Status and Prospects for Dark Sector Studies at the Deep Underground Neutrino Experiment

The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics
May. 24. 2022
Texas A&M University, College Station, Texas
Mitchell Institute (MIST), Hawking Auditorium

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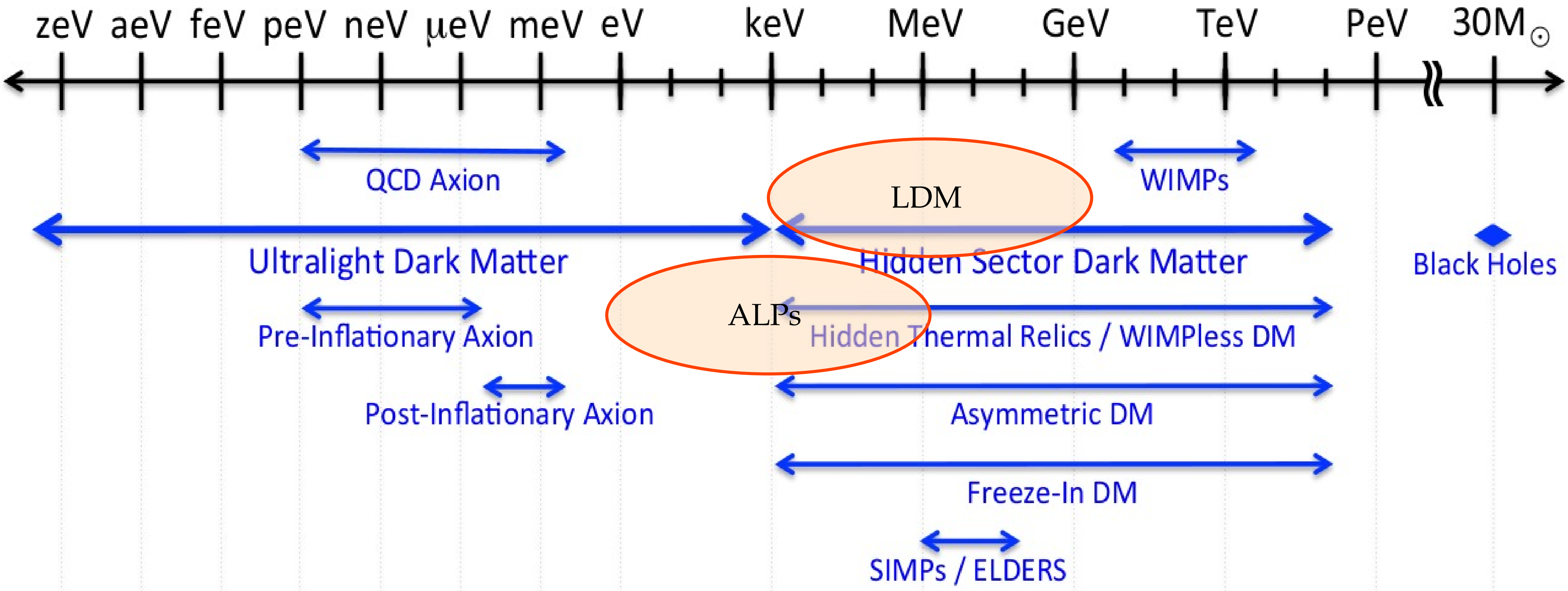
Physics Motivations of Dark Sector Studies in sub-GeV Regime

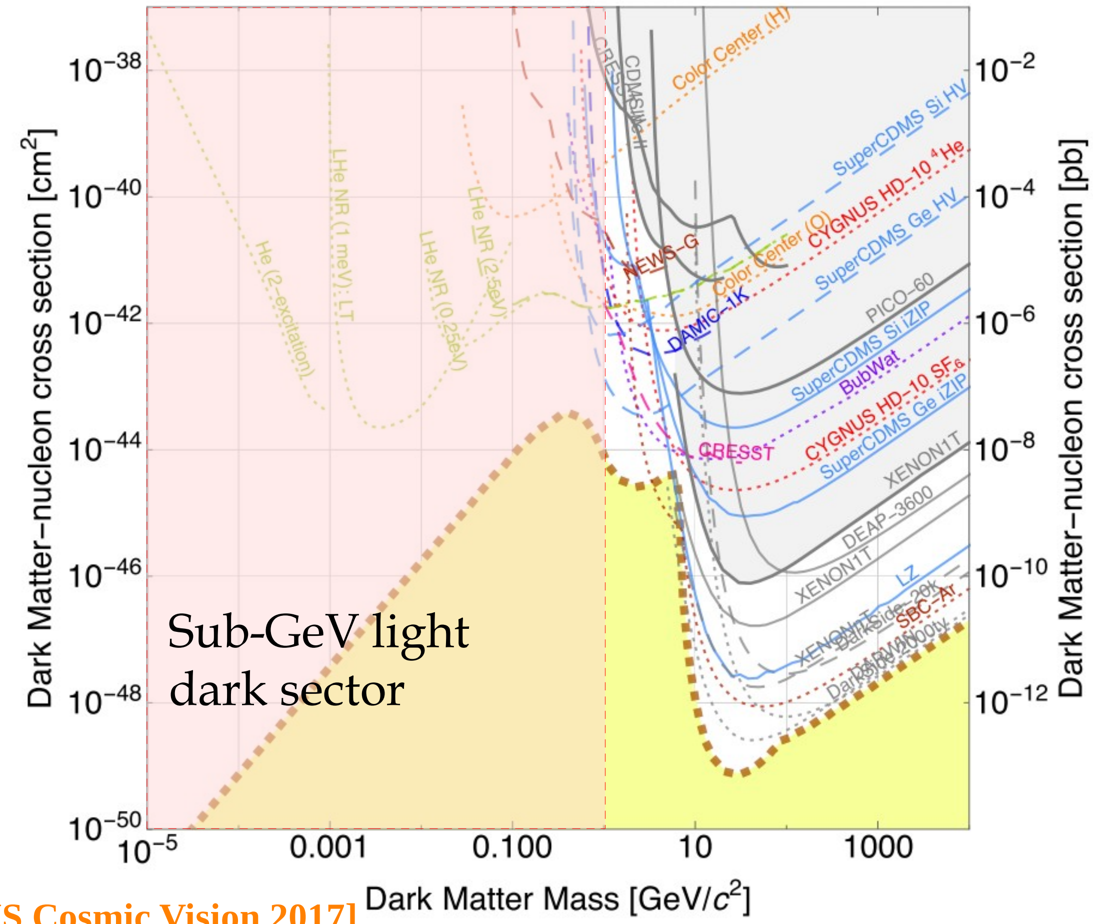
Many dark sector models in terms of their effective mass ranges.



Today, I will cover two well-motivated dark sector models,
Light Dark Matter with vector portal interaction and Axion-like particles
that can be explored by DUNE experiment.

[US Cosmic Vision 2017]

Physics Motivation of sub-GeV Dark Sector (2)

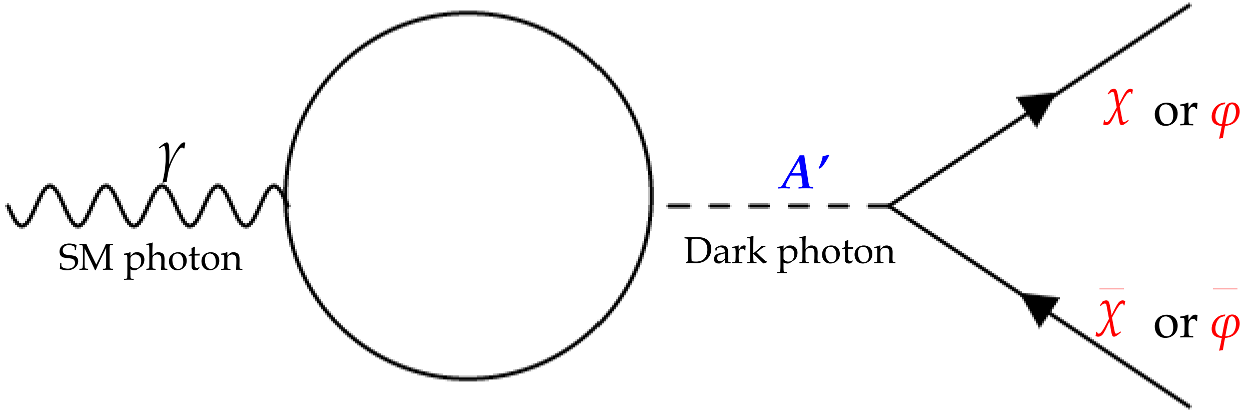


[US Cosmic Vision 2017]

- Dark matter direct detection parameter space – DM-nucleon cross section vs. DM mass. Experiments of past and future.
- Sub-GeV regime is promising:
  - **Well motivated**, **less explored**.
  - We're accessible to this region by **Accelerator-based fixed-target** experiments.
  - The most important feature of the accelerator is high-intensity of the beam accompanied by enough energy.
- DUNE meets all those requirements.

Light Dark Matter Benchmark Model

- In this model, standard model photon is **kinetically mixed with 'dark photon'.**
- Dark matter can be produced by dark photon through the 'portal interaction'.



