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Search for light dark sectors with GeV muon beams

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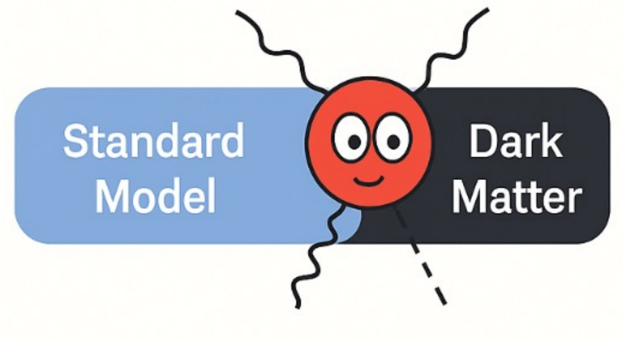
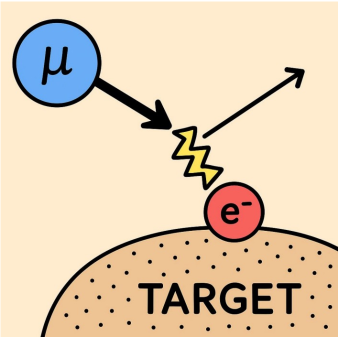
Outline

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

Introduction and Motivation

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





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

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

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

- ➔ 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 μ, τ, 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 μ 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

