Searching for Dark Photon Production Using Genetic Algorithms

Rohan Arni
High Technology High School, Lincroft NJ 07738, USA
roarni@ctemc.org

The Dark Photon

The Dark Photon

- Dark matter makes up 27% of the energy density and 85% of the matter density of the universe.

The Dark Photon

- Dark matter makes up 27% of the energy density and 85% of the matter density of the universe.
- The Standard Model does not account for dark matter, a separate dark sector is proposed

The Dark Photon

- Dark matter makes up 27% of the energy density and 85% of the matter density of the universe.
- The Standard Model does not account for dark matter, a separate dark sector is proposed
- The dark photon is a force carrier for the dark sector, similar to the photon

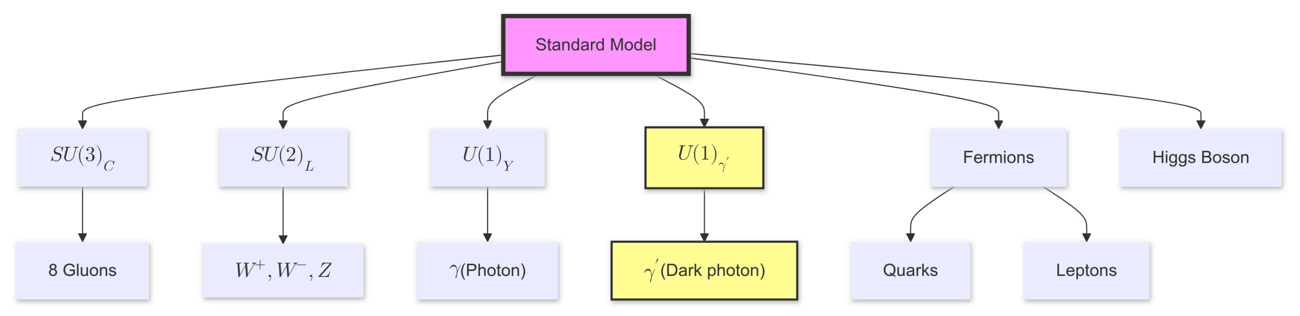
The Dark Photon

- Dark matter makes up 27% of the energy density and 85% of the matter density of the universe.
- The Standard Model does not account for dark matter, a separate dark sector is proposed
- The dark photon is a force carrier for the dark sector, similar to the photon
- New particle can be introduced to the standard model by extending SM gauge group with new $U(1)$ gauge symmetry

The Dark Photon

- Dark matter makes up 27% of the energy density and 85% of the matter density of the universe.
- The Standard Model does not account for dark matter, a separate dark sector is proposed
- The dark photon is a force carrier for the dark sector, similar to the photon
- New particle can be introduced to the standard model by extending SM gauge group with new $U(1)$ gauge symmetry
- The dark photon interacts with the SM photon via kinetic mixing.

Extended Standard Model



The Dark Photon, cont'd

The Dark Photon, cont'd

This U(1) gauge symmetry is associated with a new dark photon field, denoted as A'_μ. The Lagrangian that includes kinetic mixing between the photon and the dark photon is given by:

Kinetic Mixing Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu$$

The Dark Photon, cont'd

This U(1) gauge symmetry is associated with a new dark photon field, denoted as A'_μ. The Lagrangian that includes kinetic mixing between the photon and the dark photon is given by:

Kinetic Mixing Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

Where:

- $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength tensor, where A_μ is the SM photon field.

The Dark Photon, cont'd

This U(1) gauge symmetry is associated with a new dark photon field, denoted as A'_μ. The Lagrangian that includes kinetic mixing between the photon and the dark photon is given by:

Kinetic Mixing Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

Where:

- $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength tensor, where A_μ is the SM photon field.
- $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon field strength tensor, where A'_μ is the dark photon field.

