Search for Higgs boson decays into pseudoscalar in $\gamma\gamma\tau_{had}\tau_{had}$ final state

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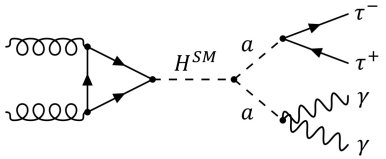
Introduction

- Discovery of the Higgs boson at 125 GeV completed the Standard Model (SM)
- The SM allows exotic decays as long as Higgs coupling measurements are preserved
- Current Higgs measurements allow $\sim 10\%$ branching ratio for non-SM decays and many BSM models predict exotic decays via light pseudoscalar bosons (eg. Extended Higgs sectors)
  - This analysis focuses on searching for the decay where one pseudoscalar decays to two photons and the other to two hadronically decaying taus

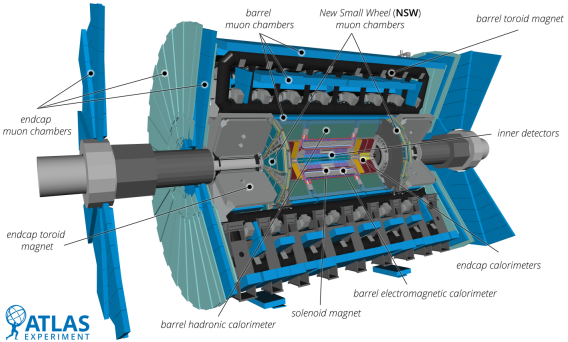


- Highlights ATLAS search for $H \to aa \to \gamma\gamma\,\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ in pp collisions at $\sqrt{s} = 13$ TeV
- Probes diphoton masses below 65 GeV, previously unexplored final state, using hadronic tau pairs to suppress background, with ATLAS data collected from 2015-2018

ATLAS Detector

- Multipurpose detector with near 4π coverage, symmetric cylindrical geometry

- **Inner Detector** ($|\eta| < 2.5$) for tracking charged particles
- **Calorimeters**: Electromagnetic ($|\eta| < 3.2$), hadronic ($|\eta| \leq 1.7$) for measuring particle energies
- **Muon Spectrometer** ($|\eta| < 2.7$) for precise muon reconstruction
- **LUCID** detector measures luminosity
- **Trigger**: L1 $<$ 100 kHz $\rightarrow$ HLT $\sim$1 kHz



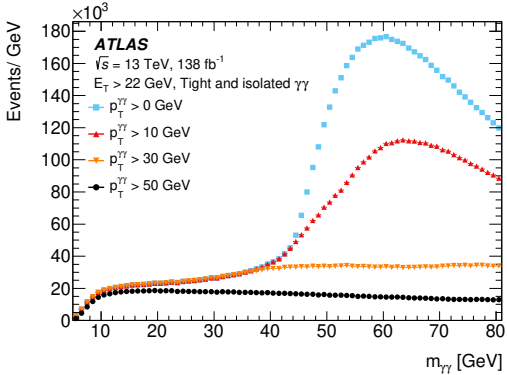
- Simulation, reconstruction, and analysis use a common software framework

Event Selection

- **Photons** : ≥ 2 photon candidates, Standard diphoton triggers (2 tight photons with $E_T >$ 20-22 GeV and isolation applied for 2017 & 2018 to reduce background)

Selection	Criteria
Kinematics	$E_T > 22\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.37$ (excluding 1.37–1.52)
Identification	Tight ID, Loose ISO
Diphoton	$p_T^{\gamma\gamma} > 50$ GeV (boosted diphoton)

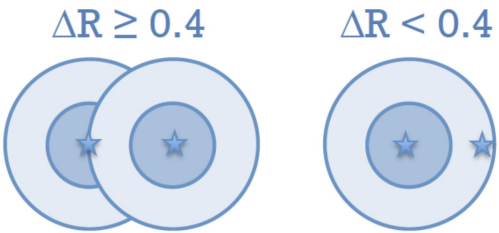
Targets diphoton pairs with low masses that are highly boosted



- Lepton veto: Veto e and μ with $p_T > 27$ GeV passing tight/medium ID and isolation

