Search for Dark Photons via Visible Decays at Fixed-Target Experiments

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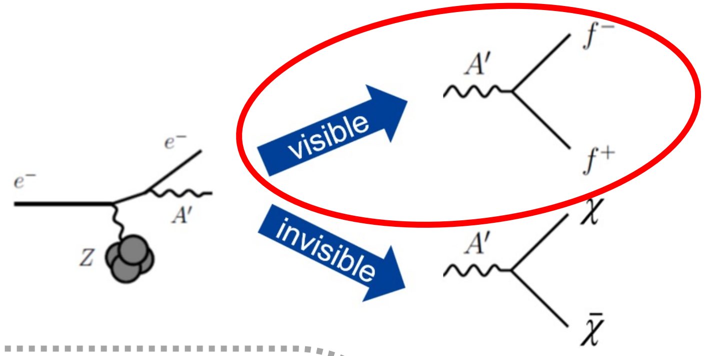
Introduction

We will focus on **visible decay**

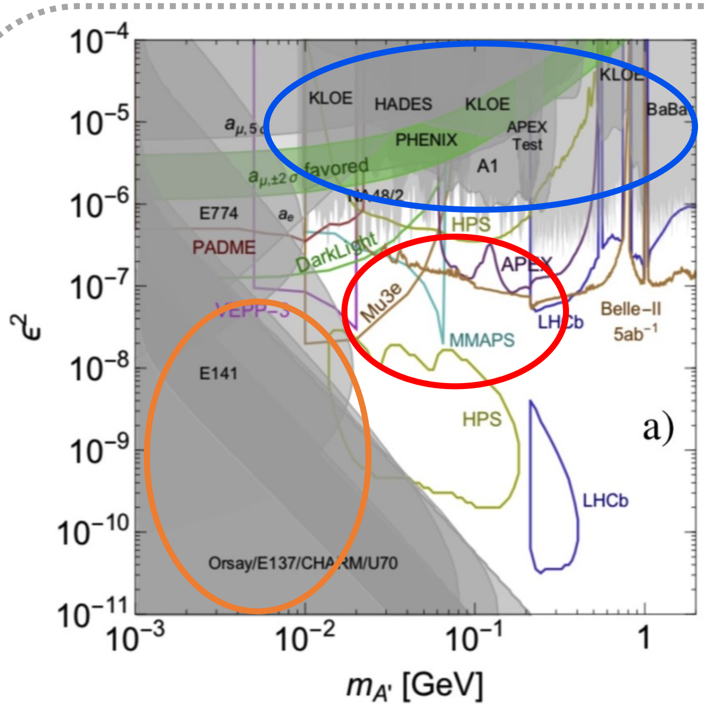


Two model parameters:
- Coupling constant ϵ
- Dark photon mass $m_{A'}$

- **Light dark matter search: dark photon**

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{,\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^2$$

According to the decay channel of dark photon, we have invisible and visible decay.



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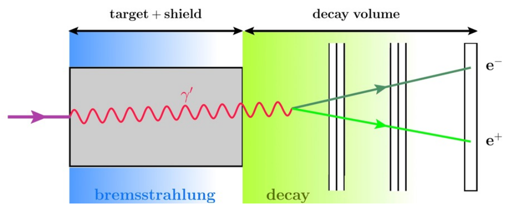
Bump hunting : High production rate

Challenging region :
- Signal rate too low for bump hunting
- Lifetime too short for beam-dump experiment

-> **Displaced vertex reconstruction needed!**

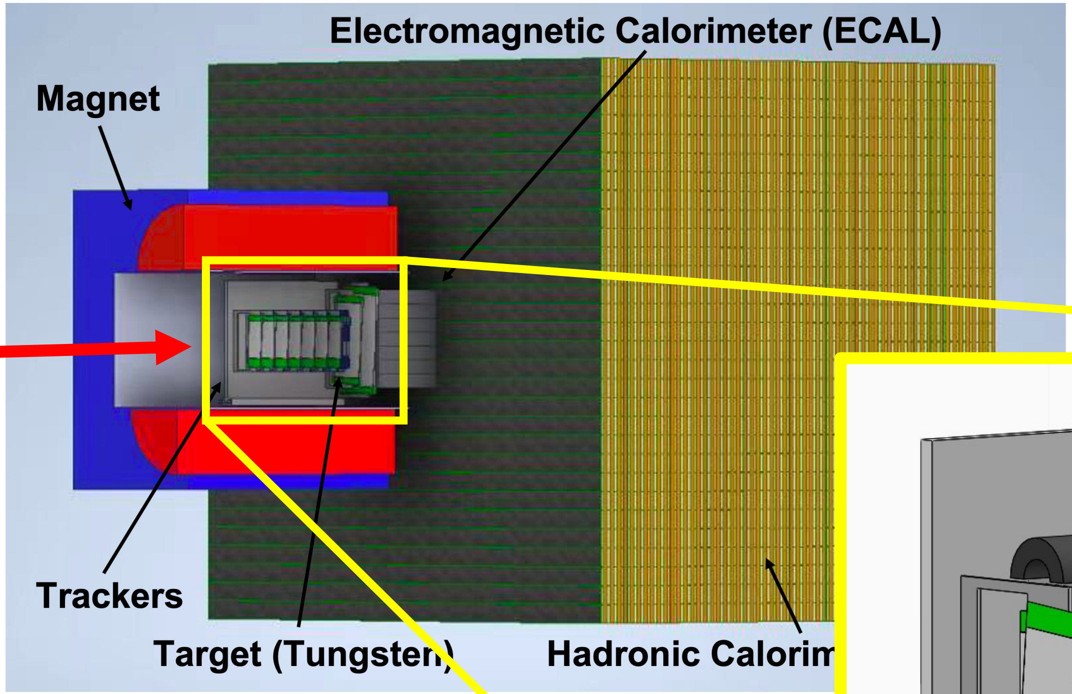
Beam-dump experiment : Long decay length



