北京大學
PEKING UNIVERSITY

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

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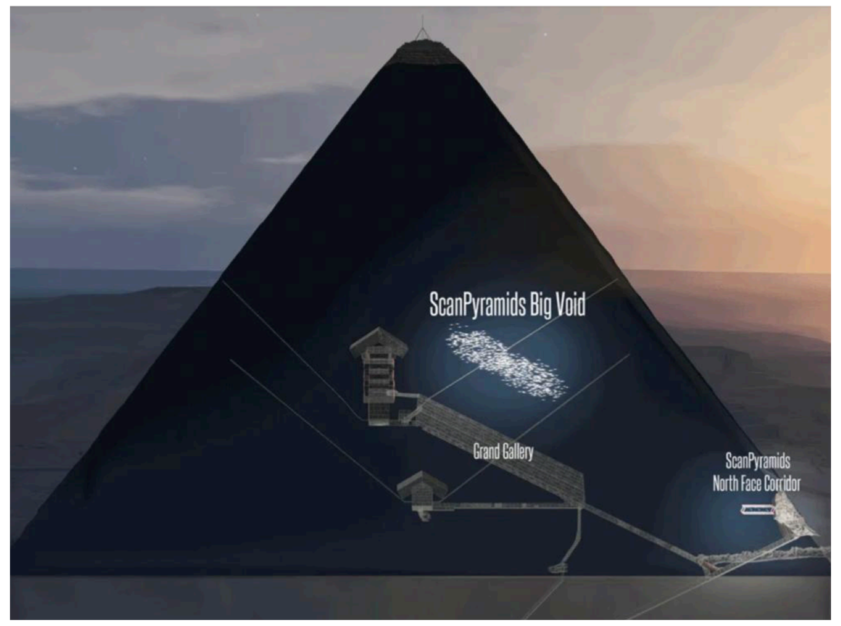
Based on arXiv:2402.13483
PKMUON homepage: https://lyazj.github.io/pkmuon-site/

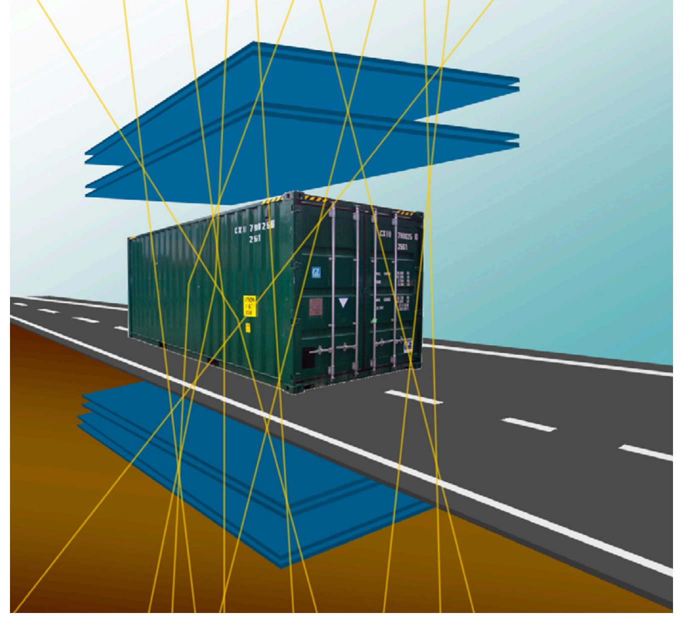
Outline

Introduction and Motivation

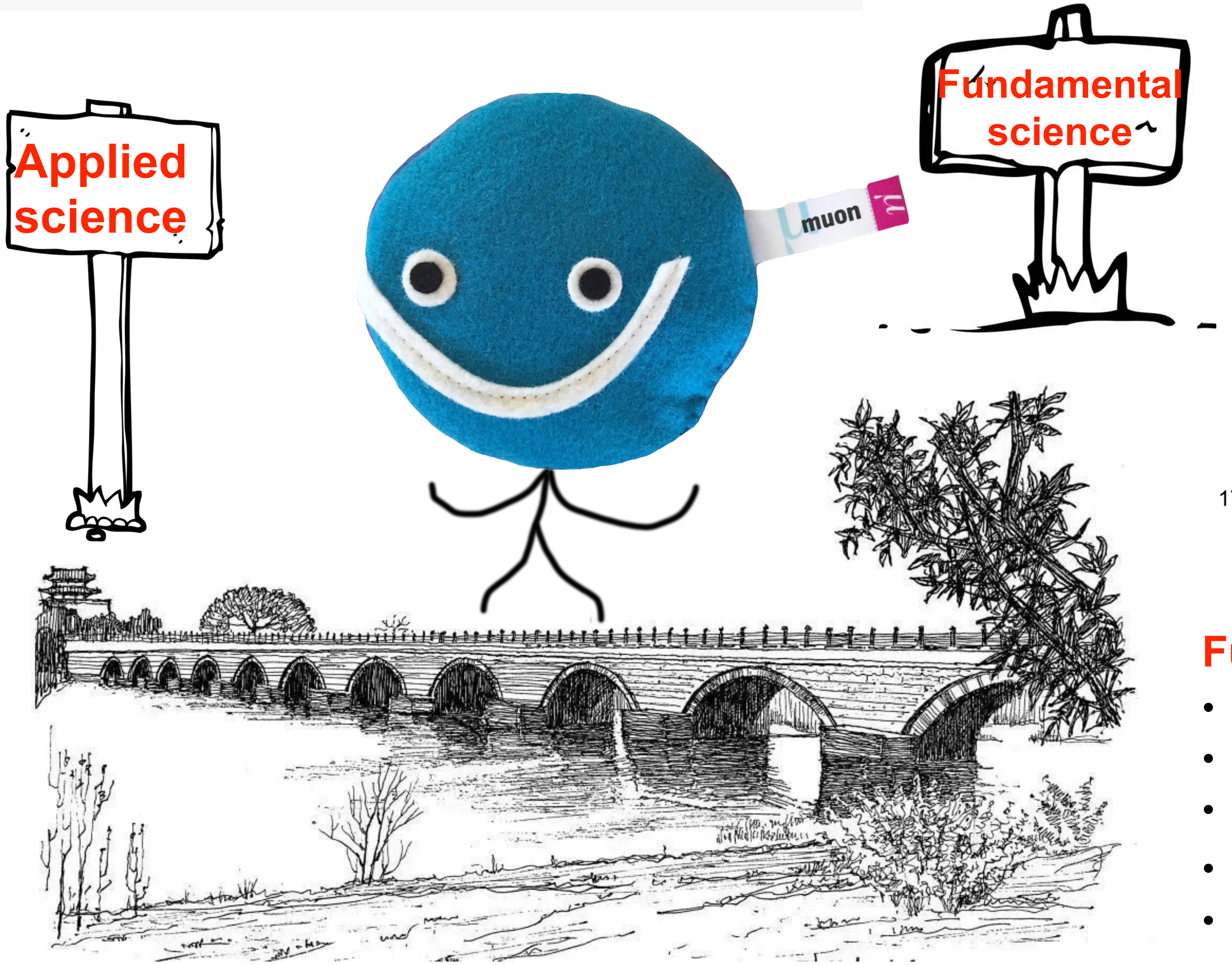
Muon: a bridge connect applied study & fundamental research



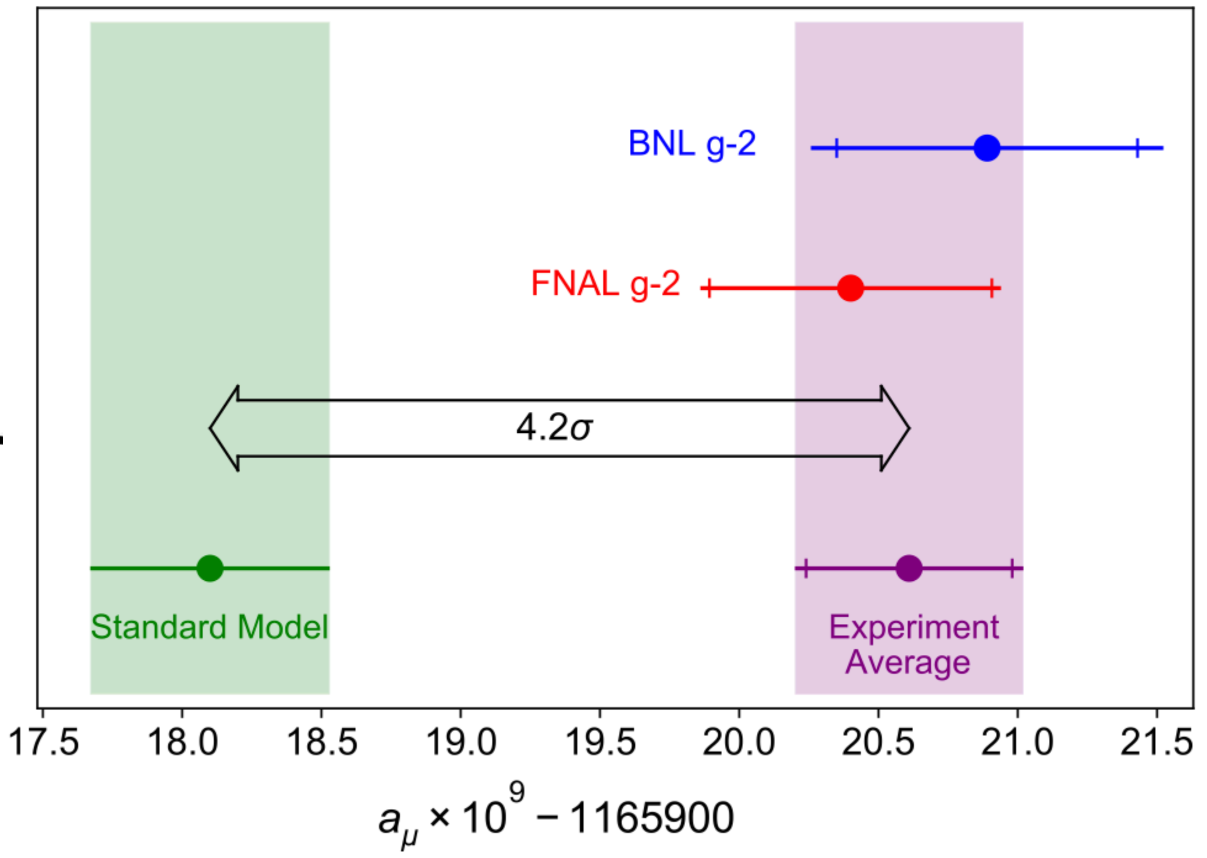
Void in Pyramid



Container inspection



Bridge in Beijing



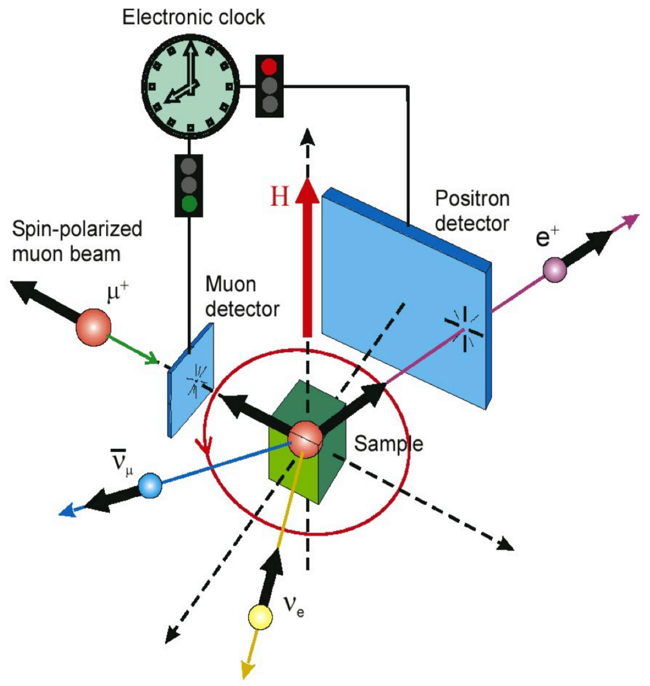
Muon g-2

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
- …

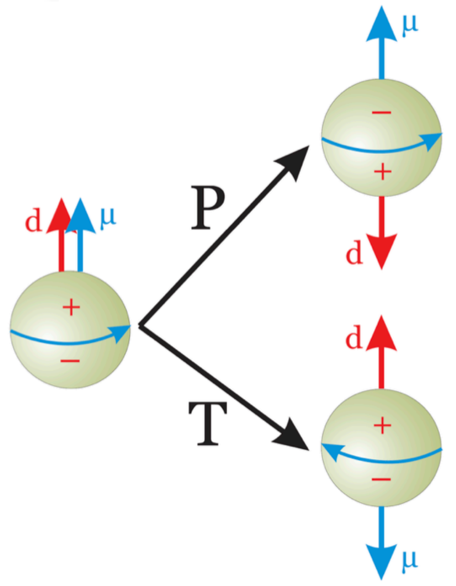
Fundamental particle physics

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

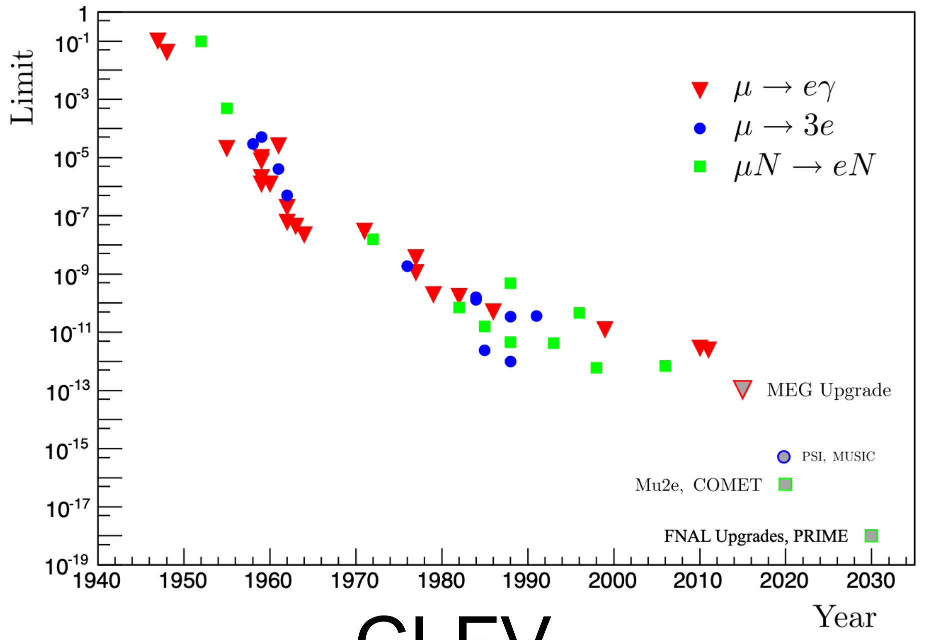


muSR

- Heavy fermion
- Superconductivity
- Quantum spin liquid
- …



EDM

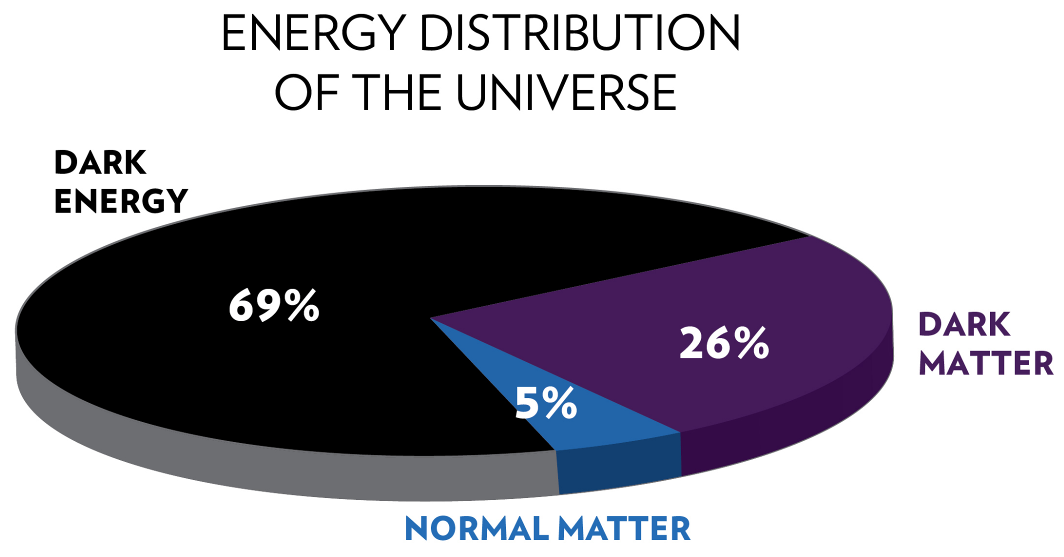


CLFV

Muon as a probe for DM

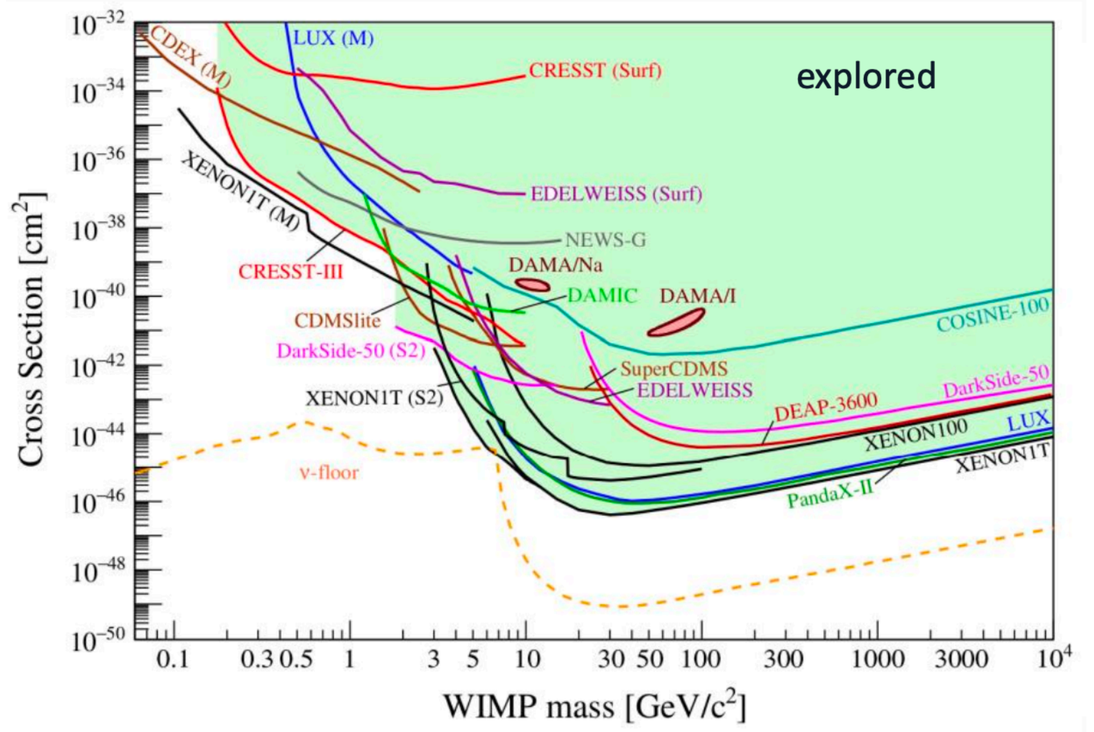
➔ **DM (Dark Matter)**

- Many astronomical observations indicate existing of DM: galactic rotation curve, Bullet cluster, Cosmic Micro wave Background, …
- A standard model of the cosmology: ~26% of dark matter, ~5% normal matter
- Evidence from Particle physics still being sought



➔ Traditional DM candidates: **WIMPs** (Weakly Interacting Massive Particles)

- Direct detection: scattering of DM with nucleus, approximated as a non-relativistic two-body scattering
- Extensively studied by many experiments: XENON1T/PandaX, …, but no observations
- What about other theoretically motivated scenarios? **low-mass or muon-philic DM**



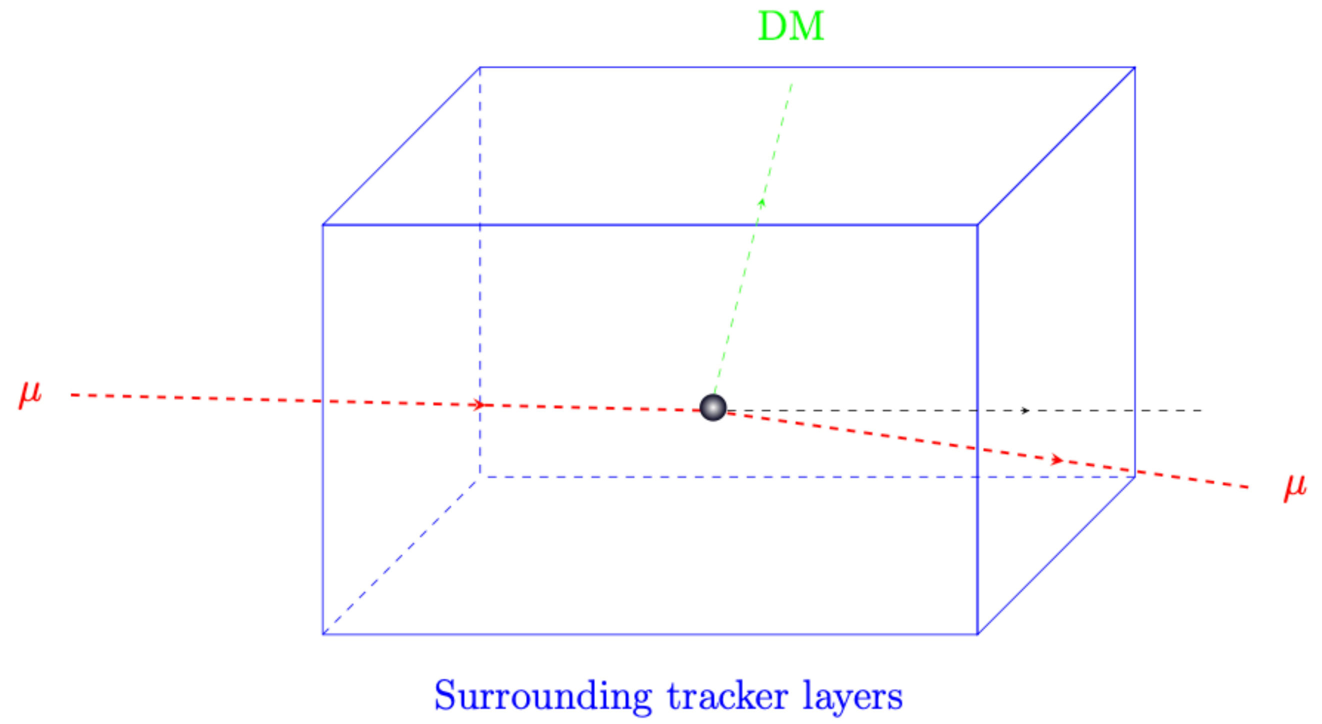
➔ Challenges for detecting low-mass DM: insufficient nucleus recoil energy

