

A Muon Beam for LDMX

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Muon beam instead of an electron beam..?

Explore dark sector particles that couple to the second-generation SM particles

Probe dark matter candidates in a higher mass range

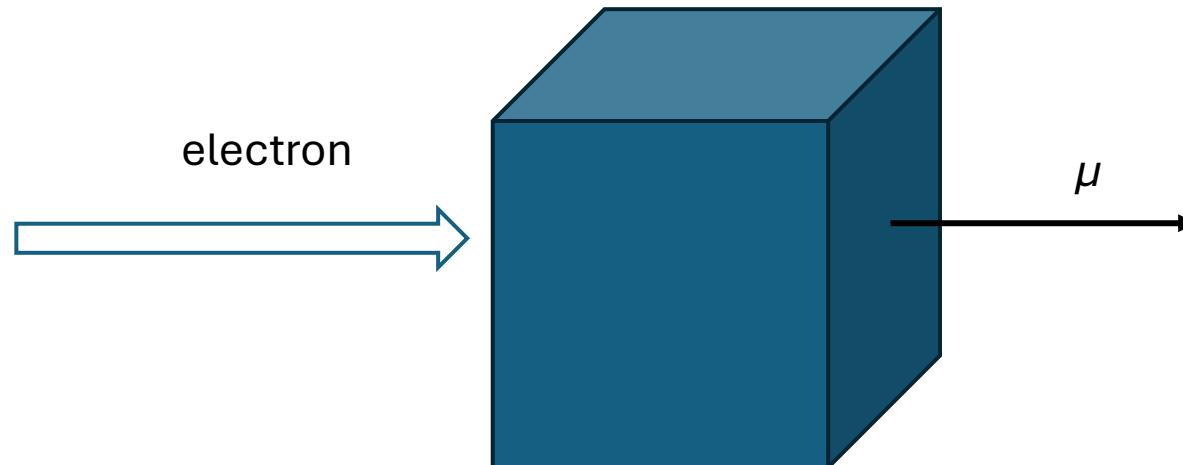
Muons penetrate deeper into the target
→ Higher interaction rates with DM

A percent level momentum resolution is possible

The bremmstrahlung background processes are suppressed by a factor of $\left(\frac{m_e}{m_\mu}\right)^2 \approx 2 \cdot 10^{-5}$

But, how do we make a muon beam??

We can shoot high energy (8 GeV) electrons onto a target and *hope* for enough muons to be emitted



We need the beam to have....

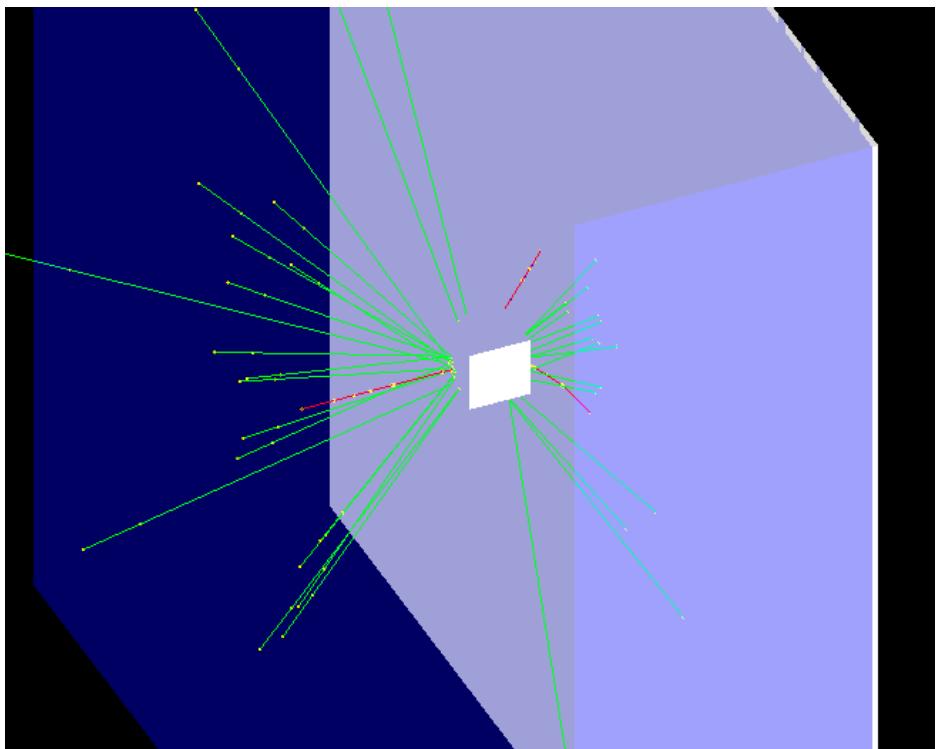
1

A good yield of muons with well-characterized phase-space distributions

- Momenta of at least 2 to 3 GeV (just a provisional value for now)
- Well collimated along the incoming electron beam direction

2

A minimal level of background particles that get produced along with



Minimizing the outgoing flux of electrons, protons, and neutrons is crucial to avoid them from interfering with the experimental setup.

What we studied:

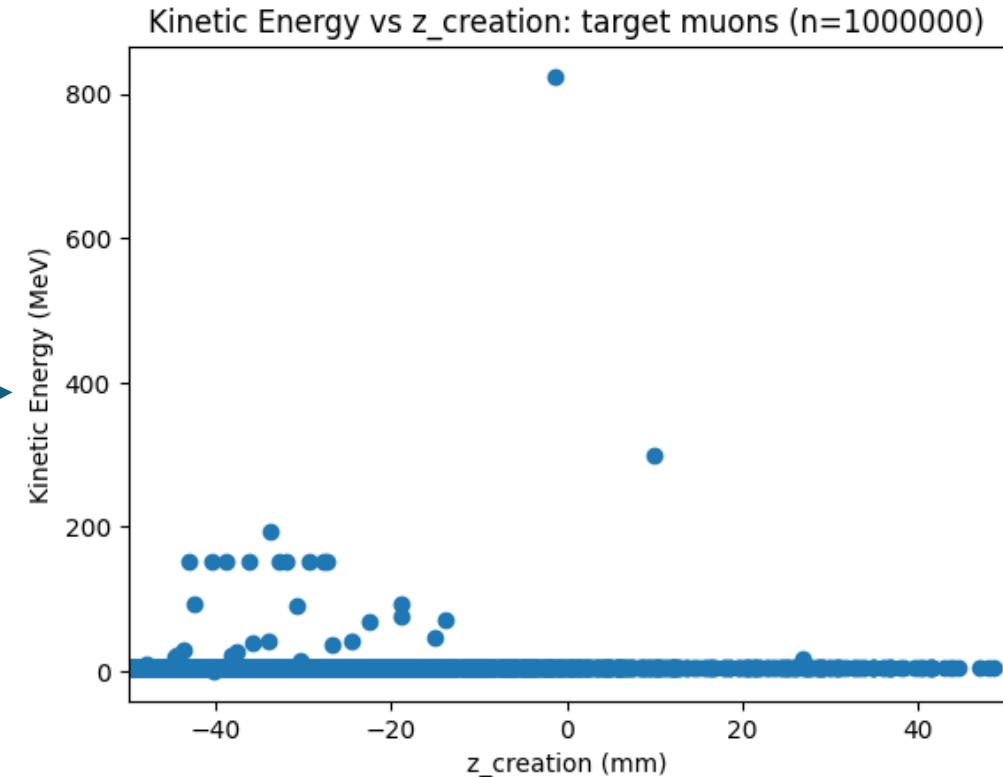
1. *Geant4* simulations to understand the physical processes, the distributions of the muons produced from them, and their yields
2. Varied target thickness to find its effects on the muon yield and background processes
3. Numerical calculations to understand the sensitivity of the resulting muon distribution in probing dark matter physics

