Muon tomography and dark matter search and MORE with RPC/GEM detectors

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on behalf of collaborators
Peking University 2024/05

arXiv:2402.13483
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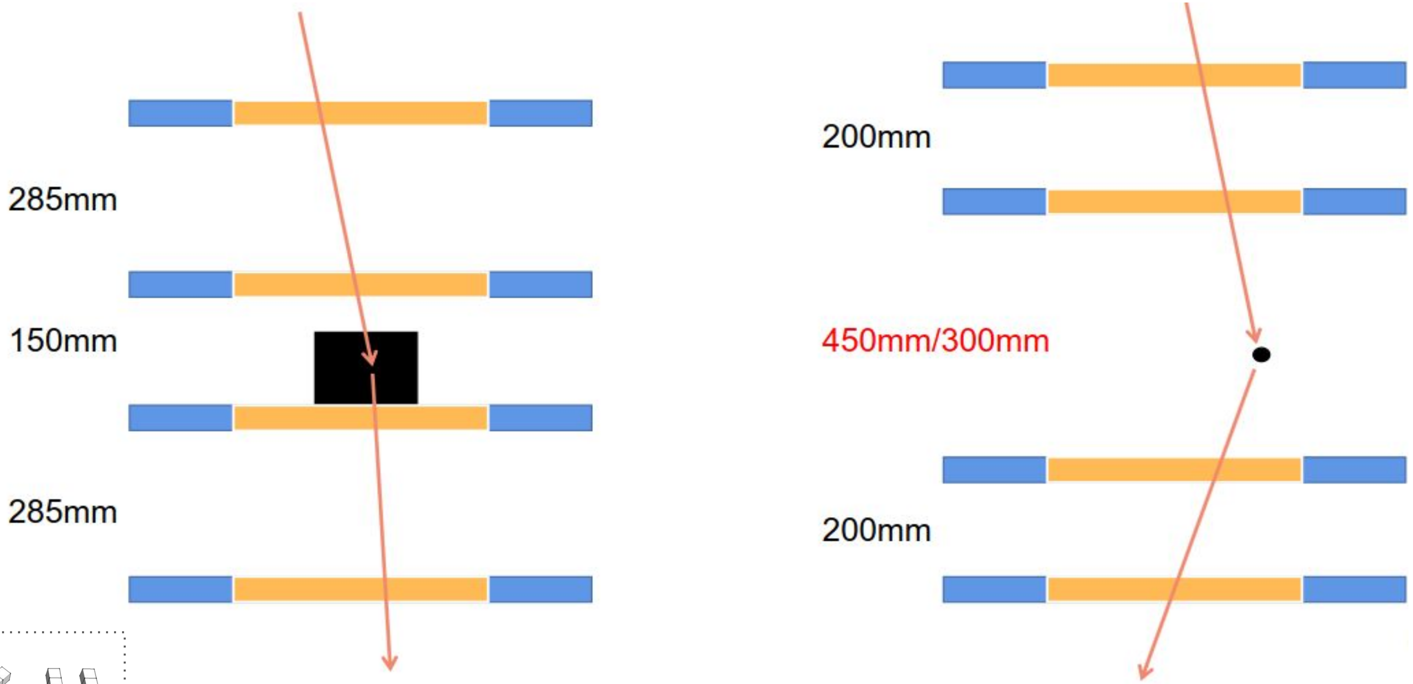
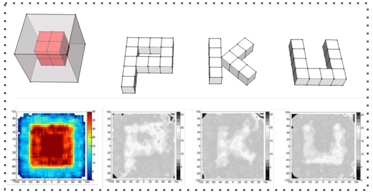
MIP2024-1, MIP2024-poster,
cdex2024-1, cdex-2024-2
https://lyazj.github.io/pkmuon-site/

Multipurpose Platform:

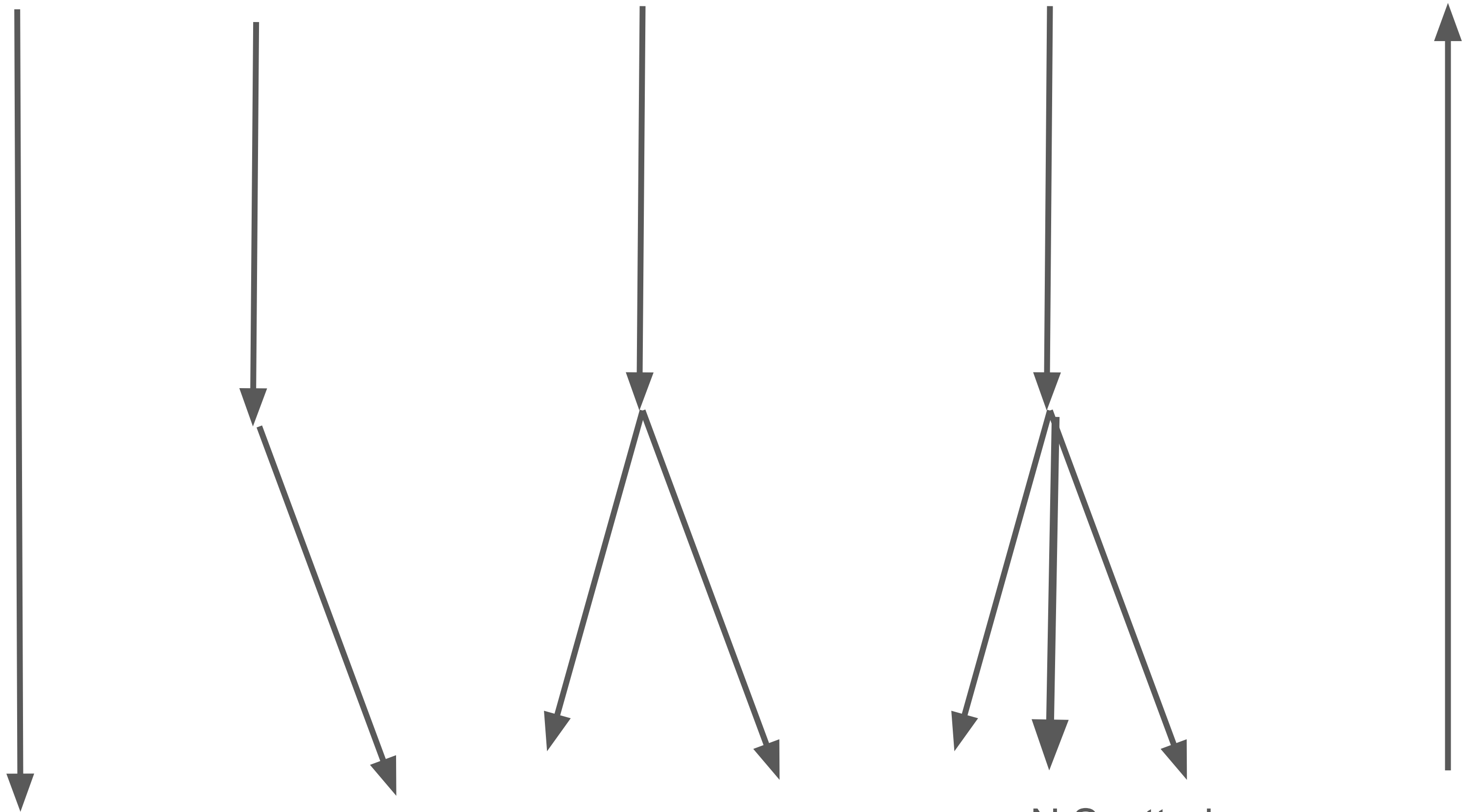
multilayer O(10×10m) RPC/GEM or other detectors





