Probing and Knocking with Muons

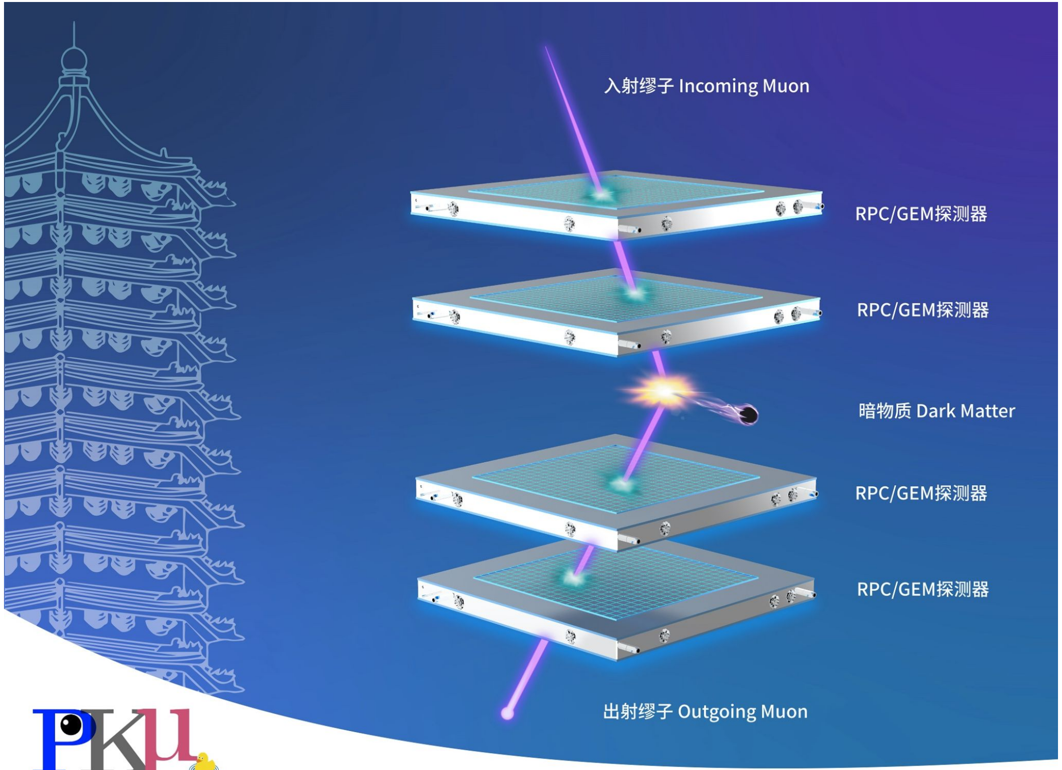
Qiang Li

Qite Li, Chen Zhou

On behalf of the PKMu Group

Peking University

2024/09



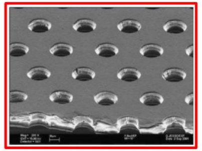
Phys.Rev.D 110 (2024) 1, 016017

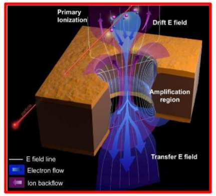
https://lyazj.github.io/pkmuon-site/categories/activities/

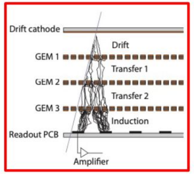
PKU Muon Detector Development

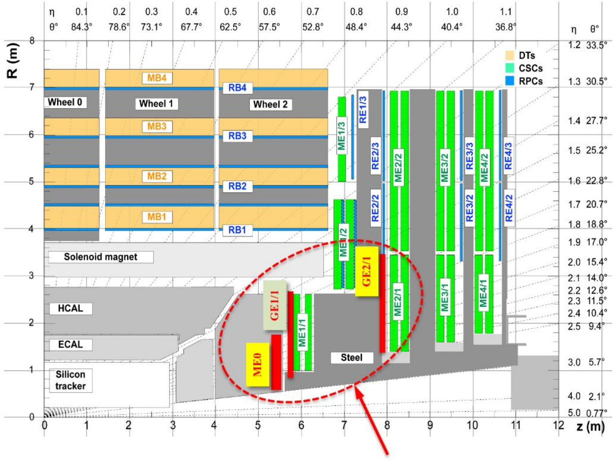
- ➔ CMS Muon Trigger RPC: assembled and tested at PKU at around 2002
- ➔ RPC R&D for nuclear physics
- ➔ CMS GEM upgrade program

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

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

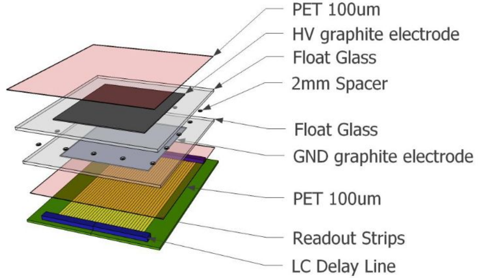
journal homepage: www.elsevier.com/locate/nima

ELSEVIER

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

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China



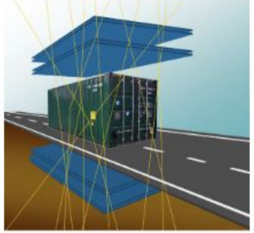
Reference:

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

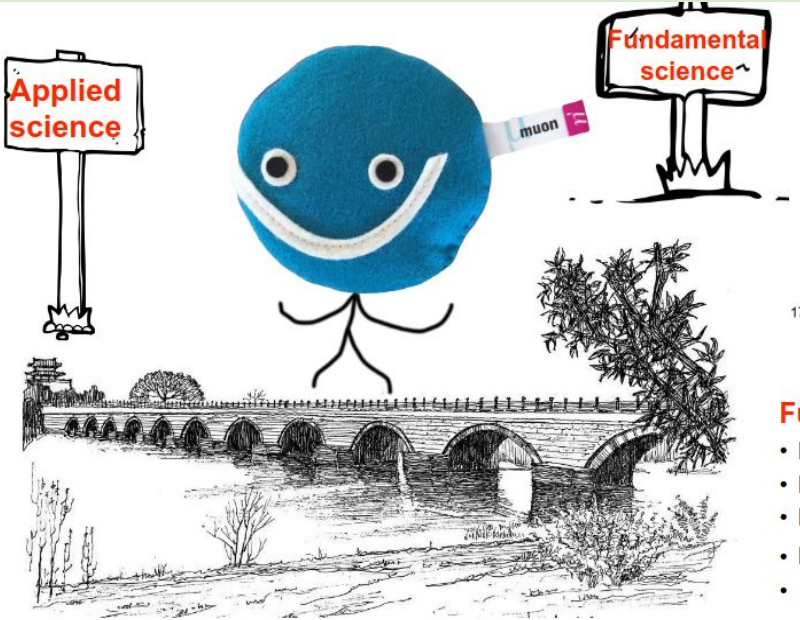
90% R134a+9% i-C_4H_{10}+1% SF_6 50ml/Min

Muon: a bridge connecting applied and fundamental particle physics

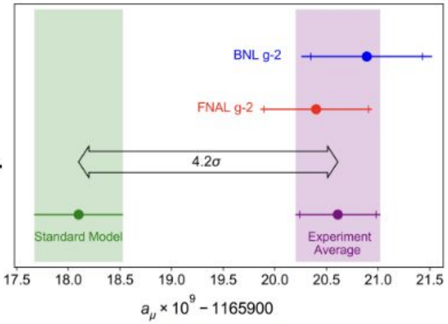
Void in Pyramid



Container inspection



Bridge in Beijing



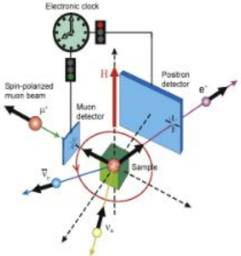
Muon g-2

Muongraphy: Non-destructive property!

- Geology:
  Rock formations, glaciers, minerals, oceans and underground carbon dioxide storage
- Archaeology:
  pyramids in Egypt, Mausoleum of Qin Shihunag
- Volcano monitor:
  Showa-Shinzan, Asama, Sakurajima in Japan, and Stromboli in Italy
- Tropic Cyclones monitor:
  Kagoshima, Japan
- Nuclear safety monitor:
  Visualization of reactor interiors, detection of spent nuclear fuel in dry storage barrels and nuclear waste
- …

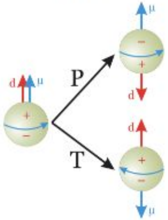
Fundamental particle physics

- Muon g-2
- Muon EDM (Electric Dipole Moment)
- Muon CLFV (Charged Lepton Flavor Violation)
- Muon-philic DM (NA64μ, MMM, ***this work***)
- …

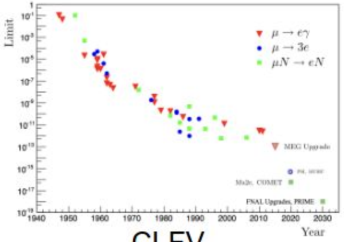


muSR

- Heavy fermion
- Superconductivity
- Quantum spin liquid
- …



EDM



CLFV

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

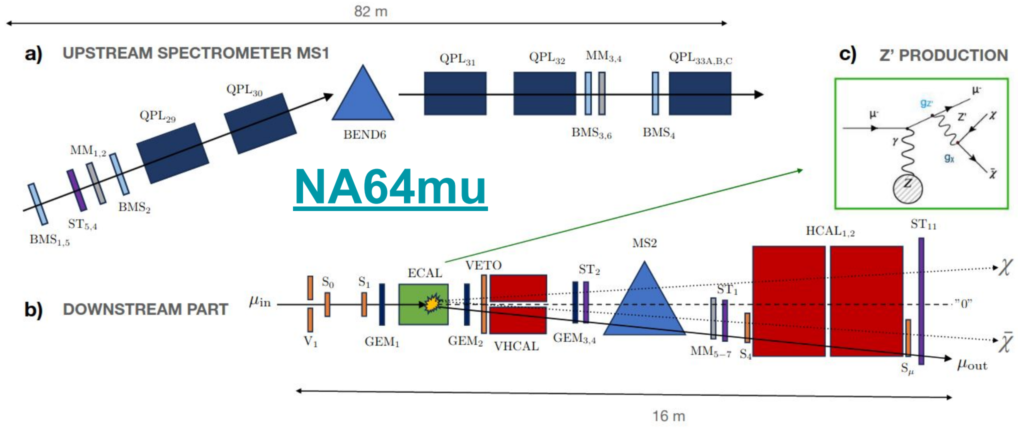
Chen Zhou (Peking University (CN)), Qiang Li (Peking University (CN)), Qite Li (Peking University)

MIP2024

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

Muon Philic Dark matter

- 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..."



