Search for the non-resonant production of Higgs boson pairs via gluon fusion and vector-boson fusion in the $bb\tau^+\tau^-$ final state in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Probing the Higgs self-coupling

Physics at LHC - Seminar

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Outline

1. Introduction and Motivation
2. ATLAS Detector
3. Signal processes, relevant production modes and final states
4. Data Acquisition
5. Event Selection
6. Boosted Decision Trees
7. Results
8. Uncertainties
9. Conclusion

Introduction

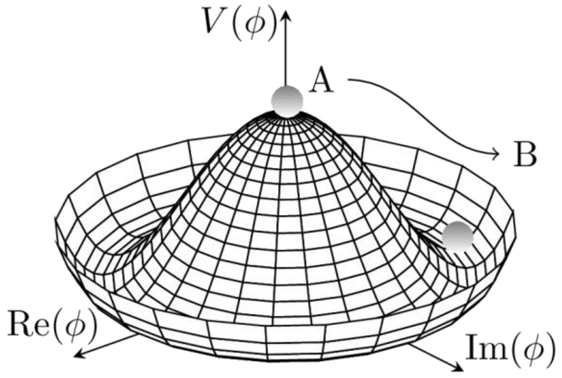
- Higgs field potential as described in the Standard Model is determined by the relation

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4 \qquad \mu^2 < 0, \lambda > 0$$

- This leads to the known "mexican hat" potential after electroweak symmetry breaking
- An excitation *h* from the minimum of this potential can be described with

$$V(h) = m_h^2 h^2 + \underline{\lambda_{hhh} v h^3} + \lambda_{hhhh} h^4$$

- m_h: Higgs-boson mass, v: vacuum expectation value (VEV), λ_{hhh}: trilinear Higgs coupling, λ_{hhhh}: quartic higgs-coupling
- So far, we only know about the *minimum* of the Higgs potential and about its interactions with fermions and gauge bosons

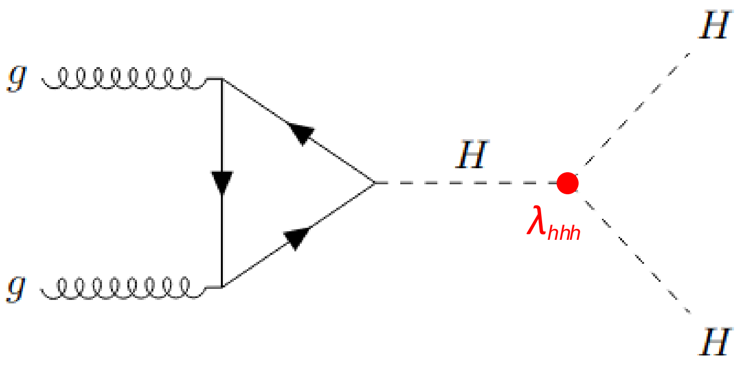


Why measure the Higgs Self-Coupling?

- More knowledge about the shape of the Higgs potential, details of electroweak symmetry breaking
- Standard Model tests
- Probing vacuum stability: The minimum of the Higgs potential might be metastable
- Additional Higgs Bosons
- Influence of higher dimensional (EFT) operators

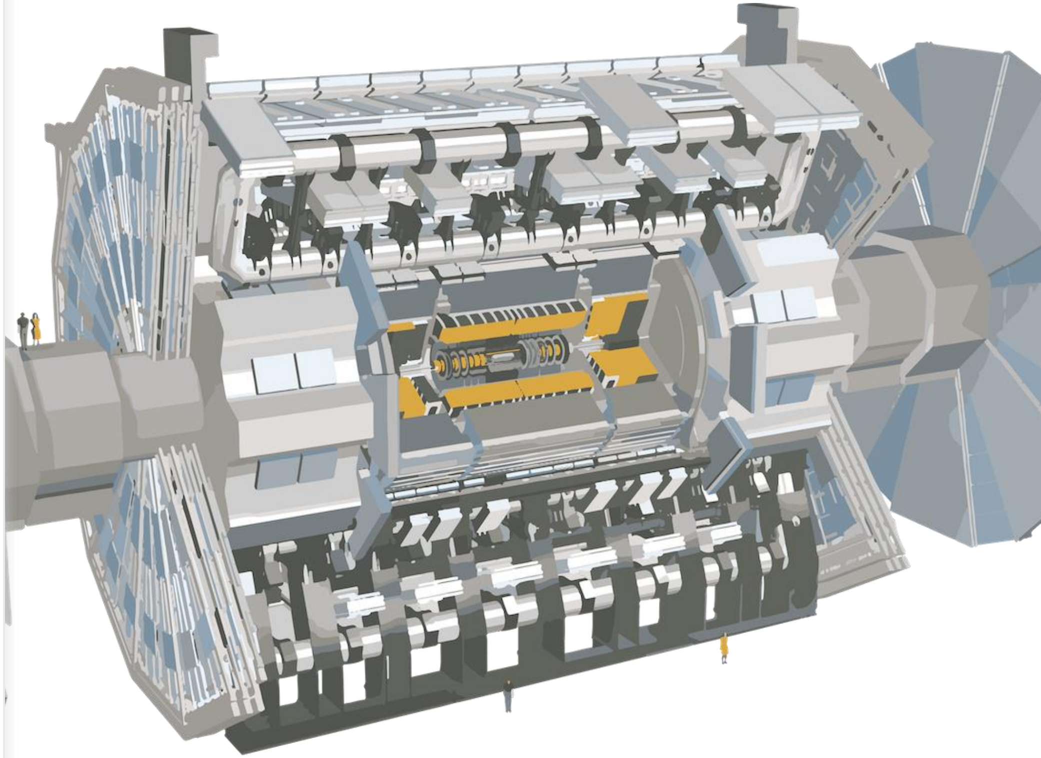
Introduction

- The interactions with itself can be probed by analysis of processes that produce di-Higgs
- For this it is useful to define a coupling modifier $\kappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM}$
- The strength of the di-Higgs production will also depend on the coupling modifiers $\kappa_V = \lambda_{vvh} / \lambda_{vvh}^{SM}$, $\kappa_{2V} = \lambda_{vvhh} / \lambda_{vvhh}^{SM}$, $\kappa_t = \lambda_{tth} / \lambda_{tth}^{SM}$



ATLAS

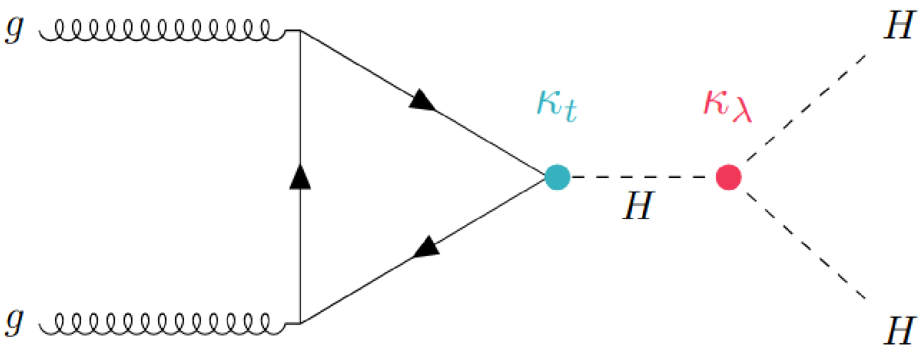
- multipurpose detector with cylindrical geometry and nearly 4π solid angle coverage
- Inner Detector: Tracks particles using silicon pixel, microstrip, and transition radiation detectors
- Electromagnetic calorimeter: Lead/LAr with high granularity, LAr for endcap/forward regions
- Hadronic calorimeter: Steel/scintillator for central region, LAr for endcap/forward regions
- Muon Spectrometer: Precision tracking and trigger chambers surround the calorimeters
- Hardware-based first-level trigger reduces event rate to <100 kHz
- Software-based second-level trigger reduces rate to ~1kHz

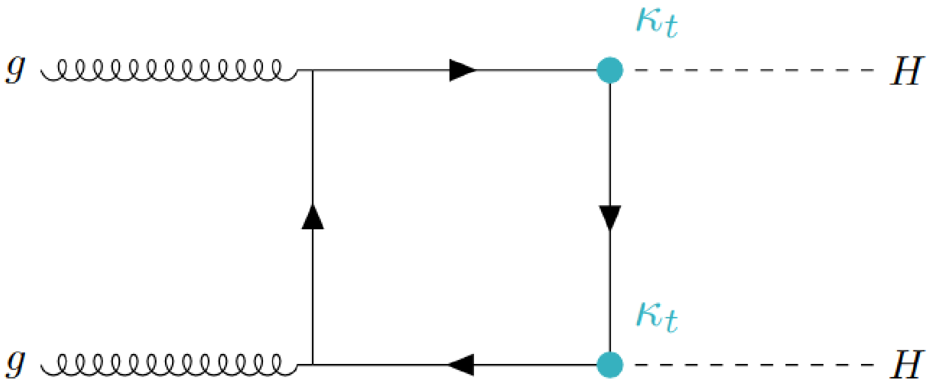


https://atlas.cern/Discover/Detector

Production modes

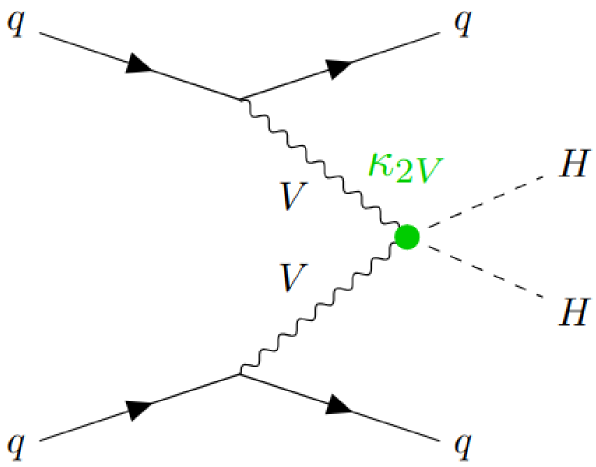
- Di-Higgs production via gluon-gluon Fusion (ggF)
- Dominant production mode with $\sigma^{\mathrm{SM}}_{\mathrm{ggF}} = 31.1^{+2.1}_{-7.2}\ \mathrm{fb}$ and m_H = 125 GeV
- For comparison: single Higgs production ~ 40 pb
- For self-coupling the first process is what we would like to measure
- Heavy negative interference between the two makes the analysis difficult
- κ_t and κ_λ contribute to the diagrams

