Searches for resonances decaying to pairs of heavy bosons in ATLAS

Alberto Annovi (INFN Pisa)

For the ATLAS collaboration

Outline

- Diboson resonances with leptonic decays
  - ATLAS-CONF-2022-066 Eur. Phys. J. C 81 (2021) 332 arXiv:2207.03925
- Higgs and Vector boson tagging
- Higgs boson pairs
  - Phys. Rev. D 106 (2022) 052001 arXiv:2209.10910
  - Phys. Rev. D 105 (2022) 092002 ATLAS-CONF-2021-052
- Vector boson + Higgs searches
  - arXiv:2207.00230 arXiv:2210.05415 arXiv:2211.02617
- Generic X searches with Z or Higgs
  - arXiv:2209.15345 ATLAS-CONF-2022-045

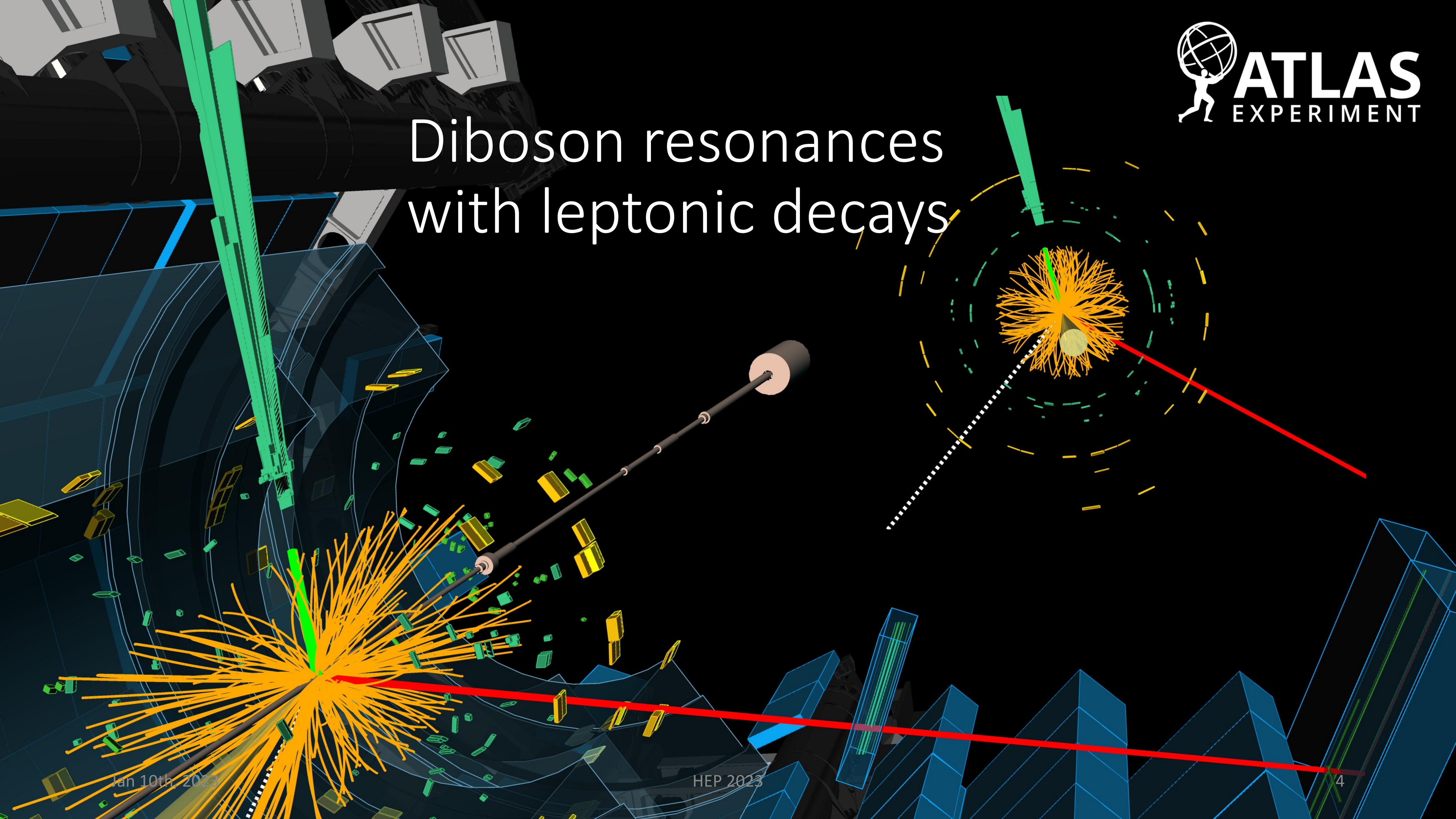
Introduction

- Many BSM models predict final states with SM bosons

- Analyses presented have heavy bosons in the final state
- When bosons decay hadronically jet reconstruction and boson tagging are key analysis ingredients
- Presented analyses use the full Run-2 dataset

- (Some) of the benchmark models used in the presented analyses are
  - Heavy Vector Triplet (HVT) and Randall-Sundrum Graviton
    - JHEP 09 (2014) 060 JHEP 01 (2013) 166 Phys. Rev. Lett. 83 (1999) 3370 Phys. Lett. B 473 (2000) 43
  - Georgi–Machacek Higgs Nuclear Physics B 262 (1985) 463 Phys. Lett. B 165 (1985) 105
  - Radion arXiv:1404.0102
  - Narrow Width heavy Higgs arXiv:1610.07922
  - Large Width heavy Higgs arXiv:1106.0034
  - Twin Higgs models JHEP 01 (2006) 126
  - Two Higgs doublets and composite Higgs
    - JHEP 06 (2019) 066 Nucl. Phys. B853, 1 (2011) JHEP 06 (2011) 020 Phys. Rep. 516, 1 (2012)
  - MSSM Nucl. Phys. B193, 150 (1981) JHEP 10 (2013) 028 Eur. Phys. J. C 73, 2650 (2013)

Diboson resonances with leptonic decays

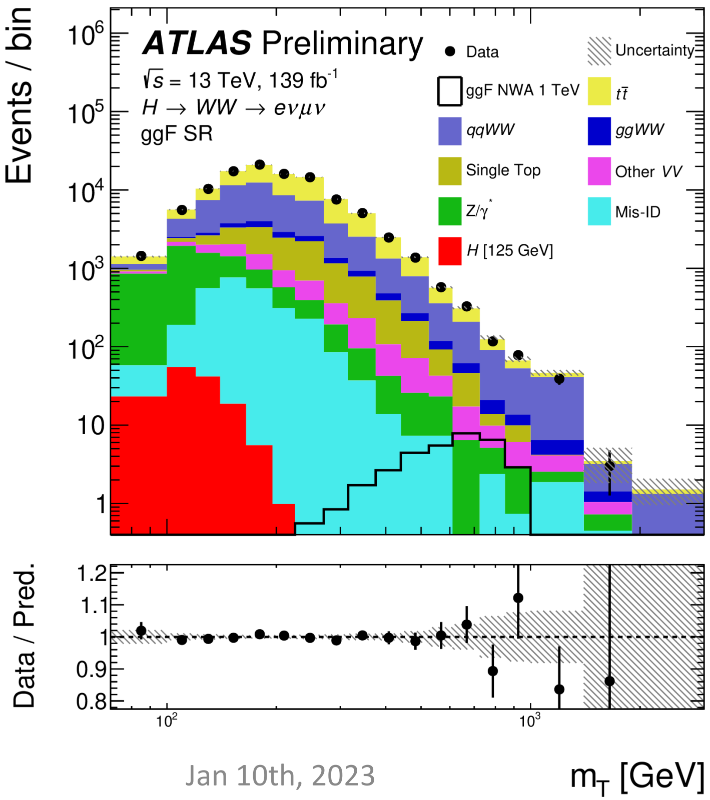


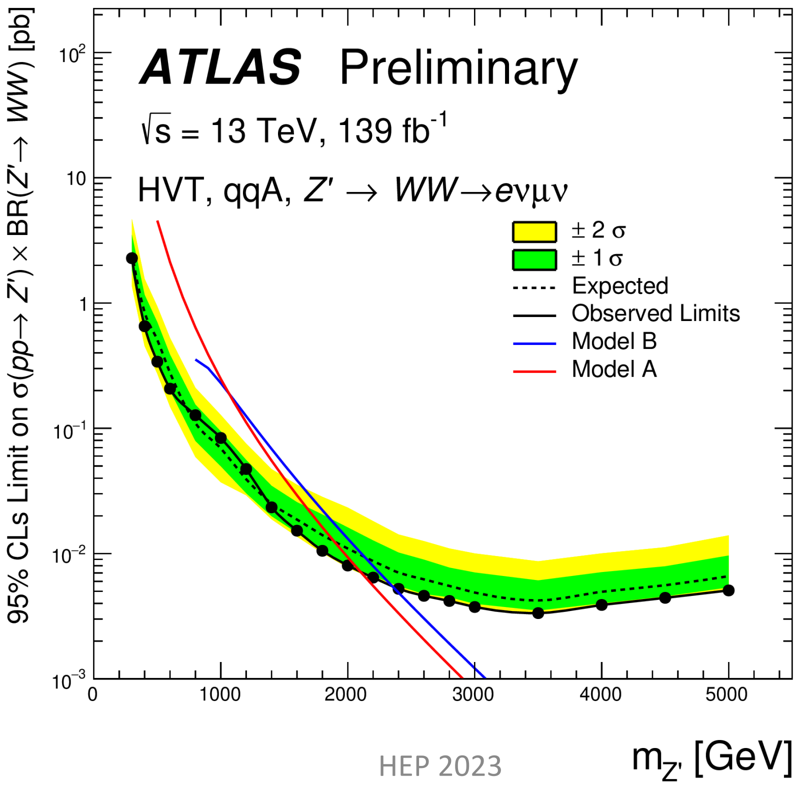
Search for Resonance (R), in the channel R→ WW → lν lν

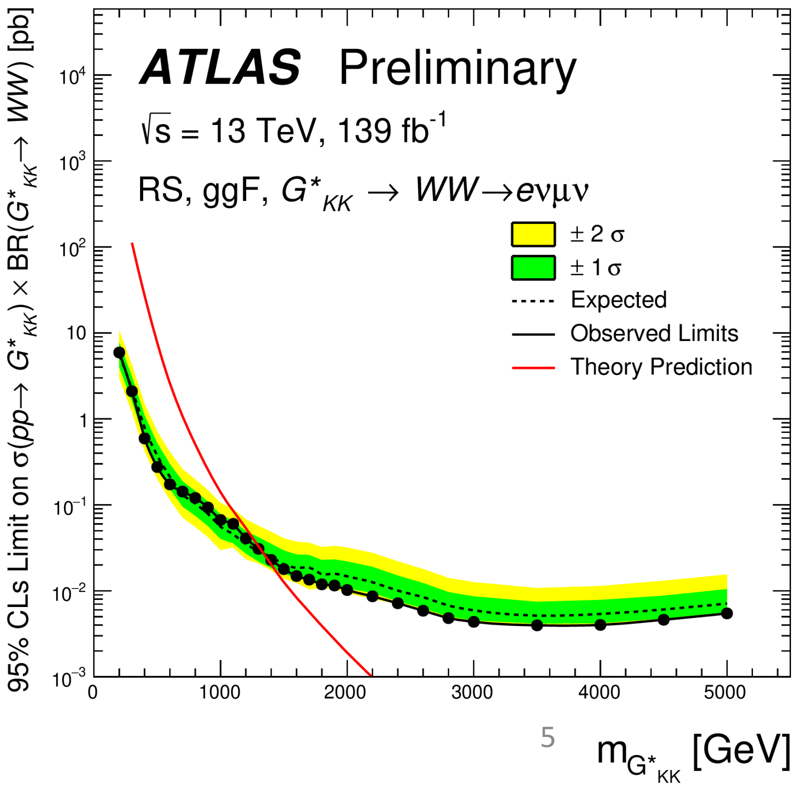
ATLAS-CONF-2022-066

- Two Different Flavour, Opposite Sign Leptons, $p_T > 25$ GeV
- Third lepton veto, $p_T > 15$ GeV
- B-jet veto
- Main Backgrounds: $t\bar{t}$, Wt, WW

Model	Obs. limit [GeV]	Exp. limit [GeV]
Radion, ggF	1090	1190
Kaluza-Klein graviton, ggF	1340	1340
Kaluza-Klein graviton, VBF	500	500
HVT scenario A, qqA	2100	1890
HVT scenario B, qqA	2350	2130



