SHiP

Search for Hidden Particles

Identifying Hidden Particles with Machine Learning at SHiP

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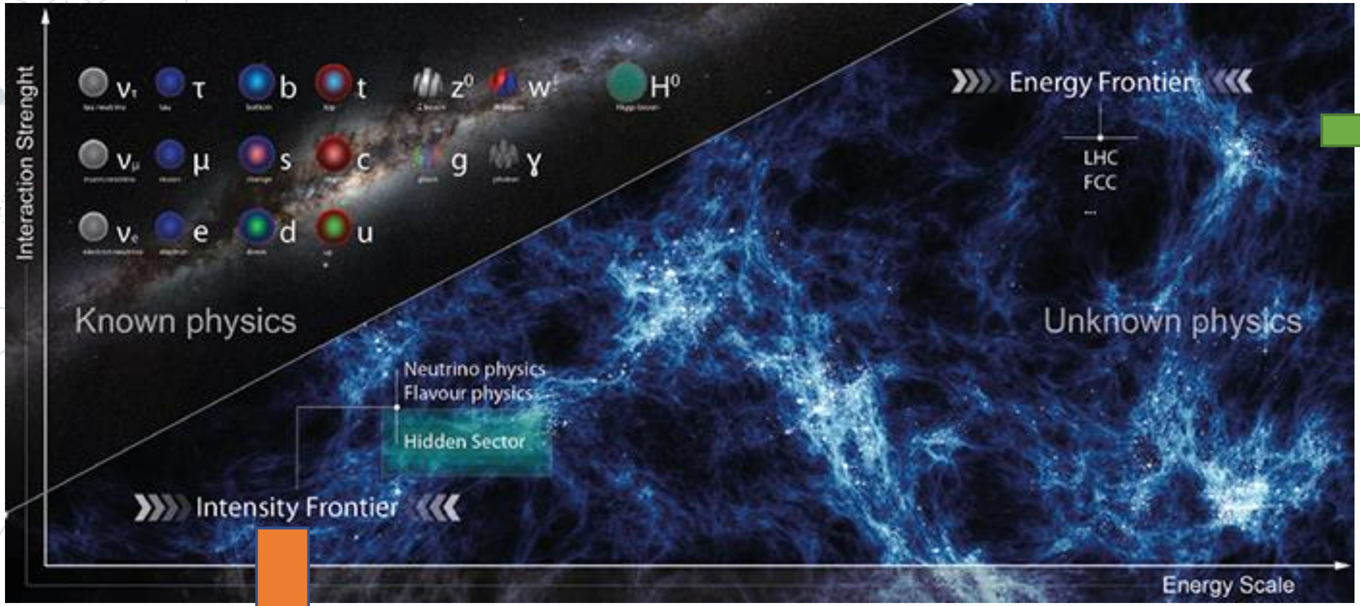
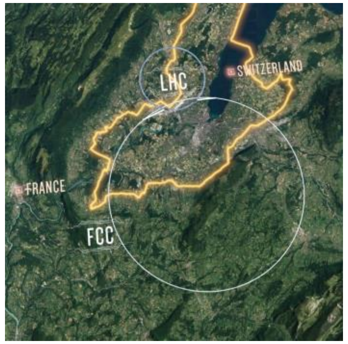
LIP Summer 2021

Why?





- Heavier particles require greater energies
- Improve Experiments
- Build New Ones
- (not so soon ☹)

SHiP

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Search for Hidden Particles

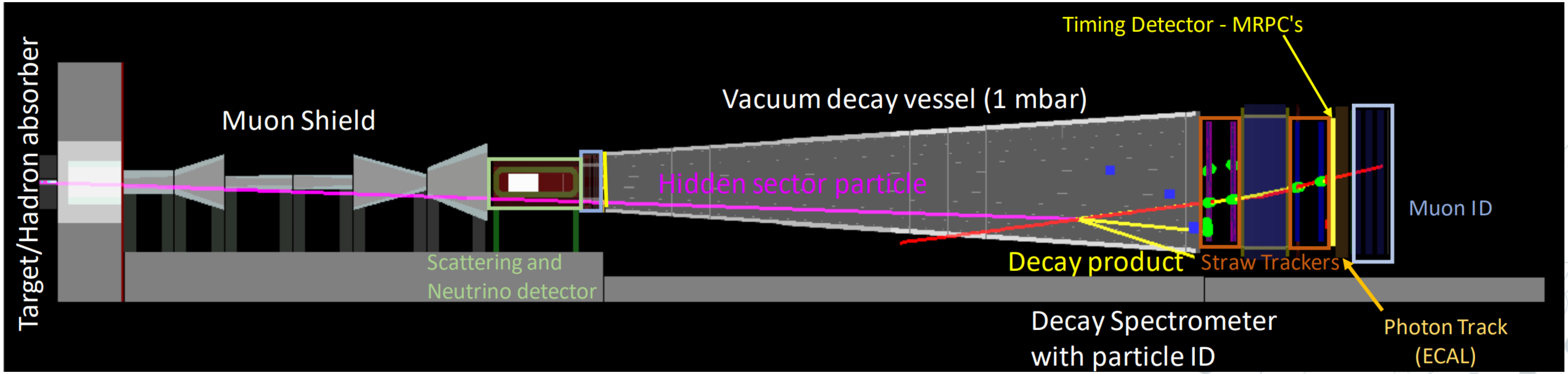
- Very weak interactions (weak couplings)
- Very rare events
- Greater collisions intensity -> (more data)
- (we can do it ☺)

