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

Based on JHEP 03 (2025) 190

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On behalf of the **ATLAS** collaboration

Higgs Hunting 2025

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ATLAS EXPERIMENT

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

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Introduction

First ATLAS analysis looking for exotic Higgs decays in the $\gamma\gamma\tau_{had}\tau_{had}$ final state:

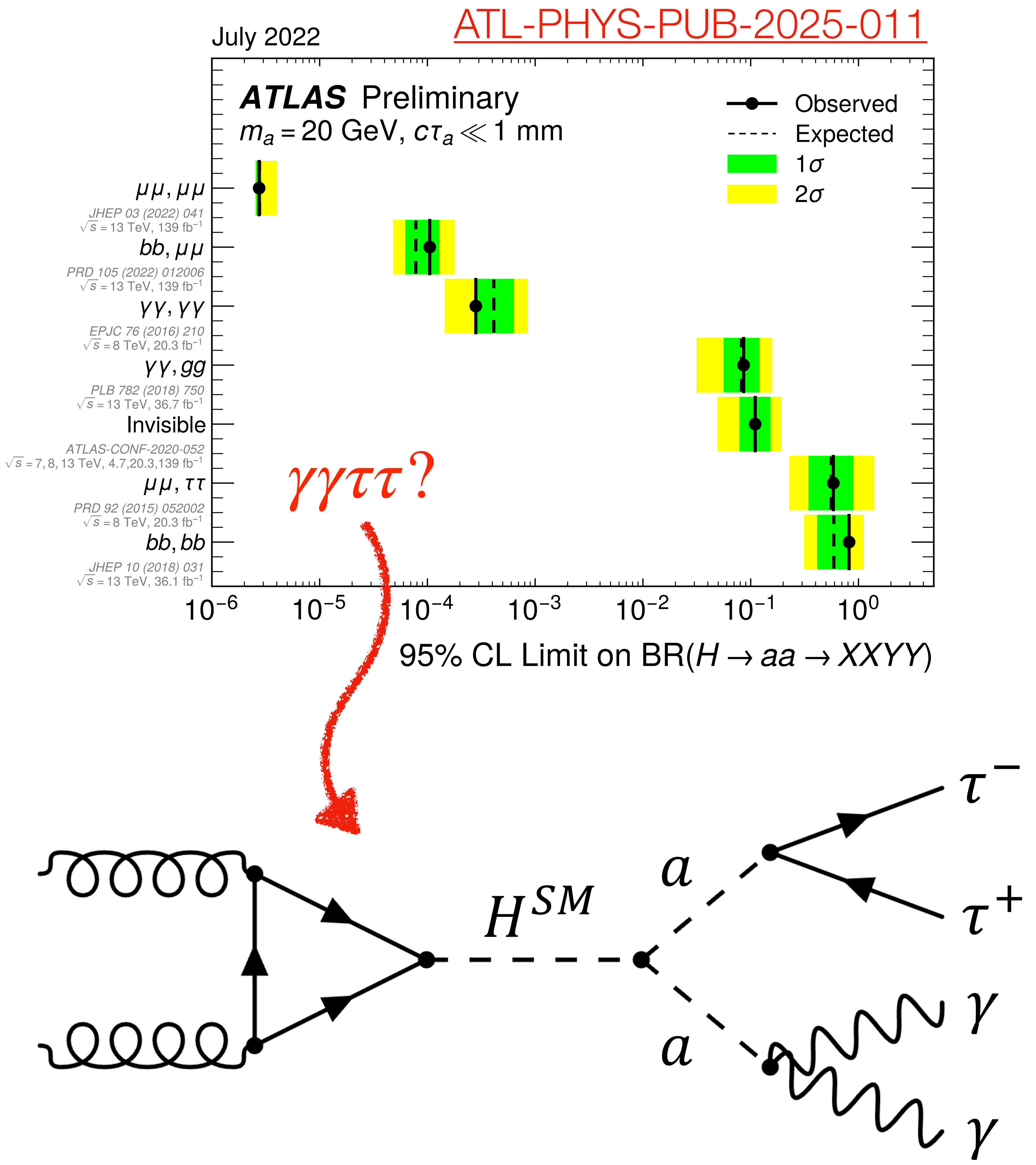
- Benefits strongly from previous $\gamma\gamma$ low mass search (2211.04172)
- Novel boosted tau pairs tagger improves low mass sensitivity (2411.09357)

Motivation:

- The diphoton channel: excellent mass resolution but low S/B
- Requiring an additional ditau reduces significantly the background
- Benefits from larger branching ratio due to the taus

Strategy:

- Describe signal and background diphoton shapes with analytical functions
- Search for event excesses over the $m_{\gamma\gamma}$ spectrum
- In the absence of signal, set limits on $\mathscr{B}\left(H \to aa \to \gamma\gamma\tau\tau\right)$



Detour: boosted ditau object

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

- **Reconstruction**: R=1.0 anti-kt jet (large-R jet) with $p_T > 50$ GeV, composed of at least two R=0.2 jets (subjets), each containing either one or three tracks
- **Identification**: BDT-based classifier is used to improve rejection against QCD jets, using $t\bar{t}X$ events as signal and all-hadronic $t\bar{t}$ events as background
- **Validation**: T&P analysis using boosted ditau objects from SM process $Z+\gamma$ with $Z \to \tau_{had}\tau_{had}$, to measure ditau **scale factors**, data-to-MC corrections:

	BDT selection	Scale factor
Medium ID	> 0.35	$1.00 \pm 35\%$ (stat) $\pm 13\%$ (syst)
Tight ID	> 0.5	$1.01 \pm 24\%$ (stat) $\pm 12\%$ (syst)

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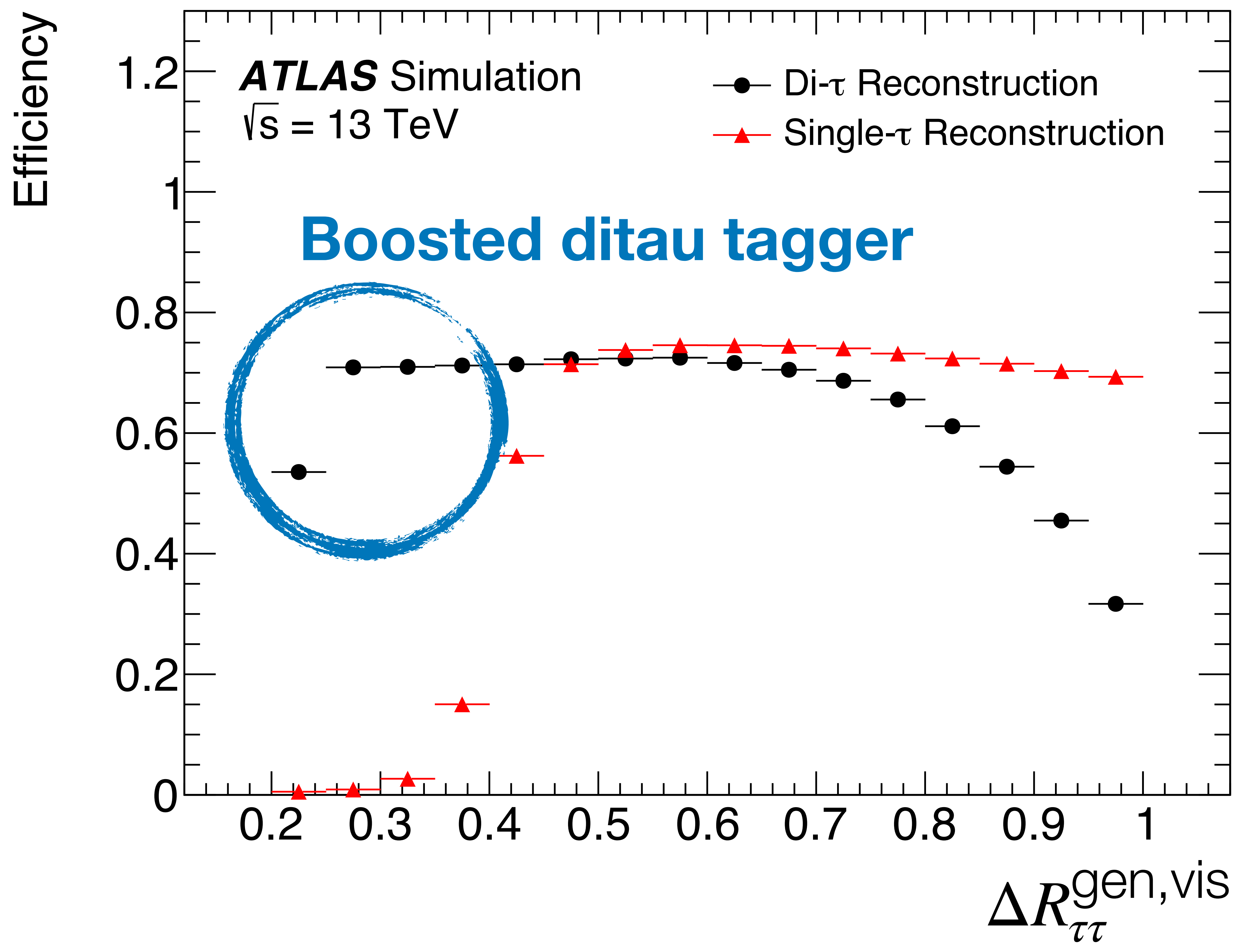


Selections

Triggers: lowest unprescaled diphoton triggers $p_T^{\gamma} > 20 - 22$ GeV

Photon selections:

Selection	Requirement
Preselection	2 loose photons
Kinematics	$E_T^{\gamma} > 22$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$
Identification	Tight ID
Isolation	Loose ISO ($\Delta R_{iso} = 0.2$)

