# Higgs pair production at the FCC-hh

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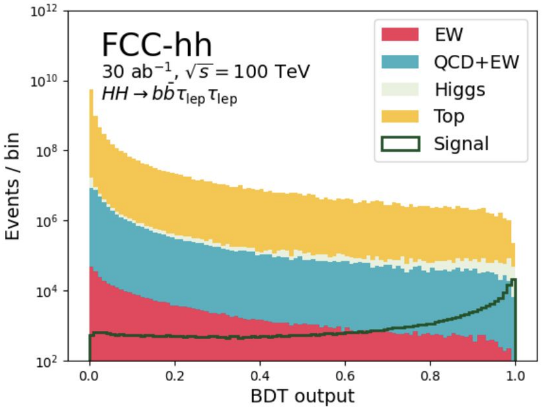
# Introduction

- **Previous studies** using a BDT were developed in 2022 (see presentation at Higgs pair by Matt Sullivan)
  - Results taking into account both $\tau_L\tau_H$ and $\tau_H\,\tau_H$
  - Very good sensitivity, comparable with published studies (https://arxiv.org/pdf/2004.03505)

| | $HH$+jet study | WIP study |
| --- | --- | --- |
| | Yield [fb$^{-1}$] | |
| Signal | 0.14 | 1.22 |
| Background | 0.96 | 38.94 |
| | $S/\sqrt{B}$ | |
| $\tau_\ell\tau_h$ | 24.97 | 32.32 |

$b\bar{b}\tau_\ell\tau_h$ comparison




**This work:** implement graph neural networks

- **GNN pipeline from Alessio Devoto** (PhD Computer Scientist, University of Rome Sapienza)
- Graph for each event, each object is a node
- Fully connected, each node has several features
- Different models tested (GCN, **GAT**)
- Systematic evaluation of performance based on relevant metrics (S vs B separation, AUC)
- Inputs and samples using official samples (EDM4HEP format) and ntuples generated with FCC analysis starterkit (same as linked in Matt's slides above)

# FCC simulation

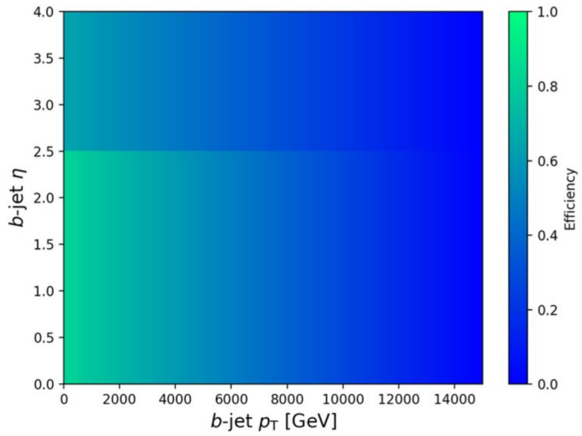
- Baseline FCC-hh detector response simulated using Delphes (v4) parameterisation

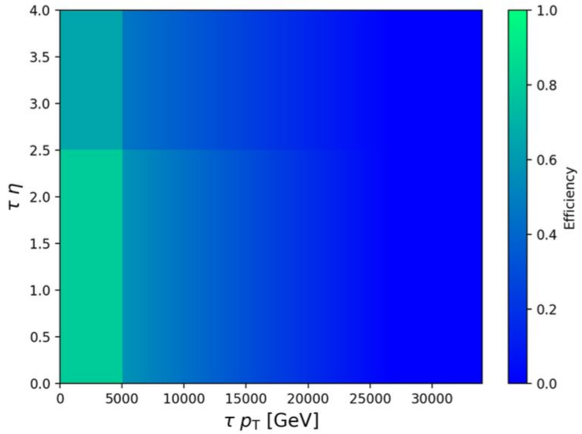
- Lepton (e, μ) and photon reconstruction employs parameterised reco/ID efficency & resolution effects

- Jet reconstruction uses Anti-kT algorithm with R = 0.4

- Object isolation calculated using cone of R = 0.3

- b-tagging, c-tagging and τ-tagging efficiency parameterised in pT, η



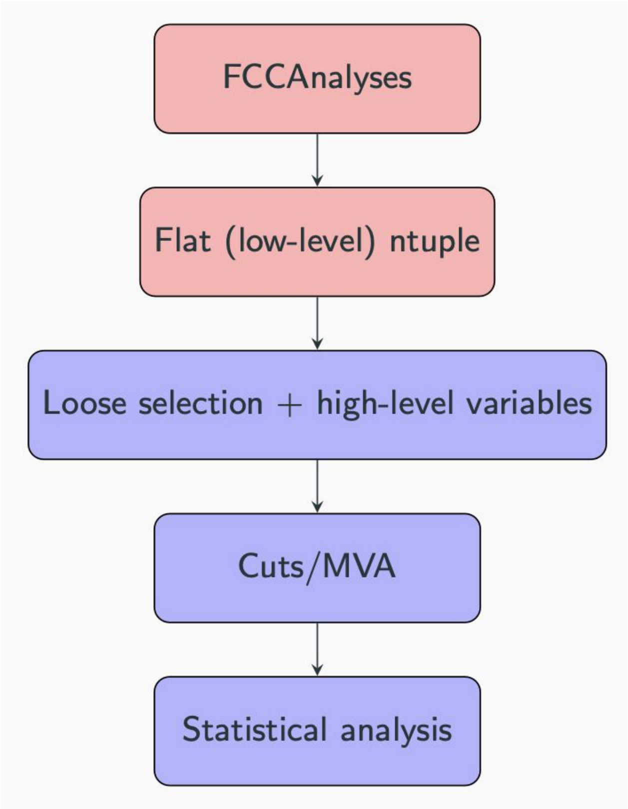
# FCCAnalysis framework

- Common RDataFrame analysis framework developed for FCC physics studies: FCCAnalyses

- Common C++ analysers, analysis-specific Python config & analysis:
    - See C. Helsens talk for example workflow
    - FCC analysis starterkit

- Inputs to analyses are produced in EDM4HEP format:
    - All available MC listed here

- Efficient analysis possible with handful of scripts



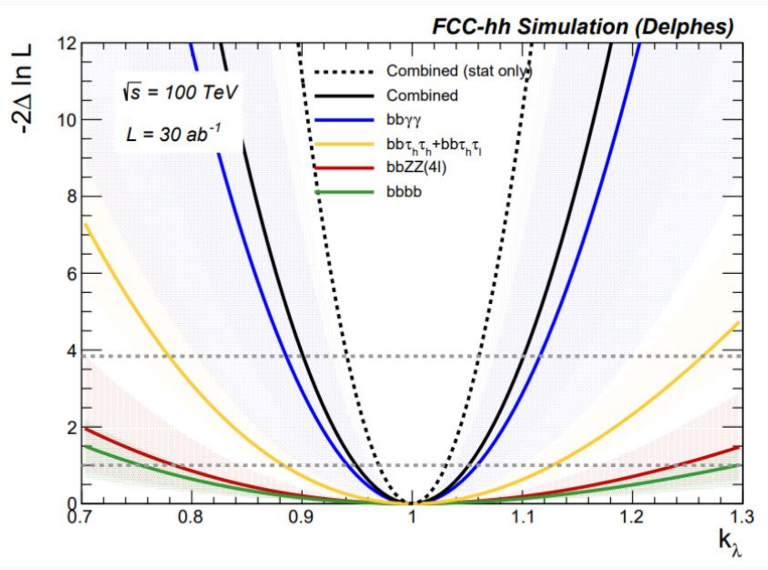
# HH at FCC

- Numerous existing studies on HH at FCC-hh:
    - HH production ($b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$)
    - HH + jet production (boosted $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, resolved $b\bar{b}\tau\tau$)

- Combination of resolved channels has expected $\delta\mu$ of 2.4-5.1%, $\delta\kappa\lambda$ of 3.4-7.8%

- Boosted $b\bar{b}\tau\tau$ can constrain $\kappa\lambda$ to within 8% alone!

- What can be improved upon?




arXiv 2004.03505

# bbtautau channel

- Focus on HH →bbττ channel

- Use more modern MVA tools to improve S/B:
  - GNN and GraphTransformers

- Use latest FCC-hh simulated samples with more complete background estimation:
  - Top backgrounds: t¯t, single top (s-/t-channel), t¯tV, t¯ tVV
  - Single Higgs backgrounds: ggF, VBF ,t¯tH, VH
  - Continuum backgrounds: QCD+EW (e.g. pp →b¯bZ /γ∗), EW (e.g.pp →HZ /γ∗)

| | bb | WW | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 34% | | | | |
| WW | 25% | 4.6% | | | |
| ττ | 7.3% | 2.7% | 0.39% | | |
| ZZ | 3.1% | 1.1% | 0.33% | 0.069% | |
| γγ | 0.26% | 0.10% | 0.028% | 0.012% | 0.0005% |

| Process | $\sigma$ [pb] |
|---|---|
| ggF $HH$ | 1.224 (NNLO$_{FT}$) |
| Inclusive $t\bar{t}$ | 35000 (NNLO) |

# preliminary selections

- Apply loose topological and kinematic cuts:
  - $b\bar{b}\tau_\ell\tau_h$ : 2 b-jets, exactly 1 e/μ and exactly 1 hadronic τ (OS)
  - $b\bar{b}\tau_h\tau_h$ : 2 b-jets, exactly 2 hadronic τ (OS), lepton veto

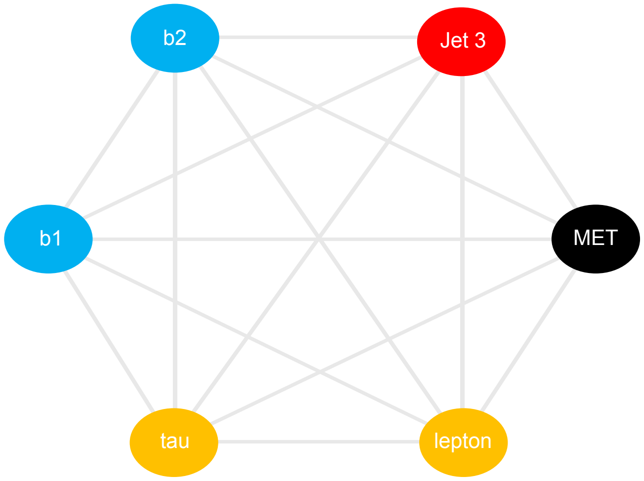
- Overlap removal prioritises taus over b-jets

| $\tau_\ell\tau_\mathrm{h}$ | | $\tau_h\tau_\mathrm{h}$ | |
|---|---|---|---|
| Selection | Efficiency | Selection | Efficiency |
| $N(b\text{-jets}) = 2$ | 0.45 | - | - |
| $b\text{-jet } p_\mathrm{T} > 30$ | 0.40 | - | - |
| $N(e,\mu) = 1$ | 0.07 | $N(e,\mu) = 0$ | 0.19 |
| $N(\tau_h) = 1$ | 0.03 | $N(\tau_h) = 2$ | 0.06 |
| $\tau_\ell\tau_h$ OS | 0.03 | $\tau_h\tau_h$ OS | 0.05 |

# GNN selection

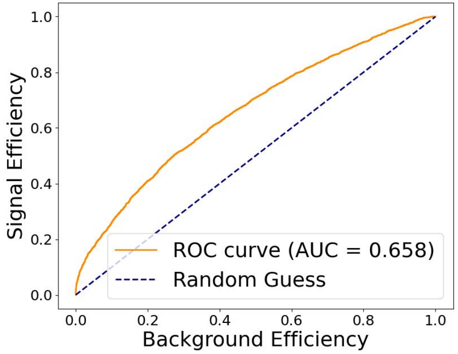
**GNN pipeline from Alessio Devoto** (PhD computer Scientist, University of Rome Sapienza)