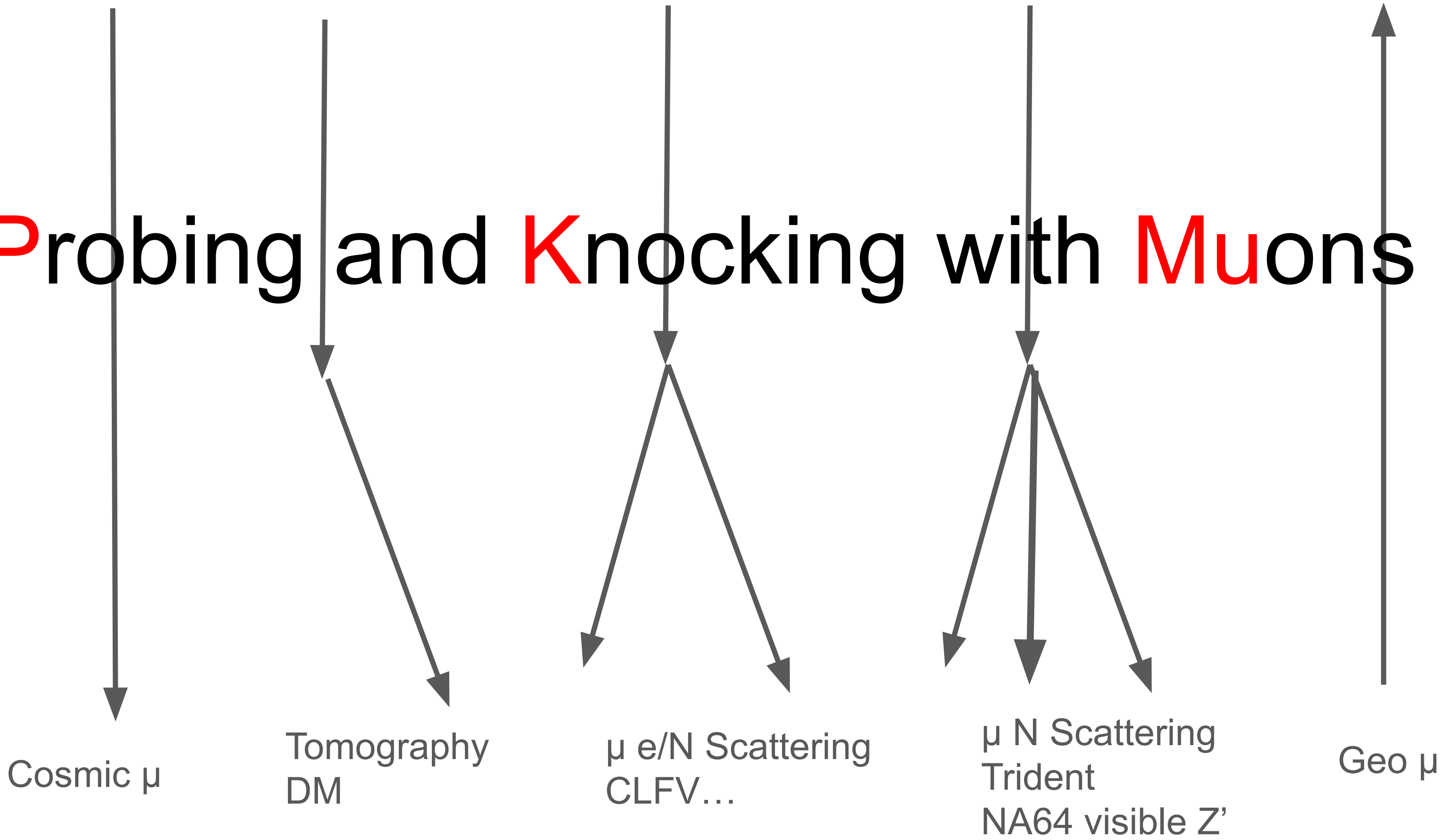
百平米、三明治构型(in/out, 中间为空气、材料等)、模块化(多个1-10平米模块、不同组协调、optional detector for 电子/光子)

Either using cosmic muons or beams, although the requirement on detector will be different (e.g., cosmic muons need larger area)



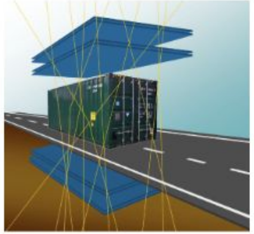
Either using cosmic muons or beams, although the requirement on detector will be different (e.g., cosmic muons need larger area)

Probing and Knocking with Muons



Muon: a bridge connect applied study & fundamental research

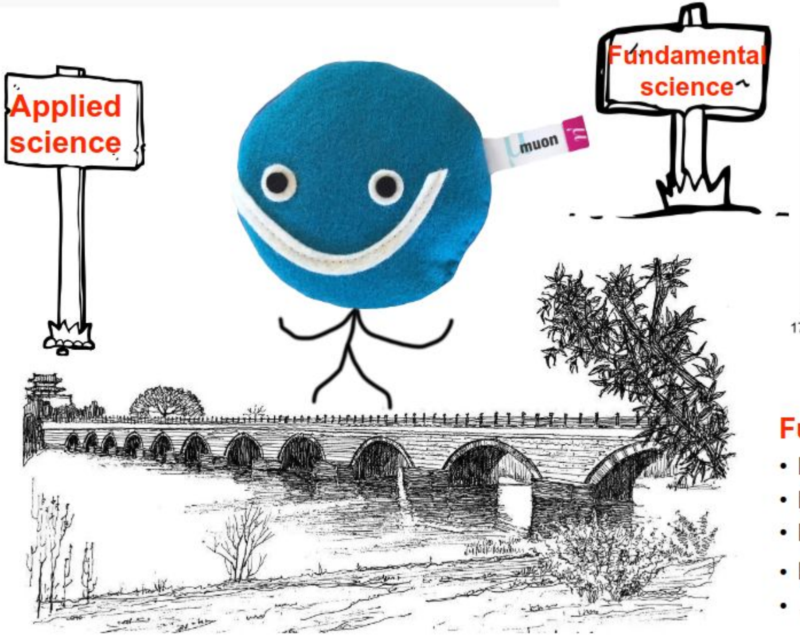
Void in Pyramid



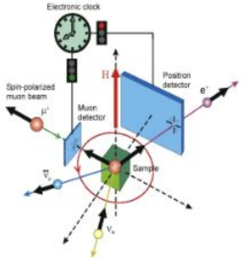
Container inspection

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
- …

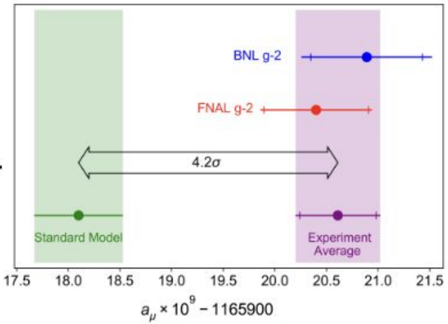


Bridge in Beijing



muSR

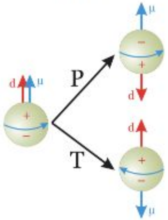
- Heavy fermion
- Superconductivity
- Quantum spin liquid
- …



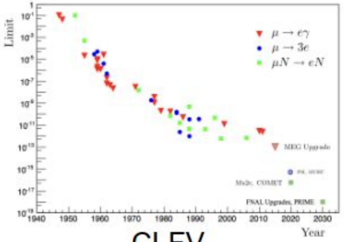
Muon g-2

Fundamental particle physics

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



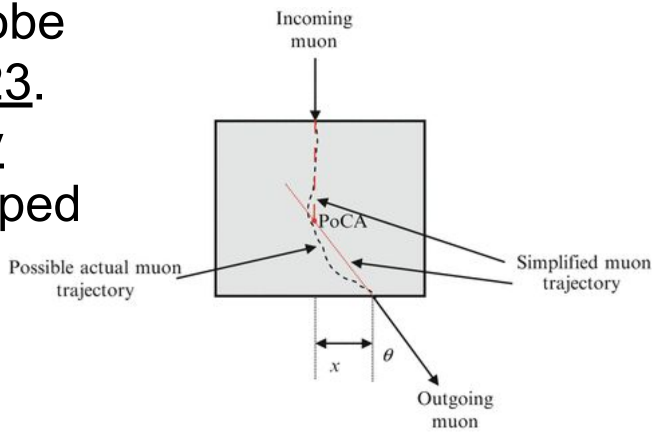
EDM



CLFV

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

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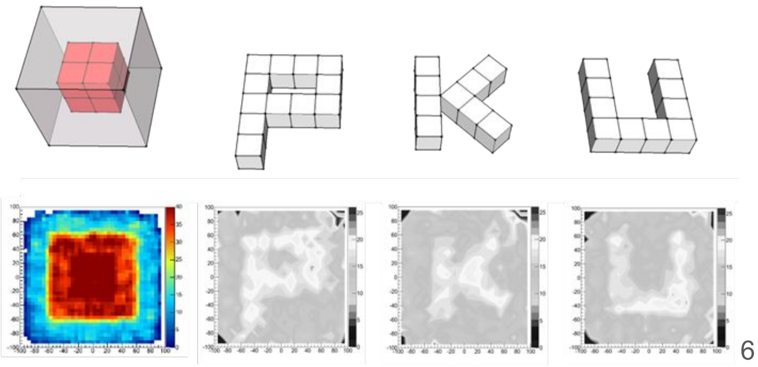
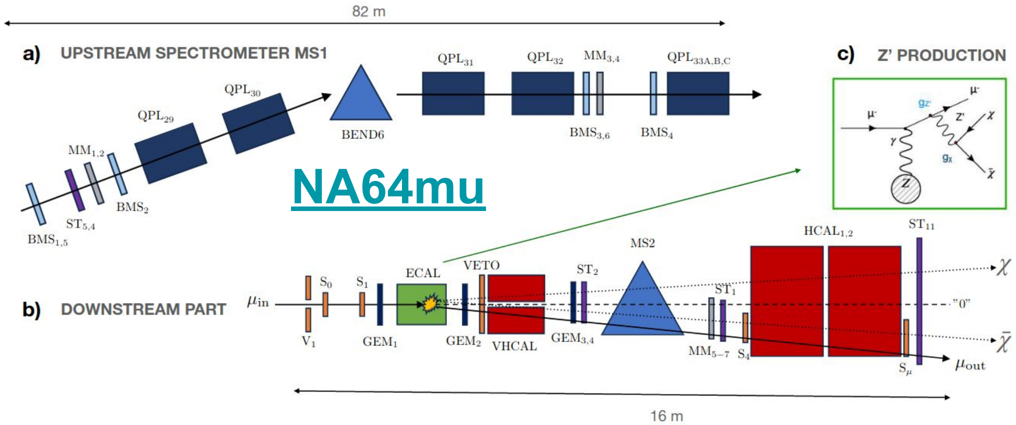
JCAP 2018



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...”



