Search for resonant Di-Higgs production using boosted bbττ final state at ATLAS

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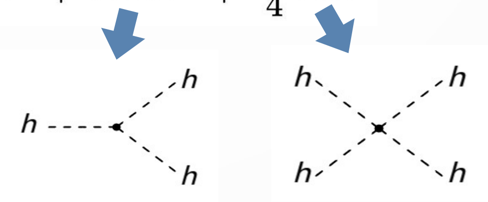
Introduction

- Standard Model (SM) predicts the self-interaction of the Higgs field.

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$= V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$



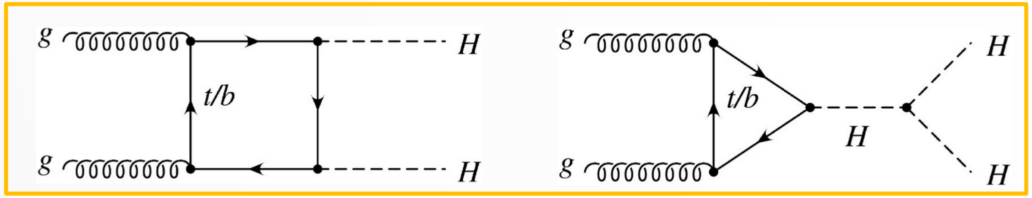
- Essential to probe the shape of the potential

Electroweak (EW) symmetry breaking	The stability of vacuum	EW phase transition	...

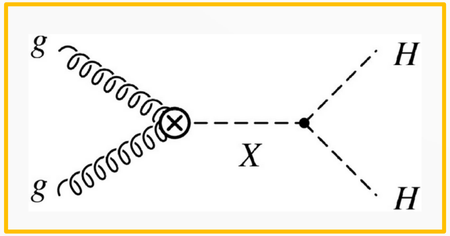
- Still far from established, any observation of Higgs pair production now is very likely a sign of physic beyond the Standard Model (BSM)

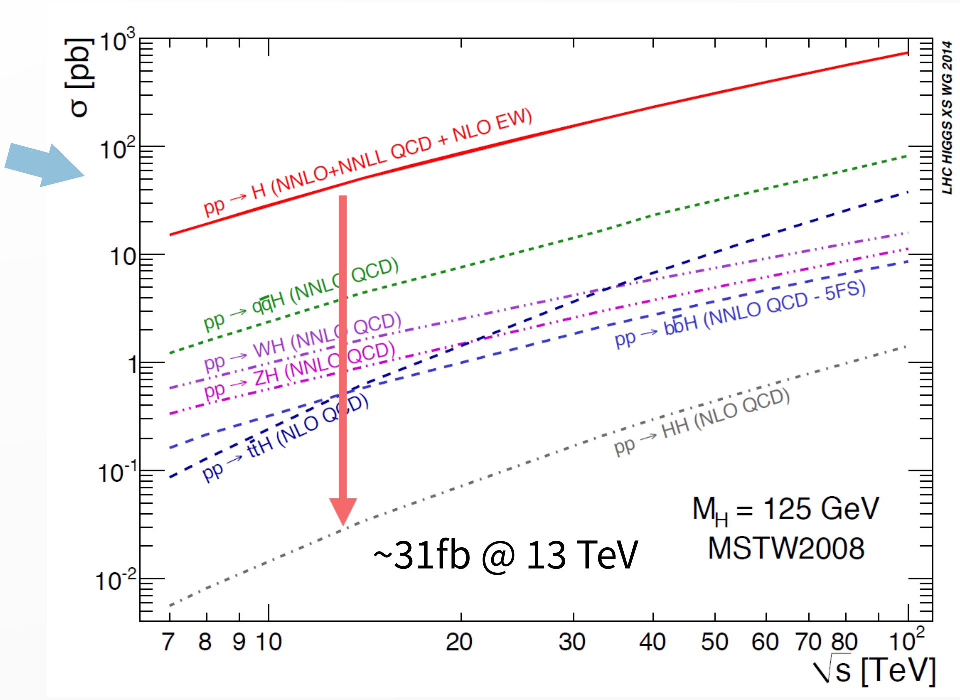
Production

- **SM: ~90% Gluon-Gluon Fusion (ggF)** and Vector Boson Fusion (VBF)



- **BSM:**
  - Anomolous couplings
    - ggF: κ_λ κ_t ; VBF: κ_λ κ_V κ_{2V}
  - New resonance decays to di-Higgs
    - EW-singlet model, two-Higgs-doublet model, Randall-Sundrum model, …





