

# Hyperparameter Optimisation of an Adversarial Neural Network in the tW channel at 13 TeV with ATLAS

Christian Kirfel

4th of April 2019

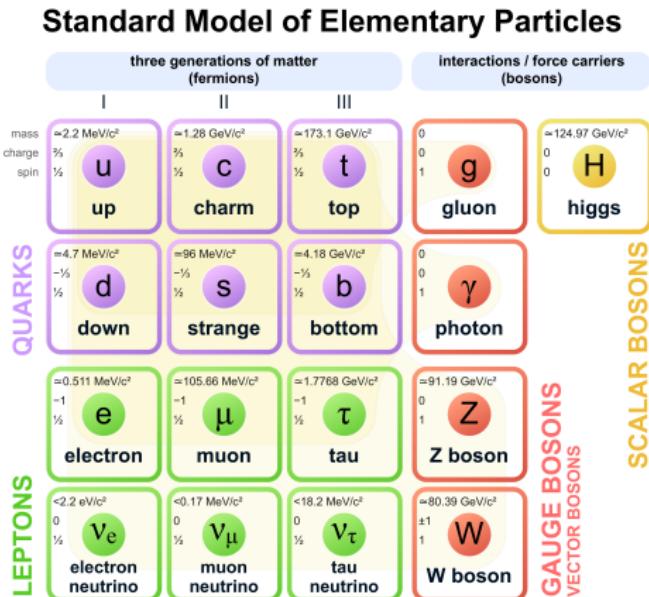
# Outline

---

- The Standard Model of particle physics
- Introducing the tW channel
- The LHC and the ATLAS detector
- Neural networks in particle physics
- Results for different approaches of adversarial neural networks

# The standard model of particle physics

---

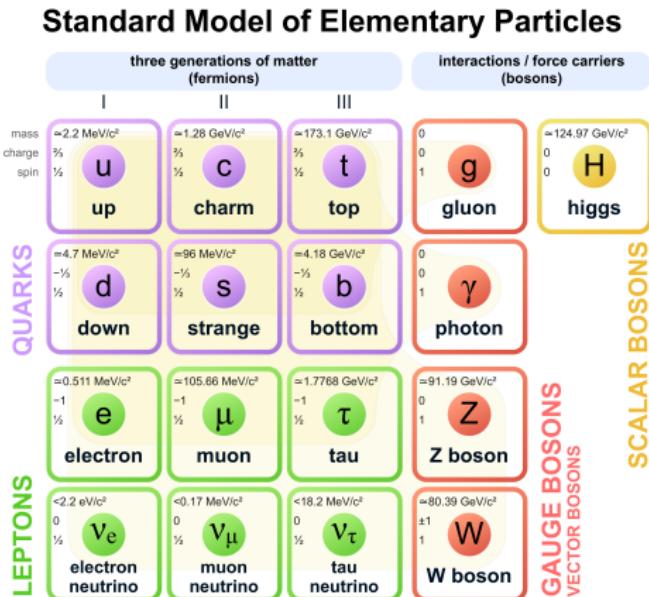


## The top-quark

- $m \sim 173 \text{ GeV}/c^2$
- $\tau \sim 5 \times 10^{-25} \text{ s}$
- Lifetime < typical hadronisation time
- Decay into a b-quark and a W-boson

# The standard model of particle physics

---

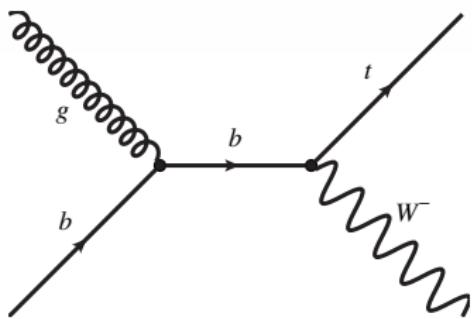


## The top-quark

- $m \sim 173 \text{ GeV}/c^2$
- $\tau \sim 5 \times 10^{-25} \text{ s}$
- Lifetime < typical hadronisation time
- Decay into a b-quark and a W-boson

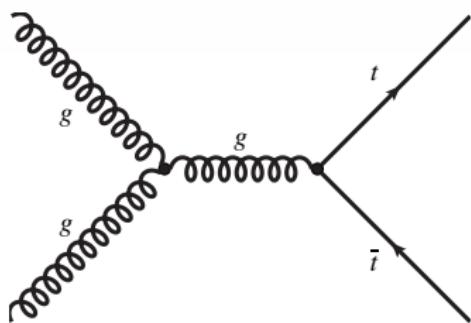
# Top production

tW single top production



- Via weak interaction
- Relatively small cross-section

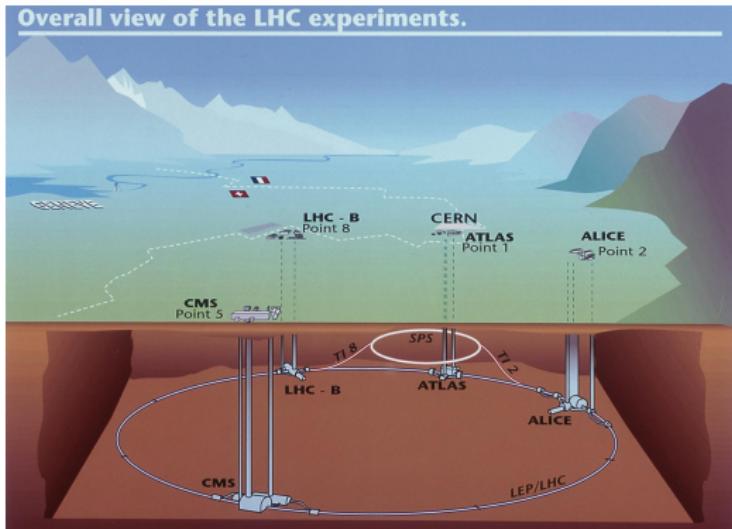
t̄t pair production



- Via strong interaction
- More than 10 times the cross-section

# The Large Hadron Collider - LHC

Overall view of the LHC experiments.