Pion decays vs. Trident process

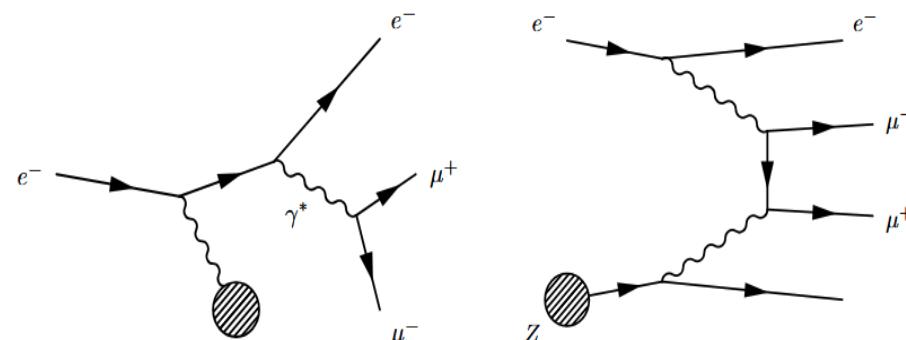
2 physical processes of muon production

a. Pion decays:
Good yield

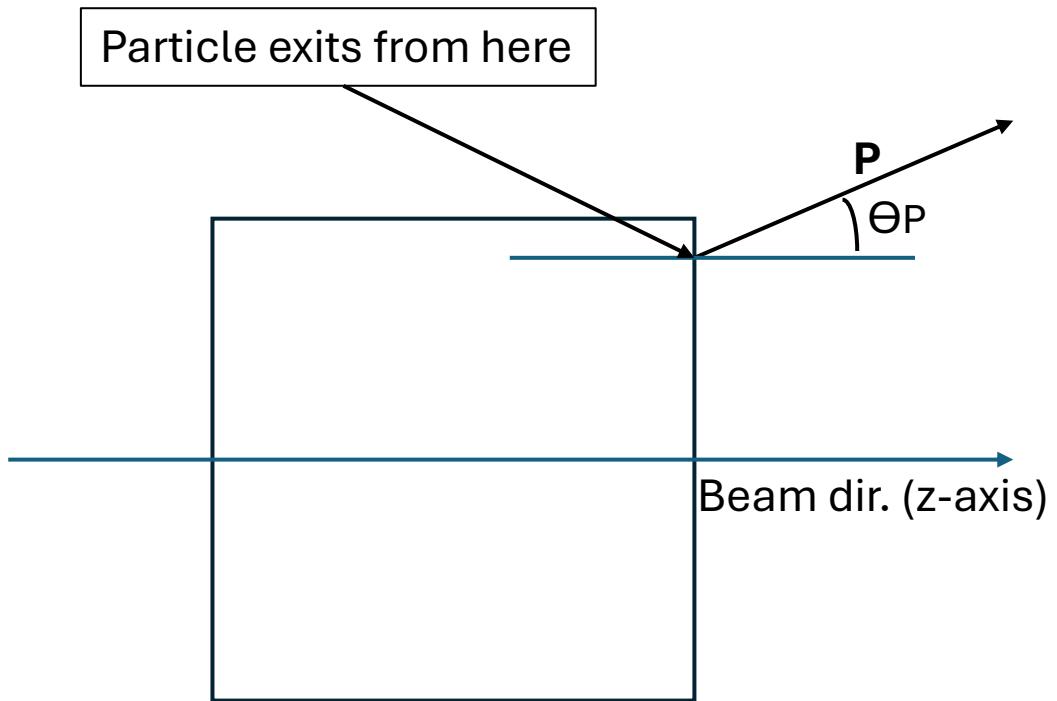
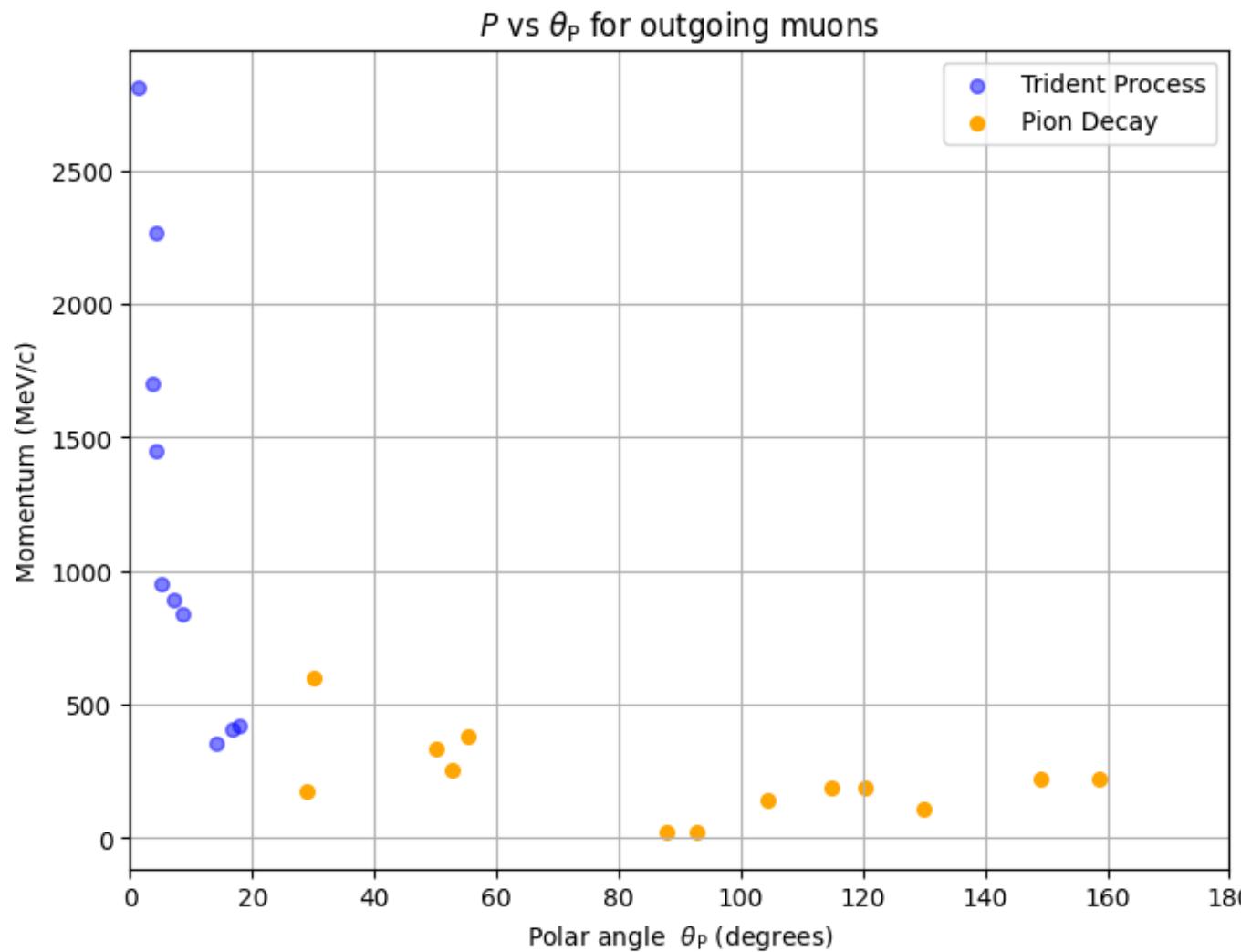
$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu\end{aligned}$$



