北京大學
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Search for light Dark Sectors with HIAF Muon Beams: HIRIBL-PKMu experiment proposal

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on behalf of the PKMuon Collaboration*

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

Outline

- ➔ Introduction and Motivation
- ➔ Experiment setup: the joint HIRIBL-PKMu experiment
- ➔ Simulation framework
  - ❖ I. Efficient signal event generation
  - ❖ II. Simulation setup
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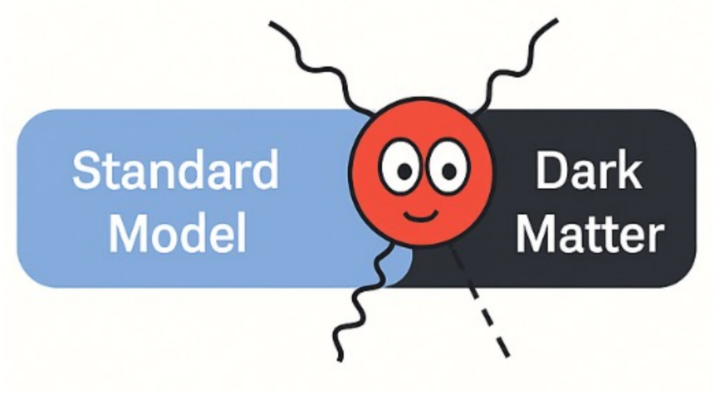
- ➔ Summary & outlook

PKμ @HFRS

Introduction and Motivation

Z' gauge boson in $L_\mu - L_\tau$ vanilla model



$$\mathcal{L} \supset -\frac{1}{4}F'_{\alpha\beta}F^{\alpha\beta\prime} + \frac{m_{Z'}^2}{2}Z'_\alpha Z^{\alpha\prime} - g_{Z'}Z'_\alpha J^\alpha_{\mu-\tau}$$

$$J^\alpha_{\mu-\tau} = \left(\bar{\mu}\gamma^\alpha\mu - \bar{\tau}\gamma^\alpha\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu - \bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\right)$$

$$\Gamma(Z' \to \bar{\nu}\nu) = \frac{\alpha_{Z'}m_{Z'}}{3}, \quad \alpha_{Z'} = g_{Z'}^2/(4\pi)$$

$$\Downarrow \quad \mathcal{L} \supseteq -g_\chi Z'_\alpha J^\alpha_\chi$$

$$J^\alpha_\chi = g_\chi \begin{cases} i\chi^*\partial^\alpha\chi + \text{h.c.}, & \text{complex scalar} \\ 1/2\overline{\chi}\gamma^\alpha\gamma^5\chi, & \text{Majorana} \\ i\overline{\chi}_1\gamma^\alpha\chi_2, & \text{pseudo-Dirac} \\ \overline{\chi}\gamma^\alpha\chi, & \text{Dirac} \end{cases}$$

$$\Gamma(Z' \to \overline{\chi}\chi) = \frac{\alpha_D m_{Z'}}{3}\left(1 + \frac{2m_\chi^2}{m_{Z'}^2}\right)\sqrt{1 - \frac{4m_\chi^2}{m_{Z'}^2}}, \quad \alpha_D = g_\chi^2/(4\pi)$$

$\mu e \to \mu e Z'$ & $\mu N \to \mu N Z'$

- The **Dark Sector** in light (sub-GeV) dark matter scenarios includes light mediators, such as a dark vector boson, and can induce feeble interactions with muons through scalar, pseudoscalar, or vectorlike particles.
- In the $L_\mu - L_\tau$ vanilla model, the **Z' vector boson** from the broken $U(1)_{L_\mu - L_\tau}$ symmetry couples directly to the second and third lepton generations, and their corresponding left-handed neutrinos.
- In this work, we investigate the vanilla $L_\mu - L_\tau$ model using a low-energy muon beam in the **1–10 GeV** range from the HIRIBL at the High Intensity Heavy-ion Accelerator Facility (HIAF), through $\mu e \to \mu e Z'$, with Z' decays invisibly. The relatively low center-of-mass energy is expected to offer enhanced sensitivity to a light Z' boson, particularly in the mass region around **10 MeV**.

https://arxiv.org/abs/2409.10128
https://doi.org/10.1103/PhysRevLett.132.211803

Z' gauge boson in $L_\mu - L_\tau$ vanilla model

$\mu e \rightarrow \mu e Z'$ & $\mu N \rightarrow \mu N Z'$

Lagrangian

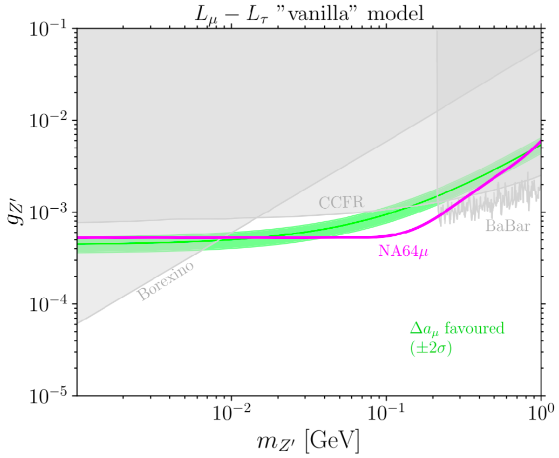
$$\mathcal{L}_{Z'} = -g Z'_\mu \left(\bar{L}_2 \gamma^\mu L_2 + \bar{l}_2 \gamma^\mu l_2 - \bar{L}_3 \gamma^\mu L_3 - \bar{l}_3 \gamma^\mu l_3 \right)$$

$$L_2 = \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \; l_2 = \mu_R, \; L_3 = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \text{ and } l_3 = \tau_R$$

