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

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

Outline

- ➔ Introduction and Motivation
- ➔ Experiment setup: the joint HFRS-PKMu experiment
- ➔ Simulation framework
  - ❖ I. Efficient signal event generation
  - ❖ II. Simulation setup
  - ❖ III. Event reconstruction and selection
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PKμ @HFRS

Introduction and Motivation

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

$\mu\, e \rightarrow \mu\, e\, \nu\bar{\nu}$

Lagrangian

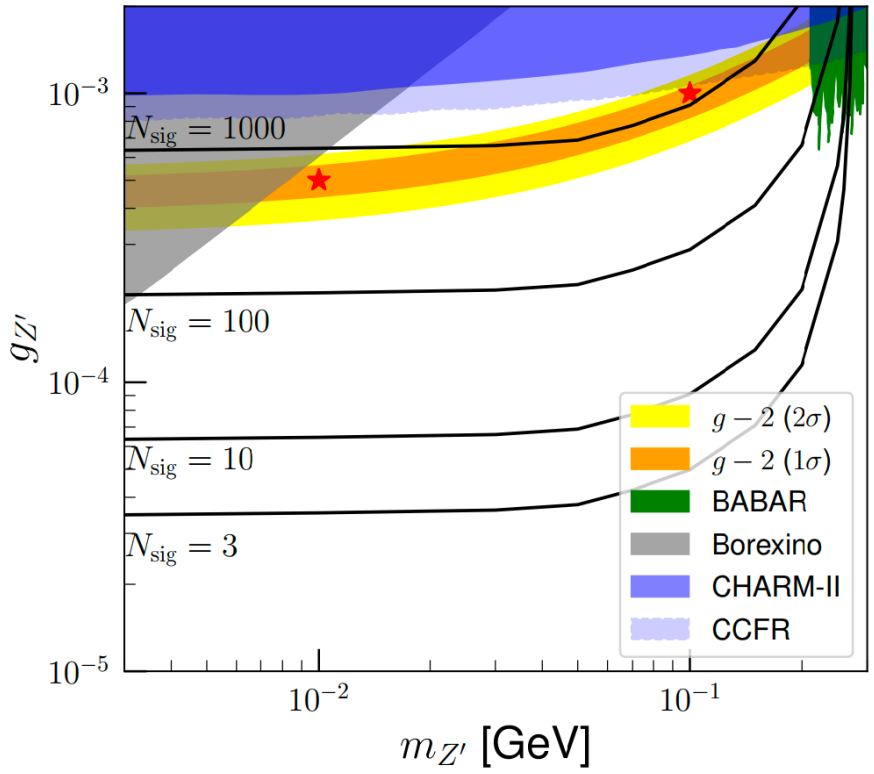
$$\mathcal{L}_{Z'} = -gZ'_\mu \left(\bar{L}_2\gamma^\mu L_2 + \bar{l}_2\gamma^\mu l_2 - \bar{L}_3\gamma^\mu L_3 - \bar{l}_3\gamma^\mu l_3\right)$$