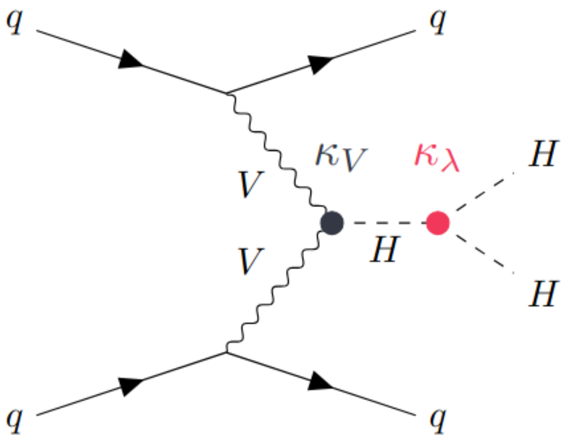


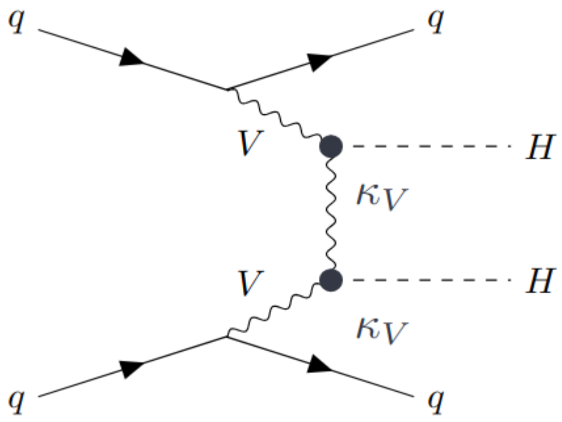


Production modes

- Di-Higgs production via Vector Boson Fusion (VBF)
- Second most dominant production mode with $\sigma^{\mathrm{SM}}_{\mathrm{VBF}} = 1.73 \pm 0.04$ fb
- **κ_V, κ_{2V}** and **κ_λ** contribute to the diagrams
- All of these have two additional light quark jets

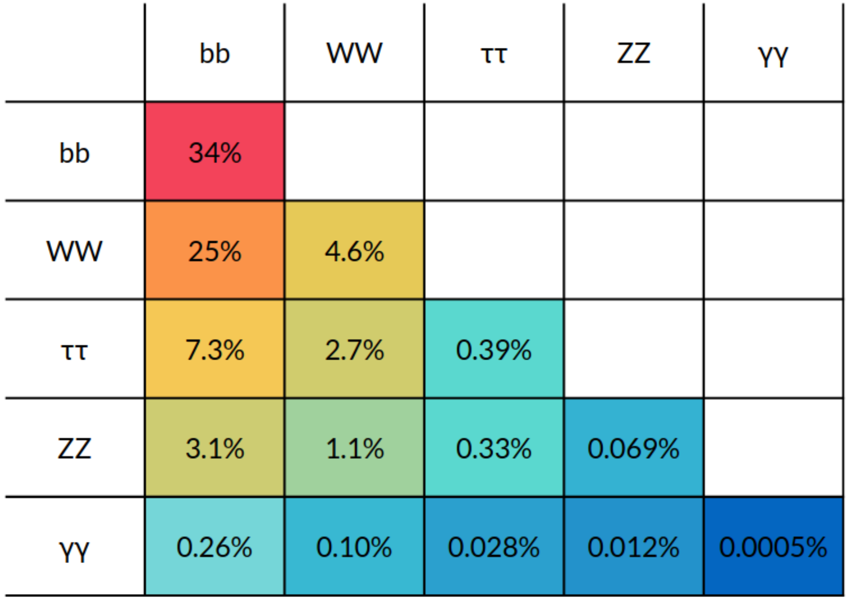






Decay modes

- The Higgs bosons produced will decay independently
- Among the most probable on-shell Higgs decays are bb and $\tau^+\tau^-$
- bbbb and bbWW can lead to very messy multi jet backgrounds
- This makes the bb $\tau^+\tau^-$ final state a very interesting candidate for di-Higgs analysis as it is relatively common and "cleaner" than other candidates

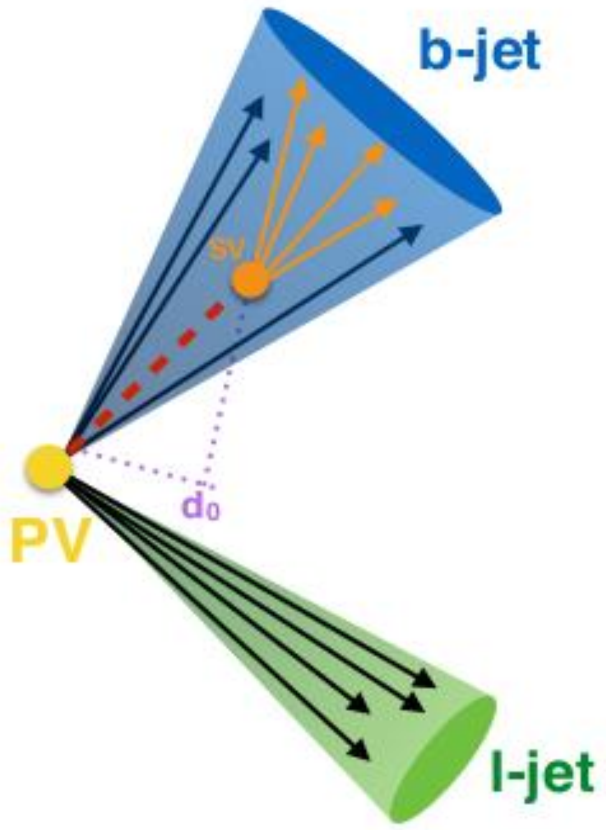


	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

https://inspirehep.net/files/a34811e0b9462ca5900081ffe6c92bdb

Decay of products

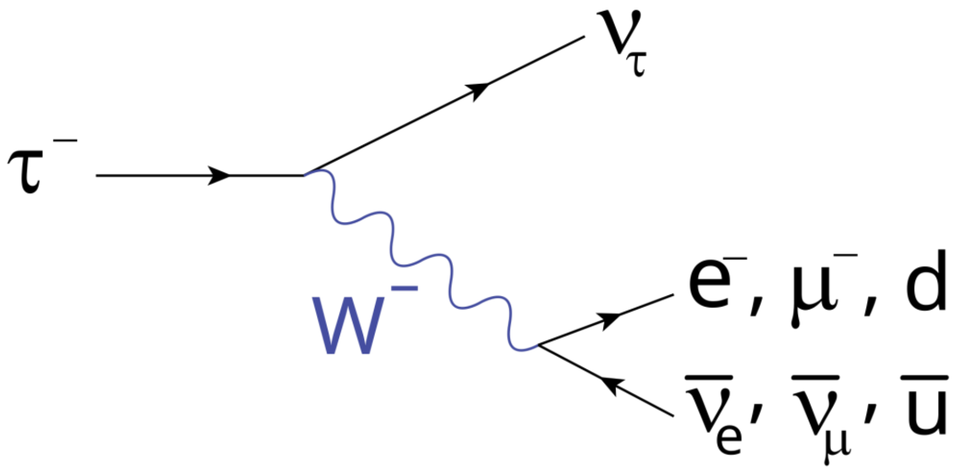
- The b quarks in the final state will (mostly) result in two b-jets, that can be reconstructed and identified using b-tagging algorithms
- The τ leptons will decay hadronically around 65% of the time, while decaying leptonically otherwise



https://www.hep.physik.uni-siegen.de/research/atlas/atlas-flavor-tagging

Decay of products

- τ leptons will decay hadronically into charged pions that can be detected as narrow jets with low track multiplicity
- Leptonic τ decay results in e/μ and missing p_T from neutrinos



https://en.wikipedia.org/wiki/Tau_(particle)

