Searching for Dark Matter with Displaced Vertex at the MUonE Experiment

PIKIMO Fall 2024

Based on arXiv: 2409.00170

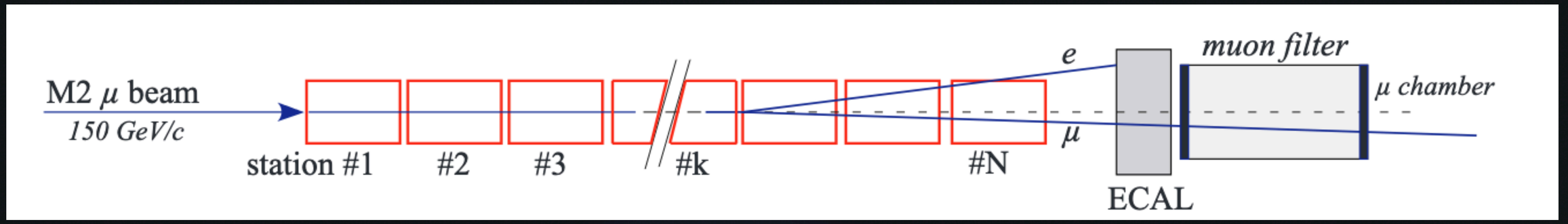
In collaboration with: Gordan Krnjaic, Duncan Rocha

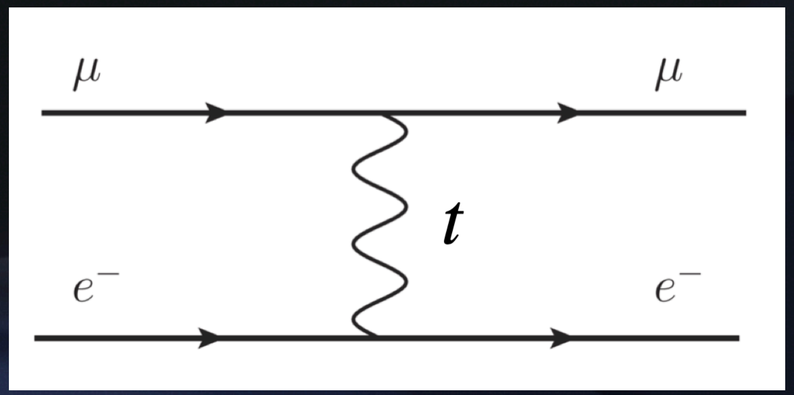
Many info from discussion with MUonE people: Umberto Marconi, Clara Matteuzi, Giovanni Abbiendi

Isaac Ruoquan Wang, Theory Division, Fermilab, 11/16/2024

The MUonE Experiment

A new way to probe displaced vertex





Aim: elastic $\mu - e$ scattering

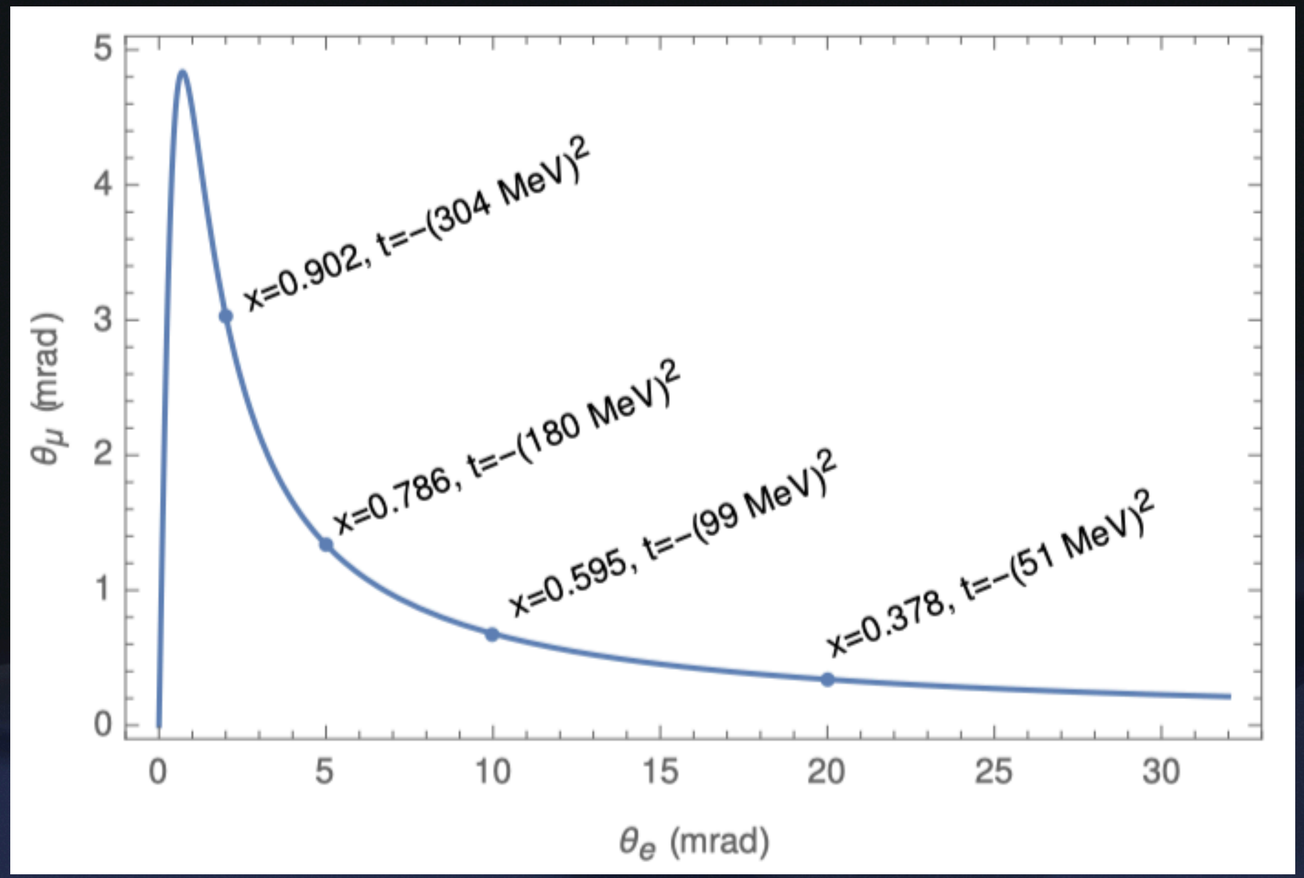
Measure: $\frac{d\sigma}{dt}$

Tech. Rep. CERN-SPSC-2019-026
10.1393/ncc/i2024-24138-4

Hadronic contribution to running $\alpha(t)$

The MUonE Experiment

Background rejection: selecting elastic scattering



arXiv: 2004.13663

θ_e and θ_μ relation:

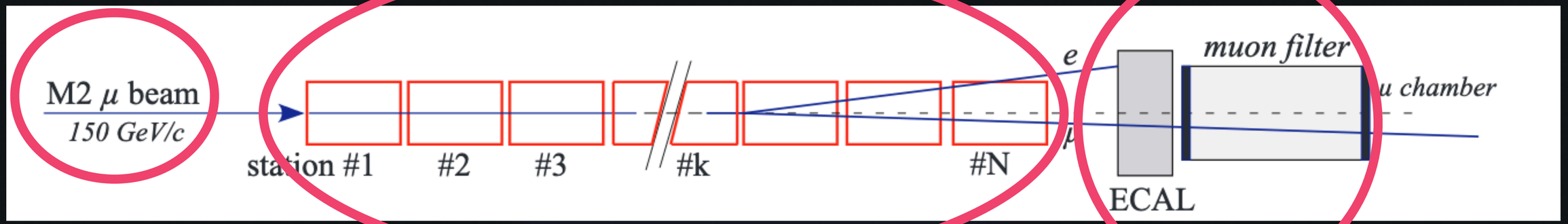
Elastic scattering: on the curve.

