Exploring the Hidden Sector of Particle Physics

Search for Dark Photons and Neutralinos

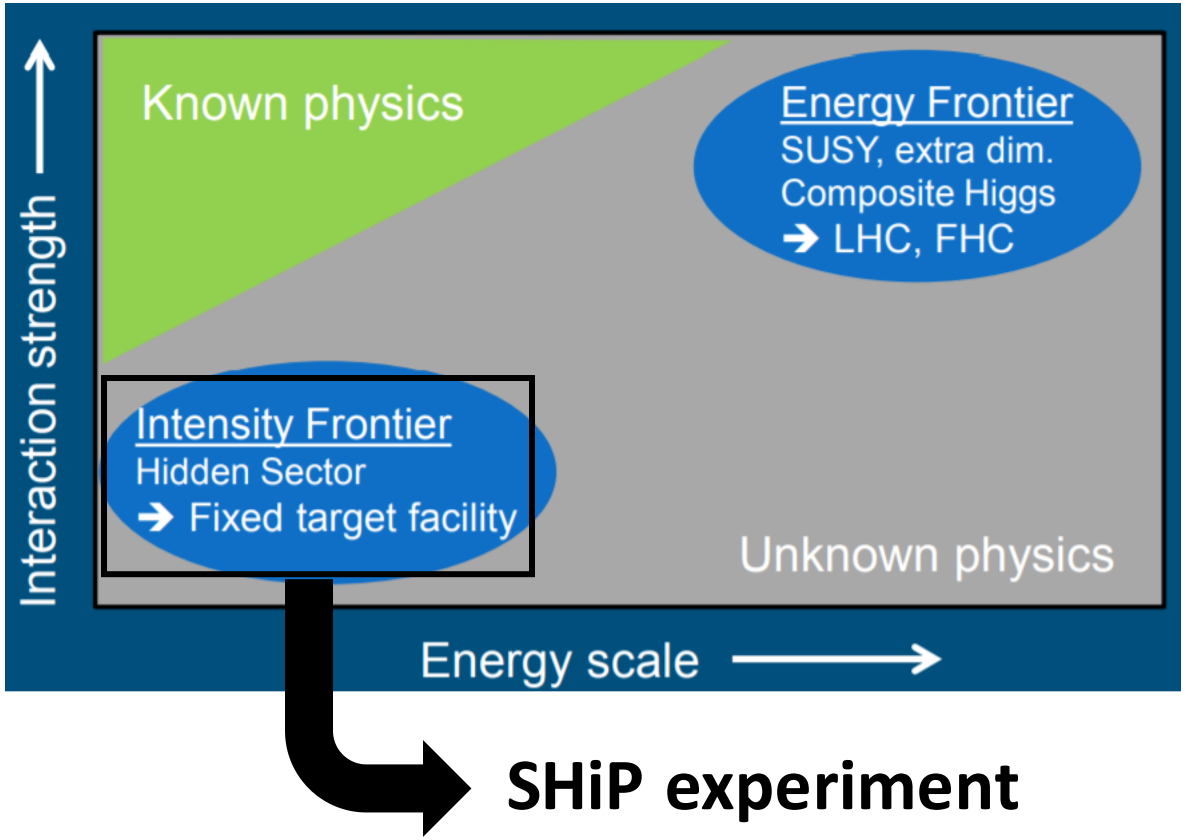
Speakers:

Francisco Safara, Raul Santos

Supervisors:

Nuno Leonardo, Guilherme Soares

Beyond the Standard Model



SHiP experiment

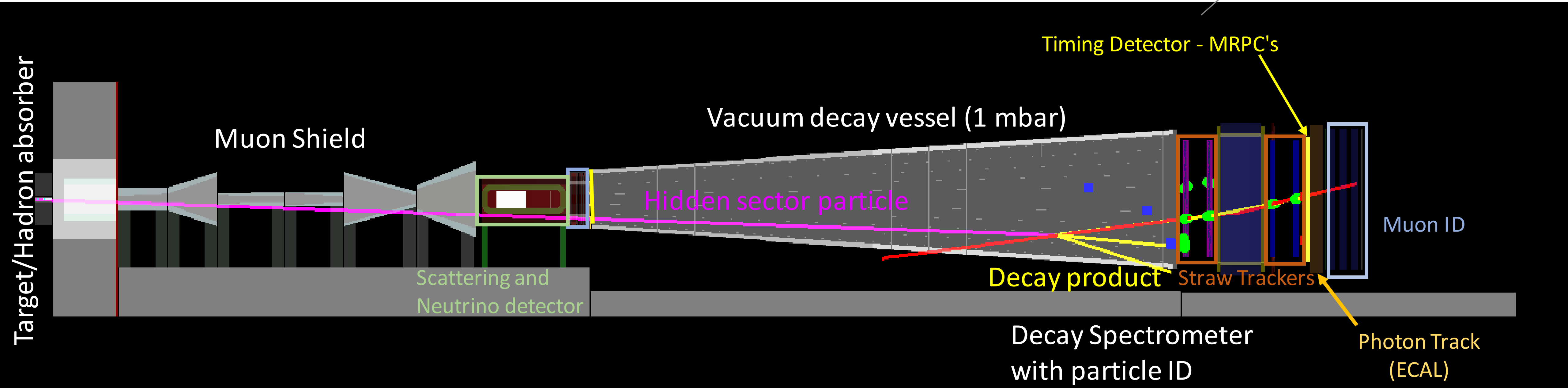
The SM has provided a consistent description of Nature's fundamental constituents and interactions. However, it fails to explain a number of observed phenomena in particle physics, astrophysics and cosmology.

SHiP - Search for Hidden Particles

SHiP is a Intensity Frontier experiment that is aimed at searching for
feebly interacting particles(FIPs) including Heavy Neutral Leptons (HNL), Dark Photons (DP) and Neutralinos.

SHiP Experiment

Developed by



High energy protons, from the SPS accelerator, hit the target and generate a stream of hadrons, which in turn can decay to the hidden sector particles

The hidden sector particles decay in the decay vessel, and their products are detected, reconstructed and analysed

Objective

- Simulate hidden particles(**Dark Photons** and **Neutralinos**) and study their kinematic properties.

