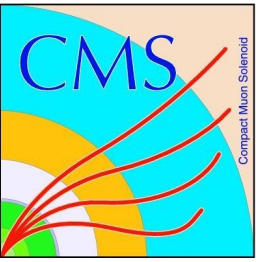
New physics with Higgs boson in boosted topologies



Francesco Carnevali
Hanyang University

On behalf of the ATLAS & CMS Collaborations

Higgs@Capri2025

6th - 10th Oct 2025

Outline

- Motivation: why boosted Higgs topologies matter
- Experimental challenges in the boosted regime
- Tagging and reconstruction techniques
- Searches and results from ATLAS and CMS collaborations
- Summary and outlook

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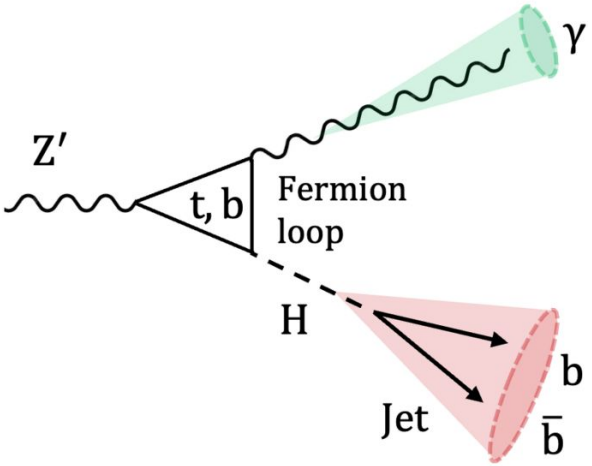
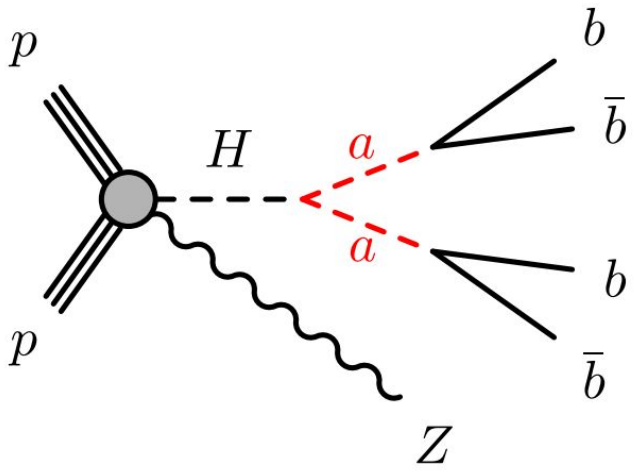
Motivation

- Many BSM models predict extended Higgs sectors or new resonances
- Multi-TeV masses accessible at the LHC
- Higgs boson (and heavy SM daughters) produced with high $p_T \rightarrow$ boosted regime
- Collimated decay products: jets, leptons, photons no longer well resolved
- Dedicated reconstruction & tagging required to preserve sensitivity
- Higgs may decay into new scalars or pseudoscalars $\rightarrow$ often light, boosted, and with overlapping final states





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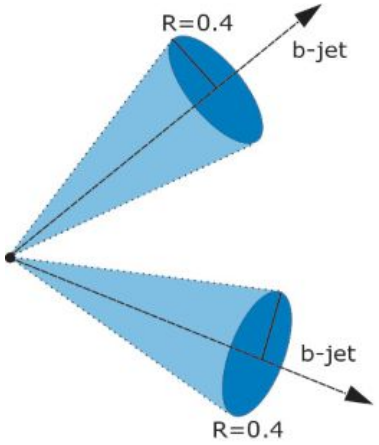
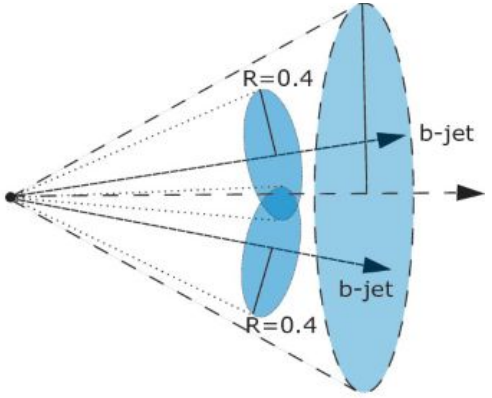
Why boosted Higgs topologies

- Key for both SM boosted Higgs and non-SM exotic decays
- Backgrounds become more challenging (e.g., QCD jets faking boosted H → bb or ττ)
- Standard reconstruction fails: overlapping decay products reconstructed as a single object
- Direct impact on exclusion limits: advanced techniques → stronger constraints in the multi-TeV regime
- How to restore the sensitivity?





