Probing and Knocking with Muons

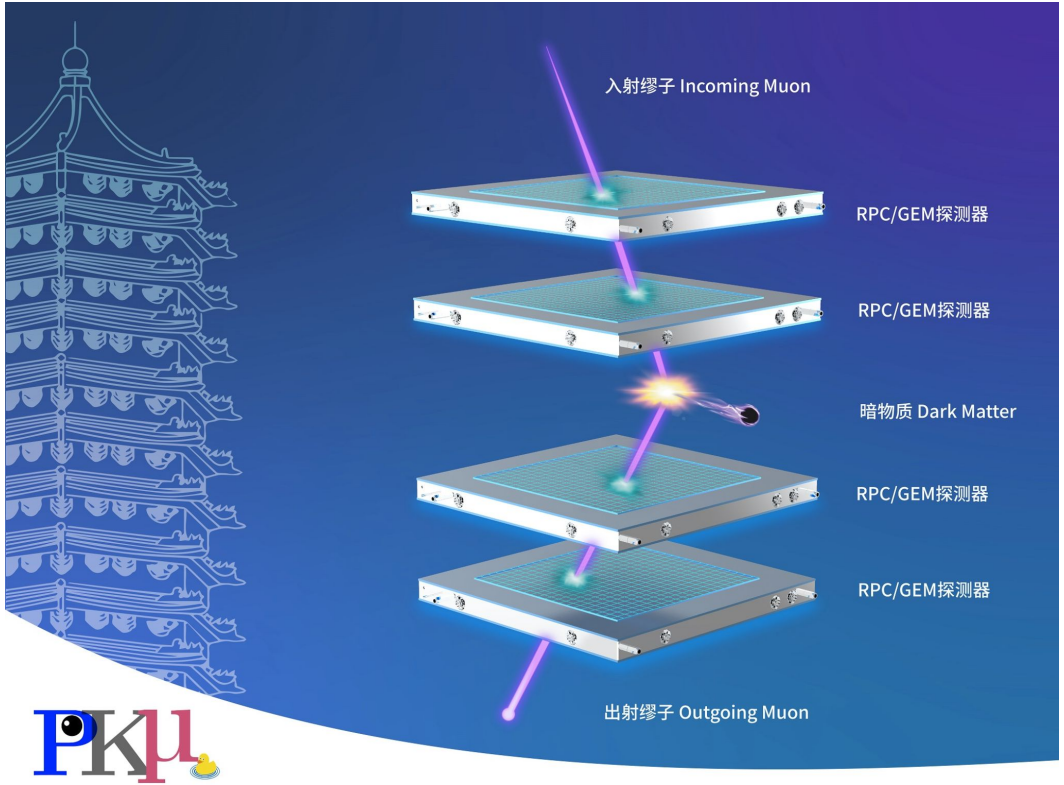
Qiang Li

Qite Li, Chen Zhou

On behalf of the PKMu Group

Peking University

2024 Fall

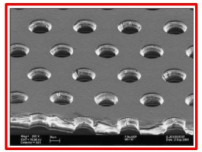


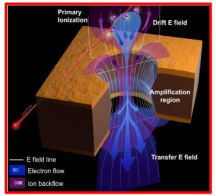
Phys.Rev.D 110 (2024) 1, 016017
arXiv:2410.20323
https://lyazj.github.io/pkmuon-site/categories/activities/

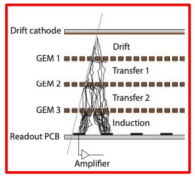
PKU Muon Detector Development

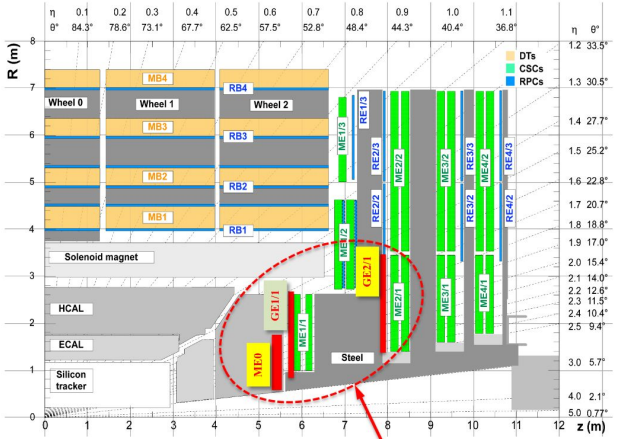
- ➔ CMS Muon Trigger RPC: assembled and tested at PKU at around 2002
- ➔ RPC R&D for nuclear physics
- ➔ CMS GEM upgrade program

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

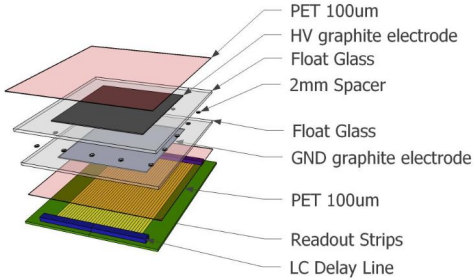
北京大学、清华大学、中山大学、北京航空航天大学

Combination of glass RPC & Delay-line Readout

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



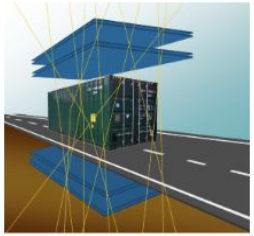
Reference:

- 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

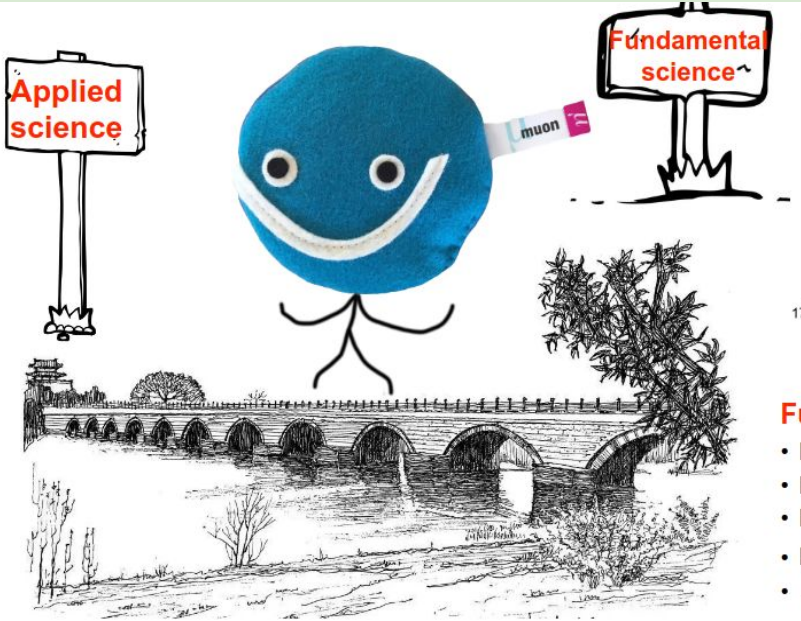
Void in Pyramid



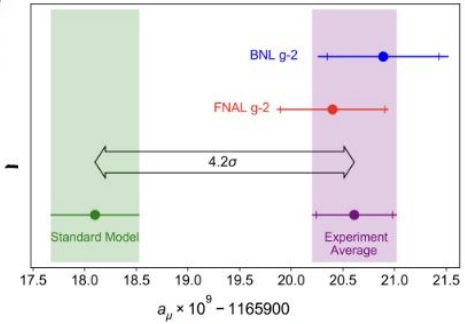
Container inspection

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
- …



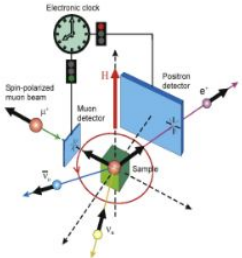
Bridge in Beijing



Muon g-2

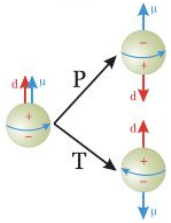
Fundamental particle physics

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

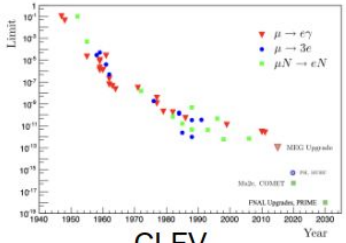


muSR

- 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

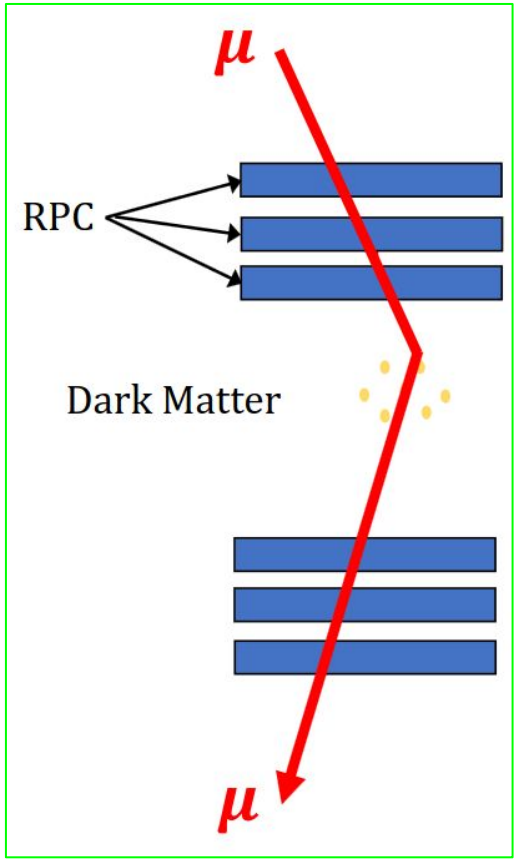
Several possible Chinese Muon beams in the near future:
Melody,
CIADS, HIAF

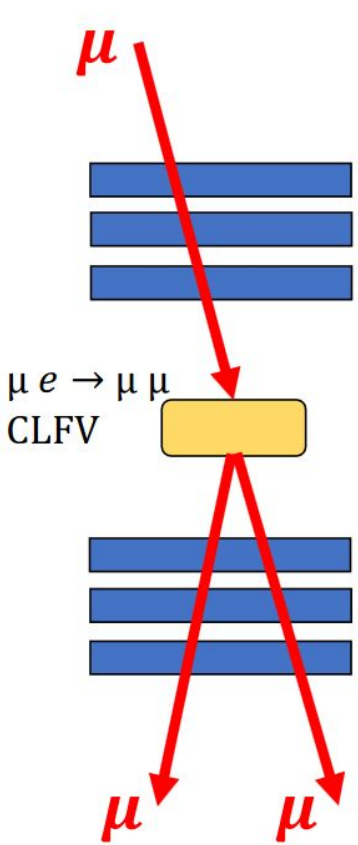
缪子散射类型的实验在国际上较为欠缺。

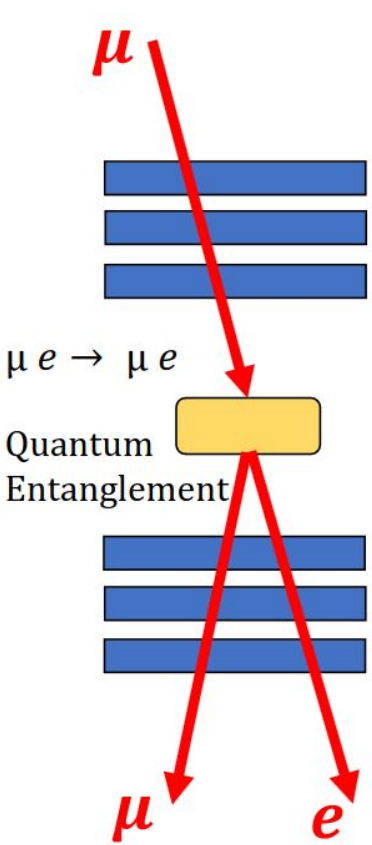
一方面，1960年代欧美的一些实验（例如Phys. Rev. **137**, B266, 1965）等侧重于探测核性质。由于当时标准模型尚未完整建立，对利用缪子进行带电轻子味道破坏、暗物质等新物理的寻找还不成熟；
另一方面，在近几个世纪，利用缪子对新物理的探索，例如美国的缪子反常磁矩实验、欧洲的缪子反常衰变的探测如MEG、Mu3e等实验，通常采用的是自由缪子或缪子衰变。
直到近年来，CERN的NA64mu（Phys. Rev. Lett. 132, 211803）和设计中的MuonE等实验才开始重新利用高能缪子（～160GeV）与靶散射，通过对缪子与核子或电子的散射来对新物理或者重要的标准模型观测量进行探索。

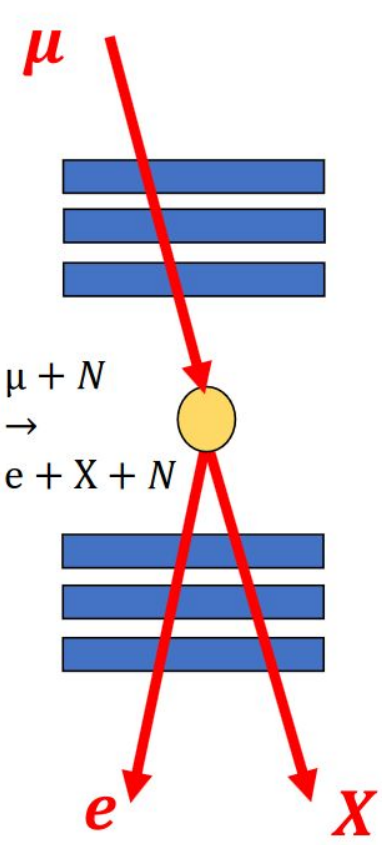
然而，**缪子散射蕴含大量的物理 课题有待挖掘，而且不同能量的 缪子束流可以 对不同的新物理空间具有敏感性**。如下所述，缪子与可能的亲缪子类型暗物质可以发生大角度散射；缪子与电子的散射可以来探测带电轻子味道破坏的新型玻色子；对GeV缪子与电子散射的精确测量也可以来验证量子纠缠（Phys. Rev. D 107, 116007 (2023)）；缪子与核子的散射则可以探测不同核子的性质，由于质心系能量相比缪子与静止电子的高，也可以探测更高能标的不同种类的新物理。

Probing and Knocking with Muons



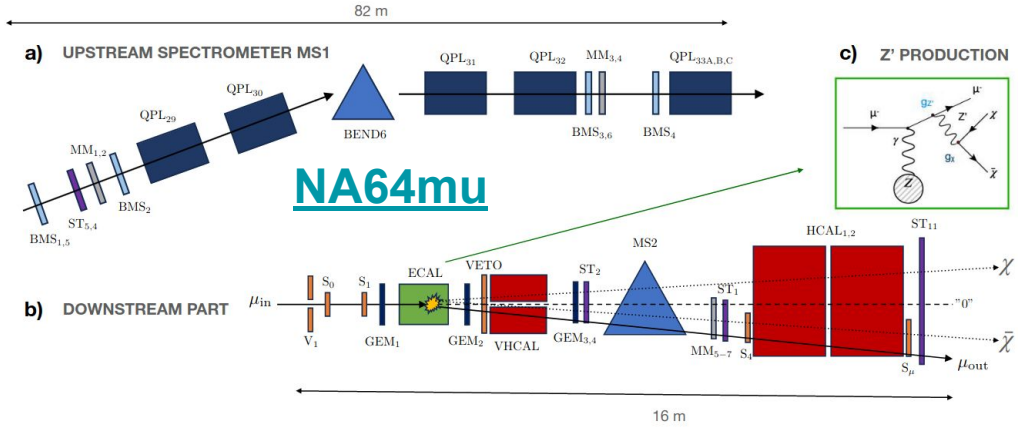






Muon Philic Dark matter

- Muon Philic Dark Matter may be possible or <u>necessary</u>!
- Electron/Muons on Target Experiments
- <u>DarkShine</u> is ~ <u>LDMX</u> based on <u>Shanghai Synchrotron Radiation Facility</u>
- <u>MMM</u> (M3) is a US proposed muon-LDMX experiment
  - Intrigued by a <u>proposal</u> 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...”