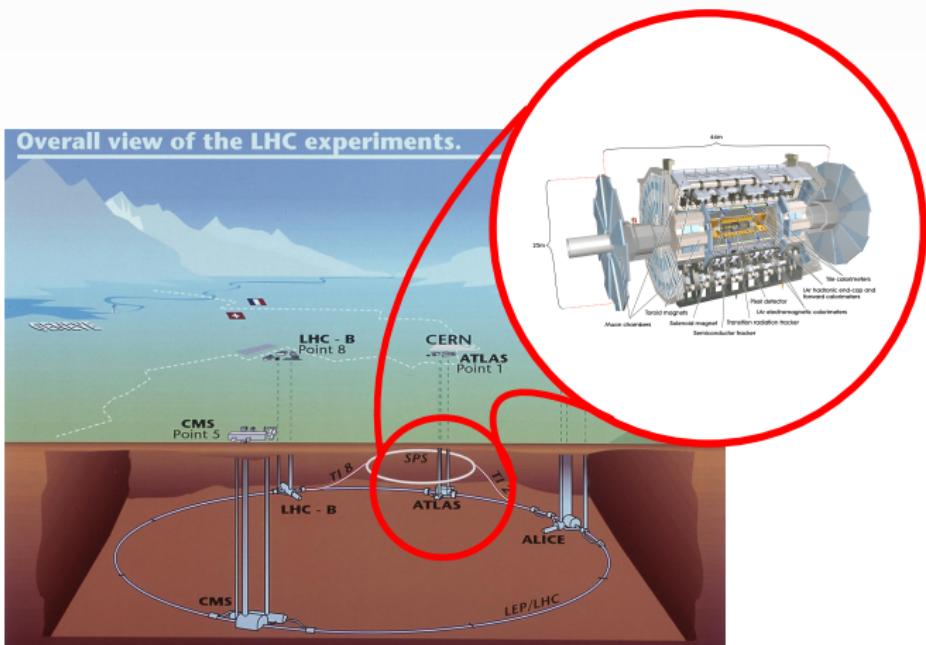


- Proton-proton collider
- $\sim 27$  km circumference

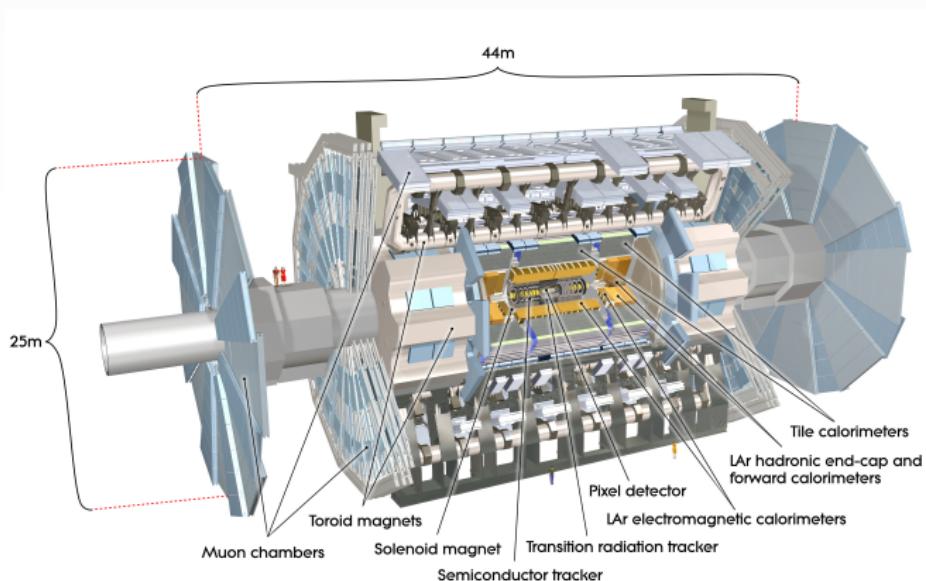
$$E_{CM} = 13 \text{ TeV}$$

$$\mathcal{L} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

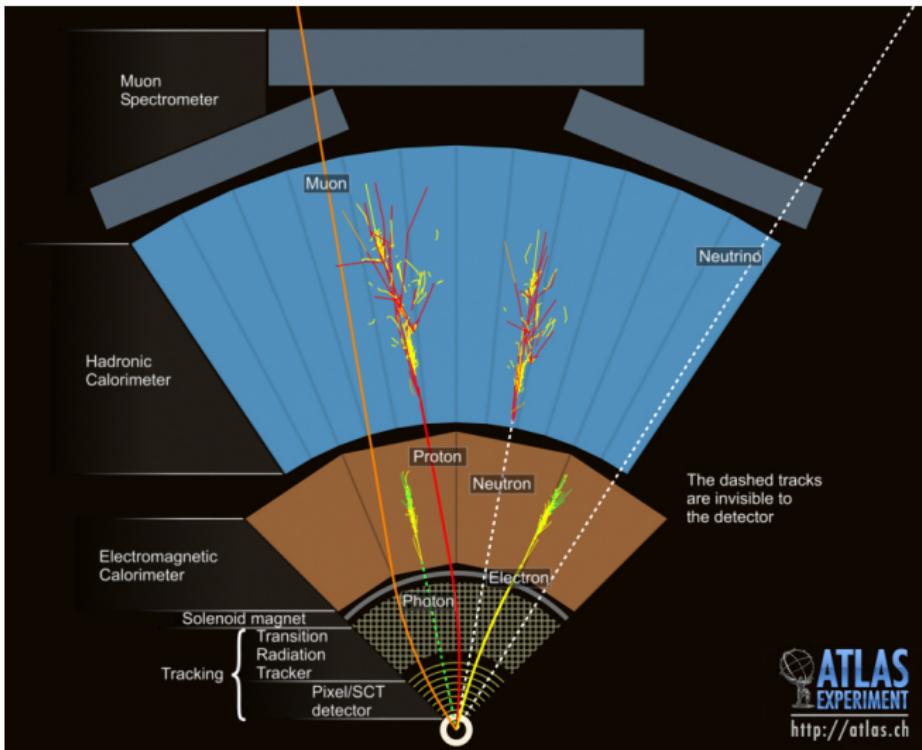
# The ATLAS experiment



# ATLAS - a general purpose detector

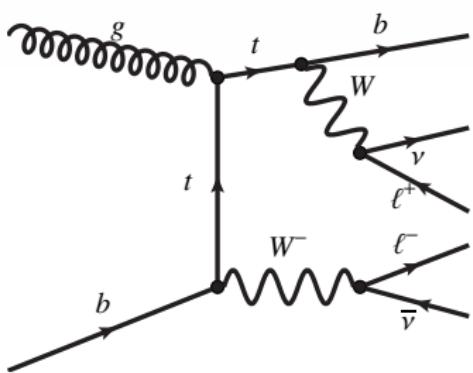


# ATLAS - object identification

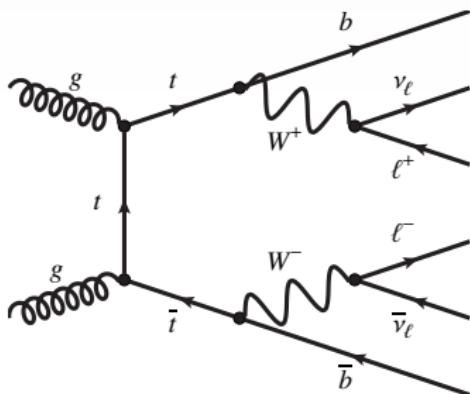


# tW to $t\bar{t}$ separation at LO

tW decay



$t\bar{t}$  decay



- $\sigma_{tW} \sim 71.7 \text{ pb}$
- 2 W, 1 b

- $\sigma_{t\bar{t}} \sim 832 \text{ pb}$
- Final state: 2 W, 2 b

# Challenge 1 - Signal to background separation

## Problem 1

- Separation of signal to background
- Signal:  $tW$
- Background:  $t\bar{t}$

## Classic approach

- Applying a cut selection

## Alternative

- Machine Learning
- In particular: Classifying neural network

# Artificial neural network

# Neural Networks - Processing information



Human senses

- Extraction of relevant info