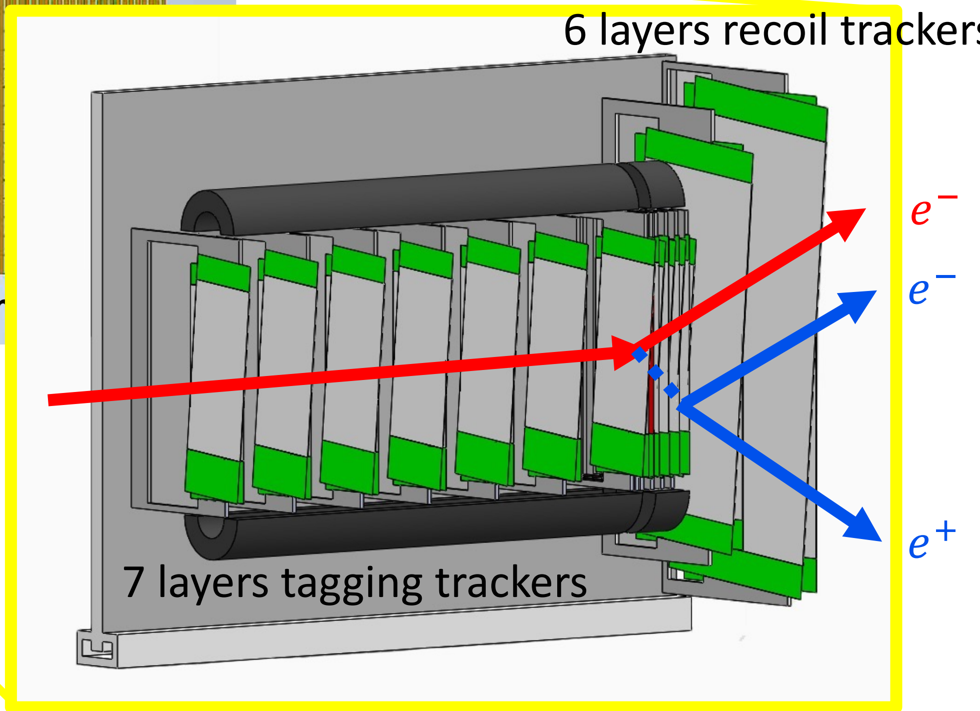
DarkSHINE Experiment at SHINE Facility

8 GeV e^- beam

from Shanghai High Repetition-Rate XFEL and Extreme Light Facility (**SHINE**)



- **Stagger strip trackers**



	Z location (mm)	Strip width (µm)
Tag tracker	[-630, -530, -430, -330, -230, -130, -30]	30
Recoil tracker	[30, 60, 90, 120, 150, 180]	

Signal and Background

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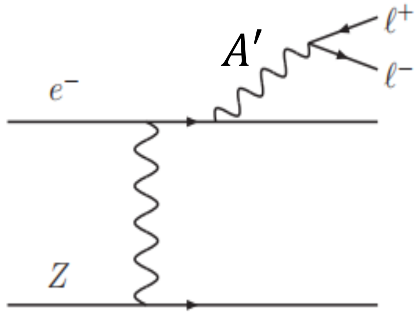
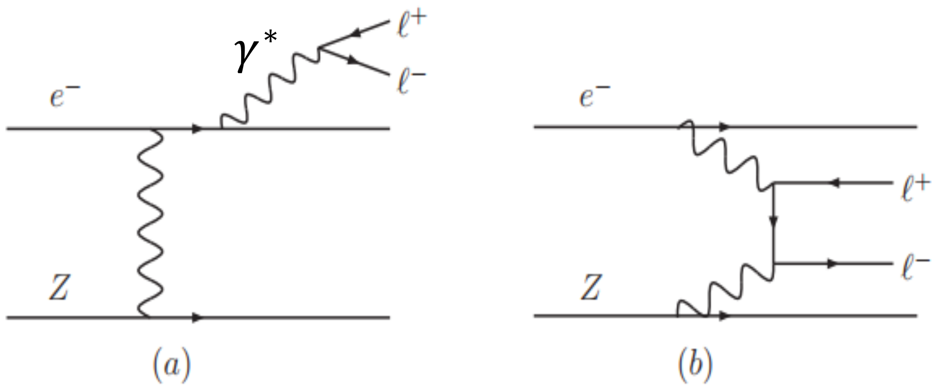
Signal



A' production and decay

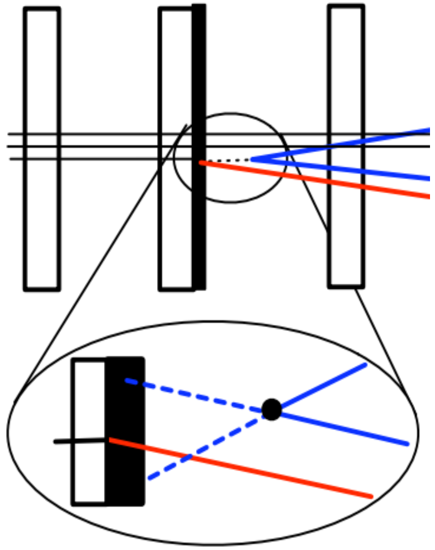
Main background
(both virtual $\gamma \rightarrow e^+e^-$)



