Master’s Study: Hunting the Higgs with an Adversary

New approach to **background sculpting** in the **Higgs diphoton decay channel**

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Outline

- **Motivations for the study:**
  - Measurements of Higgs to vector boson coupling strength
  - Diphoton channel for precision measurements
- **The study:**
  - Problem of background sculpting in diphoton channel
  - ATLAS solution
  - My solution (method, adversary, optimization)
  - Comparing adversarial network vs ATLAS (sculpting, performance)

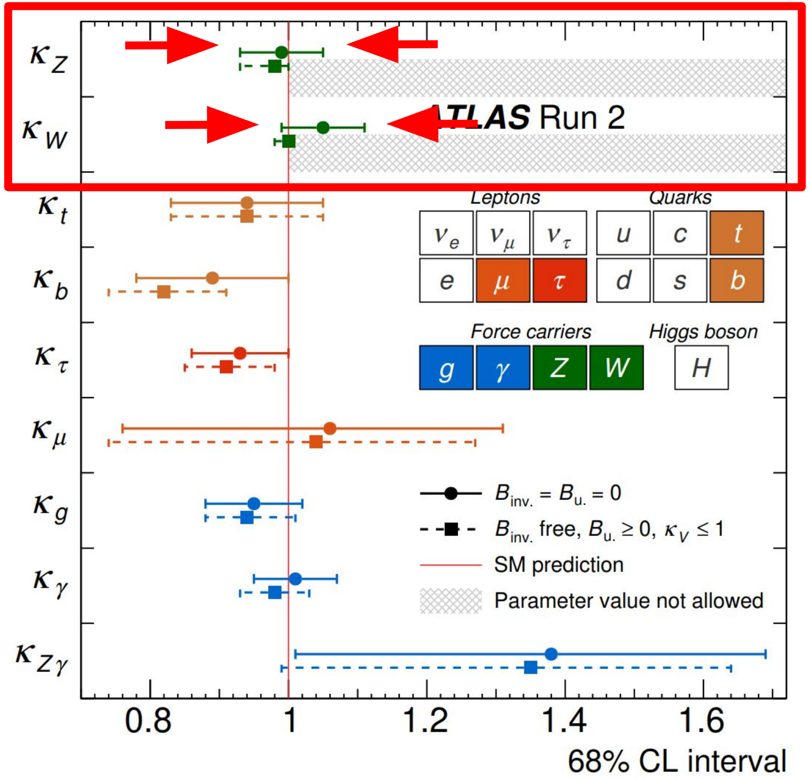
Vector-boson fusion Higgs production

VV scattering diverges with CoM energy

Higgs VV contribution exactly **cancels out divergence**

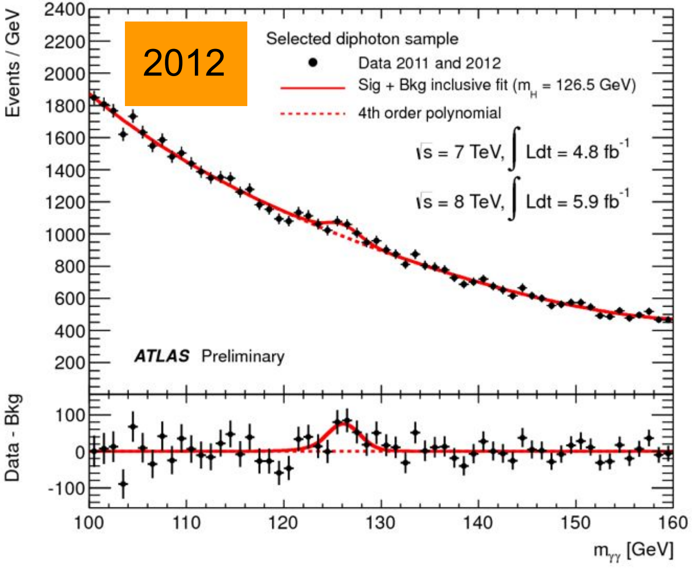
Measuring Higgs to vector boson coupling strengths is a **powerful test for the SM**

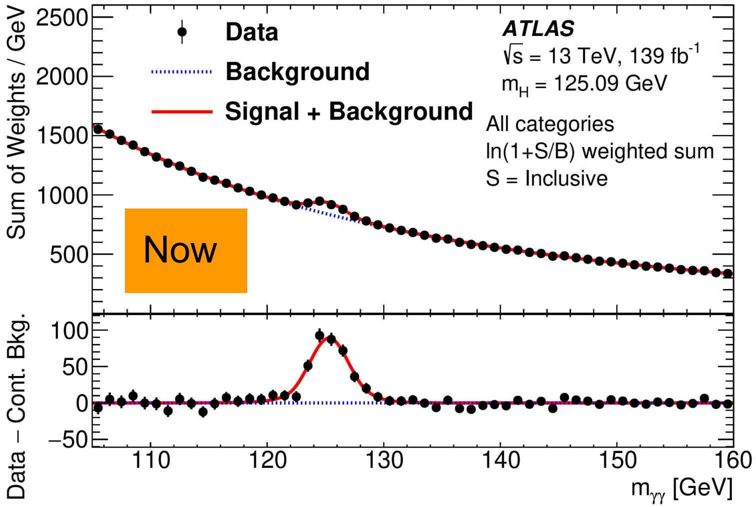
Solution: Improve classification of vector-boson fusion (VBF) Higgs events



http://cds.cern.ch/record/2814946

Higgs discovery: diphoton decay channel





First signs of Higgs in diphoton channel

Two **well reconstructed** photons, **accurately measured** kinematics

Effective background rejection

More data ⇒ **reduced statistical uncertainty**

Significant contribution to current Higgs measurements

https://cds.cern.ch/record/2627611 http://cds.cern.ch/record/2814946

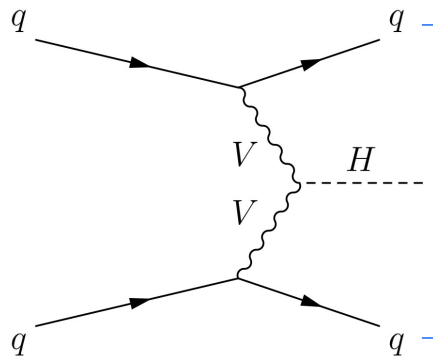
VBF Higgs to diphoton combined

Signal forms clear detector signature

VBF forms two energetic jets

Higgs forms two energetic photons

⇒



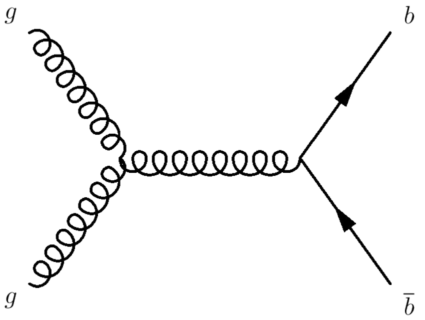
→ Jet

2 photons

→ Jet

Background formed of many combinations that radiate VBF-like jets and two photons