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

Decay

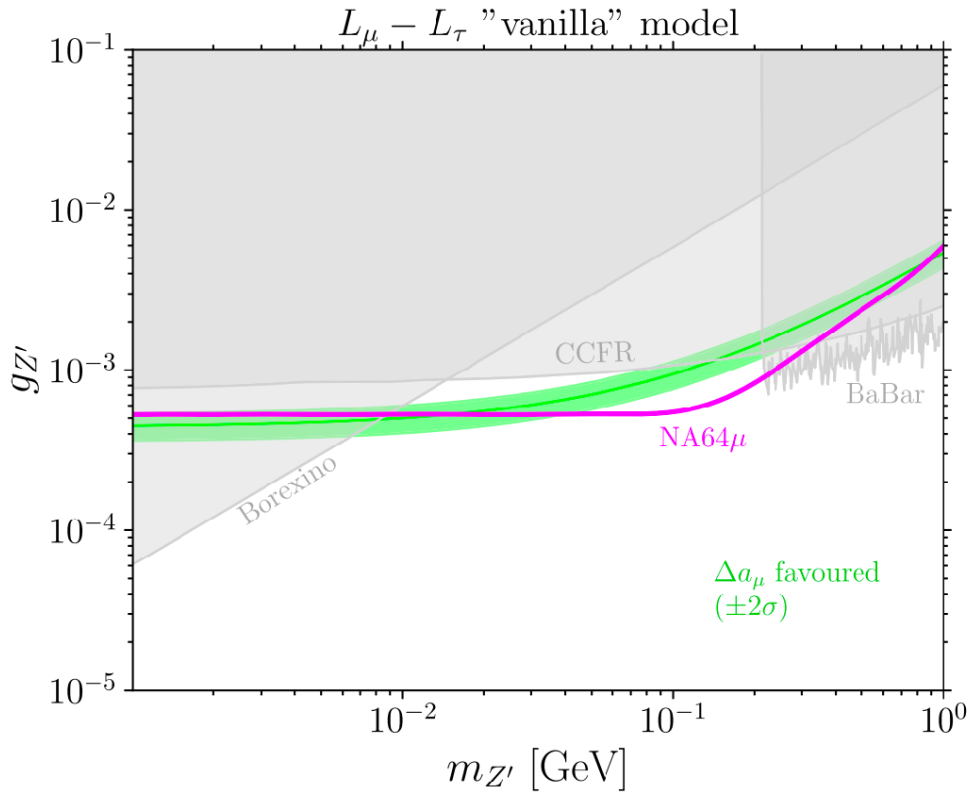
$$\Gamma(Z' \rightarrow \bar{\nu}\nu) = \frac{\alpha_{Z'} m_{Z'}}{3}$$

