A Study of Secondary Productions of Dark Sector Particles at Neutrino Experiments

PITT PACC Nu Tools for BSM at Neutrino Beam Experiments Workshop
University of Pittsburgh, Pittsburgh, PA

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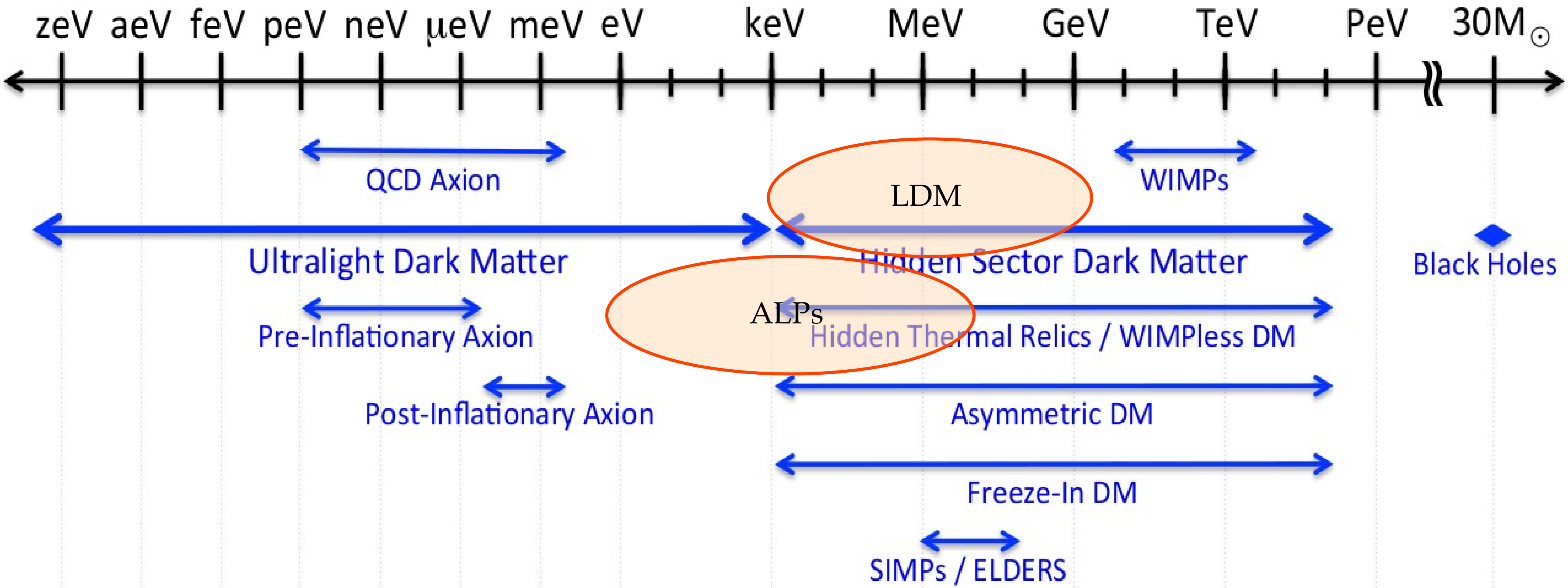
Goal of This Talk

- In this presentation, I will discuss the contribution of secondary interactions that are expected to produce dark sector particles in neutrino experiments. I will present some practical Geant4 simulation results and take a look the outputs in order to understand the contributions of secondary production processes.
- I will assume DUNE-like fixed-target experiment.
  - Dark sector particles (DSPs) from photo-induced reactions.
  - How big is the amount of signals from secondary interactions?
    - I used a standalone geant4 simulation to evaluate this.
  - Is there any model dependency?

Physics Motivations of Dark Sector Studies in sub-GeV Regime

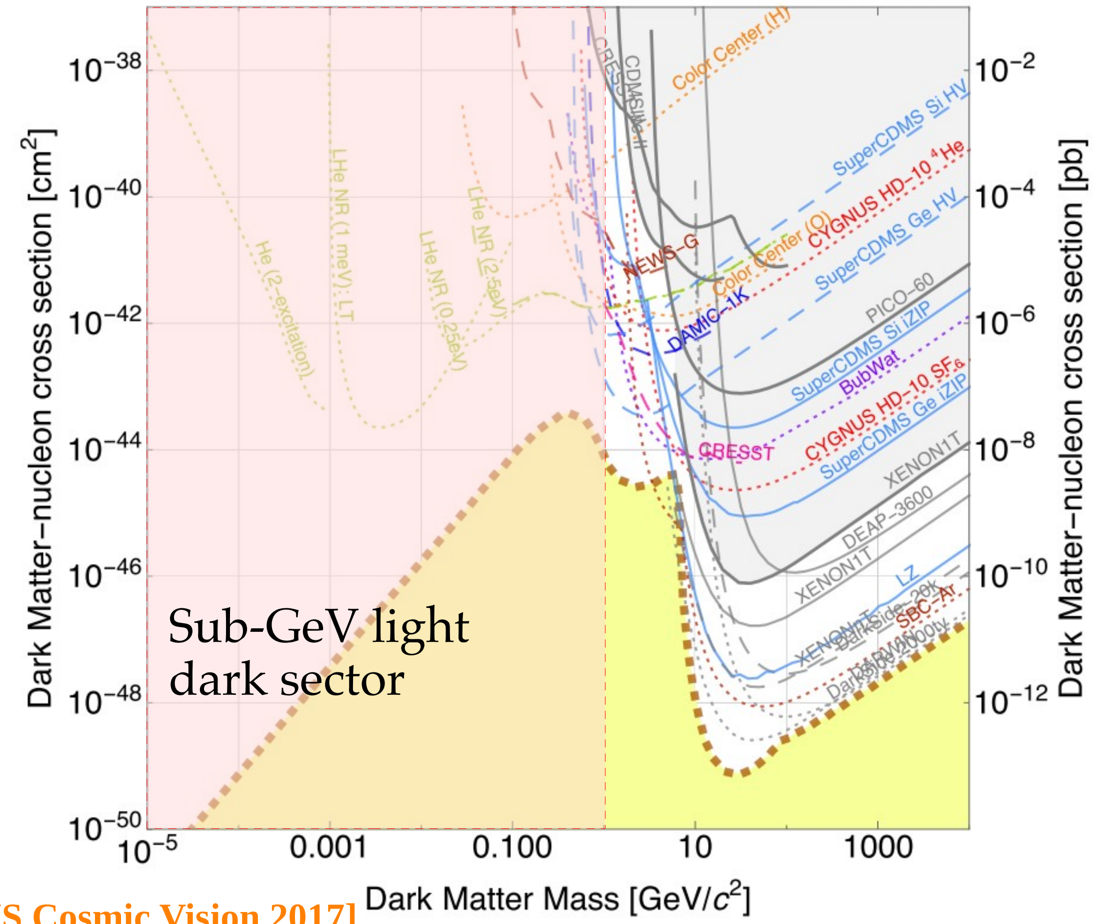
Many dark sector models in terms of their effective mass ranges.



These are well-known photo-induced dark sector particles

[US Cosmic Vision 2017]

Physics Motivation of sub-GeV Dark Sector (2)

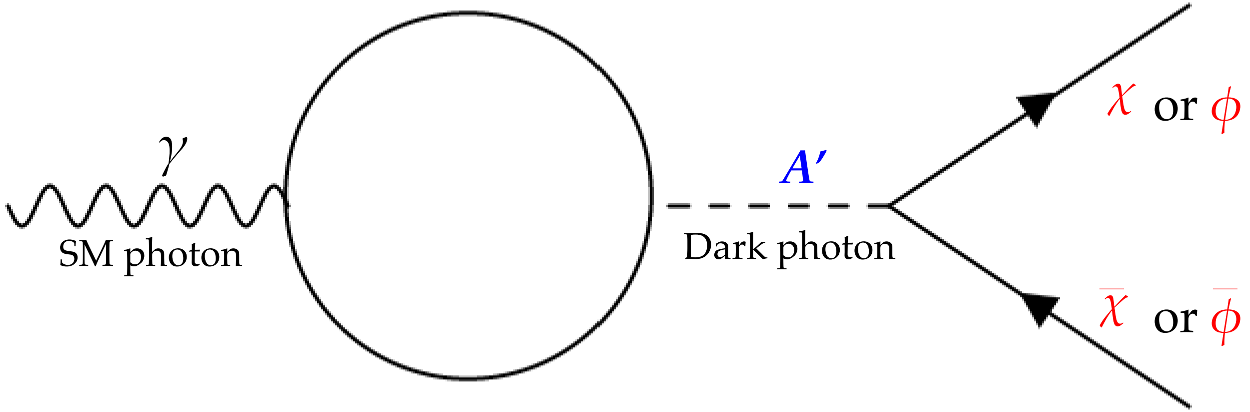


[US Cosmic Vision 2017]

- 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 can access this region by **<u>Accelerator-based fixed-target</u>** 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'.



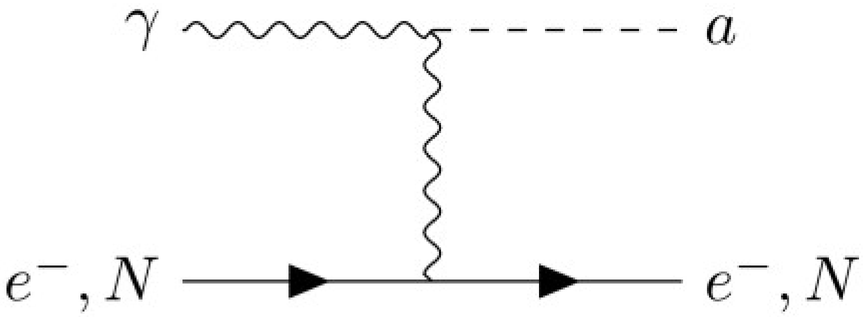
Dark matter flux ∝ Photon flux ∝ Beam intensity

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

Axion-like Particles Benchmark Model

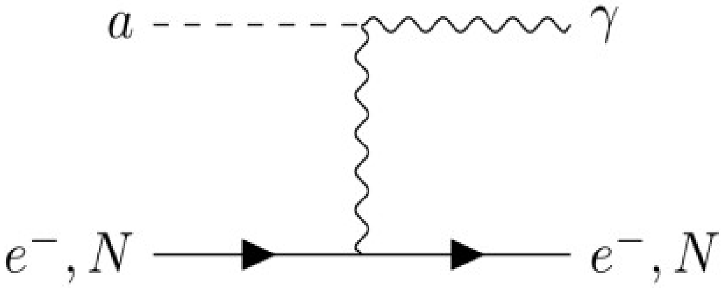
- On the other hand, we can also consider an axion-like particle scenario in this energy/mass scale.
- ALPs are general extension of QCD axion to solve strong CP problem.