- DM interactions with electrons: EDELWEISS/SENSEI, NA64/DarkShine

➔ Muon g-2 experimental results trigger studies of muon-philic DM

- ***PKMUON***: DM direct detection by scattering with atmosphere & accelerator muons in a model-independent way

IJMPA 38, No. 29n30, 2350154 (2023)

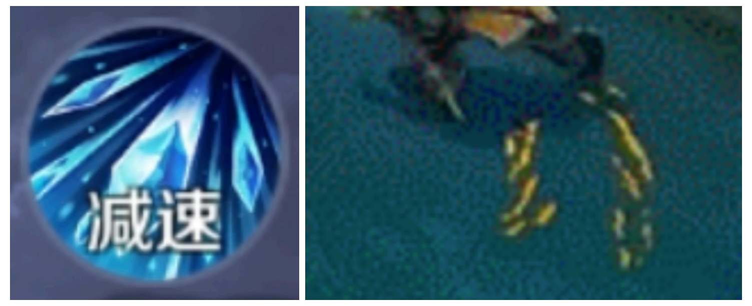


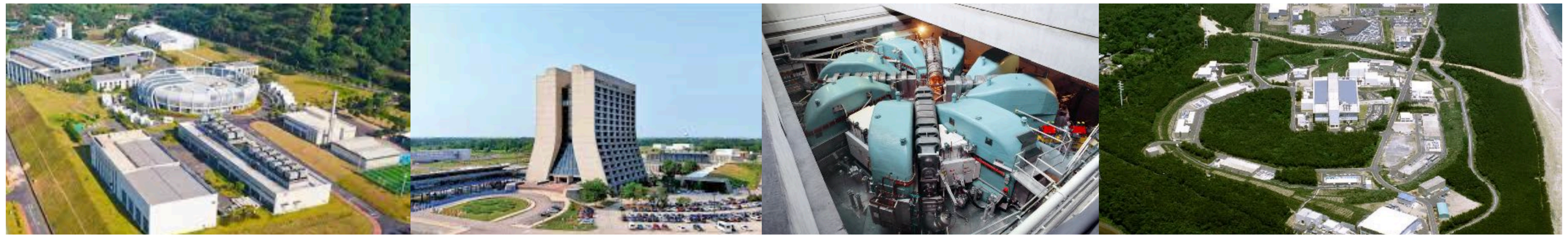
Muon as a probe for DM

➔ Exotic DM

PRL 131, 011005 (2023)

- ❖ 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 experiment
- ❖ As we will see, muon-DM scattering experiment (PKMUON) depends minority on DM velocity
- ❖ High density of exotic DM increases the probability of observation & set more stringent limit

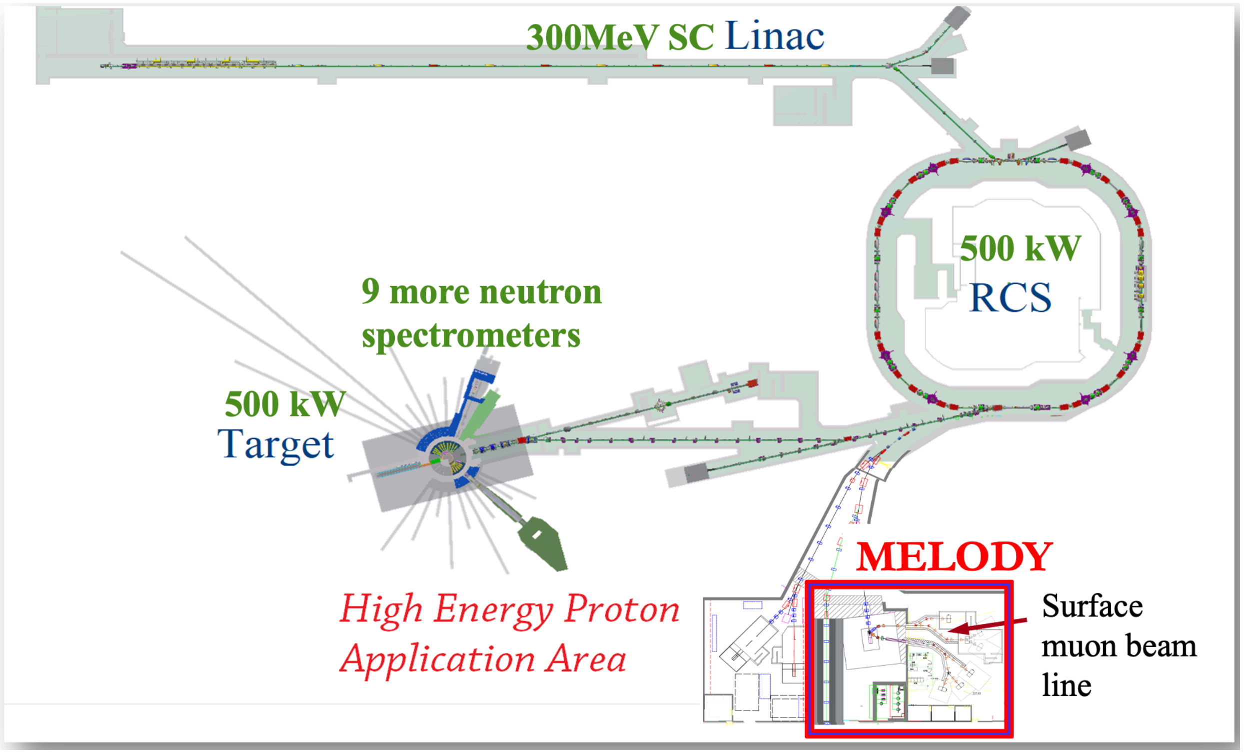




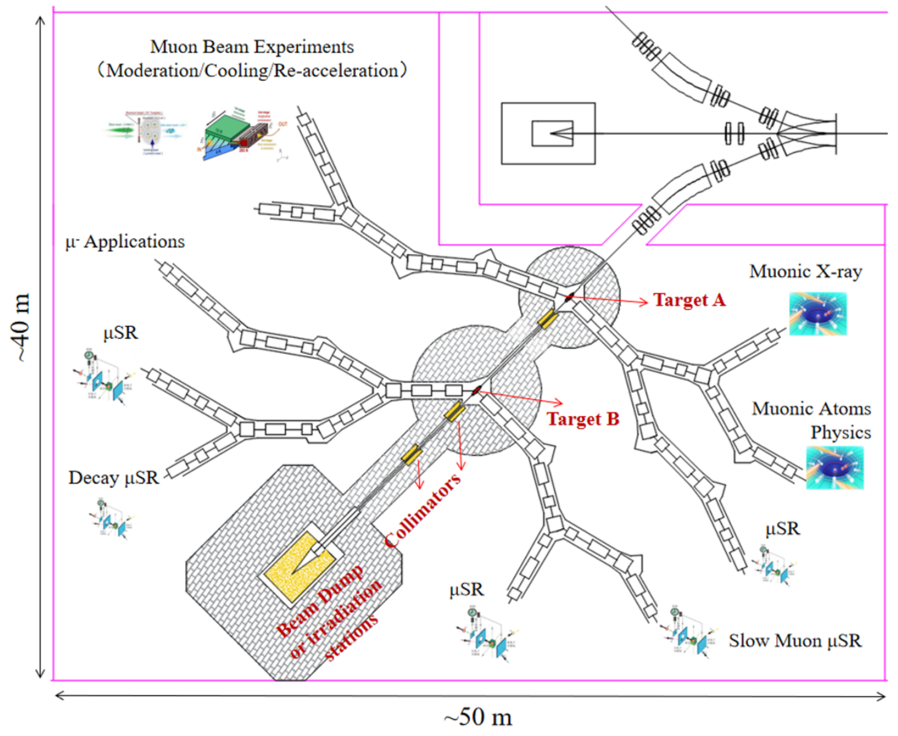
➔ Muon beams

- ❖ Existing worldwide muon sources: PSI, TRIUMF, ISIS, J-PARC, FNAL
- ❖ Chinese muon beams: Melody, CIADS, HIAF

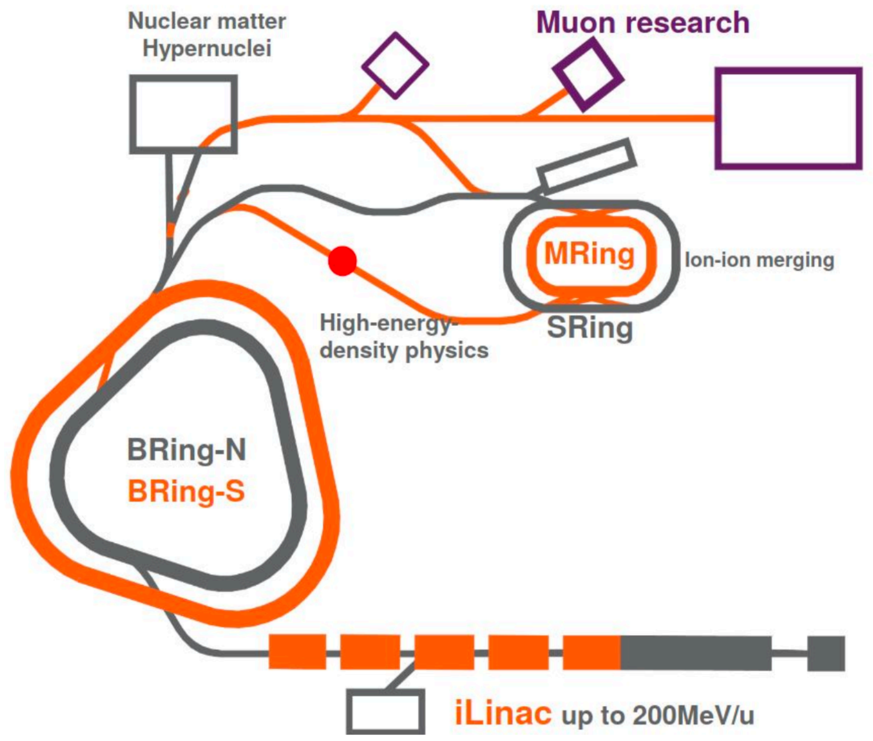
Melody @ CSNS



Muon source @ CIADS

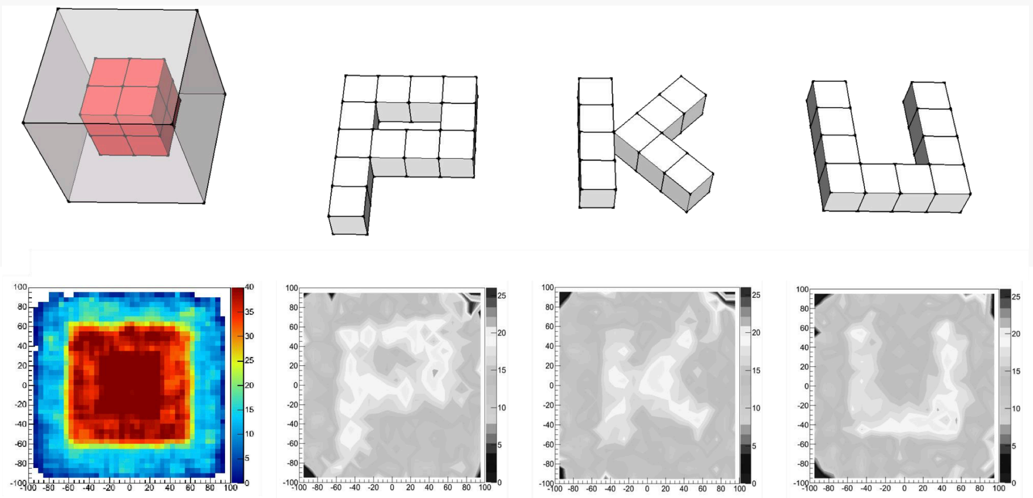


Muon source @ HIAF



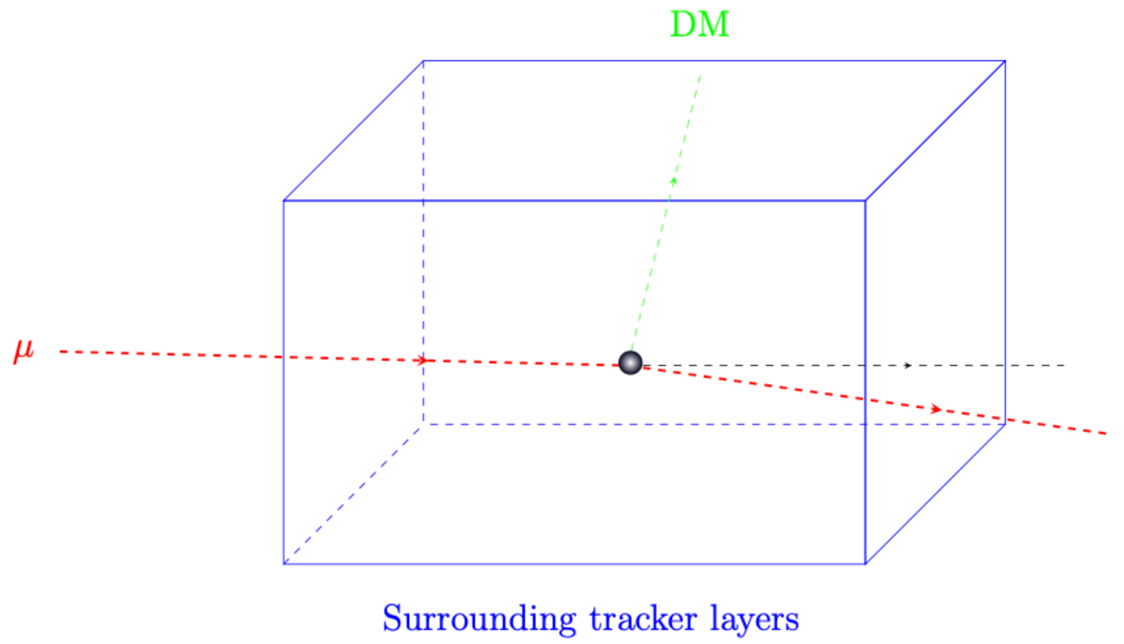
Our proposal in brief

Our proposal



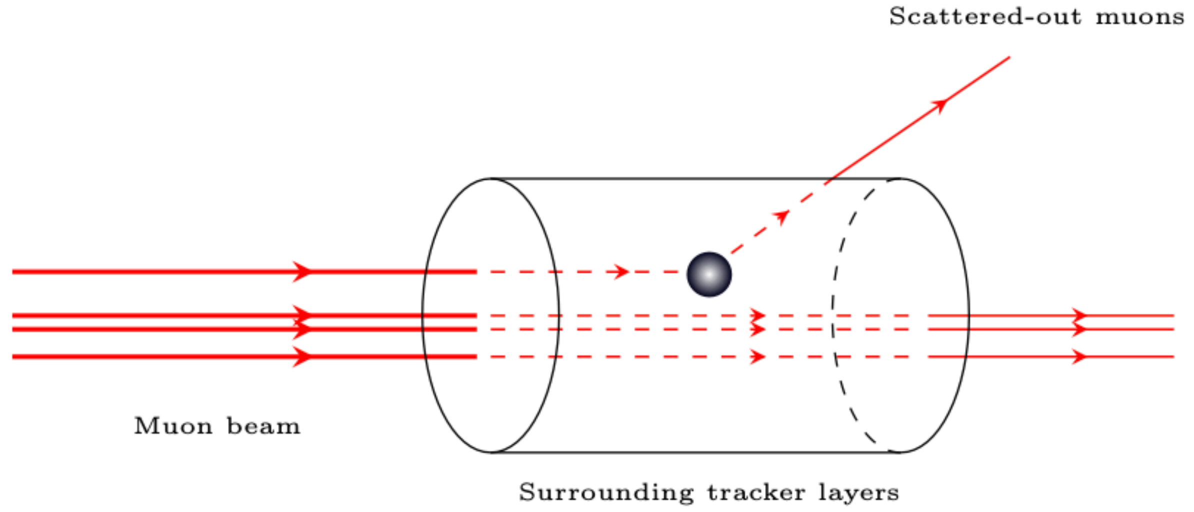
- ➔ Muon detector: RPC (Resistive Plate Chambers) & GEM (Gas Electron Multiplier)

- ➔ Phase I: Muon Tomography & Dark Matter searches using free cosmic-ray muons in a volume surrounded by tracking detectors
  - ❖ Develop muon tomography methods on both detectors and algorithm part
  - ❖ May also apply muon tomography on atmospheric and environmental sciences, on archaeology and civil engineering



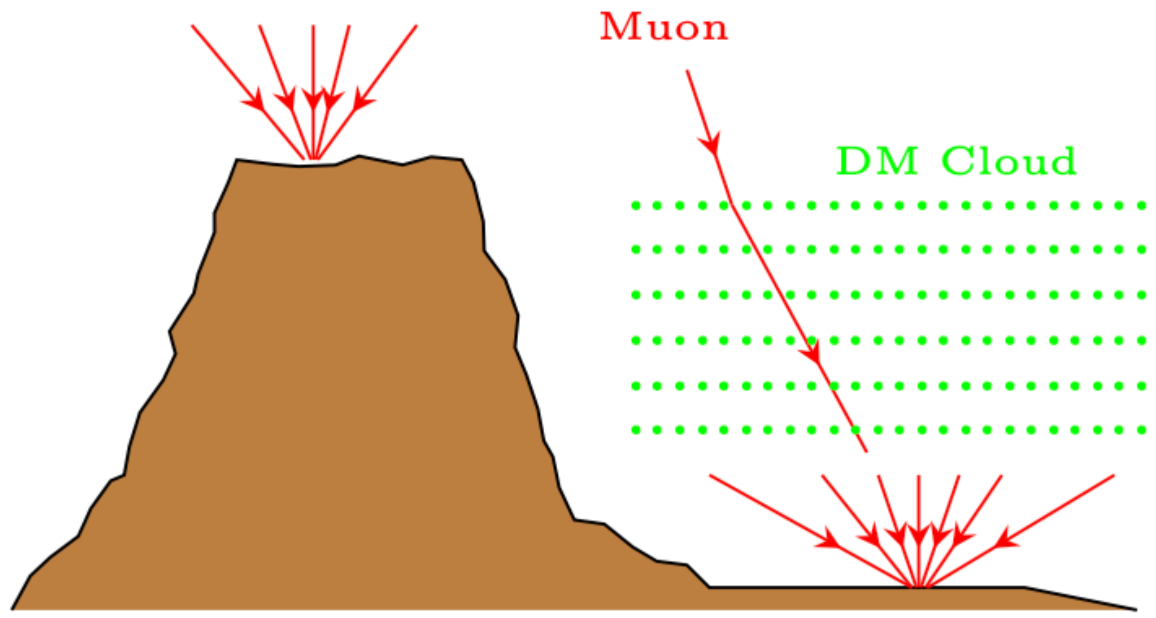
Phase I

- ➔ Phase II: Interface our device with domestic or international muon beams
  - ❖ Much larger muon intensity and focused beam
  - ❖ The detector can be made further compact and the resulting sensitivity on dark matter searches will be further improved



Phase II

- ➔ Phase III: measure precisely directional distributions of cosmic-ray muons, either at mountain or sea level
  - ❖ The differences may reveal possible information of dark matter distributed near the earth