Higgs European Strategy

Decay

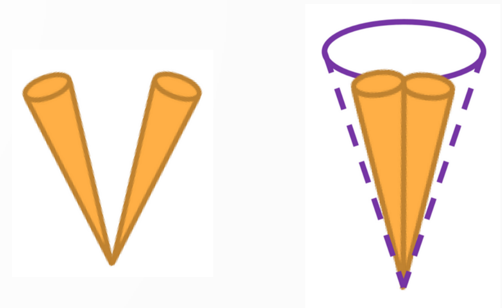
- Publications using ATLAS 2015~2016 dataset (36.1fb^{-1}) covers:
  - bbbb, bbWW, bbττ, bbγγ
  - WWWW, WWγγ
  - Data 15~16 combination result: Phys. Lett. B 800 (2020) 135103
- New publications using ATLAS Full Run2 (2015~2018, 139fb^{-1}) dataset:
  - bbbb (VBF): JHEP 07 (2020) 108
  - ★ **bbττ (boosted topology):** arXiv: 2007.14811

★ bbττ: Medium branching ratio and relatively low background benefit by τ tagging.

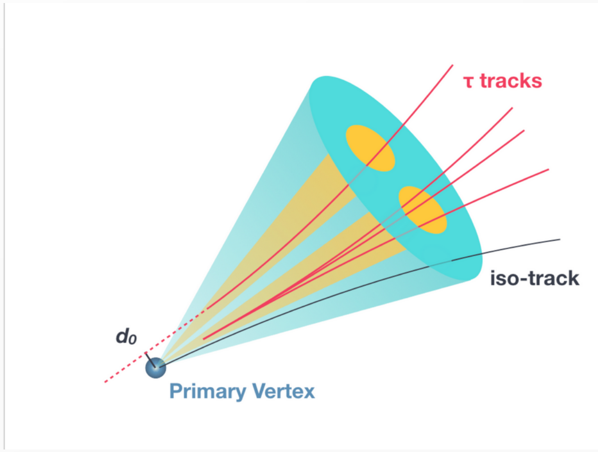
Higgs Decay	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3% ★	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.07%	
γγ	0.26%	0.10%	0.03%	0.01%	<0.001%

Boosted Analysis

- Higgs bosons pair-produced by the decay of a heavy resonance are highly lorentz boosted.
- Final state objects in H→bb and H→ττ decays cannot be reconstructed as resolved objects.
  - Reconstruct as boosted di-b-jet and di-τ
- Di-τ tagging (fully-hadronic ττ decay) is used for the first time in ATLAS
- Extend the sensitive resonance search range
  - Previous bbττ analyis (Phys. Rev. Lett. 121 (2018) 191801) use resolved objects, search range: 260 GeV ~ 1 TeV
  - Boosted analysis: 1 ~ 3 TeV



