Searching for Dark Photon Production Using Genetic Algorithms

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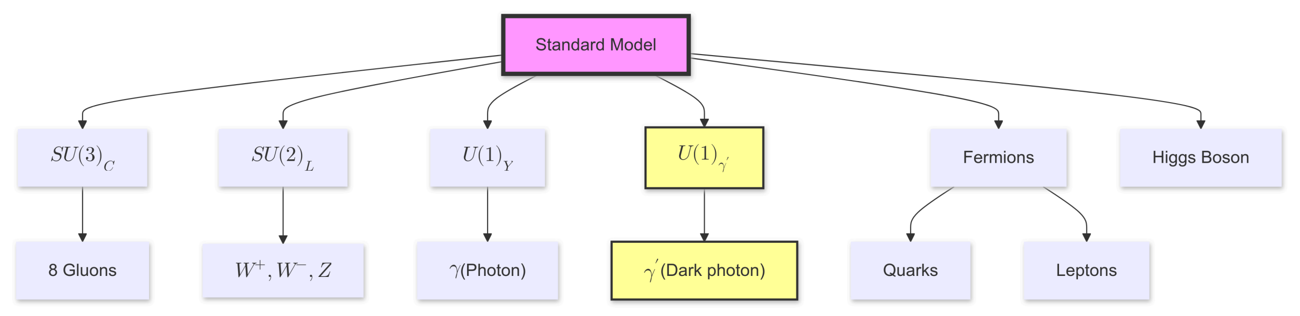
- The dark photon is a force carrier for the dark sector, similar to the photon
- New particle can be introduced to the standard model by extending SM gauge group with new $U(1)$ gauge symmetry
- The dark photon interacts with the SM photon via kinetic mixing.

Extended Standard Model



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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

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

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

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Field Redefinition

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

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

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

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Substitution

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

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

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

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- The dark photon would contribute to missing energy signatures in experiments.

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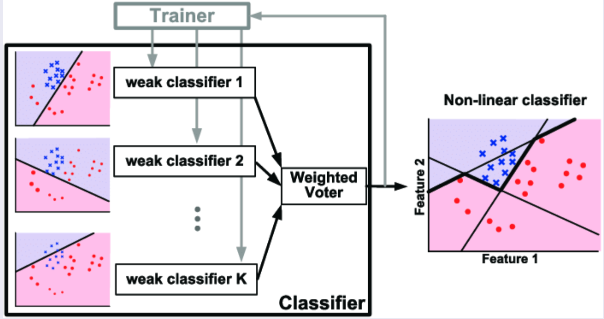
- Due to the nature of dark photon production, the resulting dataset will be imbalanced, with a majority of interaction not producing a dark photon.
- This imbalance can be accounted for with an AdaBoost model.

AdaBoost Diagram



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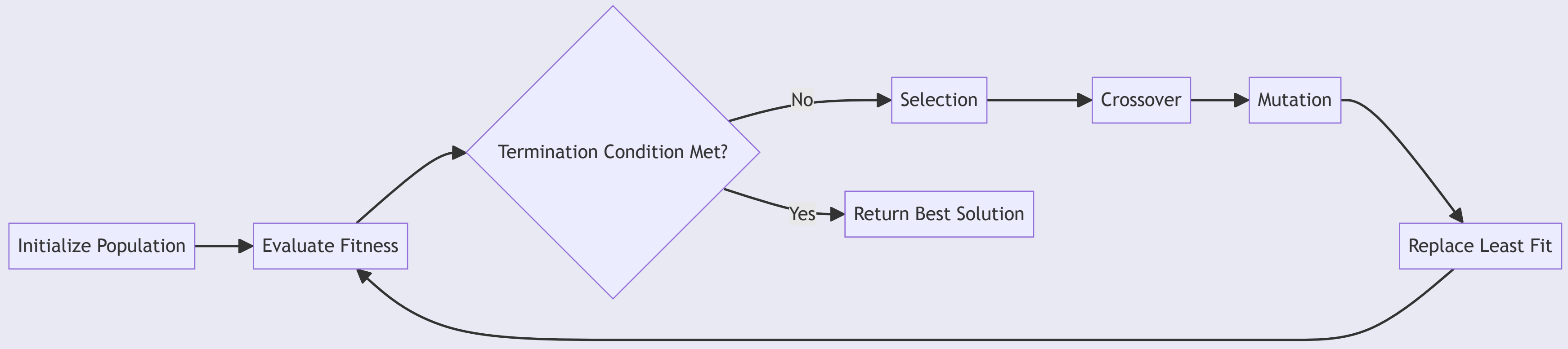
- Tuning the hyperparameters manually can take a lot of time to approach an optimal solution.
- An optimal solution to this problem can be reached with a genetic algorithm.