Phase III

Experiment setup: GEM & RPC

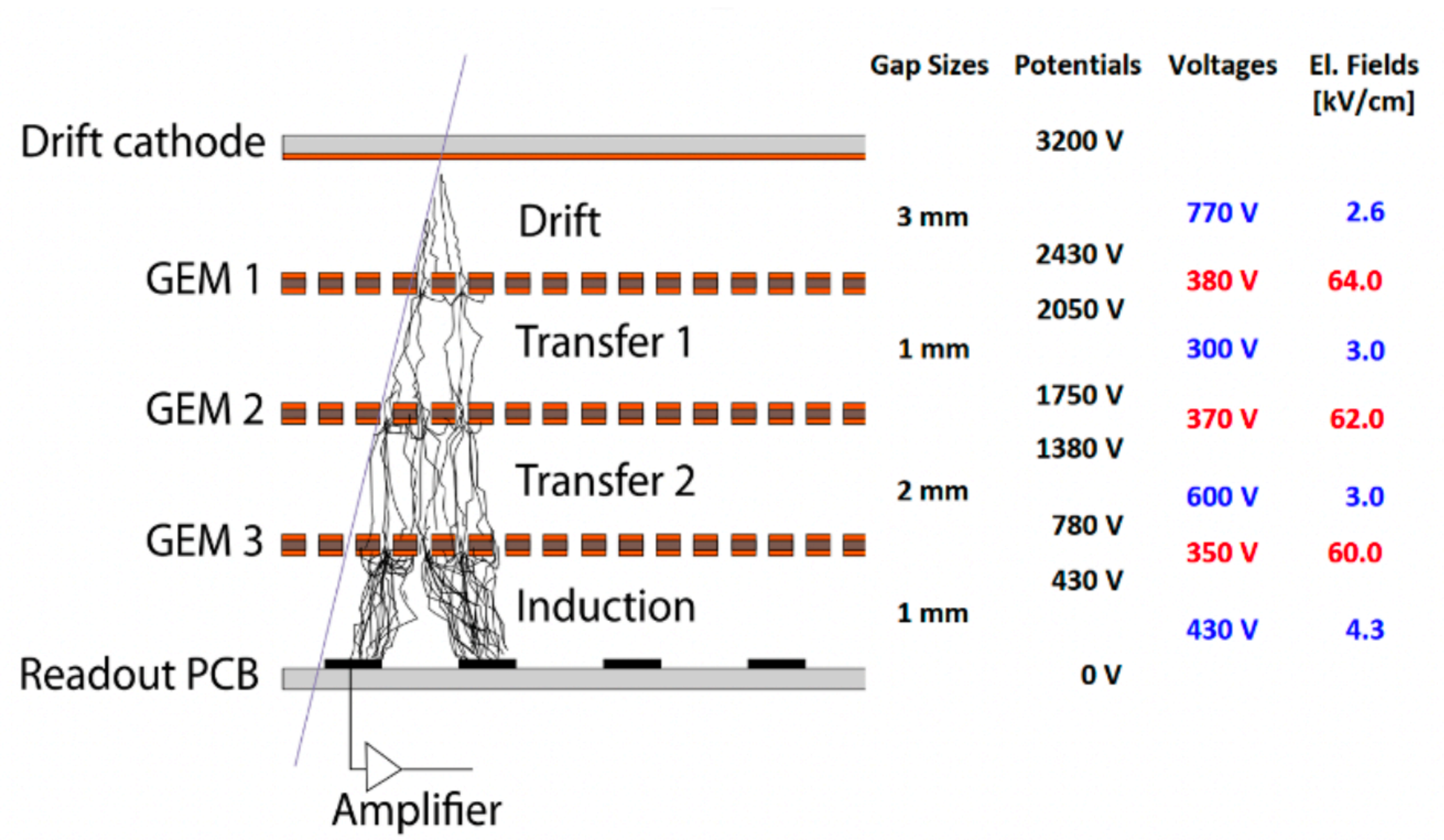
Requirements of detector for MT and DM

- Large area (~1 m^2)
- High detection efficiency (>90%)
- High spatial resolution (~1 mm)
- High timing resolution (~ 1 ns)
- Cost-effective

GEM

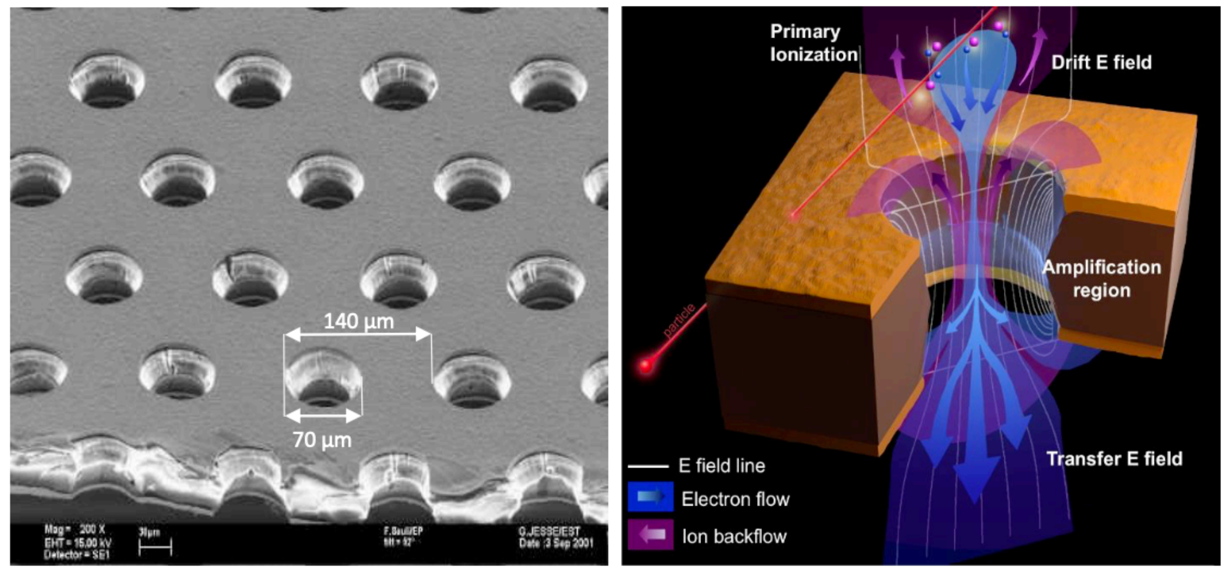
CMS TDR

- ➔ 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

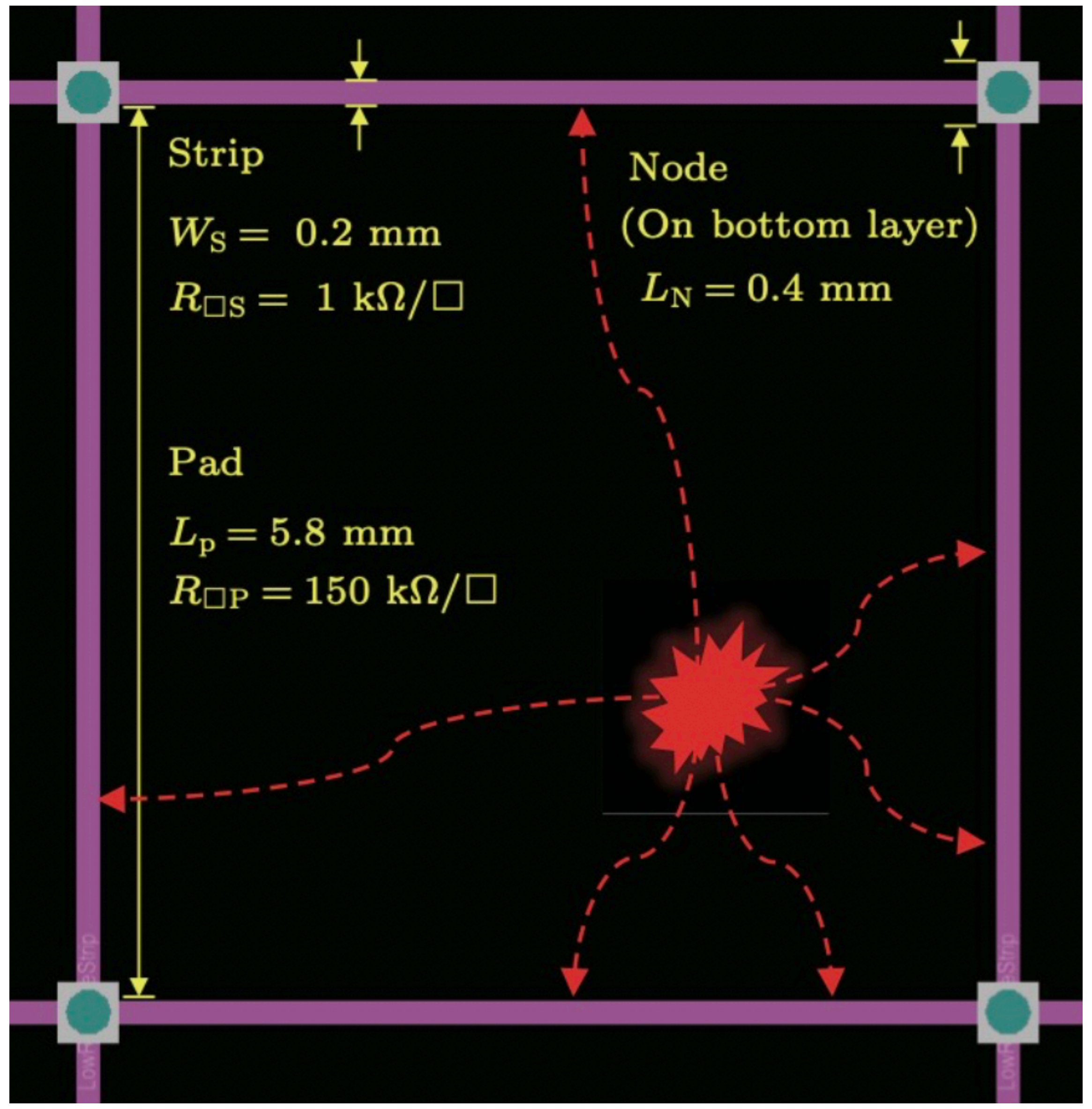


Schematic view of a triple-GEM detector

- ➔ 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



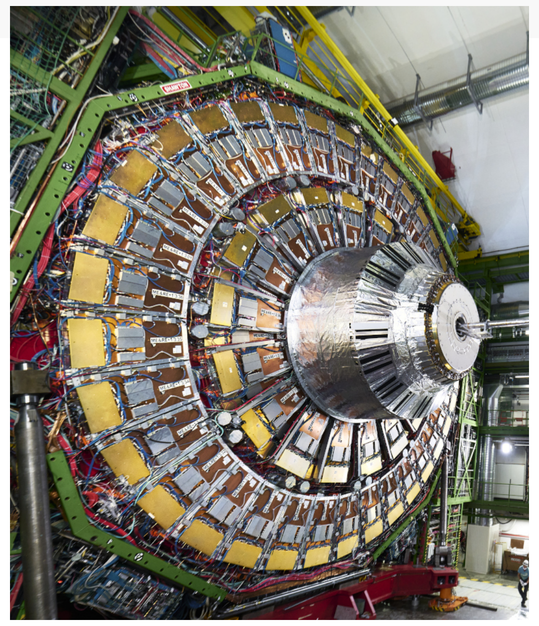
Structure diagram of the basic resistive anode cell

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

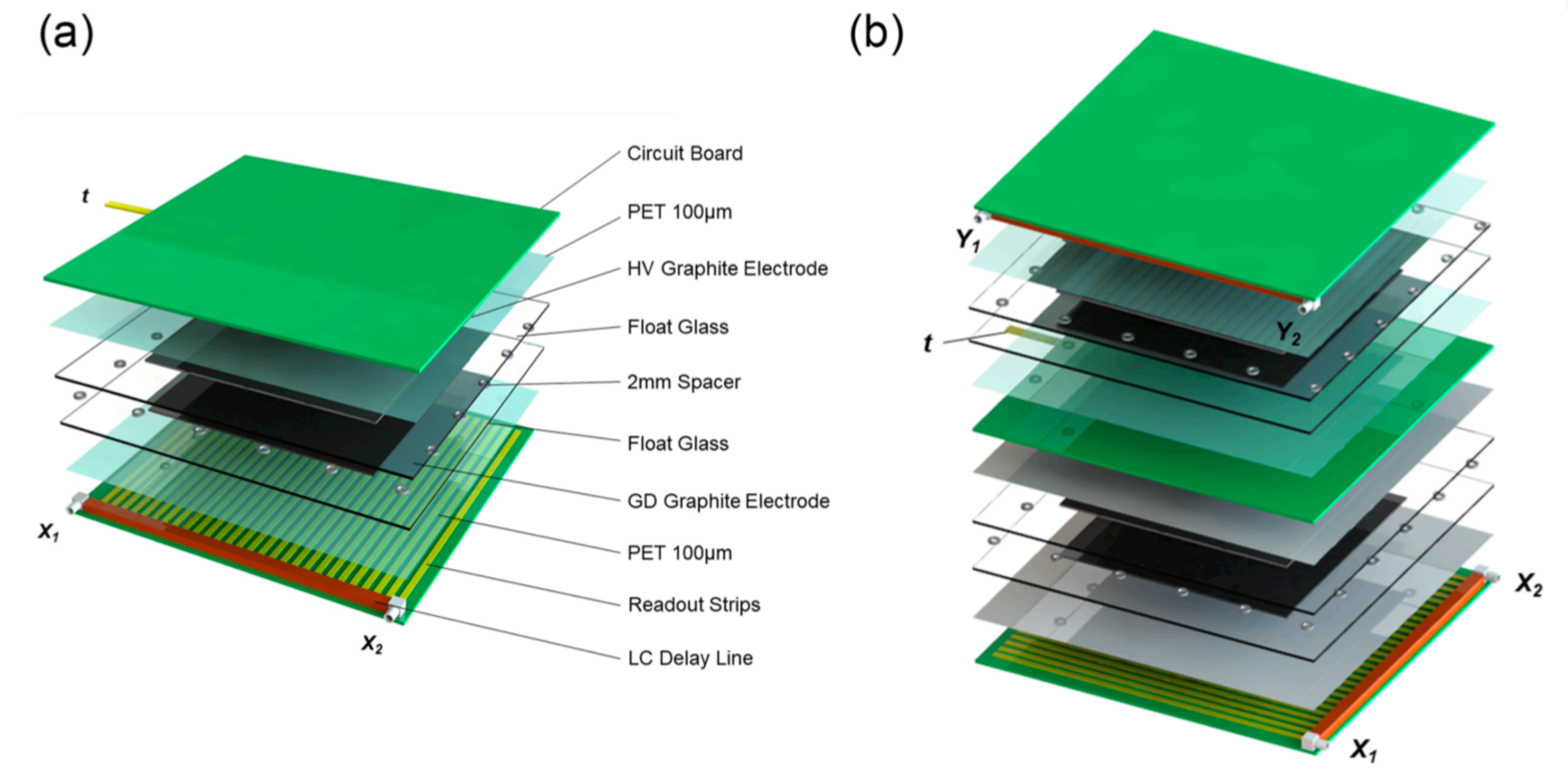
RPC

- **➔** RPC — R. Santonico(in 1980s)
  - ❖ simple and robust structure, long-term stability, good timing resolution, easy-maintenance and low cost

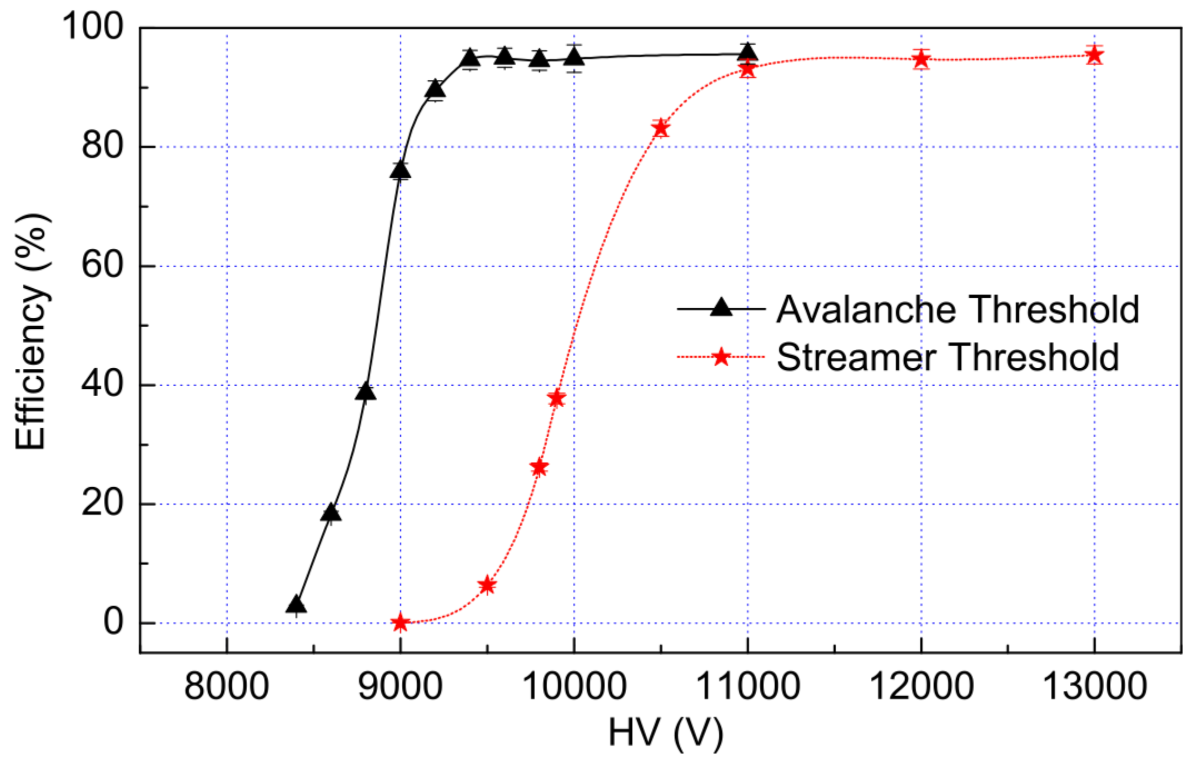
Compact Muon Solenoid



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

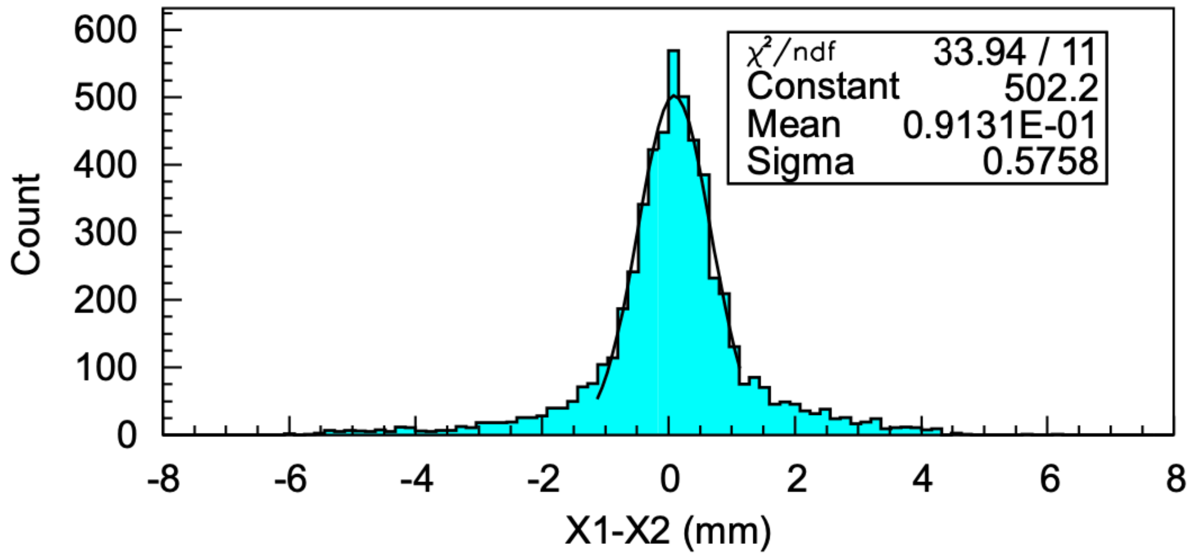


- **➔** PKU RPC R&D History
  - ❖ **CMS Muon Trigger RPCs**, assembled and tested by PKU (2002)
  - ❖ Combination of glass RPC & Decay-line Readout (Qite Li et. al.)