The experiment

Experiment details :

- 400 GeV/c protons
- 2×10^{20} p.o.t.
- 5 years running
- Discoveries through $>$ 2 decays
- Couplings $O(10^{-10})$
- Masses $< \mathcal{O}(10)\mathrm{GeV/c^2}$

- Shielding reduces background noise
- Straw trackers track particles paths
- Masses, momentums and other properties can be indirectly measured
- Timing Detectors with LIP technology

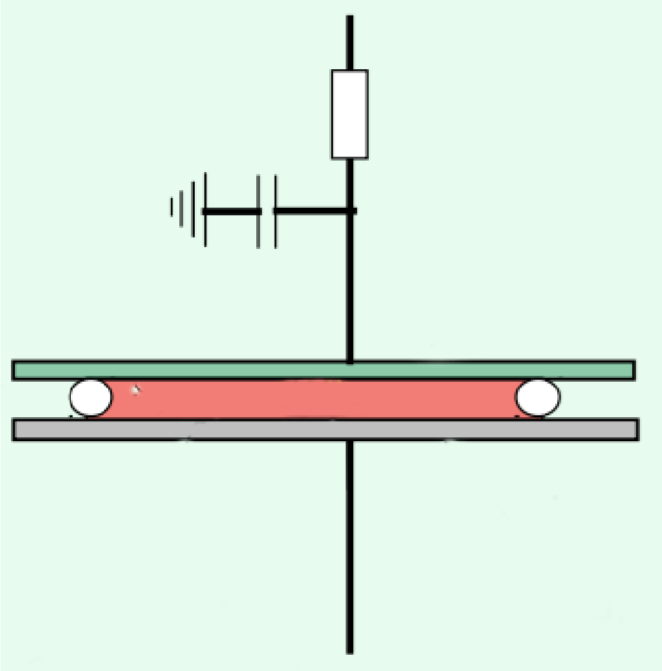


LIP’s Timing Detector (TD) based on MRPC’s

full size TD implementation prototype(1.8 m^2)

- Composed by 2 6-gap RPC’s
- The field test results yielded:
  - ✓ Great Efficiency: over 95%
  - ✓ Good time precision: under 100 ps