Production

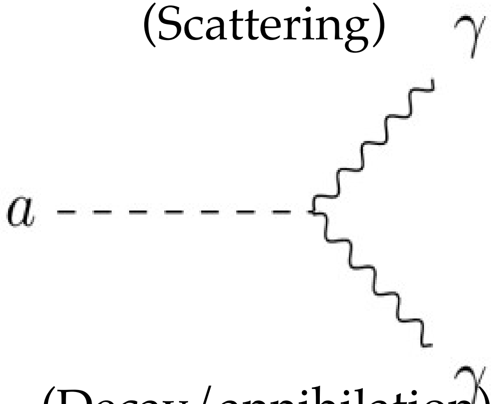


Primakoff Process

Detection



(Scattering)



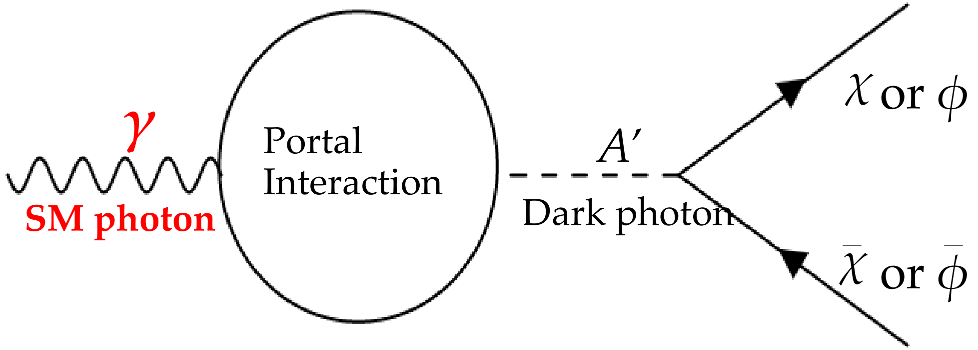
(Decay/annihilation)

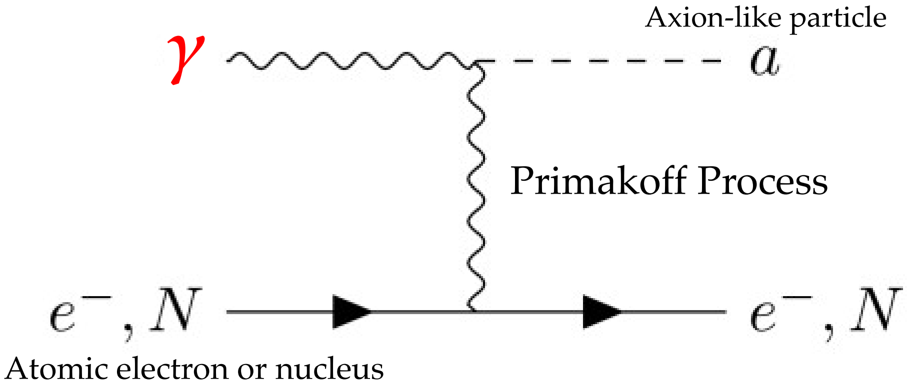
ALP flux $\propto$ Photon flux $\propto$ Beam intensity

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

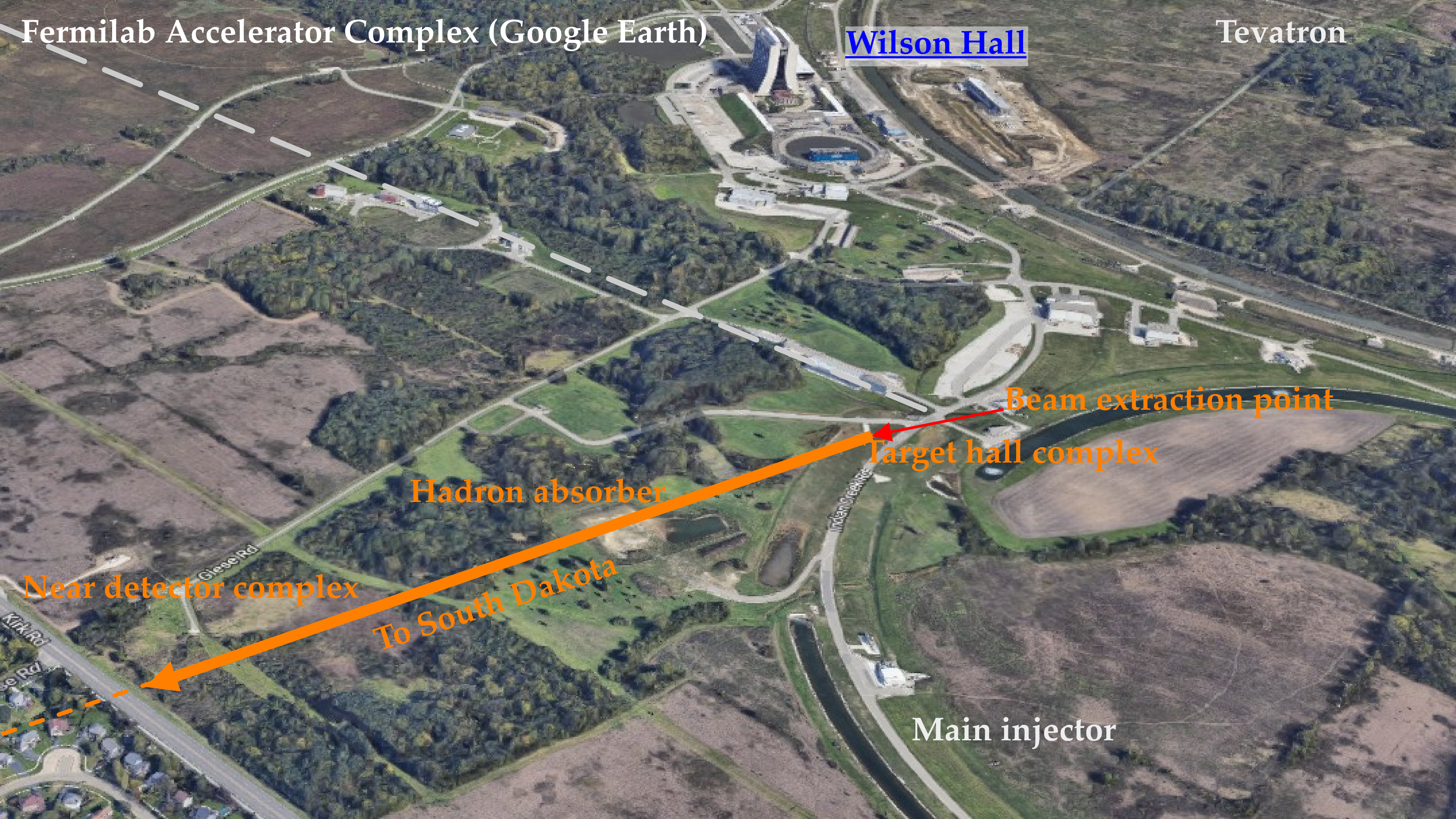
Photo-induced Dark Sector Particles Production

- These two benchmark studies are the most representative cases for **photo-induced** dark sector particles (DSPs) that we can observe in neutrino facilities.

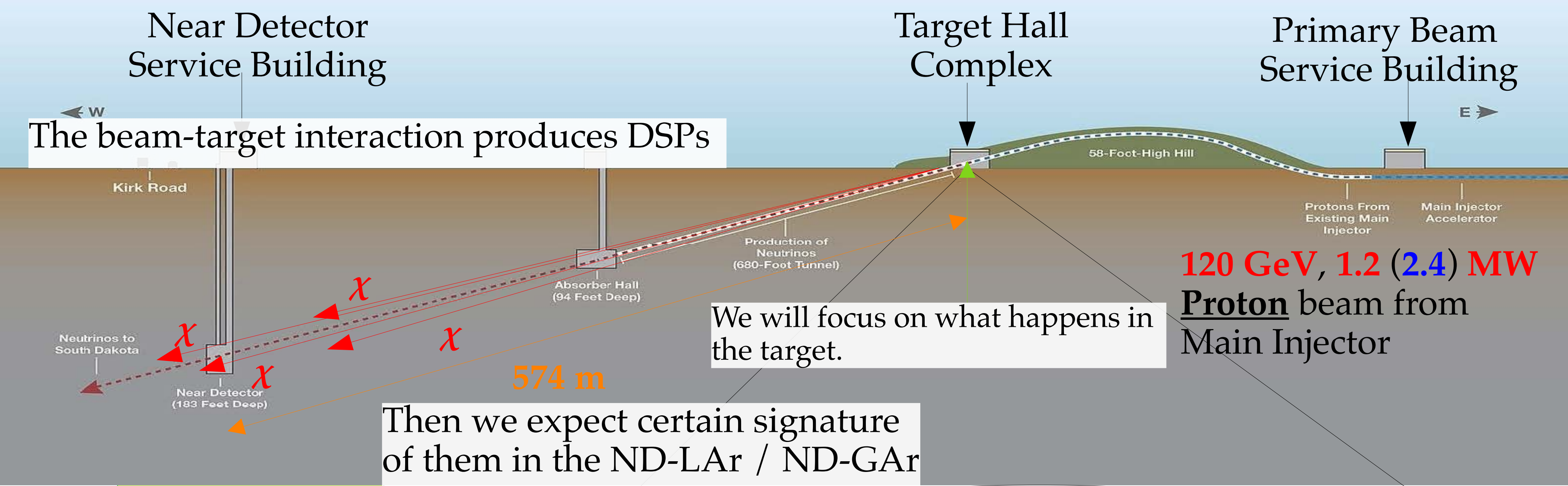




- Therefore, basically, to produce DSPs more copiously, we need an efficient **photon factory**.
- In this presentation, I will focus on what kind of processes produces photons and the estimated contributions from secondary productions where secondary production means all processes producing photons except the neutral meson decay.
- I will see the DUNE as a benchmark case.


