JCAP 2018



Prelude-2: NA64, DarkShine, LDMX, MMM

- **Muon Philic Dark Matter** may be possible or necessary!
- 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…"



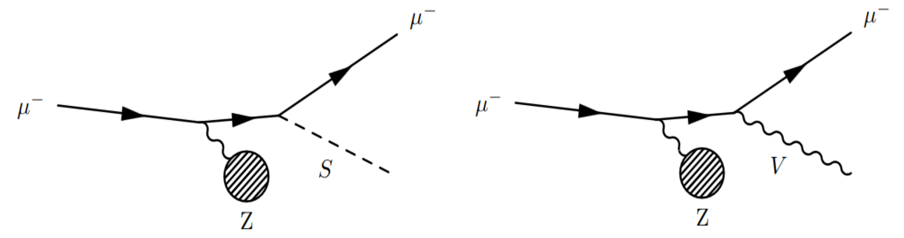


Figure 1. Dark bremsstrahlung signal process for simplified models with invisibly decaying scalar (*left*) and vector (*right*) forces that couple predominantly to muons. In both cases, a relativistic muon beam is incident on a fixed target and scatters coherently off a nucleus to produce the new particle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

Prelude-3: exotic Dark Matter

PHYSICAL REVIEW LETTERS **131,** 011005 (2023)

Dark Matter Annihilation inside Large-Volume Neutrino Detectors

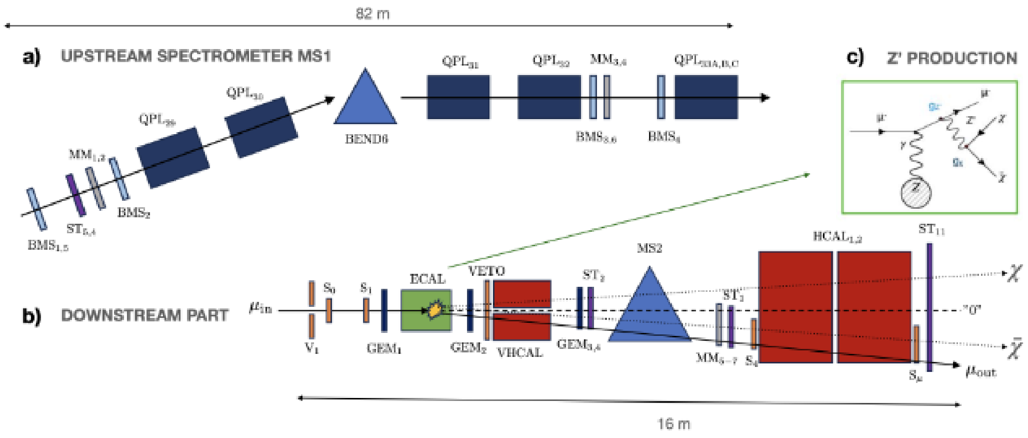
Owing to their interactions with ordinary matter, a strongly interacting dark matter component (DMC) would be trapped readily in the Earth and thermalize with the surrounding matter. Furthermore, for lighter DM, strong matter interactions allow Earth-bound DM particles to distribute more uniformly over the entire volume of the Earth rather than concentrating near the center. Together, this can make the DM density near the surface of the Earth tantalizingly large, up to $\sim f_\chi \times 10^{15}$ cm^{-3} for DM mass of 1 GeV [8–11]. Despite their large surface abundance, such thermalized DMCs are almost impossible to detect in traditional direct detection experiments as they carry a minuscule amount of kinetic energy $\sim kT = 0.03$ eV. A

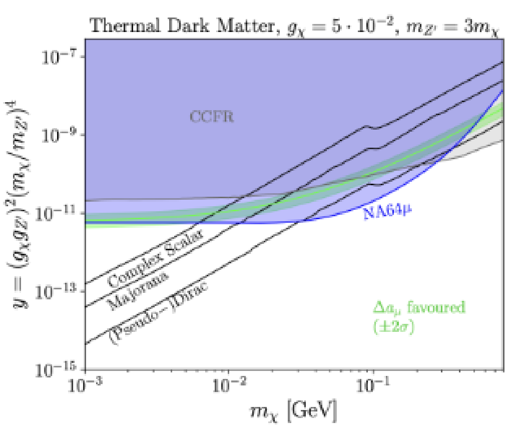
- A large amount of dark matter is concentrated near the Earth, and their speed is very low, making it difficult to cause recoil signals in experiments. (大量暗物质集中在地球附近，它们的速度很低，很难在实验中引起足够的反冲信号)