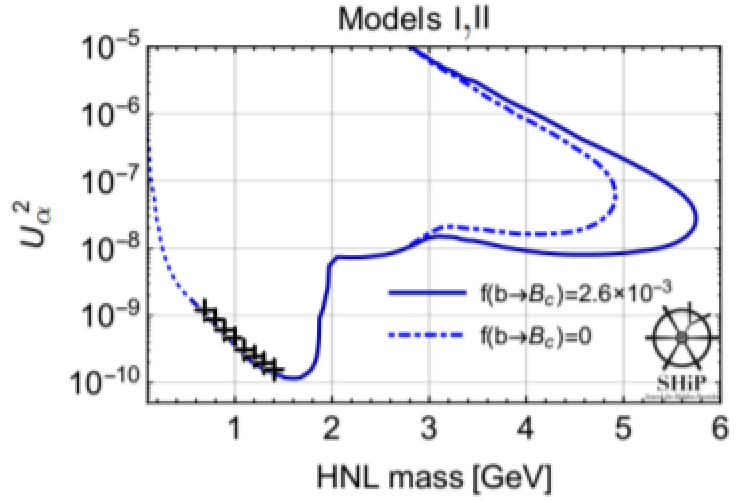
Schematic Representation of an RPC

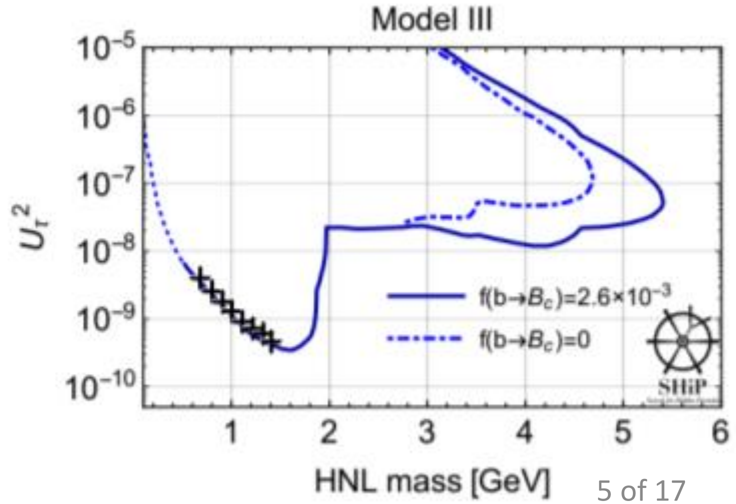


Heavy Neutral Leptons

- Hypothetical massive neutrino-like particles
- Do not couple to any Standard Model forces
- Could explain Baryon Asymmetry, neutrino mass and oscillation.
- Also a candidate for Dark Matter

Parameter spaces of the different HNL models

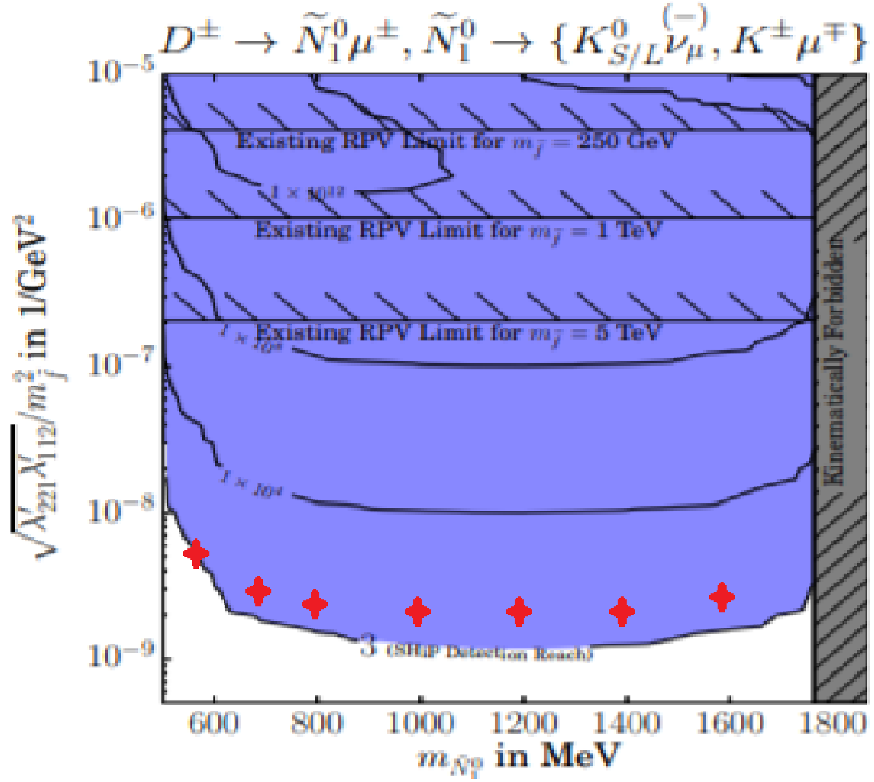




Neutralinos

- Proposed electrically neutral sfermion of the Minimal Supersymmetric Standard Model, superpartner to the Standard Model neutrino
- Truly neutral particle
- One of the candidates for Dark Matter

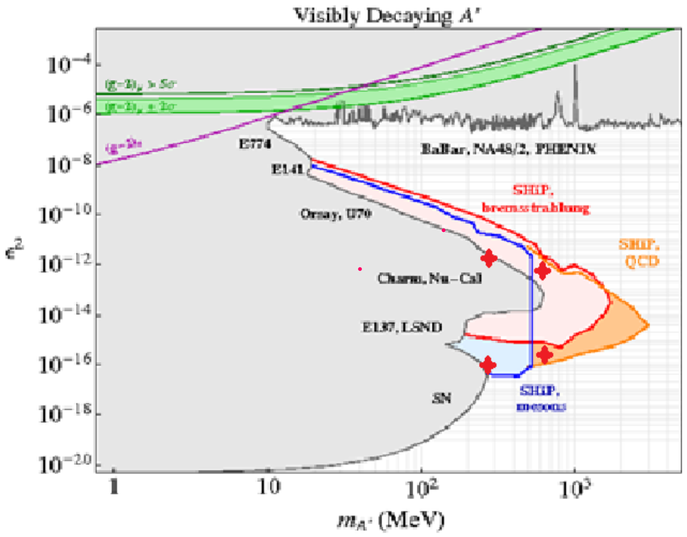
Parameter space of Neutralinos



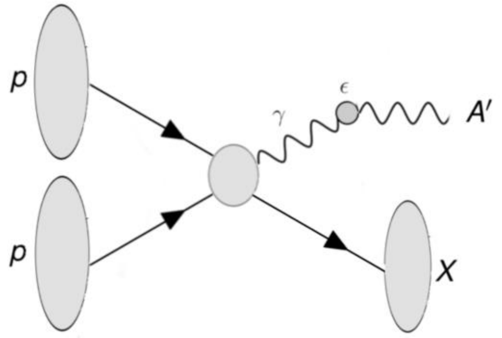
Dark Photon

- Hypothetical hidden sector particle
- Theorized to be a new gauge boson that would be a force carrier analogous to the SM photon but enabling interactions between dark matter particles
- Decay into (e+ e −),(μ +μ −) ,(τ + τ −) and other particles.
- Simplest model characterized by its mass and kinetic mixing parameter (effective coupling) with the regular photon

