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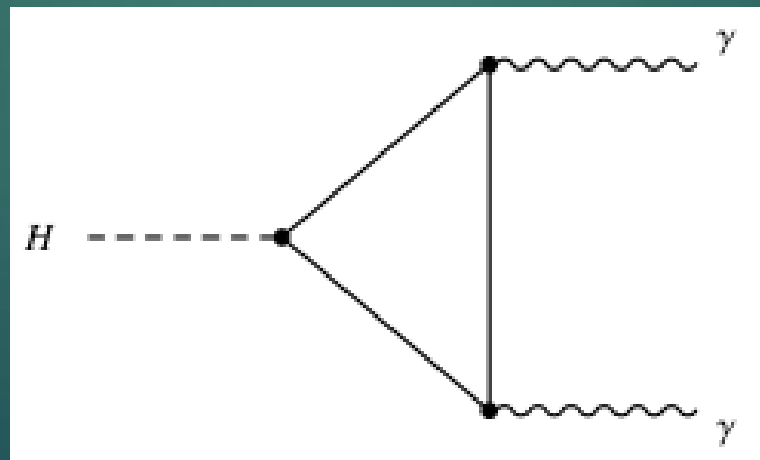
Submitted on 23 Jan 2025

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Search for an additional Higgs boson with mass $< 110\text{ GeV}$ with the CMS experiment at the LHC

Benjamin MassotEAU



Summary :

- ▶ This Higgs boson in the Standard Model
- ▶ Motivation for the search for an additional Higgs boson
- ▶ The CMS experiment
- ▶ The search for a new Higgs boson in the CMS experiment
- ▶ Discrimination between the Drell-Yan process and the diphoton decay
- ▶ Modelisation of the Drell-Yan process
- ▶ Conclusion

The Higgs boson

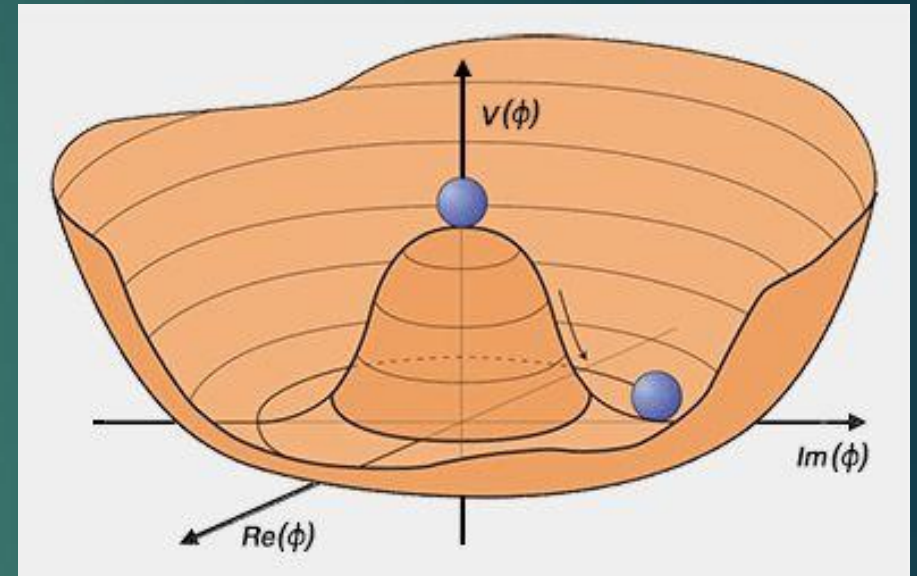
The Higgs mechanism is responsible for the spontaneous breaking of electroweak symmetry, allowing the W and Z bosons to acquire mass, as well as the fermions, thereby mixing their right-handed and left-handed components. The Higgs potential is as follows:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

With $\mu^2 < 0$, the minimum of the potential is

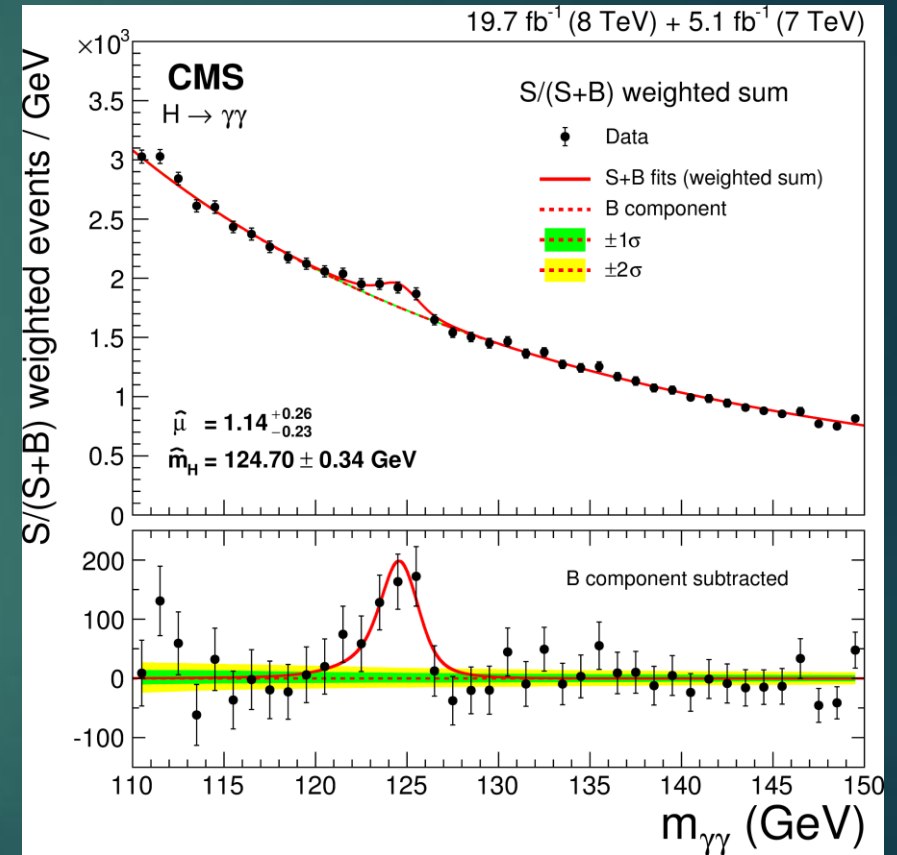
located at $v = \sqrt{-\frac{\mu^2}{\lambda}}$

This minimum is called the vacuum expectation value (vev). If we expand the Lagrangian around this vev, we notably find a mass term $\frac{m_h^2}{2} h^2$ with $m_h^2 = 2\mu^2$, reflecting the appearance of a scalar boson, a relic of this mechanism.



The Higgs boson discovery at the LHC

In 2012, the discovery of a scalar boson, compatible with the Higgs boson, was announced by the ATLAS and CMS experiments at CERN. This discovery was observed in the diphoton decay channel with a significance greater than 5σ , providing strong evidence of its existence. This marked a significant milestone in completing the Standard Model of particle physics, confirming the mechanism responsible for particle mass acquisition as predicted by the Higgs mechanism.



Motivation for the search for an additional Higgs boson

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[arXiv:2405.18149](https://arxiv.org/abs/2405.18149)
(Accepted by PLB)

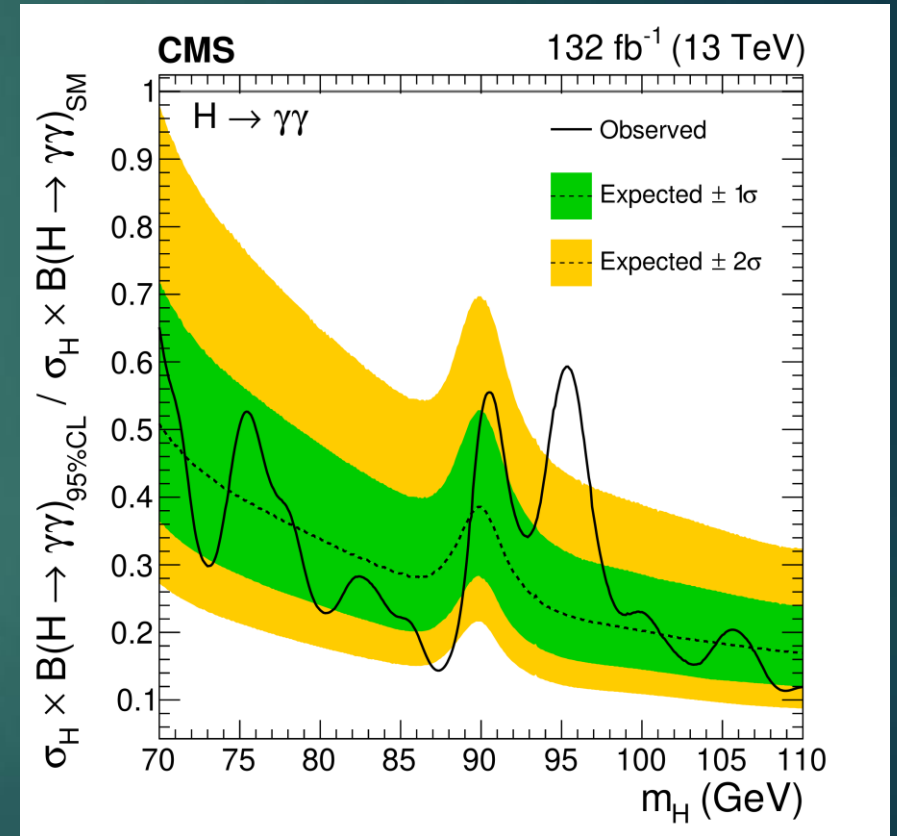
The Standard Model, however, fails to predict and explain certain phenomena:

- Dark matter, which is thought to constitute 24% of our universe.
 - Gravity at the quantum scale.
 - Neutrino oscillations.
 - The matter-antimatter asymmetry.
- ⇒ There must exist a theory beyond the Standard Model that can explain all observed and unexplained phenomena.

Certain models, such as two-Higgs-doublet models or supersymmetry, predict additional Higgs bosons with masses different from the one detected in 2012.