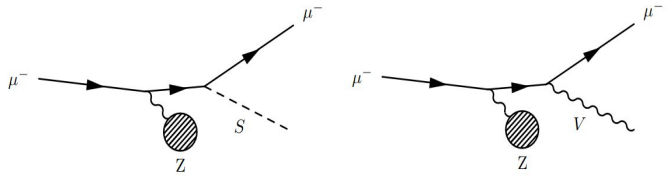


Figure 1. Dark bremsstrahlung signal process for simplified models with invisibly decaying scalar (*left*) and vector (*right*) forces that couple predominantly to muons. In both cases, a relativistic muon beam is incident on a fixed target and scatters coherently off a nucleus to produce the new particle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

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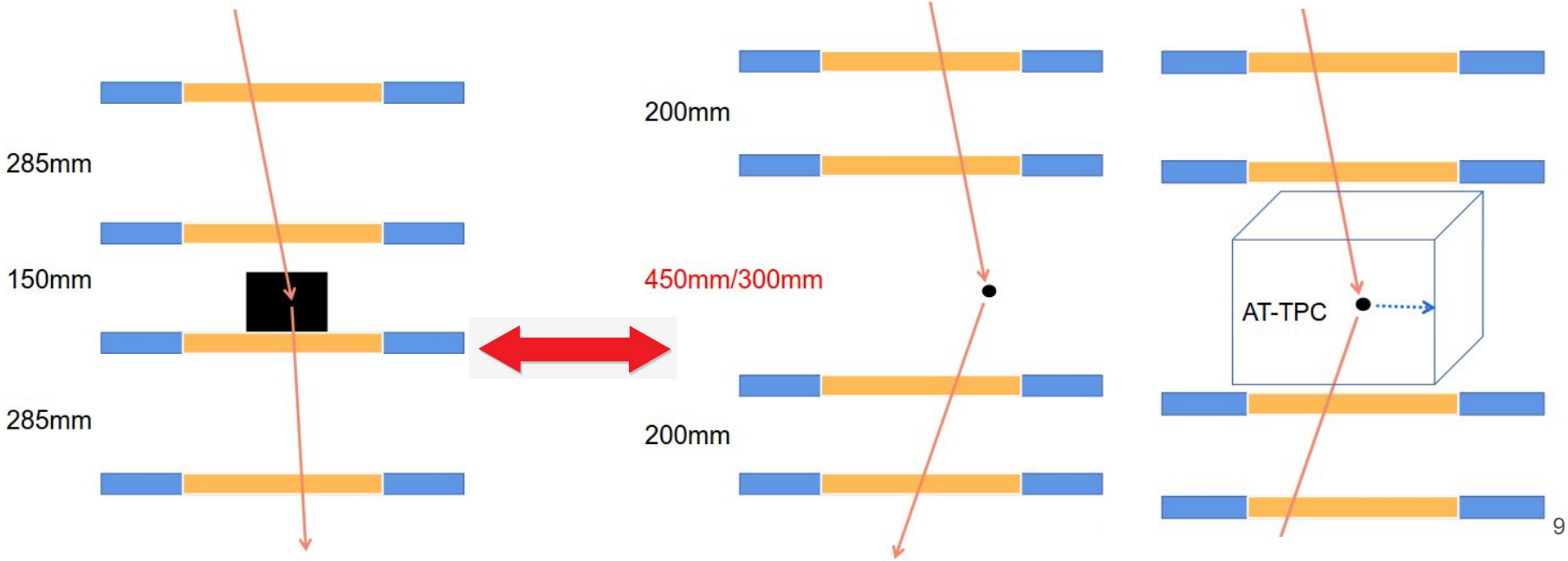
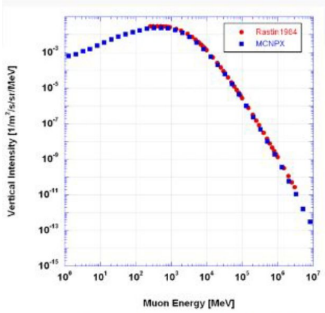


Muon DM Box experiment: Geant4 Simulation

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

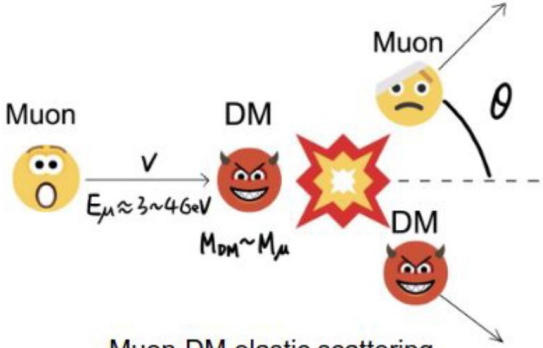
- Triple-GEM detector design refer to CMS GEM design
- Muon material interaction automatically considered by Geant4
- Reco hit position: Truth hit position smeared by GEM detector resolution (~ 200 um)



Cosmic Muon Mean energy: 3~4 GeV

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

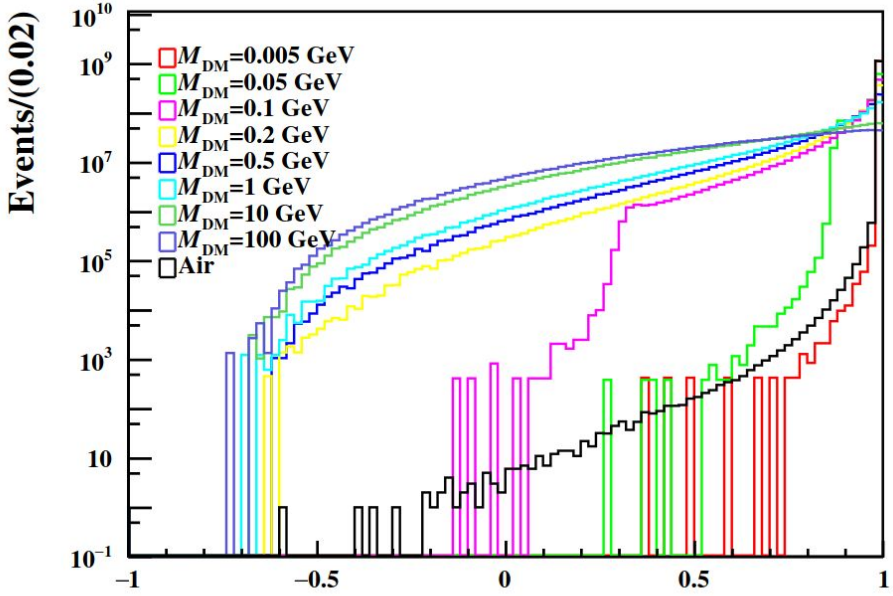
- Non-relativistic two-body elastic scattering between muon and DM following Newtonian mechanics
- Standard halo model: DM velocity distribution follows Maxwell-Boltzmann distribution
- CRY (Cosmic-ray) model: cosmic-ray muon energy and zenith angle distributions at sea-level

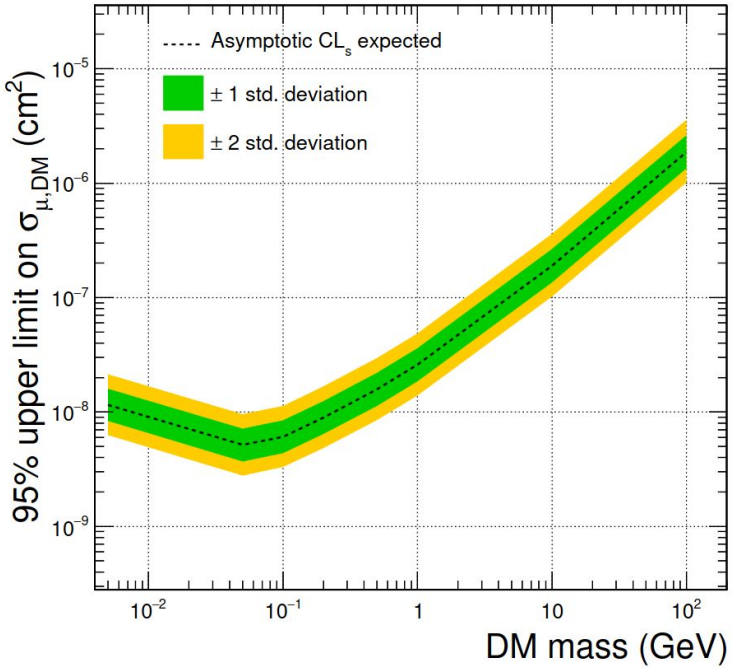


Muon-DM elastic scattering

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

Muon DM Box experiment: expected results





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

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

Current Software and Simulation Status

PKMuon Collaboration

PKMuon Collaboration

3 followers | China | https://lyazj.github.io/pkmuon-site/ | seeson@pku.edu.cn

Overview | Repositories 10 | Projects | Packages | People 2

Pinned

PKMUON_G4sim Public
Forked from yuxdPKU/PKMUON_G4sim
Geant4-based simulation of PKMUON
C++

geomu Public
Forked from lyazj/geomu
Geographic Muon Simulation
C++

pkmuon-site-src Public
Forked from lyazj/pkmuon-site-src
source code of PKMUON site
Stylus

root-easy-debug Public
Forked from lyazj/root-easy-debug
Debug CERN ROOT macros in an extremely easy way
C

PHYSICAL REVIEW D **110,** 016017 (2024)

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

(Received 23 March 2024; accepted 24 June 2024; published 19 July 2024)

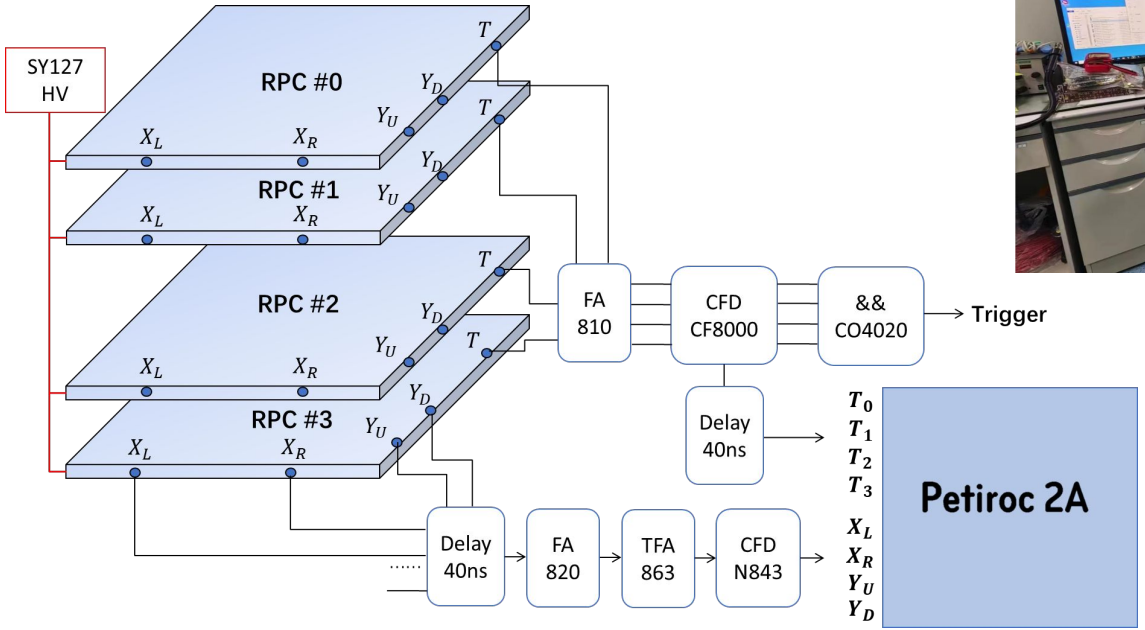
A set of new methods are proposed here to directly detect light mass dark matter through its scattering with abundant atmospheric muons or accelerator beams. A first plan is to use the free cosmic-ray muons interacting with dark matter in a volume surrounded by tracking detectors, to trace the possible interaction between dark matter and muons. Secondly, the same device can be interfaced with domestic or international muon beams. Due to the much larger muon intensity and focused beam, it is anticipated that the detector can be made further compact, and the resulting sensitivity on dark matter searches will be improved. Furthermore, it may also be possible to measure precisely directional distributions of cosmic-ray muons, either at mountain or sea level, and the differences may reveal possible information about dark matter distributed near the Earth. Specifically, methods described here can have advantages over "exotic" dark matters that are either muonphilic or slowed down due to some mechanism, and the sensitivity on dark matter and muon scattering cross section can reach as low as microbarn level.