Fermilab Accelerator Complex (Google Earth)
Wilson Hall
Tevatron
Beam extraction point
Target hall complex
Hadron absorber
Near detector complex
To South Dakota
Main injector

DSP Production

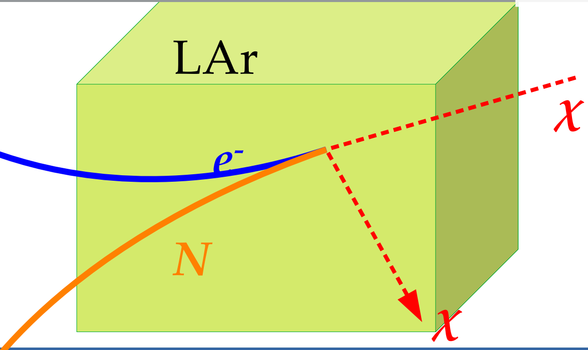


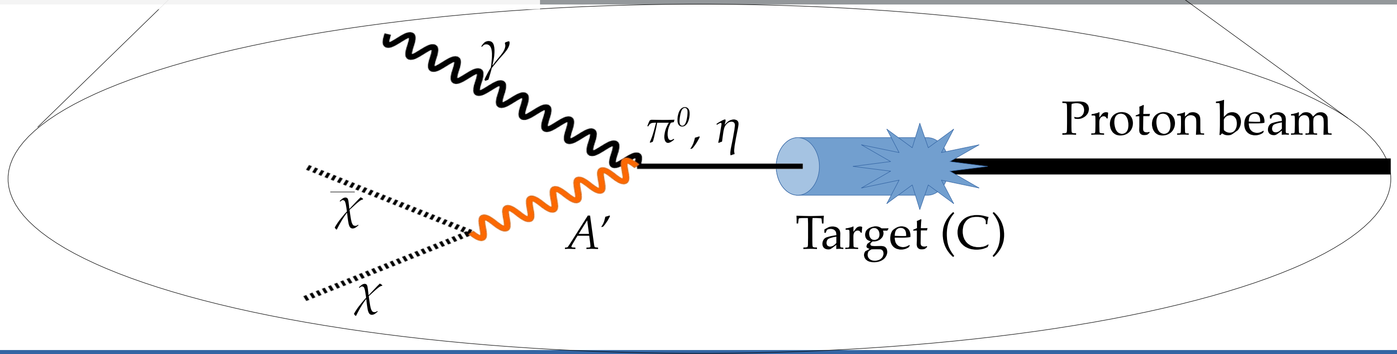
The beam-target interaction produces DSPs

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

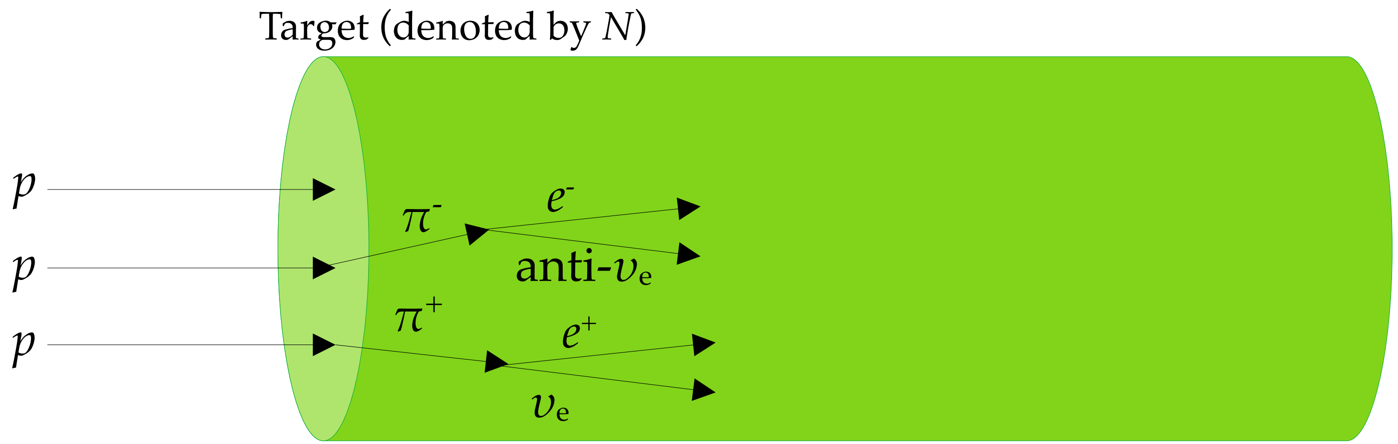
We will focus on what happens in the target.

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





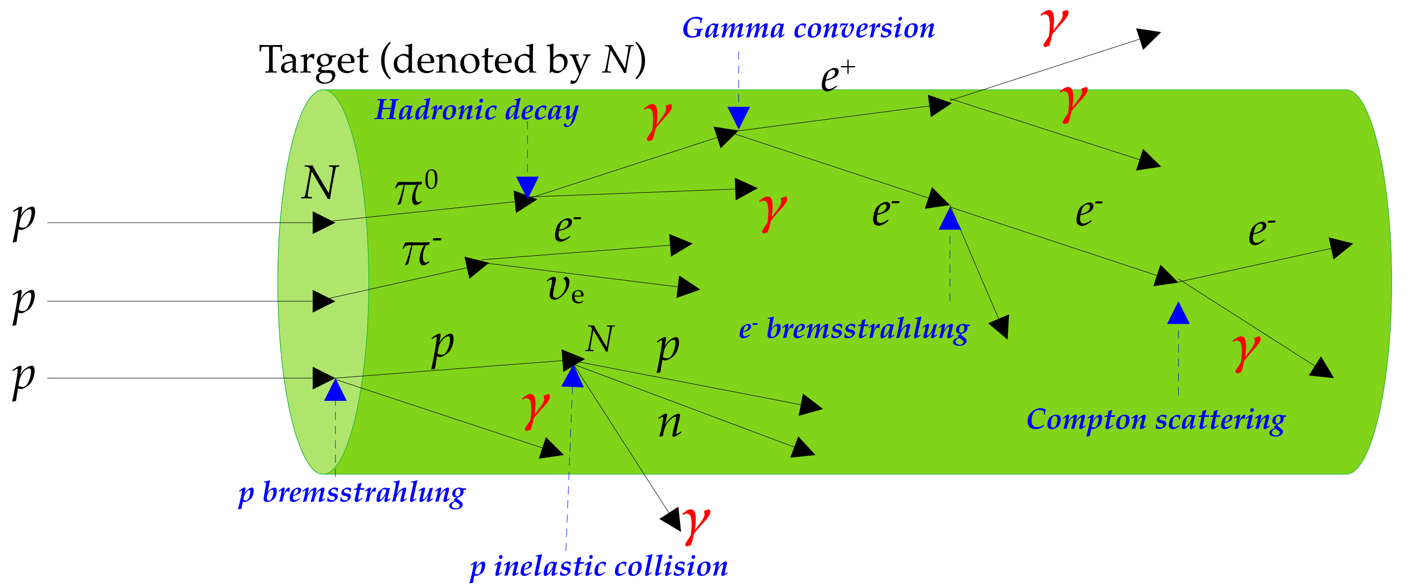
How to Produce Neutrinos in Neutrino Experiments?



Important target parameters for efficient neutrino factory?
(Here, let's not think about engineering requirement such as heat pile up).

1. Nuclear interaction length
   → Produce more charged pions.
2. Pion interaction length
   → Charged pions more easily decay into neutrinos.

How to Produce Photons in Neutrino Experiments?

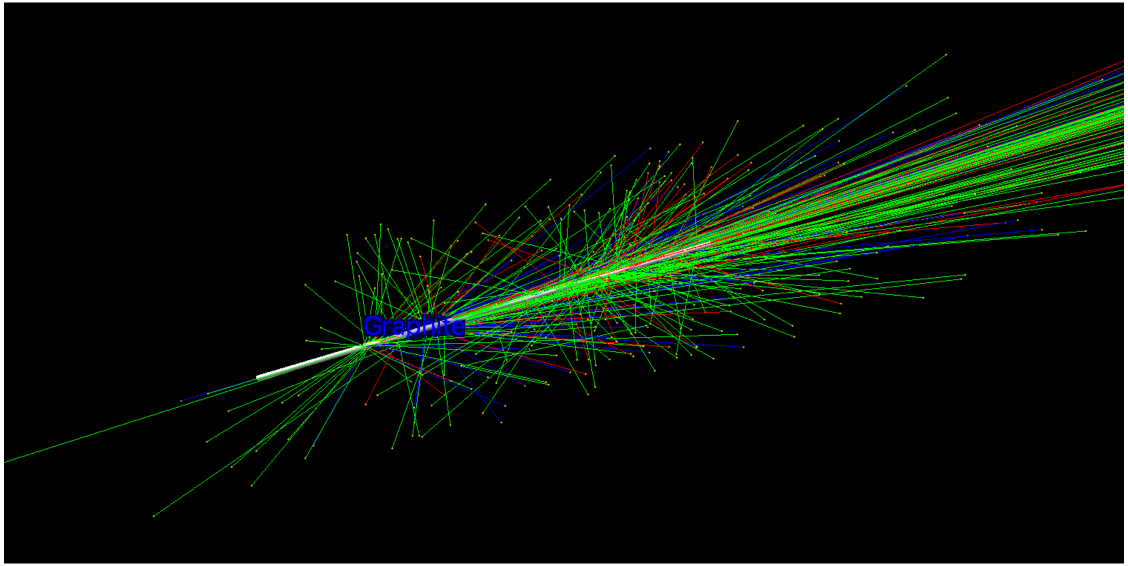


- We need very intense proton beam to obtain as many as possible photons.
- The #1 process producing energetic photon is decay of neutral mesons like π^0 and η.
  - The nuclear interaction length of the target material is a key parameter of the photon yield.
- Secondary photon production can be understood by electromagnetic shower development process
  - Nuclear interaction length is important again because it contribute to initiate an EM shower.
  - Also, radiation length matters to photon production as it directly affects the EM shower development.