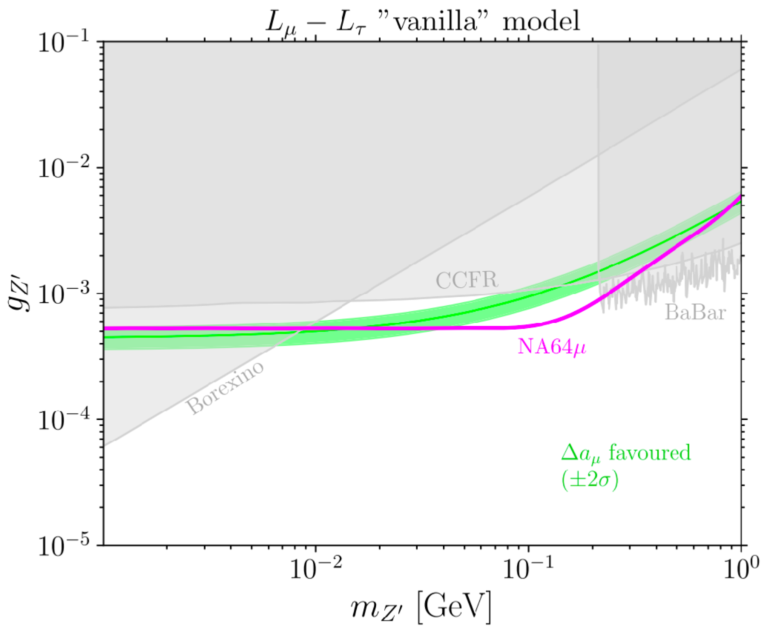
NA64-μ

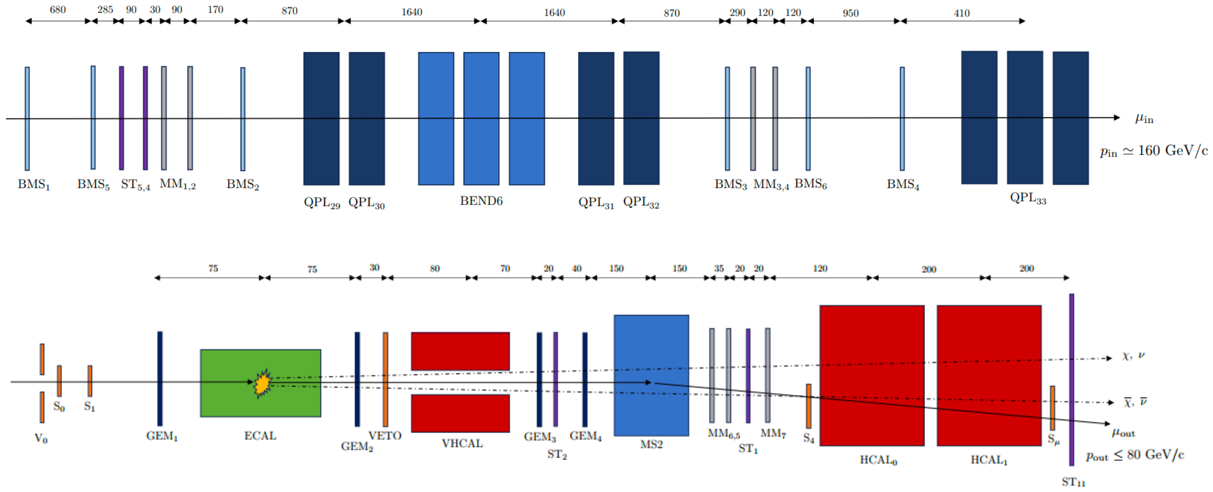
Process

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

Beam Energy

160 GeV





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

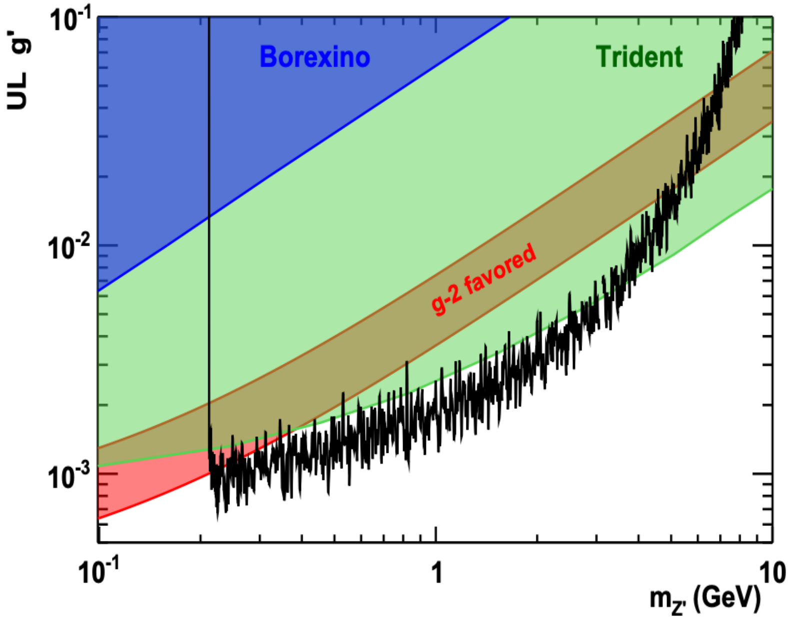
BABAR

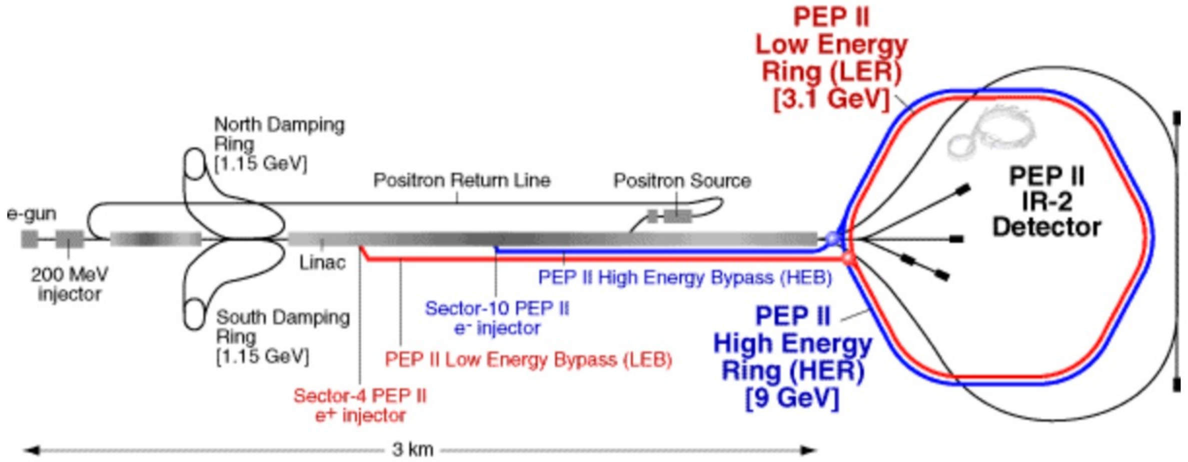
Process

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

Collision Energy

10.58 GeV

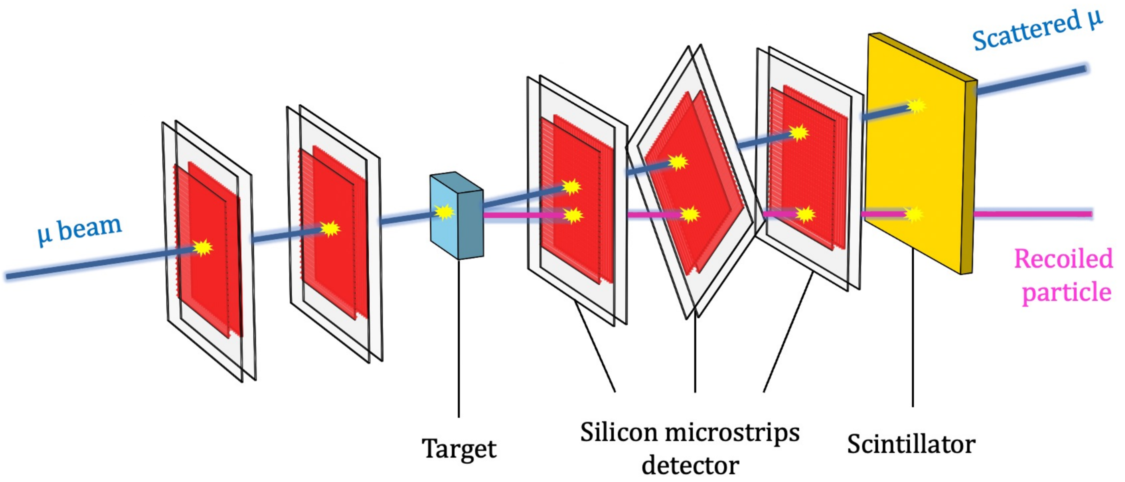


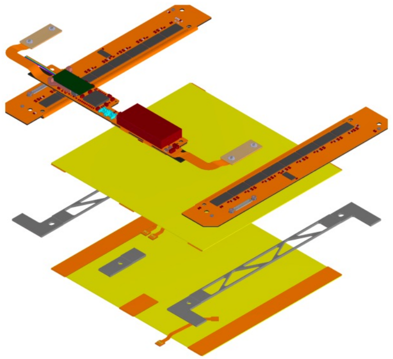


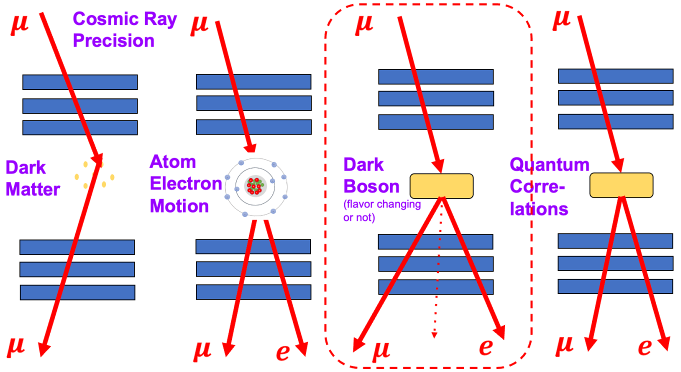
https://arxiv.org/abs/1606.03501

The Joint HIRIBL-PKMu Experiment

Geometry Configuration of the PKMu (MUonE_mimic version)

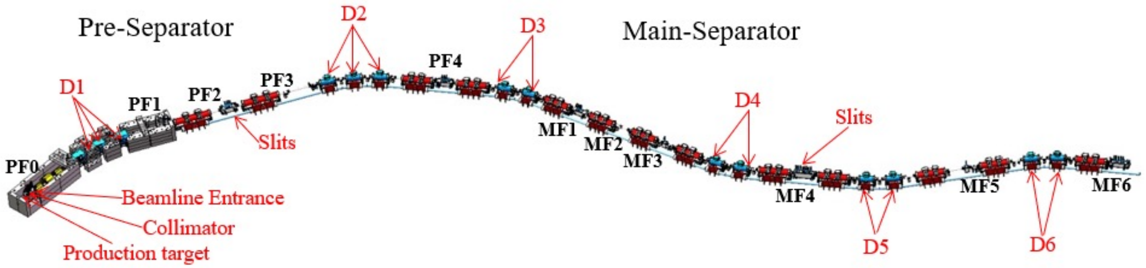






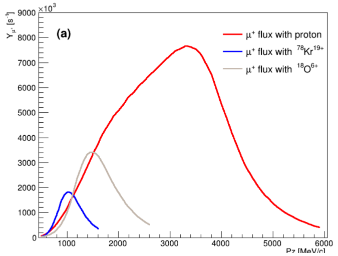
- ➔ 5 copies of **silicon strips** (2 upstream & 3 downstream)
- ➔ major distance: 500 mm / minor distance: 200 mm
- ➔ sensitive area: 100 mm × 100 mm
- ➔ **2S module** readout
- ➔ Target setting : 100 mm * 100 mm * 20 mm **graphite**

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'=±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

Event Generation and Simulation

Work flow for event generation

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