γ^* trident reaction

Bethe-Heitler trident reaction

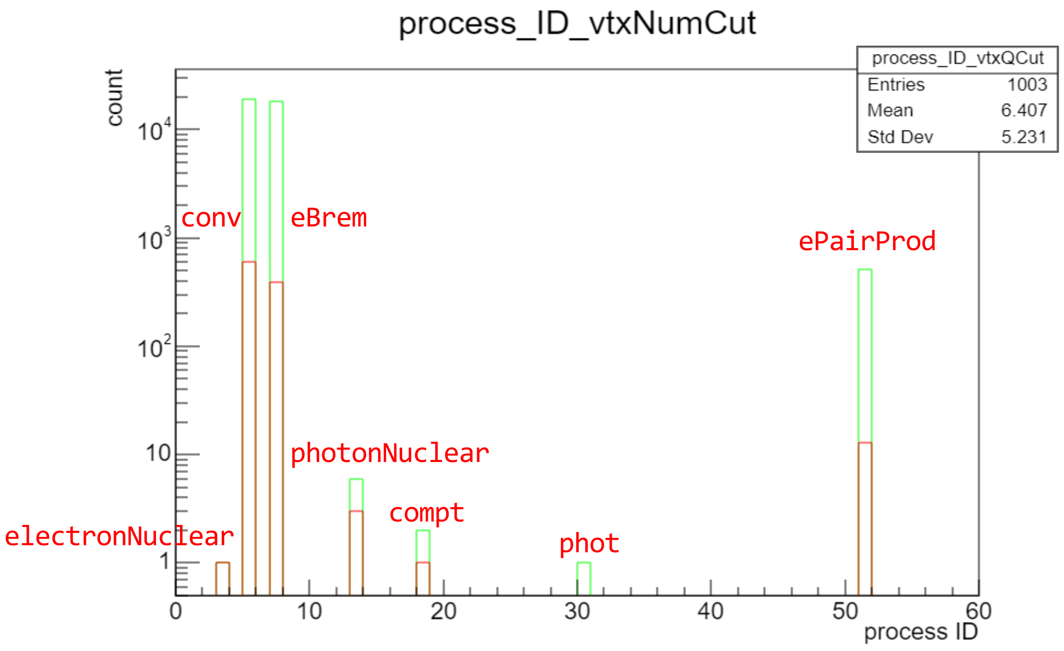
Displaced vertex



- The main signature to differentiate signal from background is the displaced vertex.

Signal and Background Separation

- Through full simulation, two major background types can be identified:
  - Bremsstrahlung + gamma conversion and electron pair production.
  - The kinematics distributions of these two processes are similar.
- To effectively exclude backgrounds, high-resolution vertex reconstruction is necessary.



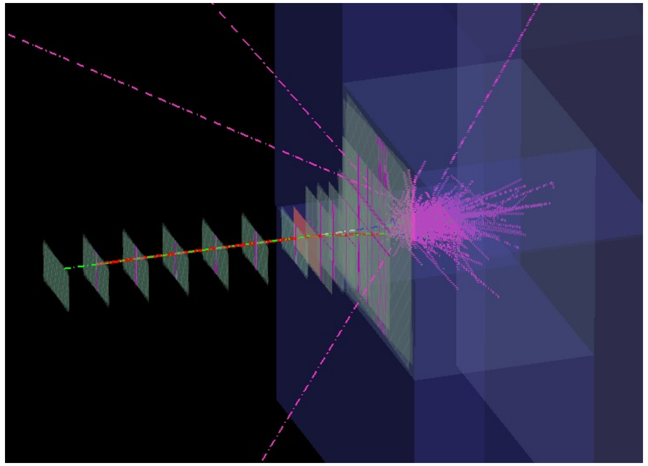
0.1 X_0 W target
3×10^{14} Electron-On-Target

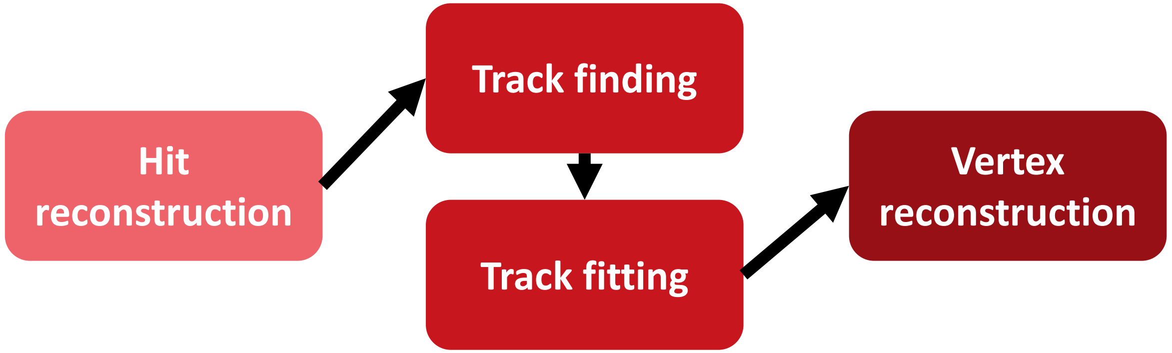
Event type	eBrem + conv	ePairProd
Production rate	2.5%	0.06%

* For each 10^4 EOT, there will be ~250 eBrem + conv events and ~6 ePairProd events, the background rate is pretty high!

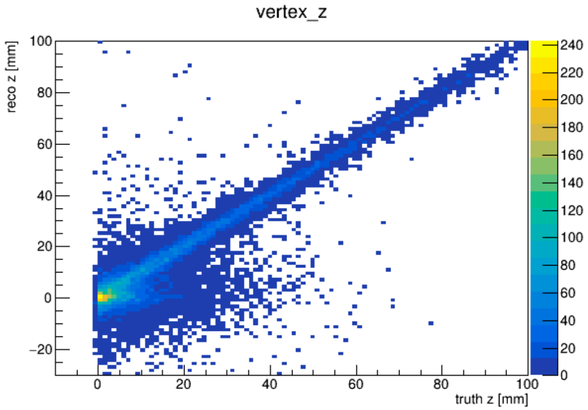
Simulation

- Full simulation study: tracking and vertex reconstruction are needed to accurately estimate the vertexing resolution and background level in visible decay searching.
- We conduct **full Geant4 simulation**, CalcHEP generator for signal production.
- We apply **full chain reconstruction** from hits to tracks and to vertexes. We adopt Kalman Filter algorithm for both tracking (GenFit) and vertexing (Rave).



