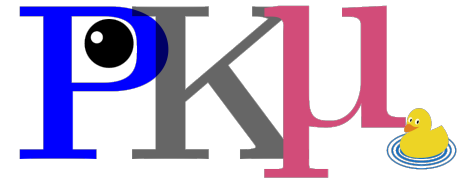




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# Search for light dark sectors with GeV muon beams

Zijian Wang

Peking University

On behalf of the PKMuon Collaboration

[Phys. Rev. D 113, 072008 \(2026\)](#)

# Outline

- Introduction and Motivation
- The Joint HIRIBL-PKMu Experiment
- Event Generation and Simulation
- Event Reconstruction and Selection
- Results
- Summary and Outlook



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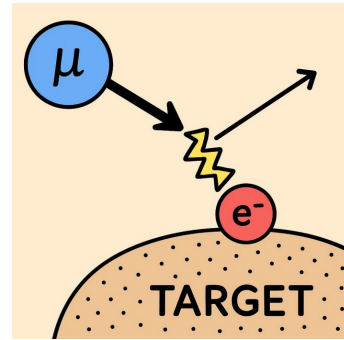
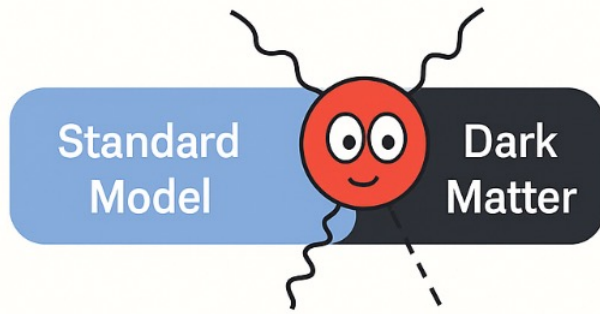


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# Introduction and Motivation

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



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

$$J_{\mu-\tau}^\alpha = (\bar{\mu}\gamma^\alpha\mu - \bar{\tau}\gamma^\alpha\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu - \bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau)$$

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

- Dark matter remains one of the deepest unsolved puzzles in particle physics. In minimal sub-GeV thermal freeze-out scenarios, the **dark sector** must contain light mediators with feeble couplings to the Standard Model — making their detection both essential and experimentally challenging.

- One of the most well-motivated and theoretically clean example is the vanilla  $L_\mu - L_\tau$  model, where a new gauge boson  $Z'$  emerges from a broken symmetry  $U(1)_{L_\mu - L_\tau}$ . It couples exclusively to  $\mu$ ,  $\tau$ , and their neutrinos — not to electrons or quarks at tree level. Naturally, muon beams are the ideal tool to probe this.

- Within this model,  $Z'$  decays invisibly into neutrinos. The signal is a missing energy event: a  $\mu$  scatters off an atomic  $e$ , and the outgoing particles carry less momentum than expected — the missing piece is carried away by the undetected  $Z'$ .

- In this work, We use a **1–10 GeV** muon beam from the **HIRIBL** facility at HIAF. The low center-of-mass energy is a deliberate advantage: it provides world-leading sensitivity to very light bosons, particularly in the  **$\mathcal{O}(10\text{MeV})$**  mass region that higher-energy experiments struggle to access.

<https://arxiv.org/abs/2409.10128>

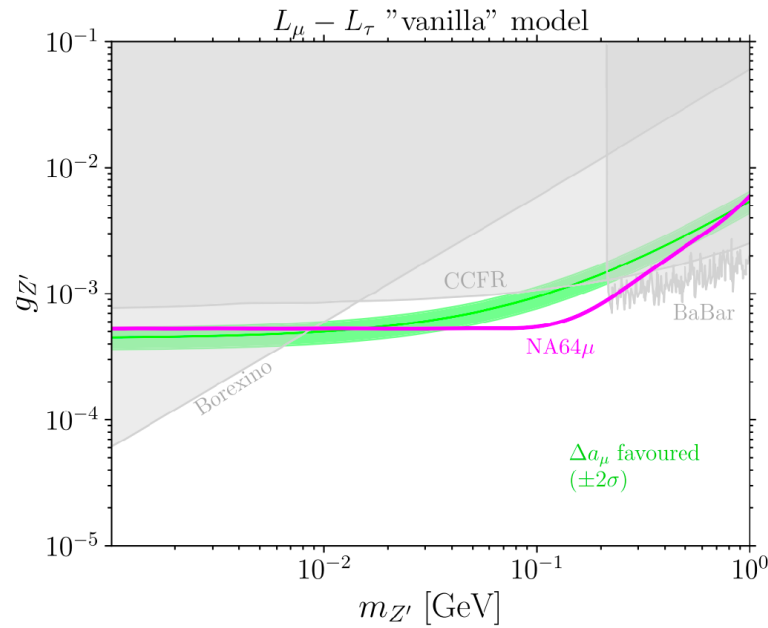
<https://doi.org/10.1103/PhysRevLett.132.211803>