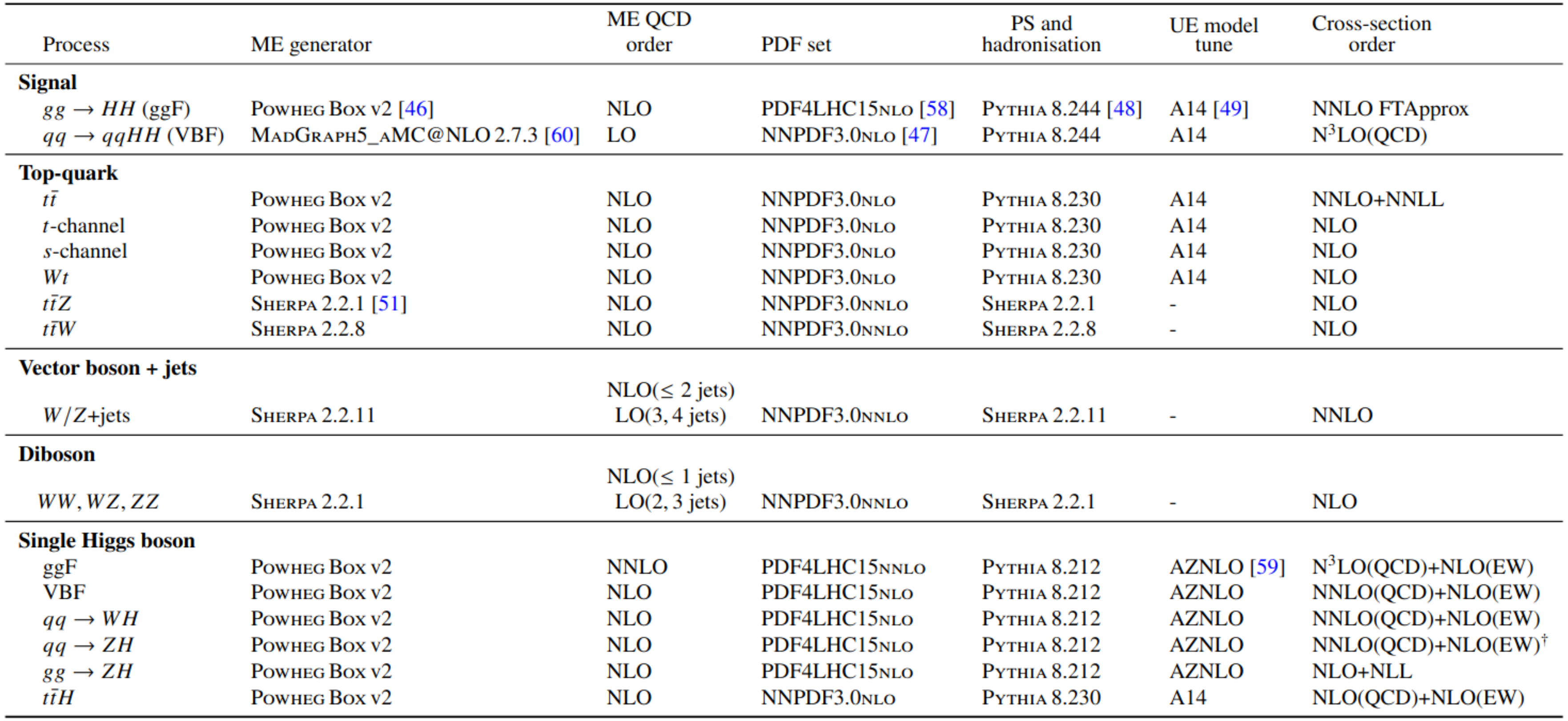
Background processes

- tt pair production
- multi-jet production
- Z/W+jets
- diboson
- single Higgs boson

Data and simulated samples

- Data used from LHC Run 2
- $\sqrt{s}$ = 13 TeV, int. luminosity 140.1 ± 1.2 fb^{-1}
- Various MC generators are used for simulating the different processes
- For correctly estimating fake $\tau_{\text{had-vis}}$ signatures a combination of real data and simulation is used

Generators used for simulation



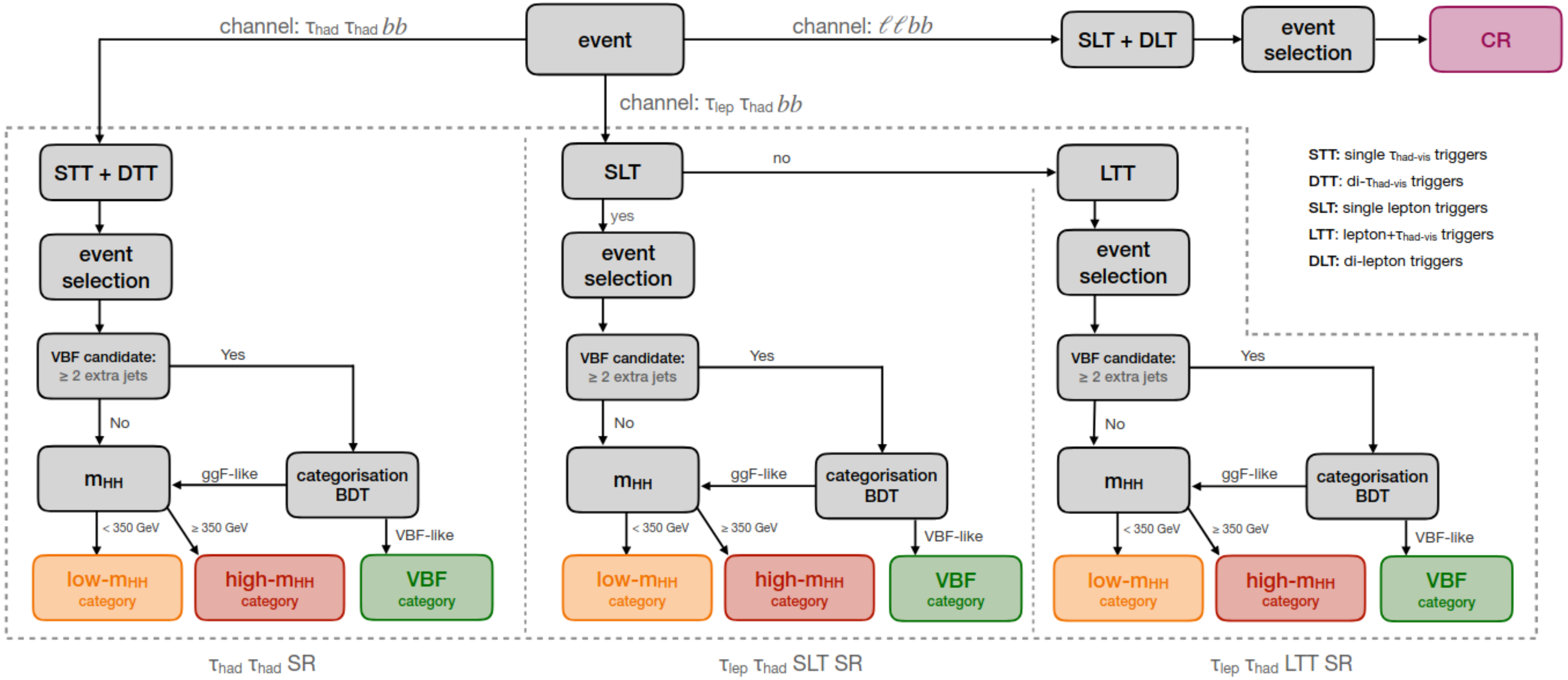
Process	ME generator	ME QCD order	PDF set	PS and hadronisation	UE model tune	Cross-section order
Signal						
$gg \to HH$ (ggF)	Powheg Box v2 [46]	NLO	PDF4LHC15nlo [58]	Pythia 8.244 [48]	A14 [49]	NNLO FTApprox
$qq \to qqHH$ (VBF)	MadGraph5_aMC@NLO 2.7.3 [60]	LO	NNPDF3.0nlo [47]	Pythia 8.244	A14	N^{3}LO(QCD)
Top-quark						
$t\bar{t}$	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230	A14	NNLO+NNLL
t-channel	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230	A14	NLO
s-channel	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230	A14	NLO
Wt	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230	A14	NLO
$t\bar{t}Z$	Sherpa 2.2.1 [51]	NLO	NNPDF3.0nnlo	Sherpa 2.2.1	-	NLO
$t\bar{t}W$	Sherpa 2.2.8	NLO	NNPDF3.0nnlo	Sherpa 2.2.8	-	NLO
Vector boson + jets						
W/Z+jets	Sherpa 2.2.11	NLO($\leq$ 2 jets) LO(3, 4 jets)	NNPDF3.0nnlo	Sherpa 2.2.11	-	NNLO
Diboson						
WW, WZ, ZZ	Sherpa 2.2.1	NLO($\leq$ 1 jets) LO(2, 3 jets)	NNPDF3.0nnlo	Sherpa 2.2.1	-	NLO
Single Higgs boson						
ggF	Powheg Box v2	NNLO	PDF4LHC15nnlo	Pythia 8.212	AZNLO [59]	N^{3}LO(QCD)+NLO(EW)
VBF	Powheg Box v2	NLO	PDF4LHC15nlo	Pythia 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$qq \to WH$	Powheg Box v2	NLO	PDF4LHC15nlo	Pythia 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$qq \to ZH$	Powheg Box v2	NLO	PDF4LHC15nlo	Pythia 8.212	AZNLO	NNLO(QCD)+NLO(EW)†
$gg \to ZH$	Powheg Box v2	NLO	PDF4LHC15nlo	Pythia 8.212	AZNLO	NLO+NLL
$t\bar{t}H$	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230	A14	NLO(QCD)+NLO(EW)

https://arxiv.org/pdf/2404.12660

Signal Regions in the Analysis

- 3 Signal Regions (SR)
  - First Region $\tau_{had}\tau_{had}$ bb
  - 2 Regions for $\tau_{lep}\tau_{had}$ bb (depending on different triggers)
- 1 Control Region (CR) for validating background models
  - $\tau_{lep}\tau_{lep}$ bb