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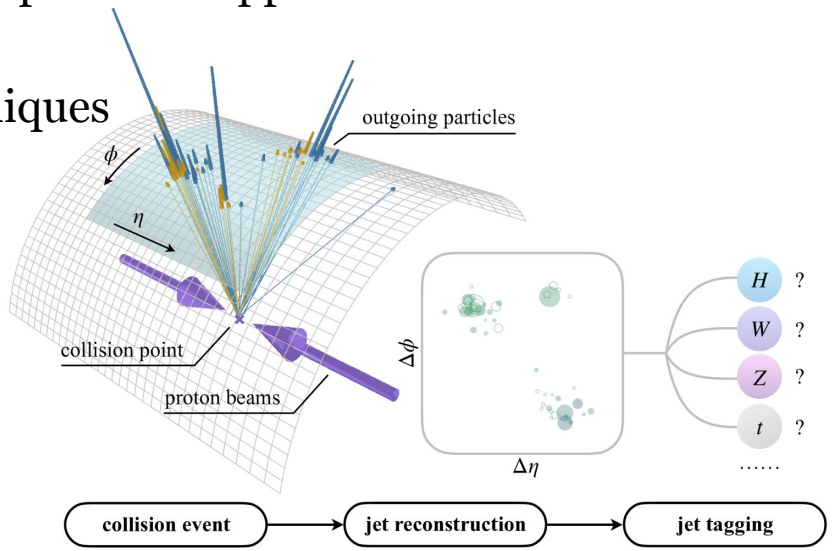
Experimental implication of boosted regime

- At high p_T, Higgs/BSM daughters become collimated ($\Delta R \lesssim 0.4$)
- Leads to new experimental challenges:
  - Jets: merged into a single "fat jet" with rich substructure
  - Leptons/photons: clusters overlap, standard isolation not valid
- Instead of a limitation → opportunity to exploit new approaches
- Motivates development of advanced techniques



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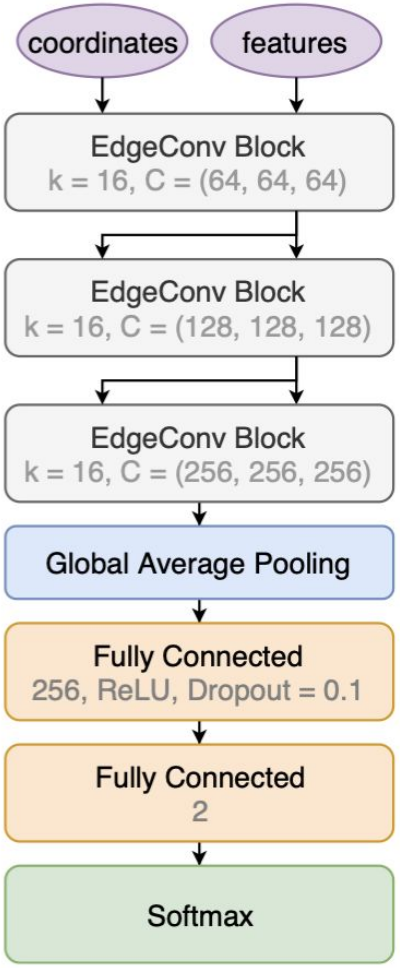
Techniques for boosted topologies

- **Jets:**
  - Substructure variables (τ_N, ECFs) capture multi-prong patterns
  - ML taggers exploit per-particle information or event topology
  - Mass regression or subject tagging
- **Merged leptons/photons:**
  - **Photons:** deconvolution of overlapping EM showers
  - **Electrons:** cluster splitting, improved track–cluster matching
  - **Taus:** boosted ditau taggers and muon-removal for overlapping muons