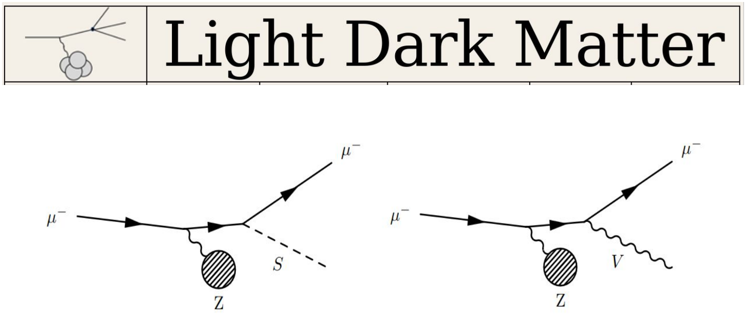


Figure 1. Dark bremsstrahlung signal process for simplified models with invisibly decaying scalar (*left*) and vector (*right*) forces that couple predominantly to muons. In both cases, a relativistic muon beam is incident on a fixed target and scatters coherently off a nucleus to produce the new particle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

Exotic Dark Matter concentrated near the Earth

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

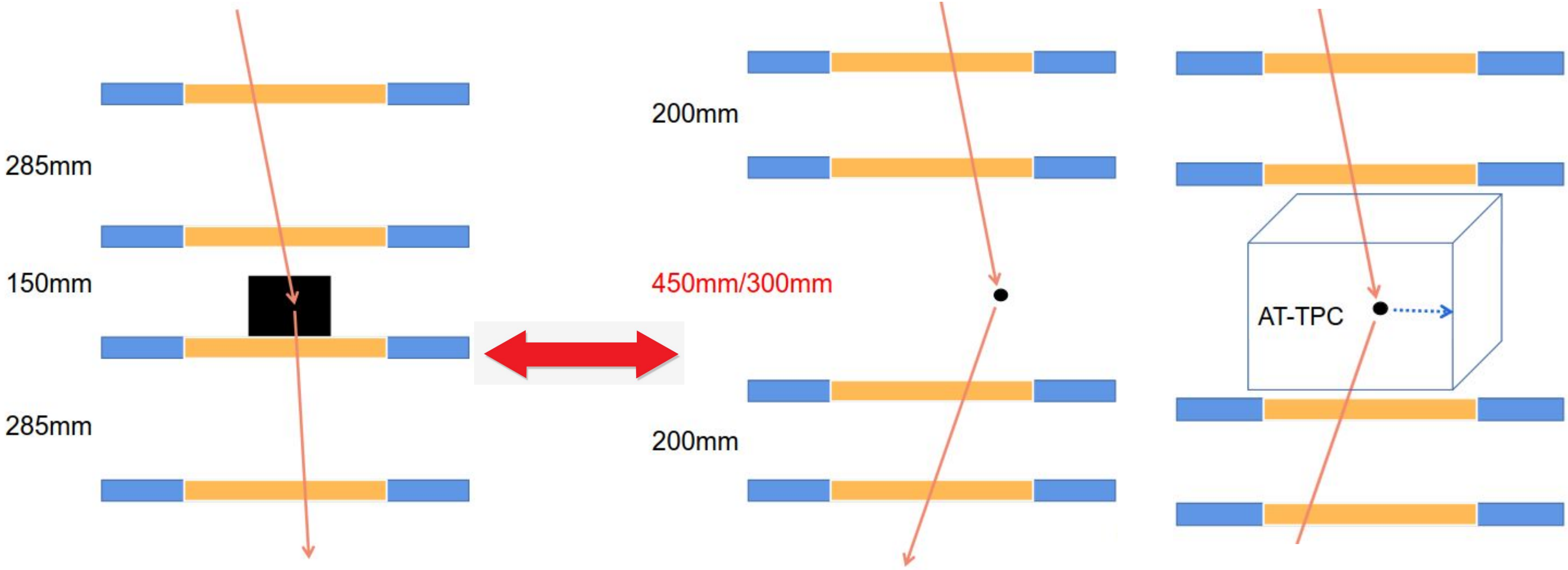
- A large amount of dark matter is concentrated near the Earth, and their speed is very low, making it difficult to cause recoil signals in experiments. (大量暗物质集中在地球附近，它们的速度很低，很难在实验中引起足够的反冲信号)
- **As we will see, muon DM scattering experiment (PKMuon) depends minorly on DM velocity**

Muon Tomography and Muon-DM scattering

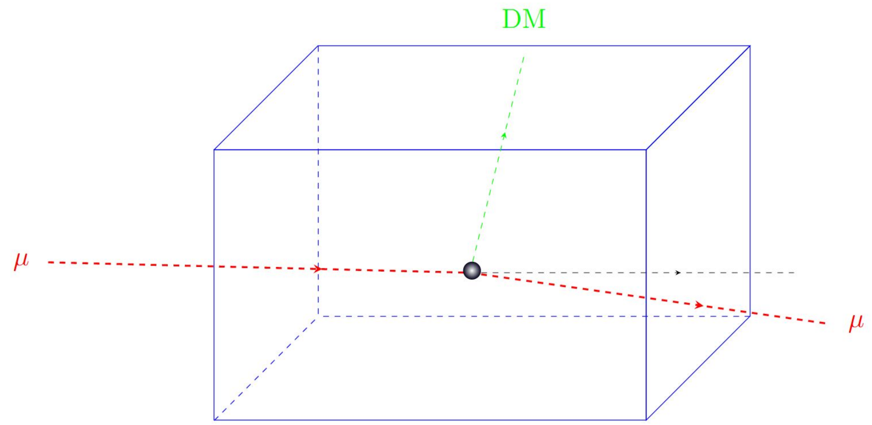
Muon Tomography 缪子成像

Dark Matter Search 暗物质寻找

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



Muon DM Box experiment: qualitative estimation



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 $\sim 1/60/\mathrm{s/cm}^2$ 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

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

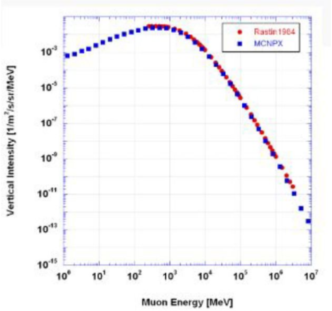
One year

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

Muon DM Box experiment: Geant4 Simulation

➔ MC simulation of GEM-based detector based on **Geant4**

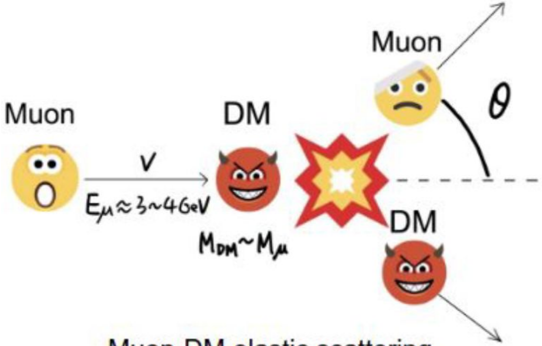
- ❖ Triple-GEM detector design refer to CMS GEM design
- ❖ Muon material interaction automatically considered by Geant4
- ❖ Reco hit position: Truth hit position smeared by GEM detector resolution (~ 200 um)



Cosmic Muon Mean energy: 3~4 GeV

➔ DM and muon scattering: **model-independent method**

- ❖ Non-relativistic two-body elastic scattering between muon and DM following Newtonian mechanics
- ❖ Standard halo model: DM velocity distribution follows Maxwell-Boltzmann distribution
- ❖ CRY (Cosmic-ray) model: cosmic-ray muon energy and zenith angle distributions at sea-level



Muon-DM elastic scattering

Different from XENON1T/PandaX: Relativistic muon hit quasi-static DM

Muon DM Box experiment: Geant4 Simulation

Cosθ distribution in air has no obvious difference between that in a vacuum. Considering cost and technical difficulty, **vacuuming of the boxes is not necessary in Phase I of the project.**