The Dark Photon, cont'd

This U(1) gauge symmetry is associated with a new dark photon field, denoted as A'_μ. The Lagrangian that includes kinetic mixing between the photon and the dark photon is given by:

Kinetic Mixing Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu$$

Where:

- $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength tensor, where A_μ is the SM photon field.
- $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon field strength tensor, where A'_μ is the dark photon field.
- ϵ is the dimensionless kinetic mixing parameter.

Diagonalizing Kinetic Terms

Diagonalizing Kinetic Terms

- Need to remove the mixing term so the kinetic terms only consist of parameters from one field.

Diagonalizing Kinetic Terms

- Need to remove the mixing term so the kinetic terms only consist of parameters from one field.
- Product $F_{\mu\nu}F'^{\mu\nu}$ should vanish to cancel $\left(\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}\right)$

Diagonalizing Kinetic Terms

- Need to remove the mixing term so the kinetic terms only consist of parameters from one field.
- Product $F_{\mu\nu}F'^{\mu\nu}$ should vanish to cancel $\left(\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}\right)$
- We can do this with a field redefinition ($\tilde{A}_\mu$ and $\tilde{A}'_\mu$).

Diagonalizing Kinetic Terms

- Need to remove the mixing term so the kinetic terms only consist of parameters from one field.
- Product $F_{\mu\nu}F'^{\mu\nu}$ should vanish to cancel $\left(\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}\right)$
- We can do this with a field redefinition ($\tilde{A}_\mu$ and $\tilde{A}'_\mu$).
- Redefinition must ensure the mixing term is eliminated and the fields are normalized.

Diagonalizing Kinetic Terms

- Need to remove the mixing term so the kinetic terms only consist of parameters from one field.
- Product $F_{\mu\nu}F'^{\mu\nu}$ should vanish to cancel $\left(\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}\right)$
- We can do this with a field redefinition ($\tilde{A}_\mu$ and $\tilde{A}'_\mu$).
- Redefinition must ensure the mixing term is eliminated and the fields are normalized.

Field Redefinition

$$\tilde{A}_\mu = A_\mu + \epsilon A'_\mu$$

$$\tilde{A}'_\mu = \sqrt{1-\epsilon^2}A'_\mu$$

$$\mathcal{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu}$$

Interactions

Interactions

Interaction Between Photon and Charged Particle

$$\mathcal{L}_{\text{int}}[\psi, \bar{\psi}, A_\mu] = eA_\mu \bar{\psi}\gamma^\mu \psi = eA_\mu J^\mu_{\text{em}}$$

Interactions

Interaction Between Photon and Charged Particle

$$\mathcal{L}_{\text{int}}[\psi, \bar{\psi}, A_\mu] = eA_\mu \bar{\psi}\gamma^\mu \psi = eA_\mu J^\mu_{\text{em}}$$

Where e is the coupling constant (the charge of the particle) and J^μ_{em} is the fermion current ($\bar{\psi}\gamma^\mu\psi$). Using our new definition of $\tilde{A}_\mu$, we can substitute:

Interactions

Interaction Between Photon and Charged Particle

$$\mathcal{L}_{\text{int}}[\psi, \bar{\psi}, A_\mu] = eA_\mu \bar{\psi}\gamma^\mu \psi = eA_\mu J^\mu_{\text{em}}$$

Where e is the coupling constant (the charge of the particle) and J^μ_{em} is the fermion current ($\bar{\psi}\gamma^\mu\psi$). Using our new definition of $\tilde{A}_\mu$, we can substitute:

Substitution

$$\mathcal{L}_{\text{int}} = e\tilde{A}_\mu J^\mu_{\text{em}}$$

$$\mathcal{L}_{\text{int}} = e(A_\mu + \epsilon A'_\mu) J^\mu_{\text{em}}$$

$$\mathcal{L}_{\text{int}} = eA_\mu J^\mu_{\text{em}} + e\epsilon A'_\mu J^\mu_{\text{em}}$$

Consequences

Consequences

- Based on the equation, the dark photon can interact with the same particles as a photon (suppressed by a factor ϵ)

Consequences

- Based on the equation, the dark photon can interact with the same particles as a photon (suppressed by a factor ϵ)
- This interaction is called the dark photon portal

Consequences

- Based on the equation, the dark photon can interact with the same particles as a photon (suppressed by a factor ϵ)
- This interaction is called the dark photon portal
- This portal opens up new interaction/production channels.

