ATLAS searches in the Higgs sector

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Sid (Luke) Baines (QMUL)
on behalf of
ATLAS Higgs, Multi-Boson and SUSY searches working group

ATLAS EXPERIMENT

CERN

Queen Mary University of London

Overview
& some 'glossary'

- Strong motivation for extended Higgs sector
  - Baryogenesis, dark matter, strong-CP problem, …
- Talk covers recent public results from ATLAS searches
  - $H \to \gamma\gamma$ low mass
  - **Brand new!** $S \to Z_d Z_d \to 4l$
  - **Brand new!** $H^{\pm} \to W^{\pm} h \to (lv/qq)bb$
  - $t \to H^{+} b \to cs\, b$
  - $H \to aa \to bb\tau\tau$
  - HH combination
  - $X \to HS \to \gamma\gamma +$ lepton(s)

All are full Run 2*, $\mathcal{L}_{\text{int}} = 140\text{fb}^{-1}$, $\sqrt{s} = 13$ TeV

Glossary of reappearing acronyms

- BDT: Boosted Decision Tree
- MC: Monte Carlo (simulations)
- SM: Standard Model
- CL: Confidence limit (on a cross-section)

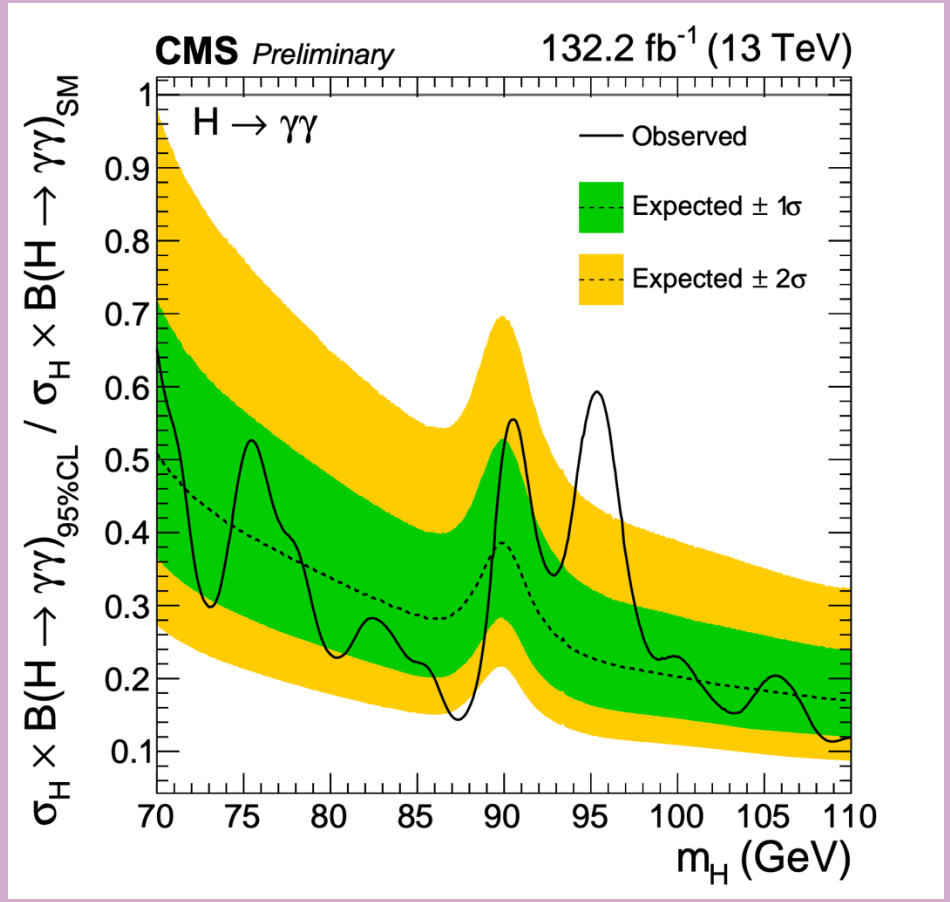
*HH combination has some channels with $\mathcal{L}_{\text{int}} < 140\text{fb}^{-1}$ due to trigger