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



MUonE

https://arxiv.org/abs/2109.10093

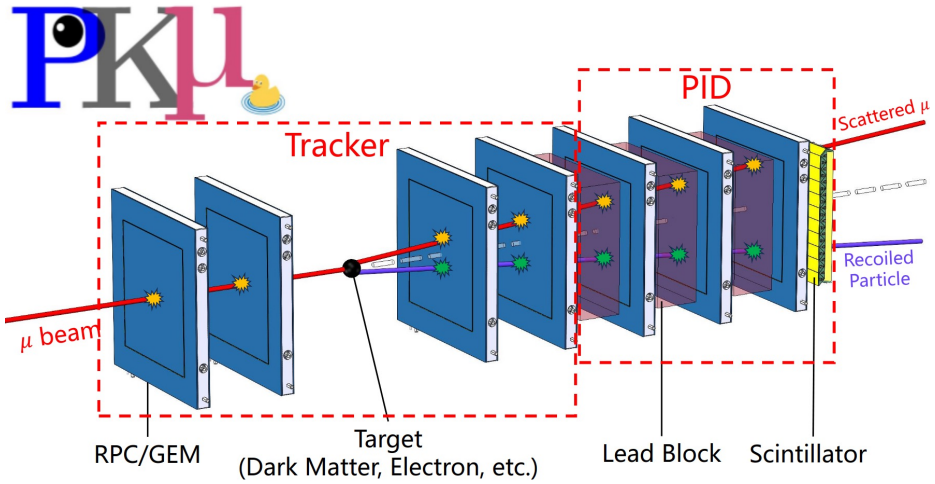


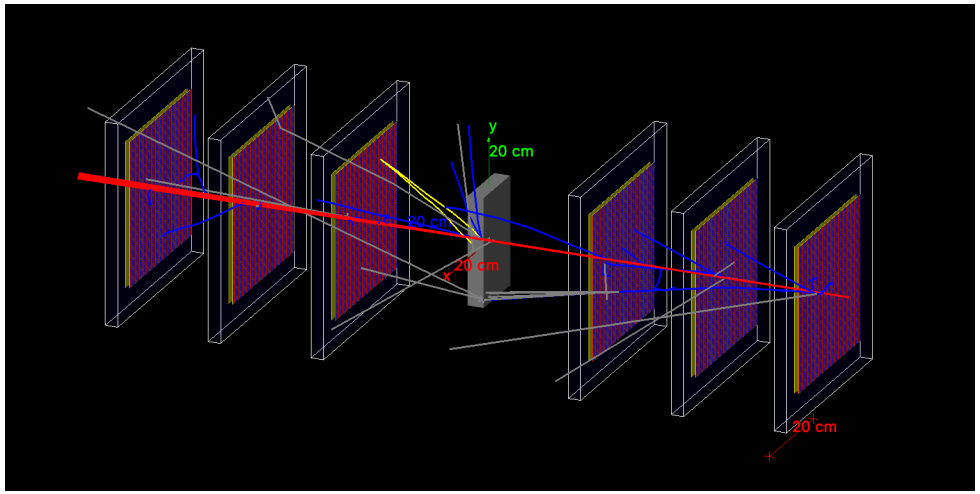
NA64

https://doi.org/10.1103/PhysRevLett.132.211803

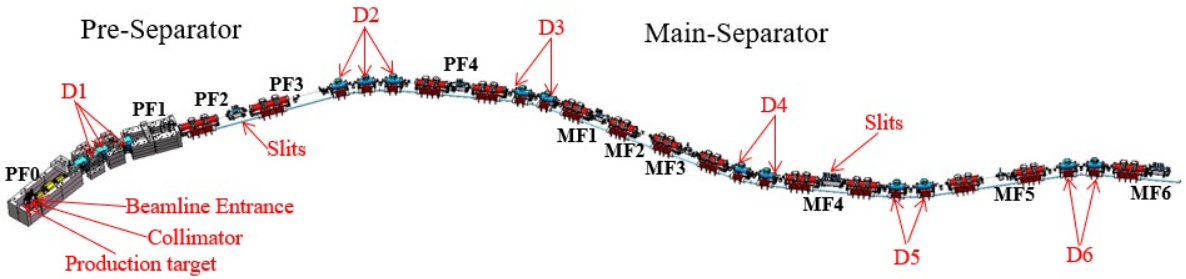
Experiment setup: *the joint HFRS-PKMU experiment*