Consequences

- Based on the equation, the dark photon can interact with the same particles as a photon (suppressed by a factor ϵ)
- This interaction is called the dark photon portal
- This portal opens up new interaction/production channels.
- For instance, in meson decays, a neutral pion π^0 can decay into a photon and a dark photon:

Consequences

- Based on the equation, the dark photon can interact with the same particles as a photon (suppressed by a factor ϵ)
- This interaction is called the dark photon portal
- This portal opens up new interaction/production channels.
- For instance, in meson decays, a neutral pion π^0 can decay into a photon and a dark photon:

Production of Dark Photon

$$\pi^0 \to \gamma + \gamma'$$

Consequences

- Based on the equation, the dark photon can interact with the same particles as a photon (suppressed by a factor ϵ)
- This interaction is called the dark photon portal
- This portal opens up new interaction/production channels.
- For instance, in meson decays, a neutral pion π^0 can decay into a photon and a dark photon:

Production of Dark Photon

$$\pi^0 \rightarrow \gamma + \gamma'$$

- The rate of such a process is proportional to ϵ^2 $(\approx 10^{-6})$.

Consequences

- Based on the equation, the dark photon can interact with the same particles as a photon (suppressed by a factor ϵ)
- This interaction is called the dark photon portal
- This portal opens up new interaction/production channels.
- For instance, in meson decays, a neutral pion π^0 can decay into a photon and a dark photon:

Production of Dark Photon

$$\pi^0 \rightarrow \gamma + \gamma'$$

- The rate of such a process is proportional to ϵ^2 $(\approx 10^{-6})$.
- The dark photon would contribute to missing energy signatures in experiments.

Machine Learning Approach

Machine Learning Approach

- The goal is to design an algorithm that can search for dark photons via missing/abnormal energy signatures.

Machine Learning Approach

- The goal is to design an algorithm that can search for dark photons via missing/abnormal energy signatures.
- A binary classification model can be used to evaluate a data point if a dark photon is produced or not.

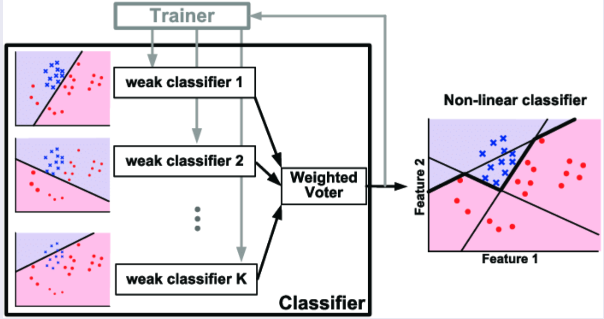
Machine Learning Approach

- The goal is to design an algorithm that can search for dark photons via missing/abnormal energy signatures.
- A binary classification model can be used to evaluate a data point if a dark photon is produced or not.
- Due to the nature of dark photon production, the resulting dataset will be imbalanced, with a majority of interaction not producing a dark photon.

Machine Learning Approach

- The goal is to design an algorithm that can search for dark photons via missing/abnormal energy signatures.
- A binary classification model can be used to evaluate a data point if a dark photon is produced or not.
- Due to the nature of dark photon production, the resulting dataset will be imbalanced, with a majority of interaction not producing a dark photon.
- This imbalance can be accounted for with an AdaBoost model.

AdaBoost Diagram



Why Genetic Algorithms?

Why Genetic Algorithms?

- The AdaBoost model has a set of hyperparameters (the number of estimators and the learning rate).