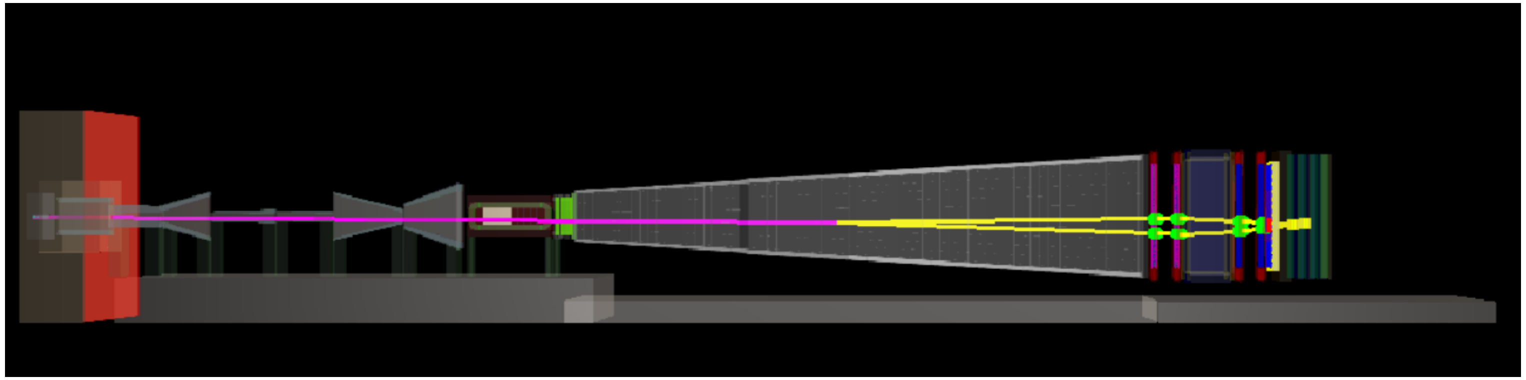
Problem? → HS particles are very rare. Their signature may be mimicked by neutrino interactions

- Use advanced techniques (ML) to distinguish between:
  - Signal: Dark Photons(DP) and Neutralinos
  - Background: neutrinos(DIS)
- Use these ML models to obtain a Signal efficiency as high as possible with virtually 0 background.

How do we simulate them?

Using the SHiP software framework (FairShip):

- Particle production is simulated using MC generators(Pythia8 for hidden particles and Genie for background) and propagation and their interaction with the detectors is achieved with Geant4.
- Using analysis software we reconstruct the particles and extract their kinematic properties.



Display of an event from our signal simulation

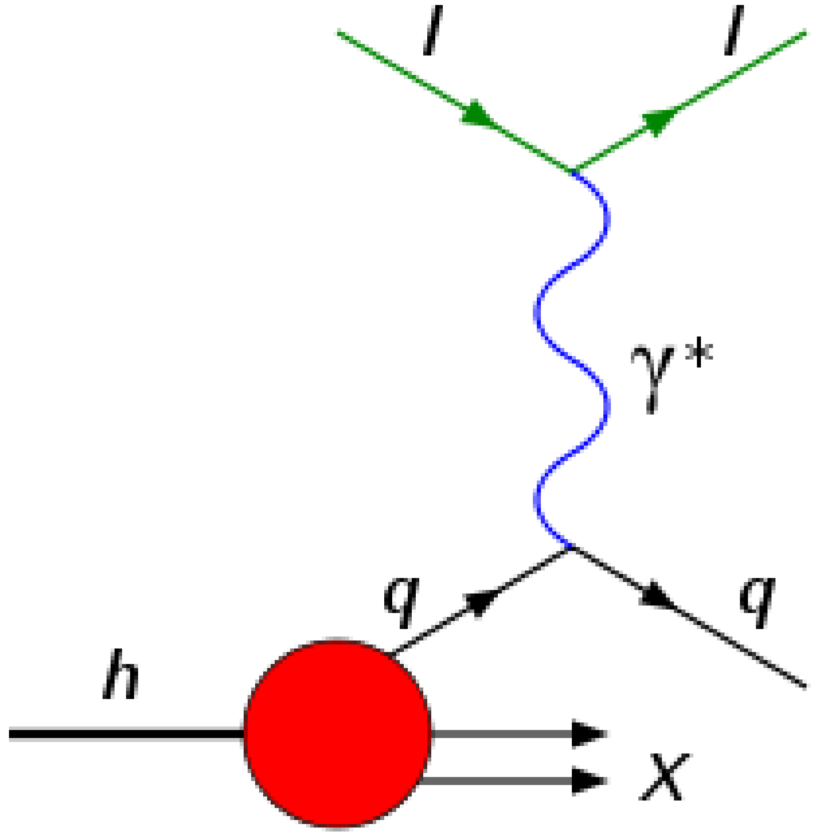
Neutrino Deep Inelastic Scattering (DIS) background

DIS is a process in which leptons (in this case, neutrinos) scatter off hadrons (from the low pressure air on the decay vessel).

Due to the high energies, the hadron is shattered and it emits many new particles.

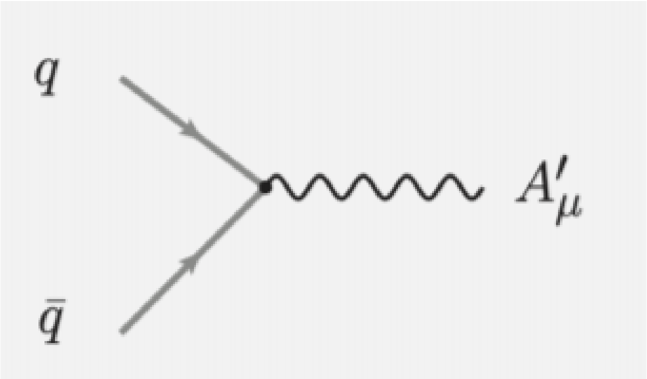
These new particles can be mistaken as decay products of the hidden sector particles.

1 million DIS events of electron neutrino (**ν_e**), muon neutrino (**ν_μ**) and corresponding anti-neutrinos are simulated (4 million total).

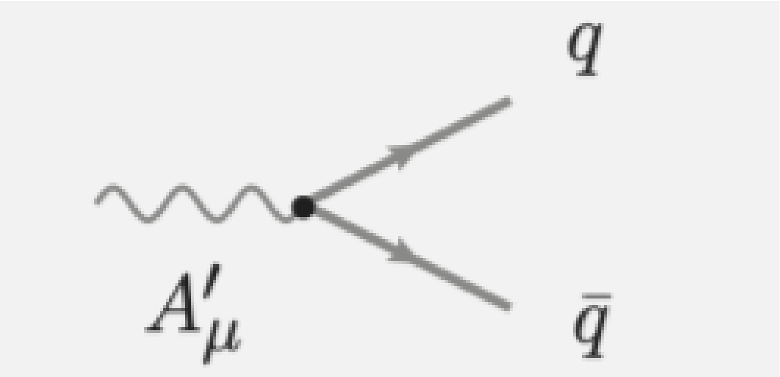


Dark Photons

Production Modes



Decay mode



- The dark photon(DP) is a hypothetical hidden sector particle, proposed as a force carrier similar to the photon of electromagnetism but potentially connected to dark matter.

