Search for Beyond Standard Model Higgs boson decays

Including low mass resonances

Sijing Zhang

On behalf of the ATLAS collaboration

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Overview

- **Motivations**

- **Latest results**
  - **gg → A, tta/tWa**
  - **H → Za, H → aa**

- **Conclusions**

References

Direct & associate production

gg → A → ττ	JHEP 12 (2024) 126
tta, a → bb	Eur. Phys. J. C 85 (2025) 886

Higgs production

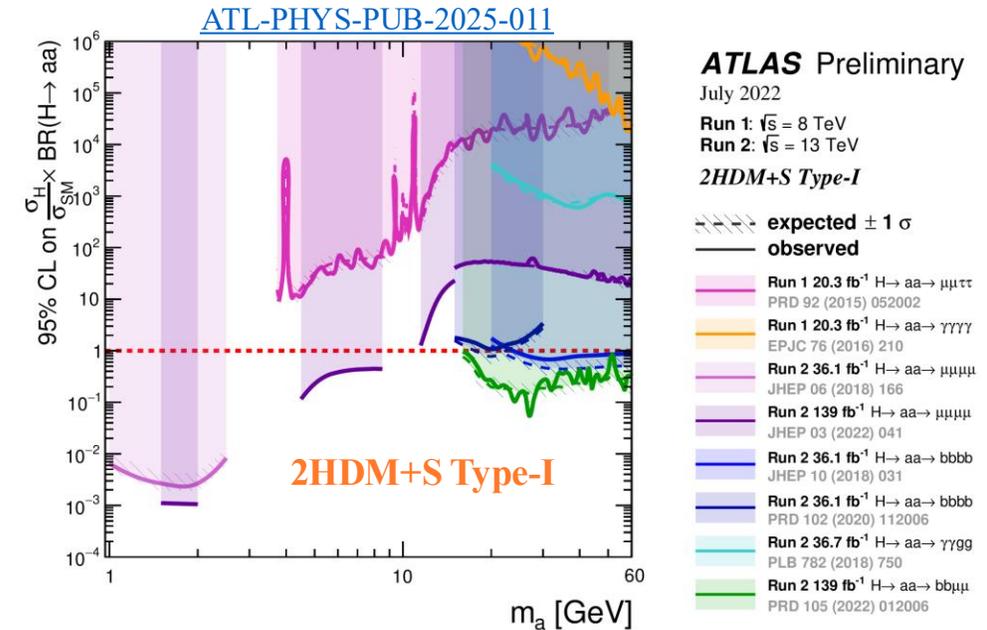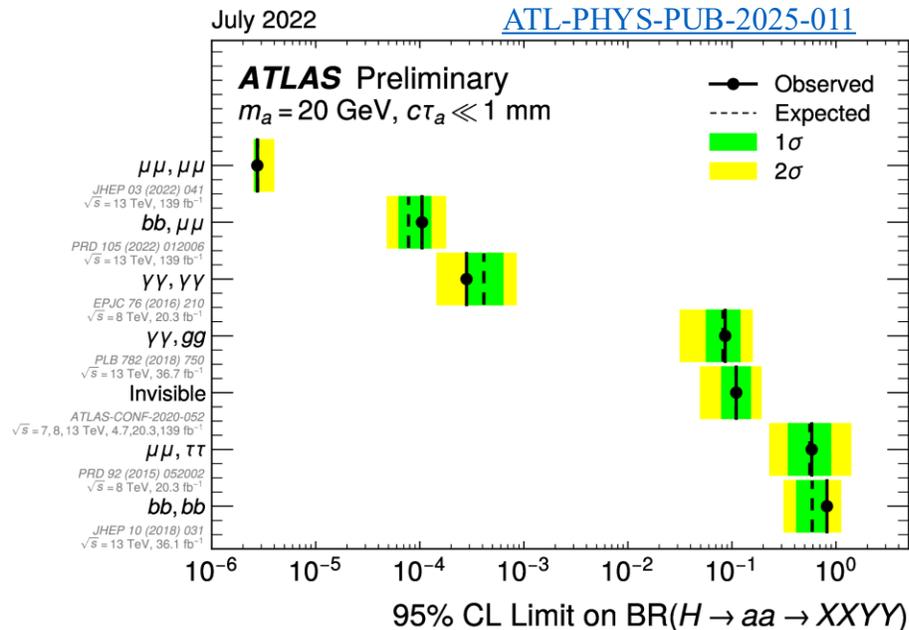|	
H → Za → ll+jets	Phys. Lett. B 868 (2025) 139671
H → aa → 4τ (merged).	arXiv:2503.05463
H → aa → 2γ2τ	JHEP 03 (2025) 190
H → aa → 4b, 6b	arXiv:2507.01165

a/A is the new light (pseudo-)scalar

Motivations: Light Scalar Searches

Models

- Many BSM models addressing the shortcomings of the SM have extended Higgs sectors and can predict light (pseudo-)scalars "a"
  - ✓ e.g. 2HDM, 2HDM+a, TRSM, portals to hidden sectors

- In many models, light scalars have Yukawa-like couplings inherited from mixing with the SM Higgs boson