$H \to \gamma\gamma$ low mass

Motivation

arXiv: 2407.07546
Submitted to: JHEP

- Previous bumps ~95GeV
  - Small (1σ) bump at ATLAS using ½ Run 2 data
  - Followed by larger 2.9σ bump at CMS (full Run 2)
- Updated ATLAS search using full Run 2
- Both model-independent & model-dependent search for narrow resonances
- Covers range: 66 – 110 GeV



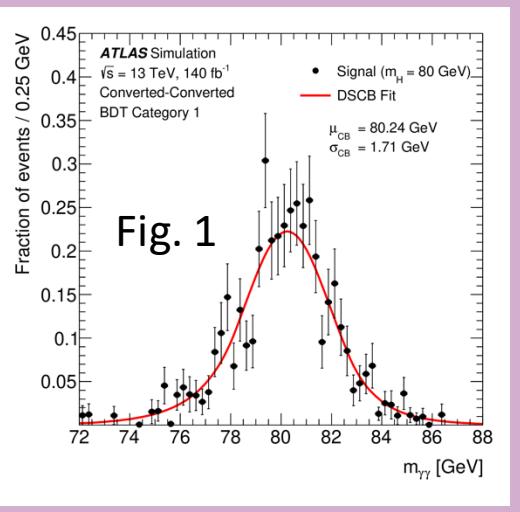
2.9σ local @ 95.4GeV with CMS full Run 2 [CMS-HIG-20-002]