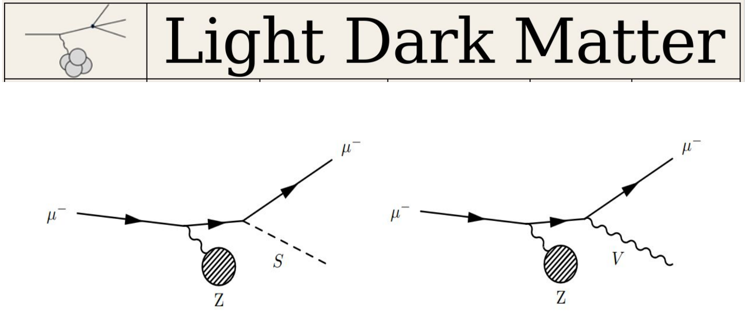


Figure 1. Dark bremsstrahlung signal process for simplified models with invisibly decaying scalar (*left*) and vector (*right*) forces that couple predominantly to muons. In both cases, a relativistic muon beam is incident on a fixed target and scatters coherently off a nucleus to produce the new particle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

Prelude-4: Melody, CIADS, HIAF Muon beams

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

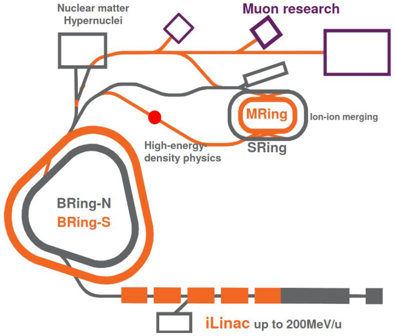
	Surface Muon	Negative Muon	Decay Muon
Proton Power （kW）	20	Up to 100	Up to 100
Pulse width (ns)	130 to 10	500	130 to 10
Muon intensity （/s）	10^5~ 10^6	Up to $5*10^6$	Up to $5*10^6$
Polarization （%）	>95	>95	50~95
Positron （%）	<1%	NA	<1%
Repetition （Hz）	1	Up to 5	Up to 5
Terminals	2	1~2	2
Muon Momentum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

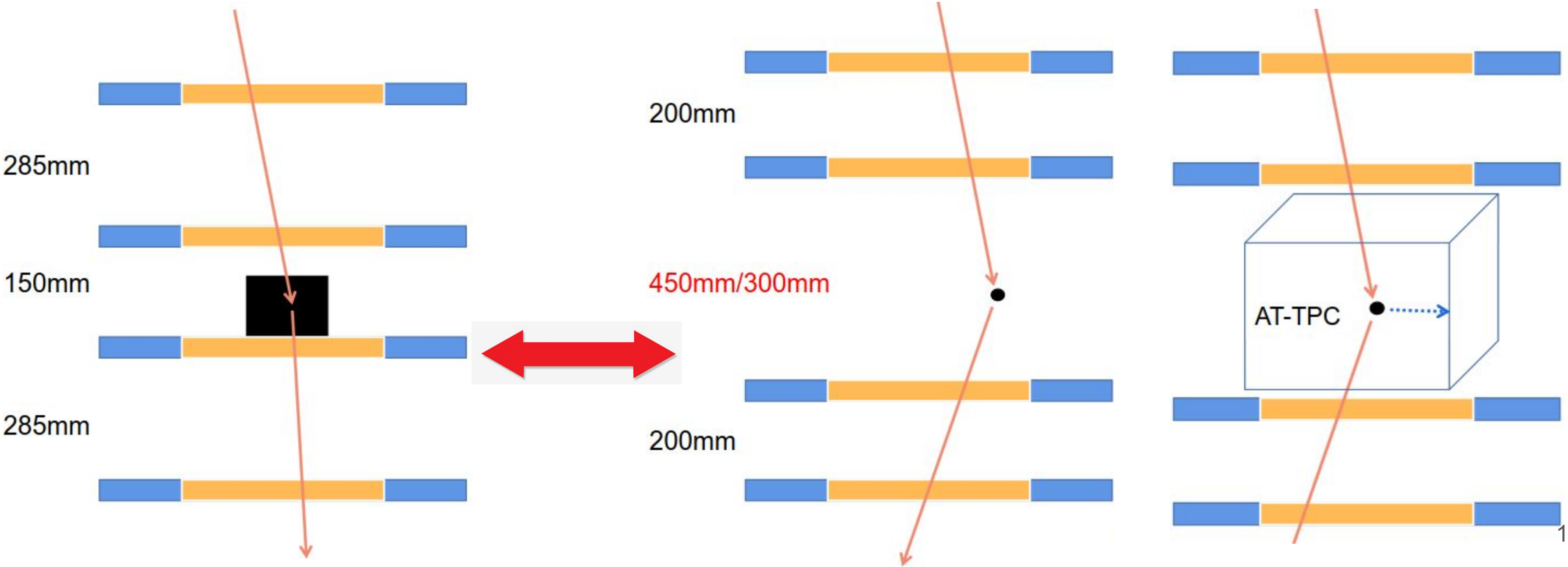
Muon Tomography and Muon-DM scattering

Probing darK Matter Using free leptONs: PKMUON

Alim Ruzi,[*] Chen Zhou,[†] Xiaohu Sun, Dayong Wang, Siguang Wang, Yong Ban,[‡] Yajun Mao,[§] Qite Li,[¶] and Qiang Li[**]
State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing, 100871, China

Muon Tomography ⟷ Dark Matter Search

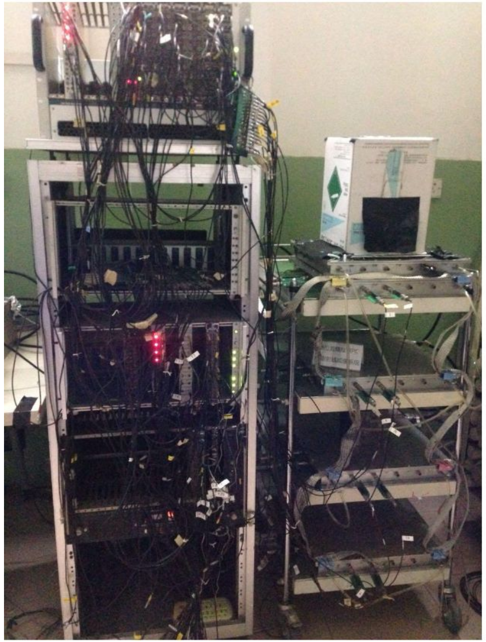
缪子成像 ⟷ 暗物质寻找



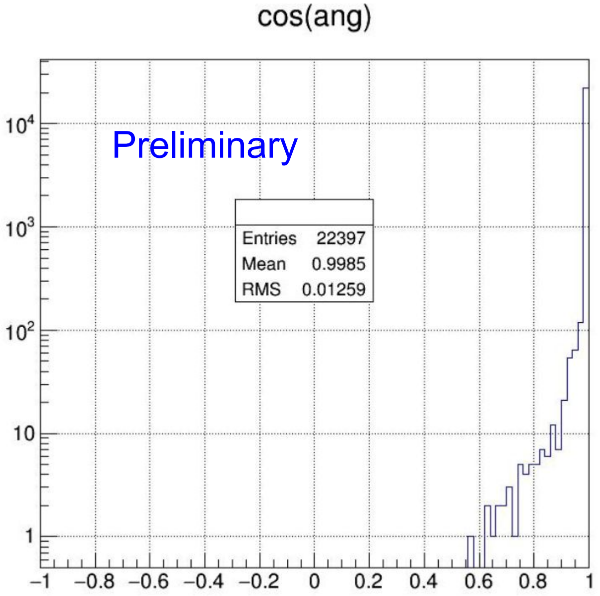
A proposed PKU-Muon experiment for muon tomography and dark matter search

Based on RPC, GEM, AT-TPC, etc.

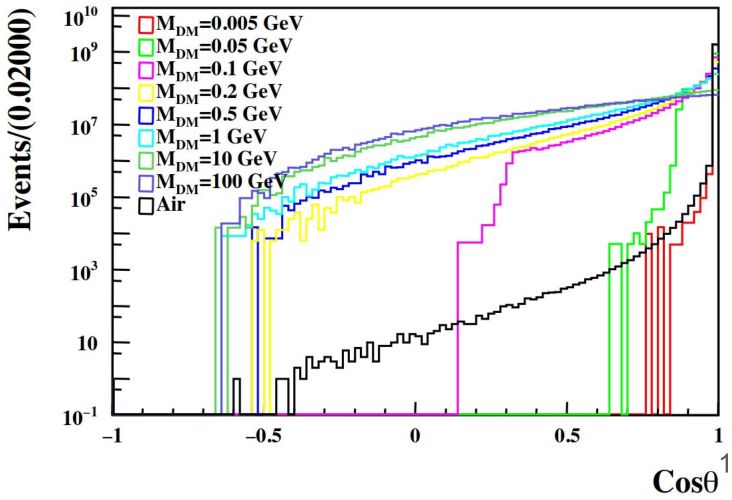
PKU RPC宇宙射线成像系统
(2013-2014) Being Upgraded!