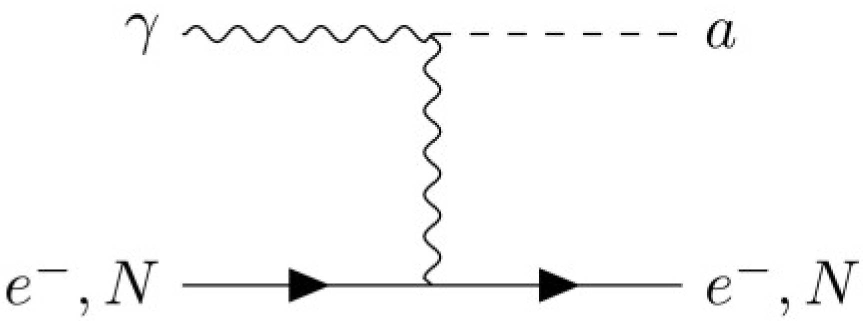
Dark matter flux ∝ Photon flux ∝ Beam intensity

DUNE, equipped with **high-intensity proton beam** provides a great opportunity to test this type of dark matter scenario.

Axion-like Particles Benchmark Model

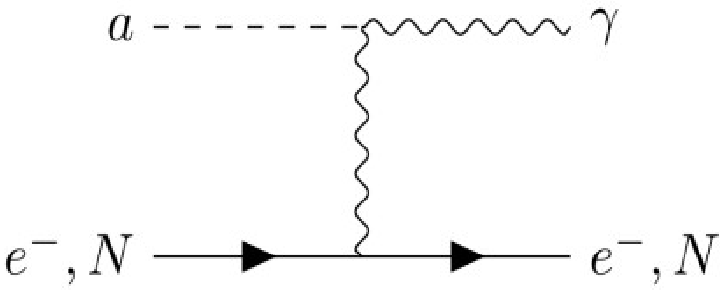
- On the other hand, we can also consider an axion-like particle scenario in this energy/mass scale.
- ALPs are general extension of QCD axion to solve strong CP problem.

Production

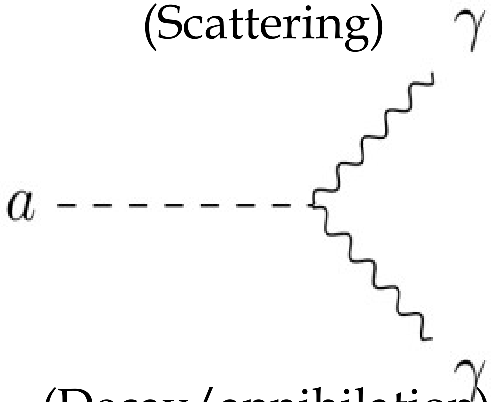


Primakoff Process

Detection



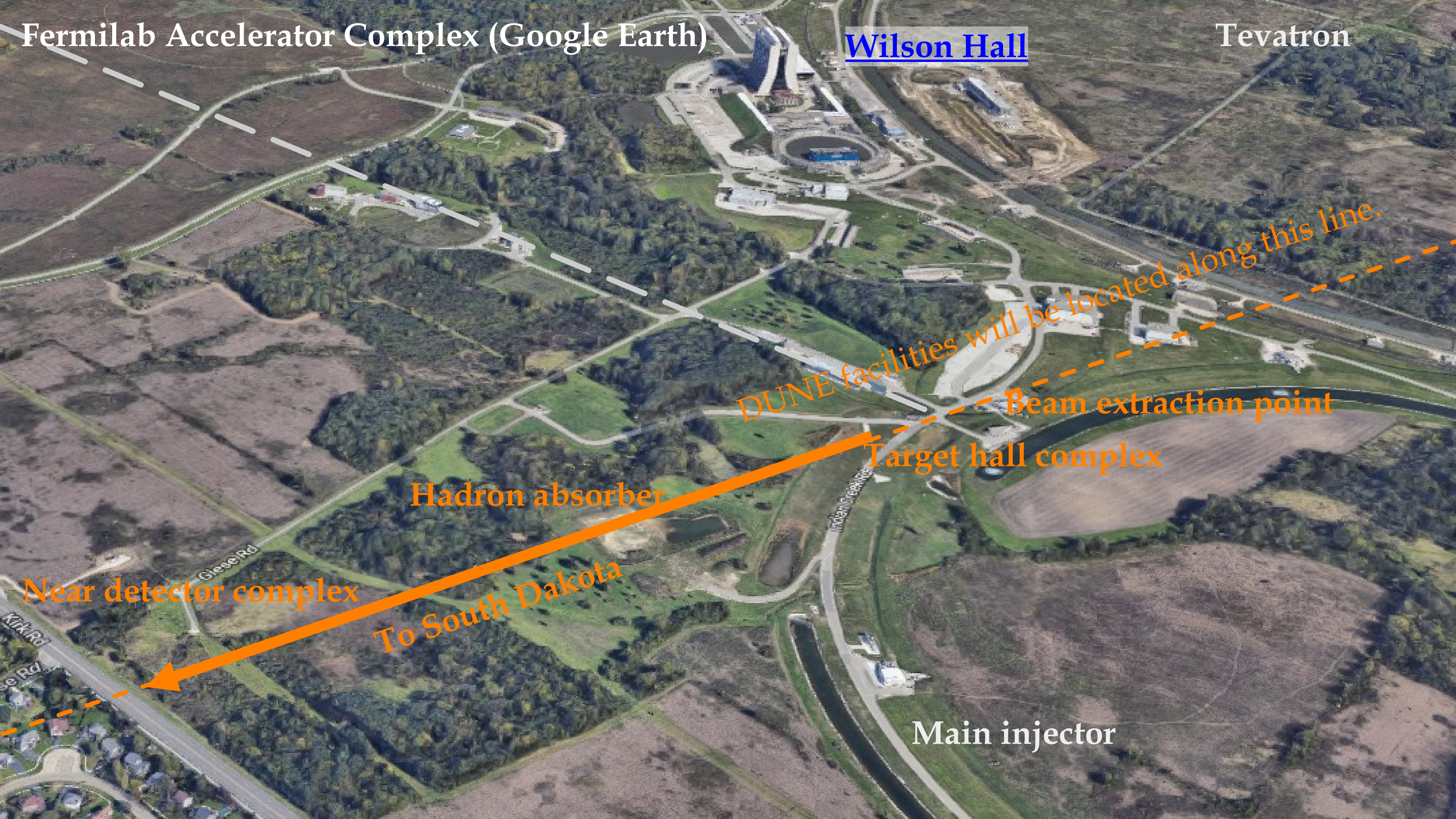
(Scattering)



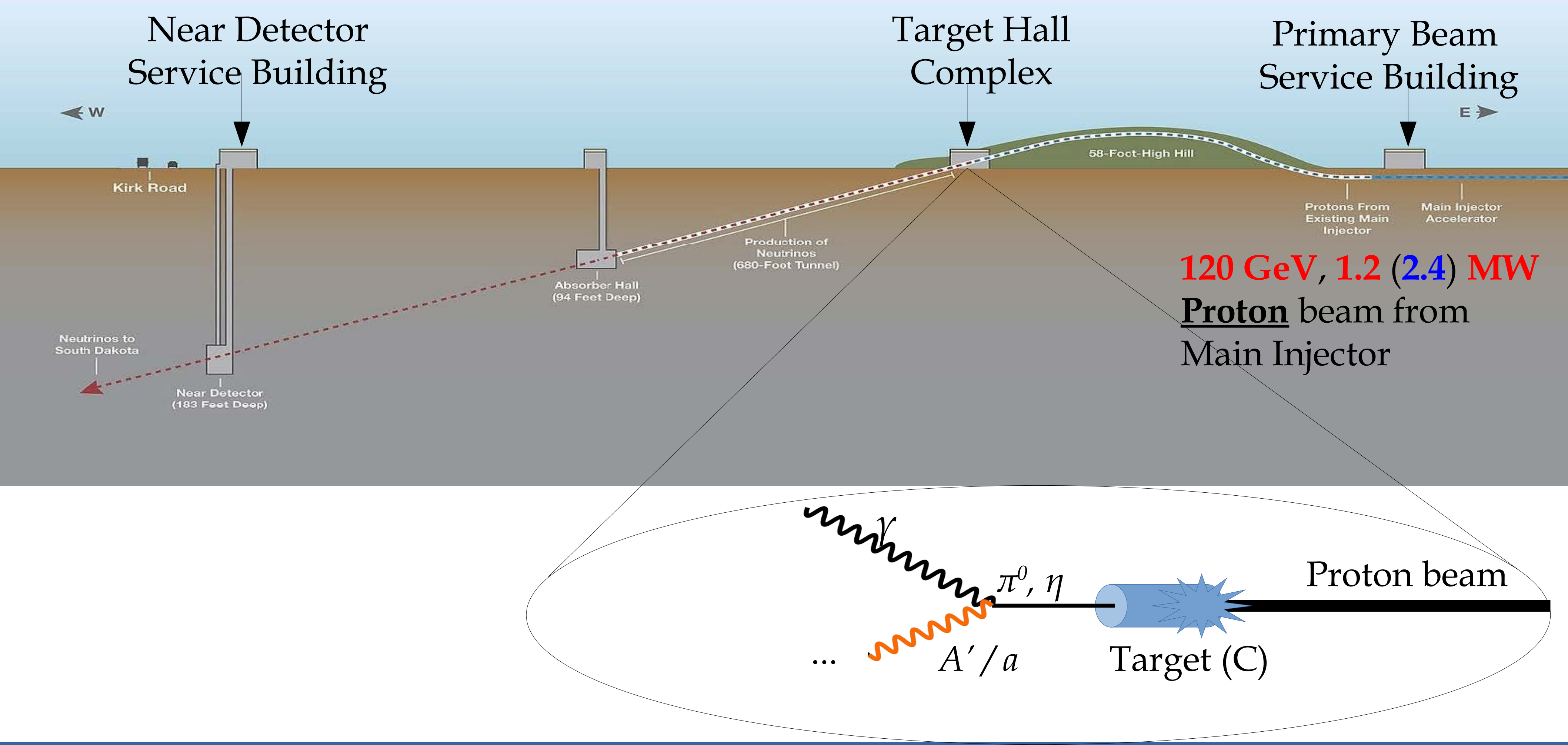
(Decay/annihilation)

ALP flux ∝ Photon flux ∝ Beam intensity

Again, **DUNE** is a great place to test this model.