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function GenerateMuEZprime (E_μ)
  $E_{\mu 1}, E_{\mu 2}, \sigma_1, \sigma_2, H_1, H_2 \leftarrow$ AdjacentGridPoints(E_μ);
  if E_μ is out of the grid range **then**
    return no $\mu e^- \to \mu e^- Z'$ 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_μ); // c.m.
  $p_{\mu x} \leftarrow p_\mu \sin\alpha \cos\phi$, $p_{\mu y} \leftarrow p_\mu \sin\alpha \sin\phi$;
  $p_{\mu z} \leftarrow p_\mu \cos\alpha$;
  $p_{ex} \leftarrow -p_{\mu x} - p_{\text{miss\_}x}$, $p_{ey} \leftarrow -p_{\mu y} - p_{\text{miss\_}y}$;
  $p_{ez} \leftarrow -p_{\mu z} - p_{\text{miss\_}z}$;
  $p_{(\mu/e)x\text{\_out}} \leftarrow p_{(\mu/e)x}$; // Boost
  $p_{(\mu/e)y\text{\_out}} \leftarrow p_{(\mu/e)y}$;
  $p_{(\mu/e)z\text{\_out}} \leftarrow \gamma(p_{(\mu/e)z} + \beta E_{(\mu/e)}/2)$;
  $\vec{p}_{\mu\text{\_out}} \leftarrow$ ThreeVector$(p_{\mu x}, p_{\mu y}, p_{\mu z})$;
  $\vec{p}_{\mu\text{\_out}} \leftarrow \vec{p}_{\mu\text{\_out}}$.RotateZAxisTo$(\hat{p}_\mu)$;
  $\vec{p}_{e\text{\_out}} \leftarrow$ ThreeVector(p_{ex}, p_{ey}, p_{ez});
  $\vec{p}_{e\text{\_out}} \leftarrow \vec{p}_{e\text{\_out}}$.RotateZAxisTo$(\hat{p}_e)$;
  return $\sigma, \vec{p}_{\mu\text{\_out}}, \vec{p}_{e\text{\_out}}$;
end function