mass of the dark photon

dark photon

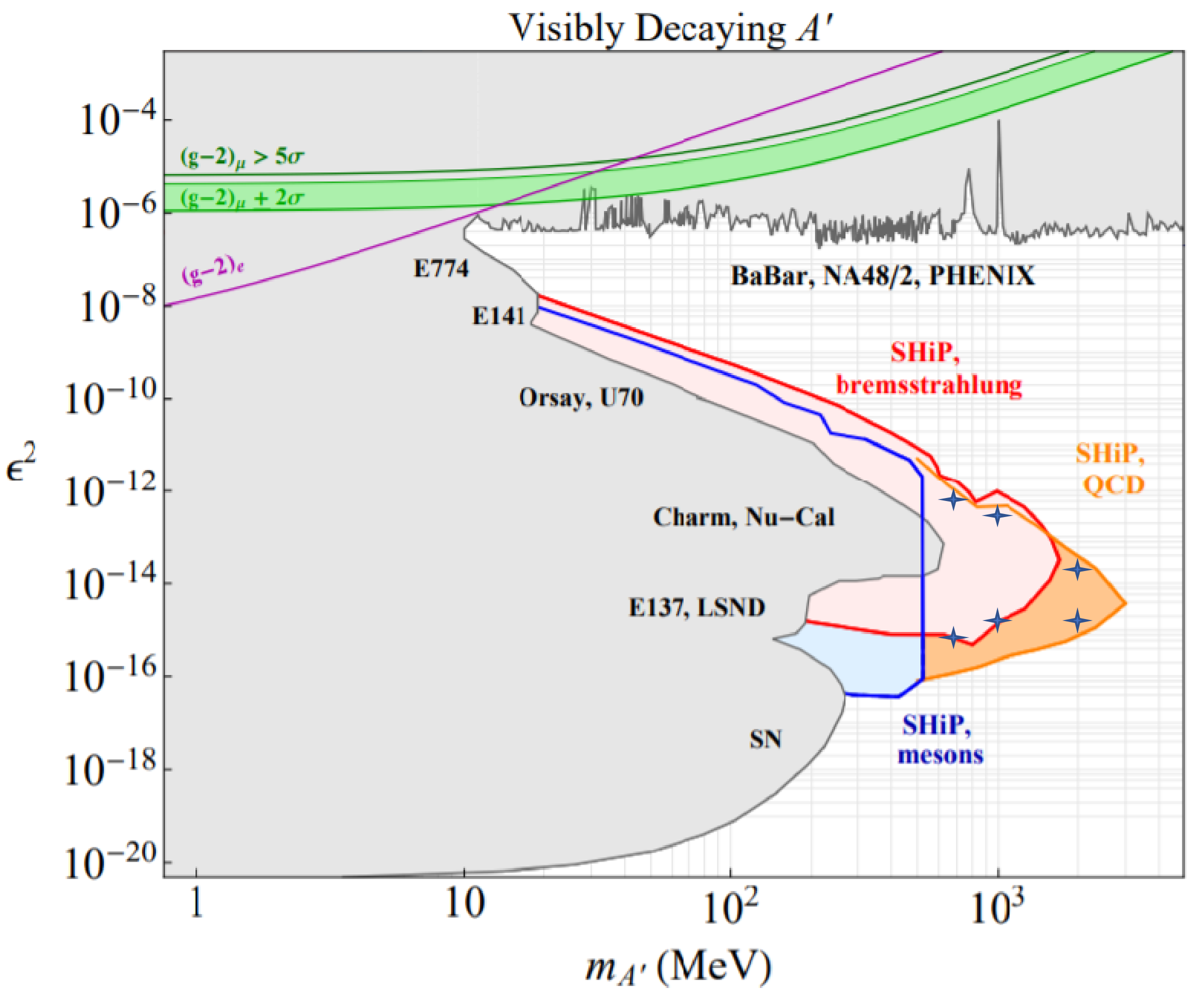
$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} + \epsilon e A'^{\mu}J^{EM}_{\mu}$$

field strength tensor

effective coupling

electromagnetic current

On the frontier of the unknown...



In this project we studied phase space in the limit of the current sensitivity.

Possible DP decays:

- e- e+
- mu- mu+
- tau- tau+
- hadrons → What I studied

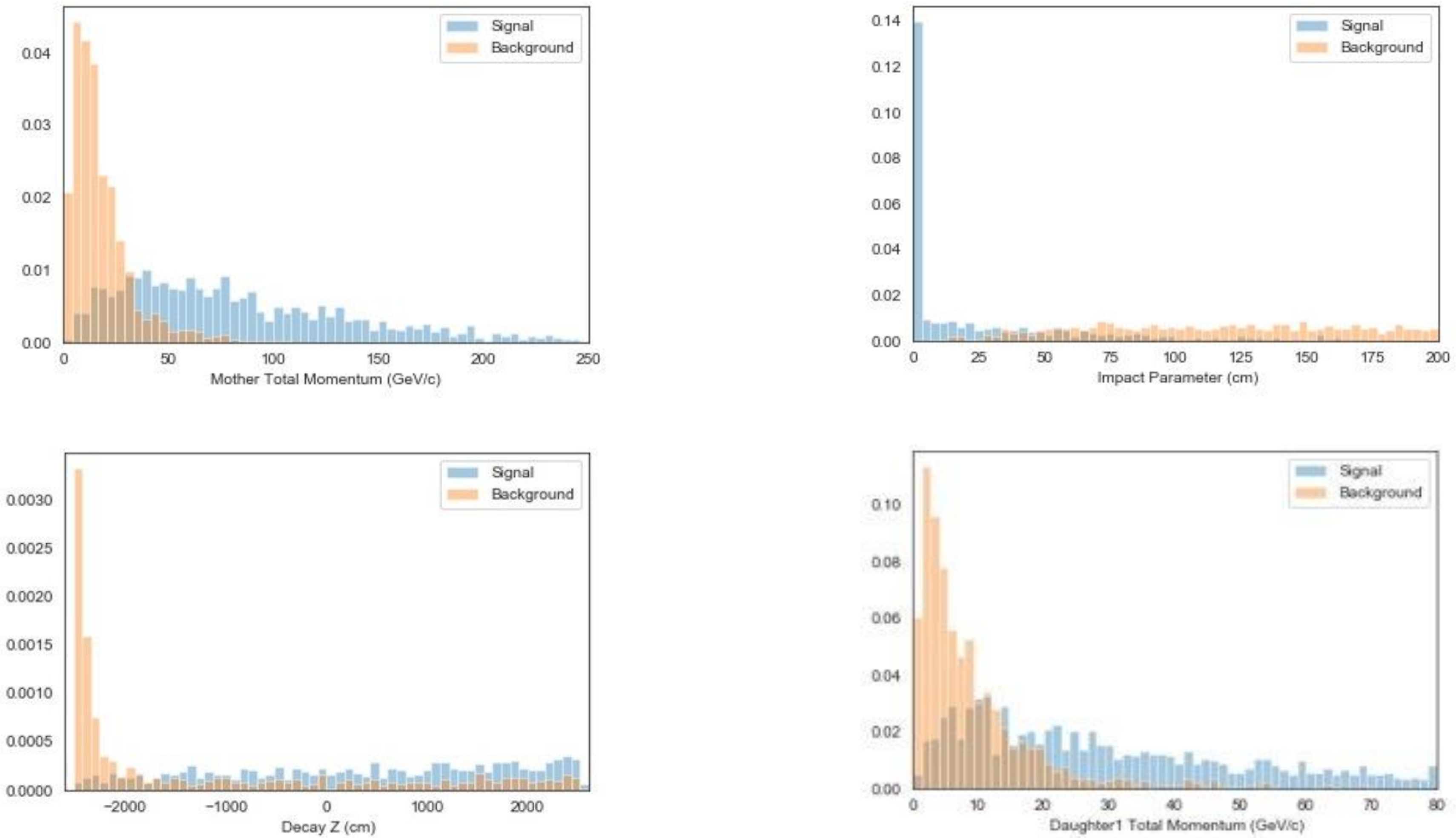
I simulated **4000** events for each point in phase space