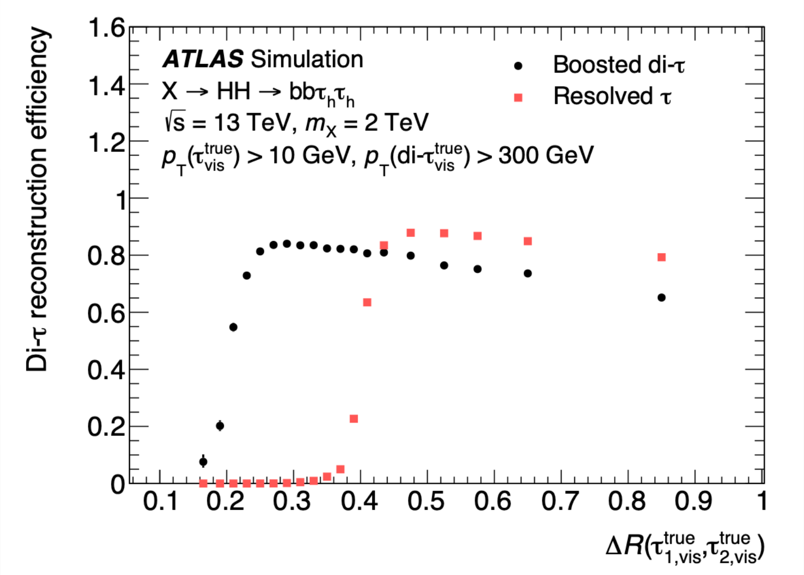
Resolved → Boosted

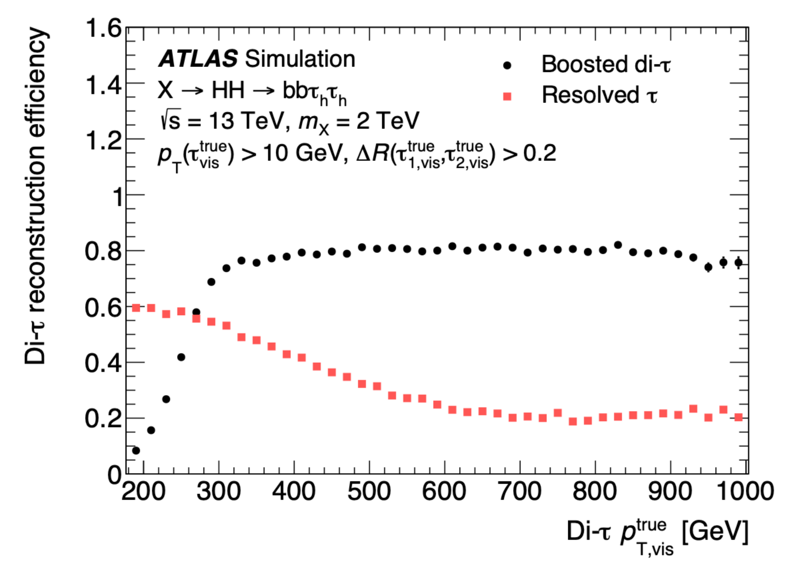


Boosted di-τ

Boosted Di-τ Tagging

- Recover reconstruction efficiency loss when the two tau hadronical decay products (τ_{had}) are close.
- Seed by anti-k_T R=1.0 jets and then reclustered into anti-k_T R=0.2 sub-jets.

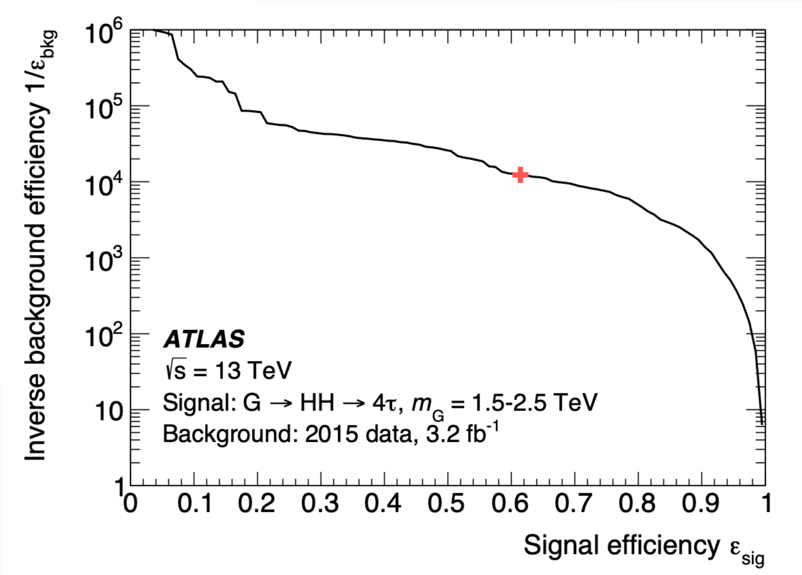


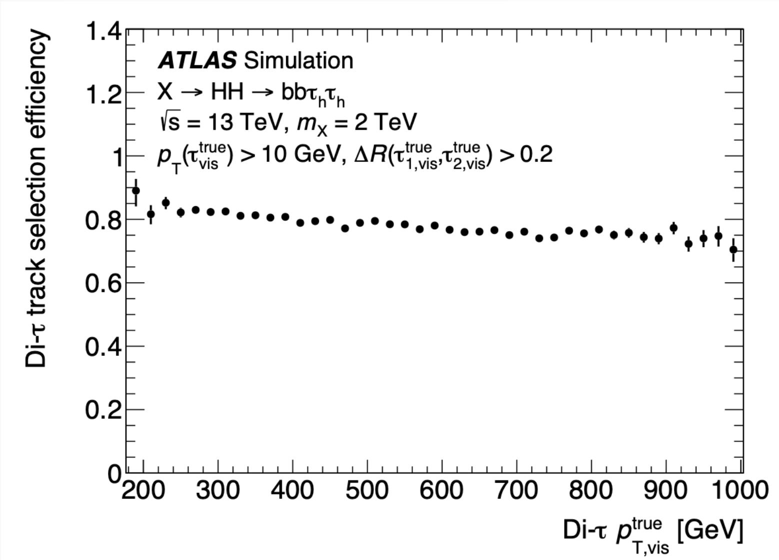


- Energy is calculated from two leading sub-jets, it is found to be close to simulated truth tau pair energy.
- Energy resolution ~2.5%

Boosted Di-τ Tagging

- Identified by a multi-variable classifier using the information from vertices, tracks and calorimeter clusters.
- Discriminate real di-τ from quark/gluon initiated jets.





- Majority of τ_{had} produce 1 or 3 charged pions
- Require N_{track}(sub-jet) = 1 or 3
- Later the charge of τ-pair is used to define opposite-/same-sign (OS/SS) regions and to reduce multi-jet background.