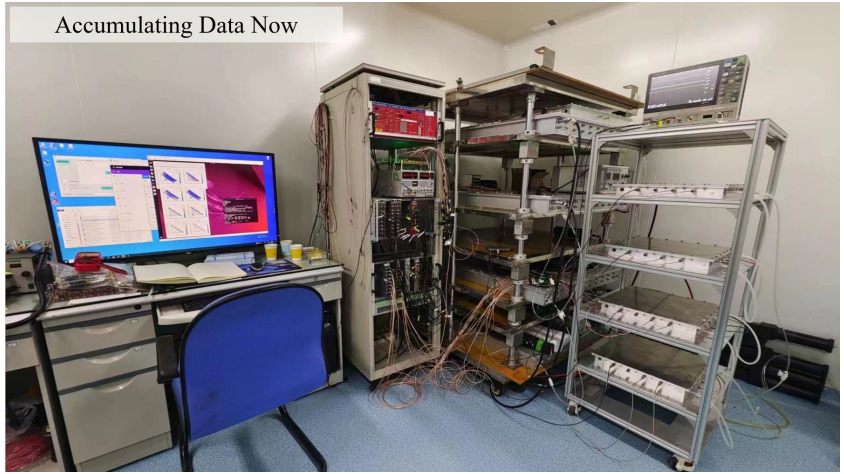
DOI: 10.1103/PhysRevD.110.016017

Current Box Exp. Status

4-station 20cm*20cm RPC for the moment

Petiroc 2A is a 32-channel front-end ASIC





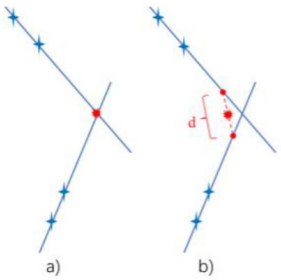
Timing and X-Y position with delay-line readout method

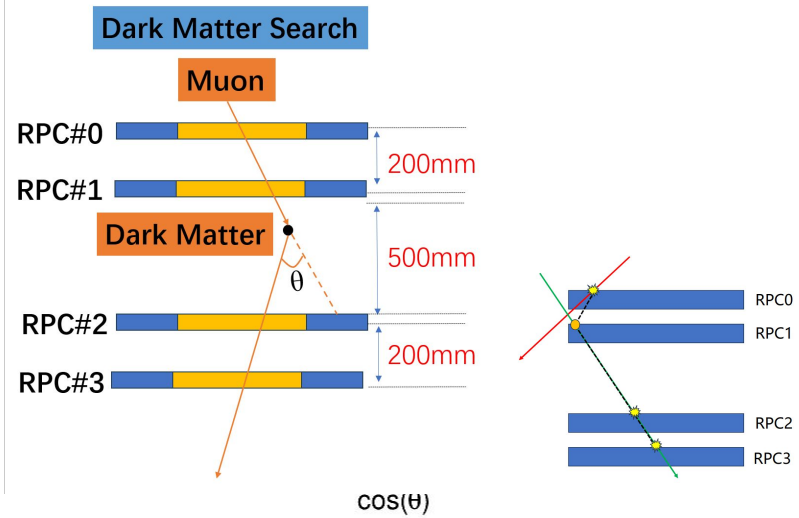
Accumulated Data

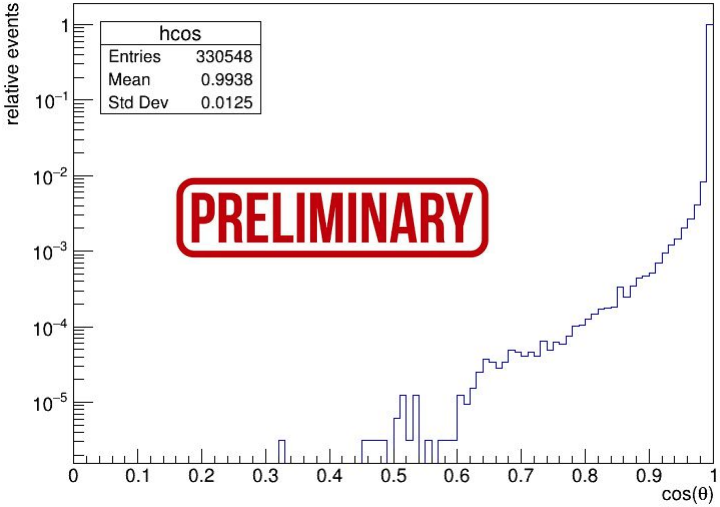
- 3+ months data taking since Jan. 2024

- 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 ar
- There are several events cos θ<0.4

- Data Analysis is ongoing



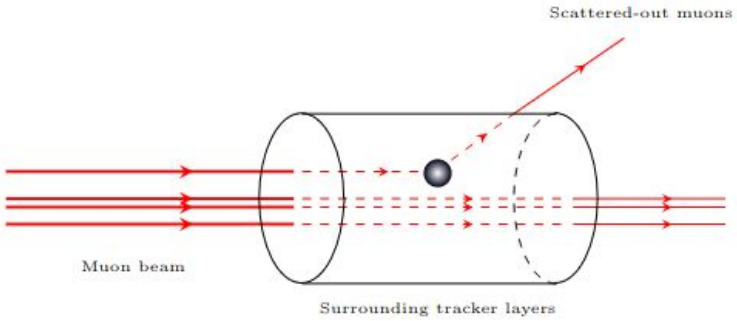




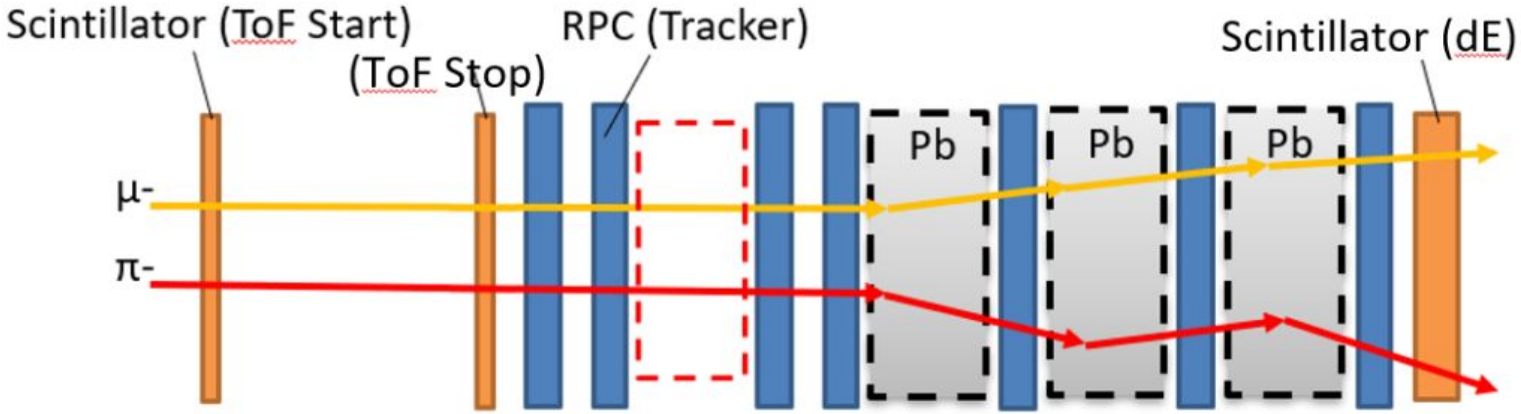
More results in [a recent report]() from Cheng-en Liu and Qite Li

Current Beam Exp. Status

Interfacing with a muon beam at e.g. HIAF



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



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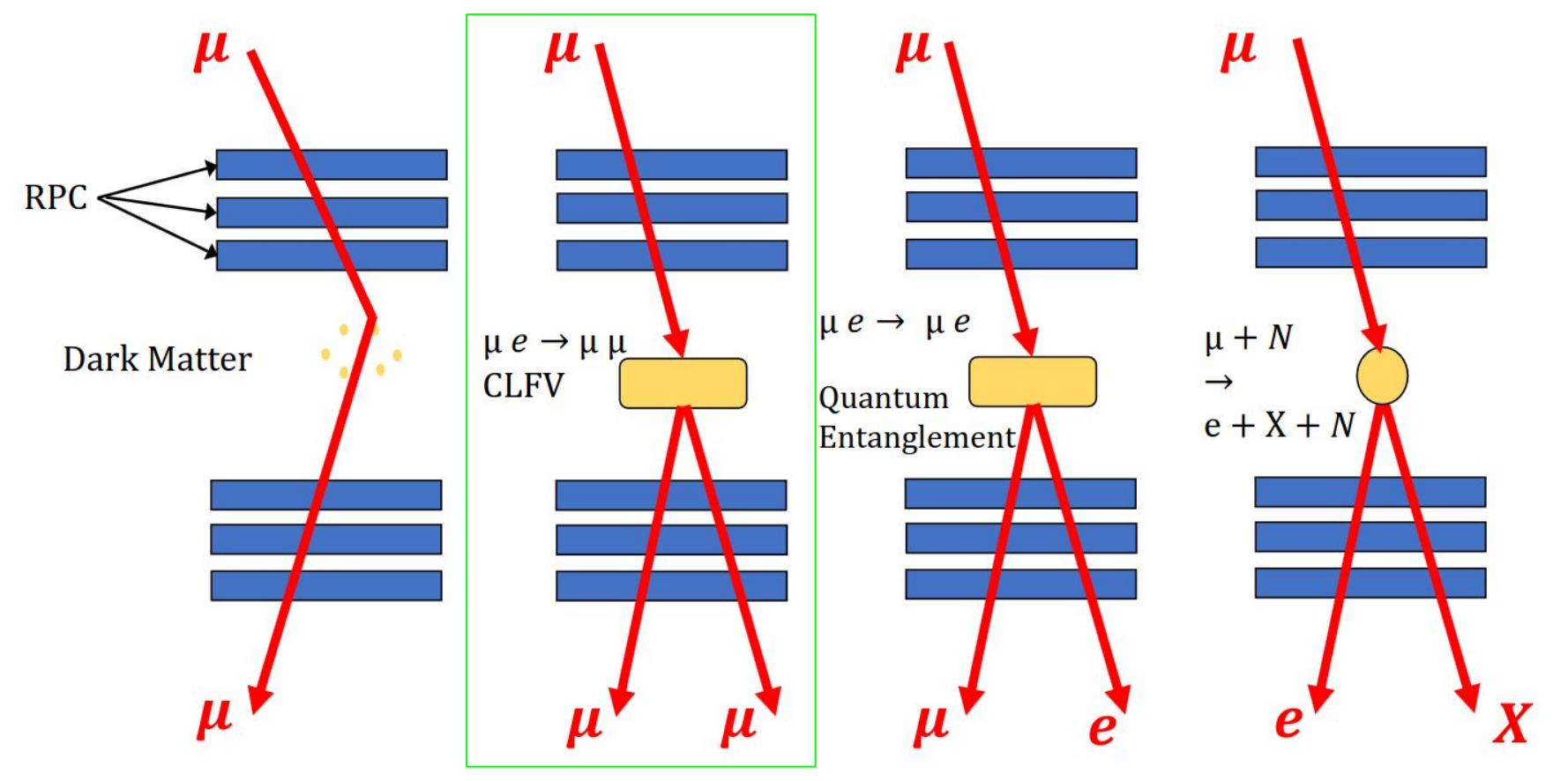
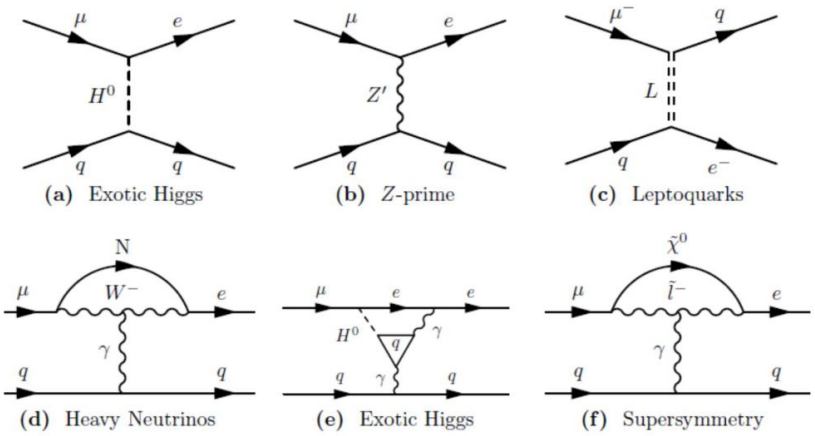


CLFV physics

CLFV Widely predicted in NP models

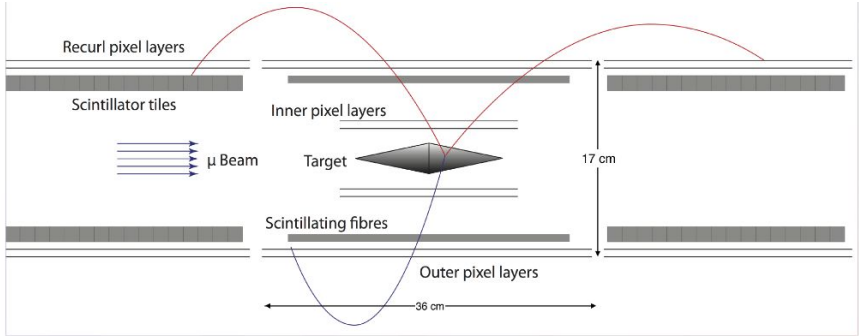


ref1 ref2

CLFV searches

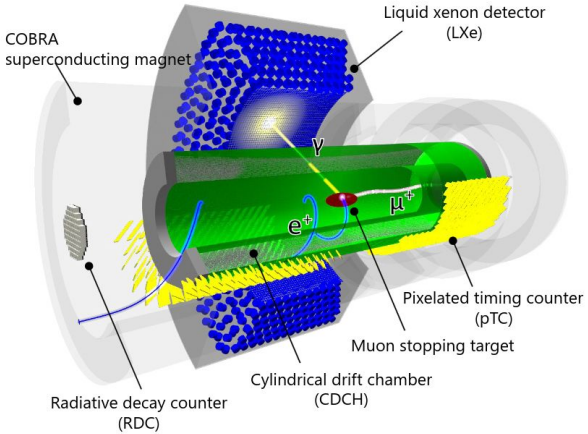
Searching with different channels (tau, mu related) can give us a better understanding of the characteristics of new physics

$\mu \rightarrow$ eee: Mu3e Experiment

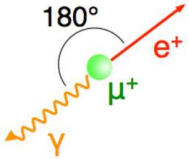


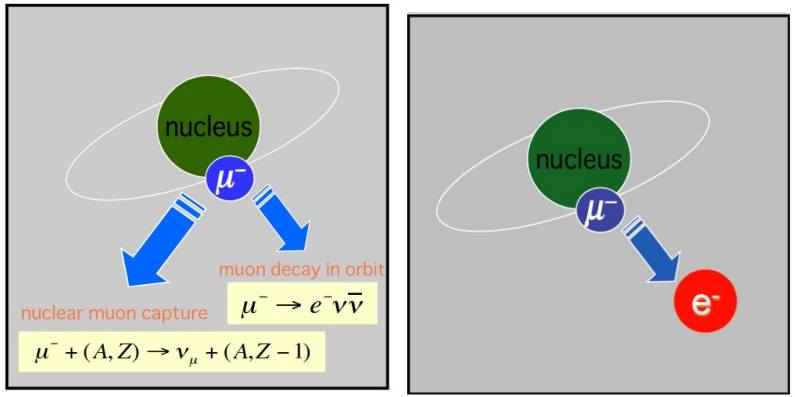
MEG: Search for $\mu^+ \rightarrow e^+\gamma$

MEG, MEG-II (PSI)