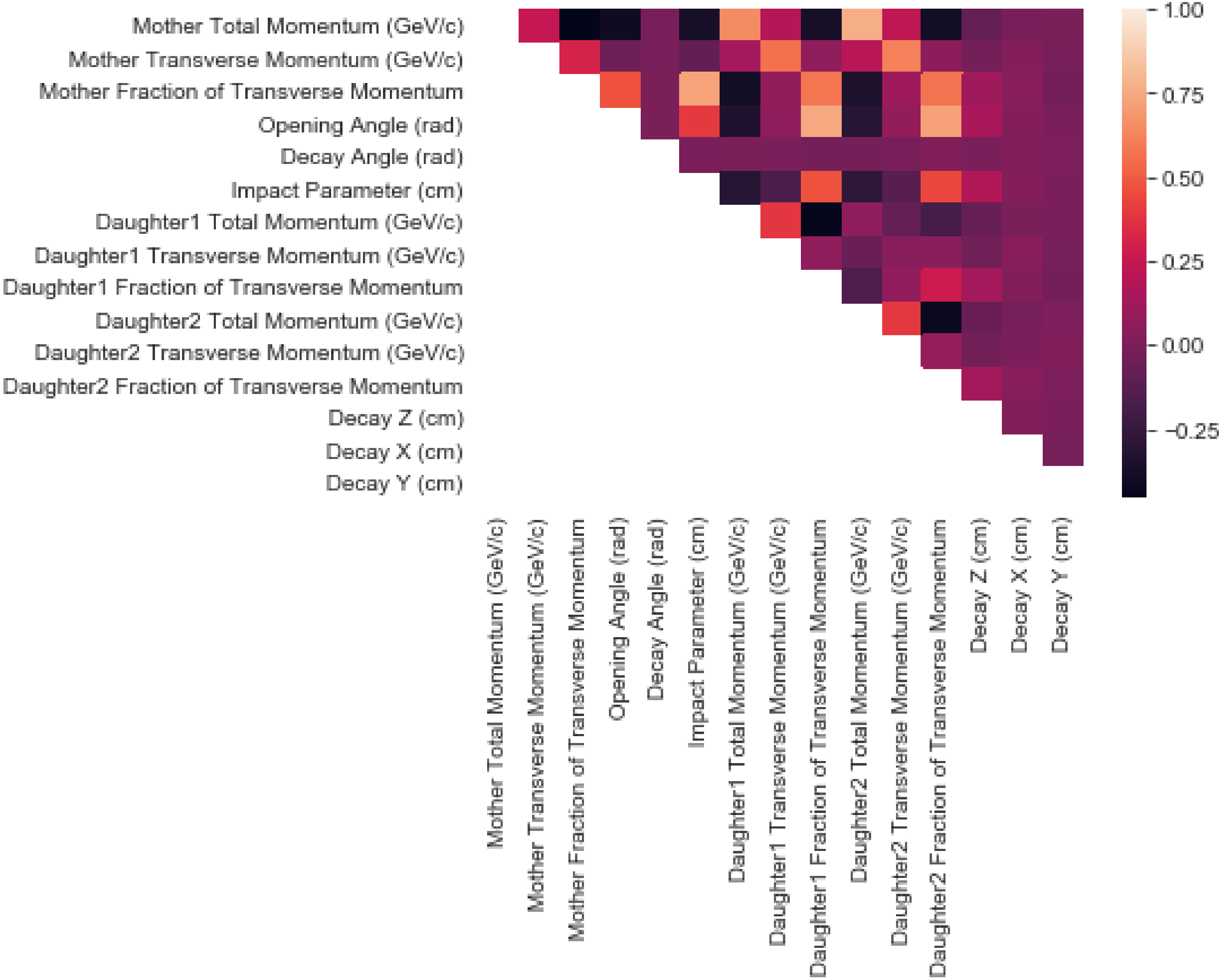
Branching Fractions
(reconstructed)

decay	frequency
$\pi^{\pm} + \pi^{\mp}$	44.6%
$X + \pi^{\pm} + \pi^{\mp}$	20.6%
$K^{\pm} + \pi^{\mp}$	4.4%
other	30.4%

We will focus on the $\pi^{\pm} + \pi^{\mp}$ decay

Some kinematic distributions (DP→$\pi^{\pm}\pi^{\mp}$)