Non-elastic (background): random

Measure: **hits, angles, pid**

The MUonE Experiment

Apparatus structure



160 GeV muon beam

40 modules: target and tracking stations

PID system

Luminosity: $\mathscr{L} = 1.5 \times 10^4 \text{ pb}^{-1}$,

2 years data taken: 2028-2030

Size not decided yet

Aiming around $1\text{m} \times 1\text{m}$

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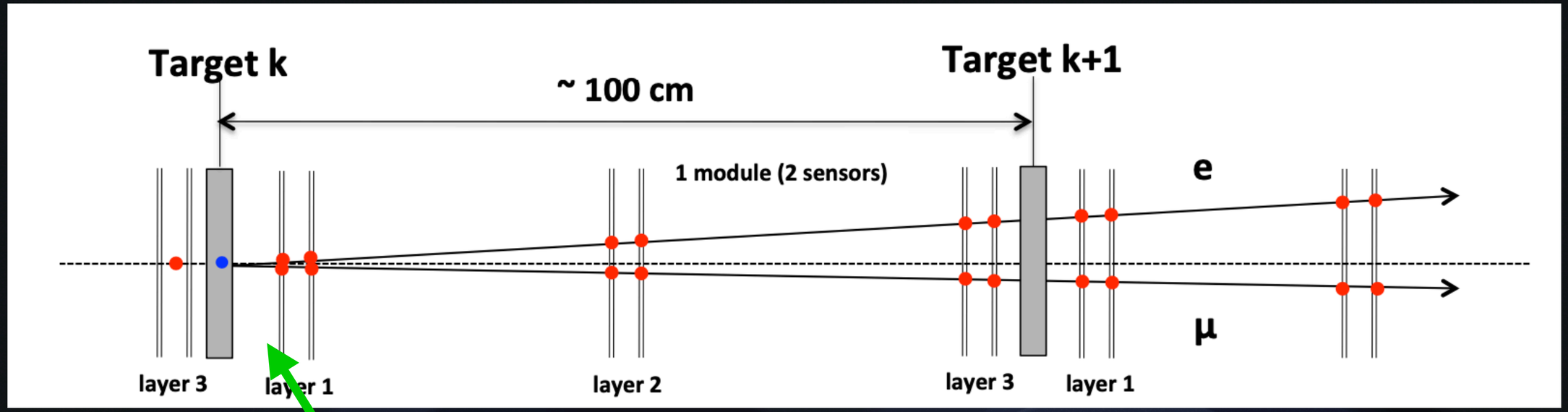
The MUonE Experiment: Modules



Beryllium target,

Thick: 1.5 cm

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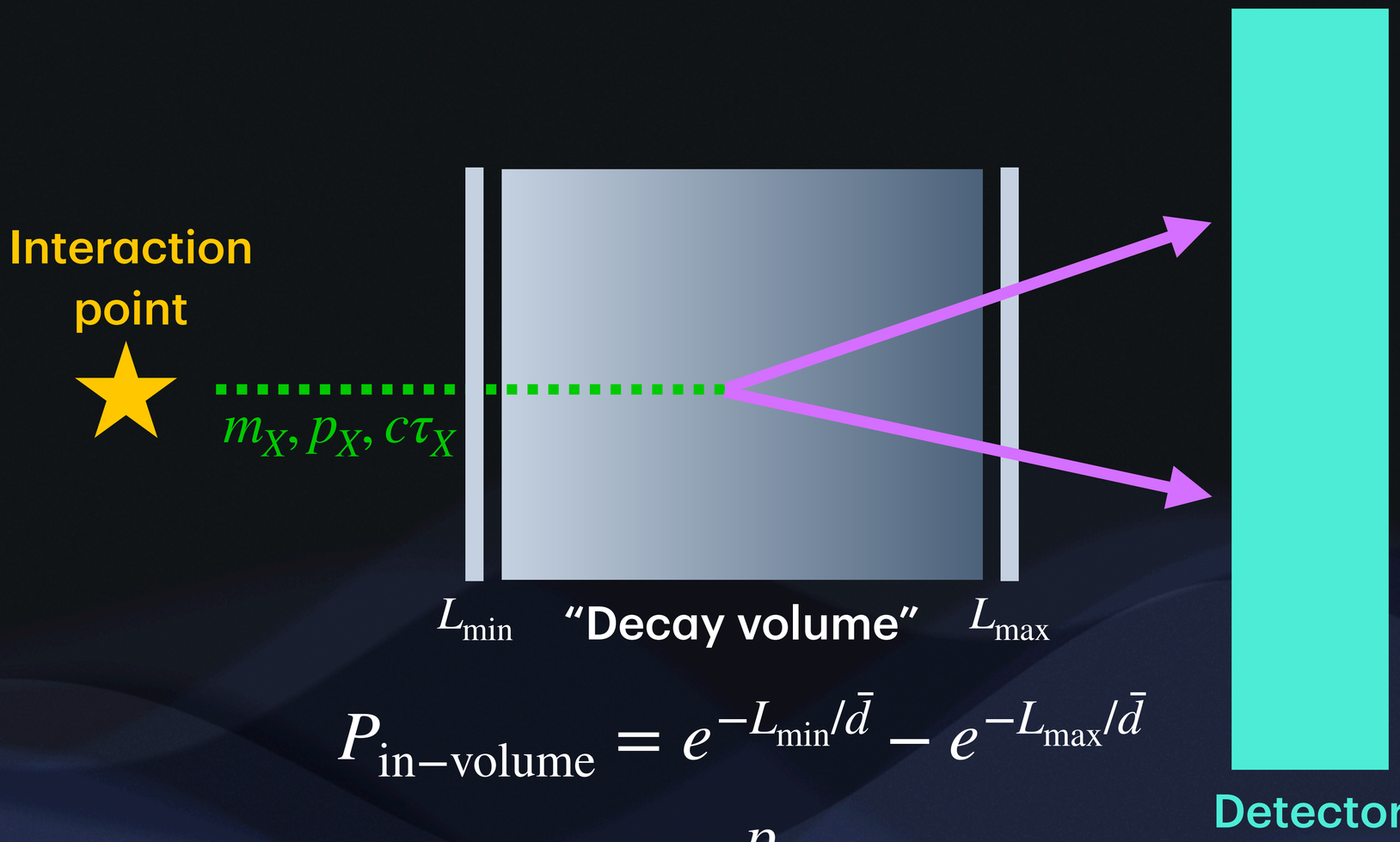
Target — 15 cm — 1st tracking layer