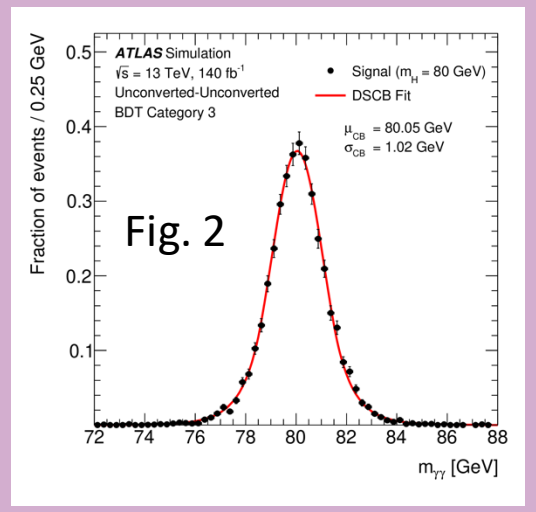
$H \to \gamma\gamma$ low mass

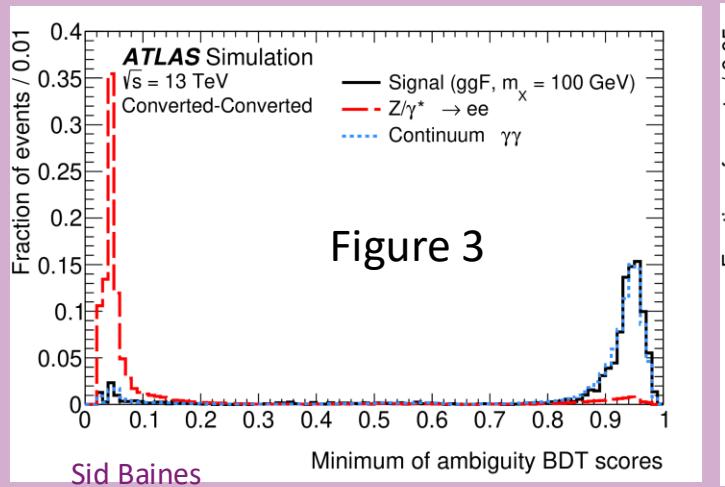
Strategy

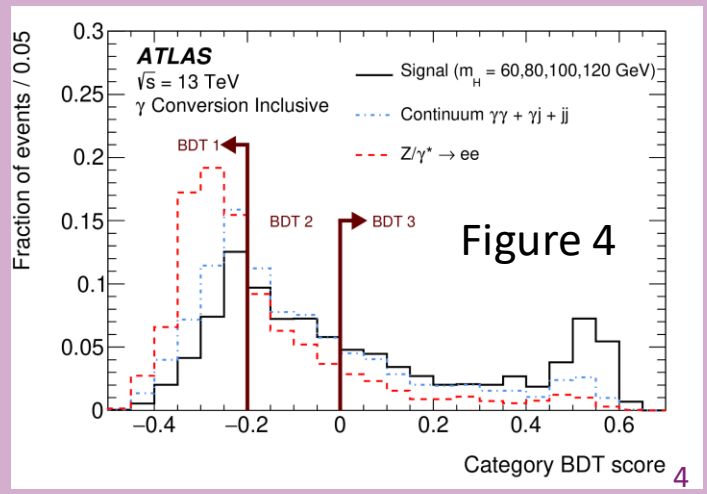
arXiv: 2407.07546
Submitted to: JHEP

- Event selection:
  - Di-photon trigger with $p_T > 20 - 22$ GeV + isolation requirement
  - Mass-dependent E_T cut to avoid trigger sculpting
- Backgrounds: 'continuum' $\gamma\gamma$ / γ+jet / jets, $Z \to ee$ photon-fakes
  - Model continuum background with double-sided crystal ball (MC/data driven) [fig. 1-2]
- Apply BDT to reject electron-fakes [fig. 3]
- For model-dependent, second BDT [fig. 4] looks for Higgs-like resonance (using SM-couplings)