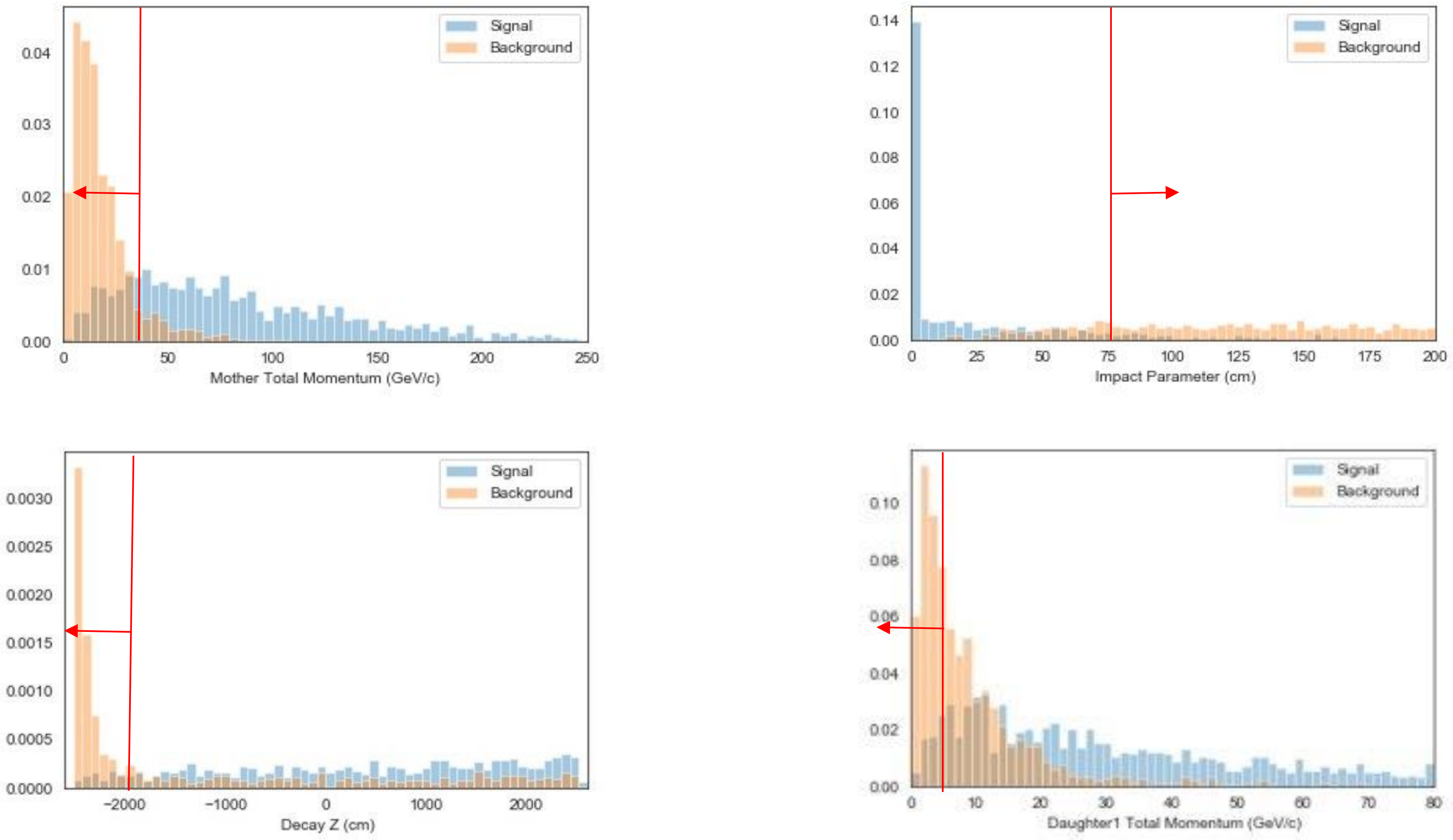


Signal Correlation Matrix

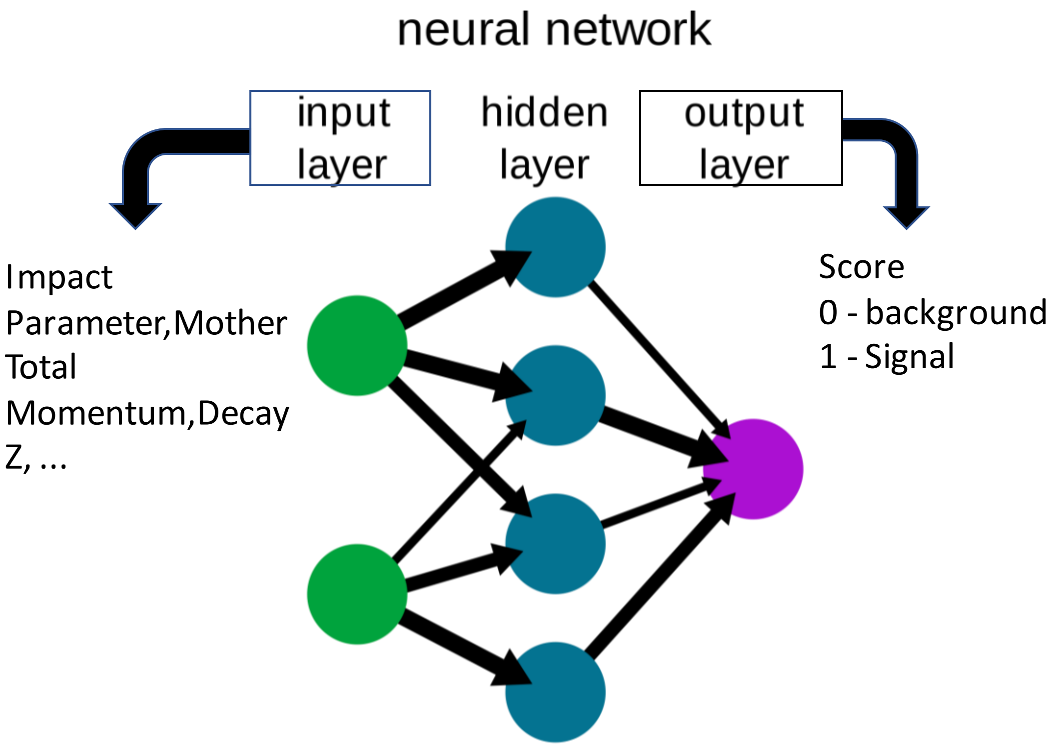
Standard analysis

cut	Signal efficiency	number of background events
	1	1099
Impact Parameter < 75 cm	0.806	157
Mother Total Momentum > 40 GeV/c	0.705	31
Decay Z > -2000 cm	0.658	1
Daughters Total Momentum > 3.5 GeV/c	0.642	0

The cuts

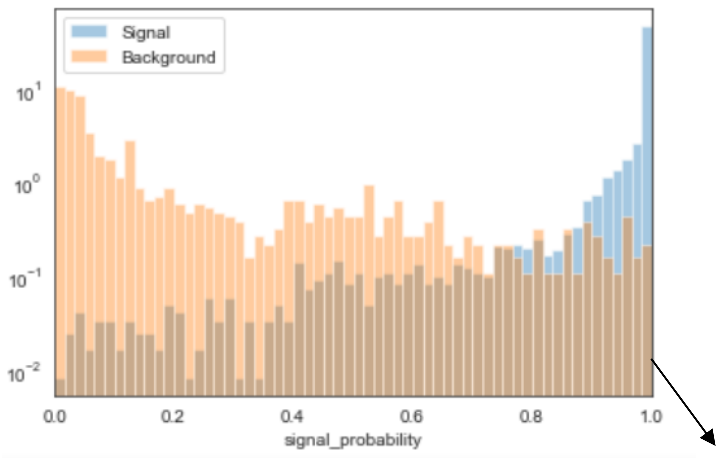

Signal
Background
0.04
0.03
0.02
0.01
0.00
0
50
100
150
200
250
Mother Total Momentum (GeV/c)
Signal
Background
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
25
50
75
100
125
150
175
200
Impact Parameter (cm)
Signal
Background
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
−2000
−1000
0
1000
2000
Decay Z (cm)
Signal
Background
0.10
0.08
0.06
0.04
0.02
0.00
0
10
20
30
40
50
60
70
80
Daughter1 Total Momentum (GeV/c)

Binary classification neural network



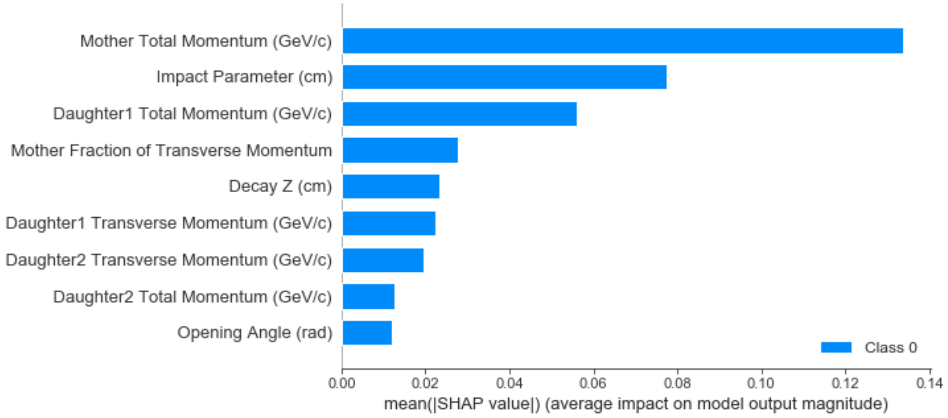
- After Training a machine learning model we can see how well it works by inspecting the **ROC curve**
- The NN is trained by providing it with labeled data: **Signal(DP)** and **Background(DIS)**
- Its performance is checked on validation data
- Figure of merit: **highest signal efficiency** for zero background