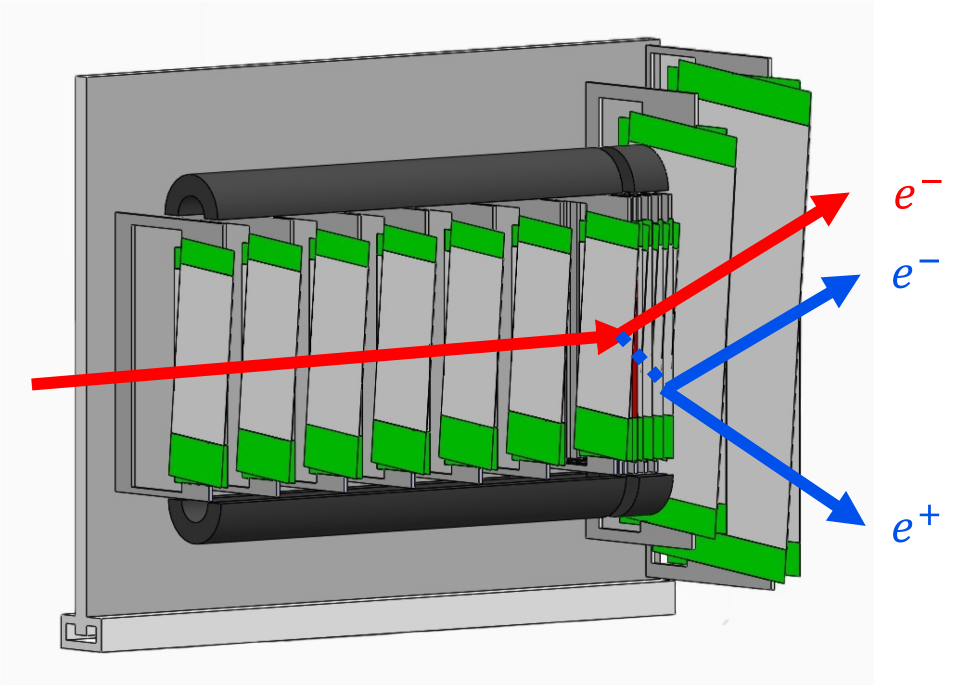


*In this study, we use truth track finding result.



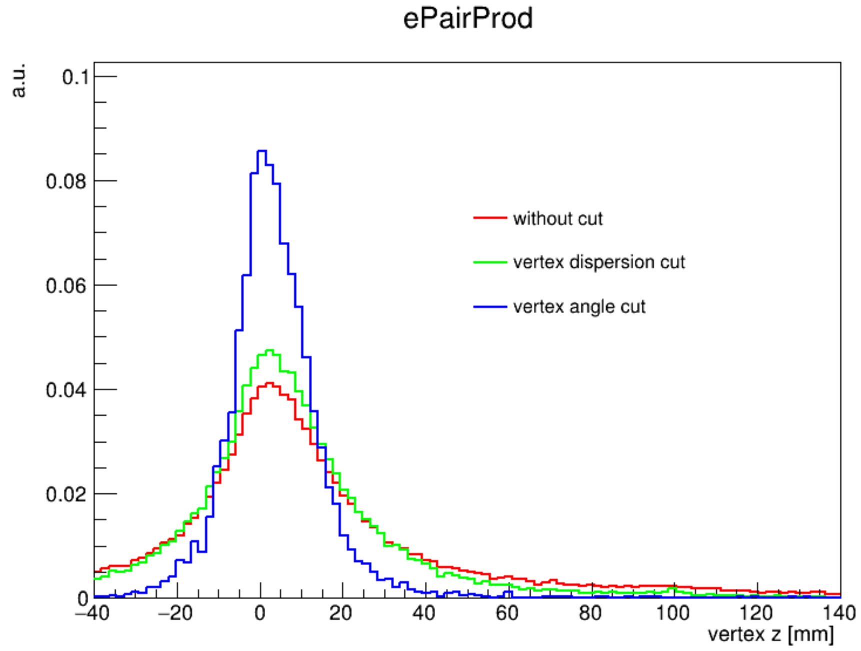
Vertexing

- We develop several methods to increase the vertexing resolution:
  - Use primary beam to reconstruct primary vertex on target, remove recoil electron track by its proximity to the primary vertex.



Vertexing

- We develop several methods to increase the vertexing resolution:
  - Use primary beam to reconstruct primary vertex on target, remove recoil electron track by its proximity to the primary vertex.
  - Define variables for vertex quality:
    - Vertex dispersion: tracks distance at the vertex z plane
    - Vertex theta: the angle between two tracks
    - Shared hit num: number of shared hits in the tracks



- Electron pair production background. Truth vertex at target.
- By adding vertex quality cut, the long tail of reconstructed vertex distribution is reduced.