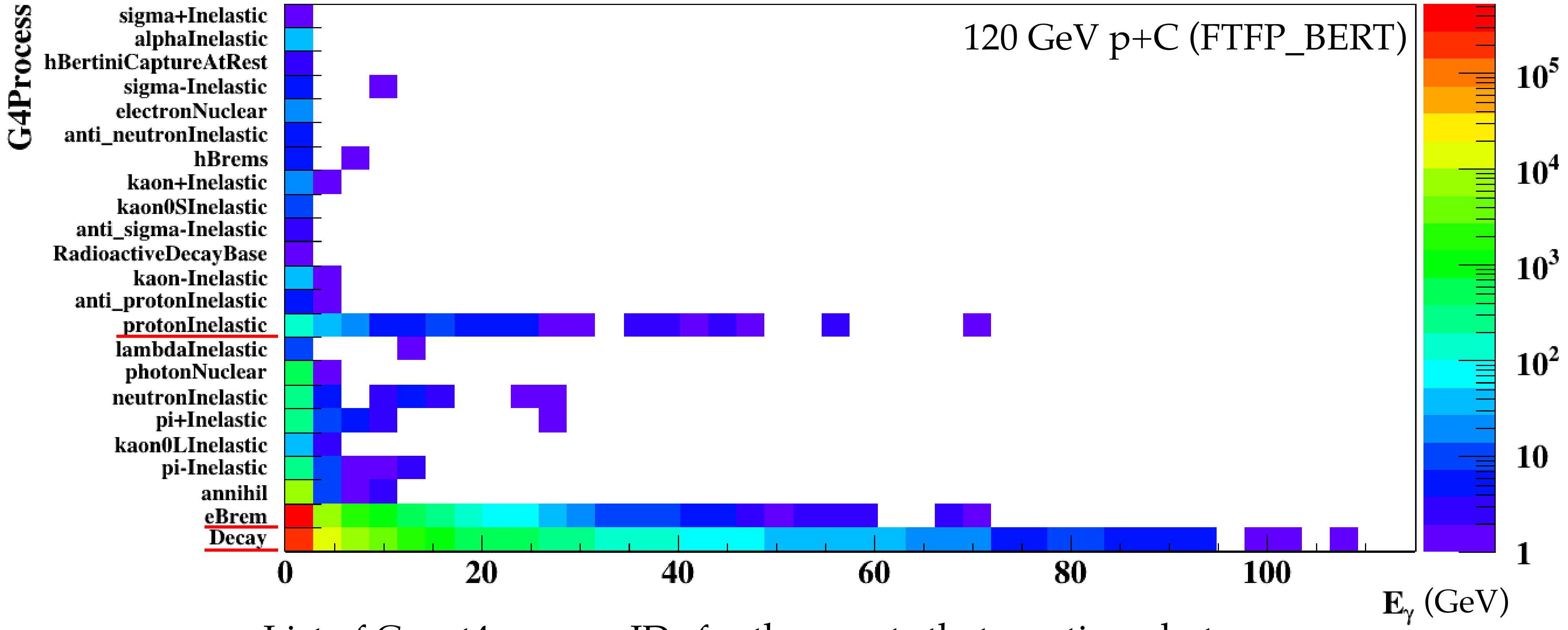
Geant4 Simulation

- I use Geant4 framework to simulate the proton and the target interaction.
- Geant4 provides very nice handling of
  - Geometry
  - Tracking
  - Detector response

Also, a concept called ‘Run management’ allows us to access all the processes while a particle propagate through the given detector material. This is an essential feature to study secondary effects.