Signal Regions in the Analysis



event

channel: $\tau_{had}\tau_{had}bb$

channel: $\ell\ell bb$

channel: $\tau_{lep}\tau_{had}bb$

SLT + DLT → event selection → CR

STT + DTT → event selection → VBF candidate: ≥ 2 extra jets

Yes → categorisation BDT

No → m_{HH}

categorisation BDT: ggF-like → m_{HH}; VBF-like → VBF category

m_{HH}: < 350 GeV → low-m_{HH} category; ≥ 350 GeV → high-m_{HH} category

$\tau_{had}\tau_{had}$ SR

SLT: yes → event selection → VBF candidate: ≥ 2 extra jets; no → LTT

Yes → categorisation BDT

No → m_{HH}

categorisation BDT: ggF-like → m_{HH}; VBF-like → VBF category

m_{HH}: < 350 GeV → low-m_{HH} category; ≥ 350 GeV → high-m_{HH} category

$\tau_{lep}\tau_{had}$ SLT SR

LTT → event selection → VBF candidate: ≥ 2 extra jets

Yes → categorisation BDT

No → m_{HH}

categorisation BDT: ggF-like → m_{HH}; VBF-like → VBF category

m_{HH}: < 350 GeV → low-m_{HH} category; ≥ 350 GeV → high-m_{HH} category

$\tau_{lep}\tau_{had}$ LTT SR

STT: single $\tau_{had\text{-}vis}$ triggers

DTT: di-$\tau_{had\text{-}vis}$ triggers

SLT: single lepton triggers

LTT: lepton+$\tau_{had\text{-}vis}$ triggers

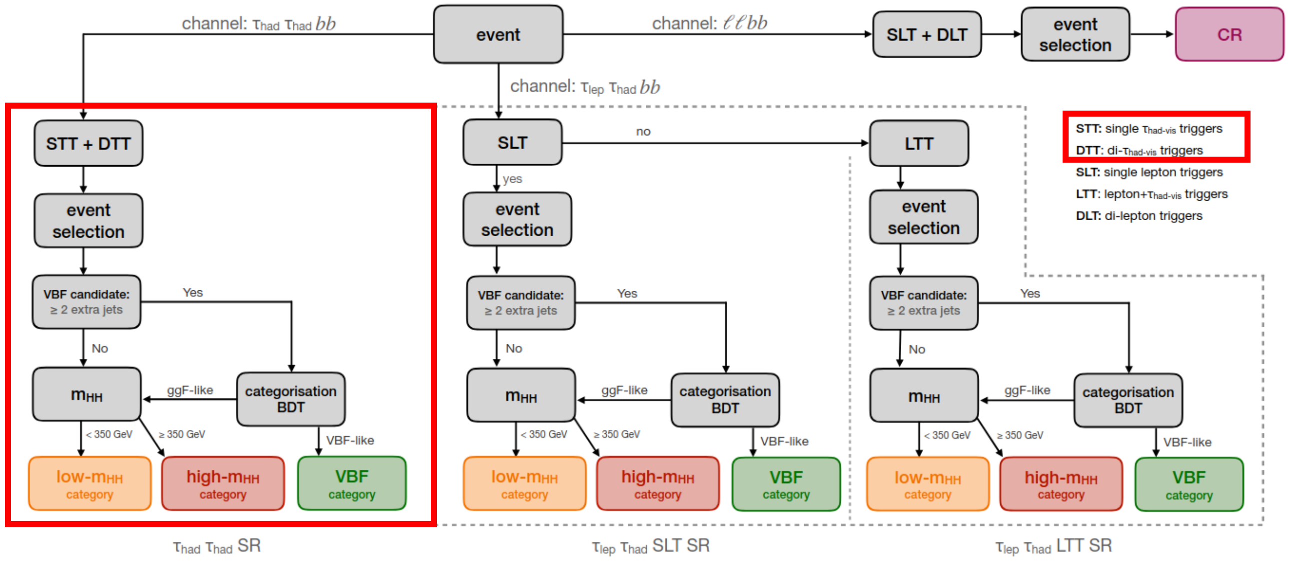
DLT: di-lepton triggers

Signal Regions in the Analysis

- General requirements for all SRs
  - $m_{\tau\tau} > 60$ GeV
  - Events must contain two b-tagged jets with $|\eta| < 2.5$
  - b-jets have to satisfy $p_T > 45$ GeV (20 GeV)

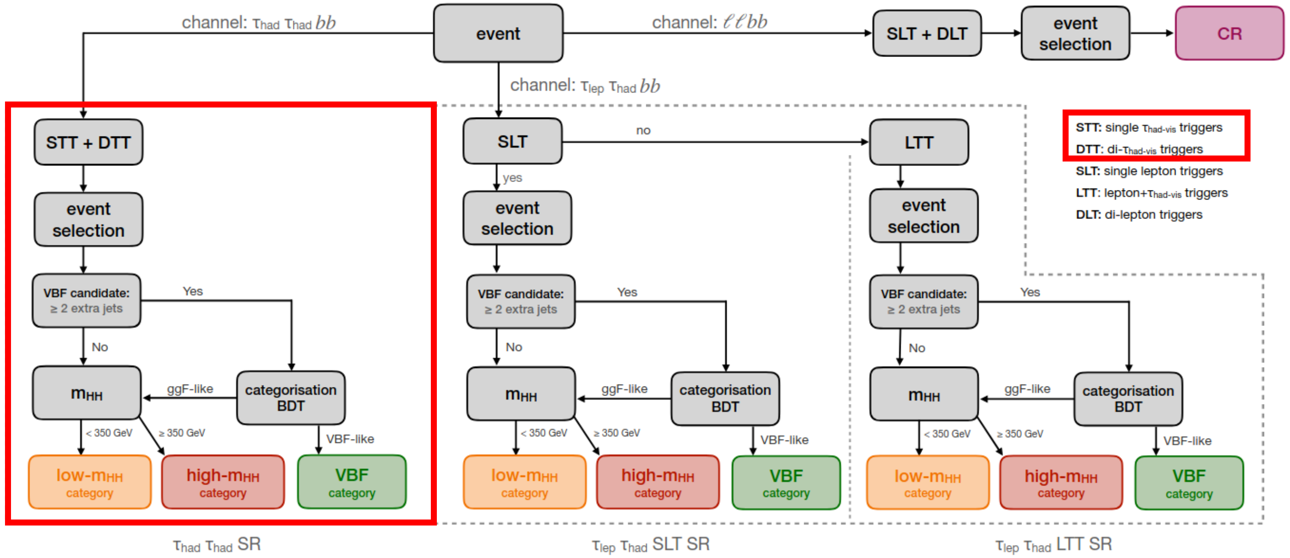
bb $\tau_{had}\tau_{had}$

- Selection using combined "single-$\tau_{had\text{-}vis}$ triggers" (STT) + "di-$\tau_{had\text{-}vis}$ triggers" (DTT)
- Two $\tau_{had\text{-}vis}$ with opposite charge are required
- No muons, electrons allowed in the final state



bb $\tau_{had}\tau_{had}$

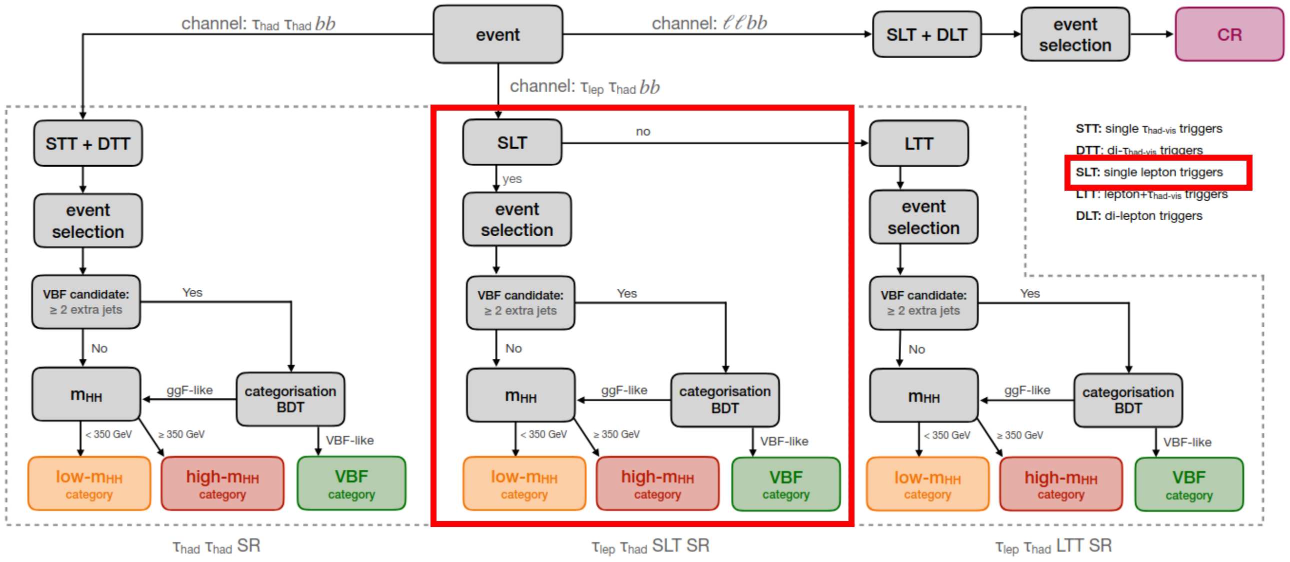
- STT selection: minimum p_T has to be 100 GeV – 180 GeV (different data taking periods)
  - There needs to be a second $\tau_{had\text{-}vis}$ present with $p_T > 25$ GeV
- DTT cuts: minimum p_T 40 GeV (leading), 30 GeV (subleading)
  - One extra jet present with $p_T > 80$ GeV and $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 2.5$
  - Or: Two extra jets with $p_T > 45$ GeV



STT: single $\tau_{had\text{-}vis}$ triggers
DTT: di-$\tau_{had\text{-}vis}$ triggers
SLT: single lepton triggers
LTT: lepton+$\tau_{had\text{-}vis}$ triggers
DLT: di-lepton triggers

bb $\tau_{lep}\tau_{had}$ (SLT)

- electrons have to satisfy p_T > 25 GeV (27 GeV)
- muons have to satisfy p_T > 21 GeV (27 GeV)
- m_{bb} < 150 GeV (reject tt background)
- One $\tau_{had\text{-}vis}$ present with opposite charge to the lepton and p_T > 20 GeV