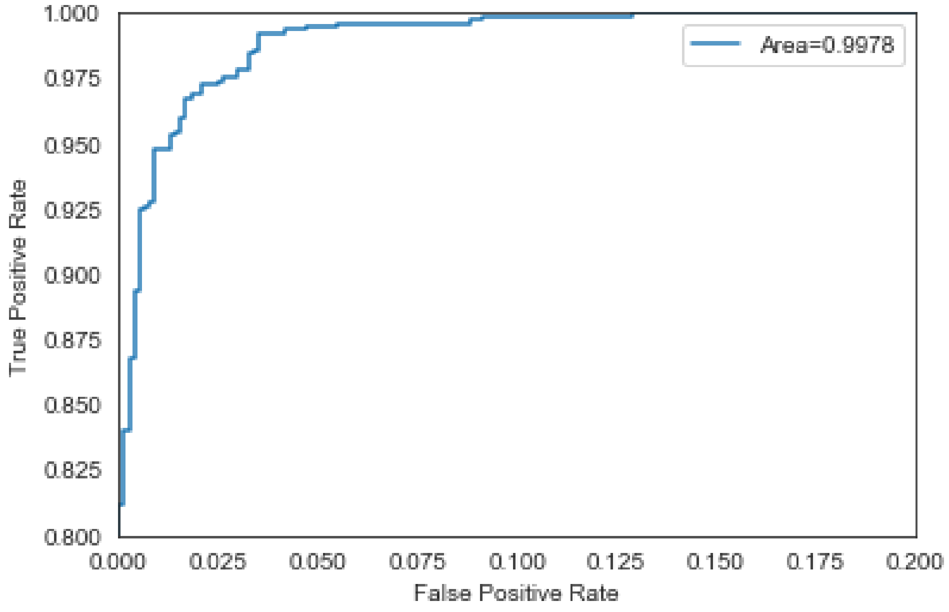
Results



threshold=0.9905

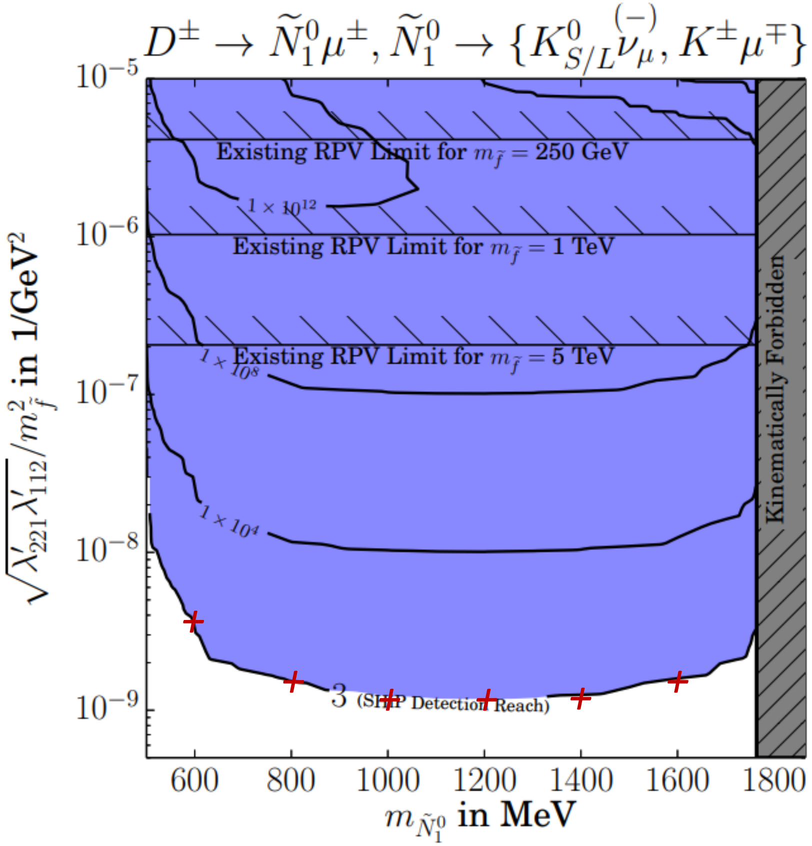
- The **Signal efficiency** of a model trained with 1099 background events and 2000 signal events is **`0.816.`**

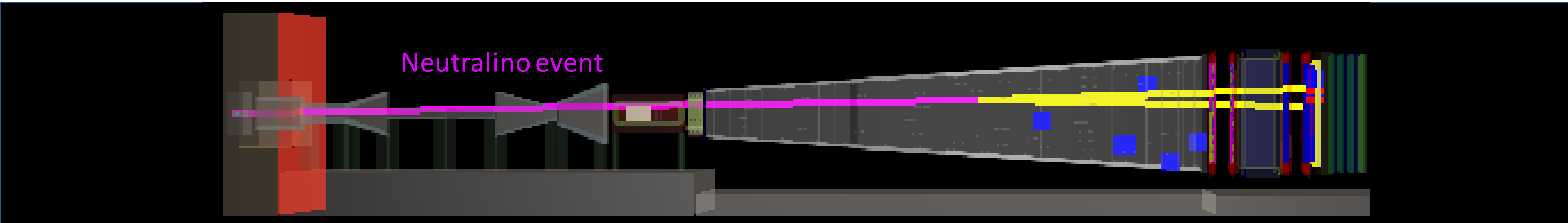




Neutralino

- Hypothetical fermion from the Minimal Supersymmetric Standard Model
- Also a candidate for dark matter





Branching Fractions

(reconstructed)

$$D^{\pm} \to \widetilde{N}_1^0 \mu^{\pm}, \widetilde{N}_1^0 \to \{K^0_{S/L} \overset{(-)}{\nu}_{\mu}, K^{\pm}\mu^{\mp}\}$$

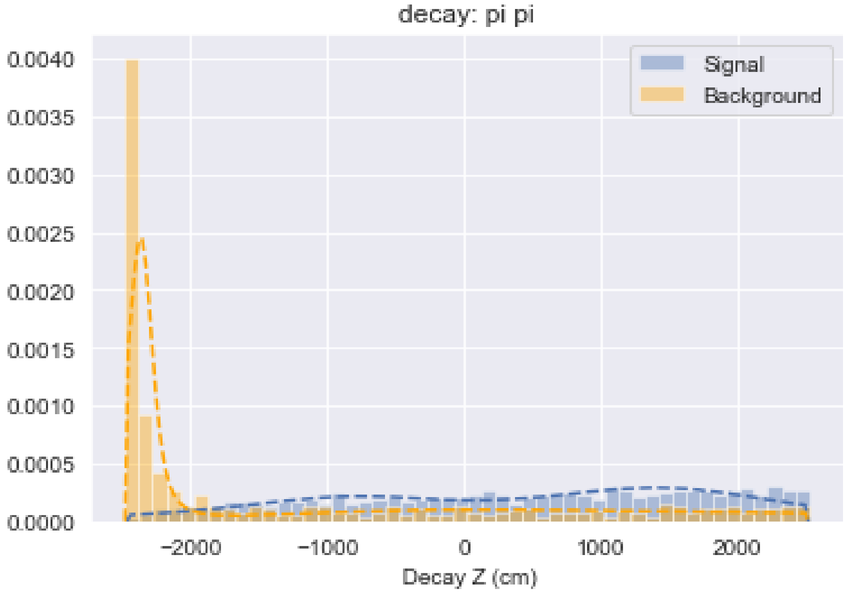
K_S^0	
$\pi^{\pm}\pi^{\mp}$	88.8%
$\pi^{\pm}\mu^{\mp}$	9.2%
$\mu^{\pm}\mu^{\mp}$	0.5%