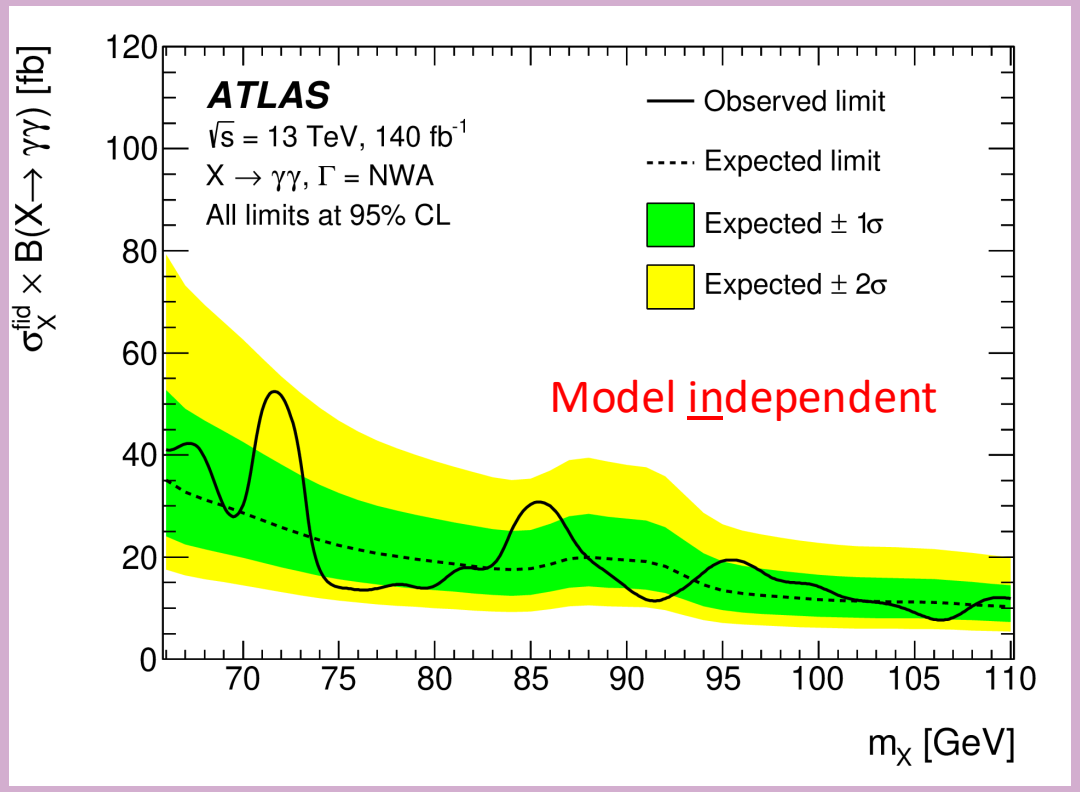
$H \to \gamma\gamma$ low mass

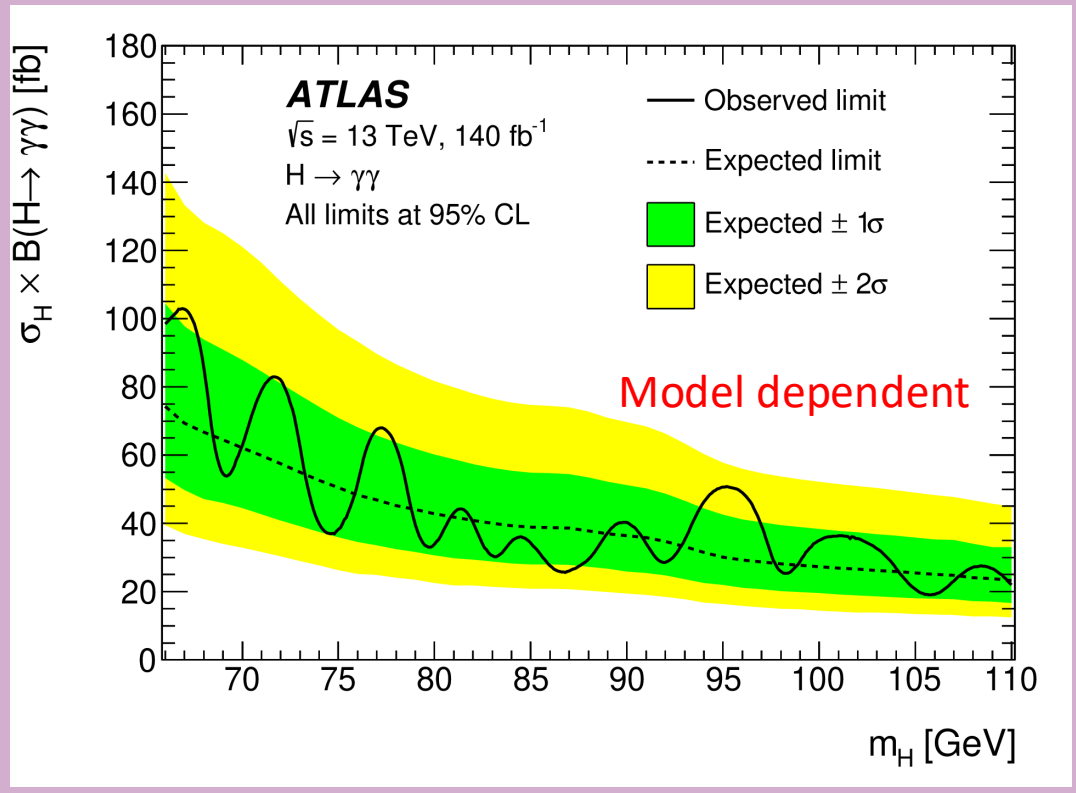
Results

arXiv: 2407.07546
Submitted to: JHEP

- No confirmation of previous excesses

95% confidence limits on cross section times branching ratio



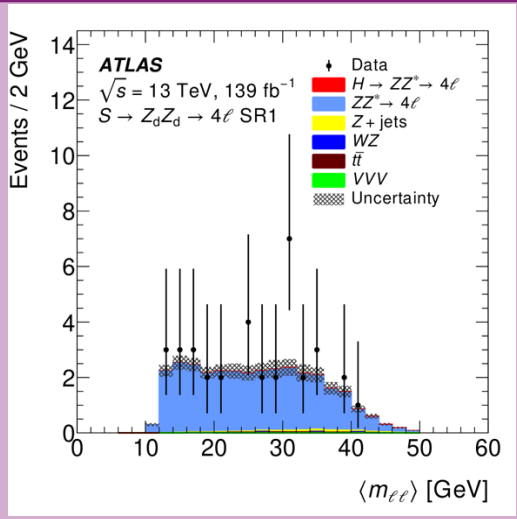


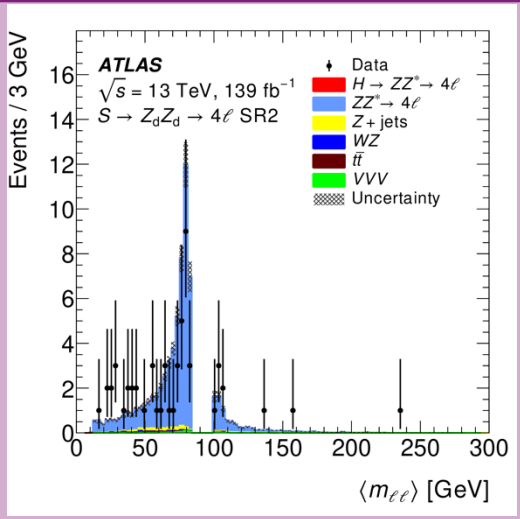
$S \to Z_d Z_d \to 4l$

Motivation & strategy

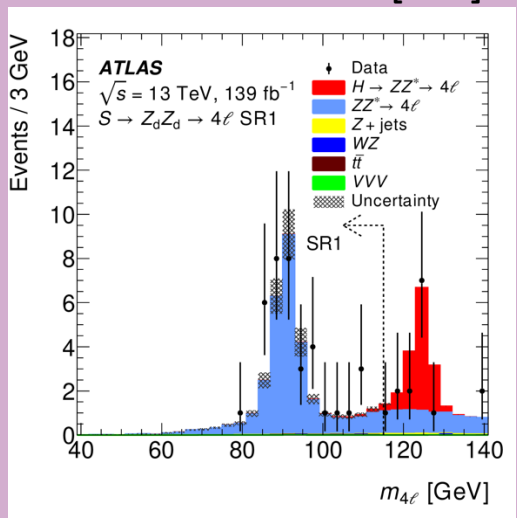
arXiv: 2410.16781
Submitted to: Phys. Lett. B

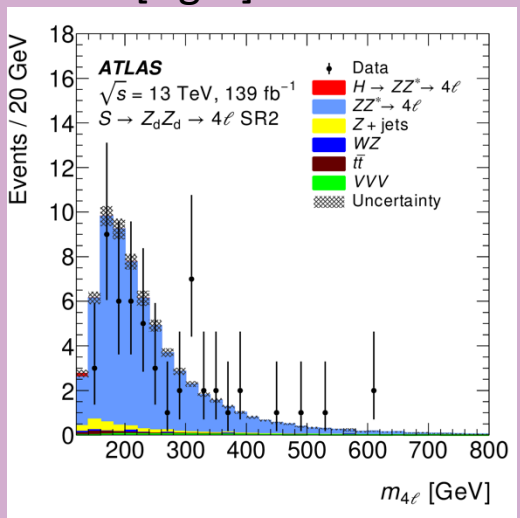
- New scalar S decaying into new spin-1 bosons Z_d
  - $m_{Z_d} \in [15, 300]$GeV