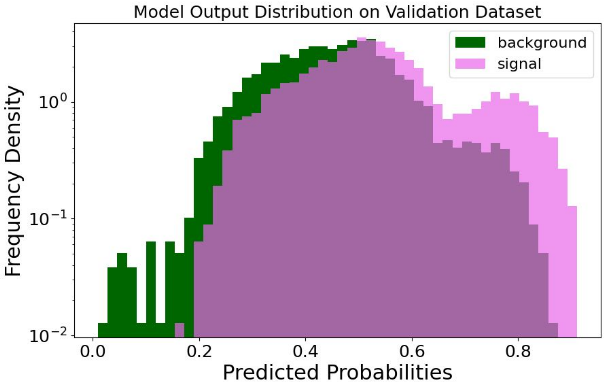
- Graph for each event, each object is a node
- Fully connected, each node has several features
- Different models tested (GCN, **GAT**)

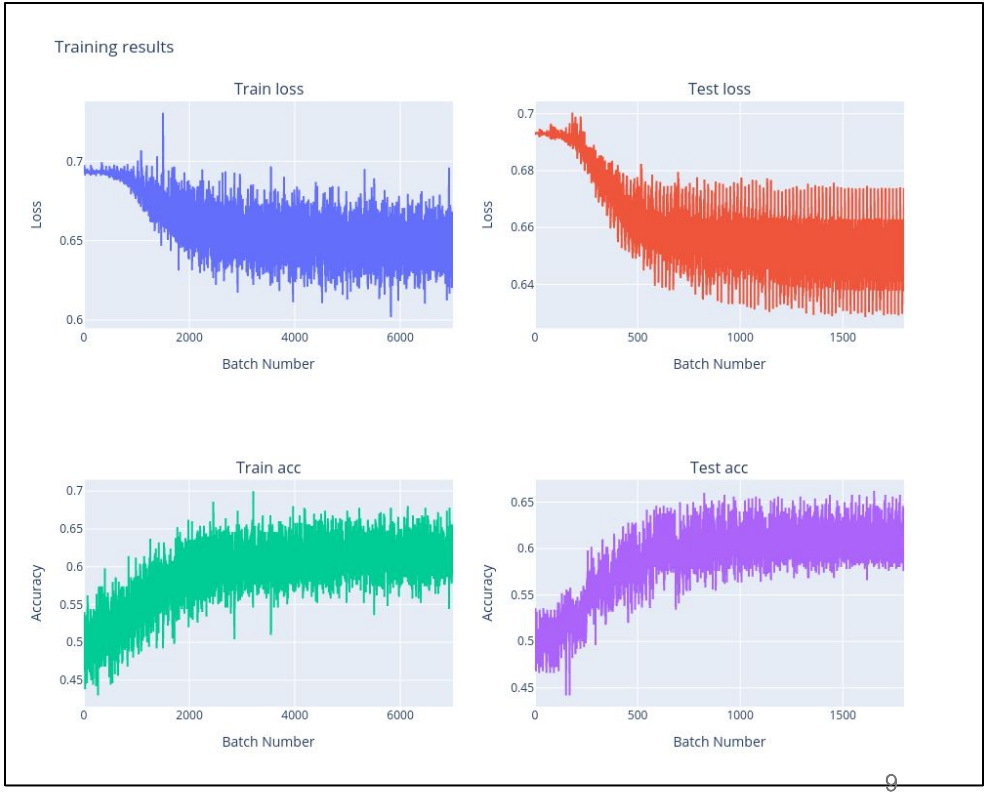



| Event 1: | pT | eta | phi |
|---|---|---|---|
| tau | 25.551097869873047 | 2.0833067893981934 | 1.6441311836242676 |
| l1 | 233.71524047851562 | 1.5203982591629028 | -2.497894525527954 |
| b1 | 209.0316162109375 | 1.6601777076721191 | 0.5068551898002625 |
| b2 | 33.84409713745117 | 1.8450242280960083 | 2.5926644802093506 |
| energy | 4.8641037940979 | nan | -0.2831399738788605 |

# GNN performance



# Additional feature nodes

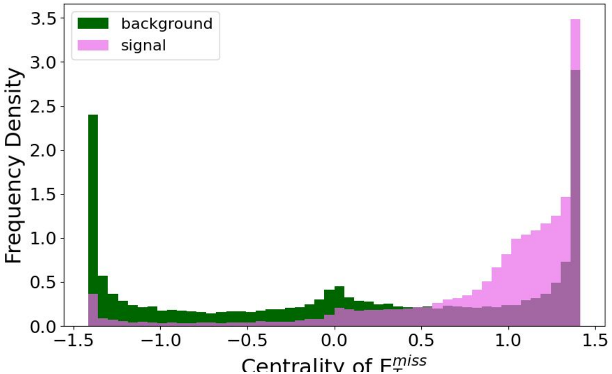
Add complex reconstructed kinematic variables

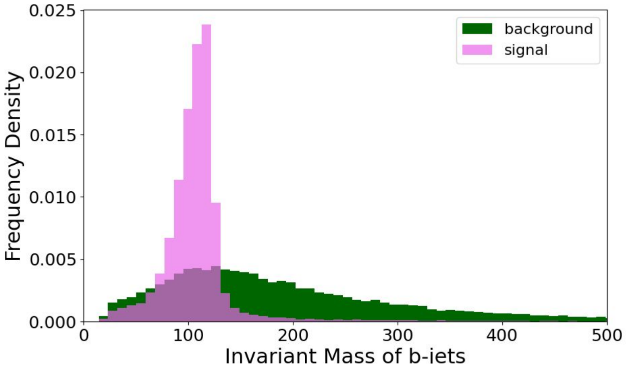
- b-jet pairs invariant mass
- tau-lepton invariant mass
- radial distances among b and tau objects and ETMiss centrality as in ATLAS di-Higgs studies

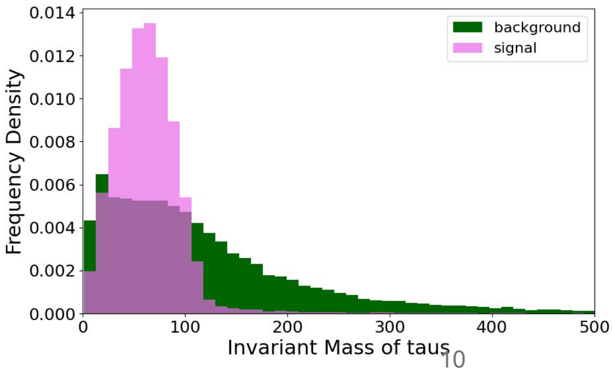
$$E_T^{miss} centrality = \frac{(x+y)^2}{\sqrt{x^2+y^2}}$$

$$x = \frac{\sin(\phi_{MET} - \phi_\tau)}{\sin(\phi_\ell - \phi_\tau)}$$

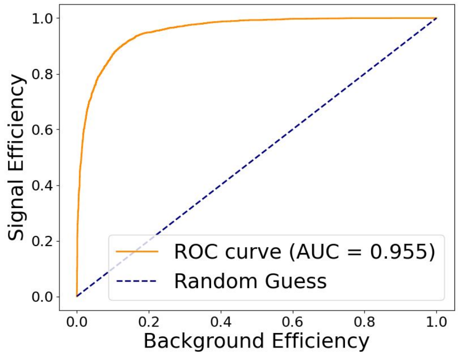
$$y = \frac{\sin(\phi_\ell - \phi_{MET})}{\sin(\phi_\ell - \phi_\tau)}$$

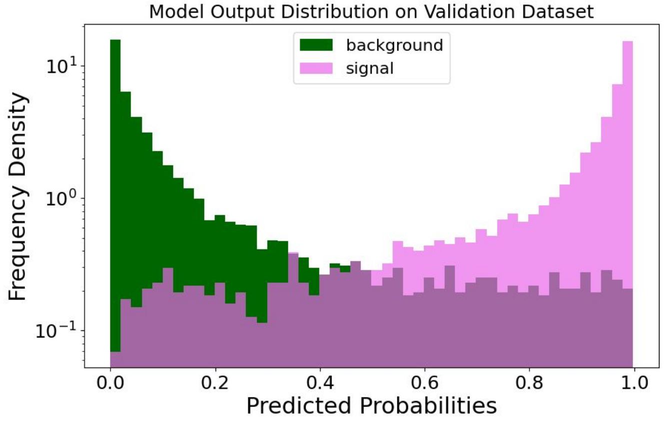


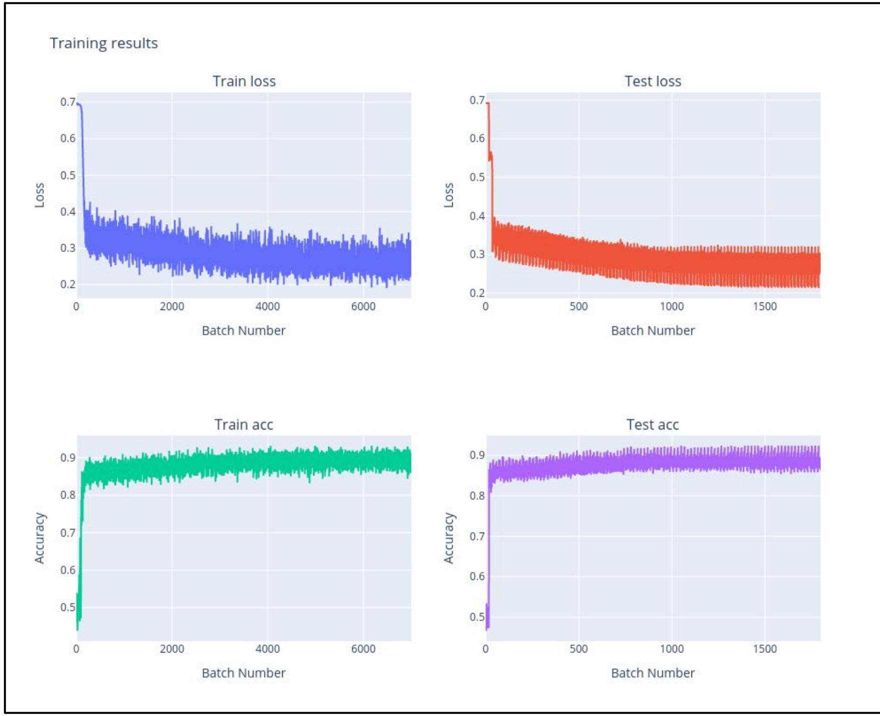



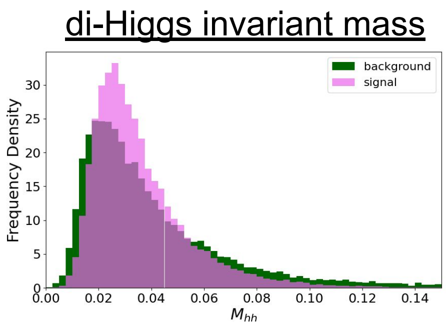
# GNN improved performance

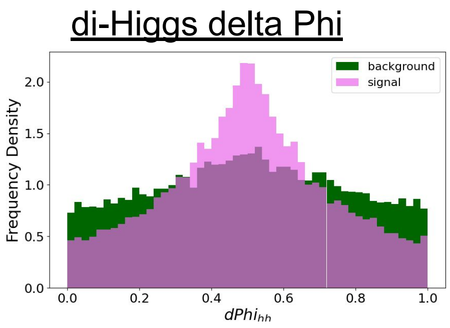


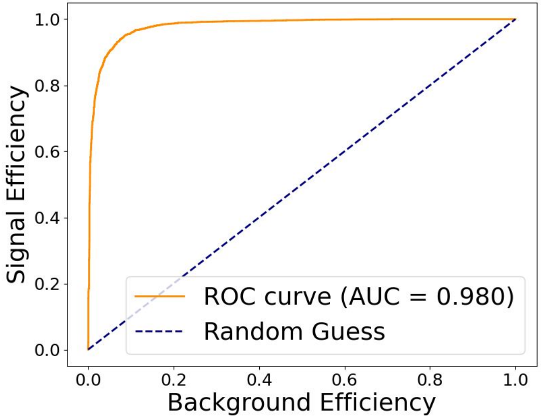



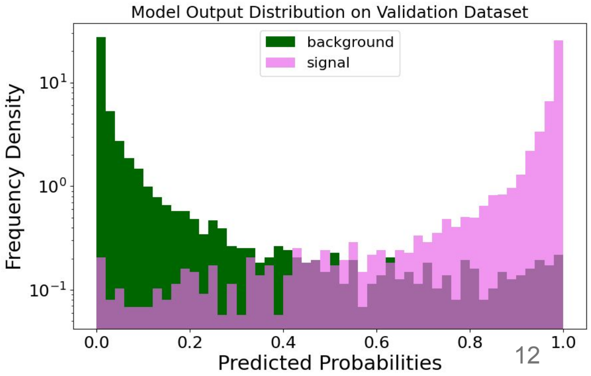
# Additional di-higgs constraints




- Adding m_hh and dphi_hh helps to further improve performance
- Possibility to not use these variables in the inputs to the GNN but use only for differential cross section measurements




the network is good enough without having to use the di-higgs system as constrain