Decay

$$\Gamma(Z' \rightarrow \bar{\nu}\nu) = \frac{\alpha_{Z'} m_{Z'}}{3}$$

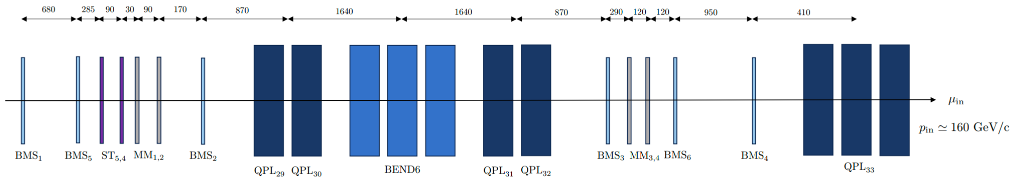
$$\alpha_{Z'} = g_{Z'}^2/(4\pi)$$

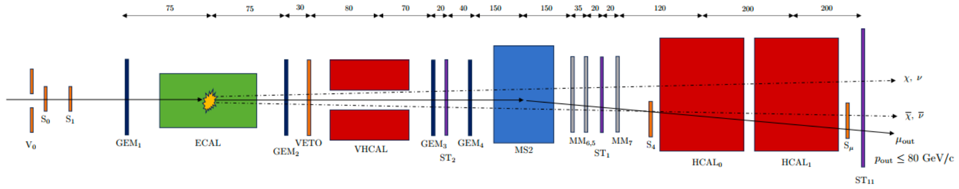


NA64-μ

Beam energy
160 GeV

Dataset of MOT
$(1.98 \pm 0.02)\times 10^{10}$





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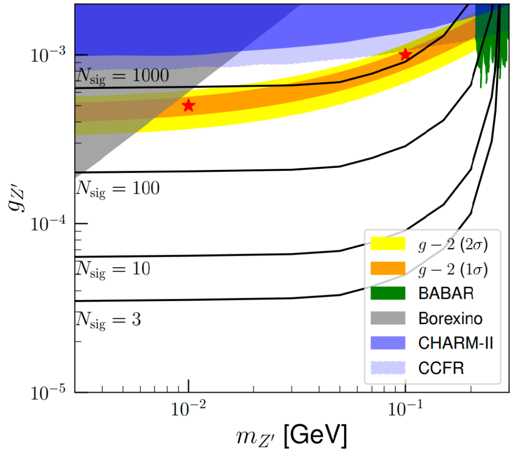
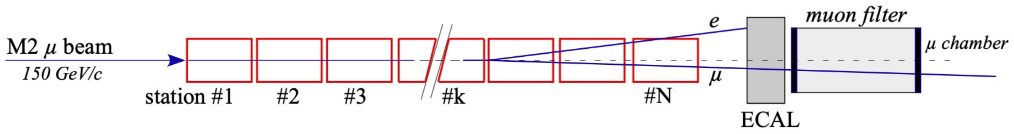
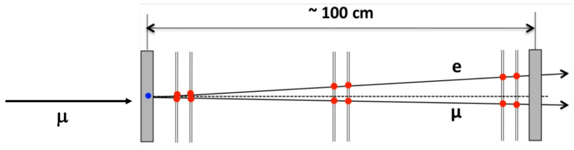


MuonE

Beam energy
160 GeV

Pheno study based on
MadGraph5_aMC@NLO v3.1.1



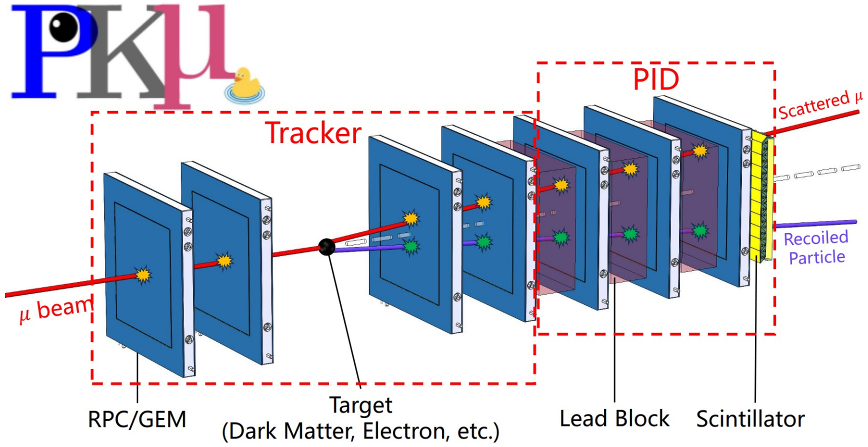


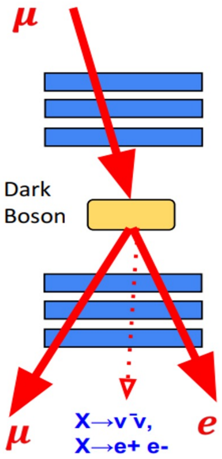
https:// arxiv.org/abs/2307.02404

https://arxiv.org/abs/2109.10093

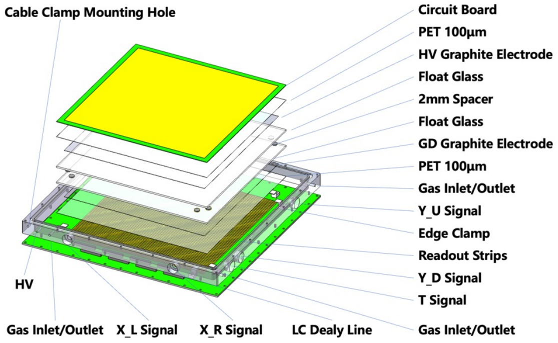
Experiment setup: *the joint HIRIBL-PKMu experiment*