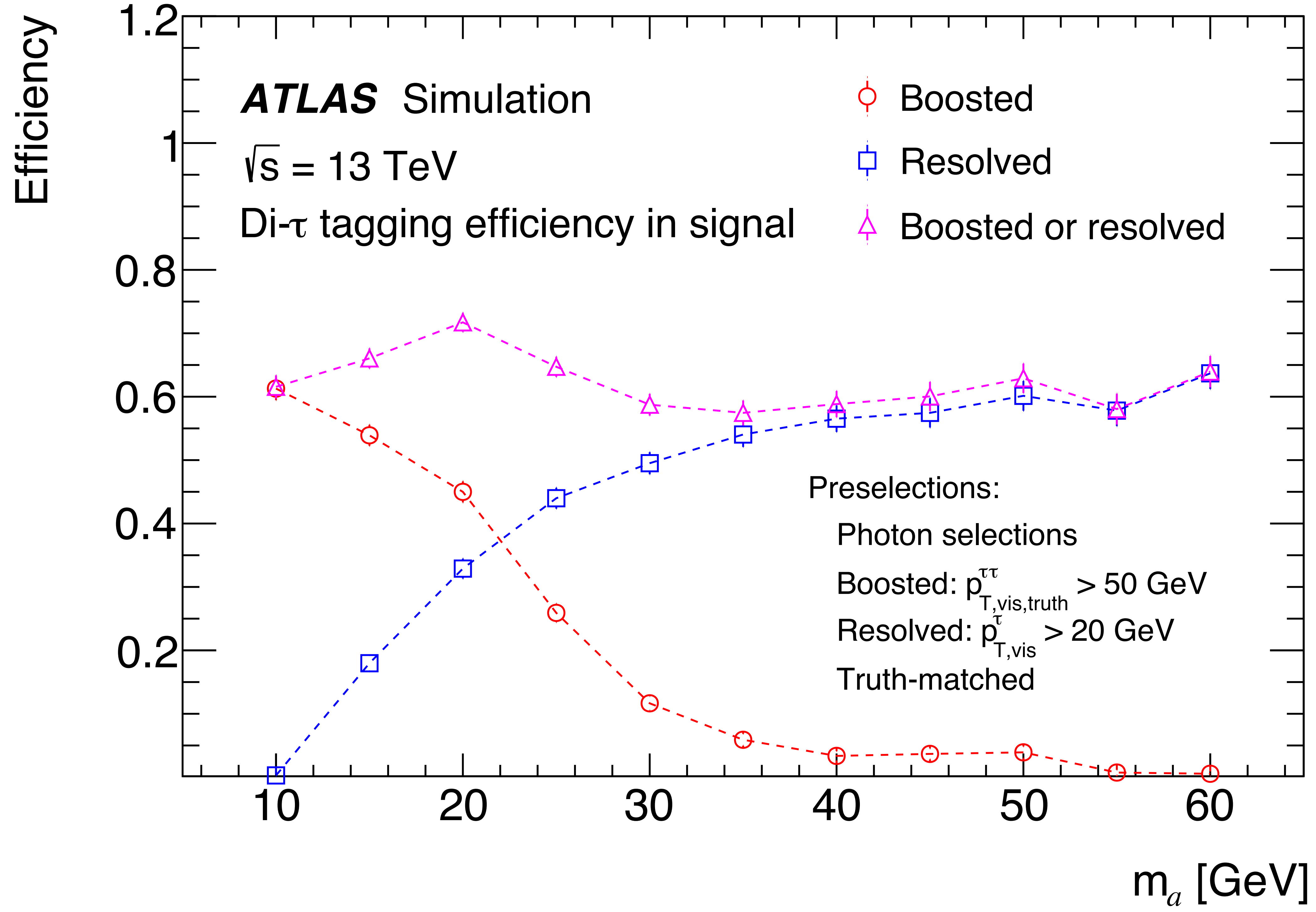
Ditau selections:

Selection	Boosted ditau object	Resolved tau
Preselection	1 boosted ditau	2 tau candidates
Kinematics	$p_T^{LRJ} > 50$ GeV, 2 subjets, 1||3 tracks per subjet	$p_T^{\tau} > 20$ GeV, $\lvert\eta^{\tau}\rvert < 2.5$, 1||3 tracks
Chargeness	OS	OS
Identification	Medium ID (BDT > 0.35)	LooseRNN ID

Event selections:

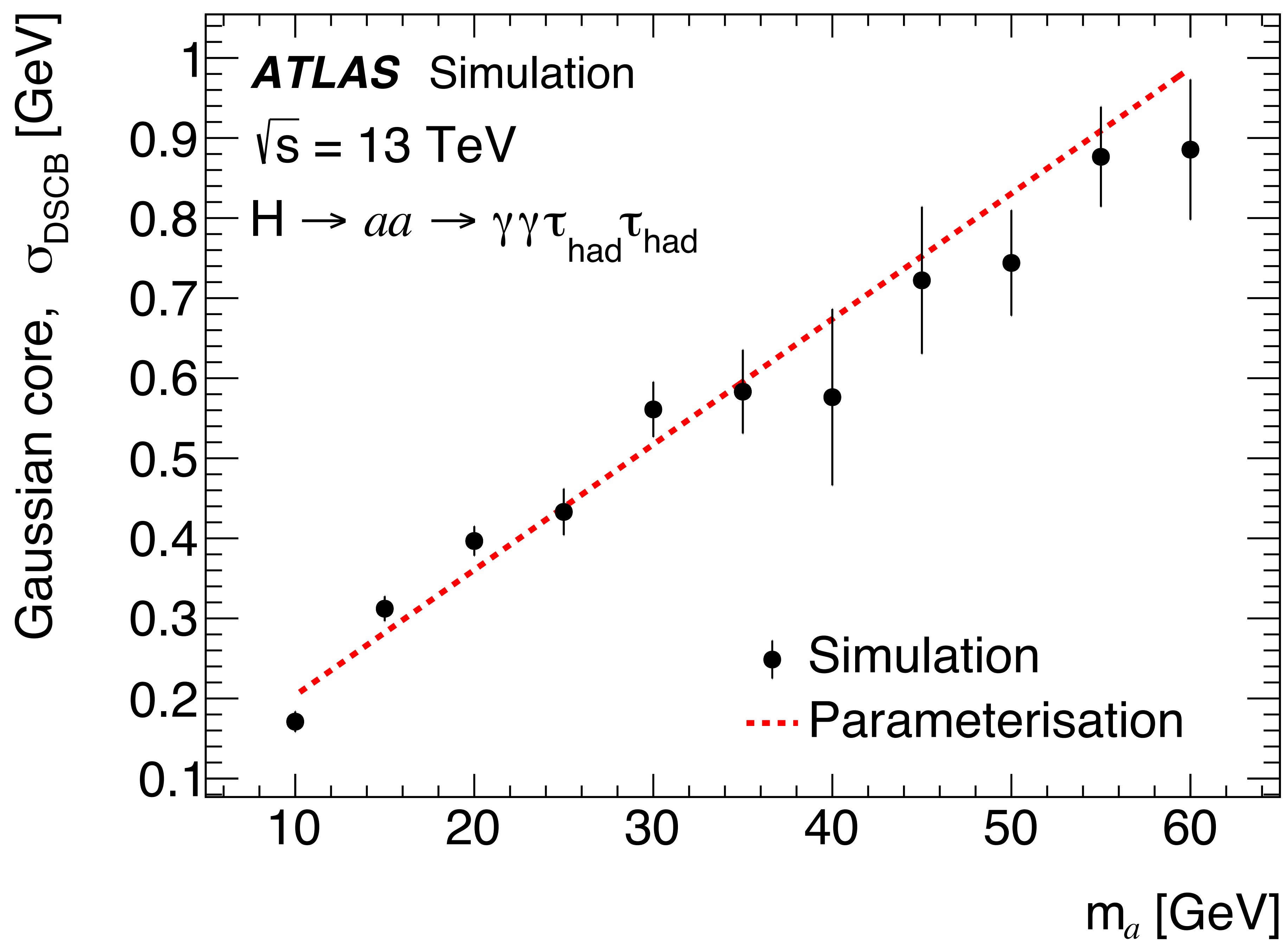
- 2 photons and either 1 boosted ditau or 2 resolved taus
- To ensure orthogonality with the lep-had channel, electrons and muon are vetoed in the analysis

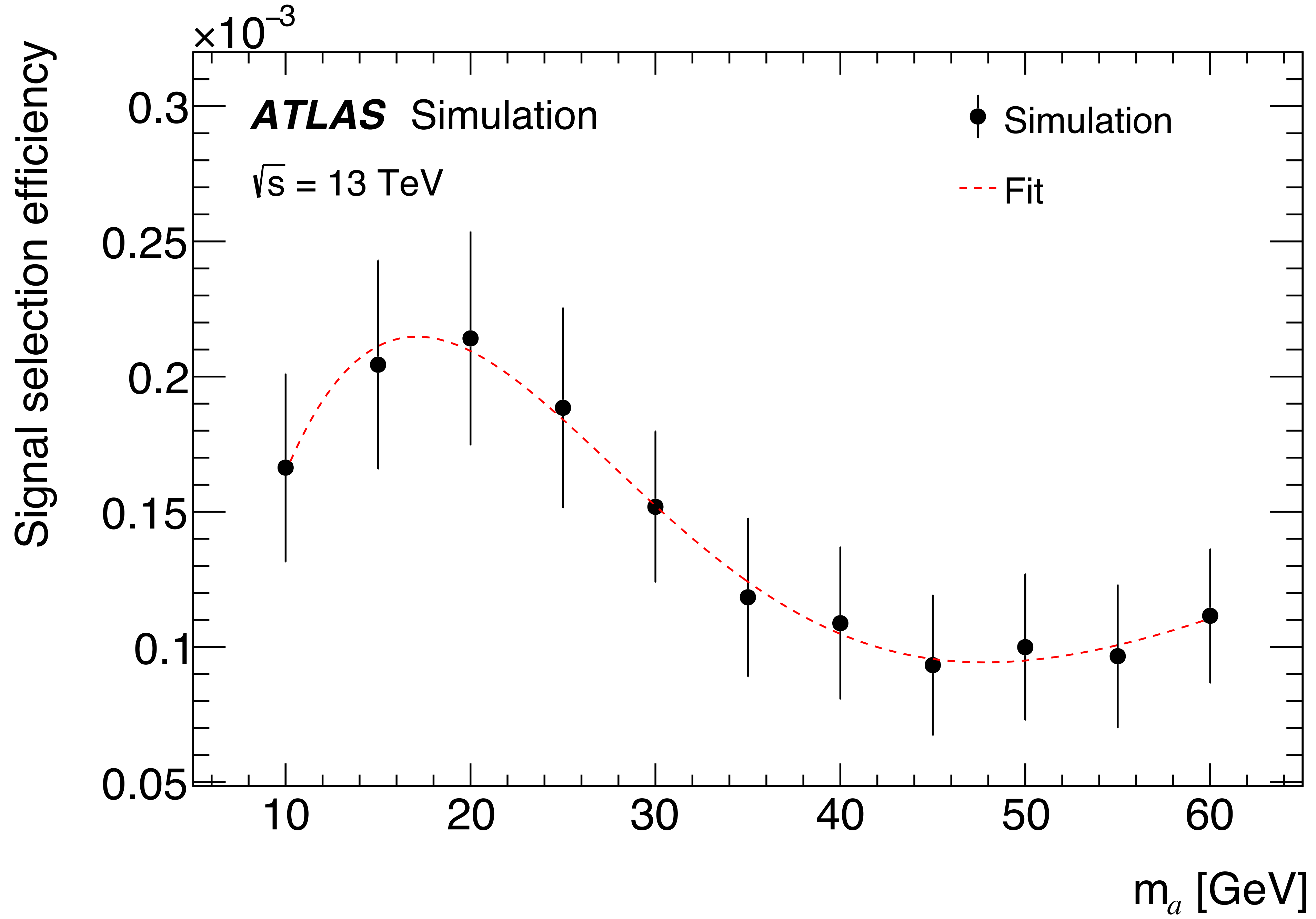
Ditau topology (resolved vs. boosted) varies significantly with the mass of the resonance:



Signal modeling

- **Signal samples** are generated in ggF using Powheg for the a-boson masses between 10 and 60 GeV in 5 GeV steps
- **Signal shape** obtained from simulated samples
  - Parametrization obtained using a Double-sided Crystal Ball (DSCB)
  - Parameters interpolated with linear trends





- **Acceptance x efficiency** decreases towards higher masses because of the boosted topology required on diphoton

Background processes

Final state affected by non-resonant background from:

<u>Irreducible</u>: real photon and tau pairs in final state

- <u>$\gamma\gamma Z(\tau\tau)$</u>: non-resonant $\gamma\gamma$ with an additional Z decaying to a tau pair
- <u>Non-resonant $\gamma\gamma\tau\tau$</u>: negligible contribution

Negligible contributions due to small cross sections!

<u>Reducible</u>

Fake ditau (jets misidentified as tau pairs):

- <u>$\gamma\gamma$</u>: $\gamma\gamma$+jets from prompt photons (shape from MC)
- <u>γj</u>: γ+jet events, where one jet is misidentified as a photon (data-driven)
- <u>jj</u>: dijet events, where both jets are misidentified as photons (data-driven)

Real ditau:

- <u>$Z(\tau\tau)$+jets</u>: Z decaying to a tau pair and jets misidentified as photons
  - *Negligible contribution after full selection*

Background processes

Final state affected by non-resonant background from:

Given that ditau candidates are almost exclusively fakes, the **irreducible** and **reducible** sources depend solely on the performance of **photon identification**.

Re-categorization:

- Irreducible source: $\gamma\gamma$ component
- Reducible source: $\gamma j + jj$ components

Strategy:

- Estimate the fraction of the $\gamma\gamma$ component ($\gamma\gamma$ purity)
- Build the full background template (reducible + irreducible)
- Fit to analytical function

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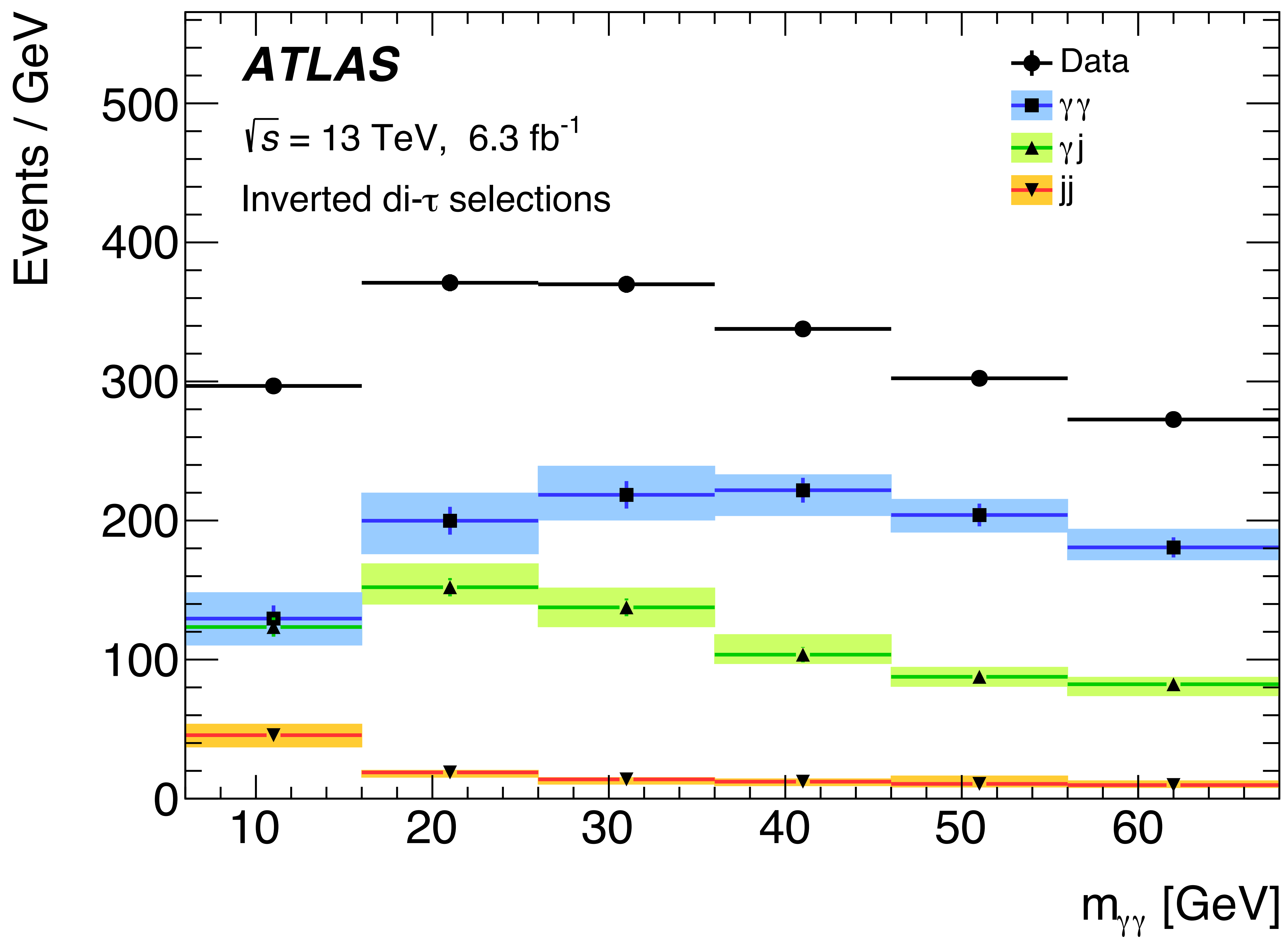
- *Negligible contribution after full selection*

Background decomposition

- Standard background estimation strategy with two photons in the final state: **2x2D method** using photon ID and ISO variables for each photon
- Assuming that diphoton purity is agnostic whether there is a true/fake ditau, inverted ditau selections (BDT < −0.2) are used
- Integrated observed purity ($\gamma\gamma$ fraction of data):

$$P^{2x2D}_{\gamma\gamma} = 0.61 \pm 0.01 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$$

- In line with previous diphoton analysis covering the same invariant mass range (~64%)



Fitting function

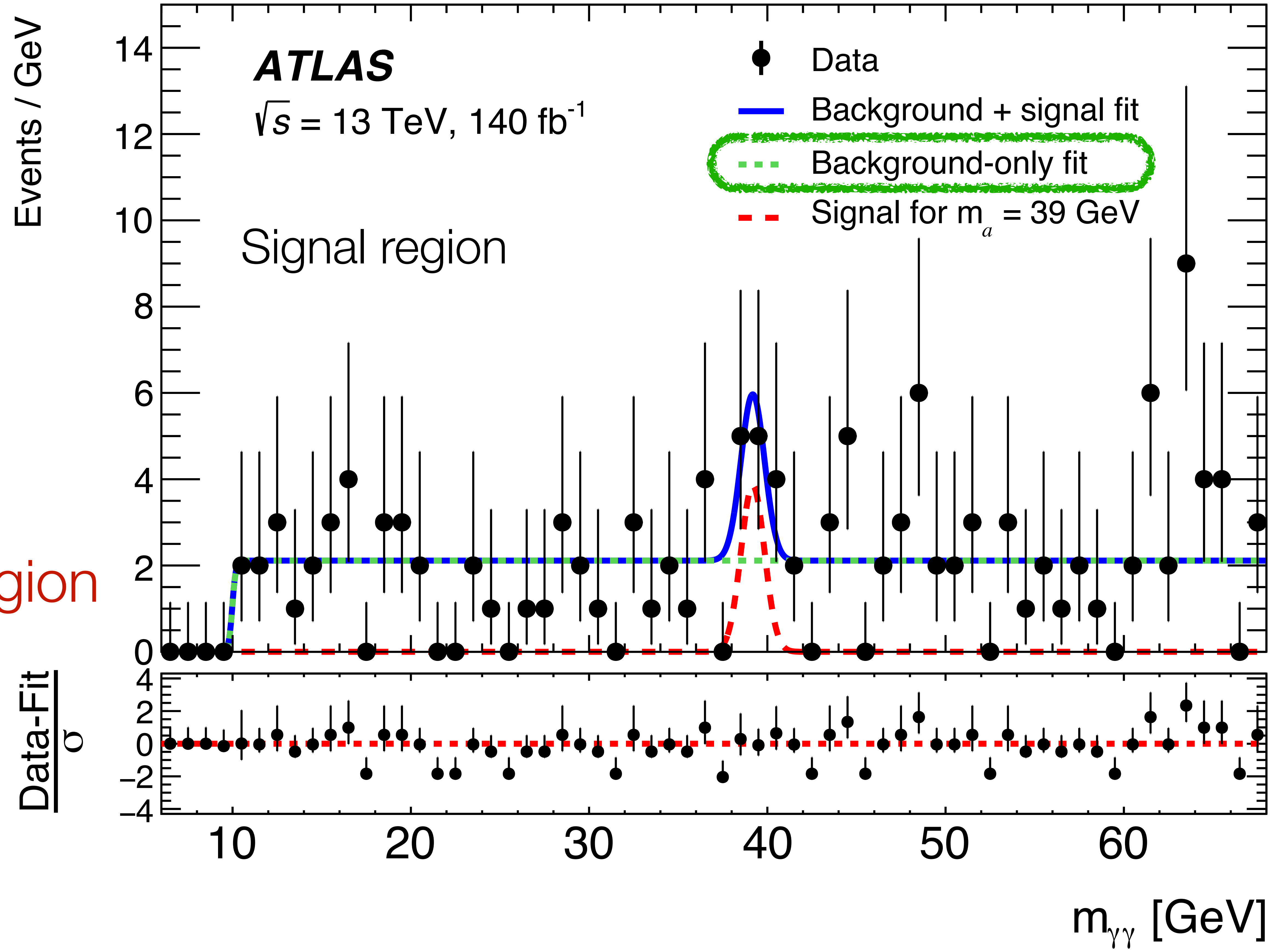
- The full background template is composed of the irreducible component from MC and the reducible component from data: $$f_B = P_{\gamma\gamma}^{2x2D}\ f_{irreducible} + (1 - P_{\gamma\gamma}^{2x2D})\ f_{reducible}$$