Vertexing

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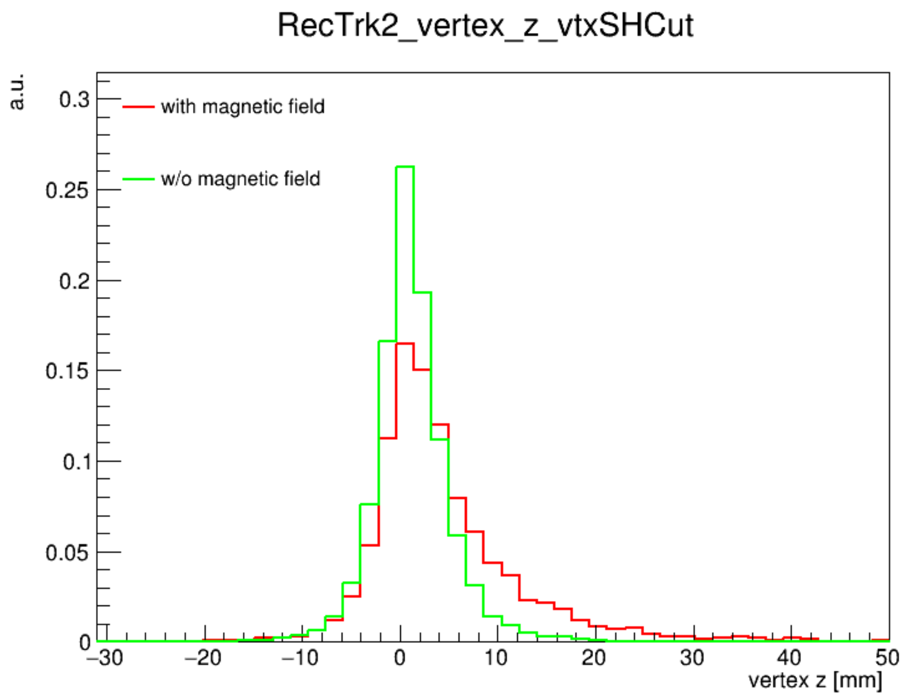
  - Define variables for vertex quality:
    - Vertex dispersion: tracks distance at the vertex z plane
    - Vertex theta: the angle between two tracks
    - Shared hit num: number of shared hits in the tracks
  - To reduce the long tail at vertex z:
    - Turning off the magnetic field, vertex resolution is improved by a factor of 2 (**from 8 mm to 4 mm**).



- By turning off the magnetic field, the vertex resolution is improved by a factor of 2 (from 8 mm to 4 mm), and the tail is reduced.

Vertexing

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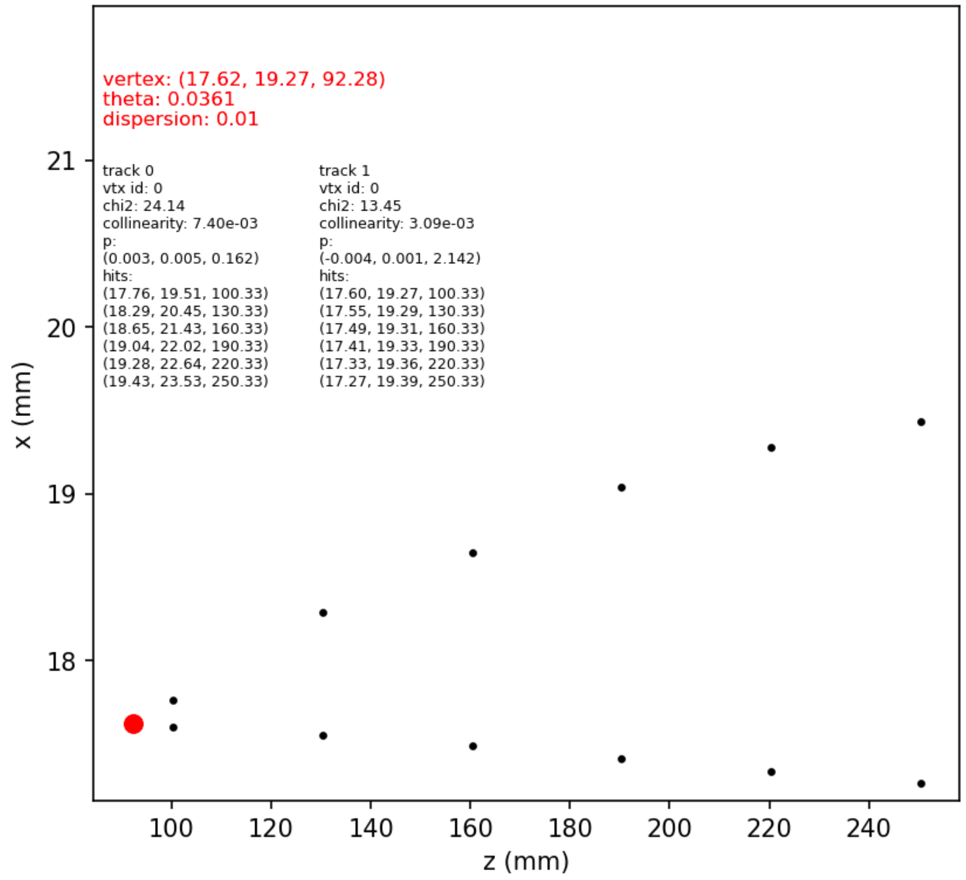
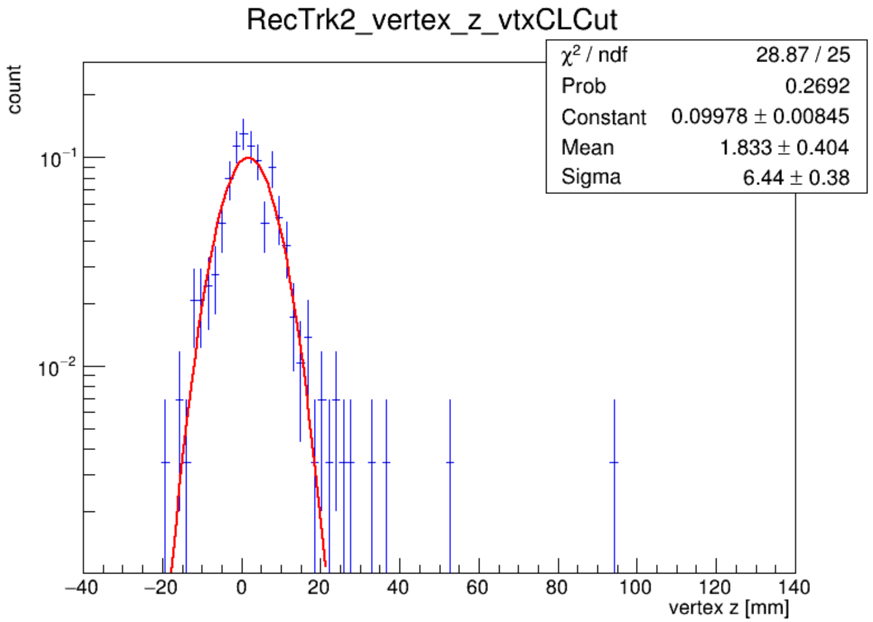
  - Use primary beam to reconstruct primary vertex on target, remove recoil electron track by its proximity to the primary vertex.
  - Define variables for vertex quality:
    - Vertex dispersion: tracks distance at the vertex z plane
    - Vertex theta: the angle between two tracks
    - Shared hit num: number of shared hits in the tracks
  - To reduce the long tail at vertex z:
    - Turning off the magnetic field, vertex resolution is improved by a factor of 2 (**from 8 mm to 4 mm**).
    - Many large reconstructed vertex z is due to scattering at tracker, we add collinearity cut on track to exclude such cases. (vertex resolution improved **from 4 mm to 3 mm**).