Genetic Algorithm Flowchart



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- The simulation was modified to add a decay channel $(\pi^0 \to \gamma + \gamma')$ 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

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

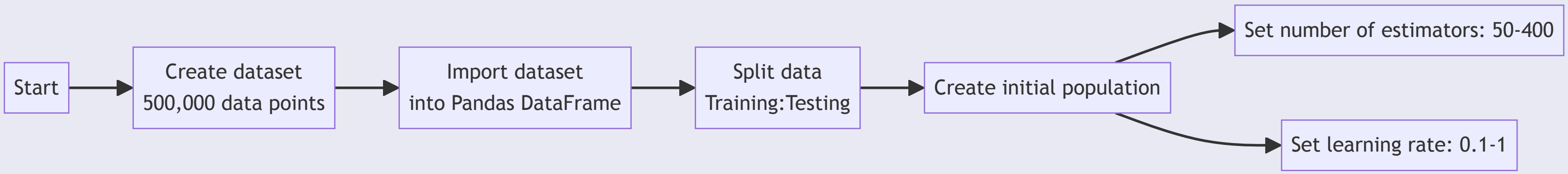
R2 Formula

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

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

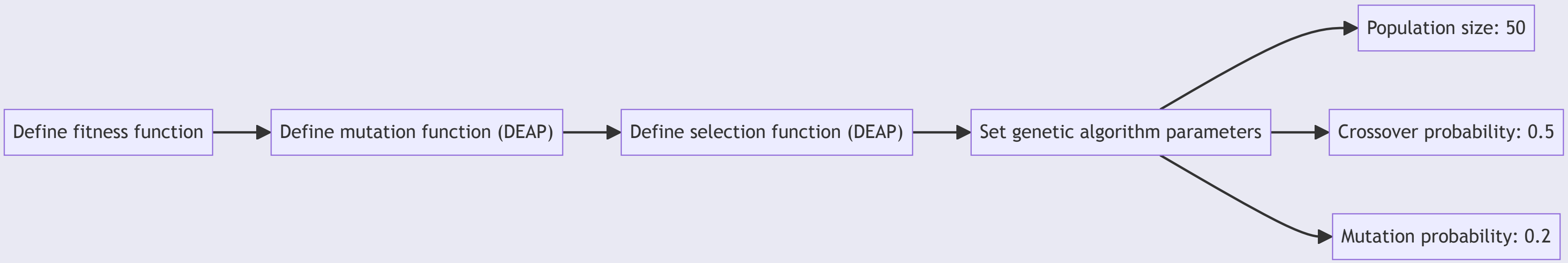
Algorithm, Pt. 1

Initialization



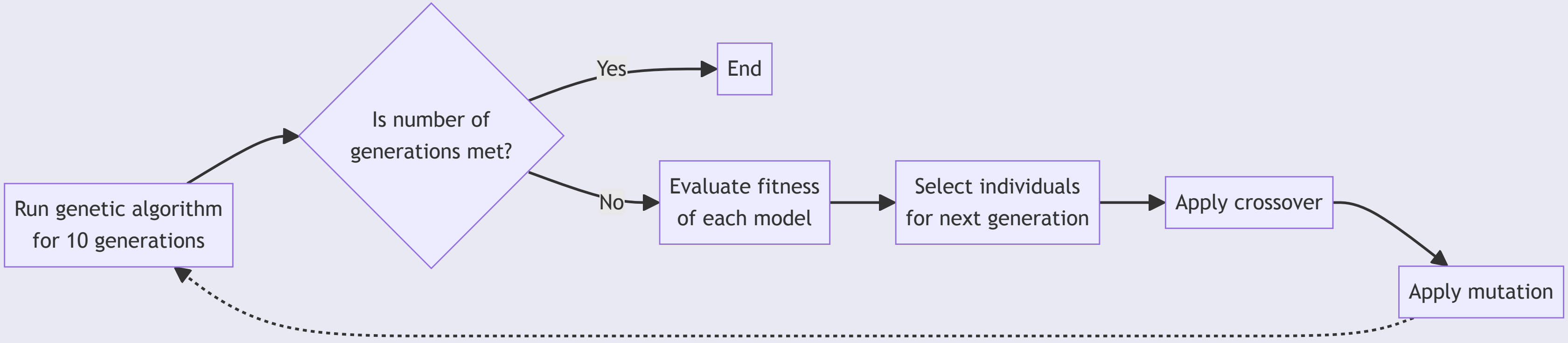
Algorithm, Pt. 2

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

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- 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.

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Questions?

Citations

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