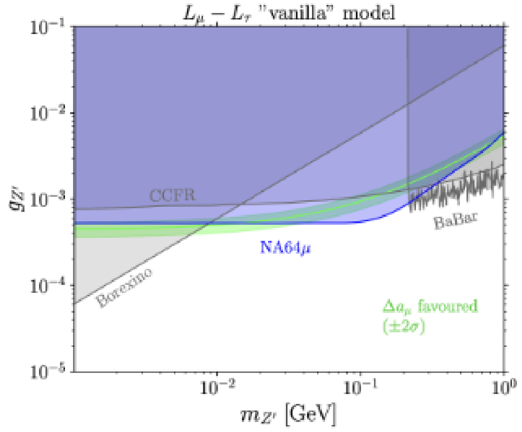
- **As we will see, muon DM scattering experiment (PKMuon) depends minorly on DM velocity**

NA64μ

- $Z'\ U(1)_{L_\mu - L_\tau}$ model
  - Z' directly couples the second and third lepton generations
  - The extension model: interactions with DM candidates
- M2 beamline at the CERN Super Proton Synchrotron
  - Incoming muon momentum 160 GeV/c
  - Total accumulated statistics: $(1.98 \pm 0.02) \times 10^{10}$ MOT
- Signal process: $\mu N \rightarrow \mu N Z', Z' \rightarrow \text{invisible}$
- No event falling within the expected signal region is observed
  - 90% CL upper limits are set in the $(m_{Z'}, g_{Z'})$ parameter space of the $L_\mu - L_\tau$ vanilla model, constraining viable mass values for the explanation of $(g-2)_\mu$ anomaly to $6-7$ MeV $< m_{Z'}$ $<$ 40 MeV, with $g_{Z'} < 6 \times 10^{-4}$.
  - New constraints on light thermal DM for values $y > 6 \times 10^{-12}$ for $m_\chi >$ 40 MeV







Exotic DM

PRL 131, 011005 (2023)

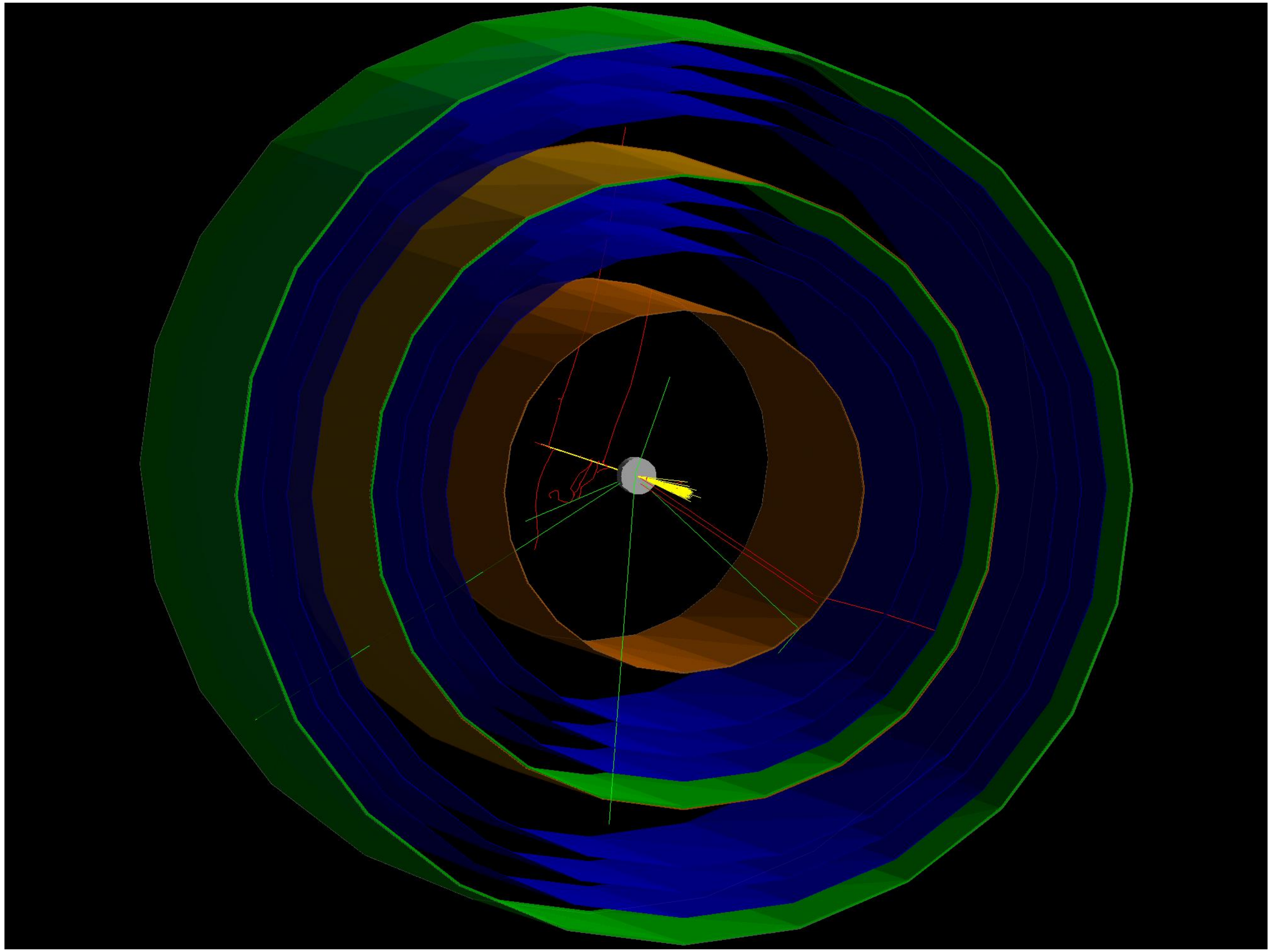
- ➔ A new species χ that interacts "strongly" with ordinary matter but that makes up only a tiny fraction $f_\chi = \rho_\chi / \rho_{\mathrm{DM}} \ll 1$ of the total DM mass density
  - Be slowed significantly by scattering with matter in the atmosphere or the Earth before reaching the target, leading to energy depositions in the detector that are too small to be observed with standard methods
  - Be trapped readily in the Earth and thermalize with the surrounding matter.
  - For lighter DM, strong matter interactions allow Earth-bound DM particles to distribute more uniformly over the entire volume of the Earth rather than concentrating near the center.
- ➔ Make the DM density near the surface of the Earth tantalizingly large, up to $\sim f_\chi \times 10^{15}\,\mathrm{cm}^{-3}$ for DM mass of 1 GeV
  - Ordinary DM density $\sim 0.3\,\mathrm{cm}^{-3}$
- ➔ Almost impossible to detect in traditional direct detection experiments as they carry a minuscule amount of kinetic energy $\sim kT = 0.03\,\mathrm{eV}$