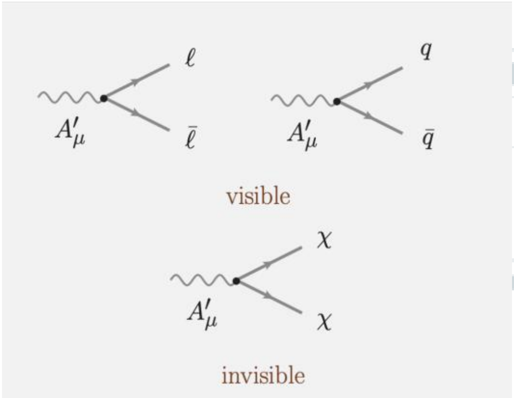
Parameter Space



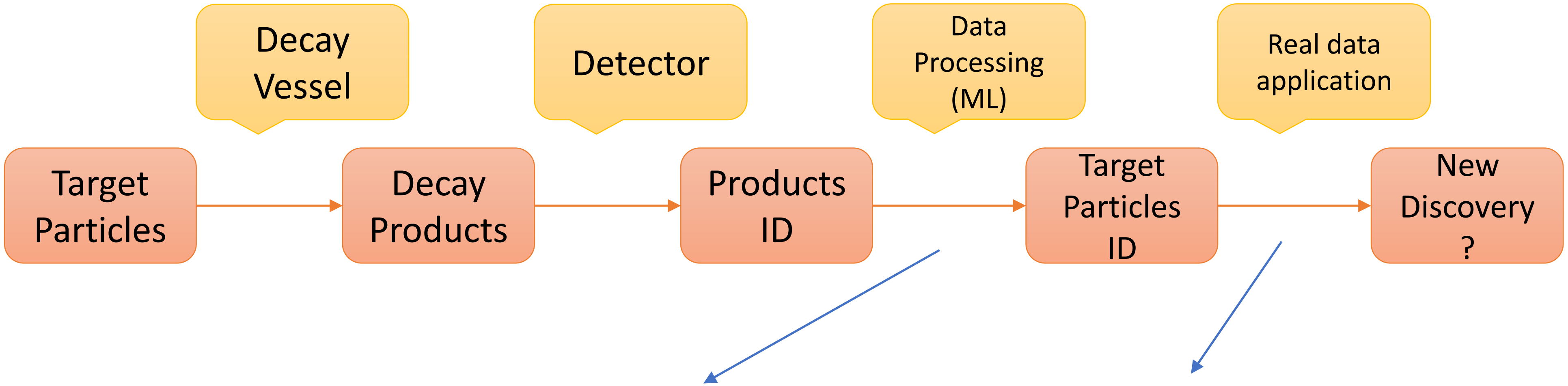
Production



Decay



Our Work



Where we come along

If we do a good job and nature is *cool* to us

- Good models
- Good selection efficiency
- Well trained neural networks

Why Machine Learning?

- At the time of this presentation, the SHiP experiment is not yet fully built
- Data can be simulated using MonteCarlo methods and the FairShip framework (based on FairRoot)
- Neural Networks can be trained for use in real data.
- The use of machine learning can aid in finding complex patterns in the data when a large number of features are involved

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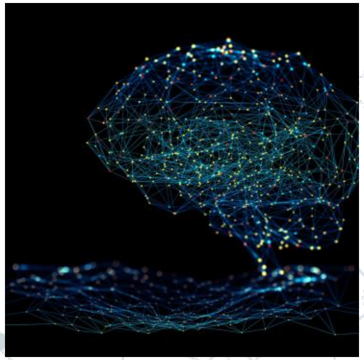
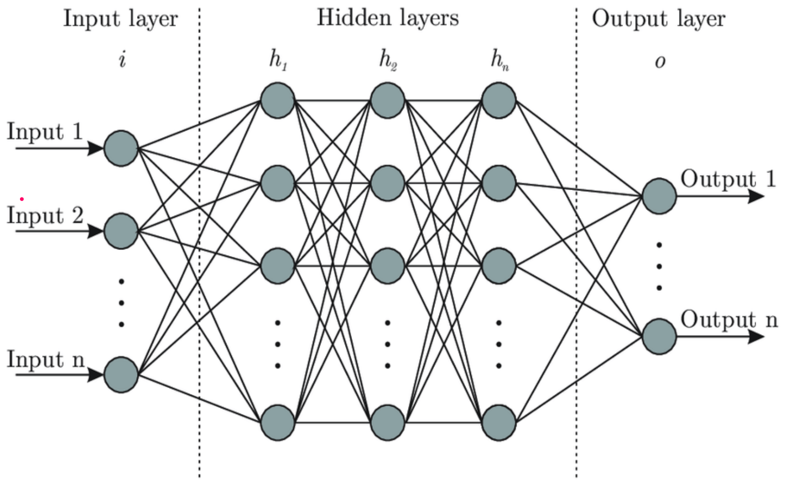