LLP Probe



$$P_{\text{in-volume}} = e^{-L_{\text{min}}/\bar{d}} - e^{-L_{\text{max}}/\bar{d}}$$

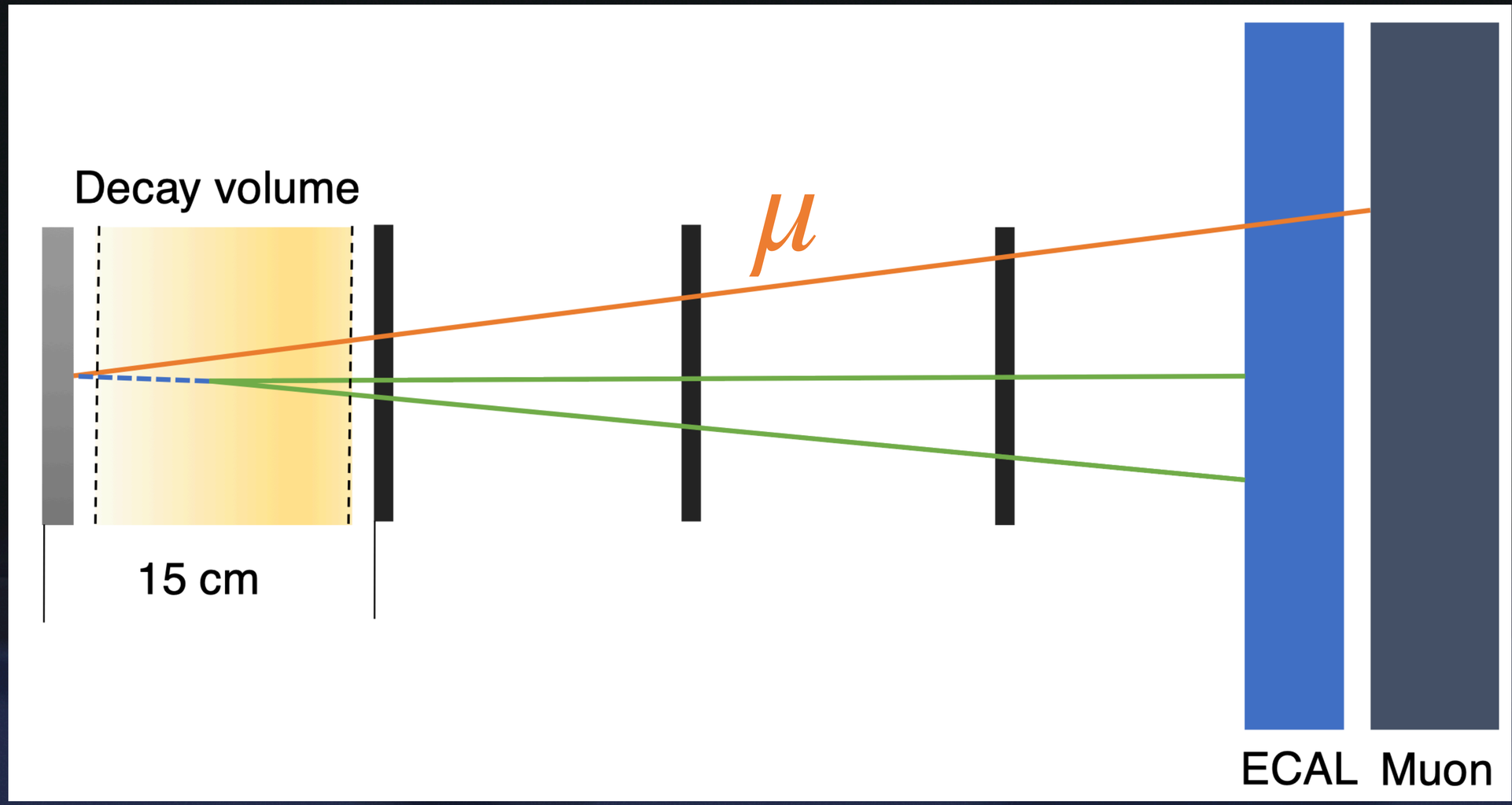
$$\bar{d} = \frac{p_X}{m_X \Gamma_X}$$

MUonE Advantage

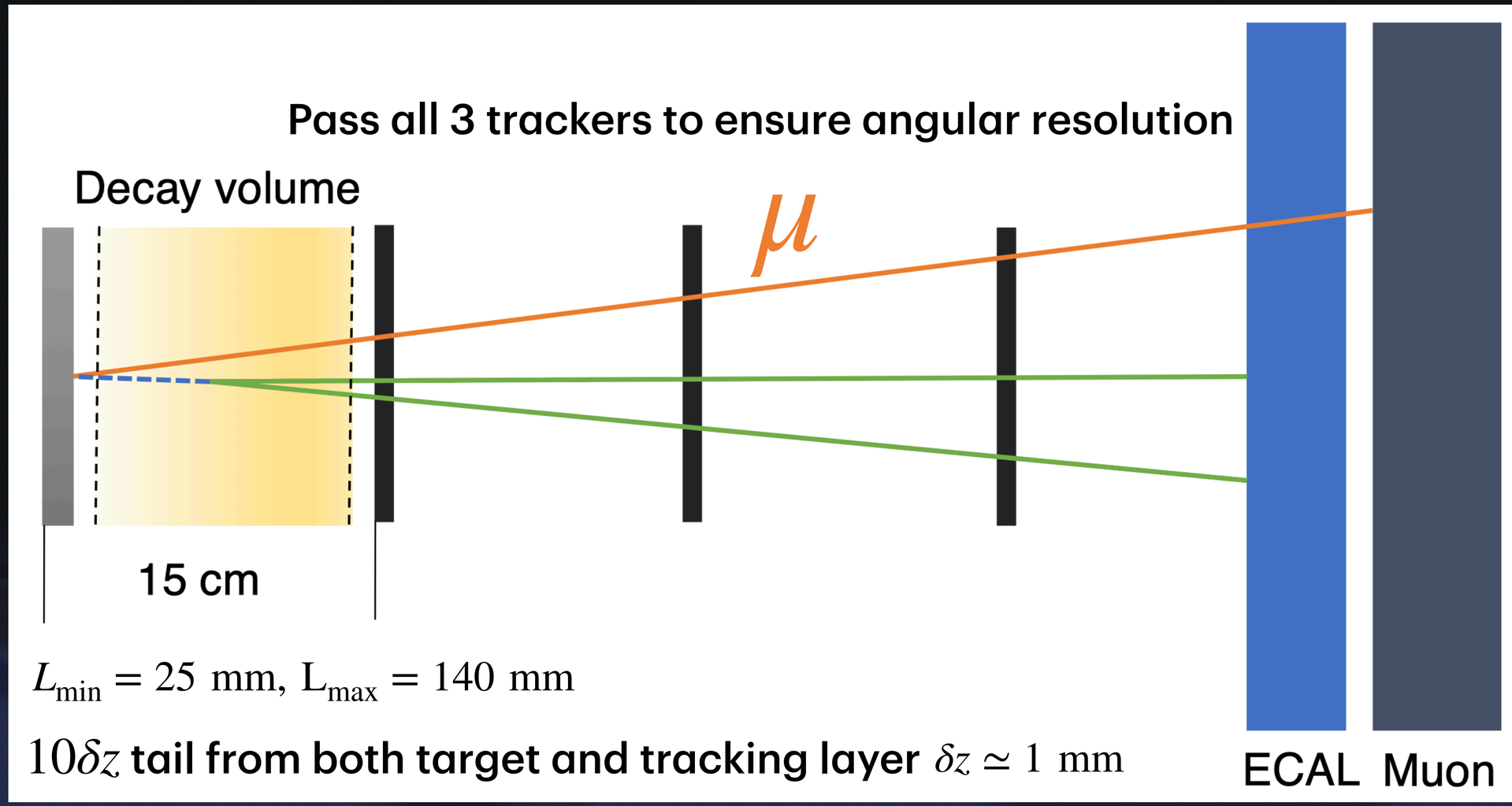
Great for Displaced Vertex

- Very high angular resolution: **motivated by background rejection**, promising for **displaced vertex reconstruction**
- High beam energy and intensity: enough dark photons to be created with high energies