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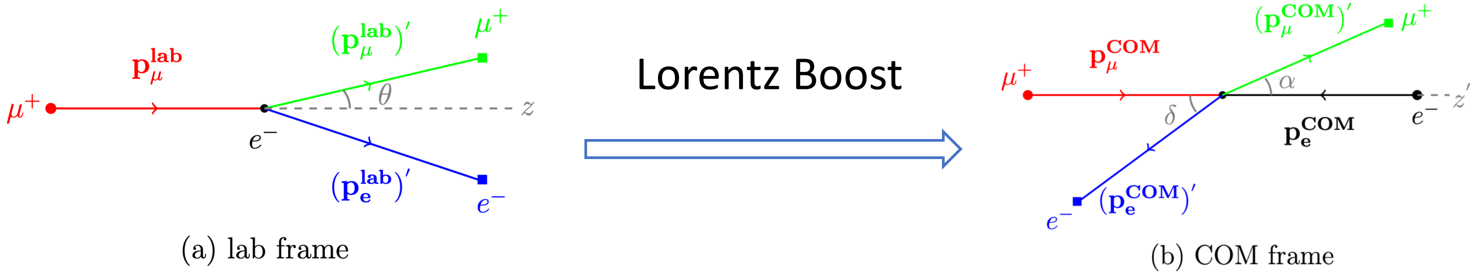
https://geant4.web.cern.ch/docs/#for-toolkit-developers
https://arxiv.org/abs/1405.0301
https://arxiv.org/abs/2410.20323



- ➔ Singnal process is appended to the inclusive physics list FTFP_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 2.5×10^{14} ~ one-year run.

1 MadGraph5_aMC@NLO (v3.5.5) generates $\mu e \to \mu e Z'$ events across a grid of beam energies E_μ and Z′ masses $m_{Z'}$.

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

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

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

Event Reconstruction and Selection

Work flow for event reconstruction

➔ **Two-stage tracking:**

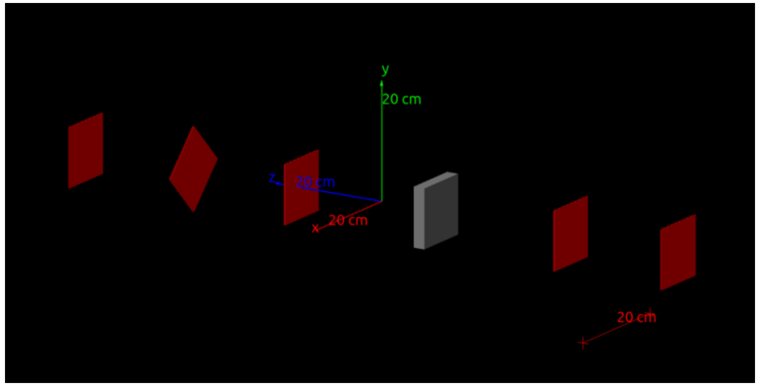
- Upstream (X–Y layers): Convert hits to pyhsical positions; fit first 2 layers → reconstruct incoming muon tracks.
- Downstream (X–Y + U–V layers): Combine X–Y hit pairs; validate using **rotated U/V modules (45°/135°)** → reconstruct outgoing tracks and resolve ambiguities that would otherwise be very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