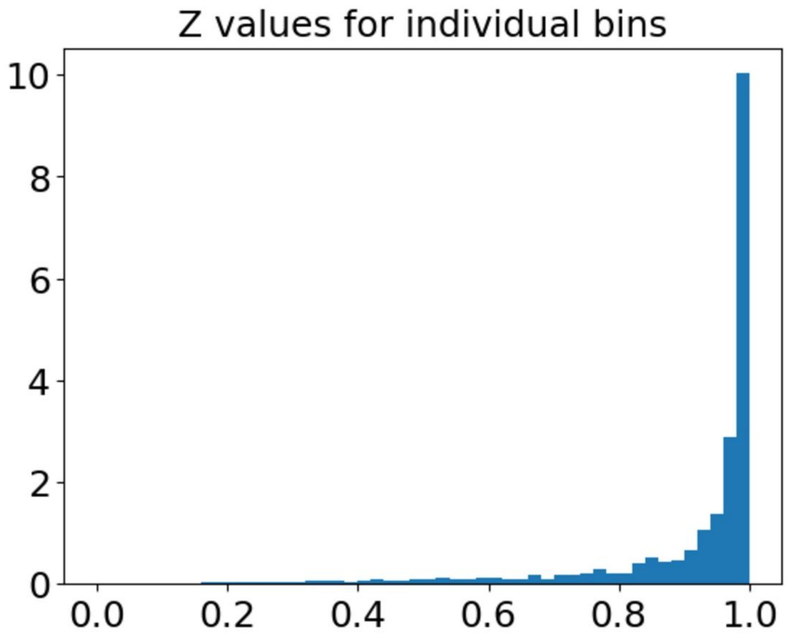
# Calculating significance

Calculate signal significance in NNoutput bins:

$$Z = N_s / \sqrt{N_b + (N_b \sigma_b)^2}$$

with a signal and background scaled to 30/ab

Next step is to compare with previous BDT study and HH+jet study (Add per-bin significance in quadrature to get final estimate)




Old BDT study:
Significance Z = 5.7σ for κλ = 1:
(2.9σ $b\bar{b}\tau_\ell\tau_h$, 4.9σ $b\bar{b}\tau_h\tau_h$)

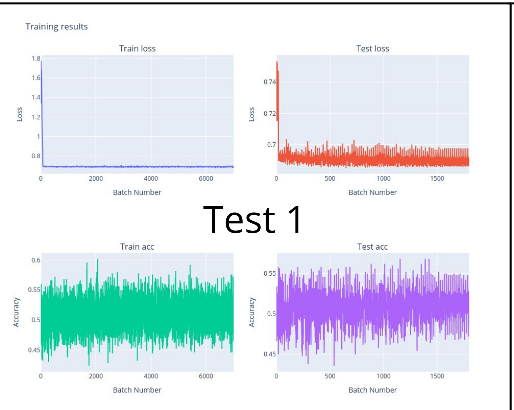
# Summary

- First estimate of sensitivity show a significance similar to BDT-based results
  - Vanilla GNN tested so far… full optimisation is ongoing
- Limited by MC statistics, so next steps is to evaluate sensitivity with full stat ttbar and add fully hadronic channel
- Explore the had-had channel
  - How should we treat fakes?
- Once the GNN are finalised, define the full analysis strategy
  - Differential cross-section?
  - k_lambda fit?

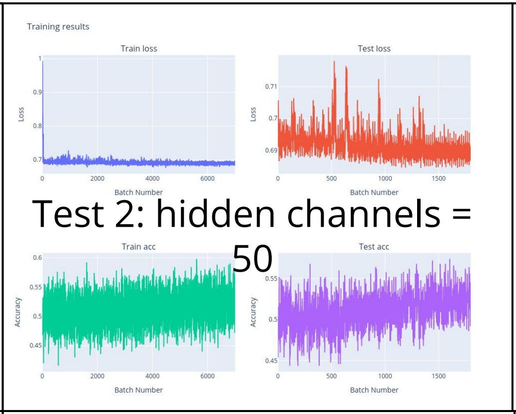
# BACKUP

| Test | epochs | Batch size | Scheduler ? | LR | Weight decay | Hidden layers | Hidden channels | model | Trainables? | Normalised? | Complex features |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 500 | No | 0.001 | 5e-4 | 2 | 18 | GCN | No | No | None |
| 2 | 100 | 500 | No | 0.01 | 5e-4 | 3 | 50 | GCN | No | No | None |
| 3 | 100 | 500 | No | 0.01 | 5e-4 | 3 | 50 | GAT | No | No | None |
| 4 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GCN | No | Yes | None |
| 5 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | None |
| 6 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | Yes | Yes | None |
| 7 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | mbb |
| 8 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | ” + dRbb |
| 9 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | ” + mtt |
| 10 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | ” + dRtt |
| 11 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | ” + Cmet |
| 12 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | ” + dpT |
| 13 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | ” + transverse mass |
| 14 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | ” + mhh |
| 15 | 100 | 500 | Yes | 1e-7 | 1e-5 | 3 | 50 | GAT | No | Yes | ” + dPhi_hh |