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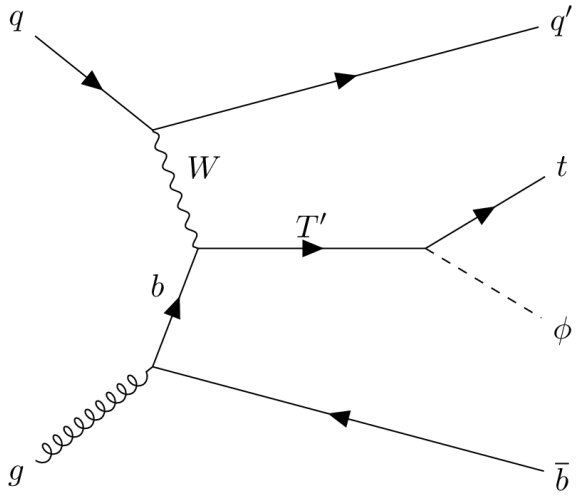
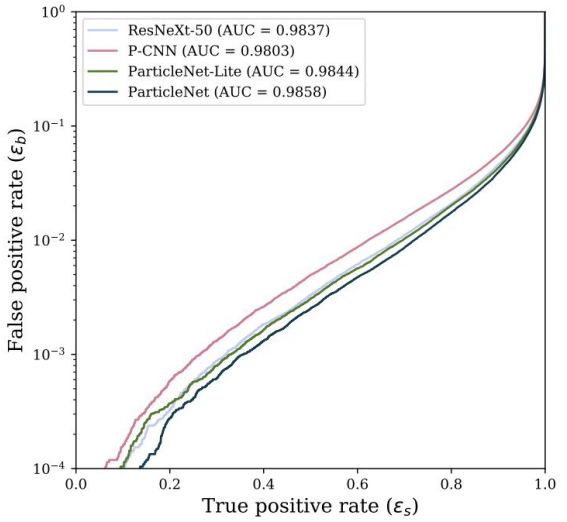
B2G-23-009, B2G-22-001

Boosted H->bb in heavy VLQ searches

- Signal process: Vector-like quarks (VLQs) decaying to t + H, with H → bb
- Mass scale: searches probe VLQ masses in the 1–2 TeV range
- Higgs bosons produced at high p_T, reconstructed as boosted fat jets
- Tagging innovation:
  - ParticleNet, a graph neural network operating on individual jet constituents
  - Learns jet substructure directly from low-level inputs
  - Provides superior discrimination of H → bb against QCD jets





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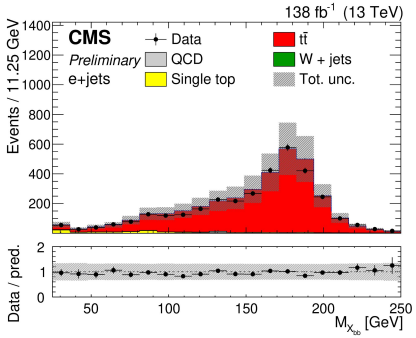
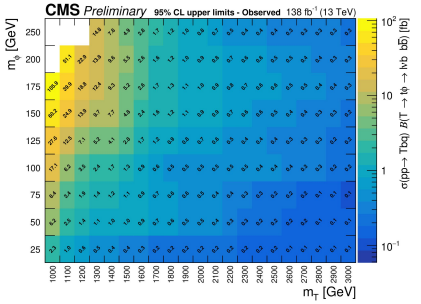
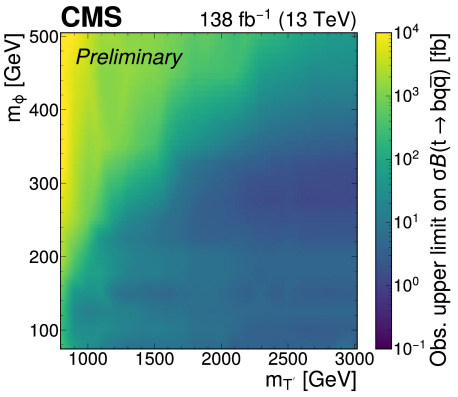
Extending searches with variable Higgs masses

- BSM models often predict additional Higgs-like states (φ) beyond the 125 GeV SM Higgs
- φ bosons can appear in vector-like quark decays, with masses typically in the 25–500 GeV range
- ParticleNetMass: regression network that improves the reconstructed jet mass resolution
- Sharper Higgs/φ mass peaks enhance signal-to-background discrimination
- Results set limits on VLQ production cross section × branching ratio as a function of VLQ and φ mass for the first time.