- Extensive search program at the LHC for different production mechanisms and in different final states
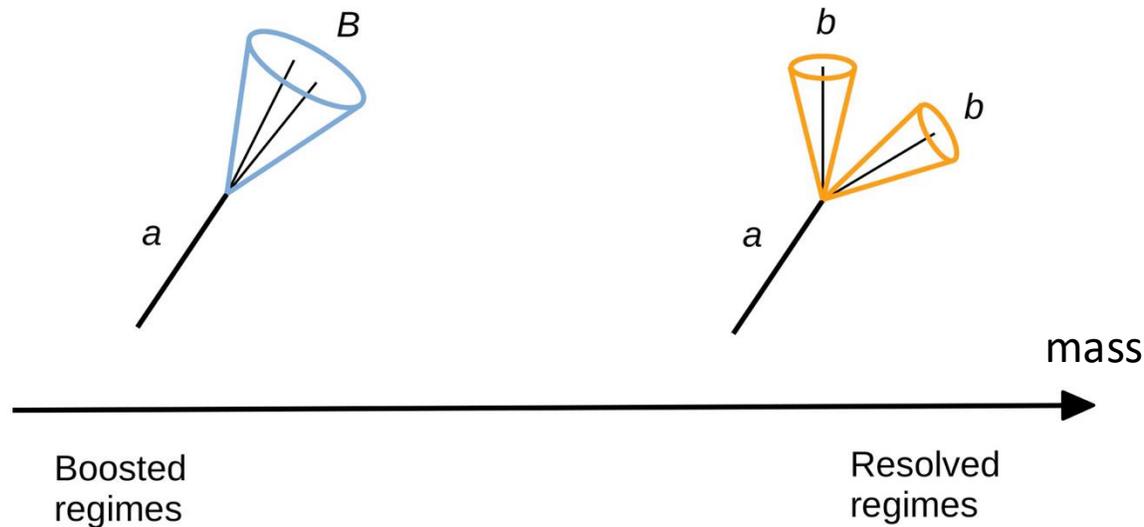 - ✓ E.g. ATLAS searches for H → **aa**
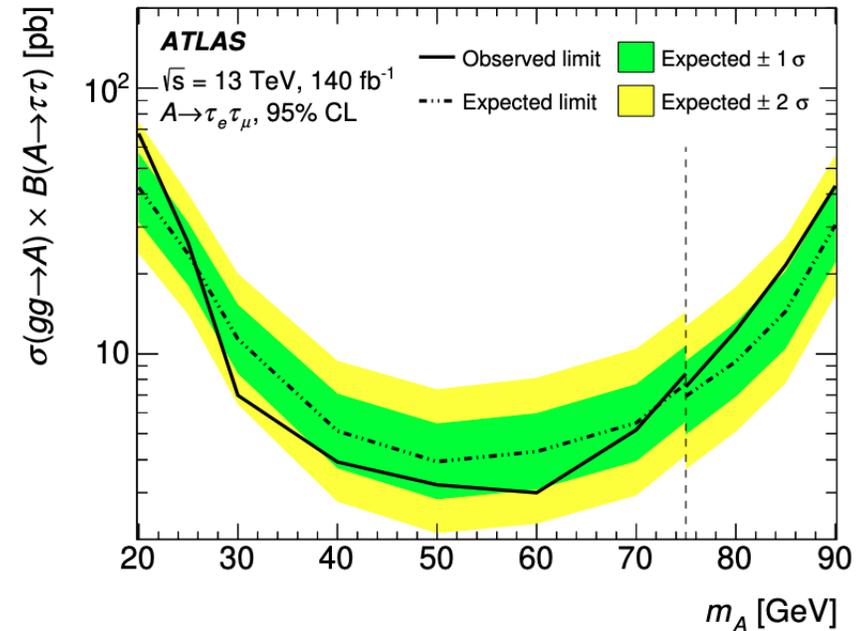
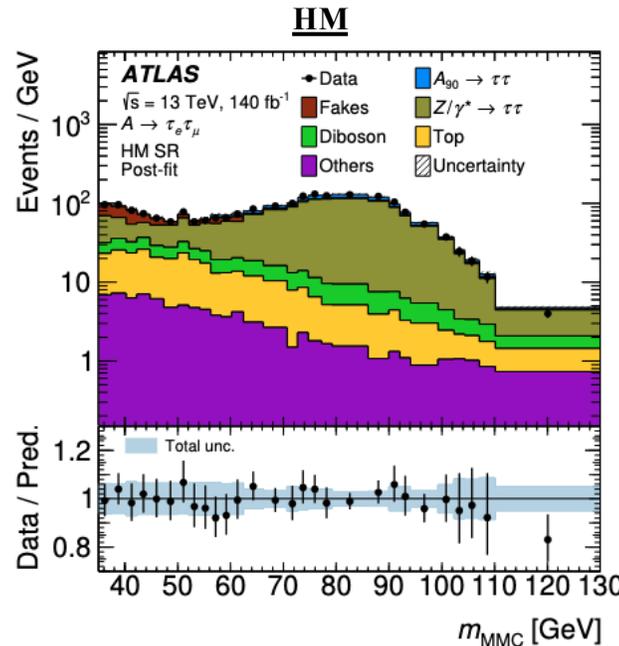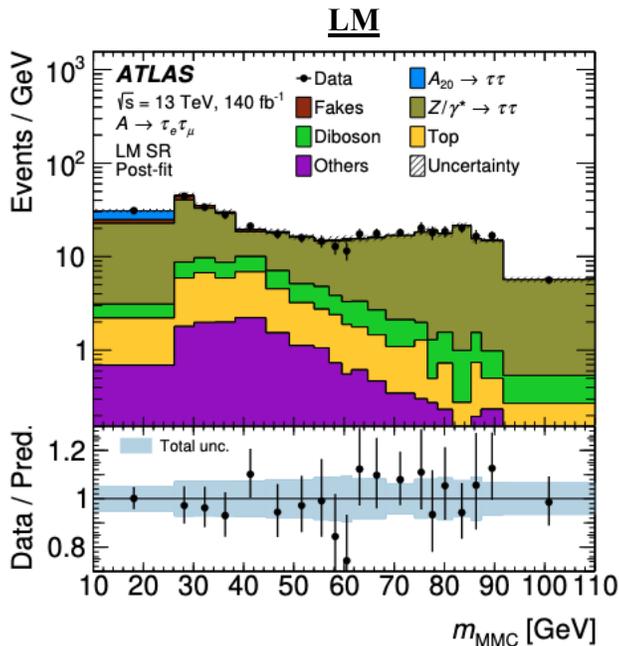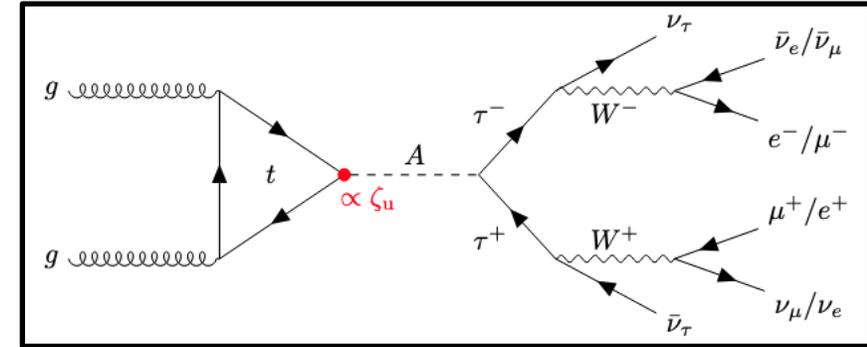# Motivations: Light Scalar Searches

Merged vs. resolved

- At lower mass of the light scalar, it will be produced with a significant Lorentz boost