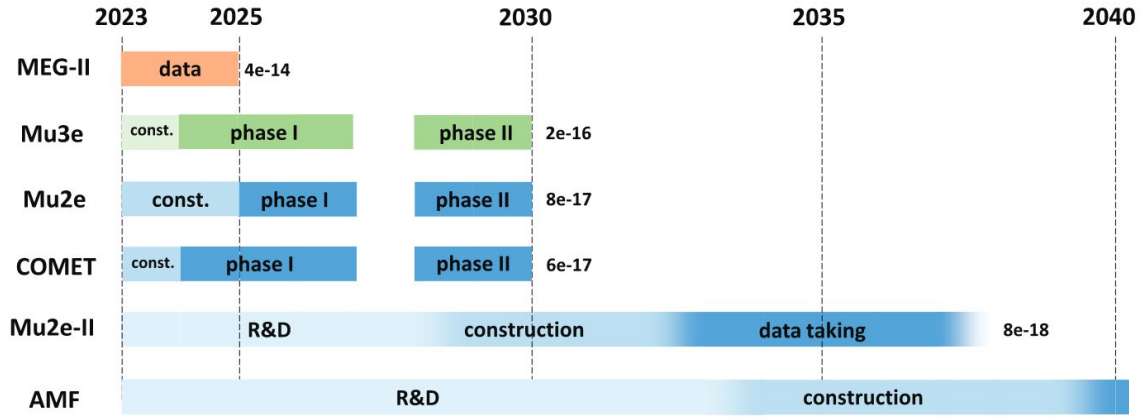
Eur. Phys. J. C (2013) 73:2365





Muon→Electron Conversion

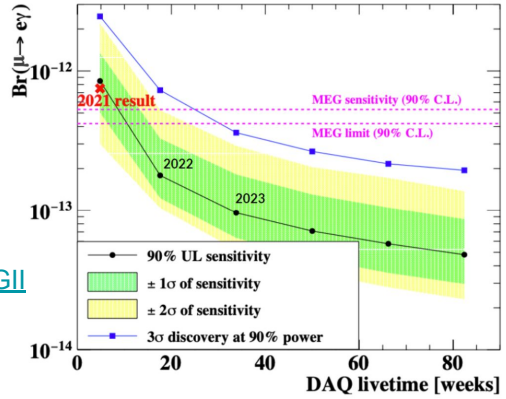
CLFV searches



$\mu^+ \to e^+\gamma$

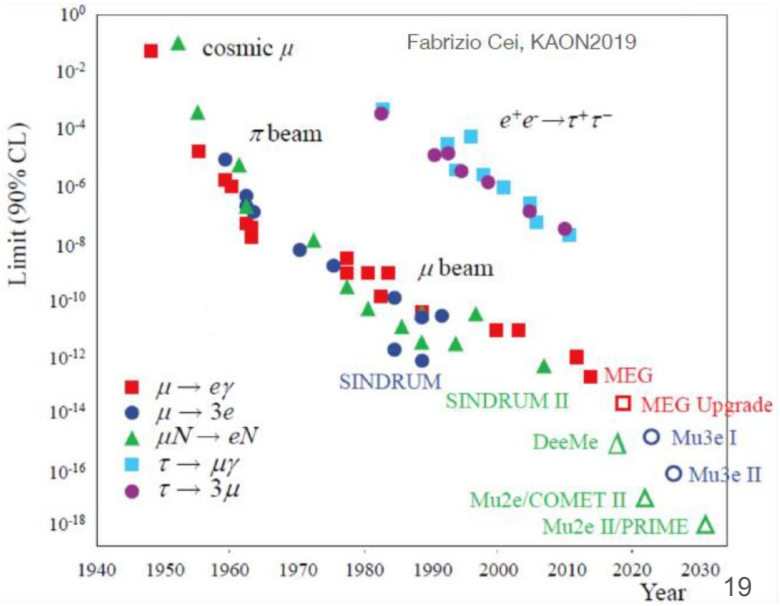
$\mu^+ \to e^+e^-e^+$

$\mu^- N \to e^- N$



MEGII

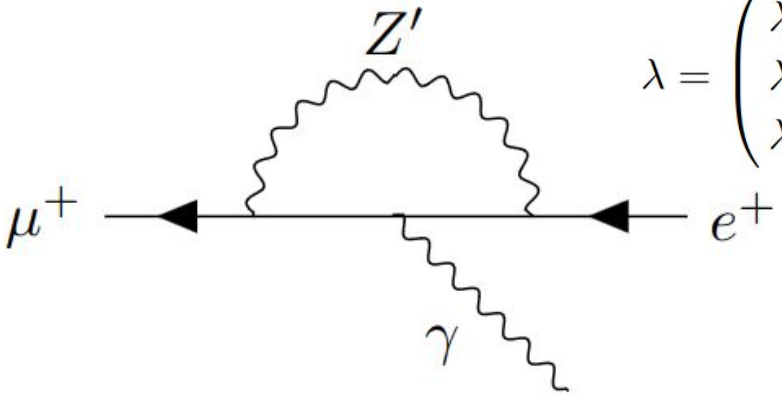
- 2024 run in preparation
- 3 more years (including 2024) to reach the goal of 6×10^{-14}
- 3σ discovery if the BR is above $\sim2\times10^{-13}$
- [Remarks]
  - PSI long shutdown in 2027-2028
  - Mu3e Phase I



A new yet economic CLFV experiment?

- $\mu \to e\gamma$
- $\mu \to eee$
- $\mu + A \to e + A$

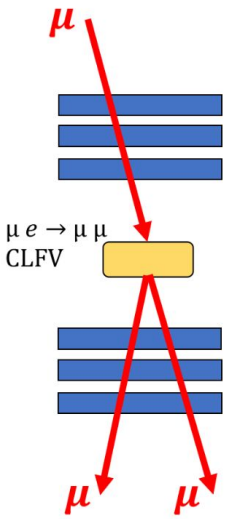
In CLFV
Z' model



$$\lambda = \begin{pmatrix} \lambda_{ee} & \lambda_{e\mu} & \lambda_{e\tau} \\ \lambda_{\mu e} & \lambda_{\mu\mu} & \lambda_{\mu\tau} \\ \lambda_{\tau e} & \lambda_{\tau\mu} & \lambda_{\tau\tau} \end{pmatrix}$$

$$\Gamma(\mu \to e\gamma) = \frac{\alpha G_F^2 m_\mu^3 M_Z^4 \left(\sin^2\theta_W \left(\sin^2\theta_W - 1/2\right)\right)^2}{4\pi^4 M_{Z'}^4}$$

$$\left(\lambda_{ee}\lambda_{e\mu} m_e + \lambda_{e\mu}\lambda_{\mu\mu} m_\mu + \lambda_{e\tau}\lambda_{\tau\mu} m_\tau + \ldots\right)^2 ;$$

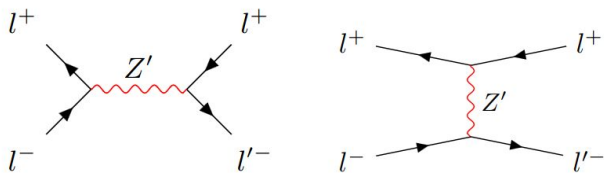


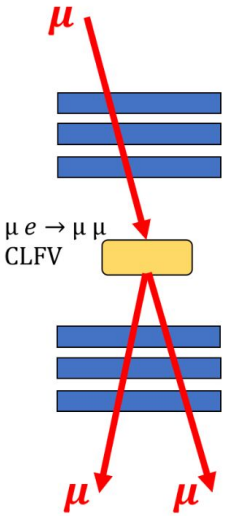
- **There might be more terms, with large cancellation**
- **No exp on μ→eμμ;** No exclusive limit on $\lambda_{e\mu}\lambda_{\mu\mu}$

Muon-Electron Threshold Scan

Muon-electron collider

CLFV





Muon-on-target

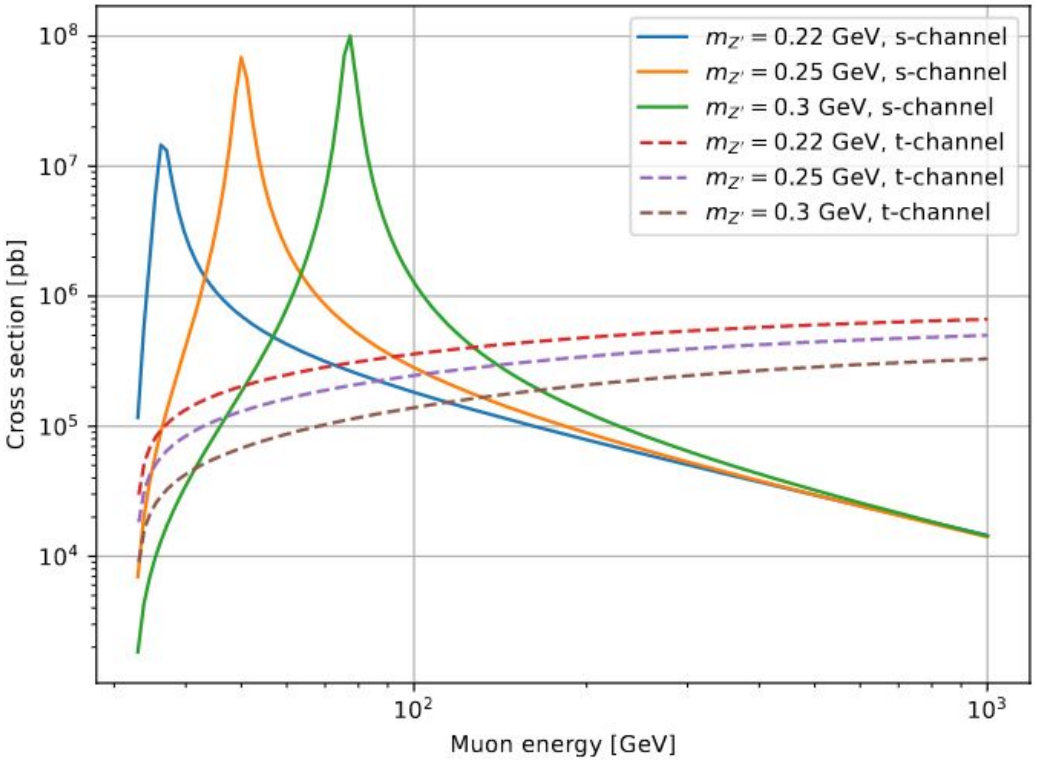
muon-electron scattering

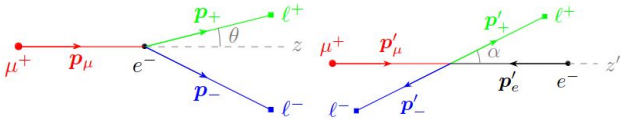
Process	$M_{Z'}$ / GeV	E_μ / GeV	E_e / MeV	E_{cm} / GeV
$\mu^+e^- \to e^+e^-$	0.11	0.93	0.511	0.1101
	0.15	11.1	0.511	0.1501
	0.20	28.2	0.511	0.1996
$\mu^+e^- \to \mu^+\mu^-$	0.22	33.6	0.511	0.2200
	0.25	50.2	0.511	0.2499
	0.30	77.2	0.511	0.2998

- μ+ e- ⟶ Z'⟶ e+ e-, μ+ μ- Charged Lepton Flavor Violation
- Resonant production Enhancement
- X=16.7 MeV Anomaly
- Connecting e-mu collider and muon beam experiments

specific beam energy leads to specific phase space

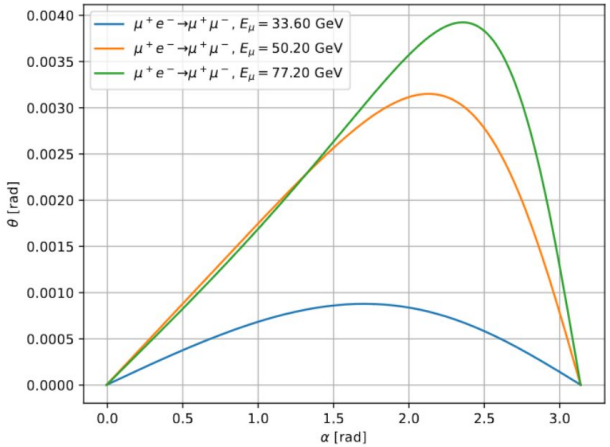
Muon-Electron Threshold Scan





(a) lab frame (b) COM frame

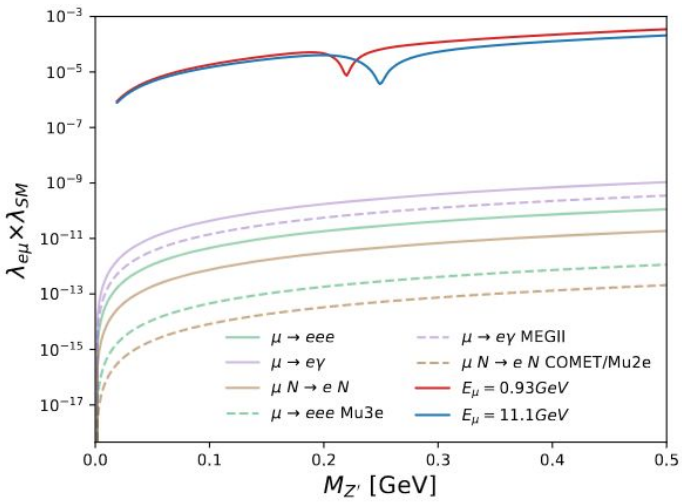
FIG. 4: The $\mu^+e^- \to \ell^+\ell^-$ process in the (a) lab and (b) COM frames.



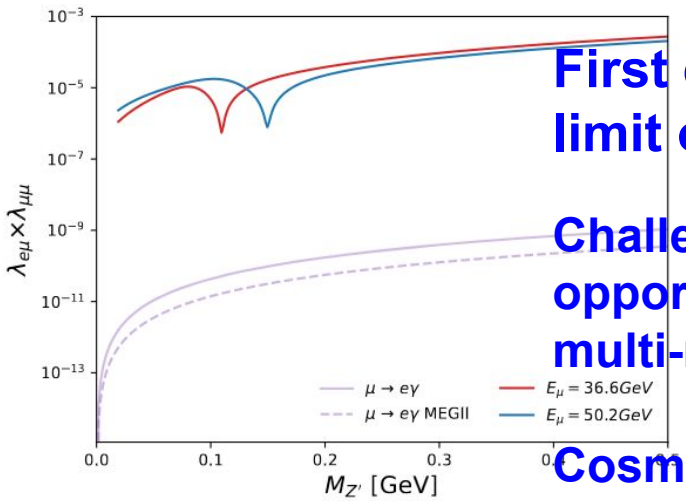
s/t–channel diagrams; on/off-resonance; outgoing angle~0.001 rad

Prospected Results by counting

$$R = \frac{dN}{dt} \cdot n \cdot dx \cdot \sigma$$



(a) $\mu^+e^- \to e^+e^-$



(b) $\mu^+e^- \to \mu^+\mu^-$

First ever exclusive limit on $\lambda_{e\mu}\lambda_{\mu\mu}$;

Challenge and opportunity on multi-muon readout

Cosmic Muon or >O(30 GeV) beam

Figure 10: The 90% C.L. upper limit of $\lambda_{e\mu} \times \lambda_{\rm SM}$ (a) and $\lambda_{e\mu} \times \lambda_{\mu\mu}$ (b). The curves are graphed with respect to $M_{Z'}$, representing the limits of the cross section times branching ratio. Additionally, exclusion lines from both present low-energy experiments (shown as solid lines in purple, green and brown) and future experiments (shown as dashed lines in purple, green and brown) are included in the plot.