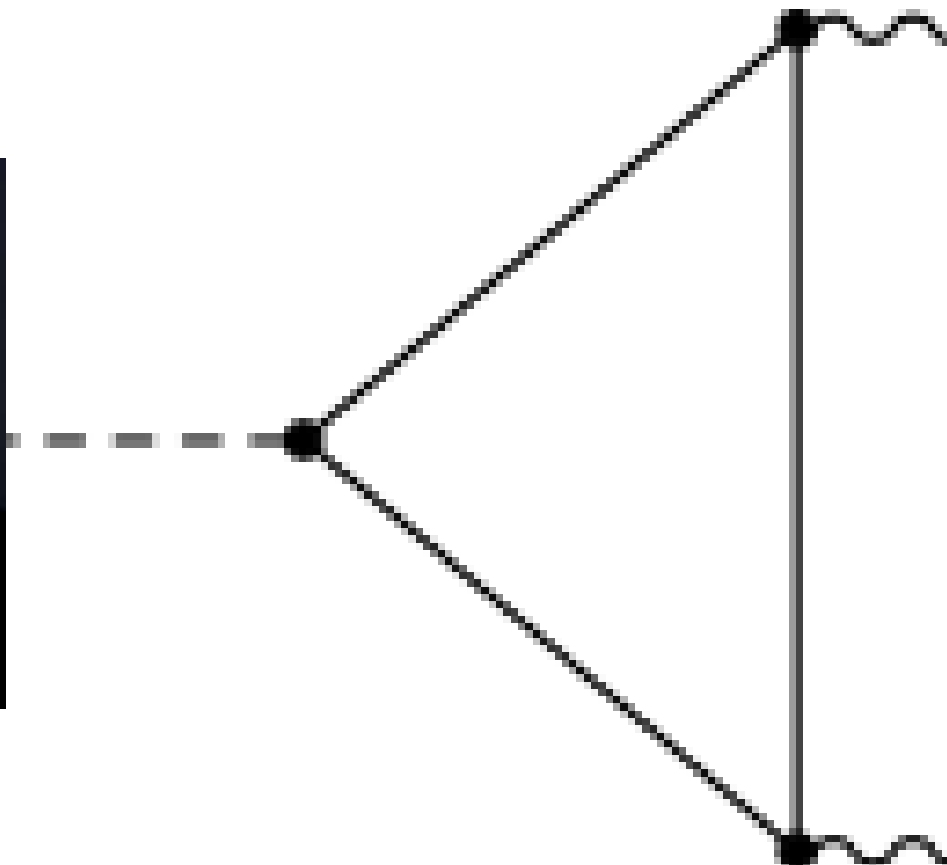
An excess was notably detected around 95.4 GeV, measured with a local significance of 2.9σ by CMS, which could correspond to an additional Higgs boson.

Meanwhile, ATLAS measured a significance of 1.7σ around the same mass [arXiv:2407.07546](https://arxiv.org/abs/2407.07546)





Higgs



Phô



Thon



Phô



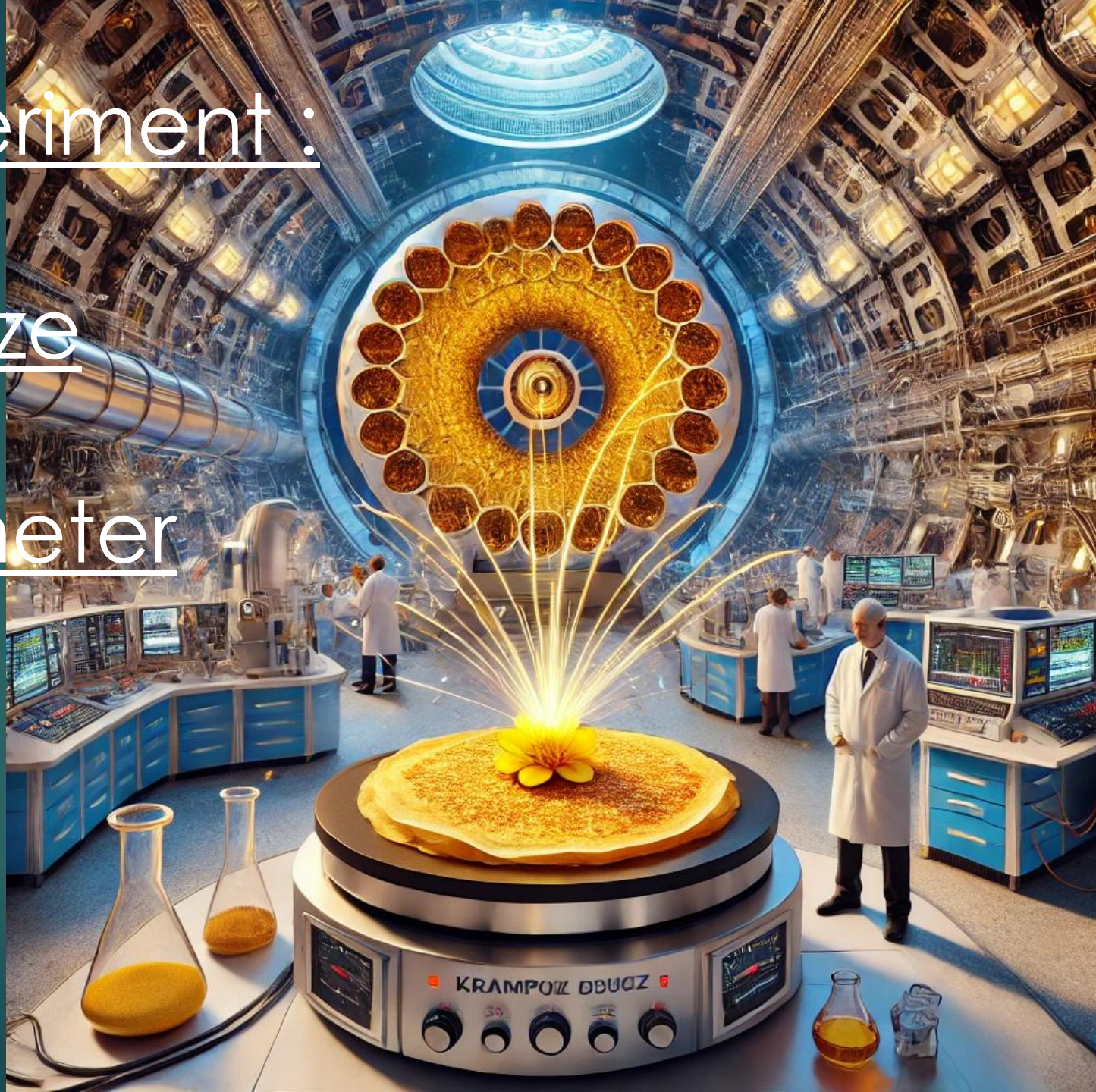
Thon

KMS experiment :