➔ Geometry configuration of the PKMuon





➔ Schematic layout of the HFRS



➔ Main parameters of the HFRS

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%

https://arxiv.org/abs/2502.20915

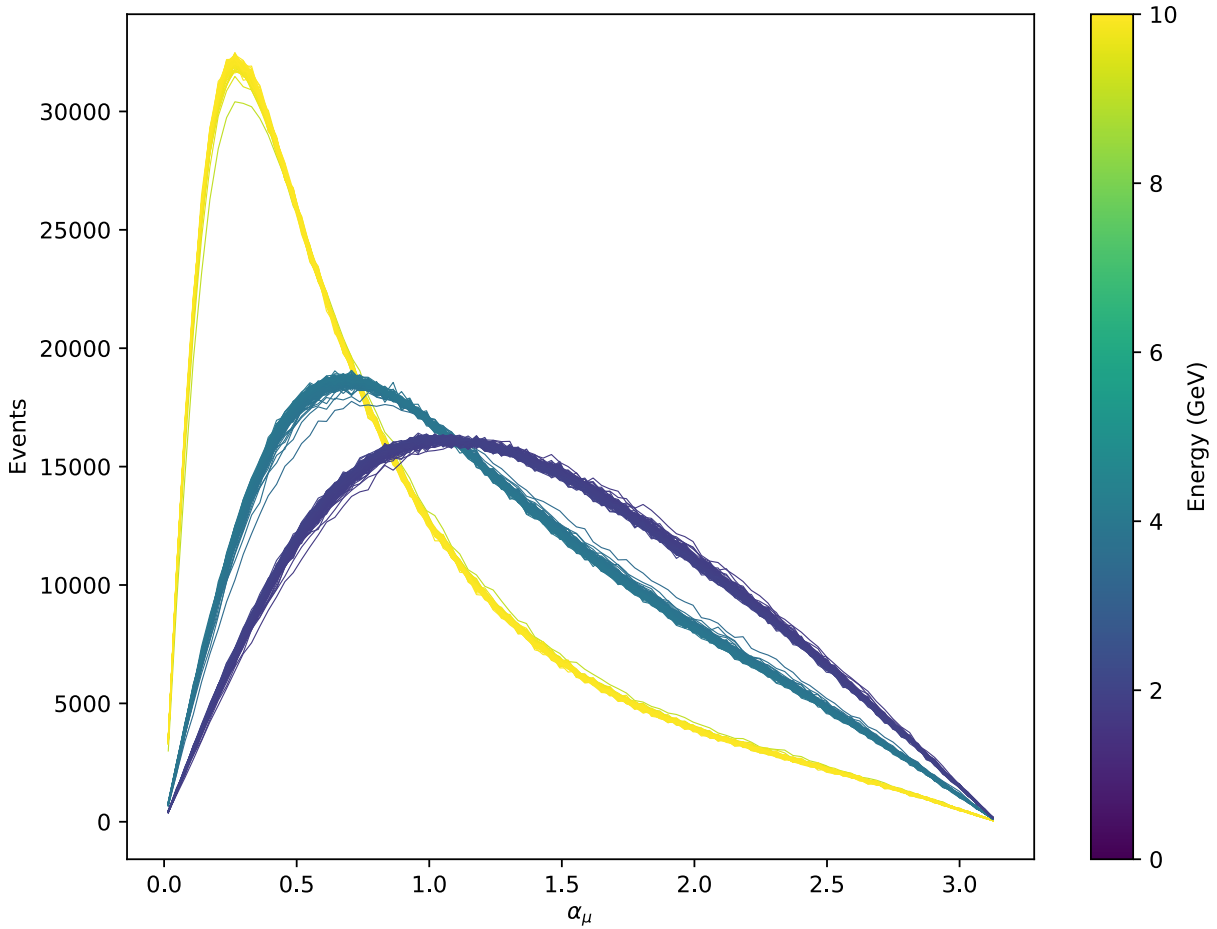
Simulation framework

MC simulation of RPC-based detector based on Madgraph & Geant4

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

- ➔ 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

MC simulation of RPC-based detector based on Madgraph & Geant4

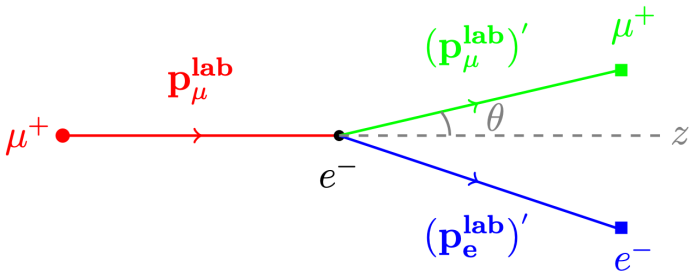
Sampler: Linear interpolation

$\mu^+e^- \to l^+l^-$ ⟹ $\mu\, e \to \mu\, e$

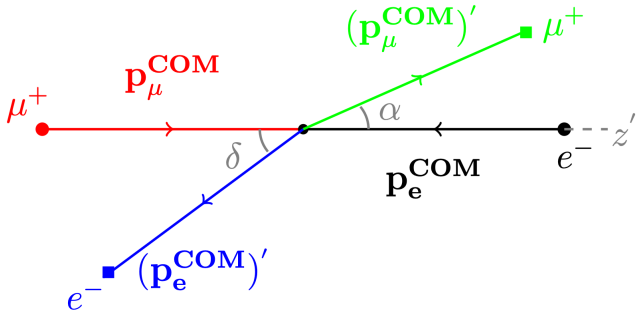
function GenerateMuELL($E_\mu, \vec{p}_\mu, m_\ell$)
  $E_{\mu 1}, E_{\mu 2}, \sigma_1, \sigma_2, H_1, H_2 \leftarrow$ AdjacentGridPoints(E_μ);
  if E_μ is out of the grid range **then**
    return no $\mu^+e^- \to \ell^+\ell^-$ happens;
  end if
  $w_1 \leftarrow \frac{E_\mu - E_{\mu 2}}{E_{\mu 1} - E_{\mu 2}}$, $w_2 \leftarrow \frac{E_{\mu 1} - E_\mu}{E_{\mu 1} - E_{\mu 2}}$;
  $\sigma \leftarrow w_1\sigma_1 + w_2\sigma_2$; // 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