Geant4 Simulation

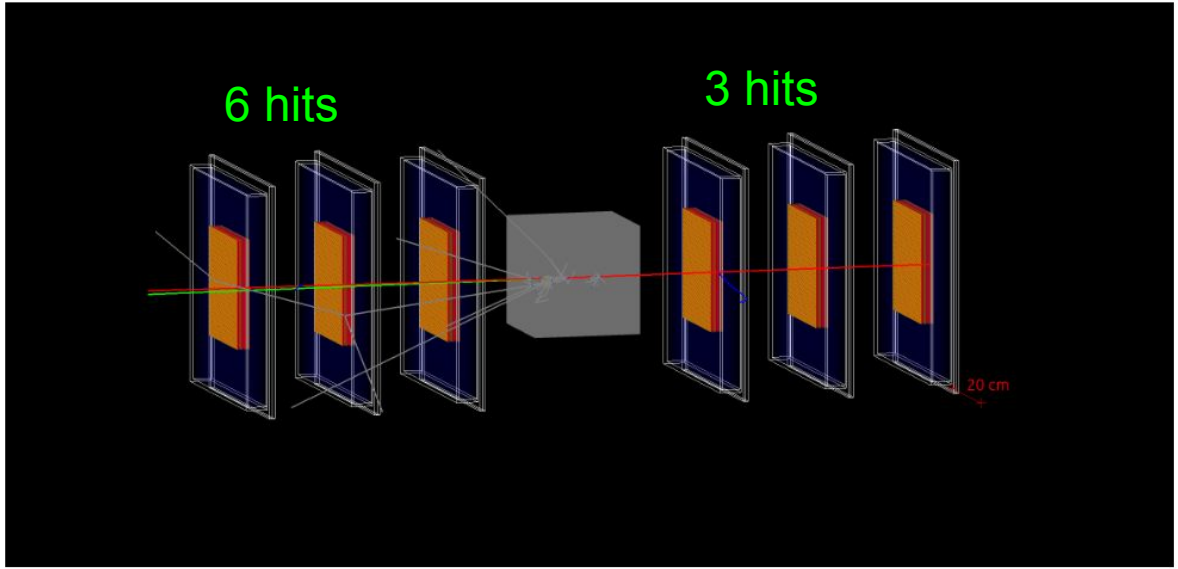


FIG. 6: Geometry configuration and $\mu^+e^- \to \mu^+\mu^-$ event display of the experiment simulation. Other tracks are shown in gray.

- **Muon can lose energy while propagating in material, before hitting with electron**
- **A plugin to interface MG with Geant4 efficiently**

Algorithm 1: Efficient $\mu^+e^- \to \ell^+\ell^-$ event generation

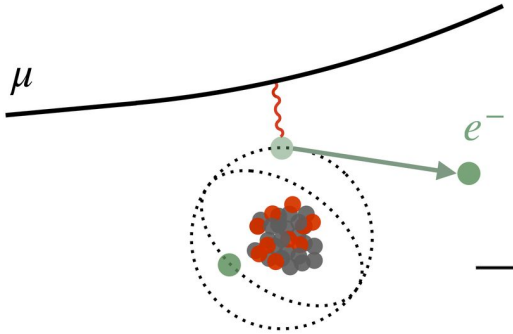
function GenerateMuELL($E_\mu, \vec{p}_\mu, m_\ell$)
  $E_{\mu 1}, E_{\mu 2}, \sigma_1, \sigma_2, H_1, H_2 \leftarrow$ AdjacentGridPoints(E_μ);
  if E_μ is out of the grid range **then**
    return no $\mu^+e^- \to \ell^+\ell^-$ happens;
  end if
  $w_1 \leftarrow \frac{E_\mu - E_{\mu 2}}{E_{\mu 1} - E_{\mu 2}}$, $w_2 \leftarrow \frac{E_{\mu 1} - E_\mu}{E_{\mu 1} - E_{\mu 2}}$;
  $\sigma \leftarrow w_1\sigma_1 + w_2\sigma_2$; // cross section
  if Random$(0,1) < w_1$ **then**
    $\alpha \leftarrow H_1$.Sample();
  else
    $\alpha \leftarrow H_2$.Sample();
  end if // equivalent to $\alpha \leftarrow (w_1H_1 + w_2H_2)$.Sample()
  $\phi \leftarrow$ Random$(0, 2\pi)$;
  $E', p', \gamma, \beta \leftarrow$ Kinematics(E_μ, m_ℓ); // see Appendix A
  $p_{x+} \leftarrow p' \sin\alpha\cos\phi$, $p_{y+} \leftarrow p' \sin\alpha\sin\phi$;
  $p_{z+} \leftarrow \gamma\,(p'\cos\alpha + \beta E'/2)$;
  $\vec{p}_+ \leftarrow$ ThreeVector(p_{x+}, p_{y+}, p_{z+}); // see Fig. 3a
  $\vec{p}_+ \leftarrow \vec{p}_+$.RotateZAxisTo($\hat{p}_\mu$);
  $\vec{p}_- \leftarrow \vec{p}_\mu - \vec{p}_+$; // $\hat{z} \leftarrow \hat{p}_\mu$ in Fig. 3a in rotation
  return $\sigma, \vec{p}_+, \vec{p}_-$;
end function

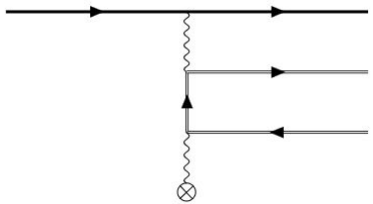
Geant4 Simulation

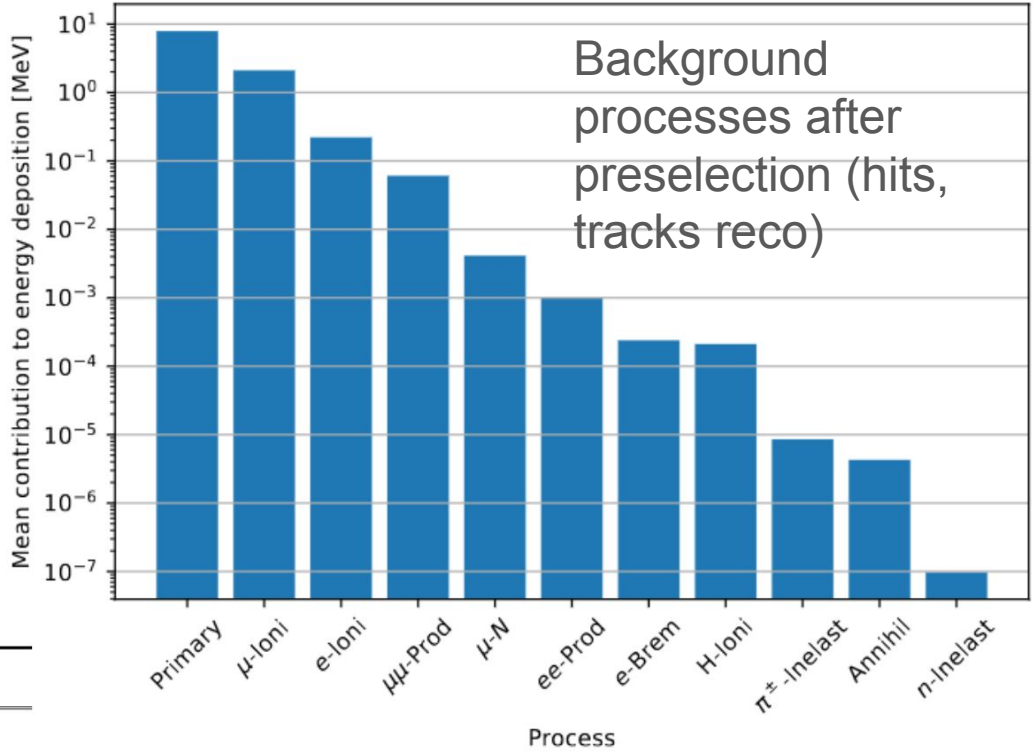
Cluster hits to 3 tracks

$$\chi^2 = \frac{1}{\sigma_t^2} \sum_{t=1}^{3} \sum_{h=1}^{3} \left(\hat{\vec{r}}_{th} \left(\vec{r}_{t1}, \vec{r}_{t3}, z_{th} \right) - \vec{r}_{th} \right)^2$$

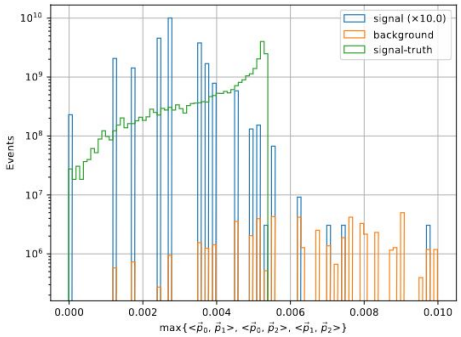
$$= \frac{1}{\sigma_t^2} \sum_{t=1}^{3} \left(\hat{\vec{r}}_{t2} \left(\vec{r}_{t1}, \vec{r}_{t3}, z_{t2} \right) - \vec{r}_{t2} \right)^2 \sim \chi^2(6),$$



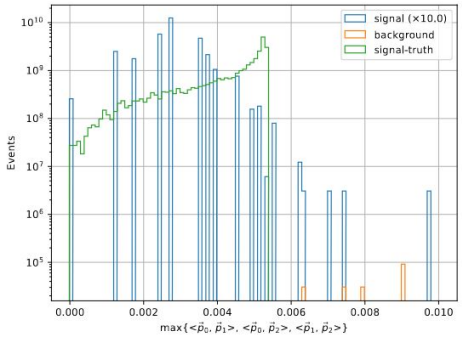




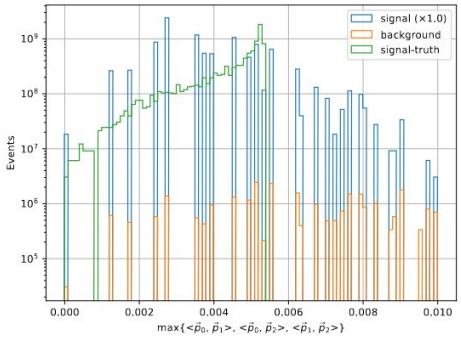
Geant4 Simulation



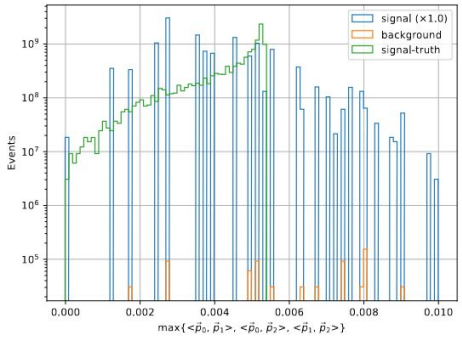
(a) 3 cm Al target



(b) 3 cm Al target, with e-veto



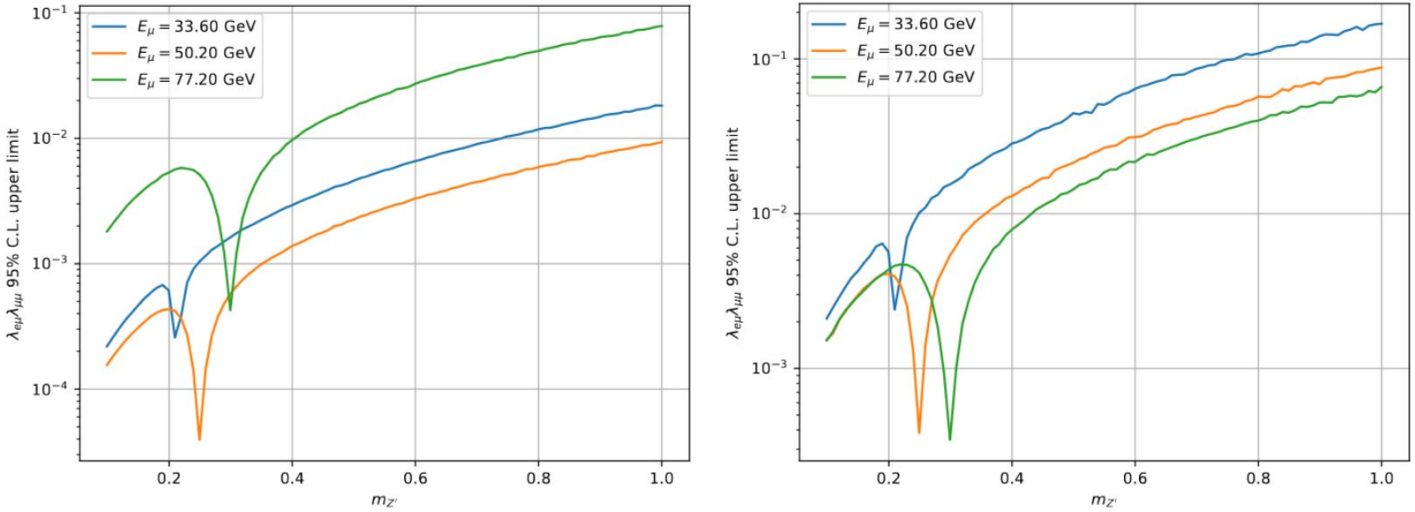
(c) 8 cm Pb target



(d) 8 cm Pb target, with e-veto

FIG. 9: $\max_{i\neq j}\{\langle \vec{p}_i, \vec{p}_j\rangle\}$ distributions of variant target, where $E_\mu = 50.2$ GeV, $m_{Z'} = 0.25$ GeV, and the $\mu^+e^- \to \mu^+\mu^-$ process is added with $\lambda_{e\mu}$ scaled to 10 (1) for Al (Pb). The yields are normalized to 3×10^{13} targeting muons corresponding to a one-year accumulation.

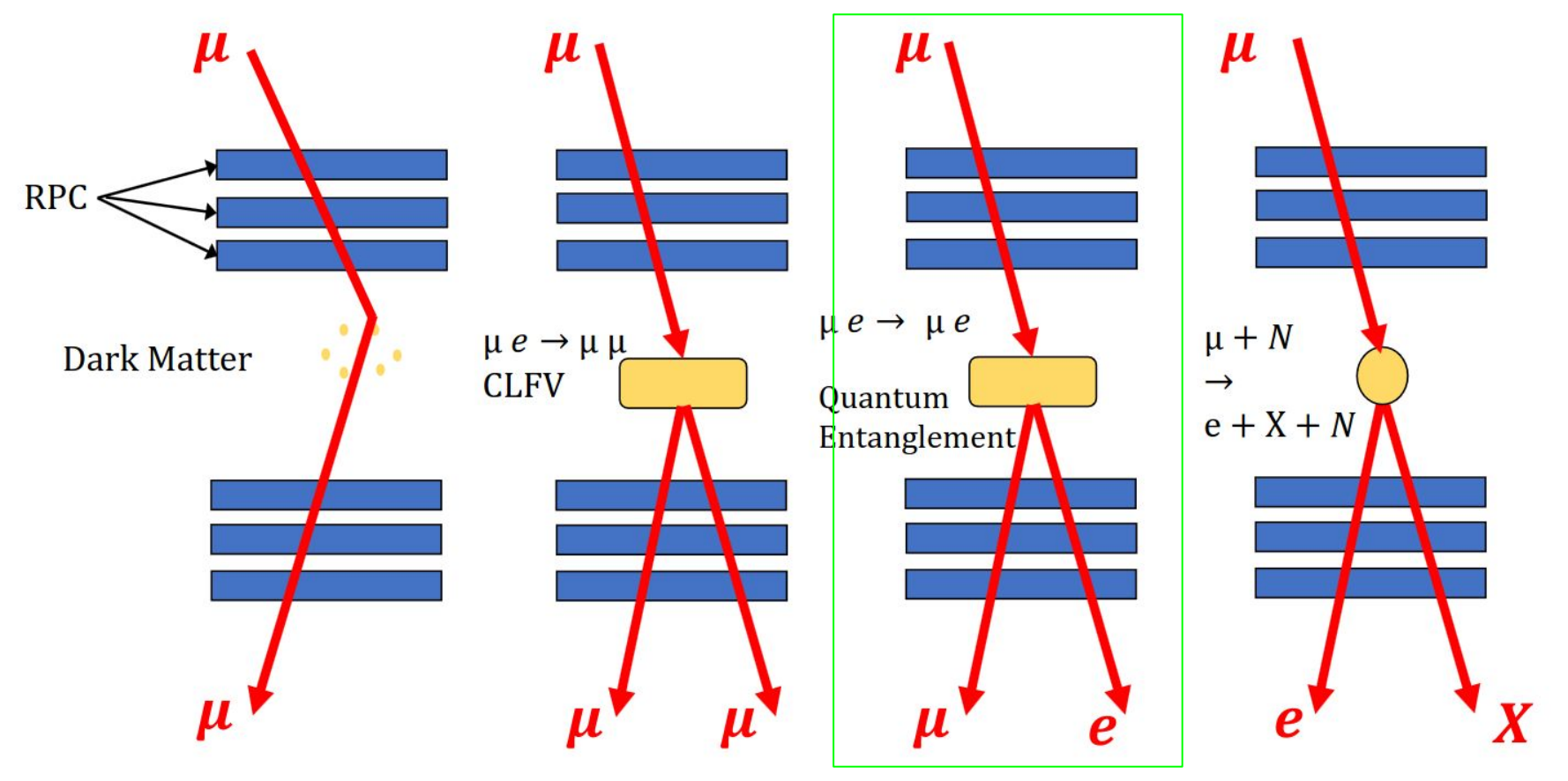
Geant4 Simulation



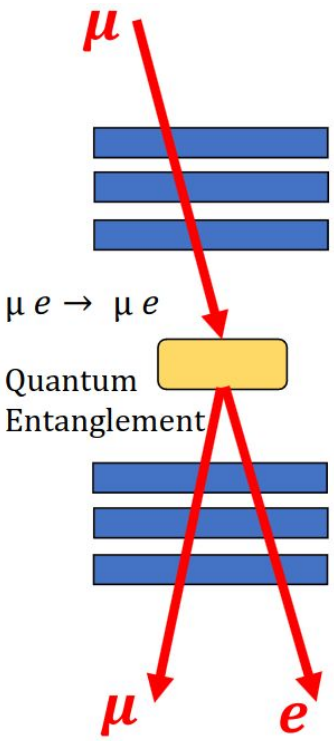
(a) 3 cm Al target, with e-veto (b) 8 cm Pb target, with e-veto

FIG. 10: 95% C.L. upper limit results of variant target. The yields are normalized to 3×10^{13} targeting muons corresponding to a one-year accumulation.