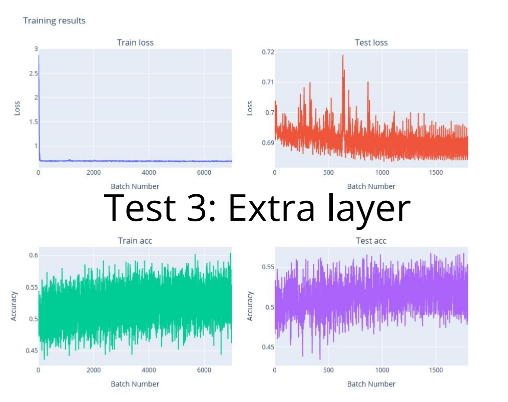
# LOSS AND ACCURACY – EDITING GNN PARAMETERS



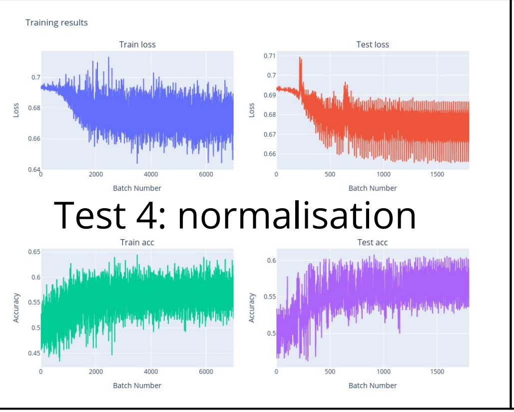

Test 1



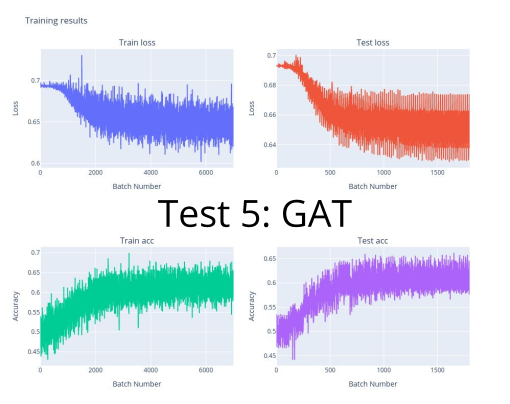

Test 2: hidden channels = 50



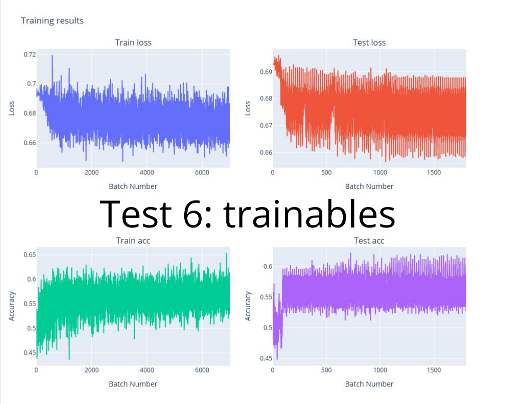

Test 3: Extra layer




Test 4: normalisation

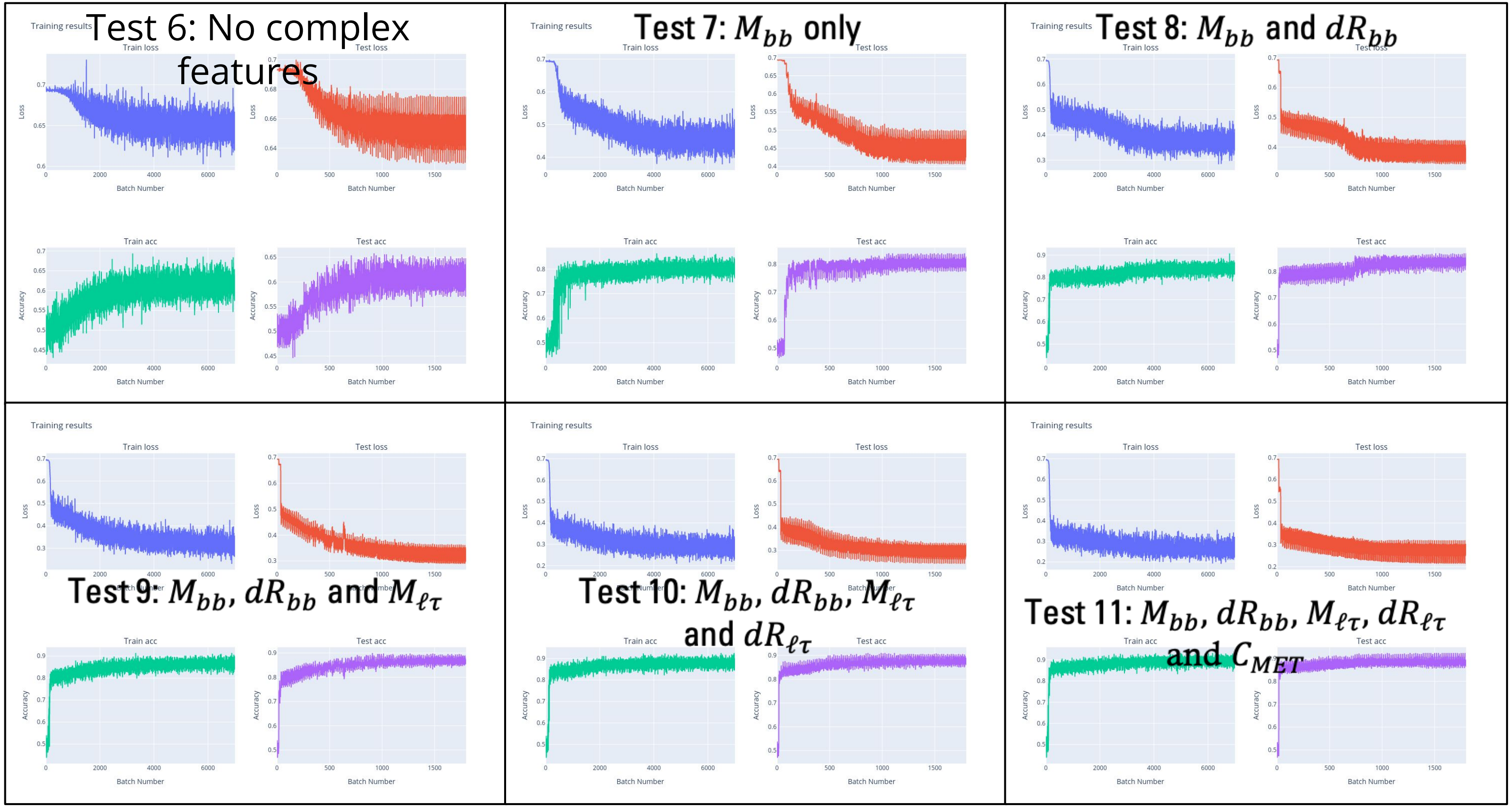



Test 5: GAT



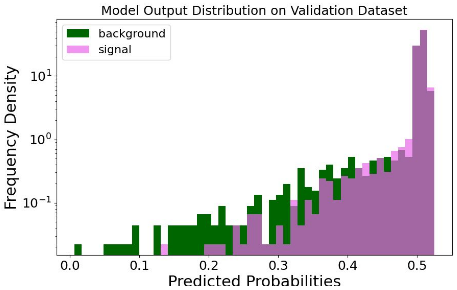

Test 6: trainables

# LOSS AND ACCURACY - ADDING COMPLEX FEATURES

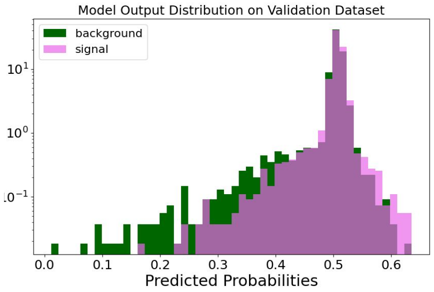


# OUTPUT DISTRIBUTIONS – GNN PARAMETERS

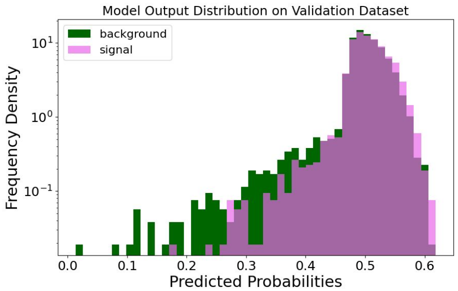
Test 1

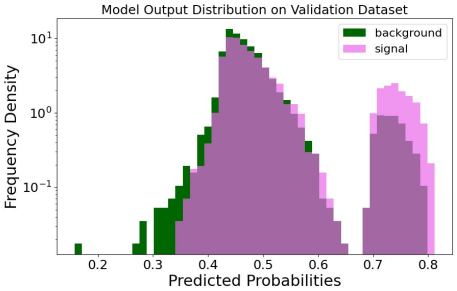



Test 2: hidden channels =

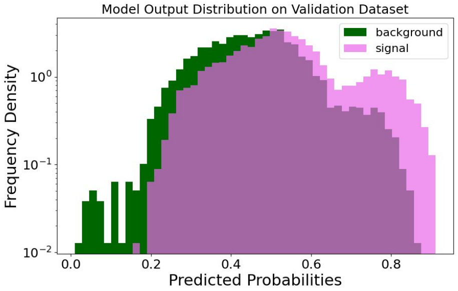



Test 3: Extra layer

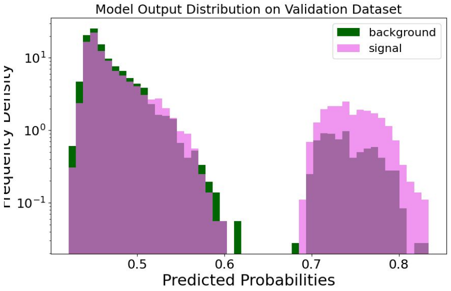



Test 4: normalisation



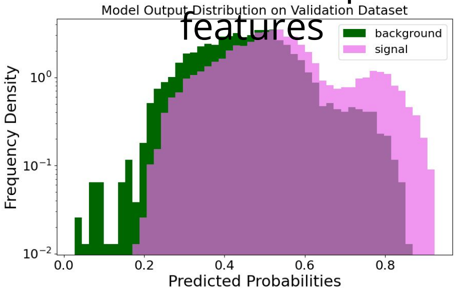

Test 5: GAT



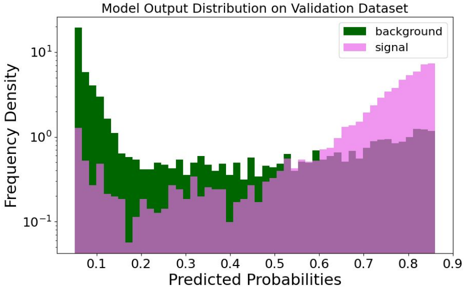

Test 6: trainables

# OUTPUT DISTRIBUTIONS

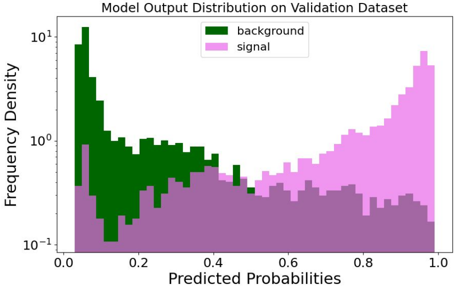
Test 5: No complex features

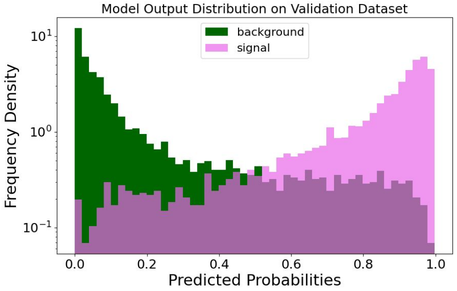



Test 7: $M_{bb}$ only

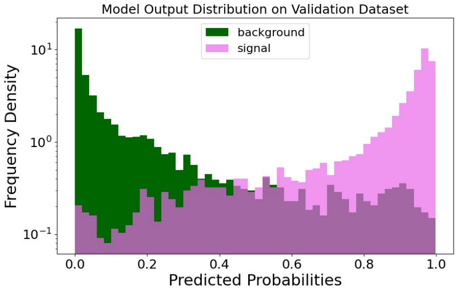



Test 8: $M_{bb}$ and $dR_{bb}$

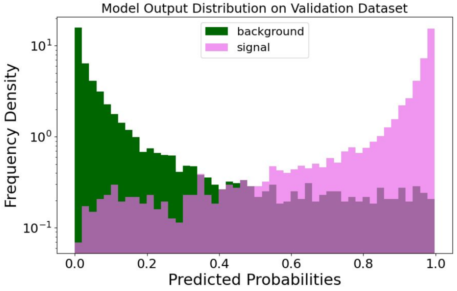



Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$



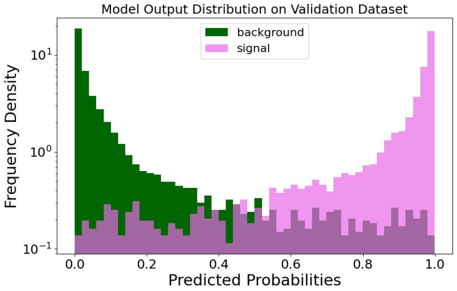

Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$



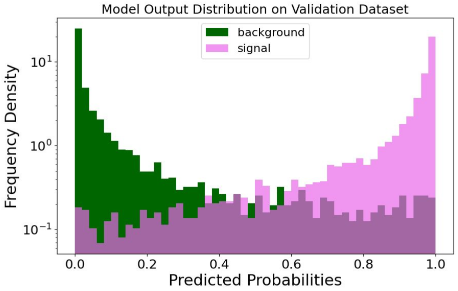

Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

## OUTPUT DISTRIBUTIONS

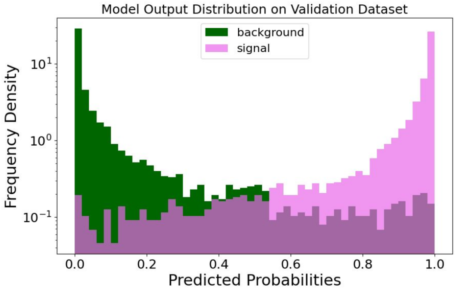
Test 12: +dpT

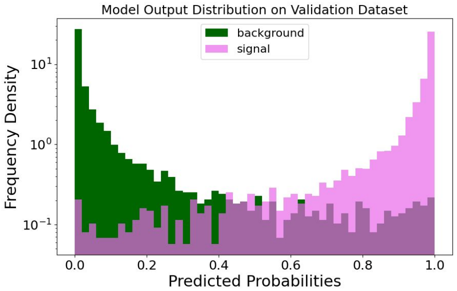