  ❑ The decay products are collimated and merged

  ❑ Motivates dedicated experimental techniques like Xbb tagger, merged $\mu\tau_{had}$ objects or boosted di-τ objects
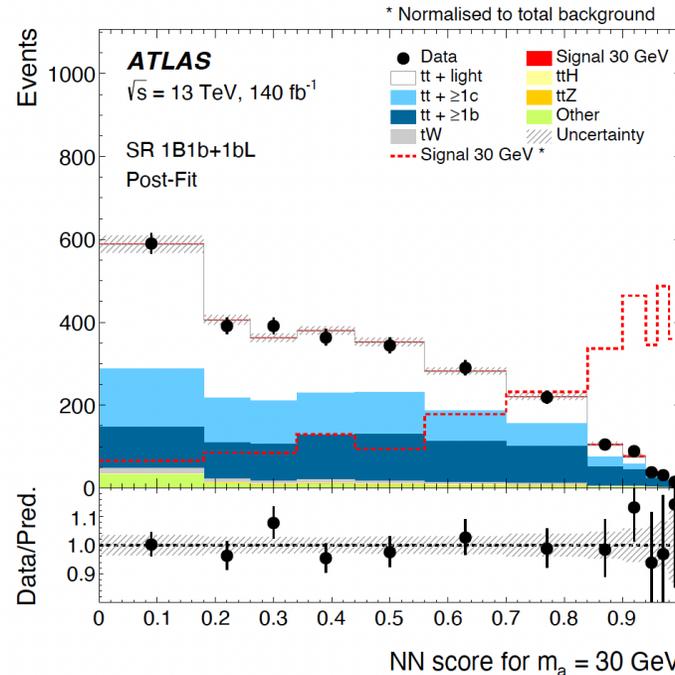

Boosted regimes | Resolved regimes | mass

Direct & associate production

gg → A → ττ

- Search for **CP-odd scalar A**, m ∈ [20, 90] GeV

- gg → A → ττ: eμ4ν final state (**τ decay leptonically**)

- **Signal selection**: exactly 1 electron and 1 muon with opposite charge (p_T >10 GeV)

- **Main background**
  - eμ produced in W, Z/γ*, SM Higgs or ττ decays; at least one lepton arising from another source

- **Main observable**: m_{MMC}, a likelihood-based estimator of di-τ invariant mass

- Two signal regions: low mass (LM) and high mass (HM) regions
  - **LM**: m_A ∈ [20, 75] GeV, m_{MMC} > 0 GeV
  - **HM**: m_A ∈ [75, 90] GeV, 35 GeV < m_{MMC} < 130 GeV

LM

HM

Largest local excess: 1.8 σ (m_A = 20 GeV)

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tta/tWa, a → bb

- Search for **light pseudoscalar a**, m ∈ [12, 100] GeV

- **tta/tWa production, a → bb decay (merged & resolved)**

- **Signal selection**: two leptons (opposite charge) and ≥ 3 jets (b-jet or B-jet; ≥ 1 b-jet)

- **Main background**: tt + jets, especially tt+bb
  - Derive re-weighting to improve modelling

- **Main observables**: number of b-tagged and Xbb tagged jets, lepton-jet and jet-jet pairing BDT scores, discrimination NN score
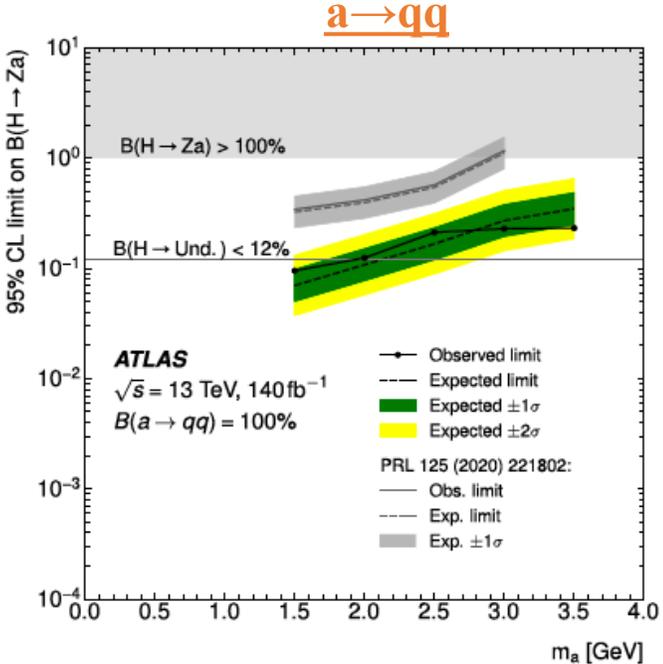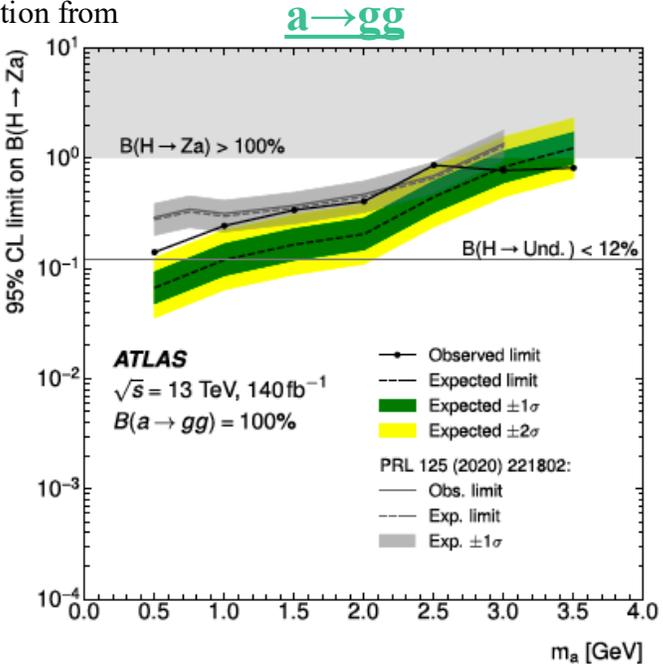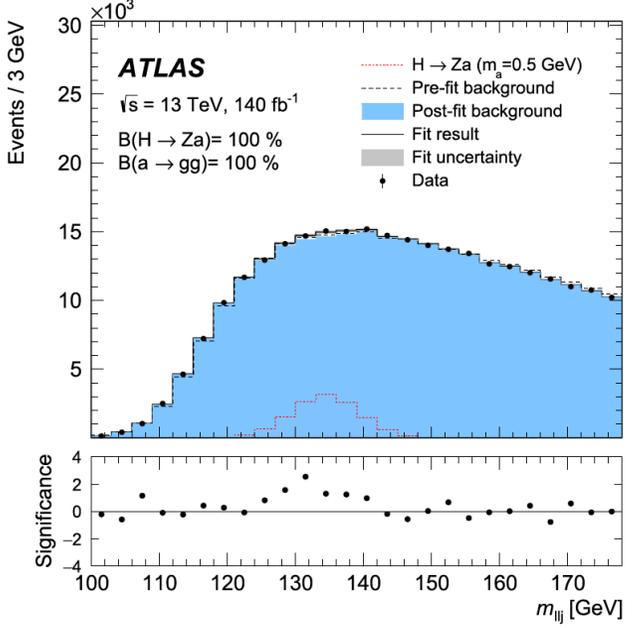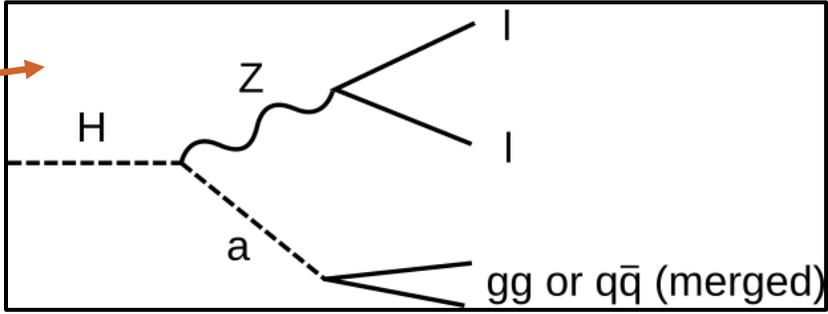