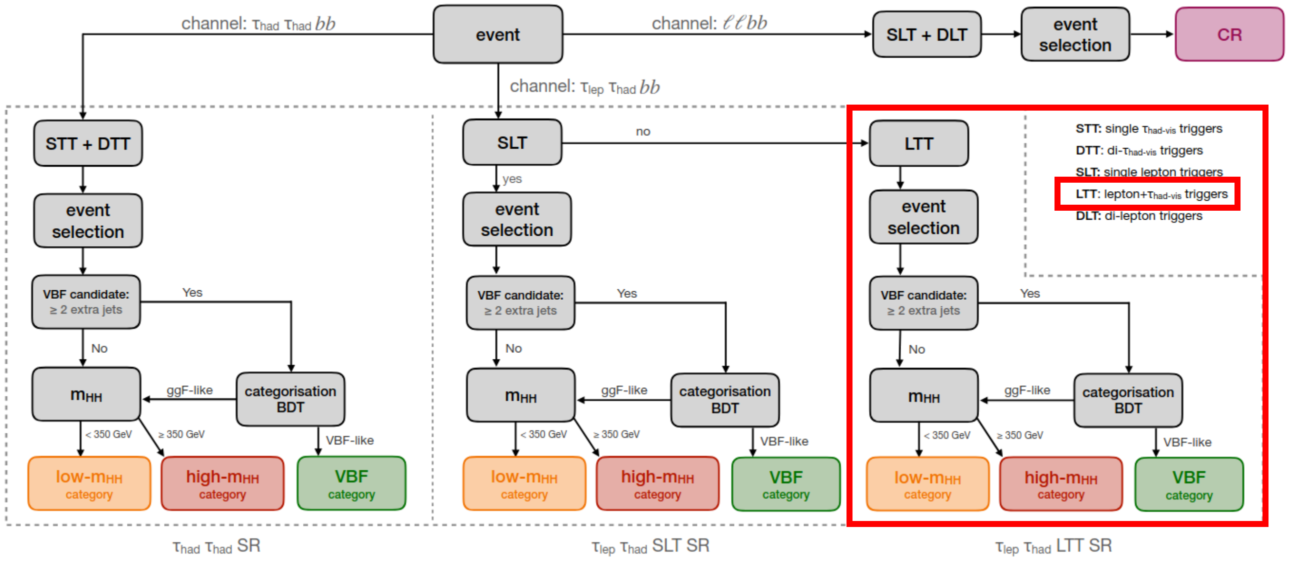


event
channel: $\tau_{had}\tau_{had}bb$
channel: $\ell\ell bb$
channel: $\tau_{lep}\tau_{had}bb$
SLT + DLT
event selection
CR
STT + DTT
SLT
no
yes
LTT
event selection
VBF candidate: ≥ 2 extra jets
Yes
No
m_{HH}
ggF-like
categorisation BDT
< 350 GeV
≥ 350 GeV
VBF-like
low-m_{HH} category
high-m_{HH} category
VBF category
$\tau_{had}\tau_{had}$ SR
$\tau_{lep}\tau_{had}$ SLT SR
$\tau_{lep}\tau_{had}$ LTT SR

STT: single $\tau_{had\text{-}vis}$ triggers
DTT: di-$\tau_{had\text{-}vis}$ triggers
SLT: single lepton triggers
LTT: lepton+$\tau_{had\text{-}vis}$ triggers
DLT: di-lepton triggers

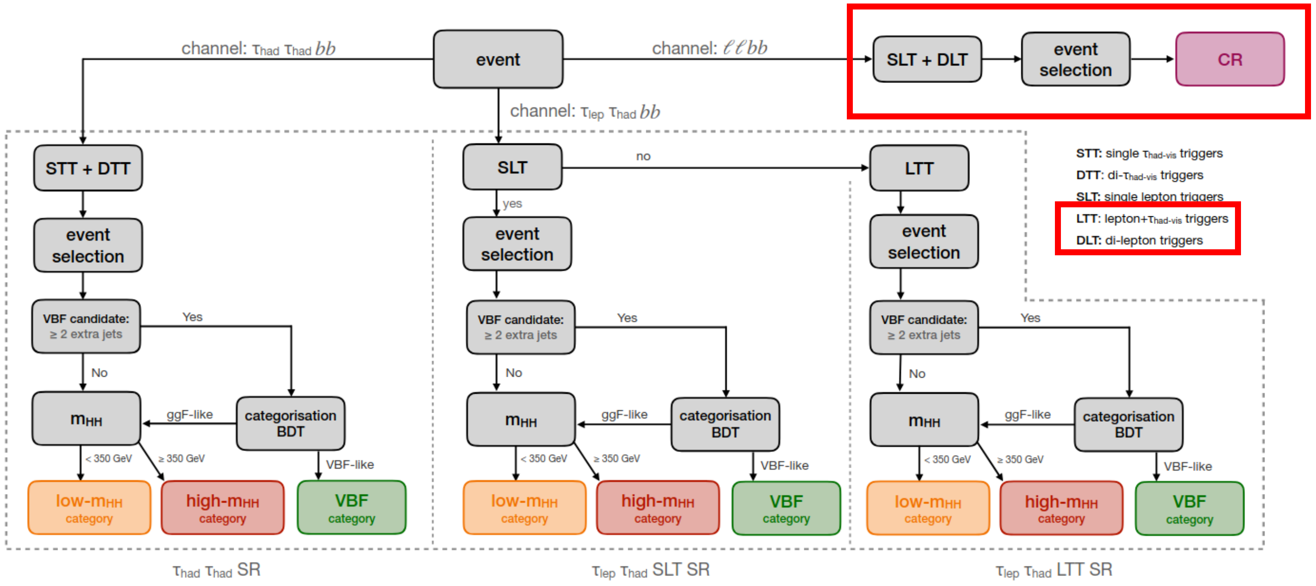
bb $\tau_{lep}\tau_{had}$ (LTT)

- electrons have to satisfy $p_T > 18$ GeV
- muons have to satisfy $p_T > 15$ GeV
- $m_{bb} < 150$ GeV (reject tt background)
- One $\tau_{had\text{-}vis}$ present with with opposite charge to the lepton and $p_T > 30$ GeV



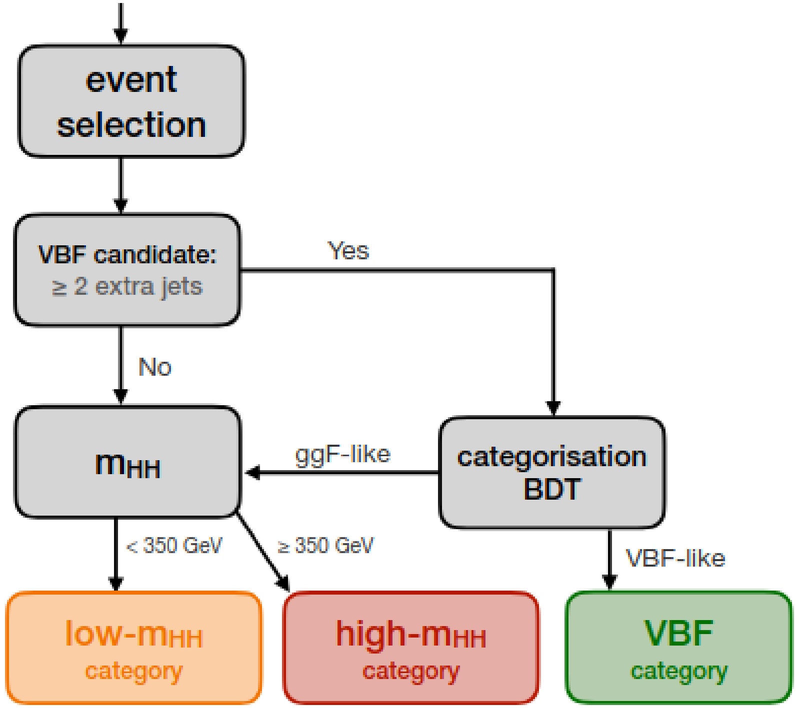
bb $\tau_{lep}\tau_{lep}$ (CR)

- Exactly two electrons or two muons
- 75 GeV < $m_{\ell\ell}$ < 110 GeV
- m_{bb} < 40 GeV or m_{bb} > 210 GeV
- Leptons have to satisfy p_T > 40 GeV
- Leading b-jet with p_T > 45 GeV



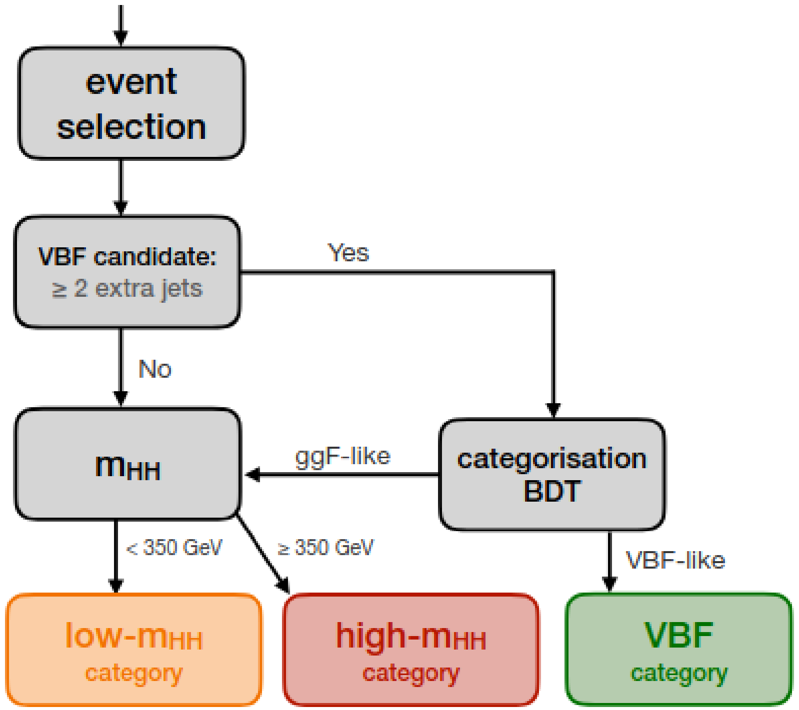
Event categorization

- In all of the SRs there are three different categories for events
- Events with ggF production get sorted into a low-m_{HH} (< 350 GeV) and a high-m_{HH} (> 350 GeV) category
- Events with VBF will be in a third category