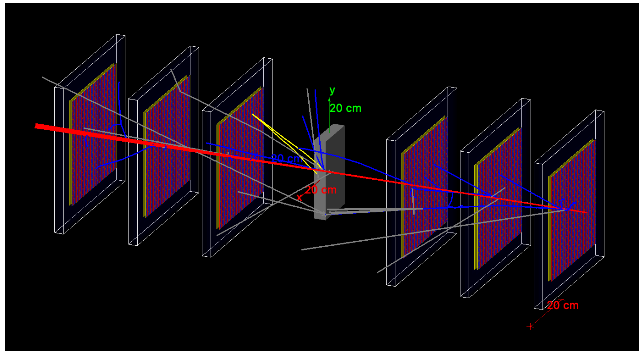
Geometry configuration of the PKMuon



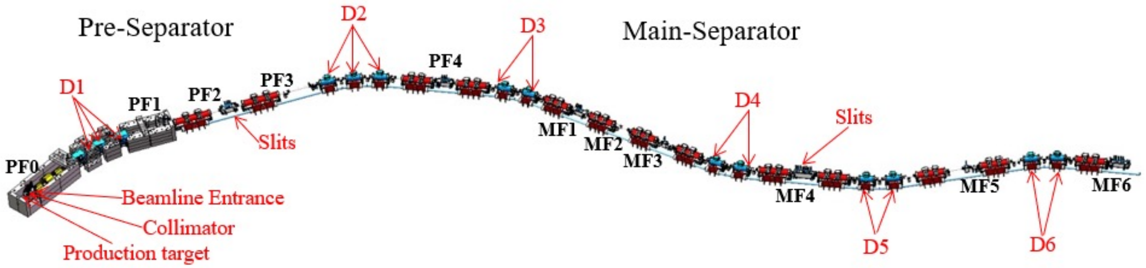


- ➔ **6 copies of RPCs** (3 RPCs per group)
- ➔ major distance: **500 mm** / minor distance: **200 mm**
- ➔ sensitive area: **280 mm × 280 mm**
- ➔ 2D pixel readout (space resolution of **0.5 mm**)



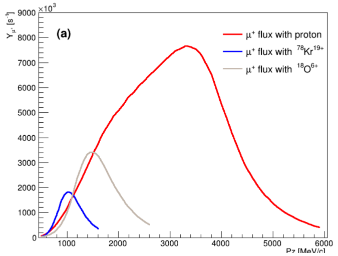


Schematic layout & Main parameters of the HIRIBL



Parameters	Value
Length [m]	192
RMS of beam spot at the target [mm]	$\sigma_x = 0.4$, $\sigma_y = 0.6$
Max. magnetic rigidity [Tm]	25
Max. angular acceptance [mrad]	x'=±30 , y'=±25
Max. momentum acceptance	±2%

	proton	$^{18}O^{6+}$	$^{78}Kr^{19+}$
μ^+ beam			
momentum [GeV/c]	3.5	1.5	1.0
flux intensity [μ^+/s]	8.2×10^6	3.5×10^6	1.8×10^6
muon purity	2.0%	0.80%	0.60%



https://arxiv.org/abs/2502.20915

Simulation framework

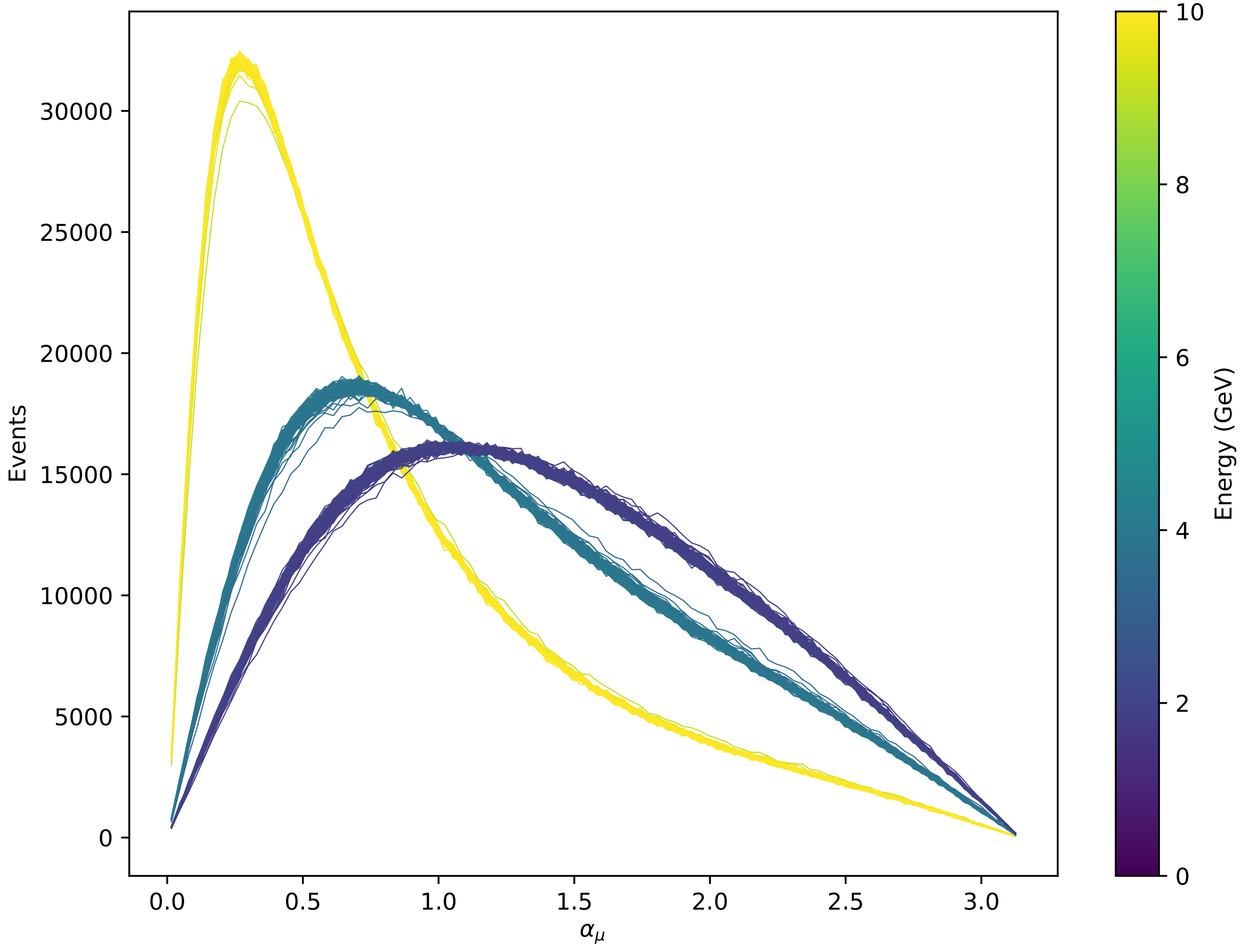
Efficient signal event generation based on MadGraph5_aMC@NLO v3.5.5