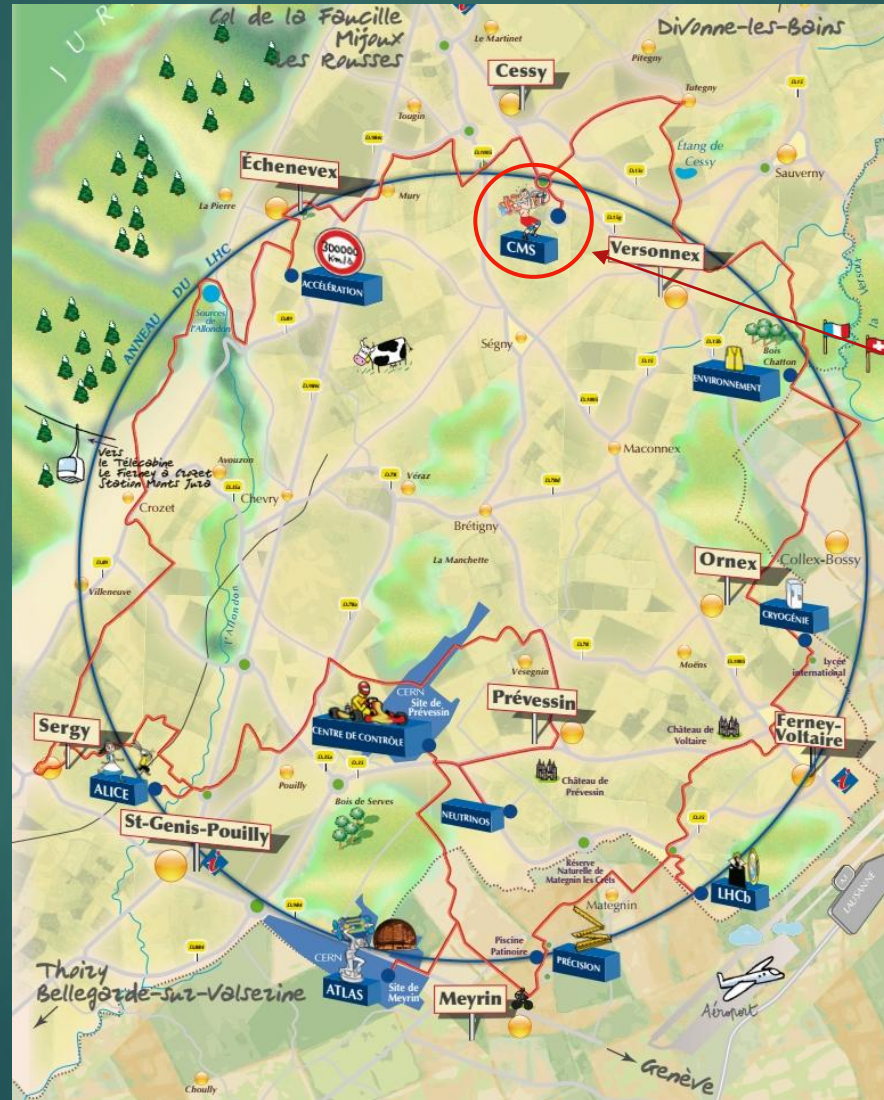
Krampouze

Meson

Spectrometer



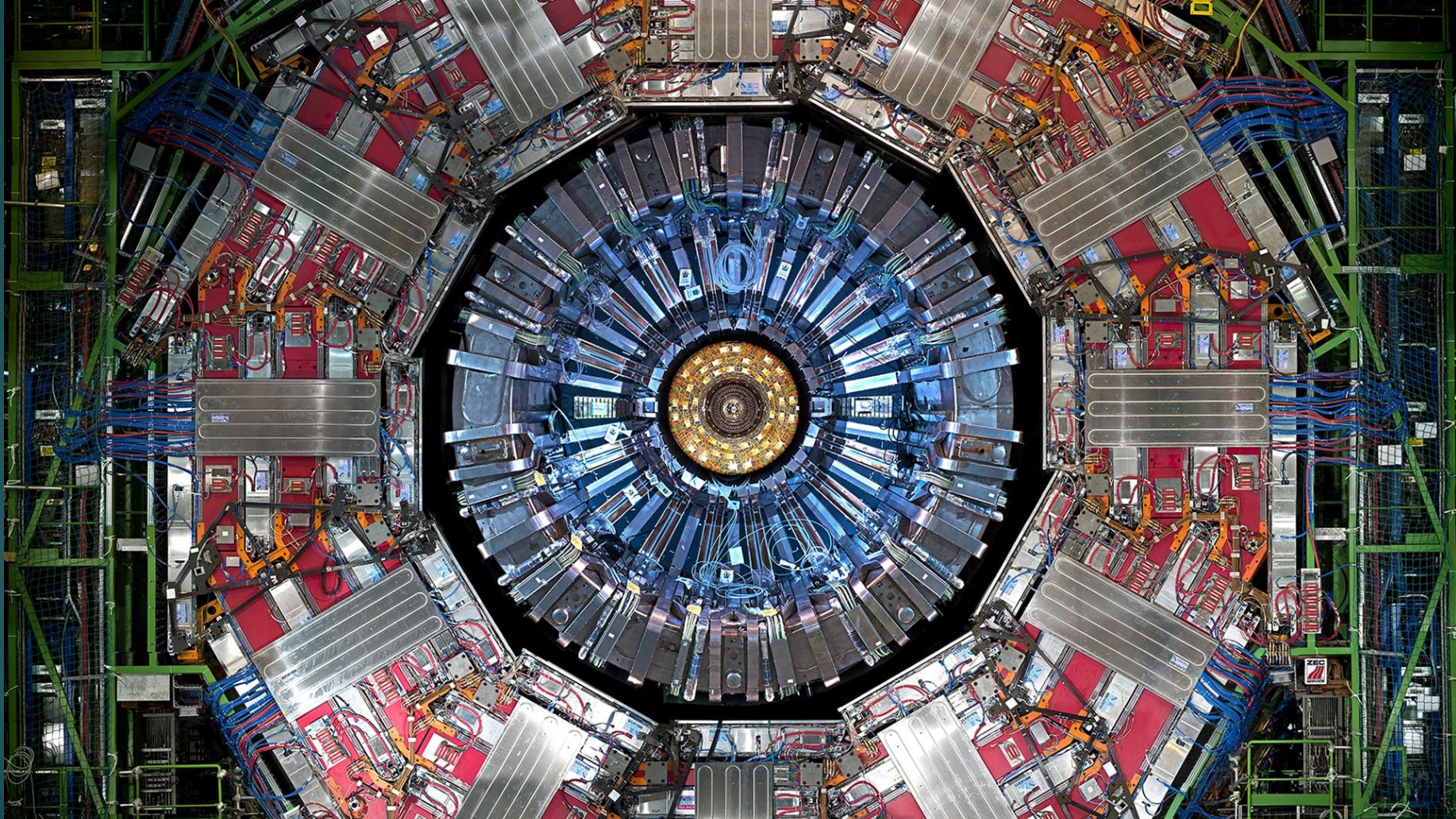
CMS experiment localisation



The farthest point from CERN's main site (~20 minutes by car)

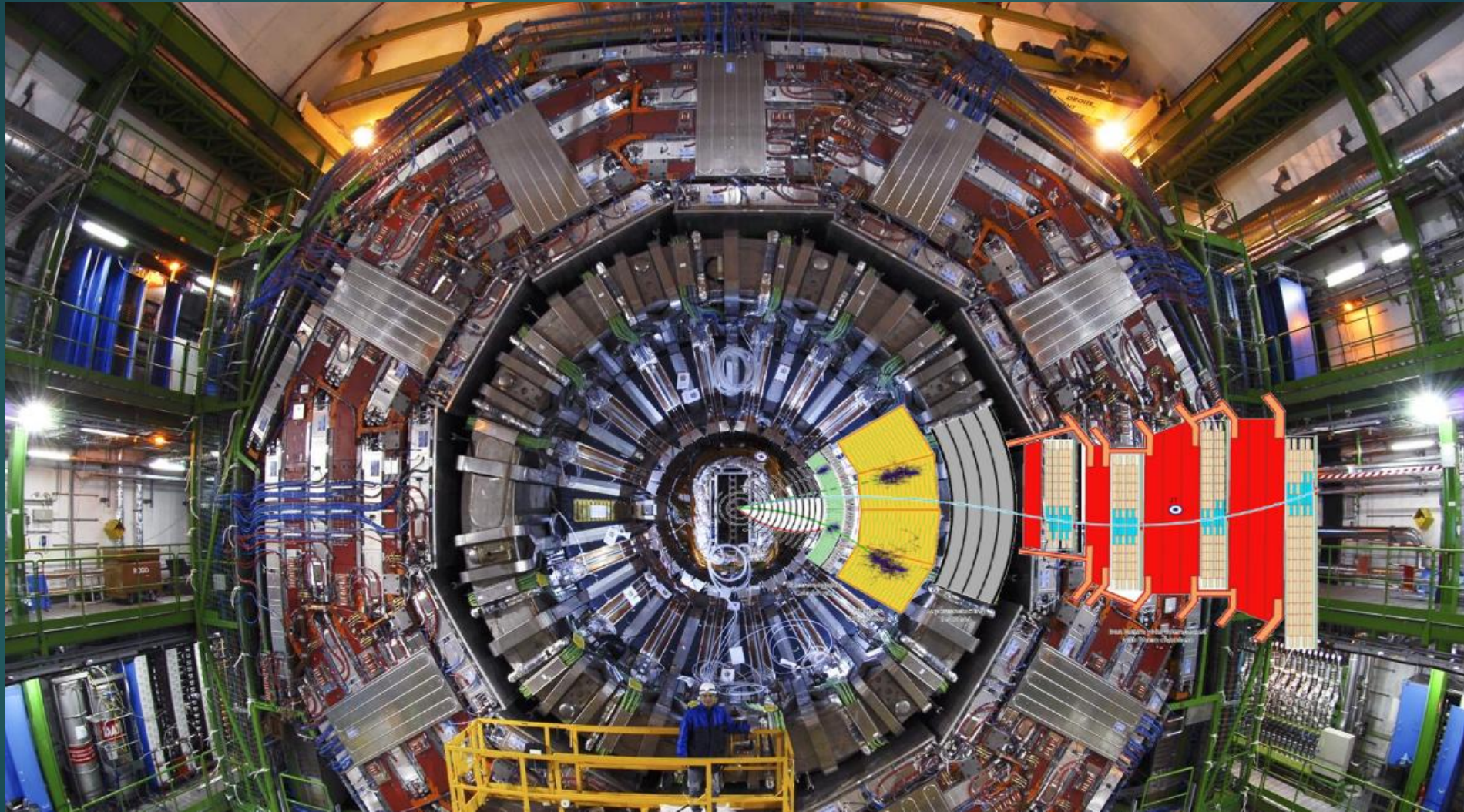
The CMS experiment

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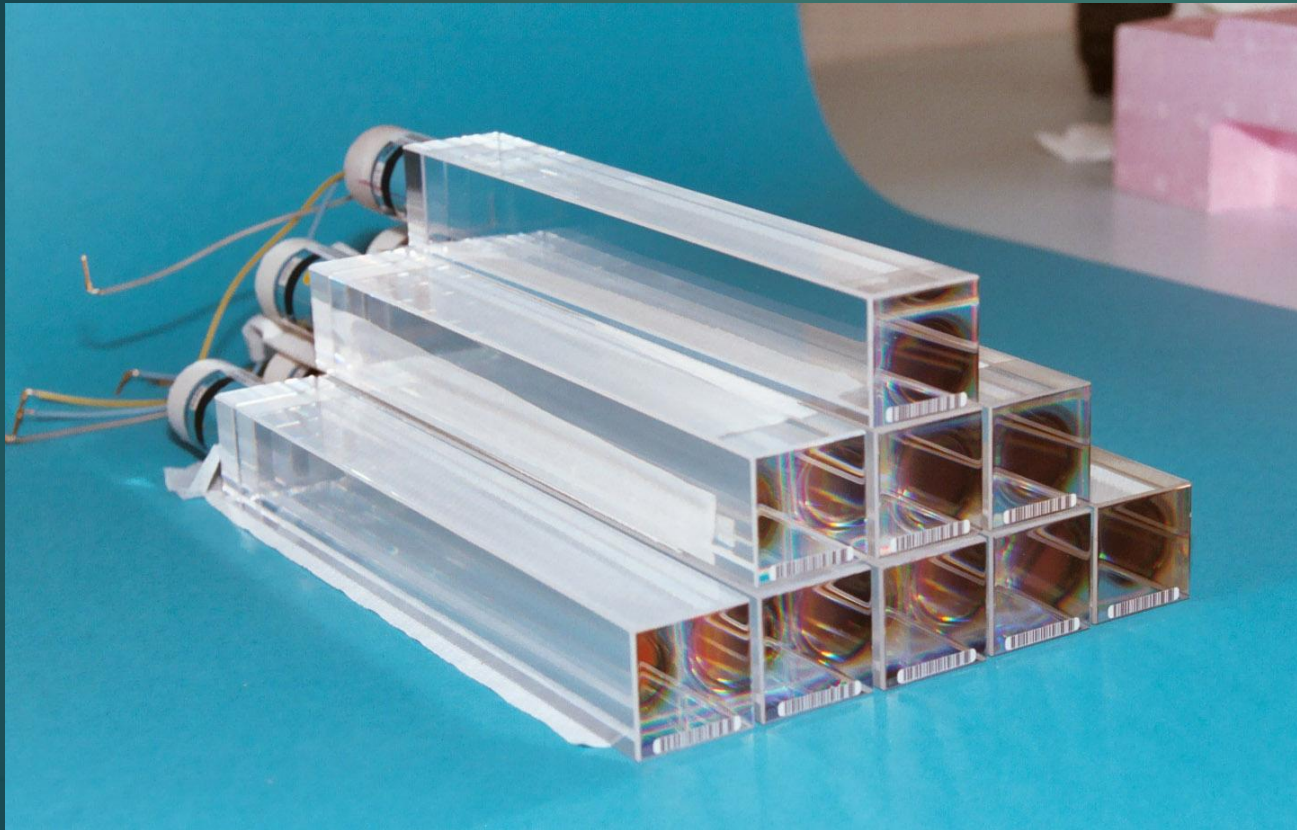
The CMS experiment

10



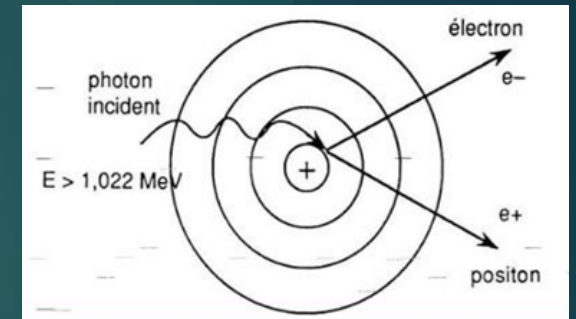
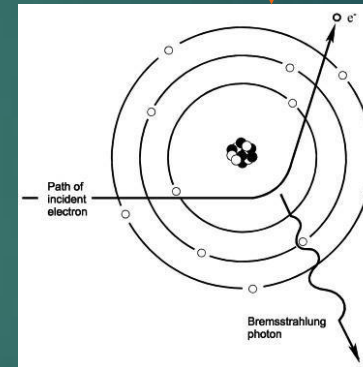
The electromagnetic calorimeter

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The high energy resolution electromagnetic calorimeter (ECAL) measures the energy of photons and electrons. It is composed of PbWO_4 (lead tungstate) crystals.