b. ‘Trident process’:
Low yield



Pion Decays vs. Trident Process

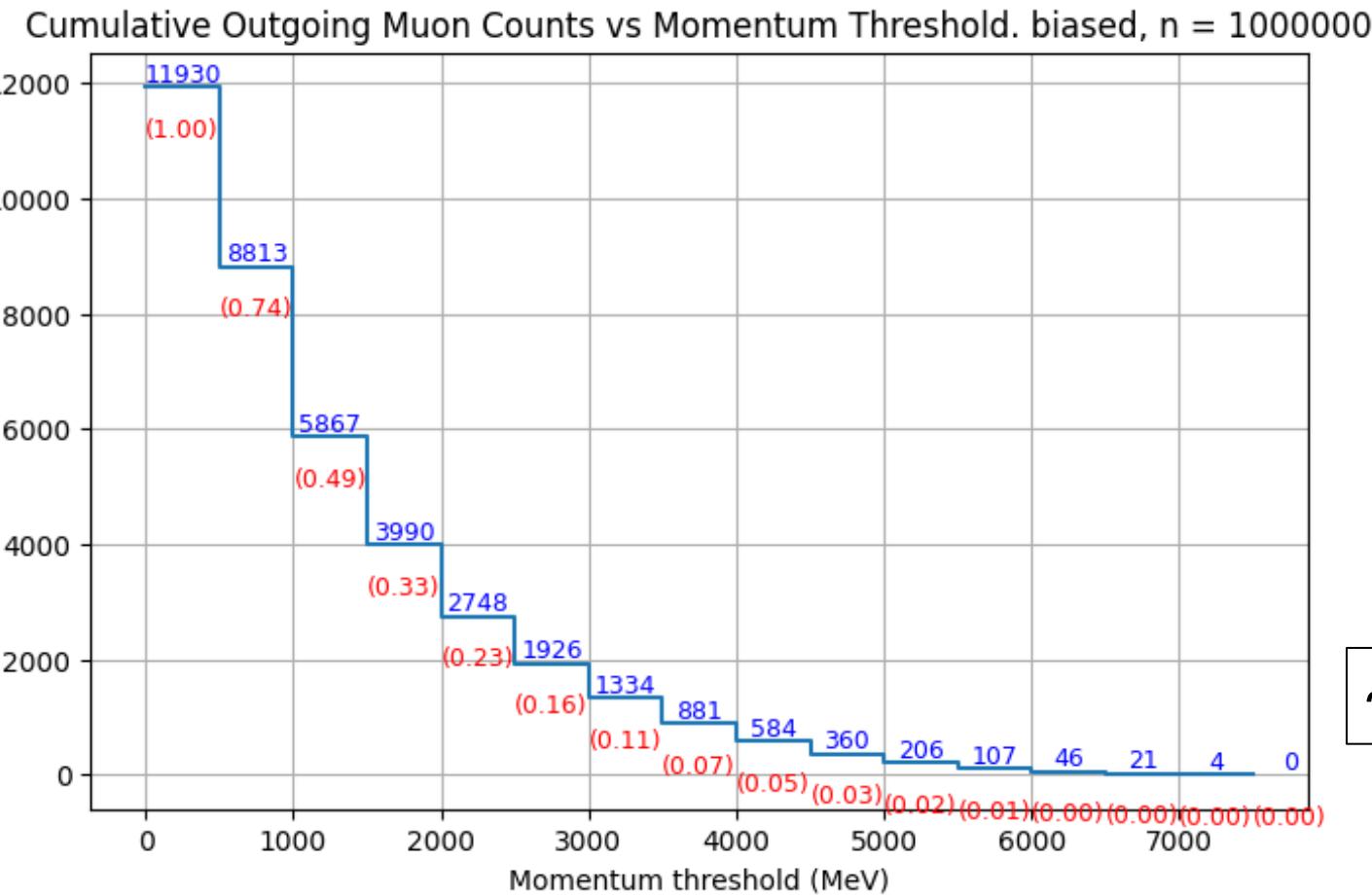


Higher momentum \rightarrow Small θ_p

Trident process tends to produce muons of higher momenta since the electrons can supply the necessary energy into a virtual photon.

But, trident processes are rare!

To understand their yield, we used biased simulations in *Geant4* (biasing factor = 1000).
The results are promising!