E_μ/GeV	$(m_{Z'})_{min}$/GeV	$(m_{Z'})_{max}$/GeV
10	0.001	0.040
4	0.001	0.020
2	0.001	0.010

LHE events: pre-acquire the cross section and kinematic distributions for interpolation

- ➔ Target setting : **210 mm * 120 mm * 30 mm Pb**
- ➔ Step limit : **1 mm**
- ➔ Scattering point : random sampling

- ➔ Energy points : **100**
- ➔ Event numbers at each energy point : **10^6**
- ➔ Total gird points : **10^8**

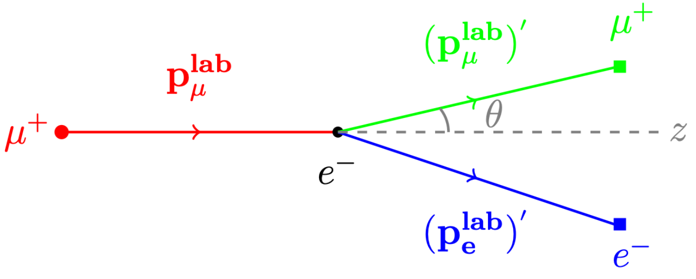


Distributions of the polar angle of the outgoing μ in the center of mass frame, colored by the varying E_μ

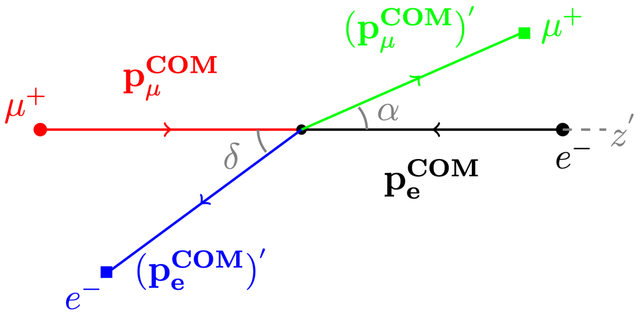
https://arxiv.org/abs/1405.0301

Simulation setup based on GEANT4 11.2.2

Reconstruction of three-body final state phase space



(a) lab frame



(b) COM frame

$$P_\mu + P_e + P_{Z'} = (E_{com}, 0,0,0)$$

$$(P_{\mu x} + P_{Z'x})^2 + (P_{\mu y} + P_{Z'y})^2 + (P_{\mu z} + P_{Z'z})^2 + m_e{}^2 = (E_{com} - E_\mu - E_e)^2$$

$$P_\mu \underbrace{P_{Z'} cos < \mu, Z' >}_{A} = \underbrace{\frac{E_{com}{}^2 + m_\mu{}^2 + m_{Z'}{}^2 - m_e{}^2}{2} - E_{com}E_{Z'}}_{B} \underbrace{- E_\mu(E_{com} - E_{Z'})}_{C}$$

$$(A^2 - C^2)P_\mu{}^2 - 2ABP_\mu + \left(B^2 - C^2 m_\mu{}^2\right) = 0$$

$$P_\mu = \frac{AB + \sqrt{A^2B^2 - (A^2 - C^2)(B^2 - C^2 m_\mu{}^2)}}{(A^2 - C^2)}$$