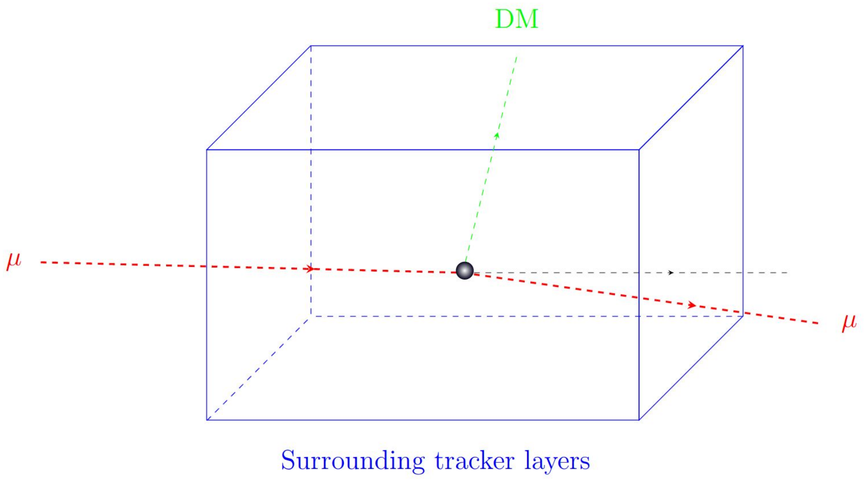
实测偏转角数据(49小时)
Real Data (49 hrs' data)



缪子穿过空气及不同质量暗物质的模拟结果
Geant4 simulation results for muon scattering with air or DM



Muon DM Box experiment: qualitative estimation



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:

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

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

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

One year

Muon DM Box experiment: Geant4 Simulation

Cos θ 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.**

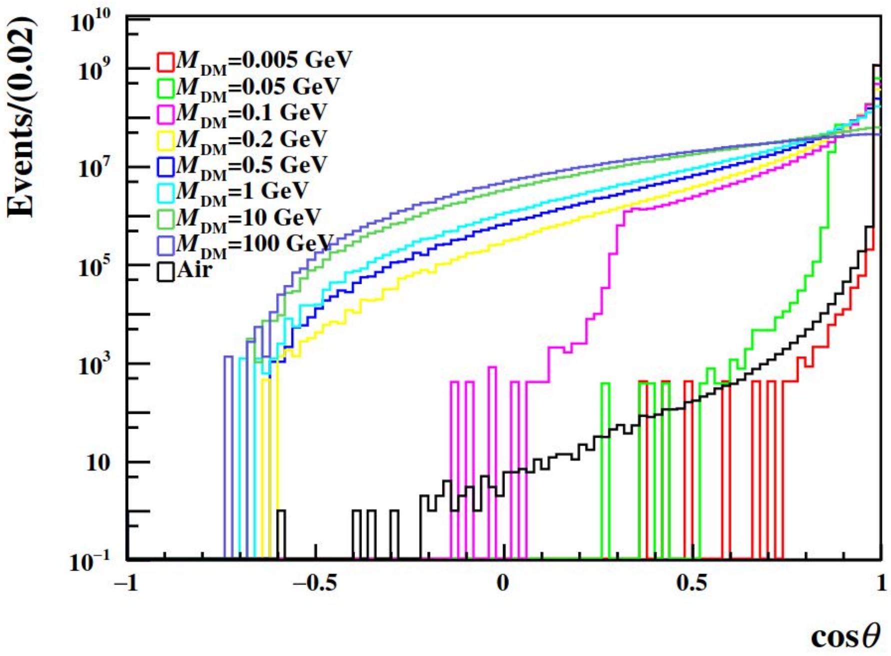
Cosθ distributions in Maxwell-Bolzmann velocity distribution and a constant velocity distribution are similar. Therefore, **our signal distribution and detection is not sensitive to the DM velocity model.**

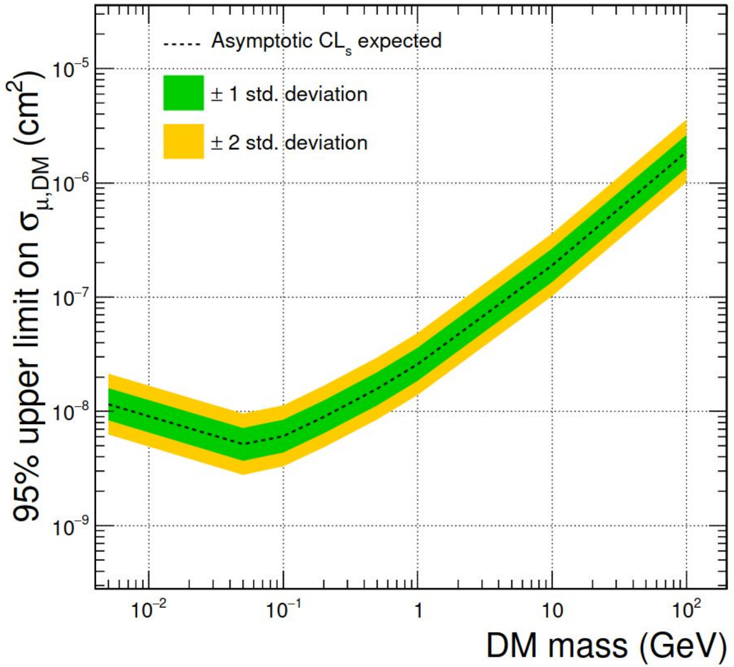
As the DM mass increases, a larger fraction occupies the region of large scattering angles, resulting a more pronounced discrepancy between the signal and background.

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.

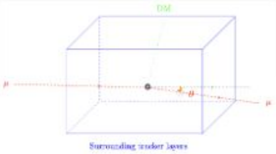
Muon DM Box experiment: Geant4 Simulation





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

Dark Matter searches in a box



- Dark Matter searches in $1\ \mathrm{m}^3$ box using GEM detector
  - 2 upper/lower layers for incoming/outcoming muon direction

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
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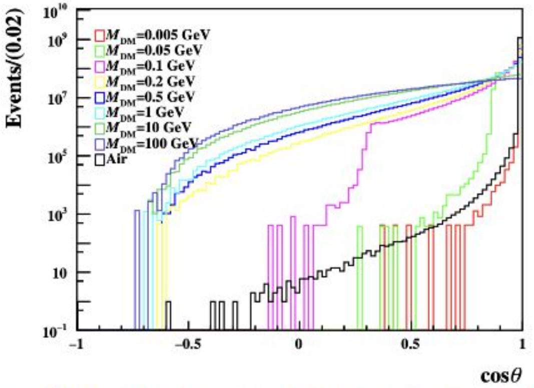
1	18.67 ± 0.01	18.66 ± 0.01
10	11.10 ± 0.01	11.10 ± 0.01
100	8.44 ± 0.01	8.43 ± 0.01

Background event numbers
&
detection efficiency in one year

- Some interesting results
  - $\cos\theta$ distribution in air has no obvious difference between that in a vacuum. Considering cost and technical difficulty, **vacuuming the boxes is not necessary in Phase I of the project.**
  - $\cos\theta$ distributions in Maxwell-Bolzmann 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**.
  - For the signal event with $M_{\mathrm{DM}} < 100$ MeV, an apparent truncation is observed, attributed to kinematics. This truncation occurs only when the DM mass is lower than the muon mass.

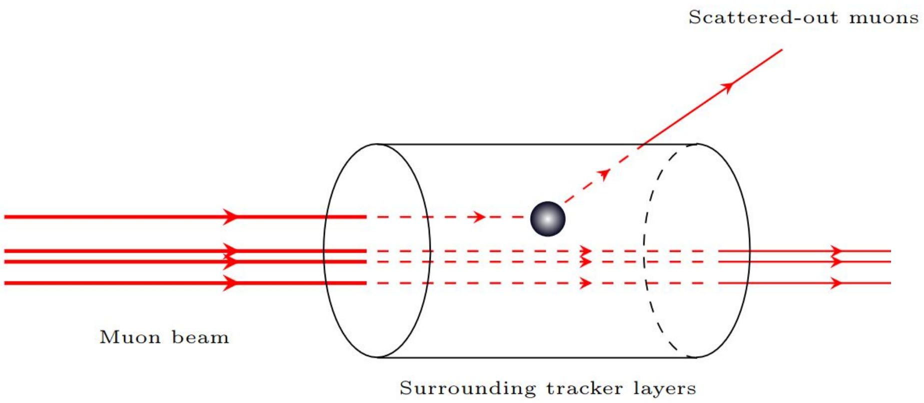


The $\cos\theta$ distributions in signal and background samples

Muon DM Box experiment: exotic scenario

Our methods can have advantages over 'exotic' DMs [59] which can be well slowed down through scattering with matter in the atmosphere or the Earth before reaching the detector target. In such a scenario, dark matter number density can be as large as 10^{15} cm^{-3}, and sensitivity on dark matter and muon scattering cross section can reach as low as $10^{-22} \sim 10^{-24}$ cm^2.