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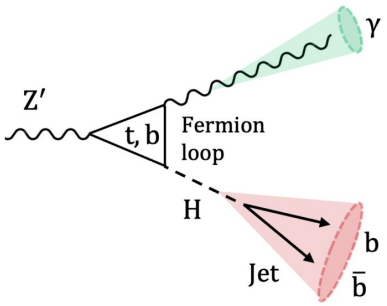
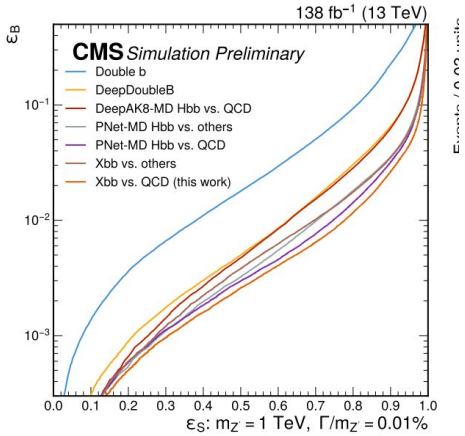
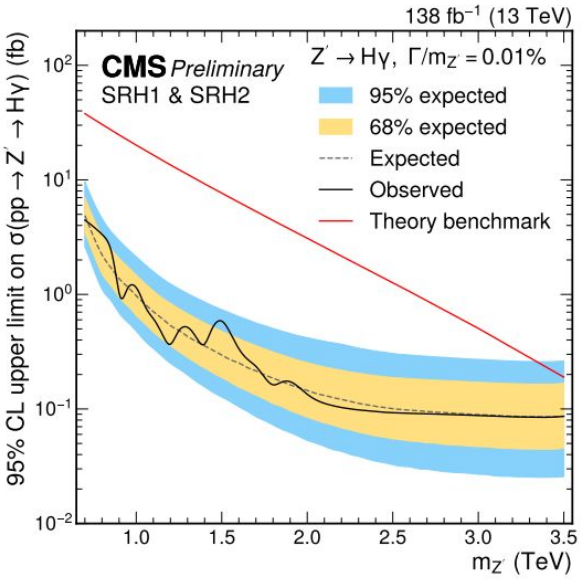
B2G-24-007

Search for Z'->Hγ, H->bb

- Hypothetical heavy neutral vector boson (Z′) predicted in several BSM models
- Searches target Z′ masses in the 1–4 TeV range
- Higgs bosons reconstructed in the boosted regime, decaying to bb inside a fat jet
- ParticleTransformer (ParT): transformer-based tagger operating on jet constituents, decorrelated from jet mass
- Combined with ParticleNetMass regression for sharper Higgs mass resolution
- Cross sections excluded for Z′ production in the 1–4 TeV mass range







HMBS-24-26

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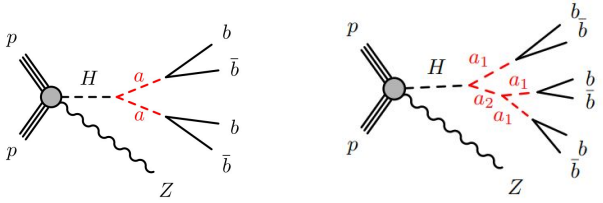
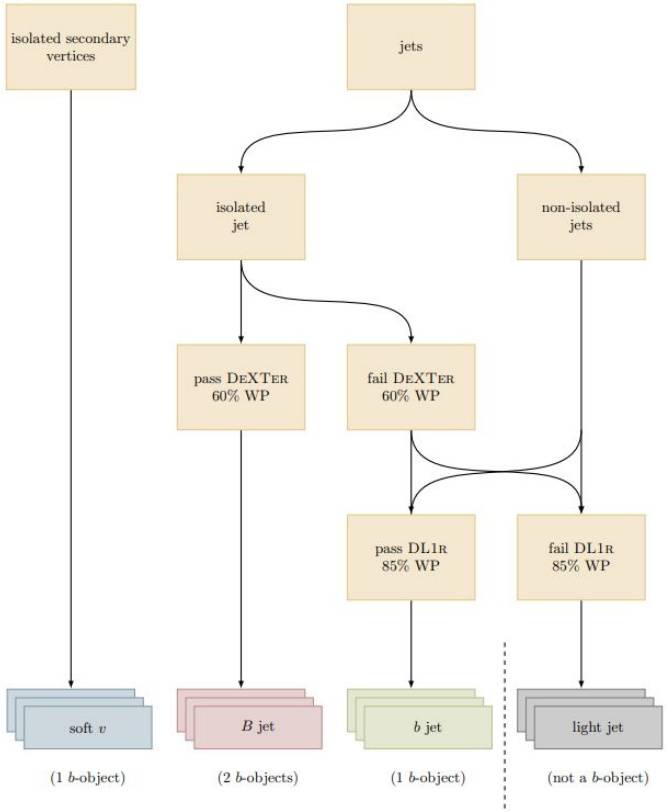
Search for $H \rightarrow a_1 a_2$ with multi-b final states