https://arxiv.org/abs/2410.20323

Reconstruction of momentum & polar angle



(a) lab frame



(b) COM frame

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

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

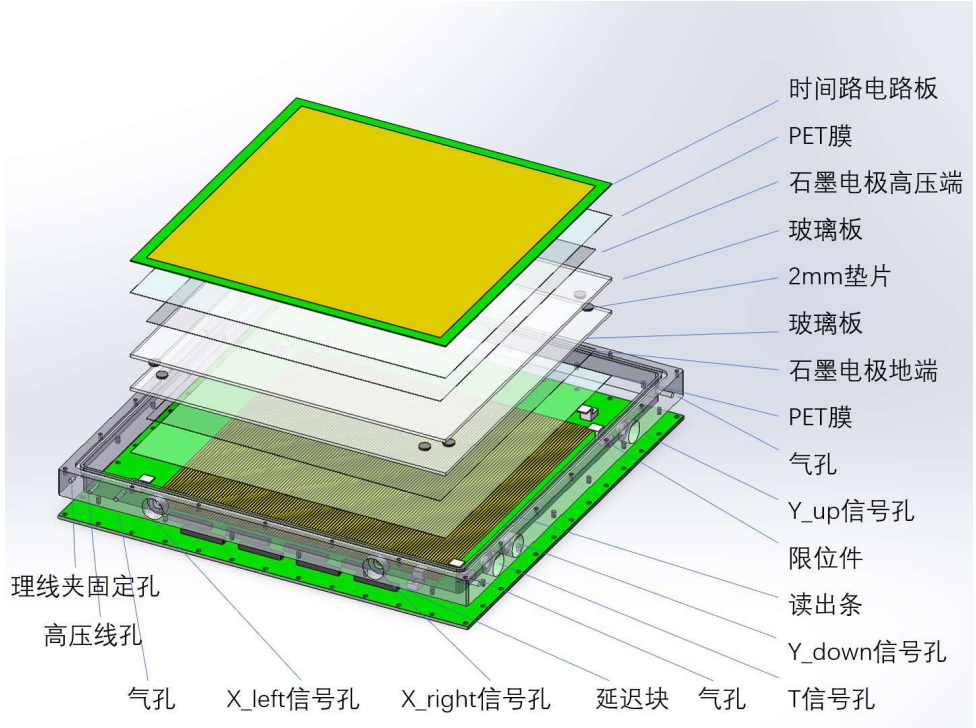
$$P_\mu \underbrace{P_{Z'} cos < \mu, Z' >}_{A} = \underbrace{\frac{{E_{com}}^2 + {m_\mu}^2 + {m_{Z'}}^2 - {m_e}^2}{2} - E_{com} E_{Z'}}_{B} \underbrace{- E_\mu (E_{com} - E_{Z'})}_{C}$$

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

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

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

Reconstruction of momentum & polar angle



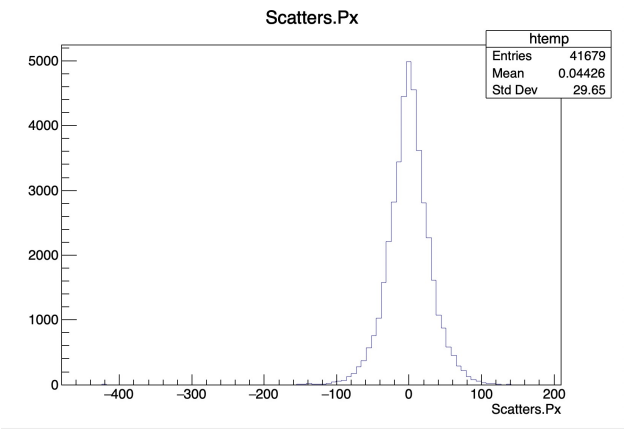
- ➔ Incoming muon: 3 hits on RPCs (layer 1, 2, 3) ✅
- ➔ Outgoing muon :3 hits on RPCs (layer 4, 5, 6) ✅
- ➔ Outgoing electron :3 hits on RPCs (layer 4, 5, 6) ❓