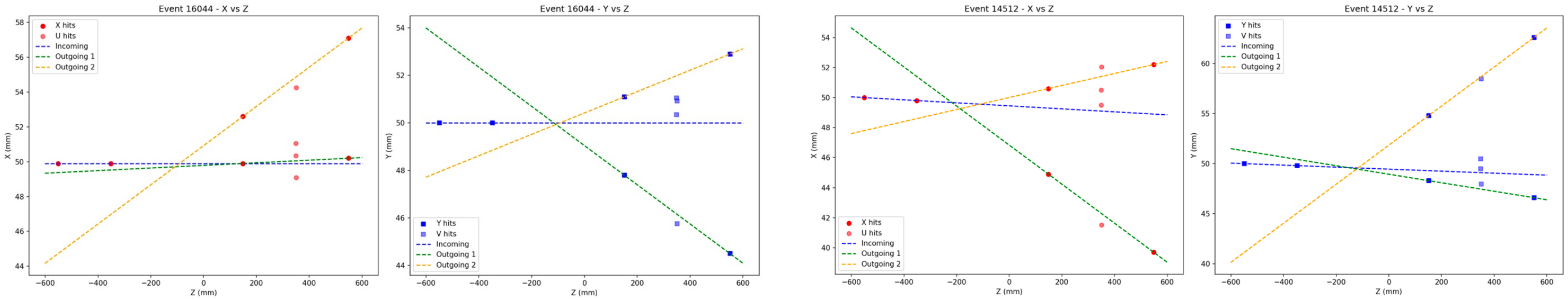
➔ **High-quality event criteria:**

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

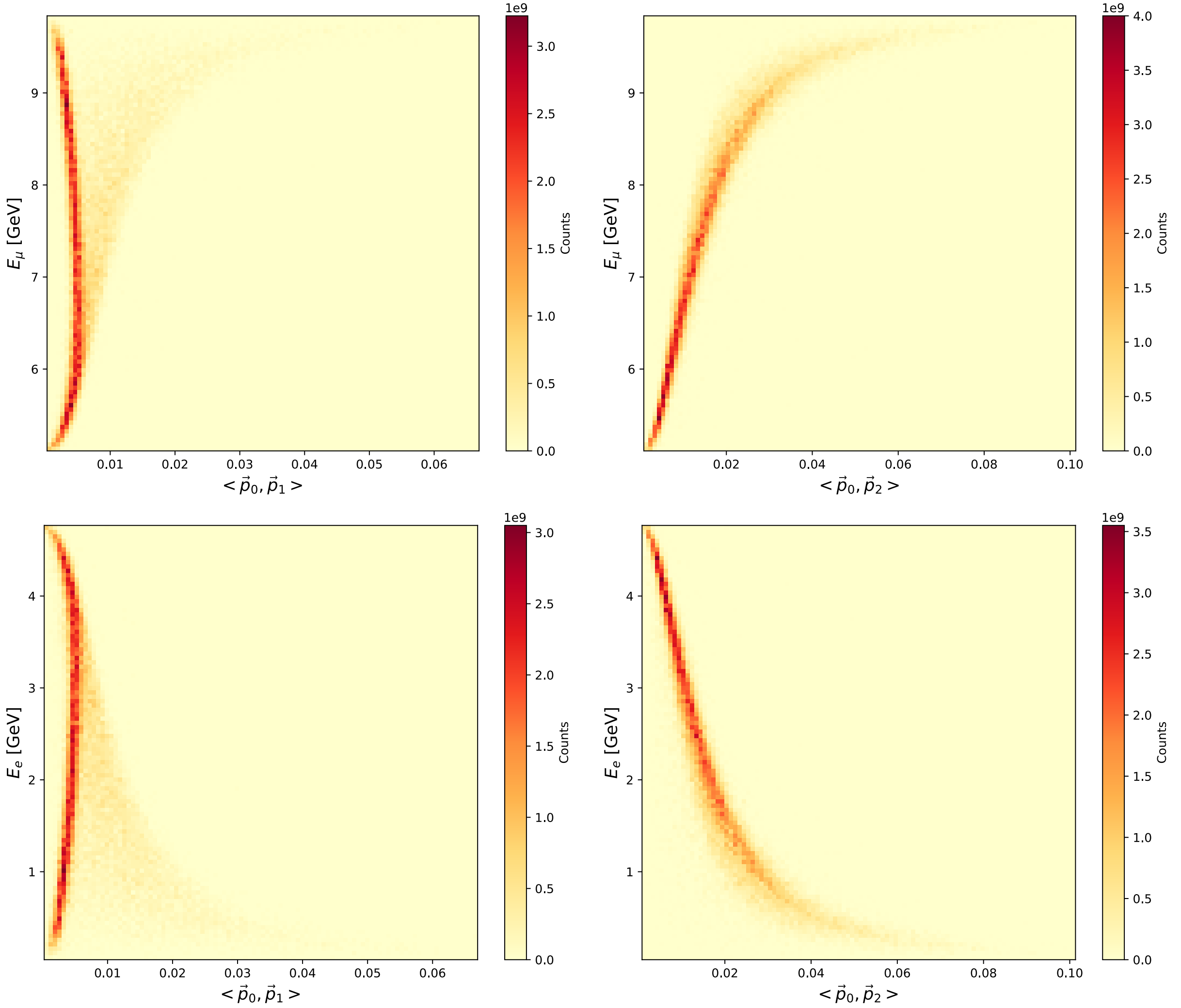
➔ **Energy and vertex validation:**

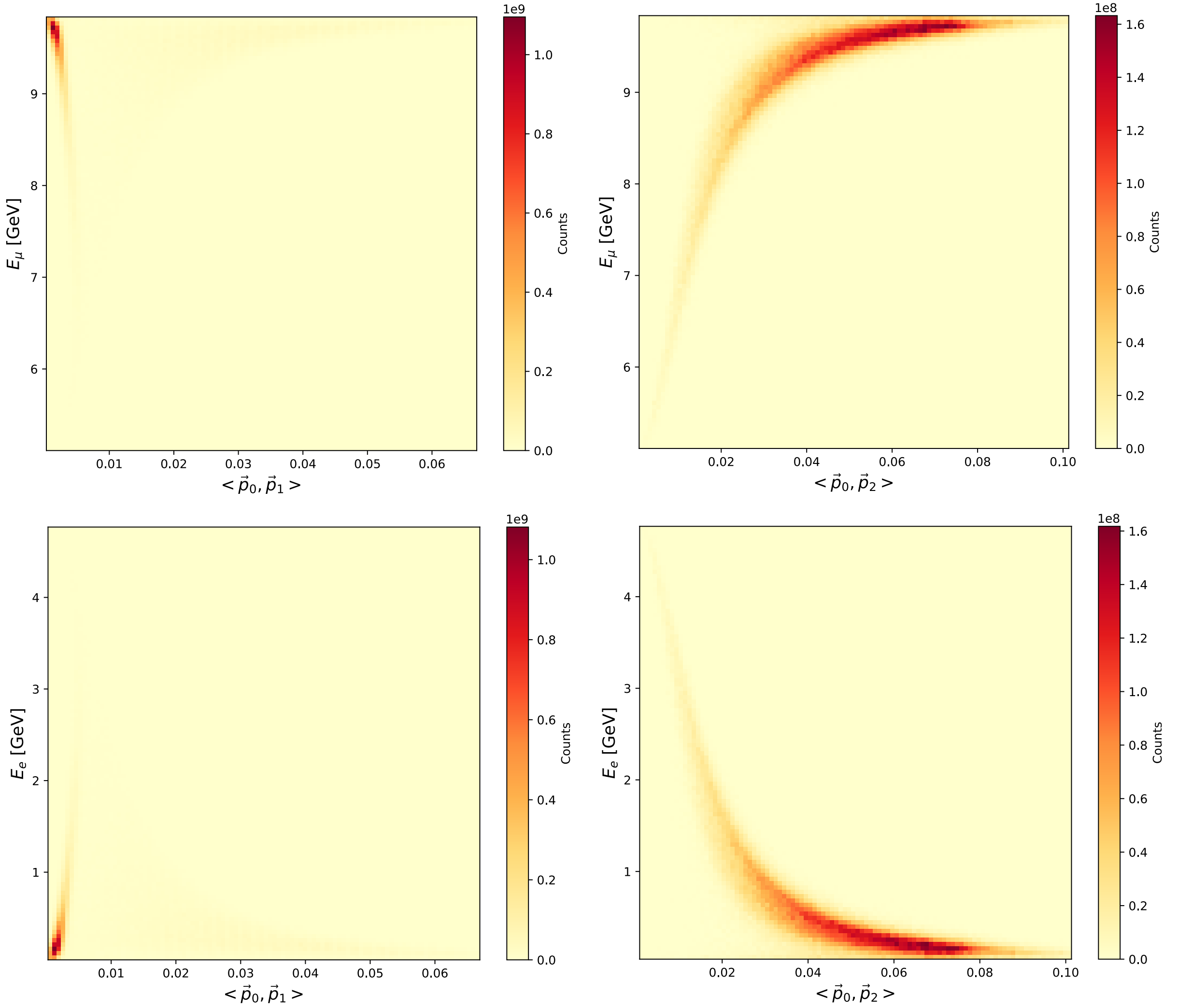
- Outgoing particle energies recorded at the 5th silicon layer.
- Reconstructed vertex confirmed near target position (**Z = –100 mm**).





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





Lower E_μ, Higher E_e, Smaller θ_μ, Smaller θ_e

Higher E_μ, Lower E_e, Larger θ_μ, Larger θ_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

$\mathrm{E_e}$

θ_e

θ_μ

- 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.