H→bb and Event selection

- H→bb is reconstructed from anti-k_T R=1.0 jets (large-R jets).
- B-tagging is performed on the two leading Variable-Radius (VR) track jets that associate with the large-R jet.

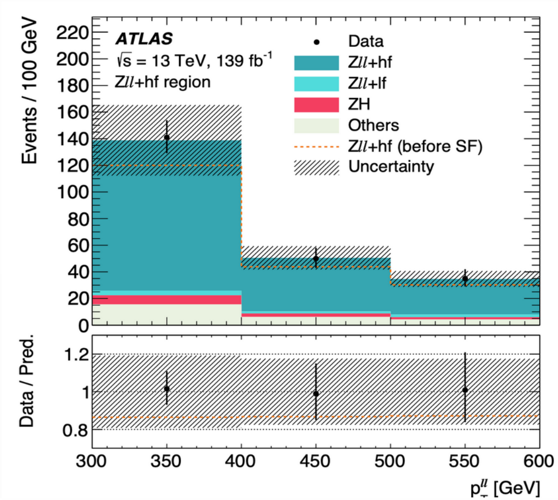
Event Selection (details in the backup)	
Trigger	Large-R jet triggers (online p_T thresholds 360~460 GeV)
Large-R jet p_T	40~50 GeV above the trigger threshold on leading jet
e/μ	Veto events with electrons or muons
# Di-τ	N ≥ 1
# Large-R jet	N ≥ 1 and ΔR (large-R jet, di-τ) > 1.0

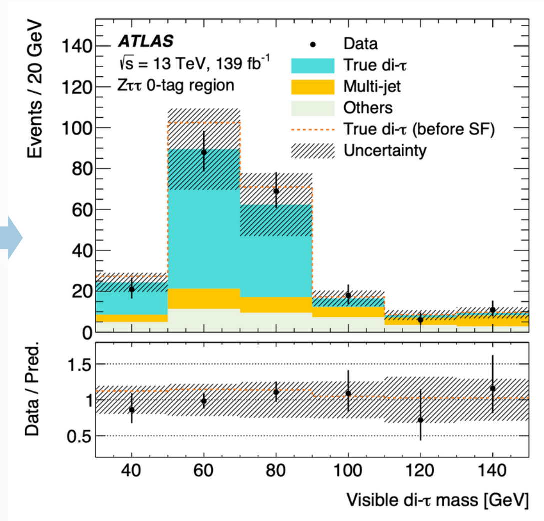
Background Estimation

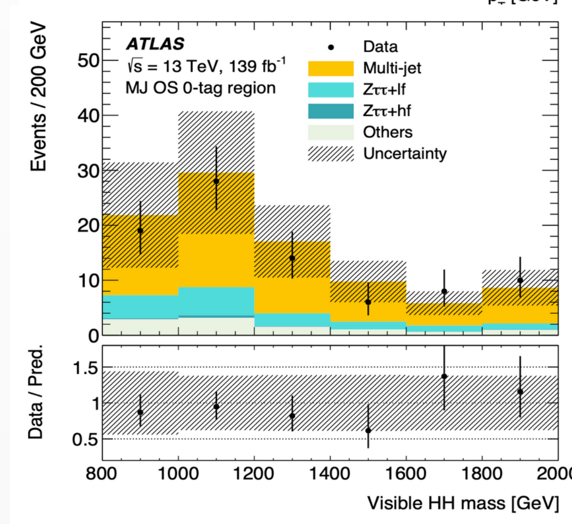
- Dominant background is Zττ + heavy flavour (hf) jets → normalised by Zee/μμ+hf CR.
- Multi-jet → Estimated by jet to di-τ fake factor calculated from 0 b-tag SS CR.

$$\mathrm{FF} = \frac{N^{\mathrm{pass}}_{\mathrm{FF\ SS}}}{N^{\mathrm{fail}}_{\mathrm{FF\ SS}}} \qquad N^{\mathrm{mis\text{-}ID}}_{\mathrm{RoI}} = N^{\mathrm{fail}}_{\mathrm{RoI}} \times \mathrm{FF}(p_{\mathrm{T}})$$

- Other minor backgrounds are estimated by simulated samples.
- Background with truth-matched di-τ are corrected by the di-τ tagging efficiency scale factor derived in a Zττ enriched region.