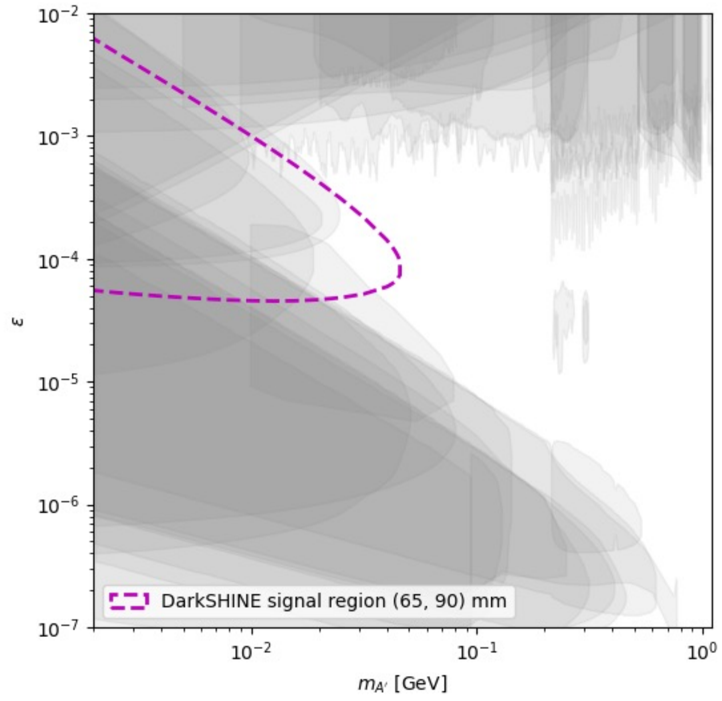


Signal Region Definition

- To define a low background region, we need to increase the distance between target and tracker, even though this will reduce the vertex resolution.
  - The distance between target and first tracker changes from 30 mm to 100 mm.
  - After several cuts, the vertex resolution can reach around 6.5 mm. Assuming gaussian distribution, take 10σ region as low background region, we take (65, 90) mm.

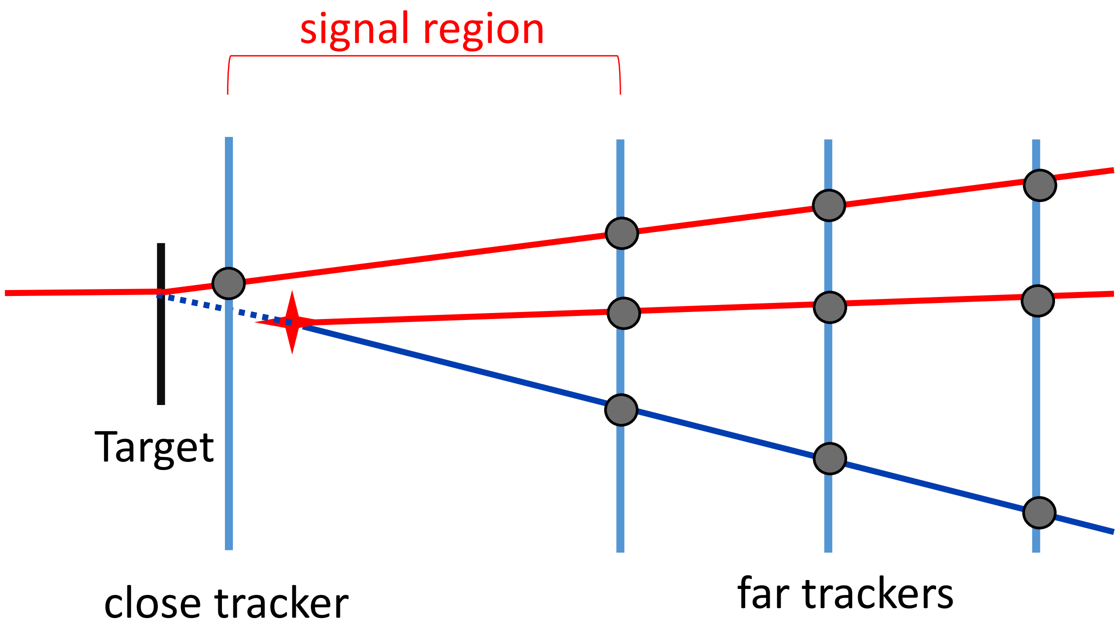


- By selecting a **displaced vertex** to achieve a low background region
  - Background: 100 out of 3E14 EOT
- 90% C.L. signal limit can be defined



Possible Improvement

- Add an extra layer of close tracker:
  - It can improve the vertex resolution in background case since it is closer to the vertex.
  - It can also be used for background veto, we can select events with single hit at close tracker.
  - Signal region is defined at between the close tracker and far trackers