- Higgs boson decays to two new scalar particles (a_1 and a_2), leading to final states with 4 or 6 b-jets.



- Tagging strategy:
  - DexTer (Deep Extreme Tagger) neural network using track-based features to identify jets with two b-hadrons ("double-b" jets)
  - DL1R deep neural network for single b-hadron tagging
  - Soft-V algorithm enhances sensitivity to displaced vertices from b-hadron decays



- Additional neural network combines jet-level and event-level information to reconstruct the Higgs boson in different topologies

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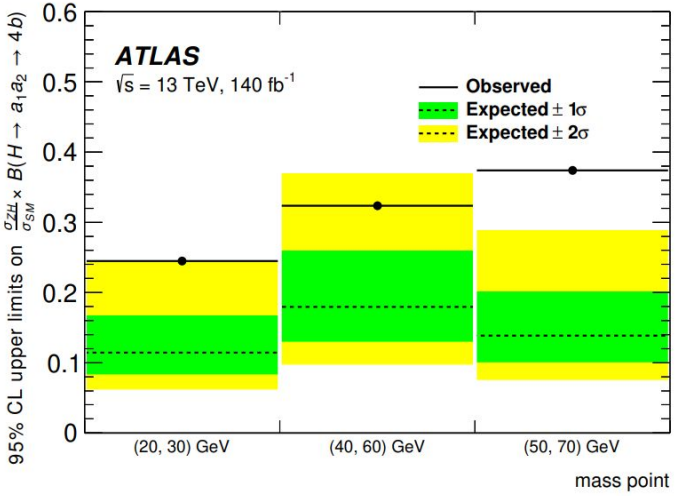