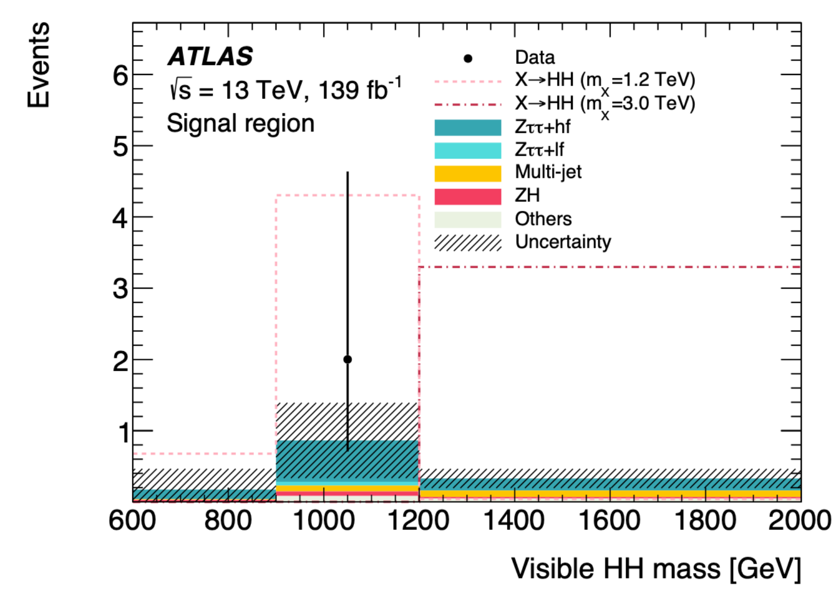


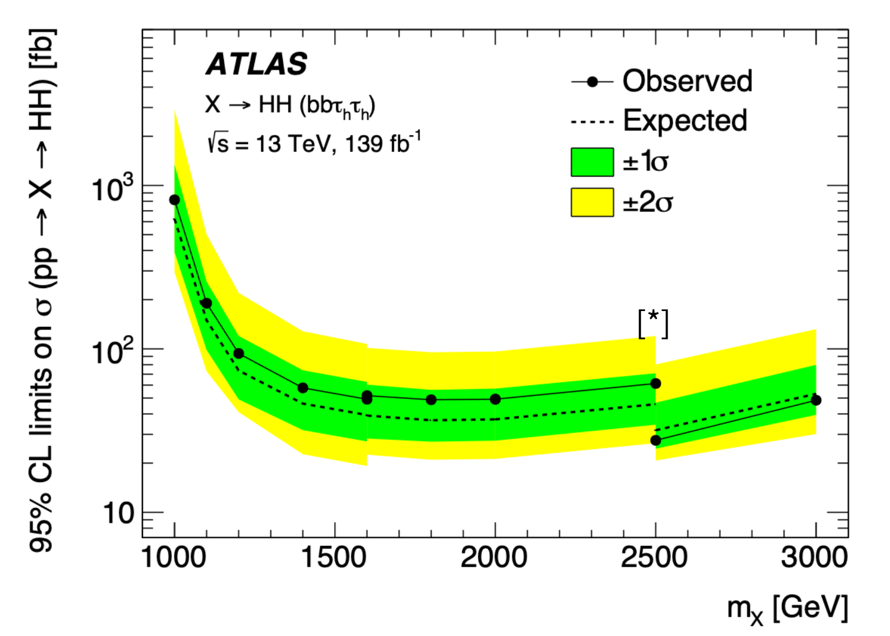




Signal Region and Result

- 2 events are observed in SR (1.36 expected)
- Additional selections are applied on visible di-Higgs mass to improve sensitivity for high resonance mass hypothesis.





- Single-bin counting experiment is performed.
- No significant excess above SM prediction.
- Set upper limits on resonant di-Higgs production via a narrow width scalar particle.