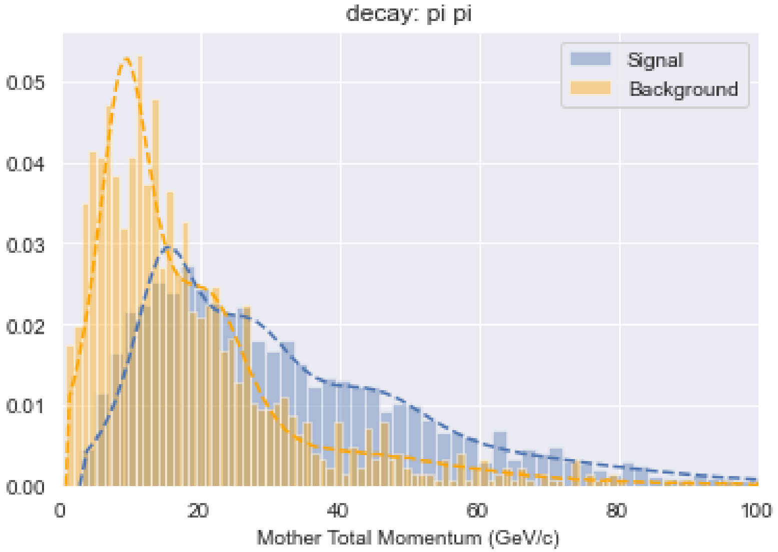
We're going to study the top 2 decays from both modes

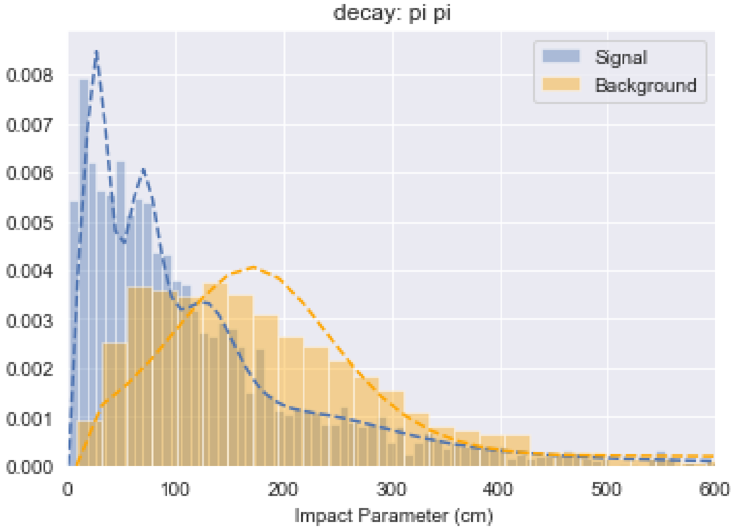
$K^{\pm}\mu^{\mp}$	
$K^{\pm}\mu^{\mp}$	83.9%
$\mu^{\pm}\mu^{\mp}$	9.1%
$\pi^{\pm}\mu^{\mp}$	2.7%
$\pi^{\pm}\pi^{\mp}$	1.9%

The neutrinos that appear on some of the decays aren't detected, so can't be reconstructed, causing there to be missing energy on the reconstruction

Some distribution plots for $\mathbf{K_S^0 \rightarrow \pi^{\pm} \pi^{\mp}}$

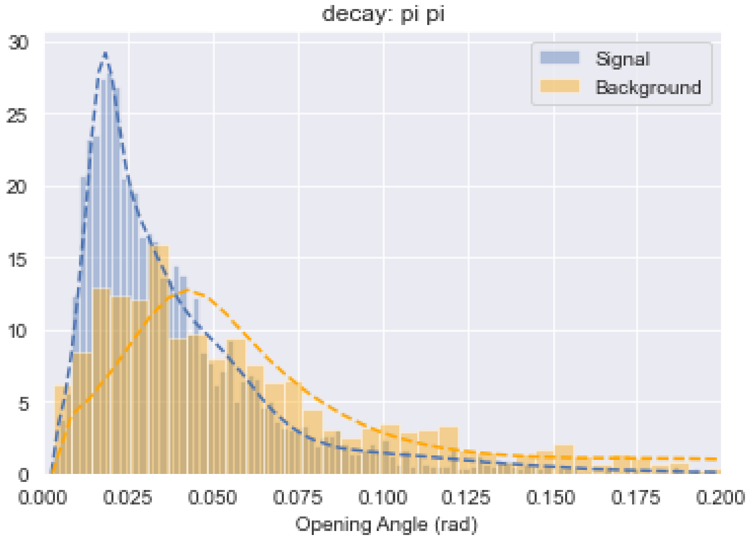






- The dashed lines are the estimated probability density functions based on the simulation data, for some of the features

- They were estimated by fitting the cumulative distribution function using a neural network

