



ttHH or the Quest for the 3rd Higgs Pair Production Mode

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Where is ttHH

THE 3rd HH PRODUCTION MODE

• At 13.6 GeV at LHC



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THE 1st EVER SEARCH IN ATLAS

Access to 3 couplings

• Very interesting for BSM searches

• Linking Higgs and top sectors

• EFT constraints

- HEFT and SMEFT models under study
- 3 final states extensively explored
 - <u>1L</u>: $HH \rightarrow b\overline{b}b\overline{b}$
 - <u>Multi-leptons</u>: non all-hadronic HH decays
 - <u>b</u><u>b</u><u>γ</u><u>γ</u>





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Main channels under investigation in *ATLAS*

DECAY MODES OF HH PAIR



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1 LEPTONS & 2 OPPOSITE SIGN LEPTONS (4b)

• Primarily target the $HH \rightarrow b\overline{b}b\overline{b}$ decay mode

- 20% of all produced $t\bar{t}HH$ events
- \rightarrow Large branching ratio

irreducible tt + jets background

- cross-section ~6 orders of magnitude bigger than $t\bar{t}HH$
- Challenging background modelling
 - Data-driven kinematic reweighting

SRs and CRs

- Defined by b-jets multiplicity with different b-tagging working points
 - \rightarrow Correct the flavour components rate by normalizing factors
- Results derived from MVA scores used in SRs



MULTILEPTONS – SAME SIGNS

• Target non all-hadronic *HH* decay modes

- *bbWW*, *bbZZ*, *bbττ*, *WW*, ...
- 7% of all produced *ttHH* events

Complementary to previous channels

- 2 charged leptons with same electric charge
- At least 3 leptons

• Irreducible background

• Large contribution from $t\bar{t}W$ in SRs

Contribution from fake/non-prompt leptons

• Data-driven approach to constraint contributions from HF and light mesons

Contribution from charge misID

• Rate estimation from $Z \rightarrow e^+e^-$



Pre-selection

- At least 2 loose leptons
 - $p_T^{leading}$ > 28 GeV
 - $p_T^{sub-leading} > 15 \text{ GeV}$
- *m*_{2*l*} ∉ [81, 101] GeV
- At least 1 b-jets at 85% with GN2
- [SS2L] exactly 2SS tight leptons
- [3L] at least 3 tight leptons

CATEGORIZATION

Graph Attention Network

- Self-attention mechanism to weight nodes
- Focus on more relevant connections
- <u>SALT</u> framework used

Multi-class training

- Objects kinematic and multiplicity features
 - isJet, isEl, isMu, isLepton, isMET, pt, eta, phi, E, PCBT, charge, isTight
- Signal vs different backgrounds
- Output:
 - logarithm of the ratio of probability of the signal class and background classes

Better performance than BDT obtained

• $\sim 20\%$ improvement on the upper limit [1L]



PROBING $C_{t\bar{t}HH}$

Standard Model Effective Field Theory [SMEFT]

- \mathcal{L}_{SM} extended with a complete basis of dimension 6 operators
- Only dim-6 is considered
- Drawback:
 - ightarrow Does not give access directly to $c_{tar{t}HH}$

• Higgs Effective Field Theory [HEFT]

- Give access to C_{ttHH}
- Drawback:
 - ightarrow Limitation for the $t\bar{t}HH$ signature

arXiv:2304.01968

SMEFT to HEFT mapping c_{ttHH} could be parametrized according SMEFT operators



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Strong quadratic dependence of σ_{ttHH} w.r.t. c_{ttHH}

$$\frac{\sigma_{ttHH}(c_{ttHH}=2)}{\sigma_{ttHH}(c_{ttHH}=0)} \sim 10$$

• Investigation of $C_{t\bar{t}HH} vs \kappa_{\lambda}$

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<u>arXiv:2304.01968</u>

SMEFT to HEFT mapping c_{ttHH} could be parametrized according SMEFT operators

<u>arXiv:2406.09971</u>



Let's turn to something rarer: $\overline{b}b\gamma\gamma$ channel

AS MUCH AS POSSIBLE

• Search for 0.26% of $t\bar{t}HH$ of events

• Among Run 2 (140 fb^{-1}) + partial Run 3 (59 fb^{-1})

0.3 expected events

Pre-selection

- Di-photon triggers
- $105 < m_{\gamma\gamma} < 160 \, GeV$
- 2 photons (tight & Iso)
- At least 2 b-jets @90% WP
 - New GN2 tagger
- No veto on leptons