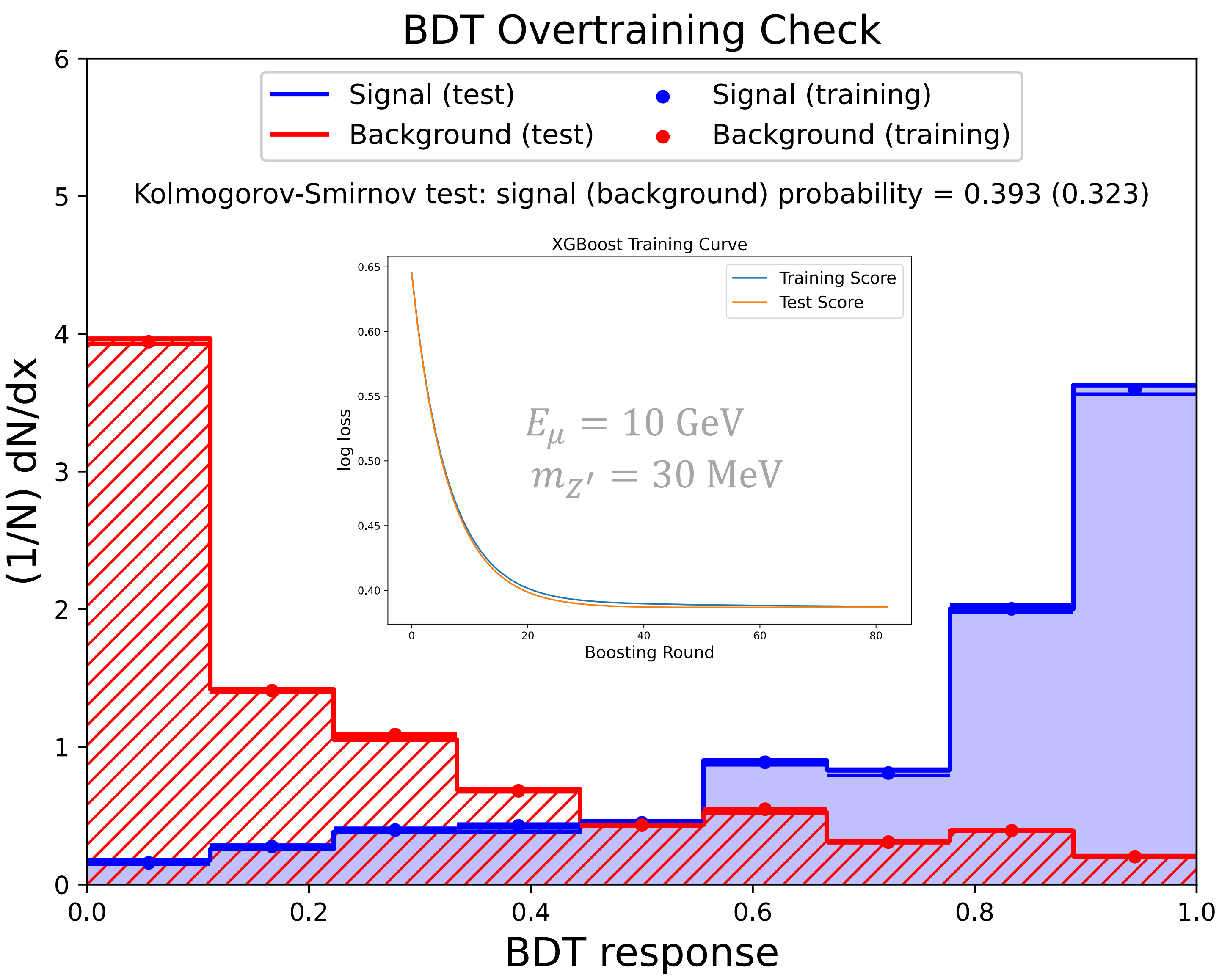
Final Selection

$\mathrm{E_e} \geq 4.25$

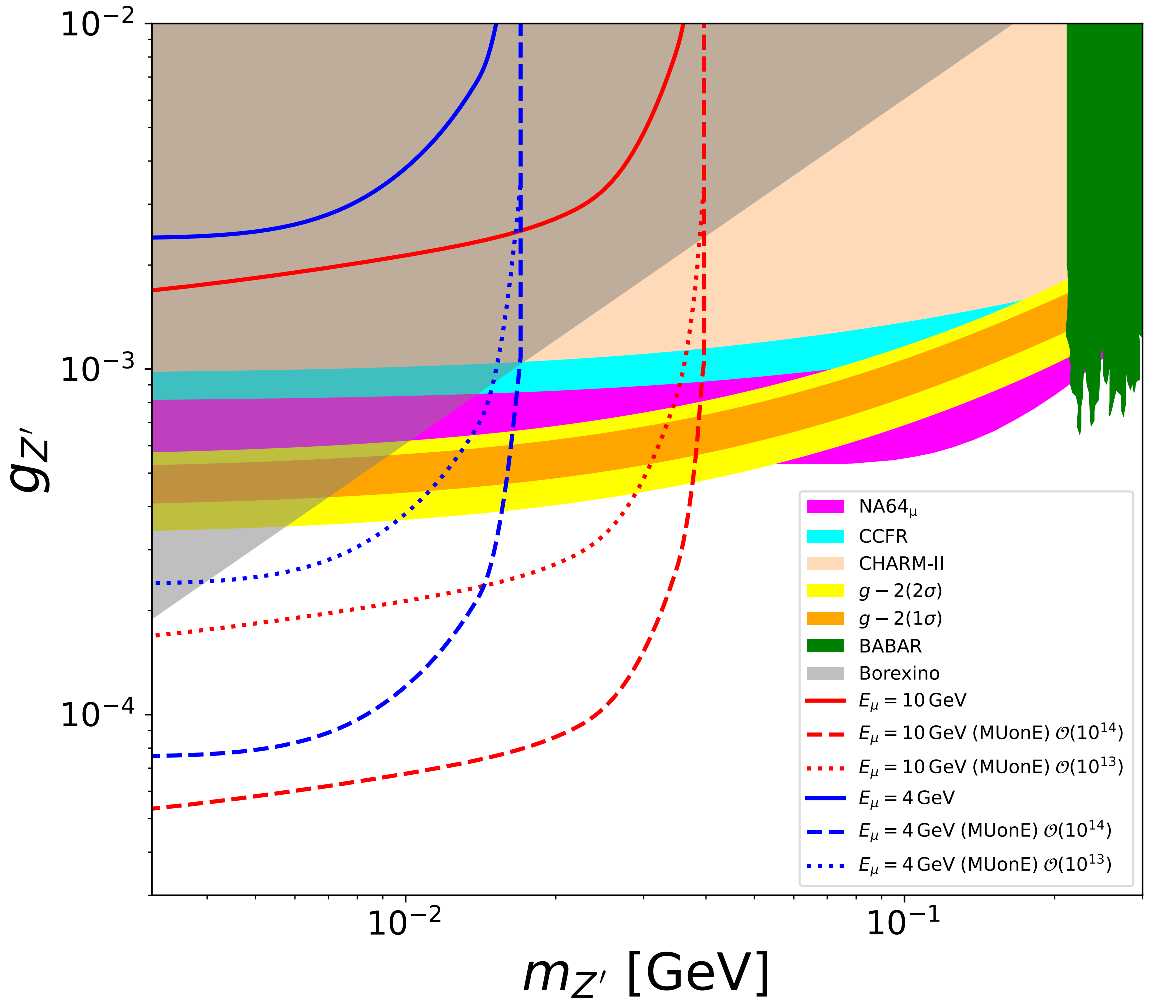
$\theta_\mathrm{e} \leq 0.02$

$\theta_\mu \geq 0.004$

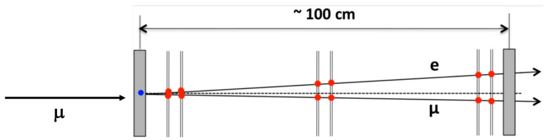
- A dedicated BDT is trained for each mass point, with the score threshold optimized to maximize signal significance.
- An additional final cut is applied to further suppress background and enrich signal.
- The SM background is reduced to a negligible level.

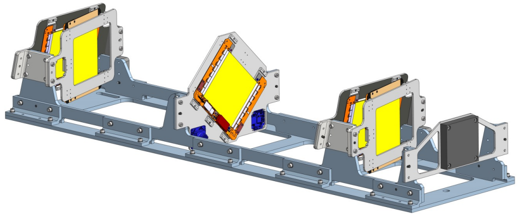


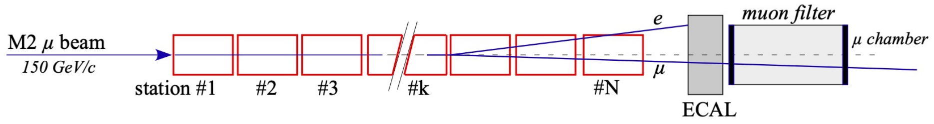
https://dl.acm.org/doi/10.1145/2939672.2939785



- **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 $\mathbf{10^{-3}}$ level around $\mathcal{O}(\mathbf{10MeV})$, 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.







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