Efficiency curves for the glass RPC

- **➔** **Glass RPC MT Prototype** in 2012
  - ❖ Effective area of the electrode: $20 \times 20\,\mathrm{cm}^2$
  - ❖ Readout electronics: decay-line, charge-division methods

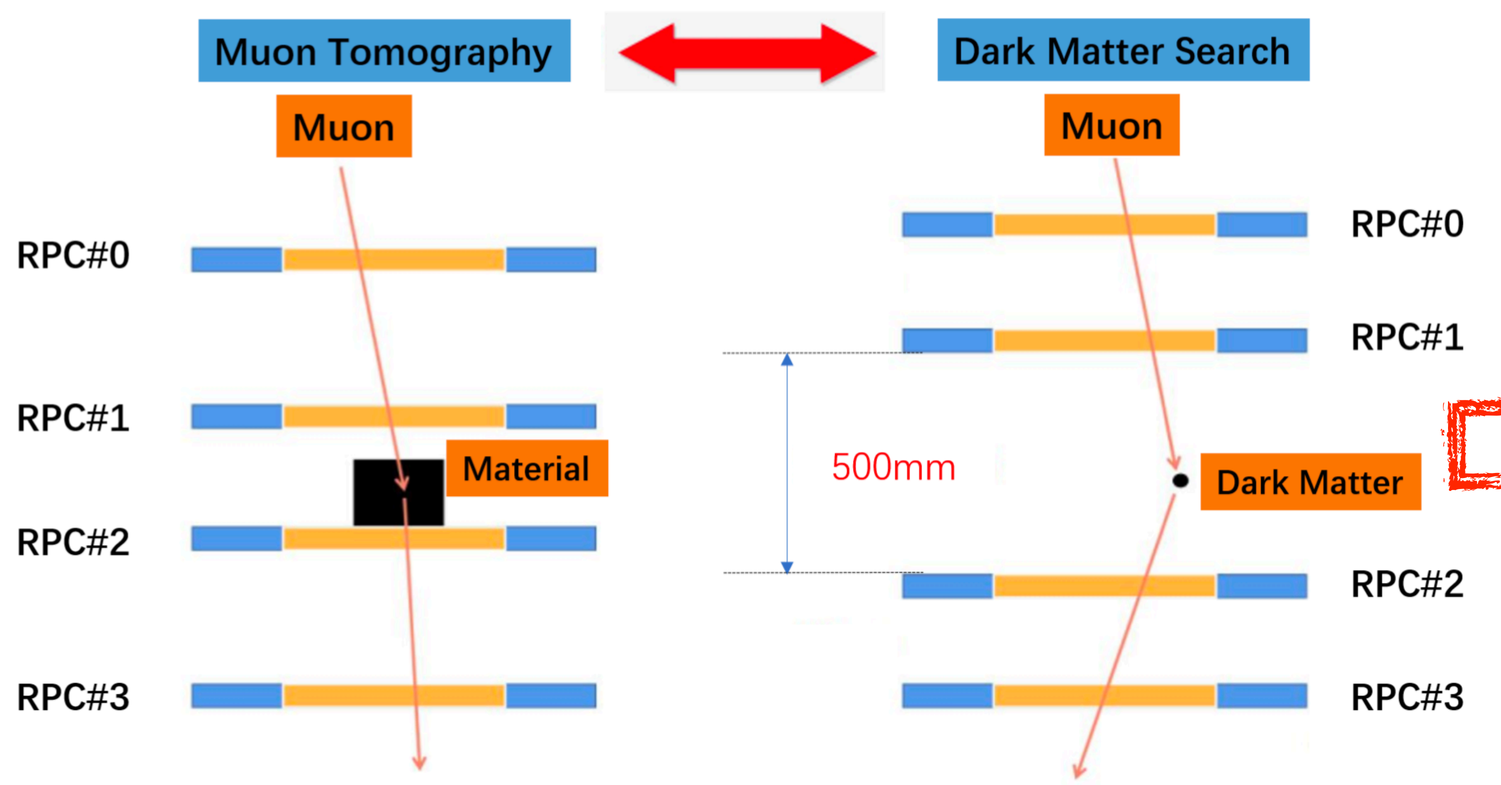


Distribution of X1-X2

- **➔** **Good and stable performance** so far!
  - ❖ Positional resolution: ~0.5 mm, detection efficiency: > 90%

RPC future upgrade plan

Step 1

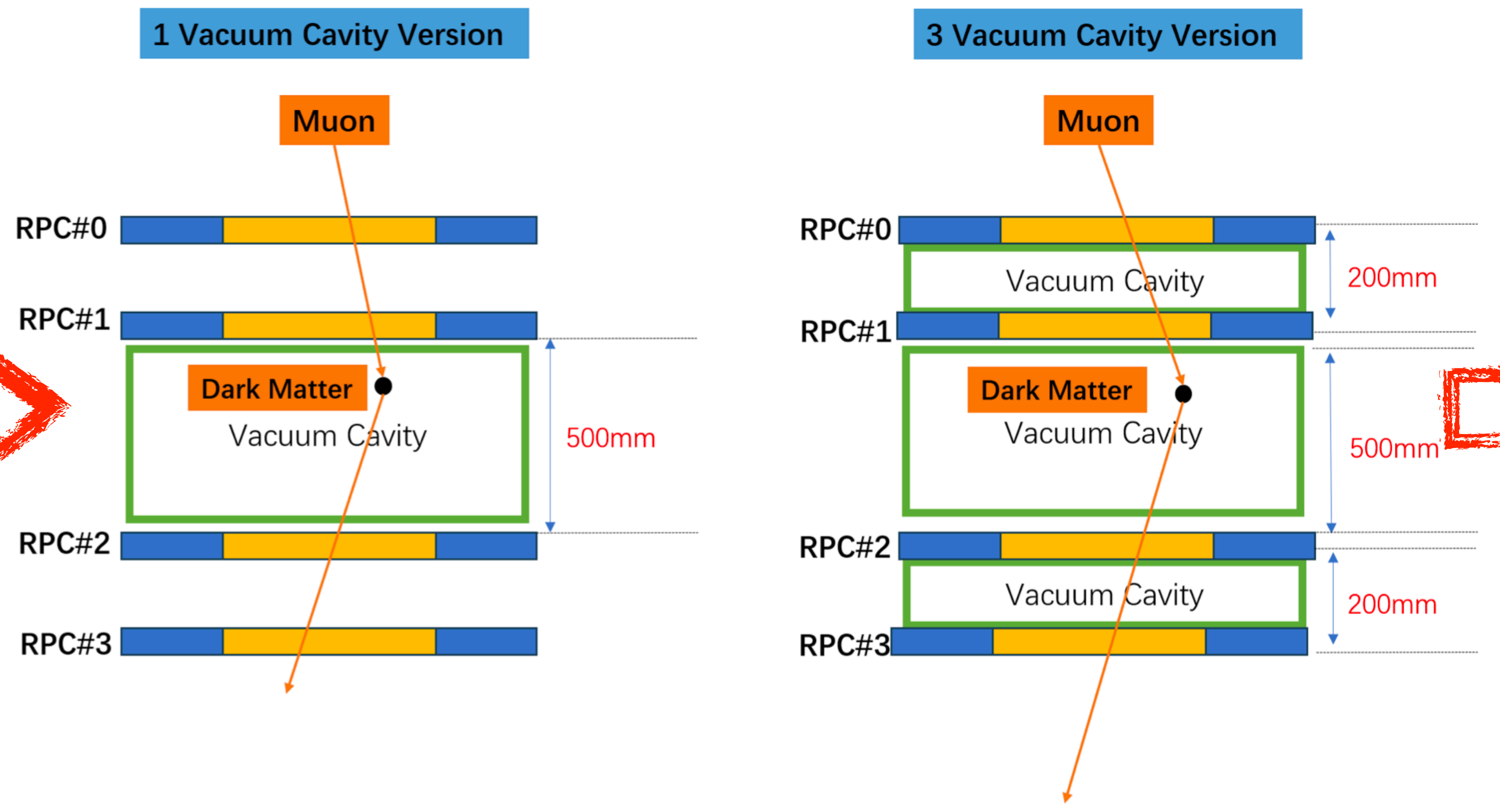


Muon Tomography & Dark Matter search

➔ Upgrade plan

- ❖ Gas system:
  Pure Freon → mixed gas (87% Freon + 8.7% C_4H_{10} + 4.3% SF_4)
  - Avalanche mode dominated, keep signal to noise ratio in a high level
- ❖ Electronic readout DAQ system:
  DAQ based on digitization ASIC
  - AGET, PETIROC, TOFPET, …

Step 2

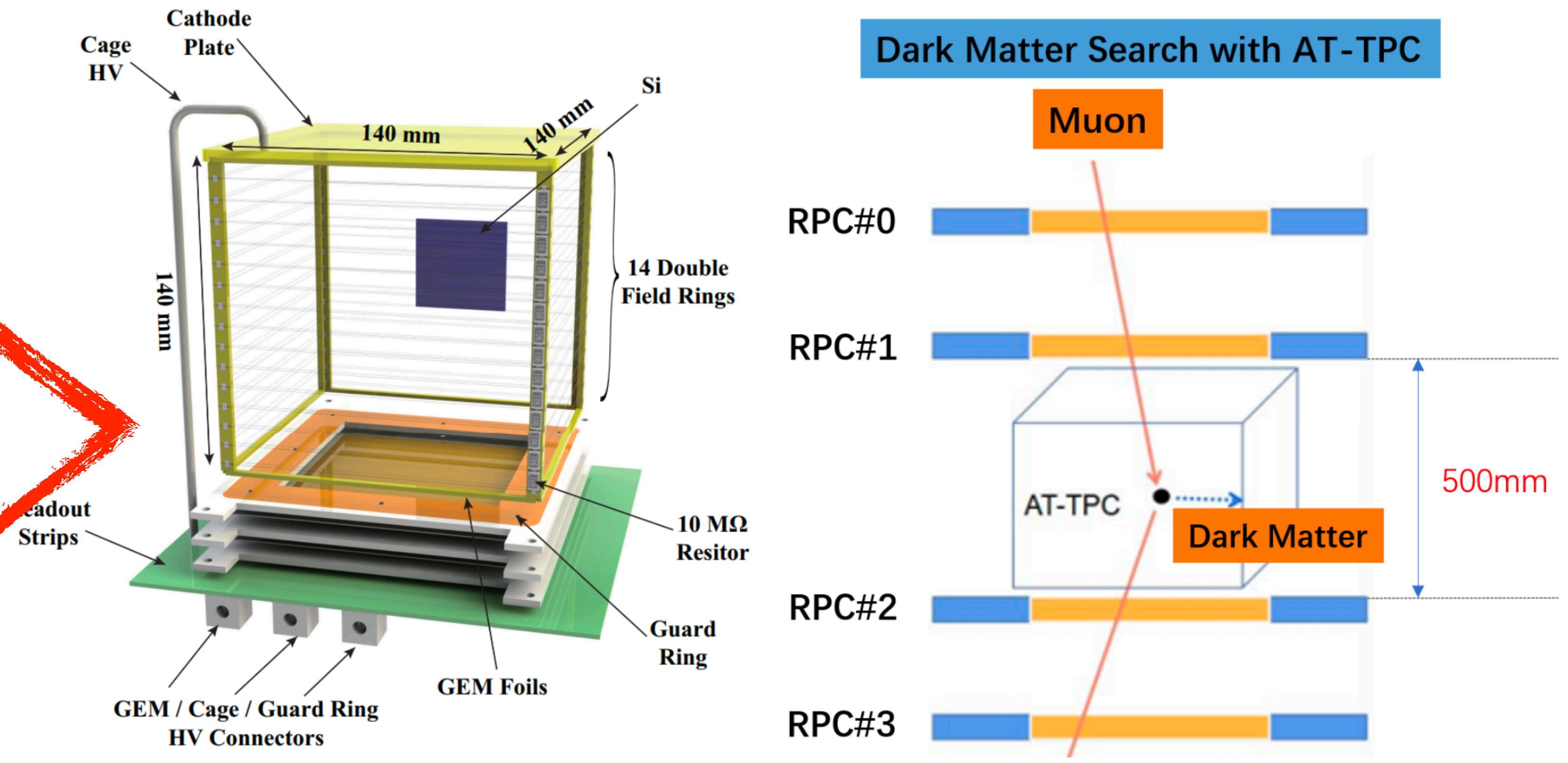


1 vacuum cavities   3 vacuum cavities

Kapton shell for **vacuum chamber**

- Minimize possible factors interfering with dark matter search

Step 3



- ❖ Structures:
  - Electronic field cage
  - double-layer GEM membrane for signal amplification
  - a 2-dimensional strip-readout structure.
- ❖ Can wok on some muon beam lines, such as MuSIC in RCNP

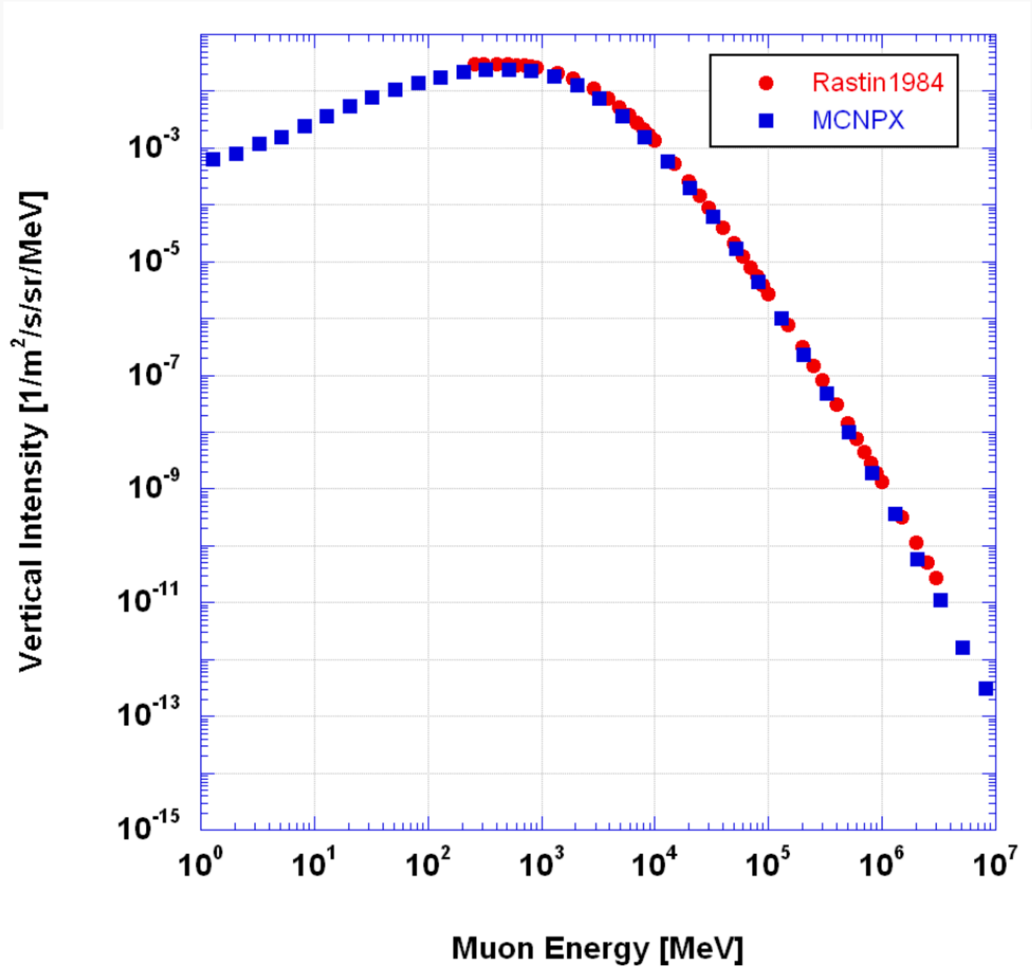
➔ **Active-Target of Time Projection Chamber (AT-TPC)**

- ❖ Working gas medium as the target material
- ❖ Advantages: recording the complete kinematic information & covering a large solid angle
- ❖ PKU has already built a small $14 \times 14 \times 14\,\mathrm{cm}^3$ AT-TPC prototype
- ❖ Plan to increase size to $25 \times 25 \times 50\,\mathrm{cm}^3$

NUCL.SCI.TECH, 32, 85 (2021)

Simulation framework

MC simulation framework



Mean energy: 3~4 GeV

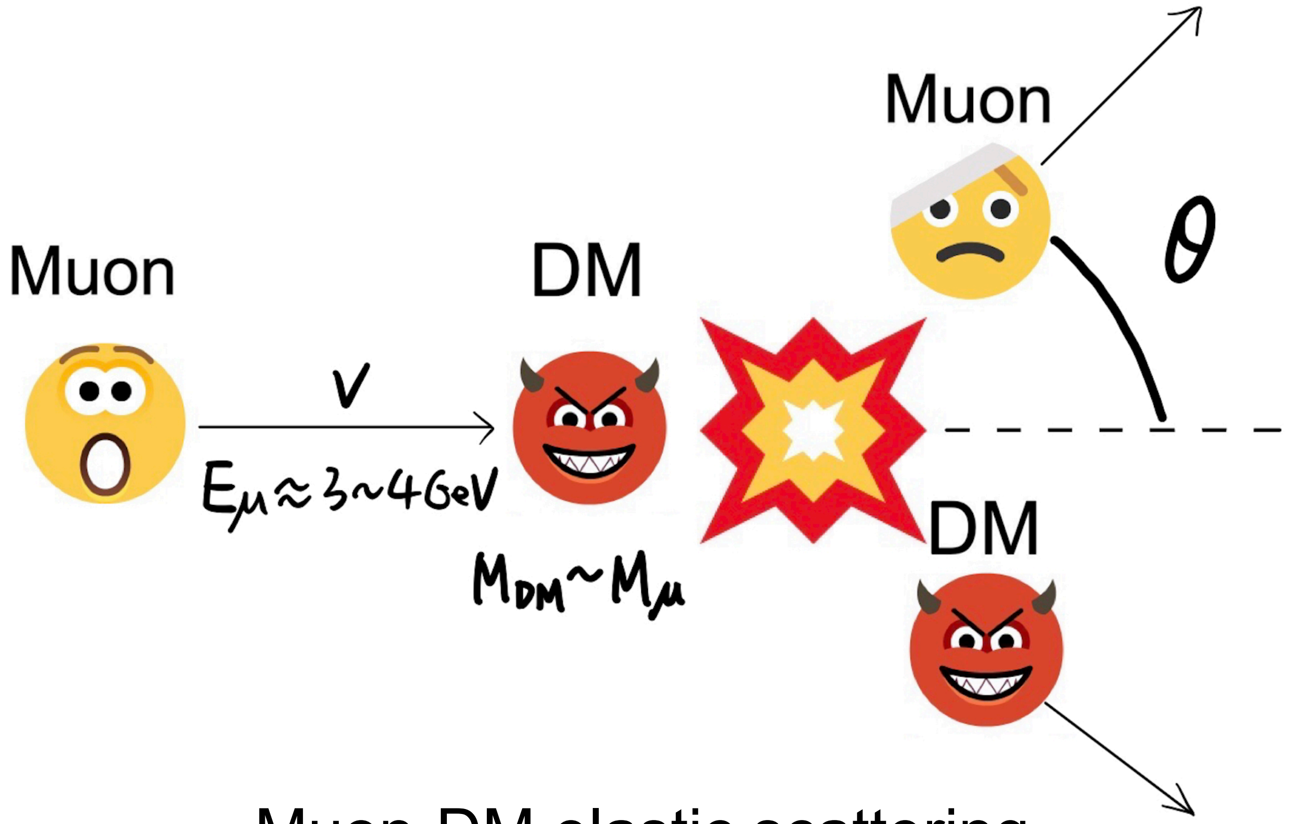
- ➔ MC simulation of GEM-based detector based on **Geant4**
  - ❖ Triple-GEM detector design refer to CMS GEM design
  - ❖ Muon material interaction automatically considered by Geant4
  - ❖ Reco hit position: Truth hit position smeared by GEM detector resolution (~ 200 um)
- ➔ DM and muon scattering: **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 scattering rate
  - ❖ Different from XENON1T/PandaX: **Relativistic muon hit quasi-static DM**

❖ DM search in $V = 1\,\mathrm{m}^3$ box:
- $\mathrm{d}N/\mathrm{d}t = \rho_{\mathrm{DM}} V / M_{\mathrm{DM}} \times \sigma_{\mu,\mathrm{DM}} \times F_\mu$
- Muon flux $F_\mu \sim 1/60\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$ at sea level
- $\rho_{\mathrm{DM}} \sim 0.3\,\mathrm{GeV/cm}^3 \Leftrightarrow N_{\mathrm{DM}} \sim 3 \times 10^5$

❖ 1 year run: $\sigma_{\mu,\mathrm{DM}} \sim 10^{-11}\,\mathrm{cm}^2$

❖ DM search in beam:
- Length $L = 1\,\mathrm{m}$
- $\mathrm{d}N/\mathrm{d}t = N_\mu \times \sigma_{\mu,\mathrm{DM}} \times L \times \rho_{\mathrm{DM}} / M_{\mathrm{DM}}$
- Intensity $N_\mu \sim 10^6/\mathrm{s}$ (CSNS Melody design)