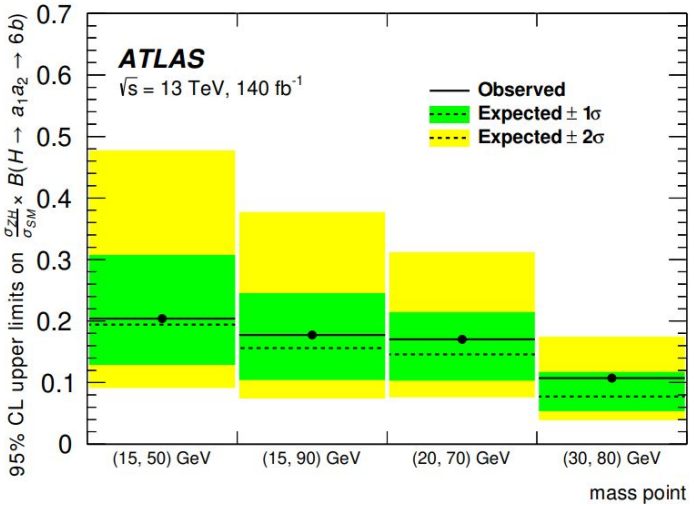

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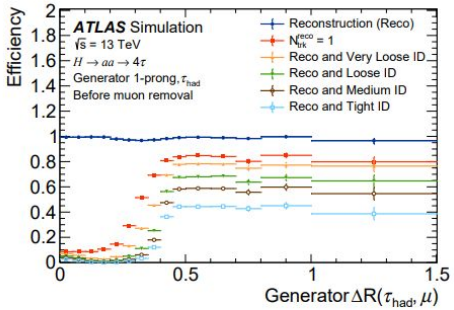
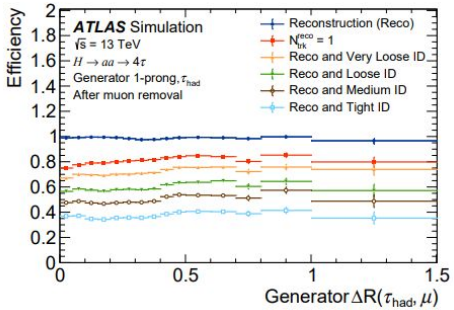
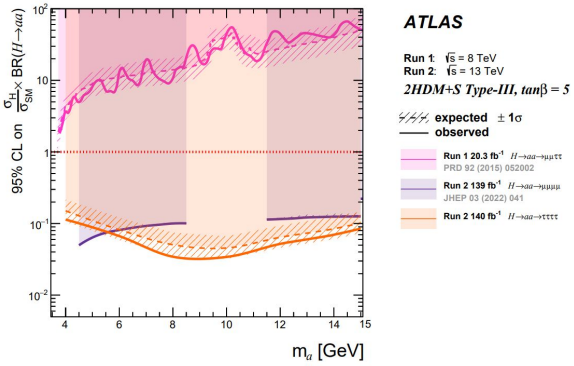
HMBS-24-25

H → aa → 4τ with boosted di-tau final state

- Higgs boson decays to a pair of new scalars (a, a), each decaying into a tau pair (ττ), leading to final states with 4 tau leptons.
- Focus on low-mass a → ττ decays, with a mass range between 4 and 15 GeV.
- Final state consists of a hadronic tau (τh) and a leptonic tau (τℓ), where τℓ decays into a muon and neutrinos.
- Hadronic tau reconstructed using AK4 jets, with muon removed from the other tau decay to avoid overlap:
  - RNN algorithm for tau identification in hadronic decays.
  - BDT algorithm for vetoing electron contamination.
- No significant excess observed; 95% CL upper limits on σ (ZH)/σSM × BR(H → aa → 4τ) set in the range of 10–30%, depending on scalar mass.







SUS-24-002

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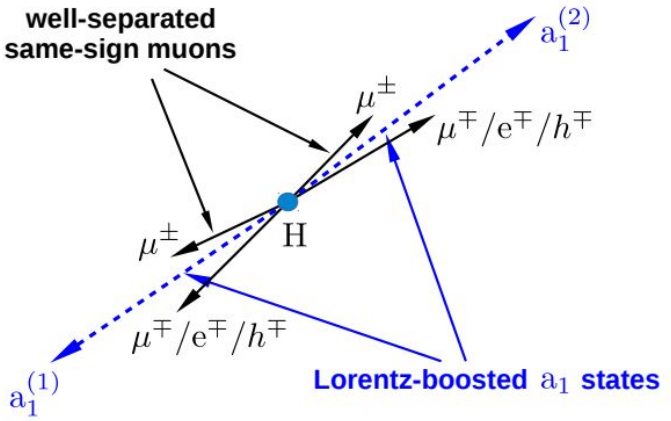
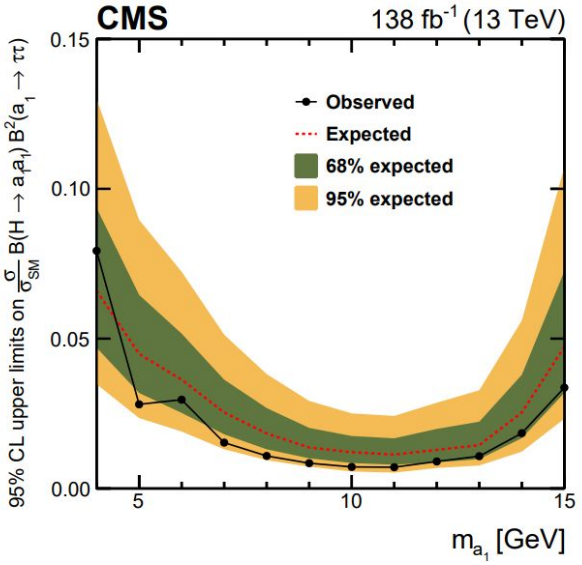
Search H → aa → 4τ or 2μ2τ

- Higgs boson decay H → aa → 4τ or 2μ2τ
- Particle (a) mass range: 4–15 GeV
- Final states: two τ leptons (τ_{mu}, τ_1-prong) and either two τ leptons or two muons
- Optimized track selection for signal enhancement
- Two same-flavor muons spatially separated
- The observed (expected) upper limits range between 0.007 (0.011) and 0.079 (0.066) across the mass range considered