- **Geometry** may be great!
- Sensitive tracking layers: detect **any extra hits** and reject background events
- PID system: background rejection
- Approved, promising timeline and funding

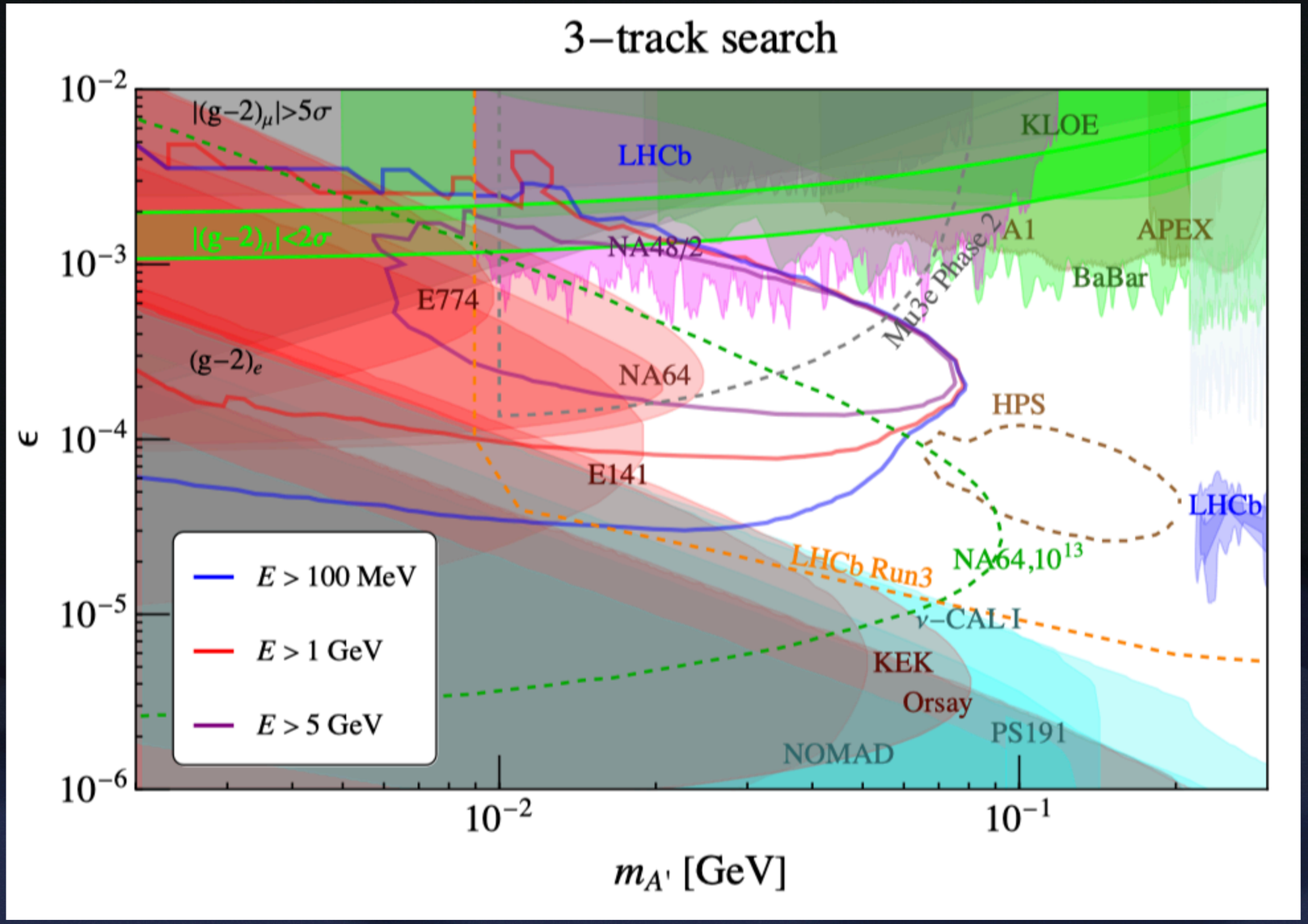
Displaced vertex @ MUonE



Displaced vertex @ MUonE



Previous Work: Dark Photon



I.Galon, D.Shih and IRW, 2202.08843

Connecting with Dark Matter?

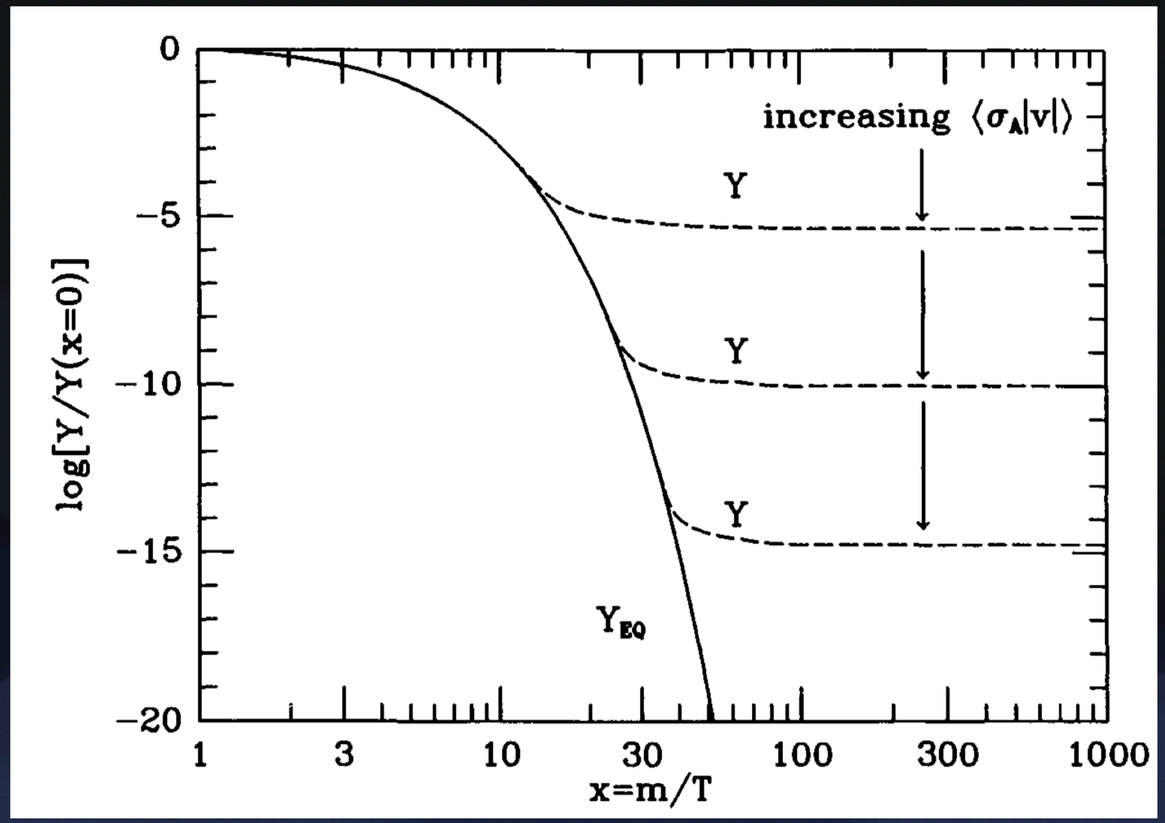
Can we directly annihilate $\bar{\chi}\chi \to A' \to$ SM (minimal case)?