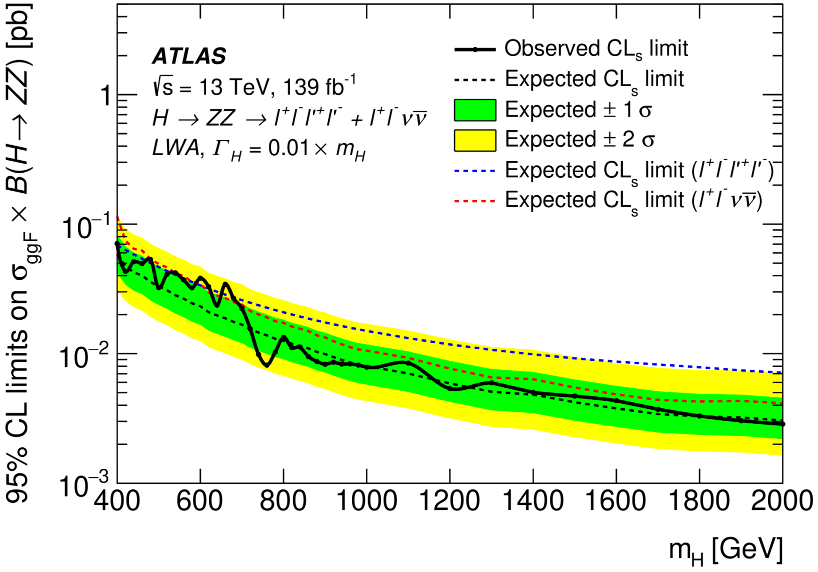


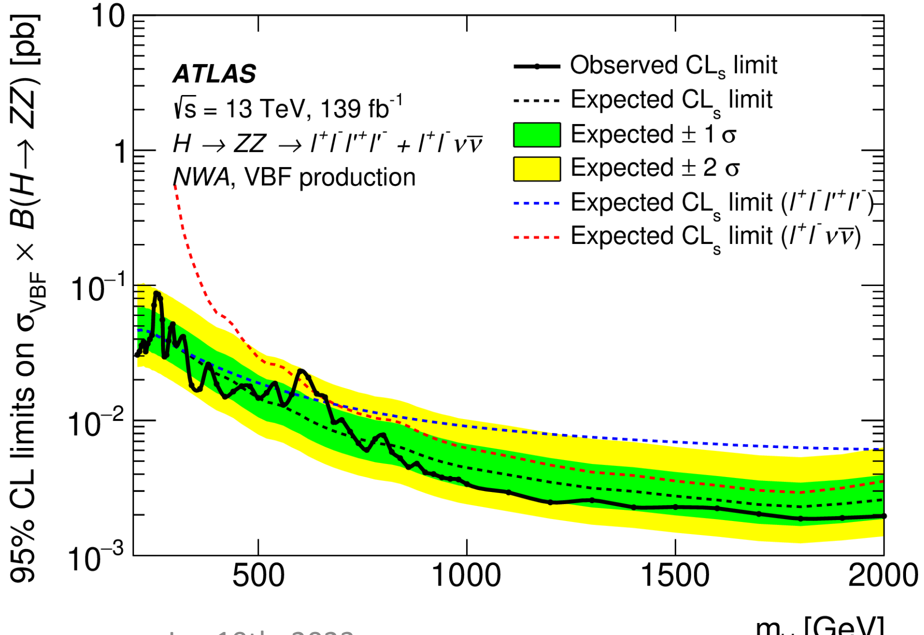


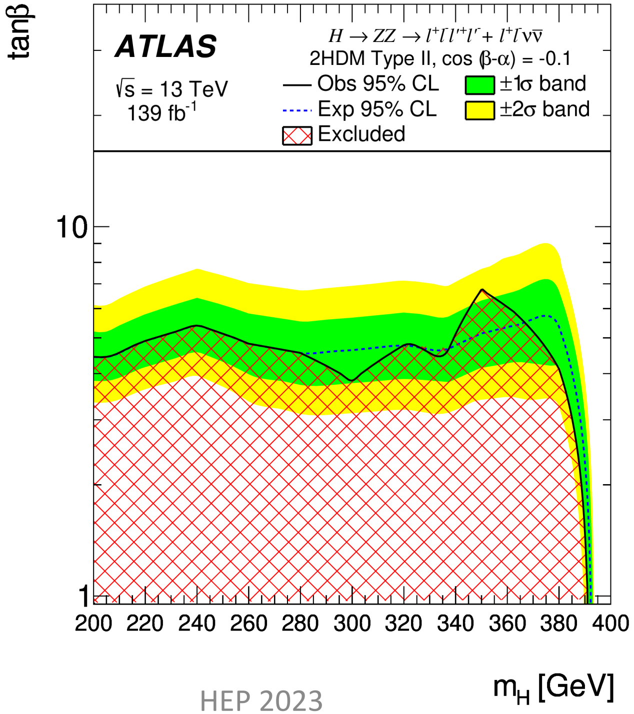
Search for R→ZZ→4l and R→ZZ→llνν

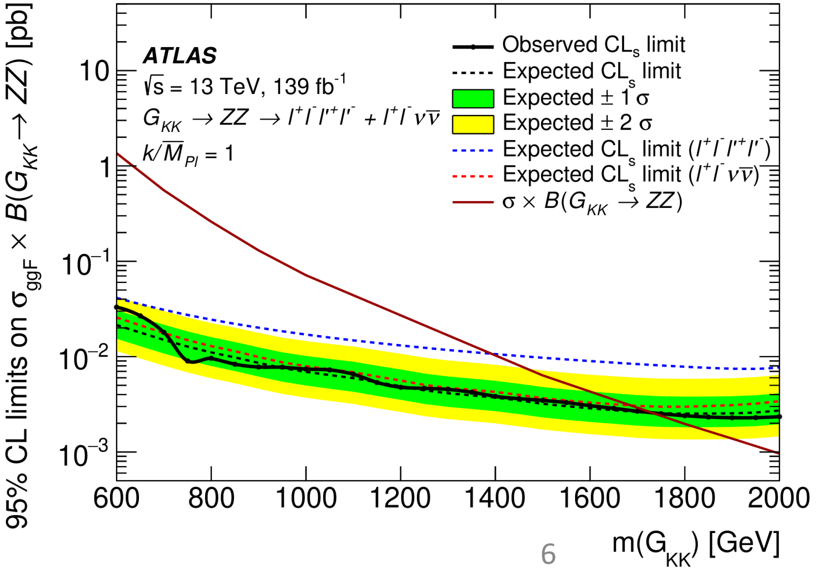
- Improvements in full Run2 analysis
  - Mass range, Particle Flow, …
- Combination of the 2 final states
- Cross-section limits in several interpretations:
  - NWA heavy Higgs with ggF+VBF, also translated to 2HDM contours
  - LWA heavy Higgs including interference modelling
  - Randall-Sundrum Graviton

Eur. Phys. J. C 81 (2021) 332



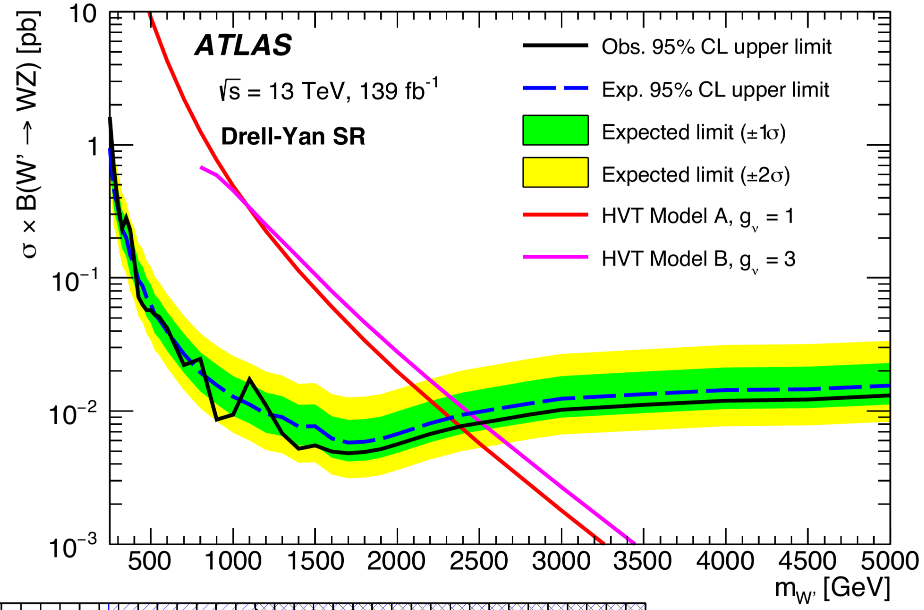


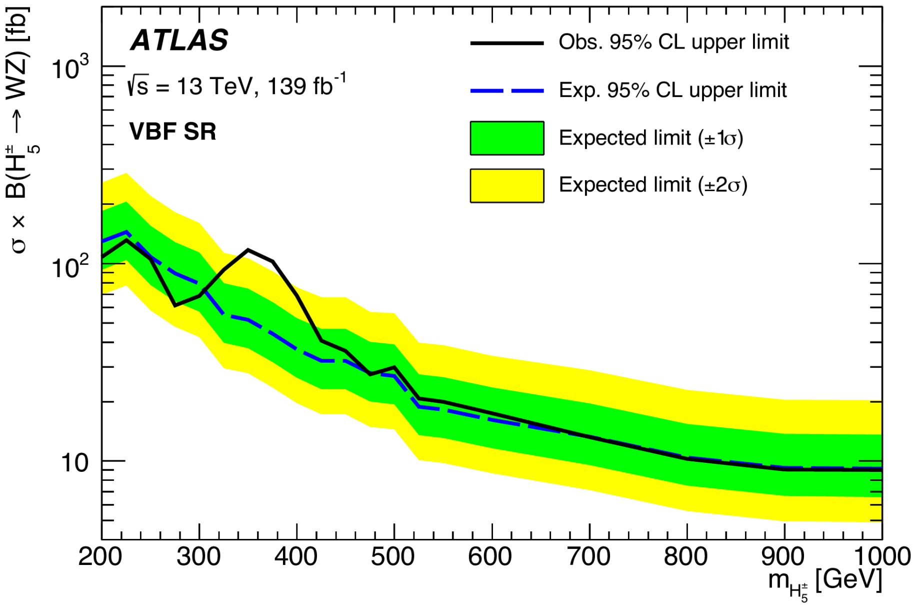




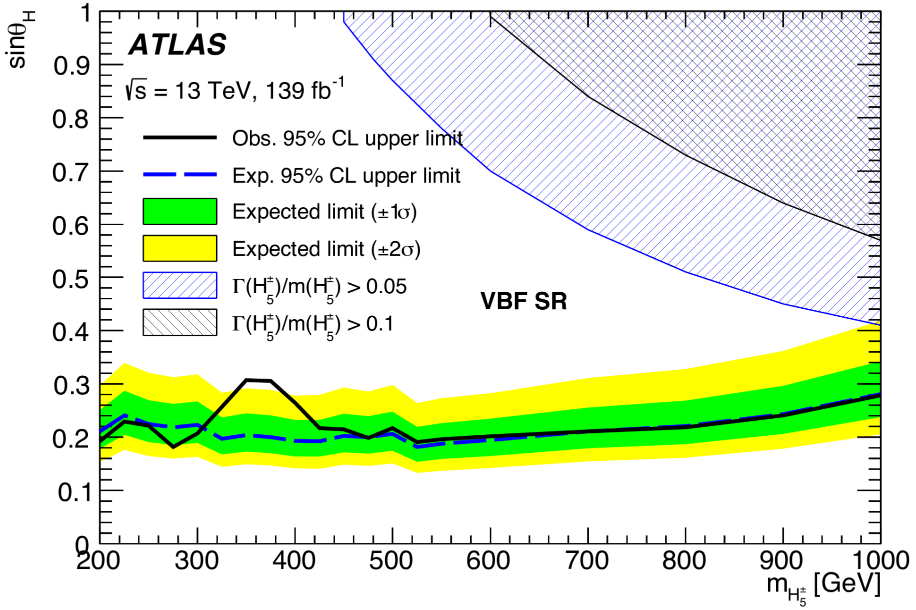
Search for WZ → lν ll

- Main selection:
  - 3 high p_T leptons
  - Missing transverse energy
  - 2 jets (in case of VBF production mode)
- Signal regions: cut based and ANN
- Resonance benchmark model:
  - Heavy Vector Triplets model
  - Georgi - Machacek (GM) Higgs Triplet Model