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 $10^7\mathrm{s}$.

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

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

The estimated rate per second:

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

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

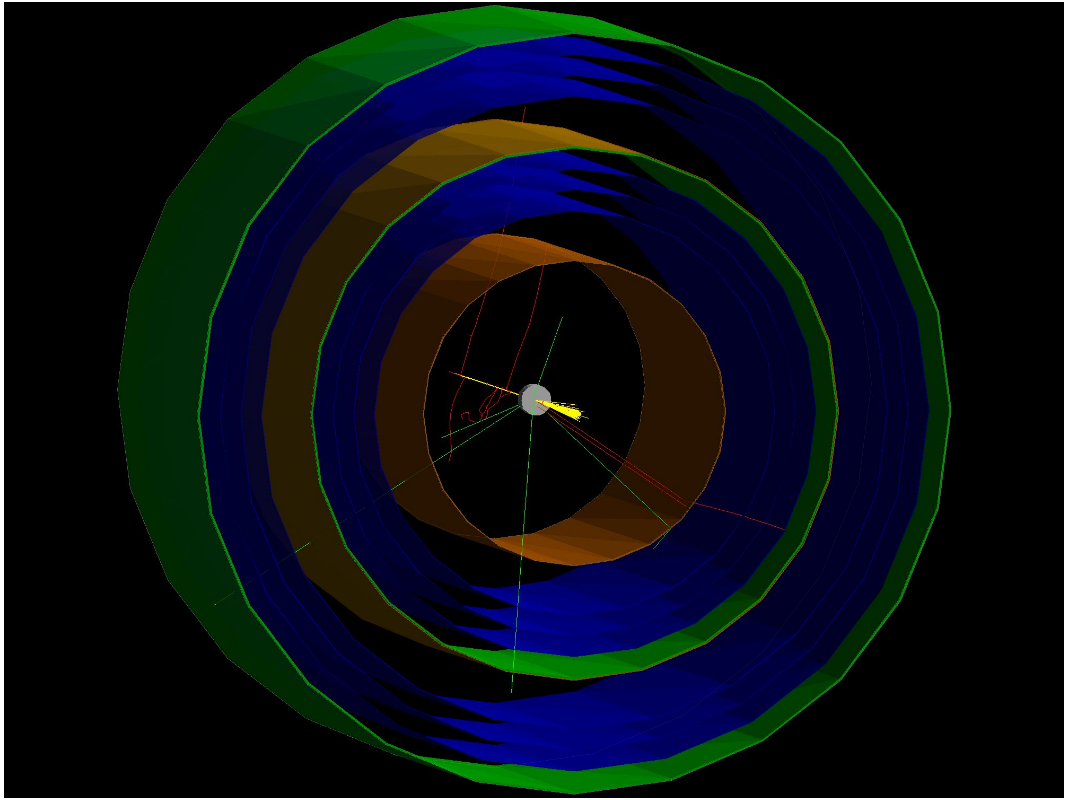
One year

Notice the surrounding area is around 100 cubic centimeters.

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.



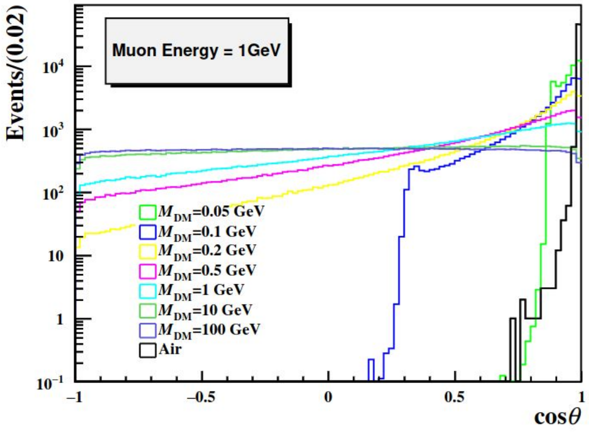
Cylindrical GEM (CGEM) detector structure for BESIII inner tracker system upgrade

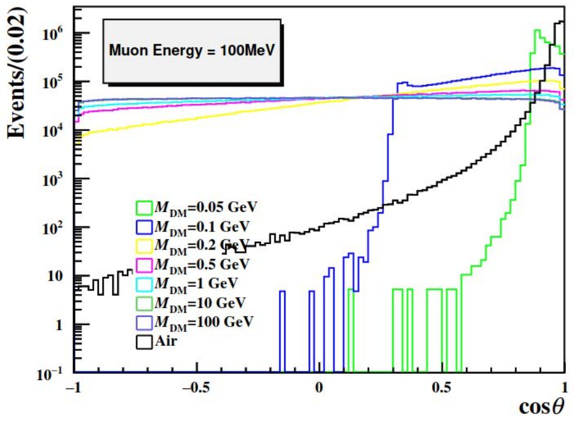
Muon DM Beam experiment: Geant4 Simulation

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

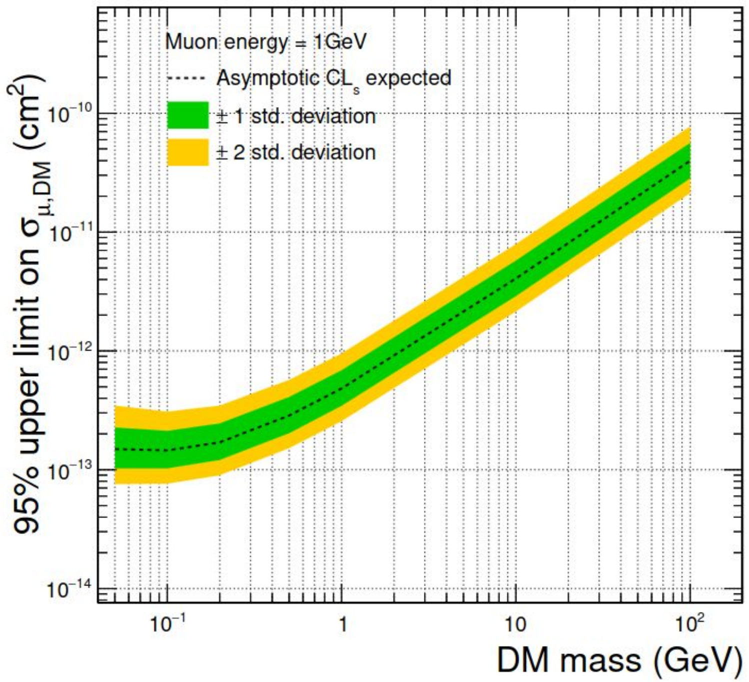
$M_{DM} \backslash E^{\mu}_{kin}$	100 MeV (%)	1 GeV (%)	10 GeV (%)
0.05 GeV	84.29 ± 0.04	74.85 ± 0.04	45.93 ± 0.05
0.1 GeV	91.74 ± 0.03	83.07 ± 0.04	58.17 ± 0.05
0.2 GeV	94.35 ± 0.02	88.16 ± 0.03	68.37 ± 0.05
0.5 GeV	95.17 ± 0.02	92.16 ± 0.03	78.91 ± 0.04
1 GeV	95.34 ± 0.02	93.88 ± 0.02	84.68 ± 0.04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

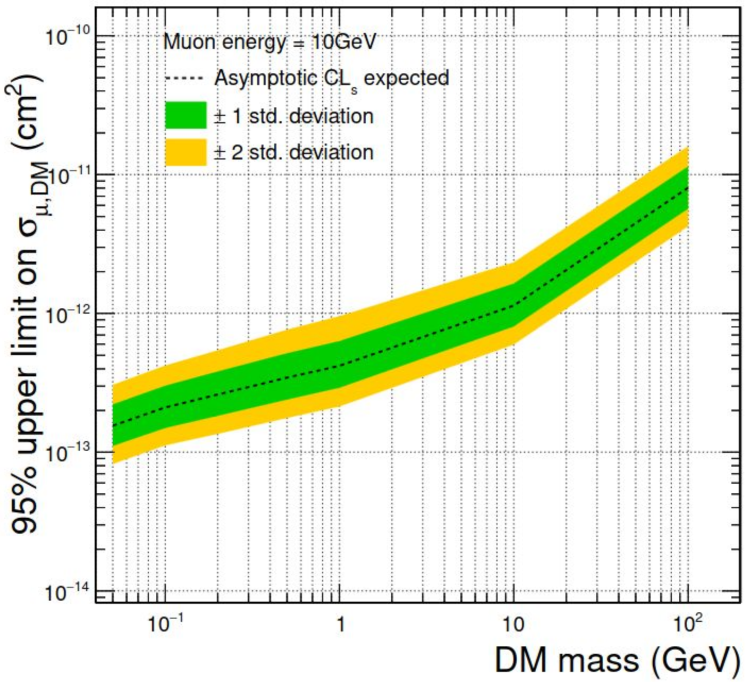
TABLE II. Signal detection efficiency under different assumptions of DM mass and muon beam energies.