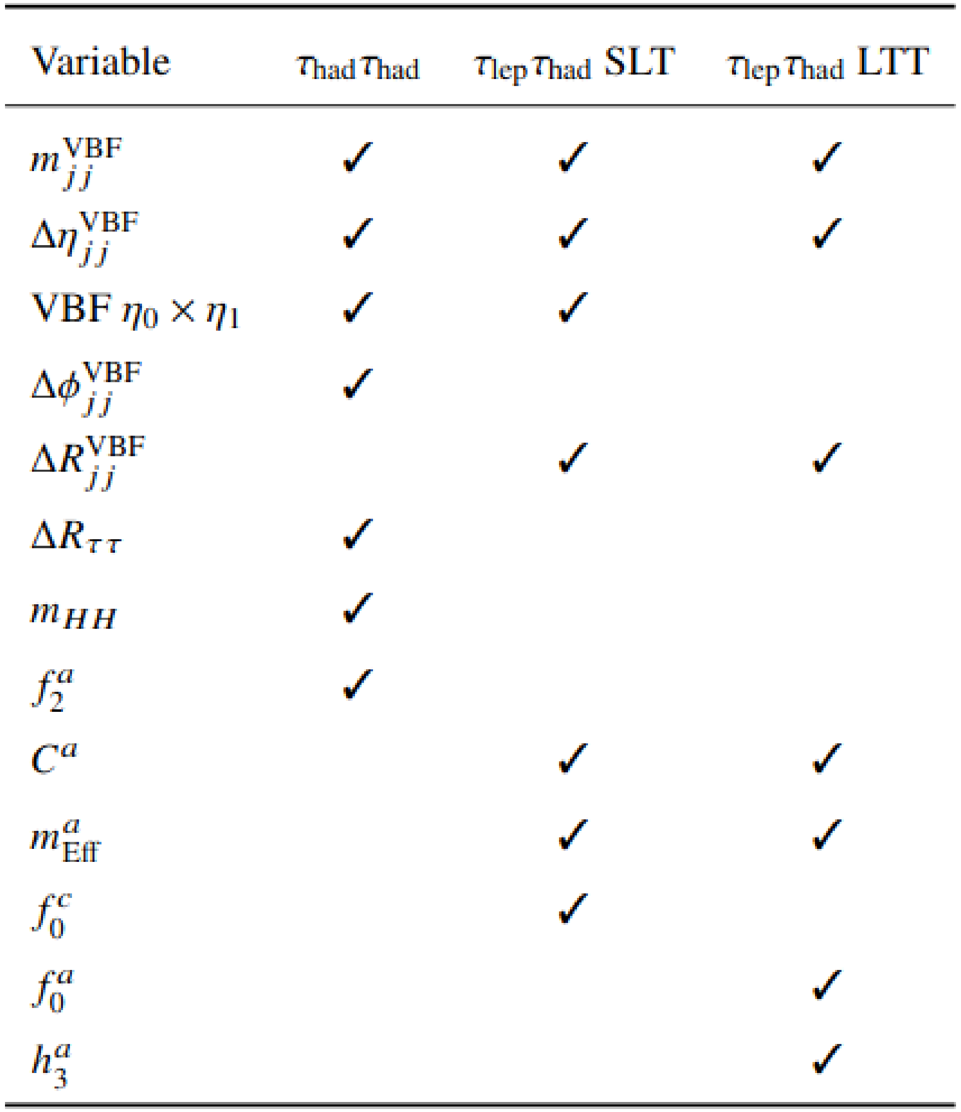
Boosted Decision Trees

- Boosted Decision Trees (BDTs) are a machine learning method used for predictions on events in this analysis
- Decision trees group data in categories using binary (yes/no) questions about its input features
- BDTs use a lot of decision trees sequentially focusing training on previous mistakes
- Total score for a certain event is computed using a weighted average over all decision trees



Input features for categorization

- Every SR uses a different set of input features
- Features used are the ones offering the best distinction between ggF and VBF events

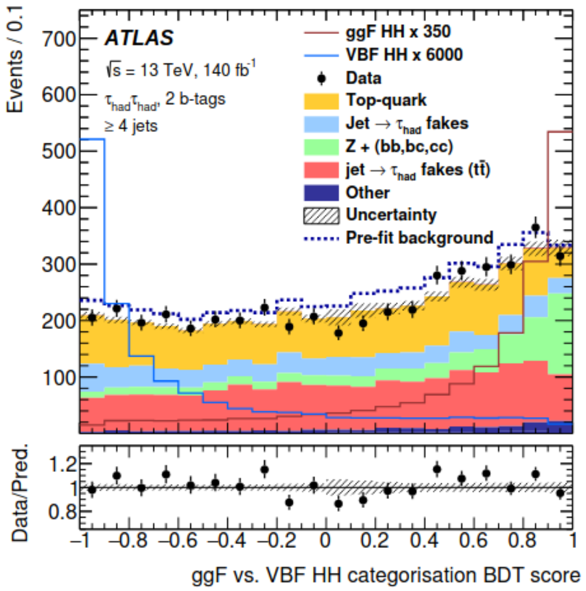


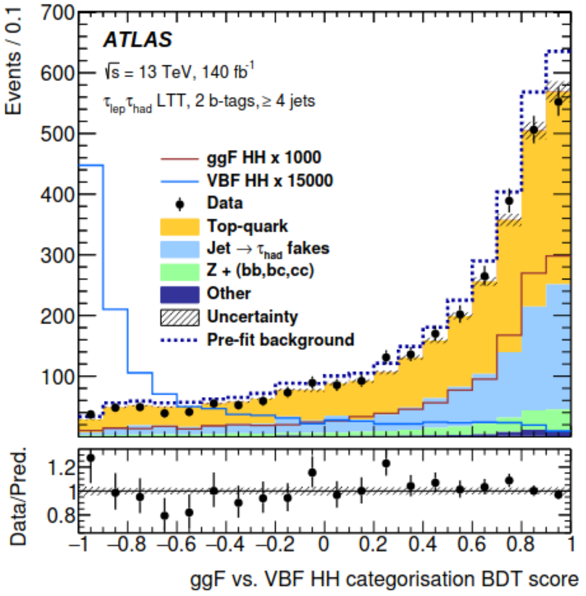
Variable	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT
m_{jj}^{VBF}	✓	✓	✓
$\Delta\eta_{jj}^{\text{VBF}}$	✓	✓	✓
VBF $\eta_0 \times \eta_1$	✓	✓	
$\Delta\phi_{jj}^{\text{VBF}}$	✓		
$\Delta R_{jj}^{\text{VBF}}$		✓	✓
$\Delta R_{\tau\tau}$	✓		
m_{HH}	✓		
f_2^a	✓		
C^a		✓	✓
m_{Eff}^a		✓	✓
f_0^c		✓	
f_0^a			✓
h_3^a			✓

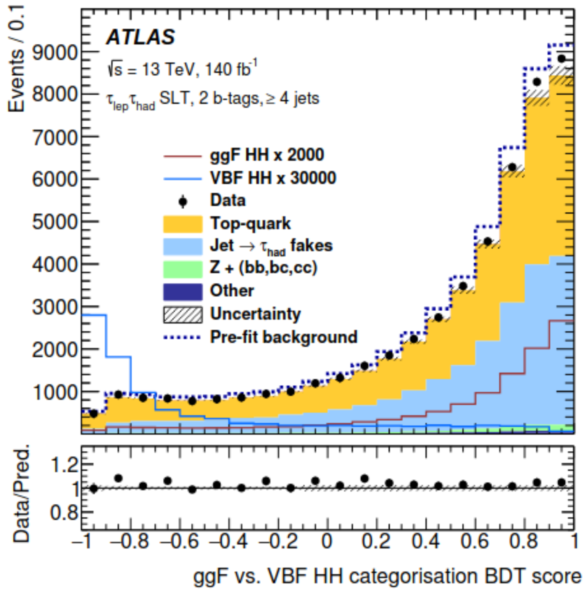
https://arxiv.org/pdf/2404.12660

Results for categorization BDTs

- BDT scores range from –1 (most VBF-like) to 1 (most ggF-like)
- This shows BDT evaluation on the data in each SR
- BDT predictions are very close to observed scores
- Signal Processes are scaled up a lot because of their very small contributions







https://arxiv.org/pdf/2404.12660

HH vs background separation with BDTs

- 9 different BDTs for the 3 different categories and 3 SRs
- Input features are a combination of:
  - m_{bb}, $m_{\tau\tau}$, m_{HH}, ΔR_{bb}, $\Delta R_{\tau\tau}$
    - ΔR_{bb} is excluded in the $\tau_{lep}\tau_{had}$ high-m_{HH} category
    - Both ΔR_{bb} and $\Delta R_{\tau\tau}$ are excluded in the $\tau_{lep}\tau_{had}$ VBF category
  - Transverse momenta of particles
  - More complex geometric variables, flow features

HH vs background separation with BDTs

- For the ggF high-m_{HH} and the VBF categories, the signal is defined as ggF HH and VBF HH production respectively with the SM hypothesis
- For ggF low-m_{HH}, the signal is defined as ggF HH production with $\boldsymbol{\kappa}_\lambda = 10$