**NA64- $\mu$**

Process  
 $\mu N \rightarrow \mu N Z'$

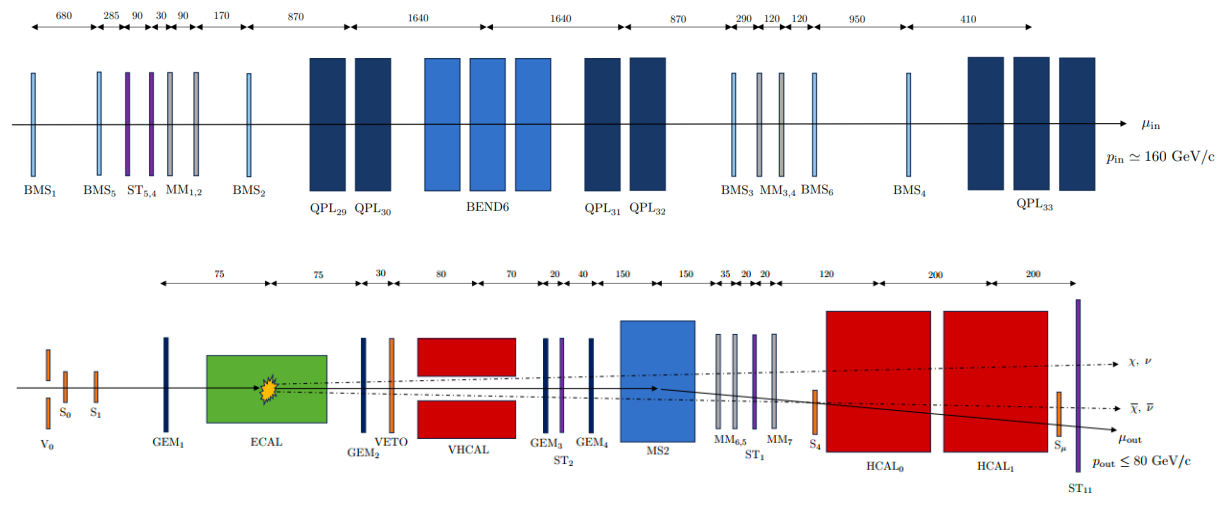
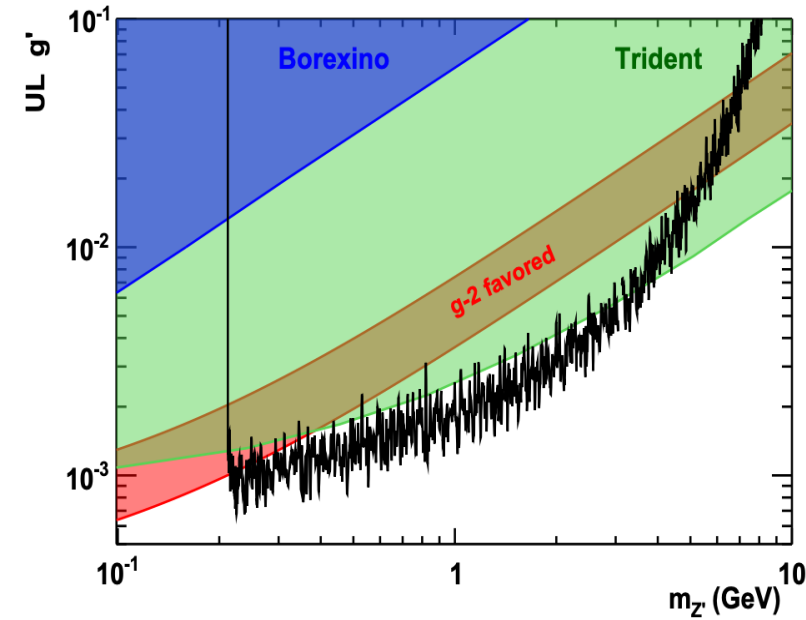
Beam Energy  
160 GeV