⇒



→ Also Jet

2 photons from other event processes

→ Also Jet

https://atlas.cern/glossary/vector-boson-fusion

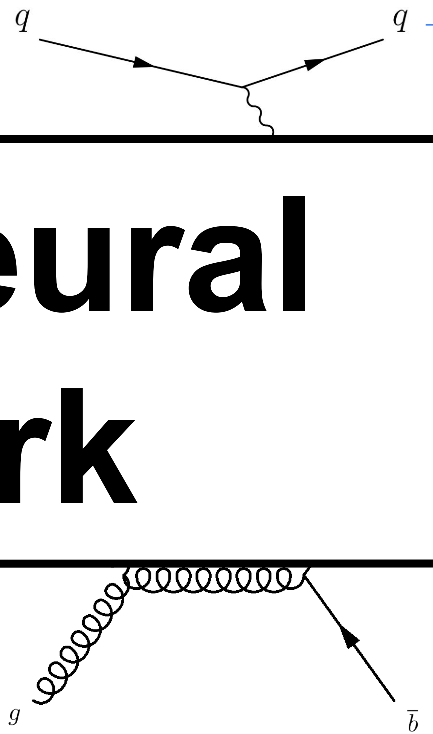
VBF Higgs to diphoton combined

Signal forms clear detector signature

VBF forms

Higgs form

Backgroun
combinations that radiate VBF-like jets and two photons ⇒



→ Jet

2 photons

Jet

→ Also Jet

photons from other event processes

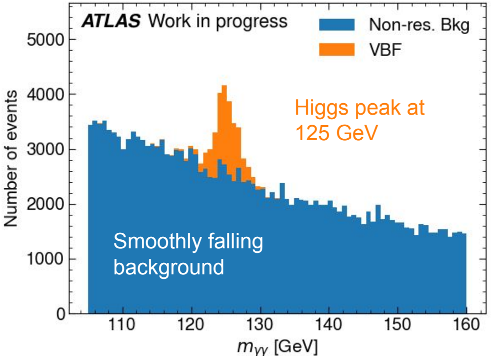
→ Also Jet

Apply Neural Network

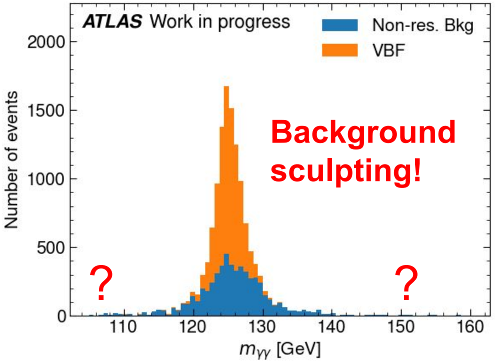
https://atlas.cern/glossary/vector-boson-fusion

Problem: Background sculpting

Original simulated distributions



Biased classification



Uncertainties in modelling of the background using **non-signal regions**

Leads to **uncertainty in number of VBF events** in signal region

Reason: **Correlations** between **background variables** and **diphoton mass**

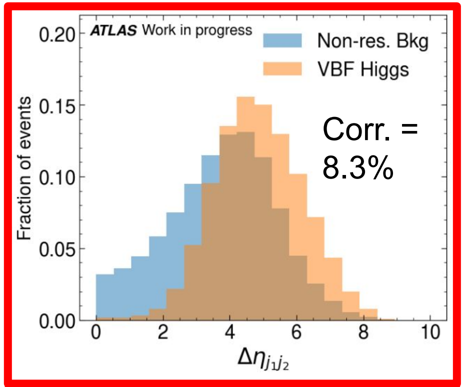
Performing mass de-correlation (ATLAS)

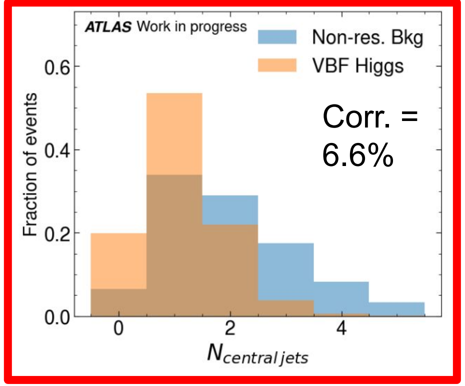
Current solution: **Removing variables** with mass correlation > 5%

No information left for classifier to learn mass

Problem: **Only ⅓ of features left** to train classifier

Limits classifier from learning differences between signal and background





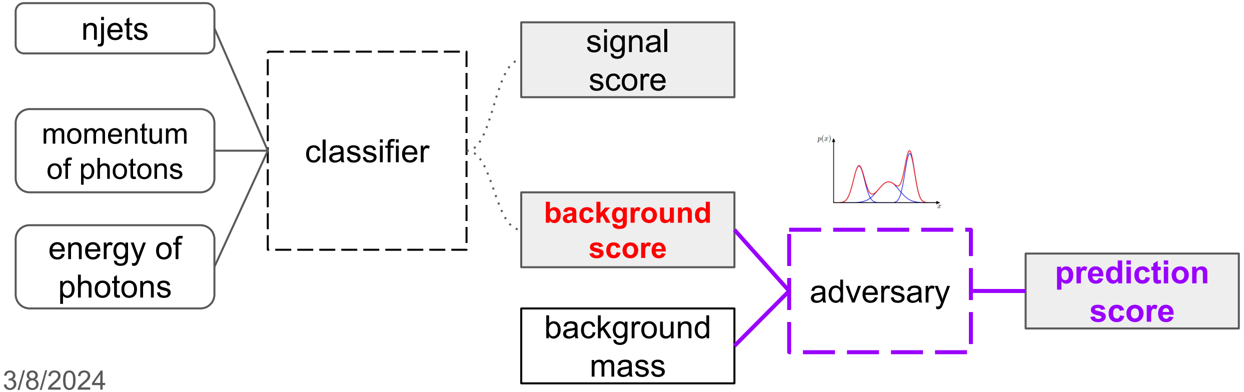
Performing mass de-correlation (This study)

Improved solution: **Adversarial network** linked in **series** with classifier ⇒ **monitor sculpting**

Adversary builds **Gaussian mixture model** (GMM) to **predict** the **background invariant mass** given the **background score**