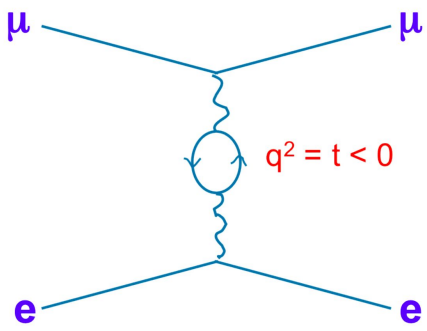
Probing and Knocking with Muons



Muon Electron Scattering



- MuonE exploits 160 GeV Muon beam to measure muon electron scattering, and a precise determination of the leading hadronic contribution to the muon g-2.
- **Muon electron scattering at lower energy (~GeV)** may be interesting to SM test itself, and Quantum entanglement probe PRD 107, 116007 (2023):



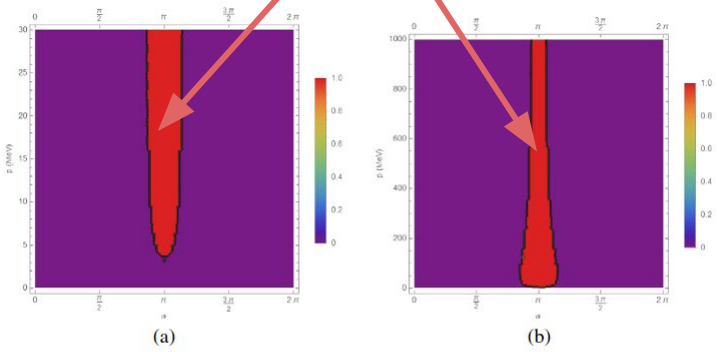
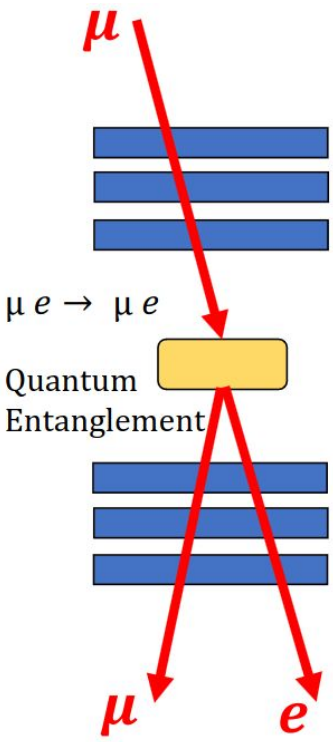
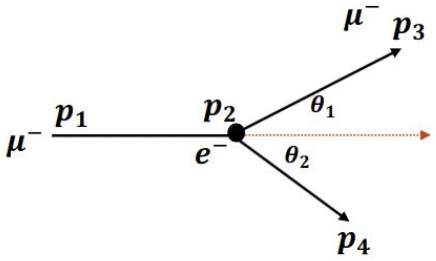


FIG. 15. The red regions correspond to the values of p and θ for which the final state is entangled at low—< 30 MeV—(a) and high—< 1 GeV—(b) energies.

Muon Electron Scattering for QE



- Lab **Frame (electron at rest)**

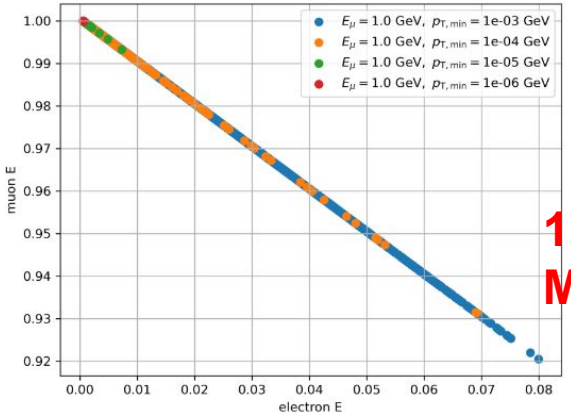


$$p_1 = (E_1, 0, 0, |\mathbf{p_1}|) \qquad p_3 = (E_3, |\mathbf{p_3}|\sin\theta_1, 0, |\mathbf{p_3}|\cos\theta_1)$$

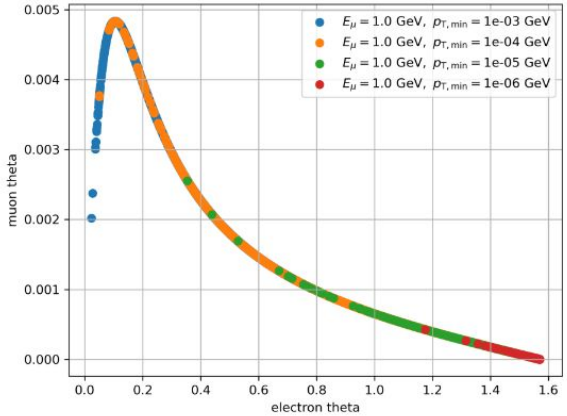
$$p_2 = (m_e, 0, 0, 0) \qquad p_4 = (E_4, |\mathbf{p_4}|\sin\theta_2, 0, |\mathbf{p_4}|\cos\theta_2)$$

Energy –Momentum relation & Energy conservation:

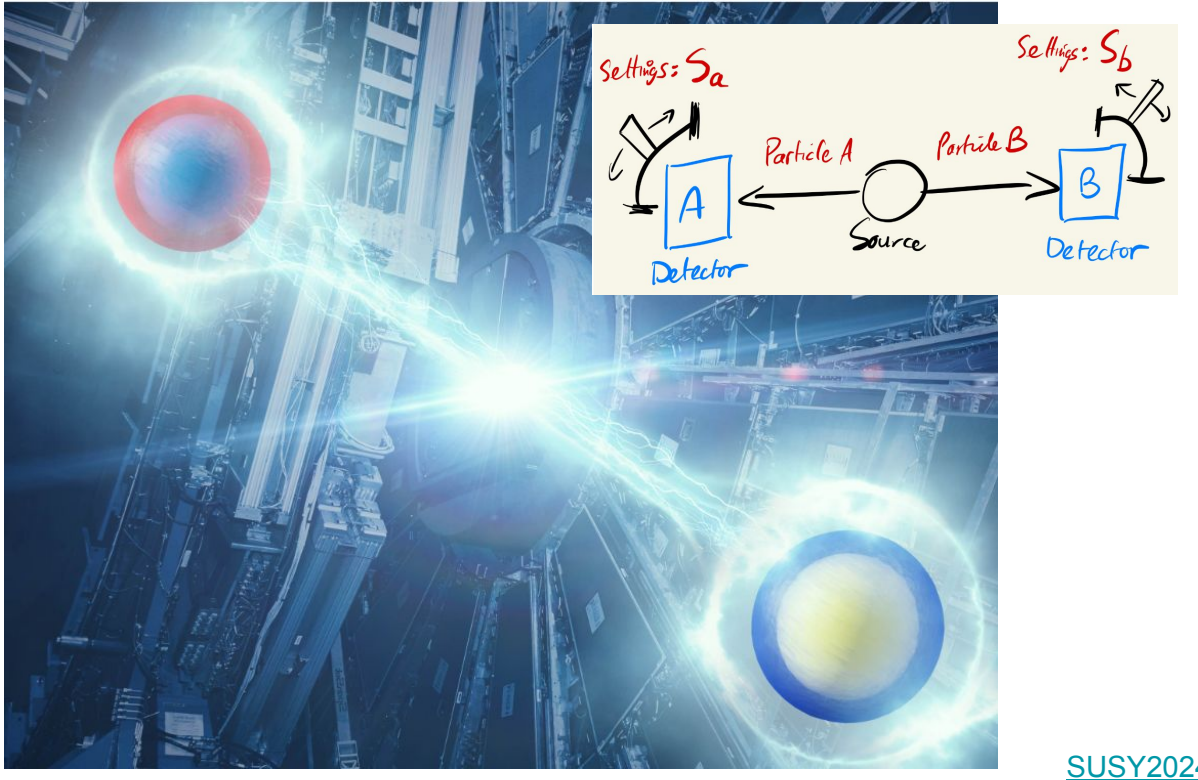
$$\mathbf{p} = \sqrt{E^2 - m^2} \qquad E_1 + m_e = E_3 + E_4$$

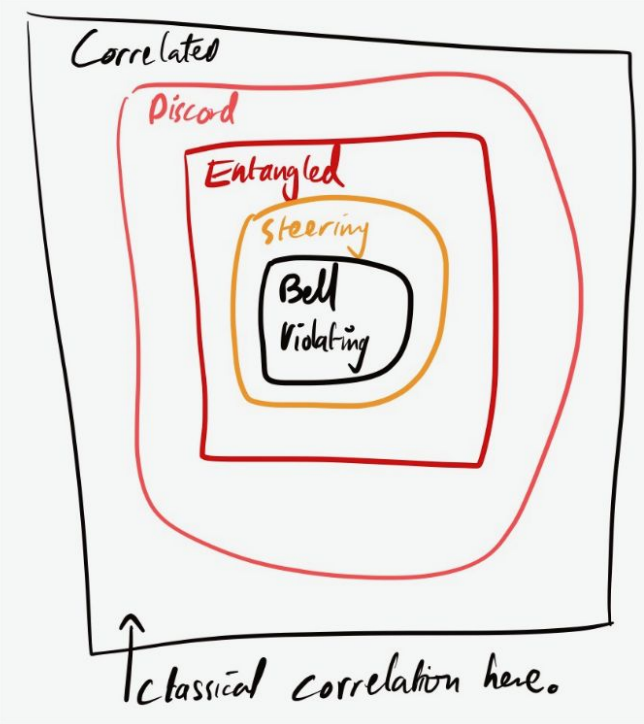


1GeV Muon



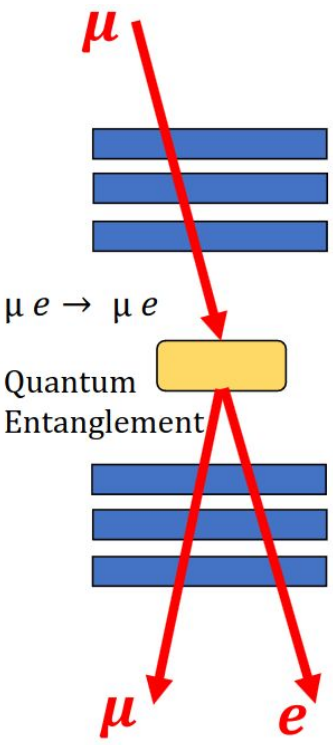
LHC experiments at CERN observe quantum entanglement at the highest energy yet





SUSY2024

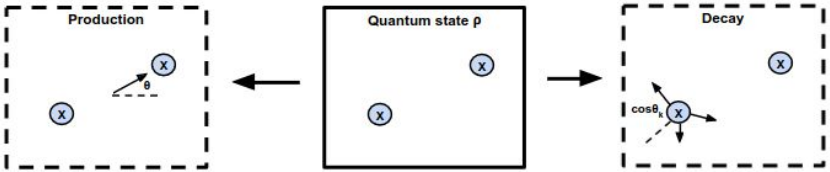
Muon Electron Scattering for QE



$$\mathcal{M}_{(\lambda_1,\lambda_2,\lambda_3,\lambda_4)}(p_1,p_2,p_3,p_4) \longrightarrow \mathcal{M}_{(\lambda_1,\lambda_2,\lambda_3,\lambda_4)}(\theta_\mu,\theta_e,E_3)$$

$$\rho = \frac{\mathcal{M}_{\lambda_3,\lambda_4}\mathcal{M}^*_{\bar{\lambda}_3\bar{\lambda}_4}}{\sum_{\text{spins}}|\mathcal{M}|^2}$$

$$\mathcal{M}_{\lambda_3,\lambda_4} = \frac{1}{4}\sum_{\lambda_1,\lambda_2}\mathcal{M}(\lambda_1,\lambda_2,\lambda_3,\lambda_4)$$



PITT-PACC-2408

Quantum Tomography at Colliders: With or Without Decays

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[1] *PITT PACC, Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara St., Pittsburgh, PA 15260, USA*

(Dated: October 14, 2024)

The interpretation of groups of particle spins at colliders as quantum states has opened up the possibility of using colliders for quantum information. While most efforts have focused on utilizing the decays of the particles to infer their spins to reconstruct the quantum density matrix, we show that the production kinematics of the particles provides sufficient information about the spins to establish quantum tomography without using the decays. We perform a comparative study, highlighting the advantages and disadvantages of using this "kinematic approach" relative to the usual "decay approach." Since the kinematic approach leverages the simplicity of scattering kinematics, this approach promises to achieve the optimal statistical results for quantum tomography at colliders.