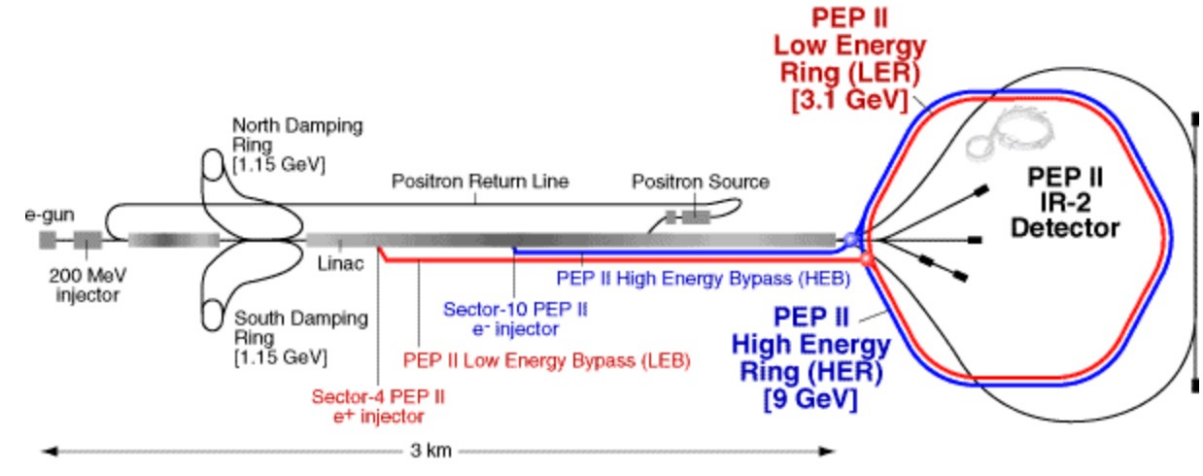
**BABAR**

Process  
 $e^+e^- \rightarrow \mu^+\mu^-Z'$

Collision Energy  
10.58 GeV



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

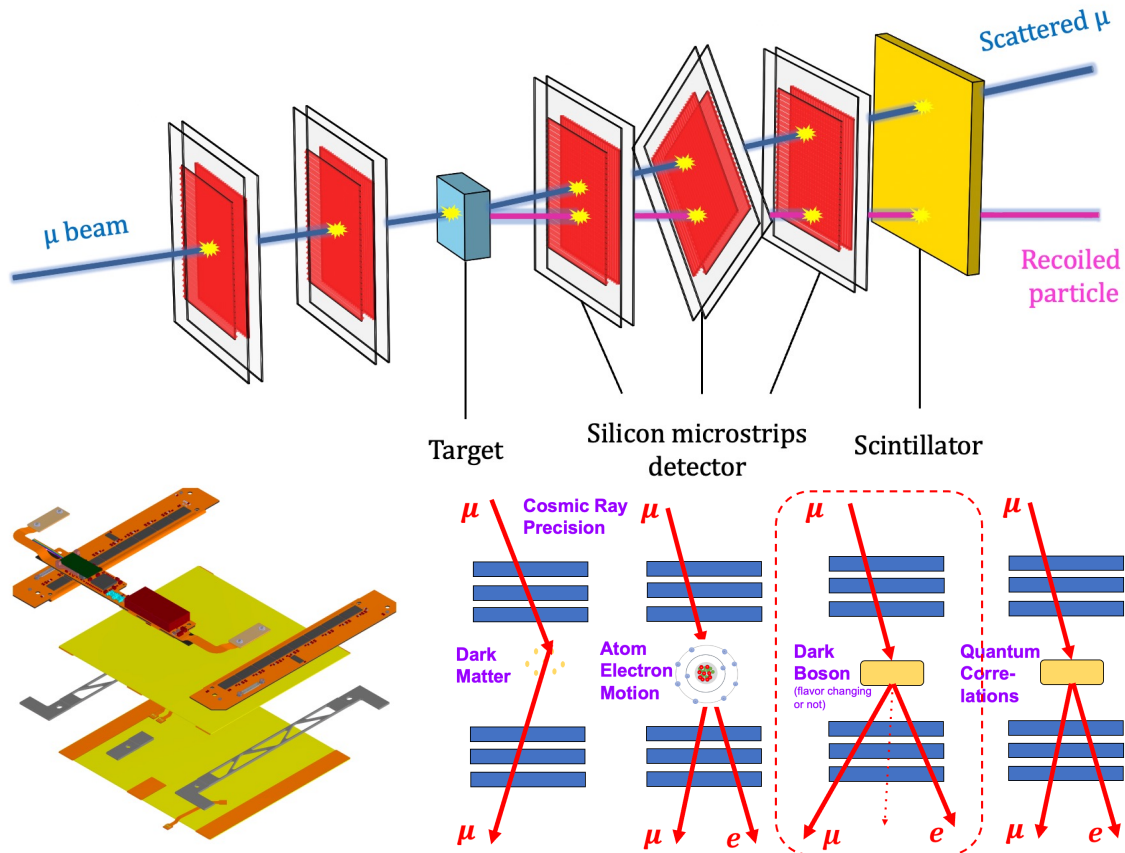


<https://arxiv.org/abs/1606.03501>

# The Joint HIRIBL-PKMu Experiment

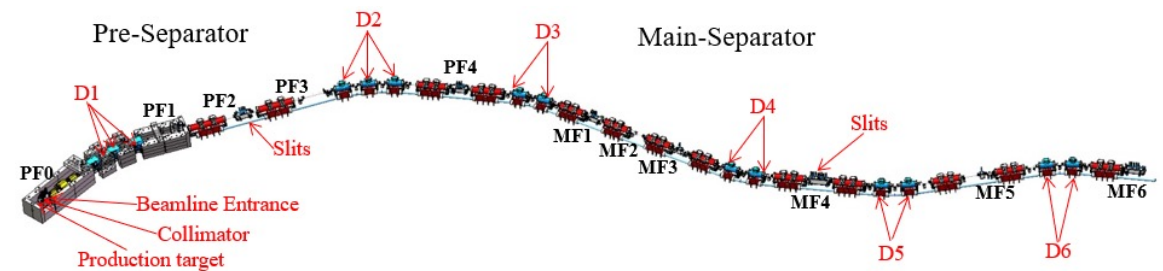
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# Geometry Configuration of the PKMu (MUonE\_mimic version)



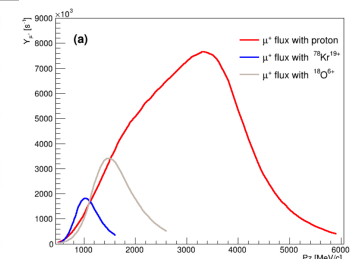
- 5 copies of **silicon strips** (2 upstream & 3 downstream)
- major distance: 500 mm / minor distance: 200 mm
- sensitive area: 100 mm × 100 mm
- **2S module** readout
- Target setting : 100 mm \* 100 mm \* 20 mm **graphite**

# 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]	$x' = \pm 30, y' = \pm 25$
Max. momentum acceptance	$\pm 2\%$

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



<https://arxiv.org/abs/2502.20915>