Fermilab Accelerator Complex (Google Earth)
Wilson Hall
Tevatron
DUNE facilities will be located along this line.
Beam extraction point
Target hall complex
Hadron absorber
Near detector complex
To South Dakota
Main injector

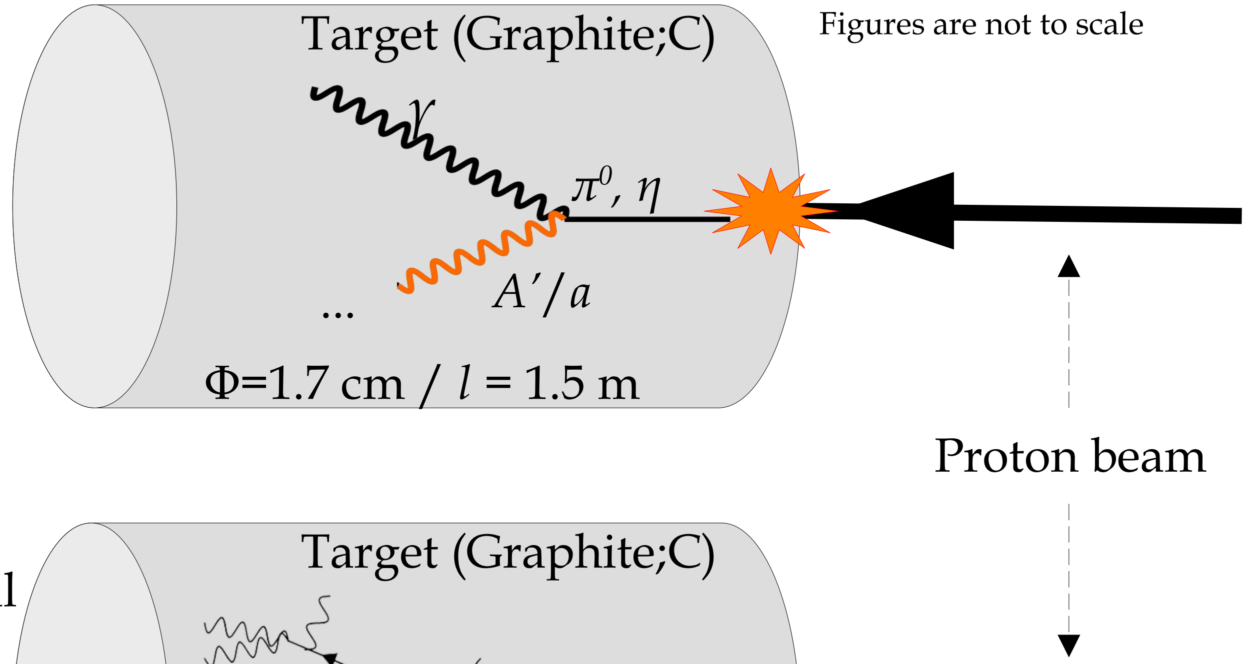
Experimental Layout - Signal Production



Signal Production Stage – GEANT4 MC Simulation

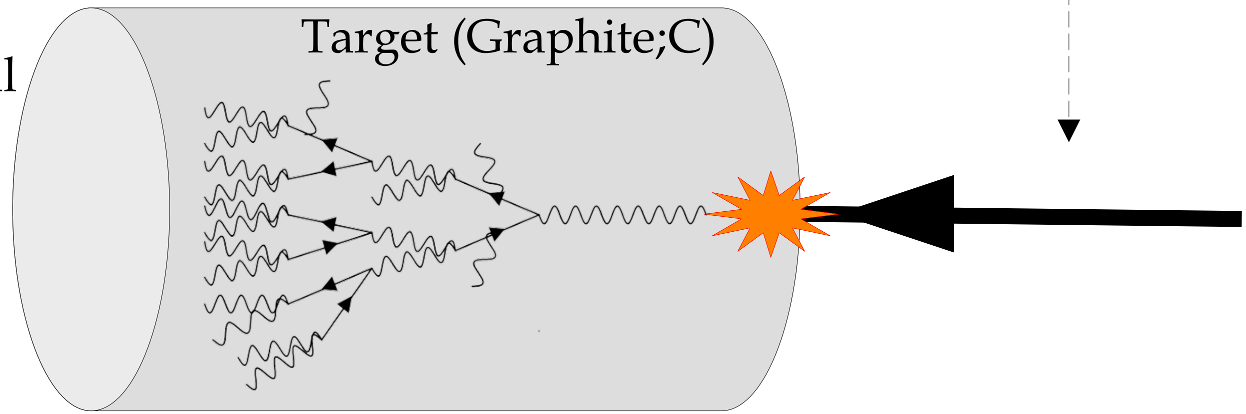
Figures are not to scale

1. Neutral meson decay

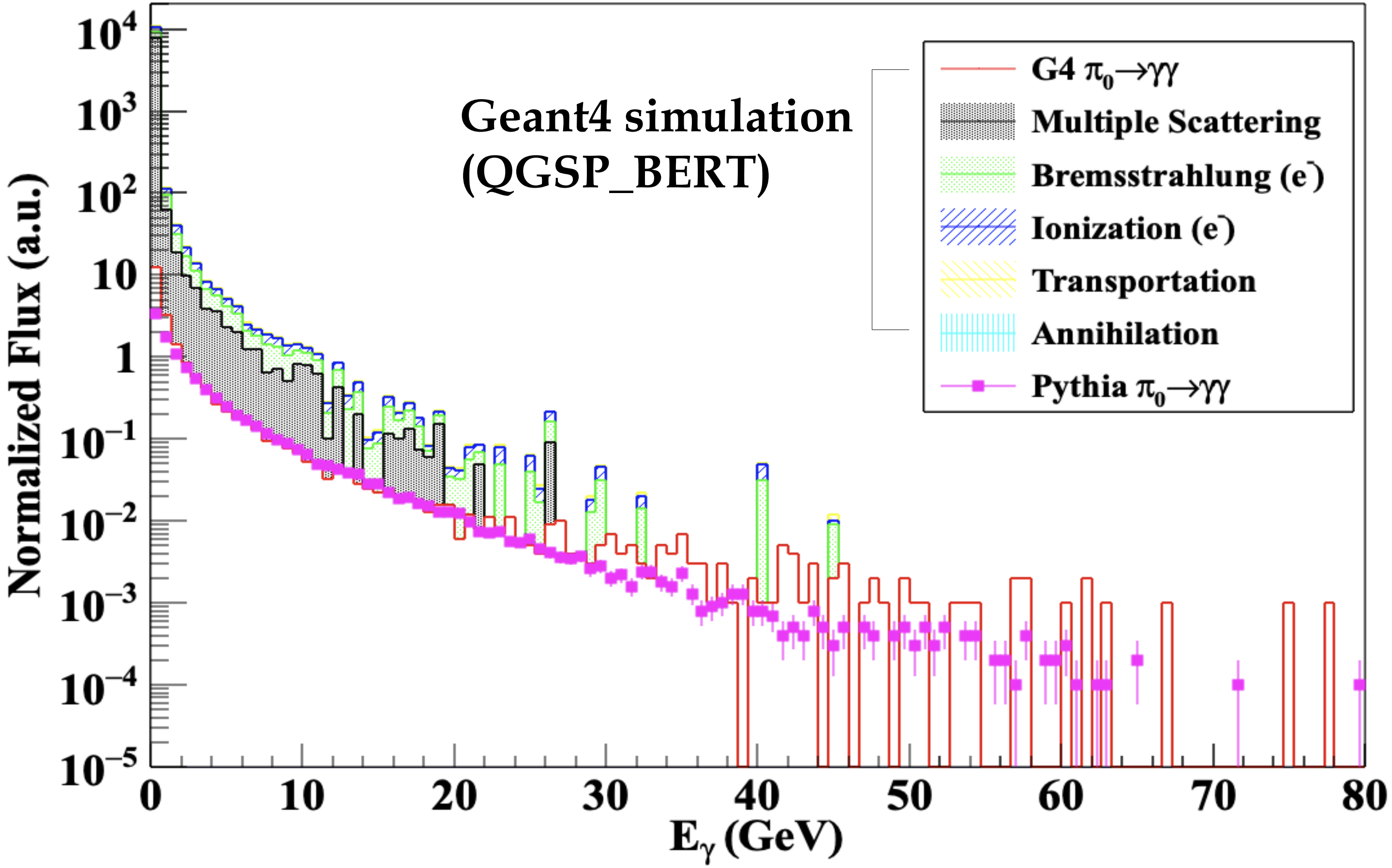


2. Photons from EM-shower
Energetic photons produced by neutral meson decay can trigger EM-shower.

This gives additional contribution to the **low-energy** photon flux



Photon Flux Breakdown



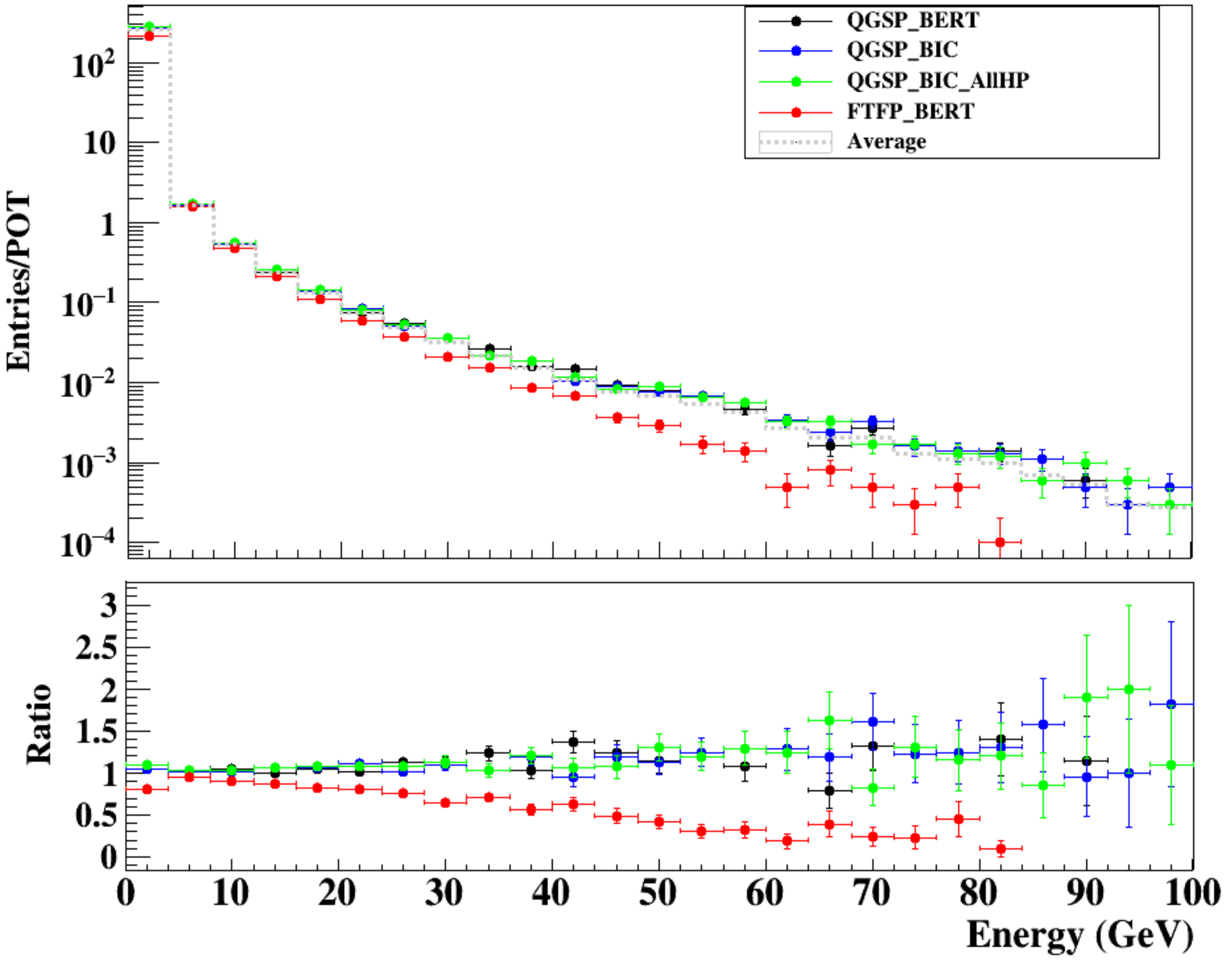
Geant4 explains both primary pion decays and secondary photon productions by cascading processes.