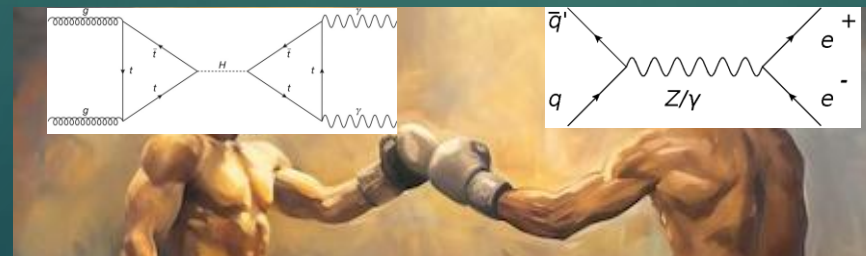
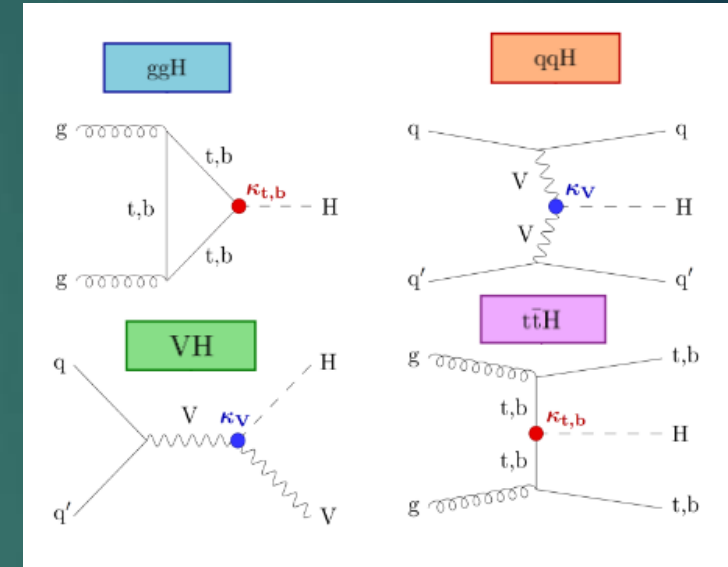
Electron : Bremsstrahlung ; Photon : Pair production



The particle cascade is then detected by photodetectors, allowing the reconstruction of the energy of the incident particle.

Low mass $h \rightarrow \gamma\gamma$ analysis

- Production mode : ggH , VBF, VH, et $t\bar{t}H$
- Diphoton invariant mass :
 - Signal search range: 70-110 GeV
 - Background fitting range: 65-120 GeV
- Backgrounds :
 - Irreducible background producing $\gamma\gamma$ (QCD)
 - γ +jets , jets+jets
 - Drell-Yan : $Z/\gamma^* \rightarrow ee$



Problem of the Drell-Yan process reduction

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To discriminate photons and electrons in the CMS experiment, both information from tracker and ECAL are used.

Electron : charged particle that leave an inner track

Photon : neutral particle that do not have such track

Some inefficiencies in the tracker misinterpret electrons as photons, especially coming from the Drell-Yan process.



Problem of the Drell-Yan process reduction

[arXiv:2405.18149](https://arxiv.org/abs/2405.18149)

(Accepted by PLB)

Run 2 solution :

Integrated luminosity : $L=132.2\text{fb}^{-1}$

Linear cut in 2D between p_T (transversal momentum) and $\log(\sum p_{T,YY}^2)$ (Sum of the square of the two transversal momenta of the tracks in the chosen vertex) such that :

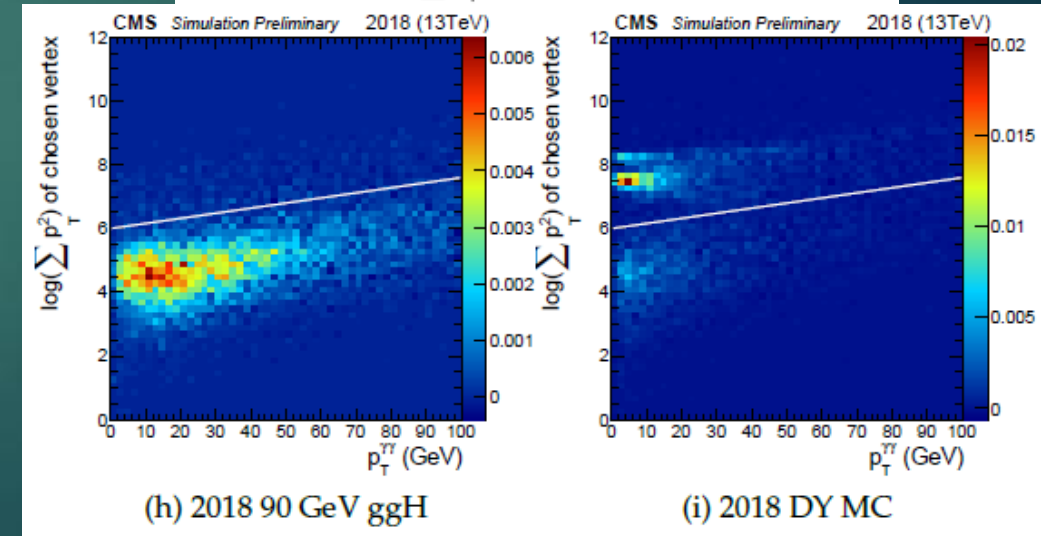
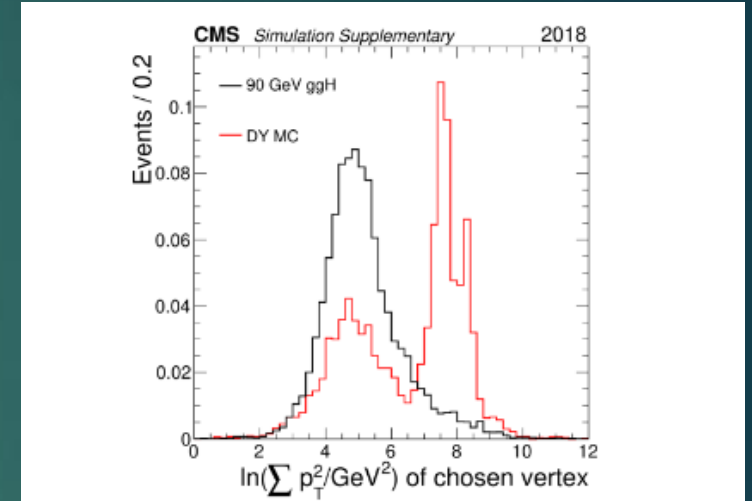
$$\log(\sum p_{T,YY}^2) \leq 0.016p_T + 6.0$$

With the additional selection $N_{\text{MatchedEle}} = 0$

Thus, we keep 92% of the signal and keep 30% of the background.

Challenge for Run 3 :

- Data format have changed since Run 3 and do not have the variables $\log(\sum p_{T,YY}^2)$ and $N_{\text{MatchedEle}}$
- We need the same results as in Run 2, or even better.



Trials with Run 3 variables on Run 2 samples

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Here, `electronIdx` indicates whether a photon originates from an electron or not (in the latter case, the variable is set to -1).

⇒ Shown to be equivalent to

$$N_{\text{matched}} = 0$$

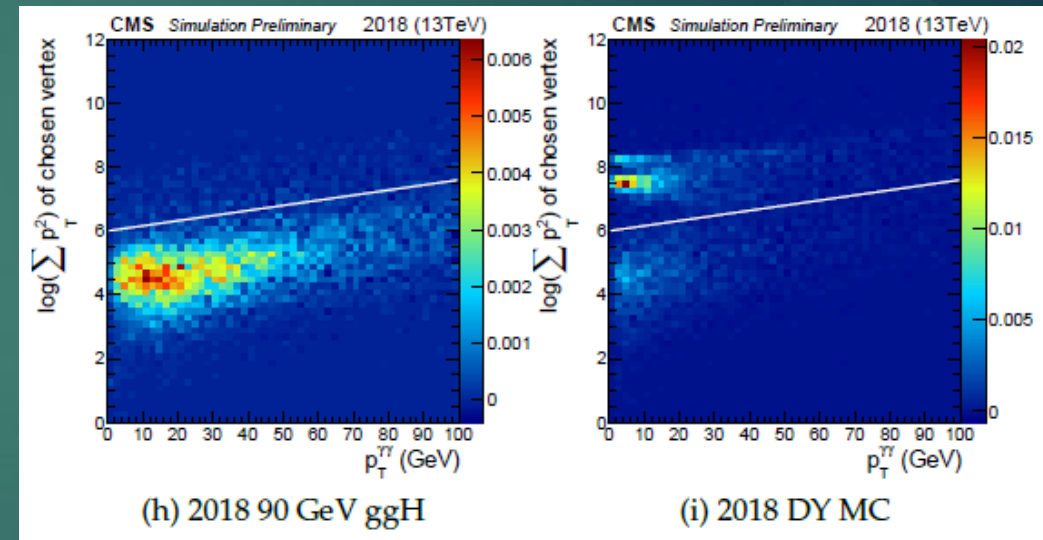
`PV_score` corresponds to the sum of the transverse momenta of the clustered objects (Not only tracks).

We can try to do a linear cut.