Results

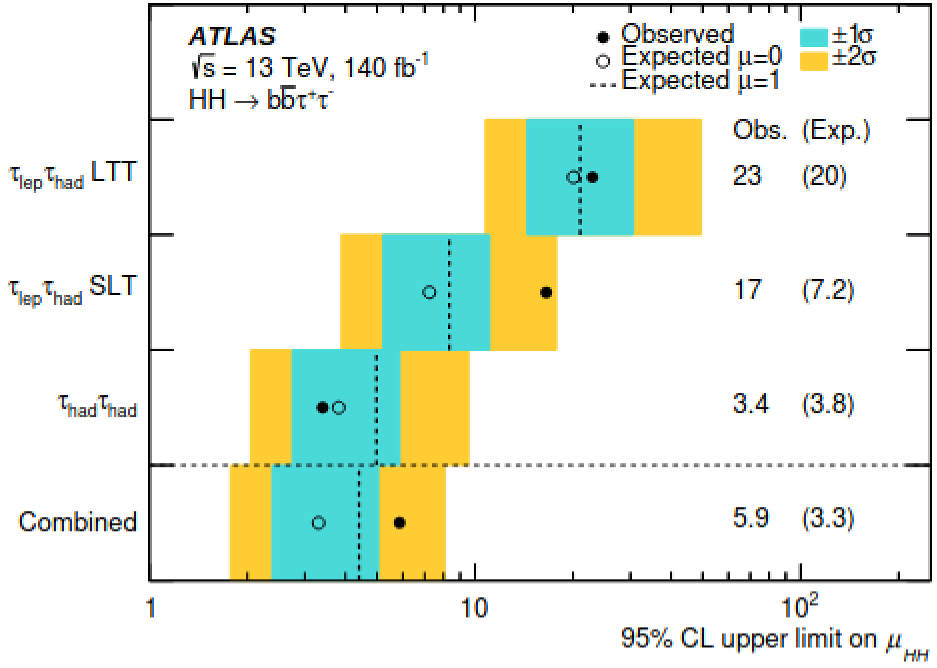
- A global likelihood function $L(\alpha,\vartheta)$ is used, combining all the nine BDT output distributions and the $m_{\ell\ell}$ distribution of the CR
- α: Parameters of interest (POI), e.g. the signal strength parameter μ_{HH} or coupling modifiers κ_{λ}, κ_{V}, κ_{2V}
- ϑ: nuisance parameters, e.g. systematic uncertainties constrained by measurements in control regions or by theoretical predictions or certain background yields

Results

- A maximum-likelihood fit to data for the function $L(\alpha,\vartheta)$ can be performed on a set α of parameters of interest to predict the most likely values of these parameters using the given data
- Performing this likelihood fit for $L(\mu_{HH},\vartheta)$ results in an estimate for the HH signal strength of $\mu_{HH} = 2.2 +/- 1.7$ with an upper bound of *5.9* at 95% CL

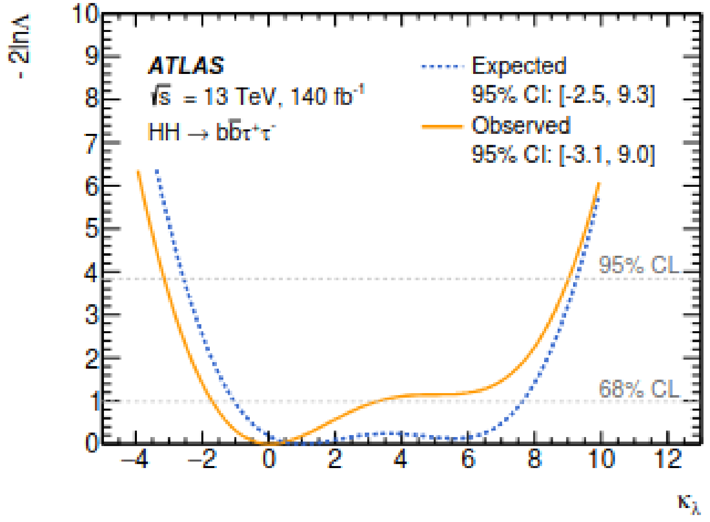
Results

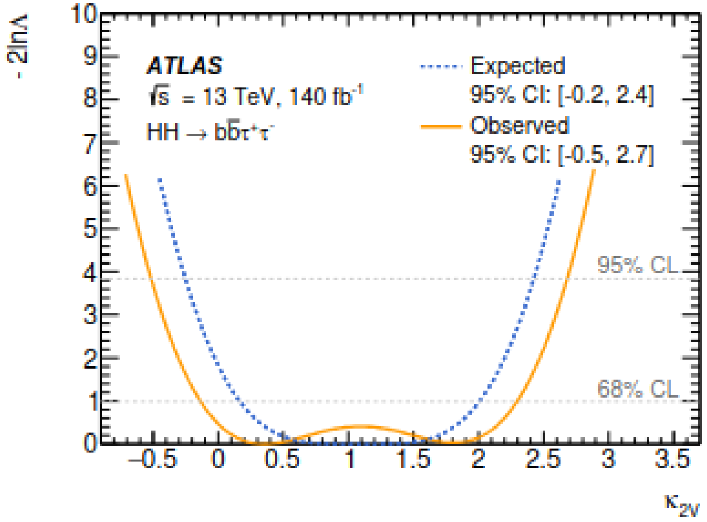
- Signal strength μ_{HH} per SR
- Shown are the 95% CL upper limits for both $\mu_{HH} = 0$ (only background) and $\mu_{HH} = 1$ (SM prediction) hypotheses

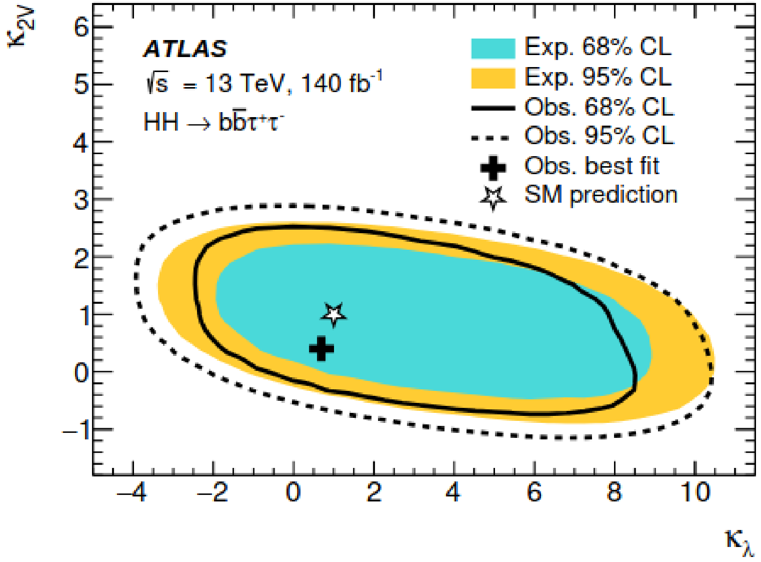


Results

- Different hypotheses for κ_λ, κ_{2V}
- Compared to "perfect" dataset ("Expected") under the SM hypothesis
- $-3.1 < \kappa_\lambda < 9.0$ (observed)
- $-0.5 < \kappa_{2V} < 2.7$ (observed)

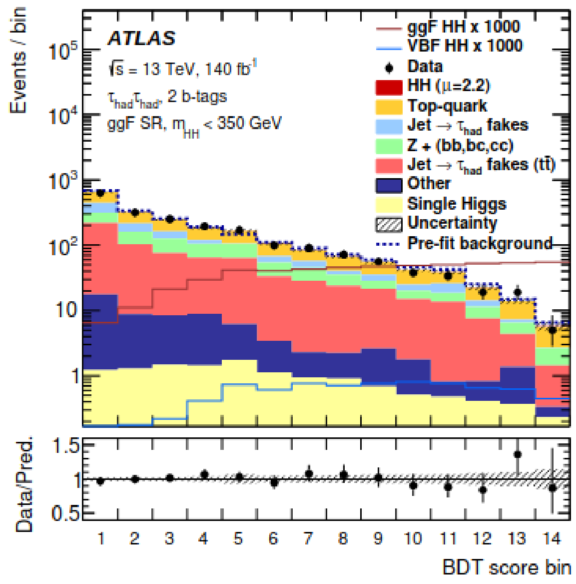


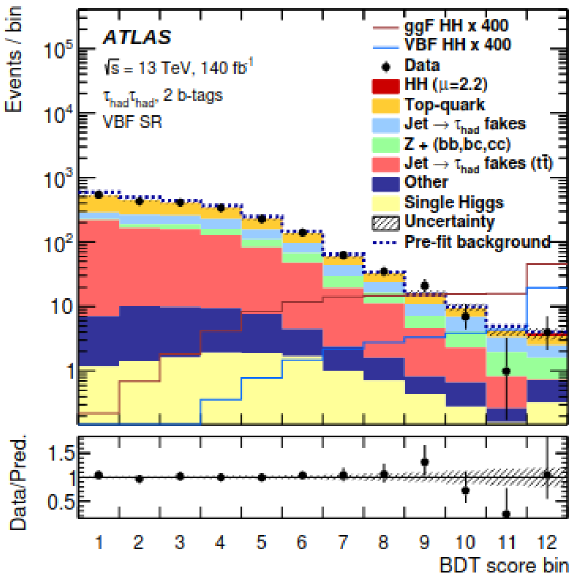


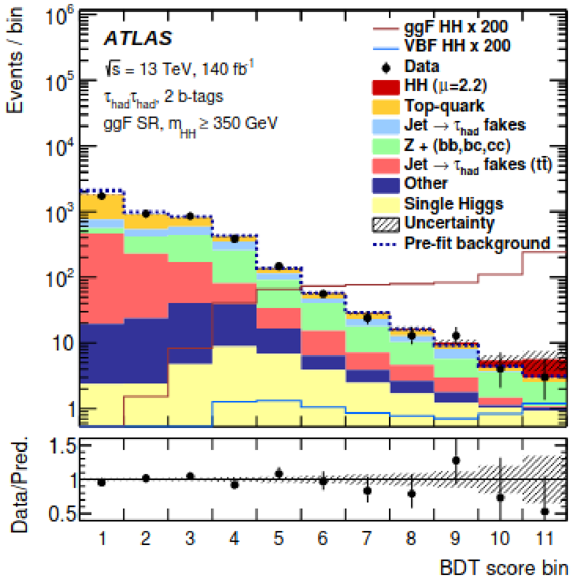


BDT results in the $\tau_{had}\tau_{had}$ SR

- This shows BDT evaluation after the likelihood fit to the data for $L(\mu_{HH},\theta)$ in each category of the $\tau_{had}\tau_{had}$ SR
- scores range from 1 (most background-like) to 11-14 (most HH-like)
- BDT predictions are very close to observed scores
- Most HH signal in the high-m_{HH} category of $\tau_{had}\tau_{had}$ SR, very high uncertainty