Decay into $\mu^{\pm}\mu^{\mp}$ pairs

One part of our work was to classify DP, HNL and Neutralinos based on their decay to $\boldsymbol{\mu}^{\pm}\boldsymbol{\mu}^{\mp}$.
Specific datasets of this decay were generated and given to us for classification.

Particle	Decay
DP	$\mu^+\mu^-$
HNL	$\nu_\mu\mu^+\mu^-$
Neutralinos	$\mu^-K^0 \rightarrow \mu^-\mu^+\nu_\mu$

Datasets
$\mu^{\pm}\mu^{\mp}$



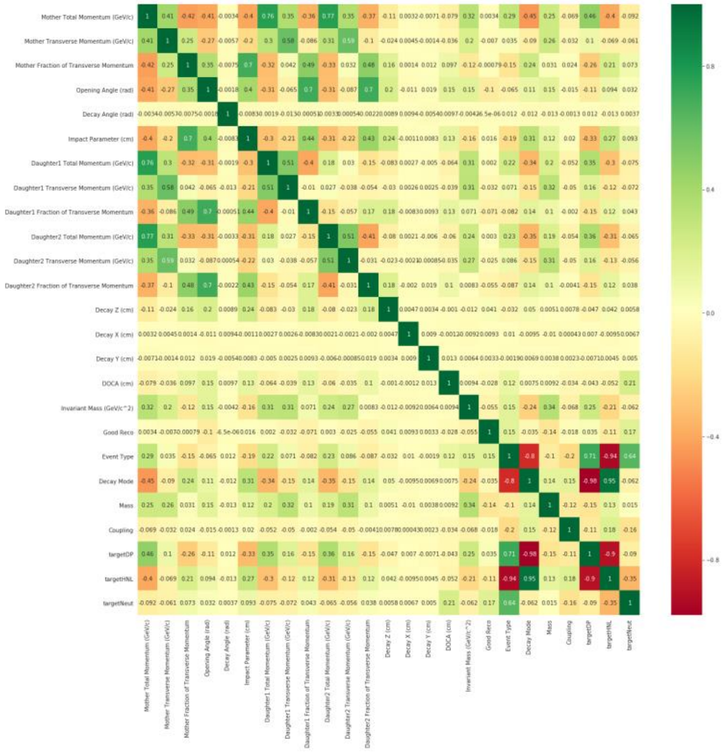
- DP
- HNL
- Neutralino

Feature Selection

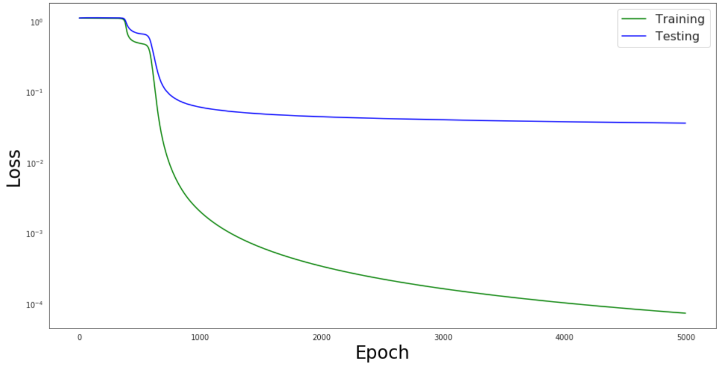
- For the multivariate analysis, a set of features are used to train the neural network and for the classification.
- Choosing the right features can make the diference between a good and bad model. Features serve as inputs for the network to learn and classify datasets.
- Redundant features slow down the whole process as well as worsen the model and promote overfitting.