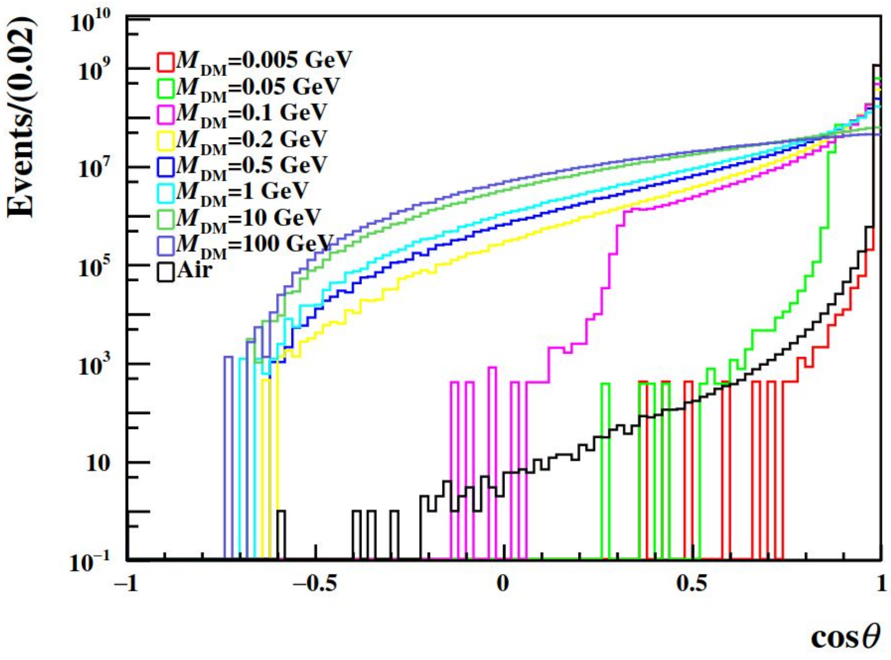
Cosθ distributions in Maxwell-Boltzmann velocity distribution and a constant velocity distribution are similar. Therefore, **our signal distribution and detection is not sensitive to the DM velocity model.**

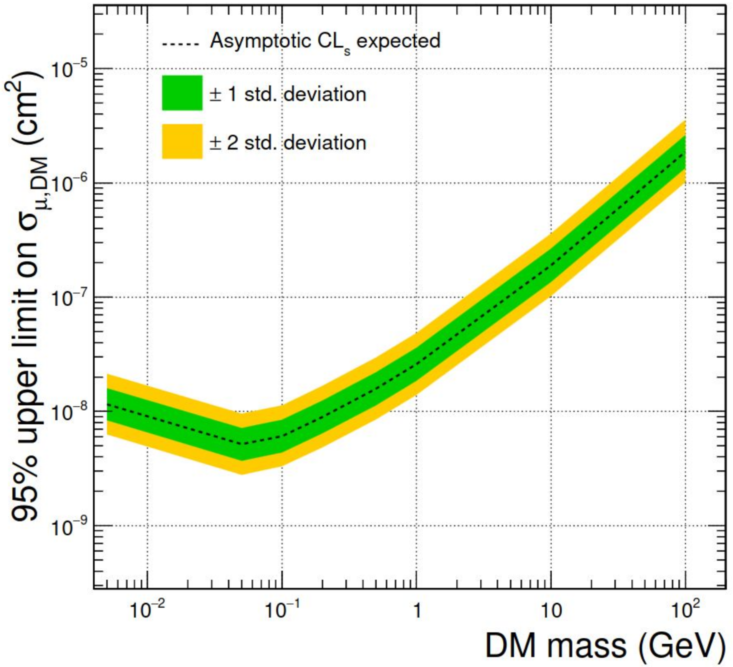
As the DM mass increases, a larger fraction occupies the region of large scattering angles, resulting a more pronounced discrepancy between the signal and background.

Background	Event Number ($\times 10^9$)	
Air	1.15	
Vacuum	1.14	
DM mass (GeV)	Constant (%)	Maxwell-Bolzmann (%)
0.005	27.10 ± 0.01	27.11 ± 0.01
0.05	29.56 ± 0.01	29.55 ± 0.01
0.1	27.66 ± 0.01	27.64 ± 0.01
0.2	25.01 ± 0.01	24.99 ± 0.01
0.5	21.47 ± 0.01	21.46 ± 0.01
1	18.67 ± 0.01	18.66 ± 0.01
10	11.10 ± 0.01	11.10 ± 0.01
100	8.44 ± 0.01	8.43 ± 0.01

TABLE I. Background event numbers corresponding to the integrated luminosity of one-year exposure with the box filled with air and vacuum, along with the signal detection efficiency under different assumptions of DM velocity distribution and mass.

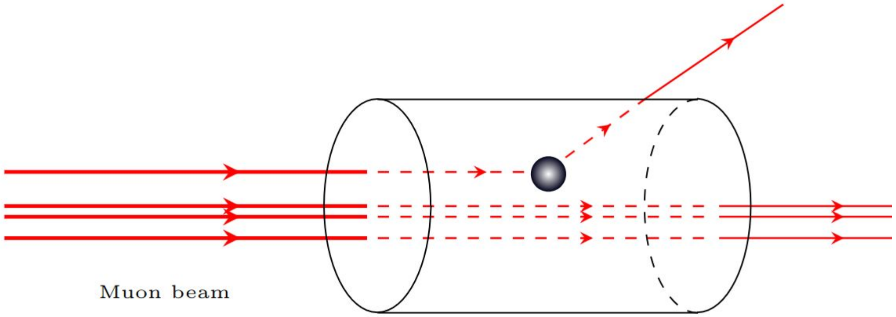
Muon DM Box experiment: expected results





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

Muon DM Beam experiment: qualitative estimation



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

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

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

The estimated rate per second:

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

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

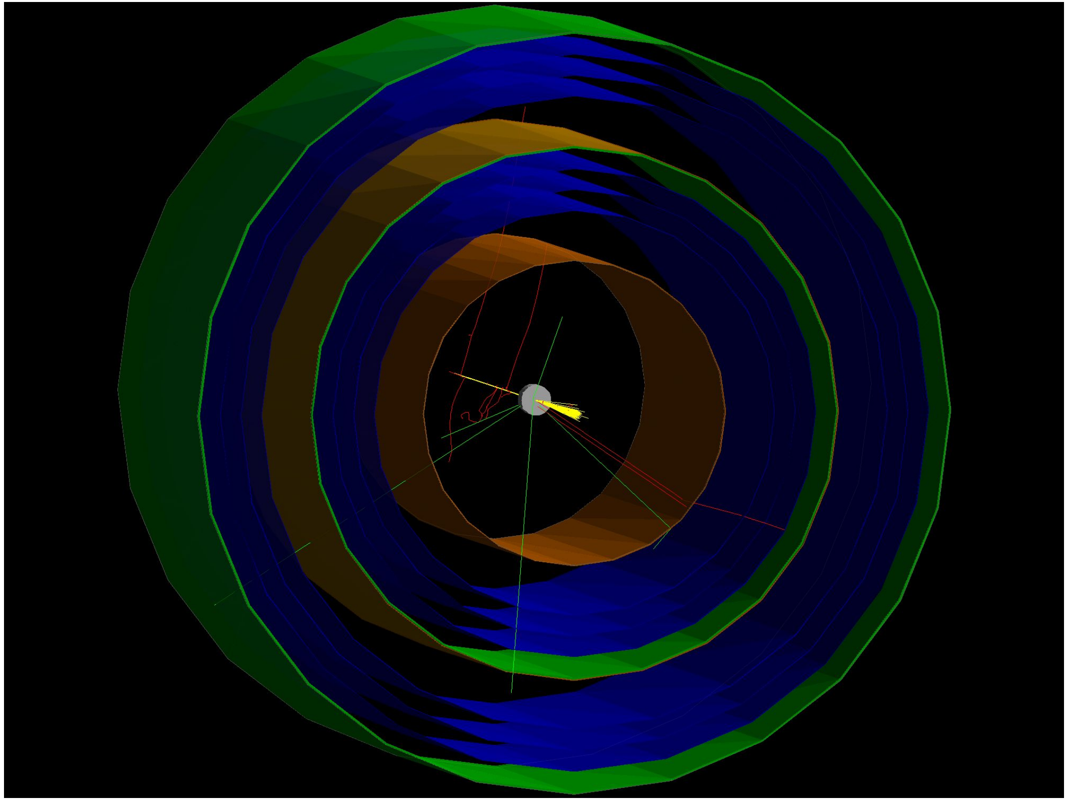
One year

Notice the surrounding area can be as small as 100 cm^2.

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.



