Vertex Reconstruction for the DarkLight Experiment

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Invariant Mass Reconstruction

To identify the dark photon, we reconstruct the invariant mass of the lepton pair:

$$m_{e^-e^+} = \sqrt{E_{tot}^2 - |\vec{p}_{tot}|^2} \tag{1}$$

where $E_{tot} = E_{e^-} + E_{e^+}$ and $\vec{p}_{tot} = \vec{p}_{e^-} + \vec{p}_{e^+}$

The energy of each lepton is given by:

$$E = \sqrt{p^2 + m_e^2} \tag{2}$$

What We Need to Reconstruct

The full 3-momentum $\vec{p} = p\hat{l}$ of each lepton requires:

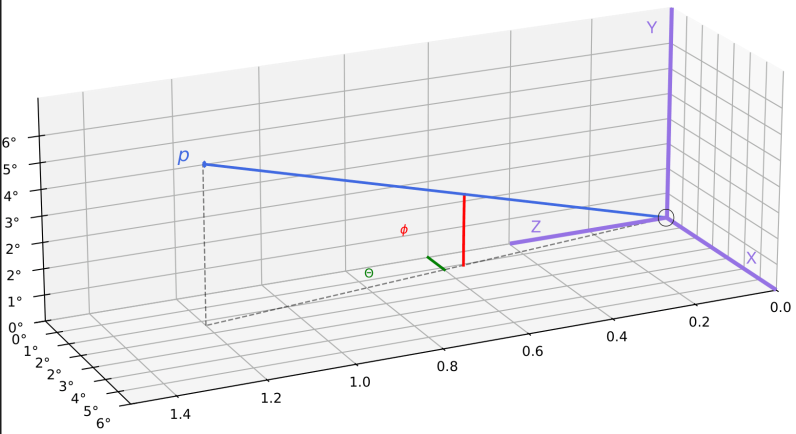
Momentum P

In-plane angle θ_{ip}

Out-of-plane angle ϕ_{oop}

These three quantities define the vertex.

Vertex Visualized



From Vertex Quantities to 3-Momentum

The three reconstructed vertex quantities $(p, \theta_{ip}, \phi_{oop})$ fully specify each lepton's 3-momentum:

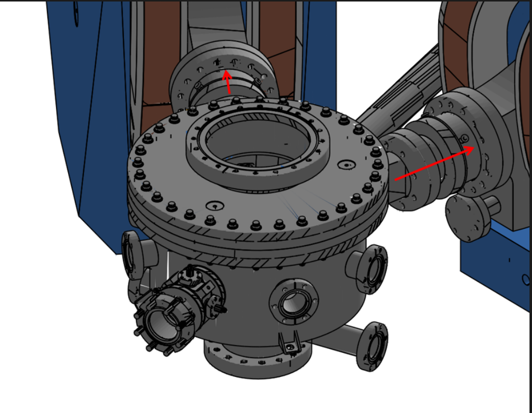
$$\hat{l} = \frac{1}{\sqrt{\tan^2\theta_{ip} + \tan^2\phi_{oop} + 1}} \begin{pmatrix} \tan\theta_{ip} \\ \tan\phi_{oop} \\ 1 \end{pmatrix} \tag{3}$$

- $\tan\theta_{ip}$ — left-right component along the non-dispersive direction
- $\tan\phi_{oop}$ — up-down component along the out-of-plane direction

The lepton 3-momentum is then $\vec{p} = p\,\hat{l}$

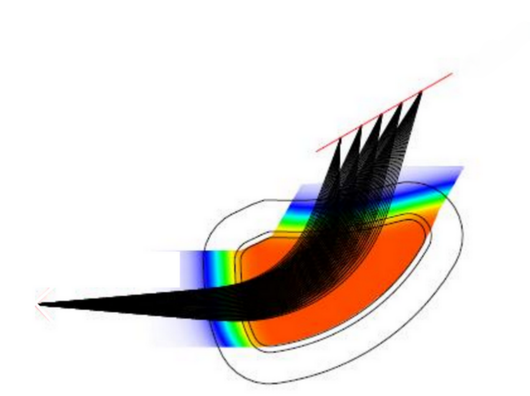
Experimental Process

- The e-linac fires a beam of electrons down the beamline
- The beam of electrons interact with the target at the centre of the target chamber, undergoing the IPC process
- The electron-positron pair travel down different spectrometer arms to the GEM detectors