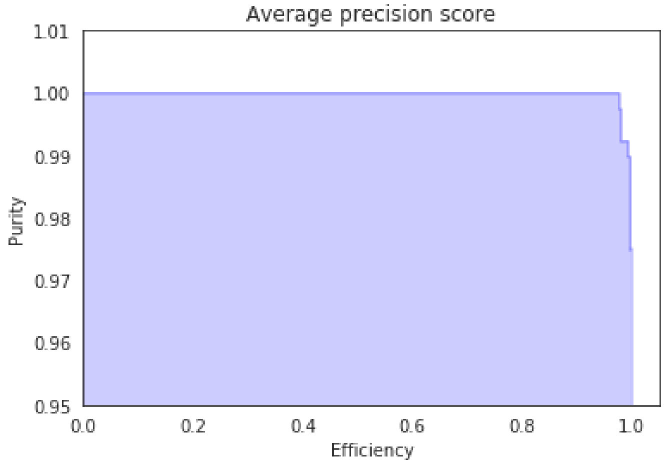
- Mother Total Momentum
- Mother Transverse Momentum
- Mother Fraction of Transverse Momentum
- Opening Angle
- Decay Angle
- Impact Parameter
- Daughter 1 Total Momentum
- Daughter 1 Transverse Momentum
- Daughter 1 Fraction of Transverse Momentum
- Daughter 2 Total Momentum
- Daughter 2 Transverse Momentum
- Daughter 2 Fraction of Transverse Momentum
- Decay X
- Decay Y
- Decay Z
- DOCA
- Invariant Mass

All Features Provided

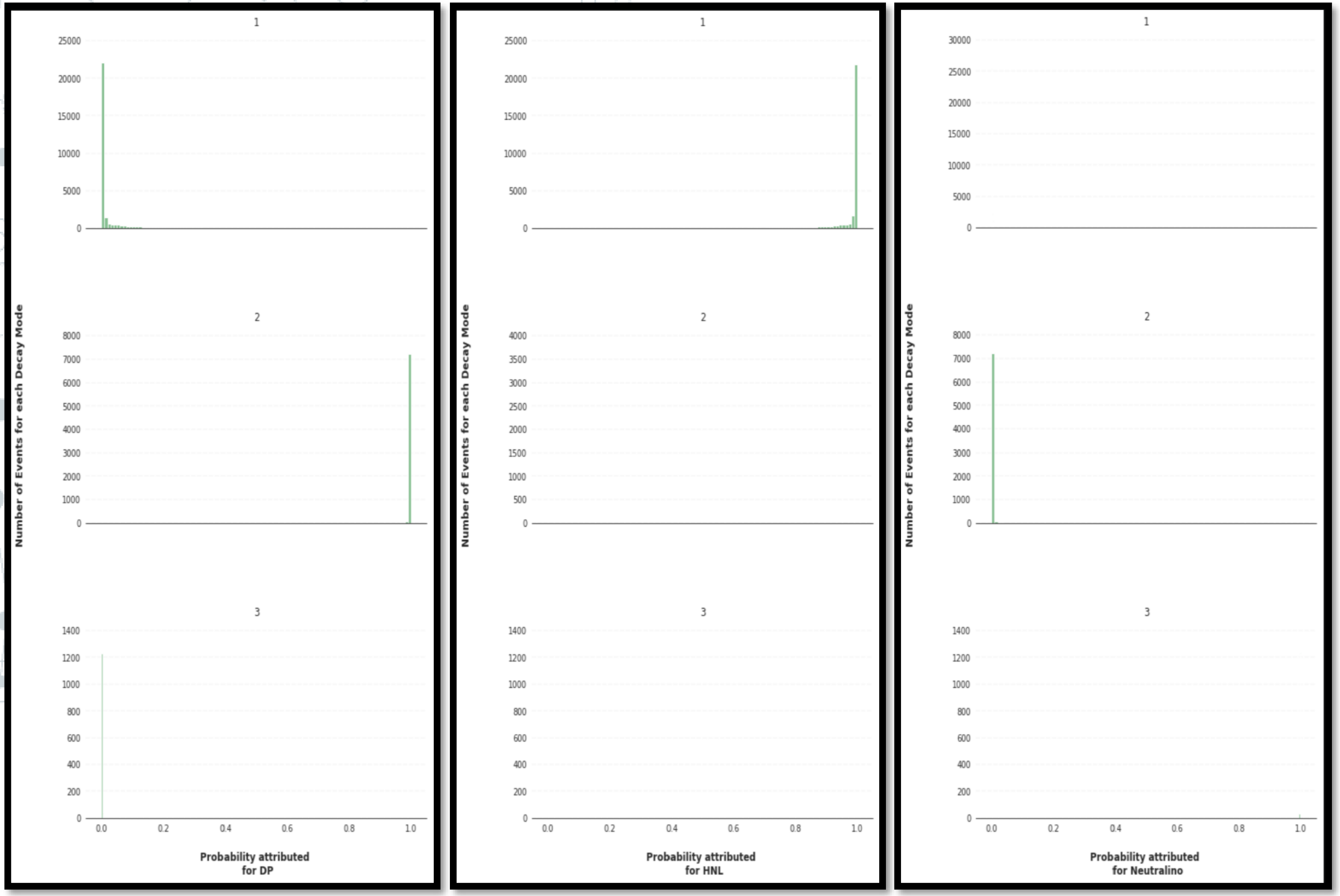


Feature Correlation Matrix with Heatmap





Results



- Some road bumps were found along the way:
  - How to prevent overfitting?
  - Feature selection -> which features are better for training?
  - Neutralino's dataset was way smaller than the others -> their weight in training was not being enough to yield good classification.