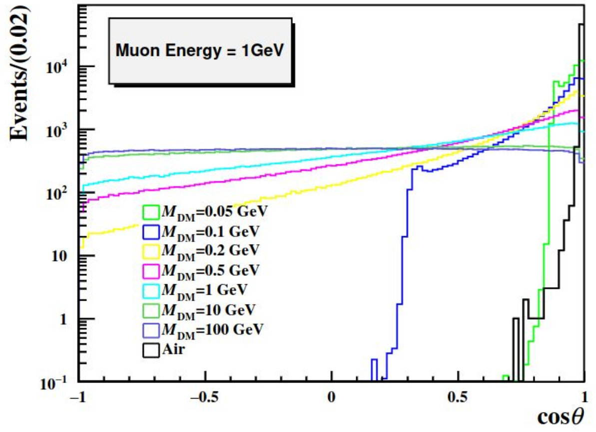
Cylindrical GEM (CGEM) detector structure for BESIII inner tracker system upgrade

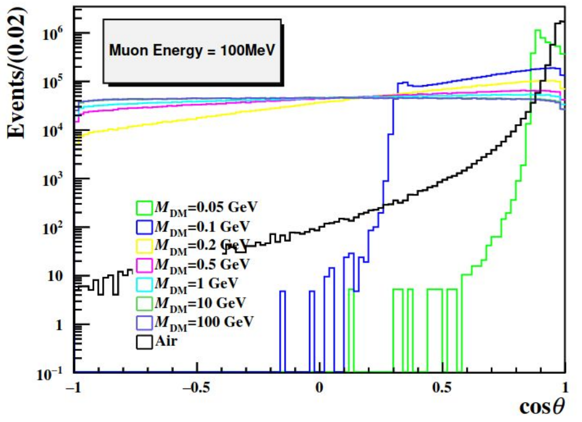
Muon DM Beam experiment: Geant4 Simulation

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

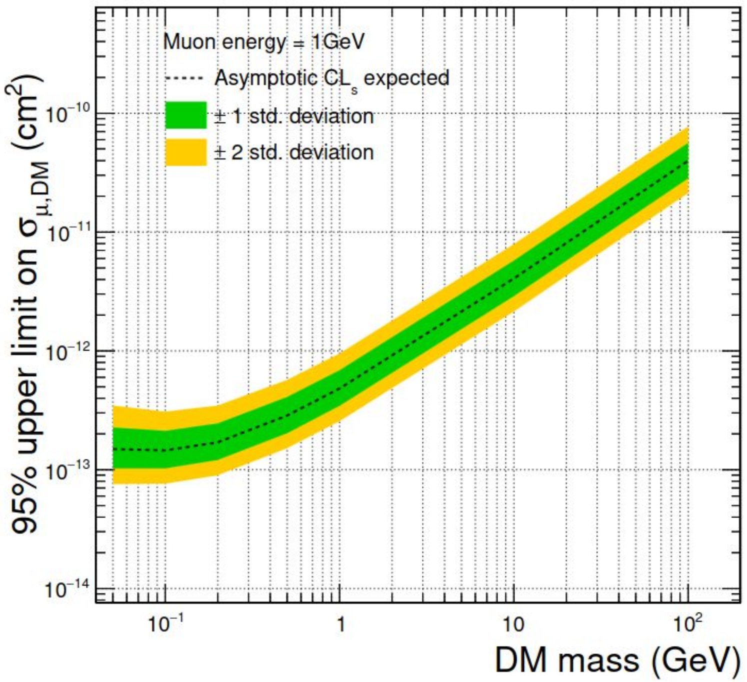
$M_{DM} \backslash E^{\mu}_{kin}$	100 MeV (%)	1 GeV (%)	10 GeV (%)
0.05 GeV	84.29 ± 0.04	74.85 ± 0.04	45.93 ± 0.05
0.1 GeV	91.74 ± 0.03	83.07 ± 0.04	58.17 ± 0.05
0.2 GeV	94.35 ± 0.02	88.16 ± 0.03	68.37 ± 0.05
0.5 GeV	95.17 ± 0.02	92.16 ± 0.03	78.91 ± 0.04
1 GeV	95.34 ± 0.02	93.88 ± 0.02	84.68 ± 0.04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

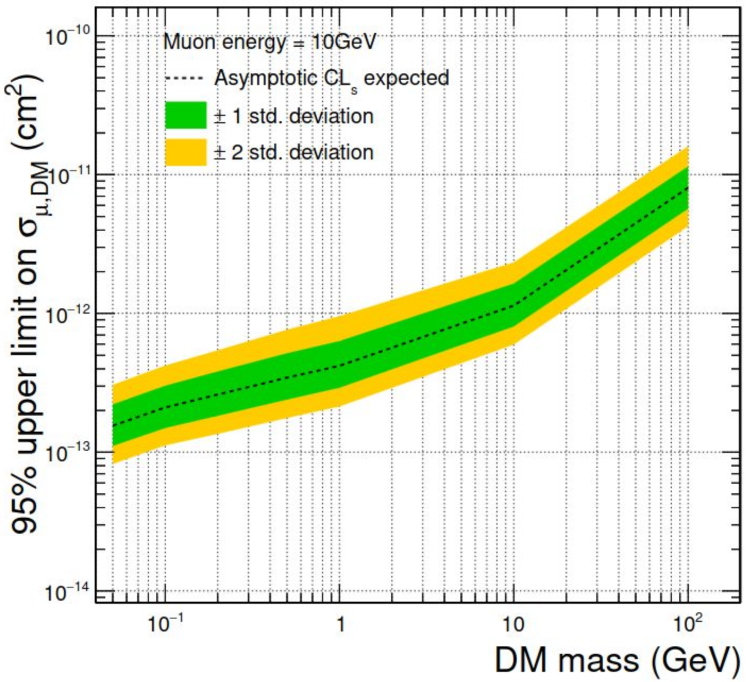
TABLE II. Signal detection efficiency under different assumptions of DM mass and muon beam energies.





Muon DM Beam experiment: Geant4 Simulation

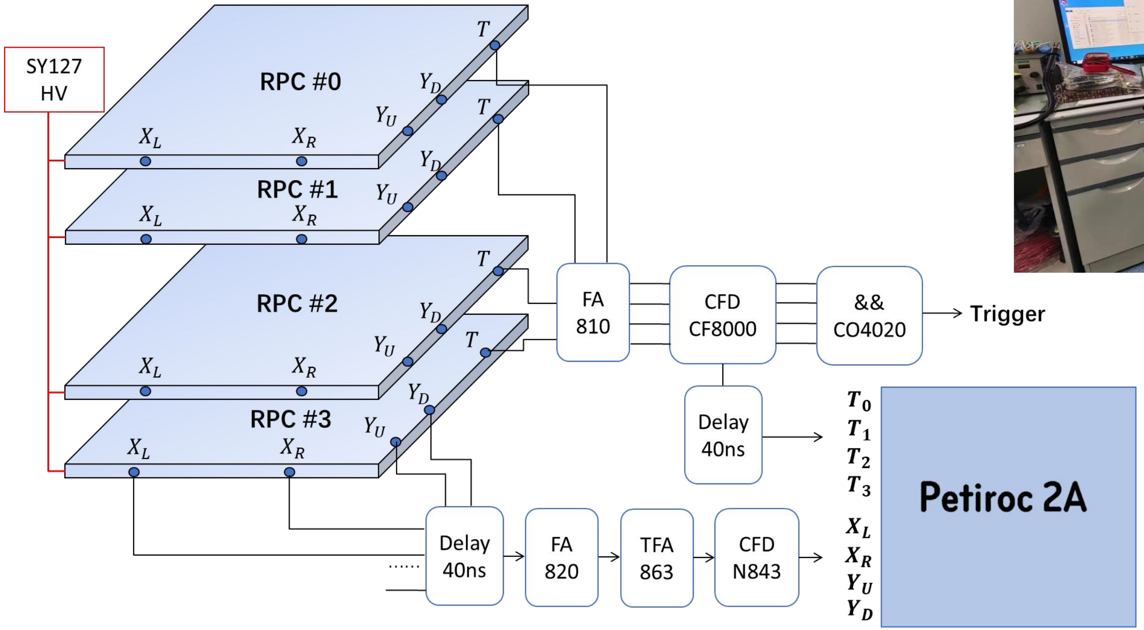


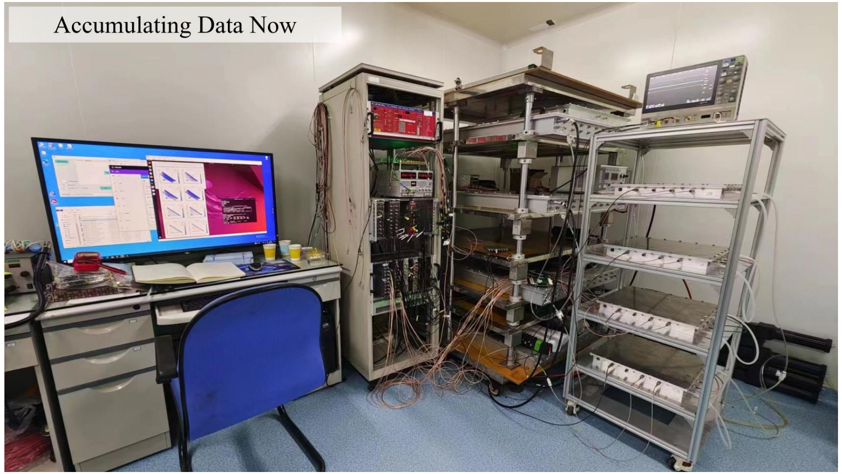


Current Box Exp. Status

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

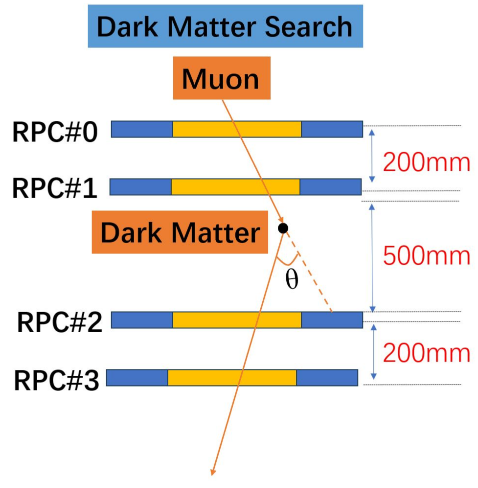
Accumulated Data

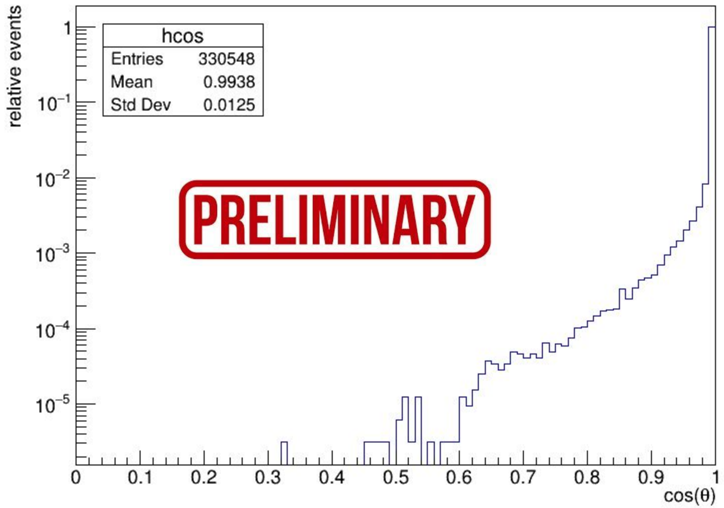
- 3+ months data taking since Jan. 2024

- Effective volume as 50cm*20cm*20cm
- Total effective events as 330548, with mean scattering angle as 0.0252 rad
- The fraction of large angle scatter events (θ>0.2rad) is around 1.6%
- There are several events with cosθ<0.4