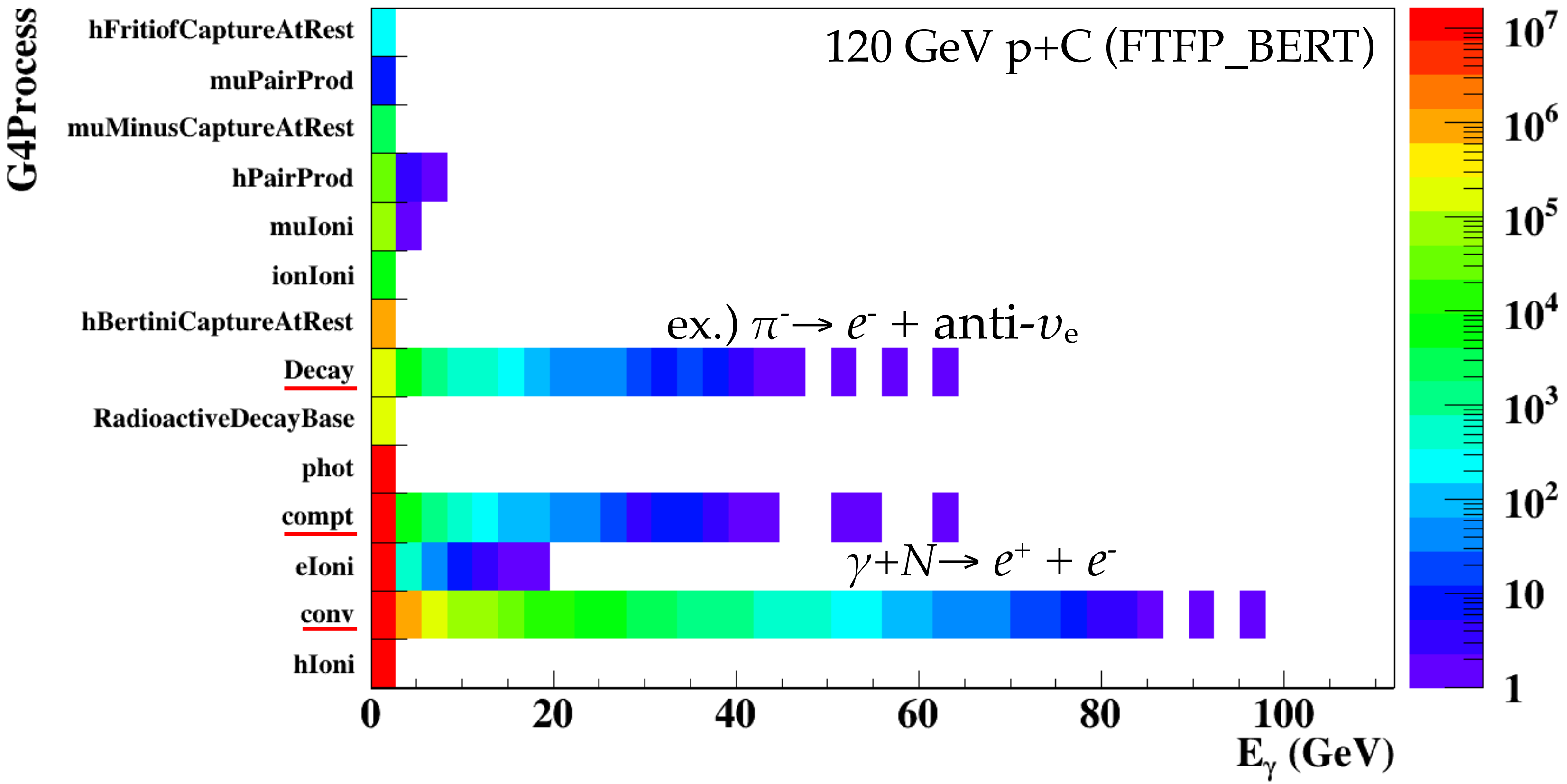


Photon Production Channels

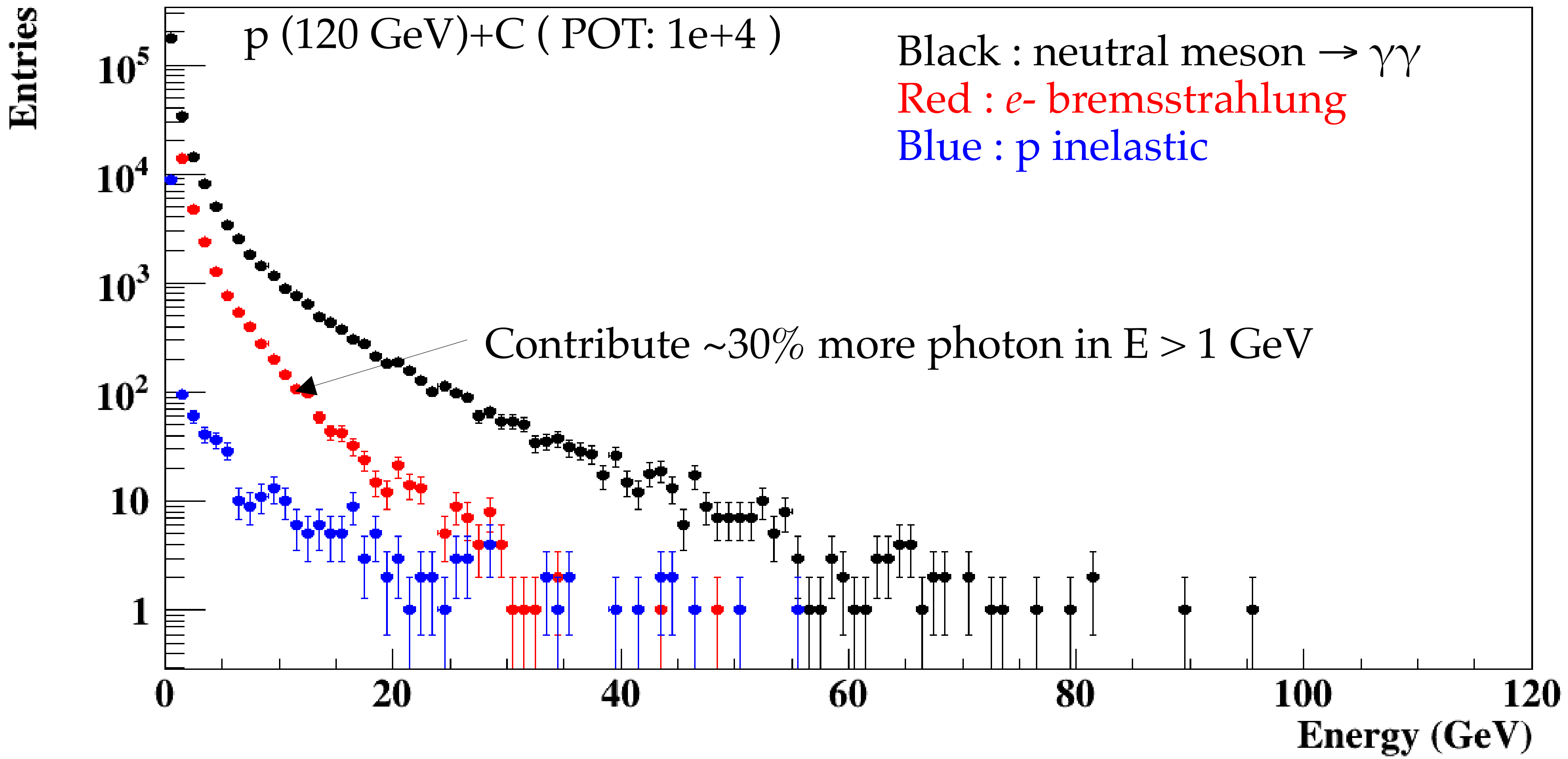


List of Geant4 process IDs for the events that creating photons.

Electron Production Channels

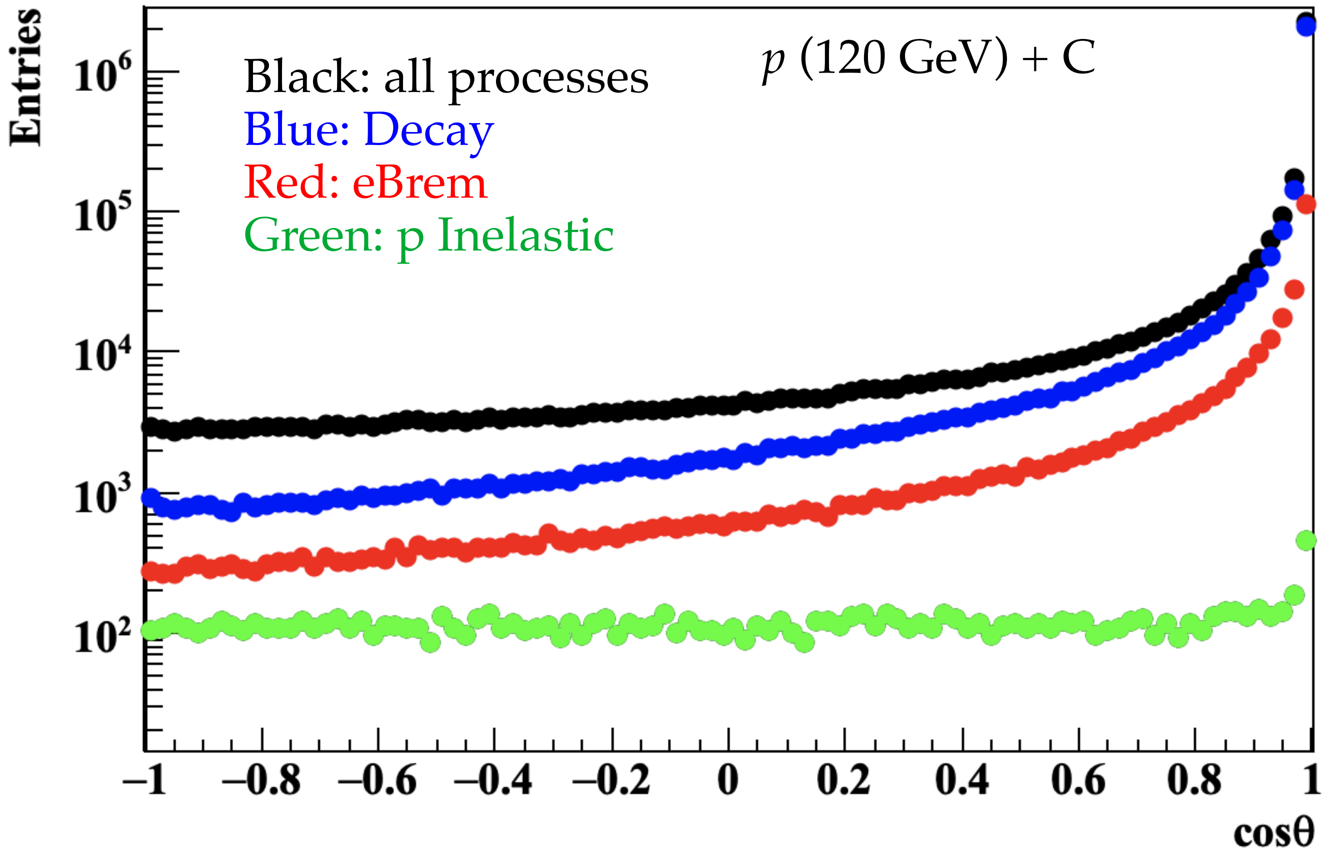


Target Simulation under DUNE Setup



Secondary process produces certainly less number of photon, however the amount is non-negligible.

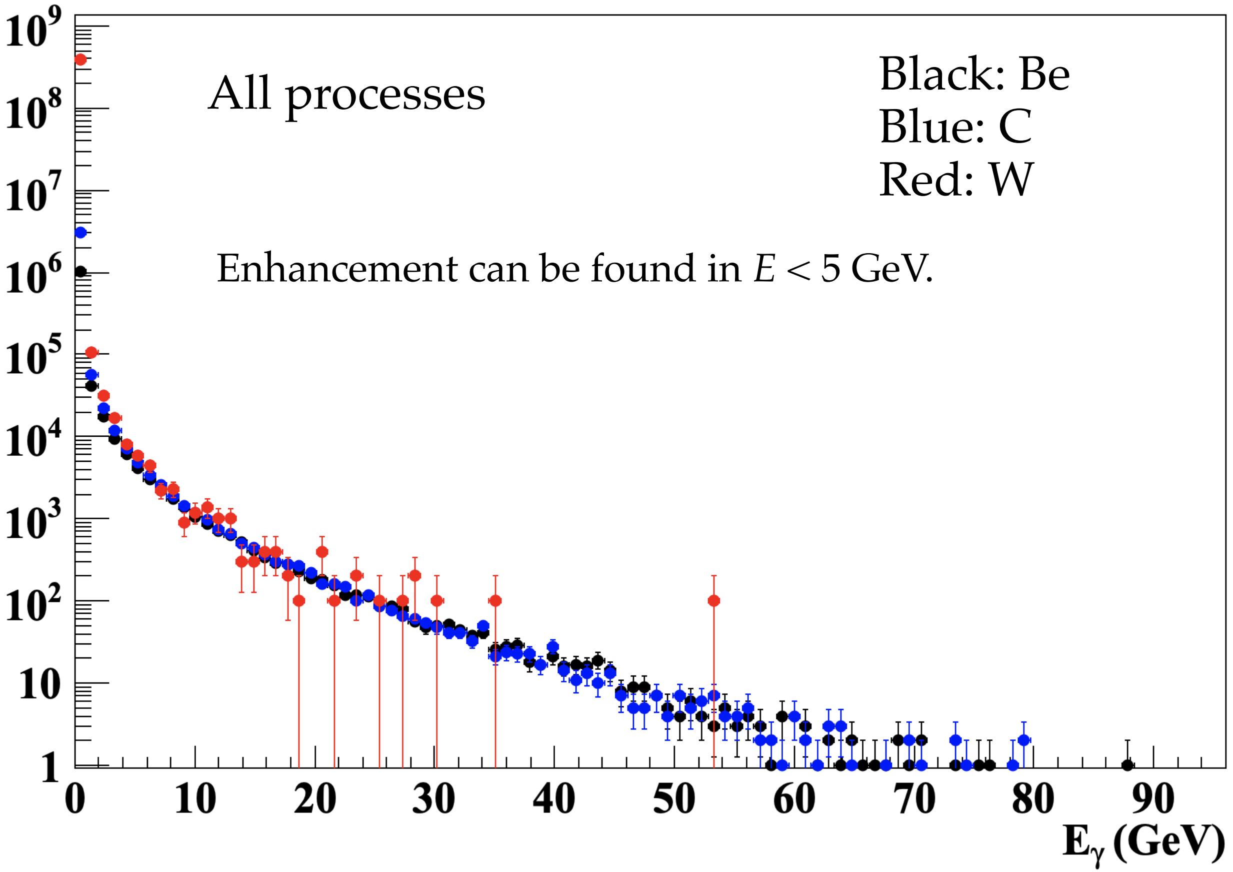
Angular distribution



Here, e-bremsstrahlung can be more enhanced by magnetic focusing horn.