# Event Generation and Simulation

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## Work flow for event generation

Algorithm 1. Efficient  $\mu e^- \rightarrow \mu e^- Z'$  event generation.

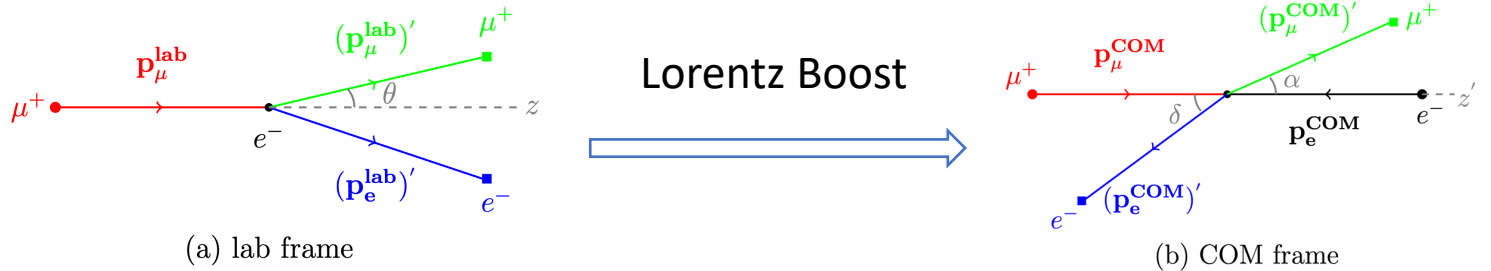
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function GenerateMuEZprime ( $E_\mu$ )
   $E_{\mu 1}, E_{\mu 2}, \sigma_1, \sigma_2, H_1, H_2 \leftarrow$  AdjacentGridPoints( $E_\mu$ );
  if  $E_\mu$  is out of the grid range then
    return no  $\mu e^- \rightarrow \mu e^- Z'$  happens;
  end if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

<https://geant4.web.cern.ch/docs/#for-toolkit-developers>

<https://arxiv.org/abs/1405.0301>

<https://arxiv.org/abs/2410.20323>



- Signal process is appended to the inclusive physics list **F'TFP\_BERT**, including all relevant electromagnetic and hadronic backgrounds.
- **Weight sampling** is performed directly on the histogram of momentum & cross section.
- $10^9$  events are generated then scaled to  $2.5 \times 10^{14} \sim$  one-year run.