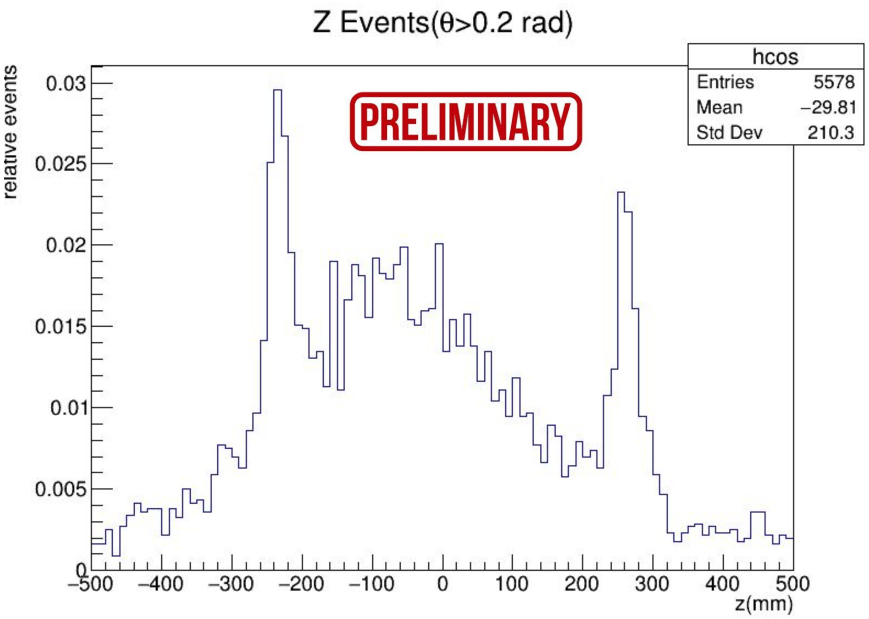
- Data Analysis is ongoing

More results in [a recent report](#) from Cheng-en Liu and Qite Li

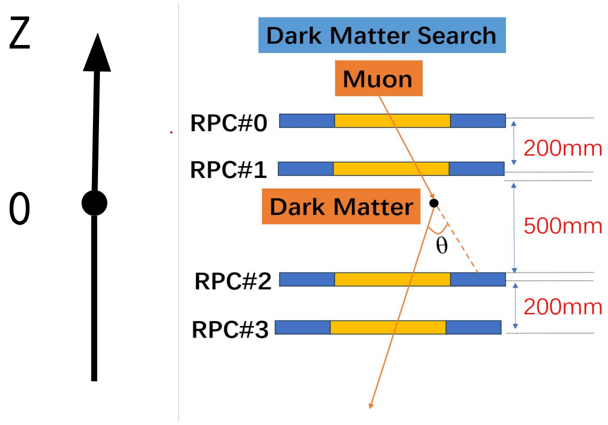


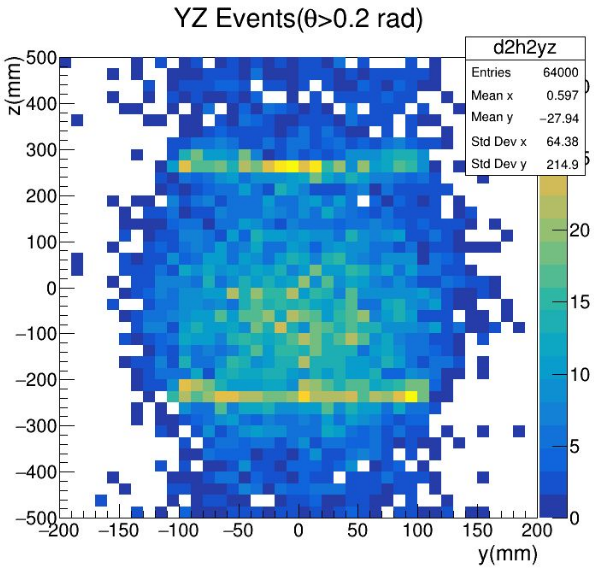


Large angle events



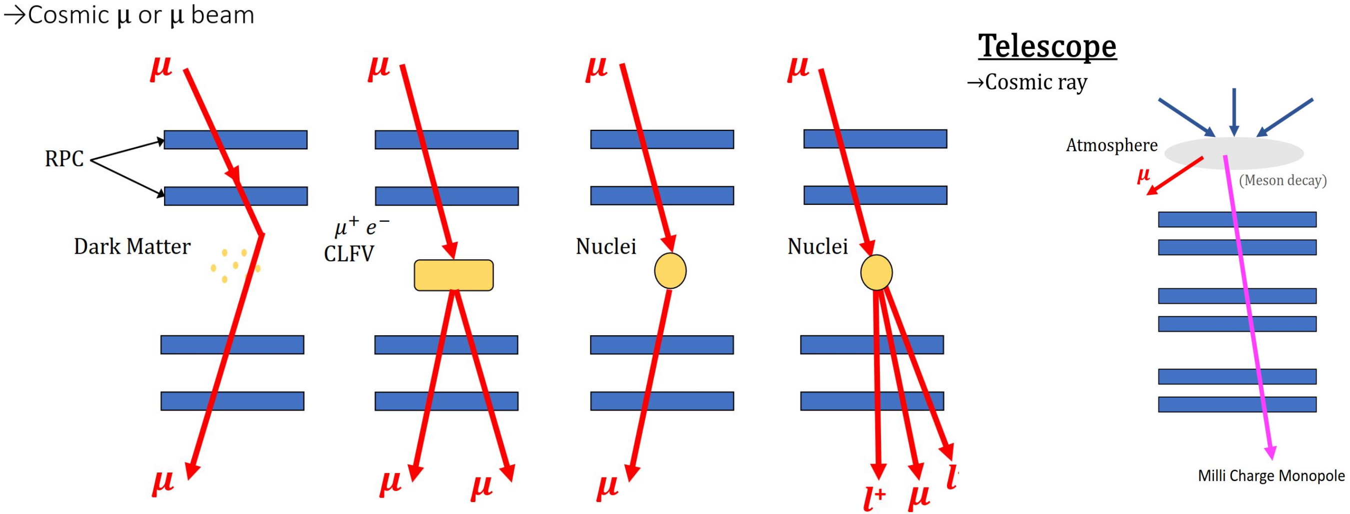
Stay Tuned!