CDS-REF

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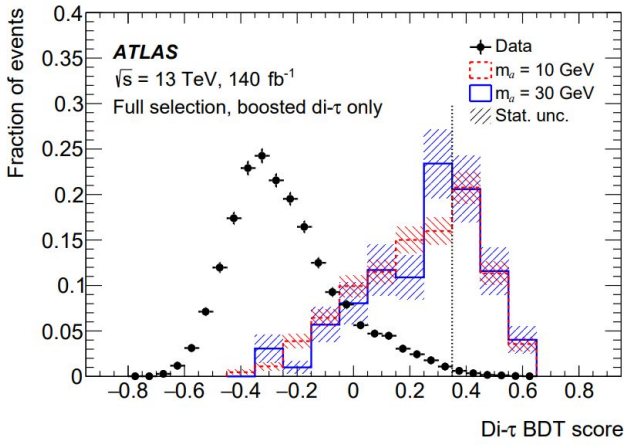
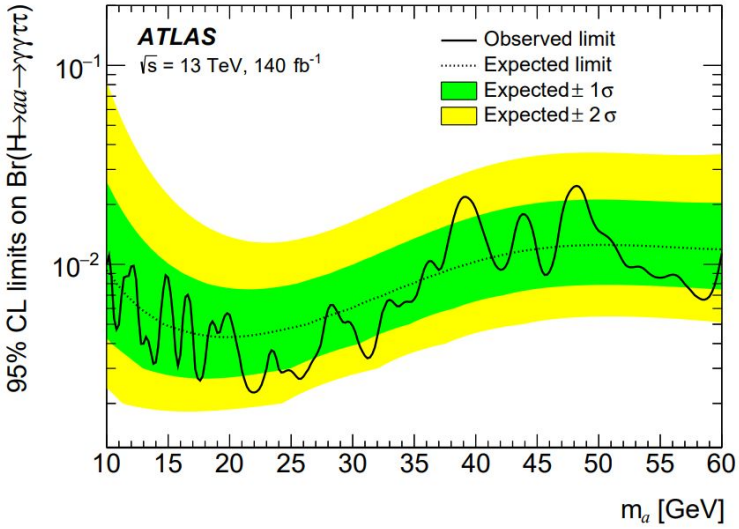
Search for H→aa→γγτ$_{had}$ τ$_{had}$

- Higgs decays to two light scalars (a, a), one decaying to γγ, the other to ττ (hadronic tau).
- Scalar mass range: 10–60 GeV for a → ττ.
- Jet reconstruction: AK10 jets capture the boosted ττ system; reclustered into two AK2 subjets depending on substructure.
- Tau tagging: BDT algorithm using track information, kinematics, and calorimeter deposits for hadronic tau identification.
- No significant excess observed; 95% CL upper limits on σ(ZH)/σSM × BR(H → aa → γγττ) in the 0.5–2% range depending on scalar mass.





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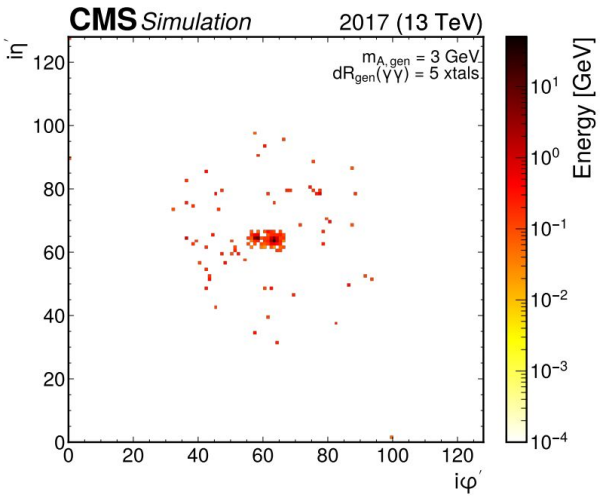
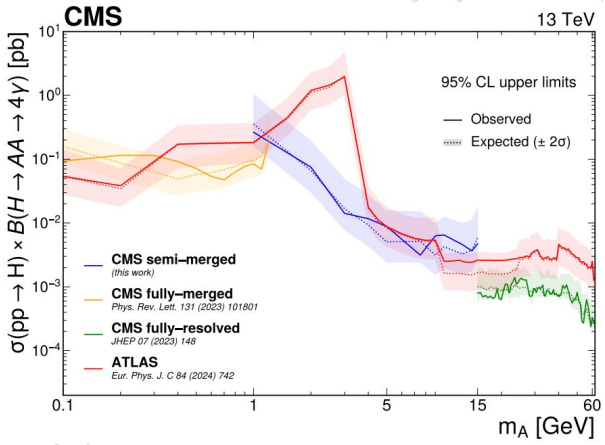
EXO24-025