With this method, the efficiency is :

- Signal efficiency= 93%
- DY efficiency= 36,4%

Not quite as good as in Run 2

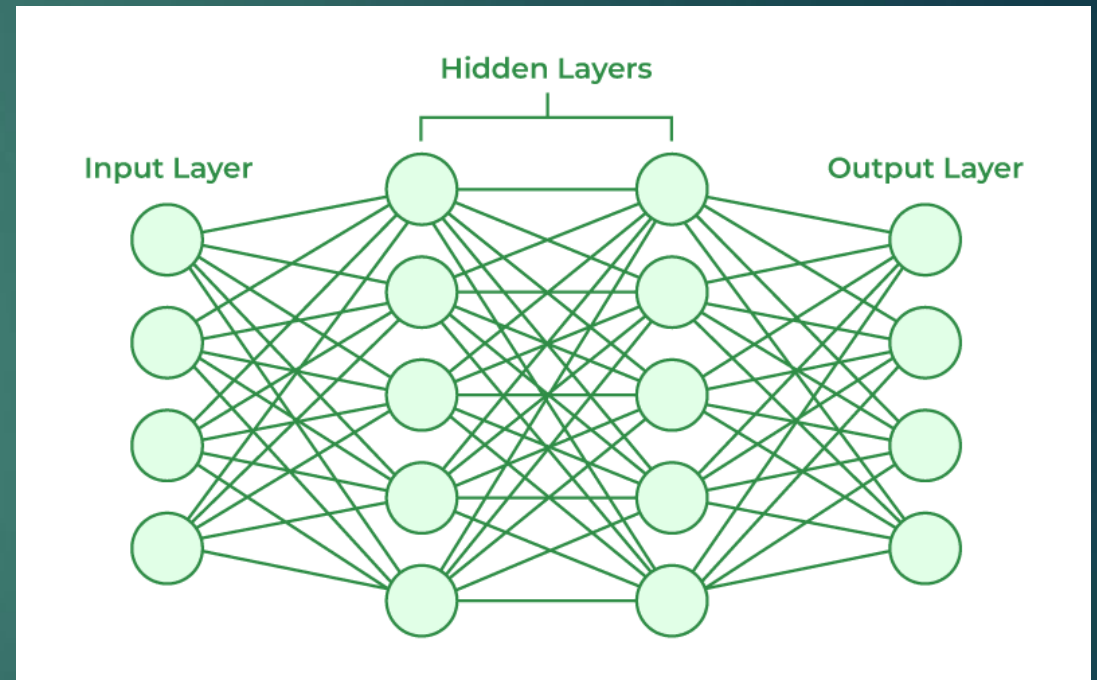


Neural Network

To discriminate the signal from our background, we're investigating using a neural network that can give us the probability of an event to belong to one or another.

We have a training set and a test set of events that we label (signal = 1 ; background = 0).

Each event will go into a unit called a neural, which is a matrix filled with scalars called weights.



Neural Network

Every output of every neural has an activation function : Identity, ReLU, sigmoid, etc...

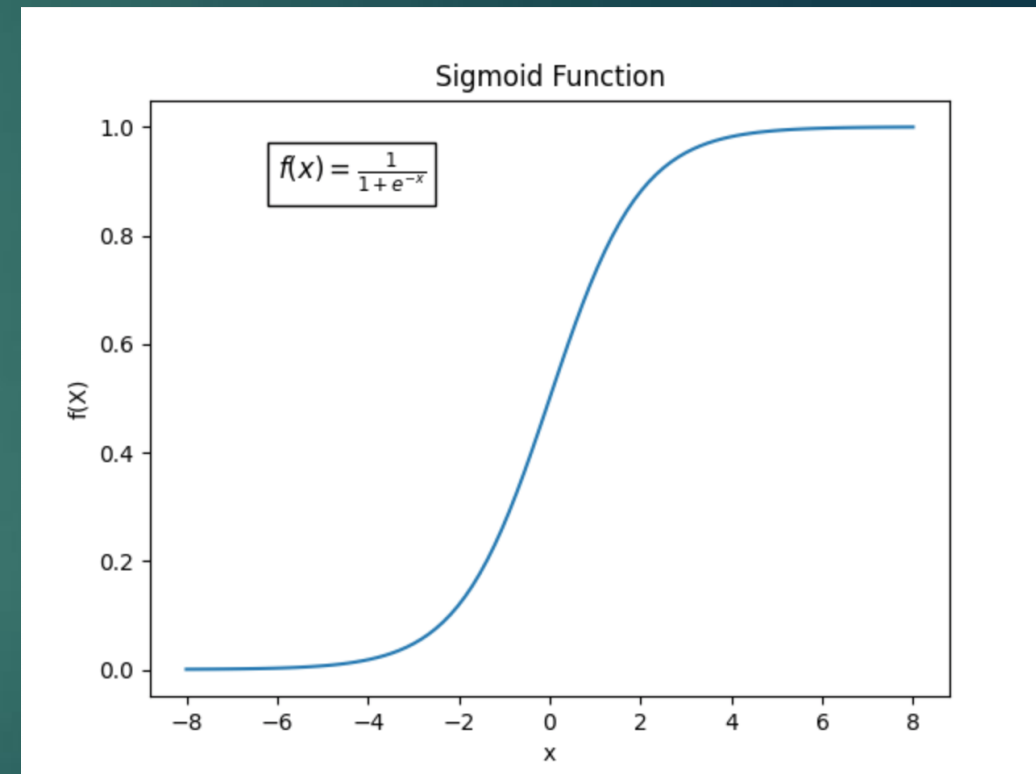
The ReLU function gives us some non linearity in the model :

$$\text{ReLU}(x) = \max(0, x)$$

The sigmoid is used to have an output between 0 and 1, so our result can be interpreted as a probability.

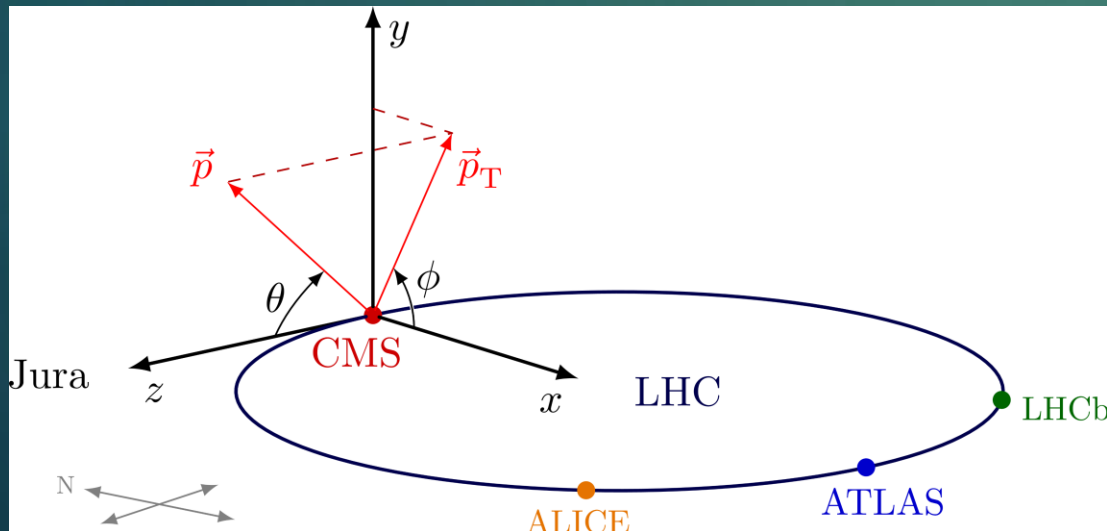
$$\sigma(z) = \frac{1}{1 + e^{-z}}$$

The result is then compared to the training set using a loss function that has to be minimized.



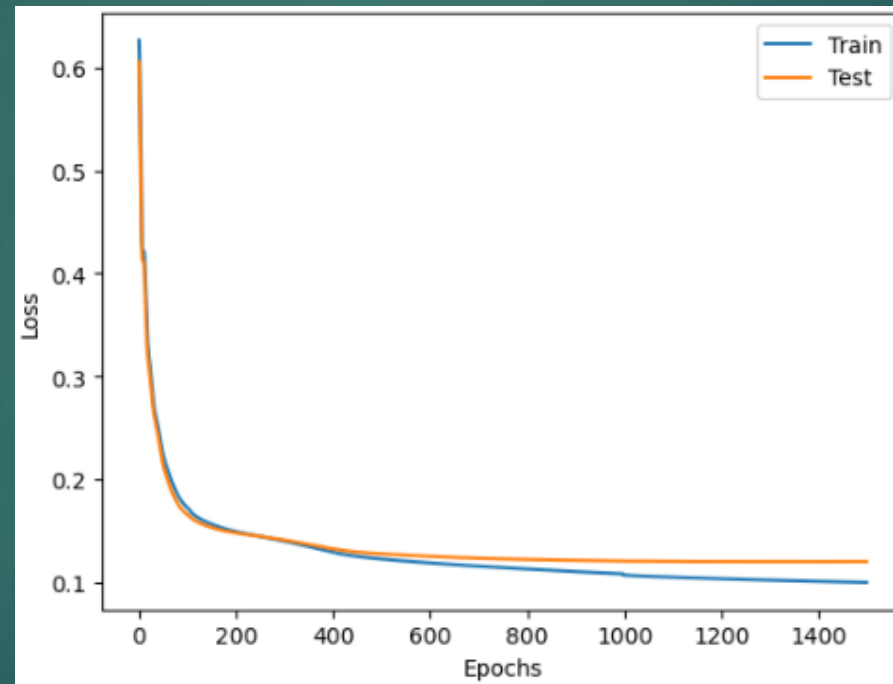
Neural Network

The list of variables used comes from the photon kinematics (η, ϕ, p_T) from the most two energetics photons (lead and sublead), informations from the primary vertex (PV_*) and from energy deposit in the ECAL and the tracker.



Neural Network

Loss function



Loss: 0.10602, Acc: 96.63% | Test Loss: 0.09577, Test Acc: 96.95%

Selection

After training the model, we can calculate the importance of the selected variables by ranking them based on the value of their gradient when a small perturbation is introduced.

We can also calculate the efficiency by performing a selection associated with the score of each event, i.e., the probability that it originates from the signal or background noise.