In this simulation, I did not implemented the horn.

Target Material Comparison (Be, C, and W)



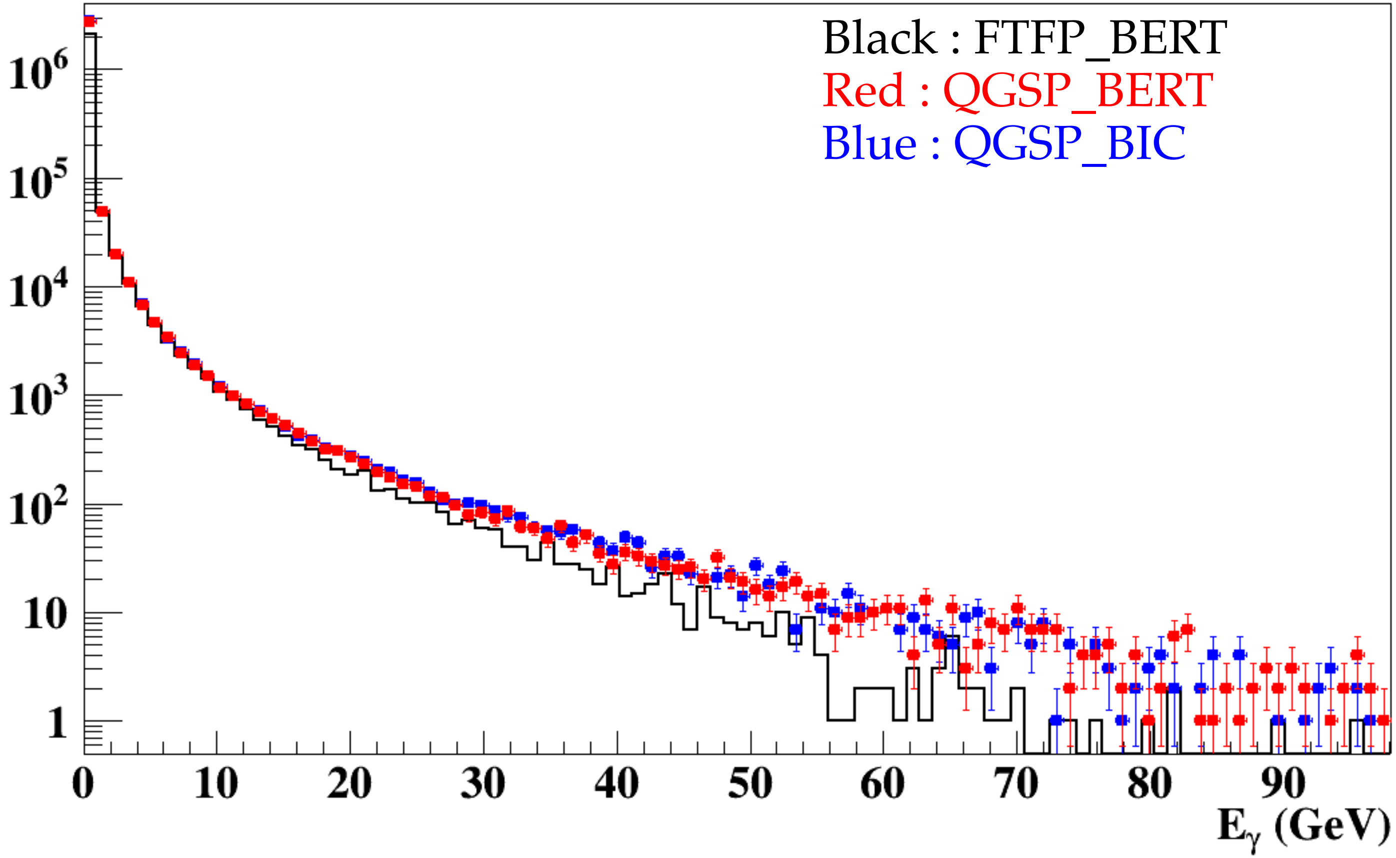
Physics Lists Comparison

Secondary production can be modeled using different physics lists in Geant4.

I chose three most favored physics list provided by Geant4.

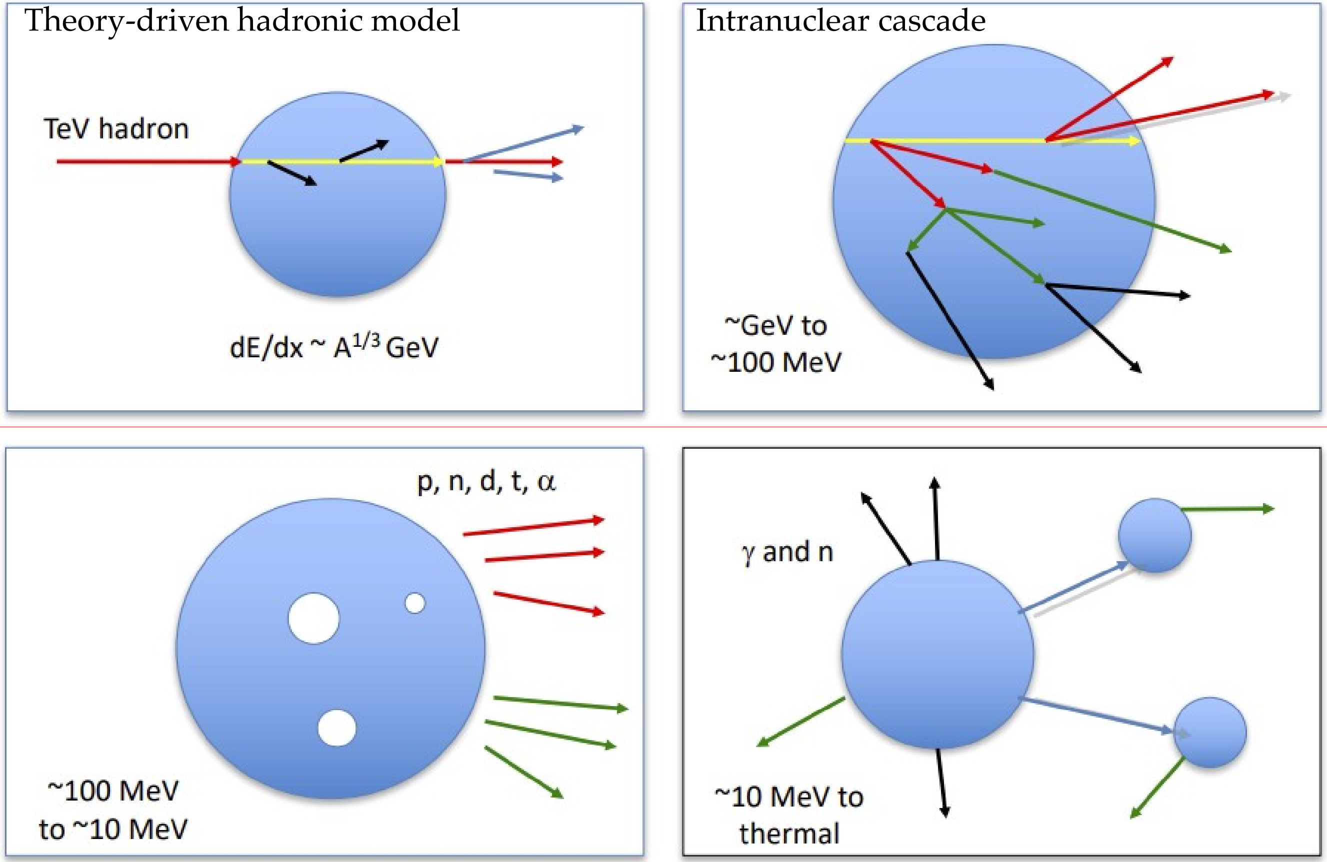
1) FTFP_BERT
2) QGSP_BERT
3) QGSP_BIC

POT for each physics list is 1e+4.