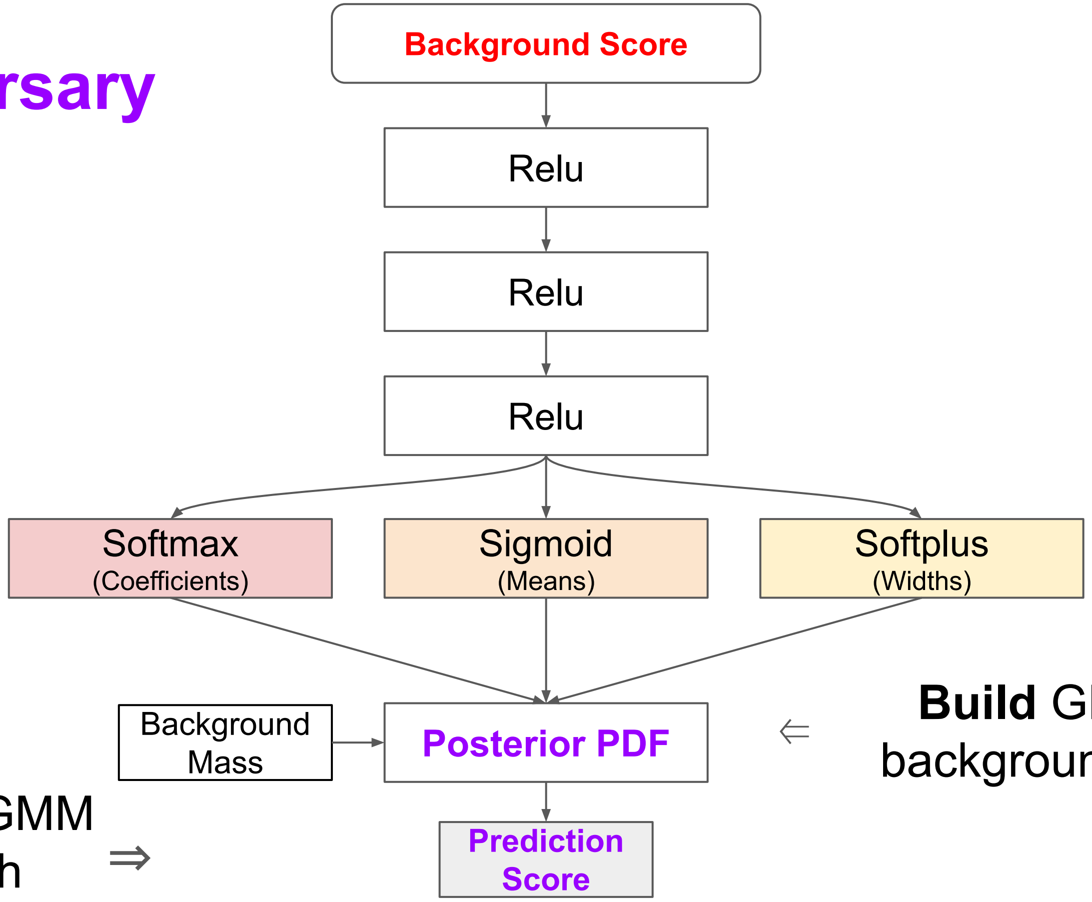
If **GMM predicts** the **background mass** from the **score**: **background sculpting** is happening

Adversary increases loss via **higher prediction score**: **information about $m_{\gamma\gamma}$ unlearned**