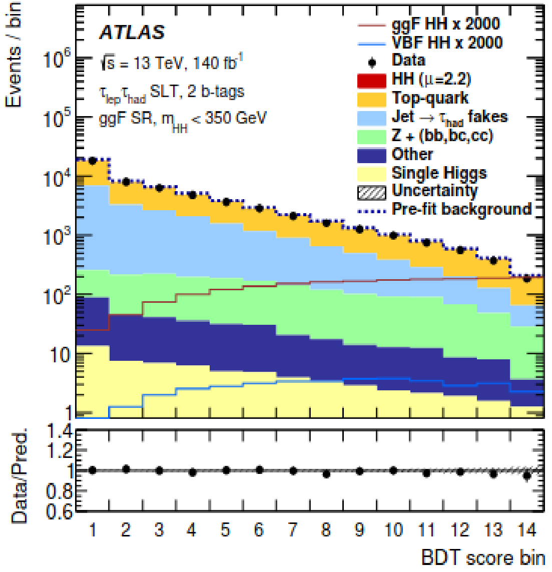


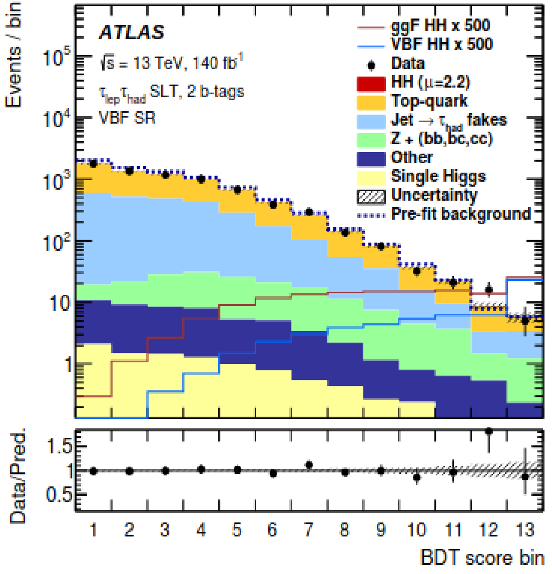


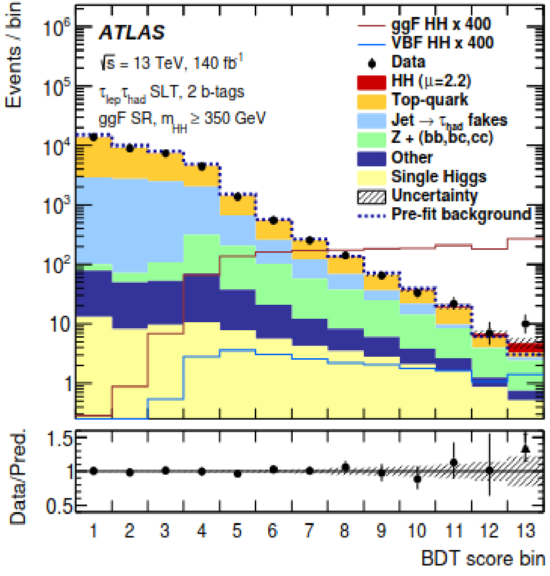
https://arxiv.org/pdf/2404.12660

BDT results in the $\tau_{lep}\tau_{had}$ SLT SR

- This shows BDT evaluation after the likelihood fit to the data for $L(\mu_{HH},\theta)$ in each category of the $\tau_{lep}\tau_{had}$ SLT SR
- BDT scores range from 1 (most background-like) to 13-14 (most HH-like)
- BDT predictions are very close to observed scores
- Most HH signal in the high-m_{HH} category of $\tau_{lep}\tau_{had}$ SR, slight deviation



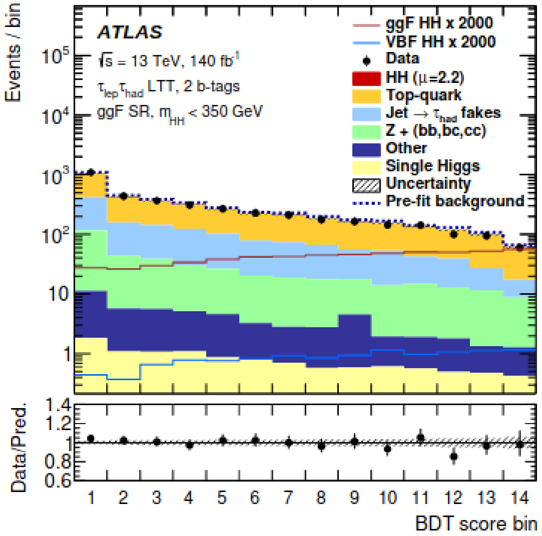


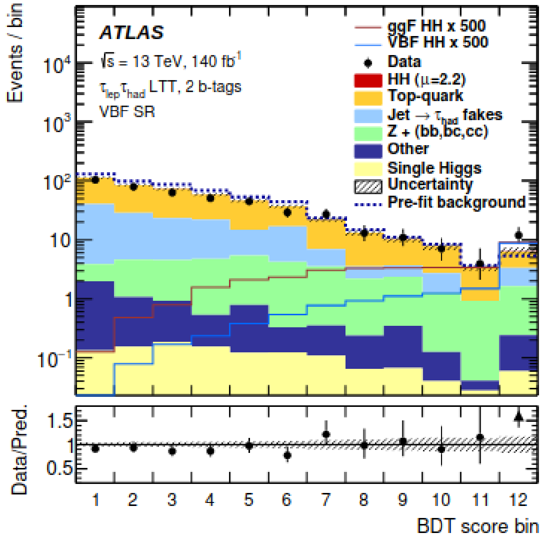


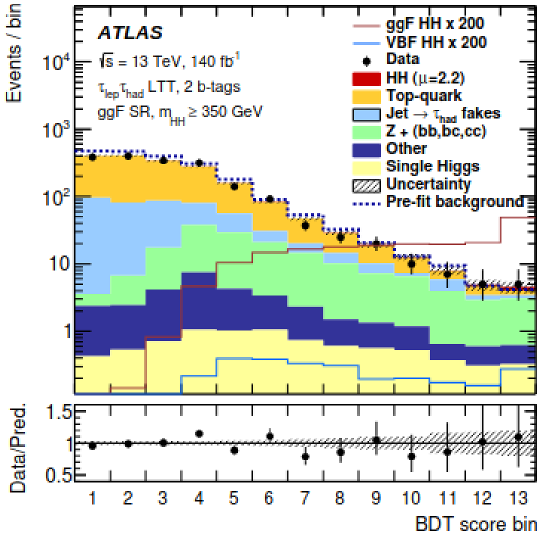
https://arxiv.org/pdf/2404.12660

BDT results in the $\tau_{lep}\tau_{had}$ LTT SR

- This shows BDT evaluation after the likelihood fit to the data for *L*(μ_{HH},ϑ) in each category of the $\tau_{lep}\tau_{had}$ LTT SR
- BDT scores range from 1 (most background-like) to 12-14 (most HH-like)
- BDT predictions are very close to observed scores
- Most HH signal in the high-m_{HH} category of $\tau_{had}\tau_{had}$ SR







https://arxiv.org/pdf/2404.12660

Uncertainties

- Big statistical uncertainty from the low number of signal events
- A lot of systematic uncertainty comes from the modeling of background processes
  - Parton showers and QCD radiation have a high theoretical modeling uncertainty
  - Especially modeling of tt (up to 10%) and Wt (up to 36%)
  - Uncertainty of 100% in the normalisation of the single Higgs boson decay into two τ leptons
- Uncertainties in the coupling modifiers due to sample reweighting for different hypotheses

Conclusion

- Full Run 2 ATLAS dataset of 140 fb^{-1} at 13 TeV was used for a search for non-resonant Higgs boson pair (HH) production in the bb $\tau+\tau-$ final state
- improved sensitivity to SM HH production and anomalous couplings (κ_{λ} and κ_{2V})
- No evidence of HH signal
- 95% CL upper limit on HH signal strength μ_{HH} = 5.9 (observed)
- 95% CI for couplings $-3.1 < \kappa_{\lambda} < 9.0$ (observed), $-0.5 < \kappa_{2V} < 2.7$ (observed)

Sources

- https://cds.cern.ch/record/1482189/files/ATL-DAQ-PROC-2012-050.pdf (Tau triggers)
- https://arxiv.org/pdf/2404.12660 (original paper)
- https://arxiv.org/pdf/2004.04240 (trilinear higgs potential)
- https://arxiv.org/pdf/1107.5909 (higgs branching ratios)