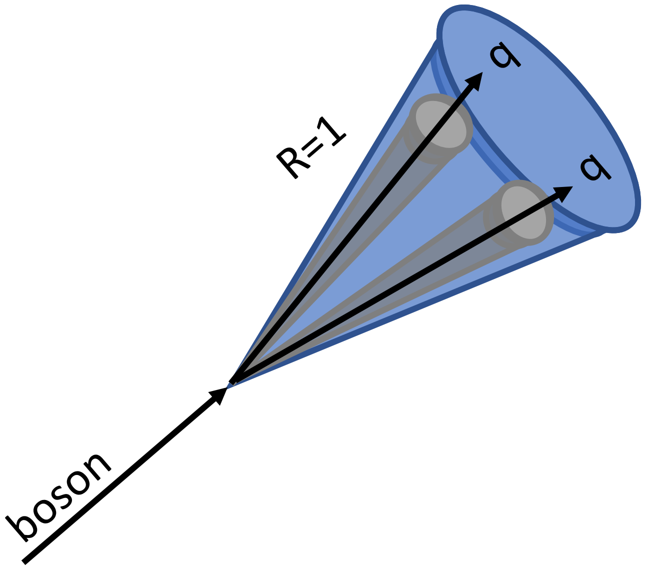
arXiv:2207.03925



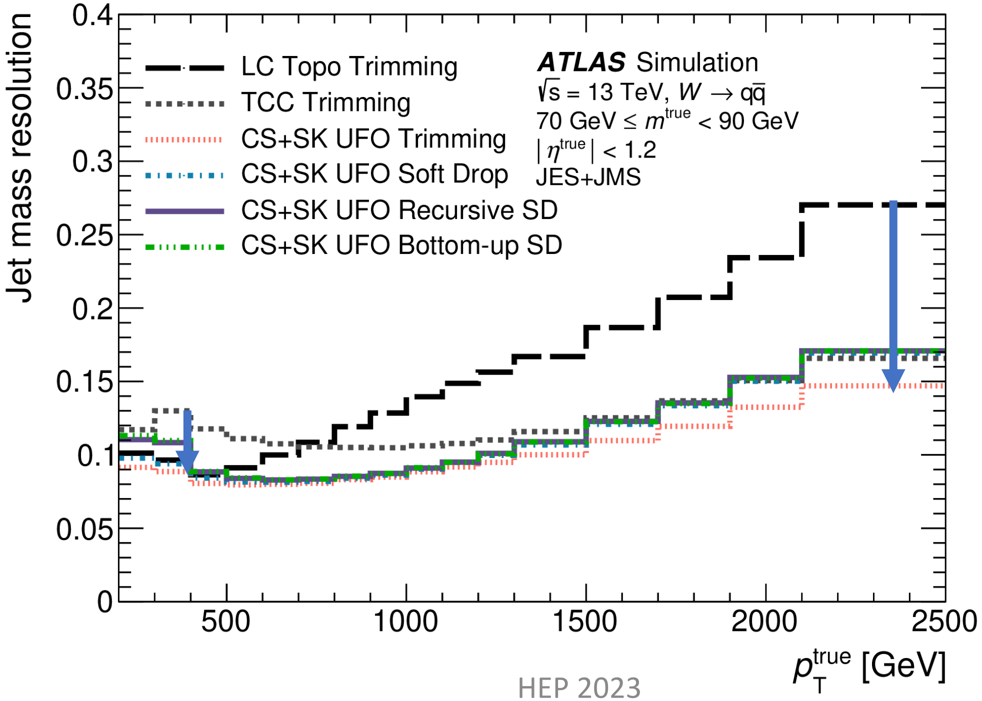
Jets techniques

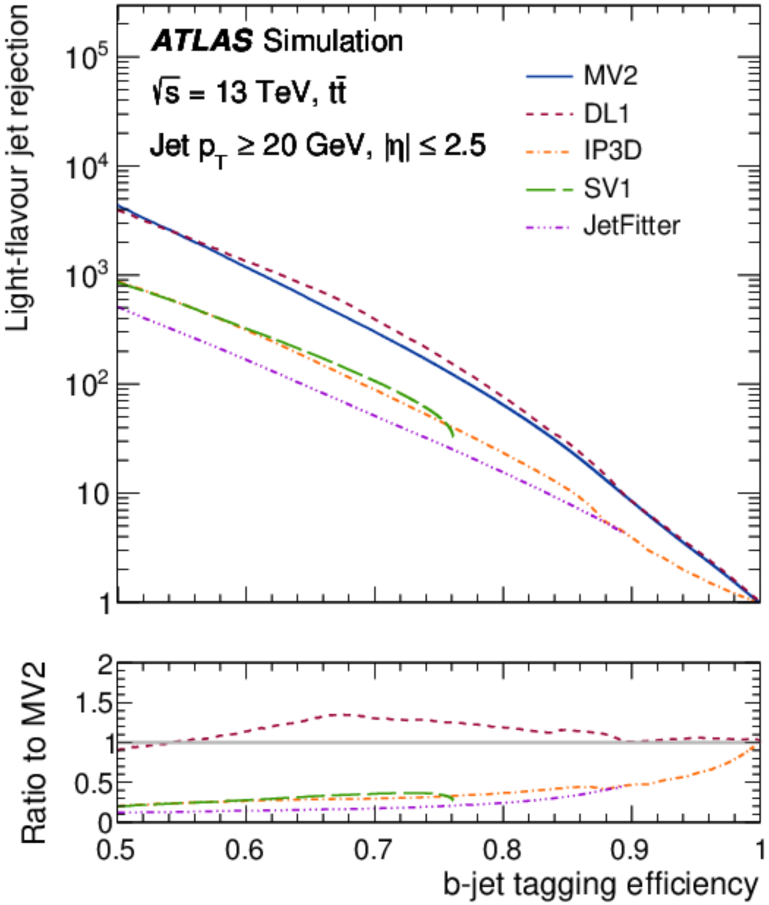
- Hadronic decays of a boson reconstructed as
  - Two resolved R=0.4 anti-k_T jets
  - Single large R=1 jet (for bosons with a large boost the jets merge)
- Use of Particle Flow and Track Calo Cluster (TCC)
  - Eur. Phys. J. C 77 (2017) 466, ATL-PHYS-PUB-2017-015
- Combined in Unified Flow Objects (UFO) for best performance
  - Eur. Phys. J. C 81 (2021) 334

- B-tagging used to identify b-quarks
- Applied to jets and variable radius track jets matched to large R jets
- High level algorithms based on MV2 and DL1



UFO jet mass resolution improvements

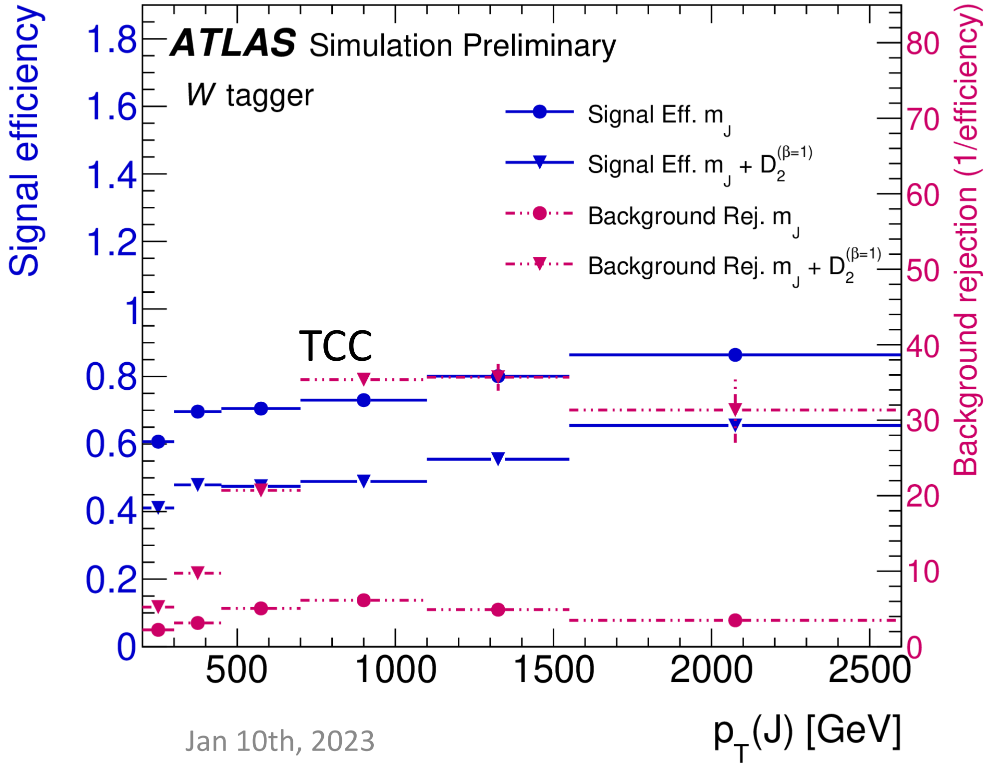




Tag W/Z boson dijet boson decays

- Boson tagging with R=1 jets and jet substructure variables
- Standard tagger uses calorimeter cluster jets
- TCC jets tagger cuts on 2 variables optimized in each p_T bin
  - Jet mass, D_2 two prong substructure
  - Efficiency and background rejection calibrated on 80 fb^{-1} data

- On going development of UFO jets tagger
- UFO tagger uses NN or 3 variables cuts on
  - Jet mass
  - D_2 two prong substructure
  - number of ID tracks



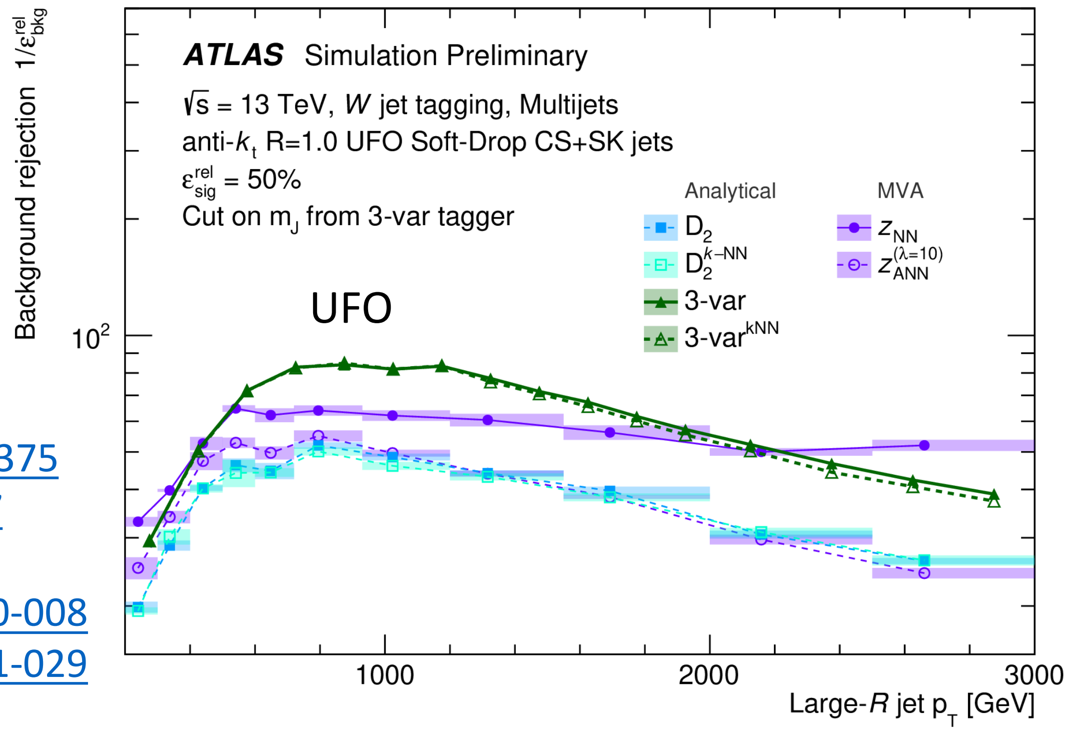
anti-k_T

[Eur. Phys. J. C 79 (2019) 375](#)

[ATL-PHYS-PUB-2020-017](#)

TCC [ATL-PHYS-PUB-2020-008](#)

UFO [ATL-PHYS-PUB-2021-029](#)

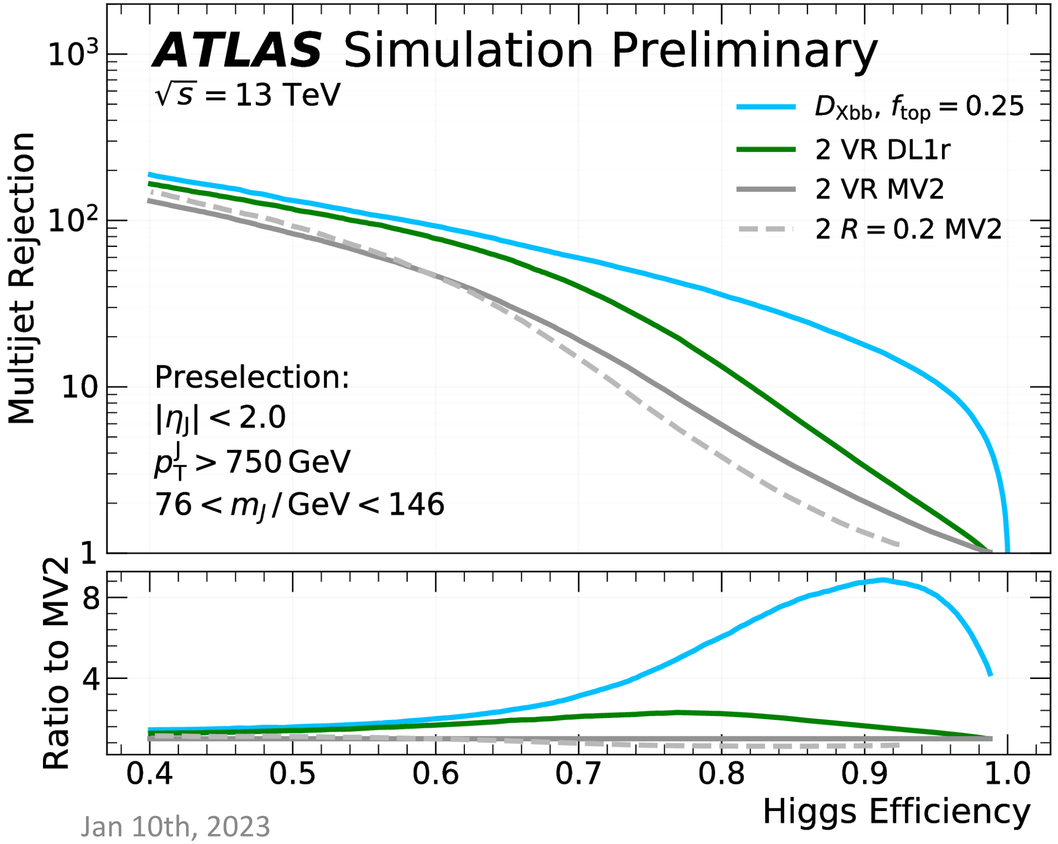


Tagging Higgs → $b\bar{b}$ decays

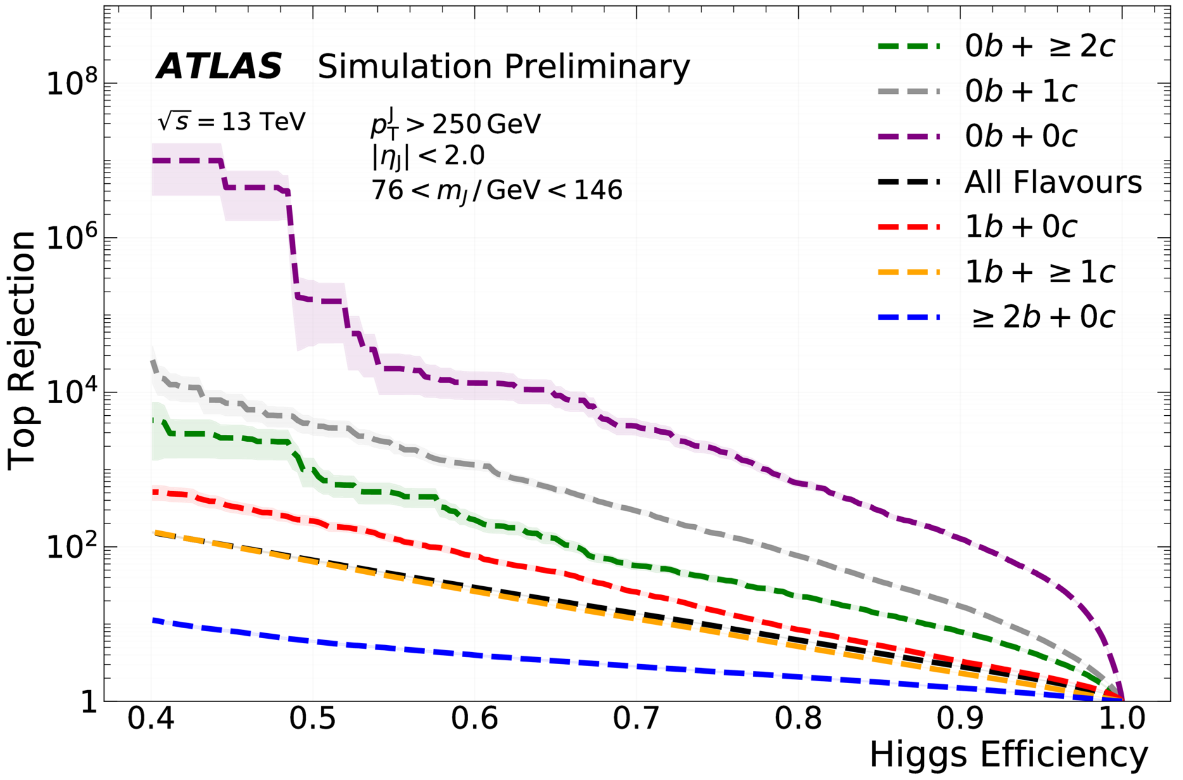
ATL-PHYS-PUB-2021-035

- Xbb tagger distinguish boosted Higgs boson $b\bar{b}$ decays from QCD jets and top quarks
- Combines flavor discriminants from up to three subjets using a feed-forward neural network
- Tag large R=1 jets