❖ 1 year run: $\sigma_{\mu,\mathrm{DM}} \sim 10^{-15}\,\mathrm{cm}^2$

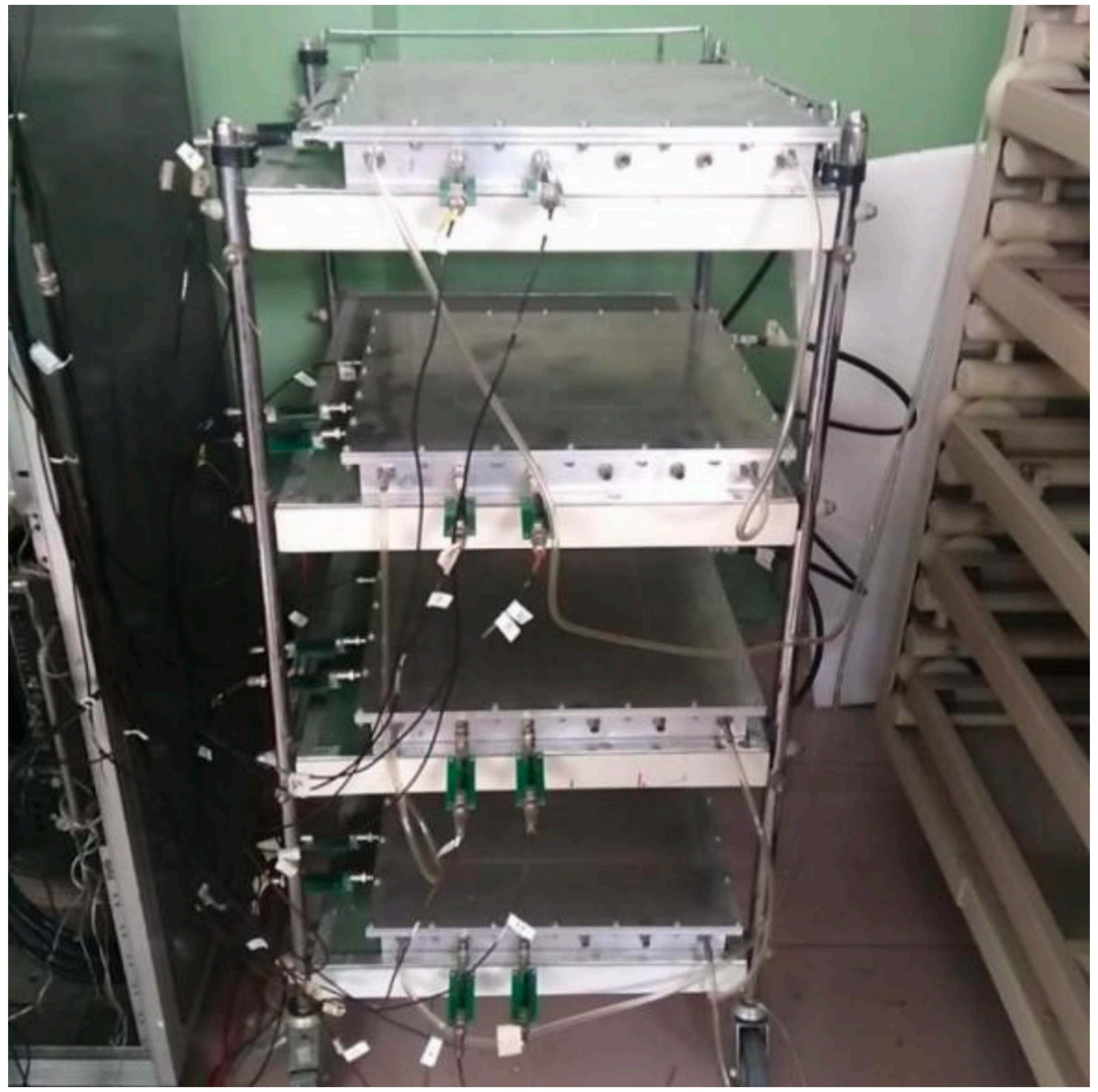


Muon-DM elastic scattering

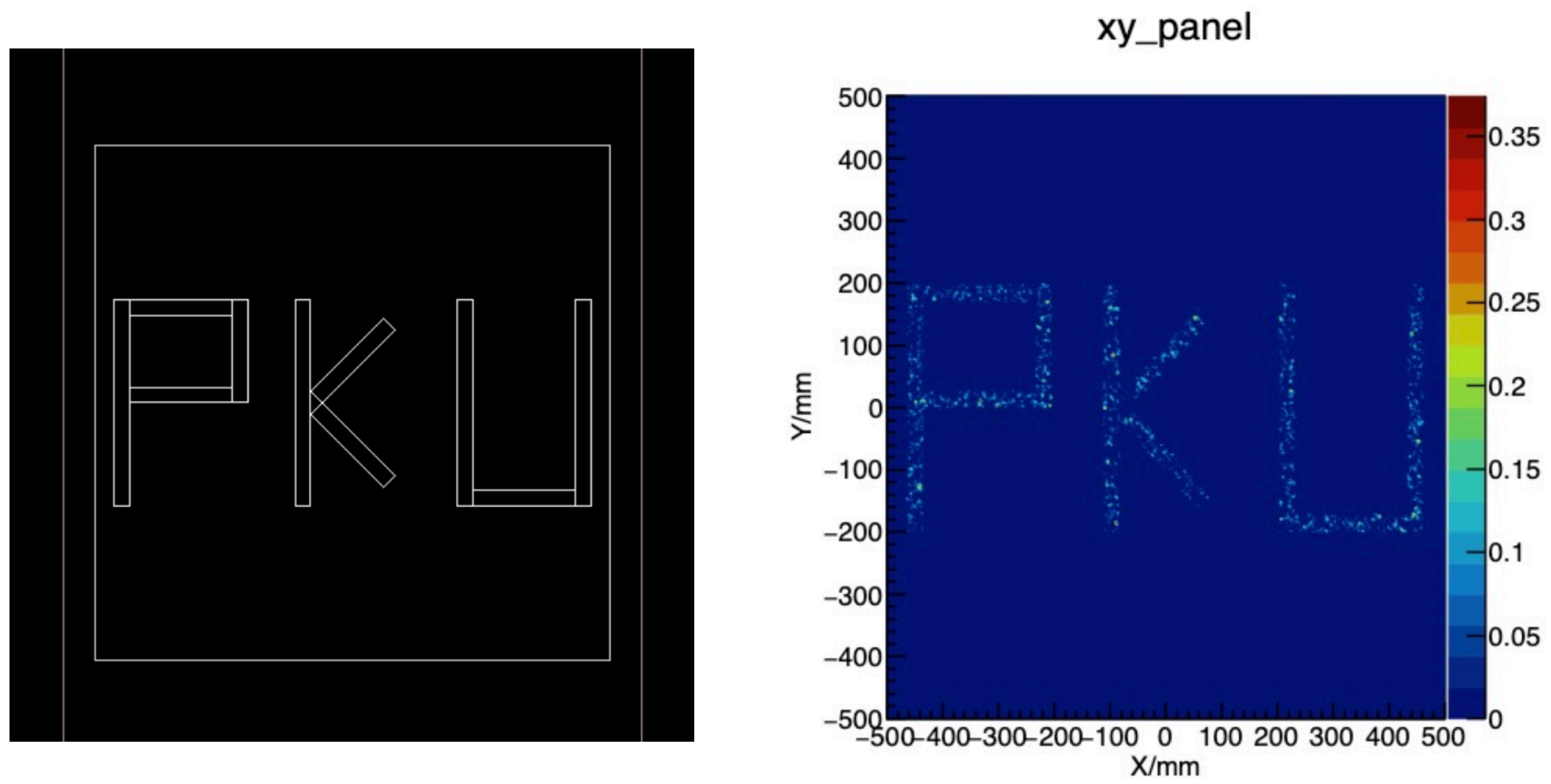
Physics program

Precise measurements of cosmic-ray muons and muon tomography

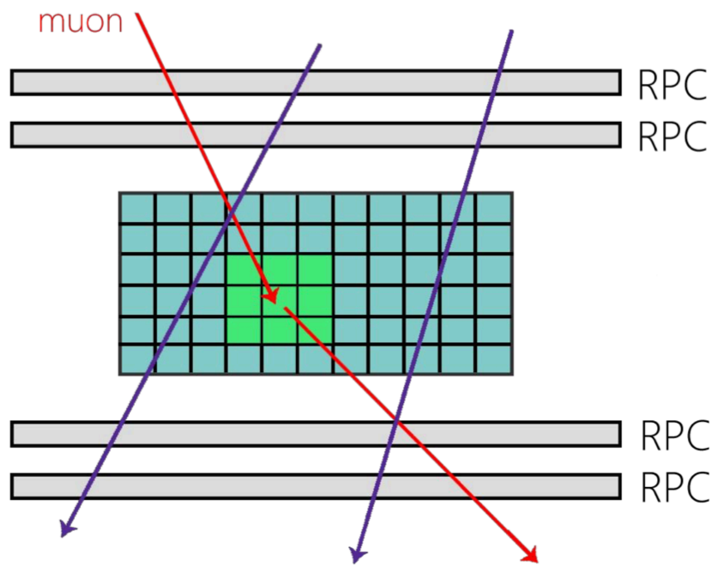
- ➔ The first differential and integral spectra of muons moving in the near-vertical direction can be measured at Beijing using RPC/GEM
- ➔ Test material placed in detection region, cosmic-ray muons undergo Multiple Coulomb Scattering
- ➔ Utilizing PoCA, MLSD, Ratio, … Algorithms to reconstruct distribution information of substances or materials in the detection area
- ➔ May also apply muon tomography on atmospheric and environmental sciences, on archaeology and civil engineering



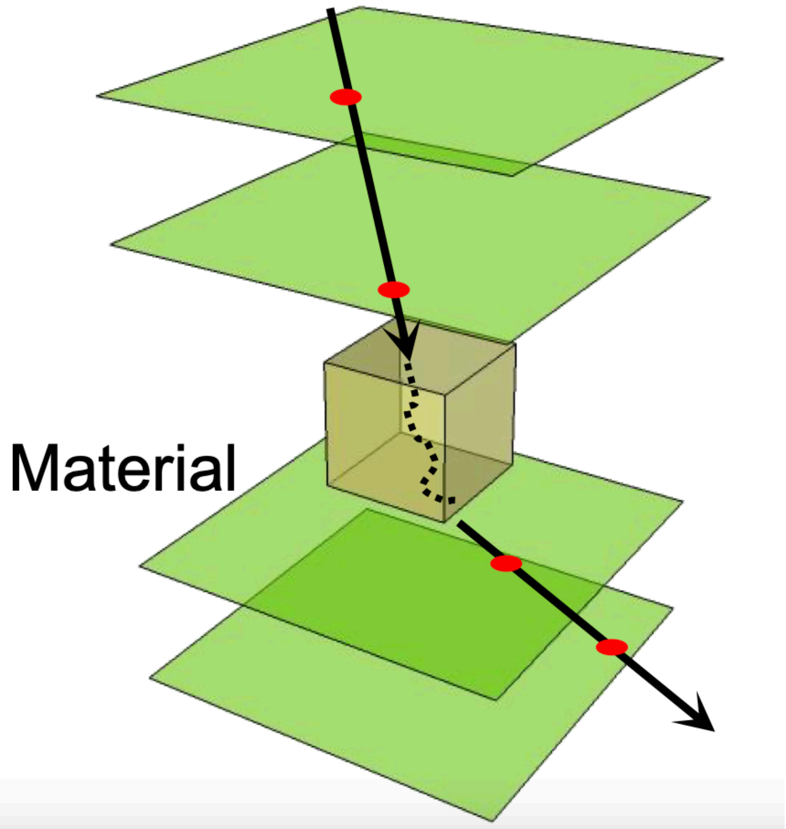
PKU MT system



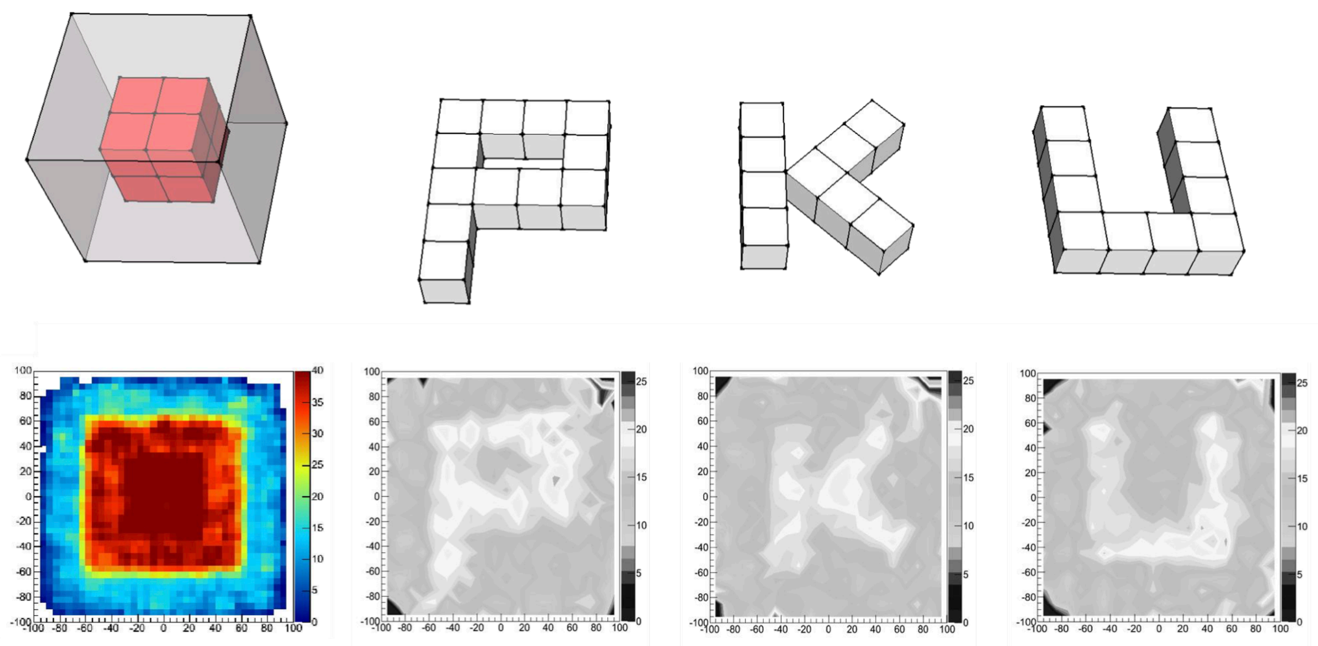
Geant4 visualization of PKU Pb blocks (Left)
PoCA point 2D imaging (Right)



PoCA point reconstruction

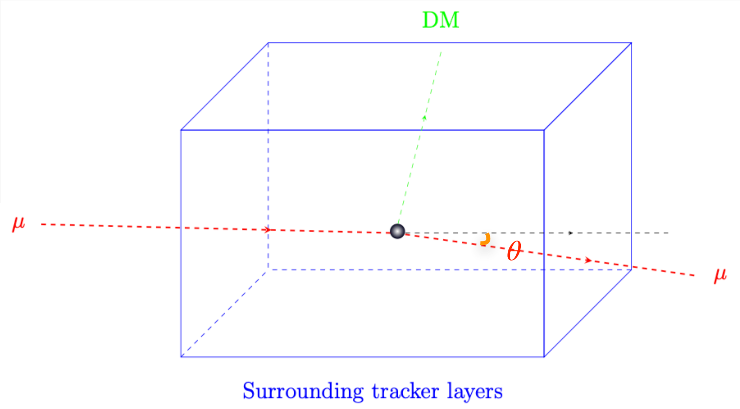


Muon undergo multiple scattering



Imaging results of lead block wrapped in a iron shell and the iron letters PKU

Dark Matter searches in a box

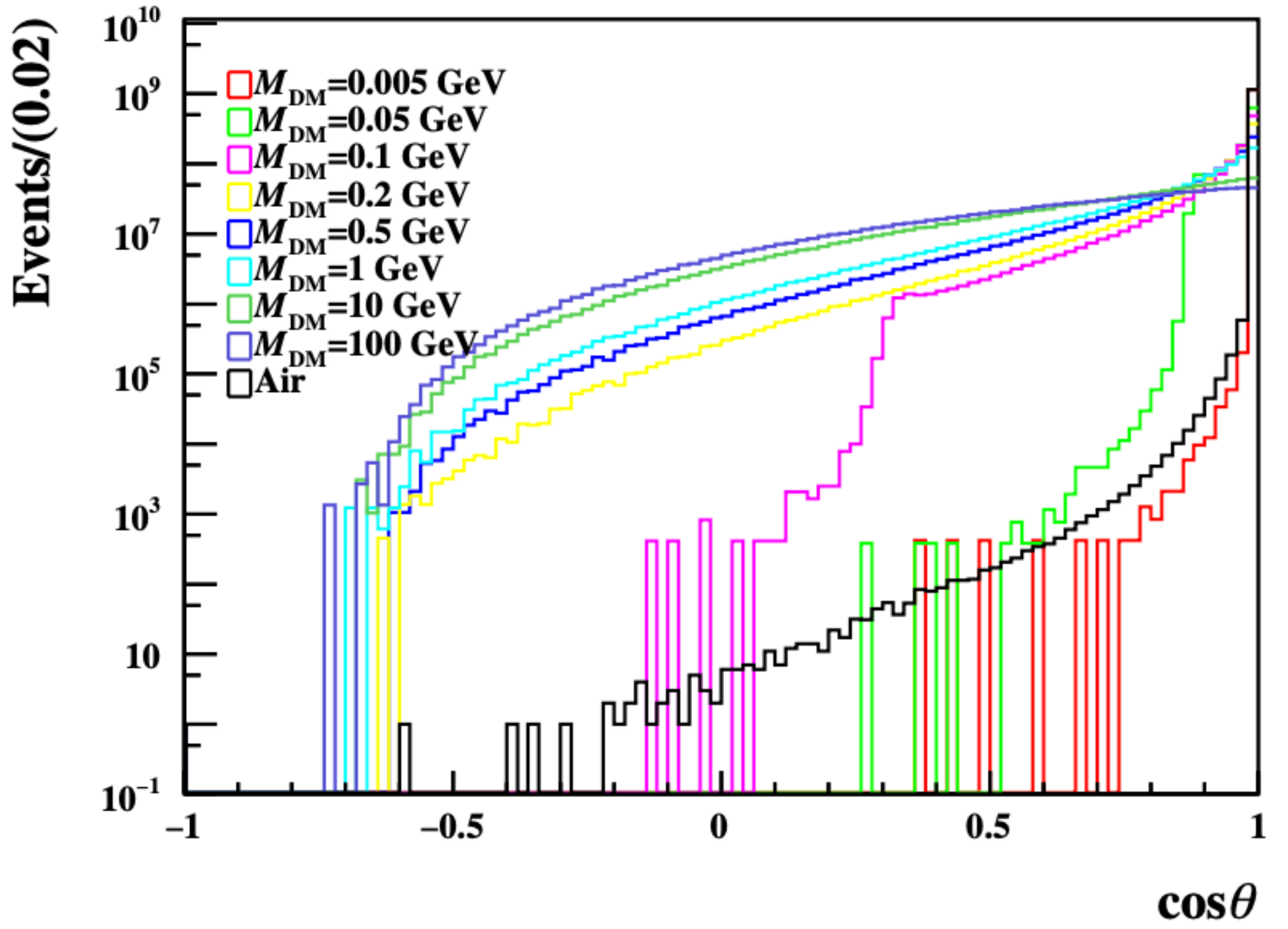


- ➔ Dark Matter searches in $1\ \mathrm{m}^3$ box using GEM detector
  - ❖ 2 upper/lower layers for incoming/outcoming muon direction

- ➔ 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.

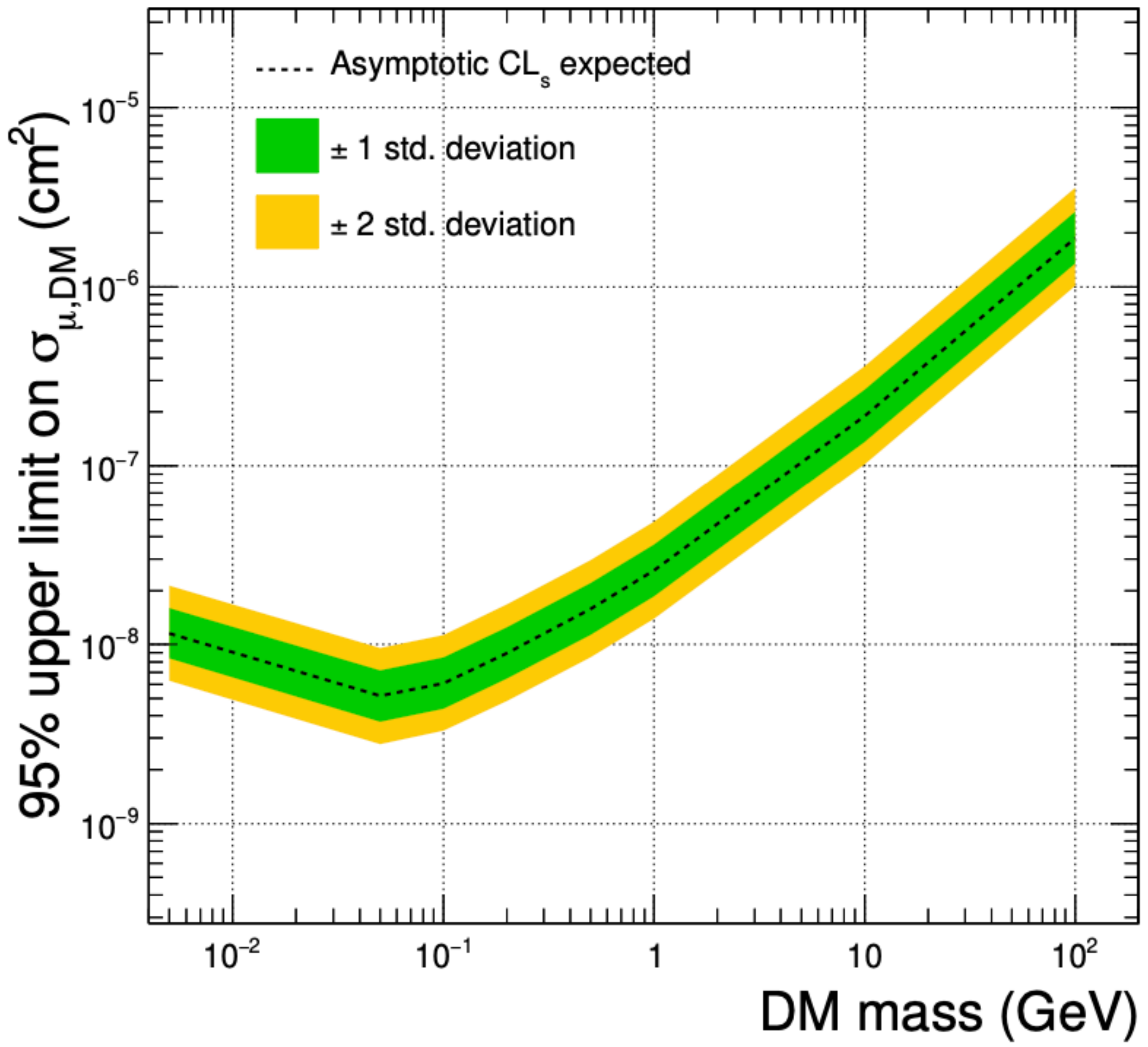
Background	Event Number ($\times 10^9$)	
Air	1.15	
Vacuum	1.14	
DM mass (GeV)	Constant (%)	Maxwell-Bolzmann (%)
0.005	27.10 ± 0.01	27.11 ± 0.01
0.05	29.56 ± 0.01	29.55 ± 0.01
0.1	27.66 ± 0.01	27.64 ± 0.01
0.2	25.01 ± 0.01	24.99 ± 0.01
0.5	21.47 ± 0.01	21.46 ± 0.01
1	18.67 ± 0.01	18.66 ± 0.01
10	11.10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