- Impossible for machines

Human brain

- Web of neuron cells
- Input from surrounding cells
- Single combination → action



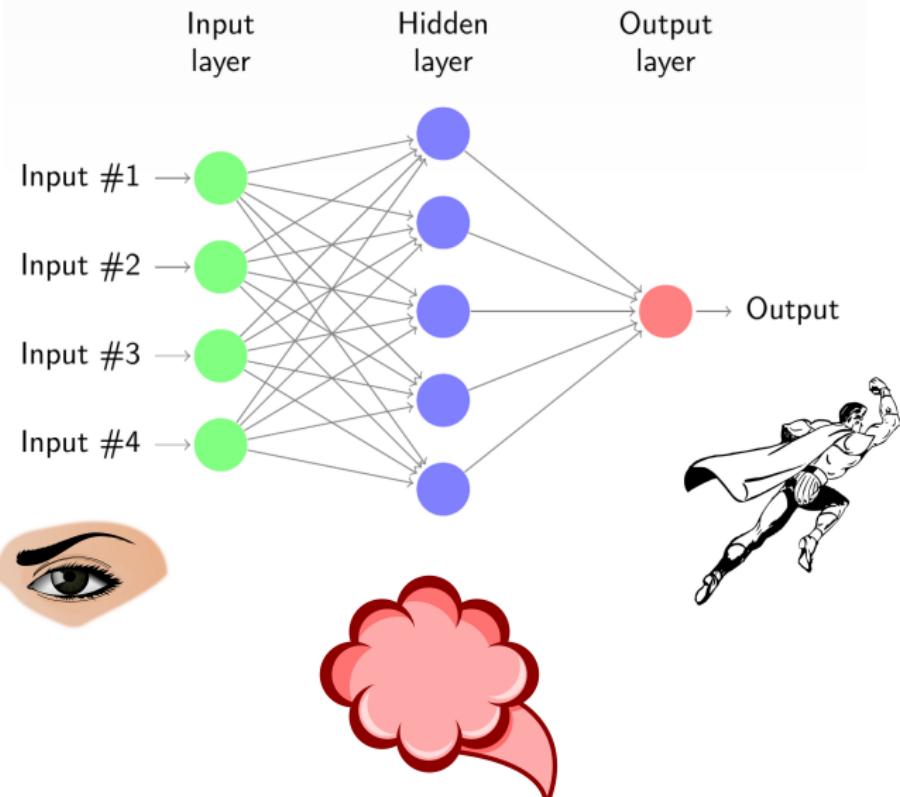
Input variables

- Preprocessed by user
- e.g. kinematic variables

Net of nodes

- Nodes = simple processors
- Connected by linear function
- Combination forms non-linear model

# Neural network structure



# Neural Networks - Choosing the next step



Evaluation of an action

- Simple perceptions: pain, satisfaction
- Expectation

Decision for a next step

- Trial and error
- Learning from experience



Loss function

- Supervised learning: compare to the desired outcome
- Loss = estimator for quality

Optimisation

- Back-propagation impact of parameters' on the loss
- Adjust parameters to minimise plot

# Classifier training

# Parameters and hyper-parameters

## Parameters

- Affected during training
- Mainly: weight and bias

## Hyper-parameters

- Set before the training
- Optimisation by testruns
- Nodes, Layers, optimiser, momentum, activation.....