Test 13: + transverse mass




Test 14: + mhh

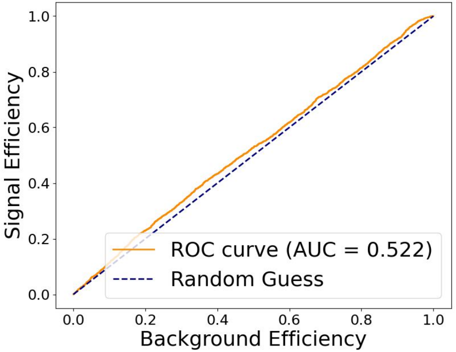


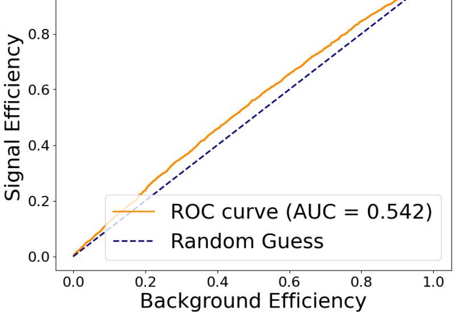

Test 15: + dPhi_hh

ROC CURVE

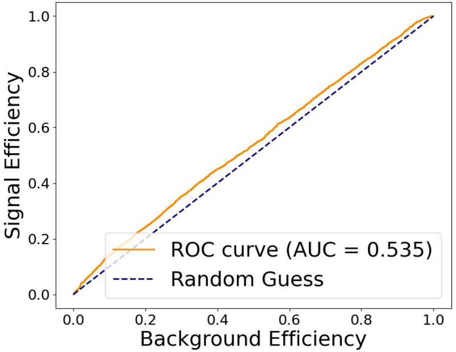
Test 1

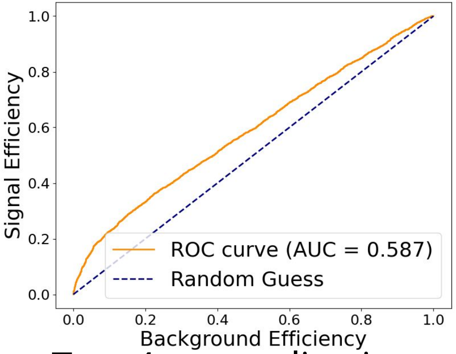



Test 2: hidden channels = 50

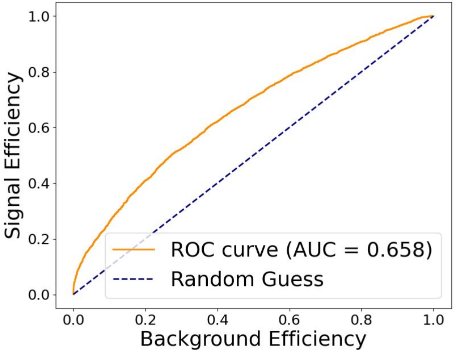



Test 3: Extra Layer

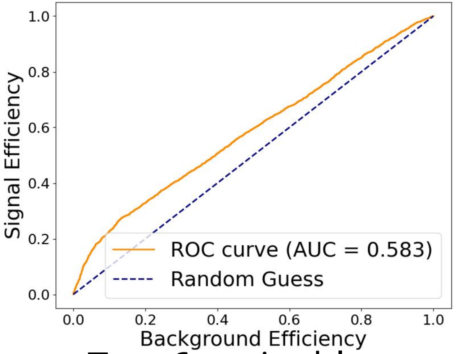



Test 4: normalisation



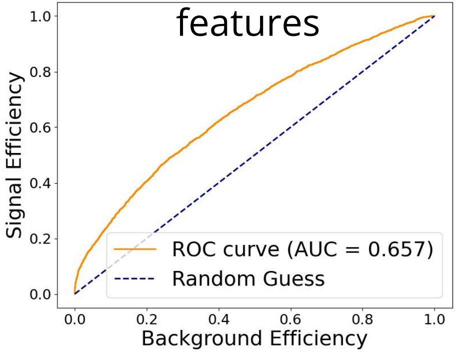

Test 5: $GAT$



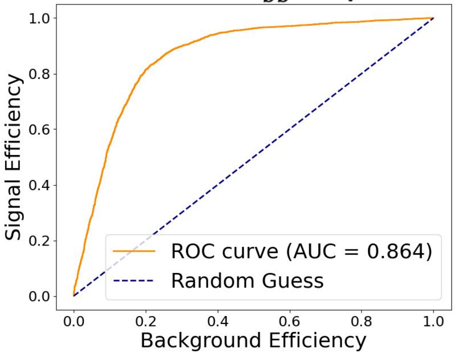

Test 6: trainables

## ROC CURVE

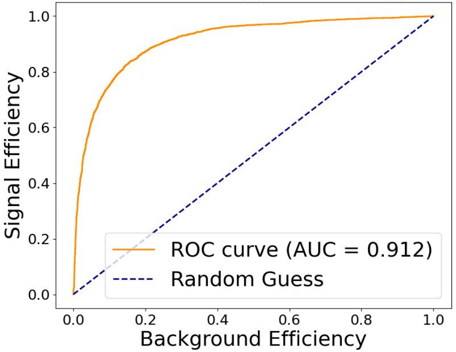
Test 5: No complex features

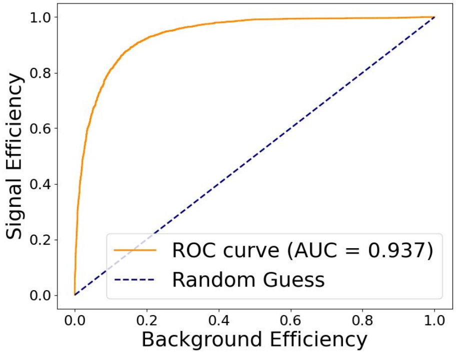



Test 7: $M_{bb}$ only

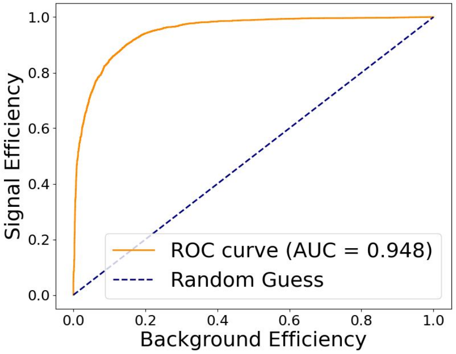



Test 8: $M_{bb}$ and $dR_{bb}$

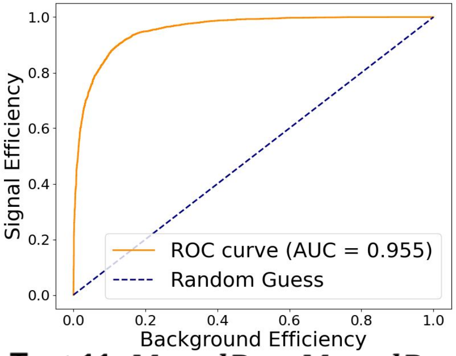



Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$



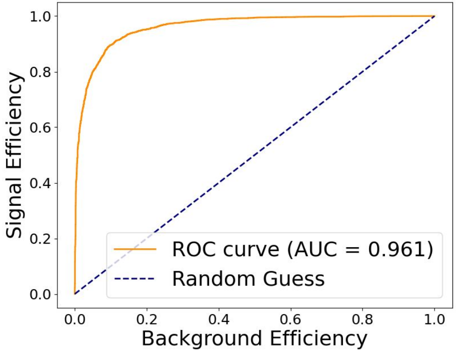

Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$



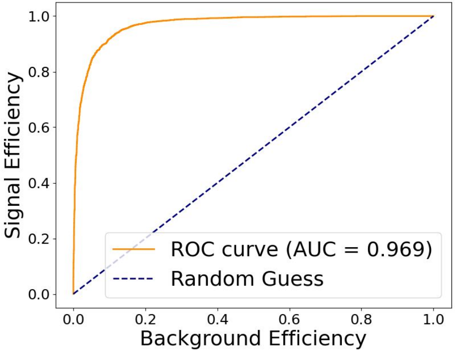

Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

## ROC CURVE

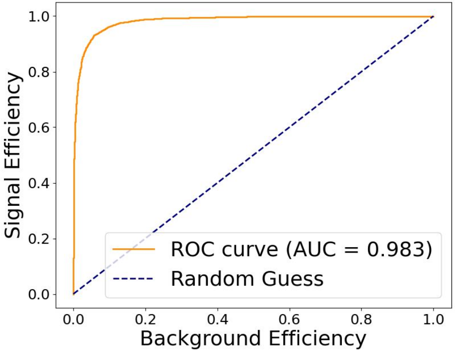
### Test 12: +dpT

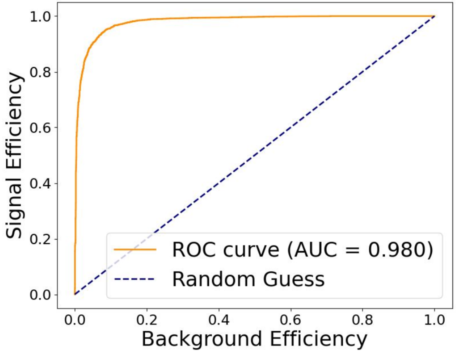



### Test 13: + transverse mass




### Test 14: + mhh



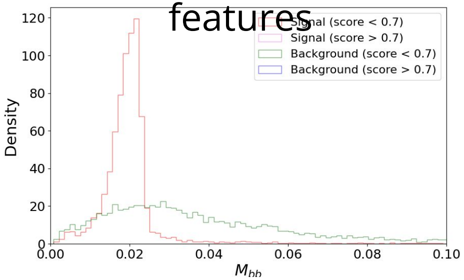

### Test 15: + dPhi_hh

## FEATURE LEARNING

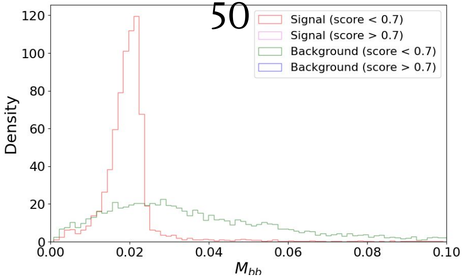
- Cut data above and below GNN score of 0.7.
- Plotted complex variables for each iteration.
- What GNN gives high and low probabilities gives indication of how and what it is learning.