Largest local excess: 2.0 σ (m$_a$ = 30 GeV)
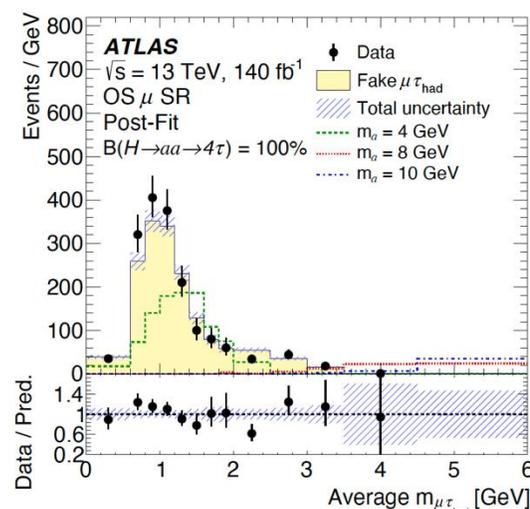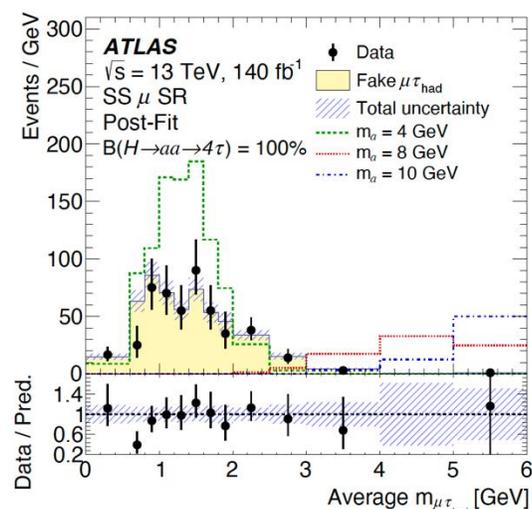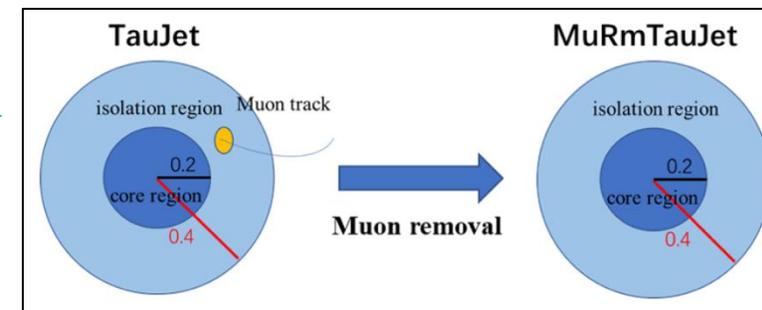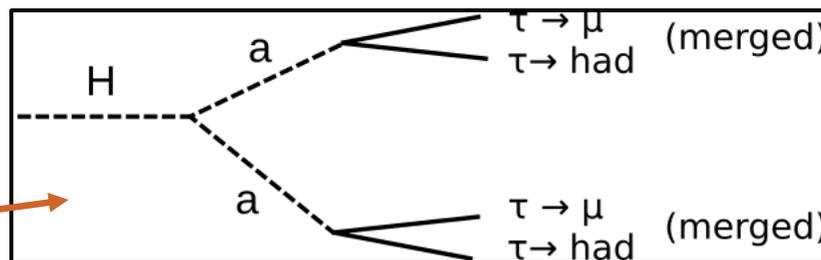
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Higgs production

H→Za→ll+jets

- Search for **light scalar a**, m ∈ [0.5, 3.5] GeV

- **H → Za production**

  - **Z→ll, a → gg/qq decay (merged)**

- **Signal selection**: two leptons from Z boson and ≥ 1 jet

- **Main background**: Z+jets, especially tt+bb

  - Derive NN-based re-weighting to improve modelling

- **Main observables**: dilepton-jet invariant mass m_{llj}, NN-based mass estimation from jet observables, classification NN score
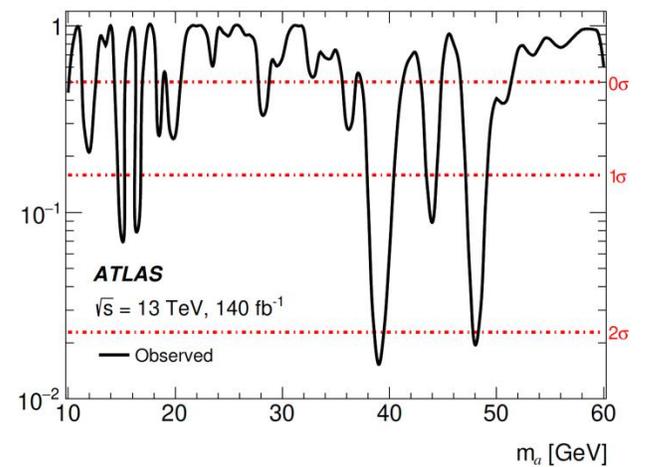