More info at: ATL-PHYS-PUB-2018-014

The Adversary



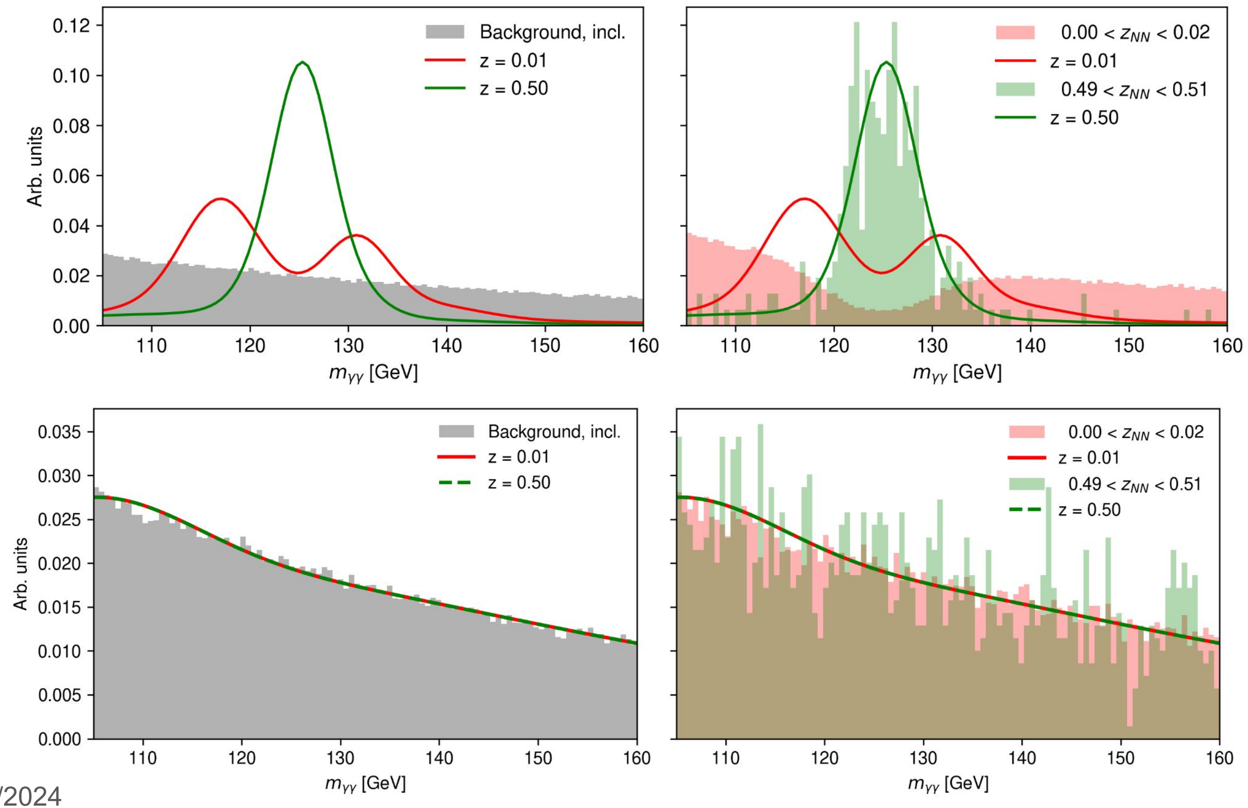
⇐ **Build** GMM of background mass

Compare GMM with truth background mass ⇒

Sculpting performance

Classifier
Only

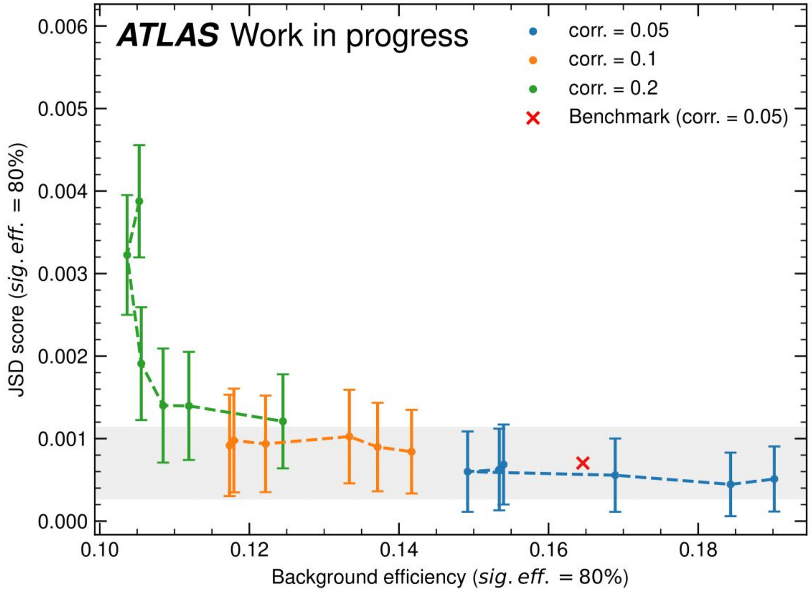
Classifier
+
Adversary



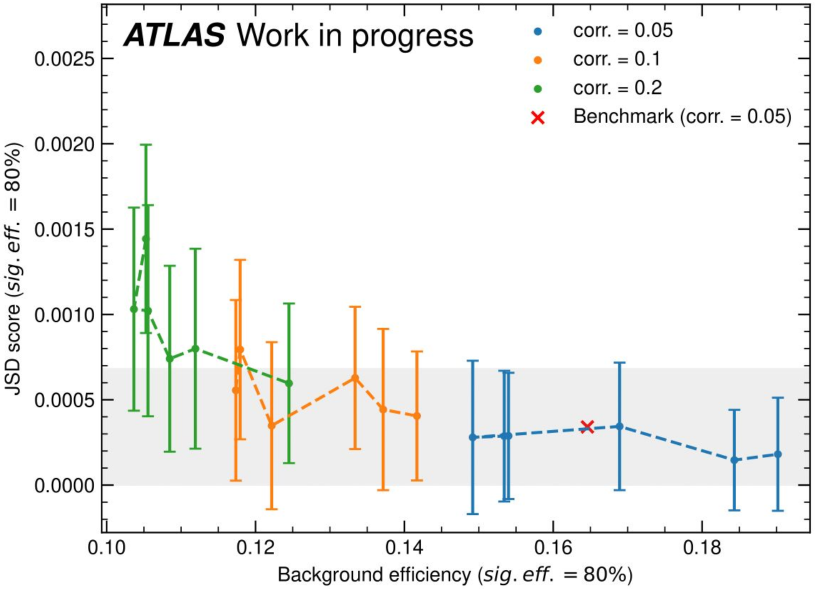
Optimising the ANN

Parameter	Value	Selected value
Training set correlation	[0.05, 0.1, 0.2]	0.1
Regularisation strength	[0.1875, 0.375, 0.75, 1.5, 3, 6]	0.1875

Inclusive region



Higgs region



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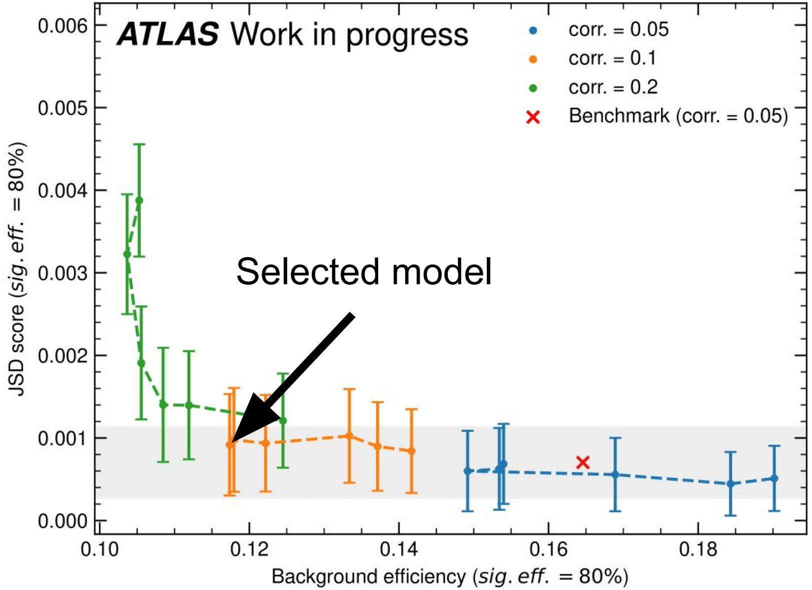
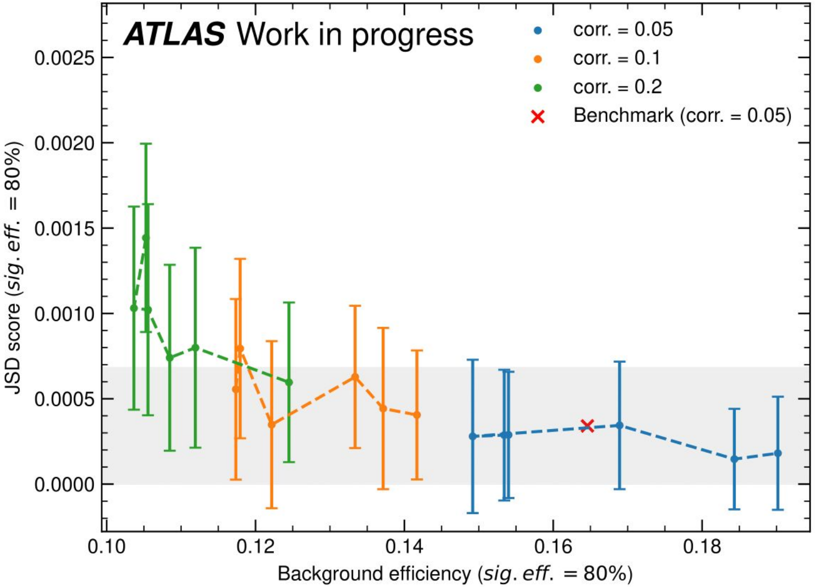