Larger $\langle \sigma v \rangle$: less DM.

To have correct DM abundance,

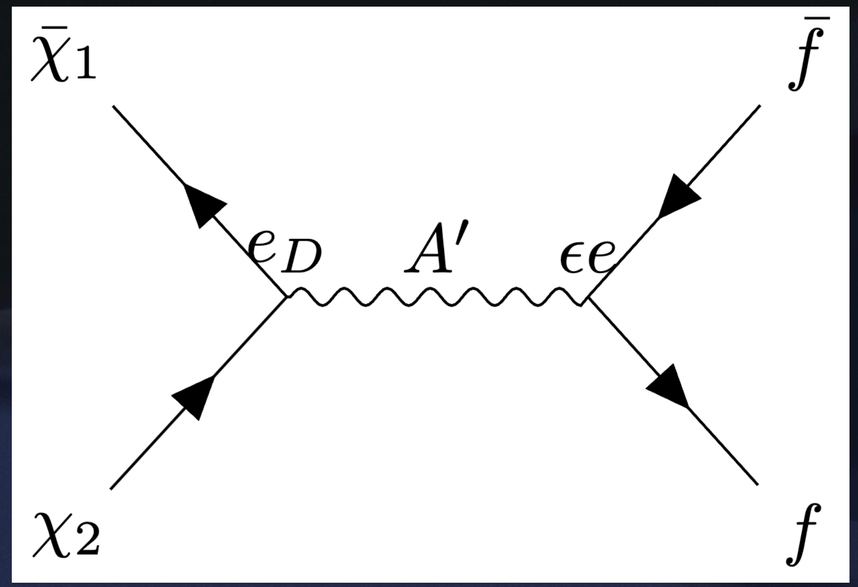
Typically ϵ falls into prompt region!

MUonE can do nothing with this prompt decay.



Next Minimal Case: Inelastic DM

- Have a pair of pseudo-Dirac fermions: χ_1, χ_2
- $\mathscr{L} = A'_\mu \bar{\chi}_2 \gamma^\mu \chi_1 +$ kinetic terms, small mass splitting.
- Annihilation channel:



arXiv: hep-ph/0101138

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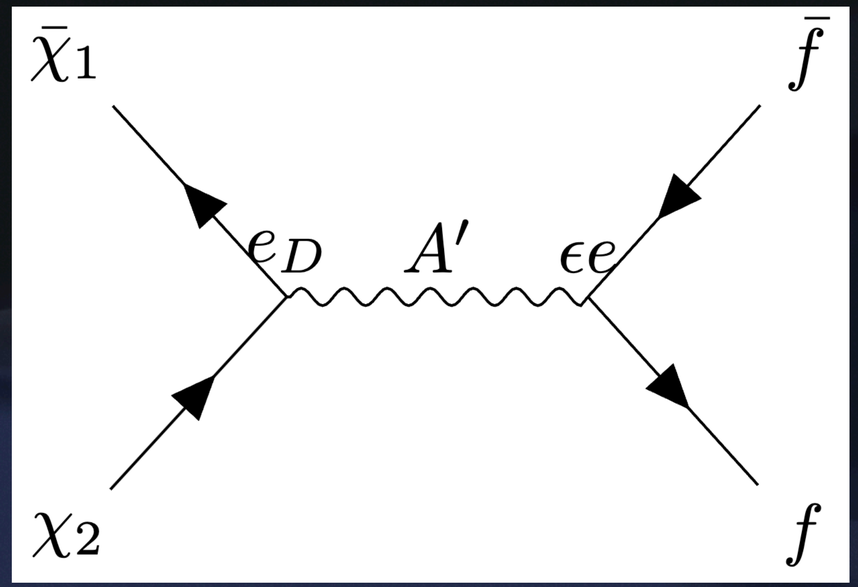


How many parameters?

- $m_{A'}$
- $\Delta \equiv m_2 - m_1$
- m_2
- ϵ

arXiv: hep-ph/0101138

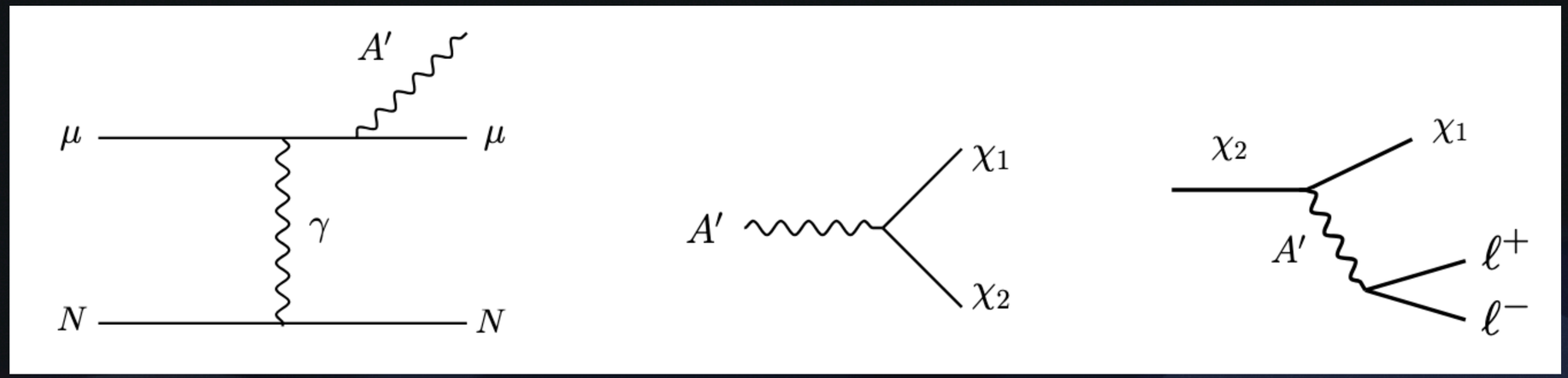
Parameter Space of Interest

Which is compatible with DM?