Largest local excess: 1.5 σ (m_a = 0.5 GeV) [a →gg]

H→aa→ττττ

- Search for **light scalar a**, m ∈ [4, 15] GeV

- **H→aa production, a→ττ→μμτ_{had} τ_{had} (merged)**

  - Decay products of τ_l τ_{had} are mixed in the detector

- **Object identification:**

  - **a muon-removal technique** is used to reconstruct **merged di-τ decays**

- **Signal selection:** exactly two μτ_{had} objects (hadronic τ with opposite-charge μ inside**)** with mass < 15 GeV, and combined invariant mass slightly below Higgs mass (missing neutrinos)

- **Main background**: events with fake τ_{had} with non-prompt μ from hadron decays

  - Estimate with tight-to-loose data-driven method

- **Main observable**: (corrected) **average mass** of μτ_{had} objects

No excess observed

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H →aa → ɣɣτ_had τ_had

- Search for **light scalar a**, m ∈ [10, 60] GeV

- **H→aa production, a→ɣɣ, a→τ_had τ_had (merged & resolved)**

- **Signal selection**: two photons with either one boosted di-τ candidate or two resolved τ leptons

- **Main background**: continuum ɣɣ, ɣ+jet, and jet-jet events (jets misidentified as photons or τ_had

  - Data-driven method is used to estimate the background

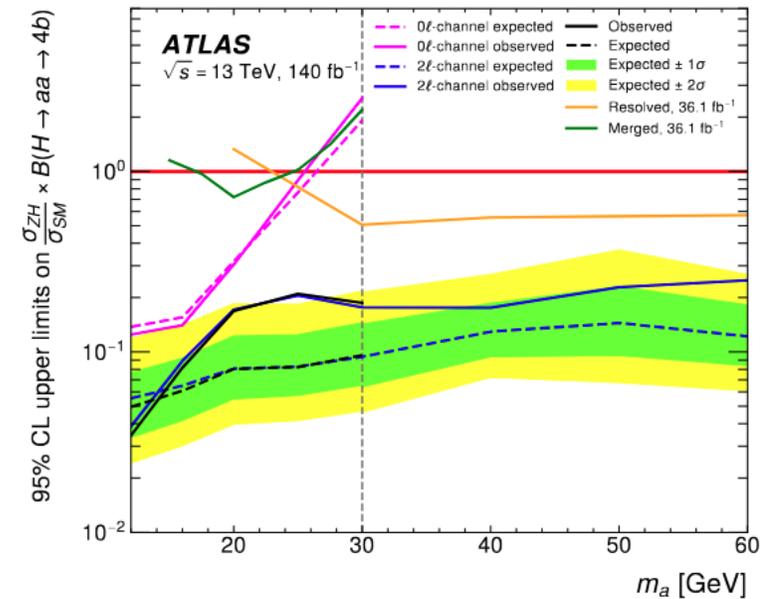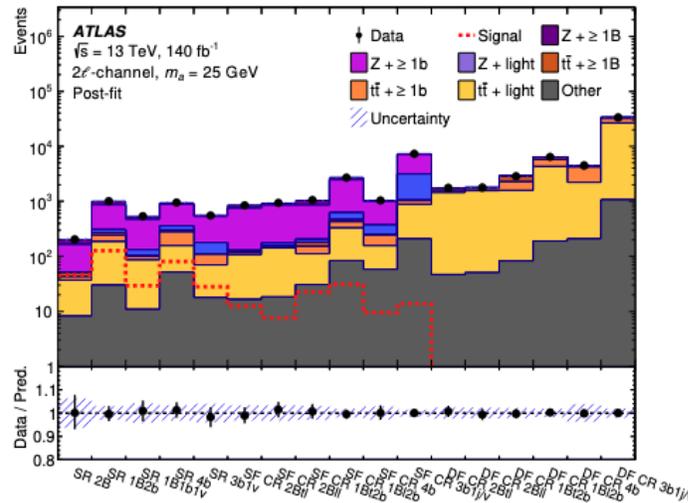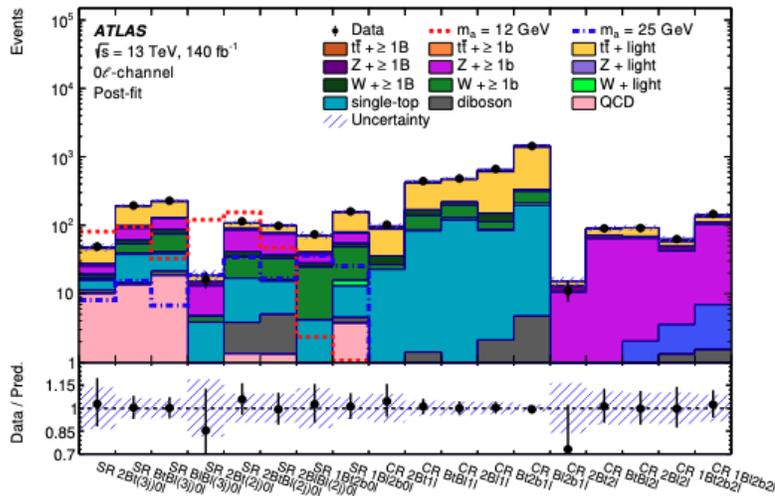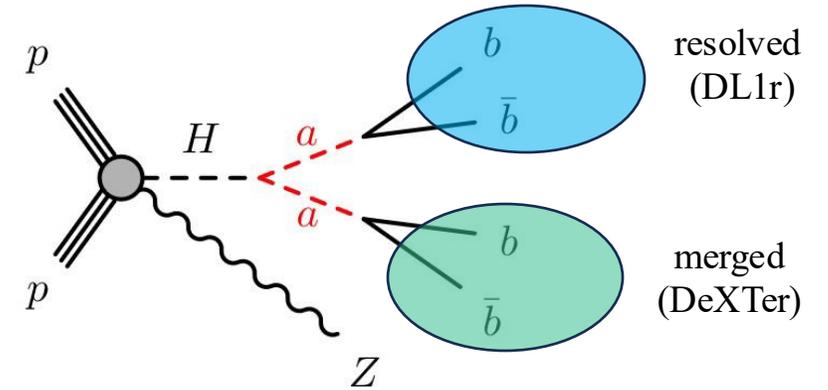- **Main observable**: invariant diphoton mass $m_{\gamma\gamma}$

resolved or merged

Largest local excess: 2.2 σ (m_a = 39 GeV)
2.1 σ (m_a = 48 GeV)