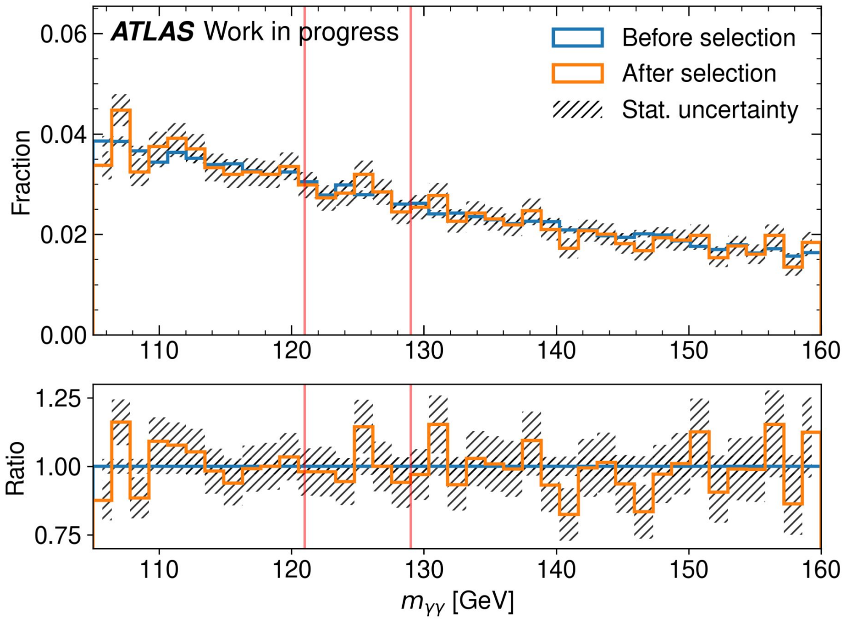
Higgs region



Comparing ANN with ATLAS solution

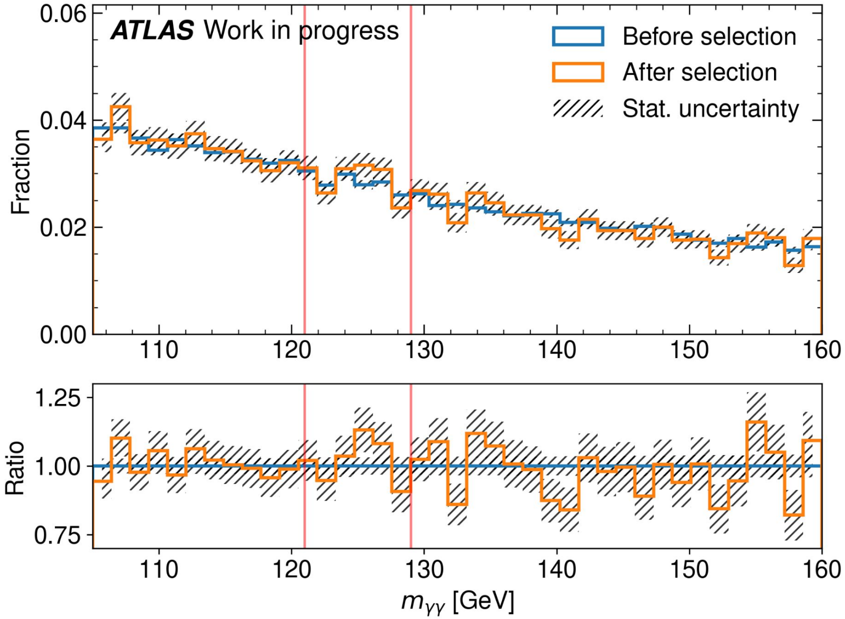
ANN solution

80% signal eff.



ATLAS solution

80% signal eff.



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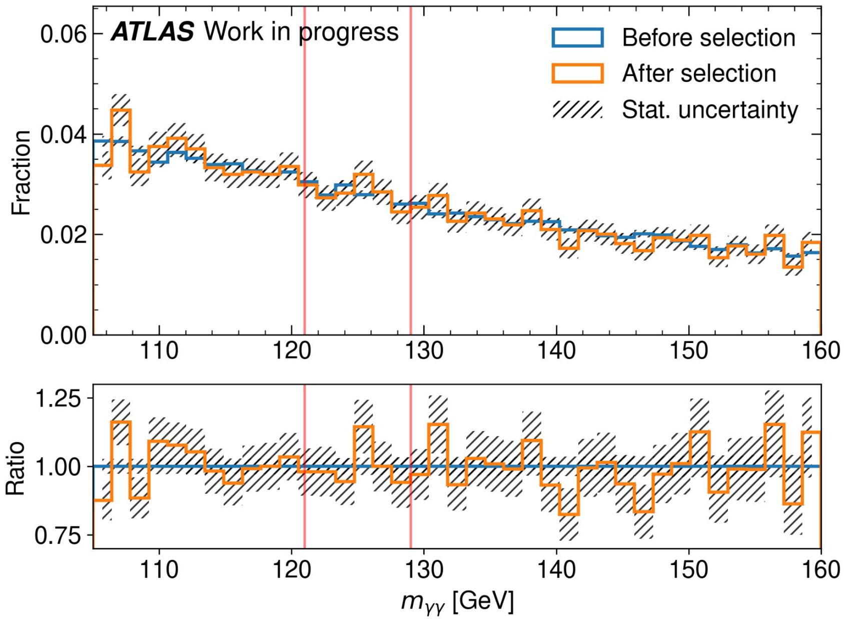
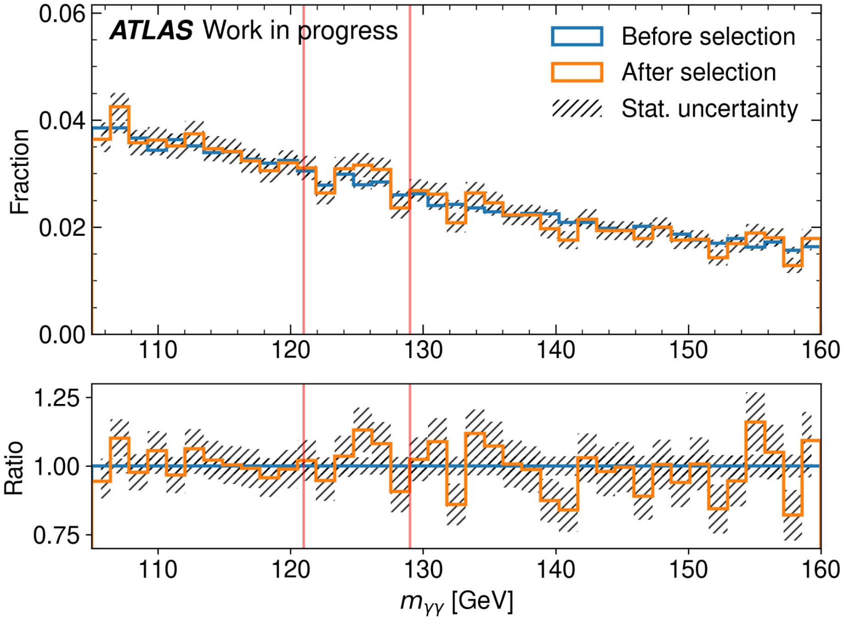


JSD inclusive = **9±6 × 10^{-4}**

JSD Higgs = **6±5 × 10^{-4}**

ATLAS solution

80% signal eff.