- The background template is modeled with a Fermi-Dirac (sigmoid function) and an exponent:

$$f_{FD-Exp}(m_{\gamma\gamma};\vec{\theta}) \propto \frac{1}{1 + e^{-\left(m_{\gamma\gamma} - \delta_{FD}\right)/\tau_{FD}}} \times e^{-\lambda_{Exp}\ m_{\gamma\gamma}}$$

Describes the turn-on

Describes the smoothly continuous region



Fitting range: [6,68] GeV, search range: [10,60] GeV

Systematic uncertainties

- Analysis sensitivity is largely **statistically limited**
- Largest systematic comes from the boosted ditau reconstruction at low masses
  - Will be improved in future analysis
- Theory uncertainties (PDF and QCD scale related) are largest contribution at high masses

Source	Uncertainty	
In $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$ [%]		
	m_a = 10 GeV	m_a = 50 GeV
Boosted di-τ object	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	$< 0.08\,\sigma_{\text{stat}}$ 0.16 events	$< 0.01\,\sigma_{\text{stat}}$ 0.06 events

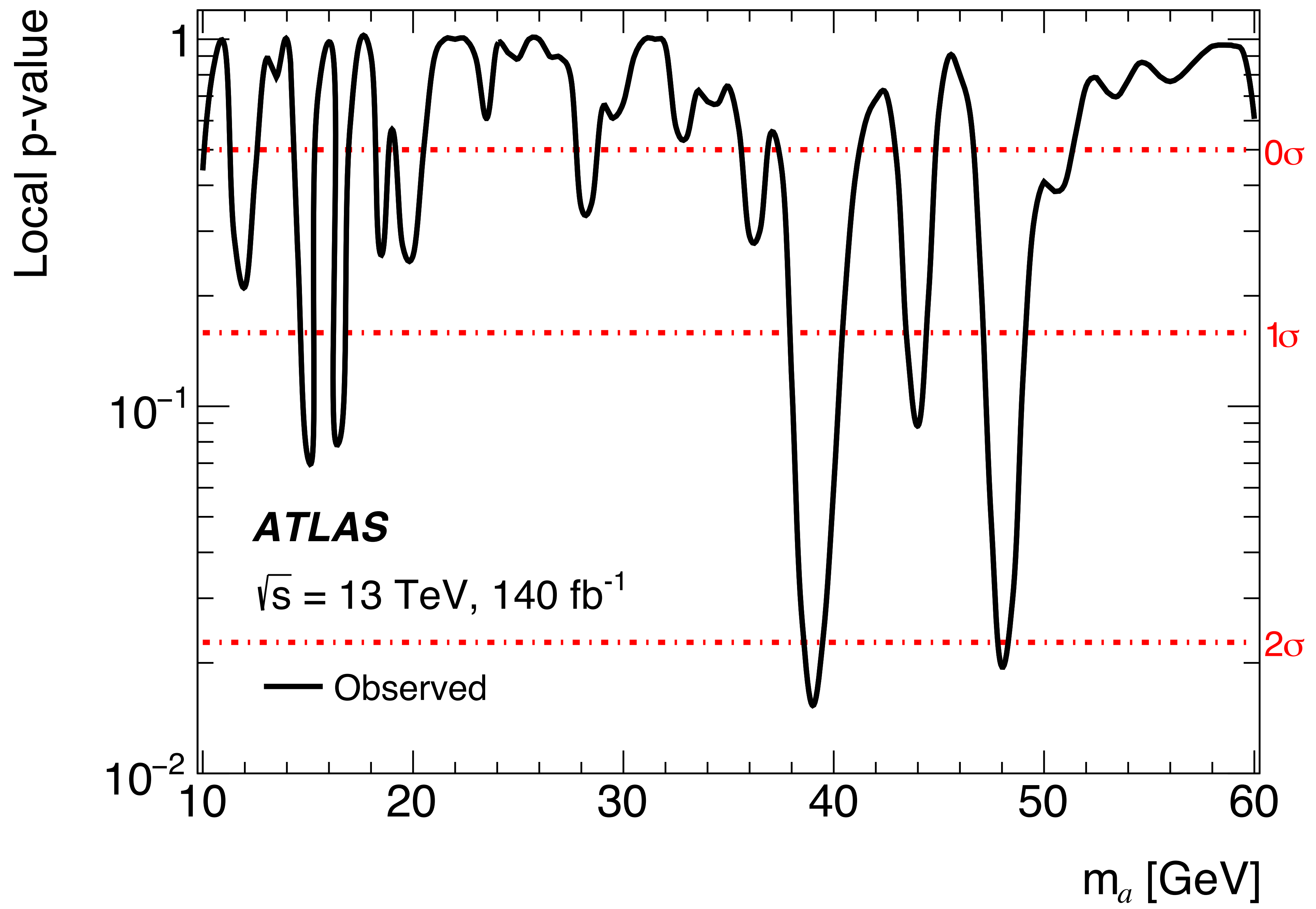
Results

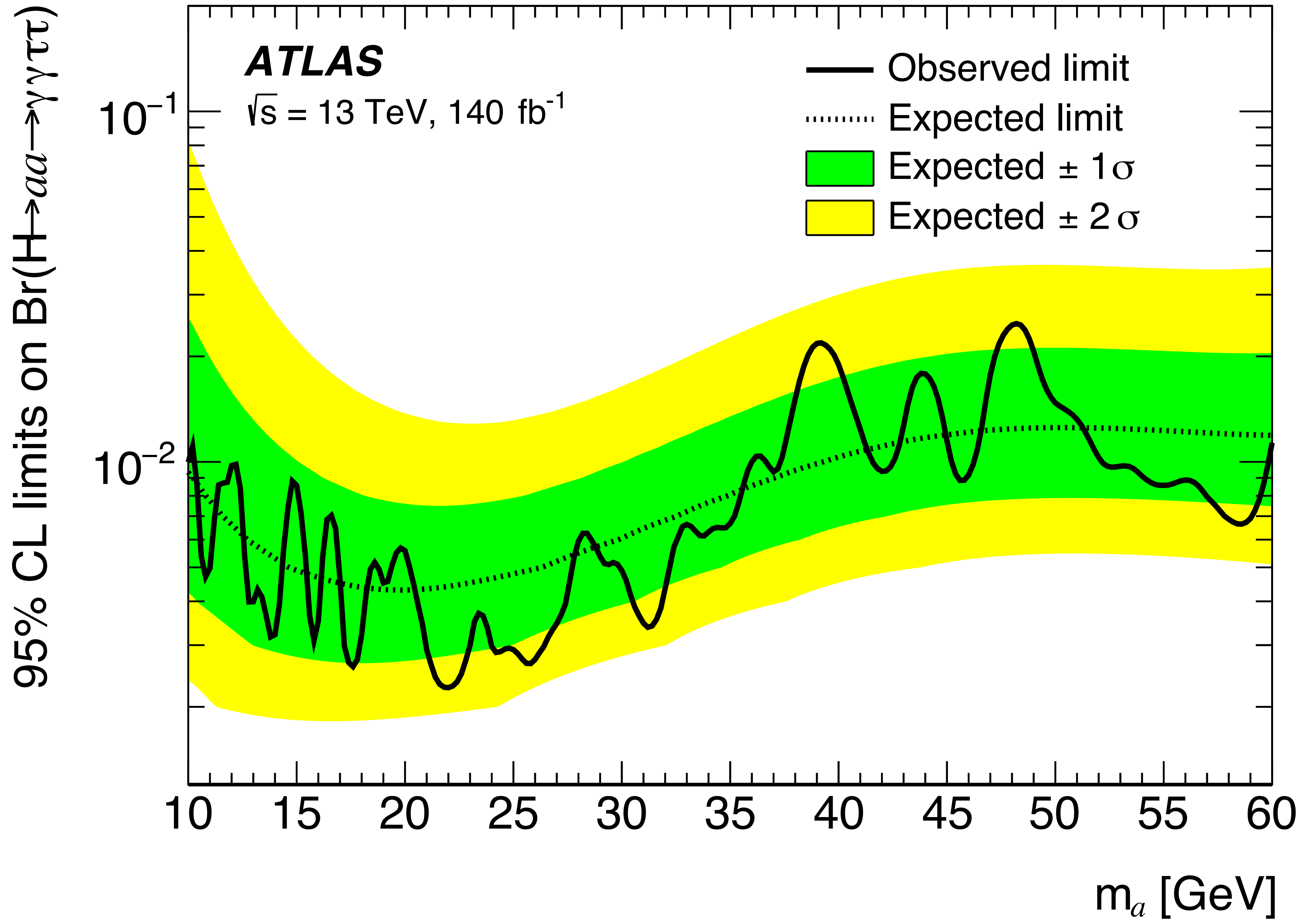
Unbinned background-only fit performed

- Fit range: [6, 68] GeV, 129 events

No deviations with respect to background-only hypothesis

- Search range: [10,60] GeV (at least 5σ from the fit edges)
- Largest deviations observed at 39 and 48 GeV, corresponding to a ~2σ local significance