ZH, H→aa→4b

- Search for **light scalar a**, m ∈ [12, 60] GeV

- **ZH, H→aa production, a → bb decay (merged & resolved)**

- **Signal selection**: two leptons or E_T^{miss} (2 𝜈) from the Z decay, and ≥ 3 b-objects: b-tagged jets, double b-tagged jets or displaced vertices outside of jets

- **Main background**: Z+jets, tt
  - Derive re-weighting to improve modelling

- **Main observables**: number of b-objets, NN-based quadruplet selection (object pairing), discrimination BDT score

Largest local excess: 2.83 σ (m_a = 25 GeV)

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ZH, H →a₁a₂ → 4b/6b

New! *first ever search for H → a₁a₂!*

- **Same analysis** did search for decays to two scalars of different mass H→a₁a₂→4b

  - **Same analysis strategy**

- **H cascade** decay: H→a₁a₂→3a₁→6b

  - **Slightly different strategy: no explicit pairing of b-objects, just discrimination BDT score**

    All a₁→bb resolved or merged!

Largest local excess: 3.28 σ (m_{a1, a2} = 50, 70 GeV)
[2.57 σ global]

Largest local excess: ~1 σ (m_{a1, a2} = 30, 80 GeV)
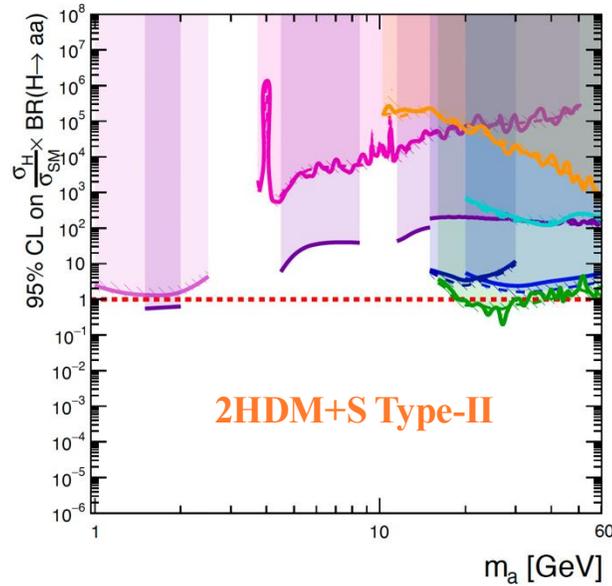
Conclusions

- Many new exciting results for light scalar searches with ATLAS run 2 datasets

  - Both direct & associate production, and Higgs portal

  - Improved techniques (particularly on merged topologies) helped enlarge the searching range towards low masses

    - Can be pushed further by exploring different *a* masses and signal configurations

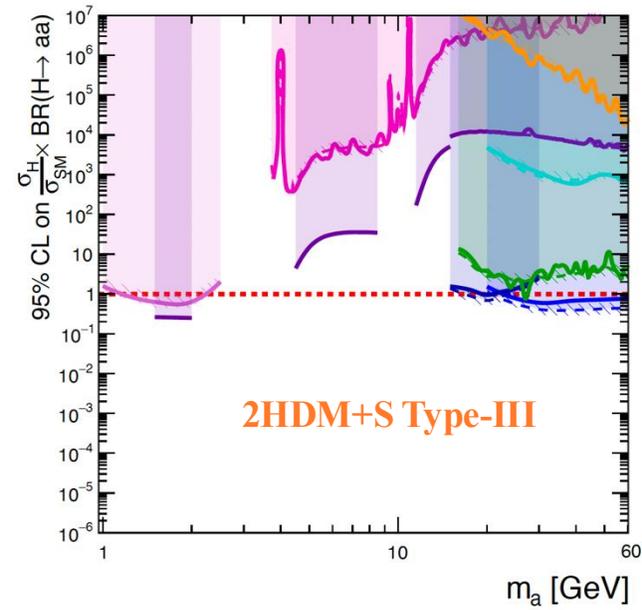- Looking forward for the new results with Run 3 datasets!

BackUp

Models

- **2HDM**
  - **5 particles**: CP even h and H, CP odd A, and 2 charged H± bosons
- **2HDM+a**
  - **6 particles**: CP even h and H, CP odd A_1 and A_2 (new pseudoscalar a mixes with CP odd A), and 2 charged H± bosons
  - type-II Yukawa sector: Higgs bosons *A*, *H*, and *H*± are all constrained to be mass-degenerate and heavier than around 600GeV
  - type-I Yukawa sector: allow the extra Higgs bosons to be even lighter than the 125GeV Higgs boson
- **Two-Real-Singlet Model (TRSM)**
  - a model that enhances the Standard Model (SM) scalar sector by two real singlets that obey a Z2 x Z2' symmetry.
  - **3 particles:** h1 (125 GeV), h2, h3

2HDM+S plots

tta/tWa, a→bb: Objects

b-jets and B-jets

- **b-jets** refer to AK4 jets originating from a single b-hadron.

  – They are identified using the `DL1r tagger`.

- **B-jets** are a boosted bb pair identified as one single object.

  – They include track information up to $R = 0.8$.
  – They are identified using the `DeXTer tagger`.

- Additionally, a **μ-in-jet p_T correction** is performed, where the soft muons that are lost during the overlap removal are added back to the 4-momentum.

- The **invariant mass of the B-jets** is corrected using a DNN regression method.