## Learning rate

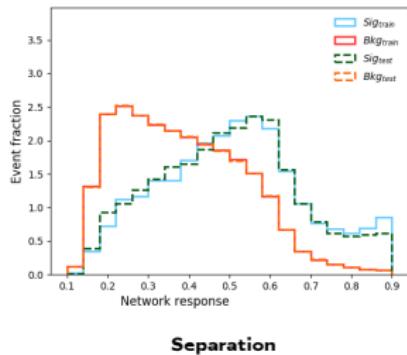
- Step-parameter of the optimiser
- Large: Oscillations
- Small: Inefficient training

## Setup of the classifier

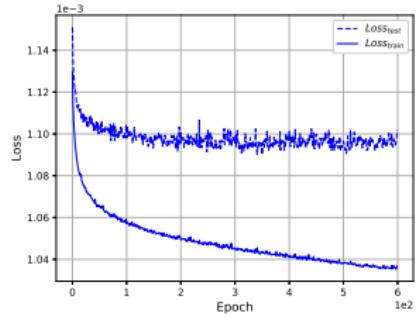
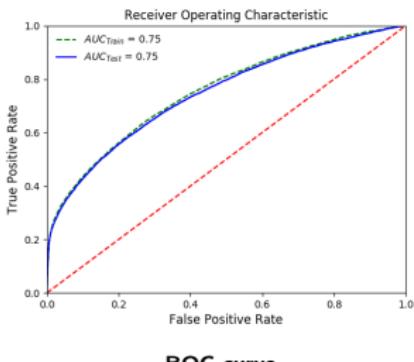
### Hyper-parameter scan results

- Input: 14 variables motivated by a BDT variable scan.
- Hidden layers: 6 elu layers  $\times$  128 nodes each
- Output layer: 1 sigmoid node
- Optimisation: SGD, **learning rate = 0.06**, momentum = 0.3, no nesterov, no decay
- Duration: 600 epochs

# Simple network results



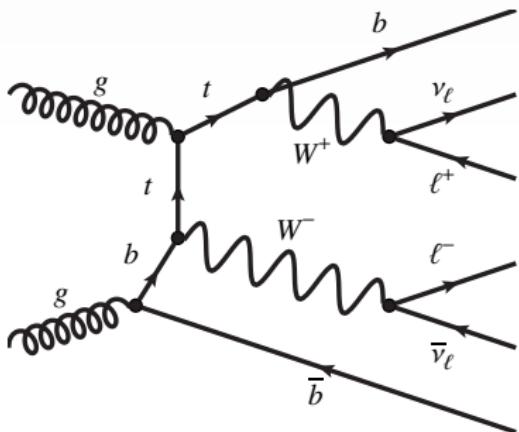
Separation



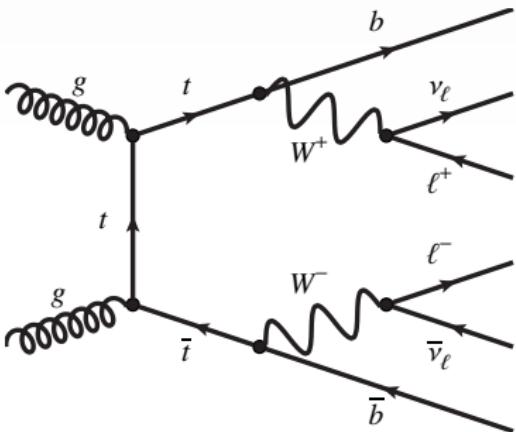
Losses

# tW to $t\bar{t}$ separation at NLO

tW decay at NLO



$t\bar{t}$  decay



- Identical final state
- Especially problematic in 2j2b region

- Interference at NLO
- Different Monte Carlo generators

## Interference in Monte Carlo

### Amplitude

$$\begin{aligned} |\mathcal{A}|^2 &= |\mathcal{A}_{tW}|^2 + 2\mathcal{R}\{\mathcal{A}_{tW}\mathcal{A}_{t\bar{t}}^*\} + |\mathcal{A}_{t\bar{t}}|^2, \\ &\equiv \mathcal{S} + \mathcal{I} + \mathcal{D}. \end{aligned}$$

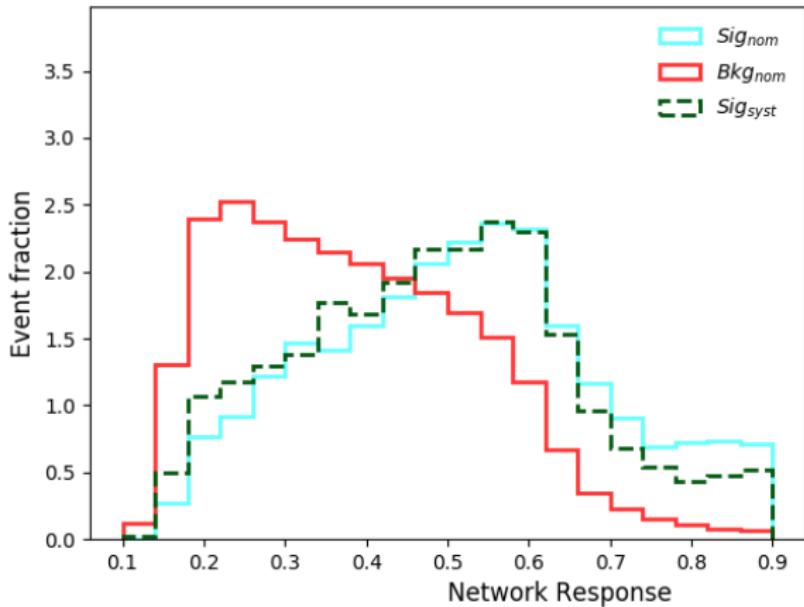
### Diagram Removal - DR

$$|\mathcal{A}_{DR}|^2 = \mathcal{S}.$$

### Diagram Subtraction - DS

$$\begin{aligned} |\mathcal{A}_{DS}|^2 &= \mathcal{S} + \mathcal{I} + \mathcal{D} - \tilde{\mathcal{D}}, \\ &\approx \mathcal{S} + \mathcal{I}. \end{aligned}$$