Background event numbers
&
detection efficiency in one year



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

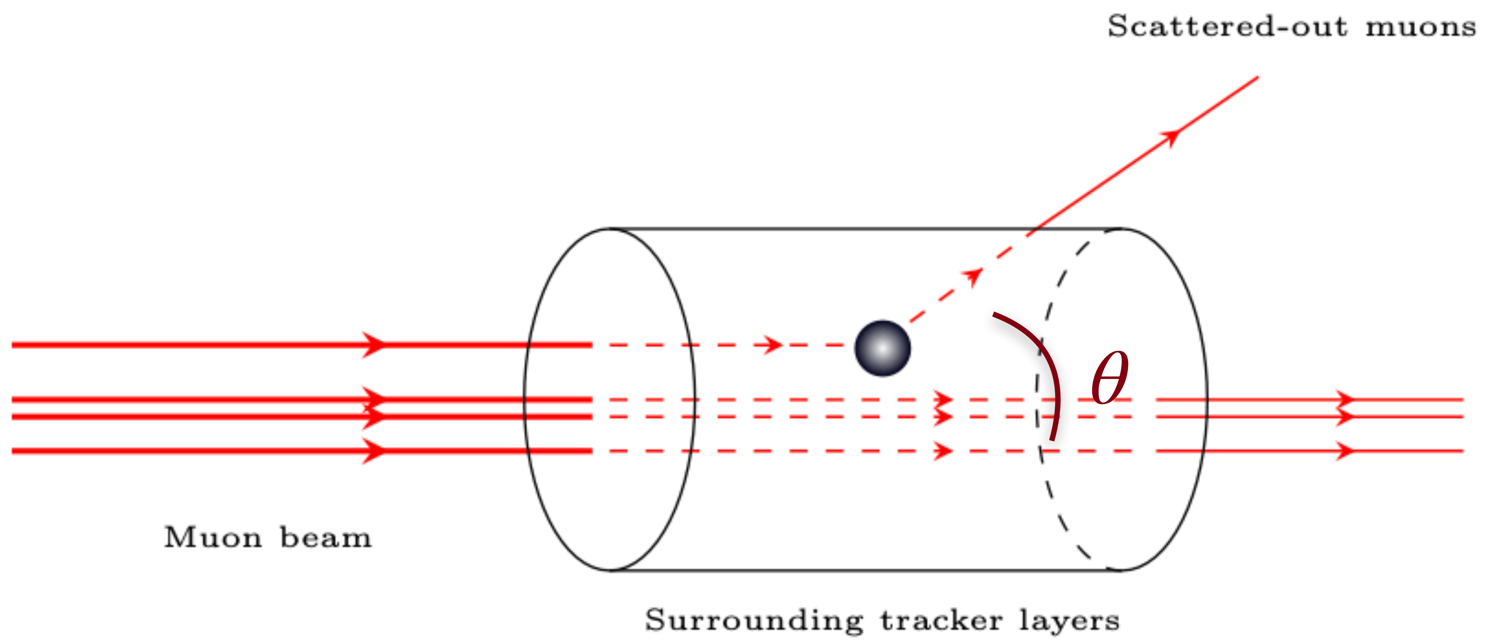
Dark Matter searches in a box



General statistics tool — Higgscombine

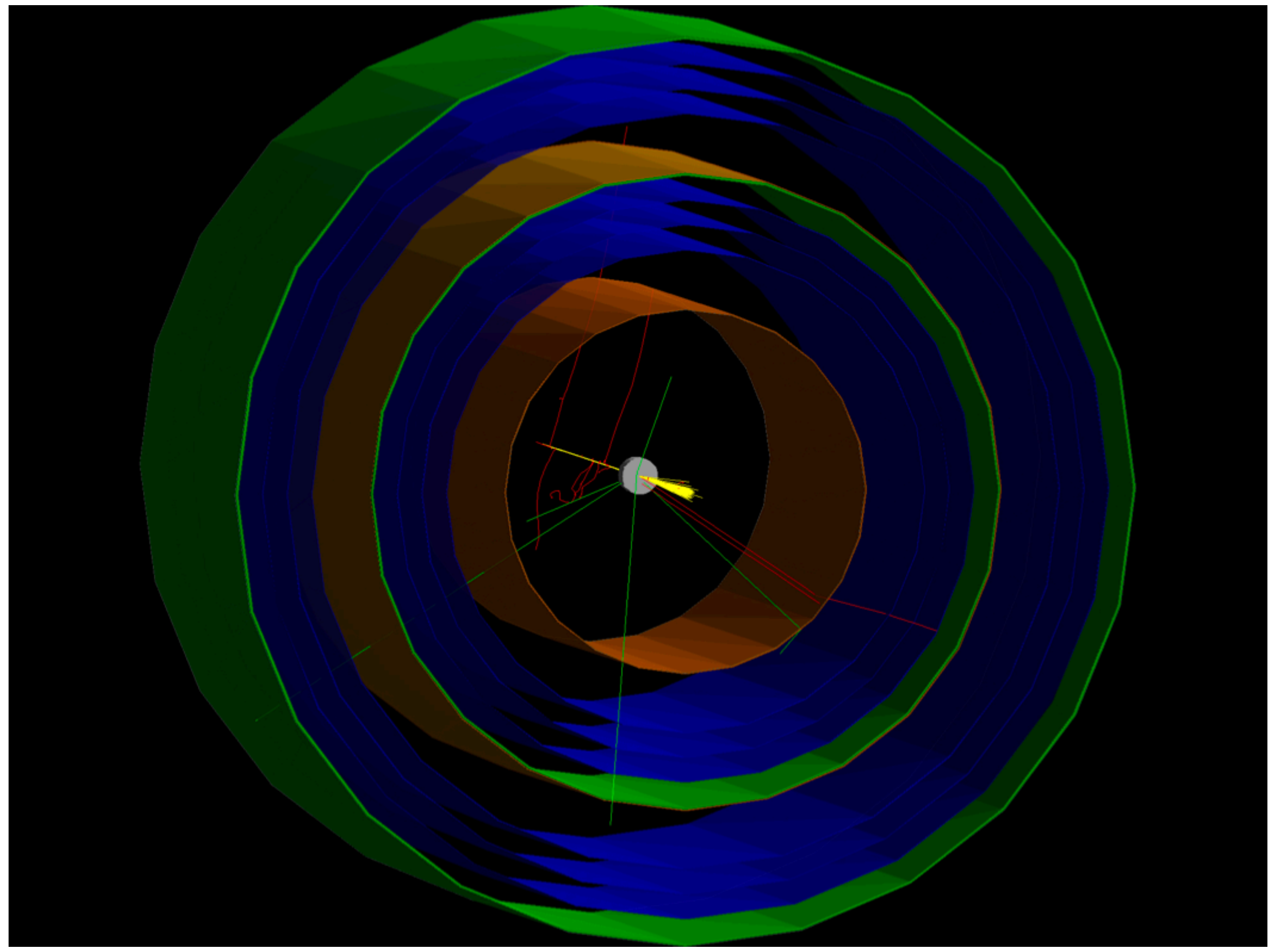
- "Asimov" data is used
- Binned maximum likelihood fits
- UL determined by CLs method
- Only take statistical uncertainty into consideration
- ULs on cross-section for sub-GeV DM and muon interaction: $10^{-7} \sim 10^{-9}\,\mathrm{cm}^2$
- In "exotic" DM scenario, dark matter number density can be as large as $10^{15}\,\mathrm{cm}^{-3}$, sensitivity on $\sigma_{\mu,\mathrm{DM}}$ can reach as low as $10^{-22} \sim 10^{-24}\,\mathrm{cm}^2$

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

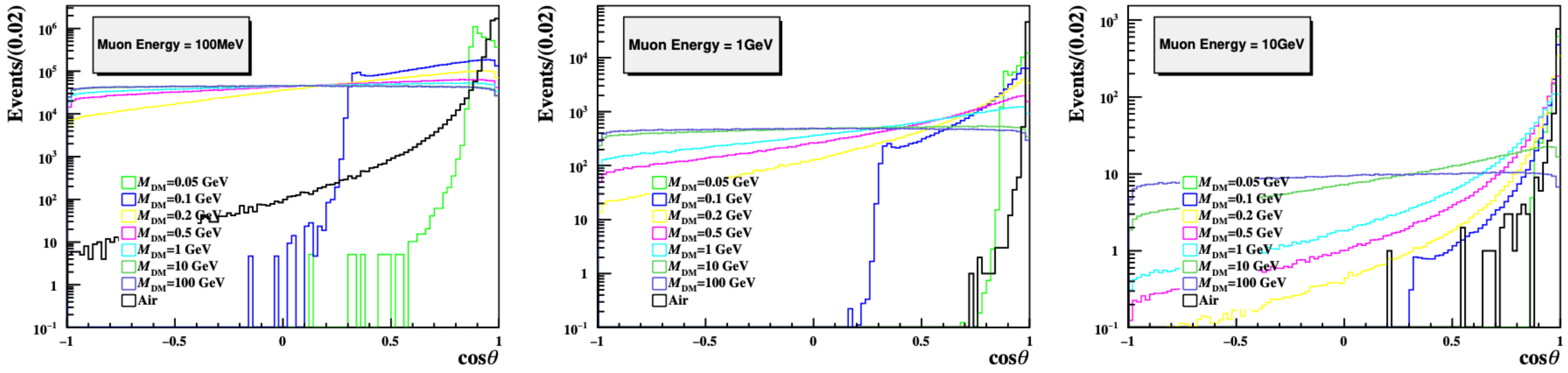


Orange surfaces: drift cathodes
Blue surfaces: GEM foils
Green surfaces: PCBs
Yellow lines: muons tracks
Red curves: electron tracks
Green lines: photons

$M_{DM} \backslash E^{\mu}_{kin}$	100 MeV (%)	1 GeV (%)	10 GeV (%)
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

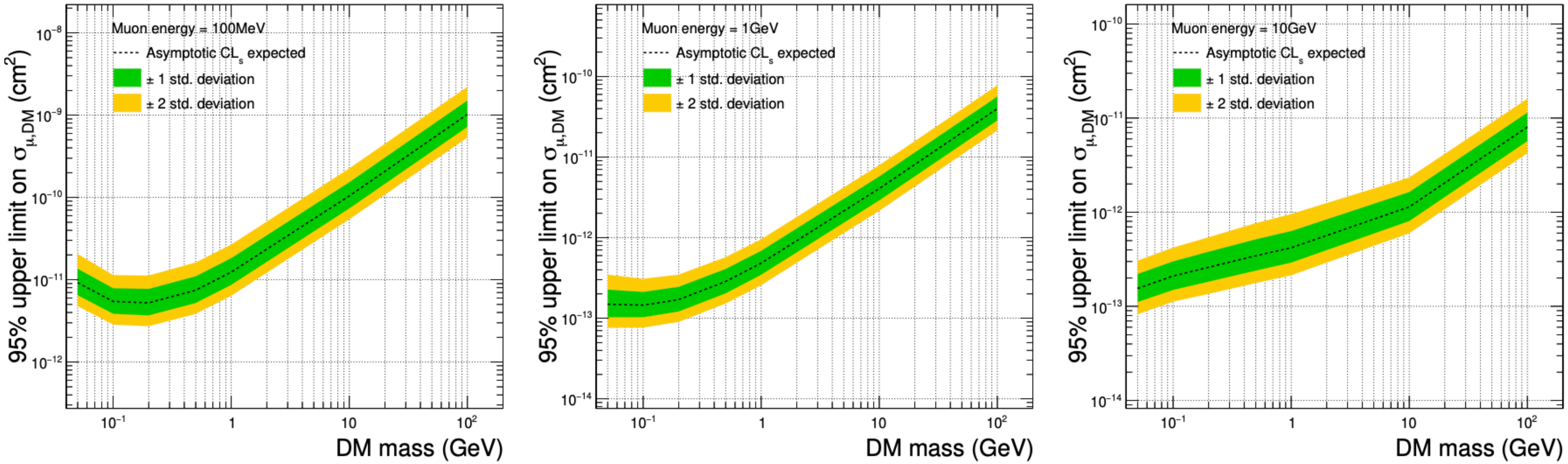
Detection efficiency in different muon beam energies & DM mass assumptions

Dark Matter searches using muon beams



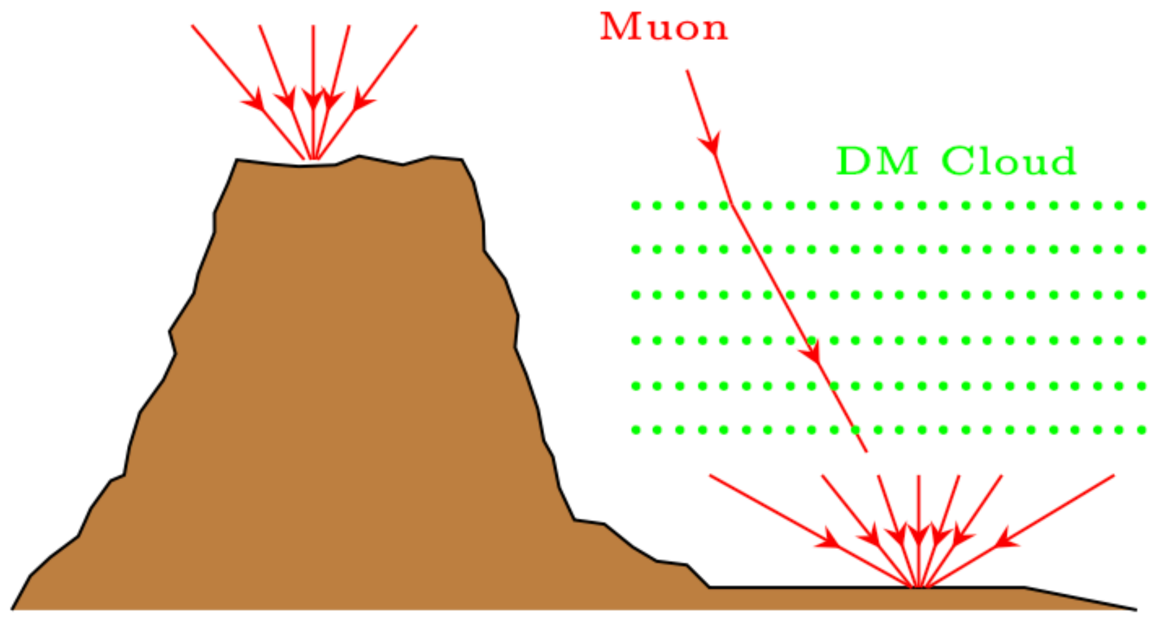
Muon Intensity $I = 10^6\,\mathrm{s}^{-1}$ (consistent with CSNS Melody design)

- $P_\mu = 100\,\mathrm{MeV}$, ULs on $\sigma_{\mu,\mathrm{DM}} : 10^{-9} \sim 10^{-12}\,\mathrm{cm}^2$
- $E_\mu = 1\,\mathrm{GeV}$, ULs on $\sigma_{\mu,\mathrm{DM}} : 10^{-11} \sim 10^{-13}\,\mathrm{cm}^2$
- $E_\mu = 10\,\mathrm{GeV}$, ULs on $\sigma_{\mu,\mathrm{DM}} : 10^{-12} \sim 10^{-13}\,\mathrm{cm}^2$

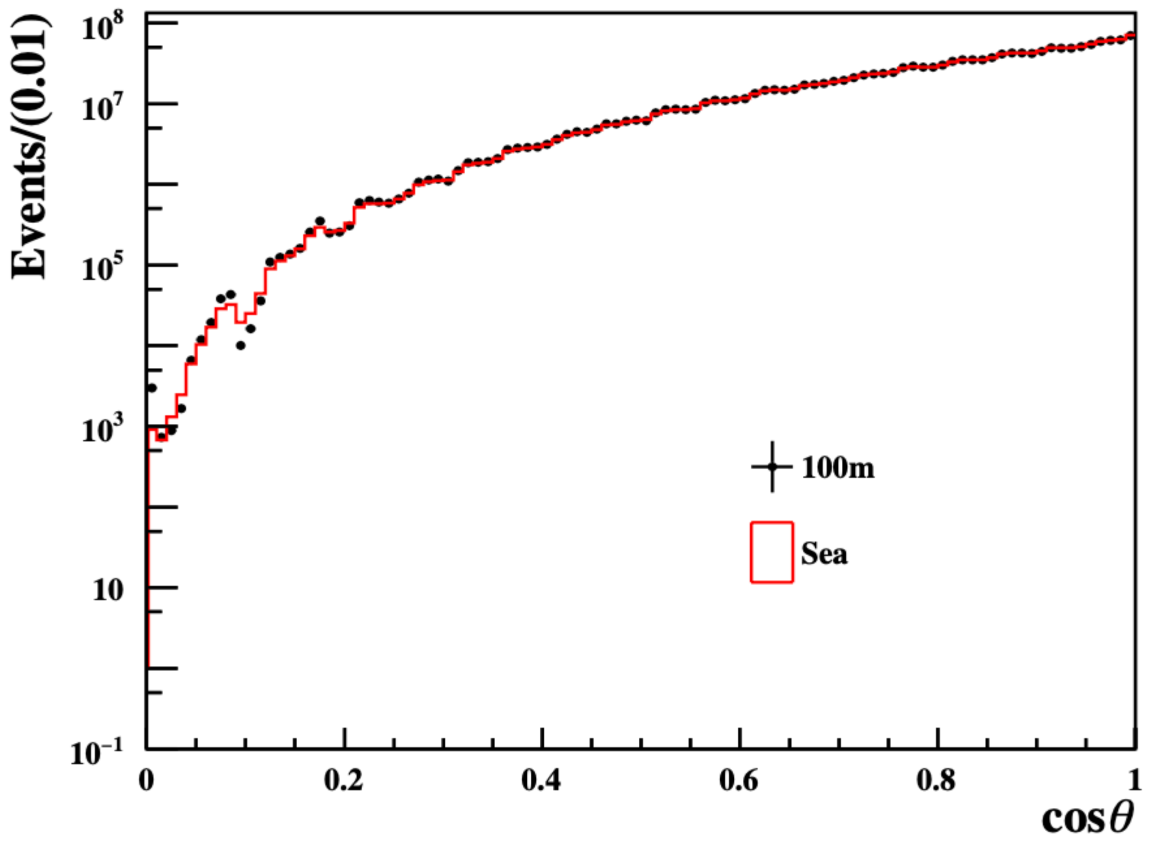


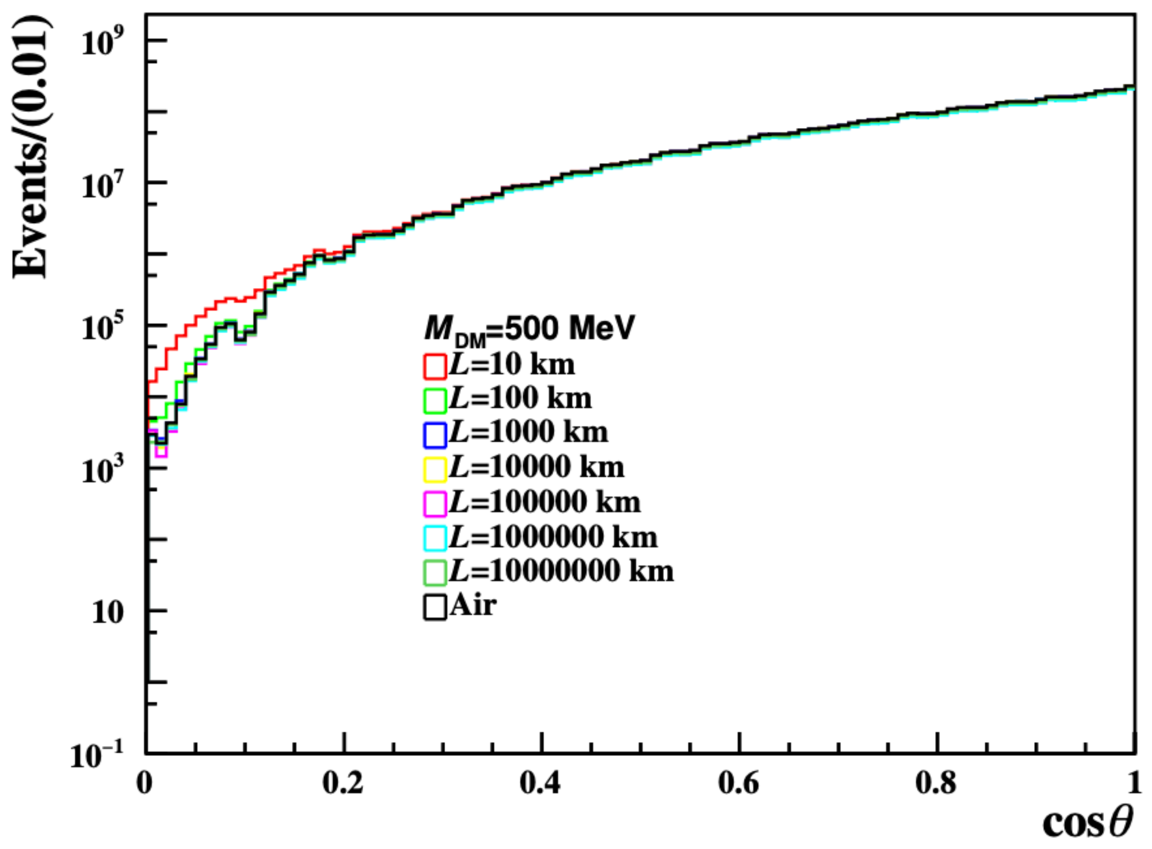
Sensitivities can be enhanced in the exotic scenario as mentioned previously.

Dark Matter searches between mountain and sea level



- Cosmic Muon direction at different altitudes
- Place two layers of Gem detectors, both at the sea level and in a mountain with a latitude of 100 m, to measure the flying direction of cosmic-ray muons
- Extend the native Geant4 physics list by introducing the muon-DM elastic scattering process
  - Manually set by mean free path L
  - $L = 1/(n_{\mathrm{DM}} \times \sigma_{\mu,\mathrm{DM}}),\ n_{\mathrm{DM}} = \rho_{\mathrm{DM}}/M_{\mathrm{DM}}$
- χ^2 test method
  - $\chi^2/\mathrm{ndf} \Rightarrow p$-value
  - For M_{DM}=500 MeV, $L = 10(100)\,\mathrm{km}$ ($\sigma_{\mu,\mathrm{DM}} = 1.67 \times 10^{-6(-7)}\,\mathrm{cm}^2$) can be rejected by high confidence level
- Sensitivities can be enhanced in the exotic scenario as mentioned previously.