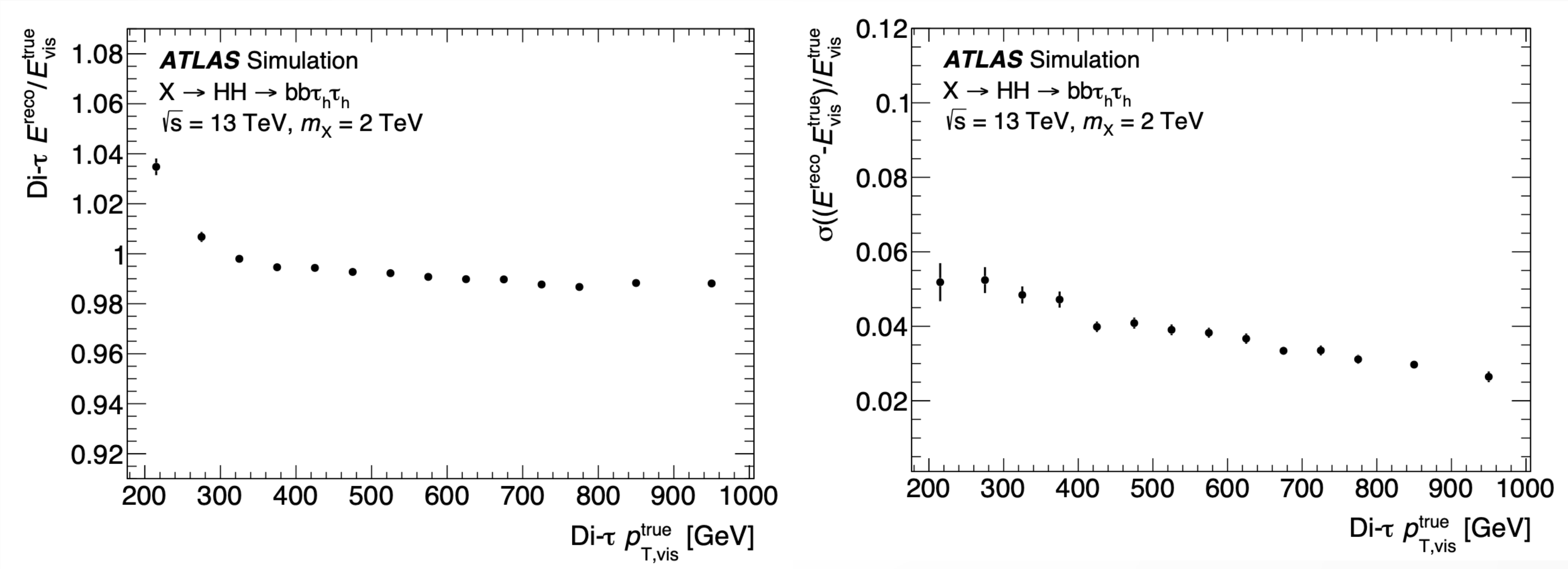
[*] Discontinuoity due to different selections on visible m_{HH}

Summary

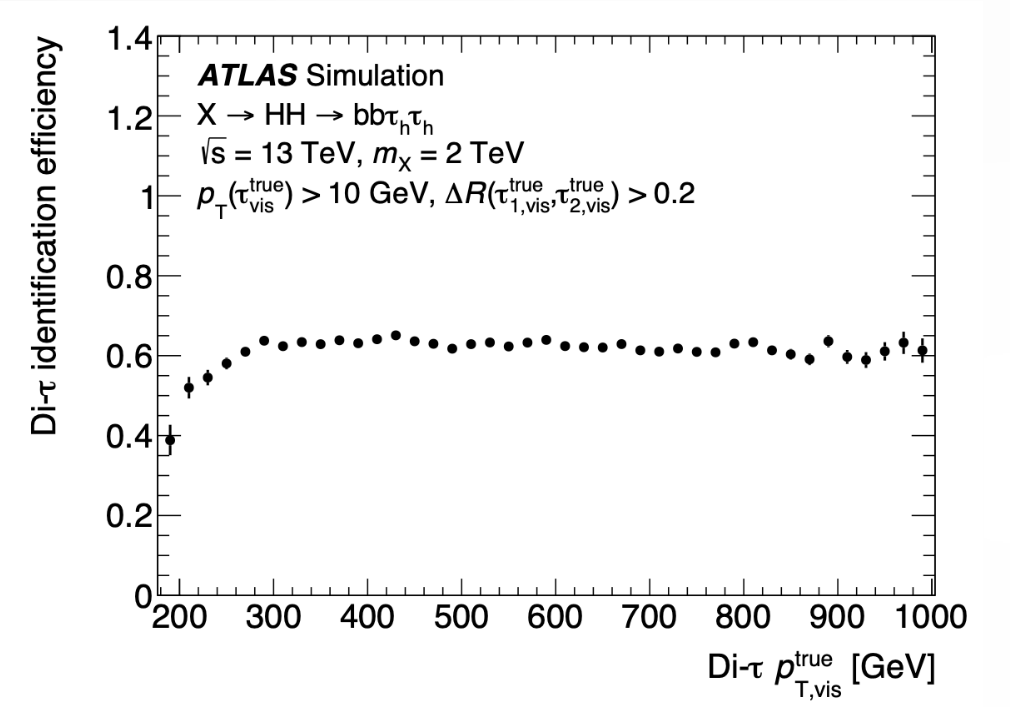
- Di-Higgs production can be enhanced by new resonance particle that decays to HH.
- Present a search for such process using $bb\tau\tau$ final state with boosted topology.
- With full Run2 ($139 fb^{-1}$) dataset, no excess is observed.
- Upper limits are set on resonant di-Higgs production cross section via narrow width scalar.