Upper limits computed on the branching ratio

$$\mathscr{B}(H \to aa \to \gamma\gamma\tau\tau)$$

- Observed upper limits range from 0.2% to 2%

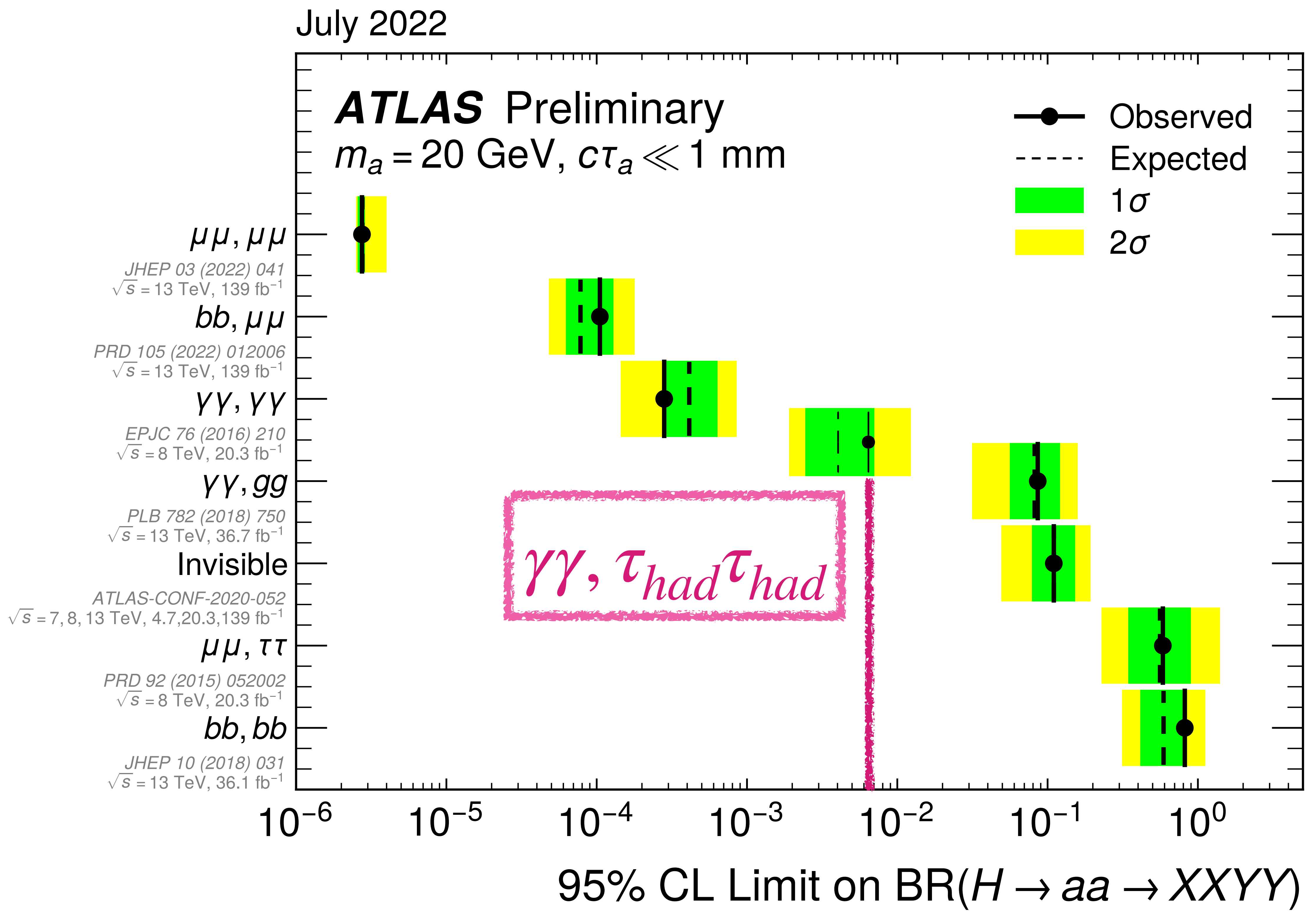
Summary

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

- Relies on the excellent resolution of boosted diphotons and novel low-p_T boosted ditau reconstruction techniques
- No significant deviations w.r.t SM backgrounds

Upper limit at 95% CL on $\mathcal{B}\left(H \rightarrow aa \rightarrow \gamma\gamma\tau\tau\right)$ observed around 0.7% for masses between 10 and 60 GeV

- Result in the bulk of other exotic decay upper limits
- Sensitivity limited by statistics
- Largest systematic uncertainty from boosted ditau tagger for masses below 25 GeV



Thank you!

Backup

Analysis strategy

Complicated reconstruction of complete final state:

- Ditau mass resolution worsened due to E_T^{miss}
- Search for diphoton resonances with a reconstructed tau pair

Main factors limiting the lowest attainable mass:

- Diphoton trigger thresholds at ~20 GeV
- Isolation cone ($\Delta R_{\gamma\gamma}$ = 0.2)

$$m_{\gamma\gamma} \approx \Delta R_{\gamma\gamma}\sqrt{p_T^{\gamma_1} p_T^{\gamma_2}}$$

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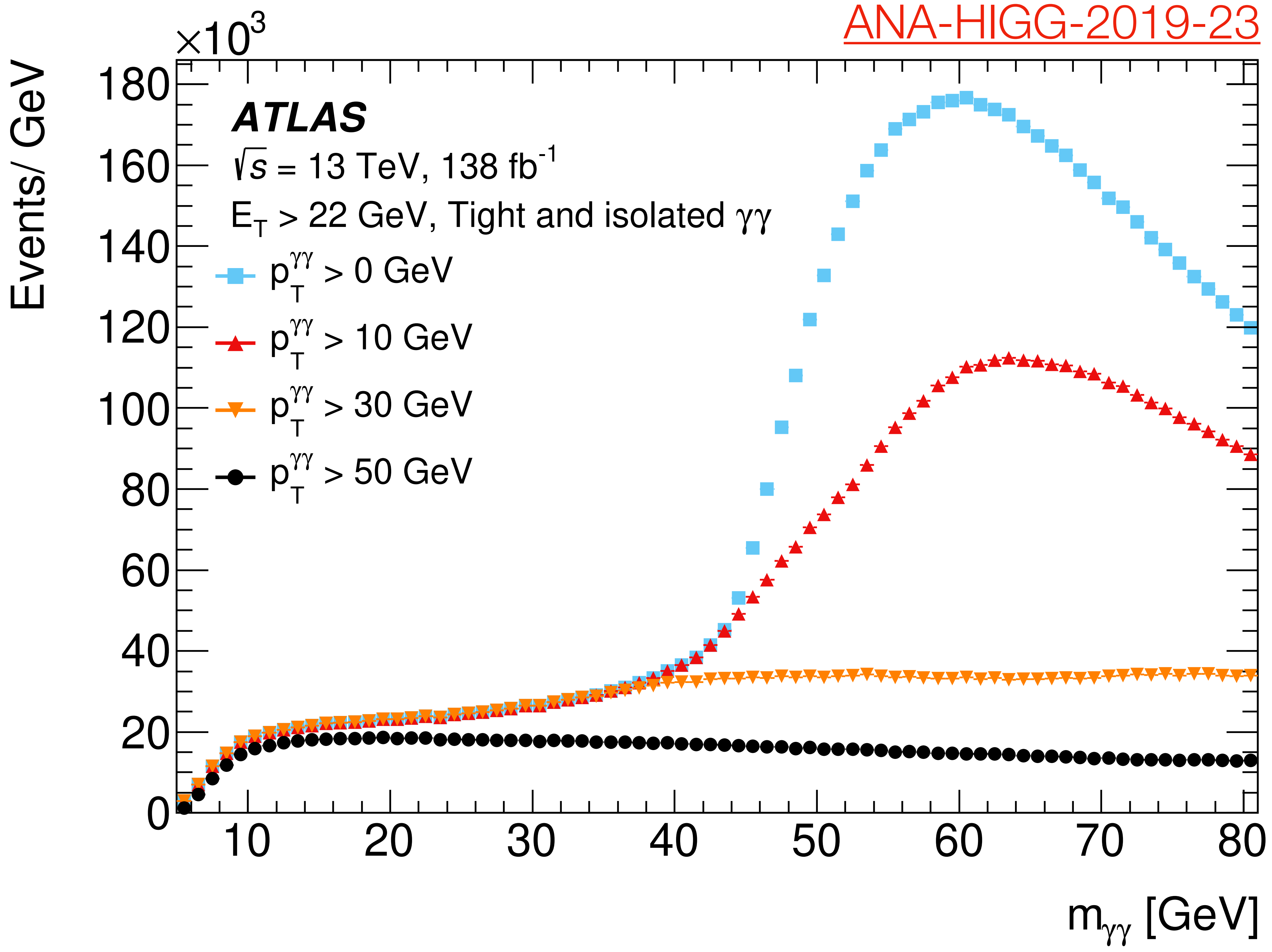


Boosted diphoton selection: smoothens out diphoton background shape

- Diphoton system required to have large transverse momentum $p_T^{\gamma\gamma}$ (almost natural since recoils against a ditau)

Procedure:

- Describe signal and background diphoton shapes with analytical functions
- Search for event excesses over the $m_{\gamma\gamma}$ spectrum
- In the absence of signal, set limits on $\mathscr{B}\left(H \to aa \to \gamma\gamma\tau\tau\right)$

Triggers

Lowest unprescaled diphoton triggers are chosen to attain the lowest invariant mass possible.