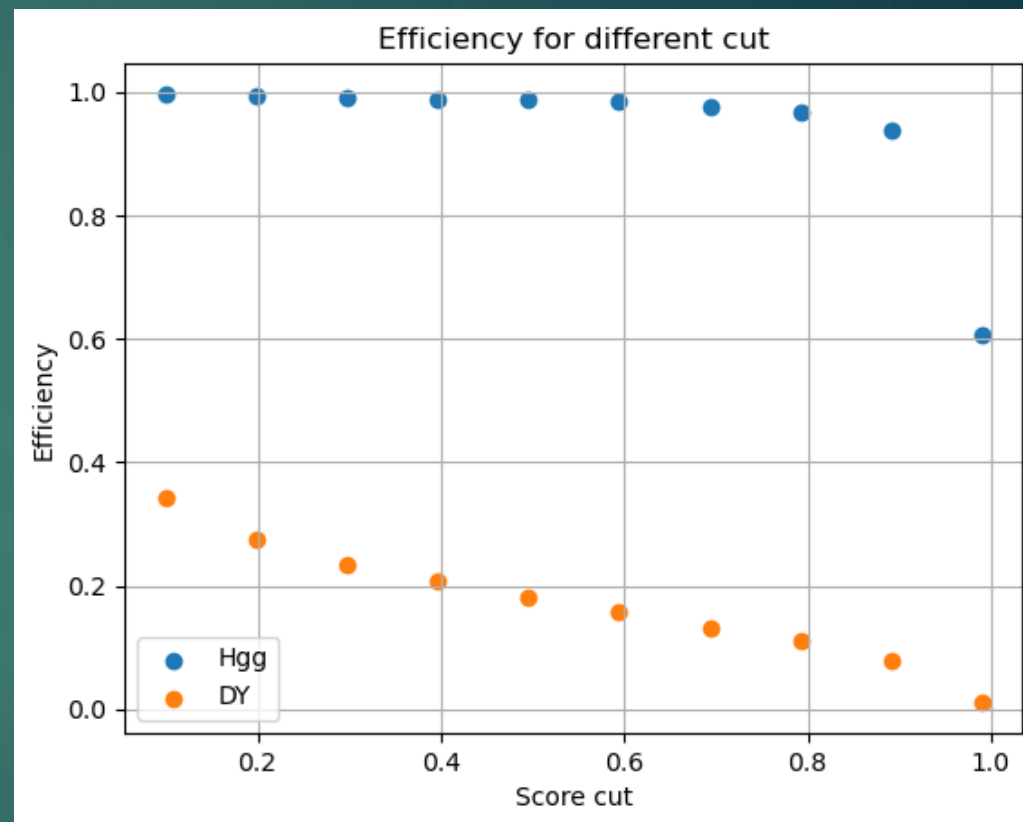
The best possible cut is 0.90.

$\text{Eff}_s = 94\%$

$\text{Eff}_{\text{bkg}} = 6\%$

But this is only true for a signal at 90GeV

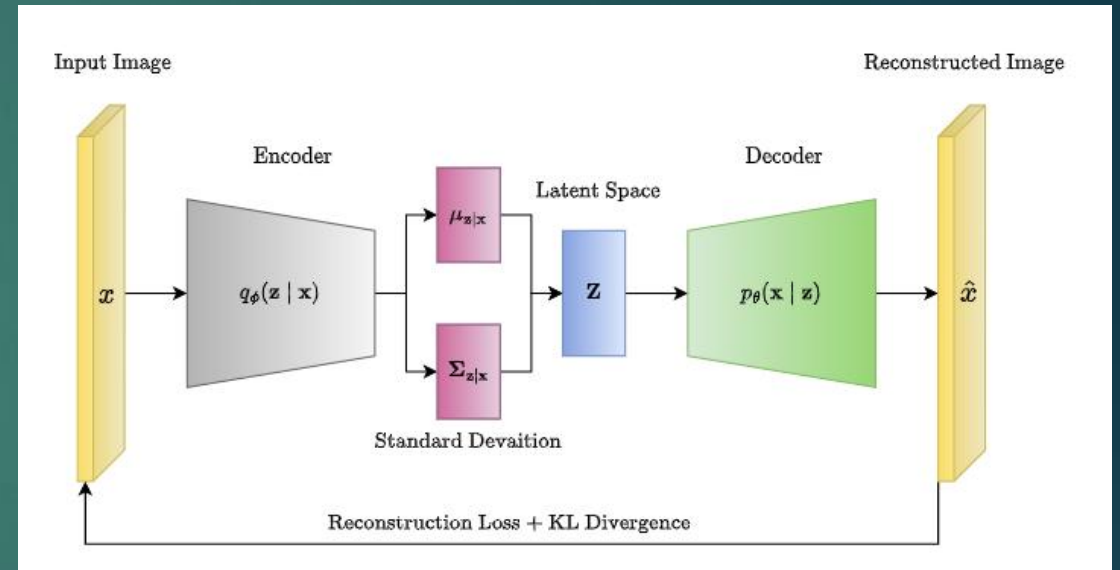
Work still on going...



Background modeling

The number of Monte Carlo events is not enough to do a proper modeling so we are investigating using a data augmentation algorithm. The technique selected is called a variational autoencoder.

The idea is to encode a distribution into a latent space and then decode it to generate a similar one with greater statistics.



Diphoton BDT

A diphoton BDT (boosted decision tree) have been trained to discriminate prompt diphoton events from the QCD events (γ +jet,jet+jet).

The score is then used to divide photon events into 4 classes such that we have the best efficiency for all of them.



Background modeling challenge

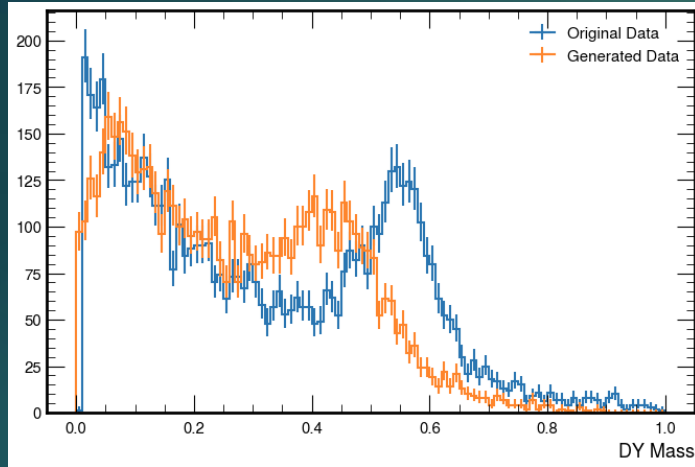
78 events	<p>Class 0</p> <p>Likely photons</p>	<p>Class 1</p> <p>Possibly photon and electron or jets</p>	418 events
1239 events	<p>Class 2</p> <p>Possibly photon and electron or jets</p>	<p>Class 3</p> <p>Likely not photons</p>	1576 events