Exotic DM is slowed down near the Earth, and its density is highly enhanced

Muon DM Beam experiment: Geant4 Simulation

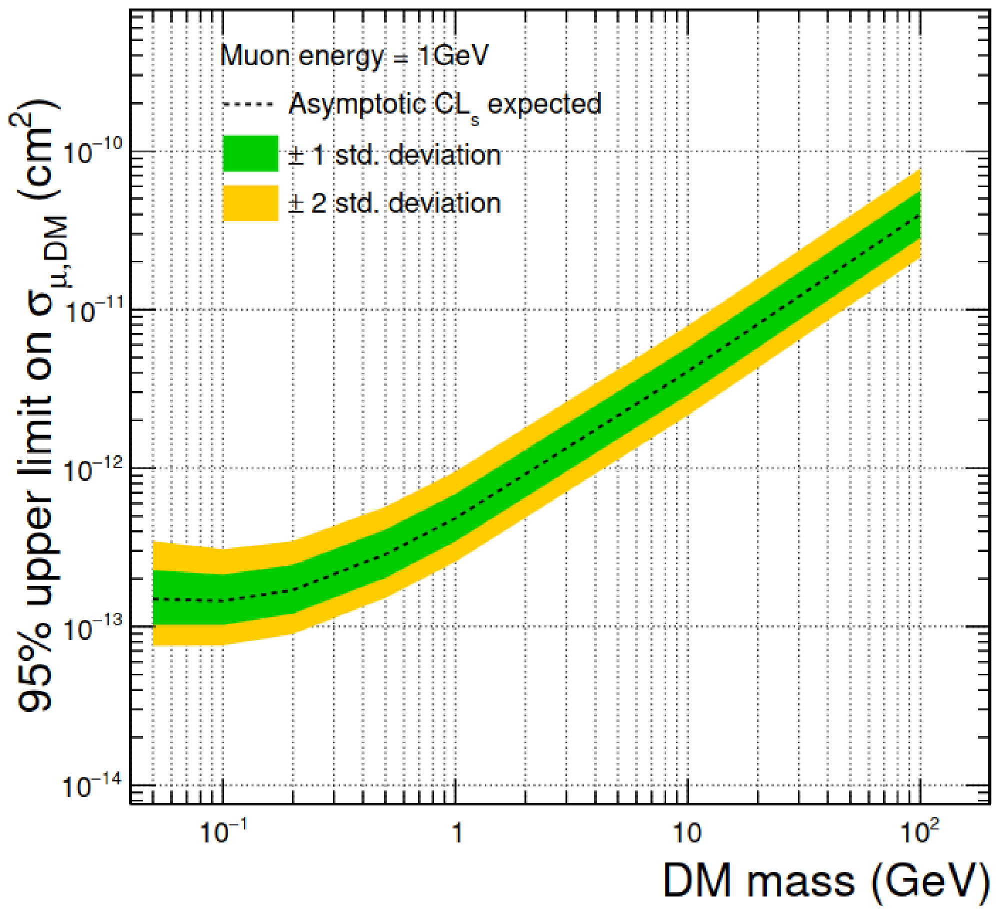
Simulating 1 GeV muon beam hit lead plate passing through GEM detector: the inner diameter of our CGEM detector is designed to be 50 mm, **which is 5 times the beam spot**.