Diphoton triggers have evolved during Run2 to cope with increasing luminosity and rates.

- From 2017, isolation at trigger level is applied on both photon candidates

Year	2015	2016 up to D3	2016 from D3	2017 & 2018
L1 item	L1_2EM10VH	L1_2EM15VH	L1_2EM15VH	L1_2EM15VHI
HLT item	2g20_tight	2g20_tight	2g22_tight	2g20_tight_icalovloose
luminosity $[fb^{-1}]$	3.2	33.4		44.0+58.8

Events recorded with **prescaled triggers** used for background shape estimation.

- Very limited statistics due to large prescalings on the L1 item
- Only loose identification required

Year	2015	2016	2017	2018
HLT item	2g20_loose	2g20_loose	2g20_loose	2g20_loose
luminosity $[fb^{-1}]$	0.32	3.30	1.56	1.08

Object selections

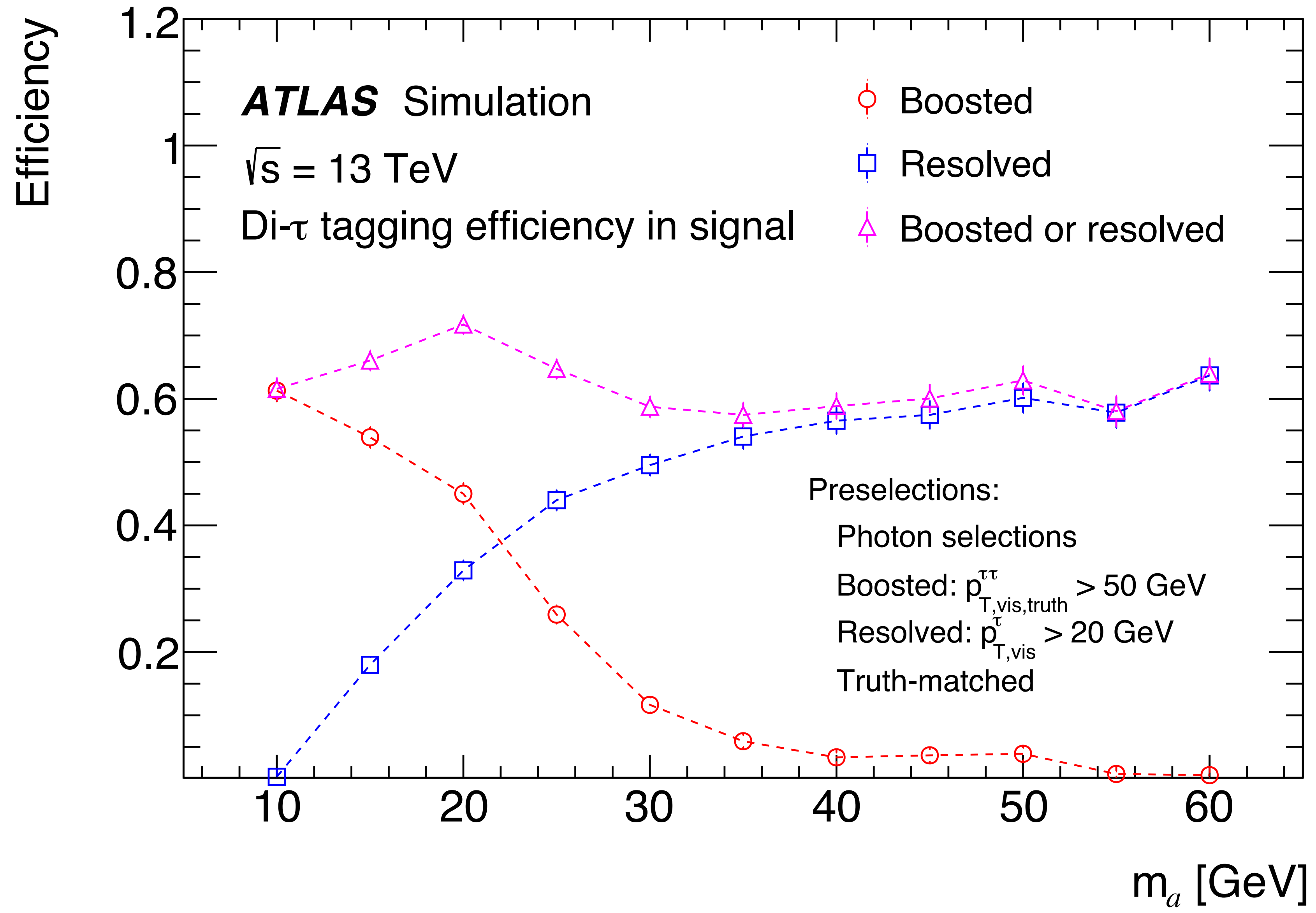
Ditau topology (resolved vs. boosted) varies significantly with the mass of the resonance:

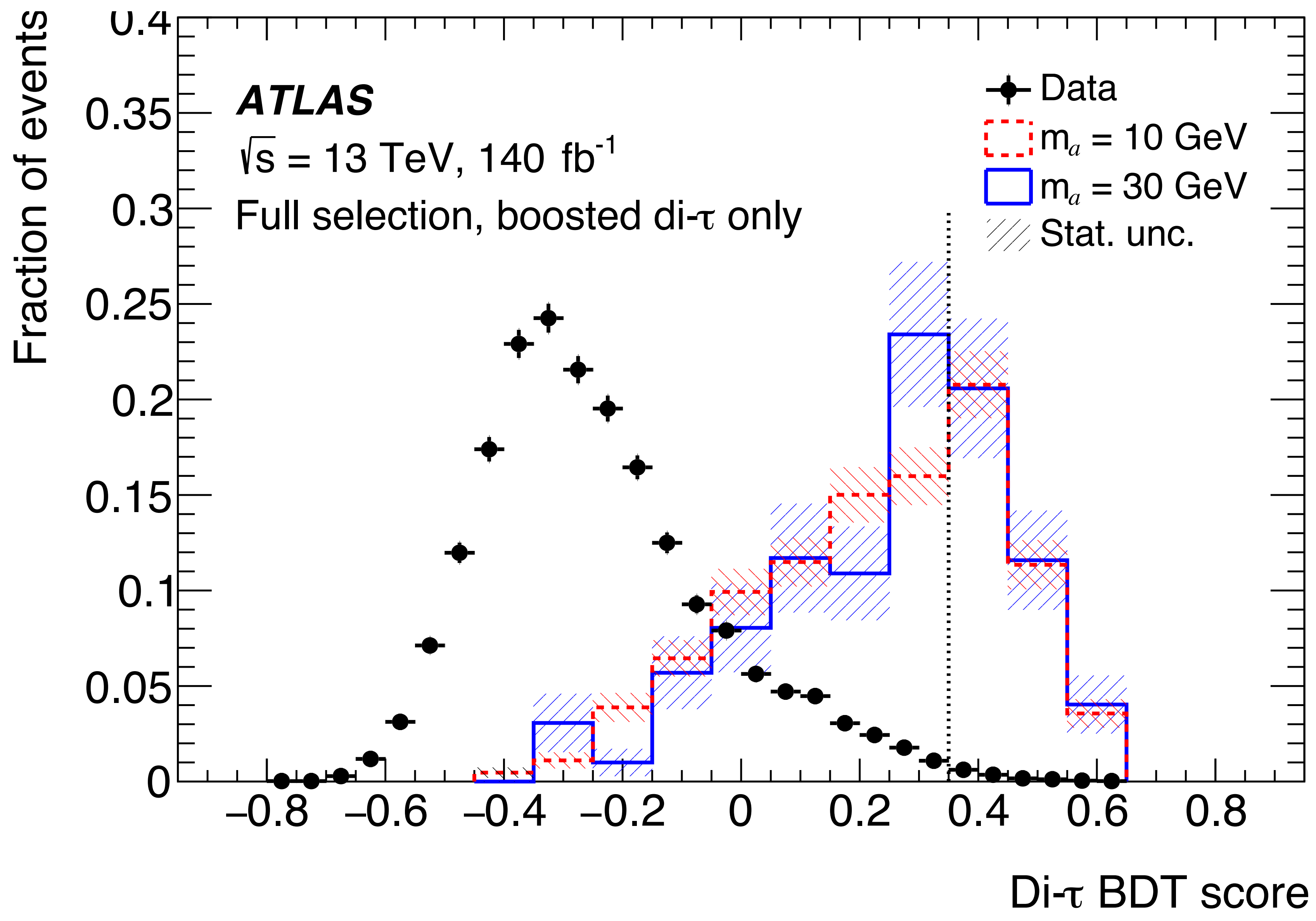
Ditau selections:

Selection	Boosted ditau	Resolved ditau
Preselection	1 boosted ditau with 2 subjets	2 tau candidates
Kinematics	1||3 tracks per subjet	$p_T > 20$ GeV, $\|\eta\| < 2.5$, 1||3 tracks
Chargeness	OS	OS
Identification	$BDT > 0.35$	LooseRNN ID

Photon selections:

Selection	Requirement
Preselection	2 loose photons, with $\|\eta^{\gamma}\| < 2.37$
Trigger	Any unprescaled diphoton trigger
Identification	Tight ID
Isolation	FixedCutLoose ($\Delta R_{iso} = 0.2$)
Additional	$p_T^{\gamma\gamma} > 50$ GeV





To ensure orthogonality with the lep-had channel, electrons and muon are vetoed in the analysis.

Object overlap removal:

- Select photon if $\Delta R\left(\gamma, \tau\tau\right) < 0.5$
- Select resolved ditau if $\Delta R\,(\text{boosted } \tau\tau, \text{ resolved } \tau\tau) < 1.0$ due to much larger systematics from the boosted tagger

Event selections

In the **signal region**, largest decrease in efficiency comes from ditau reconstruction (down to less than 0.1%).