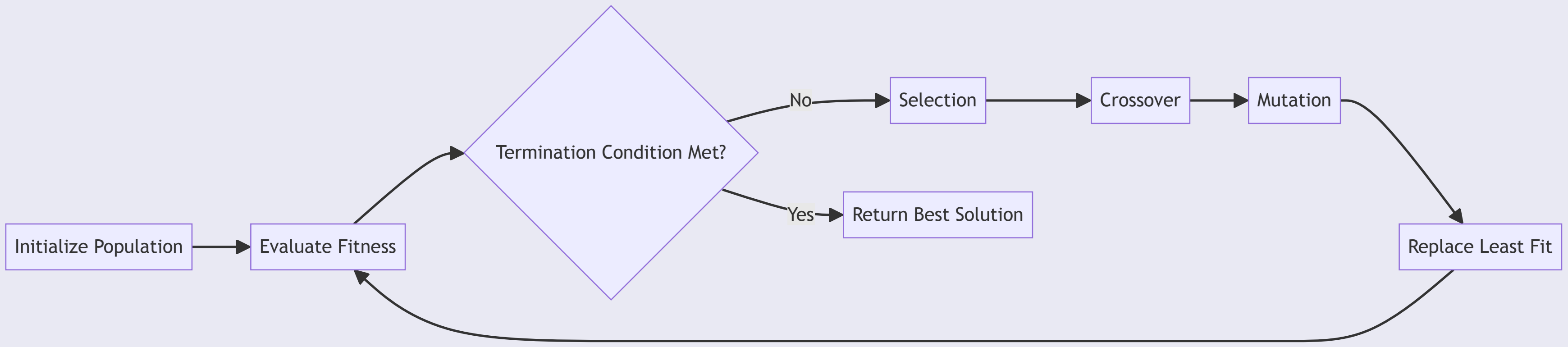
Why Genetic Algorithms?

- The AdaBoost model has a set of hyperparameters (the number of estimators and the learning rate).
- Tuning the hyperparameters manually can take a lot of time to approach an optimal solution.

Why Genetic Algorithms?

- The AdaBoost model has a set of hyperparameters (the number of estimators and the learning rate).
- Tuning the hyperparameters manually can take a lot of time to approach an optimal solution.
- An optimal solution to this problem can be reached with a genetic algorithm.

Genetic Algorithm Flowchart



Data Simulation

Data Simulation

- Simulated proton-proton collisions at 14 TeV using `Pythia3.8` on a 2021 MacBook Pro (M1 Pro, 32 GB RAM)

Data Simulation

- Simulated proton-proton collisions at 14 TeV using `Pythia3.8` on a 2021 MacBook Pro (M1 Pro, 32 GB RAM)
- The simulation was modified to add a decay channel $(\pi^0 \rightarrow \gamma + \gamma')$ with a branching ratio of 10^{-6}

Data Simulation

- Simulated proton-proton collisions at 14 TeV using `Pythia3.8` on a 2021 MacBook Pro (M1 Pro, 32 GB RAM)
- The simulation was modified to add a decay channel $(\pi^0 \rightarrow \gamma + \gamma')$ with a branching ratio of 10^{-6}
- The dark photon was defined as a stable massless particle that is color neutral, chargeless, and has a spin of 1

Data Simulation

- Simulated proton-proton collisions at 14 TeV using `Pythia3.8` on a 2021 MacBook Pro (M1 Pro, 32 GB RAM)
- The simulation was modified to add a decay channel $(\pi^0 \rightarrow \gamma + \gamma')$ with a branching ratio of 10^{-6}
- The dark photon was defined as a stable massless particle that is color neutral, chargeless, and has a spin of 1
- To gather data from the simulation, the program calculated:
  - the scalar sum of jet transverse momenta (HT) by summing the total visible energy
  - the missing transverse energy (MET) by summing total energy produced by neutrinos and dark photons
  - the razor variable of mass scale (MR)
  - the razor variable (R^2), which quantifies the balance of energy and momentum.
  - boolean flag that checked if a dark photon was produced.