JSD inclusive = **7±4 × 10^{-4}**

JSD Higgs = **3±3 × 10^{-4}**

Comparing ANN with ATLAS solution

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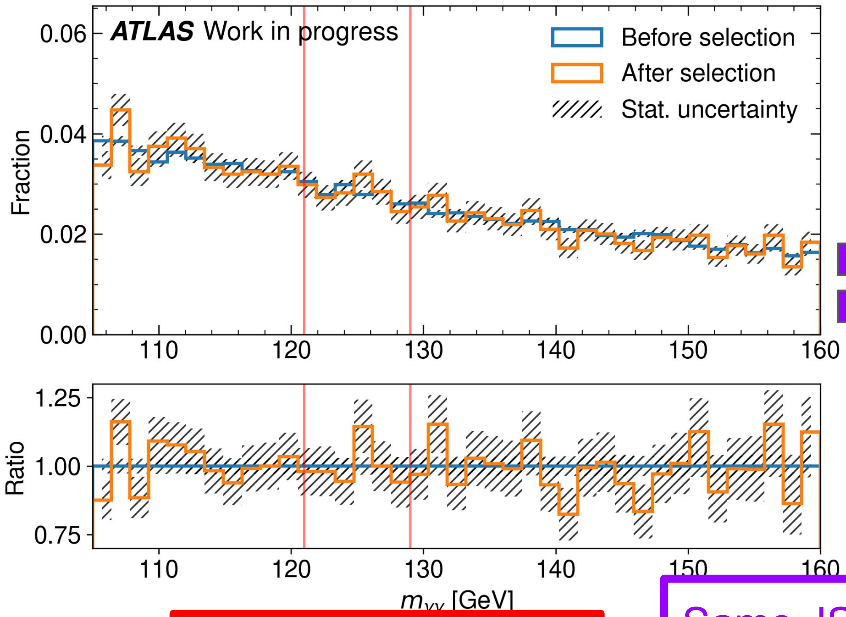
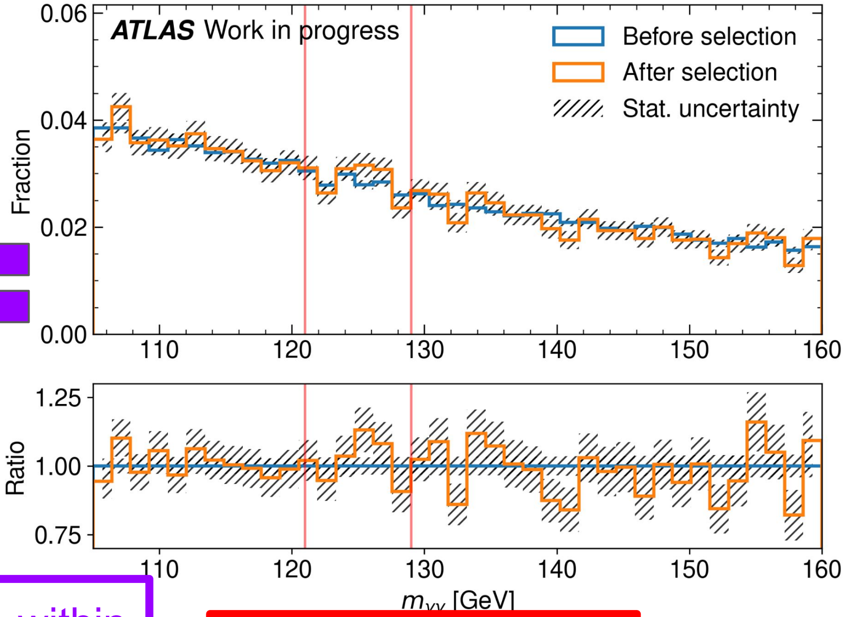


ATLAS solution 80% signal eff.



JSD inclusive = **9±6** × **10^{-4}**

JSD Higgs = **6±5** × **10^{-4}**

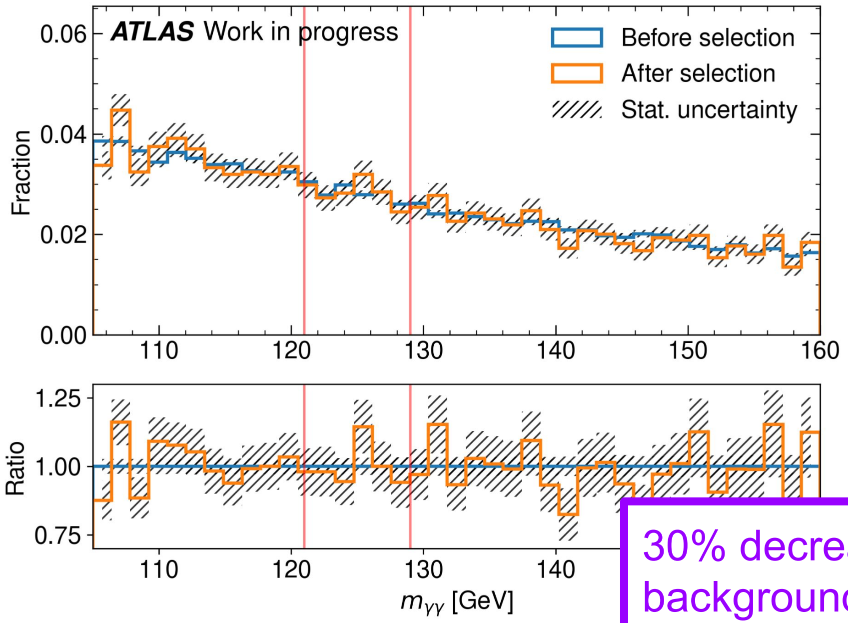
Same JSD to within uncertainty

JSD inclusive = **7±4** × **10^{-4}**

JSD Higgs = **3±3** × **10^{-4}**

Comparing ANN with ATLAS solution

ANN solution 80% signal eff.