Multiple scattering contributes to low energy regime.

Bremsstrahlung gets bigger portion as the photon energy increases.

If you compare the magenta data points to the red histogram, you can find good agreement, but at the same time, it shows secondary contributions can not be ignored.

Photon Flux Simulations from Various G4 Physics Lists



Also we're studying different hadron physics models that provided by Geant4.

Currently, QGSP_BERT is the default physics list that we use in the DUNE neutrino flux MC.

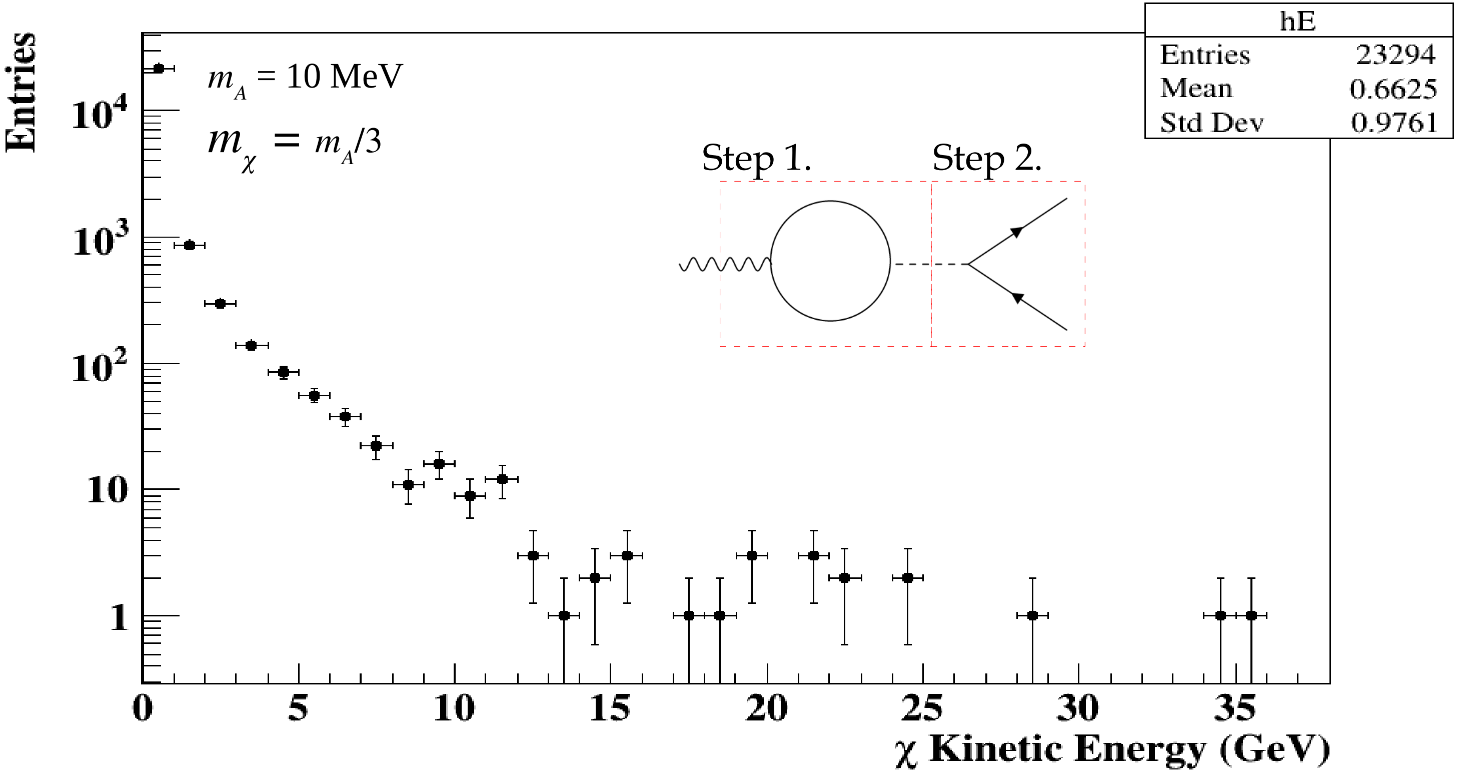
However, there are some validation studies like [FERMILAB-FN-1109-SCD] led by Dr. Leo Aliaga that says FTFP_BERT explains better the actual experimental results (NA49).

We adopted those discrepancies as a systematic uncertainty of the simulation.