- Heavy A', avoid secluded annihilation $\chi_1\chi_2 \to A'A'$. $m_{A'} > m_1 + m_2$!
- Naturally, $\alpha_D \gg \epsilon^2\alpha_e$
- Now A' decays into $\chi_1 + \chi_2$, promptly with $\mathbf{BR} \simeq 1$. Then χ_2 has displaced decay.
- $\Gamma_{\chi_2} = \dfrac{4\alpha_D\alpha\epsilon^2\Delta^5}{15\pi m_A'^4}$, $\Delta \equiv m_2 - m_1$, small mass splitting and heavy $m_{A'}$ suppresses decay rate.

Inelastic DM: Signals @ MUonE

- A' decays promptly, for the region where DM abundance is good.
- χ_2 decays into $\chi_1 + A', A' \to l^+l^-$, displaced vertex!



arXiv: 2108.13422,

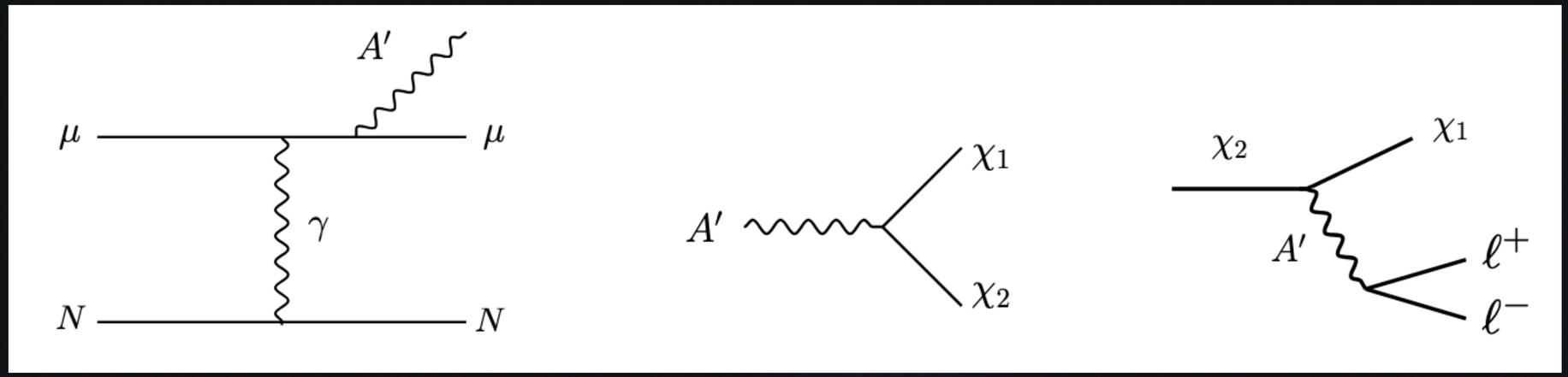
G. Krnjaic, D. Rocha, IRW: arXiv: 2409.00170

$$\bar{d}_{\chi_2} = 10 \text{ cm} \left(\frac{m_{A'}}{100 \text{ MeV}}\right)^4 \left(\frac{20 \text{ MeV}}{\Delta}\right)^5 \left(\frac{10^{-7}}{\epsilon^2 \alpha_D}\right)$$

To produce heavy A':

Consider μN scattering

Inelastic DM: Signals @ MUonE



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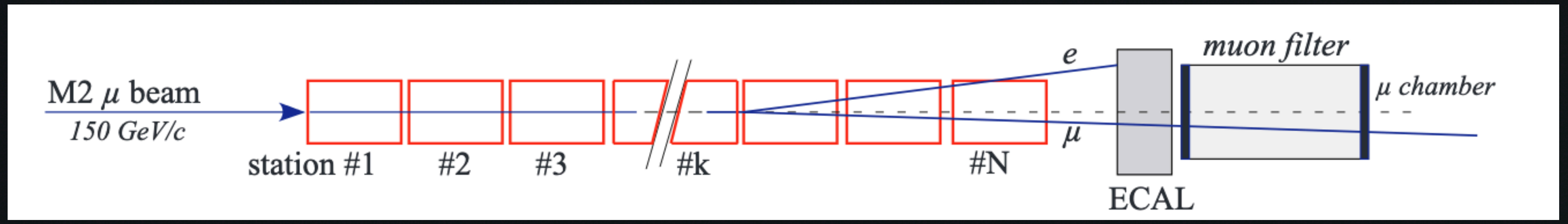
Final state:

- Primary muon
- Displaced l^+l^-

Exactly 3 tracks!

PID: Entering the ECAL



Energy loss: may affect ECAL efficiency

Source of loss: penetrating following modules....

Strategies: use only **last 5 modules**, apply an **energy threshold** for track simulations

Impact: mainly for primary electrons. But do we really necessarily need to see it?

I.Galon, D.Shih and IRW, 2202.08843

G. Krnjaic, D. Rocha, IRW: arXiv: 2409.00170

Summary for Signal Selection

- Final state: 3 tracks.
- Minimal energy threshold: 5 GeV.
  - Note: Not a real analysis-level cut. Just mimicking the detector response for energy loss! (Theorists....)
- Displaced vertex tracks have an opening angle larger than 1 mrad. (To ensure resolution)
- Decay “in volume”.
- Pass through 3 tracking layers in the same module
- Pass through the ECAL
- Only last 5 modules.