Particle	Positives	True Positives	Model Sensitivity
Dark Photon	7545	7318	0.99959
HNL	28756	28756	0.99217
Neutralino	1298	1295	1.00000

Key: 1-HNL; 2-DP; 3-Neutralino

The mother particle candidates for detected $\pi^{\pm}\mu^{\mp}$ pairs

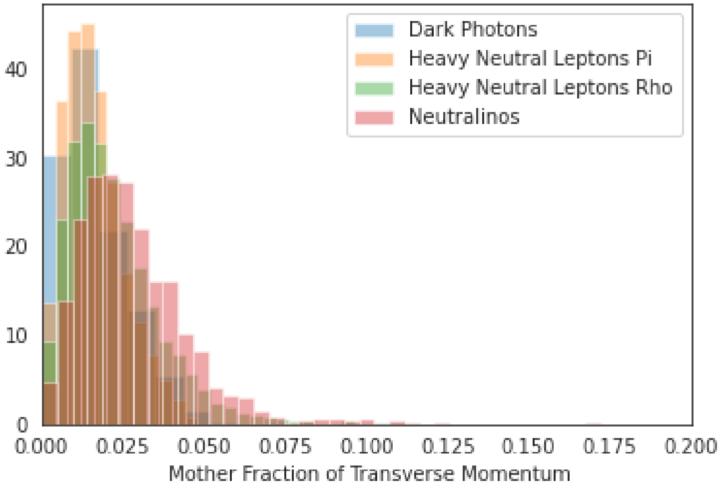
In-code labeling	Particle Type	Decay mode and subsequent decays
0	Neutralino	$K^0\nu_\mu \rightarrow \pi^{\pm}\pi^{\mp}$ (detected as $\pi^{\pm}\mu^{\mp}$)
1	Dark Photon	Decay to Hadrons ($\pi^{\pm}\pi^{\mp}$ samples detected as $\pi^{\pm}\mu^{\mp}$)
2	Heavy Neutral Lepton	$\pi^{\pm}\mu^{\mp}$
3	Heavy Neutral Lepton	$\rho^{\pm}\mu^{\mp} \rightarrow \pi^0\pi^{\pm}\mu^{\mp}$

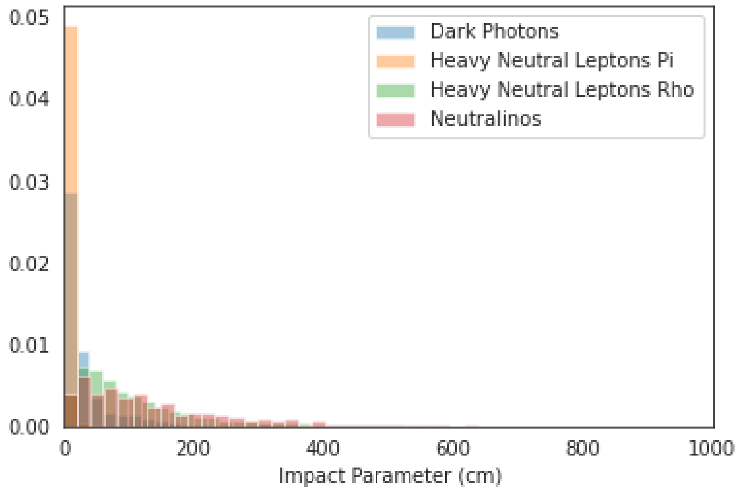
Features and Feature Selection

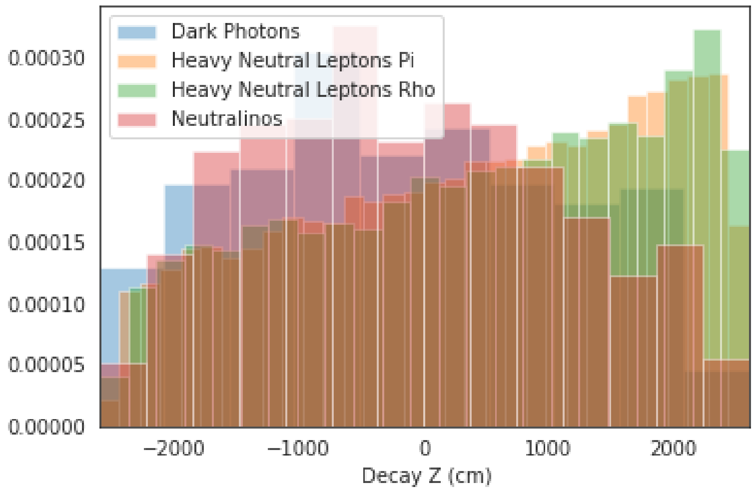
- Mother Total Momentum
- DOCA
- Daughter 1 Total Momentum
- Daughter 2 Total Momentum