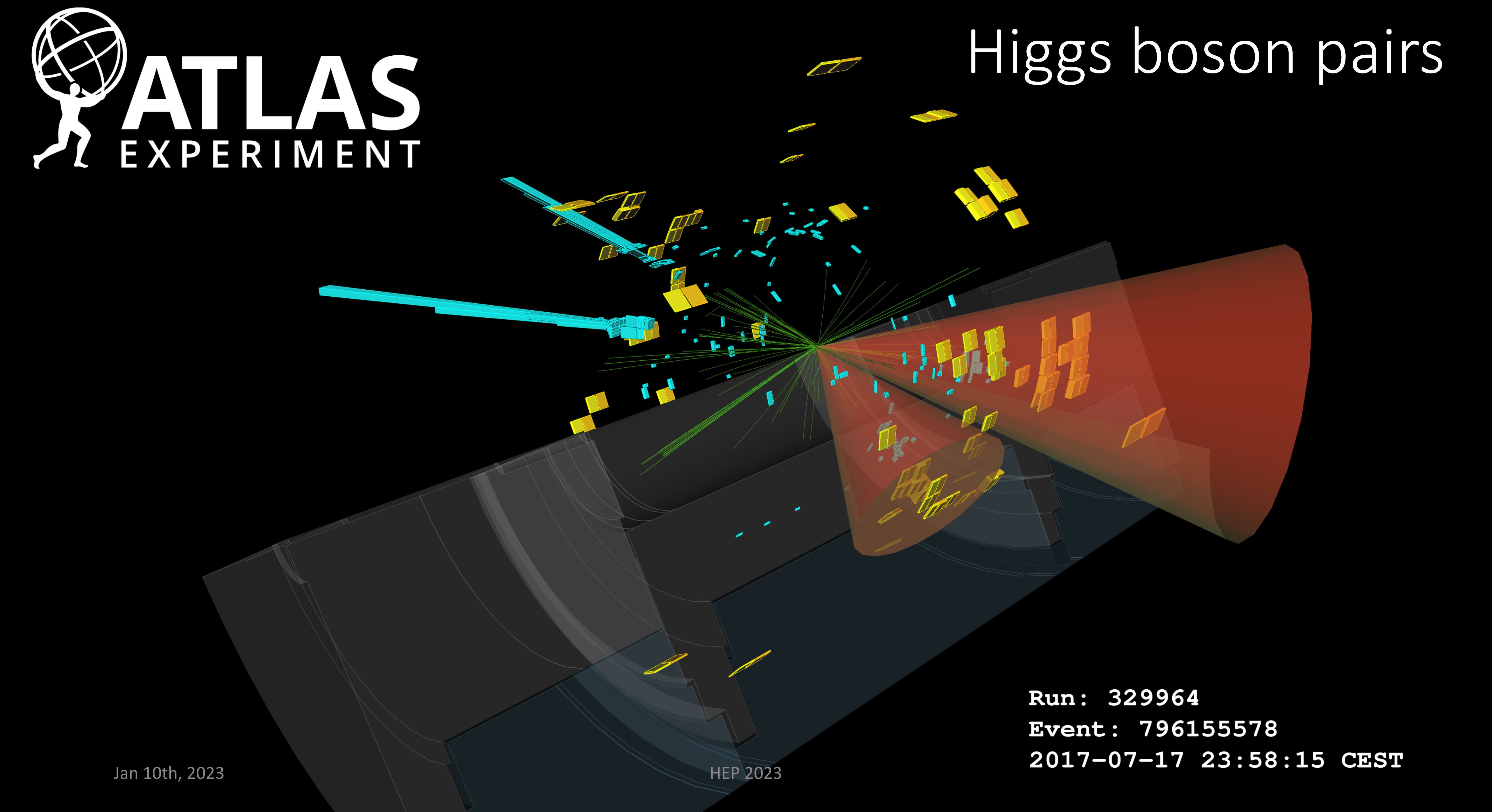
ATL-PHYS-PUB-2020-019



Top rejection vs Higgs efficiency



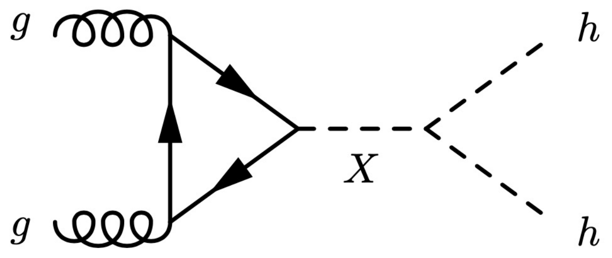
Higgs boson pairs



Searches for resonances decaying to Higgs boson pairs

HH→ $b\bar{b}\gamma\gamma$

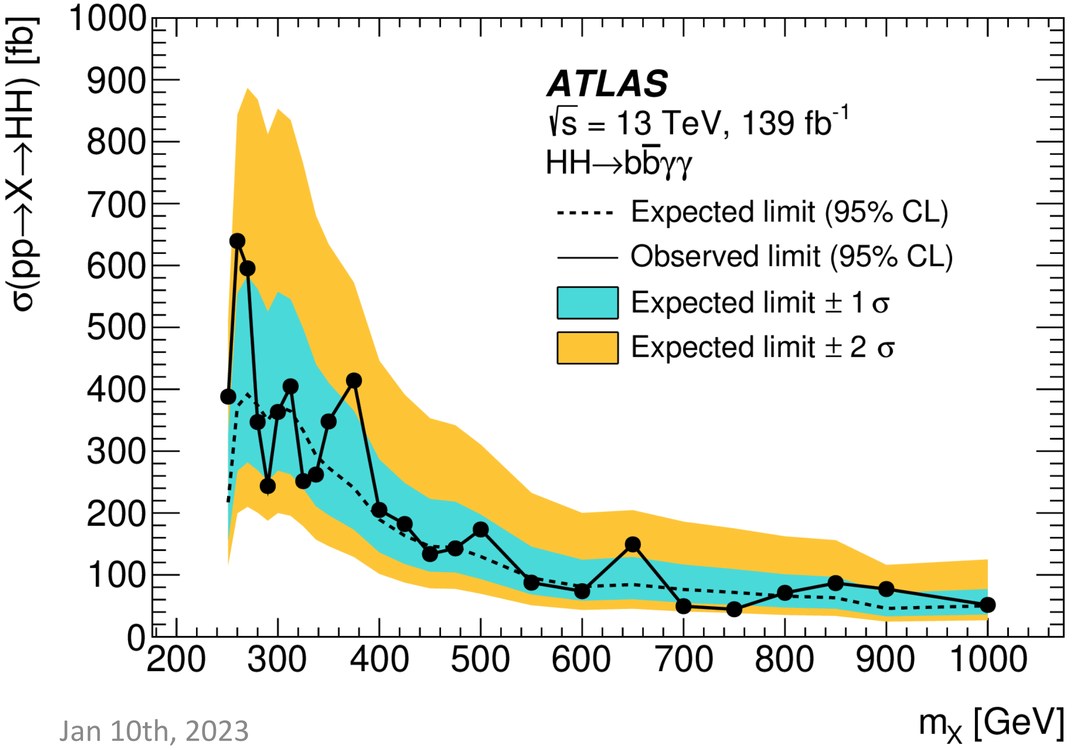
- Selection
  - 2 tight, isolated photons
  - ≥2 jets : p_T>25 GeV, b-tagging
- Fit of the $m_{\gamma\gamma}$
  - for every $m(b\bar{b}\gamma\gamma)$ mass point

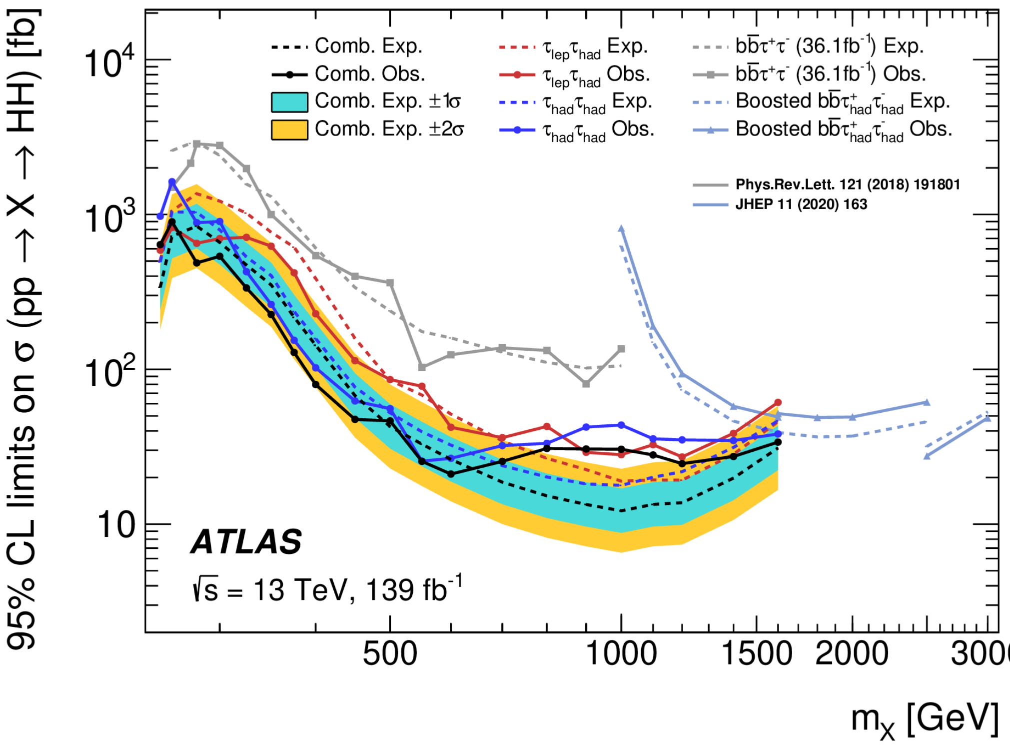


HH→ $b\bar{b}\tau^+\tau^-$

- Require 2 b-jets and 2 OS τ leptons
- Final state $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$
- Backgrounds: $t\bar{t}$, single top, V+jets, diboson, SM Higgs

Phys. Rev. D 106 (2022) 052001





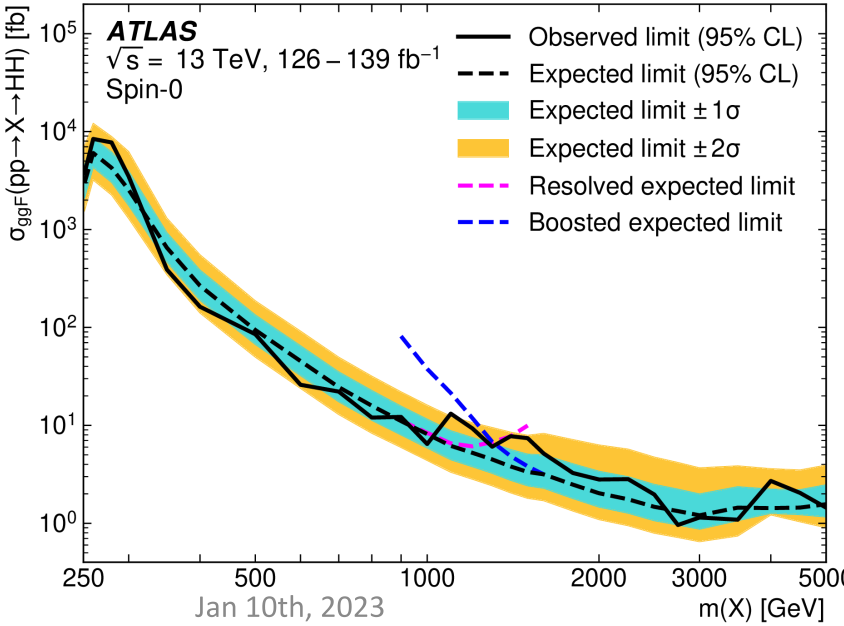
arXiv:2209.10910

Higgs pair production in $b\bar{b}b\bar{b}$ channel and combination

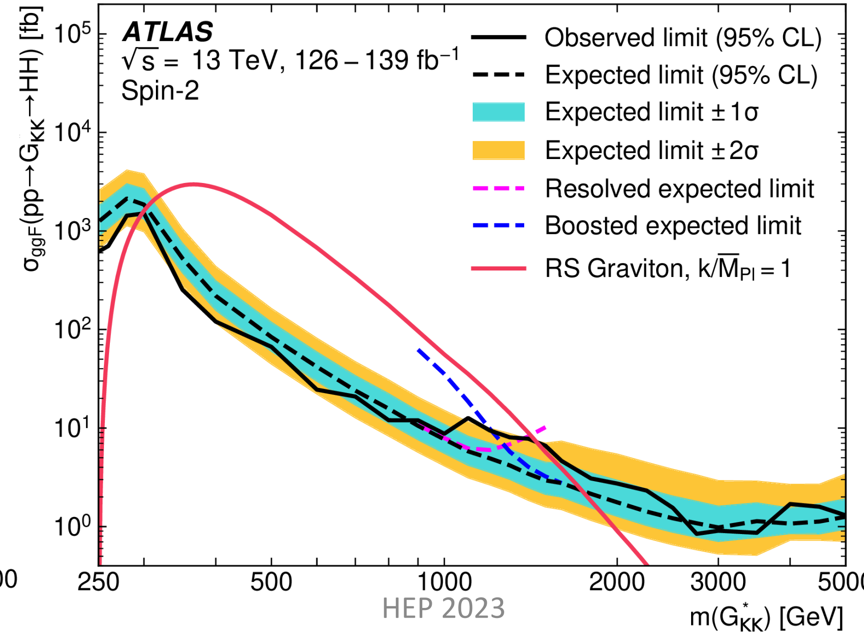
Phys. Rev. D 105 (2022) 092002

- $b\bar{b}\,b\bar{b}$ is the channel with largest BR for HH (34%)
- Resolved channel (4 b-jets):
  - Machine learning-based jet pairing algorithm
  - Neural network-based background reweighting
- Boosted channel (2 large-R jets):
  - Variable radius track jets
  - Extended resonance mass range (to 5 TeV)