Data Calculations

More in-depth calculations:

MR Formula

$$MR = \sqrt{(E_1 + E_2)^2 - (p_1^z + p_2^z)^2}$$

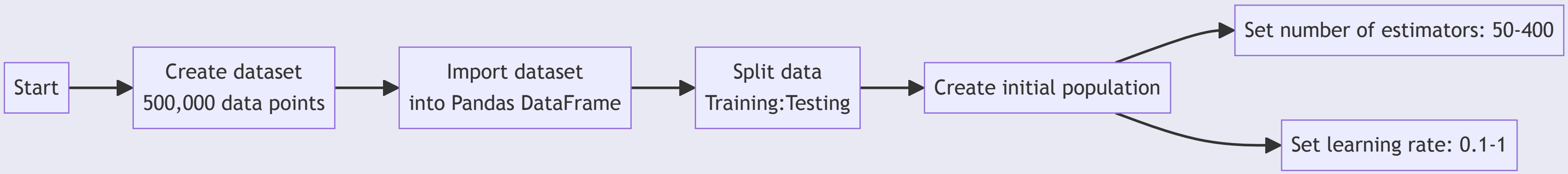
R2 Formula

$$R^2 = \left(\frac{M_T}{MR}\right)^2$$

$$M_T = \sqrt{2|\vec{p}_T^{\,vis}||\vec{MET}|(1 - \cos(\Delta\phi))}$$

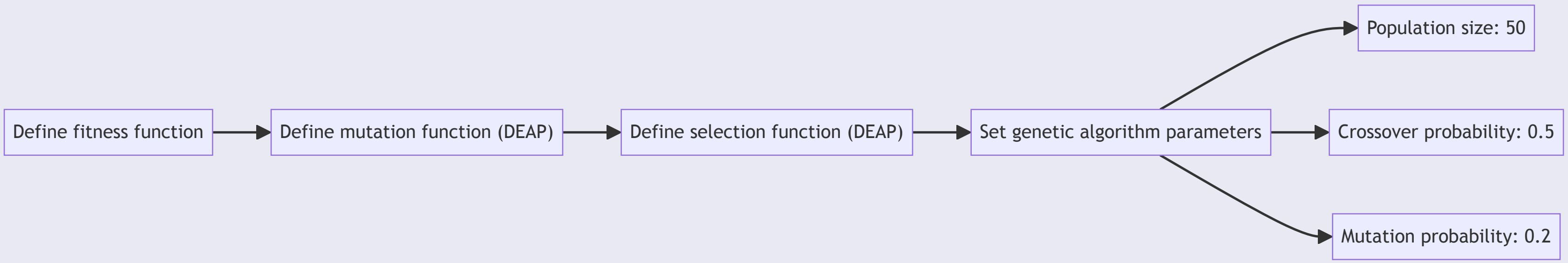
Algorithm, Pt. 1

Initialization



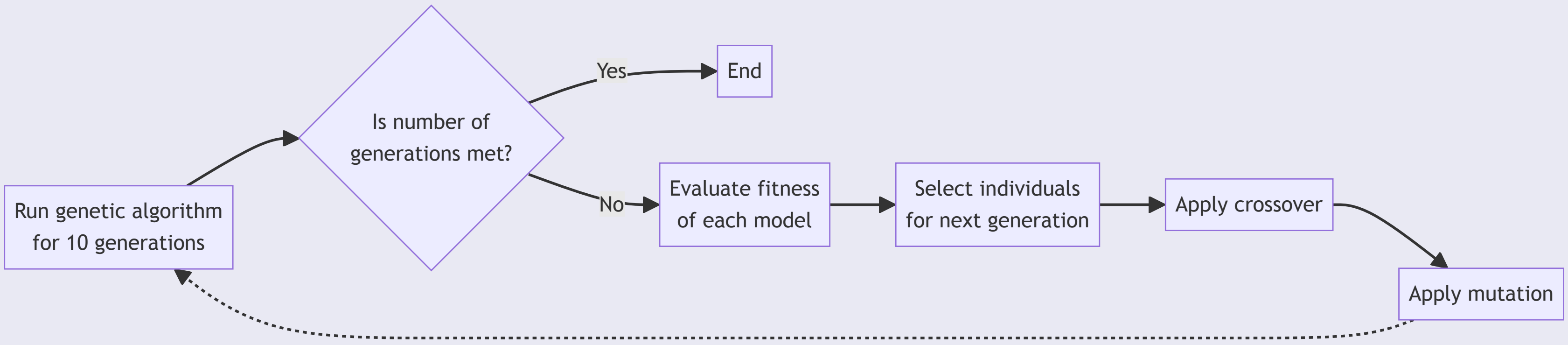
Algorithm, Pt. 2

Genetic Algorithm Creation



Algorithm, Pt. 3

GA Execution



Data Snapshot

- In the data set, only 25 out of 500,000 data points indicated that a dark photon was produced.

Snapshot of Simulation Data

Event Number	HT	MET	MR	R^2	Dark Photon Produced?
352806	94.775	0.000	14000.000	0.000000	False
417824	48.964	0.000	14000.000	0.000000	False
469847	196.721	0.000	14000.000	0.000000	False
407746	118.227	1.069	13983.157	2.585e-06	False
469848	105.605	0.000	14000.000	0.000000	False

Genetic Algorithm Output Data

Genetic Algorithm Data

Generation	Num. Evals	Avg. Fitness	Std. Dev Of Fitness	Min Fitness	Max Fitness
1	33	0.999929	1.91844e-05	0.99988	0.99995
3	27	0.999949	6.00333e-06	0.99992	0.99995
5	28	0.99995	1.11022e-16	0.99995	0.99995
7	34	0.999949	4.58258e-06	0.99992	0.99995
9	28	0.999949	4.58258e-06	0.99992	0.99995
10	40	0.99995	1.4e-06	0.99994	0.99995

Final Model Results

Final Model Results

- After algorithm execution, the algorithm converged on a solution with a fitness of 0.99995.

Final Model Results

- After algorithm execution, the algorithm converged on a solution with a fitness of 0.99995.
- The hyperparameters of the model are:

Final Model Hyperparameters

Number of Estimators	Learning Rate
319	0.1

Final Model Results

- After algorithm execution, the algorithm converged on a solution with a fitness of 0.99995.
- The hyperparameters of the model are:

Final Model Hyperparameters

Number of Estimators	Learning Rate
319	0.1

- Evaluating the model on the testing dataset resulted in an accuracy of 99.995%.

Final Model Results

- After algorithm execution, the algorithm converged on a solution with a fitness of 0.99995.
- The hyperparameters of the model are:

Final Model Hyperparameters

Number of Estimators	Learning Rate
319	0.1

- Evaluating the model on the testing dataset resulted in an accuracy of 99.995%.
- However, the accuracy for instances where a dark photon was produced stood at 80%.

Final Model Results

- After algorithm execution, the algorithm converged on a solution with a fitness of 0.99995.
- The hyperparameters of the model are:

Final Model Hyperparameters

Number of Estimators	Learning Rate
319	0.1

- Evaluating the model on the testing dataset resulted in an accuracy of 99.995%.
- However, the accuracy for instances where a dark photon was produced stood at 80%.
- Model had no false positives.

Conclusions

Conclusions

- The GA was successful in finding a model with a high accuracy, as shown by a model accuracy of 99.995% on the testing dataset.

Conclusions

- The GA was successful in finding a model with a high accuracy, as shown by a model accuracy of 99.995% on the testing dataset.
- However, the accuracy for instances where a dark photon was produced stood at 80%.