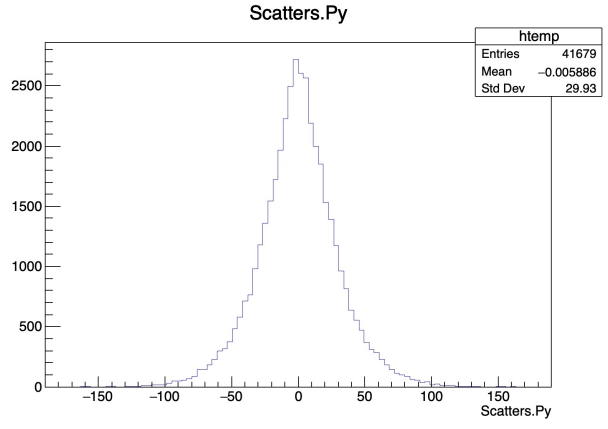
```
event_95:
  - [0, 1, 2, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, ..., 3, 3, 3, 3, 3, 3, 3, 4, 4, 4, 4, 5]
  - [-13, -13, -13, 11, 11, 11, 11, 11, 11, ..., 11, 11, 11, -13, 11, 11, 11, -13]
  - [0.25, 0.25, 0.25, -3.75, -3.25, -2.75, ..., 1.25, 0.25, 0.75, 1.25, 1.25, 0.75]
  - [-0.25, -0.25, -0.25, -3.25, -3.25, -2.25, ..., 0.25, 0.25, -0.25, 0.25, 0.75]
  - [-658, -458, -258, 242, 242, 242, 242, ..., 242, 242, 442, 442, 442, 442, 642]
  - [1.82, 1.09, 1.3, 0.24, 0.0969, 0.00608, ..., 0.218, 2.16, 0.395, 0.0742, 2.48]
event_96:
  - [0, 1, 2, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 4, 5, 5, 5]
  - [-13, -13, -13, 11, 11, 11, 11, 11, 22, ..., 11, 11, -13, -13, -13, 11, 11, 11]
  - [-0.25, 0.25, 0.25, -26.8, -26.2, -25.8, ..., 0.75, 0.75, 0.25, 0.75, 0.75]
  - [-0.25, -0.25, -0.75, -19.8, -19.8, ..., -2.75, -3.75, -5.25, -5.75, -5.25]
  - [-658, -458, -258, 242, 242, 242, 242, ..., 242, 242, 242, 442, 642, 642, 642]
  - [2.42, 1.76, 0.989, 0.119, 0.452, 0.377, ..., 0.981, 1.01, 2.46, 0.202, 0.485]
```

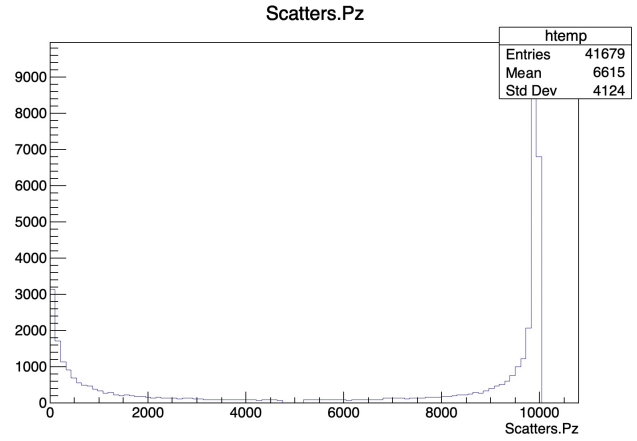
- ➔ New RPC readout: 2D pixel readout
- ➔ Spatial resolution: 5 mm
- ➔ Electronic signal confusion ！！！