Narrow Width Scalar (X)



Spin 2 graviton (G)



Higgs pair production in $b\bar{b}b\bar{b}$ channel and combination

Phys. Rev. D 105 (2022) 092002

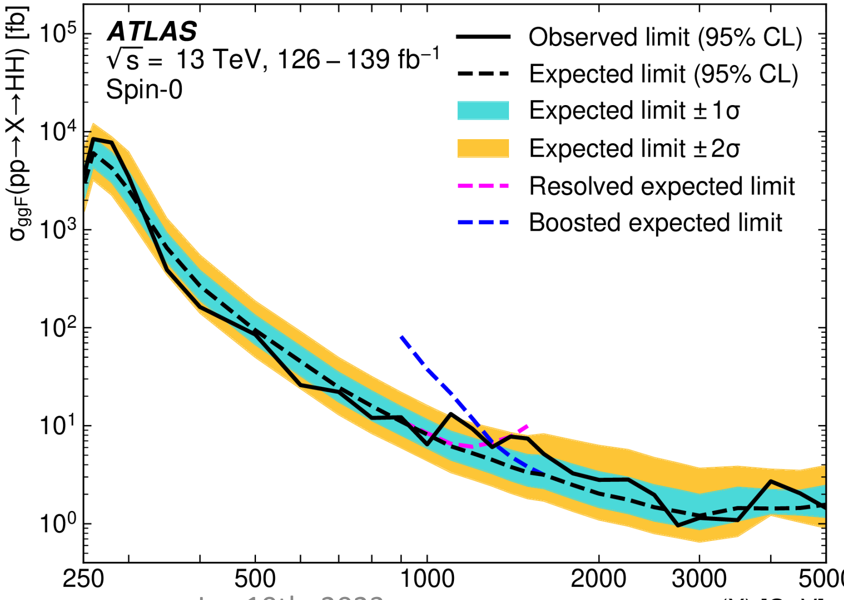
ATLAS-CONF-2021-052

- $b\bar{b}\,b\bar{b}$ is the channel with largest BR for HH (34%)
- Resolved channel (4 b-jets):
  - Machine learning-based jet pairing algorithm
  - Neural network-based background reweighting
- Boosted channel (2 large-R jets):
  - Variable radius track jets
  - Extended resonance mass range (to 5 TeV)

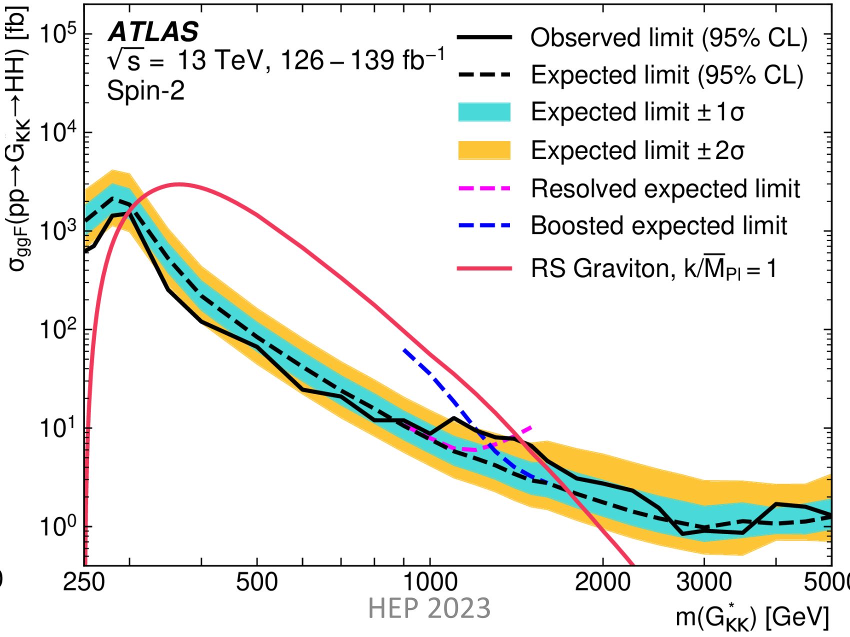
Combination of $b\bar{b}\,b\bar{b}$ + $b\bar{b}\,\tau\tau$ + $b\bar{b}\,\gamma\gamma$

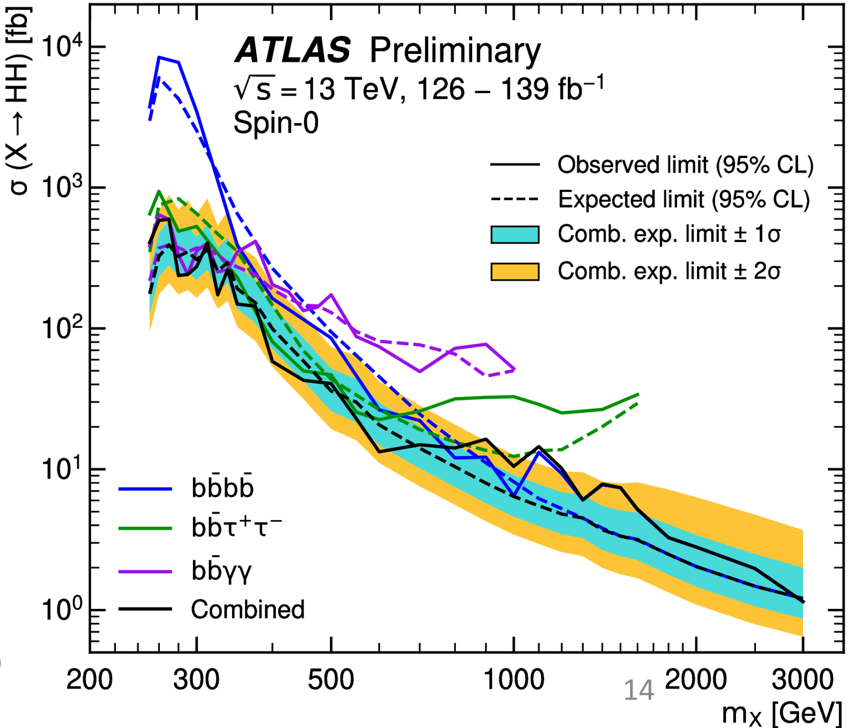
The largest excess is at m_X = 1.1 TeV local (global) significance of 3.2σ (2.1σ).

Narrow Width Scalar (X)

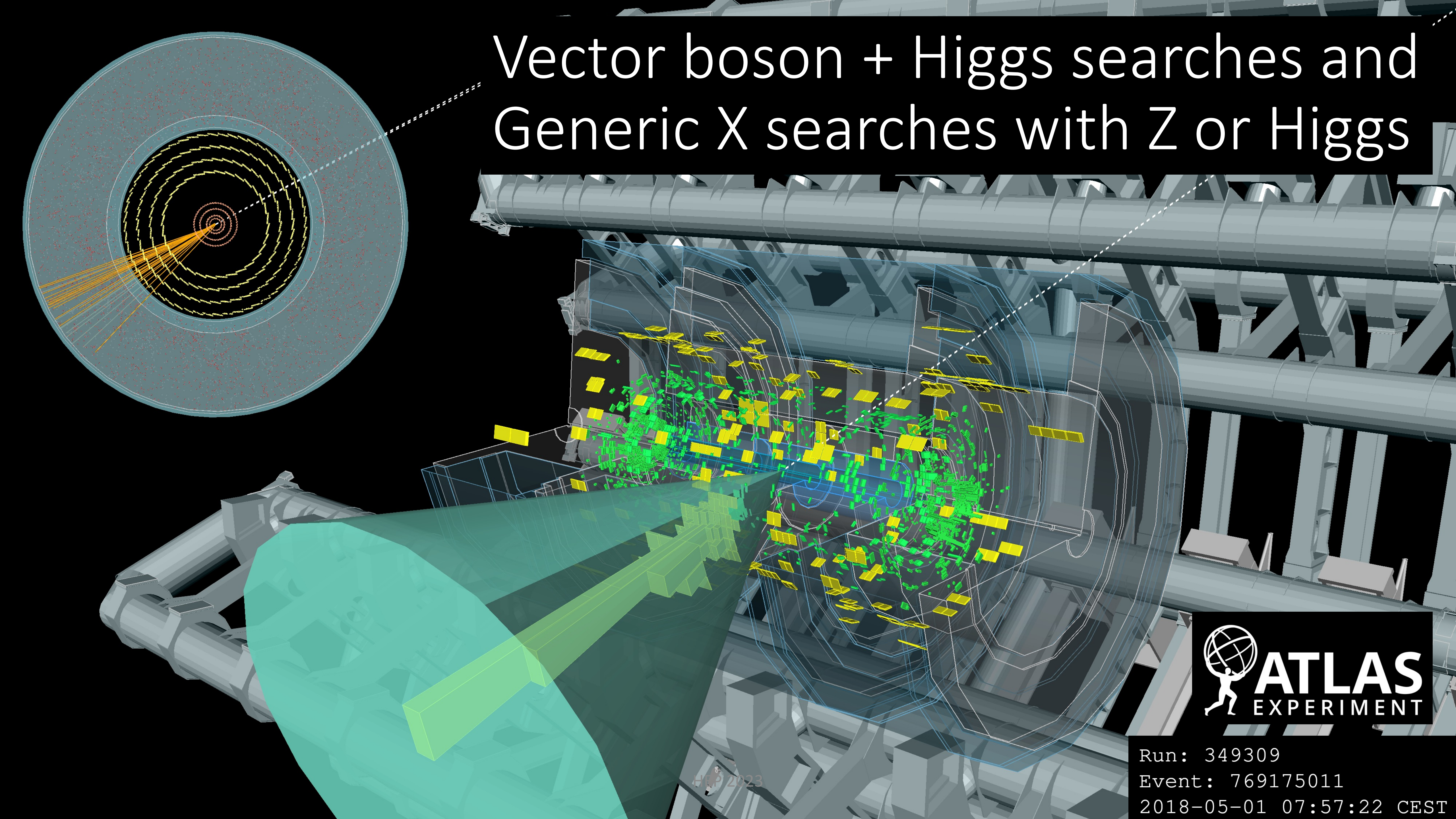


Spin 2 graviton (G)





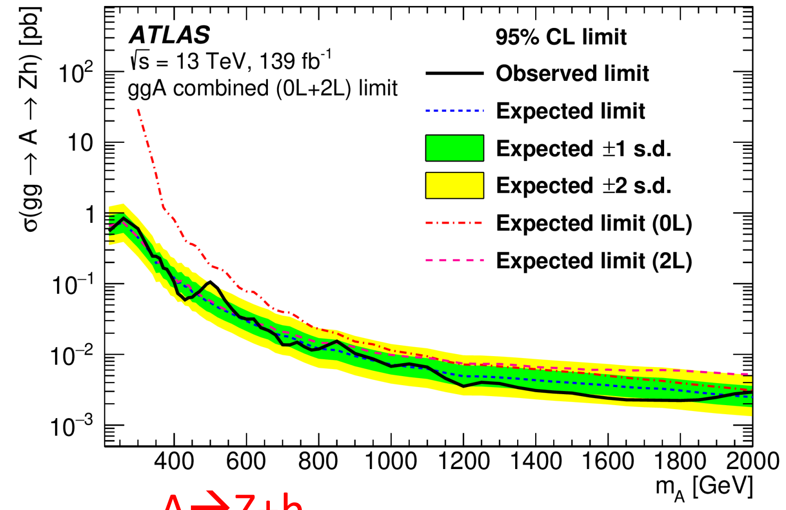
Vector boson + Higgs searches and Generic X searches with Z or Higgs



Search for new resonances decaying into W/Z + Higgs

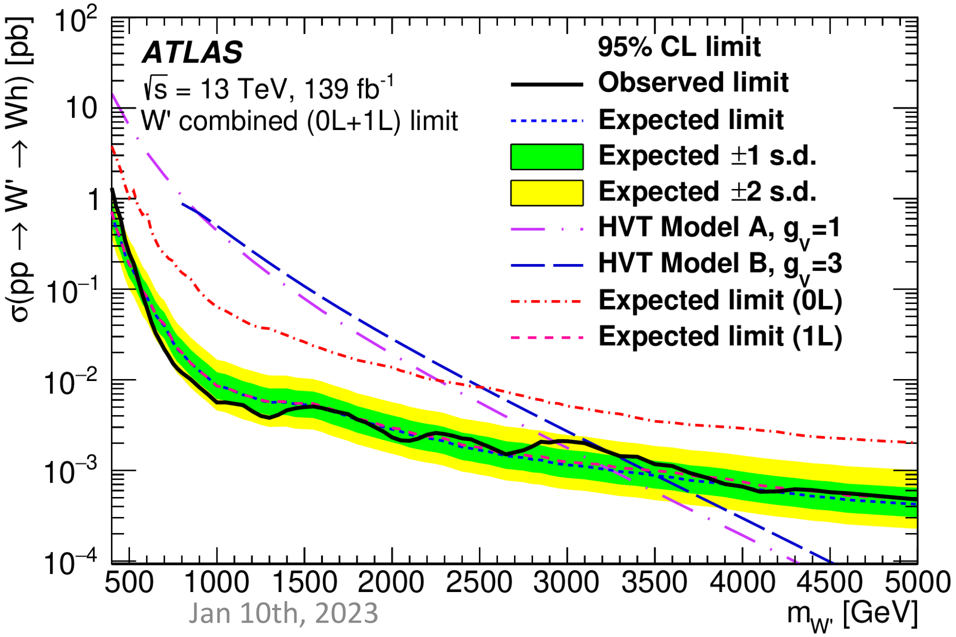
- pp→W'/Z'→W/Z+h (W/Z→ $l\nu$/ll/$\nu\nu$ h→$b\bar{b}$)
- pp→A(+$b\bar{b}$)→Z+h (Z→ ll/$\nu\nu$ h→$b\bar{b}$)
- H identified with 1 or 2 b-tags
  - in resolved or merged jets channels
- W/Z channels with 0,1,2 (charged) lepton
- Limits extracted from fits of $m_{T,Vh}$ and m_{Vh} discriminants
- Interpreted as HVT, 2HDM models.