Magnetic Optics

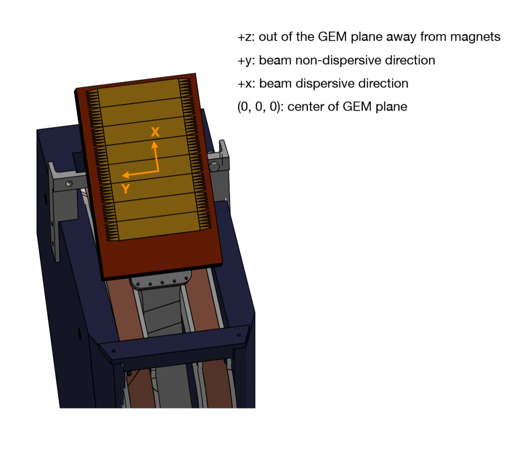
- The dipole spectrometer acts as a magnetic lens, analogous to an optical lens
- The final position of the particle is completely independent of the incident angle of the particle



Particles of similar momenta arrive at the same positions on the focal plane regardless of initial angle

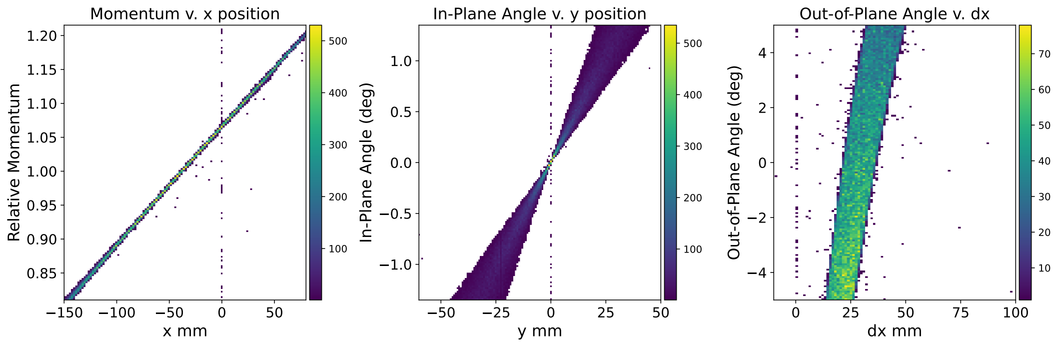
GEM Detectors

- Two triple-GEM detectors per arm, 40×25 cm
- Incident leptons ionize the drift gas, initiating a Townsend avalanche
- Outputs: hit positions (x, y) and slopes (dx, dy)
- These four observables are the inputs to vertex reconstruction



X is dispersive, Y is non-dispersive

Why the Observables Matter



Each detector observable encodes a different vertex quantity; together (x, y, dx, dy) carry all the information needed to reconstruct $(p$, θ_{ip}, and $\phi_{oop})$

Polynomial Reconstruction

- The magnetic transport from vertex to GEM is continuous and differentiable → polynomial expansion
- We represent each vertex quantity as a polynomial sum of detector observables:

$$q(x, y, dx, dy) = \sum_{k=0}^{d} \left(\sum_{a=0}^{k} \sum_{b=0}^{k-a} \sum_{c=0}^{k-a-b} c_{a,b,c,k-a-b-c} \cdot x^a \, y^b \, dx^c \, dy^{k-a-b-c} \right) \quad (4)$$

Where q can be p, θ_{ip}, ϕ_{oop}

This looks something like: $q(x, y, dx, dy) = a_{(0000)} + a_{(1000)}\, x + a_{(0100)}\, y + a_{(0010)}\, dx + a_{(0001)}\, dy + a_{(2000)}\, x^2 + a_{(1100)}\, x \cdot y + a_{(1010)}\, x \cdot dx + \ldots$

Coefficient Training

- For M training events, the polynomial expansion is encoded in a matrix A of size $M \times N$
- The reconstruction problem becomes a linear system solved via LSM:

$$Ac = q \rightarrow \nabla ||Ac - q||^2 = 0 \rightarrow A^T Ac = A^T q \implies c = (A^T A)^{-1} A^T q \tag{5}$$