Dark Matter Energy Spectrum

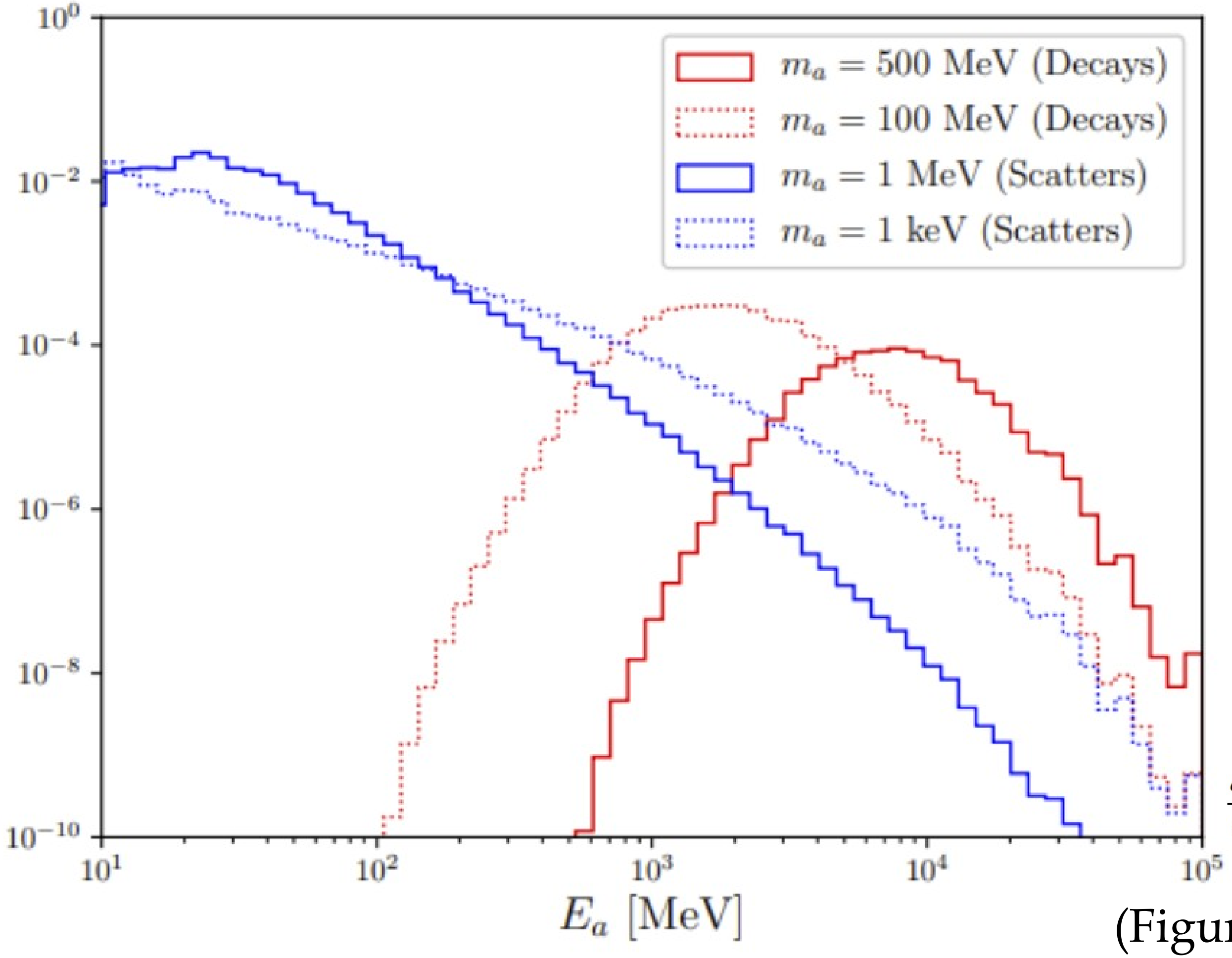
- Once we obtained photon flux from the simulation of proton beam and target, we can convert it to the signal energy spectrum to know its probability density function in a certain kinematic variables that we're interested..

- Step 1 is conversion of standard model photon into dark photon.
- Step 2 is annihilation of dark photon into dark matter pair.

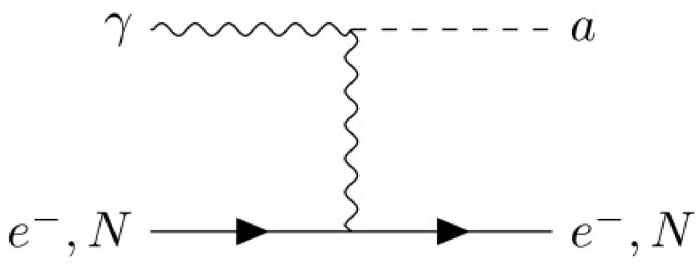


- Energy spectrum of dark matters with mass assumptions of m_A = 10 MeV and $m_\chi = m_A/3$.

ALP Flux



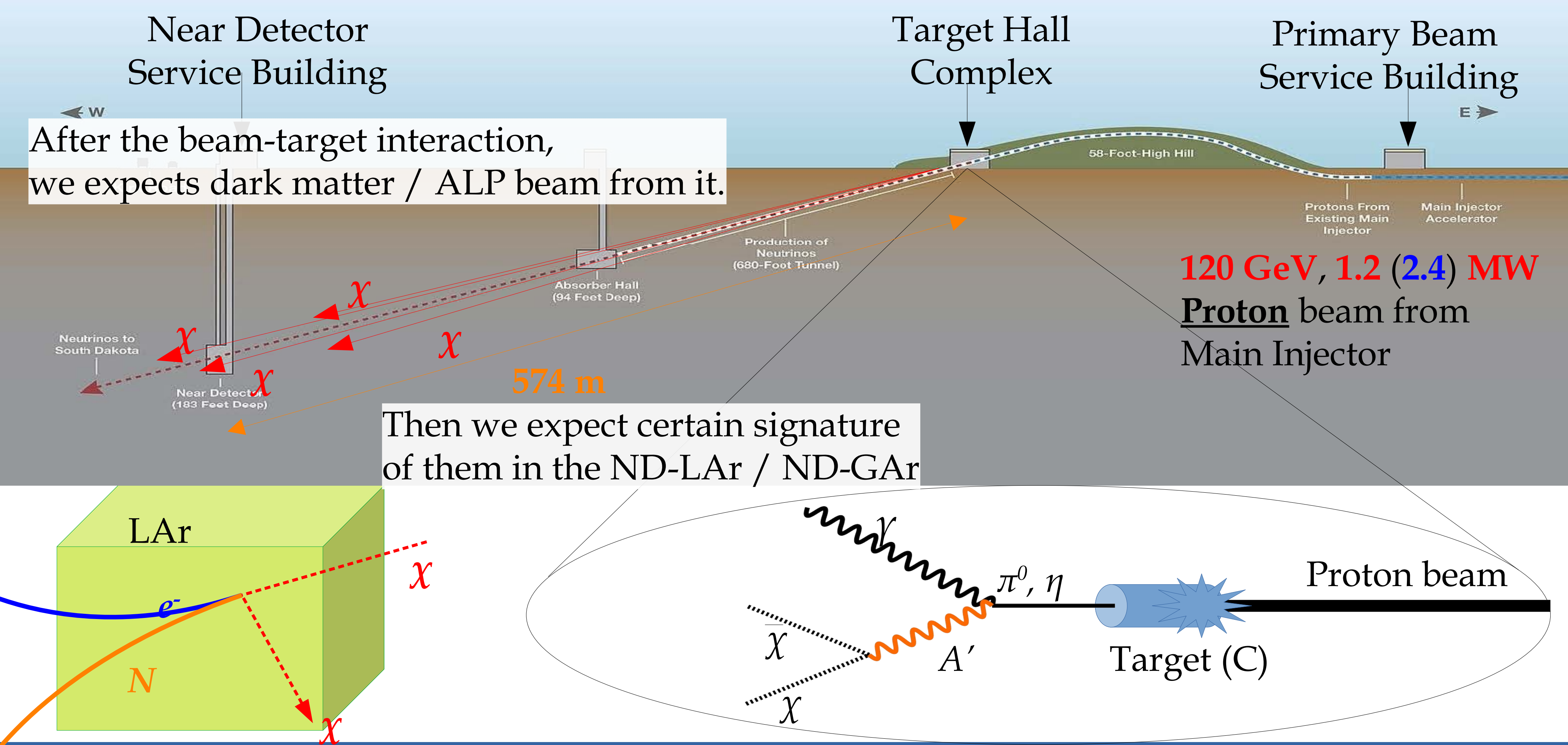
- Similarly, energy spectrum of ALP can be taken from the photon flux and this process takes into account Primakoff process.
- Plot shows spectra with different mass hypotheses and different detection mechanisms.



$$\frac{d\Phi_a}{dE_a} = \frac{1}{\sigma_{PE}} \int_0^{\pi} \int_0^{\pi} \int_0^{2\pi} \frac{\partial^2 \Phi_\gamma}{\partial E_\gamma \partial \theta_\gamma} \frac{d\sigma^{\gamma\to a}}{d\theta_a} \delta(E_a - E_\gamma) \times \Theta(\theta_{ND} - \theta_{a,z}) d\phi'_a d\theta'_a d\theta_\gamma$$

(Figures from Adrian Thompson, DPF 2021)

Dark Matter Beam Production



After the beam-target interaction, we expects dark matter / ALP beam from it.