Hadronic Interactions as the Energy Scale of the Interaction

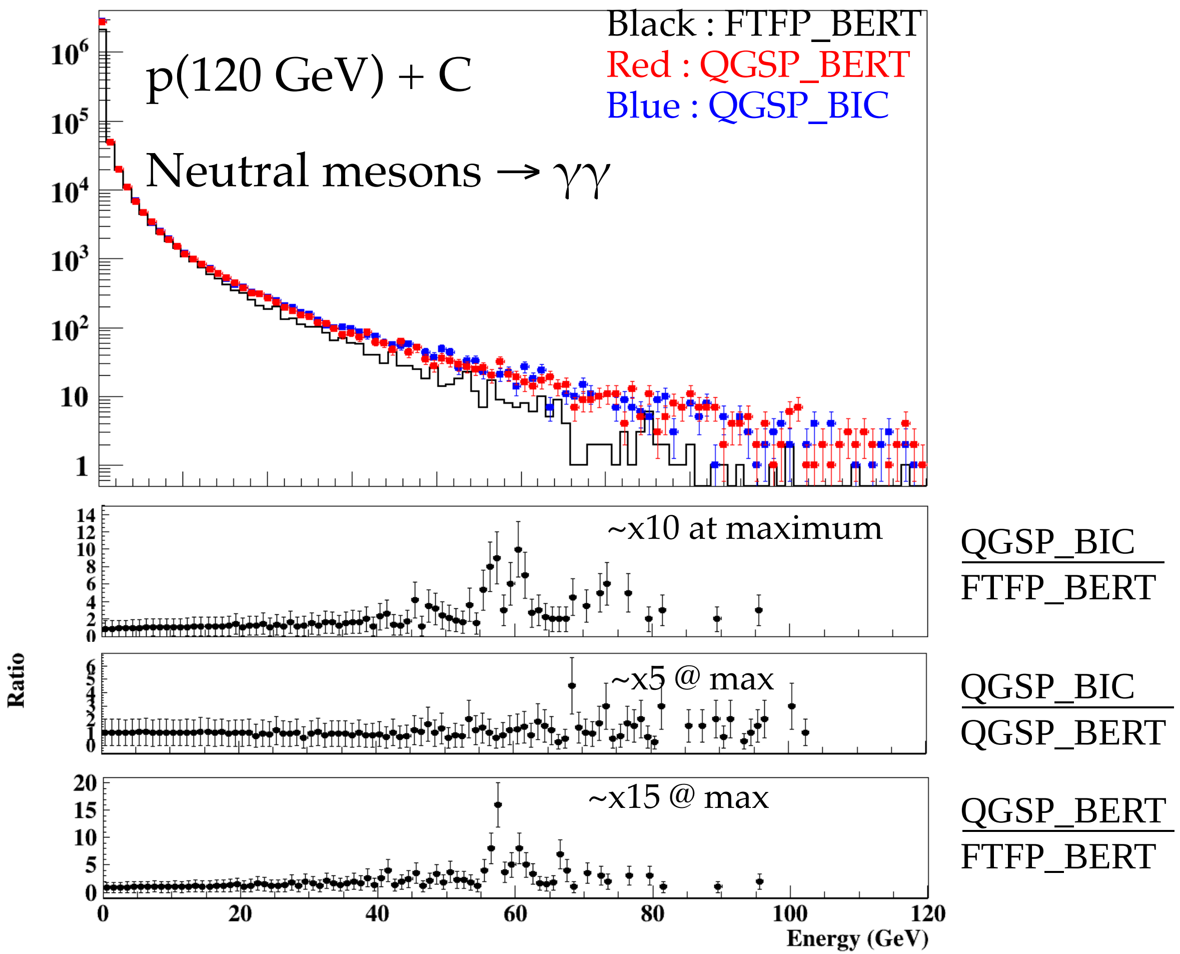
QGSP,
FTFP



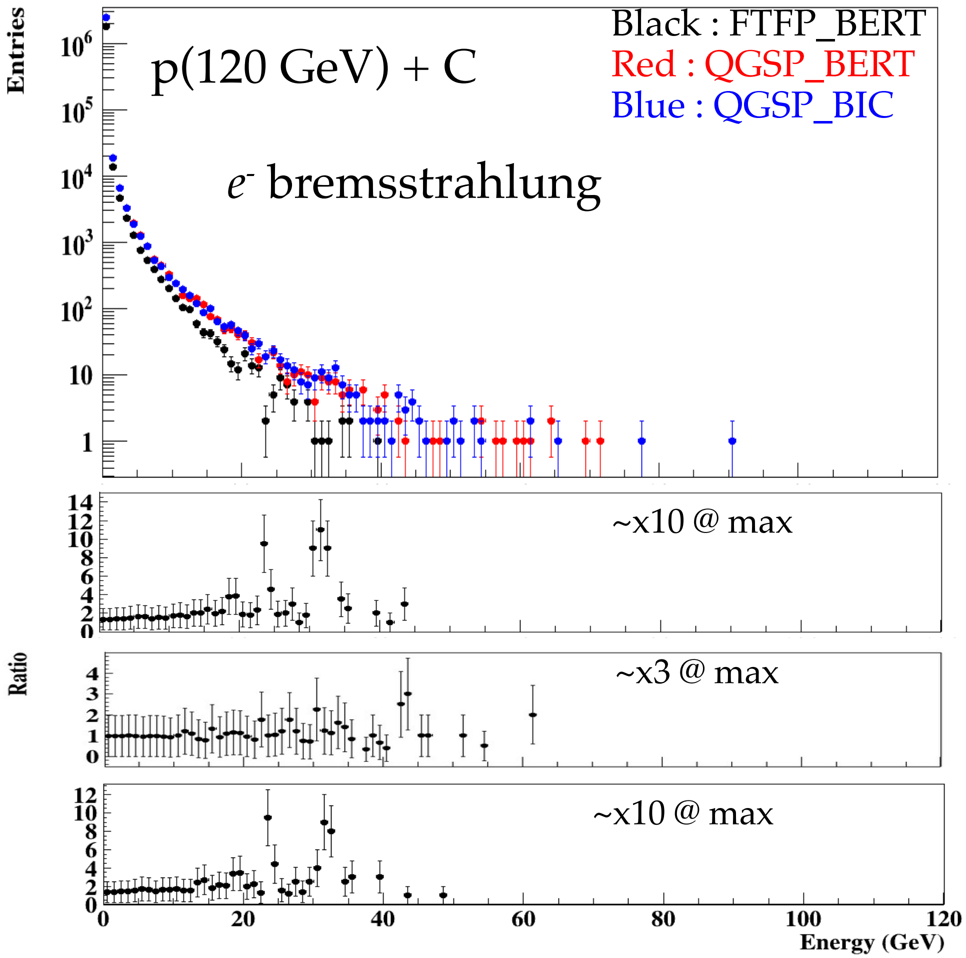
Bertini-style cascade
Binary ion cascade

Picture from Dennis Wright (G4 tutorial 2019)