Event Selection

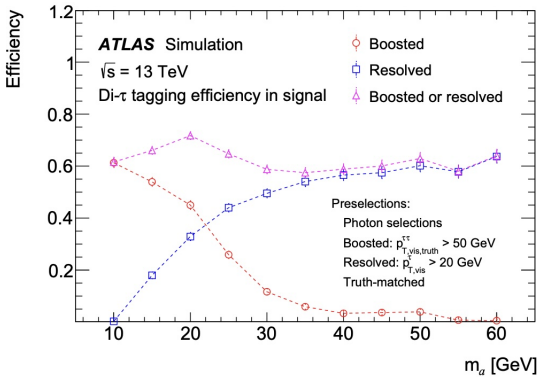
- **Tau leptons** : Require either two resolved τ_{had} jets or a boosted di-τ object (two τ-jets merged) ; if both, select resolved for smaller ID uncertainties

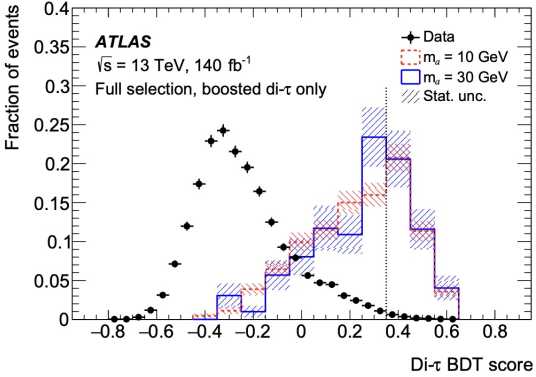


Boosted tau pairs fail standard tau reconstruction - a dedicated tagger is used to improve the low-mass search

Selection	Boosted Tau	Resolved Tau
Jet definition	Large-R jets $R = 1.0$, $p_T > 50\,\text{GeV}$	Small radius jets $R = 0.4$, $p_T > 20\,\text{GeV}$
Charge & Tracks	$q_{\text{lead}} \times q_{\text{sub-lead}}$ = -1 & 1 or 3 tracks	$q_{\text{lead}} \times q_{\text{sub-lead}}$ = -1 & 1 or 3 tracks
ID	BDT Medium ID on di-tau candidate	Loose RNN ID on individual taus
Kinematics	$\Delta R < 0.4$	$\lvert\eta\rvert < 2.5$, excluding $1.37 < \lvert\eta\rvert < 1.52$

Di-tau Identification and Efficiency





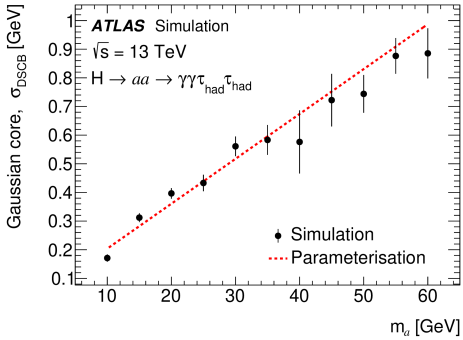
- The ditau topology (resolved versus boosted) exhibits a strong dependence on the resonance mass scale
- BDT score > 0.35 in boosted di-τ BDT score distribution is the Medium di-τ identification working point

Signal Modelling

- Fits diphoton mass ($m_{\gamma\gamma}$) from simulation using a Double-Sided Crystal Ball (DSCB)

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\text{low}} \le t \le \alpha_{\text{high}} \\ \dfrac{e^{-0.5\alpha_{\text{low}}^2}}{\left[\frac{\alpha_{\text{low}}}{n_{\text{low}}}\left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t\right)\right]^{n_{\text{low}}}} & \text{if } t < -\alpha_{\text{low}} \\ \dfrac{e^{-0.5\alpha_{\text{high}}^2}}{\left[\frac{\alpha_{\text{high}}}{n_{\text{high}}}\left(\frac{n_{\text{high}}}{\alpha_{\text{high}}} - \alpha_{\text{high}} + t\right)\right]^{n_{\text{high}}}} & \text{if } t > \alpha_{\text{high}}, \end{cases}$$