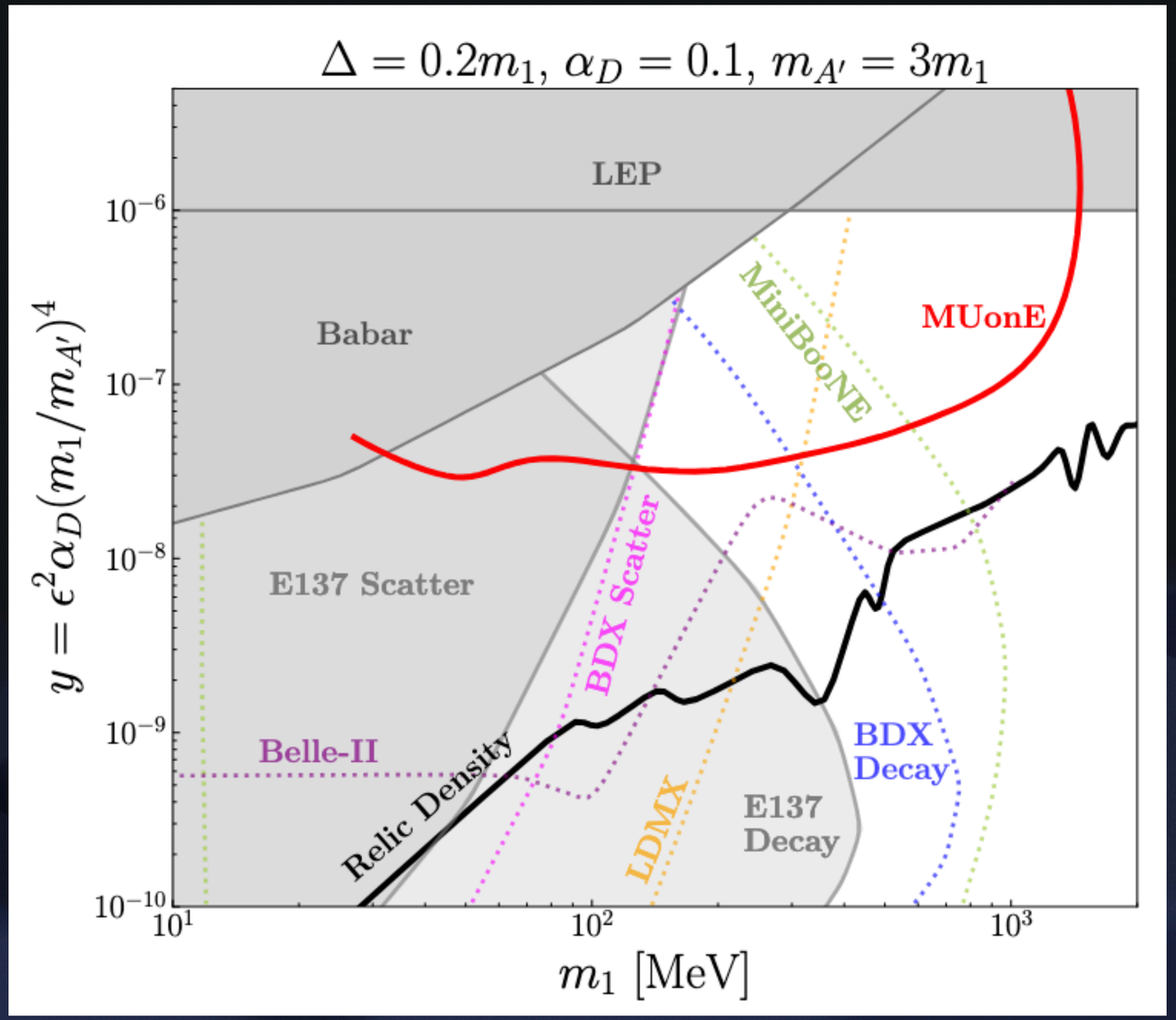
G. Krnjaic, D. Rocha, IRW: arXiv: 2409.00170

Backgrounds

2 types

- Prompt vertex, but mis-reconstructed: saved by $10\ \delta z$ tail from target and tracking layer. **Safe!**
- SM displaced vertex from inelastic scattering: $K^0 \to \pi\pi$, $\Lambda \to p\pi$, etc. Hadronic process from μN scattering. Typically too many particles and rejected by extra hit, but not guaranteed. Need PID to reject the remainings. Simulation: all rejected as long as PID per-particle fake rate less than 2.2%.

Result



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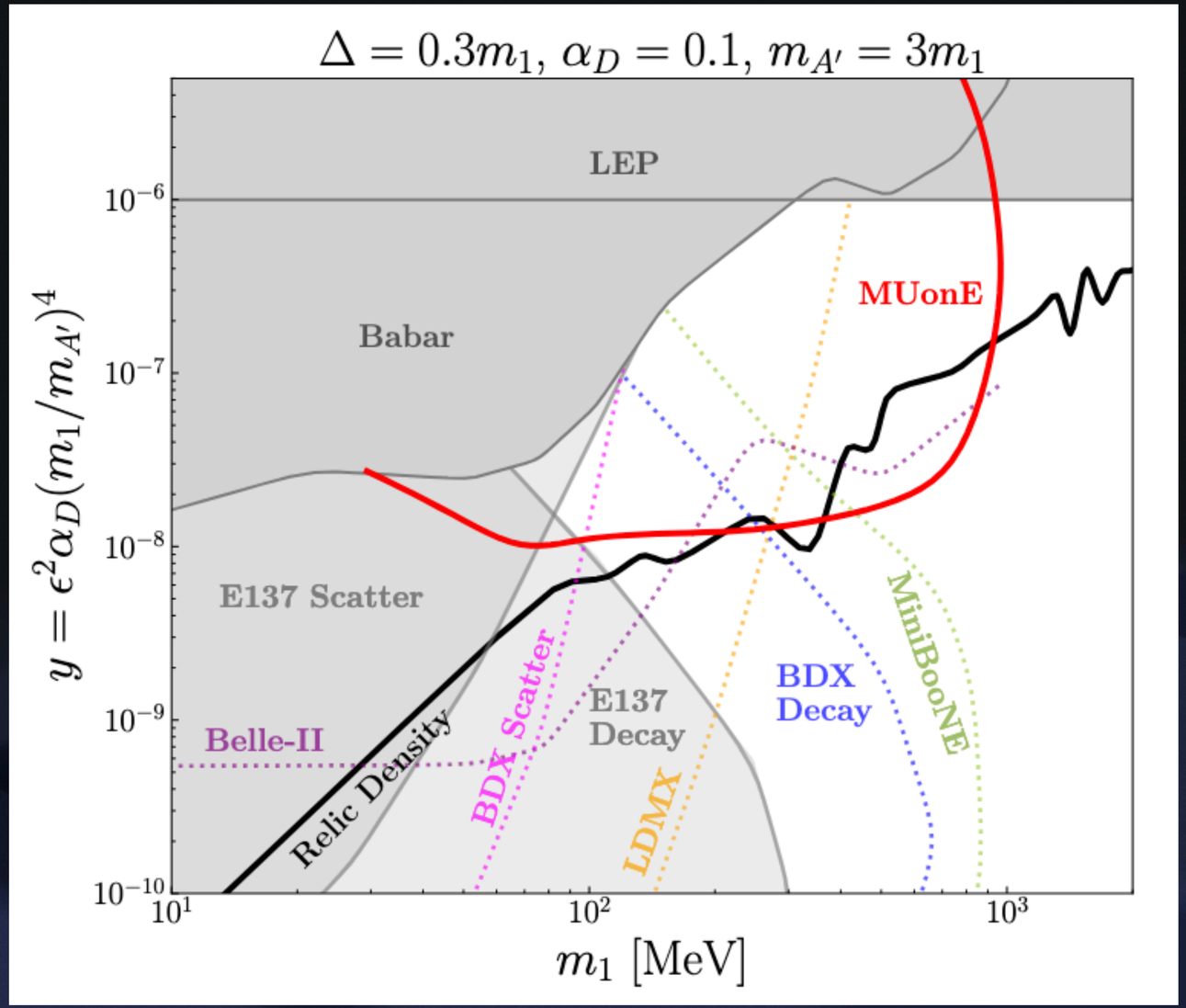