Conclusions

- The GA was successful in finding a model with a high accuracy, as shown by a model accuracy of 99.995% on the testing dataset.
- However, the accuracy for instances where a dark photon was produced stood at 80%.
- This dataset had an extreme imbalance, explaining the 80% accuracy on data points where a dark photon was produced in the testing set.

Conclusions

- The GA was successful in finding a model with a high accuracy, as shown by a model accuracy of 99.995% on the testing dataset.
- However, the accuracy for instances where a dark photon was produced stood at 80%.
- This dataset had an extreme imbalance, explaining the 80% accuracy on data points where a dark photon was produced in the testing set.
- This can be countered with using more advanced classification techniques (RL, XGBoost, etc.)

Conclusions

- The GA was successful in finding a model with a high accuracy, as shown by a model accuracy of 99.995% on the testing dataset.
- However, the accuracy for instances where a dark photon was produced stood at 80%.
- This dataset had an extreme imbalance, explaining the 80% accuracy on data points where a dark photon was produced in the testing set.
- This can be countered with using more advanced classification techniques (RL, XGBoost, etc.)
- However, there were no false positives, meaning that this algorithm could be used in beam experiments to find data to support the idea that dark photons are produced in these proton-proton experiments.

Acknowledgements

Acknowledgements

I would like to thank:

- Dr. Richard Oppenheim and Dr. Bruce Cortez (ex-AT&T Research) for their feedback and guidance for this project.
- The University of Chicago and the organizers of the TeVPA conference for giving me an opportunity to share my research.

Questions?

Citations

- Aguilar-Arevalo, A.A.: Search for Dark Matter in the Beam-Dump of a Proton Beam with MiniBooNE. Journal of Physics: Conference Series **912**, 012017 (2017). https://doi.org/10.1088/1742-6596/912/1/012017
- Batley, J., et al.: Search for the dark photon in decays. Physics Letters B **746**, 178–185 (2015). https://doi.org/10.1016/j.physletb.2015.04.068
- Battaglieri, M., et al.: Dark Matter Search in a Beam-Dump EXperiment (BDX) at Jefferson Lab an Update on PR12-16-001 the BDX Collaboration. (2018).
- Berkane, A., Boussahel, M.: Dark Photon as an Extra U(1) Extension to the Standard Model with General Rotation in Kinetic Mixing. (2021).
- Celentano, A., et al.: New Production Channels for Light Dark Matter in Hadronic Showers. Physical Review D **102**(7), 075026 (2020). https://doi.org/10.1103/physrevd.102.075026
- Chatrchyan, S., et al.: Search for Supersymmetry with Razor Variables In PP Collisions Ats=7 TeV. Physical Review D **90**(11), 112001 (2014). https://doi.org/10.1103/physrevd.90.112001
- Cushman, P., et al.: Snowmass CF1 Summary: WIMP Dark Matter Direct Detection. (2013). https://doi.org/10.48550/arxiv.1310.8327
- De Napoli, M.: Production and Detection of Light Dark Matter at Jefferson Lab: The BDX Experiment. Universe **5**(5), 120 (2019). https://doi.org/10.3390/universe5050120
- Deb, K.: Genetic Algorithm in Search and Optimization: The Technique and Applications. (1998). http://repository.ias.ac.in/82743/
- Dutra, M., et al.: MeV Dark Matter Complementarity and the Dark Photon Portal. Journal of Cosmology and Astroparticle Physics **2018**(03), 037–037 (2018). https://doi.org/10.1088/1475-7516/2018/03/037
- Fabbrichesi, M., et al.: The Dark Photon. (2020).
- Leung, Y., et al.: Degree of Population Diversity - a Perspective on Premature Convergence in Genetic Algorithms and Its Markov Chain Analysis. IEEE Transactions on Neural Networks **8**(5), 1165–1176 (1997). https://doi.org/10.1109/72.623217
- Novaes, S.: Standard Model: An Introduction. (2000). https://arxiv.org/pdf/hep-ph/0001283v1.pdf
- Tong, D.: Gauge Theory.