- DSCB has a Gaussian core plus power-law tails modeling detector effects and radiation
- Parameters fitted for each mass hypothesis (m_a) and linearly interpolated

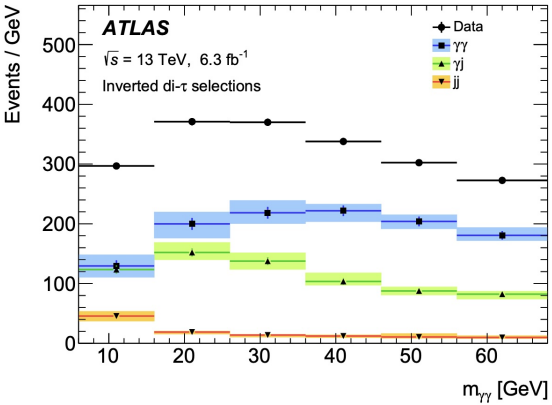


- Model matches simulation within 2.5%, taken as systematic uncertainty

Background Estimation

- **Irreducible:** continuum diphoton ($\gamma\gamma$) from two real photons - Obtained from simulation
- **Reducible:** Jets faking photons or hadronic taus (γj and jj)
  - Estimated from control data samples with inverted photon ID

- Tau backgrounds are negligible ($\sim$ 1%)
  - Background composition depends on photon identification performance
- Apply **inverted di-τ selections** (Boosted: BDT < -0.2 & same charge Resolved: same charge or fail Loose ID) to model fake τ- in both sources
- Relative fractions estimated with the 2x2D sideband method (isolation & ID)
- Diphoton purity: 0.61 ± 0.01 (stat) $\pm\, 0.04(syst)$



Background Modeling & Uncertainties

Modeling & Validation:

$$f(m_{\gamma\gamma}) = N \frac{1}{1 + e^{-(m_{\gamma\gamma}-\delta)/\tau}} e^{-\lambda m_{\gamma\gamma}}$$

- Sigmoid: low-mass turn-on
- Exponential: high-mass fall-off
- Fit: 6–68 GeV (restricted 10–60 GeV)

Uncertainties:

- Main systematic uncertainties:
  - Boosted ditau reconstruction (low mass)
  - Theoretical uncertainties (high mass)
- Overall dominated by statistics

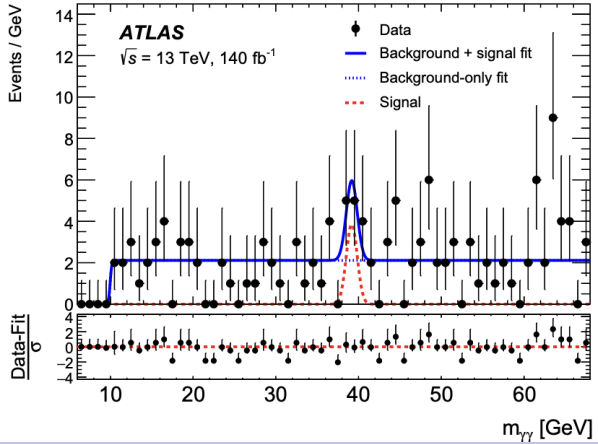
- Template variations are created to validate using photon ID, $\gamma\gamma$ purity, di-τ
  - Yield shifts: $\leq 10\%$ (di-τ), $\leq 4\%$ ($\gamma\gamma$)
- Modeling Bias evaluated using Spurious signal
- Spurious signal $\leq 13\%$ of stat. uncertainity
- Gaussian Process smoothing reduces statistical fluctuations (scale: 1–2 GeV)

Source	Uncertainty	
In $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$ [%]		
	m_a = 10 GeV	m_a = 50 GeV
Boosted di-τ reconstruction efficiency	63	0.8
Theory	9.9	27
Pile-up reweighting	4.5	
Resolved τ reconstruction, identification and energy scale	0.3	4.0
Photon energy resolution	3.0	
Photon identification efficiency	2.9	
Signal shape modelling	2.5	
Photon isolation efficiency	2.4	
Photon trigger efficiency	1.1	
Photon energy scale	< 1.0	
Luminosity	0.8	
Trigger on closely spaced photons	0.8	< 0.1
In background modelling		
Spurious signal	< 0.08 σ_{stat} 0.16 events	< 0.01 σ_{stat} 0.06 events