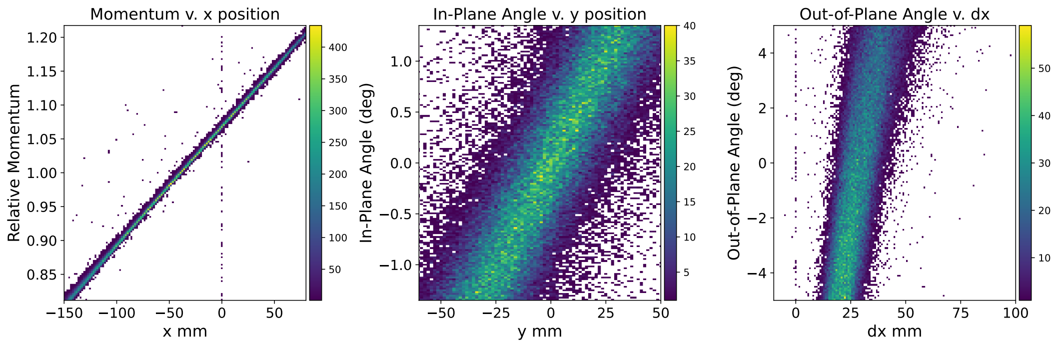
- LASSO adds an L_1 penalty:

$$\min \left(||Ac - q||^2 + \alpha \sum |c_i| \right) \tag{6}$$

- Optimal polynomial degree and α are selected by minimizing MSE over a scan of degrees $N = 1\text{–}8$

$$MSE = \frac{1}{n} \sum (Y_{pred} - Y_{true})^2 \tag{7}$$

MSC Effects on Detector Observables



Multiple scattering between the GEM planes smears the slope observables dx and dy, while target scattering additionally corrupts the Y position — directly degrading θ_{ip} and ϕ_{oop} reconstruction

Sensitivity to Invariant Mass

Vertex quantities — physical smears σ propagated through local sensitivity slopes:

$$\Delta M_p = s_p \cdot \sigma_p, \qquad \Delta M_\theta = s_\theta \cdot \sigma_\theta, \qquad \Delta M_\phi = c_\phi \cdot \sigma_\phi^2 \quad \text{(quadratic)}$$

$$\Delta M_{\text{vtx}} = \sqrt{\left(\Delta M_p^{(e)}\right)^2 + \left(\Delta M_\theta^{(e)}\right)^2 + \left(\Delta M_\phi^{(e)}\right)^2 + \left(\Delta M_p^{(p)}\right)^2 + \left(\Delta M_\theta^{(p)}\right)^2 + \left(\Delta M_\phi^{(p)}\right)^2}$$

GEM detector observables — smears $\hat{\sigma}$ are the RMS residuals of the trained regression model on held-out data, propagated through the same sensitivity slopes:

$$\widehat{\Delta M}_j = s_j \cdot \hat{\sigma}_j \quad \text{for } j \in \{x, y, dx, dy\} \quad \text{per arm}$$

$$\Delta M_{\text{GEM}} = \sqrt{\sum_j \left(\widehat{\Delta M}_j^{(e)}\right)^2 + \sum_j \left(\widehat{\Delta M}_j^{(p)}\right)^2}$$

Reconstruction Resolution Across Conditions

Condition	Quantity	Deg	OLS	LASSO
Electron Arm				
No MSC/TGT	p	3, 4	12.95 keV	13.00 keV
	θ_{ip}	2, 4	$0.04°$	$0.03°$
	ϕ_{oop}	2, 4	$0.38°$	$0.35°$
MSC+Target	p	3, 5	19.54 keV	18.65 keV
	θ_{ip}	5, 6	$0.44°$	$0.44°$
	ϕ_{oop}	5, 5	$1.49°$	$1.50°$
Positron Arm				
No MSC/TGT	p	2, 5	21.75 keV	18.52 keV
	θ_{ip}	2, 3	$0.03°$	$0.03°$
	ϕ_{oop}	2, 4	$0.26°$	$0.25°$
MSC+Target	p	3, 5	22.77 keV	23.22 keV
	θ_{ip}	4, 5	$0.29°$	$0.29°$
	ϕ_{oop}	3, 5	$1.10°$	$1.08°$

MSC-only condition omitted for brevity; momentum remains robust across all conditions