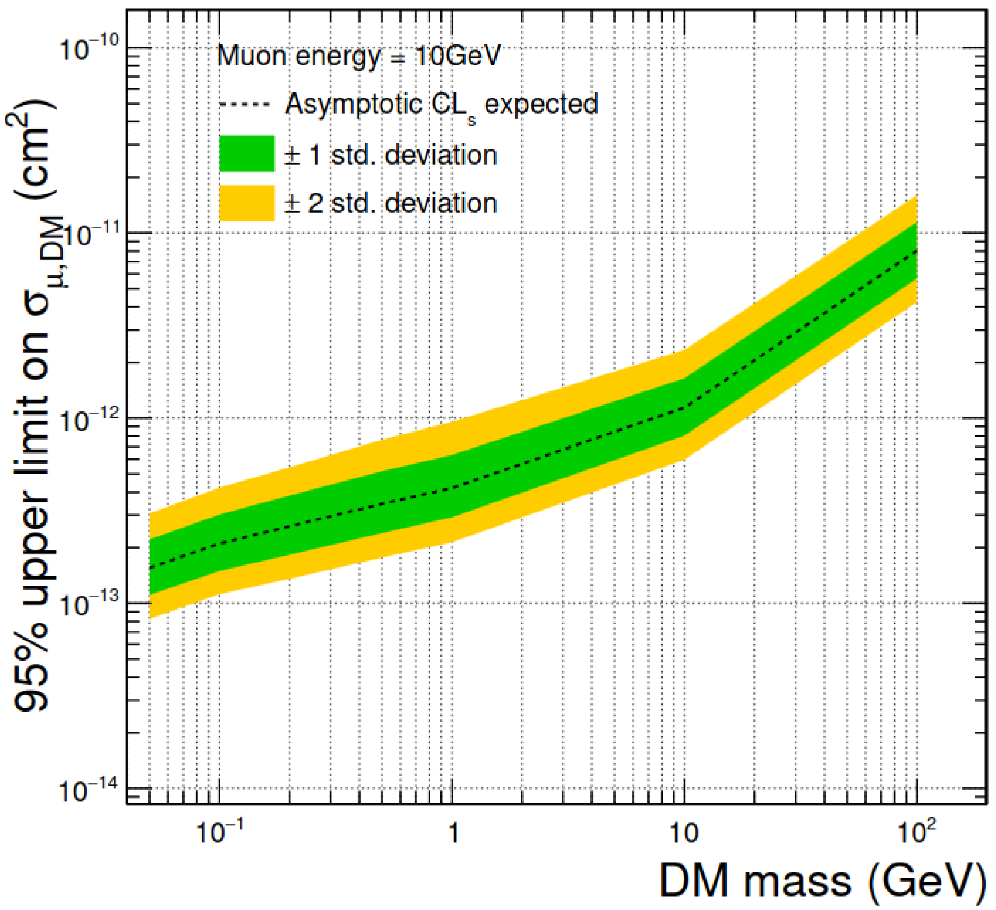
Orange surfaces are drift cathodes. The blue surfaces are GEM foils. The green surfaces are PCBs. The yellow lines are muons tracks. The red curves are electron tracks. The green lines are photons.