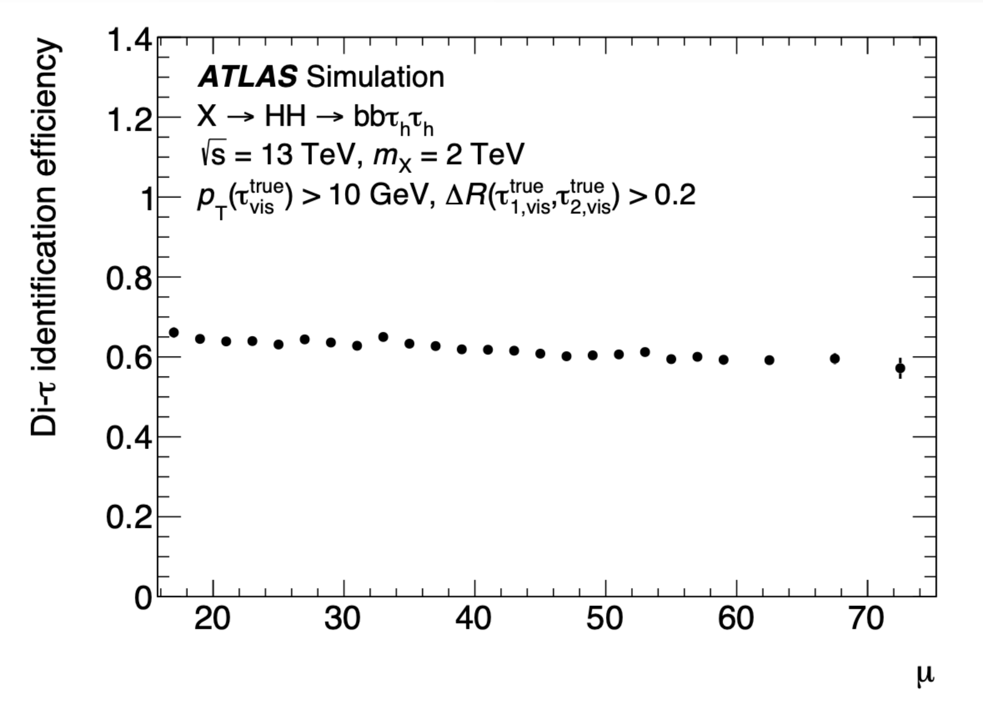
Thanks for listening!

Additional Materials



Energy scale and resolution of the di-τ reconstruction as a function of the p_T of the di-τ system at generator level.





identification efficiency of boosted di-τ objects, as a function of their p_T at generator level and the number μ of pile-up interactions.

	LRJ	VR track jet	Di-τ	Electron	Muon
p_T	$p_T > 300$ GeV	$p_T > 10$ GeV	Di-τ $p_T > 300$ GeV Subjet $p_T > 50$ GeV	$p_T > 7$ GeV	$p_T > 7$ GeV
η	$\|\eta\| < 2.0$	$\|\eta\| < 2.5$	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.0$	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	$\|\eta\| < 2.5$
WP	-	For b-tagging: 70%, MV2C10	Medium	ID: Loose, No isolation requirements	ID: Loose, Isolation: FixedCutLoose
Other		Two leading track jets in LRJ are considered for b-tagging $N_{Track} > 1$ Events with collinear VR track jets are vetoed	$2 \leq N_{subjets} \leq 3$, $\Delta R_{lead,subl} < 0.8$, $N_{tracks} = 1$ or 3, $S = q^{lead} \cdot q^{sublead} = \pm 1$ S=+1 (SS) for fake estimation, S=–1 (OS) for signal regions Events with fail-ID di-taus (0.4 < BDT < 0.72) used in fake estimation		

Analysis Regions

|Δϕ|>1

Fake Factor Calculation (SS, 0-tag)

Fake Factor Validation (OS, 0/1-tag)

→ Estimate multi-jet background.

|Δϕ|<1 & OS

Di-τ Efficiency Measurement (0-tag)

Di-τ Efficiency Validation (1-tag)

→ Calibrate di-τ ragging efficiency.

Signal Region (2-tag)

di-τ

Z+hf jets Control Region (2-tag)

di-e/μ

→ Correct Z+heavy flavour (hf) jets normalisation.

|Δϕ| is between MET and di-τ
SS/OS (Same Sign / Opposite Sign)
→ charge product of the two leading di-τ sub-jets

Selection on m_{HH}^{vis}	> 0 GeV	> 900 GeV	> 1200 GeV
$Z\tau\tau$+hf	$0.89 \pm 0.25^{+0.37}_{-0.35}$	$0.75 \pm 0.21^{+0.47}_{-0.37}$	$0.17 \pm 0.05 \pm 0.07$
$Z\tau\tau$+lf	$0.05 \pm 0.05 \pm 0.03$	$0.05 \pm 0.05 \pm 0.03$	-
Multi-jet	$0.18 \pm 0.03 \pm 0.14$	$0.17 \pm 0.03 \pm 0.13$	$0.09 \pm 0.02 \pm 0.07$
ZH	$0.11 \pm 0.01 \pm 0.04$	$0.09 \pm 0.01 \pm 0.03$	$0.02 \pm$ - ± 0.01
Others	$0.13 \pm 0.05^{+0.15}_{-0.07}$	$0.13 \pm 0.05^{+0.15}_{-0.07}$	$0.05 \pm 0.03^{+0.12}_{-0.03}$
Sum of backgrounds	$1.36 \pm 0.26^{+0.42}_{-0.38}$	$1.19 \pm 0.23^{+0.51}_{-0.40}$	$0.33 \pm 0.07^{+0.16}_{-0.10}$
Data	2	2	0