Control regions can be built by varying either the photonID or the ditau BDT/tauID and chargeness ($Q = q_1 \times q_2$):

Photon selections-based regions

Object / Selection	Preselection	CR	SR
γ	$E_T > 22$ GeV	Loose'X-not-tight ID (X=4 for nominal)	Tight ID Loose Iso
$\gamma\gamma$	$p_T^{\gamma\gamma} > 50$ GeV	Loose prescaled diphoton triggers	Standard diphoton triggers Trigger matched

Ditau selections-based regions

Object / Selection	Preselection	CR	VR	SR
Resolved $\tau\tau$	$p_T^{\tau} > 20$ GeV $\|\eta^{\tau}\| < 2.5$ 1||3 prong	$Q \neq -1$ || $!\texttt{LooseID}_{\tau_1}$ || $!\texttt{LooseID}_{\tau_2}$		$Q = -1$ $\texttt{LooseID}_{\tau_1}$ $\texttt{LooseID}_{\tau_2}$
Boosted $\tau\tau$	$N_{subjets} \geq 2$ 1||3 prong per subjet	$Q \neq -1$ $-0.5 < BDT < -0.3$	$Q \neq -1$ $-0.3 < BDT < -0.2$	$Q = -1$ $BDT > 0.35$
$\tau\tau$		1 boosted || 1 resolved $\tau\tau$	1 boosted $\tau\tau$	1 boosted || 1 resolved $\tau\tau$

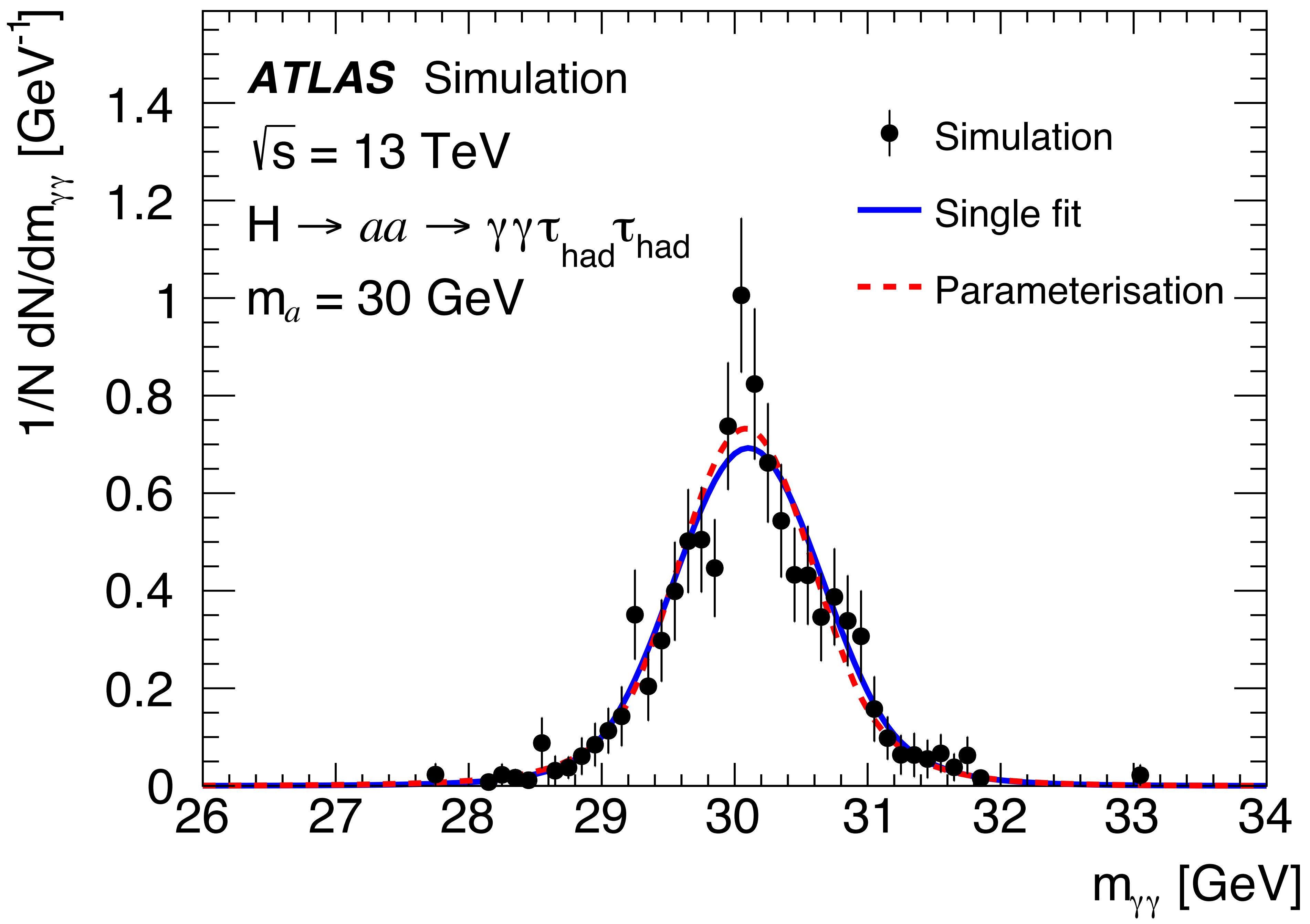
Any combination of photon and ditau selections results in a new data-driven CR (as long as the signal leakage is small), particularly: LPX$\gamma\gamma$+CR$\tau\tau$ (X=2,3,4,5), SR$\gamma\gamma$+CR$\tau\tau$, SR$\gamma\gamma$+VR$\tau\tau$.

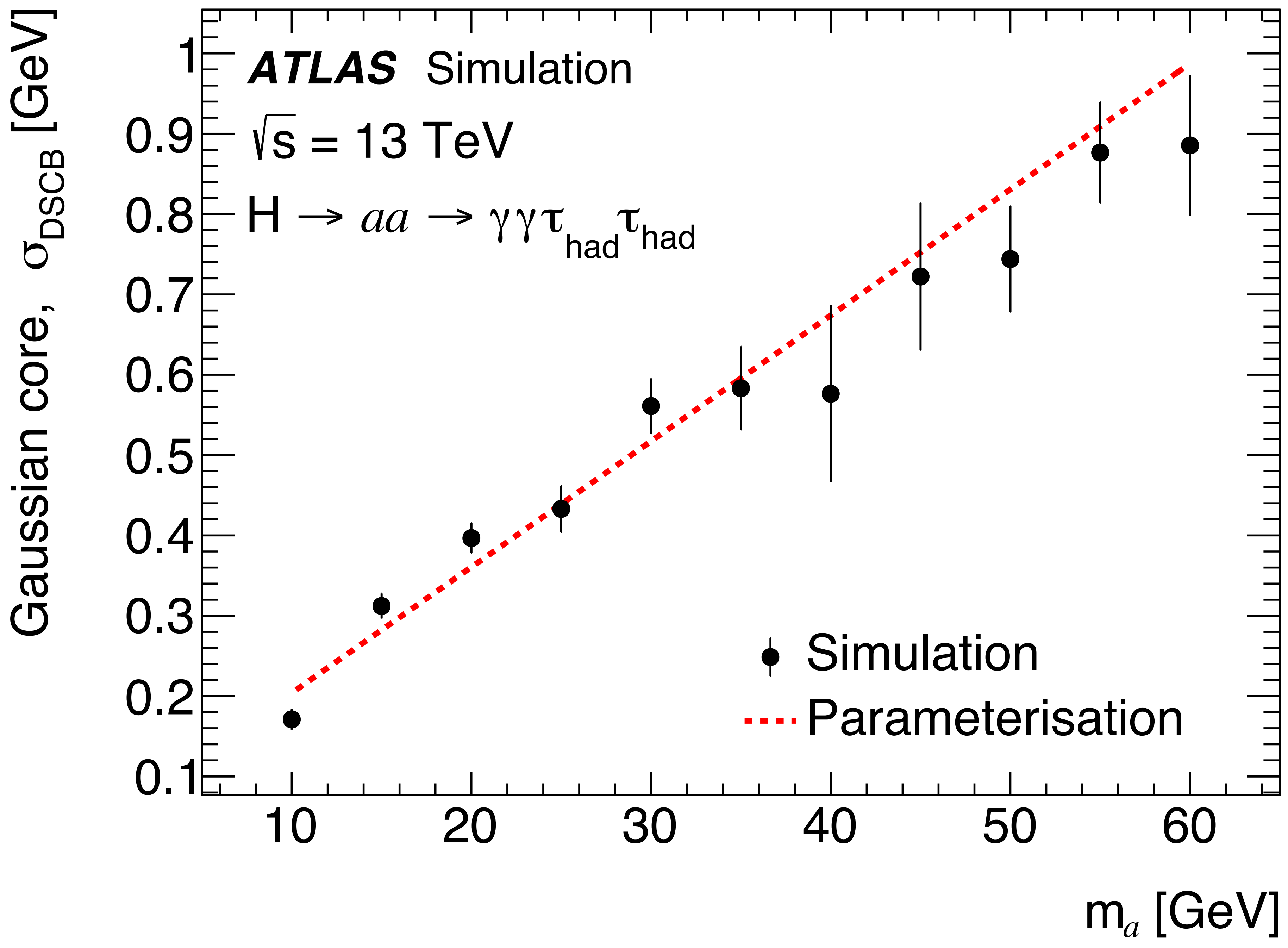
Signal modeling

Signal shape obtained from simulated samples

- Signal parametrization obtained using a Double-sided Crystal Ball (DSCB)
- Width dominated by detector resolution

DSCB parameters interpolated with linear trends for complete signal model for masses between 10 and 60 GeV.