Data Augmentation example : Mass

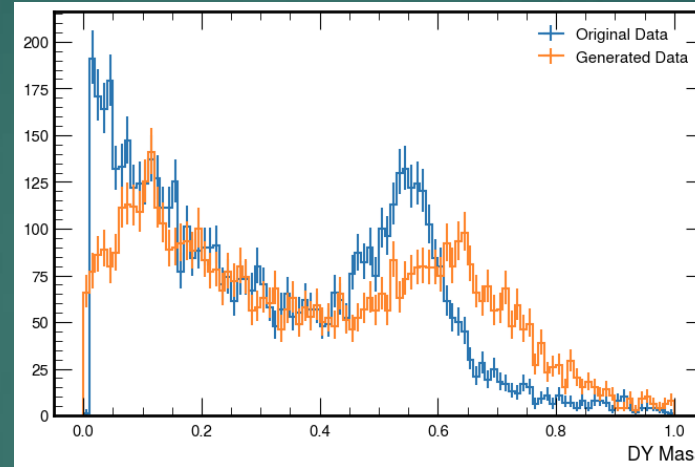
24

The number of events are the same for both trained and generated events

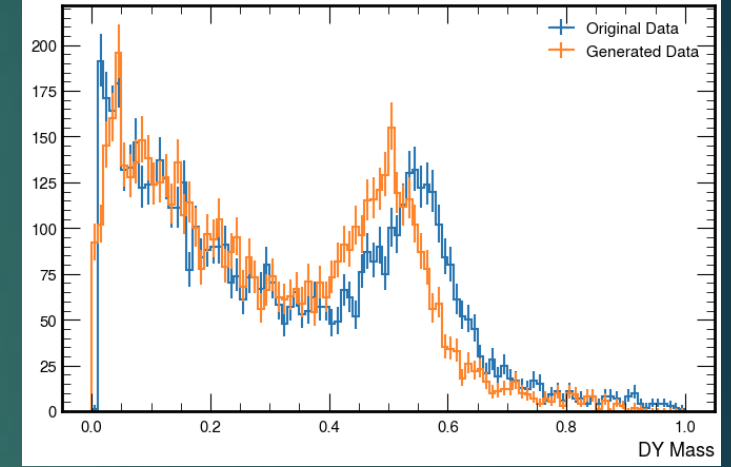
Epoch = 100



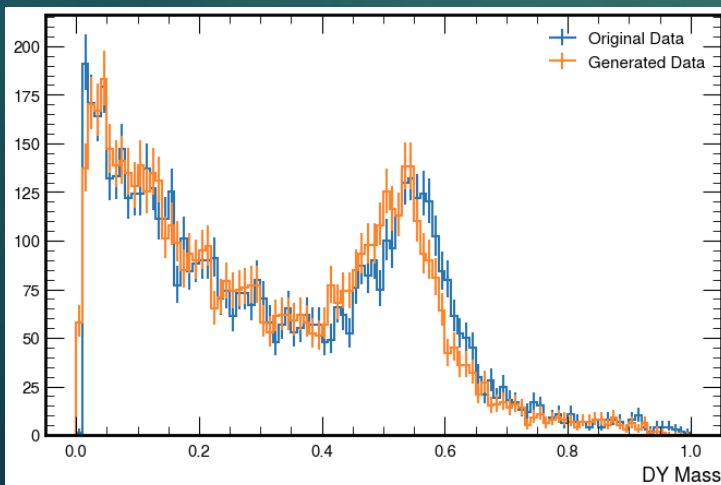
Epoch = 300



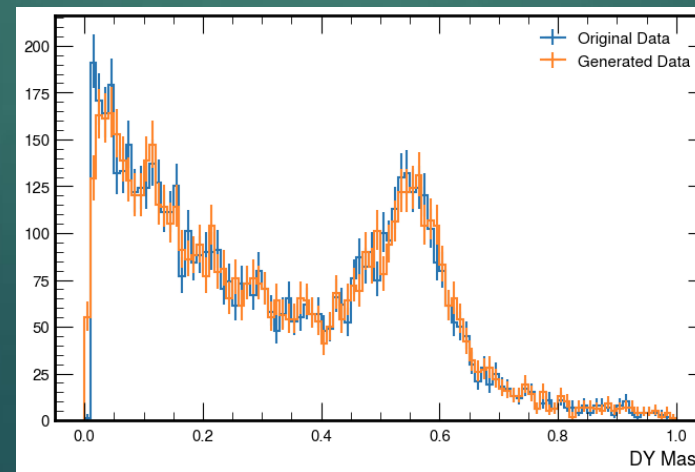
Epoch = 500



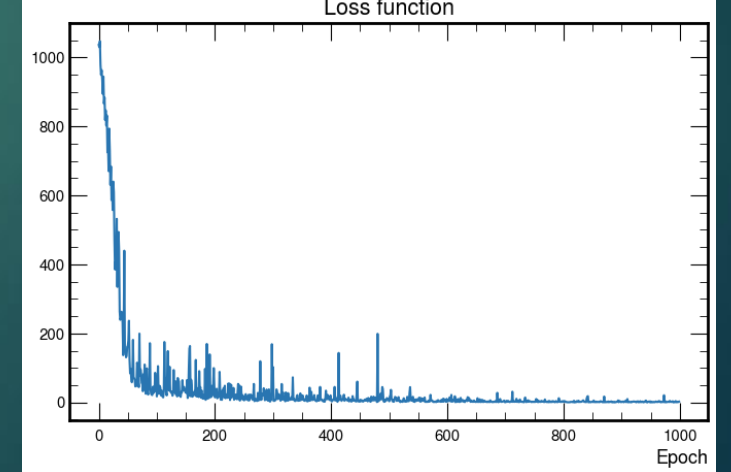
Epoch = 700



Epoch = 1000



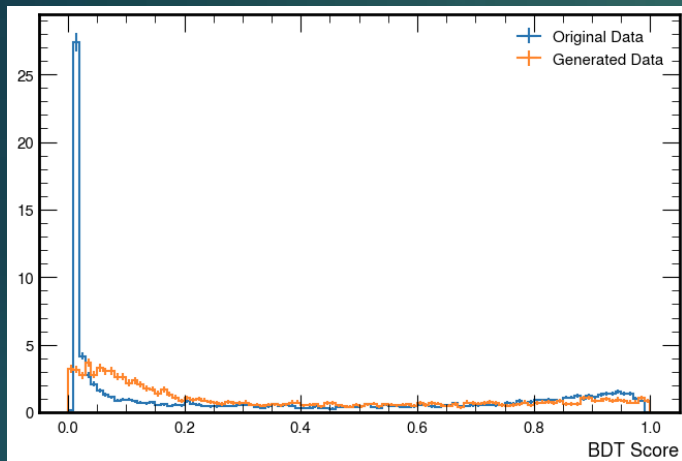
Loss function



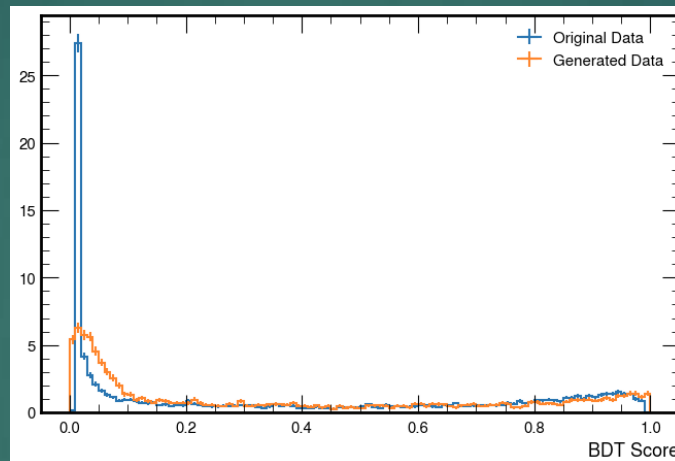
Data Augmentation example : BDT

25

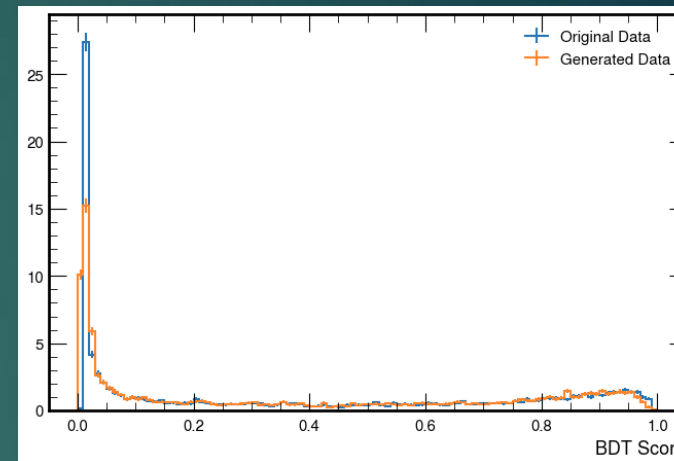
Epoch = 100



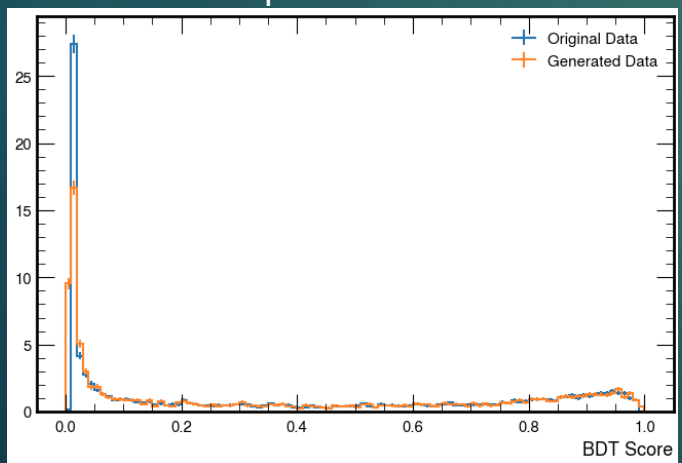
Epoch = 500



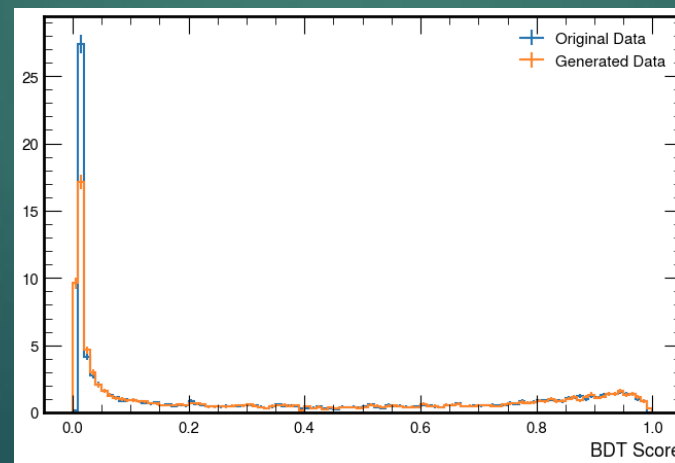
Epoch = 1500



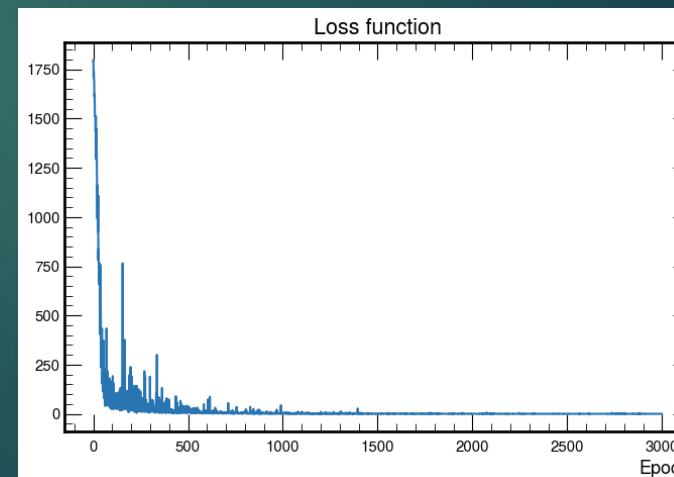
Epoch = 2500



Epoch = 3000



Loss function



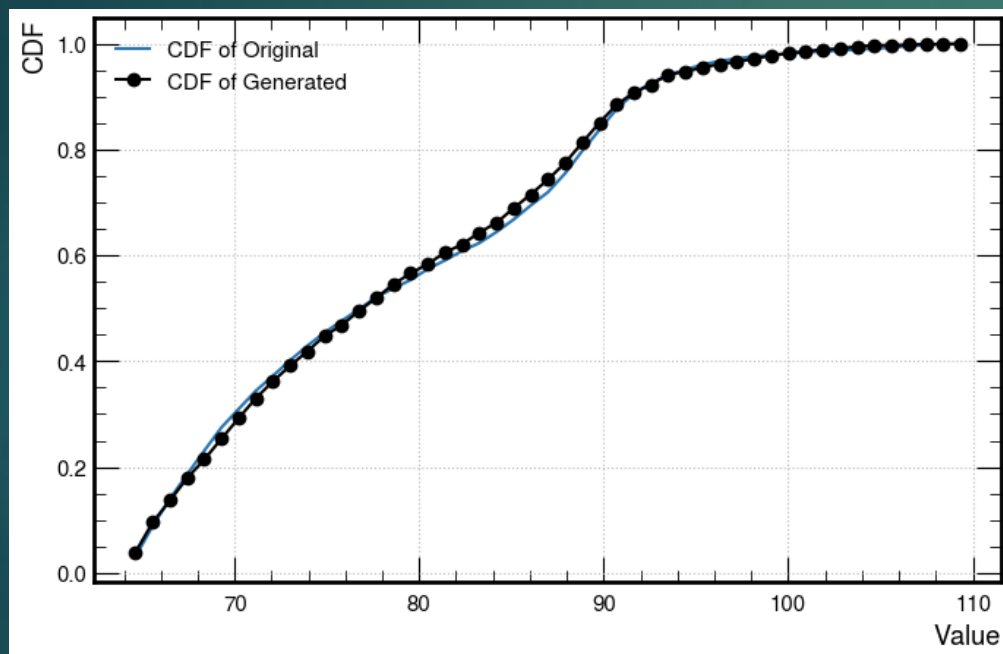
Data Augmentation

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$$(x \geq X) \mathbb{P} = (x)_{X \mathbb{F}}$$