MadGraph5\_aMC@NLO (v3.5.5) generates  $\mu e \rightarrow \mu e Z'$  events across a grid of beam energies  $E_\mu$  and  $Z'$  masses  $m_{Z'}$ . 1

Events are produced with  $g_{Z'} = 1$  and later reweighted to any coupling via a **global cross-section factor**. 2

GEANT4 (v11.2.2) simulates detector interactions, with  $\mu e \rightarrow \mu e Z'$  implemented as a discrete process following the generated kinematics. 4

**Energy interpolation** between grid points ensures smooth cross-section and kinematic distributions, preserving angular correlations while accelerating generation. 3

# Event Reconstruction and Selection

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## Work flow for event reconstruction

→ **Two-stage tracking:**

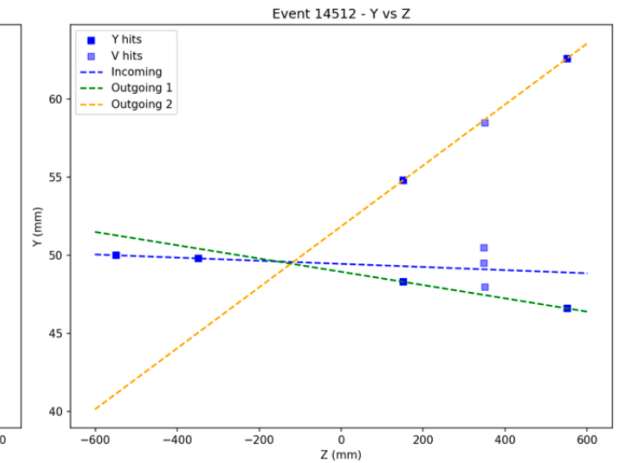
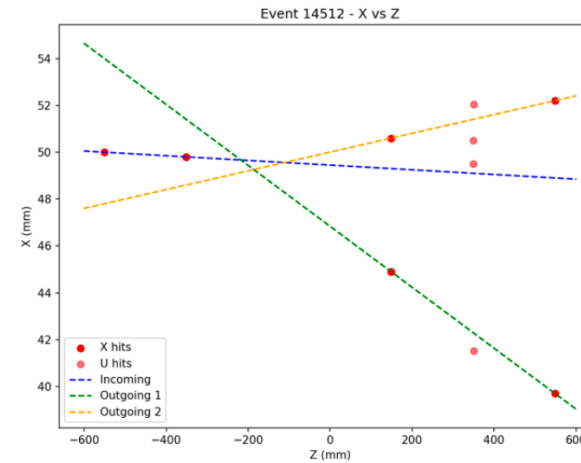
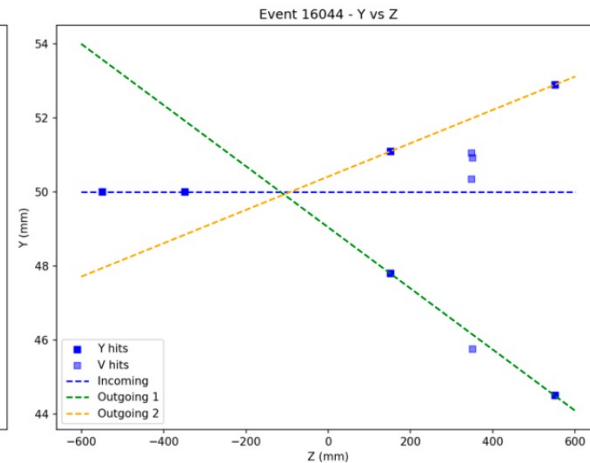
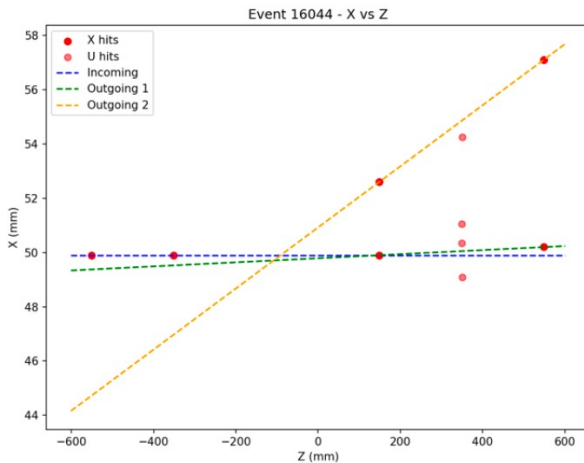
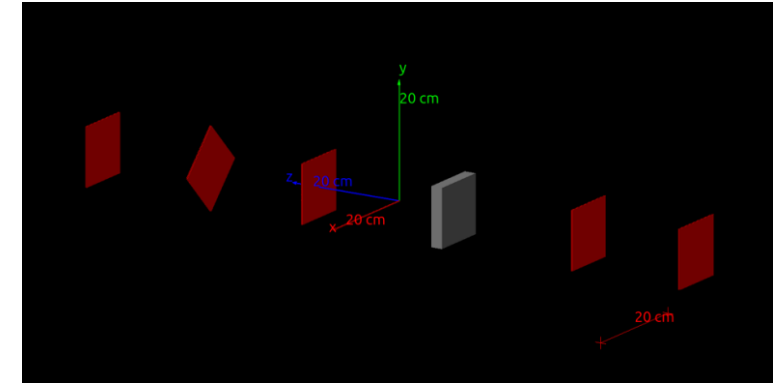
- Upstream (X–Y layers): Convert hits to physical positions; fit first 2 layers → reconstruct incoming muon tracks.
- Downstream (X–Y + U–V layers): Combine X–Y hit pairs; validate using **rotated U/V modules (45°/135°)** → reconstruct outgoing tracks and resolve ambiguities that would otherwise be very difficult to handle.