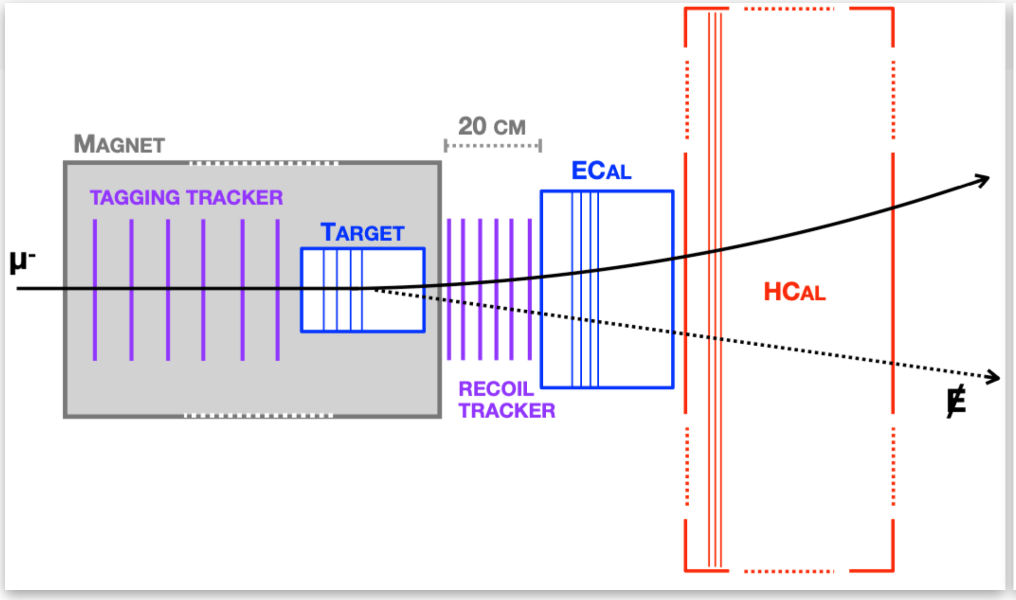




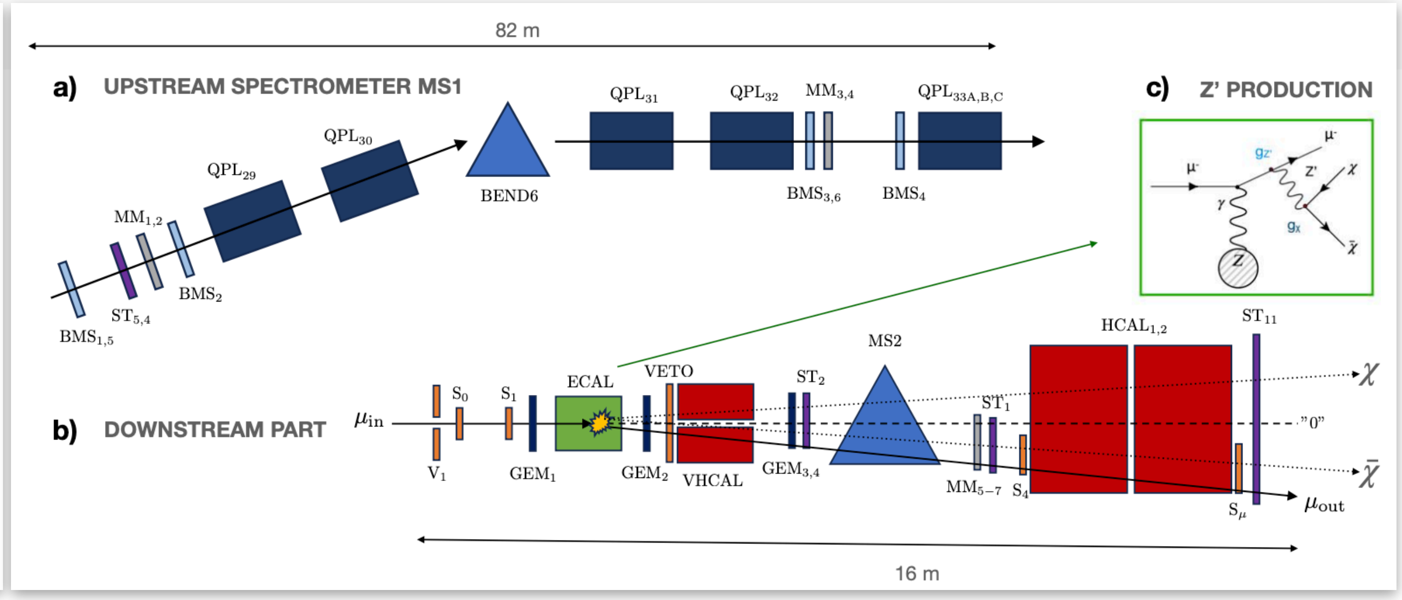
Future possibility

Next step: Muon on target, …

- An Muon-LDMX Experiment in China
  - NA64μ, MMM, FNAL-μ, Muon collider, …
  - Look for the muon deflection caused by scattering with DM as well as the the energy loss pattern of muons
  - Needs further optimization R&D studies, especially when interfacing with domestic muon beams with lower energy



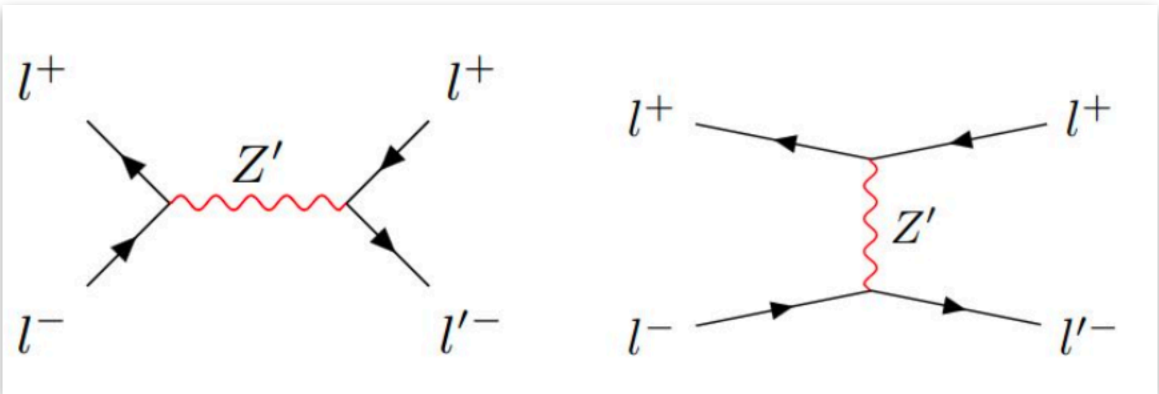
MMM



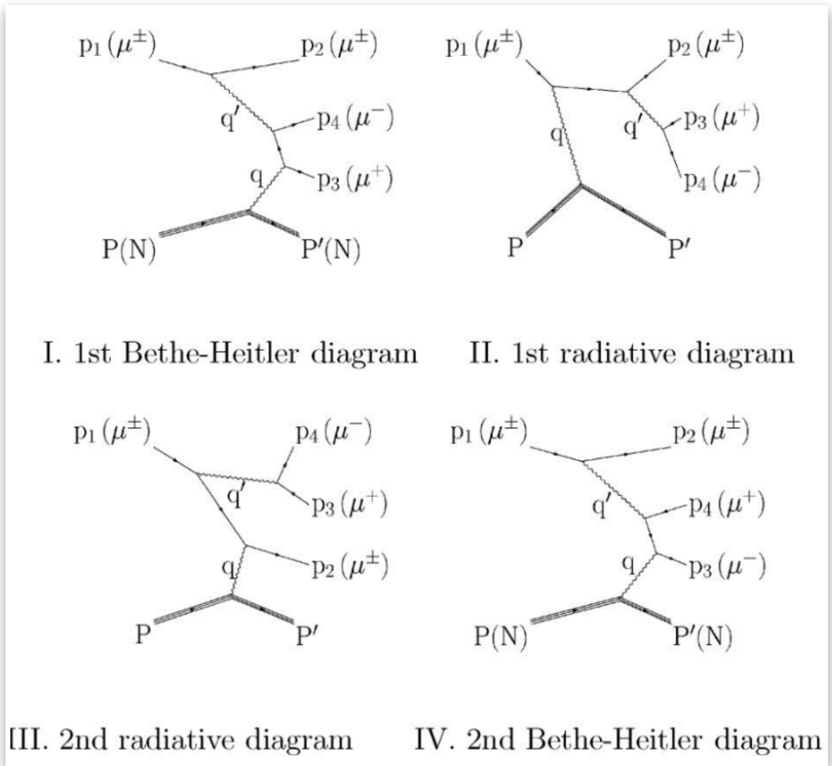
NA64μ

- Muon-Electron Threshold Scan
  - $\mu^+e^- \to Z' \to e^+e^-, \mu^+\mu^-, \chi\chi$: (Charged) Lepton Flavor Violation (DM)
  - Resonant production Enhancement
  - Connecting e-mu collider and muon beam experiments
  - Cosmic-ray muon on target (e^-), limits on $\lambda_{\mu\mu} \times \lambda_{\mu e}$
  - Muon Trident Production

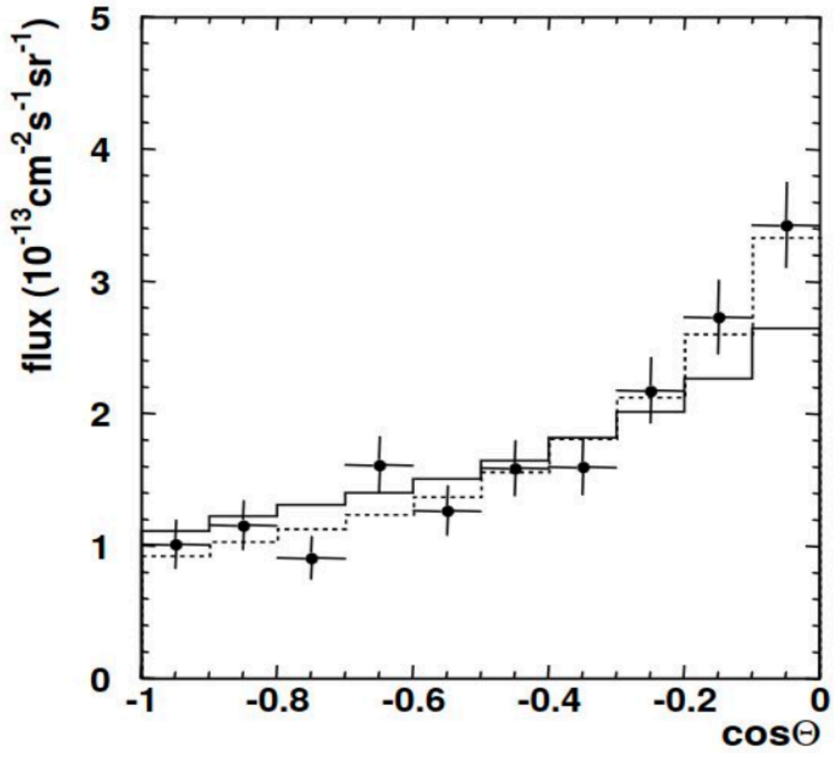
CLFV



Muon Trident Production



- Geo-Muon
  - Super-Kamiokande and MACRO previous measurements
  - Upgoing muon from $\nu_\mu \xrightarrow{\text{Hit}}$ Rock
  - Connection with neutrino physics & geo-physics



Upward going muon flux observed in Super-K as a function of the zenith angle

Summary & outlook

Summary

- ➔ Muon is an unique and powerful bridge to connect applied studies and fundamental researches
  - ❖ Muon Tomography & DM search
- ➔ PKU has foundation on RPC and GEM detector
  - ❖ Glass RPC & CMS triple-GEM
- ➔ PKMUON program with promising physical possibility
  - ❖ Muon Tomography
  - ❖ DM searches in a box
  - ❖ DM searches using muon beams
  - ❖ DM searches between mountain and sea level
- ➔ More physical possibility ongoing under research
  - ❖ Muon-LDMX Experiment in China, CLFV, Muon Trident, Geo-Muon, …

Thanks for your attention!

PKMUON timeline

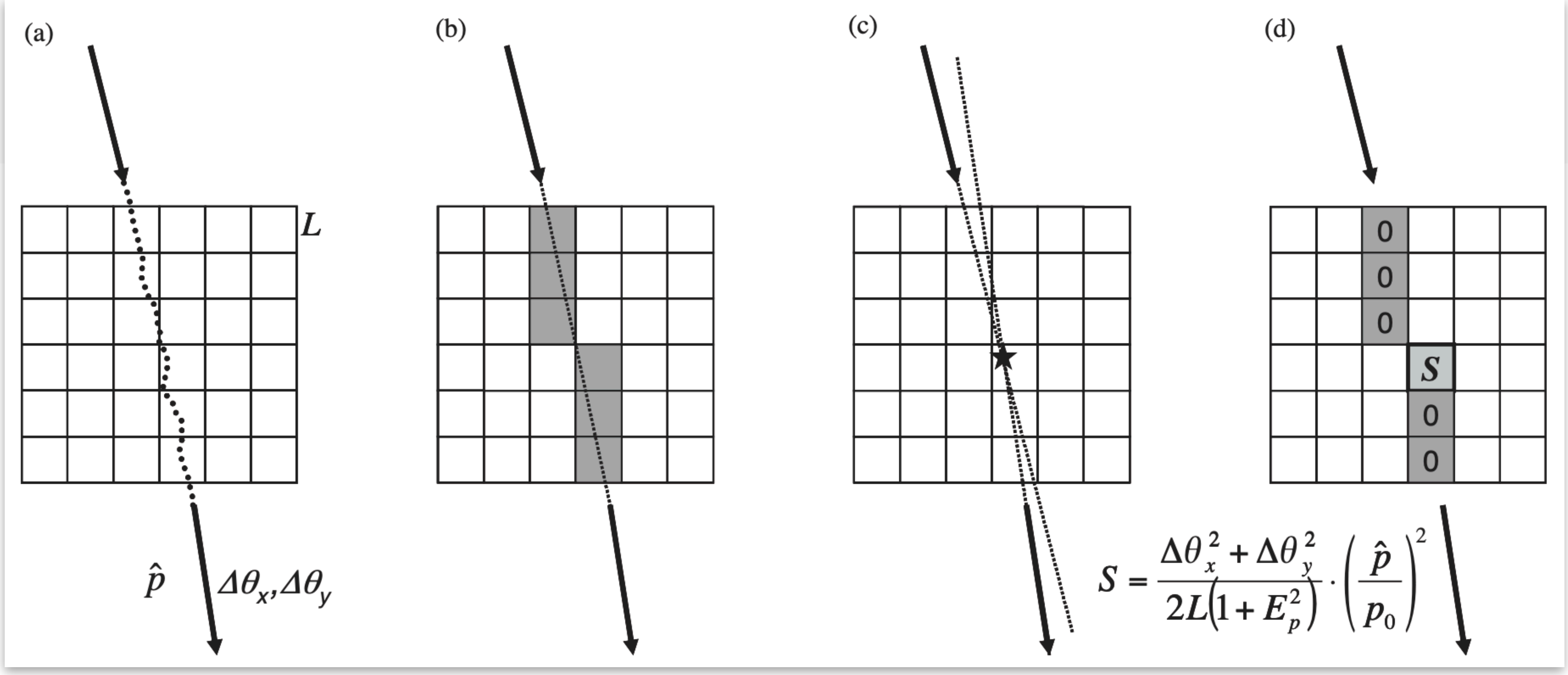
A proposed PKU-Muon experiment for muon tomography and dark matter search

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

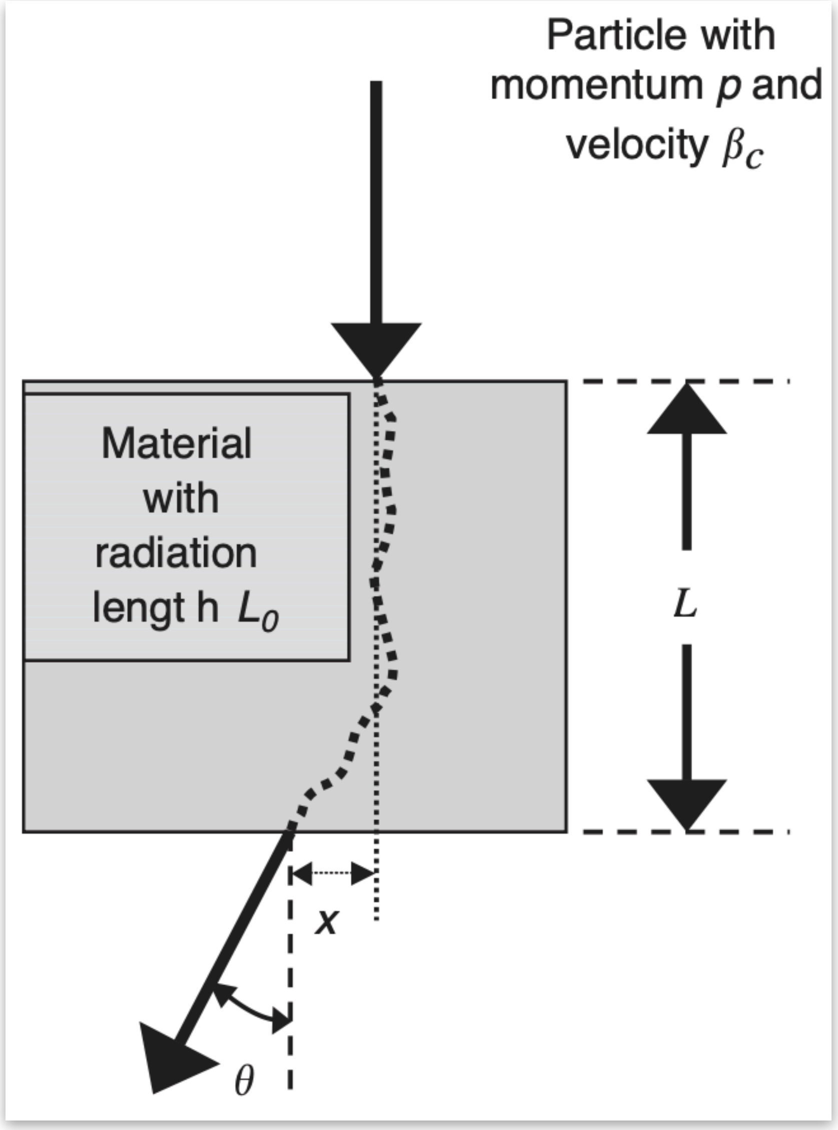
- **Muon Tomography**
  - RPC (~0.5 year), GEM (~1 year)
  - Algorithm development & fast detection (~1 year)
    - Engineering, Archaeology (2-5 years)
  - Muon Radar: cosmic muon precision measurement
    - Various altitude & direction and/or momentum (~1-2 years)
    - Connects with Atmospheric science (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