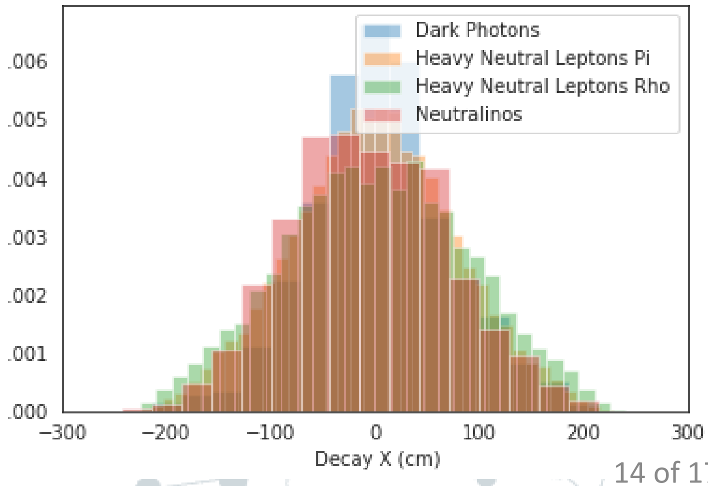
- Mother Transverse Momentum
- Decay Z
- Daughter 1 Transverse Momentum
- Daughter 2 Transverse Momentum

- Mother Fraction of Transverse Momentum
- Impact Parameter
- Daughter 1 Fraction of Transverse Momentum
- Daughter 2 Fraction of Transverse Momentum

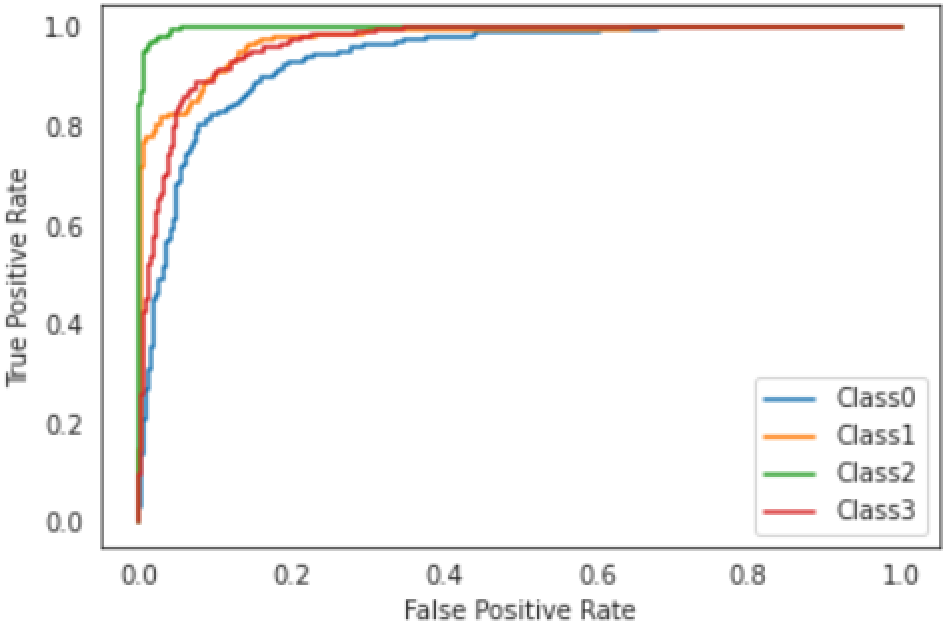








Merit Figures



Roc curves for the decay modes presented

Decay Mode	Area under dev ROC curve	Area under val ROC curve	Model Sensitivity (TP/Events)
(0) Neut	0.9552	0.9254	0.7414
(1) DP	0.9736	0.9668	0.7946
(2) $HNL\ (\pi^{\pm}\mu^{\mp})$	0.9997	0.9967	0.9519
(3) $HNL\ (\rho^{\pm}\mu^{\mp})$	0.9747	0.9529	0.8254

Final Remarks for the $\boldsymbol{\pi^{\pm}\mu^{\mp}}$ analysis

- There were no signs of overfitting in the selected model, with similar efficiencies for both development and validation samples
- The differences in sensitivity displayed for different decay modes were in accordance with predictions, particularly the standout success of the $\pi^{\pm}\mu^{\mp}$ mode for HNLs (decay mode 2).

Final Project Remarks

- Both of the models presented achieved the desired merit figures and would be fit for use in the discovery of real particles .
- Even though the models employed different methods for selecting the features, the same ones prevailed in both , making the selection more trustworthy.

Final Questions?