Statistical Analysis

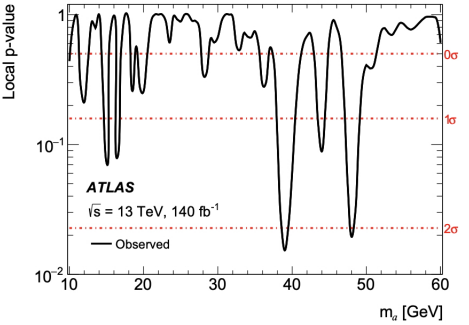
- Statistical analysis performed via likelihood fit to the diphoton invariant mass spectrum
- Analysis is statistically limited

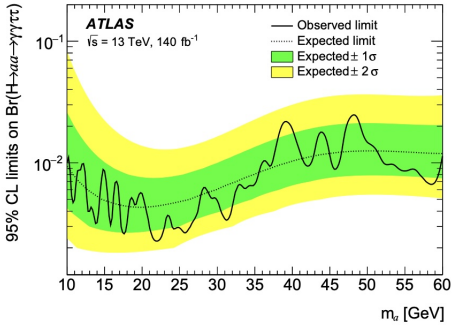
- The diphoton invariant mass distribution of events satisfying the analysis selections
- smooth background describes data, narrow excess tested near 40 GeV
- Data–Fit/σ shows no significant deviation



Results

- Diphoton invariant mass $m_{\gamma\gamma}$ in 6–68 GeV
- Search limited to 10–60 GeV to avoid edge effects
- Largest excesses observed at 39 GeV (2.2σ) and 48 GeV (2.1σ) from p-value scan (σ values correspond to the local significance)





- Observed 95% CL upper limits on $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$ range from 0.2% to 2%
- Best sensitivity in mass range 10–35 GeV
- No significant excess found

Summary

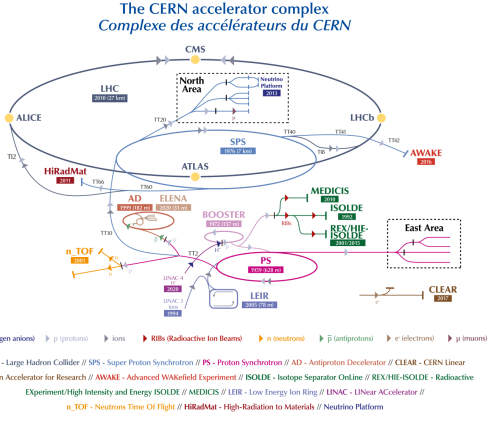
- Search for Higgs decays to pseudoscalar resonances in $\gamma\gamma\tau_{had}\tau_{had}$ final state using $140\ \mathrm{fb}^{-1}$ of pp collision data at $\sqrt{s} = 13\,\mathrm{TeV}$
- Resolved and boosted di-τ topologies are considered with high P_T diphoton system
  - New algorithm for collimated hadronic τ pairs, improving low-mass sensitivity
- Observed (expected) 95% CL upper limits on Branching ratio range from 0.2% (0.5%) to 2% (1%), with variations mainly due to statistical fluctuations
- Sensitivity mainly limited by statistics and no significant deviations from Standard Model backgrounds observed
- Largest systematic uncertainty from boosted ditau tagger below 25 GeV - will be improved in future analysis
- First search in this channel at the LHC contributing to the broader H→aa search across different final states

Thank You!