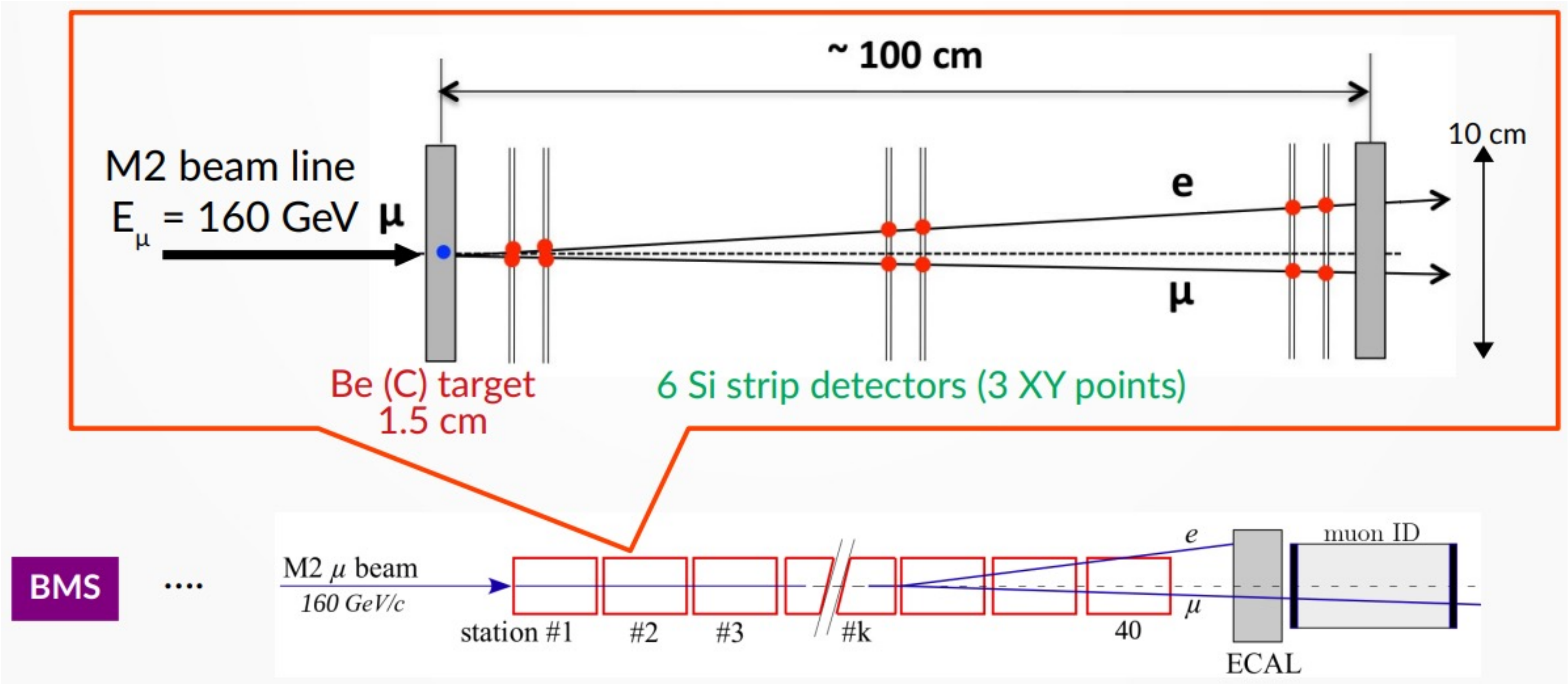


	Background (ePairProd)
total	1000000
Single hit at close tracker	7200
Vertex angle < 0.02 rad	10

- After **single hit cut** and **vertex angle cut**, the ePairProd at target background can be greatly suppressed.
- The main background becomes electron pair production at the close tracker. Consider change the close tracker to drift chamber to reduce multiple scattering.
- Further study is ongoing.

MUonE Experiment

- MUonE experiment is designed to measure the differential cross section of the elastic scattering process $\mu^{\pm}e^{-} \rightarrow \mu^{\pm}e^{-}$. Given the high angular resolution of tracking system, it is also suitable for searching the dark photon at visible decay channel.



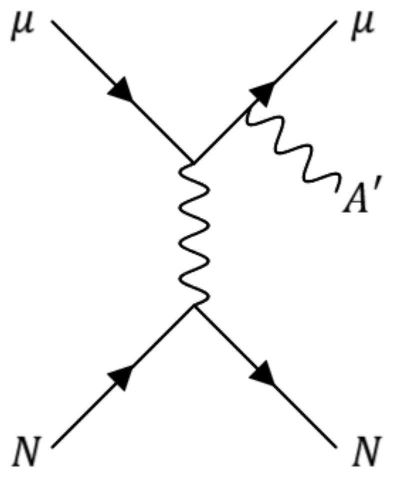
*Plot taken from 1st Europe-China-Japan Workshop on Muon Physics