AS MUCH AS POSSIBLE

• Search for 0.26% of $t\bar{t}HH$ of events

• Among Run 2 (140 fb^{-1}) + partial Run 3 (59 fb^{-1})

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• Relying on $H \rightarrow \gamma \gamma$ fit strategy

- Targeting 2 photons and at least 2 b-jets
- Very good resolution on $m_{\gamma\gamma}$ (~1.5 GeV)

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Shape & yields from MC samples (*fit with double sided crystal ball*)



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Shape & yield from data sidebands (unbinned fit with exponential + blinded signal region)

Sidebands $\doteq m_{\gamma\gamma} \in [105, 120] \cup [130, 160]$

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SEPARATION & CATEGORIZATION

4 BDTs to identify signal from backgrounds

 $\gamma\gamma + jets$

For each BDT

 $t\bar{t}(H\to\gamma\gamma)$

H & HH



Hyperparameters Optimization Optuna Framework Smaller dataset "Best" parameters 2 Rounds Signal vs

γγ+jets

γγ+jets score

BDT

n Trainings with XGBoost

single H/HH

H Score

BDT

ttH

ttH Score

BDT

Signal Separation



Hyperparameters optimization

• Separate training

SEPARATION & CATEGORIZATION

4 BDTs to identify signal from backgrounds

 $\gamma\gamma + jets$

 $t\bar{t}(H\to\gamma\gamma)$

- H & HH
- tīγγ

- For each BDT
 - Hyperparameters optimization
 - Separate training

• 2 requirements for categorization

- Counting significance is maximized
- A min. number of events in sidebands is requested
- \rightarrow 1 category based on 8 cuts on scores
 - Found via dual annealing method

One of the main point of this analysis strategy is to lower the requirement



Signal Separation

LOWERING THE REQUIREMENT

Definition of CR and SR

• Use of data CR to constraint continuum background shape in signal categories

CR: 2 b-jets

SR: 3+ b-jets

• Assuming the independence of photon reconstruction from b-jets



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Definition of CR and SR

• Use of data CR to constraint continuum background shape in signal categories

CR: 2 b-jets

SR: 3+ b-jets

• Assuming the independence of photon reconstruction from b-jets

• Ensuring same modelling

- Varying the shapes as an impact of less than 0.5%
 - Accounted as a systematic

Category	data β slope	$\gamma\gamma bar{b}\ eta$ slope	N in data sidebands
CR	0.02637 ± 0.00275	0.02250 ± 0.00006	6616
SR - 1	0.00695 ± 0.01004	0.02039 ± 0.00060	35
SR - 2	0.01554 ± 0.01537	0.02024 ± 0.00102	12
SR - 3	0.49985 ± 0.08291	0.02014 ± 0.00210	1
			*Table to be updated



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SEPARATION PERFORMANCE

∳ Data

ttHH

H + HH

🗕 ttH

yybb + ttyy

Trainings results









Entry

10

10⁰

10

10

10

Ratio

0.0

ATLAS Work in progress

0.4

0.6

0.8

score hyper pt ttyy

1.0

0.2

R2+pR3 *t*t̄(*HH* → *b*b̄γγ)

SEPARATION PERFORMANCE

Trainings results









Signal Regions after categorization

- Descent sensitivity obtained
 - Compared to other channels...
 - ...and with $100 \times$ smaller BR





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tĪH

OTHER EXPERIMENTS

CMS SEARCH



• CMS released the 1st ever search for $t\bar{t}HH$

- Targetting $\gamma \gamma + XX$, $X \in [b, W^{\pm}, \tau^{\pm}]$ with Run 2 dataset [138 fb⁻¹]
- Similar modelling strategy
 - Different treatment of uncertainty attached to continuum background modelling
- Categorization based on single BDT
 - 2 SRs derived from 2 tightest cuts
 - Dedicated BDT to identified b-jets coming from ${\cal H}$

95% CL upper limit on $\mu_{t\bar{t}HH}$ = 120 (86)





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Multiple BSM models probed • HEFT

- $\kappa_{\lambda}, \kappa_t, c_{2g}, c_g, c_2$
- Similar sensitivity on the constraint of c_2 , κ_t than H and HH search
- 2HDM
 - targeting heavy neutral CP-even Higgs produced with top quarks
- VLQ
 - Searching for heavy top partner pair production

No deviation observed



PAS HIG-23-004





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PREPARING THE FUTURE

A production mode relevant at future colliders

• A faster growing cross-section

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• Ratio between modes

vs ggF 39 (13.6 TeV) → 14 (100 TeV) vs VBF 2.1 (13.6 TeV) → <1 (100 TeV)