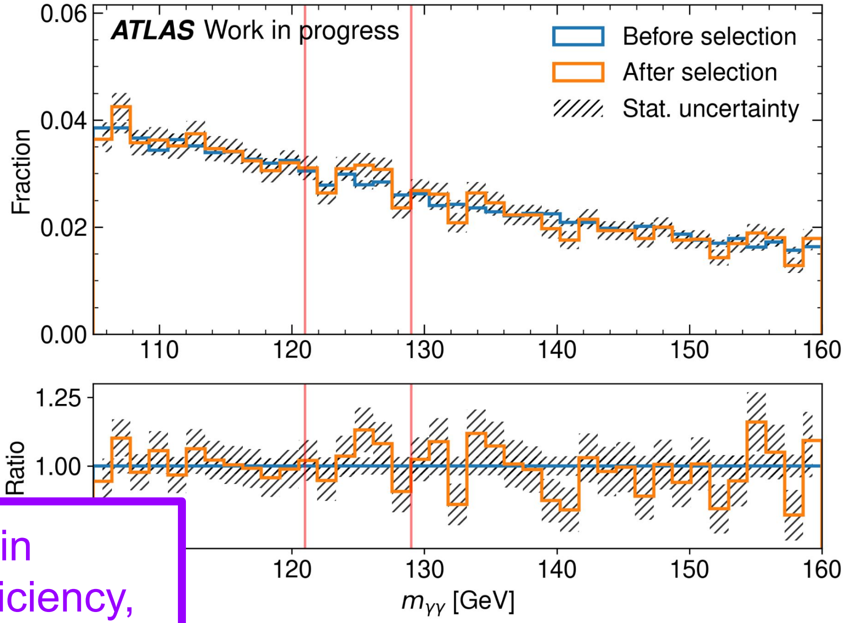


JSD inclusive = **9±6** $\times$ **10^{-4}**

JSD Higgs = **6±5** $\times$ **10^{-4}**

Background efficiency = **0.117**

ATLAS solution 80% signal eff.



30% decrease in background efficiency, same level of sculpting

<

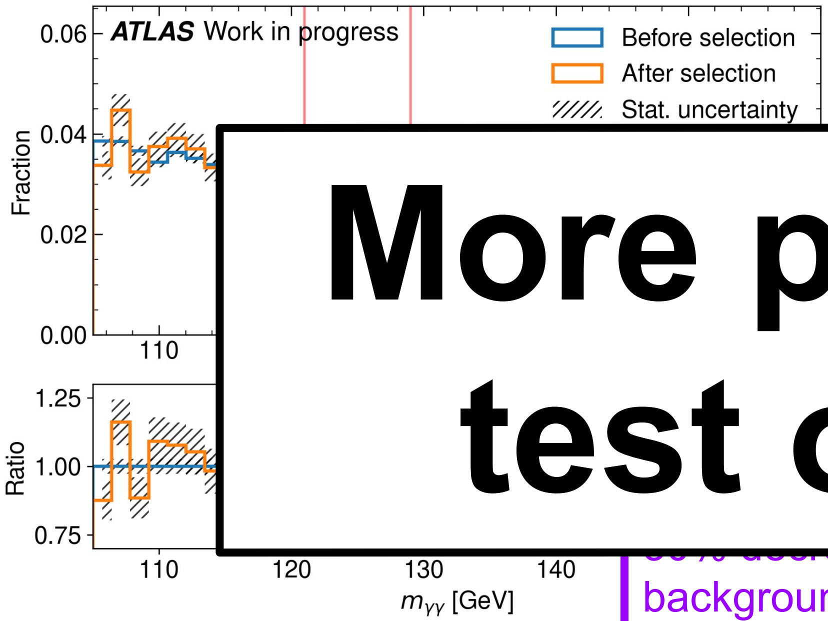
JSD inclusive = **7±4** $\times$ **10^{-4}**

JSD Higgs = **3±3** $\times$ **10^{-4}**

Background efficiency = **0.165±0.002**

Comparing ANN with ATLAS solution

ANN solution 80% signal eff.



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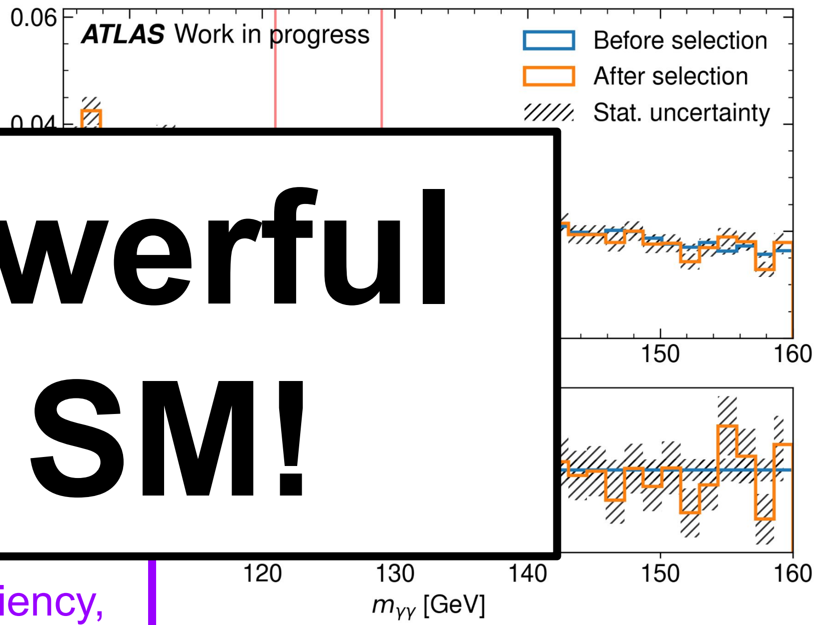
ATLAS solution 80% signal eff.



JSD inclusive = **7±4 × 10^{-4}**

JSD Higgs = **3±3 × 10^{-4}**

Background efficiency = **0.165±0.002**

background efficiency,
same level of sculpting

<

More powerful test of SM!

Summary

Background sculpting in Higgs diphoton channel introduces uncertainties

Adversarial network implemented for **active mass de-correlation**

New approach allows to **use more correlated variables**

30% higher signal purity over ATLAS, same level of sculpting

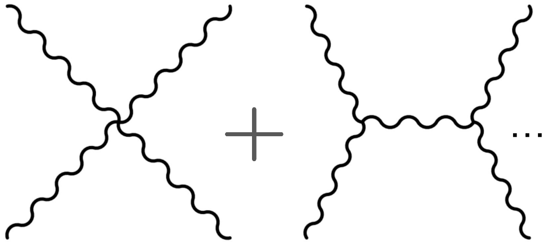
Reduces VBF uncertainties, **more powerful test of SM**

Backup

Vector-boson fusion Higgs motivation (cont.)