## INVARIANT MASS OF B-JETS

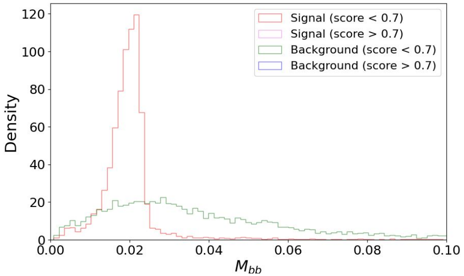
### Test 1: No complex features

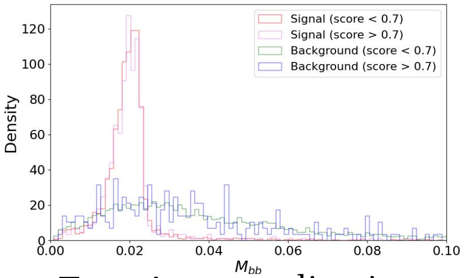



### Test 2: hidden channels = 50

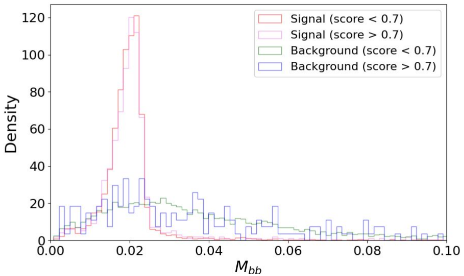



### Test 3: Extra Layer

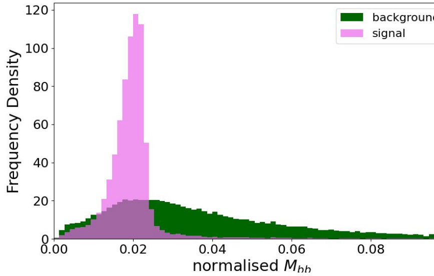



### Test 4: normalisation



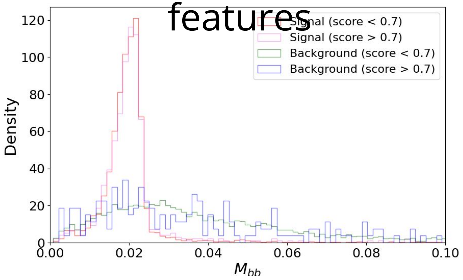

### Test 5: $GAT$



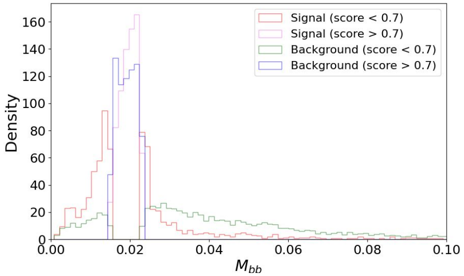

### Test 6: trainables

# INVARIANT MASS OF B-JETS

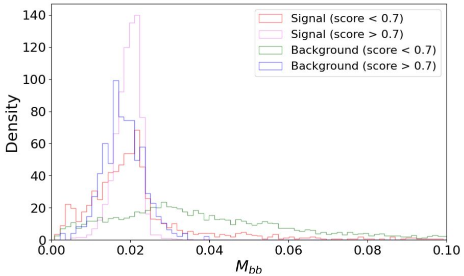
Test 5: No complex features

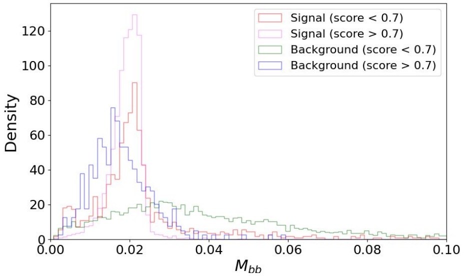



Test 7: $M_{bb}$ only

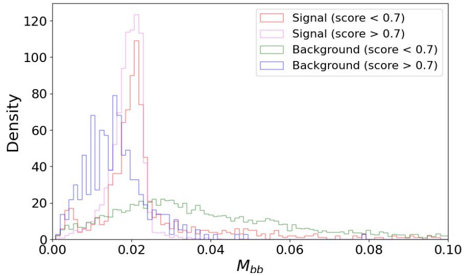



Test 8: $M_{bb}$ and $dR_{bb}$

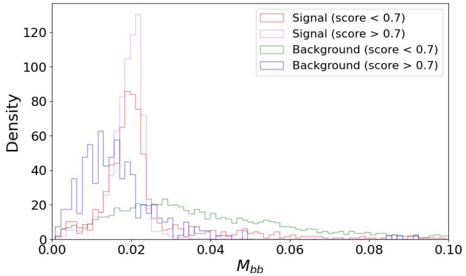


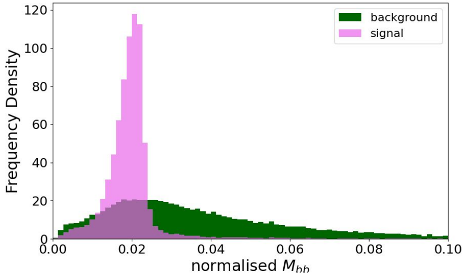

Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$




Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$

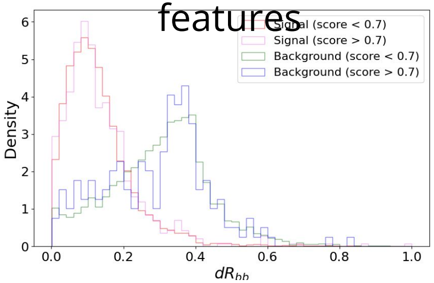



Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

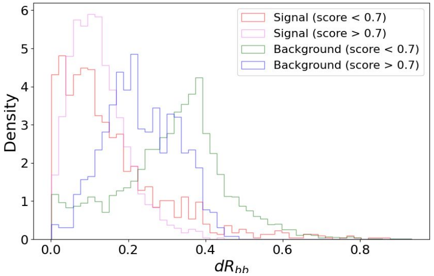


## DISTANCE BETWEEN B-JETS

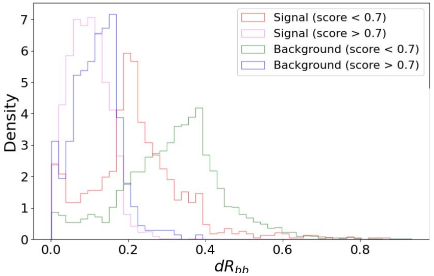
### Test 5: No complex features

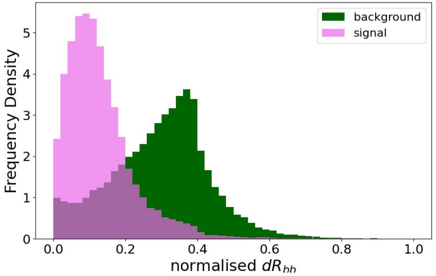


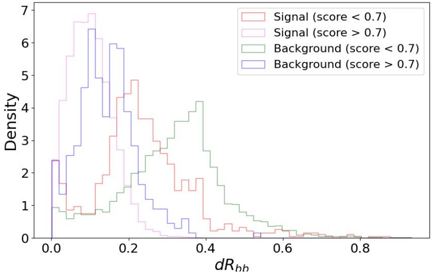

### Test 7: $M_{bb}$ only



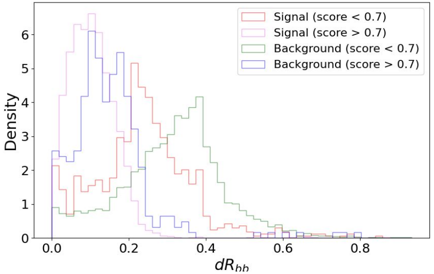

### Test 8: $M_{bb}$ and $dR_{bb}$



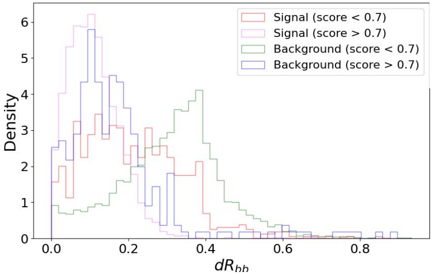




### Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$



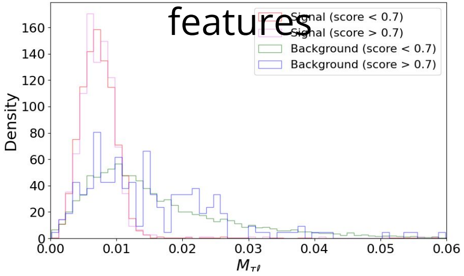

### Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$



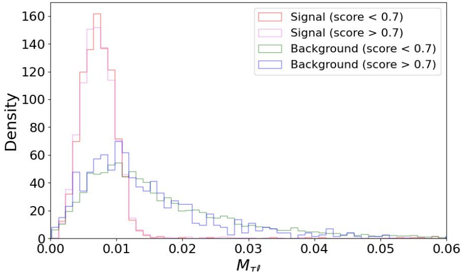

### Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

## INVARIANT MASS OF LEPTONS

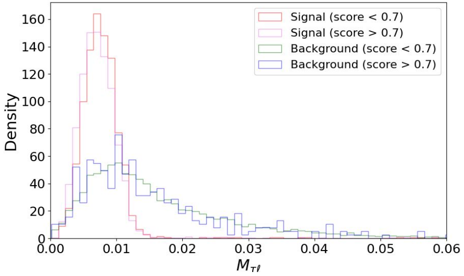
Test 5: No complex features

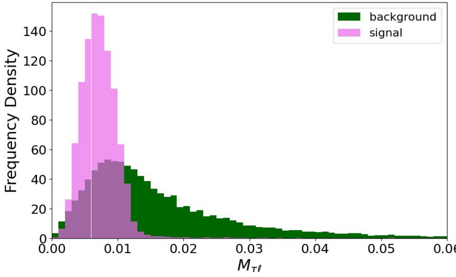


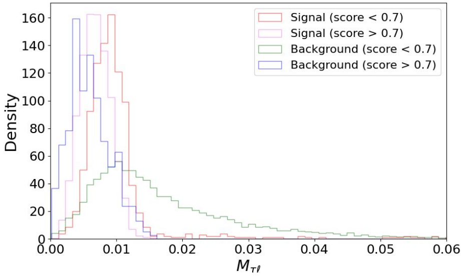

Test 7: $M_{bb}$ only



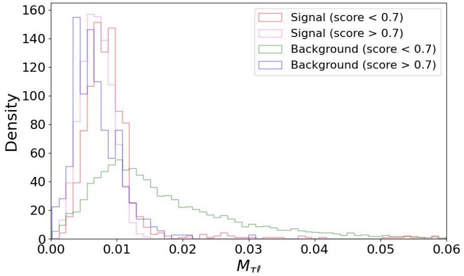

Test 8: $M_{bb}$ and $dR_{bb}$



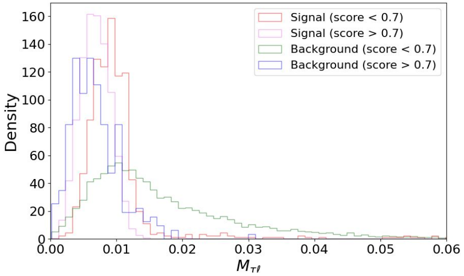




Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$



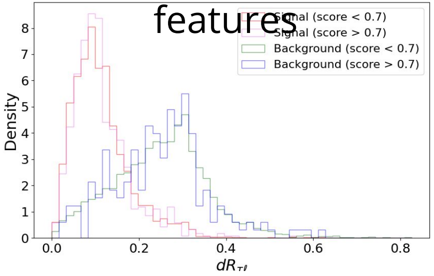

Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$



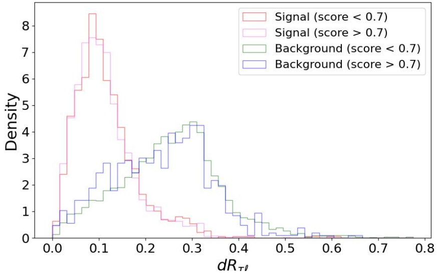

Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

## DISTANCE BETWEEN LEPTONS

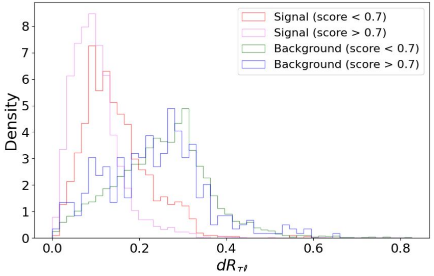
Test 5: No complex features

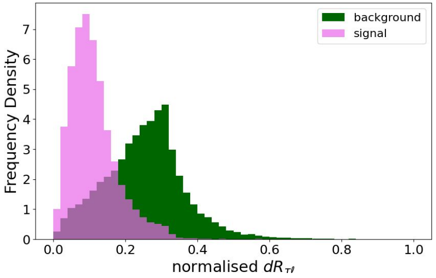