PREPARING THE FUTURE

A production mode relevant at future colliders

- A faster growing cross-section
 - Ratio between modes

vs ggF

 $39 (13.6 \text{ TeV}) \rightarrow 14 (100 \text{ TeV})$

vs VBF

2.1 (13.6 TeV)
$$\rightarrow$$
 < 1 (100 TeV)

• A probe of Higgs self-coupling

- Increased sensitivity toward a higher value of the self-coupling.
 - Could help to dissipate the non SM degeneracy
 - Constructive interference involved compared to the destructive one for ggF-HH

• A unique topology for BSM physics

• Unique access to *C_{ttHH}*

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<u>arXiv:2406.09971</u>



PREPARING THE NEAR FUTURE

• 1^{st} search of the $t\bar{t}HH$ signature is ongoing in ATLAS

CMS provided 1st ever results

• bbγγ channel will greatly benefit of full run 3 statistics

- Statistically limited channel
- mc23e campaign will add $\sim 110 \, fb^{-1}$

Huge gain in sensitivity possible

- Additional channels ($b\overline{b} au au$)
- High rate of ML developments (GAT, GNN, ...)

BACKUP

VARIATION OF σ_{ttHH} W.R.T. κ_{λ}

arXiv:1401.7340



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SAMPLES

• Shared with $HH \rightarrow b\bar{b}\gamma\gamma$ analysis

- Benefit of the strong involvement of the *HH* team
- ptag: 6490/6491

• 3 main categories

- Signal $t\bar{t}(HH \rightarrow b\bar{b}\gamma\gamma)$
- Resonant background
 - $ggF \rightarrow H$, $VBF \rightarrow H$, ttH, VH, tWH, tHjb
 - $ggF \rightarrow HH, VBF \rightarrow HH$
- Continuum background
 - $\gamma \gamma + jets$ decomposed in $\gamma \gamma \overline{b}b + t \overline{t} \gamma \gamma$

Signal [*ttHH*]

DSID		Generator	PDF (ME)	PDF+Tune (PS)	Prod. Mode	Events in AOD
545837	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF30NLO	A14NNPDF23LO	$t\bar{t}HH(HH \rightarrow b\bar{b}\gamma\gamma)$	(Run2) 1,018k (FS) (Run3) 600k (FS)	

Resonant background [H & HH]