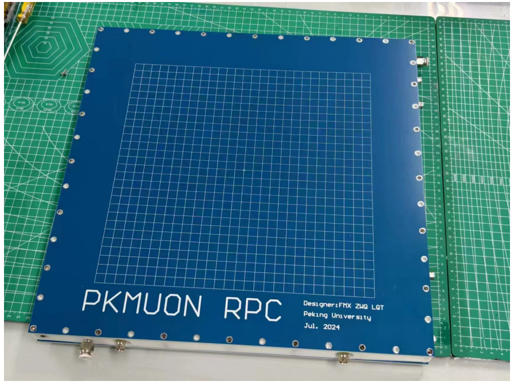




Future

Interfacing Cosmic Muon or Muon beam

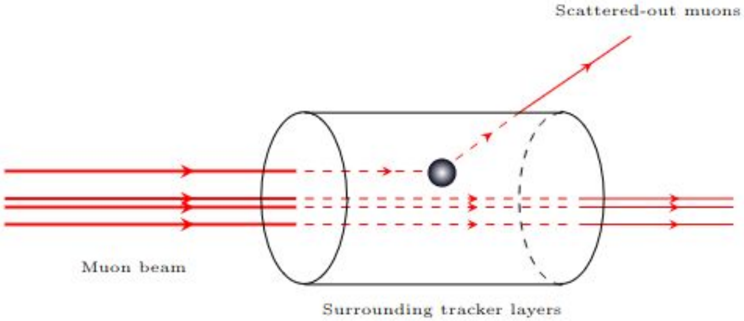


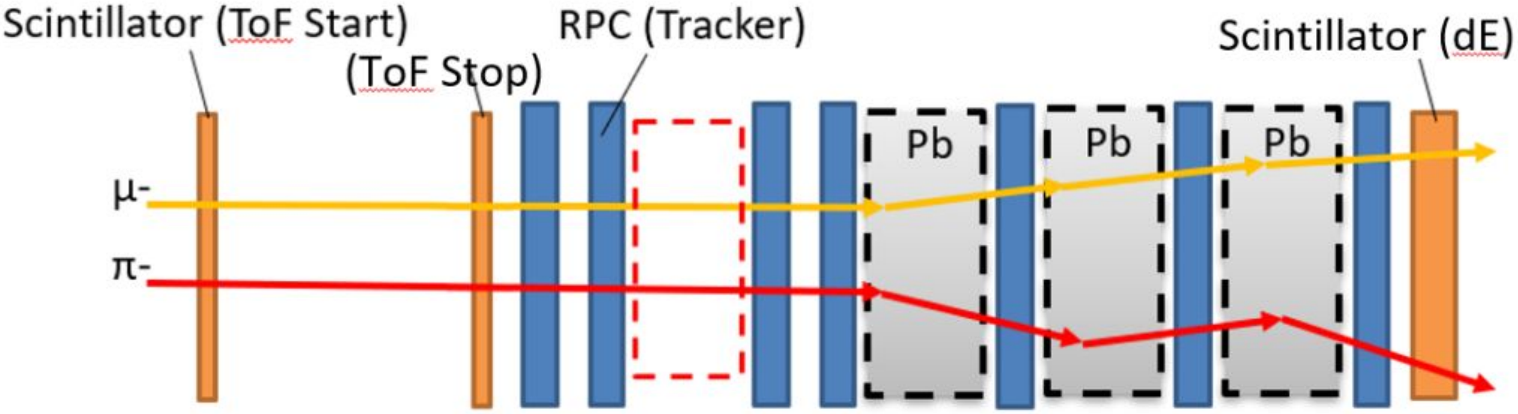


More physics program:
CLFV, Muon-Nuclei scattering …

Larger area
RPC or GEM
being produced

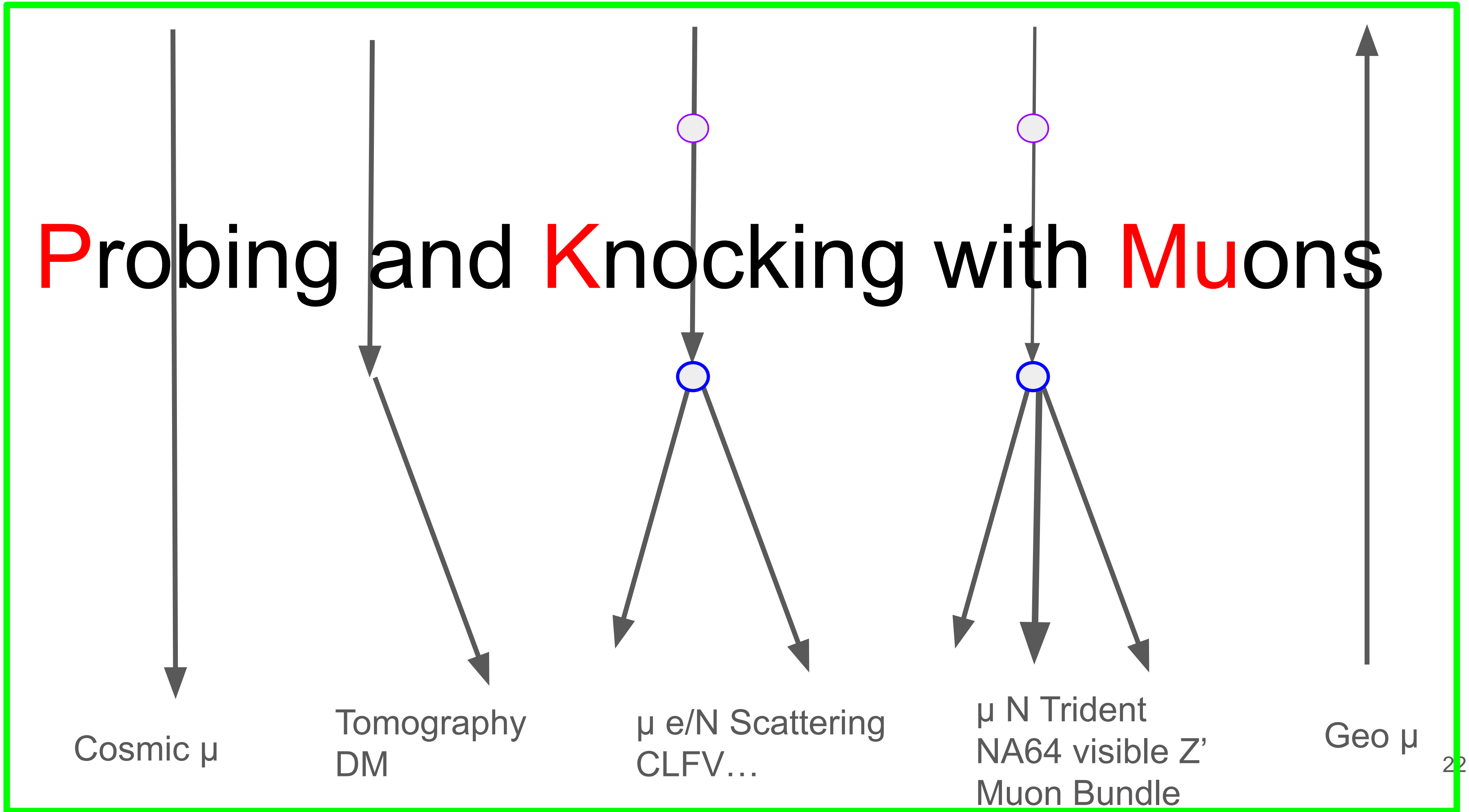
Interfacing with a muon beam at HIAF





Backup

Probing and Knocking with Muons



Melody, CIADS, HIAF Muon beams

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

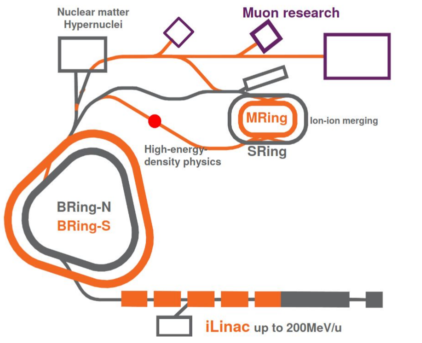
	Surface Muon	Negative Muon	Decay Muon
Proton Power (kW)	20	Up to 100	Up to 100
Pulse width (ns)	130 to 10	500	130 to 10
Muon intensity (/s)	10^5~ 10^6	Up to $5*10^6$	Up to $5*10^6$
Polarization (%)	>95	>95	50~95
Positron (%)	<1%	NA	<1%
Repetition (Hz)	1	Up to 5	Up to 5
Terminals	2	1~2	2
Muon Momentum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

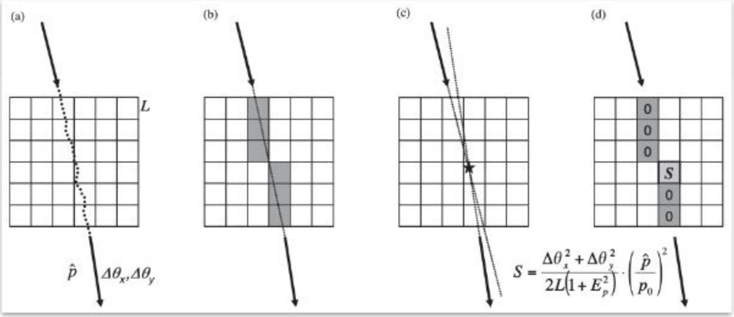
- **BRing-N**: 34Tm, 569m, 3Hz
- **SRing**: 17(25)Tm, 270.5m, accumulation/compression
- **BRing-S**: 86Tm, 3Hz, superconducting
- **MRing**: 45Tm, superconducting, beam merging

	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
HIAF-U	**3.0**	$^{238}U^{35+}$	2×10^{12}	**2032**
	9.1	$^{238}U^{92+}$	1×10^{12}	
	25	p	4×10^{14}	

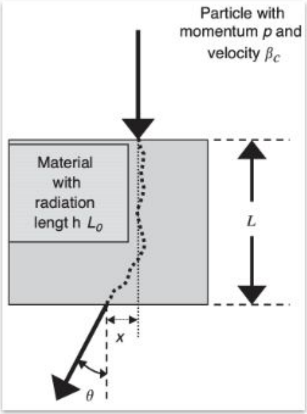


~30 MeV, ~100 MeV, ~1GeV

PoCA



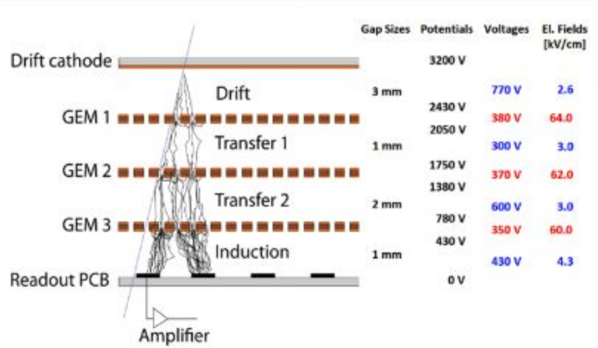
- ➔ The point of closest approach (PoCA) algorithm
- ➔ The angular scattering distribution is approximately Gaussian
  - ❖ $\sigma_\theta = \frac{13.6\,\text{MeV}}{\beta cp}\sqrt{\frac{L}{L_0}}[1 + 0.038\ln\frac{L}{L_{\text{rad}}}] \approx \frac{13.6}{p}\sqrt{\frac{L}{L_0}}$
  - ❖ p: momentum, βc: velocity, L: depth of the material, L_{rad}: radiation length of the material
- ➔ Scattering strength: establish a nominal muon momentum (3 GeV, for example), and define the mean square scattering of nominal muons per unit depth of a material
  - ❖ $\lambda_{\text{mat}} = (\frac{13.6}{p_0})^2\frac{1}{L_{\text{rad}}} \approx \sigma^2_{\theta_0,\text{mat}}$
  - ❖ depends only on material radiation length, and varies strongly with material Z
- ➔ Multiple muons income and scatter with material, and we measure it in two orthogonal planes x and y. If we know the path length L_i and the momentum p_i of each muon through the material:
  - ❖ $\hat{\lambda} = \frac{1}{N}\sum_{i=1} N(\frac{p_i^2}{p_0^2}\cdot\frac{\theta_{xi}^2 + \theta_{yi}^2}{2L_i})$