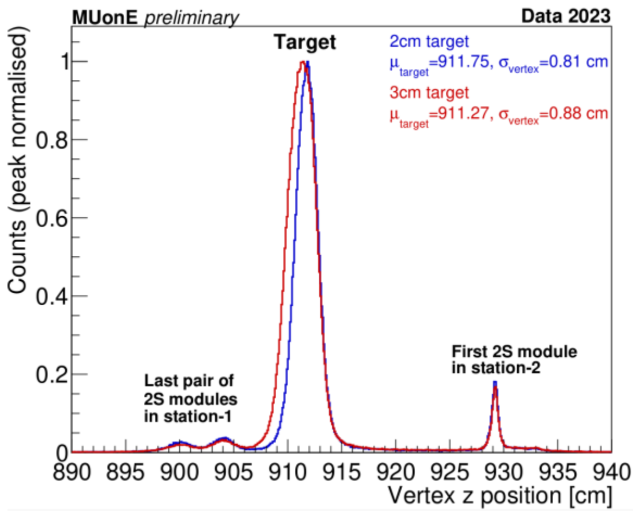
Comparison of DarkSHINE and MUonE

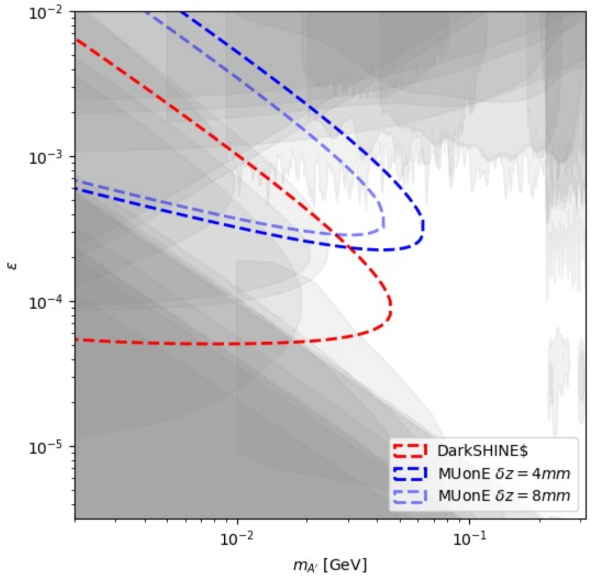
- Dark photon production via muon bremsstrahlung in μN scattering process:
  - DarkSHINE uses tungsten target and MUonE uses beryllium target, DarkSHINE has a higher production rate.
  - MUonE has 20 times higher beam energy than DarkSHINE, more sensitive to short lifetime signals.
  - **Complementarity** between DarkSHINE and MUonE.

	Target	EOT(MOT)
DarkSHINE	W, $0.1X_0$	3×10^{14}
MUonE	Be, $5\times0.08X_0$	1.3×10^{15}

- Requiring > 10σ (vertex resolution) to achieve low background region
  - Assuming signal efficiency ~ 60%
  - Sensitivity increases if vertex resolution improves from 8 mm to 4 mm



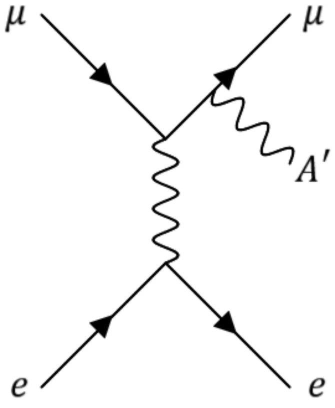


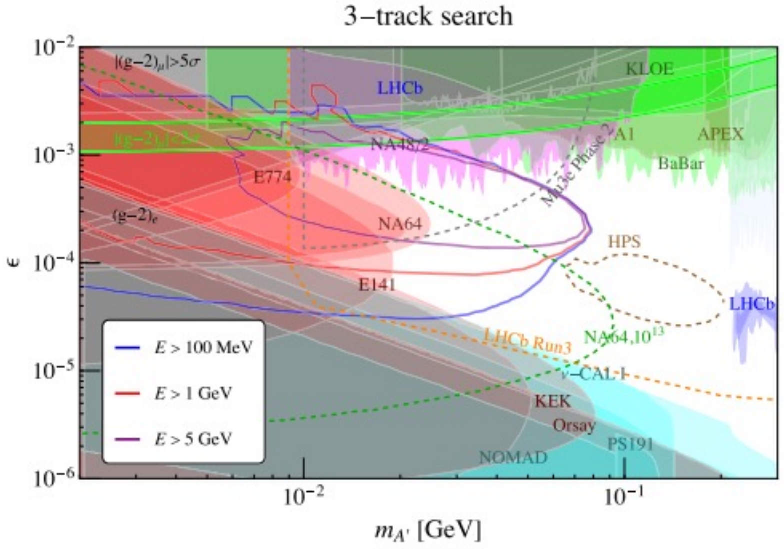


Visible Decay Search at MUonE

- MUonE can also search for dark photon production in μe scattering process.
  - There has been a phenomenology study of visible decay search at MUonE in 2023.
  - However, the analysis is somewhat simplified using fast simulation with strong assumptions.
    - E.g. vertexing resolution has been assumed to be 1mm.
  - More realistic checks with full reconstruction of displaced vertex is needed.

- What can we do at MUonE?
  - Full analysis of visible decay search based on **full simulation and data**.
  - Improve vertexing resolution based on the experience at DarkSHINE.
  - MUonE has the potential for search for other muon-philic BSM particles.





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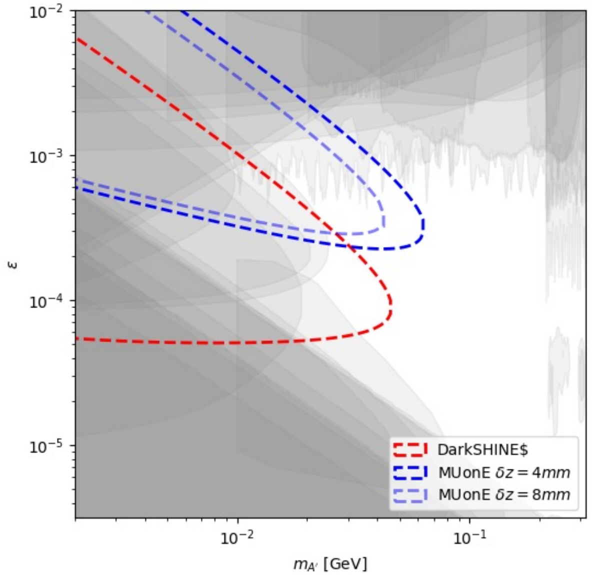
Summary

- Fixed-target experiments such as DarkSHINE and MUonE have the potential for search of the dark photon visible decay.
- In the preliminary study at **DarkSHINE**, full simulation based on Geant4 and vertex reconstruction algorithm based on Rave have been established.
  - Several methods to improve vertex resolution have been explored.
  - A low-background region is achieved, and the signal sensitivity reaches unexplored parameter space at $m_{A'} = 40\ \mathrm{MeV}, \epsilon = 10^{-4}$.
  - New detector setup to further extend signal region is under evaluation.
- The methodology of visible decay search can be easily applied to **MUonE.**
  - Optimizing vertexing algorithm based on the geometry and beam of MUonE.
  - Ability to search for muon-philic BSM physics.



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Thank You

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