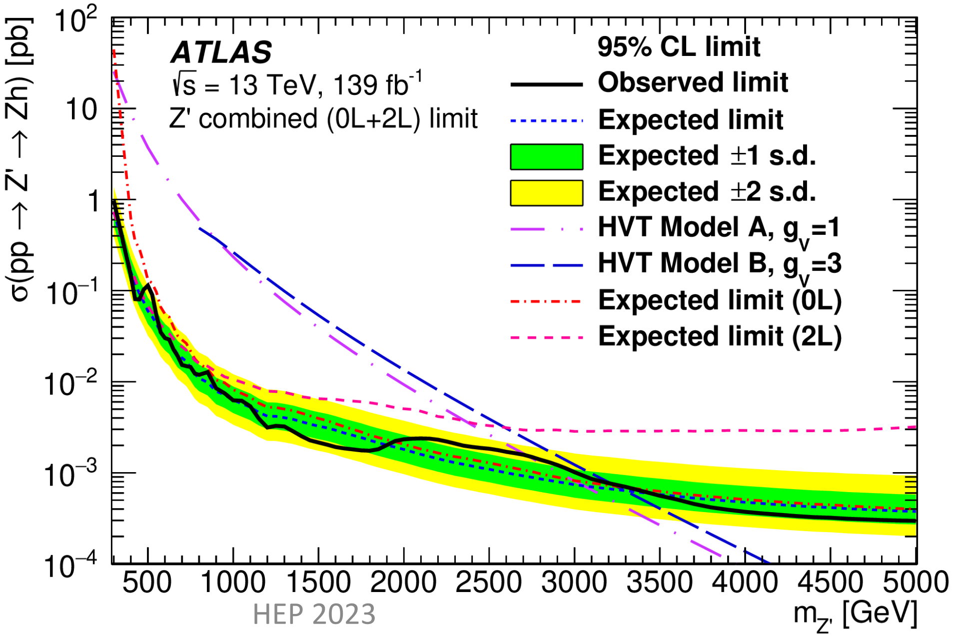
arXiv:2207.00230

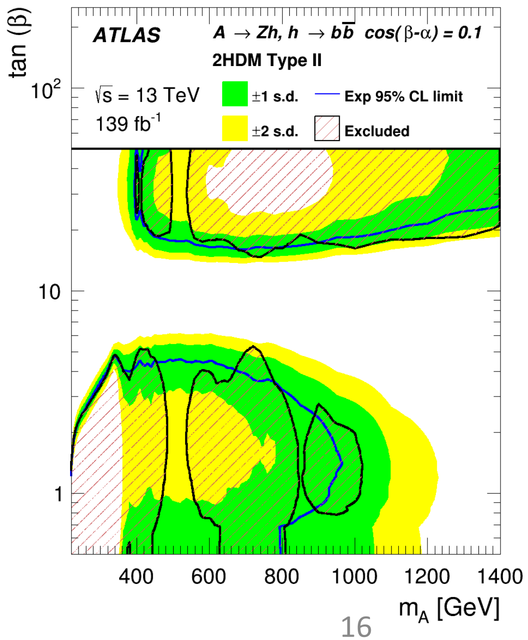


A→Z+h

W' and Z'





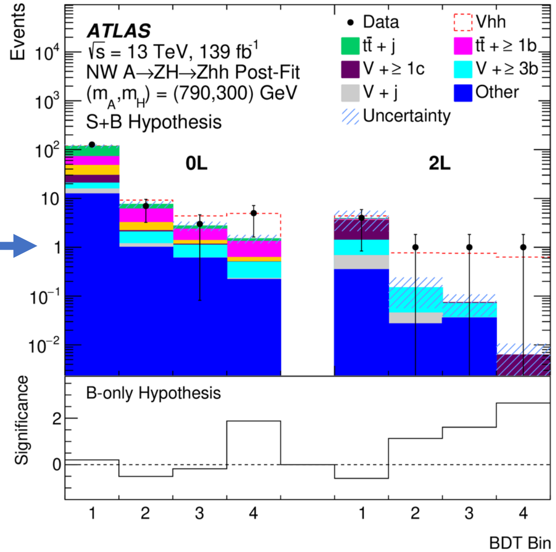


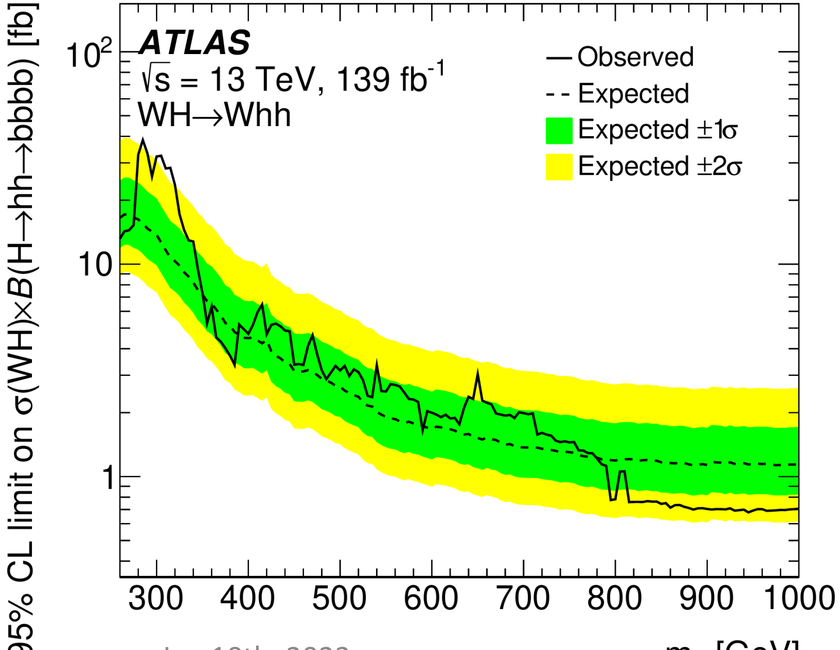
Search for resonances in the W/Z + hh final state

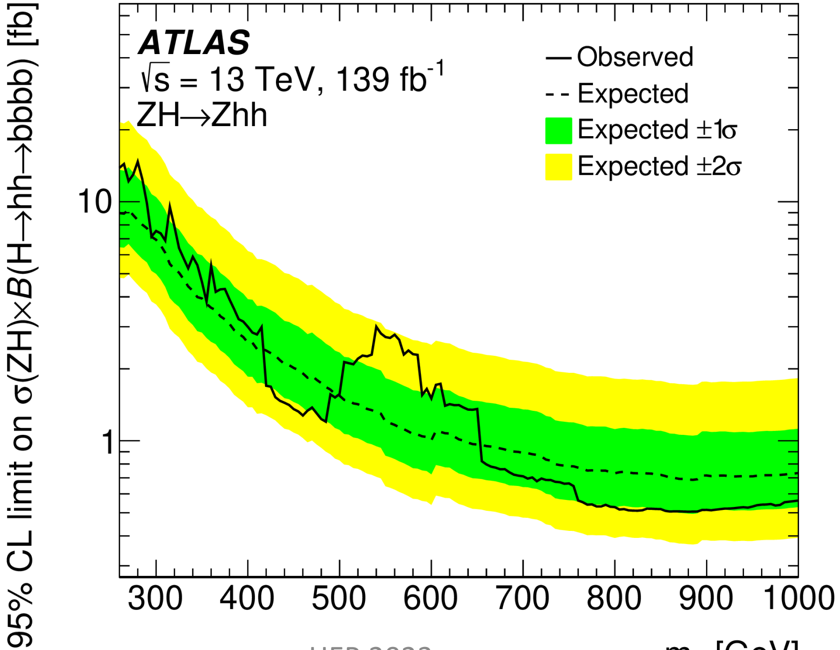
[arXiv:2210.05415](https://arxiv.org/abs/2210.05415)

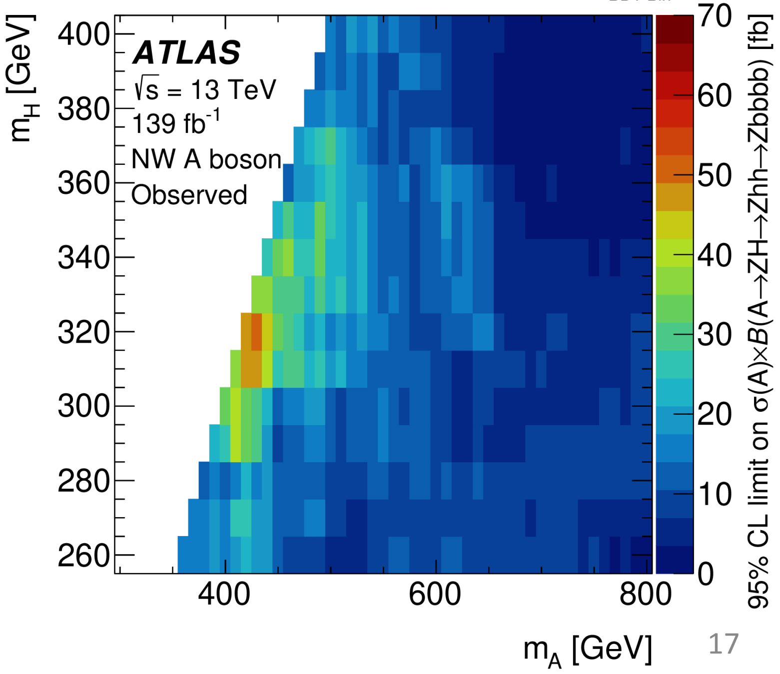
- Search for
  - pp→ V + H with H → hh → 4 b and W/Z→ $l\nu$/ll/$\nu\nu$
  - pp→ A → Z+H with H → hh → 4 b and Z→ ll/$\nu\nu$
- hh reconstructed as 4 b-jets with quality b-tags
- W/Z channels with 0,1,2 (charged) lepton
- Limits for the Heavy Vector Triplet and the two-Higgs-doublet model