→ **High-quality event criteria:**

- **One hit per upstream layer, two hits per downstream layer** → unambiguous tracks.
- Vertex determined by **minimizing track distances** along the beam axis.

→ **Energy and vertex validation:**

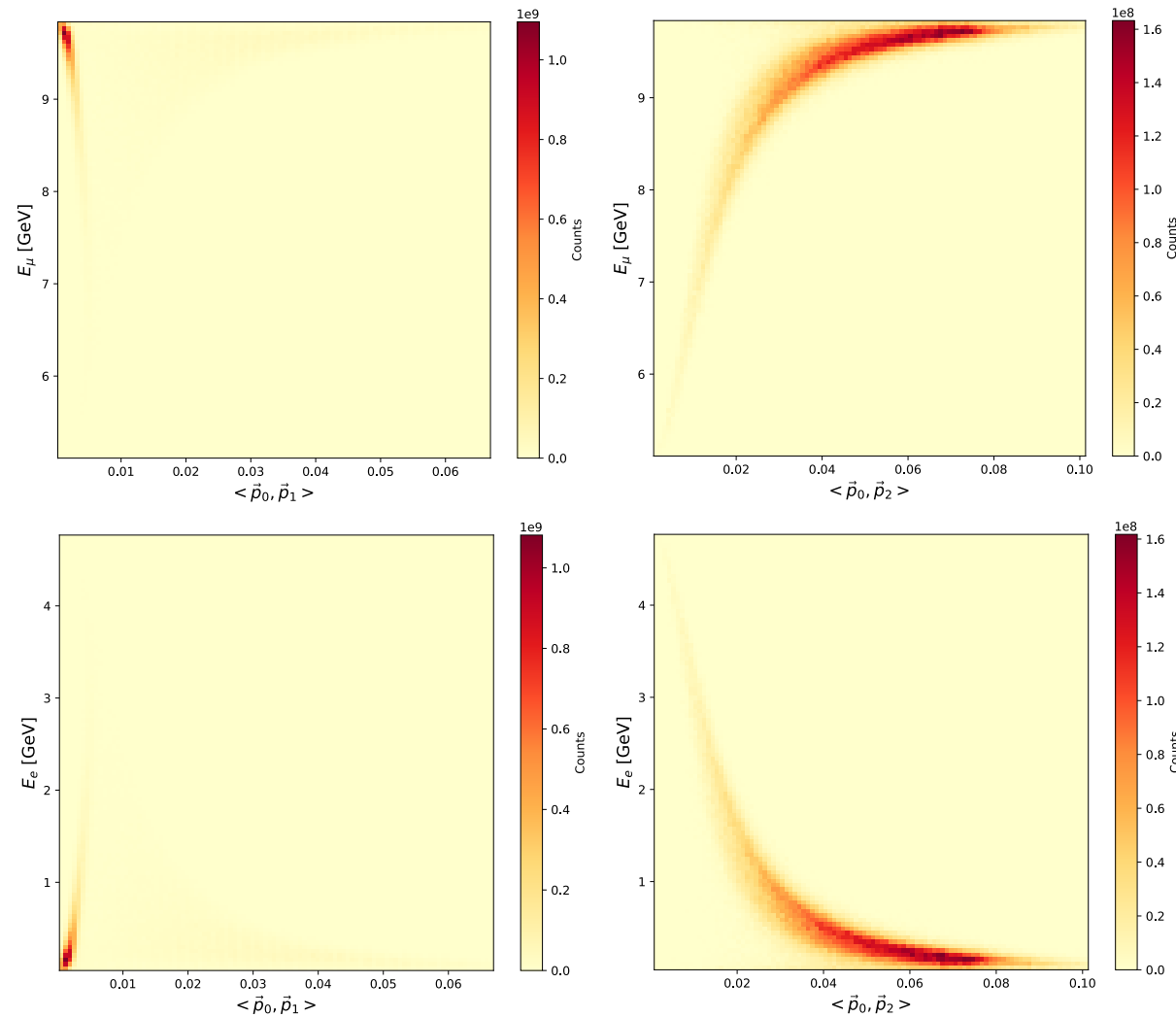
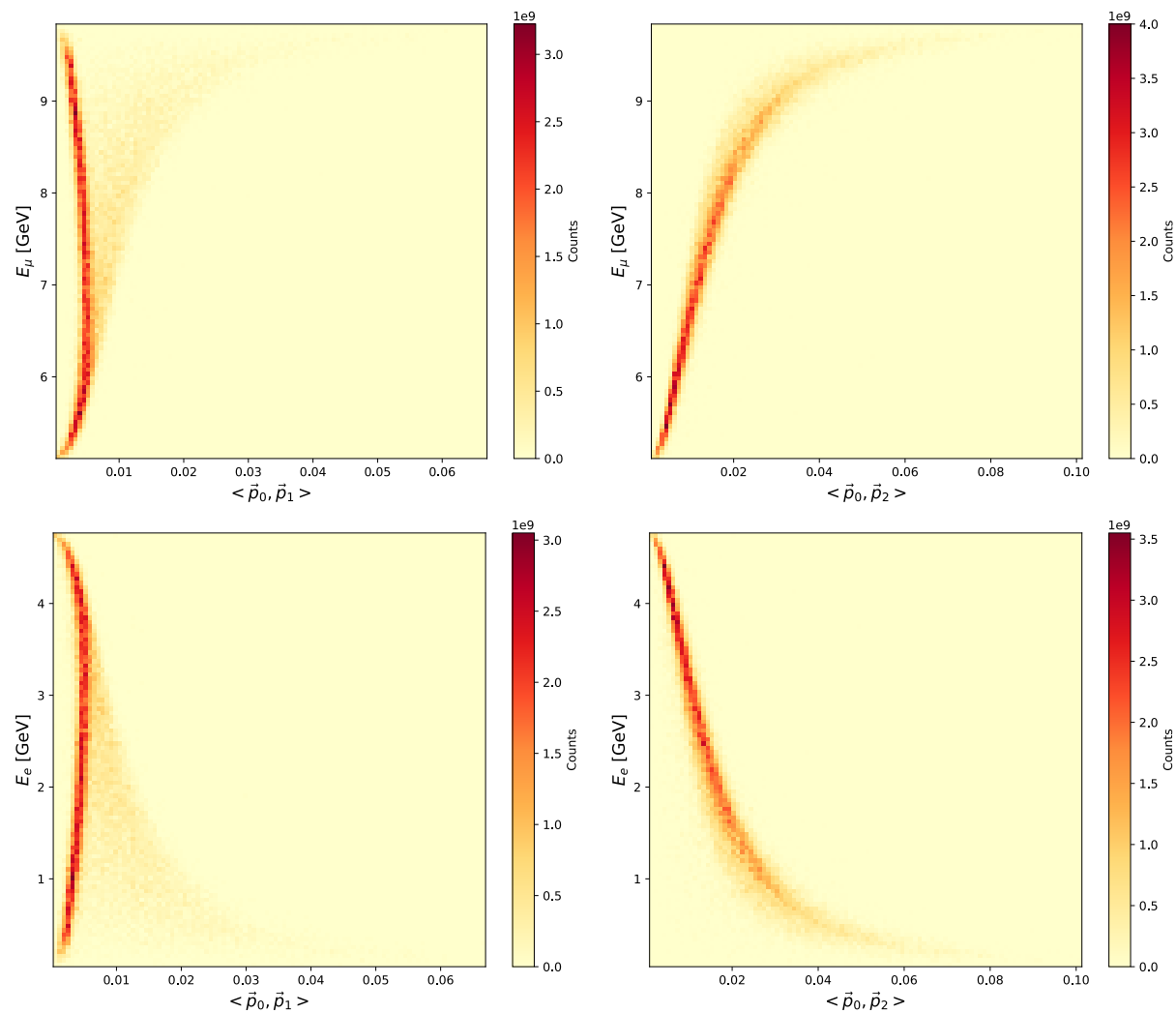
- Outgoing particle energies recorded at the 5th silicon layer.
- Reconstructed vertex confirmed near target position (**Z = -100 mm**).