## Sensitivity to systematic uncertainty



# Adversarial Neural Network

## Challenge 2 - Sensitivity to systematic uncertainties

### Problem 2

- Minimal sensitivity to the systematic uncertainty
- Nominal:  $tW\_DR$ , ( $t\bar{t}$ )
- Systematic:  $tW\_DS$

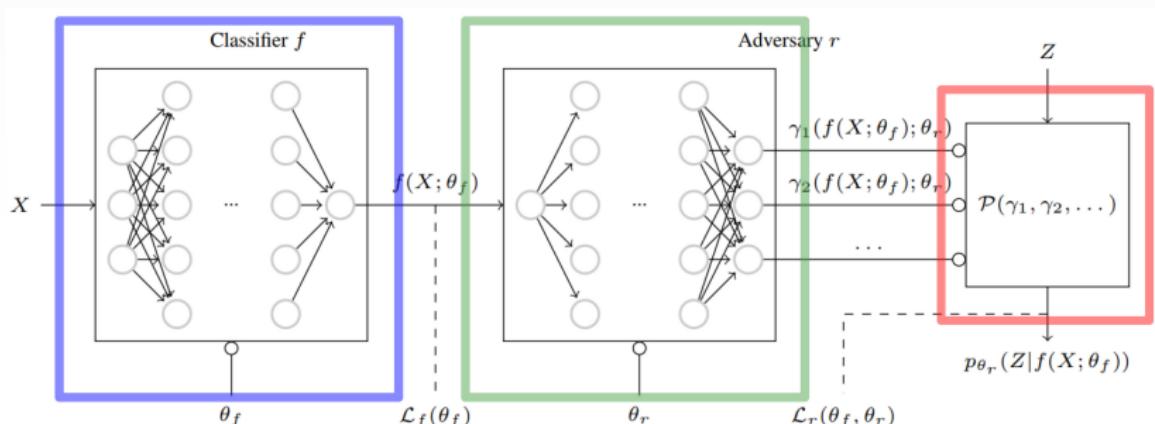
### Presented solution

- Addition of a second classifier for nominal to systematics separation
- Bad performance → low sensitivity

### Implementation

- Feed output into a second net
- Iterative training
- Combined loss function → Minimax problem

# Adversarial neural network

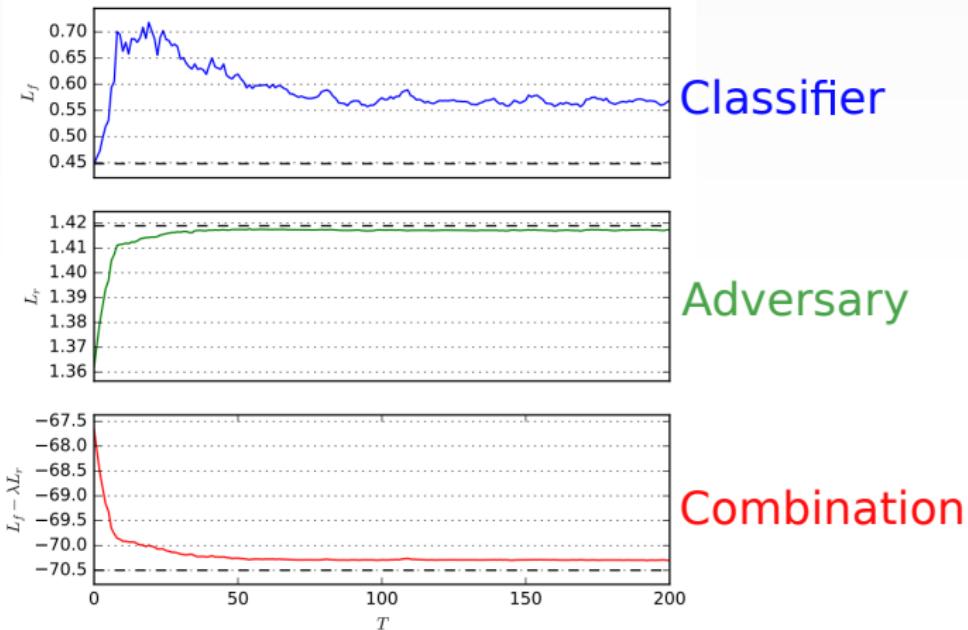


(arXiv:1611.01046)

$$\mathbb{E}(\theta_f, \theta_r) = \mathcal{L}_f(\theta_f) - \lambda \mathcal{L}_r(\theta_f, \theta_r)$$

# Expected ANN losses

LOSS



## Training time

(arXiv:1611.01046)

# Adversarial training

# Approach 1

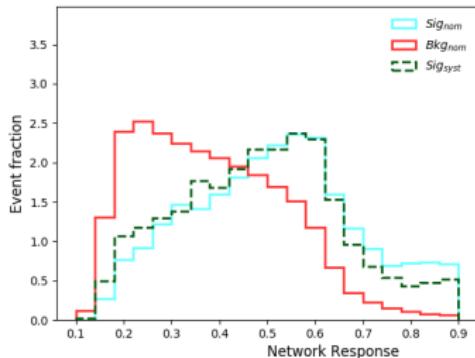
## Run 1

- Same hyper-parameters for both networks
- Adversary uses only 3 layers

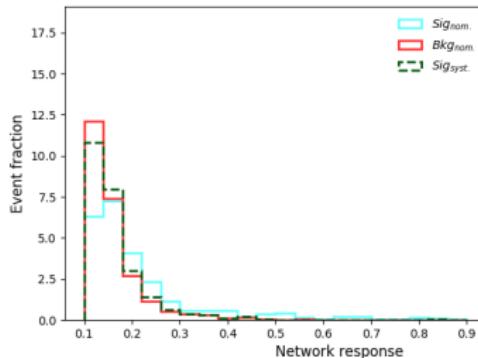
## Setup

- Input: Classifier output
- Hidden layers: 3(6) elu layers  $\times$  128 nodes each
- Output layer: 1 sigmoid node
- Optimisation: SGD, learning rate = 0.06, momentum = 0.3, no nesterov, no decay
- Duration: 400 iterations
- $\lambda = 10$