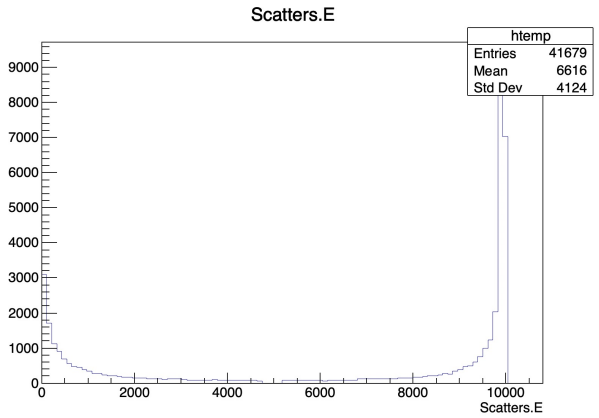
Reconstruction of momentum & polar angle

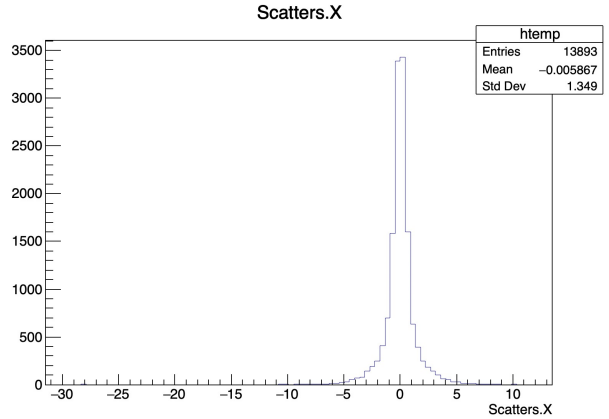
- ➔ E_μ = 10 GeV
- ➔ m_μ = 10 MeV
- ➔ Events number: 10^6
- ➔ Single rate: ~1%