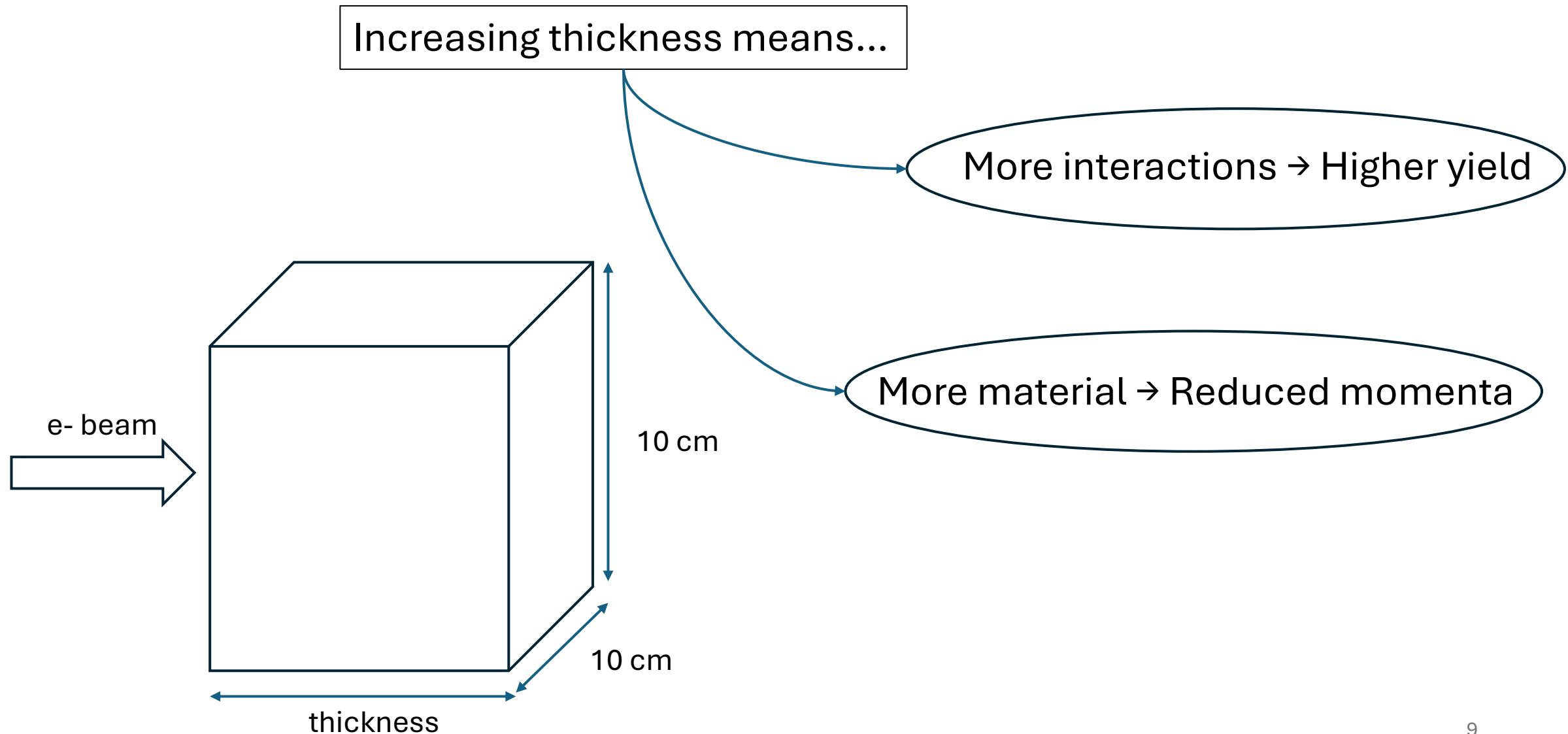


We can expect ≈ 2 muons of
 $p > 2$ GeV per 10^6 electrons

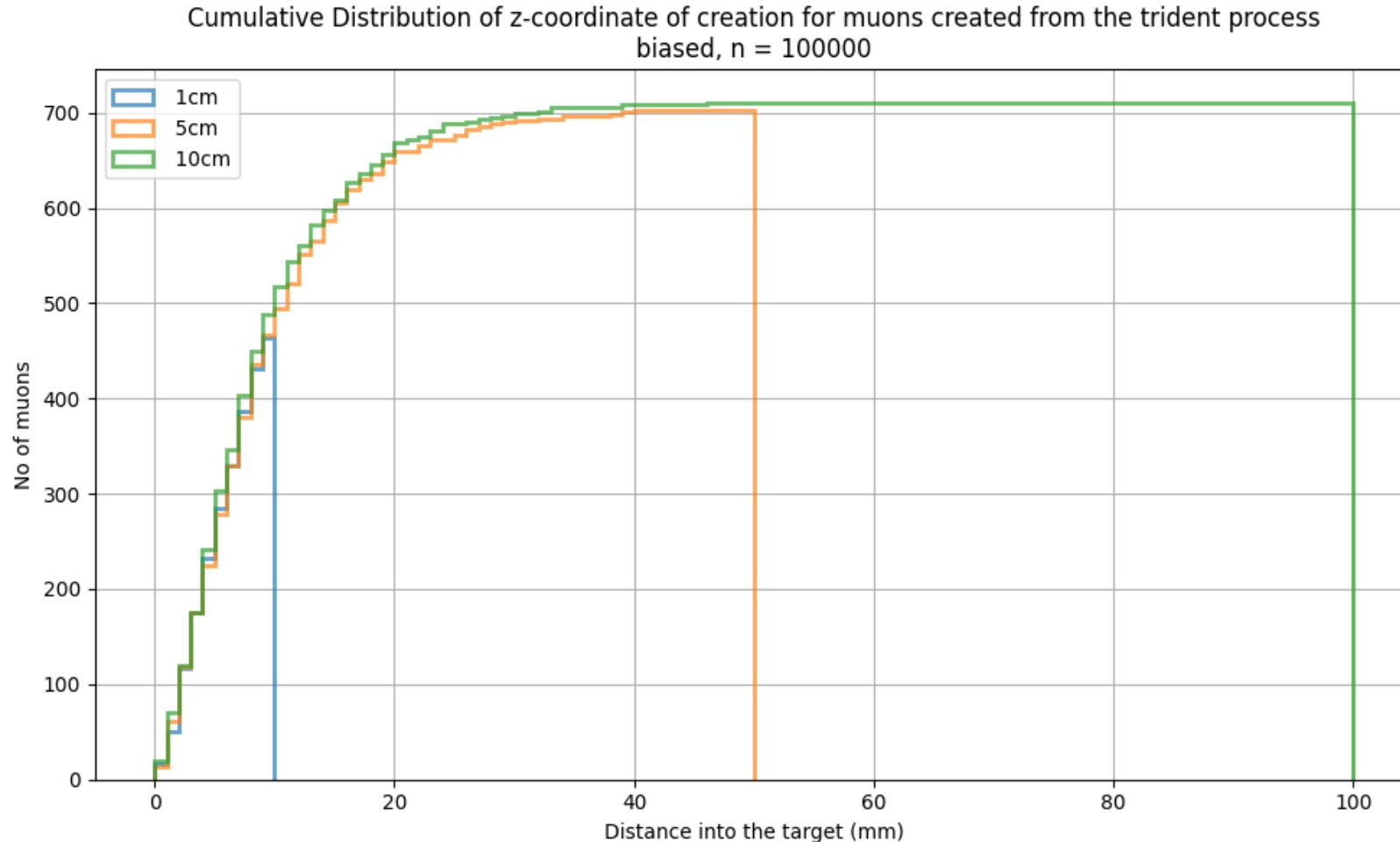
SLAC:
Pulses of 10^5 electrons at 1 MHz