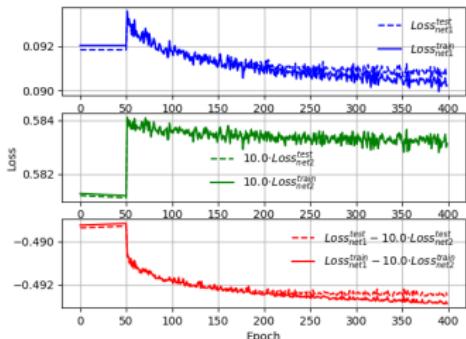
# Approach 1 - Run 1 - Results



Simple



Adversarial



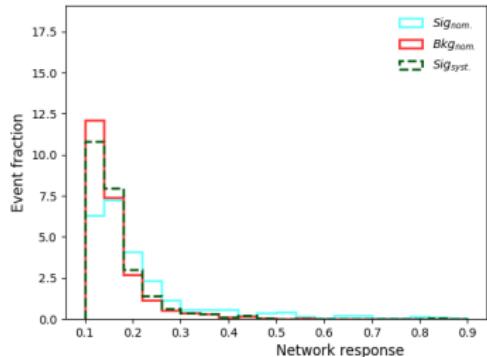
- Inferior separation
- Only combined losses depend on  $\lambda$
- Systematics drawn to background

# Approach 1 - Optimisation

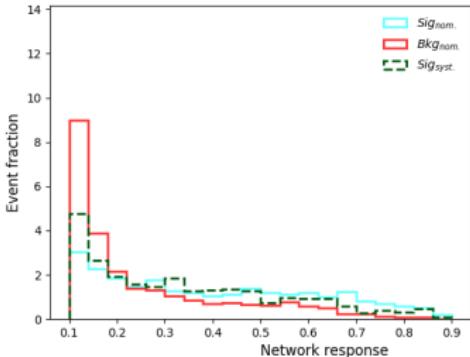
## Setup of the adversary

- Input: Classifier output
- Hidden layers: 3 elu layers  $\times$  32 nodes each
- Output layer: 1 sigmoid node
- Optimisation: SGD, **learning rate** = 0.001, momentum = 0., no nesterov, no decay
- Duration: 400 iterations
- $\lambda = 0.1$

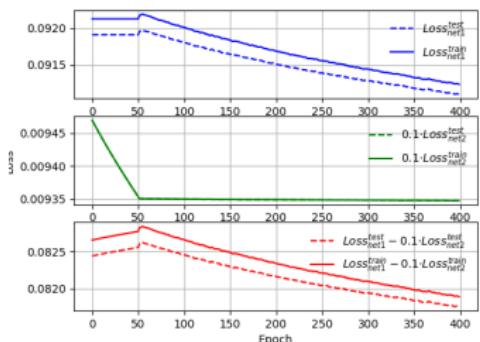
# Approach 1 - Run 2 - Results



Run 1

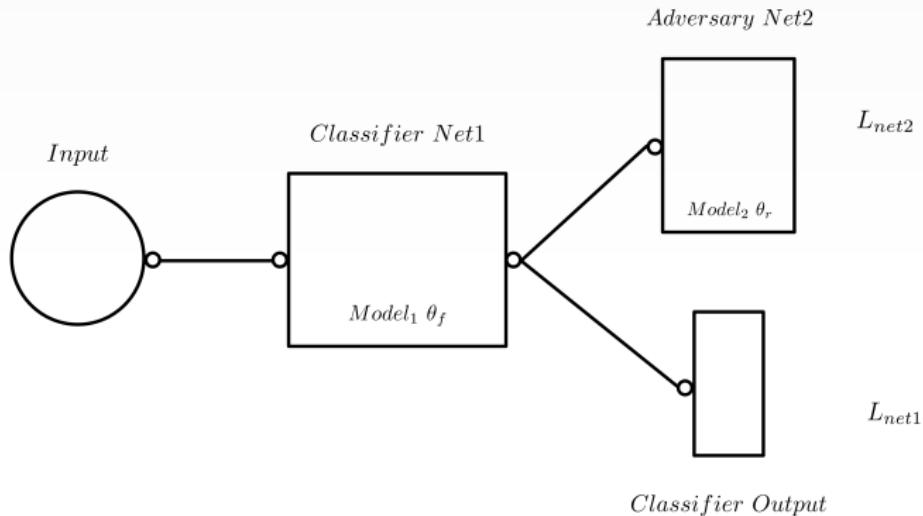


Run 2



- Improved separation
- Slightly improved sensitivity
- Only combined losses depend on  $\lambda$