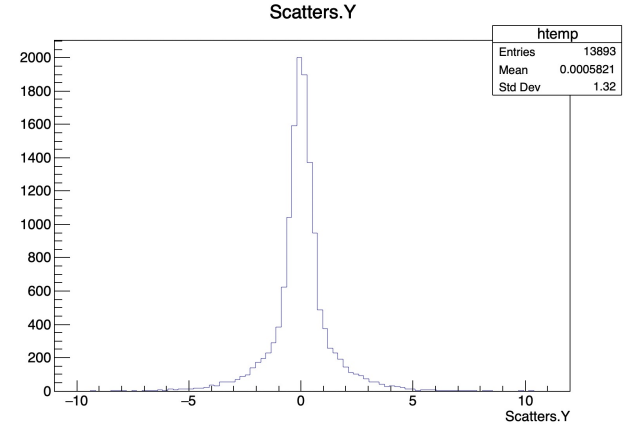


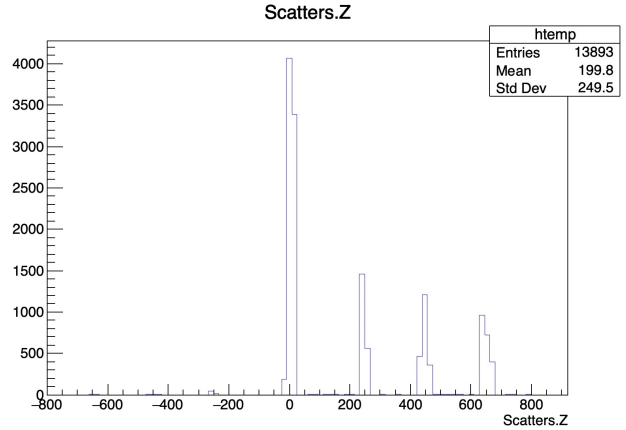




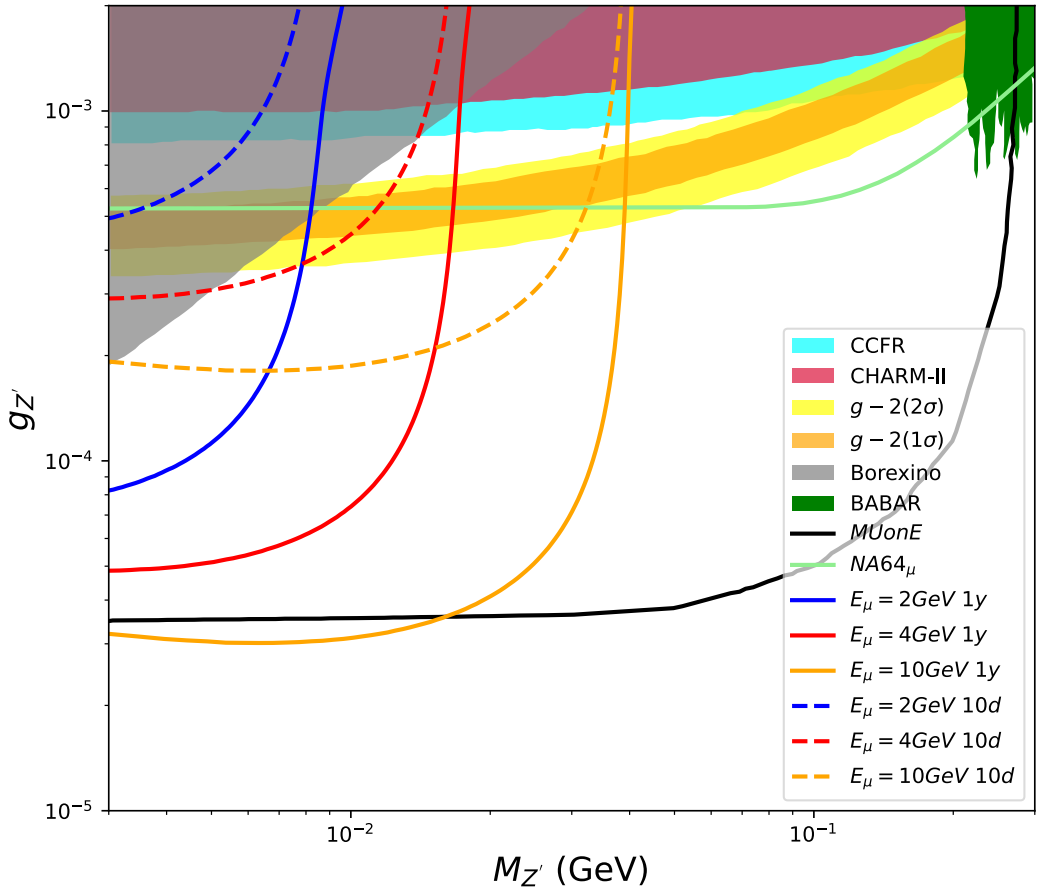








Results



Preliminary result based on MadGraph

Samples — *Done*

- ➔ Muon energy: 3 (10 GeV, 4 GeV, 2 GeV)
- ➔ Zprime mass: 3 * 100
- ➔ Event number of each: 10^7
- ➔ Total statistics: 3 * 10^9 (non-normalized)

Analysis — *Ready*

- ➔ Reconstruct positions and angles
- ➔ Minimal Chi2 matching
- ➔ 3D line fit
- ➔ Compute process contributions
- ➔ Drop multiple scattering events
- ➔ Store MC truth
- ➔ Split signal and background

Summary & Outlook

- ➔ Search for Z' gauge boson (in $L_\mu - L_\tau$ vanilla model) through $\mu\, e \rightarrow \mu\, e\, \nu\bar{\nu}$
- ➔ Combine HIAF-HFRS muon beam & PKMuon RPC-based detector system
- ➔ Generate samples using Madgraph & Geant4 at 10^9 muon yield on target
- ➔ Reconstruct momentum & angle of muon/eletron
- ➔ Split signal and background by MC truth

Some kind of cut like coordinate?
Scintillator?
2 layer or 3 layer?
Hits fitting?
Any suggestions are welcome!

Stronger sensitivity for Z' at low mass region around 10 MeV!

Still working on it ^_^

Backup