GEM

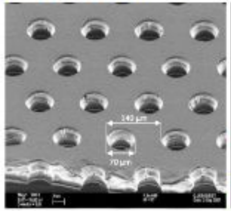
[CMS TDR]

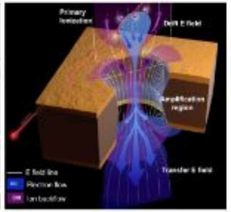
- ➔ Triple-GEM detector installed in the CMS experiment
  - ❖ Improve trigger capabilities and muon measurements
  - ❖ Excellent performance: rate > $10\ \mathrm{kHZ/cm^2}$, time resolution ~ 8 ns, spatial resolution ~ 200 μm



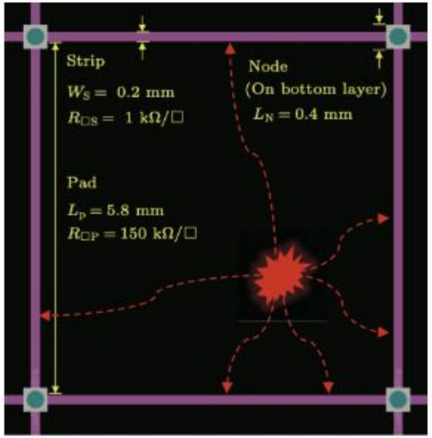
Schematic view of a triple-GEM detector

- ➔ Electron amplification structure and flexible readout structures





- ➔ Pixel readout VS [resistive anode readout method]
  - ❖ Challenge: Large amount of small pixels
  - ❖ Good comparable spatial resolution but less electronic channels



Structure diagram of the basic resistive anode cell

- ➔ Design our exclusive readout for the specific requirements of PKU-Muon GEM detectors.
  - ❖ Hit position reconstruction algorithm ongoing

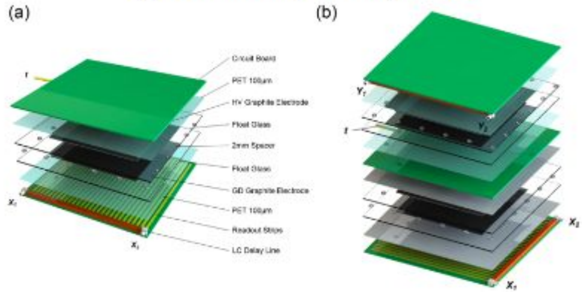
[MIP2024-1]

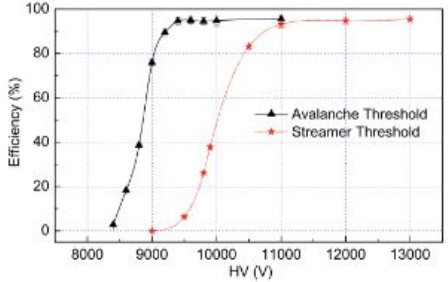
RPC

- ➔ RPC — R. Santonico(in 1980s)
  - ❖ simple and robust structure, long-term stability, good timing resolution, easy-maintenance and low cost
- ➔ PKU RPC R&D History
  - ❖ **CMS Muon Trigger RPCs**, assembled and tested by PKU (2002)
  - ❖ Combination of glass RPC & Decay-line Readout (Qite Li et. al.)
- ➔ **Glass RPC MT Prototype** in 2012
  - ❖ Effective area of the electrode: $20 \times 20\,\mathrm{cm}^2$
  - ❖ Readout electronics: decay-line, charge-division methods
- ➔ **Good and stable performance** so far!
  - ❖ Positional resolution: ~0.5 mm, detection efficiency: > 90%

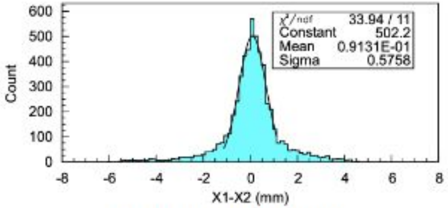
Compact Muon Solenoid

(a) Prototype glass RPC
(b) One RPC with two structure get X and Y signals respectively





Efficiency curves for the glass RPC



Distribution of X1-X2

MIP2024-1

Exotic DM

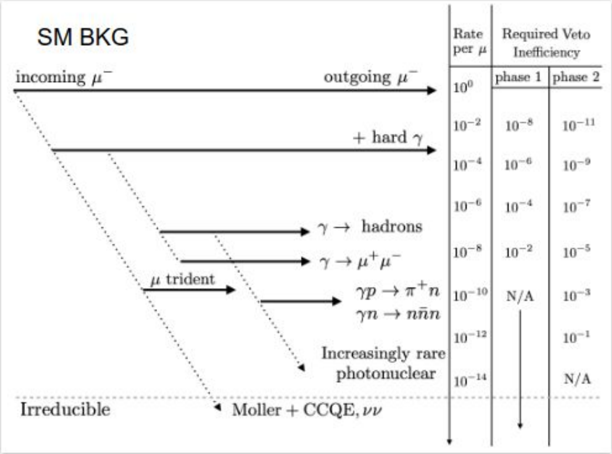
PRL 131, 011005 (2023)

- ➔ A new species χ that interacts "strongly" with ordinary matter but that makes up only a tiny fraction $f_\chi = \rho_\chi / \rho_{\rm DM} \ll 1$ 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 $\sim kT = 0.03\,\mathrm{eV}$

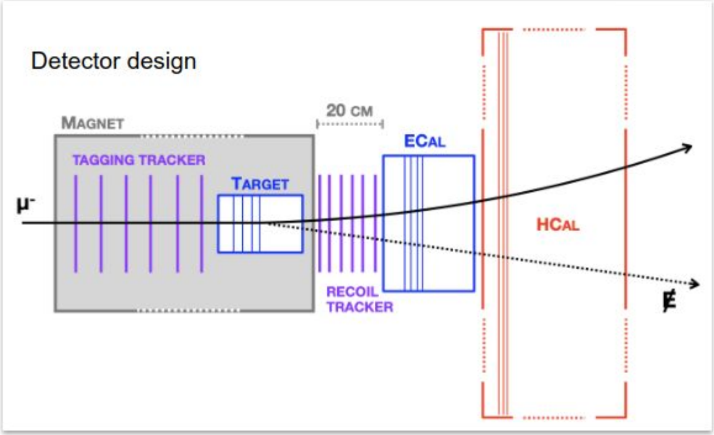
Exotic DM is slowed down near the Earth, and its density is highly enhanced

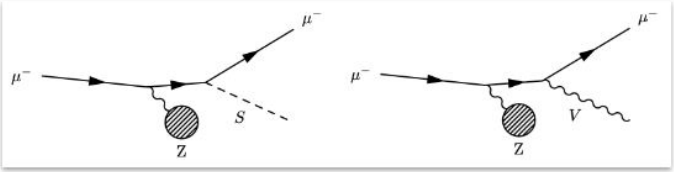
MMM

- ➔ Motivated by $(g-2)_\mu$ anomaly
- ➔ M^3 (Muon Missing Momentum) based at Fermilab (LINK)
  - ❖ New fixed-target, missing-momentum search strategy to probe invisibly decaying particles that couple preferentially to muons
- ➔ Advantage:
  - ❖ Bremsstrahlung backgrounds suppressed
    - Bremsstrahlung rate is suppressed by $(m_e/m_\mu)^2 \approx 2\times10^{-5}$
  - ❖ Compact experimental design
    - Lower muon beam energy (15 GeV vs. 100-200 GeV) allows for greater muon track curvature and more compact design
- ➔ SM-induced BKG are studied



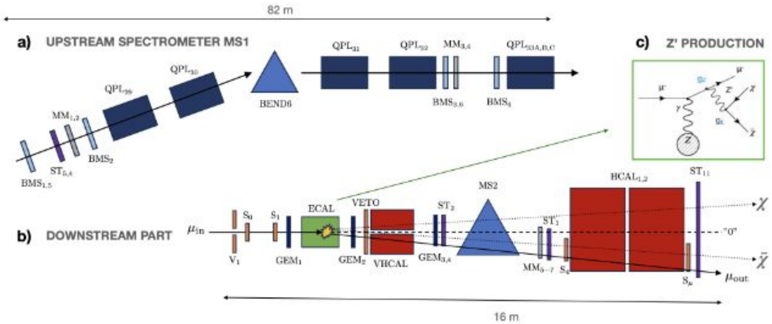
Rate per μ	Required Veto Inefficiency phase 1	phase 2
10^0		
10^{-2}	10^{-8}	10^{-11}
10^{-4}	10^{-6}	10^{-9}
10^{-6}	10^{-4}	10^{-7}
10^{-8}	10^{-2}	10^{-5}
10^{-10}	N/A	10^{-3}
10^{-12}		10^{-1}
10^{-14}		N/A