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

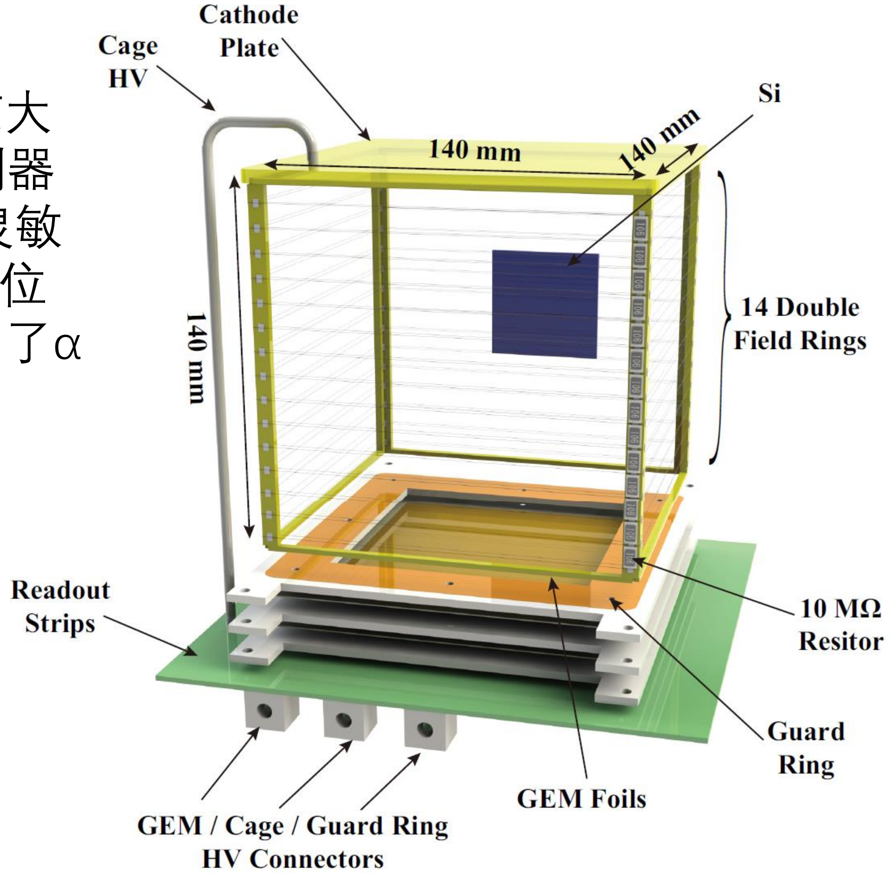
Muon DM Beam experiment: Geant4 Simulation

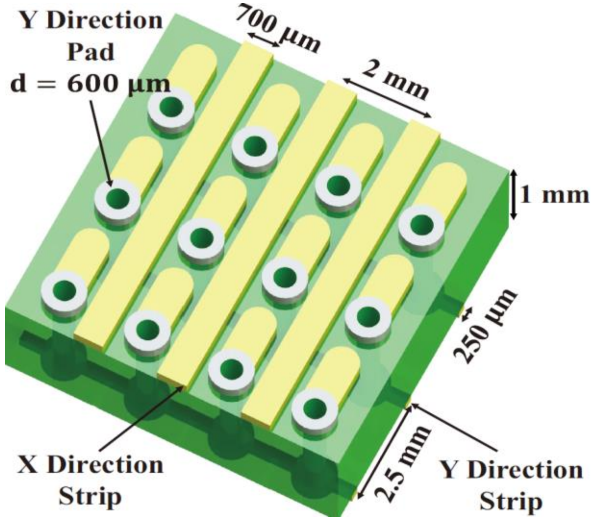




北京大学 PKU AT-TPC研发

为了研究不稳定核的集团结构相关物理，北京大学核物理实验团队研制了一个基于厚GEM探测器放大的 活性靶时间投影室(AT-TPC)原型机，灵敏体积为14cm*10cm*10cm，测试了其时间分辨位置分辨等性能，进行了三维径迹重建，观察到了α在He上的弹散径迹。





组成部件：

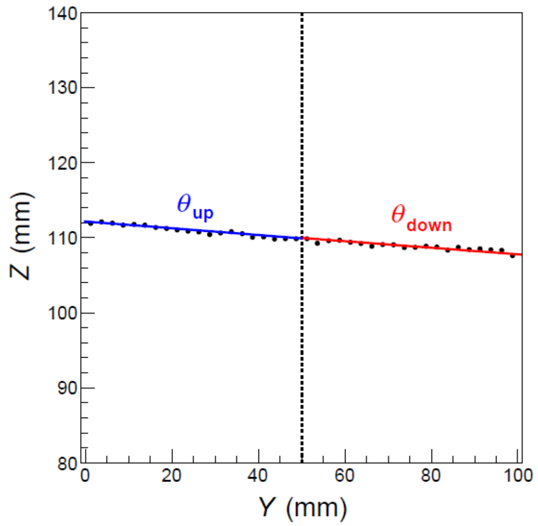
- 漂移区
- 14×双层场笼+均压电阻
- 厚GEM*2
- 保护环改善电场均匀性
- 128路二维读出条读出
- 相关电子学获取系统
- 辅助探测器