$\sim 10^{13}$ useable muons over 3-4 years

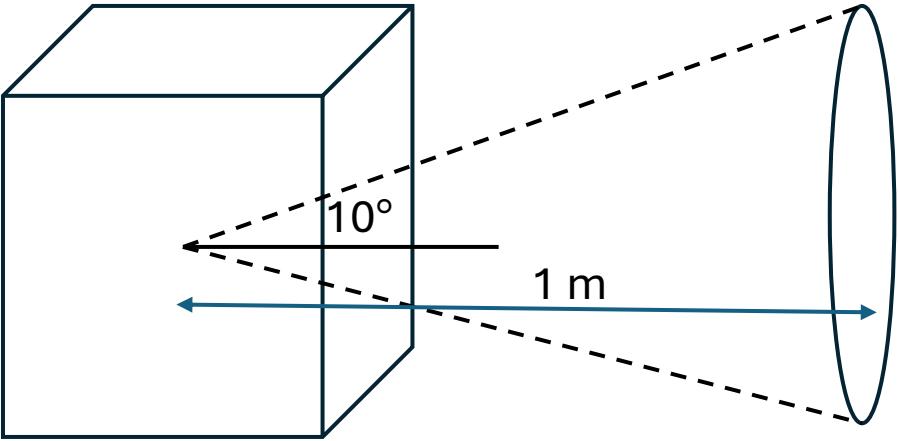
Target thickness



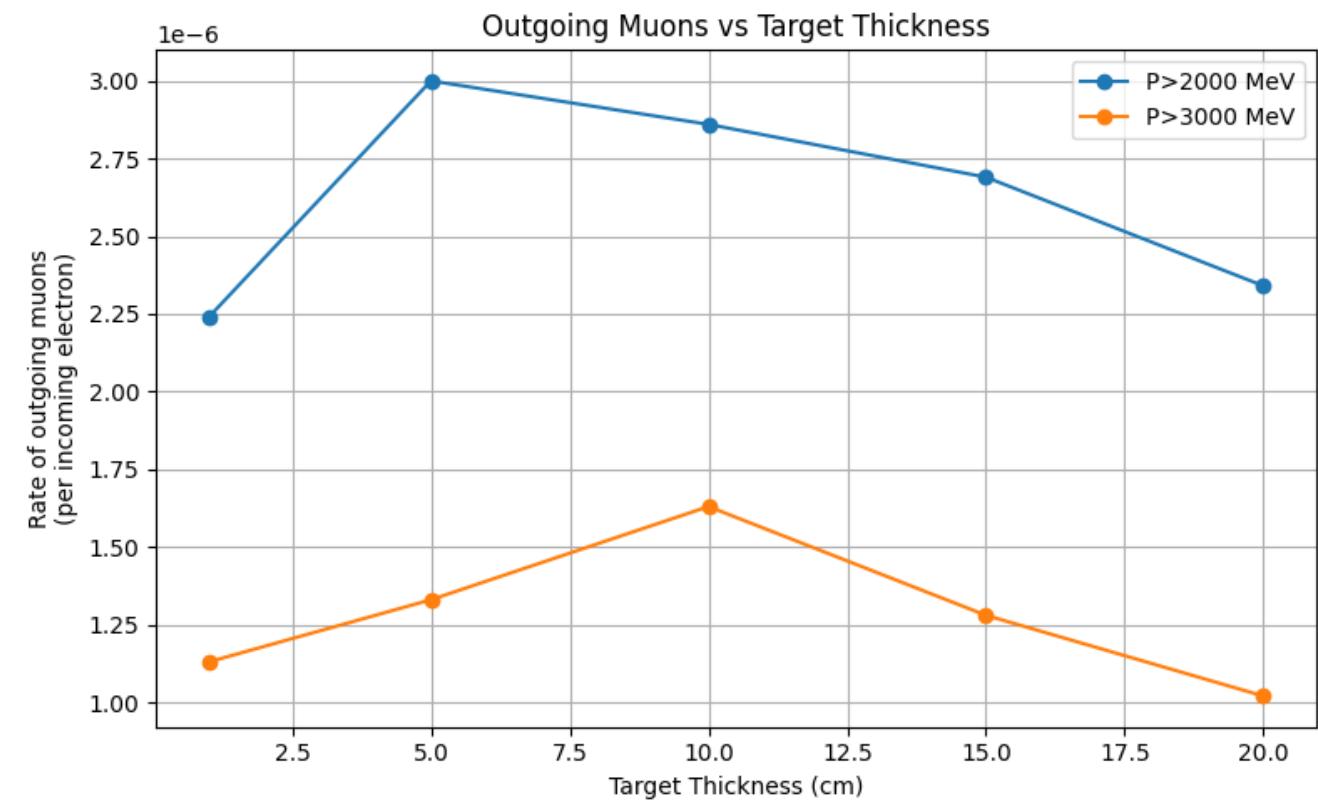
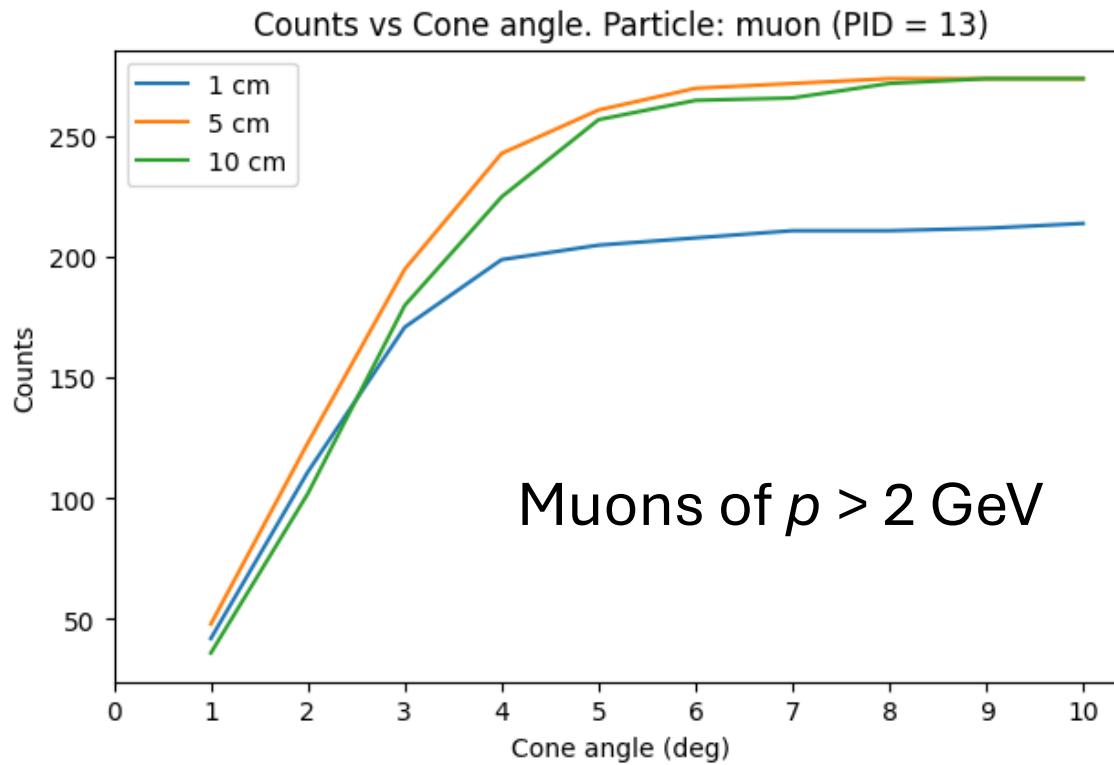
In the case of muons...