BDT discriminant →





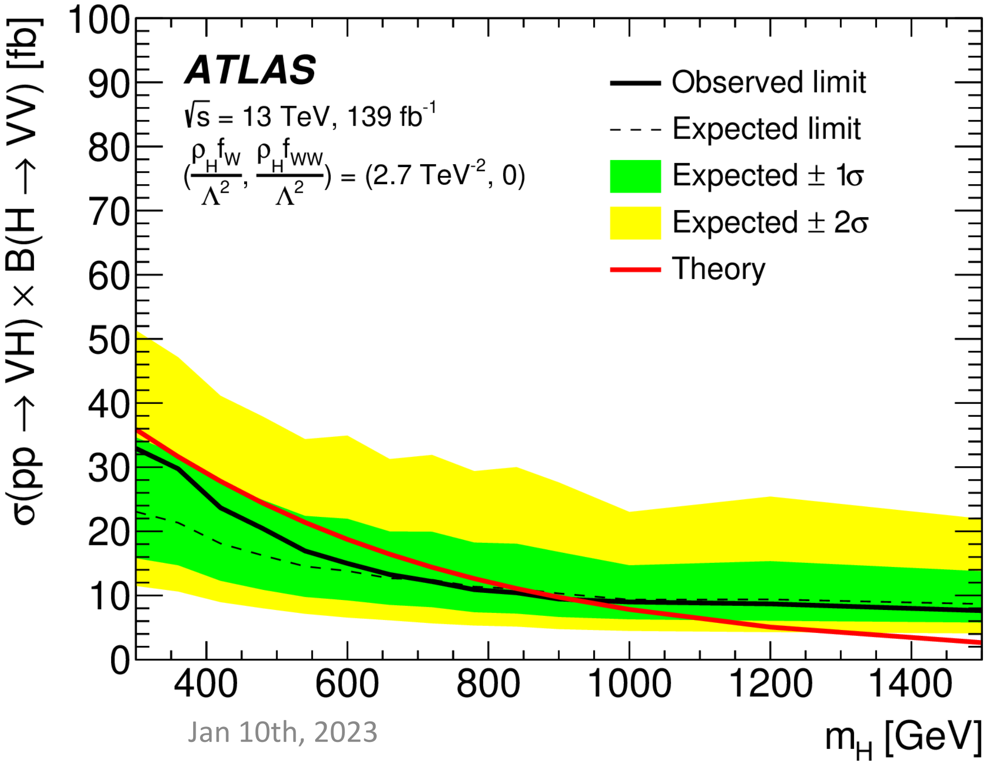


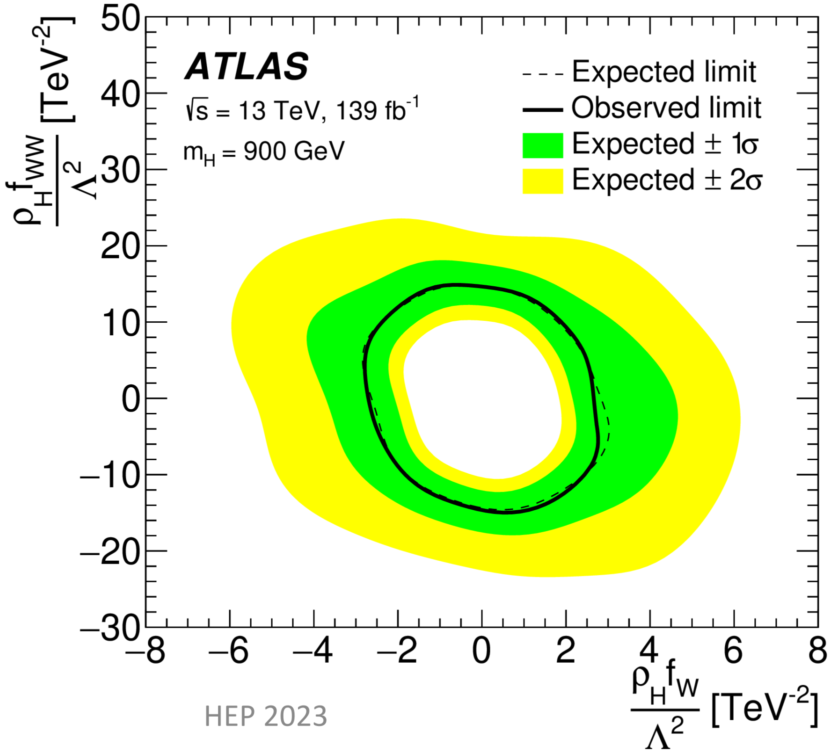


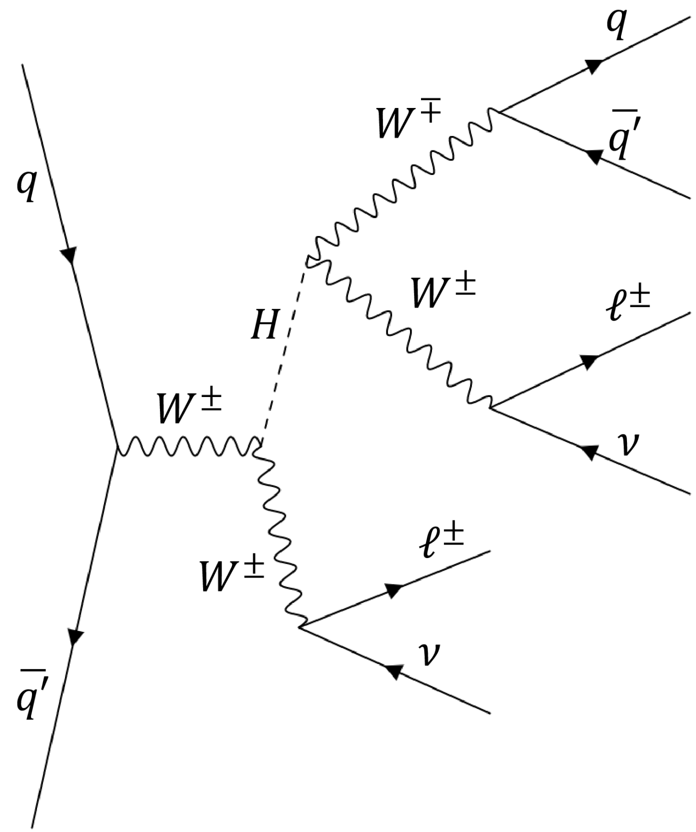
Search for heavy Higgs boson

arXiv:2211.02617

- Search for heavy Higgs boson produced in VH channel with same-sign di-lepton final state
- Hadronic W→jj with W-tagger based on anti-k_T jets
- Dim-4 and dim-6 interactions with SM particles
  - free parameters: f_W, f_{WW} and H_{mass}

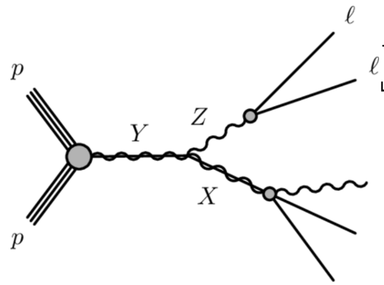


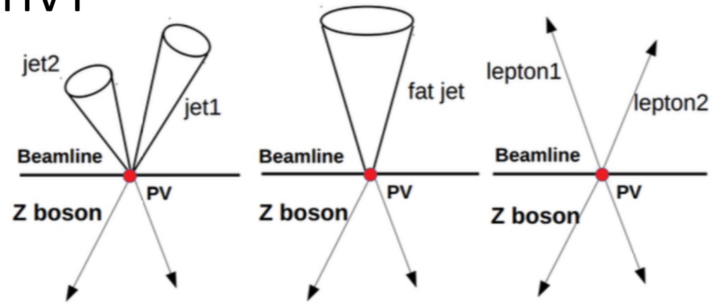


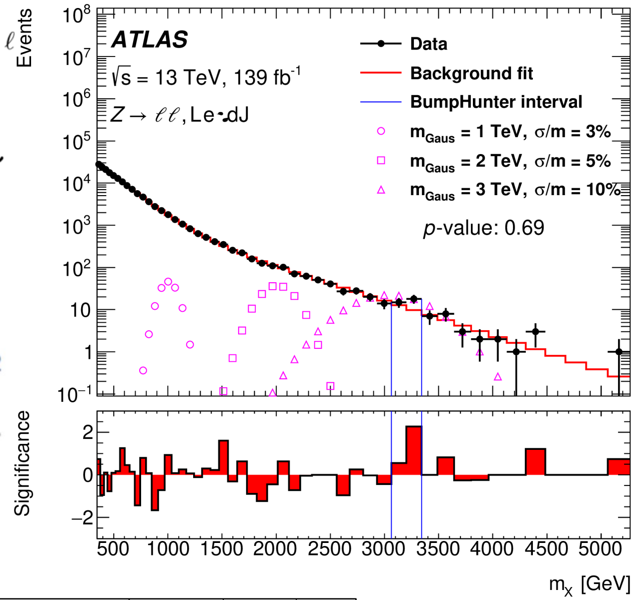


Search for Z+X and Y→Z+X

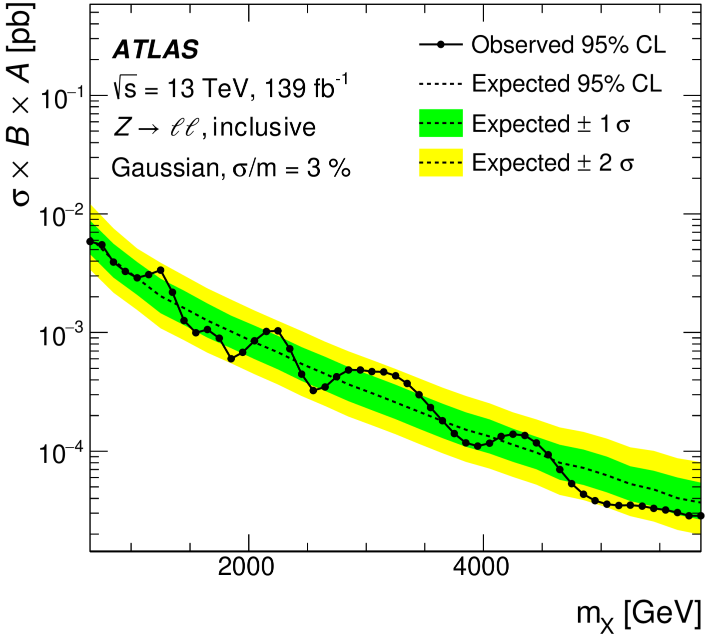
- Select high-p_T Z→ll (p_T > 100 GeV)
- Use 6 "lead" categories for X: small-R, large-R jets, b-jet, e, μ, γ
- X candidate formed with all reconstructed objects (except the Z)
- Signals: model-independent gaussian-shaped and HVT
- Search for local excesses in m_X and m_{ZX} spectra
- HVT upper limits with topology: W'→ZW→llqq

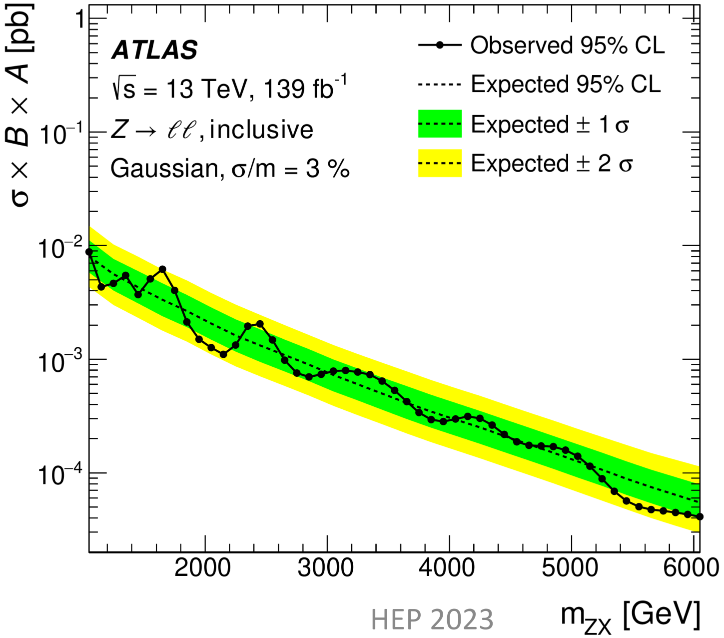


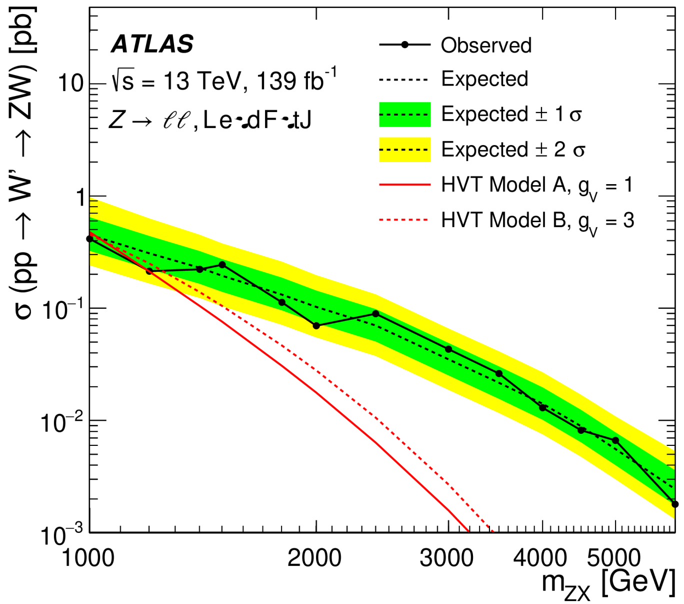




model-independent gaussian signals







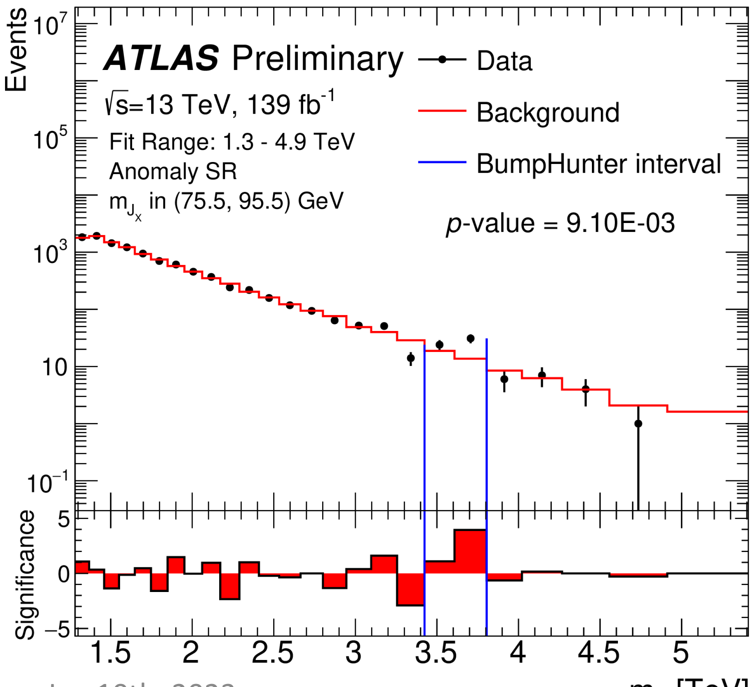
HVT

arXiv:2209.15345

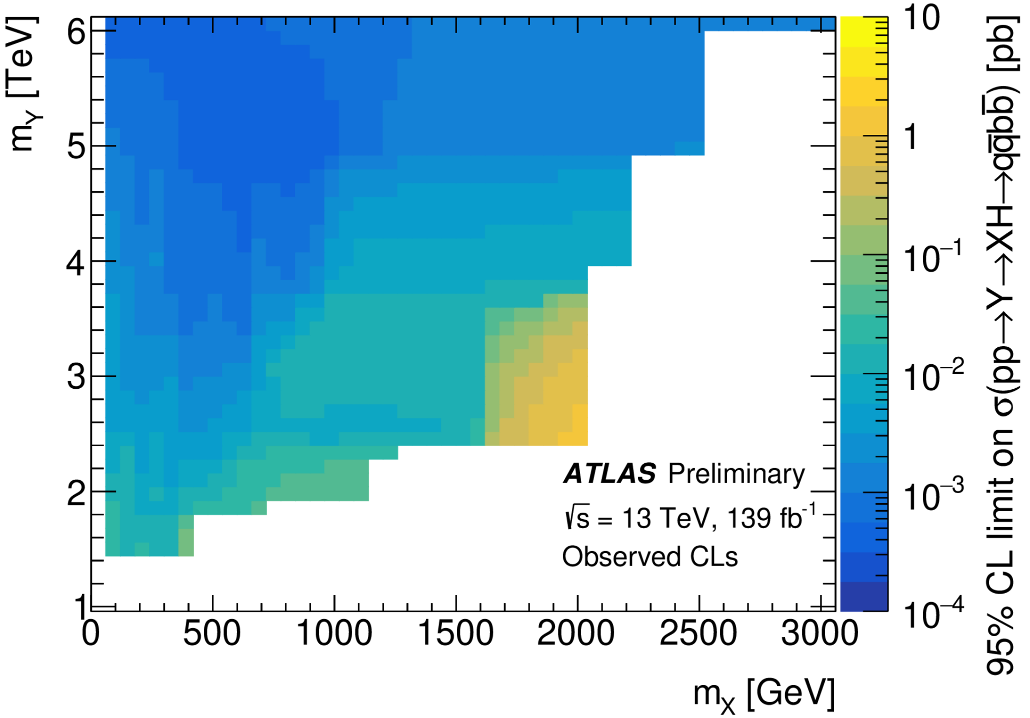
Search for resonances in the channel Y → X+Higgs → $q\bar{q}$ $b\bar{b}$