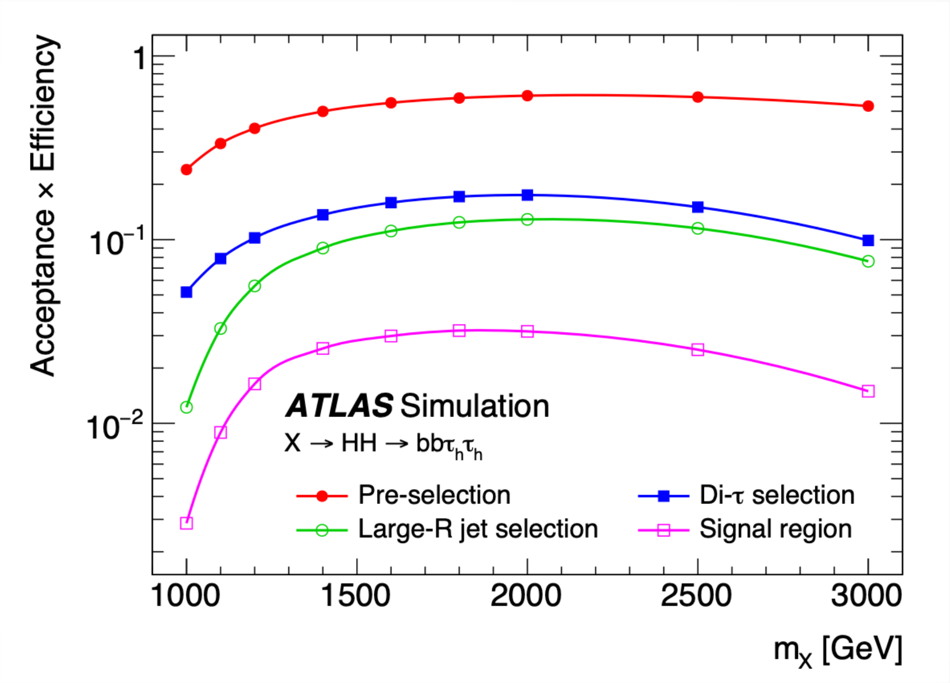


Table 5: Efficiencies (in percent) at each stage of the event selection for various signal mass hypotheses.

Selection	1.0 TeV	1.1 TeV	1.2 TeV	1.4 TeV	1.6 TeV	1.8 TeV	2.0 TeV	2.5 TeV	3.0 TeV
Trigger and object definitions	24.1	33.4	40.4	50.0	55.7	59.1	60.9	59.8	53.4
Di-τ pre-selections: $p_T > 300$ GeV, $\|\eta\| < 2.0$ (exclude 1.37-1.52)	19.5	28.6	36.1	47.0	53.7	58.0	60.3	59.5	51.9
Requirements on the number, p_T, ΔR and charges of sub-jets in the di-τ object	8.75	13.1	16.9	22.2	25.6	27.5	28.3	25.7	18.3
Di-τ BDT-based identification	6.04	9.20	11.9	15.9	18.5	20.0	20.4	17.5	11.5
Requirements on number of tracks of two leading sub-jets of the di-τ object	6.01	9.14	11.9	15.8	18.5	19.9	20.3	17.4	11.5
Di-τ tagger efficiency correction	5.04	7.67	9.94	13.3	15.5	16.7	17.0	14.6	9.63
Trigger-dependent p_T requirements of the large-R jet	1.65	4.34	7.28	11.7	14.4	16.0	16.5	14.4	9.47
Large-R jet pre-selections: $\Delta R > 1.0$ w.r.t the di-τ object, $p_T > 300$ GeV, $\|\eta\| < 2.0$ and $m_J < 50$ GeV	1.36	3.67	6.24	10.2	12.6	14.1	14.6	13.0	8.59
Two b-tagged track-jets, including b-tagging efficiency correction	0.43	1.21	2.13	3.28	3.86	4.09	4.05	3.20	1.91
Opposite charge of two leading sub-jets of di-τ, $\Delta\varphi$(di-τ, MET) < 1, large-R jet mass window and visible HH invariant mass selection	0.28	0.87	1.60	2.49	2.91	3.11	3.08	2.45	1.46