Search H→AA→4γ in Partially Merged Topologies

- Higgs boson decaying via H → AA → 4γ
- Light pseudoscalar A mass range: 1–15 GeV
- At low masses, the angular separation ΔR between photons is comparable to ECAL crystal size
- Challenging to reconstruct all 4 photons; analysis requires 3 reconstructed photons
- Graph Neural Network (GNN) applied directly on ECAL crystal energy deposits, bypassing particle flow reconstruction
- Upper limits are set on the product of the Higgs boson production cross section and the branching fraction B(H→AA→γγγγ), which range from 0.264 to 0.008 pb





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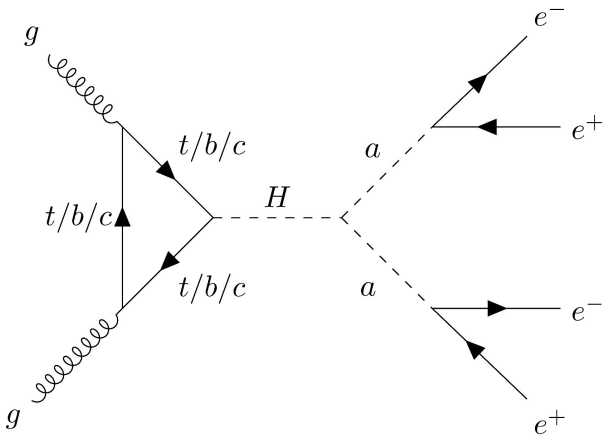
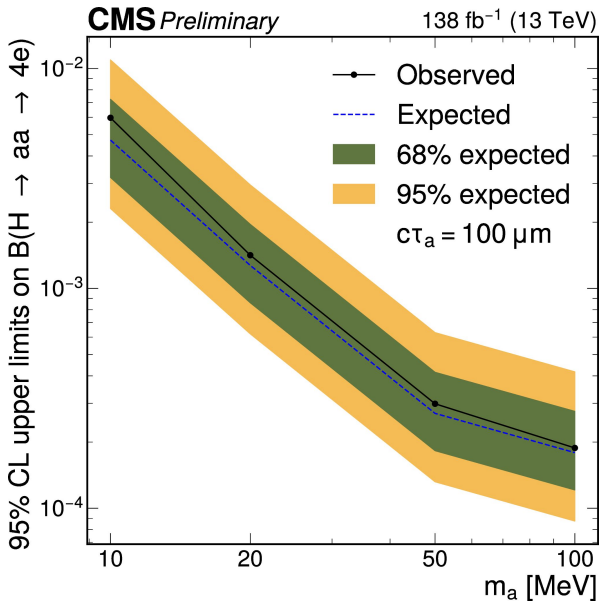
EXO-24-031

Search H → aa → 4e

- Higgs boson decay H → aa → 4e
- Axion-like particle (ALP) mass range: 10–100 MeV
- Highly collimated decays: electron pairs can merge into single objects
- Track information allows probing lower mass hypotheses
- XGBoost algorithm combining information from ECAL, HCAL, and tracks
- Sensitivity: upper limits on H → aa → 4e branching fraction down to ~10^{-5}
- Interpretation in an effective ALP-Higgs coupling model





Conclusions

- Searches focused on boosted Higgs topologies in BSM scenarios.
- Advanced reconstruction techniques exploit low-level jet and track information using graph- and transformer-based neural networks, as well as BDT/RNN for tau identification.
- Dedicated strategies for merged and collimated decay products, including reclustering and handling of overlapping photons, taus, and b-jets.
- Analyses highlight the power of per-particle and substructure-aware ML algorithms to enhance signal extraction in challenging topologies.
- Continued development of boosted object reconstruction and ML-based tagging will improve sensitivity to rare or exotic Higgs decays in future LHC data.

THANK YOU!