Process Comparisons



Process Comparisons

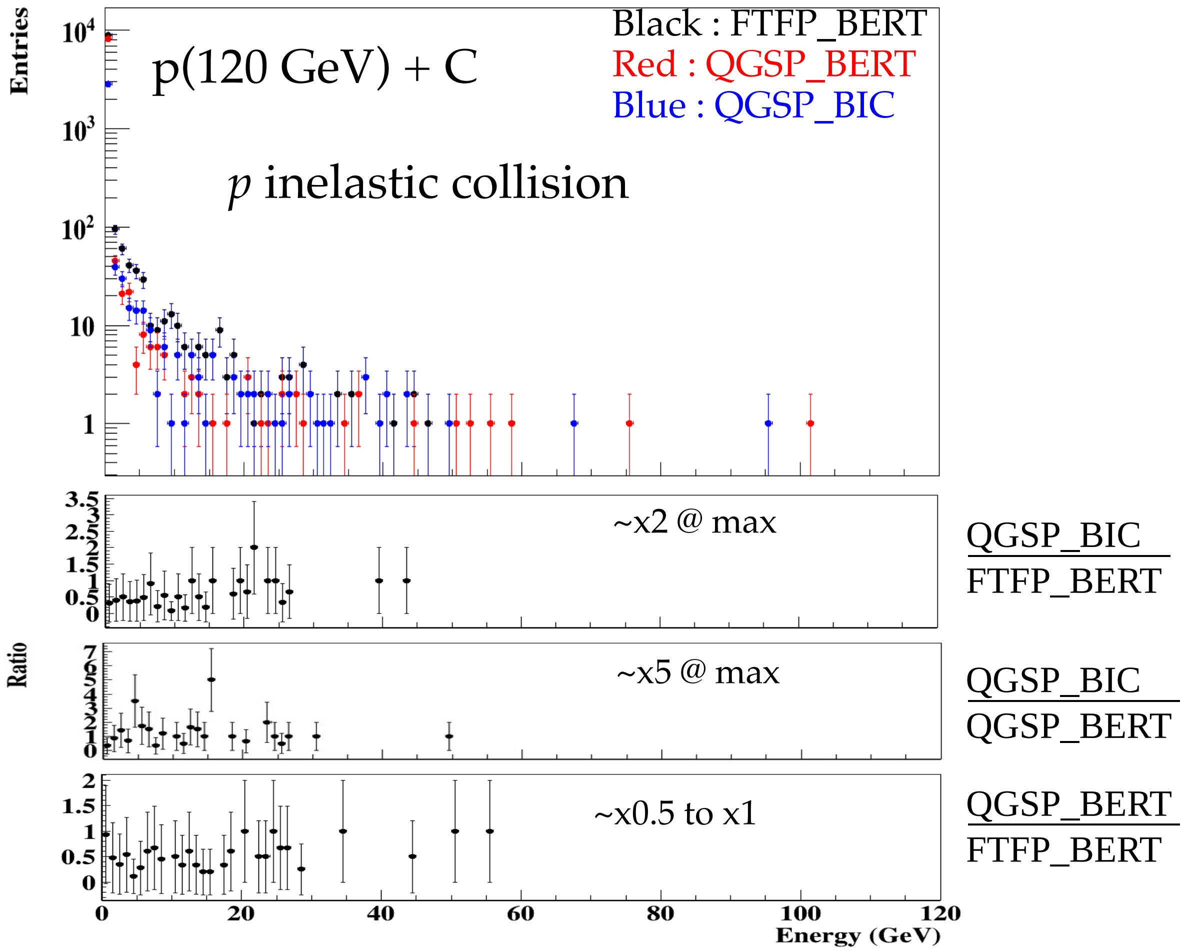


$\frac{\text{QGSP\_BIC}}{\text{FTFP\_BERT}}$

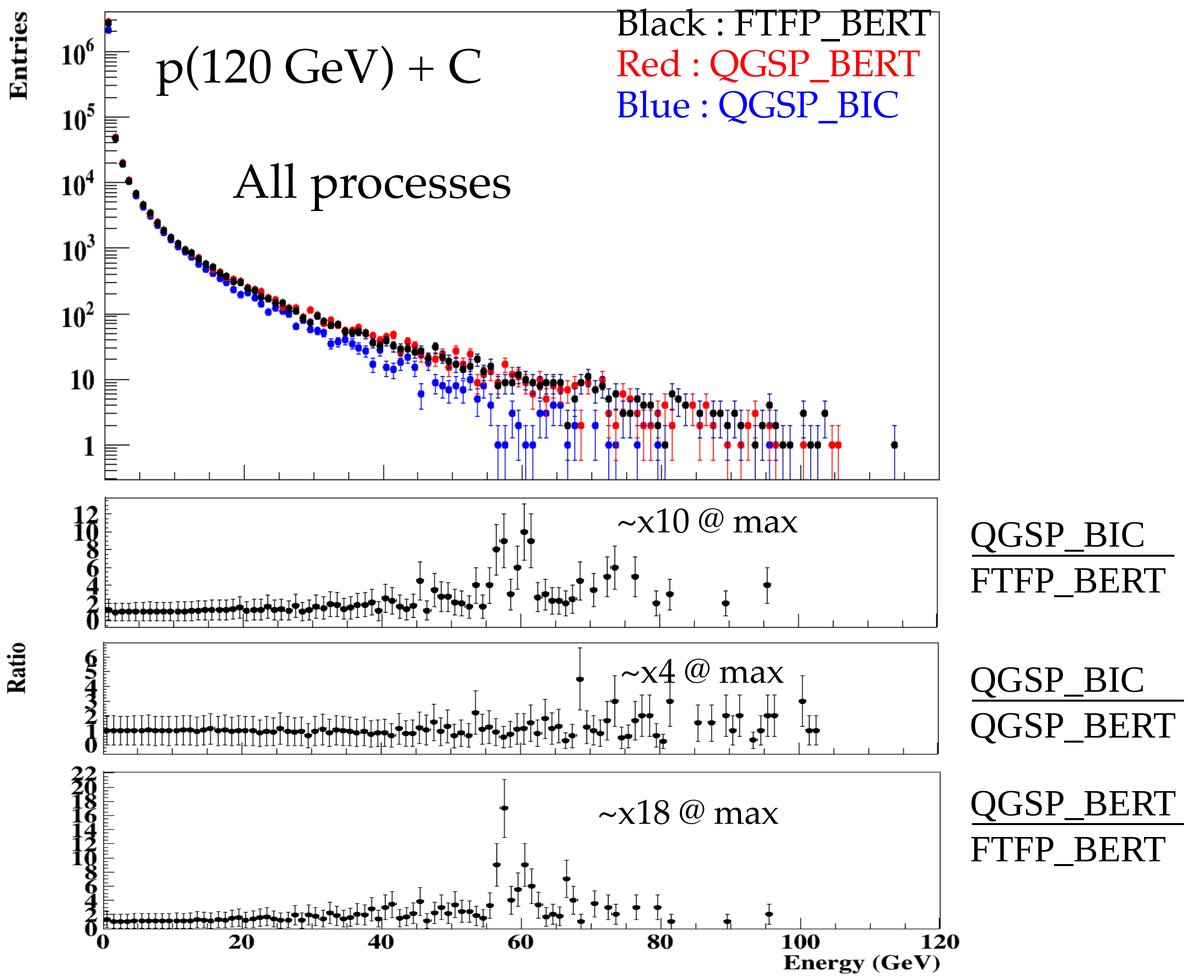
$\frac{\text{QGSP\_BIC}}{\text{QGSP\_BERT}}$

$\frac{\text{QGSP\_BERT}}{\text{FTFP\_BERT}}$

Process Comparisons



Process Comparisons



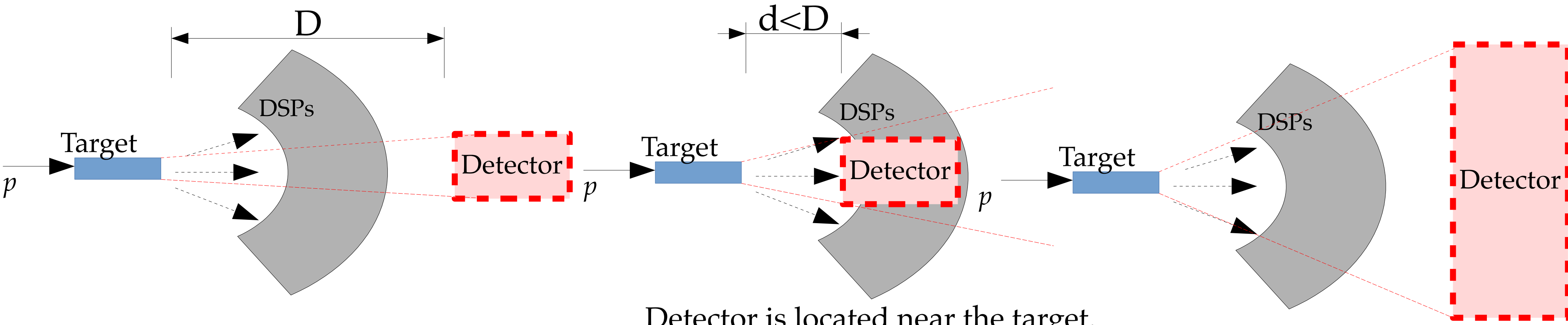
Conclusion

- Today I have discussed secondary productions about possible photo-induced BSM signatures.
- Primarily, photo-induced BSM signals come from energetic neutral meson decays and this is mainly depending on nuclear interaction length of target material.
  - If the target works as a good hadronic calorimeter absorber, it will increase the amount of meson decays.
- Secondary productions could be occur through the electromagnetic interaction followed by the meson decays.
  - If the target works like a good electromagnetic calorimeter absorber, it will increase the amount of secondary photon production.
- I presented my Geant4 simulation results. Some remarks from the result were:
  - Electron bremsstrahlung is the biggest source of photon among the secondary processes.
  - Photons produced by e- bremsstrahlung are pretty much in forward direction.
  - Target material is important if we are interested in low-energy physics.
  - We observed model-dependency of the simulation result and this dependency comes from the implementation of QCD interaction models.

Q & A

Backup slides

How to Collect Photons More Efficiently?

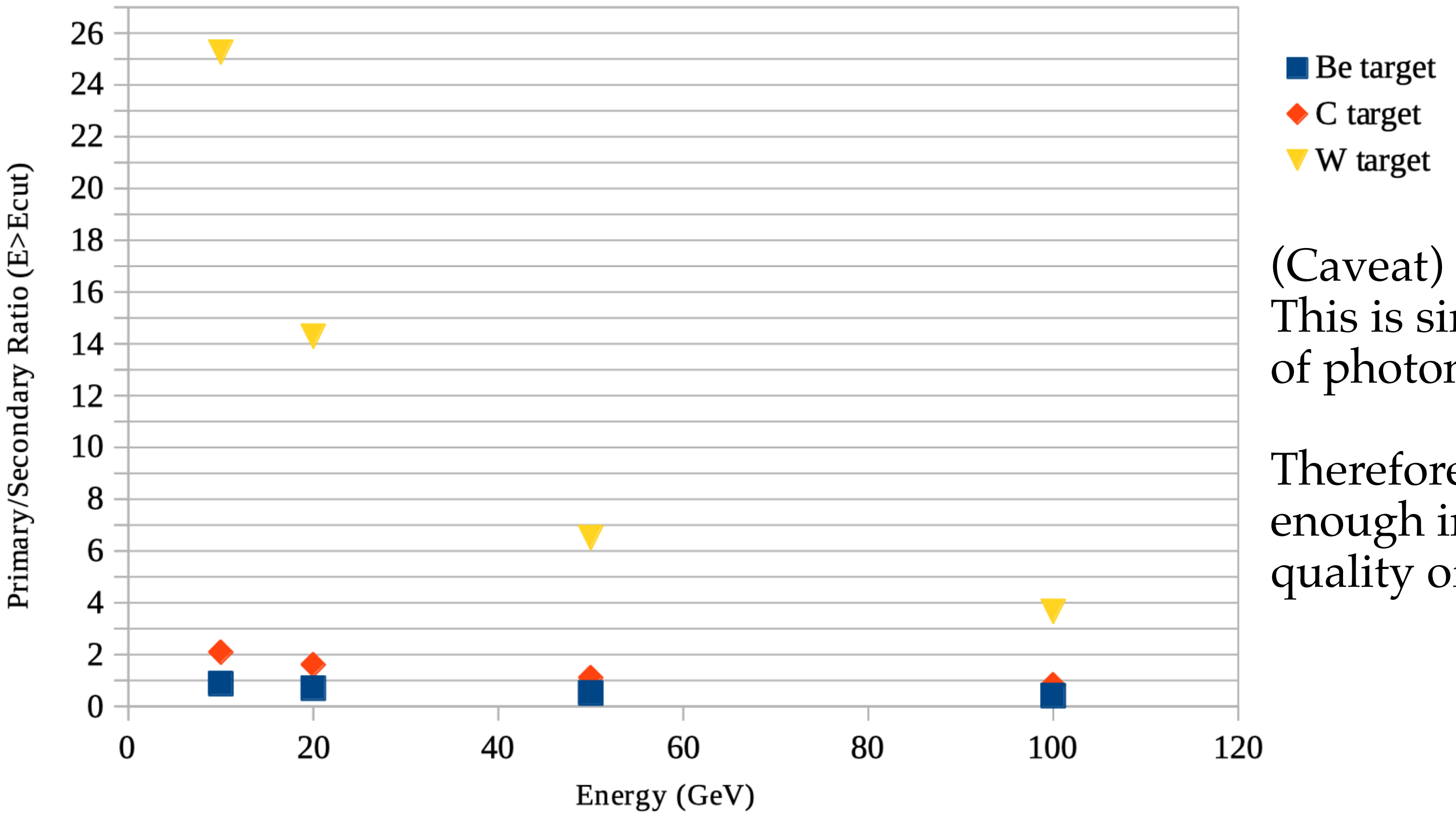


Detector is located near the target.

Bigger detector

- To collect as many photons as possible, one of the important design parameters is:
  - Geometrical coverage: considering the angular distribution of produced photon, the photon counting efficiency will increased in wide energy range as the geometrical coverage enlarged.
- Geometrical coverage can be the function of multiple independent parameters like volume of the detector, or the distance between the target and the detector.

Primary/Secondary Photon Count Ratio



(Caveat)
This is simply comparing numbers of photons produced in the target.

Therefore this does not gives you enough information about the quality of photons.