$$R = P_e{}^2 + m_e{}^2 - E_e{}^2 \sim 0.1\%$$

Simulation setup based on GEANT4 11.2.2

Algorithm 1: Efficient $\mu e \to \mu e Z'$ event generation

function GenerateMuEZprime(E_μ)
 $E_{\mu1}, E_{\mu2}, \sigma_1, \sigma_2, H_1^*, H_2^* \leftarrow$ AdjacentGridPoints(E_μ);
 if E_μ is out of the grid range **then**
  return no $\mu e \to \mu e Z'$ happens;
 end if
 $w_1 \leftarrow \frac{E_\mu - E_{\mu2}}{E_{\mu1} - E_{\mu2}}$, $w_2 \leftarrow \frac{E_{\mu1} - E_\mu}{E_{\mu1} - E_{\mu2}}$;
 $\sigma \leftarrow w_1\sigma_1 + w_2\sigma_2$;
 if Random(0, 1) $< w_1$ **then**
  $\vec{p}_\mu, \vec{p}_e, \vec{p}_{miss} \leftarrow H_1^*$.Sample(); // LAB
 else
  $\vec{p}_\mu, \vec{p}_e, \vec{p}_{miss} \leftarrow H_2^*$.Sample();
 end if
 $\vec{p}_\mu, \vec{p}_e, \vec{p}_{miss}, \gamma, \beta, \alpha, \phi \leftarrow$ Kinematics(E_μ); // COM
 $p_{\mu x} \leftarrow p_\mu \sin\alpha\cos\phi$, $p_{\mu y} \leftarrow p_\mu \sin\alpha\sin\phi$;
 $p_{\mu z} \leftarrow p_\mu \cos\alpha$;
 $p_{ex} \leftarrow -p_{\mu x} - p_{miss\_x}$, $p_{ey} \leftarrow -p_{\mu y} - p_{miss\_y}$;
 $p_{ez} \leftarrow -p_{\mu z} - p_{miss\_z}$;
 $p_{(\mu/e)x\_out} \leftarrow p_{(\mu/e)x}$; // Boost
 $p_{(\mu/e)y\_out} \leftarrow p_{(\mu/e)y}$;
 $p_{(\mu/e)z\_out} \leftarrow \gamma\left(p_{(\mu/e)z} + \beta E_{(\mu/e)}/2\right)$;
 $\vec{p}_{\mu\_out} \leftarrow$ ThreeVector($p_{\mu x}, p_{\mu y}, p_{\mu z}$);
 $\vec{p}_{\mu\_out} \leftarrow \vec{p}_{\mu\_out}$.RotateZAxisTo($\hat{p}_\mu$);
 $\vec{p}_{e\_out} \leftarrow$ ThreeVector(p_{ex}, p_{ey}, p_{ez});
 $\vec{p}_{e\_out} \leftarrow \vec{p}_{e\_out}$.RotateZAxisTo($\hat{p}_e$);
 return $\sigma, \vec{p}_{\mu\_out}, \vec{p}_{e\_out}$;
end function

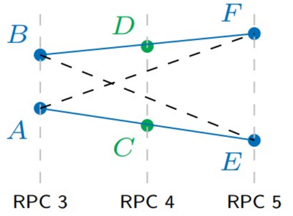
- ✓ Signal process is appended to the inclusive physics list FTFP_BERT
- ✓ Weight sampling is performed directly on the histogram of 4-momentum & cross section
- ✓ Signal proportion is scaled to $10^{-3} \sim 10^{-2}$

Reconstruction scheme 1

- ➔ Energy-weighted averaging of electron hits
- ➔ Separate muon and electron through PID
- ➔ Electron hits selection: reaction point & hits on RPC 3/4
- ➔ Hits pattern matching on RPCs [1,1,1,2,2,2]
- ➔ Fit lines of muon & electron separately

Reconstruction scheme 2

- ➔ Energy-weighted averaging of electron hits
- ➔ Hits pattern matching on RPCs [1,1,1,2,2,2]
- ➔ Minimum χ^2 & fit lines



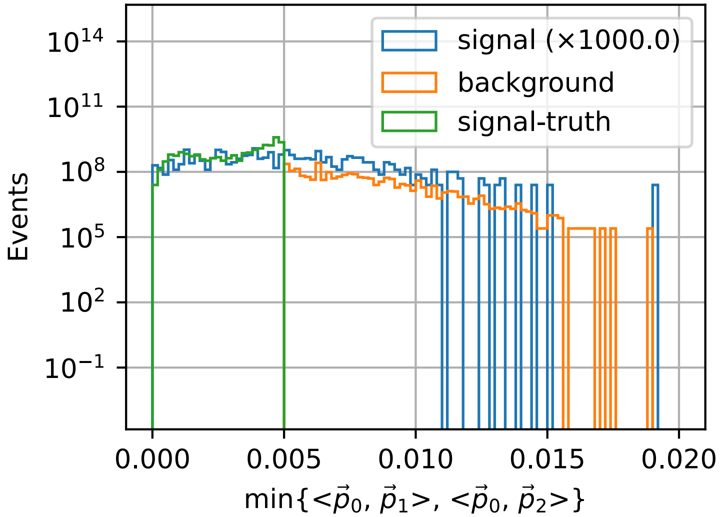
https://geant4.web.cern.ch/docs/#for-toolkit-developers
https://www.sciencedirect.com/science/article/abs/pii/S0168900203013688?via%3Dihub
https://www.sciencedirect.com/science/article/pii/S0168900216306957?via%3Dihub
https://ieeexplore.ieee.org/document/1610988/
https://arxiv.org/abs/1405.0301
https://arxiv.org/abs/2410.20323