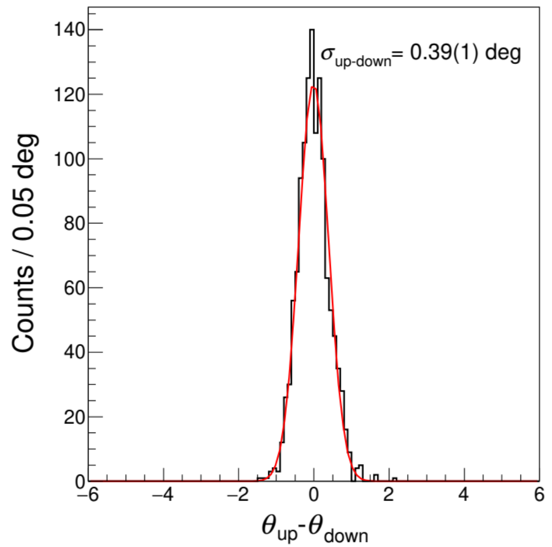
- 工作混合气体： $^{4}\mathrm{He}(96\%) + \mathrm{CO_2}(4\%)$
- 气压400~500 mbar
- 场笼高压2150V，GEM膜高压820V，场笼环高压890V

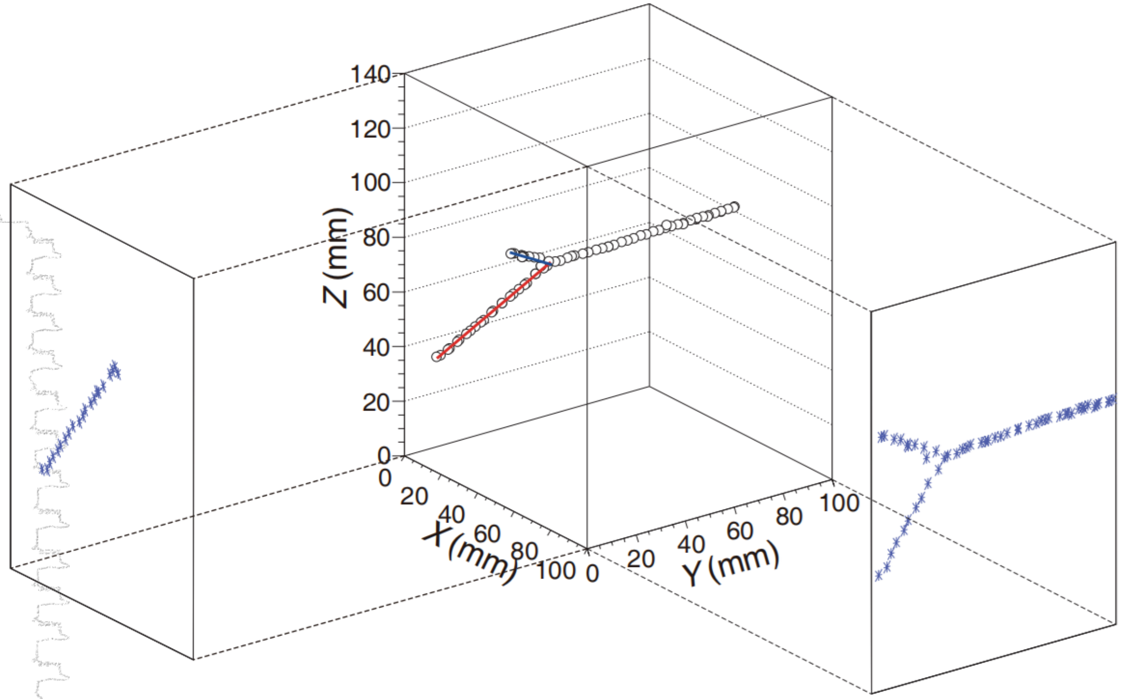
相关文章：

- Jin-Yan Xu, **Qi-Te Li*** et al., ***Nucl. Sci. Tech.***, 29 (2018) 97.
- 许金艳, 阳黎升, **李奇特***等. ***原子能科学技术***, 054 (2020) 1068.
- Yang, LS, Xu, JY., **Li, QT.*** et al. ***Nucl. Sci. Tech.***,32 (2021) 85.