Backup

PoCA

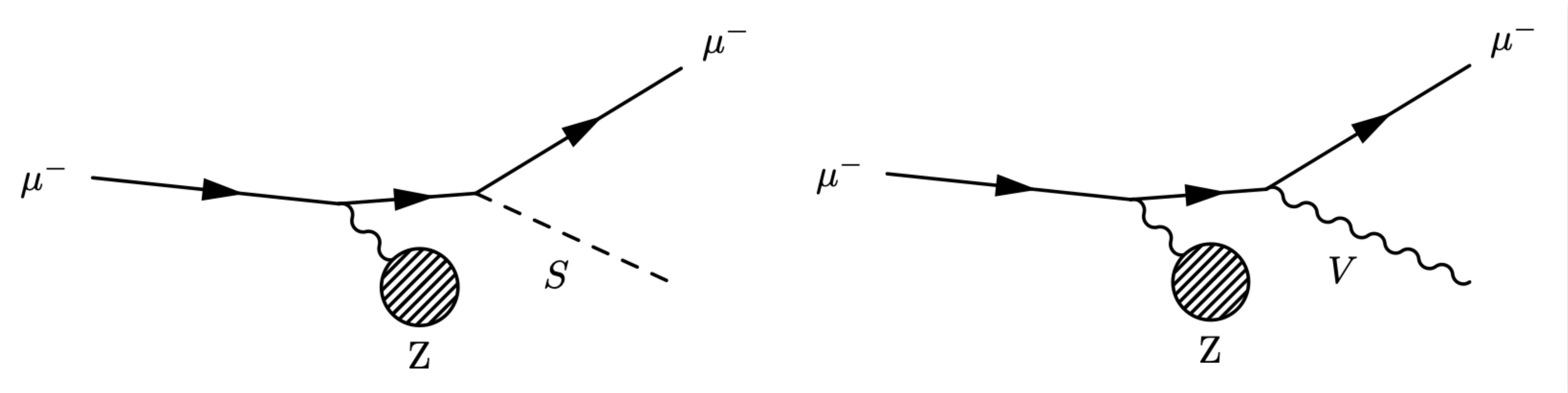


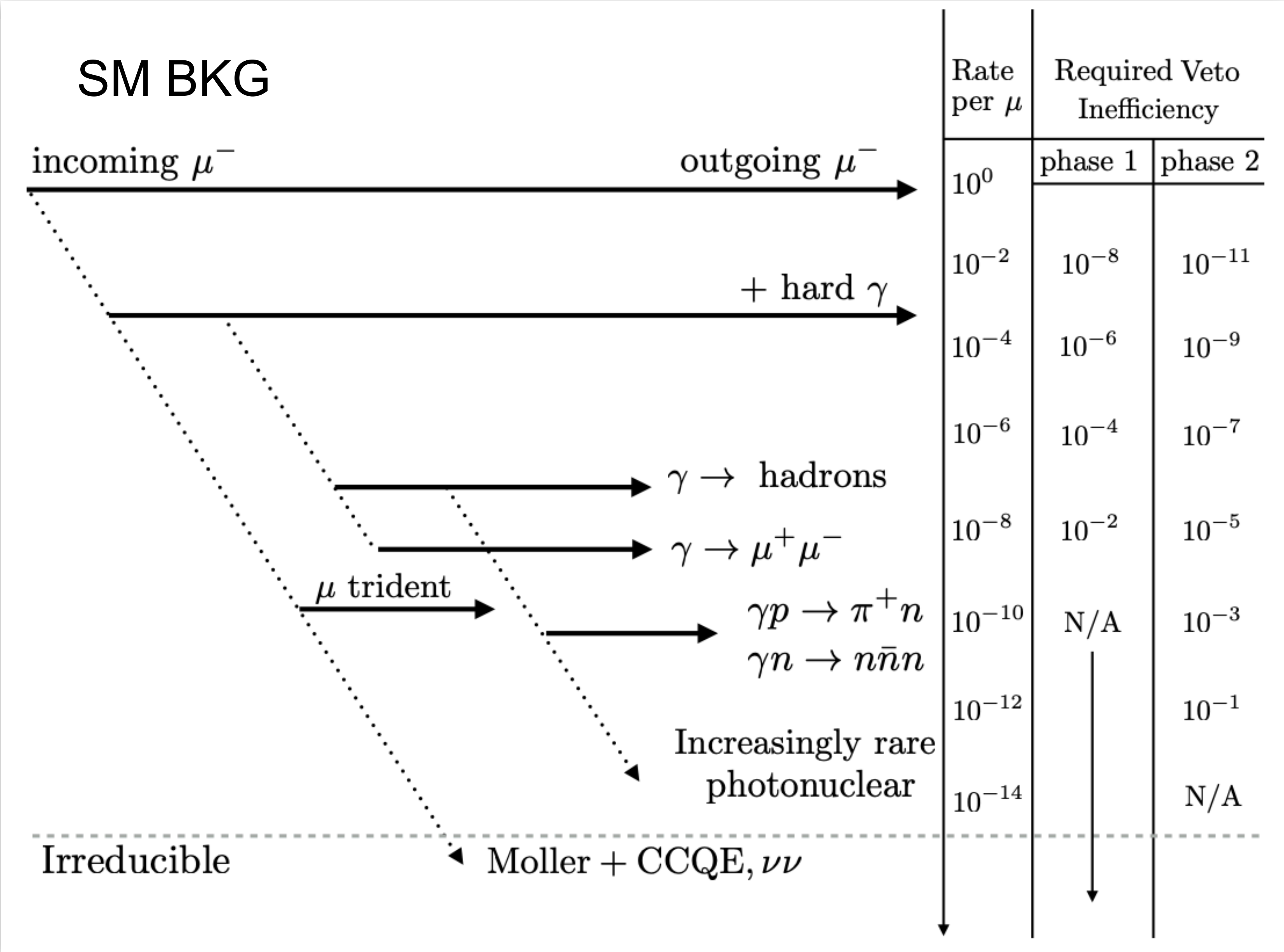
- The point of closest approach (PoCA) algorithm
- The angular scattering distribution is approximately Gaussian
  - $$\sigma_\theta = \frac{13.6\,\mathrm{MeV}}{\beta c p}\sqrt{\frac{L}{L_0}}[1 + 0.038 \ln \frac{L}{L_{\mathrm{rad}}}] \approx \frac{13.6}{p}\sqrt{\frac{L}{L_0}}$$
  - p: momentum, βc: velocity, 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
  - $$\lambda_{\mathrm{mat}} = (\frac{13.6}{p_0})^2 \frac{1}{L_{\mathrm{rad}}} \approx \sigma^2_{\theta_0,\mathrm{mat}}$$
  - 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:
  - $$\hat{\lambda} = \frac{1}{N}\sum_{i=1} N(\frac{p_i^2}{p_0^2} \cdot \frac{\theta_{xi}^2 + \theta_{yi}^2}{2L_i})$$

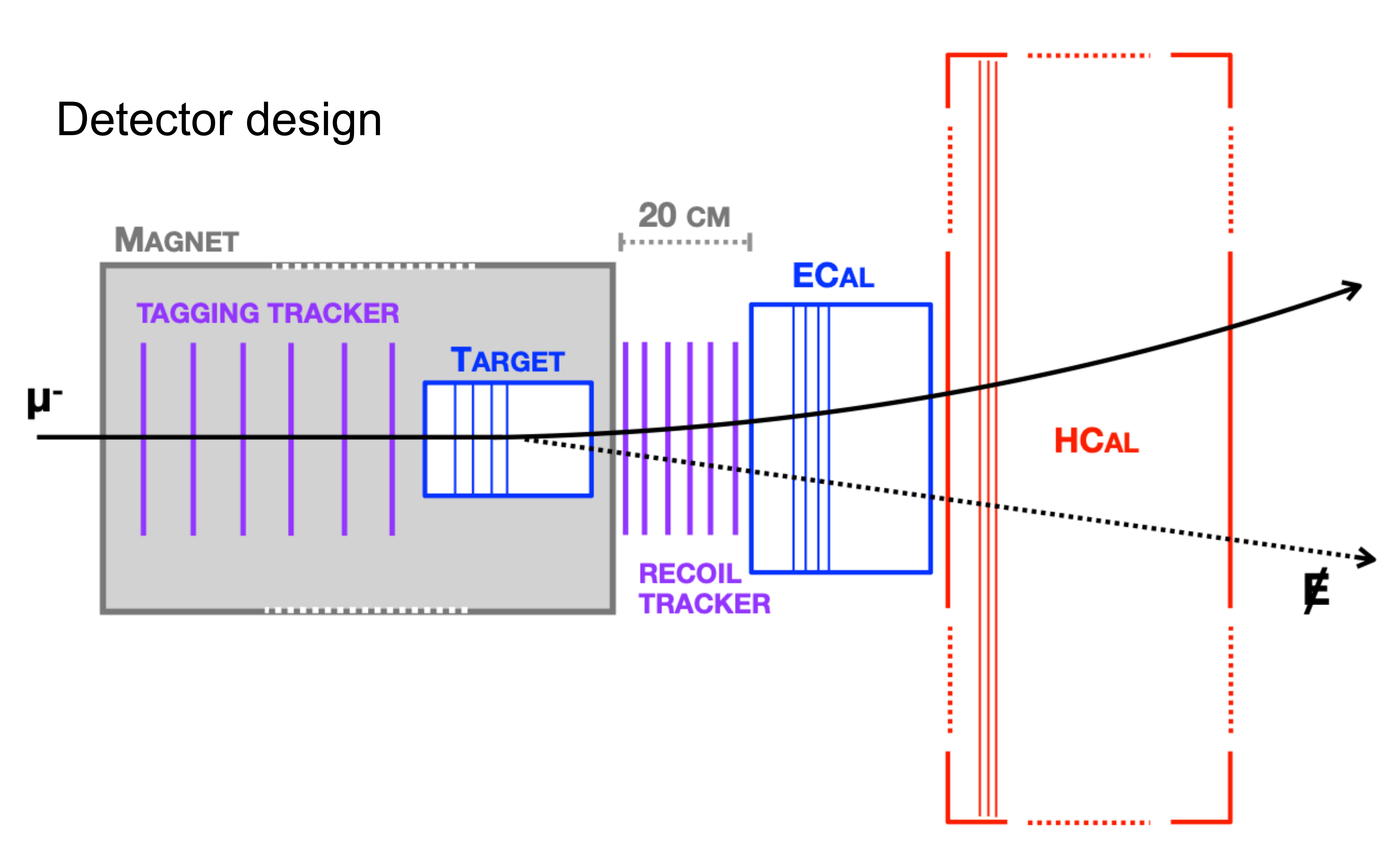


MMM

- ➔ 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 $(m_e/m_\mu)^2 \approx 2 \times 10^{-5}$
  - ❖ 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







MMM

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

Phase 1

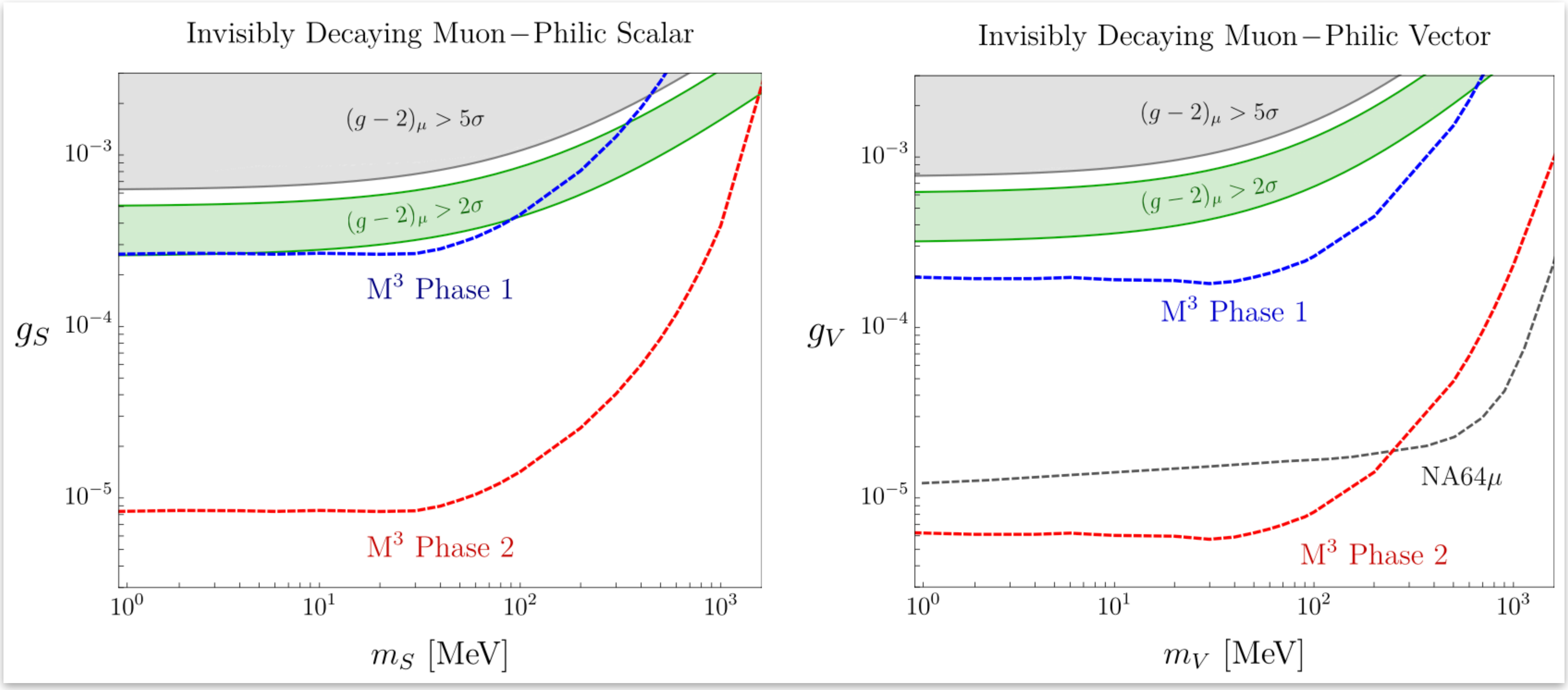
- muon energy = 15 GeV
- muon intensity = 10^{10} MOT (muons on target)
- Target Thickness = 50 X_0 (about 25 cm for tungsten/silicon)

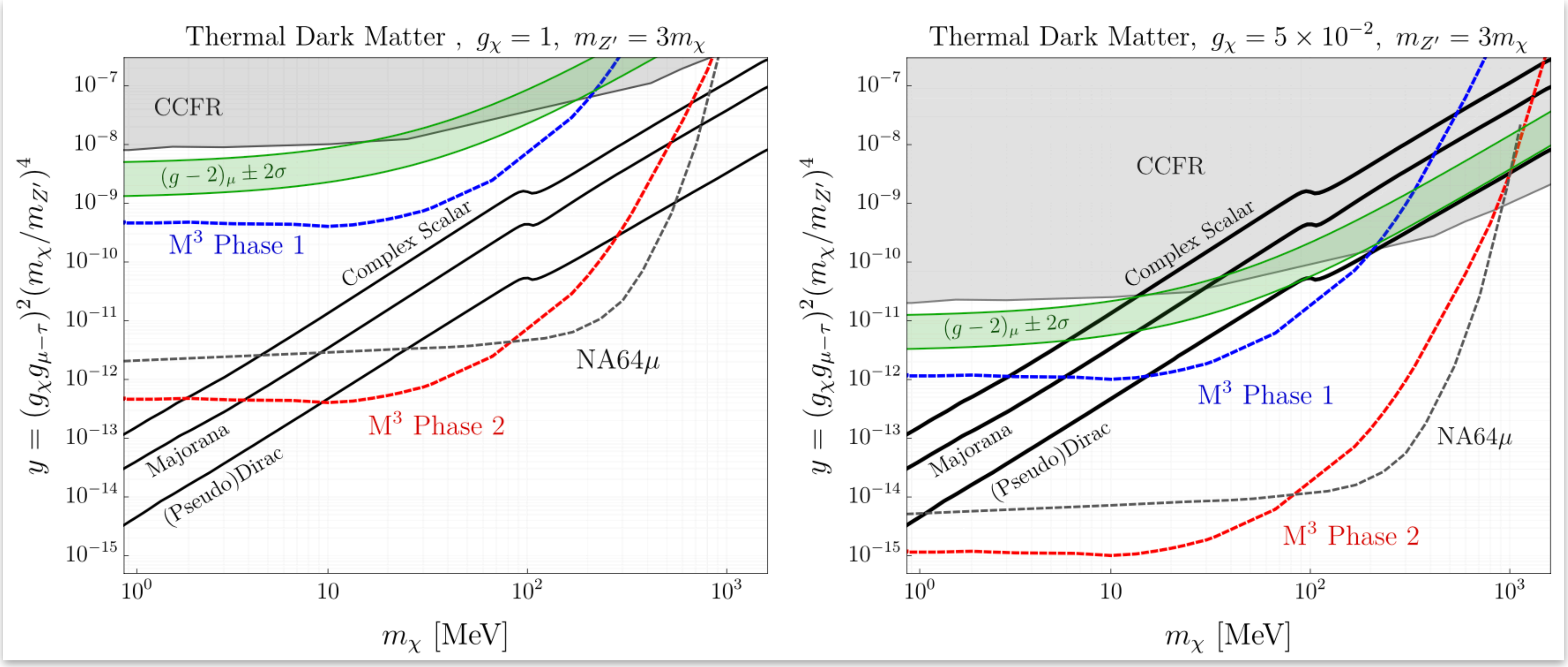
Phase 2

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

- ➔ Expected results

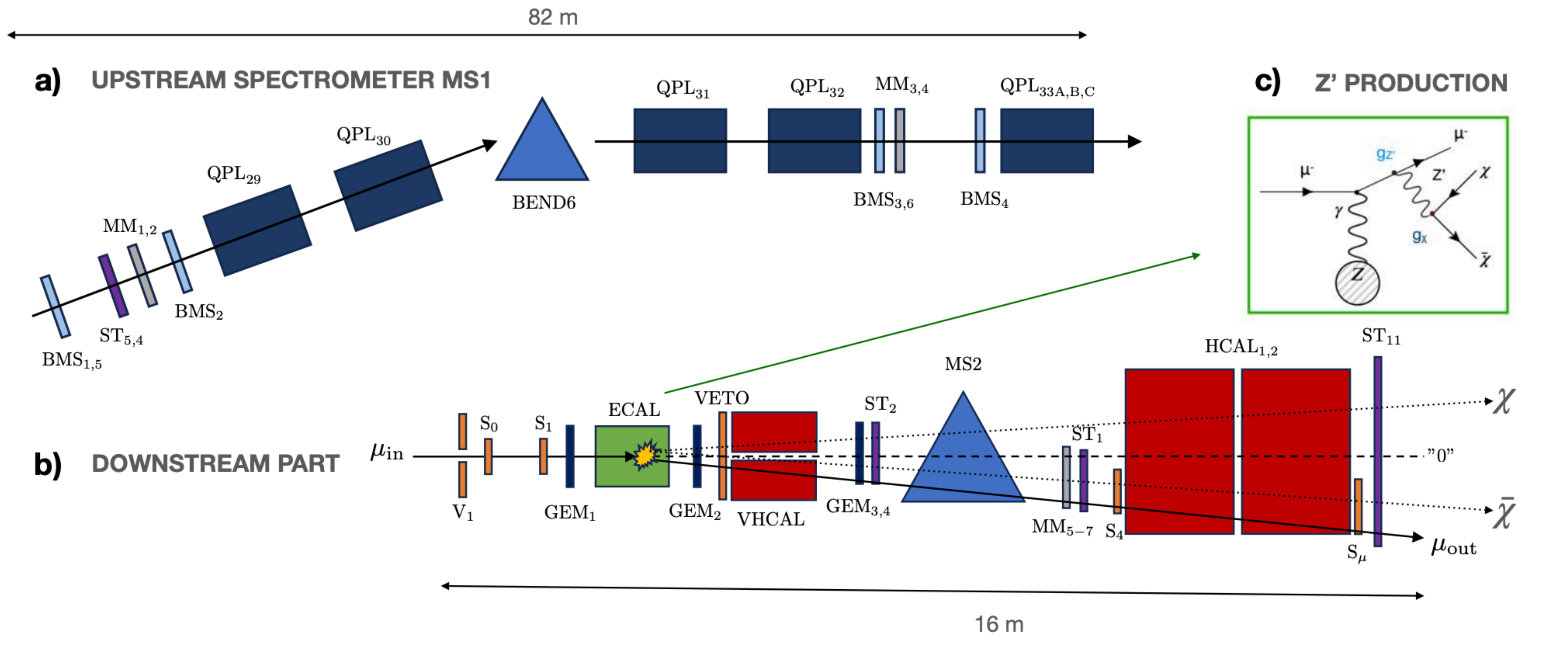
Phase 1 with $\sim 10^{10}$ muons on target can test the remaining parameter space for which light invisibly-decaying particles can resolve the $(g-2)_\mu$ anomaly, while Phase 2 with $\sim 10^{13}$ muons on target can test much of the predictive parameter space over which sub-GeV dark matter achieves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

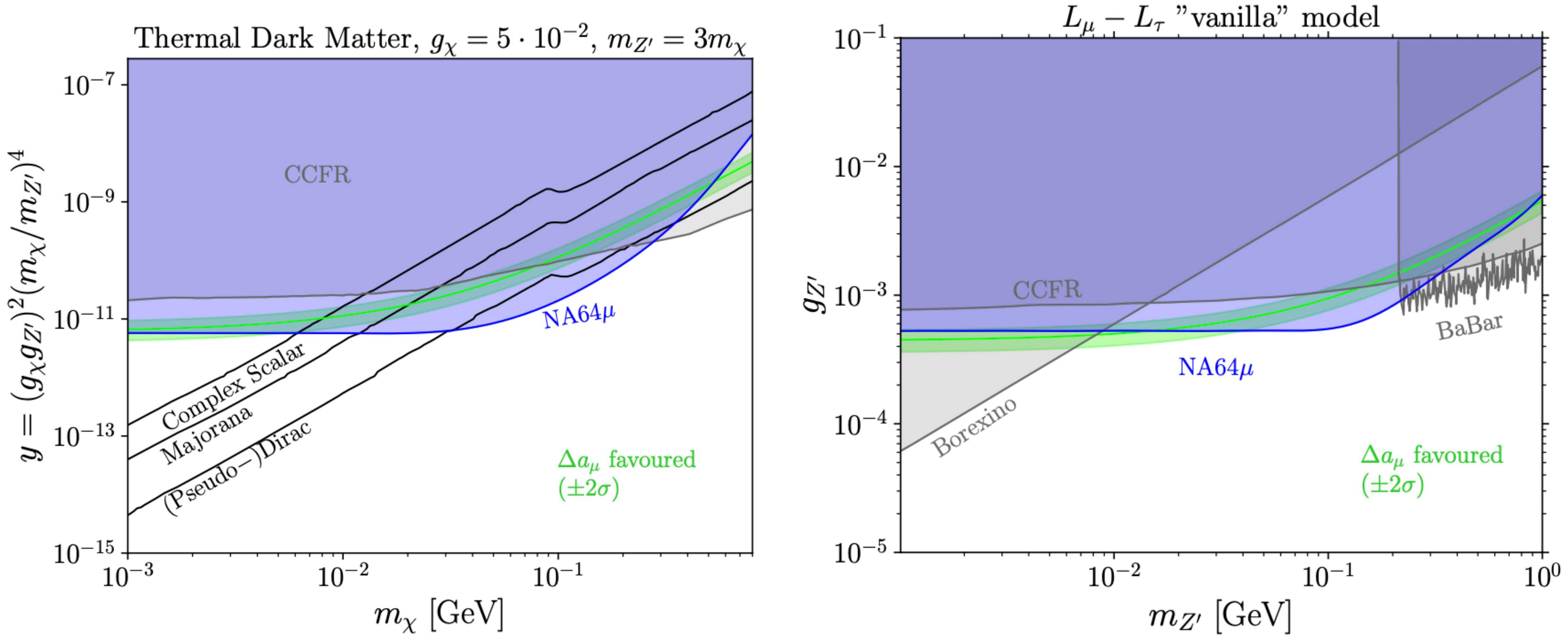




NA64μ LINK

- ➔ 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_χ > 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