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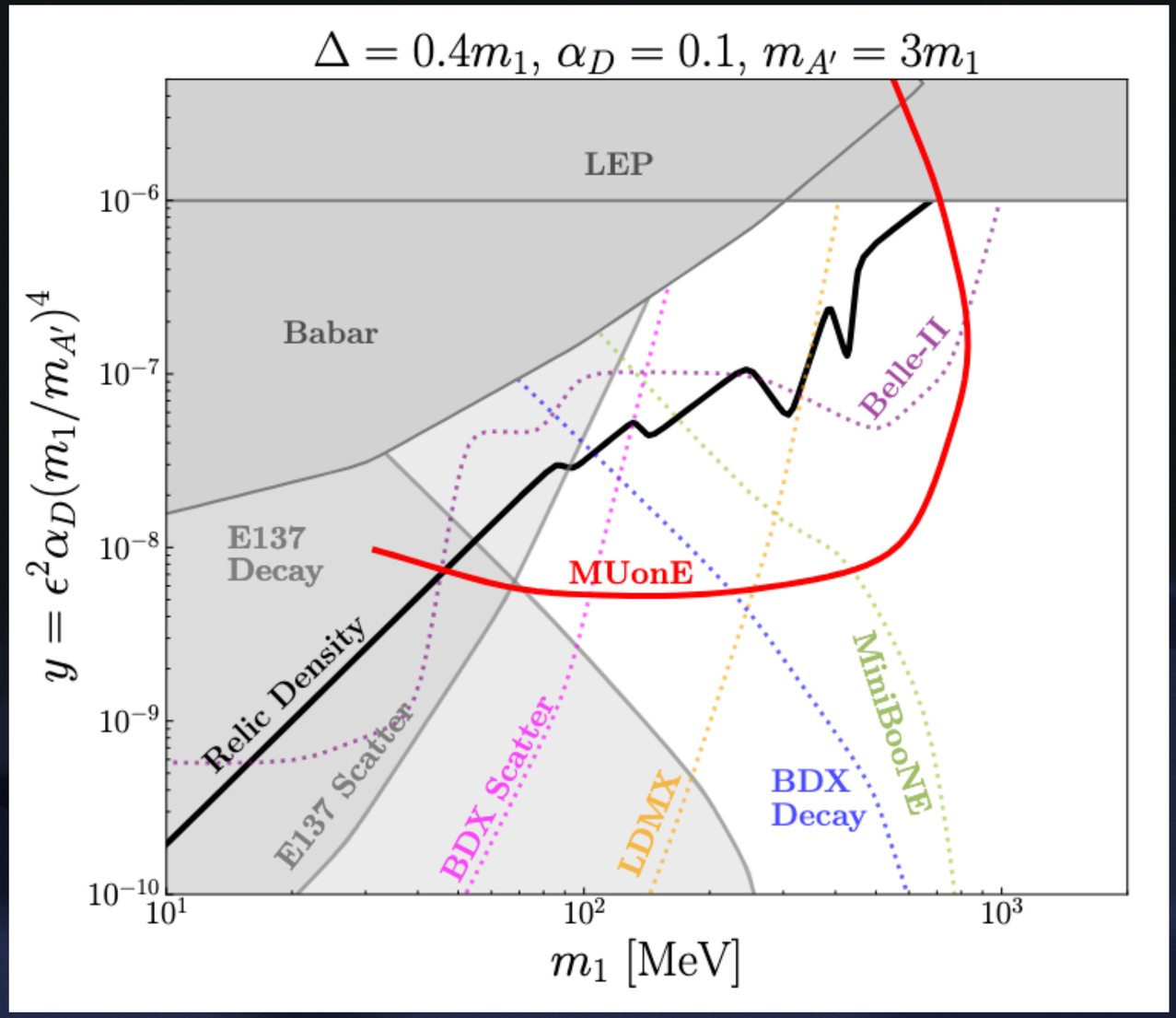

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What Makes it Successful?

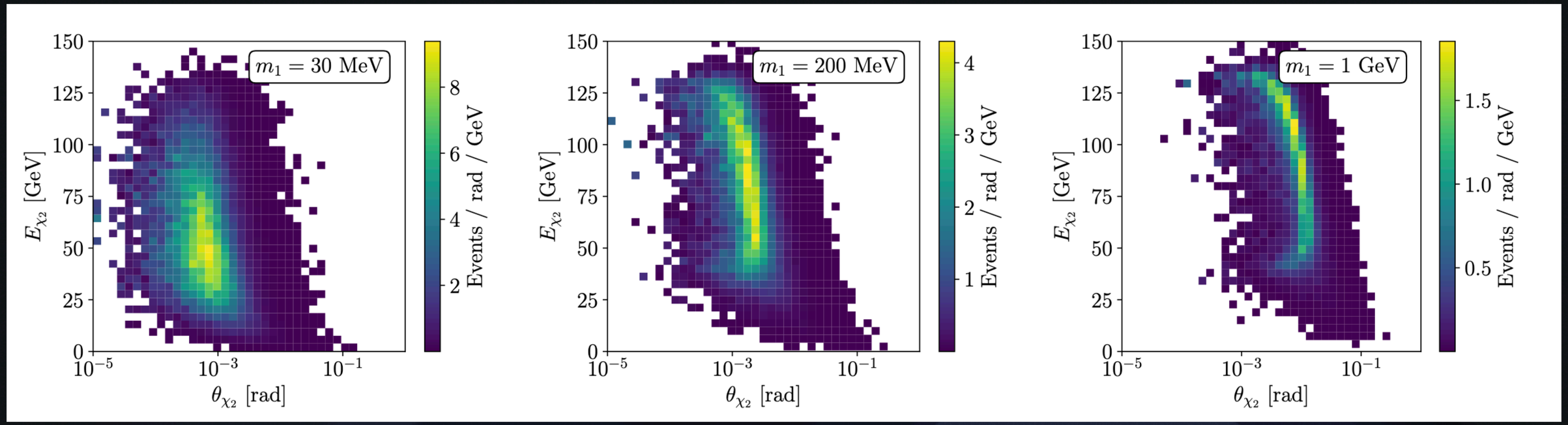
- Geometry falls into that region!
- ECAL has a strong bg rejection ability (keep it, please!)
- Large luminosity, large beam energy.
- No any additional setup required. Just the original experimental plan!

Summary

- Dark photon is a highly motivated scenario with various extensions.
- Dark photon can be connected with dark matter in various ways.
- MUonE, as an SM-motivated experiment, is sensitive to the long-unprobed ‘gap’ of dark photon and dark matter.
- No any additional equipment needed! Very efficiency and economy.
- We encourage more works to probe BSM physics on SM-motivated experiments. New window for BSM search!

Backups

Inelastic DM: Production



χ_2 is very energetic and forward-moving!

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Backgrounds: hadronic process

- Deep-inelastic scattering (DIS): perturbative, large momentum transfer (Q^2), large muon deflection angle
  - Safely rejected: DIS $\theta_\mu > 10\ \mathrm{mrad}$, while signal always have $\theta_\mu < 10\ \mathrm{mrad}$
- Soft QCD: non-perturbative. Simulated by Pythia8. Typically have too many particles.
  - Mostly rejected by extra hits on the trackers/ECAL. Result not sensitive to the minimal energy required to be detected ranging from 100 MeV to 5 GeV.
  - If not rejected by extra hit, use PID to reject.

Background: PID rejection

Can bg events contain real electrons so that even PID can't reject?

- $K^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, etc. Dominant. No real e displaced.
- $K^0 \to \pi e \nu$, 1 e displaced.
- $K^0 \to \pi^0\pi^0$ with one $\pi^0 \to e^+e^-\gamma$, 2 e displaced.
- If 4-track search, in some very rare cases one e comes from the primary vertex and fakes the primary e. Mostly it's $K^\pm$ faking the primary e.
- Primary μ always there.

Background simulation

- No real e: 3500 bg events before PID. Requires PID per-particle fake rate < 1.6%.
- 1 real e: 6 events before PID.
- 2 real e: 0 events before PID. All having some other particles hitting on the ECAL/trackers.