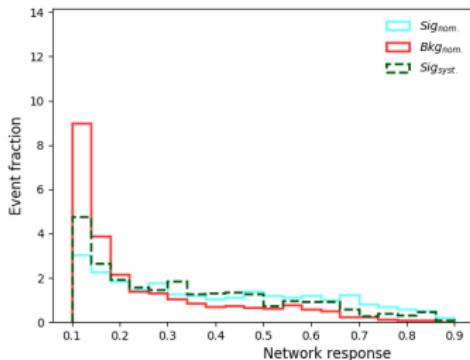
## Approach 2



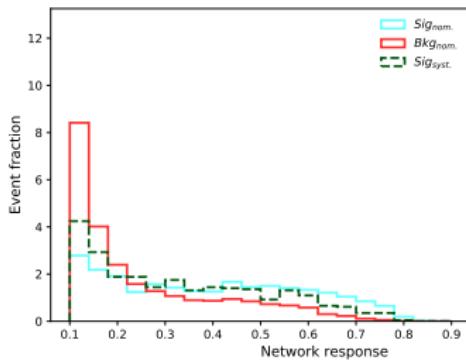
Input the last hidden layer to the adversary

- More information provided
- Possible danger: Missing last decision step

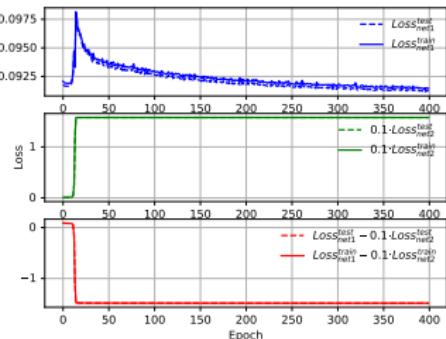
## Approach 2 Results



Approach 1



Approach 2



- Even better separation
- Still visible disagreement
- Losses behave as expected

## Approach 3

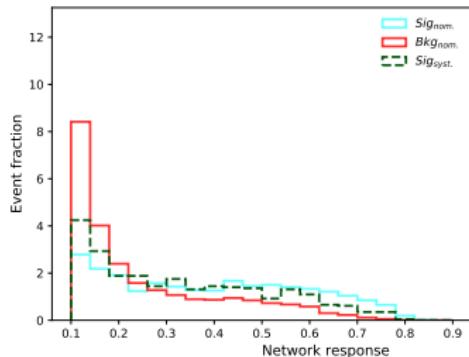
### Assumption

Dimension of the hidden layer is too high

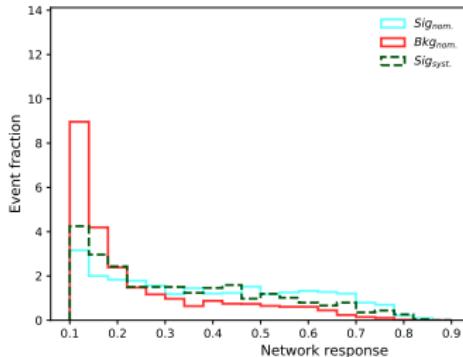
### Easy workaround

- Add an intermediate layer
- Reduced to 16 nodes

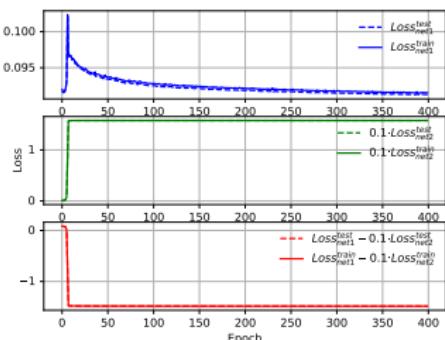
# Approach 3 Results



Approach 2



Approach 3



- No clear further improvement
- Higher stability

# Conclusions

## Network performance

- Classic approach does not deliver expected results
- Changing the input results in slight improvements on the sensitivity

## Insights

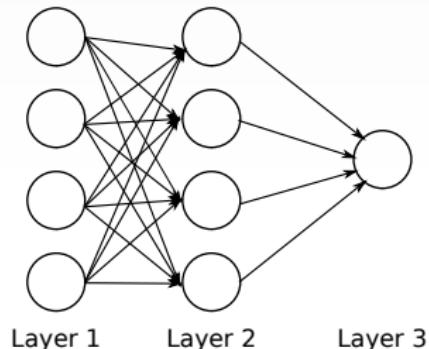
- Classifier and adversary need to be trained as a combination
- The complex architecture of the adversary is not justified by just putting in the classifier's output
- Learning rate is the central hyper-parameter for the loss behaviour



<https://xkcd.com/1838/>

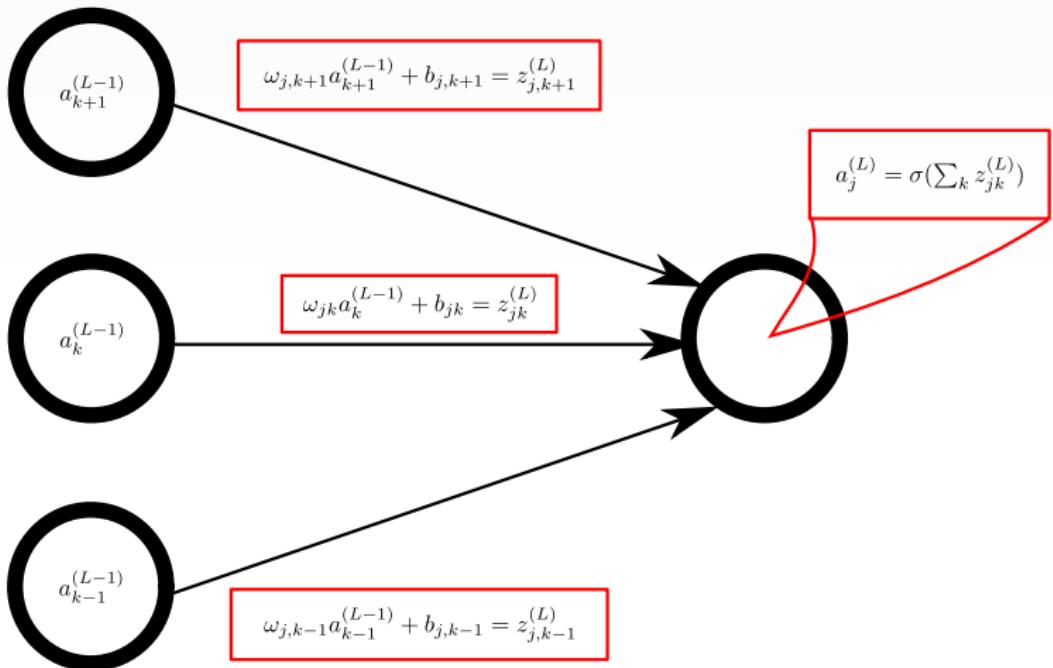
# Neural Networks

- Built of layers of simple processors called nodes
- Each node is connected to each node in the surrounding layers
- The connection is built by a linear function with a weight  $\omega$  and a bias  $b$  and a non linear activation function  $\sigma$
- Learning is accomplished by backpropagation and a step optimizer