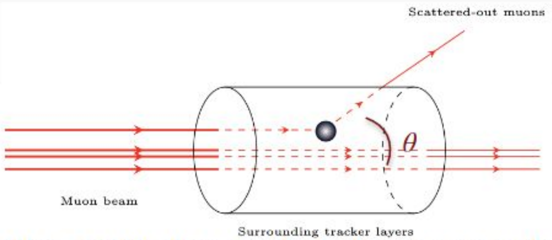


Muon DM Beam experiment: Geant4 Simulation



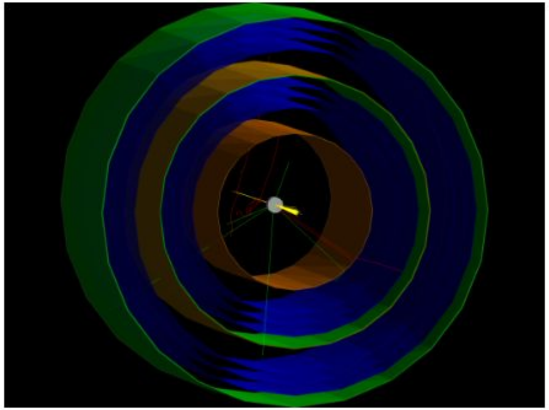


Dark Matter searches using muon beams



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

- ➔ Adopt cylindrical GEM (CGEM) detector structure
  - ❖ To suit detection environment of the beam experiment
  - ❖ Have been used in the upgrade of BESIII inner tracker system
- ➔ MELODY design: the diameter of the beam spot ranges from 10 mm to 30 mm
  - ❖ Profile of beam in the xy plane follows a Gaussian distribution
  - ❖ In our study, ϕ=10 mm is chosen; the inner diameter of CGEM is designed to be 50 mm (5σ)
- ➔ Two layers of GEM detectors are stacked together, reconstructing outcoming muon direction



Orange surfaces: drift cathodes
Blue surfaces: GEM foils
Green surfaces: PCBs
Yellow lines: muons tracks
Red curves: electron tracks
Green lines: photons

$M_{DM} \backslash E^{\mu}_{kin}$	100 MeV (%)	1 GeV (%)	10 GeV (%)
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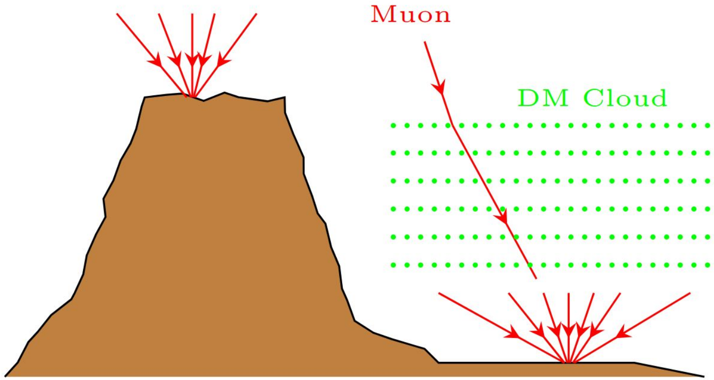
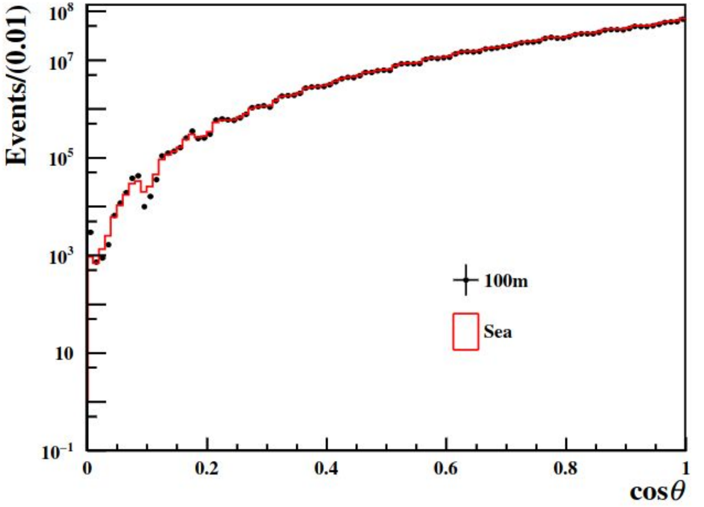
0.5 GeV	95.17 ± 0.02	92.16 ± 0.03	78.91 ± 0.04
1 GeV	95.34 ± 0.02	93.88 ± 0.02	84.68 ± 0.04
10 GeV	95.35 ± 0.02	95.36 ± 0.02	94.06 ± 0.02
100 GeV	95.43 ± 0.02	95.37 ± 0.02	95.37 ± 0.02

Detection efficiency in different muon beam energies & DM mass assumptions

Cosmic Muon direction at different altitudes

Such type of precision measurement itself should be an interesting topic





We extend the native Geant4 physics list by introducing the muon-DM elastic scattering process.

FIG. 19. The $\cos\theta$ distributions at the mountain and sea levels in the background sample.

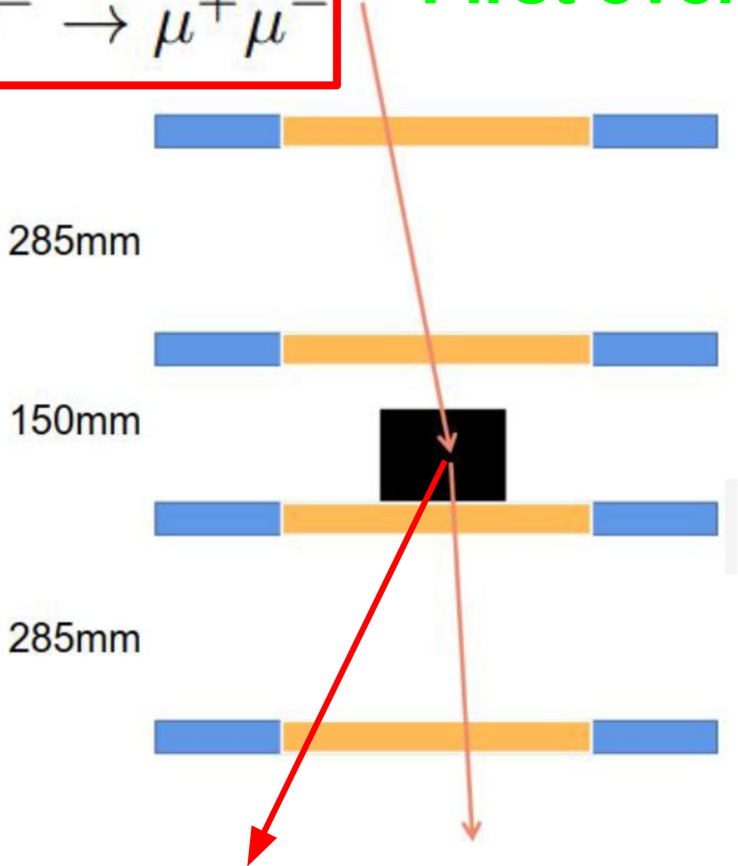
signal assumptions are lower then 5σ. It indicates that the rejection ability for $M = 500$ MeV DM is about $\sigma_{\mu,\mathrm{DM}} = 10^{-7} \sim 10^{-8}$ cm^2 for 1 m^2 detectors placed at a mountain with a latitude of 100 m and the sea level after one-year data taking.

Sensitivities can be enhanced in the exotic scenario as mentioned previously.

Cosmic **Mu+** - Electron Scattering

$\mu^+ e^- \rightarrow \mu^+ \mu^-$

First ever limit on CLFV Lmm*Lme?!



Cosmic muon on target exp.