DSIDGeneratorPDF (ME)PDF Hune (PS)Prod. ModeEvents in ADD603559POWHEG + PYTHLAS + EVTGENPDFLHC21Al4NNPDF23L0SM PgF HL ($\lambda_{\pm} = 1$, $\lambda_{VV} = 1$, $\lambda_{VU} = 3$)(Ru2) 353(AF3)52576MADGRAPH + PYTHLAS + EVTGENNPDF30NL0AZNLOCTEQ6 $BWFH(\lambda_{\pm} = 1, \lambda_{VV} = 1$, $\lambda_{VU} = 3$)(Ru2) 353(AF3)343981POWHEG + PYTHLAS + EVTGENNPDF30NL0AZNLOCTEQ6 $BGH = 1$ (Ru2) 352(AF3)340214POWHEG + PYTHLAS + EVTGENNPDF30AZNLOCTEQ6 $BFH = 1$ (Ru2) 352(AF3)346145POWHEG + PYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 $BFH = 1$ (Ru2) 342(AF3)345146POWHEG MINLO [11] + PYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 M^+H (Ru2) 342A 5(K5)601484POWHEG MINLO [11] + PYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 M^-H (Ru2) 342A 5(K5)601435POWHEG MINLO [11] + PYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 M^-H (Ru2) 342A 5(K5)601436POWHEG MINLO [11] + PYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 M^-H (Ru2) 206/S(K5)60153POWHEG MINLO [11] + PYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 M^-H (Ru3) 206/F(K5)60154POWHEG + DYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 M^-H (Ru3) 206/F(K5)60155POWHEG + DYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 M^-H (Ru3) 206/F(K5)60156POWHEG + DYTHLAS + EVTGENNNPDF30AZNLOCTEQ6 M^-H (Ru3) 206/F(K5)616153POWHEG + DYTHLAS + EVTGEN <t< th=""><th></th><th>-</th><th></th><th></th><th></th><th></th></t<>		-				
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602422 FOWING + FTHINS + EVTOLIX PDF4LHC21 A14NNPDF23LO unit (Run3) 1570k (FS) 345315 POWHEG + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO bbH (Run2) 390k (FS) 601710 PDF4LHC21 A14NNPDF23LO bbH (Run2) 1390k (FS) 346677 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHjb (Run3) 950k (FS) 346759 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHjb (Run3) 950k (FS) 545639 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHjb (Run3) 950k (FS) 545639 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHW (Run3) 980k (FS)	346525	POWHEG + PVTHIA8 + EVTGEN	NNPDF30	A14NNPDF23LO	ttH	(Run2) 7785k (FS)
345315 POWHEG + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO bbH (Run2) 390k (FS) 601710 PDWHEG + PYTHIA8 + EVTGEN PDF4LHC21 A14NNPDF23LO bbH (Run2) 400k (FS) 346677 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO Hjb (Run2) 1988k (FS) 545636 NNPDF30 A14NNPDF23LO Hjb (Run2) 1988k (FS) 346759 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO HW (Run2) 1045k (FS) 545639 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO HW (Run2) 1045k (FS)	602422	TOWIEG + I THING + EVIGEN	PDF4LHC21	A14NNPDF23LO		(Run3) 1570k (FS)
601710 FORMEGY FTENENG FEVTOLIX PDF4LHC21 A14NNPDF23LO (Run3) 400k (FS) 346677 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHjb (Run2) 1988k (FS) 545636 NNPDF30 A14NNPDF23LO tHjb (Run2) 1988k (FS) 346759 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHW (Run2) 1045k (FS) 545639 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHW (Run3) 980k (FS)	345315	DOWNEG + DVTHIA8 + EVTGEN	NNPDF30	A14NNPDF23LO	bbH	(Run2) 390k (FS)
346677 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHjb (Run2) 1988k (FS) 545636 NNPDF30 A14NNPDF23LO tHjb (Run2) 1988k (FS) 346759 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHjb (Run2) 1988k (FS) 545639 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHW (Run2) 1045k (FS) 545639 NNPDF30 A14NNPDF23LO tHW (Run3) 980k (FS)	601710	TOWILD FITTILLS FETTOLIS	PDF4LHC21	A14NNPDF23LO		(Run3) 400k (FS)
545636 NNPDF30 A14NNPDF23LO unjb (Run3) 950k (FS) 346759 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHW (Run2) 1045k (FS) 545639 NNPDF30 A14NNPDF23LO tHW (Run3) 980k (FS)	346677	MGMCatNLO + PVTHLA8 + EVTGEN	NNPDF30	A14NNPDF23LO	tHjb	(Run2) 1988k (FS)
346759 MGMCatNLO + PYTHIA8 + EVTGEN NNPDF30 A14NNPDF23LO tHW (Run2) 1045k (FS) 545639 NNPDF30 A14NNPDF23LO tHW (Run3) 980k (FS)	545636	MOMCauleo +11111Ao + EVIOEN	NNPDF30	A14NNPDF23LO		(Run3) 950k (FS)
545639 NNPDF30 A14NNPDF23LO (Run3) 980k (FS)	346759	MGMCatNLO + PYTHLA8 + EVTGEN	NNPDF30	A14NNPDF23LO	tHW	(Run2) 1045k (FS)
	545639	MOMCallVLO + 1 1 THIA6 + EVICEN	NNPDF30	A14NNPDF23LO		(Run3) 980k (FS)

Continuum background $[\gamma \gamma + jets]$

DSID	Generator	PDF (ME)	PDF+Tune (PS)	Prod. Mode	Events in AOD
700980 700711	SHERPA 2.2.14	NNPDF30NNLO	γγ+(γ	$\gamma\gamma{+}0{,}1{(\rm NLO){,}2{,}3{(\rm LO){,}}}\ m_{\gamma\gamma}\in(90,175)~{\rm GeV}$	(Run2) 1211376k (AF3)
					(Run3) 606450k (AF3)
	SHERPA 2.2.14	NNPDF30NNLO		$\gamma\gamma + b\bar{b}(\text{NLO}), m_{\gamma\gamma} \in (90, 175) \text{ GeV}$	(Run2) 39330k (AF3)
					(Run3) 15980k (AF3)
542860	MGMCatNLO + PYTHIA8 + EVTGEN	NNPDF30NLO	A14NNPDF23LO	tive (noallhad)	(Run2) 4990k (AF3)
				<i>ii y y</i> (iloannad)	(Run3) 1190k (FS)
542859	MGMCatNLO + PYTHIA8 + EVTGEN	NNPDF30NLO	A14NNPDF23LO	$t\bar{t}\gamma\gamma$ (allhad)	(Run2) 4850k (AF3)
					(Run3) 2000k (FS)



4/29/2025

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