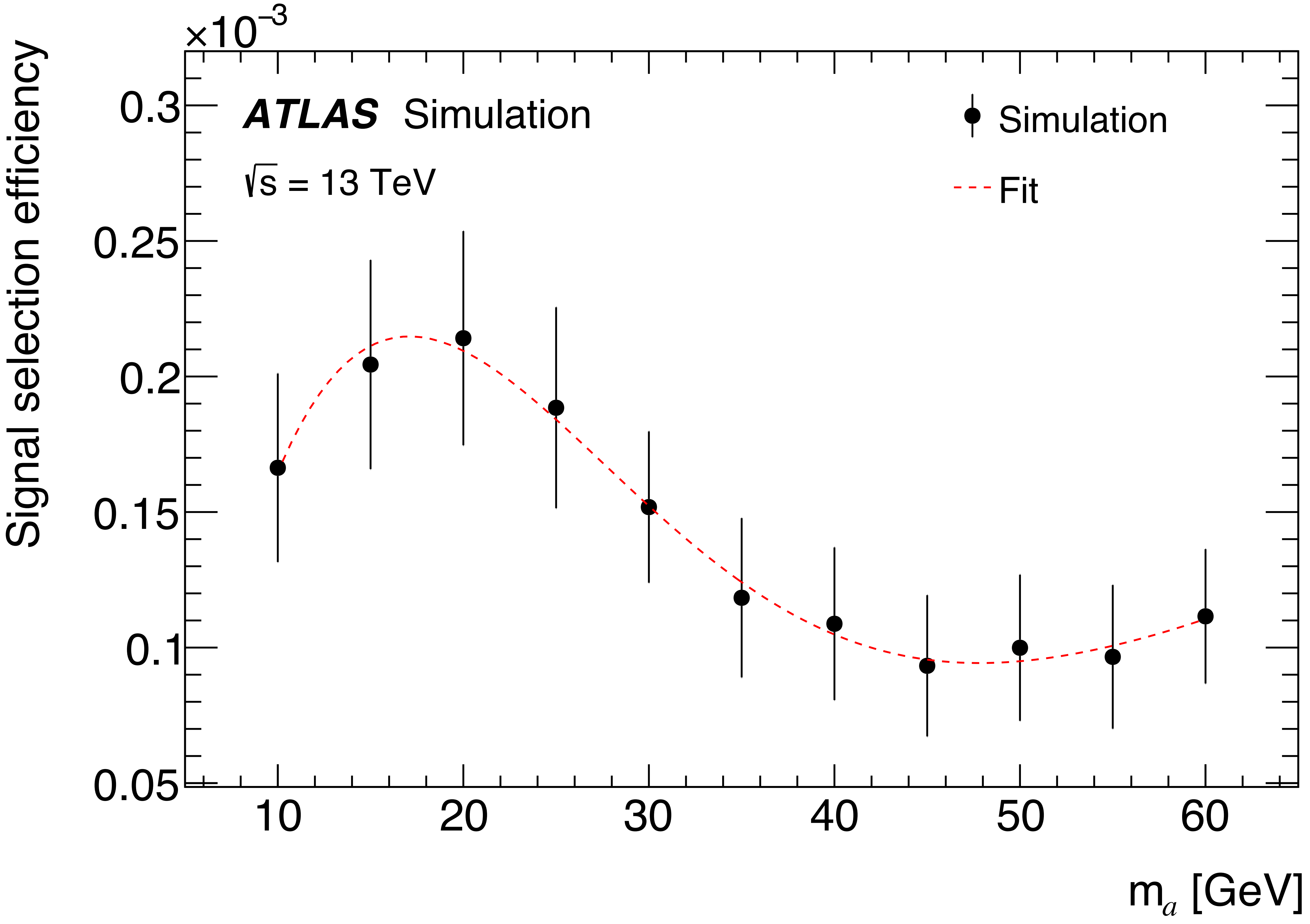
Signal selection efficiency

- Limit for $\mathscr{B}(H \rightarrow aa \rightarrow \gamma\gamma\tau\tau)$ requires the total signal selection efficiency (acceptance x efficiency) ε_a:

$$\sigma_{gg\rightarrow H} \cdot \mathscr{B}(H \rightarrow aa \rightarrow \gamma\gamma\tau\tau) = \frac{N_{sig}^{reco}}{\varepsilon_a \cdot \mathscr{L}_{int}},$$

$$\varepsilon_a \equiv \frac{N_{selected}}{N_{total}} = \varepsilon_{filters} \times \frac{N_{selected}}{N_{generated}}$$

- Total signal efficiency using signal MC samples, accounting for the filter efficiencies as well
- Values span from ~0.01% to ~0.02%
- Efficiency decreases towards higher masses because of the boosted topology required on diphoton
- Shape related to interplay between resolved and boosted regimes of the ditau reconstruction



Background decomposition

Standard background estimation strategy with two photons in the final state: 2x2D method (two-dimensional ABCD) using photon ID and ISO variables for each photon

- Assuming that diphoton purity is agnostic whether there is a true/fake ditau, inverted ditau selections are used
- Inverted ditau selections: BDT < -0.2 and $Q \neq -1$ for boosted ditau; one of the taus fail the LooseRNN ID or $Q \neq -1$ for resolved ditau ($Q = q_{\tau_1} \times q_{\tau_2}$)

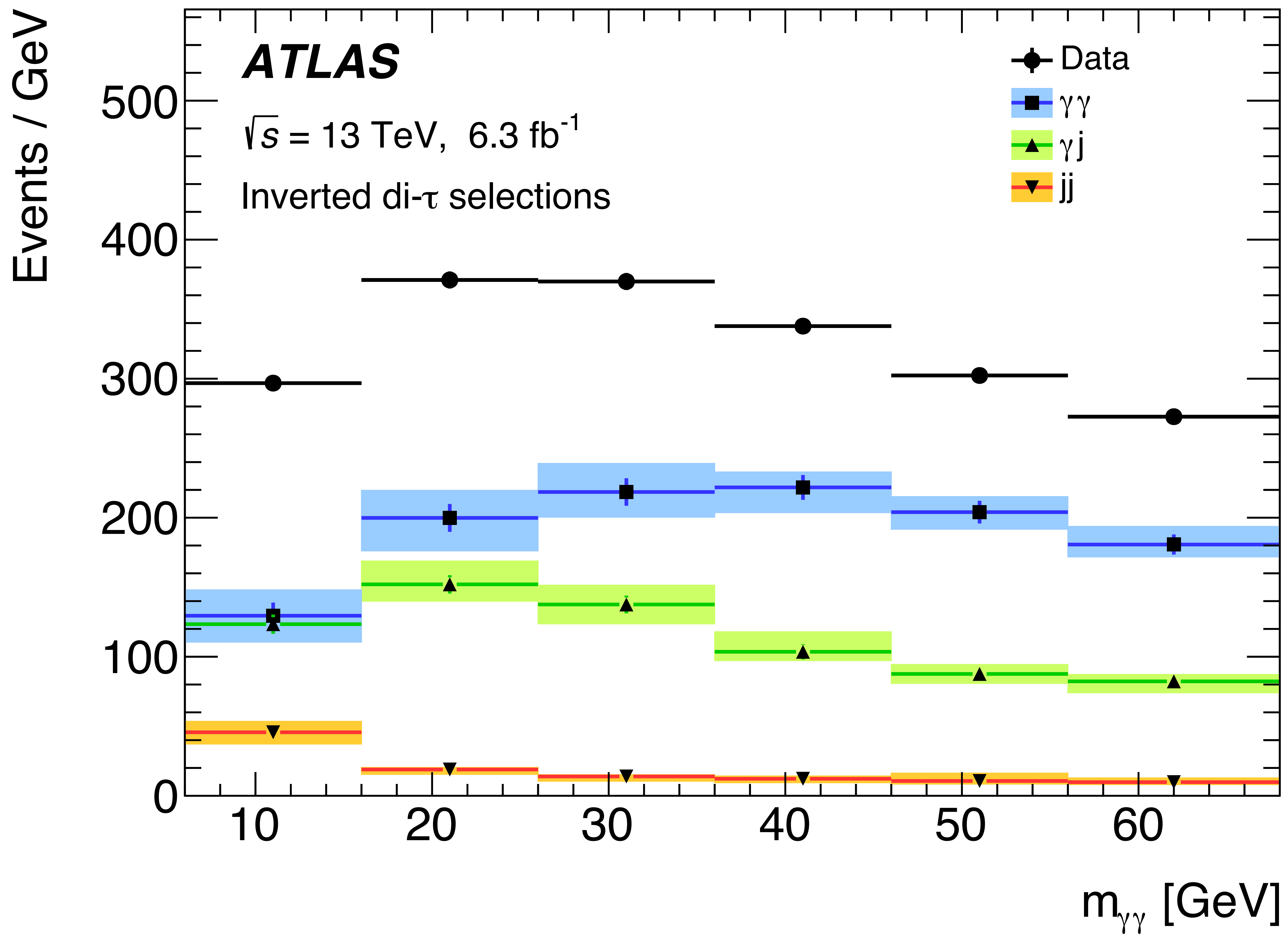
Prescaled diphoton triggers are used (no ID nor isolation selections at trigger level)

- Large binning (10–12 GeV) to avoid unblinding

Total observed purity ($\gamma\gamma$ fraction of data):

$$P^{2x2D}_{\gamma\gamma} = 0.61 \pm 0.01 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$$

In line with previous diphoton analysis covering the same invariant mass range (~64%)



Background template sources

The full background shape is modeled by fitting an analytical function to a template composed by both reducible and irreducible sources:

- **Irreducible ($\gamma\gamma$): SR photons from prompt diphoton production MC**
  Standard triggers, tight ID and loose ISO photons
- **Reducible ($\gamma j + jj$): CR photons from data**
  Loose prescaled triggers, loose ID photons

Combine both components using the integrated diphoton purity obtained with the 2x2D method:

$$f_B = P_{\gamma\gamma}^{2x2D}\ f_{irreducible} + (1 - P_{\gamma\gamma}^{2x2D})\ f_{reducible}$$

- The degree of ditau identification is uncorrelated with the quality of the photon pair selection
  → CR ditau selections are used due to stat

Background fit bias (spurious signal)

A bad description of the background shape can potentially absorb/induce signals.

- Estimated from S+B fits to background-only templates: S different than zero is the fit bias
- The fit bias is estimated for all the background template variations
- Eventually, the corresponding systematic uncertainty is obtained from the envelope of the observed spurious signal computed in the aforementioned background template variations
- Another criteria to choose the background function, on top of the flexibility of the function and the quality of the obtained fits