PKU AT-TPC位置和角度分辨率和三维重建径迹







漂移方向时间分辨&位置分辨

- 对每一个事件产生的径迹用一条直线拟合

$$t_i = T_i^F - T_i^D$$

- 得出一个残差分布，取其标准偏差
    - 定义标准偏差为时间分辨
    - 时间分辨：6.6-15.5 ns
    - 位置分辨：0.1-0.15 mm

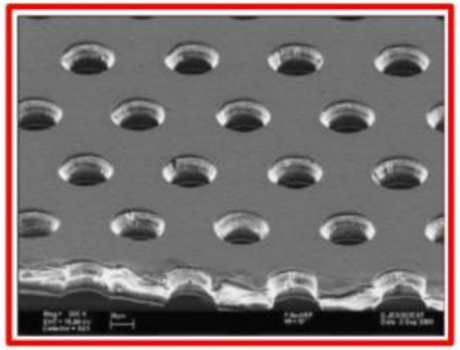
角度分辨：

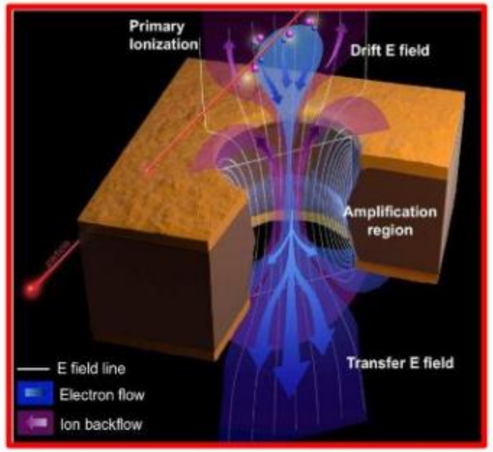
- 对每一个事件产生的径迹分成两部分，分别用一条直线拟合
- 拟合两条直线的倾角差谱
- 角度分辨：

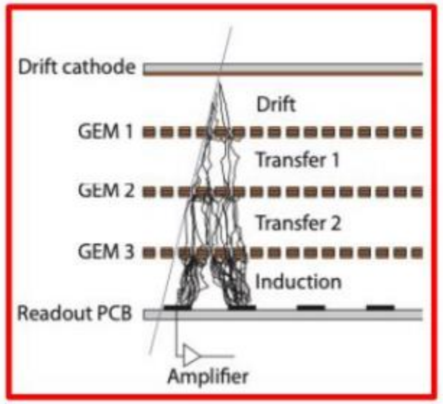
$$\sigma_{track} = \frac{\sigma_{up-down}}{\sqrt{2}} = 0.28°$$

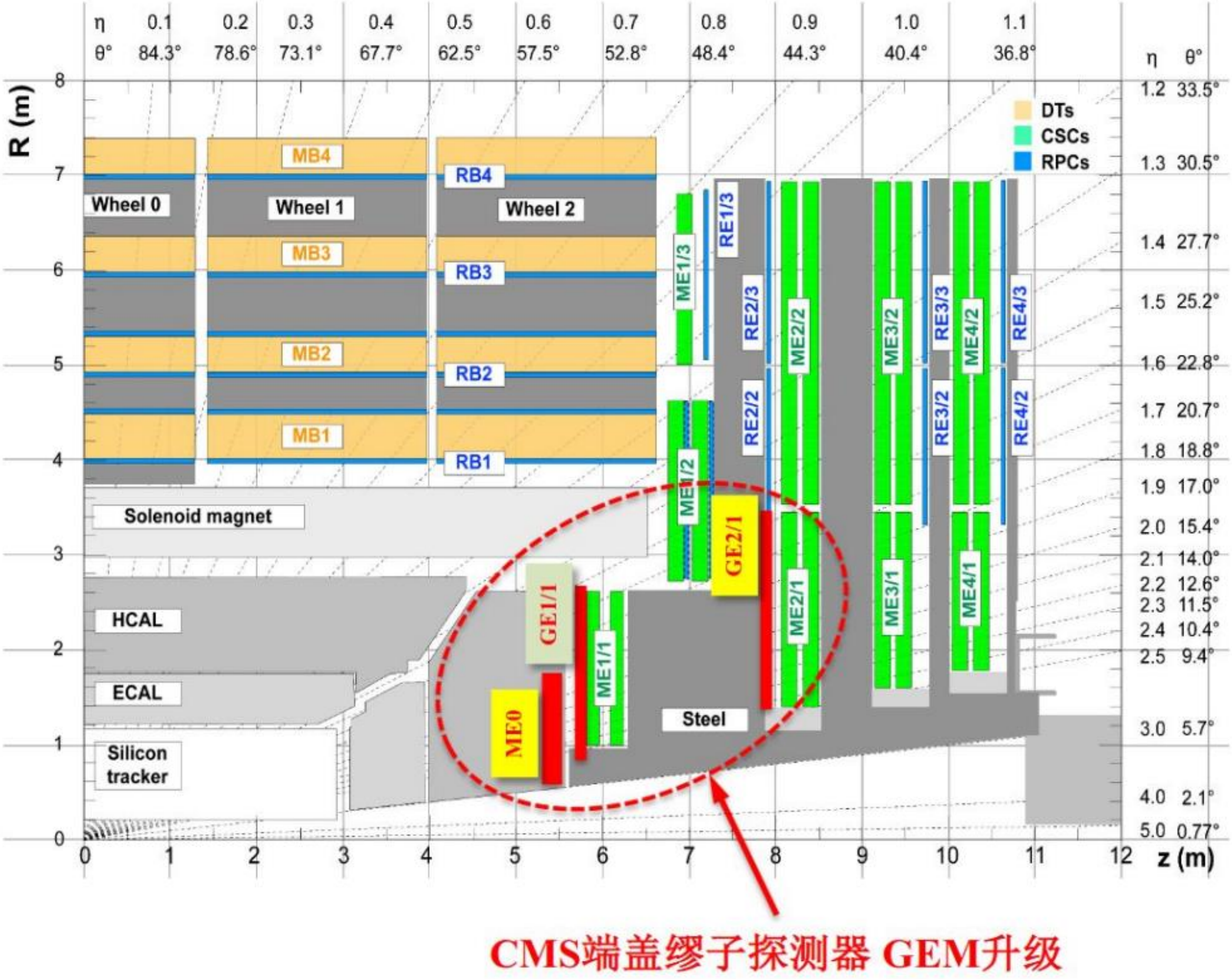
← 在兰州RIBLL1终端利用束流和α源进行了测试，下图展示了α在He上散射粒子三维重建径迹