- 1 μ → 2 μ
- ~10^3 mu/s for 1 m^2 detector
- Generator simulation?
    - Energy Convolution
- Time variation Z'

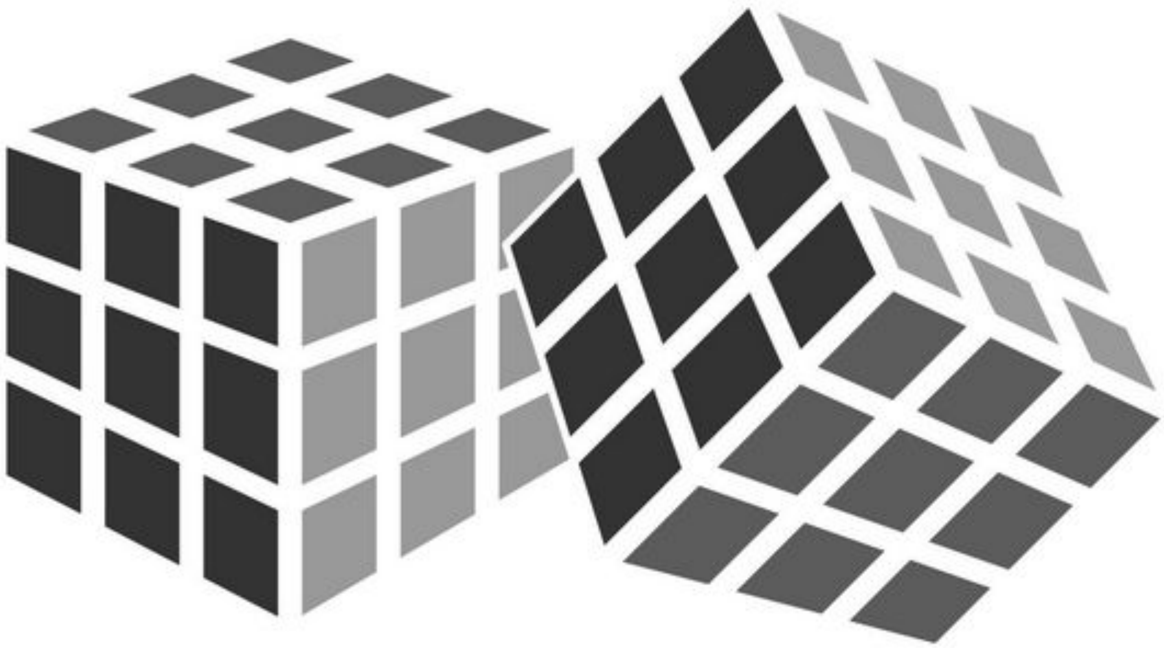
- mu+Nuclei->leptoquark?
- 1μ → 3μ in next page!

A proposed PKU-Muon experiment for muon tomography and dark matter search

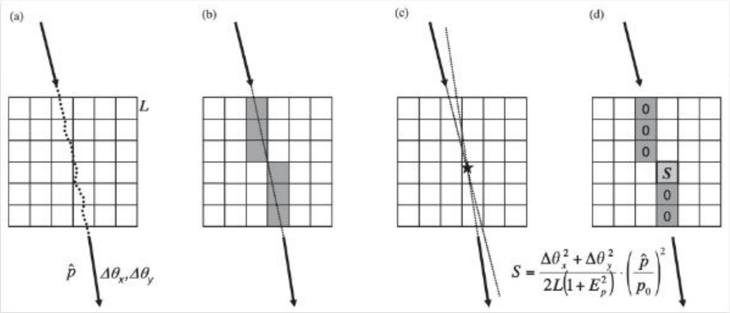
Based on RPC, GEM, AT-TPC, etc.

- **Muon Tomography**
  - RPC (~0.5 year), GEM (~1 year)
  - Algorithm development & fast detection (~1 year)
    - Engineering, Archaeology (2-5 years)
  - Muon Radar: cosmic muon precision measurement
    - Various altitude & direction and/or momentum (~1-2 years)
    - Connects with Atmospheric science (2-3 years)
- **Muon Dark Matter Scattering (also Axion?)**
  - RPC (~0.5-1 year), GEM (~1-1.5 year), AT-TPC (~1-2 year)
  - DM in a box (~0.5-2 year)
  - Angle difference at different altitudes (~2-4 years)
- **Various kinds of experiments with Muon Beam** (~5-10 years)
  - DM in a box Or MMM-type → DM, CLFV

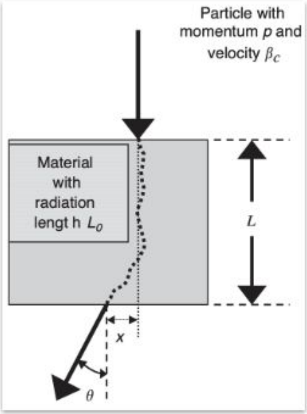
Muon-Box → Magicube → Cube-Telescope?



PoCA

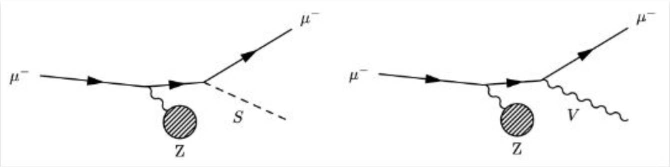


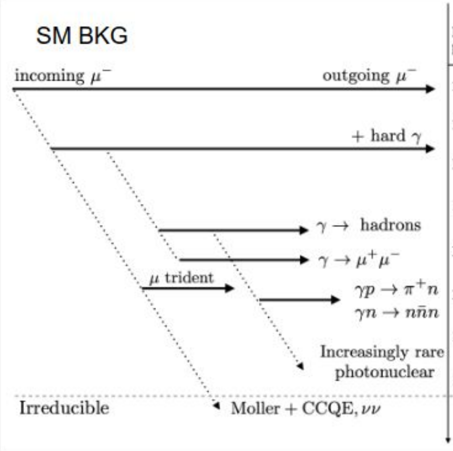
- ➔ The point of closest approach (PoCA) algorithm
- ➔ The angular scattering distribution is approximately Gaussian
  - ❖ $\sigma_\theta = \frac{13.6\,\text{MeV}}{\beta c p}\sqrt{\frac{L}{L_0}}[1 + 0.038\ln\frac{L}{L_{\text{rad}}}] \approx \frac{13.6}{p}\sqrt{\frac{L}{L_0}}$
  - ❖ p: momentum, βc: velocity, 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:
  - ❖ $\hat{\lambda} = \frac{1}{N}\sum_{i=1}^{N}(\frac{p_i^2}{p_0^2} \cdot \frac{\theta_{xi}^2 + \theta_{yi}^2}{2L_i})$



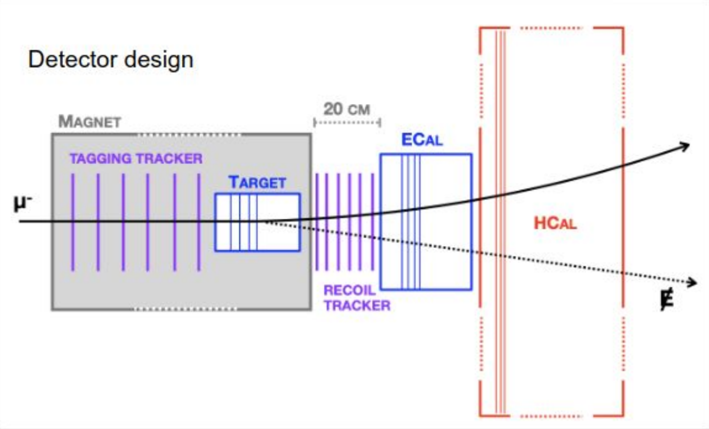
MMM

- ➔ 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



MMM

- ➔ Two phases
  - ❖ Phase 1: MTest beamline
  - ❖ Phase 2: Neutrino (NM4) Beamline

Phase 1

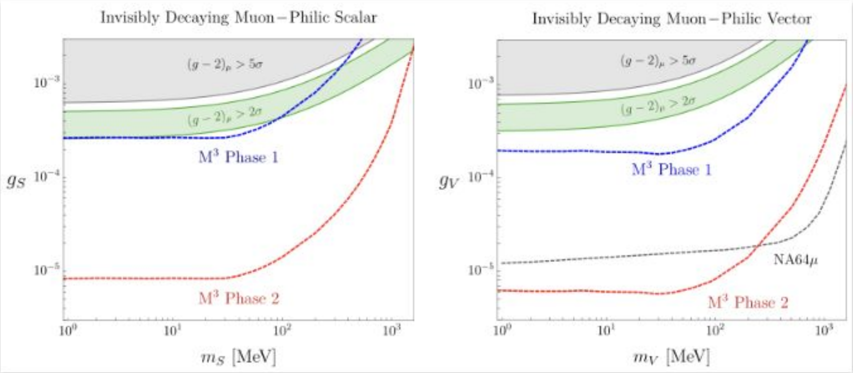
- muon energy = 15 GeV
- muon intensity = 10^{10} MOT (muons on target)
- Target Thickness = 50 X_0 (about 25 cm for tungsten/silicon)

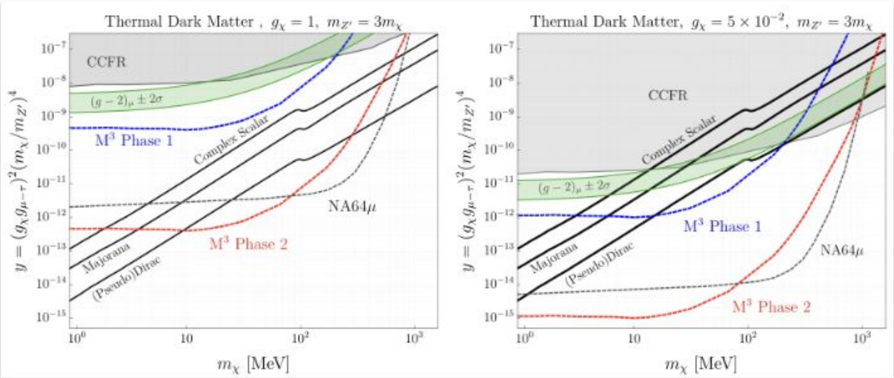
Phase 2

- muon energy = 15 GeV
- muon intensity = 10^{13} MOT
- Target Thickness = 50 X_0