120 GeV, **1.2** (**2.4**) **MW** **Proton** beam from Main Injector

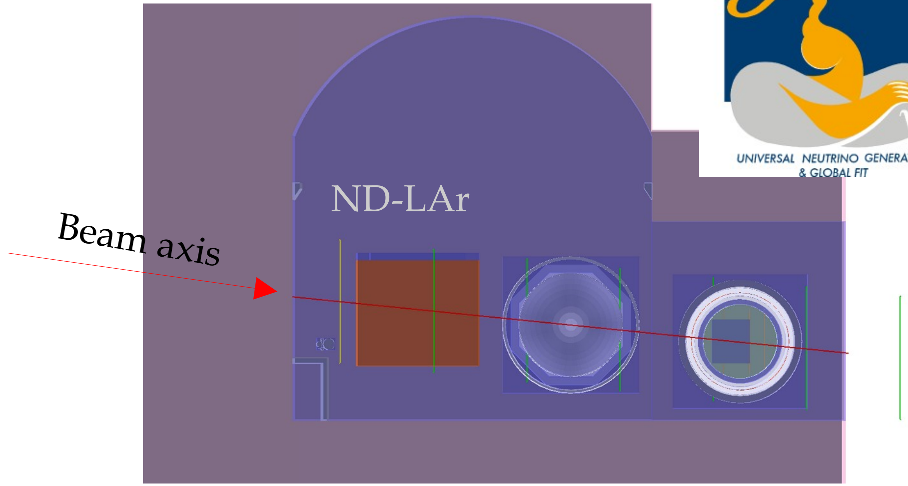
Then we expect certain signature of them in the ND-LAr / ND-GAr

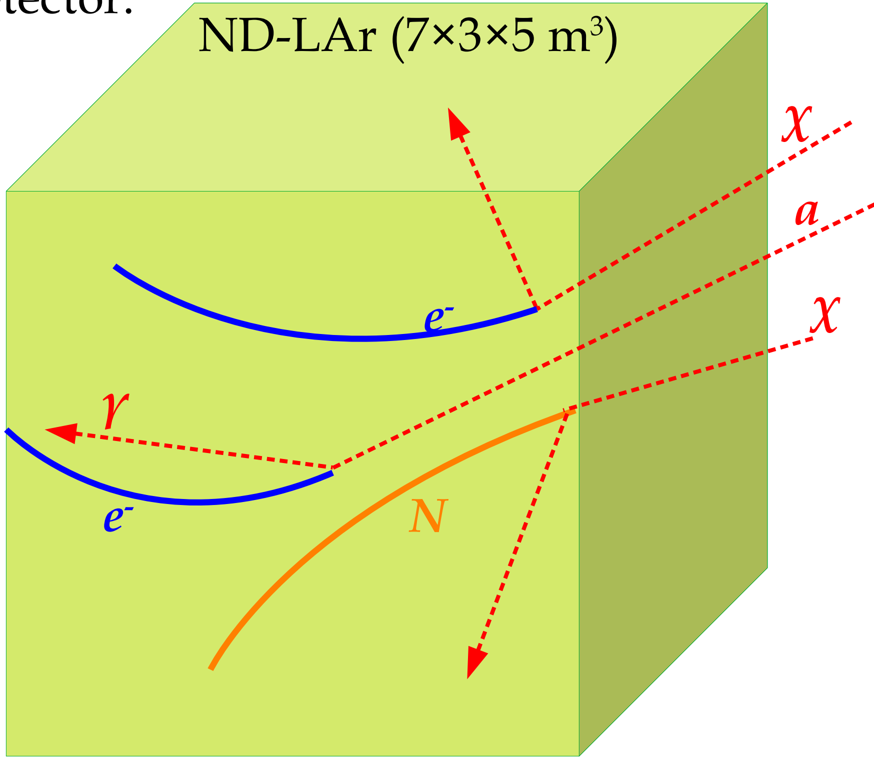
Signal – Detector Interaction: GENIE 3 (Signal)

Signal candidates are scattered-off particles inside the detector:

1. LDM-e^-,N scattering ($\varphi+e^-, N \rightarrow \varphi+e^-, N$)

2. ALP scattering ($a+e^-, N \rightarrow \gamma+e^-, N$)





In order to produce such events, we use GENIE 3 with DM package with the detailed geometrical description of ND.
(developed by Dr. Joshua Berger)

Signal – Detector Interaction: GENIE 3 (Background)

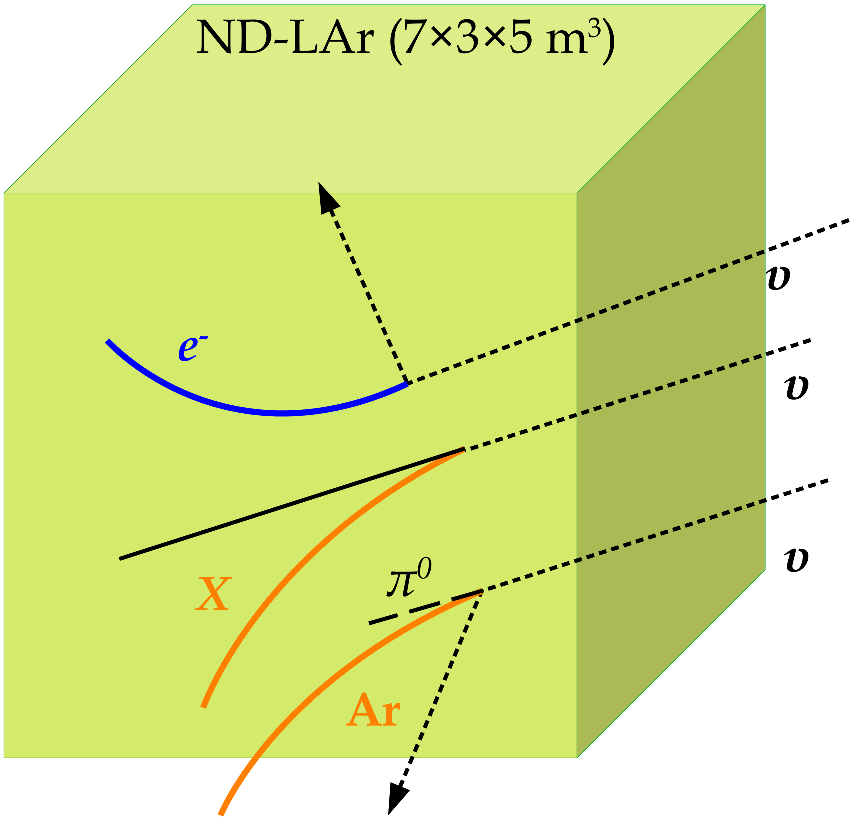
For both ALP and LDM, the main feature of the signal events is **electron/nuclei scatterings.**

- LDM : (φ+e^-, $N \rightarrow \varphi$+$\boldsymbol{e^-}$, $\mathbf{N}$)

- ALP : (a+e^-, $N \rightarrow \gamma$+$\boldsymbol{e^-}$, $\mathbf{N}$)

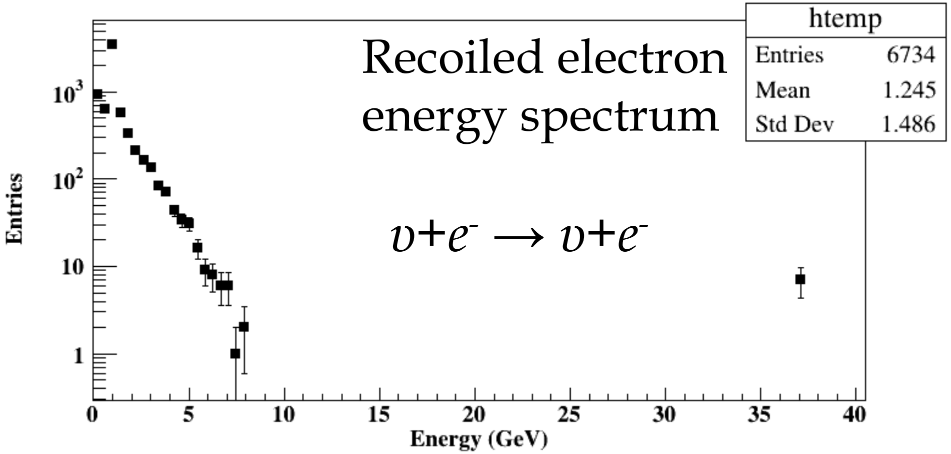
Therefore, they share similar background events and mainly its about neutrino-electron / nuclei scattering.