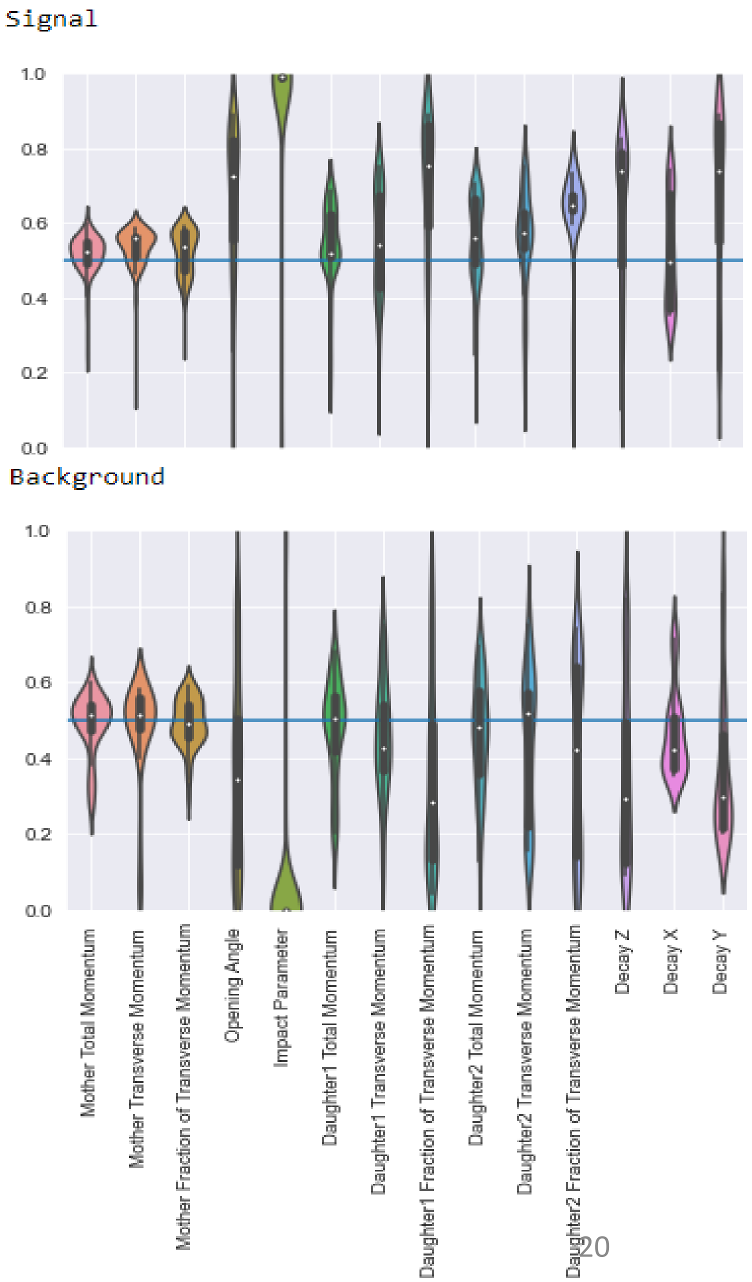


Violin plots of the probability values for $\mathbf{K^{\pm}\,\mu^{\mp}}$

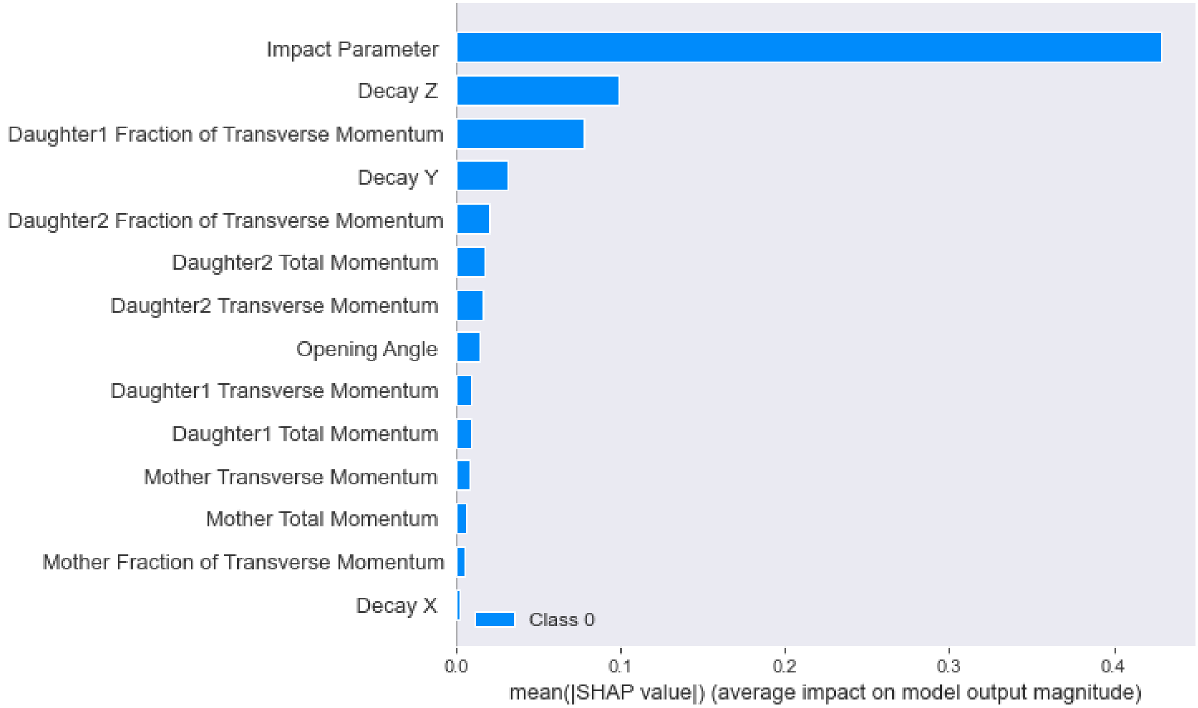
- These represent the probabilities that come directly from the estimated distributions.

- In this case, there is a clear separation between **signal** and **background** for the **Impact Parameter**

- The next step in the method is to pass these probabilities onto a **binary classification neural network**



Binary Classification from the estimated probabilities (**K$^{\pm}$ μ$^{\mp}$**)



Relative importance of the parameters to the trained neural network

- The network was trained on **symmetrical data** (same number of signal as background), so there is some extra, **remaining data** of a single class (either signal or background), used for validation

- It is very important that **no background** gets confused with the signal, so, by varying the **decision threshold** we can get the **False Positives** to be zero

The **Impact Parameter** is the most important parameter to the network, as viewed on the violin plots

Classification Results

(for all 4 decays)

- To guarantee that there was no overfitting, it was used a validation split of ¼ of the total data, with the training data the remaining ¾
- The area under the ROC curve (**AUC**) was always 1 (for the symmetric validation data)
- It was possible to assure zero **False Positives** at the cost of some **False Negatives** (meaning some signal events got mistaken as background events) by moving the **decision threshold**

out of the 4 million neutrino DIS events

Decay	Background (total)	Threshold	Signal Efficiency
$K^{\pm}\ \mu^{\mp}$	92	0.5	99.92%
$K^{\pm}\ \mu^{\mp} \rightarrow \mu^{\pm}\ \mu^{\mp}$	433	0.59	99.89%
$K_S^0 \rightarrow \pi^{\pm}\ \pi^{\mp}$	1143	0.98	99.21%
$K_S^0 \rightarrow \pi^{\pm}\ \mu^{\mp}$	1380	0.99924	96.19%

- The pre-processing of the probabilities, according to the feature distribution, proved to be really effective in making the classification problem easier for the neural network

The typical method of neural network classification using the raw, properly normalized, data, was tried on the decay with the most symmetrical data ($K_S^0 \rightarrow \pi^{\pm}\ \pi^{\mp}$) and the obtained signal efficiency was of about 10%, much lower than what obtained here.

Conclusions

- We have studied New Physics particles -- Dark Photons and Neutralinos -- in the framework of the SHiP experiment (data simulation and analysis)

- We found some interesting ML models that can be used to distinguish the **background** from the **signals** with a relatively high degree of precision.

- We can highlight the NN method with pre-processing of the feature probabilities, which can attain a **Signal Efficiency** of nearly 100% for the tested decays.

Questions?

Backup Slides

Decay	signal	background
$K^{\pm}\ \mu^{\mp}$	3532	92
$K^{\pm}\ \mu^{\mp} \rightarrow \mu^{\pm}\ \mu^{\mp}$	386	433
$K_S{}^0 \rightarrow \pi^{\pm}\ \pi^{\mp}$	2786	1143
$K_S{}^0 \rightarrow \pi^{\pm}\ \mu^{\mp}$	289	1380