- ➔ Expected results

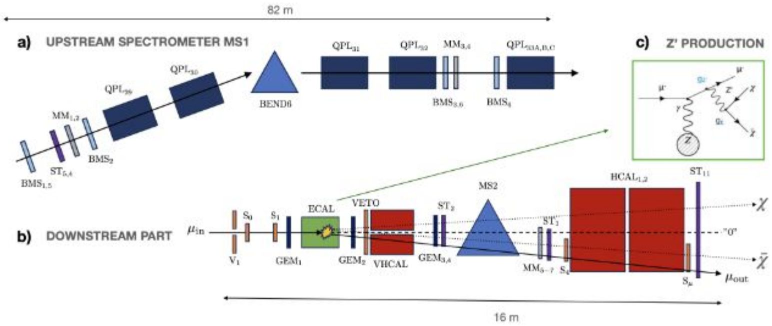
Phase 1 with $\sim 10^{10}$ muons on target can test the remaining parameter space for which light invisibly-decaying particles can resolve the $(g-2)_\mu$ anomaly, while Phase 2 with $\sim 10^{13}$ muons on target can test much of the predictive parameter space over which sub-GeV dark matter achieves freeze-out via muon-philic forces, including gauged $U(1)_{L_\mu - L_\tau}$.

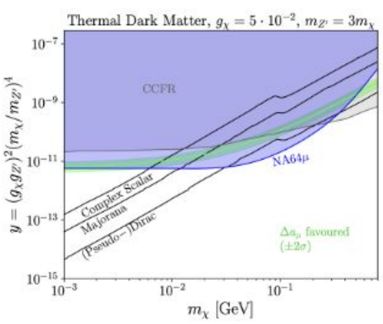


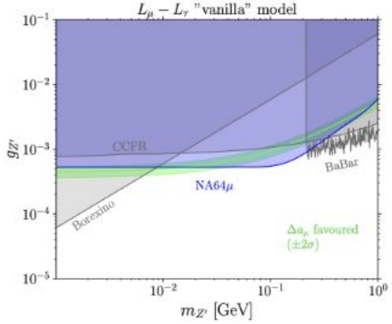


NA64μ

- ➔ $Z'\ U(1)_{L_\mu - L_\tau}$ 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







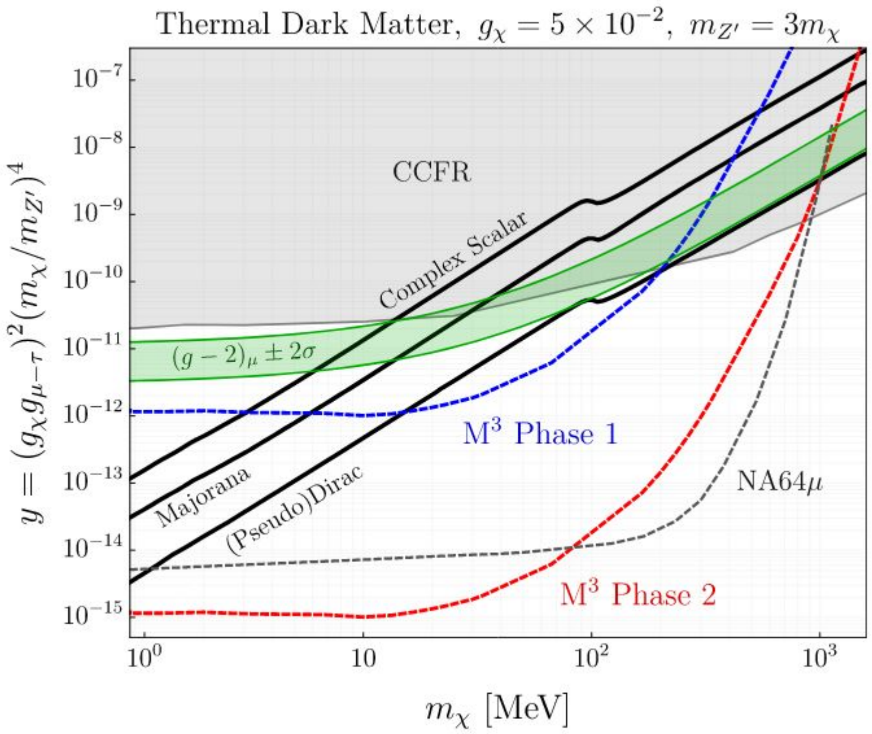
Exotic DM

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

Ref: MMM



US MMM projected sensitivity.

Notice the limit is set on couplings and not directly on muon-DM scattering cross sections.

However, the Phase I result should correspond to
Xsec ~ 10^-33 cm^2

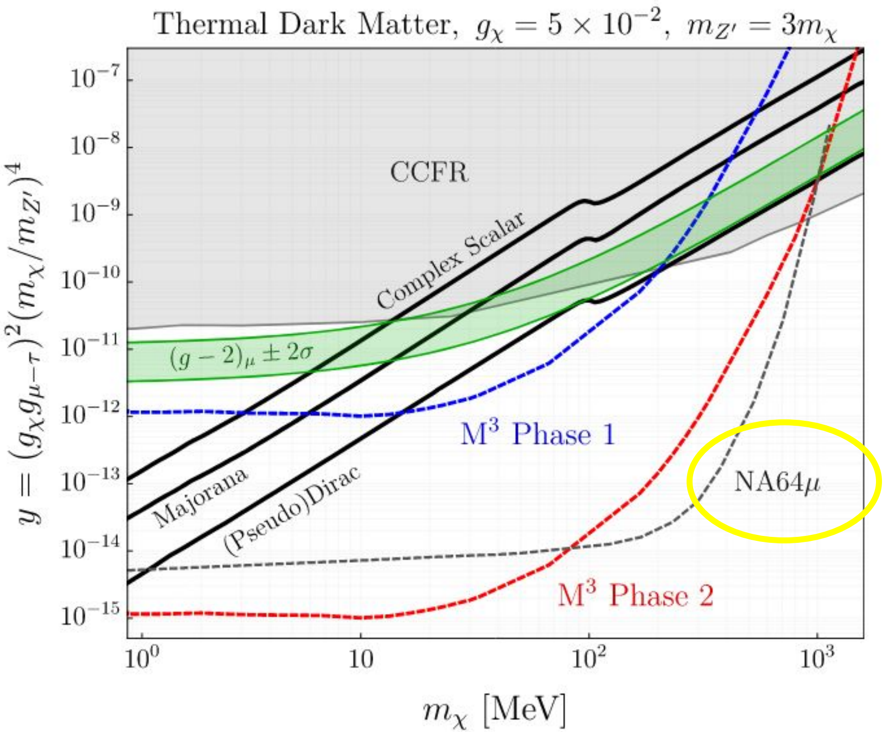
And Phase 2 results will be much stronger.

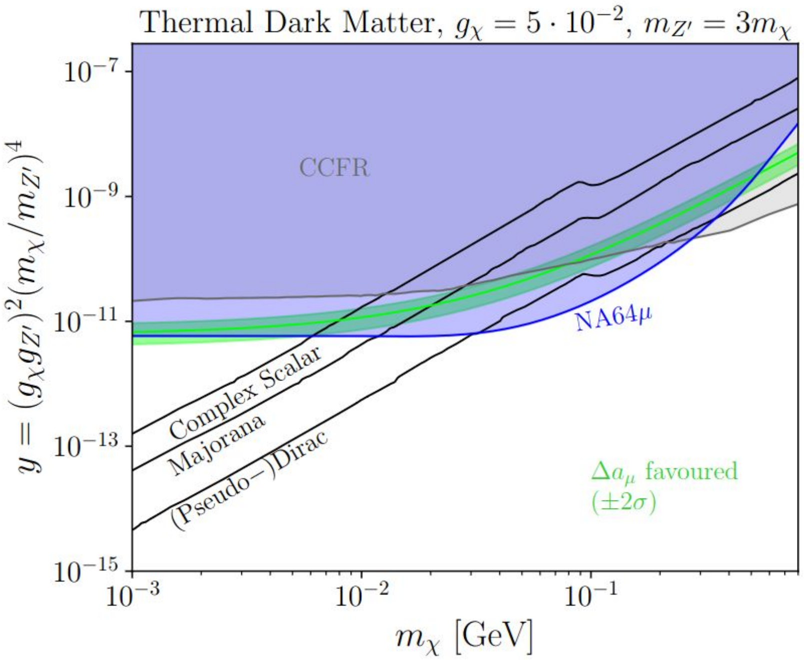
For lower energy muon beam, we might be exploring lower DM mass region.

Ref: MMM

VS

Ref: NA64mu





Ref: [DarkShine]

VS

Ref: [NA64e]