Higgs in SM solves diverging VV scattering

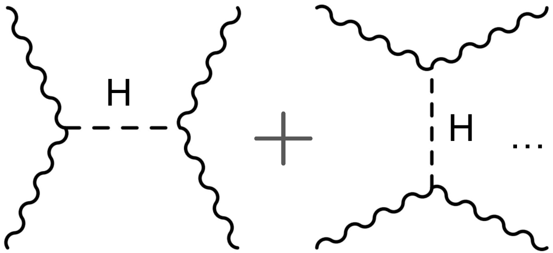
No Higgs



$$\mathcal{M}_{NoHiggs}\left(W_L^+W_L^+ \to W_L^+W_L^+\right) = -g^2\frac{S}{4M_W^2}$$

$S = (\text{CoM energy})^2$

With Higgs



$$\mathcal{M}_{Higgs}\left(W_L^+W_L^+ \to W_L^+W_L^+\right) = g_{HWW}^2\frac{S}{M_W^4}$$

$g_{HWW} = \frac{gM_W}{2}$

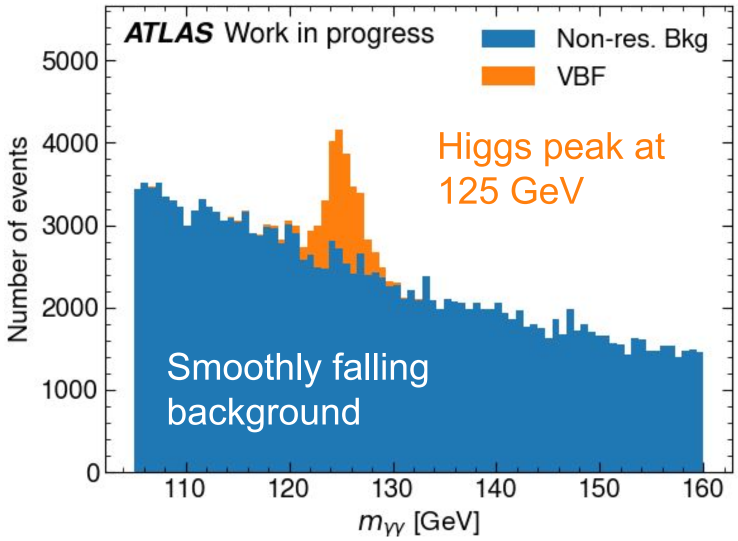
Similarly for diverging ZZ scattering…

Divergent terms exactly cancel to provide finite value!
Higgs coupling strength to vector bosons extremely sensitive to new physics!

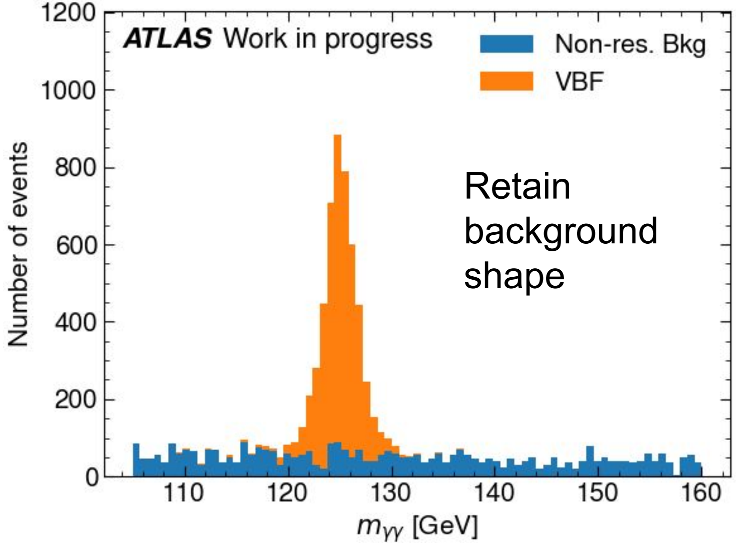
Ideal background classification

Signal and background obtained through simulated LHC collisions and ATLAS detector response

Original simulated distribution



Ideal classification



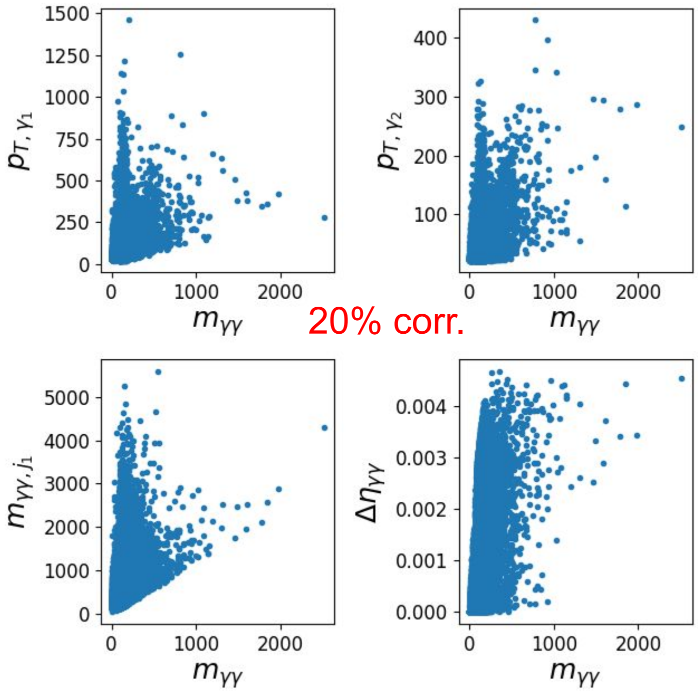
Why does background sculpting happen?

Reason: Many background features are **highly correlated** with the **mγγ**

Take the network's perspective:

- Network uses these correlations to **learn mγγ**
- Good performance = **accept everything in Higgs region**

30% corr.



20% corr.

Note on size of lambda

$$L_{modified} = L_{clf} - \lambda L_{adv}$$

Lambda controls how strongly to penalise weight updates when sculpting is detected

- **Too small** lambda would allow some mass information to still be learned

  ⇒ Sculpting begins to take place

- **Too large** lambda would over-penalise weight updates even for statistical fluctuations

  ⇒ Stunting training process

Performance metrics

Discriminating power:

- Background efficiency at 80% signal efficiency

Level of background sculpting:

- Measure entropy (difference) between original and accepted background distributions
- Jensen-Shannon divergence was used (Symmetrised version of Kullback-Leibler divergence)
- Report entropy for **inclusive region (105 GeV to 160 GeV)** and **Higgs region (121 GeV to 129 GeV)**

$$\boxed{\mathrm{KL}(P\|Q) = -\sum_i P_i \log\left(\frac{Q_i}{P_i}\right)}$$

JSD Score

JSD is the sculpting metric used in the ATLAS analysis

Find **entropy** between distributions P and Q

Symmetrised version of KL divergence

$$\mathrm{JSD}(P\|Q) = \frac{1}{2}\mathrm{KL}(P\|M) + \frac{1}{2}\mathrm{KL}(Q\|M)$$

$$\text{where } M = \tfrac{1}{2}(P+Q)$$

Difference between this ANN and a GAN

In a **GAN** there is a **generator** network and an **discriminator** network

Generator tries to **replicate** data while **discriminator** tries to **distinguish** between **real** data and **fake** data

In our study we do not try to replicate data

We instead **use an adversary to control the background sculpting** of a classifier based on its classification of background events

GAN = make good counterfeit data

This ANN = stop classifier from exploiting mass correlation