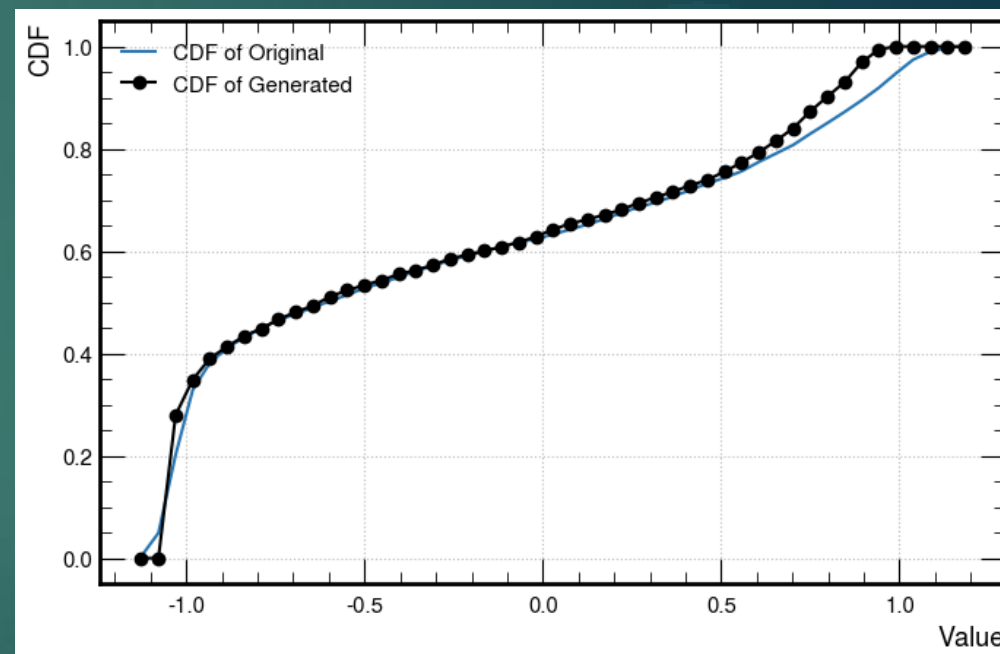
$$\text{KS Stat} = \max_{\text{bin}} (F_{\text{reel}}, F_{\text{VAE}})$$

CDF of the mass distribution



KS Statistics = 0.03
P-value = 0.23

CDF of the BDT distribution

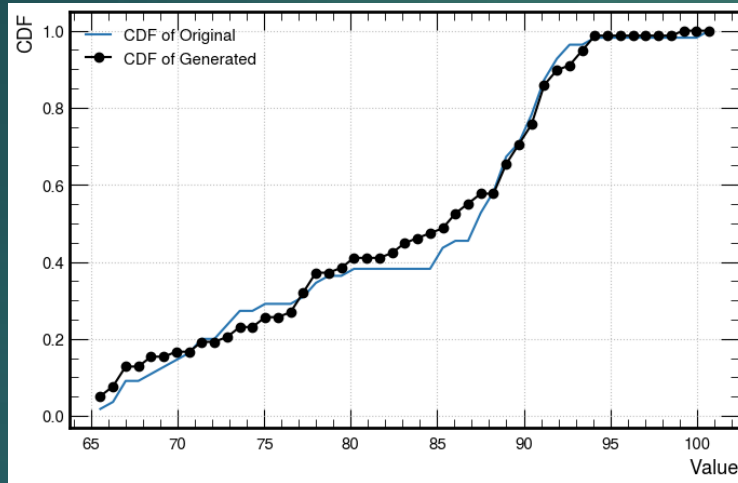


KS Statistics = 0.13
P-value = 10^{-22}

CDF for each classes

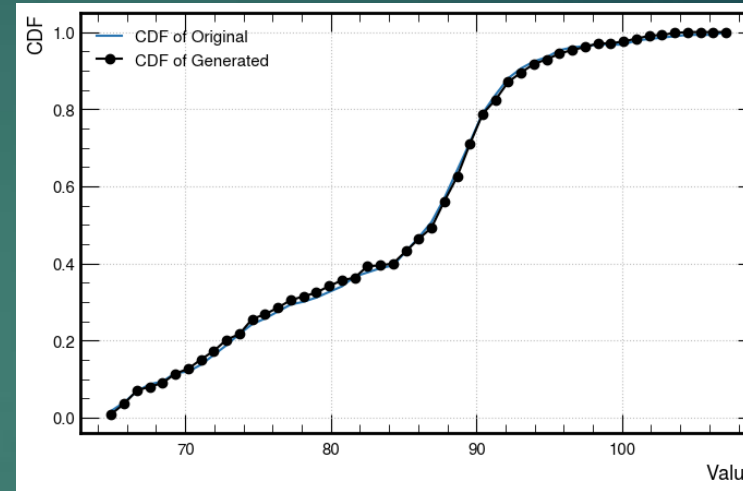
Class 0

KS Stat = 0.096
P-Value = 0.43



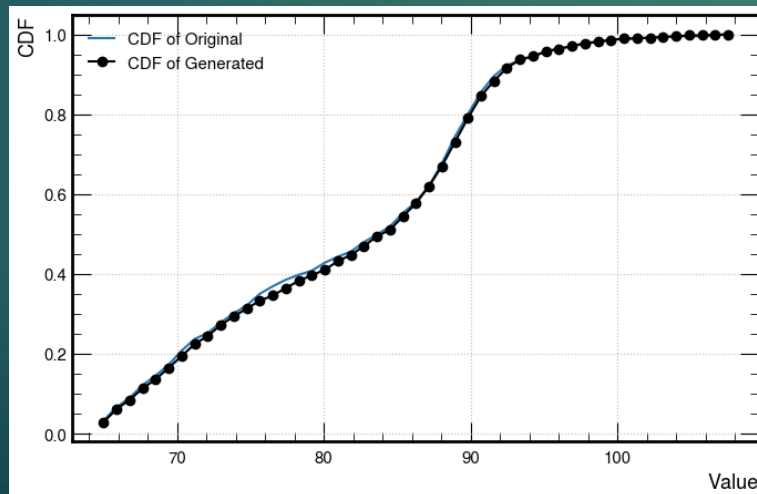
Class 1

KS Stat = 0.050
P-Value = 0.25



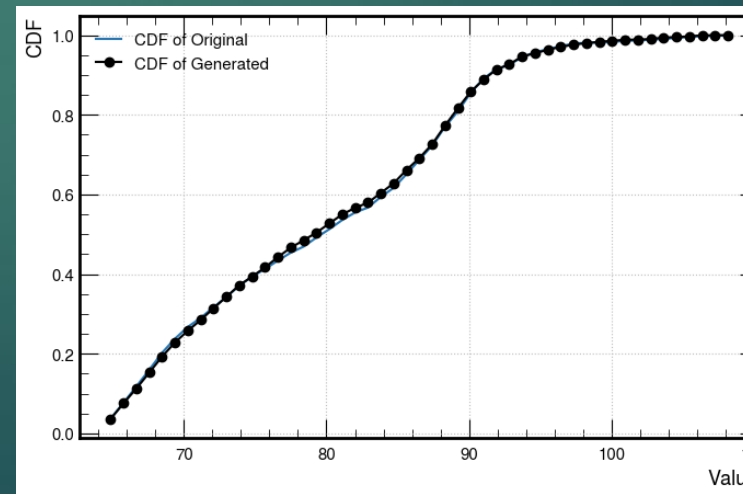
Class 2

KS Stat = 0.031
P-Value = 0.17



Class 3

KS Stat = 0.018
P-Value = 0.67



Conclusion

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- ▶ The strategy of the analysis is still on going :
 - ▶ A neural network is being currently investigated to discriminate $h \rightarrow \gamma\gamma$ events from $Z \rightarrow ee$ events
 - ▶ The VAE has to be optimized and then fit to a function to see if the results are better than without
 - ▶ The VAE has to be test with mass,diphoton BDT and DY suppression neural network score

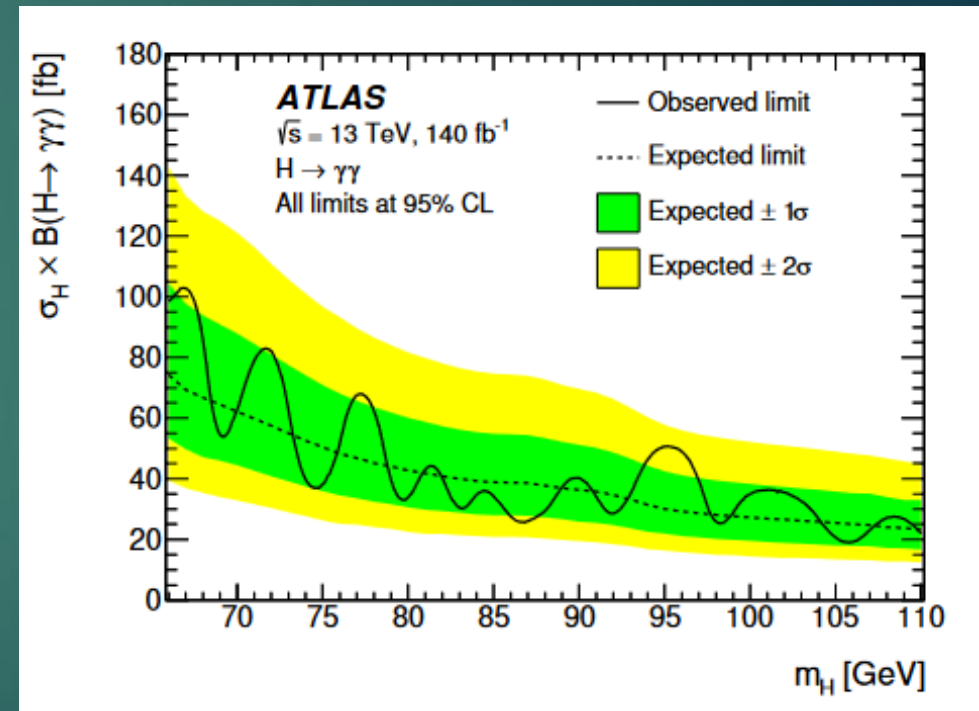
THANKS FOR YOU ATTENTION

Back ups

Plot ATLAS for Run 2 search of low mass Higgs Boson

With the full Run 2 data, ATLAS has found an excess around 95.4 GeV with a significance of 1.7σ . Which is less than CMS (2.8σ). Giving us a combined excess of 3.8σ .

[arXiv:2407.07546](https://arxiv.org/abs/2407.07546)



Neural Network

For each neural, the corresponding result is $z = \sum_i f(w_i x_i + b)$, we do this for every neural for each layers. This is called the forward propagation.

Then we compute the loss function. For a classifier, it corresponds to the binary cross entropy : $BCE(x) = -\sum y_n \ln(x_n) + (1 - y_n) \ln(1 - x_n)$. Then, we perform a backpropagation, corresponding to the correction of the weights such that the loss function can be minimized.