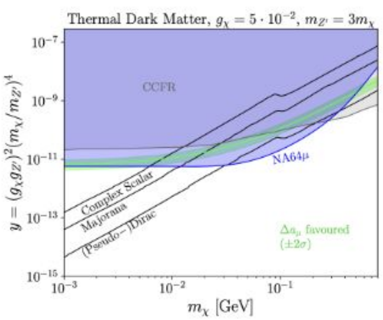


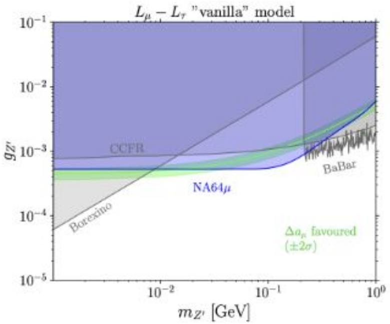


NA64μ

- 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: $\mu N \to \mu N Z', Z' \to \text{invisible}$
- 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



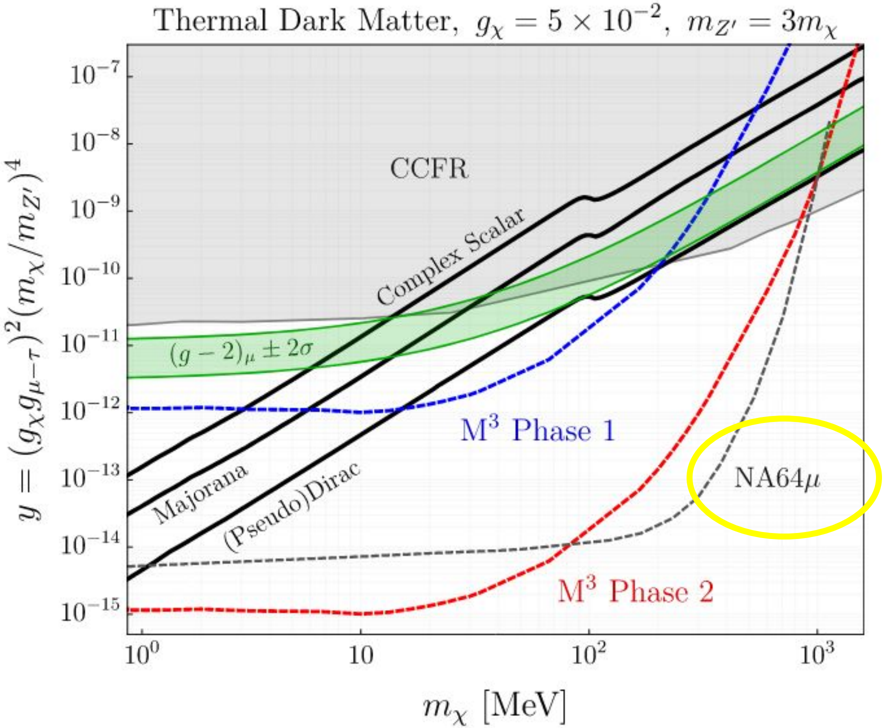


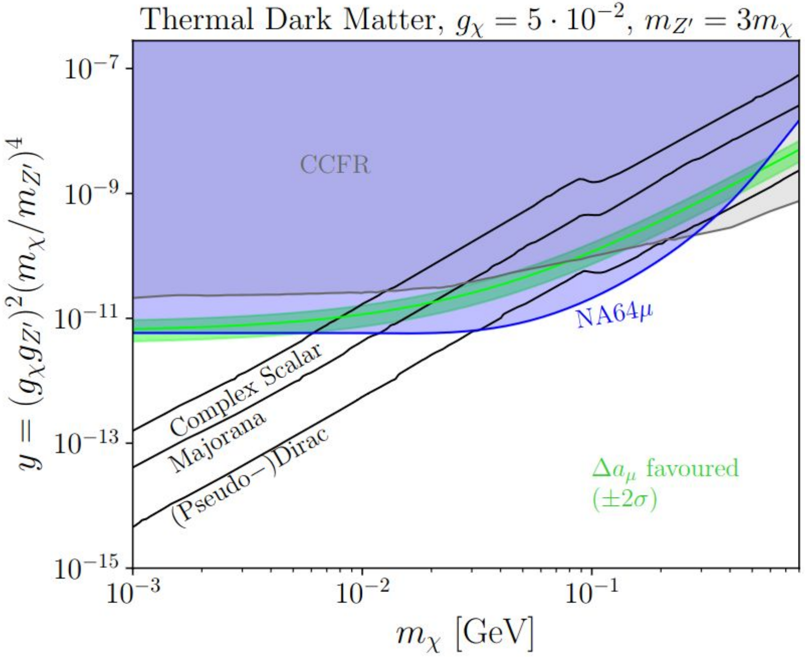


Ref: MMM

VS

Ref: NA64mu

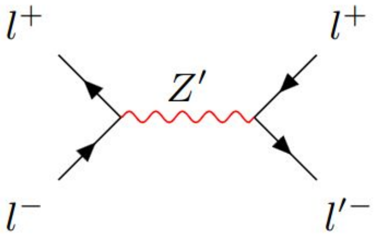


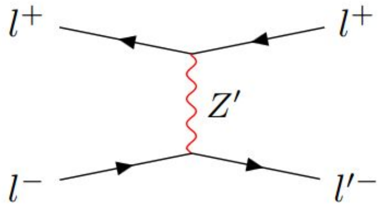


Muon-Electron Threshold Scan

Muon-electron collider

CLFV





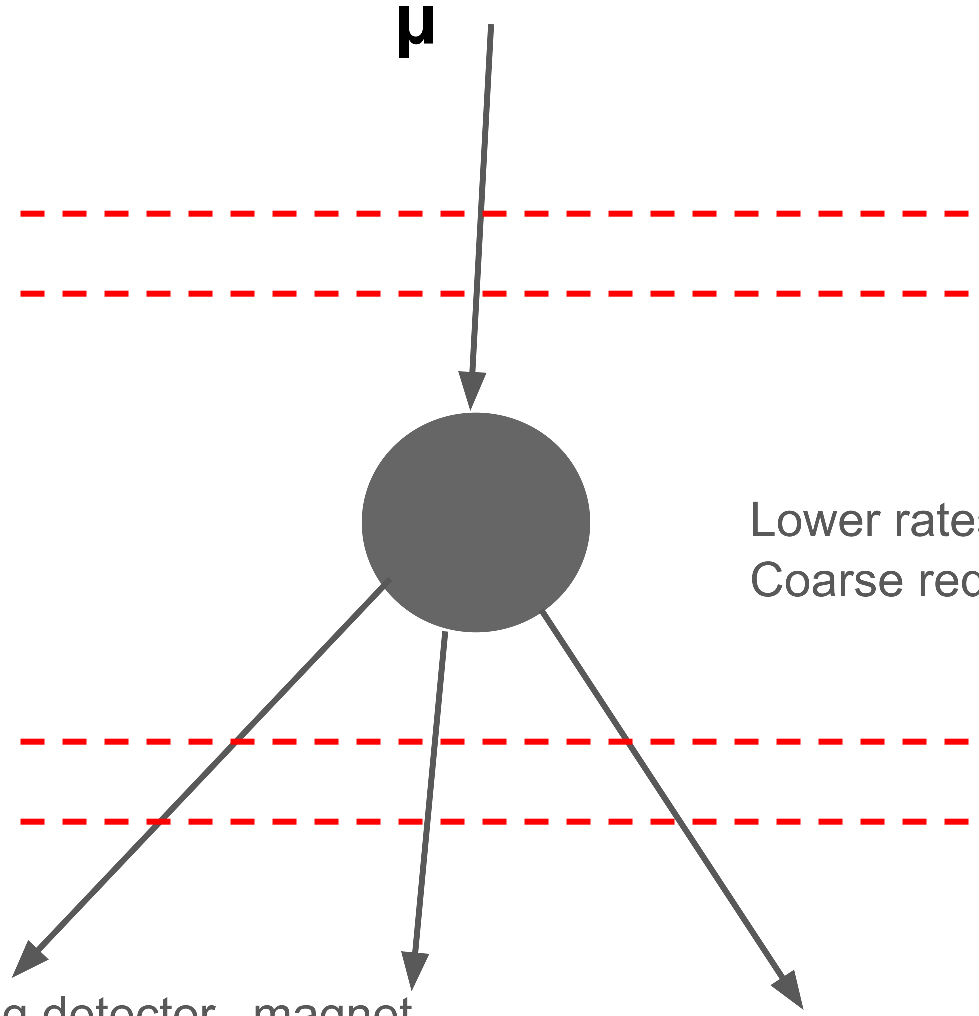
Muon-on-target

Process	$M_{Z'}$ / GeV	E_μ / GeV	E_e / MeV	E_{cm} / GeV
$\mu^+e^- \to e^+e^-$	0.11	0.93	0.511	0.1101
	0.15	11.1	0.511	0.1501
	0.20	28.2	0.511	0.1996
$\mu^+e^- \to \mu^+\mu^-$	0.22	33.6	0.511	0.2200
	0.25	50.2	0.511	0.2499
	0.30	77.2	0.511	0.2998

- μ+ e- ⟶ Z’⟶ e+ e-, μ+ μ- Charged Lepton Flavor Violation
- μ+ e- ⟶ Z’⟶ X X Lepton Flavor Violation DM
- Resonant production Enhancement
- <u>X=16.7 MeV Anomaly</u>
- Connecting e-mu collider and muon beam experiments

specific beam energy
Leads to
specific phase space

Cosmic Muon Collider



Shields (Momentum Selector) + Muon Detectors

Lower rates ⟶
Coarse requirement on detector

Shields (Momentum Selector) + Muon Detectors

Optional: timing detector, magnet…