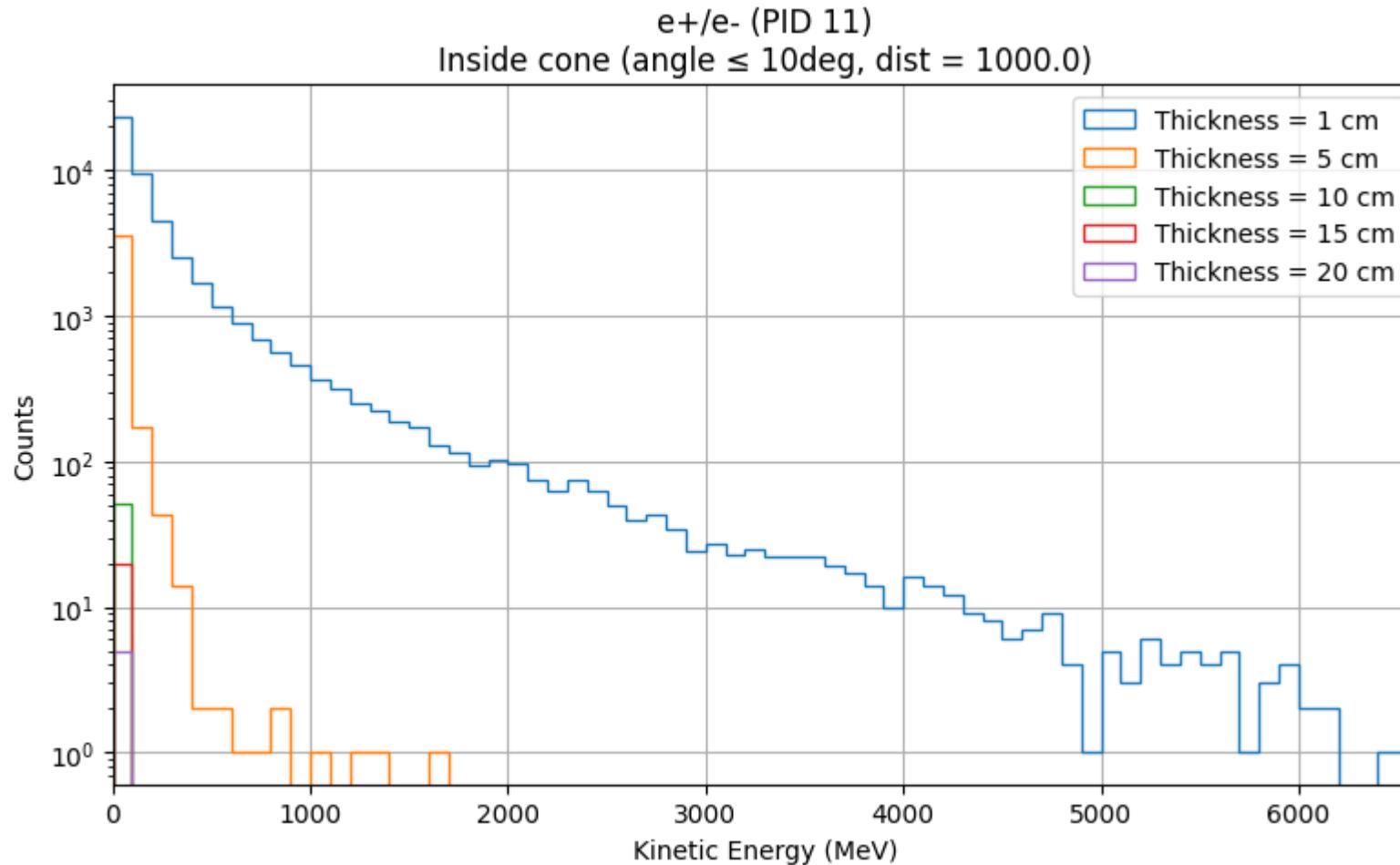
The creation process saturates withing around 5 cm inside the target



Let's see what goes into this “cone” region.
The experiment is a few meters downstream.

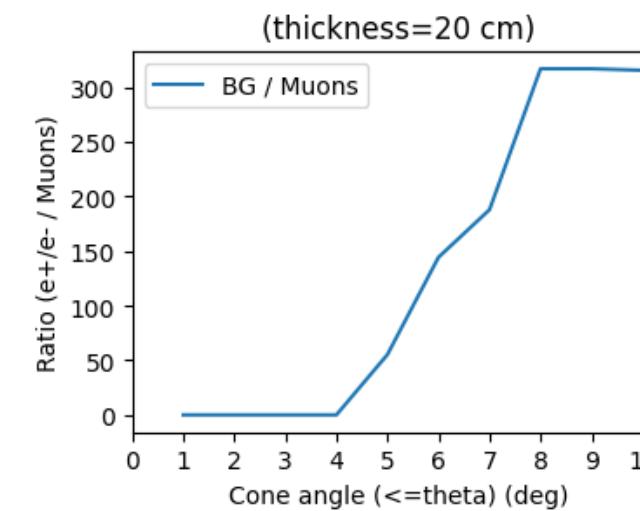
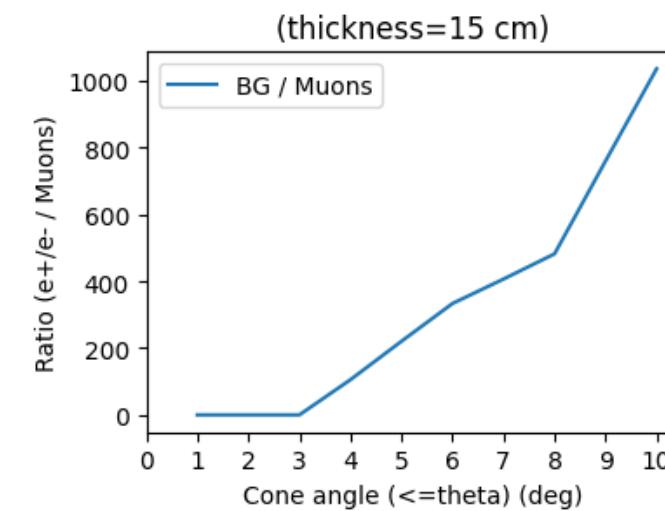
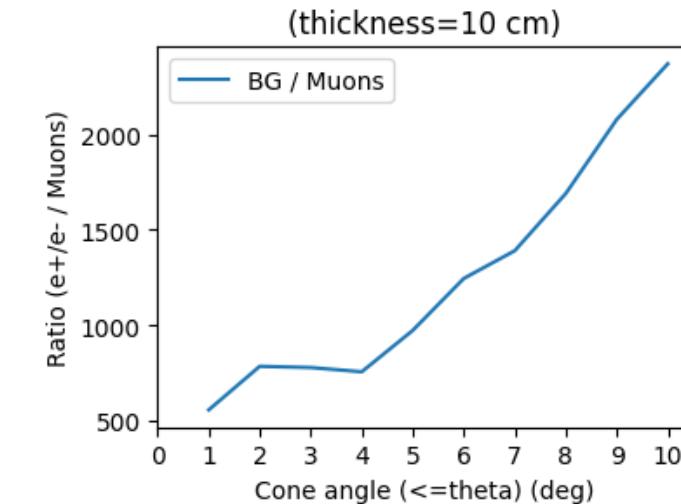
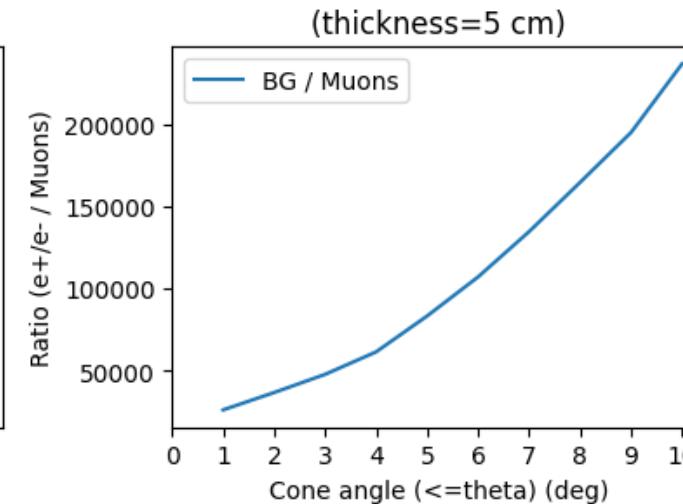
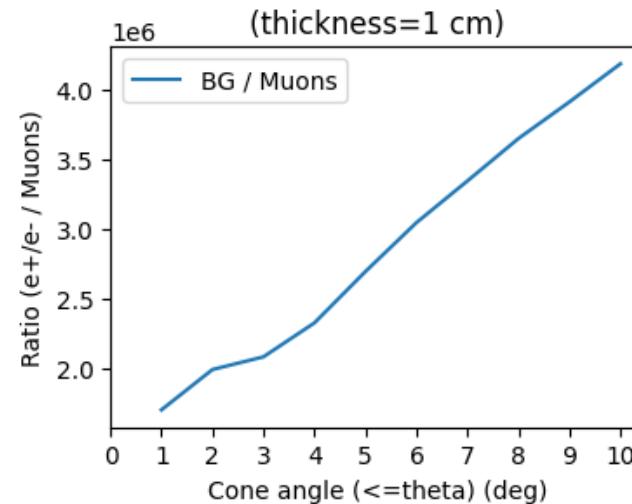


In the case of background particles...