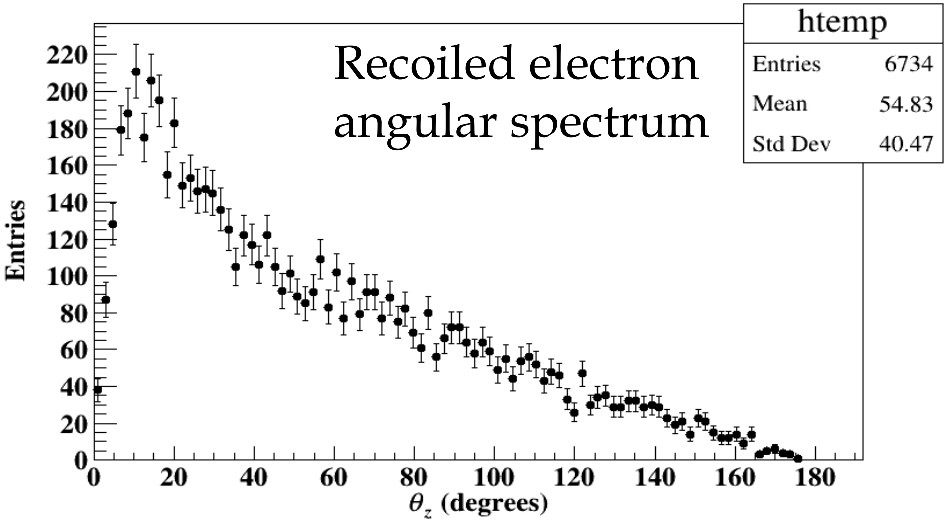
1. υ-e^- scattering (υ+$e^- \rightarrow \upsilon$+$\boldsymbol{e^-}$)
2. υ_e+Ar→**e-** + X
3. υ+Ar→ υ+**Ar**+π^0

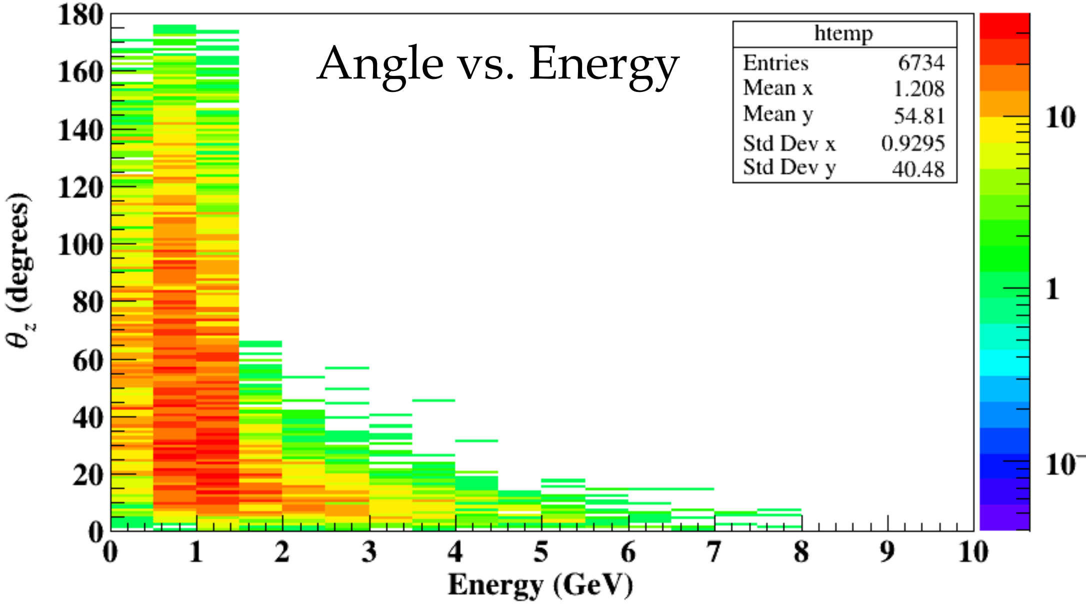


To obtain such background features, we use neutrino flux simulation. (Laura Fields)

Example GENIE MC Result (Background)







Work-flow / Future Plan / Summary

Signal

p-Target interaction
(Standalone GEANT4 simulation)
→ Photon flux
→ Dark matter / ALP flux

(we don't have ALP-LAr scattering simulation yet...)

GENIE MC – BDM module
DM/ALP-LAr event generation
→ Recoiled electrons, ...

ALP decay

Detector simulation

Background

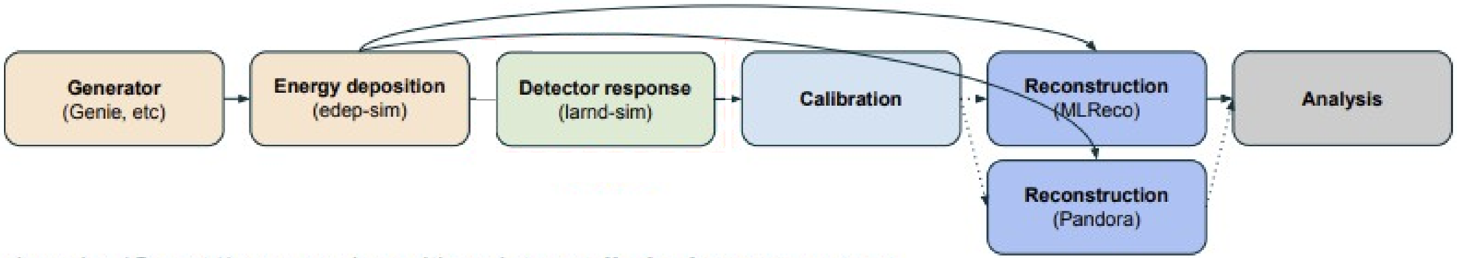
p-Target interaction
(G4LBNF by Laura Field)
→ Neutrino flux

GENIE MC
υ-LAr event generation
→ Recoiled electrons, ...

Detector simulation

Sensitivity estimation taking into account **experimental details**

Detector Simulation Framework



- After the event generator study, the next job is energy deposition simulation.
  - This can be done by software called '**Edep-sim**'.
- Feed the result from **Edep-sim** to **larnd-sim** to do some detector response simulation.
- Calibration simulation.
- Reconstruction.

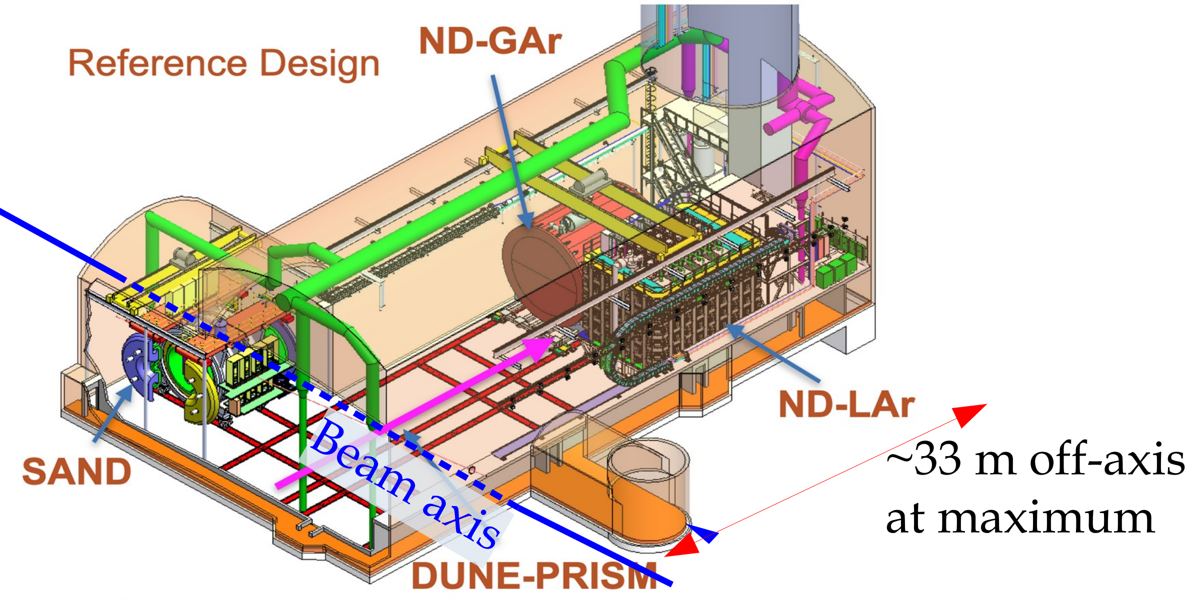
1) **MLReco**: utilizes machine learning techniques.
2) **Pandora**: a compiled framework of multiple reconstruction algorithms.

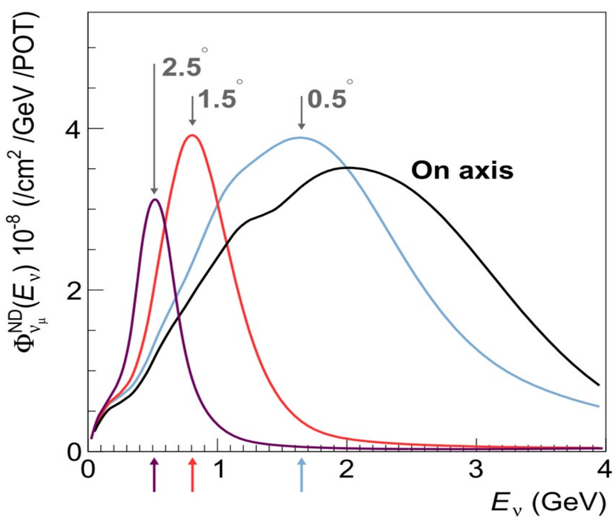
Peter Madigan | BERKELEY LAB

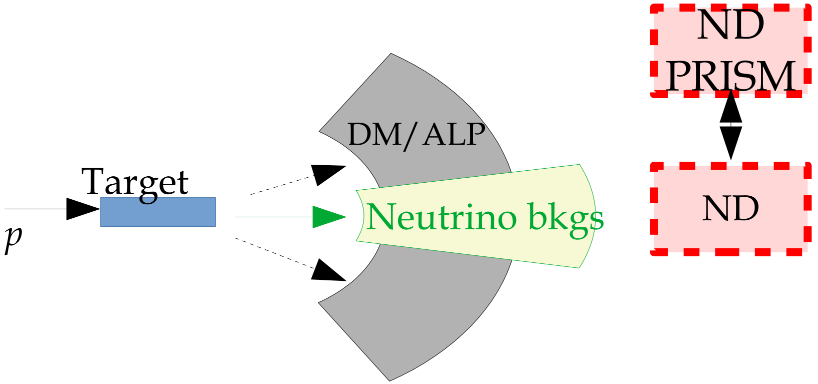
Figure from Peter Madigan, May. 2022, DUNE Collaboration Meeting