Signal

$$E_\mu = 10 \text{ GeV} \quad m_{Z'} = 30 \text{ MeV}$$

Background



Lower  $E_\mu$ , Higher  $E_e$ , Smaller  $\theta_\mu$ , Smaller  $\theta_e$

Higher  $E_\mu$ , Lower  $E_e$ , Larger  $\theta_\mu$ , Larger  $\theta_e$

# Results

---

## Hyperparameters

TEST\_SIZE = 0.20

MAX\_ROUNDS = 1000

MAX\_DEPTH = 4

LEARNING\_RATE = 0.1

LAMBDA = 10

- Use 80% of the events for training and hold out 20% for validation.
- Hyperparameters are tuned by monitoring the ROC curve and the log-loss evolution.

## Input Features

$E_e$

$\theta_e$

$\theta_\mu$

- Only  $E_e$  is used.
- $E_e$  can be directly measured by the ECAL, and it is strongly correlated with the muon energy through kinematics.
- It carries a lot of discriminating power on its own.

## Final Selection

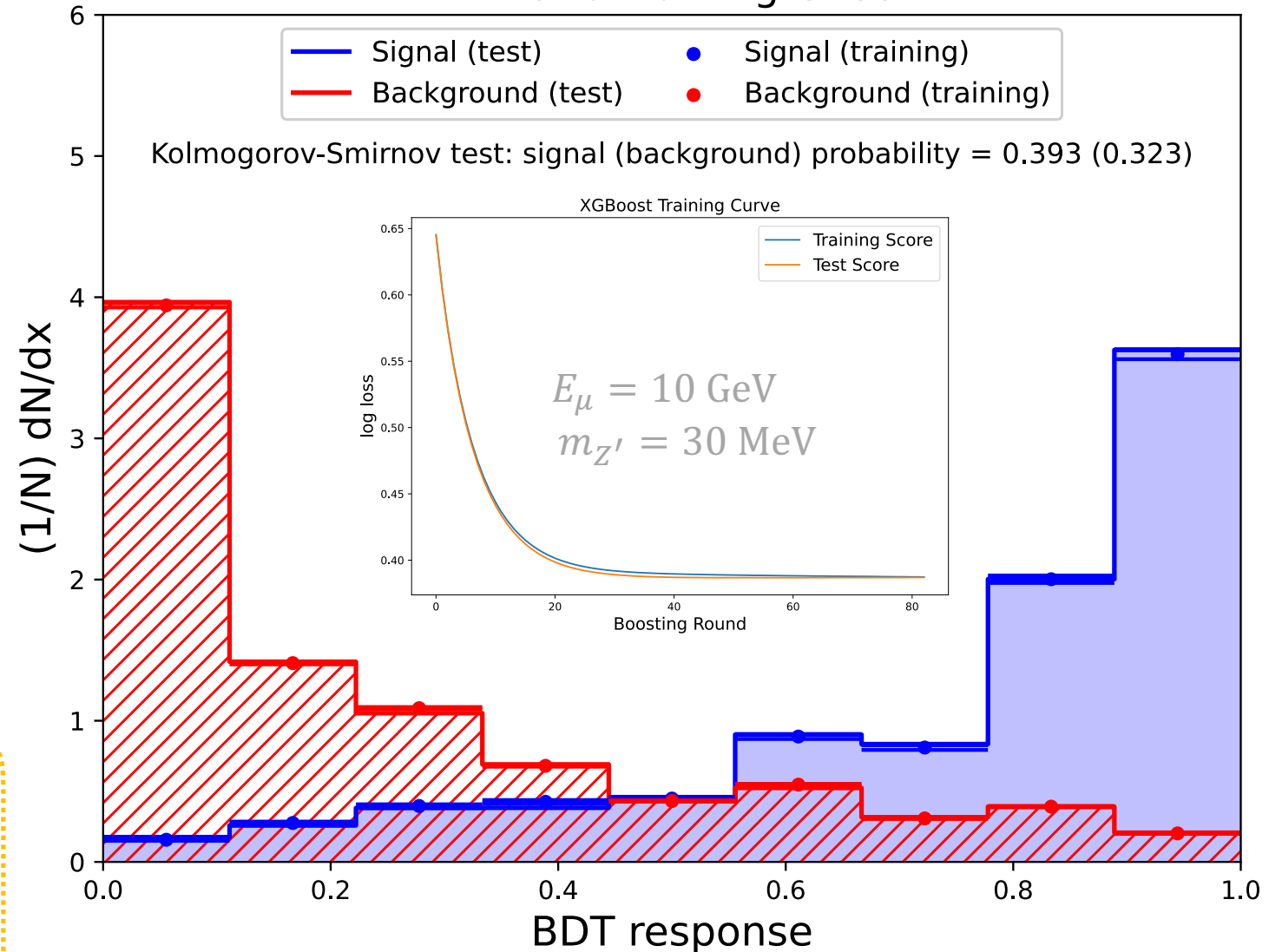
$E_e \geq 4.25$

$\theta_e \leq 0.02$

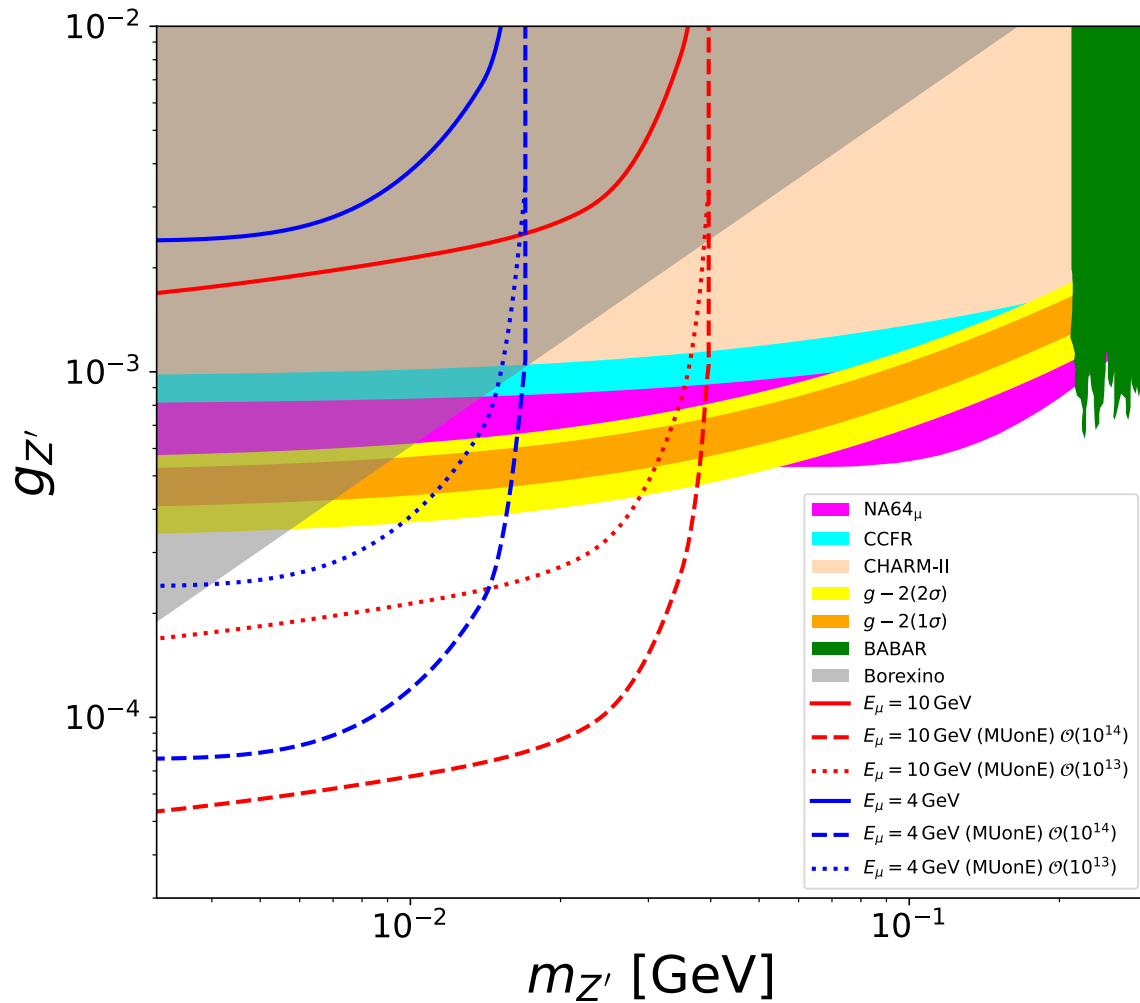
$\theta_\mu \geq 0.004$

- A dedicated BDT is trained for each mass point, with the score threshold optimized to maximize signal significance.
- An additional final cut is applied to further suppress background and enrich signal.
- The SM background is reduced to a negligible level.