Electrons inside the cone

Electrons inside the cone



Learnings:

To minimize background inside beamline,

1. Increase target thickness
2. Use a smaller cone angle

Sensitivity Calculations

Given the estimates of...

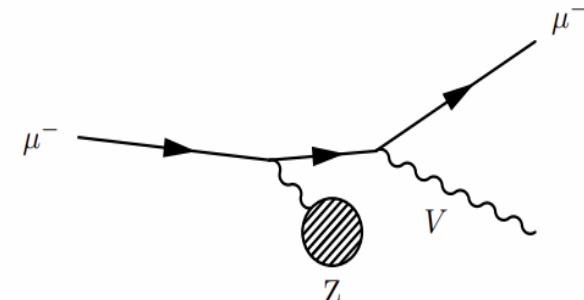
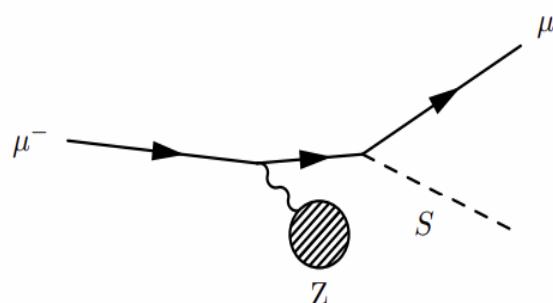
Total number of muons to be used throughout the experiment

Their energy distribution

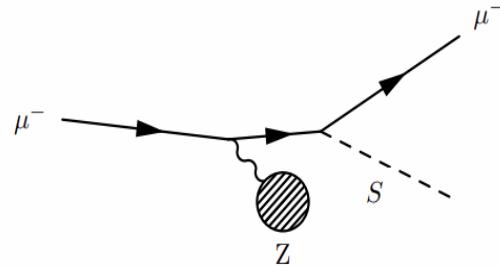
We can calculate...

Number of DM particles that would be produced throughout the experiment as a function of their mass

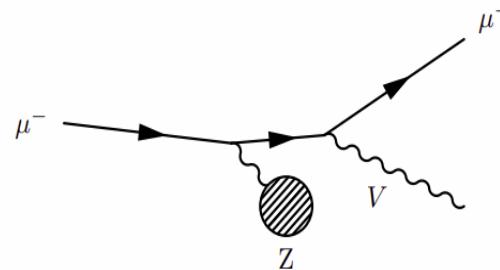
- Assume that 10^{13} muons hit a Tungsten target of thickness 50 radiation lengths (X_0)
- Use analytical expressions from the following paper: “*M3 : A New Muon Missing Momentum Experiment to Probe $(g - 2)\mu$ and Dark Matter at Fermilab*” by Y. Kahn et al. (2018)



Cross Sections for DM Productions



$$\frac{d\sigma}{dx} \Big|_S \simeq \frac{g_S^2 \alpha^2}{4\pi} \chi_S \beta_S \beta_\mu \frac{x^3 [m_\mu^2(3x^2 - 4x + 4) + 2m_S^2(1 - x)]}{[m_S^2(1 - x) + m_\mu^2 x^2]^2}$$



$$\frac{d\sigma}{dx} \Big|_V \simeq \frac{g_V^2 \alpha^2}{4\pi} \chi_V \beta_V \beta_\mu \frac{2x [x^2 m_\mu^2(3x^2 - 4x + 4) - 2m_V^2(x^3 - 4x^2 + 6x - 3)]}{[m_V^2(1 - x) + m_\mu^2 x^2]^2}$$

$$\beta_{S,V} = \sqrt{1 - m_{S,V}^2 / (xE_{\text{beam}})^2}, \quad \beta_\mu = \sqrt{1 - m_\mu^2 / E_{\text{beam}}^2}$$

$m_{S,V}$ = mass of the scalar/vector particle

$x = E_{S,V}/E_{\text{beam}}$:

E_{beam} = Energy of the incoming muon beam

$E_{S,V}$ = Energy of the scalar/vector particle

$g_{S,V}$ = Coupling strength

Cross Sections...

Total cross section: integrate over all possible energies of S, V

$$\sigma(E_{beam}, m_{S,V}) = \int_{x_{min}}^{x_{max}} dx \left(\frac{d\sigma}{dx} \right)_{S,V}$$

$$x = E_{S,V}/E_{beam};$$

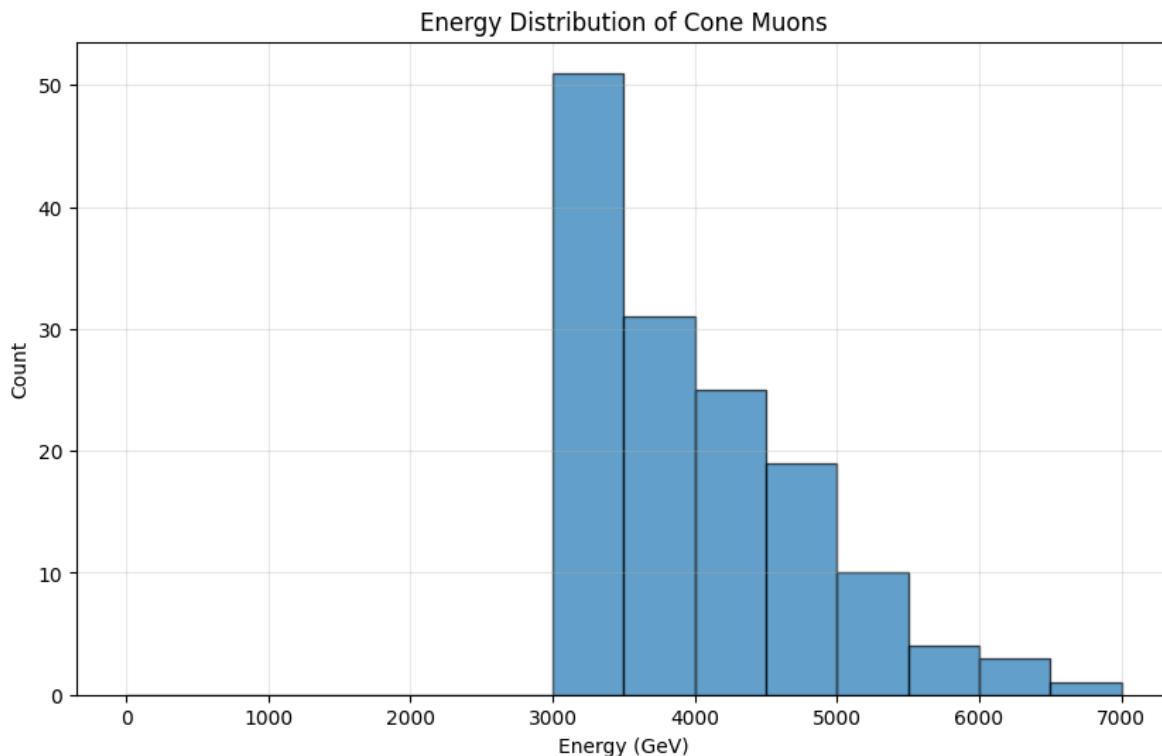
x_{min} is subjective to experimental conditions since S, V need a minimum energy to be separated from the backgrounds. We chose $x_{min} \in \left\{ \frac{1}{3}, \frac{1}{2}, \frac{2}{3} \right\}$