H →aa → bbττ

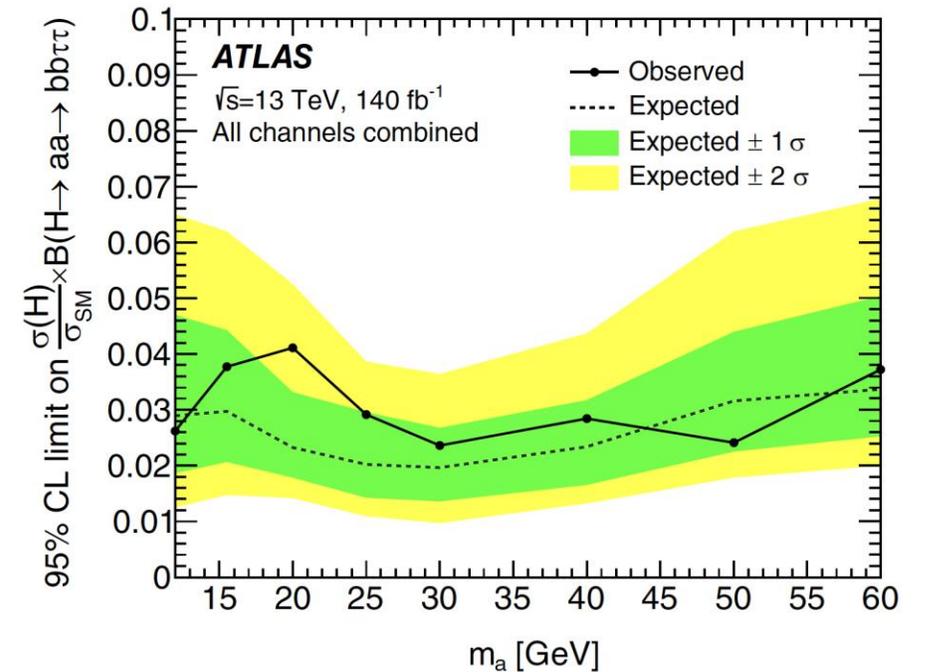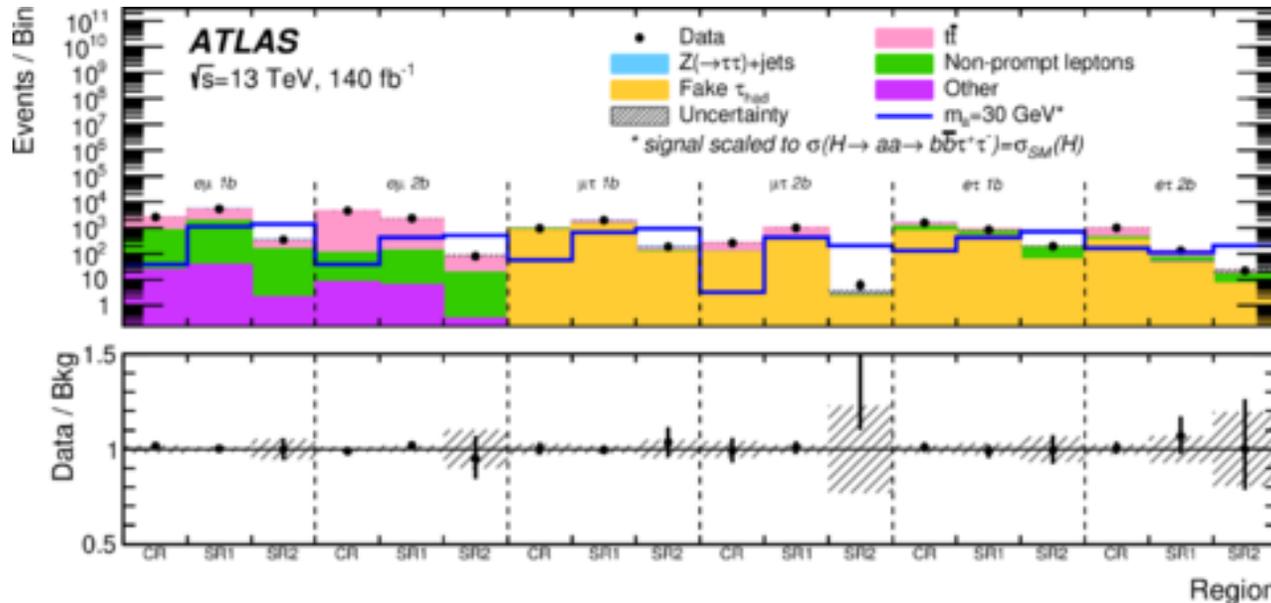- Search for **light scalar a**, m ∈ [12, 60] GeV

- **H→aa production, a→bb, a→ττ**

- **Signal selection:**

  - 3 channels (τ decay)**: e**μ, eτ$_{had}$, μτ$_{had}$

  - 3 categories per channel (b jets): =1 bjet, >1 bjet, 1 DeXTer double b-jet

- **Main background**: tops, Z+jets, fake leptons, fake taus

  - Data-driven method is used to estimate the background

- **Main observable:** Parameterized NN score

Largest derivation: 0.055 (m$_a$ = 20 GeV)

H→aa→ττττ: Muon removal technique
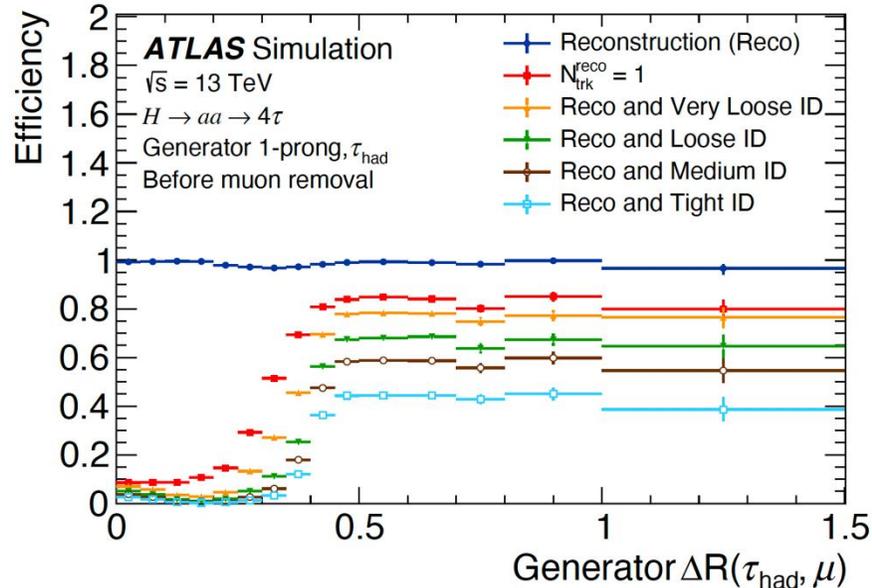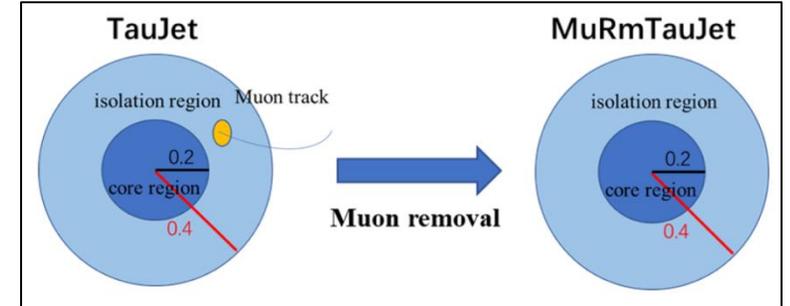
- **Motivation**