https://arxiv.org/abs/2410.08303

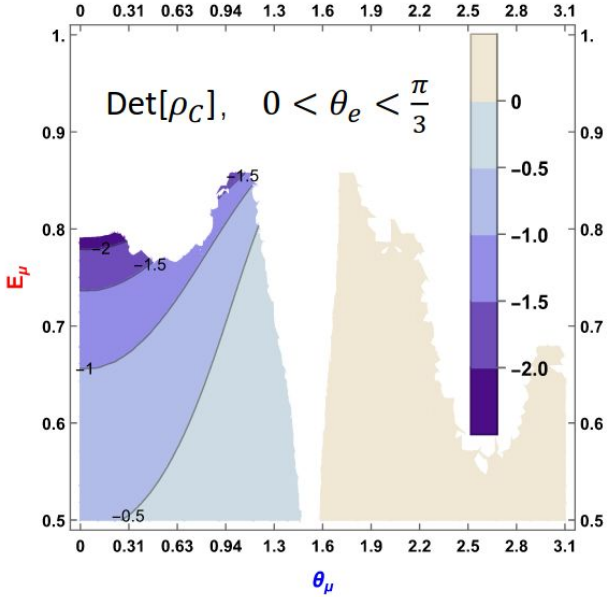
Peres-Horodecki criterion ref ref2

- **Theory prediction**

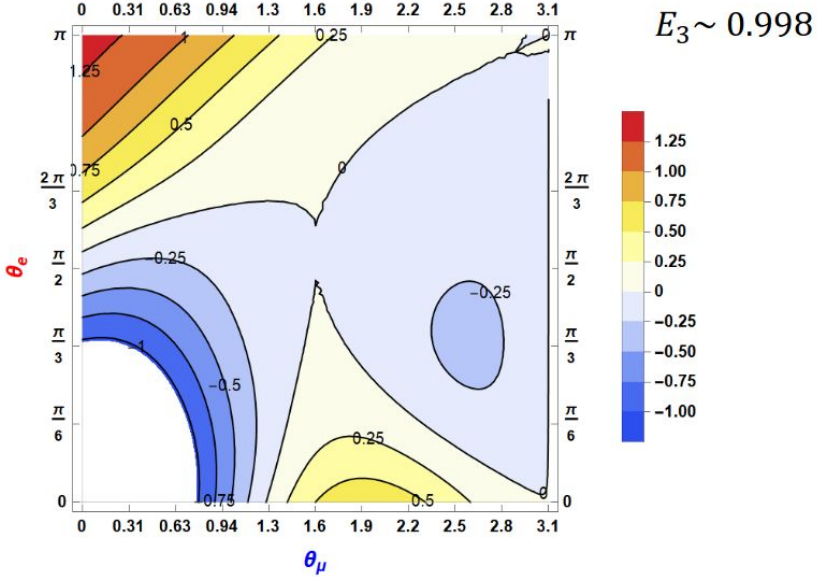
$$\rho_C \equiv \begin{bmatrix} 1+B_3^+ + B_3^- + C_{33} & C_{11}+C_{22}+i(C_{12}-C_{21}) \\ C_{11}+C_{22}+i(C_{21}-C_{12}) & 1-B_3^+ - B_3^- + C_{33} \end{bmatrix}$$

$$\Delta \equiv -C_{33} + |C_{11}+C_{22}| - 1 > 0$$

Det[ρ_C], any negative value indicates QE presence



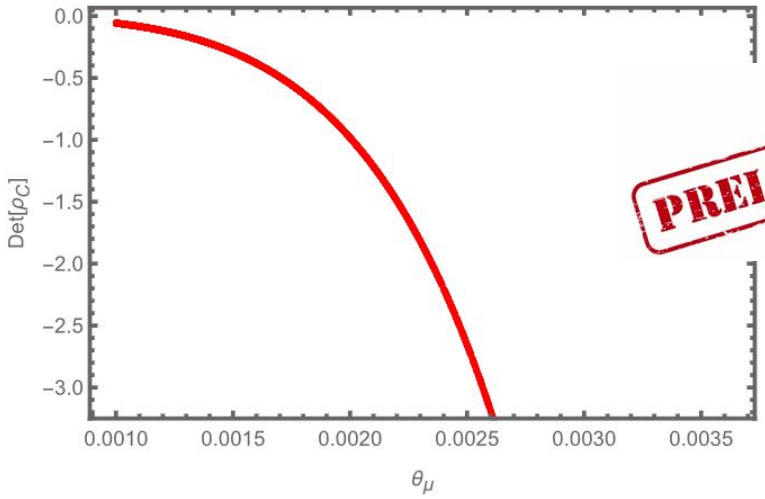
Det[ρ_C]<0

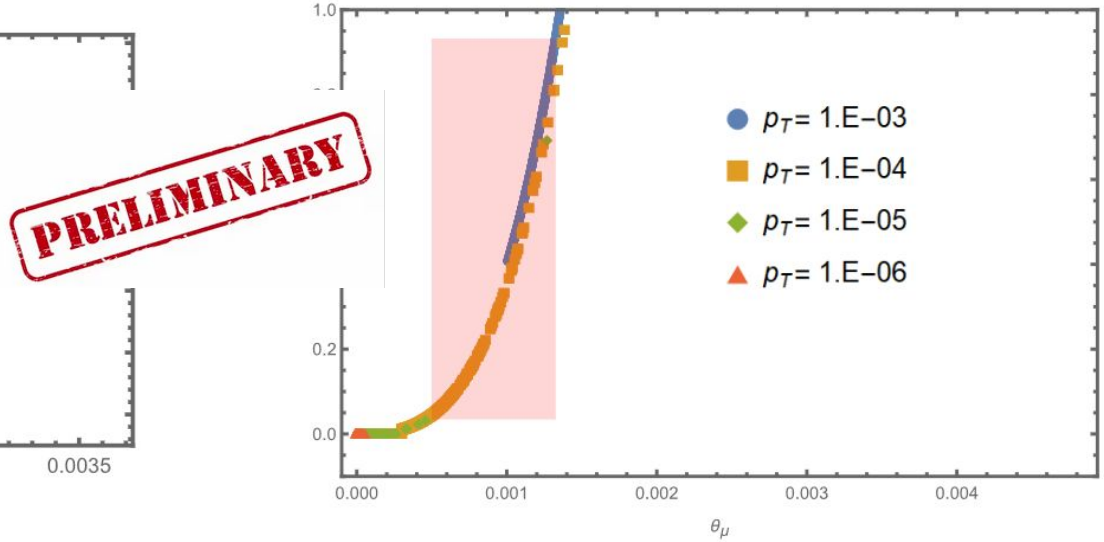


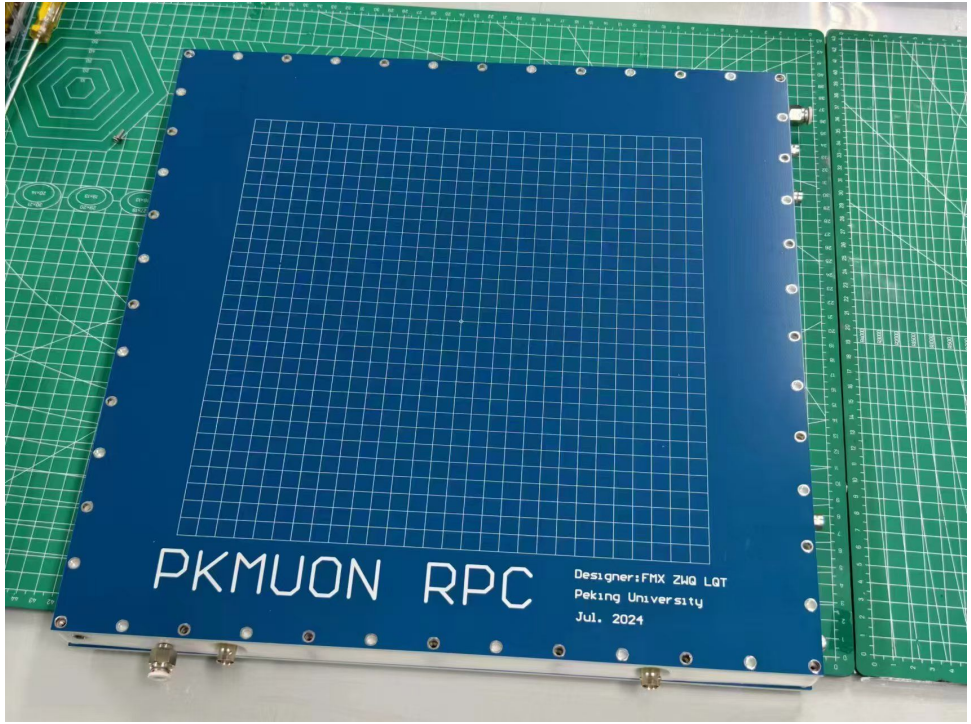
Simulated QE results

$$\mathcal{C}[\rho] = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\} \in [0,1],$$

$$\rho_C \equiv \begin{bmatrix} 1 + B_3^+ + B_3^- + C_{33} & C_{11} + C_{22} + i(C_{12} - C_{21}) \\ C_{11} + C_{22} + i(C_{21} - C_{12}) & 1 - B_3^+ - B_3^- + C_{33} \end{bmatrix}$$

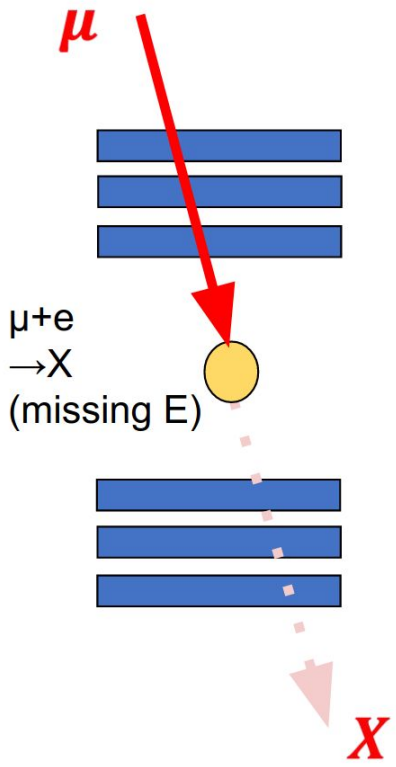





PKMUON RPC
Designer:FMX ZWQ LQT
Peking University
Jul. 2024

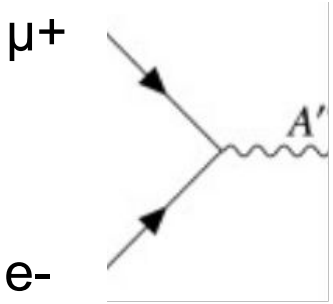

LET'S GO TOGETHER

Flavor Changing Dark X

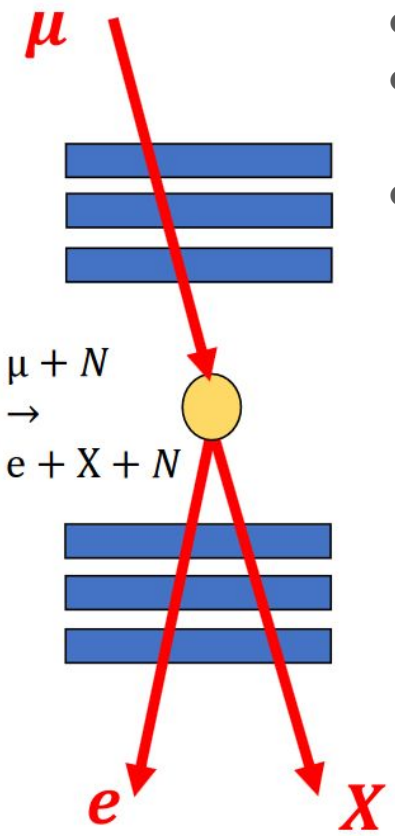


- Muon electron (mu+ e-) annihilation into missing energy signal
- Similar proposal (ERC supported POKER) for e+e- annihilation
  - Phys. Rev. D 88 (2013), 114015
  - Phys.Rev.D 104 (2021) 9, L091701
  - Exp results with NA64
- Muon beam energy can be lowered down
  - If X mass is small enough
- Can be interpreted as Br(mu->e+X) for low mass X
  - and compared with TWIST
- To be implemented within G4
  - Our own implementation
  - Or using DMG4

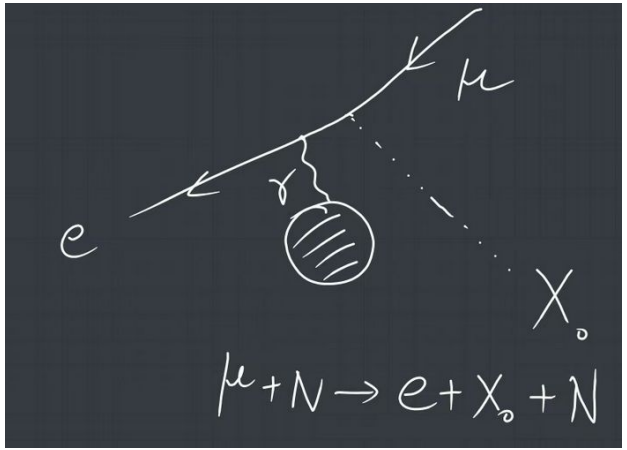
POKER
POsitron resonant annihilation into darK mattER



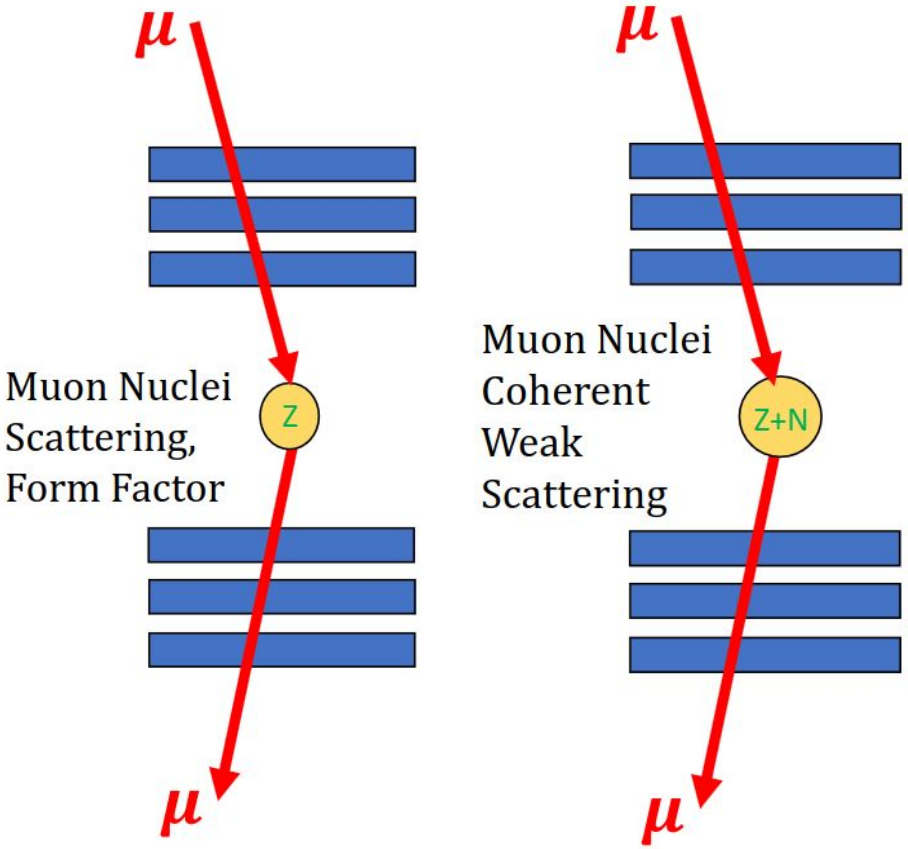
Muon's two body 'decay'