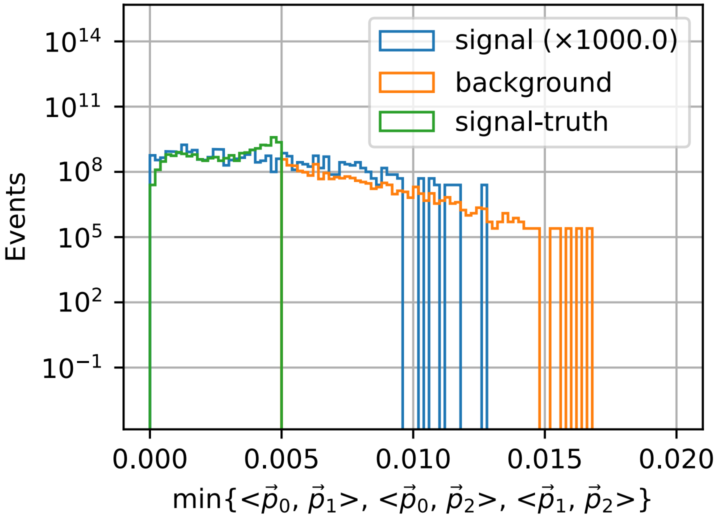
Event reconstruction and selection

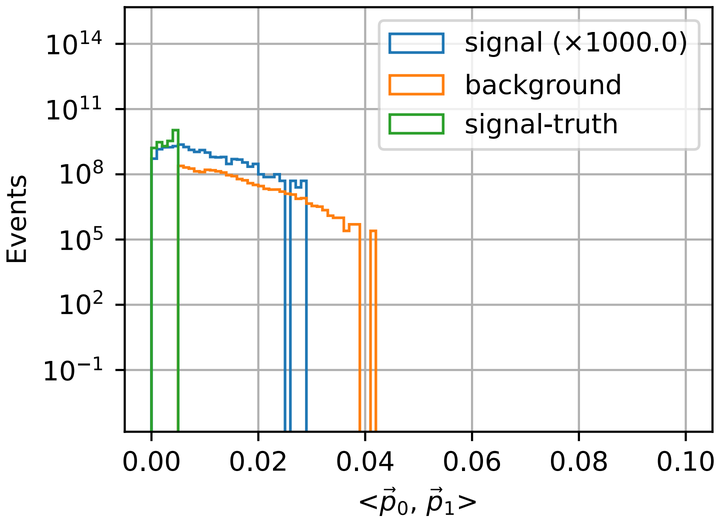
Reconstruction scheme 1

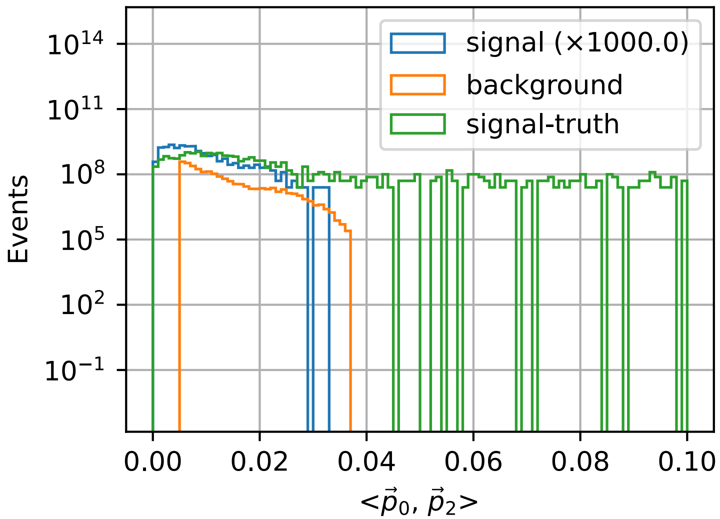
- ➔ $E_\mu = 10\ \text{GeV},\ m_{Z'} = 10\ \text{MeV}$
- ➔ Event selection: $\chi^2 < 6$

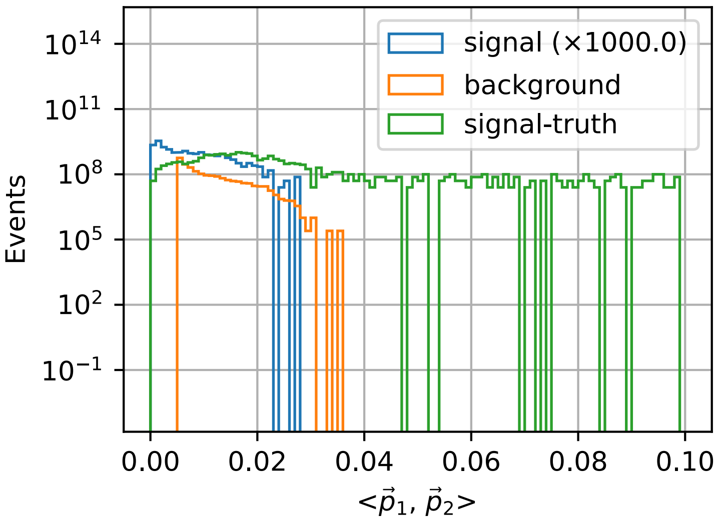
  $$\min_{i\neq j}\langle\overrightarrow{p_i},\overrightarrow{p_j}\rangle \geq 0.005$$
- ➔ Yield: 10^{10}(normalized to $2.5\times10^{14} \sim 1y$)
- ➔ The signal in the large-angle scattering area is not significant enough