PKU GEM (Gas Electron Multiplier) R&D Efforts









北京大学、清华大学、中山大学、北京航空航天大学

CMS Phase II Upgrade Program

GE2/1 GEM：探测器部件生产进展

PKU Lab

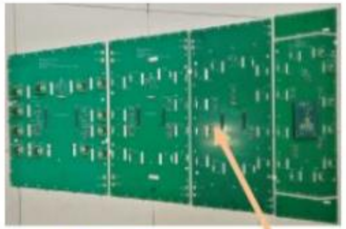
北大基地生产的第一个CMS GEM模块

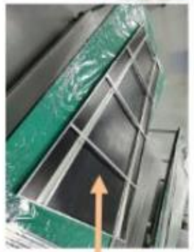
北大基地GEM测试设备

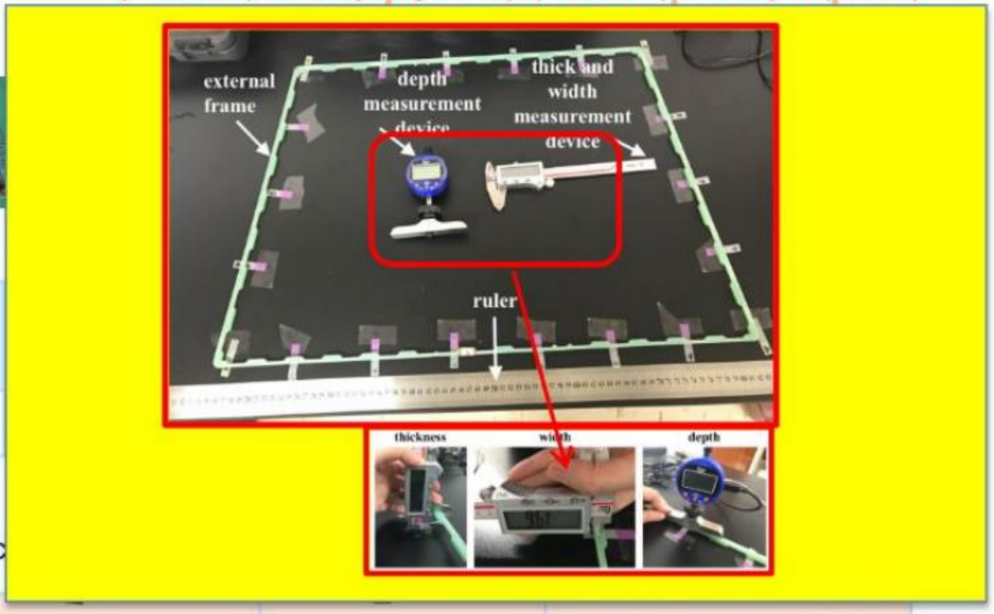
Module Components

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 %	27.6 %

(> 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！