  - **In** $\mu\tau_{had}$ objects, the presence of the **muon inside the** τ_{seed} **jet** reduces the τ_{had} reconstruction and RNN identification efficiency

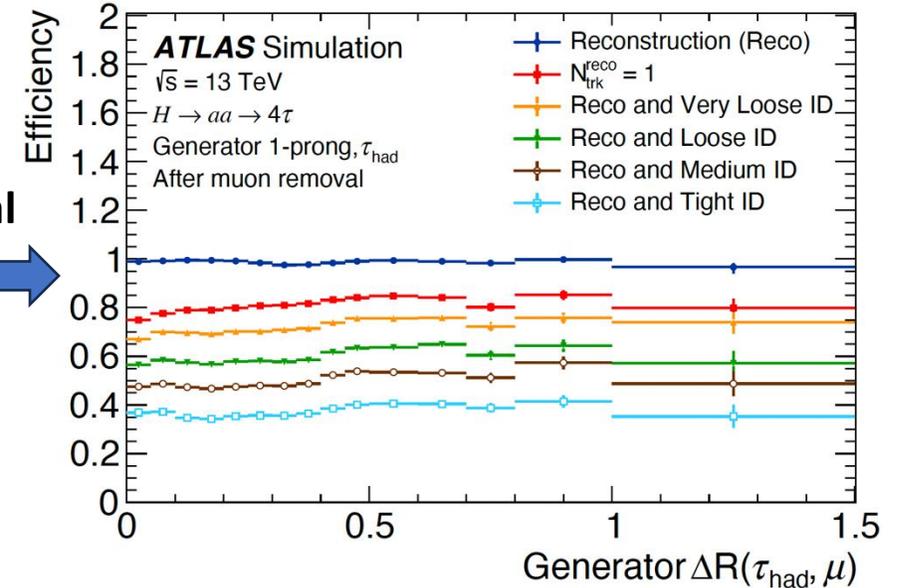- **Merged** $\tau_\mu\tau_{had}$ **correction algorithm**:

  - **Overlapped muons** are removed from **tau seed jet**.

    - Both the Muon tracks and associated energy will be removed
    - The tracks and calorimeter energy clusters associated with the reconstructed muon within $\Delta R(\mu, \tau_{had}) < 0.4$ are removed from the inputs used for τ_{had} reconstruction and from the inputs to the RNN and BDT identification algorithm
  - Re-calculate the relevant tau identification variables after muon removal.
  - Use the official tau performance results for the analysis
  - An extra efficiency uncertainty was extracted for the muon removal method
  - The τ_{had} four-momentum is corrected to the same energy scale as for the isolated τ_{had} using a MC-based correction method.
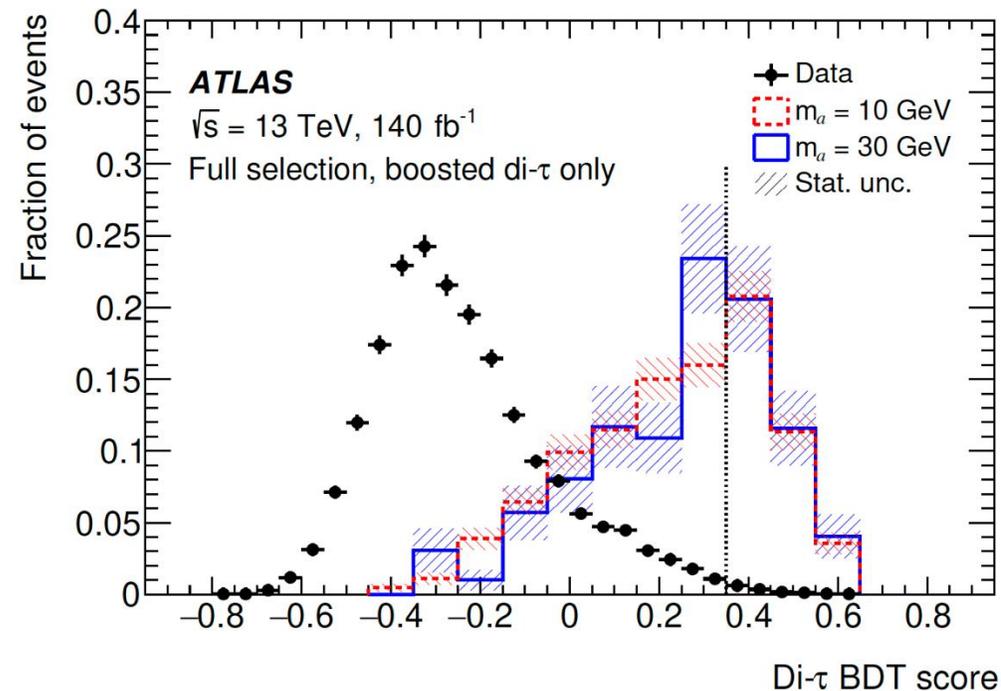 - Similar algorithm was developed in high pT regime focusing on $G \to HH \to 4\tau$ (TAUP-2023-02)

H →aa → ɣɣτ$_{had}$τ$_{had}$: boosted di-τ object

- boosted di-τ object

  - two τ$_{had-vis}$ that are within $\Delta R < 0.4$

  - Reconstruct: via a custom algorithm with the substructure of large-radius jet

  - R=1.0, $p_T > 50$ GeV

  - Subjets (≥2, each jet contain 1 or 3 associated tracks): $p_T > 10$ GeV (anti-kt algorithm R=0.2)

  - BDT score > 0.35 (medium ID)

Largest local excess: 2.2 σ ($m_a = 39$ GeV)
2.1 σ ($m_a = 48$ GeV)