$$x_{max} = 1 - \frac{m_\mu}{E_{beam}}$$

This limiting case is when the muon comes to rest after the process

Energy distribution of μ

Since we also have a distribution of energies, we chose to convolve the energy distribution of muons with $KE > 3 \text{ GeV}$ to obtain a weighted cross-section



$$\sigma_{\text{weighted}}(m_{S,V}) = \sum_{E_{S,V}} \sigma(E_{S,V}, m_{S,V}) \cdot p(E_{S,V})$$

Energies are binned with 500 MeV binwidth and midpoints are taken as $E_{S,V}$.

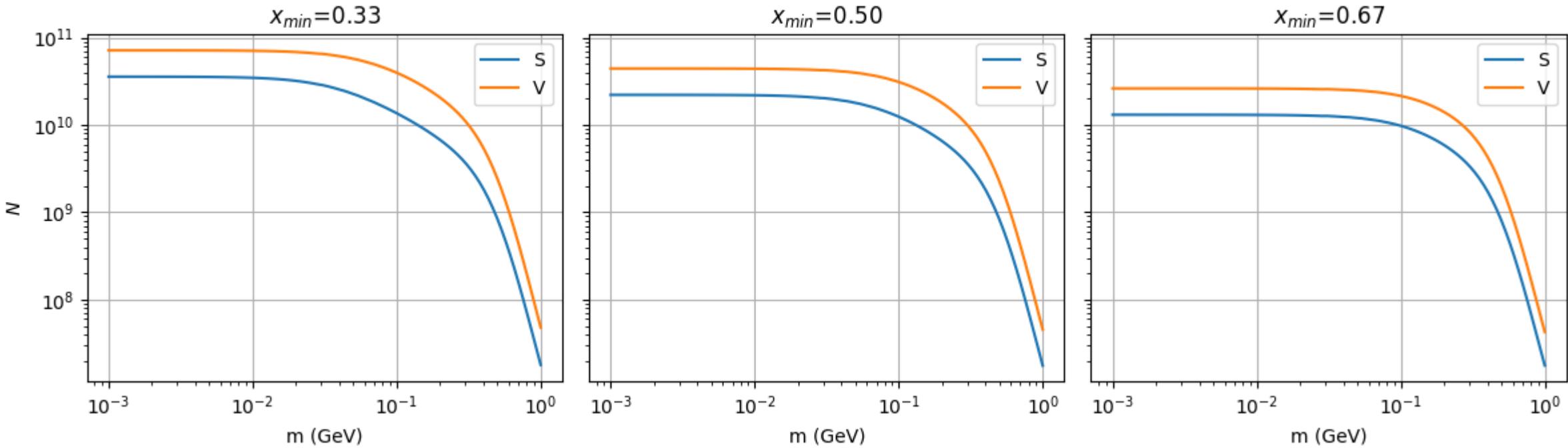
$p(E_{S,V})$ is the relative fraction of that energy.

Sensitivity Calculations

$N_{S,V} = N_\mu n_W l \sigma_{weighted}$ as a function of $m_{S,V}$

; assuming $N_\mu = 10^{13}$, $l = 50 X_0$, $g_{S,V} = 1$

$N(S, V)$ as a function of $m(S, V)$, μ on Target=1e13.0, Weighted cross section, $g_S = g_V = 1$

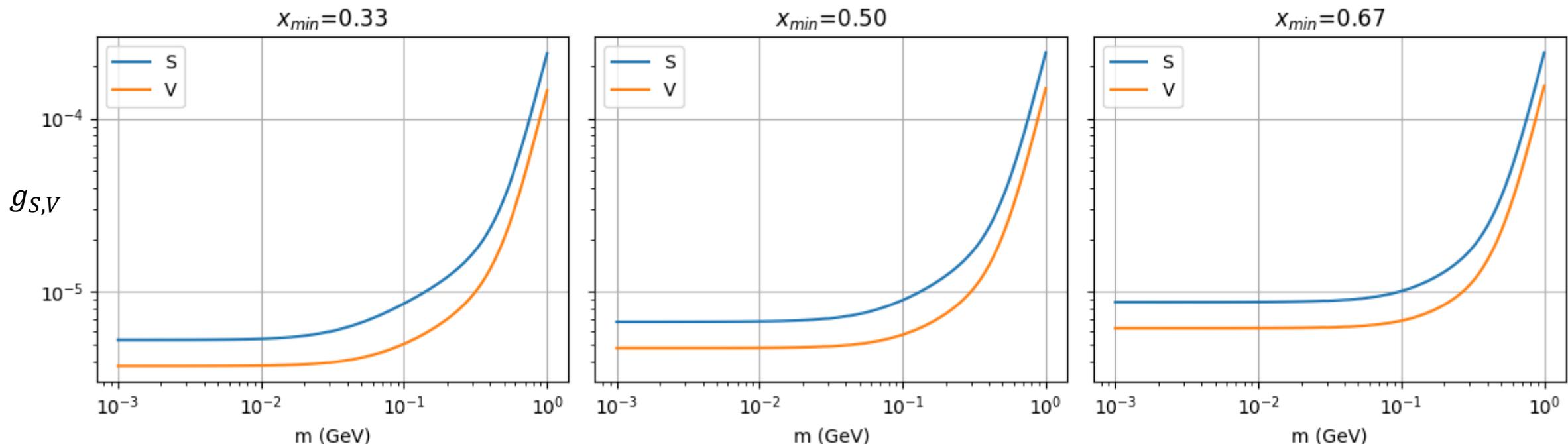


Sensitivity Calculations

$g_{S,V}$ required for $N_{S,V} = 1$ as a function of $m_{S,V}$

; assuming $N_\mu = 10^{13}$, $l = 50 X_0$, $g_{S,V} = 1$

$g(S, V)$ as a function of $m(S, V)$ for $N(S, V) = 1$, μ on Target=1e13.0, Weighted cross section.



Conclusions and Future Directions

- Simulate the detector setup to obtain accurate estimates for the minimum energy of the muons required.
- Incorporate beam line specifications in simulations.
- There is promise that we can use muons in the experiment from these initial estimates!

Thank you!

- Thanks to Prof. Bertrand Echenard, Prof. David Hitlin, and their group for their wonderful support and mentoring towards the project
- Thanks to the William H. and Helen Lang SURF Fellowship for the funding contributed towards the project