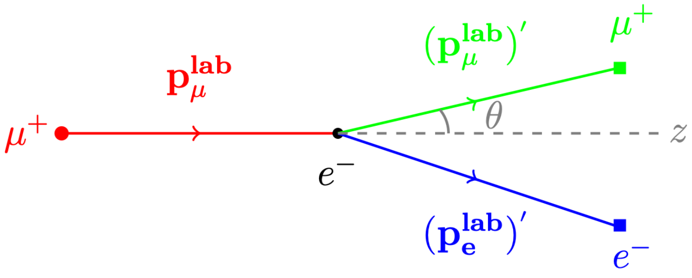
Summary and Outlook

- 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 $\mu e \to \mu e Z'$ 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 $\mathcal{O}(10\mathrm{MeV})$ 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 reaches $10^{-4} \sim 10^{-5}$.
- 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.

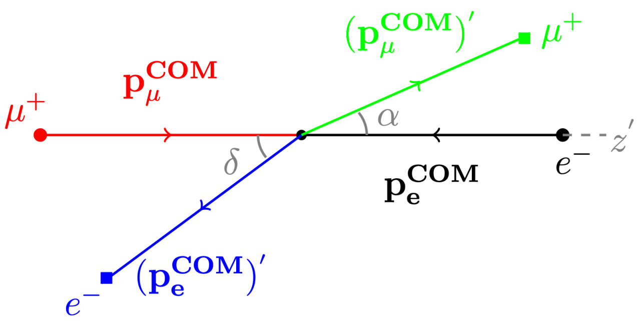
Thank You

Back Up

Three-body final state phase space



(a) lab frame



(b) COM frame

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

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

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

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

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

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