Reconstructed γ^* Mass

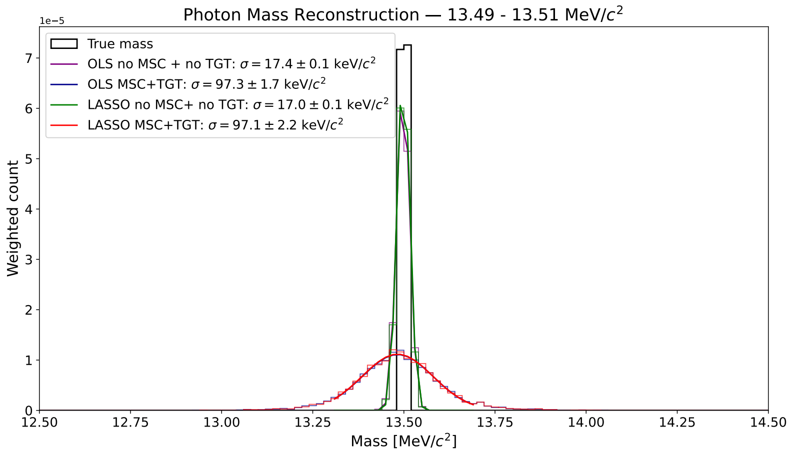


Figure: Reconstructed invariant mass $M_{e^+e^-}$ for a simulated $\gamma^* \rightarrow e^+e^-$ signal at 13.5 MeV$/c^2$, shown across two training conditions (No MSC/TGT, MSC+Target) for both OLS and LASSO.

Mass Uncertainty: Vertex vs. GEM Observables (MSC+Target)

Vertex quantities — smears from physical scattering estimates:

Method	$\Delta M_p^{(e)}$	$\Delta M_\theta^{(e)}$	$\Delta M_\phi^{(e)}$	$\Delta M_p^{(p)}$	$\Delta M_\theta^{(p)}$	$\Delta M_\phi^{(p)}$	**Total**
OLS	17.03	92.33	2.77	12.77	60.85	1.49	**112.65**
LASSO	16.25	92.33	2.80	13.02	60.64	1.45	**112.45**

GEM detector observables — smears from model residuals $\hat{\sigma}$:

Method	$\Delta M_x^{(e)}$	$\Delta M_y^{(e)}$	$\Delta M_{dx}^{(e)}$	$\Delta M_{dy}^{(e)}$	$\Delta M_x^{(p)}$	$\Delta M_y^{(p)}$	$\Delta M_{dx}^{(p)}$	$\Delta M_{dy}^{(p)}$	**Total**
OLS	5.02	108.89	27.35	28.74	5.24	60.47	16.34	12.17	**132.50**
LASSO	4.48	108.01	27.13	29.69	5.26	60.47	16.13	11.79	**131.86**

All values in keV/c^2. The y observable dominates both estimates, reflecting the large ip angular smear introduced by target scattering. OLS and LASSO agree to within $< 1\,\%$ in both cases.

Mass Resolution → Signal/Background Discrimination

A bump hunt: a Gaussian signal peak on a Poisson-distributed QED continuum.

If the analysis window is matched to a halved peak width σ_m:

- Signal S unchanged — total integrated area is preserved
- Background $B \to B/2$ — continuum scales with window width
- Poisson noise $\sqrt{B} \to \sqrt{B/2} = \sqrt{B}/\sqrt{2}$

Significance:

$$Z = \frac{S}{\sqrt{B}} \quad \longrightarrow \quad Z_{\text{new}} = \frac{S}{\sqrt{B/2}} = \sqrt{2}\,Z$$

Halving σ_m buys a $\sqrt{2}$ improvement in ϵ^2 reach — provided the integration window tracks the new resolution.

Conclusions and Outlook

- Polynomial regression pipeline developed to reconstruct $M_{e^+e^-}$ from GEM observables for the DarkLight experiment
- OLS and LASSO agree to within $< 1\,\%$ — LASSO offers marginal improvement via coefficient sparsity
- In-plane angle θ dominates the mass uncertainty budget under target-in conditions
- GEM-based and vertex-based uncertainty estimates are consistent, validating the propagation method
- Next steps (this week) will be reconstruction evaluation for momentum after target

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