DUNE PRISM

(Precision Reaction-Independent Spectrum Measurement)



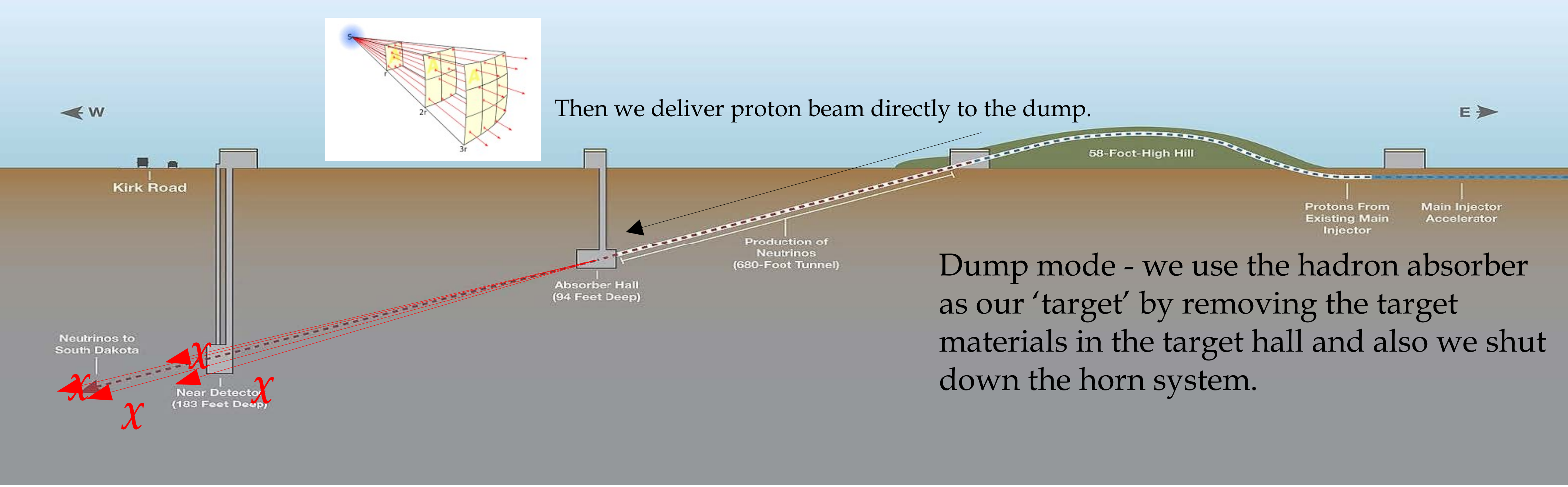




- DUNE Precision Reaction-Independent Spectrum Measurement (PRISM) is introduced to control systematic uncertainties of neutrino oscillation parameters.
- Since the effect of focusing horn and lighter mass of neutrinos in comparison to the dark matter mass, the neutrino flux has more tendency of being headed in a forward direction while the heavier dark sector particle tends to have wide angular spectrum. This feature enhances the signal-to-background ratio effectively.

[Flux from Laura Fields http://home.fnal.gov/~ljf26/DUNEFluxes/]

LDM Search using DUNE Dump Mode(or Off-Target)



Then we deliver proton beam directly to the dump.

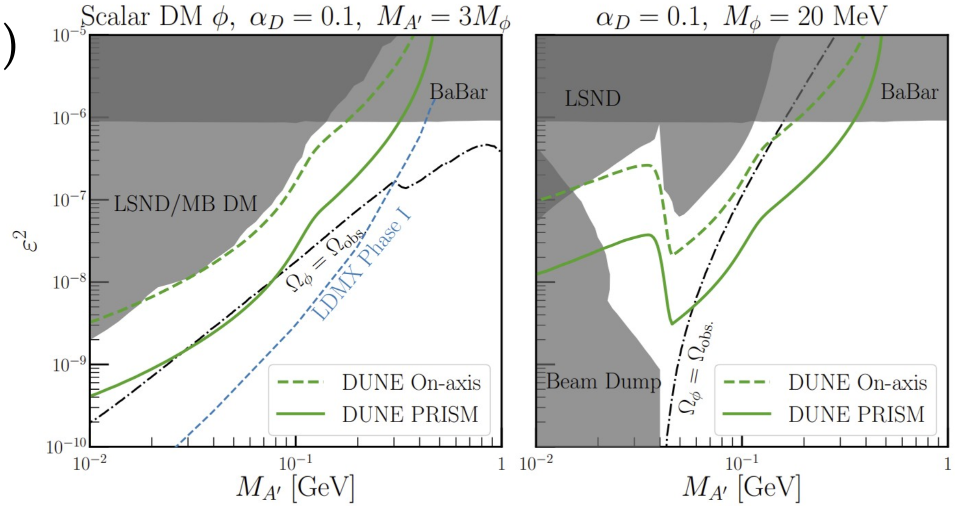
Dump mode - we use the hadron absorber as our 'target' by removing the target materials in the target hall and also we shut down the horn system.

- 'DUNE Beam Dump Mode' is an operation mode of DUNE proposed earlier this year.
- In this configuration, **signal** flux **enhancement** is expected.
  - because we have shorter distance from the interaction point to detector (574 m → ~300 m)
- **Reduction** of **background** flux is also expected.
  - The dump **absorbs** most of charged mesons, so it prevents neutrino production.

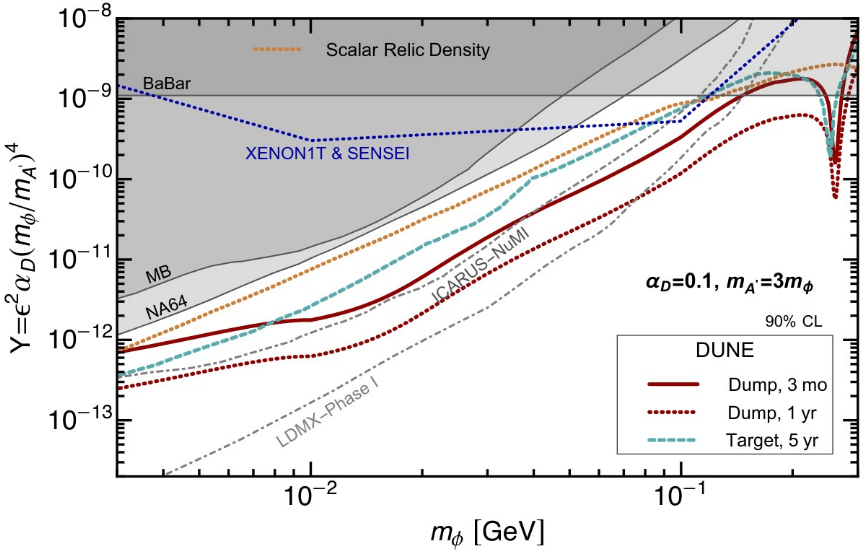
Check Doojin Kim's talk for more detailed analysis results including expected sensitivity reachs and more...

Preliminary Sensitivity Study, LDM (1)

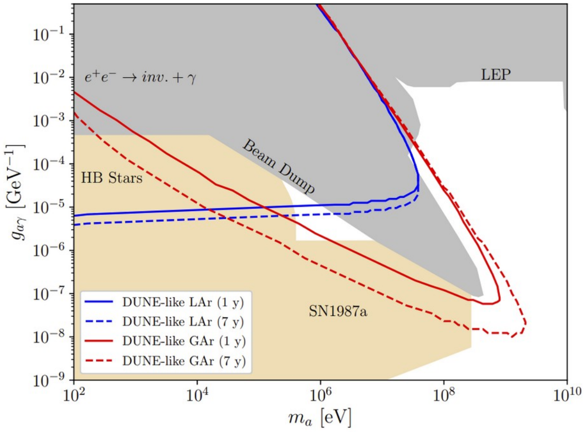
1)



2)



3)



1) Valentina De Romeri, Kevin J. Kelly, and Pedro A. N. Machado, Phys. Rev. D **100**, 095010

2) soon to be published… **(Check Doojin's talk for details)**

3) Vedran Brdar et. al, Phys. Rev. Lett **126**, 201801

These are theoretical studies that shows promising results and shows competitiveness of DUNE.

Summary

- DUNE is a very promising experiment to probe sub-GeV dark sector thanks to its high-intensity proton beam and precision near detector with various possible operation strategies.
- Simulation work-flow is presented.
- Geant4 and GENIE based event generator studies are finished.
- For both LDM and ALP, theoretical preliminary studies shows promising results. Now we're working on to take into account experimental details in these results to move forward.