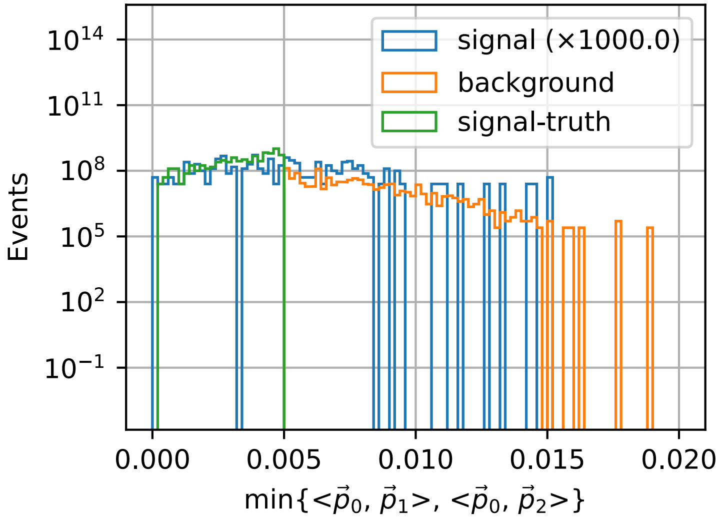
Event reconstruction and selection

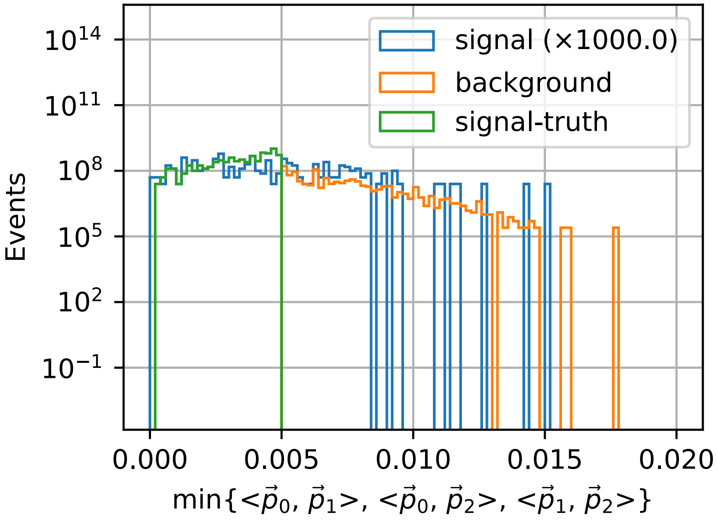
Reconstruction scheme 2

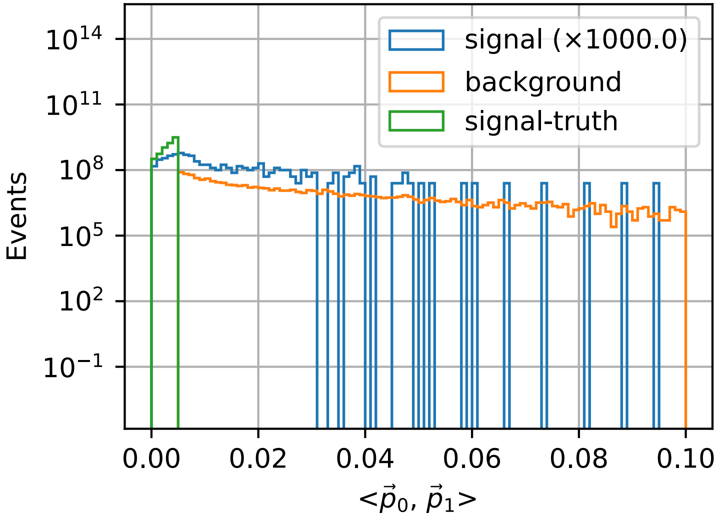
- ➔ $E_\mu = 10\ \text{GeV},\ m_{Z'} = 10\ \text{MeV}$
- ➔ Event selection: $\chi^2 < 6$

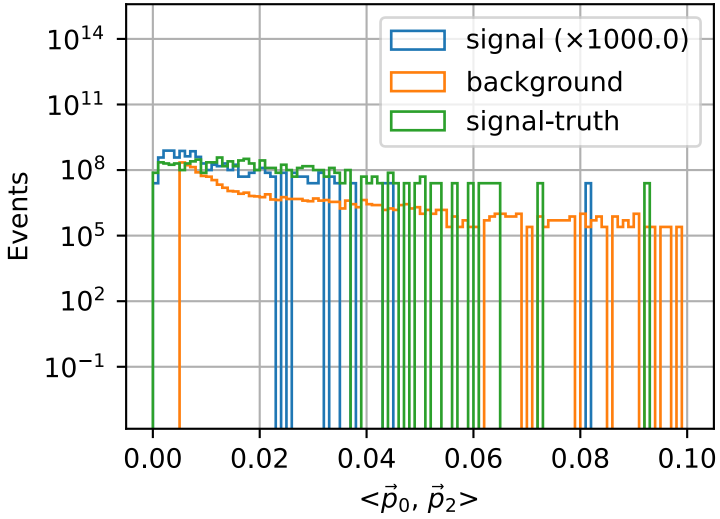
$$\min_{i\neq j}\langle\vec{p_i},\vec{p_j}\rangle \geq 0.005$$