- Lepton family number violation by searching for $\mu \to e\, X_0$
- Previous limit from the Twist Collaboration: [Phys. Rev. D 91, 052020 (2015)]
- We are aiming at muon on target searches (**works also for X_0 heavier than muon**).
  - Require Calorimeter to veto backgrounds
  - Can also be put under flavor changing Dark Matter

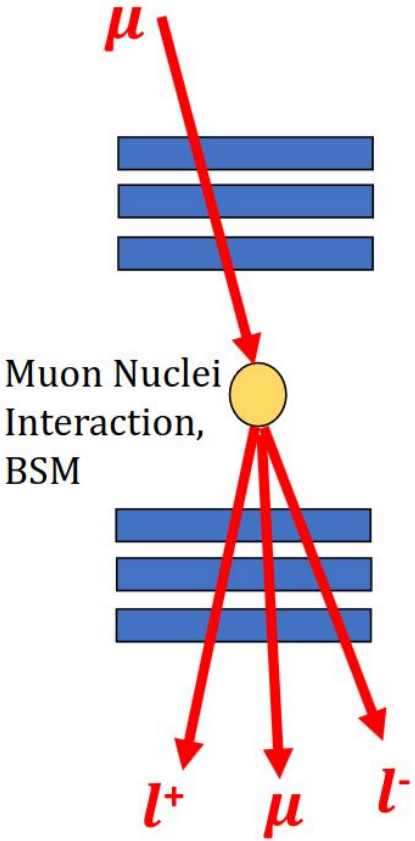


Muon nuclei scattering

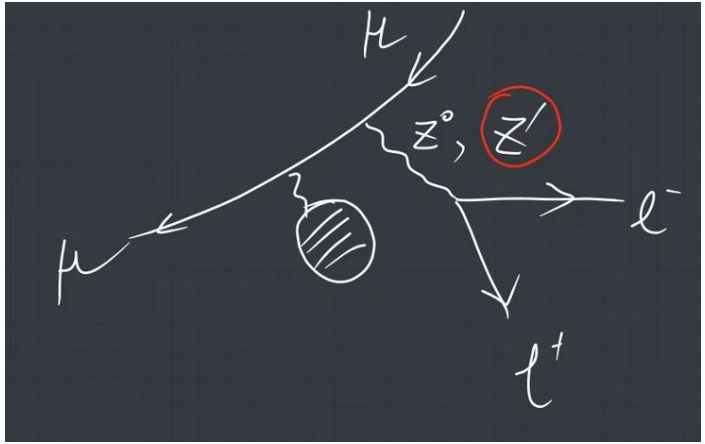


- Various scattering experiment to measure nuclei structure
  - JLAB 12-24 GeV electron scattering
  - CERN COMPASS and AMBER muon project
- **With 0.1-1 GeV Muon beam, we may measure independently**
  - Nuclei (charge) form factor
  - Coherent Weak scattering
  - …

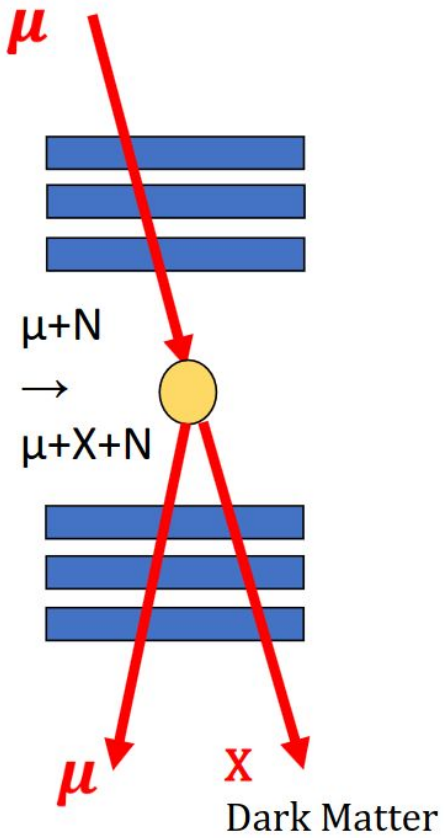
Muon nuclei scattering



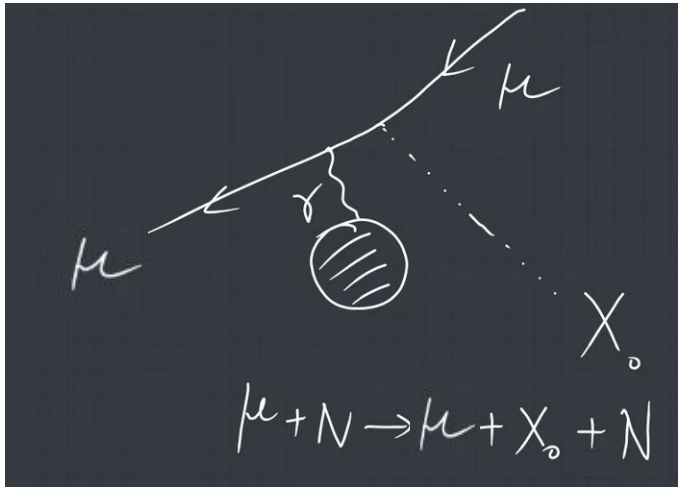
- Rare Muon Nuclei scattering processes to be measured and explored.
- Verify Geant4 Simulation Tool
- **Sensitive to various BSM, including**
  - **the Zprime CLFV,**
  - **or DM decays into visible signals**



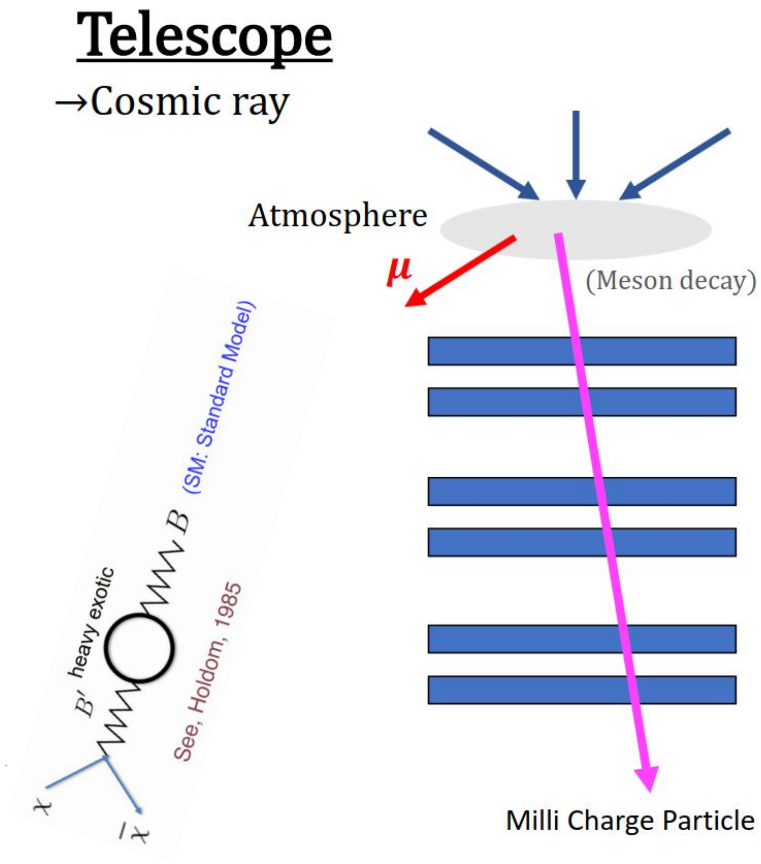
Dark Matter from Muon nuclei scattering



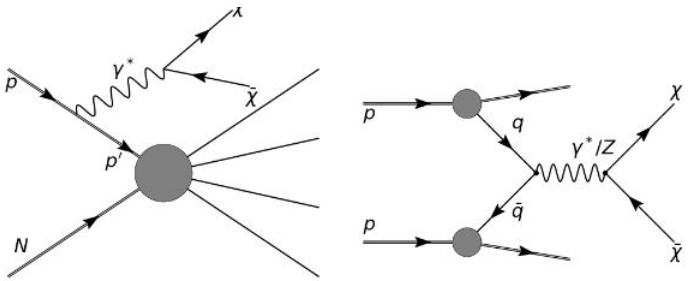
- Exploration of the Muon g−2 and Light Dark Matter explanations in NA64 with the CERN SPS high energy muon beam
- Our limit may be weak than NA64mu.
- Can still be used to verity Geant4 Simulation Tool



Milli-Charged Particle Searches



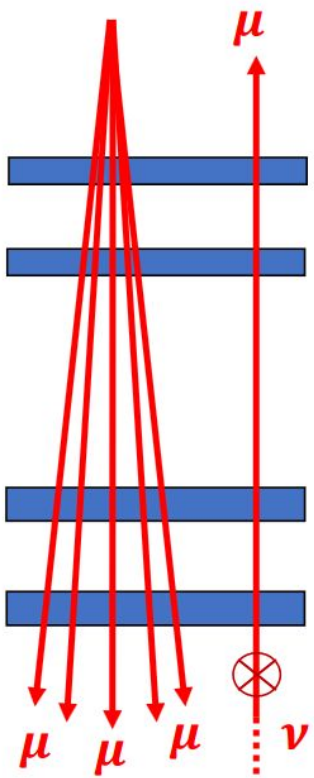
- Heavy millicharged particles may be produced from the atmosphere when high energy cosmic rays collide with nuclei
  - Theoretical predictions here
- **Can be detected at PKMu detectors**
  - **PID and optimization to be done.**



Also from meson decay

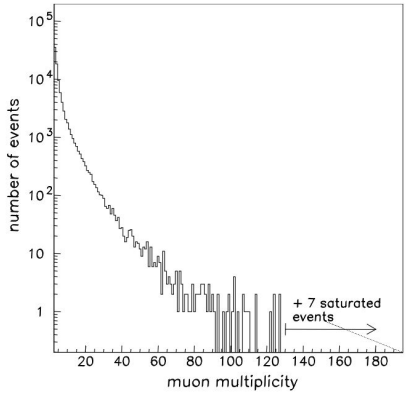
FIG. 2. Feynman diagrams for MCP production through proton bremsstrahlung (left) and the Drell-Yan process (right).

Muon Bundle from Cosmic Ray



Muon bundle

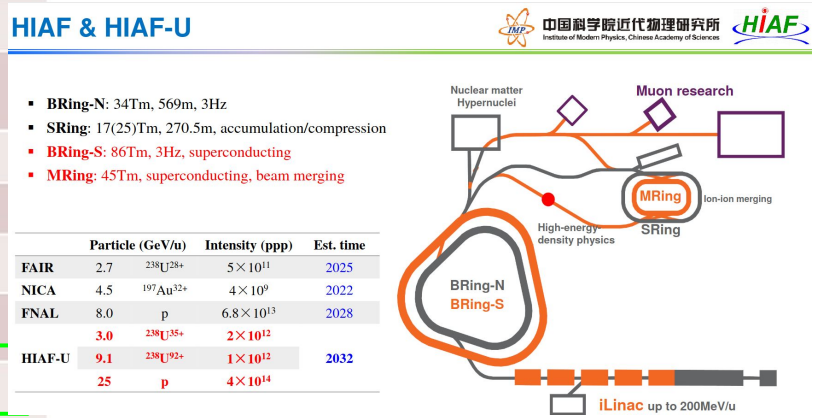
- Multi-muon bundles in cosmic ray showers detected, e.g., with the DELPHI detector at LEP
  - Could be sensitive to heavy ion elements in CR
- With large area PKMu detectors, it is possible to detector muon bundles and trace back to the origin points in the atmosphere (~O(10) km)
- Again, challenges and opportunities to read out muli-muons!



Melody, CIADS, HIAF Muon beams

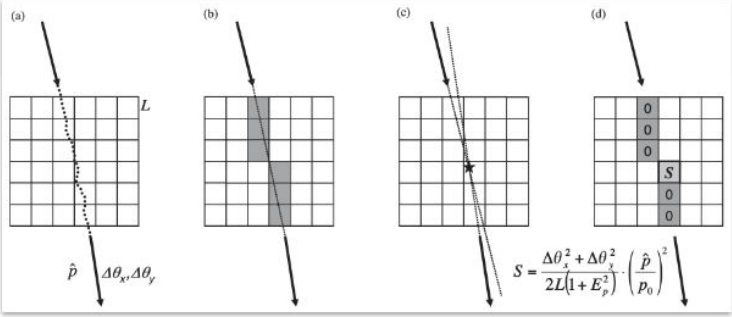
Melody: approved and the first Chinese Muon beam will be built in 5 years.

	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

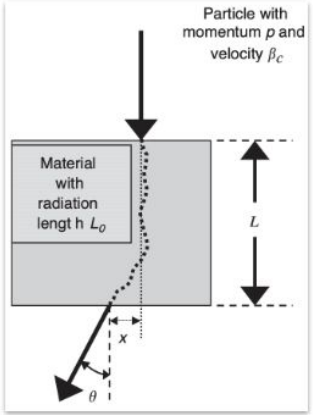


~30 MeV, ~100 MeV, ~1GeV

PoCA

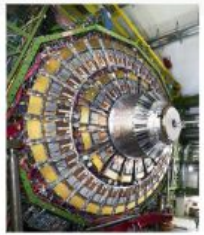


- ➔ The point of closest approach (PoCA) algorithm
- ➔ The angular scattering distribution is approximately Gaussian
  - ❖ $$\sigma_\theta = \frac{13.6\,\mathrm{MeV}}{\beta c p}\sqrt{\frac{L}{L_0}}[1 + 0.038\ln\frac{L}{L_{\mathrm{rad}}}] \approx \frac{13.6}{p}\sqrt{\frac{L}{L_0}}$$
  - ❖ p: momentum,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

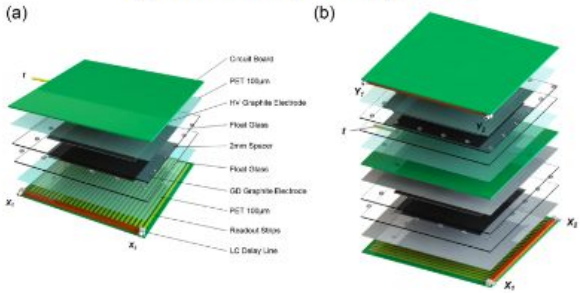


RPC

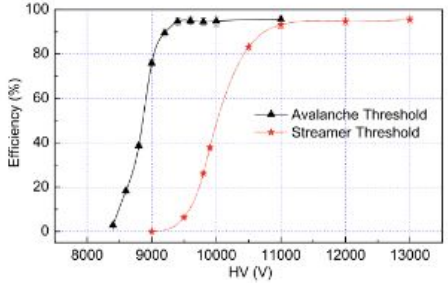
Compact Muon Solenoid



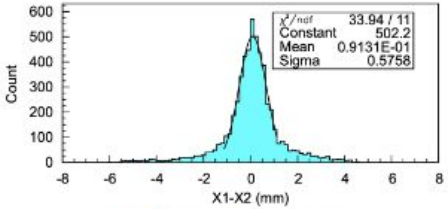
(a) Prototype glass RPC
(b) One RPC with two structure get X and Y signals respectively



- ➔ 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%



Efficiency curves for the glass RPC



Distribution of X1-X2

MIP2024-1