ATLAS-CONF-2022-045

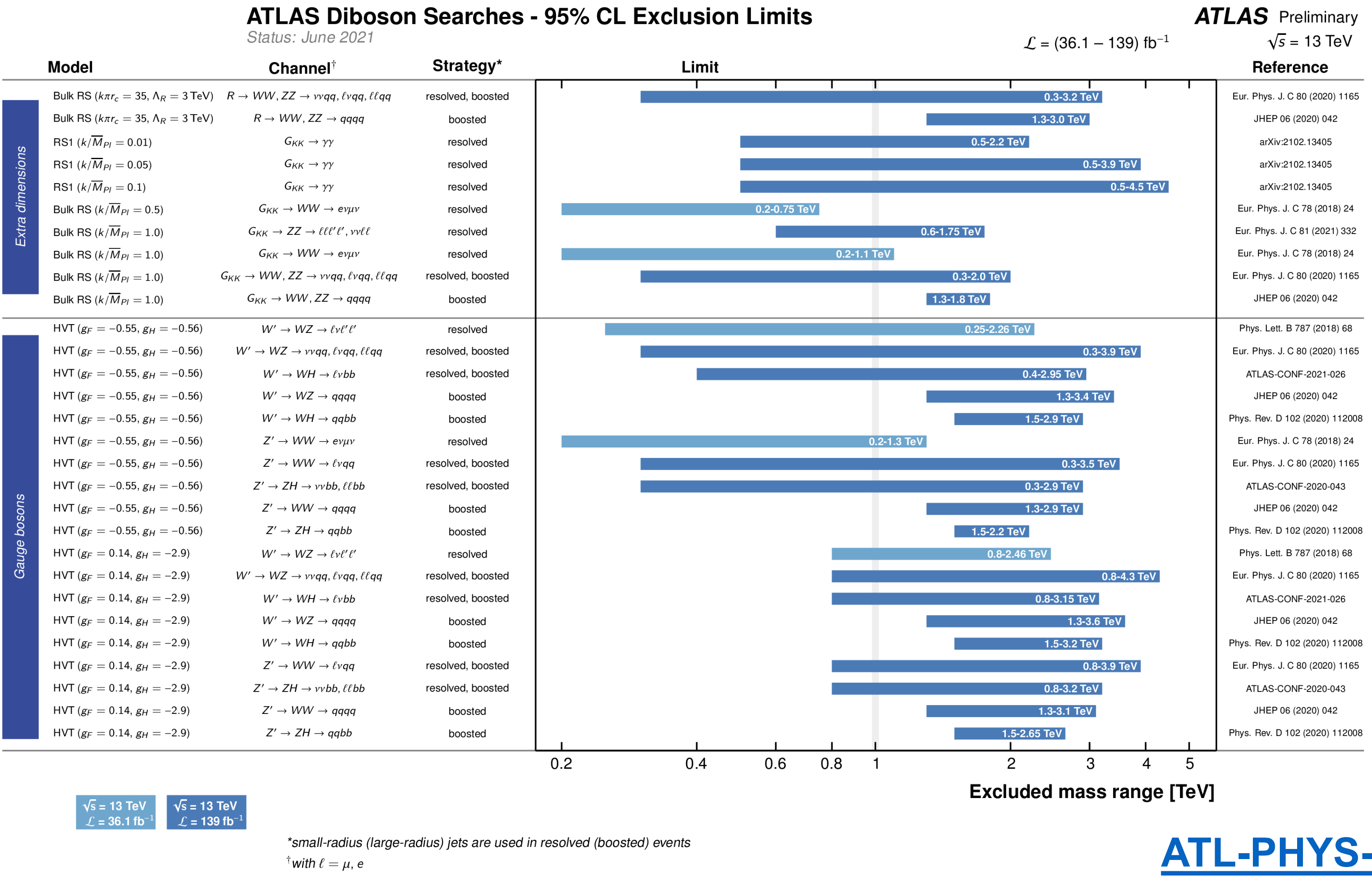
- At High Y mass (~1-6TeV), Y Reconstructed with two large-R jets
- Additional resolved region defined for less boosted X
  - X reconstructed with two small-R jets
- H Candidate identified using the Xbb tagger



- Model-independent discovery region
  - Use fully unsupervised variational recurrent neural network to tag X resonance
- HVT signal used as benchmark
- The most significant excess has a global significance of 1.47 σ.



Summary



- Reviewed many ATLAS Run-2 searches with boson final states
- Jet reconstruction and boson tagging are essential
  - Several improvements developed and included in analyses
- Further developments on going for Run-3

ATL-PHYS-PUB-2021-018

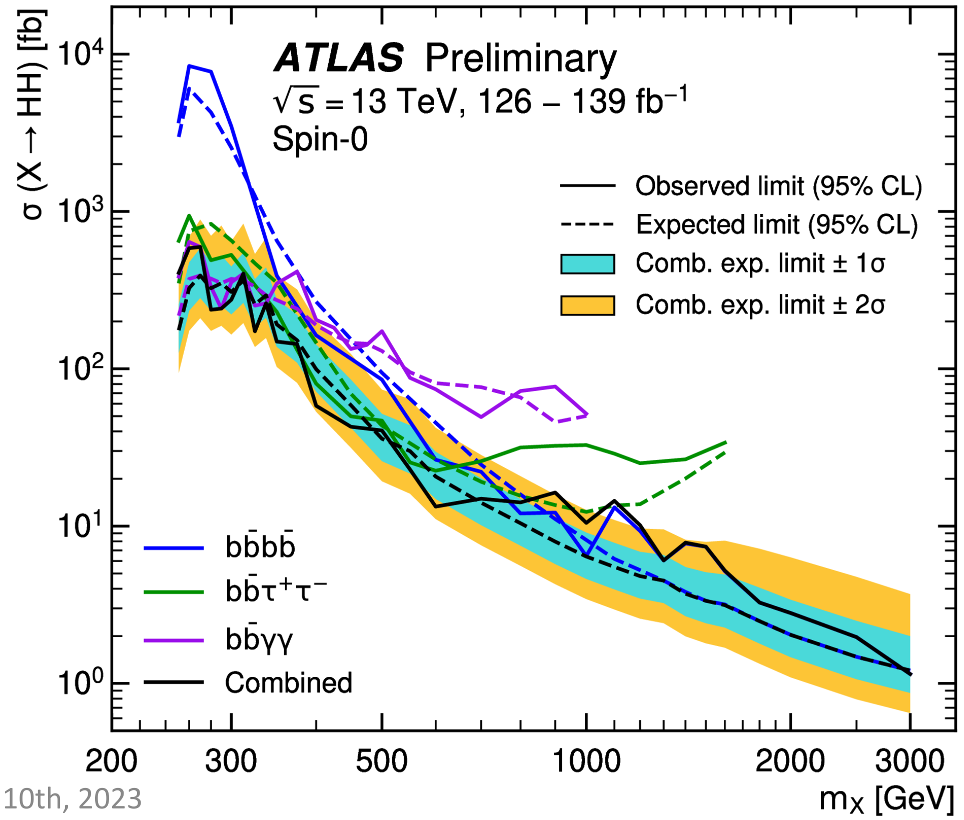
Thanks for your attention

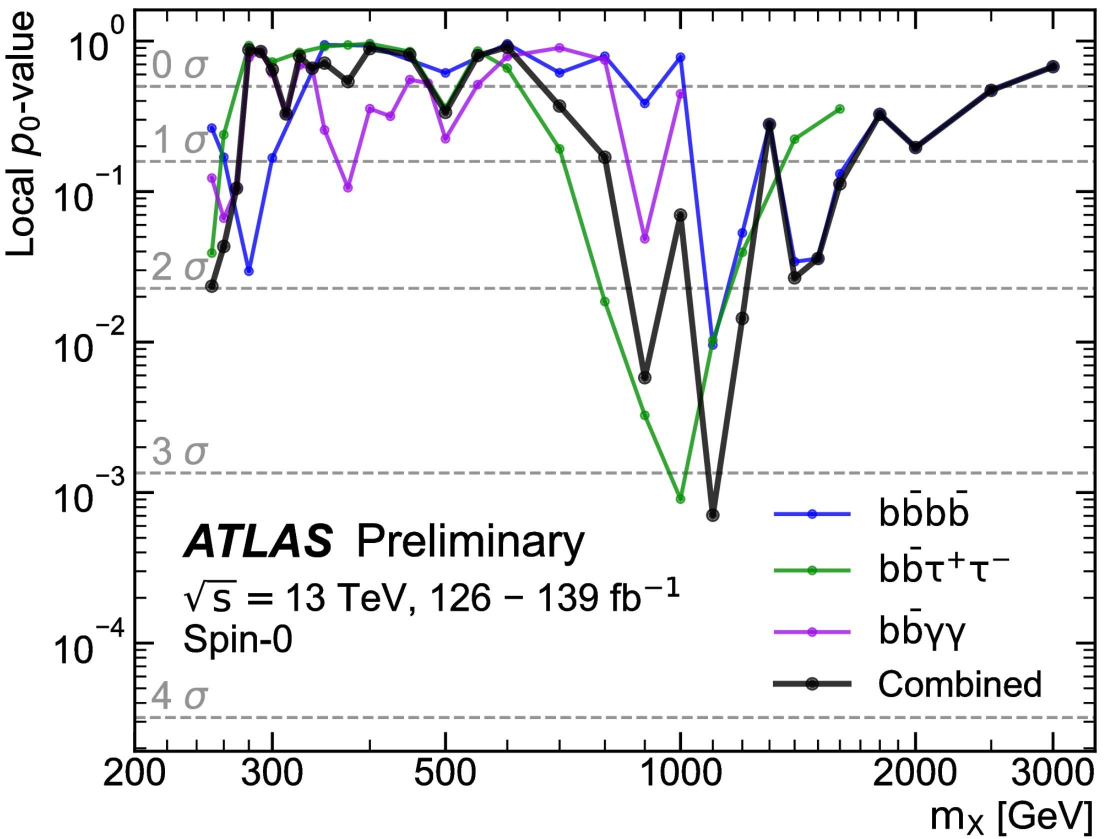
Combination of searches for resonant Higgs pair production

ATLAS-CONF-2021-052

- Combination of $b\bar{b}\,b\bar{b}$ + $b\bar{b}\,\tau\tau$ + $b\bar{b}\,\gamma\gamma$
- The largest excess is at m_X = 1.1 TeV
  - local (global) significance of 3.2σ (2.1σ).

	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$ resolved (boosted)
$\mathcal{B}(HH \to x\bar{x}y\bar{y})$	$2.6 \cdot 10^{-3}$	0.073	0.339
$\mathcal{L}_{\text{int}}$ [fb^{-1}]	139	139	126 (139)
Discriminant	$m_{\gamma\gamma}$	MVA outputs	m_{HH}
Resonance mass (m_X) range [GeV]	251–1000	251–1600	251–1500 (900–3000)



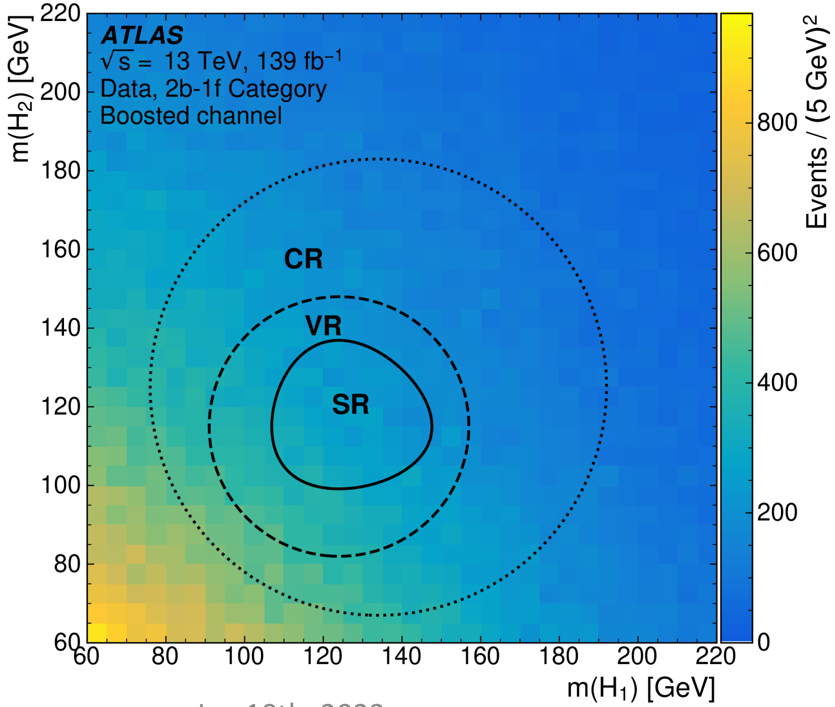


Search for resonant Higgs pair production in $b\bar{b}\,b\bar{b}$ channel

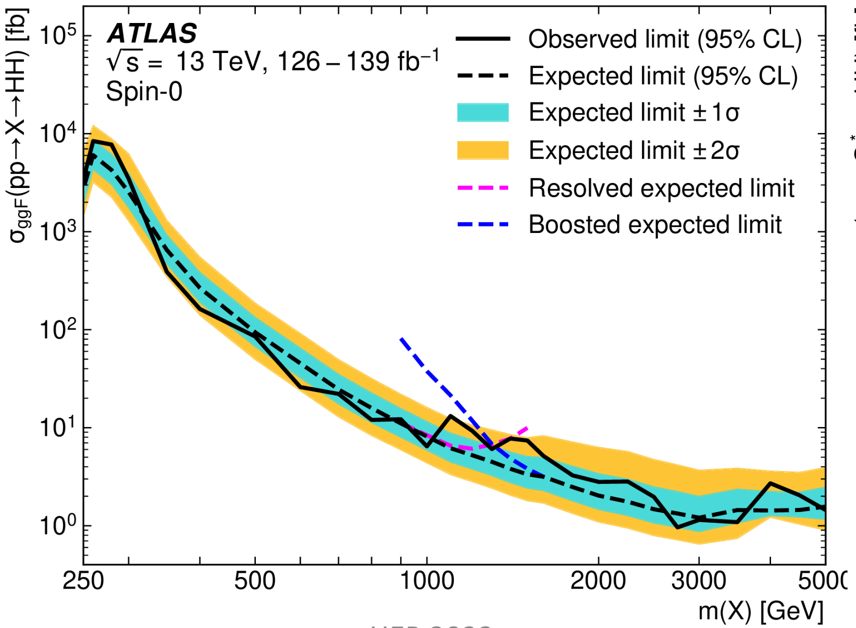
[Phys. Rev. D 105 (2022) 092002](#)

- Resolved channel (4 b-jets):
  - Machine learning-based jet pairing algorithm
  - Neural network-based background reweighting
- Boosted channel (2 large-R jets):
  - Variable radius track jets
  - Extended resonance mass range (to 5 TeV)

- Channel with largest BR for HH (34%)
- Backgrounds QCD multi-jet and ttbar
- Both channels use 3 regions in the Higgs candidate mass plane to extrapolate background in signal region with uncertainty



Narrow Width Scalar (X)



Spin 2 graviton (G)