$$z_j^L = \omega_{jk}^L a_k^{L-1} + b_k$$
$$a_j^L = \sigma(z_j^L)$$

# Neural Networks



Forward Propagation in a neural network

## Choosing the next step

- In supervised learning truth tagged training data allows to calculate a cost function to estimate a model's quality. For example crossentropy:

$$C = -(y \log p + (1 - y) \log(1 - p)) \quad (1)$$

- Backpropagation estimates the parameters' impact on the cost function using the partial derivatives

$$\frac{\partial C}{\partial a_k^{L-1}} = \sum_{j=1}^N \frac{\partial z_j^L}{\partial a_k^{L-1}} \frac{\partial a_j^L}{\partial z_j^L} \frac{\partial C}{\partial a_j^L}$$

- Each parameter is then updated according to its impact on the cost function

# Adversarial Neural Networks

---

- Originally introduced as Generative adversarial neural networks to overcome weaknesses of generative networks [2]
- Adds a second network controlling the dependency on features with large systematic uncertainties.
- The adversarial structure of the networks creates a minimax game
- Combined loss function

# Optimisers

---

- Gradient Descent: Update parameters in the opposite direction of the error gradient
- Stochastic Gradient Descent: Gradient Descent but for each training example separately
- Adaptive Moment Estimation, Adam: adaptive learning rate based on exponentially decaying mean of past gradients and past square gradients.
- Others
- <https://towardsdatascience.com/types-of-optimization-algorithms-used-in-neural-networks-and-ways-to-optimize-gradient-95ae5d39529f>

## Learning rate, momentum, decay

- Learning rate: Step-length in gradient direction

$$\theta' = \theta - lr \cdot g \quad (2)$$

- Momentum: create an adaptive and weight dependent learning rate

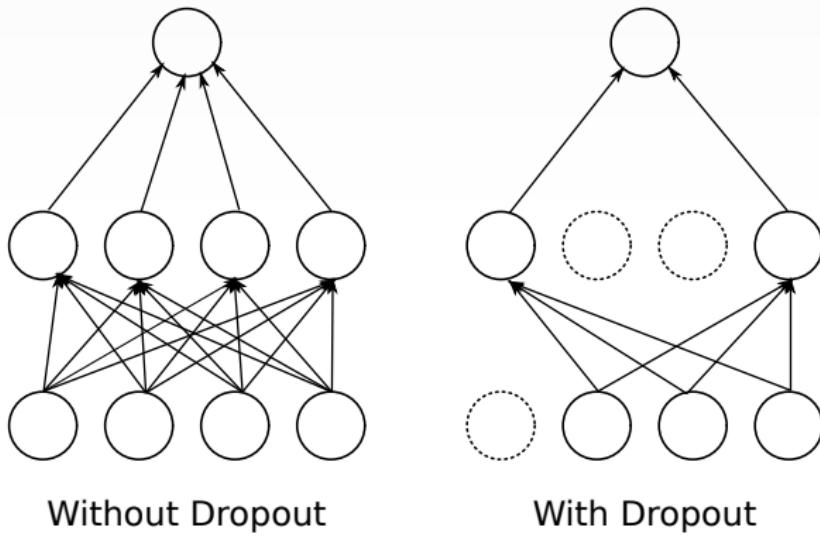
$$\nu' = \alpha\nu - \epsilon \frac{1}{m} \nabla_{\theta} \sum_j L(f(\hat{y}^j; \theta), y^j) \quad (3)$$

$$\theta' = \theta + \nu \quad (4)$$

- Decay: Decrease the learning rate over the course of the training

$$\epsilon' = \frac{\epsilon}{1 + \phi t} \quad (5)$$

# Dropout



Caption

## Technical details

---

- The neural networks were built using Keras [1] with tensorflow [3] as backend

# Variables

---

Variable
$p_T^{\text{miss}}$
$  \eta_{jet1}  $
$  \eta_{jet2}  $
$  \eta_{lep1}  $
$  \eta_{lep2}  $
$p_T_{jet1}$
$p_T_{jet2}$
$p_T_{lep1}$
$p_T_{lep2}$
$\phi_{jet1}$
$\phi_{jet2}$
$\phi_{lep1}$
$\phi_{lep2}$

Simple kinematic variables

Variable
$m_{lep1} + m_{jet2}$
$p_T_{lep1} + p_T_{lep2} + p_T^{\text{miss}}$
$p_T_{jet1} + p_T_{jet2}$
$m_{lep1} + m_{jet1}$
$p_T_{lep1} - p_T_{jet1}$
$R_{lep1} - R_{jet2}$
$R_{lep1, lep2} - R_{jet2}$
$m_{lep2} + m_{jet1}$
$p_T_{jet2}$
$R_{lep1} - R_{jet1}$
$R_{lep1} - R_{jet1}$
$R_{lep2} - R_{jet2}$
$\text{Centrality}_{lep2} + \text{Centrality}_{jet2}$
$R_{lep2} - R_{jet1}$

Complex variables