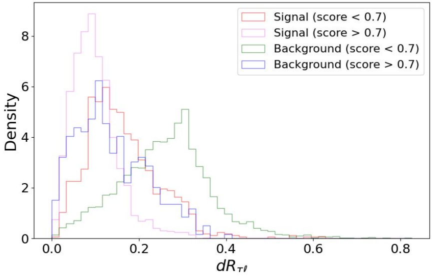

Test 7: $M_{bb}$ only



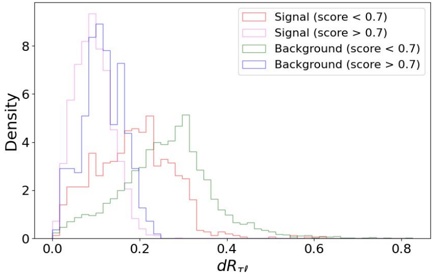

Test 8: $M_{bb}$ and $dR_{bb}$



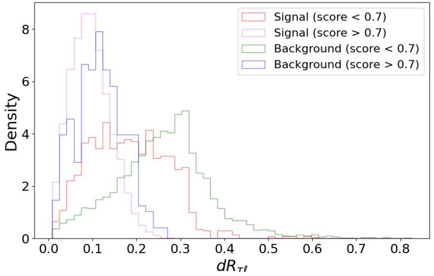




Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$



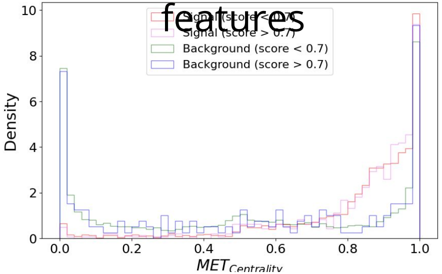

Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$



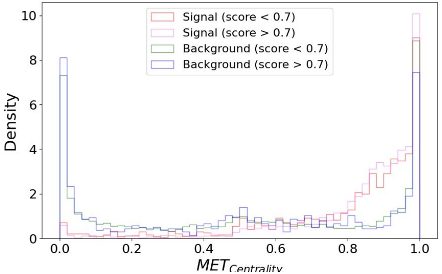

Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

## CENTRALITY OF MET

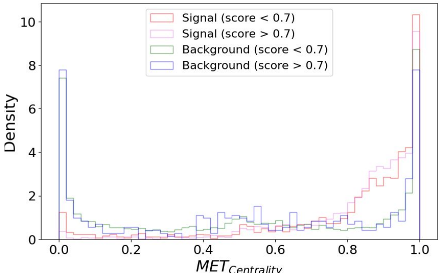
Test 5: No complex features

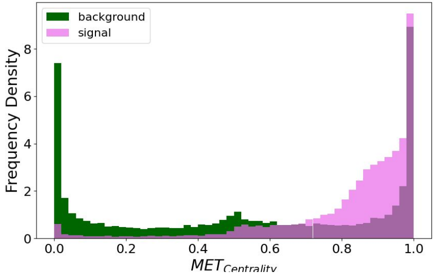


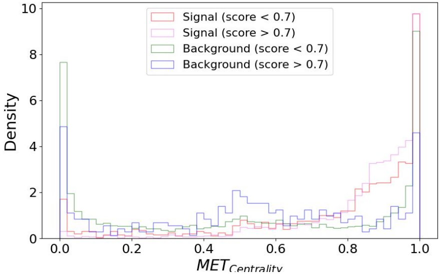

Test 7: $M_{bb}$ only



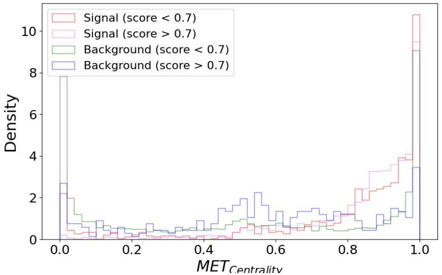

Test 8: $M_{bb}$ and $dR_{bb}$



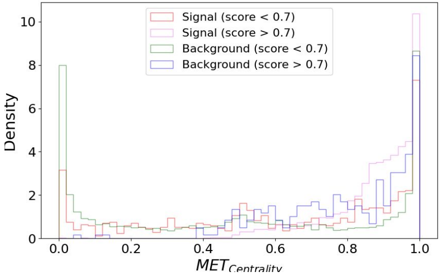




Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$



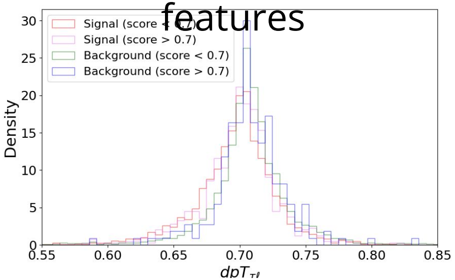

Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$



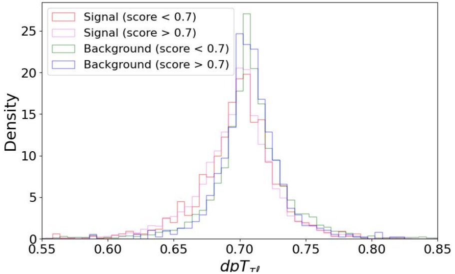

Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{bb}$ and $C_{MET}$

# DIFFERENCE IN PT VALUES (LEPTONS)

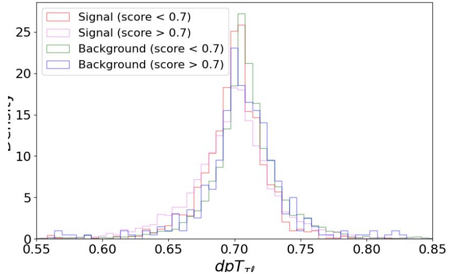
## Test 5: No complex features

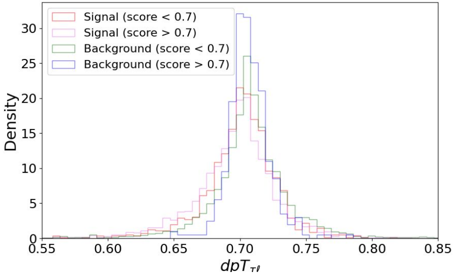



## Test 7: $M_{bb}$ only

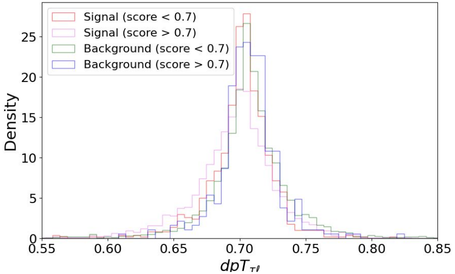



## Test 8: $M_{bb}$ and $dR_{bb}$

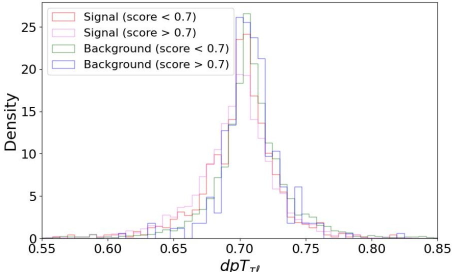


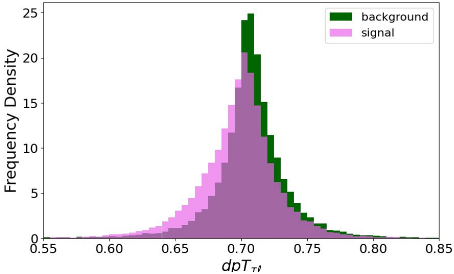

## Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$




## Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$

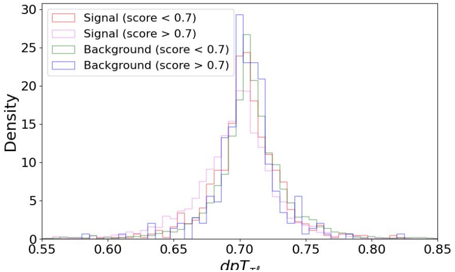



## Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

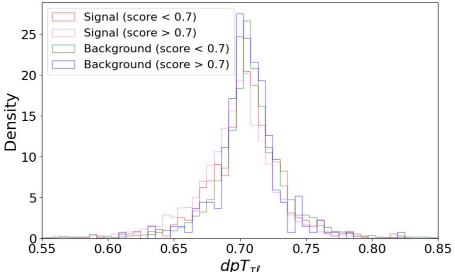


## DIFFERENCE IN PT VALUES (LEPTONS)

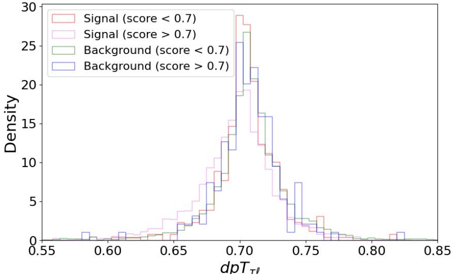
# Test 12: +dpT

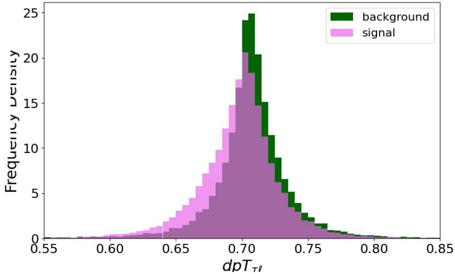


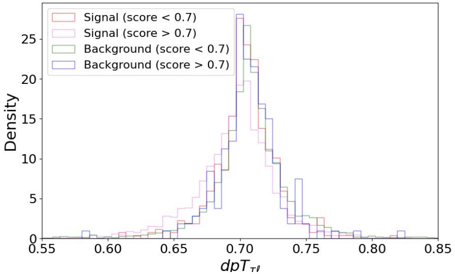

# Test 13: +transverse mass




# Test 14: +mhh



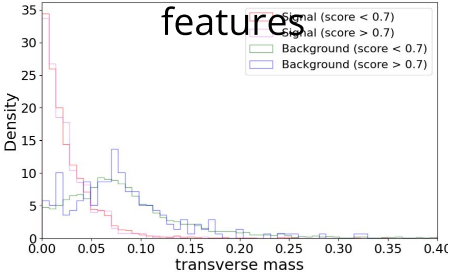



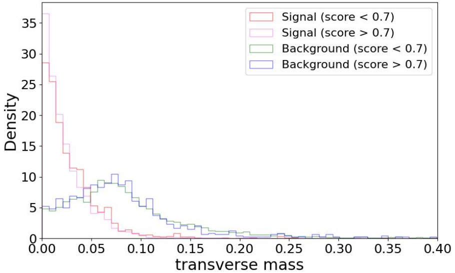

# Test 15: $+dPhi_{hh}$

TRANSVERSE MASS

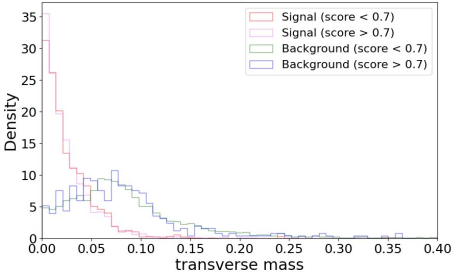
Test 5: No complex features

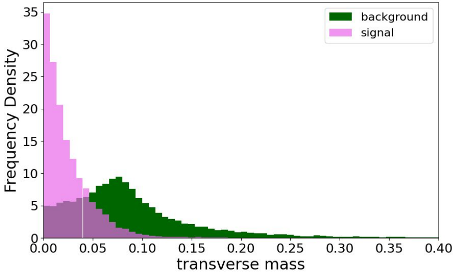


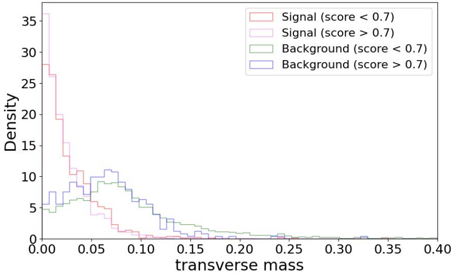

Test 7: $M_{bb}$ only



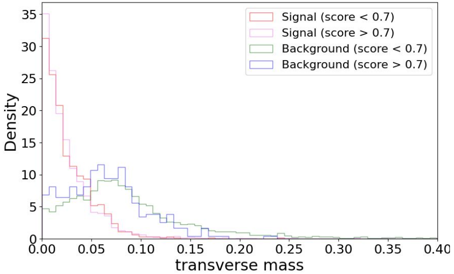

Test 8: $M_{bb}$ and $dR_{bb}$



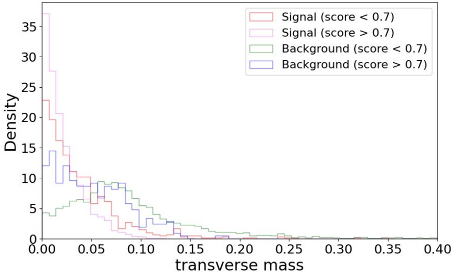




Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$



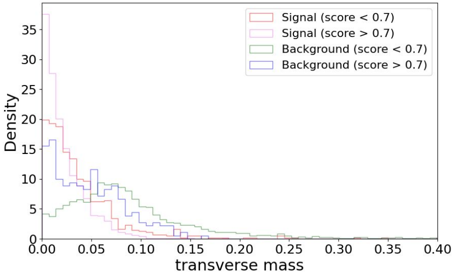

Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$



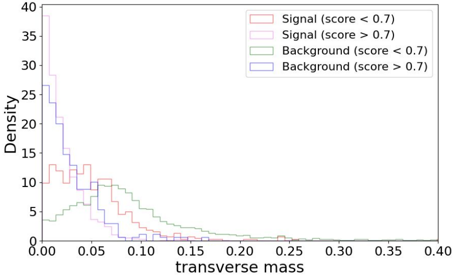

Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

TRANSVERSE MASS

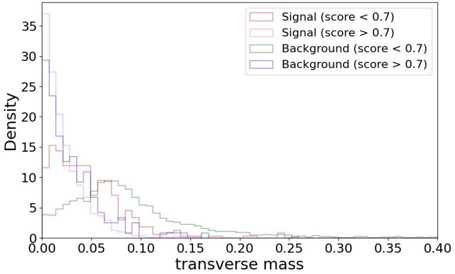
## Test 12: +dpT

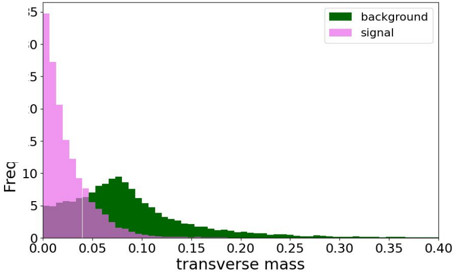


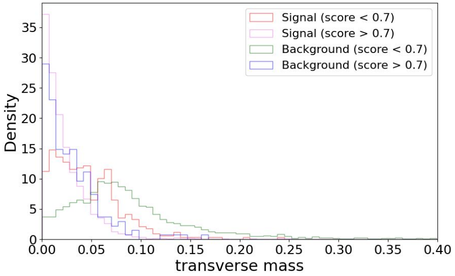

## Test 13: + transverse mass




## Test 14: + mhh



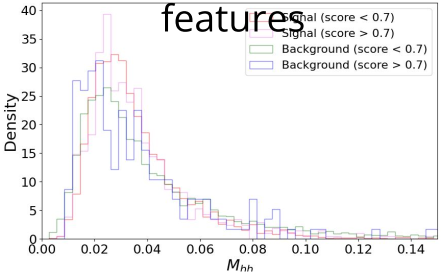



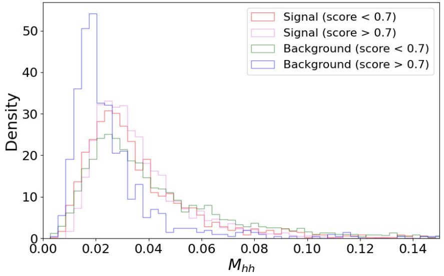

## Test 15: + dPhi_hh

INVARIANT MASS OF TWO HIGGS

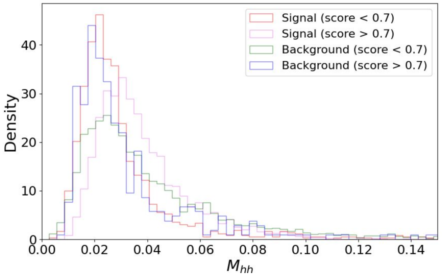
Test 5: No complex features

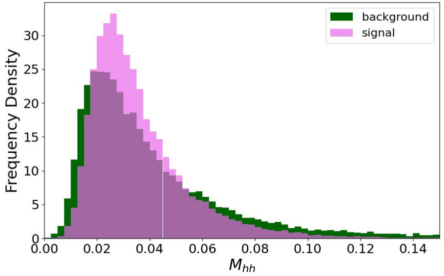


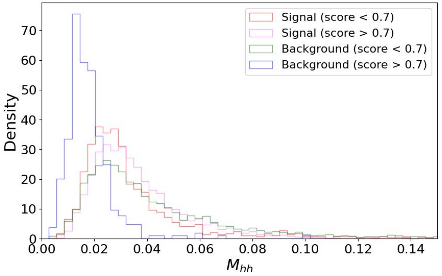

Test 7: $M_{bb}$ only



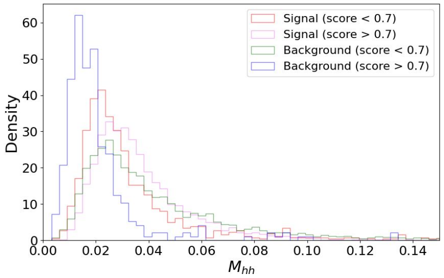

Test 8: $M_{bb}$ and $dR_{bb}$



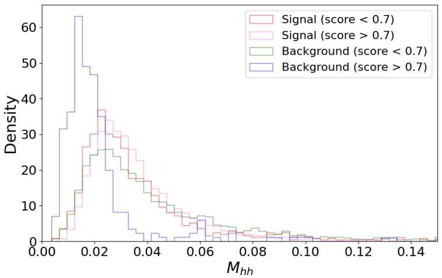




Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$



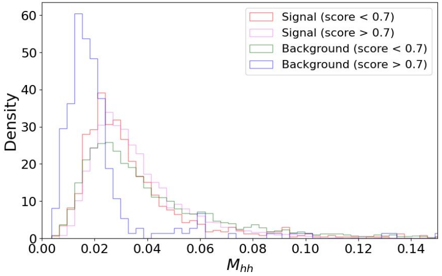

Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$



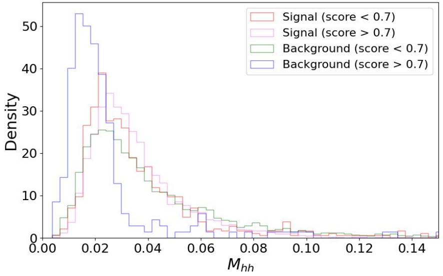

Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

## INVARIANT MASS OF TWO HIGGS

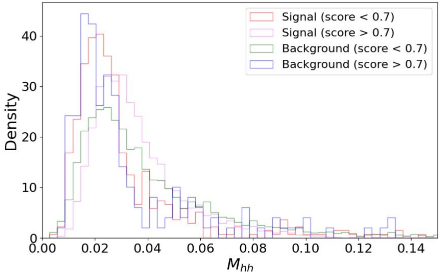
Test 12: +dpT

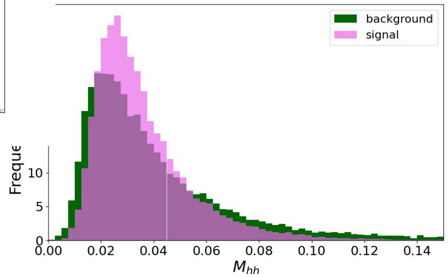


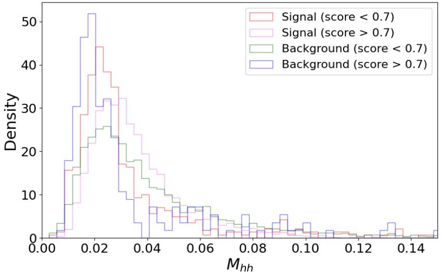

Test 13: + transverse mass




Test 14: + mhh



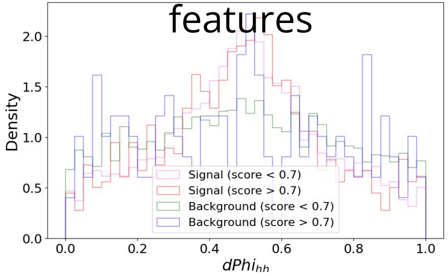



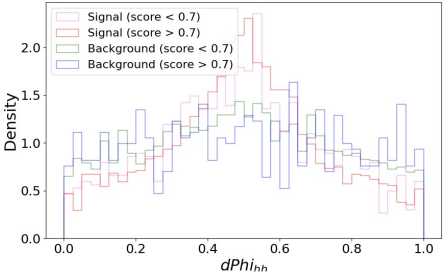

Test 15: + dPhi_hh

## DIFFERENCE IN PHI OF TWO HIGGS

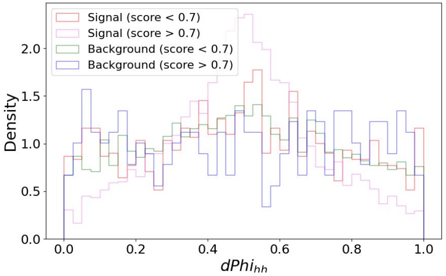
Test 5: No complex features

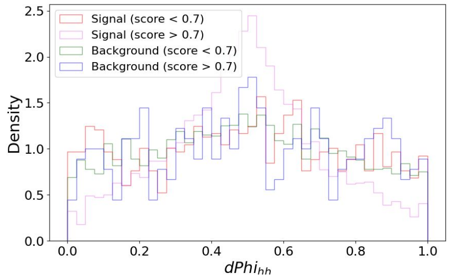



Test 7: $M_{bb}$ only

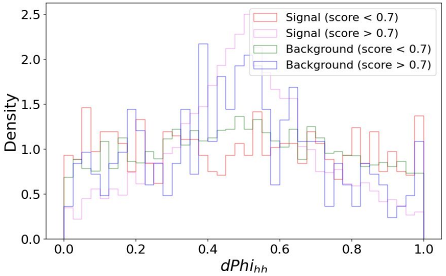



Test 8: $M_{bb}$ and $dR_{bb}$

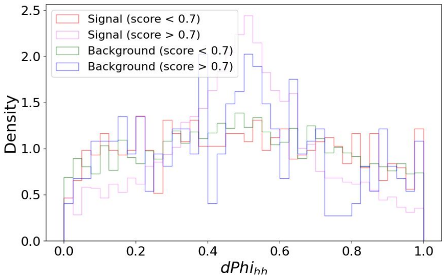


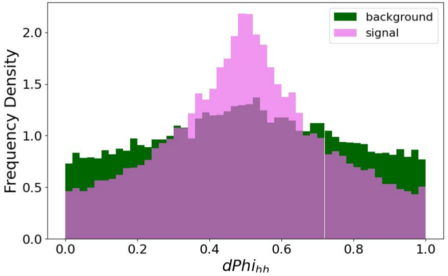

Test 9: $M_{bb}$, $dR_{bb}$ and $M_{\ell\tau}$




Test 10: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$ and $dR_{\ell\tau}$

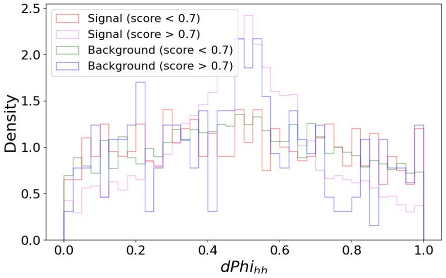



Test 11: $M_{bb}$, $dR_{bb}$, $M_{\ell\tau}$, $dR_{\ell\tau}$ and $C_{MET}$

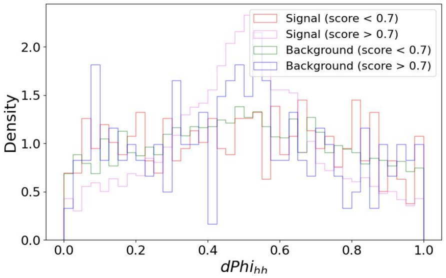


DIFFERENCE IN PHI OF TWO HIGGS

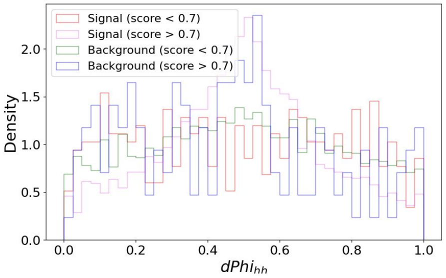
Test 12: +dpT

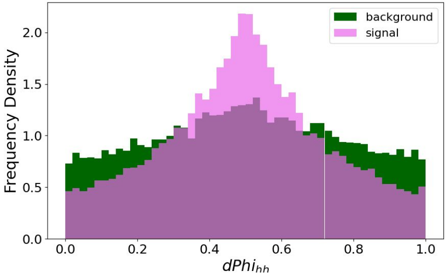


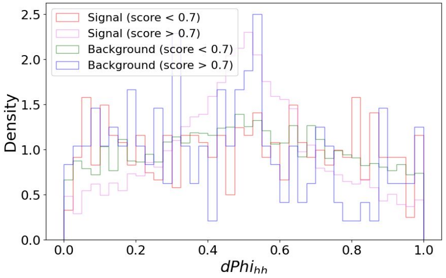

Test 13: + transverse mass




Test 14: + mhh




Test 15: + dPhi_hh