## BDT Overtraining Check



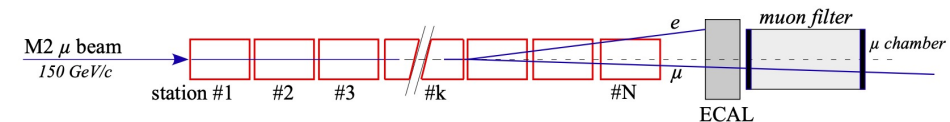
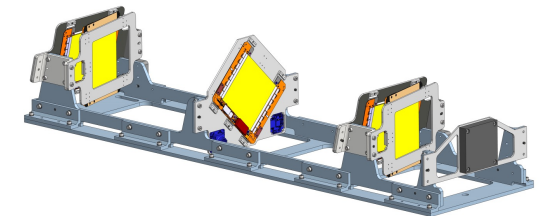
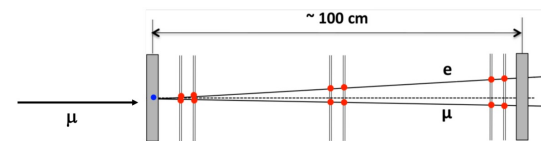
<https://dl.acm.org/doi/10.1145/2939672.2939785>



<https://arxiv.org/abs/2307.02404>  
<https://arxiv.org/abs/2109.10093>  
[https://doi.org/10.1016/0370-2693\(90\)90146-W](https://doi.org/10.1016/0370-2693(90)90146-W)

<https://doi.org/10.1103/PhysRevLett.66.3117>  
<https://arxiv.org/abs/1606.03501>  
<https://doi.org/10.1103/PhysRevLett.107.141302>

- **100 mass points** analyzed for each beam energy (**4 GeV & 10 GeV**).
- For each point, Optimal BDT threshold chosen to maximize signal significance; final event selection applied.
- 95% C.L. upper limits on  $g_{Z'}$  derived using the likelihood test statistic :  $Z = 2(\mu s + b \log(b/(\mu s + b))) \sim \chi^2(1)$ .
- We reach sensitivity at the  **$10^{-3}$**  level around  **$\mathcal{O}(10\text{MeV})$** , which is already competitive with existing experiments.
- A multi-station telescope setup, such as the 40-station **MUonE** experiment with 10 cm lead targets replacing graphite, could surpass all current experimental constraints in the low-mass region.
- With a conservative estimate of  $10^{13}$  MOT per year, the MUonE-inspired search would still provide world-leading constraints on the light  $Z'$  dark boson.



# Summary and Outlook

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- We proposed a muon-on-target experiment with GeV muon beam to search for light dark sector particles within the  $L_\mu - L_\tau$  model, focusing on the process  $\mu e \rightarrow \mu e Z'$  where the  $Z'$  decays invisibly.
- The detector design follows the **PKMu** concept with silicon tracking 2S modules, enabling precise vertex/track reconstruction and angular measurements.
- By applying a dedicated reconstruction algorithm and **BDT-based selection**, we achieved effective background suppression and obtained competitive upper limits on the coupling  $g_{Z'}$ .
- For **4 GeV & 10 GeV muon beam** with a **20 mm graphite target**, the projected sensitivity for upper limit reaches the  $10^{-3}$  level in  $\mathcal{O}(10\text{MeV})$  mass region at 95% C.L. corresponding to a one-year run; under the **MUonE** setup with 40 stations and 10 cm Pb targets, given the same background suppression capacity, the expected upper limit could reach  $10^{-4} \sim 10^{-5}$ .
- The proposed **HIRIBL-PKMu** experiment establishes a solid foundation for future precision muon physics studies and opens up a new avenue for exploring dark sector physics at low energies.

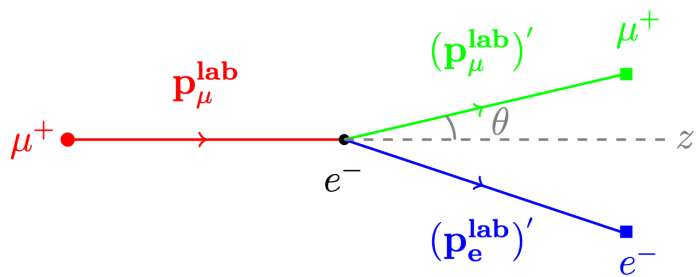
# Thank You

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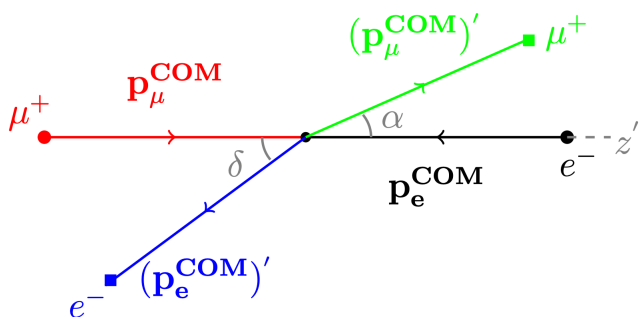
# Back Up

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### Three-body final state phase space



(a) lab frame



(b) COM frame

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

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

$$P_\mu P_{Z'} \cos \langle \mu, Z' \rangle = \frac{E_{com}^2 + m_\mu^2 + m_{Z'}^2 - m_e^2}{2} - E_{com} E_{Z'} - E_\mu (E_{com} - E_{Z'})$$

**A**
**B**
**C**

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

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

# The Kinematics of the Theoretical Calculation for $\mu e \rightarrow \mu e$ Elastic Scattering.