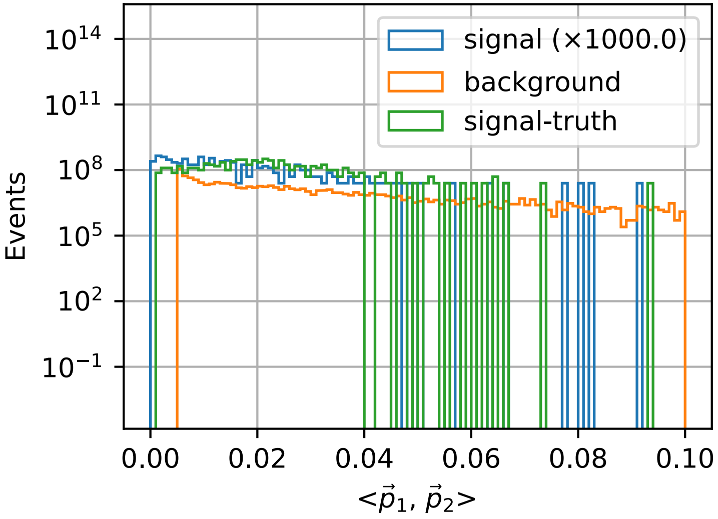
- ➔ Yield: 10^{10}(normalized to $2.5\times10^{14} \sim 1y$)
- ➔ The signal rate is improved compared with scheme 1



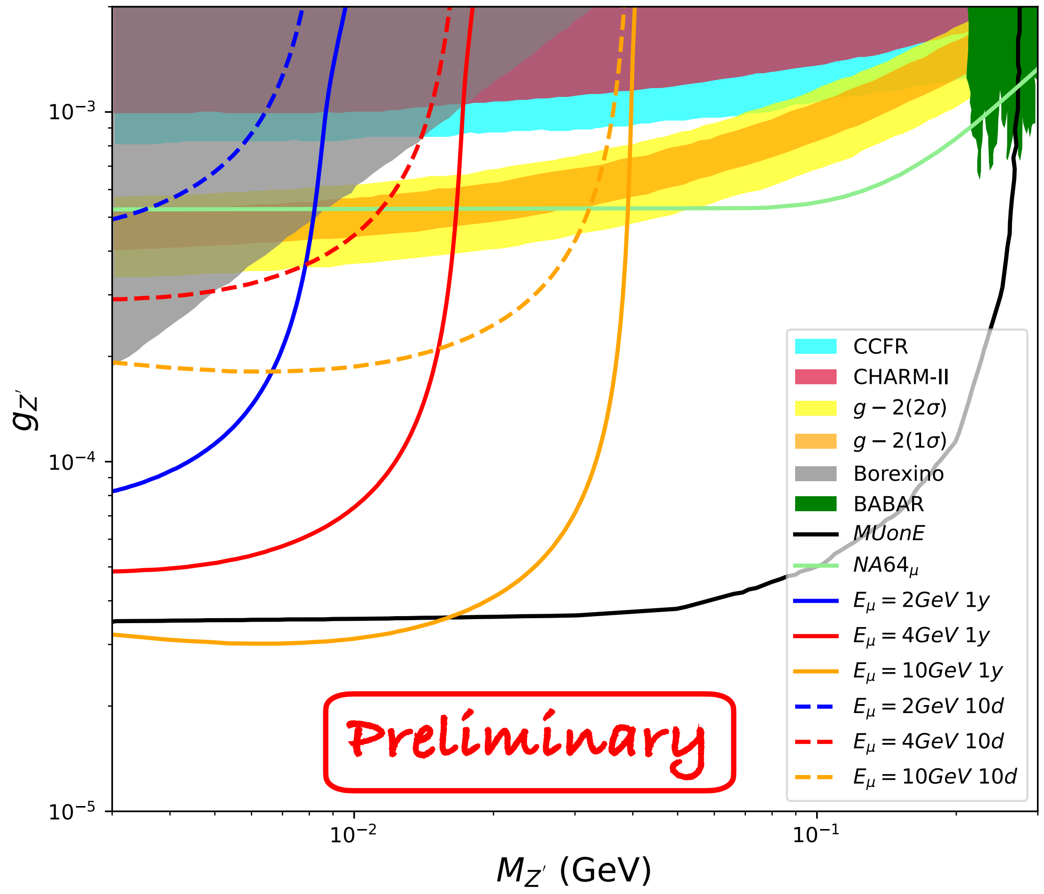








Results



Preliminary result of upper limit

based on MadGraph5_aMC@NLO v3.5.5

- ➔ This is a preliminary simulation performed at the **generator level** using MadGraph5_aMC@NLO v3.5.5. As illustrated in the figure, **1–10 GeV muon beam is expected to provide enhanced sensitivity to the sub-GeV Z′ region**, exceeding both current experimental constraints and theoretical projections.

- ➔ Due to **limitations in the detector response to electrons**, we observe that the signal rate in the large-angle scattering region remains suboptimal after electron reconstruction. This indicates potential for further improvement in sensitivity. As a next step, we plan to apply **new detector configurations**—such as the integration of **silicon microstrip**, which offers improved electron detection performance—and to develop **more advanced electron reconstruction algorithms** aimed at optimizing signal efficiency.

Summary & Outlook

➔ We study the search potential for **Z' boson** based on a muon on-target experiment proposal, through $\mu e \rightarrow \mu e X$, with X decays invisibly.

➔ We focus on the usage of the **1-10 GeV muon beam** from the HIRIBL-HIAF facility and aim to find high sensitivity on **10 MeV Z' range**.

➔ By generating samples using MadGraph5_aMC@NLO v3.5.5 and simulating the RPC-based detector system of the PKMuon experiment using GEANT4 11.2.2, we have successfully achieved the generation of signal and background events.

➔ To enhance the accuracy of **electron reconstruction** and improve signal-to-background separation, particularly in the large-angle scattering region, we are working on optimizing detector simulation configurations and implementing more advanced reconstruction algorithms suited to the characteristics of the PKMuon experiment.

Thank You

Backup