BackUp

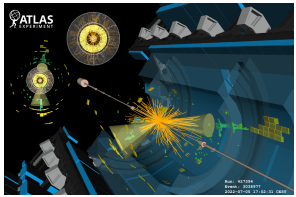
CERN Large Hadron Collider (LHC)

- World's most powerful particle accelerator
  - 27 km circular collider located at CERN
- Accelerates protons to near light speed in opposite directions within ultra-high vacuum beam pipes
- Beams are steered by superconducting electromagnets cooled to 1.9 K
- Proton-proton collisions allow probing of fundamental physics at the smallest scales
- Currently in Run 3 and preparing for the High-Luminosity LHC phase starting in August 2030
- Four major detectors:
  ATLAS, CMS, ALICE, and LHCb



ATLAS detector

- 46m long and 25m in diameter cylindrical detector
- Explores fundamental building blocks of matter & forces
- Probes deep questions about matter,energy,space,time
- Detects particles from ultra-high-energy proton collisions
- Key role in the Higgs boson discovery, confirming the Standard Model
- Different subsystems :
  - Inner Detector: Tracks charged particle paths with high precision
  - Calorimeters: Measure particle energies during absorption
  - Muon Spectrometer: Identifies and measures muon momentum
  - Magnet system: Bends charged particles to determine momentum

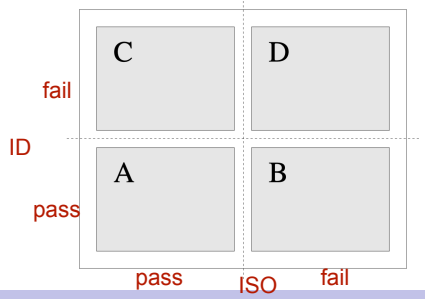


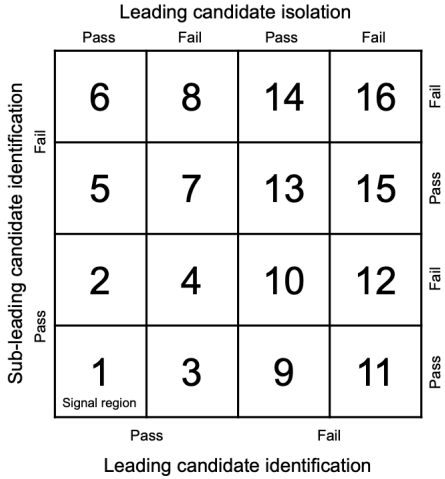
Data and Simulated Event Samples

- **Dataset:** 139.5 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV (ATLAS Run 2, 2015–2018)
- Events selected with diphoton triggers (varying E_T thresholds and isolation)
- **Signal MC:** Full simulation using Geant4
  - $H \to aa \to \gamma\gamma\,\tau_{\text{had}}\tau_{\text{had}}$, with $m_a = 10$–60 GeV in 5 GeV steps
  - Generated via ggF with Powheg+Pythia 8.245 (AZNLO tune), PDF4LHC15
- **Background MC:** Fast calorimeter simulation used
  - Dominant: $\gamma\gamma$ + jets, modeled with Sherpa 2.2.4
  - MEPS@NLO merging, NNPDF3.0nnlo PDFs
- **Pile-up:** Simulated with Pythia 8.186 (A3 tune), reweighted to match data
- Signal–background interference neglected (narrow-width approximation)

2x2D sideband method

- Signal region: both photons tight + isolated
- Sideband regions: fail ID or fail isolation
- γ-jet (γj): leading photon is real, subleading is a mis-identified jet
- jet-γ ($j\gamma$): leading photon is a mis-identified jet, subleading is real
- jet-jet (jj): both photon candidates are mis-identified jets





Statistical Analysis

- The signal hypothesis $H \to aa \to \gamma\gamma\tau_{\text{had}}\tau_{\text{had}}$ is tested via an unbinned likelihood fit of the diphoton invariant mass $m_{\gamma\gamma}$ distribution in the range 6–68 GeV (search performed in 10–60 GeV to avoid edge effects).
- Parameter of interest: branching ratio

$$\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau) = \sigma_{\text{ggF}} \times \text{BR} \times \epsilon,$$

  with gluon-fusion cross-section $\sigma_{\text{ggF}} = 48.5 \pm 2.4\,\text{pb}$ and selection efficiency $\epsilon \sim (1.0 - 2.2) \times 10^{-4}$, mass-dependent.
- Systematic uncertainties incorporated as nuisance parameters with Gaussian constraints, covering:
  - Theoretical: scale variations, PDFs.
  - Experimental: luminosity, pile-up, trigger, photon and τ-lepton reconstruction/ID/energy scale.
  - Signal shape parameterization and background modeling bias.