  - $m_S \in [30, 115]$GeV **or** $[130, 800]$GeV
- Event selection: 4-leptons
  - Includes requirements on P_t, angular separation, pairwise-combined mass values, and more
- Backgrounds:
  - Dominant: non-resonant $ZZ^* \to 4l$ modelled using MC
  - Additional: $t\bar{t}$, Z+jets estimated using data-driven
- Split into signal regions
  - SR1: $m_{4l} < 115$GeV
  - SR2: $m_{4l} > 130$GeV
- Fit $\langle m_{ll} \rangle$, the average dilepton mass





$\langle m_{ll} \rangle$ [above] and m_{4l} [below] fits for SR1 [left] and SR2 [right]

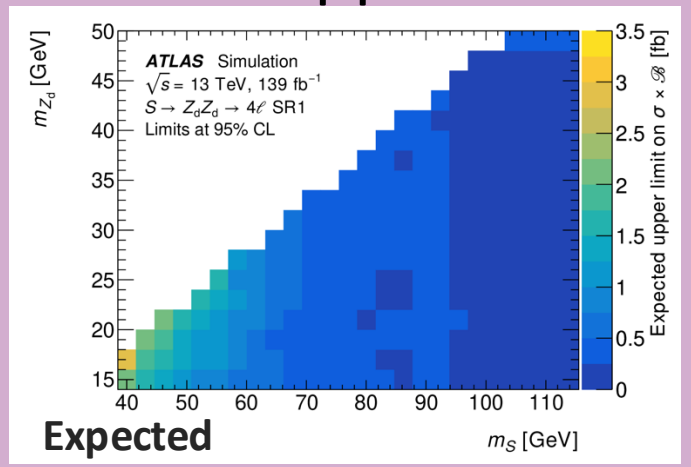


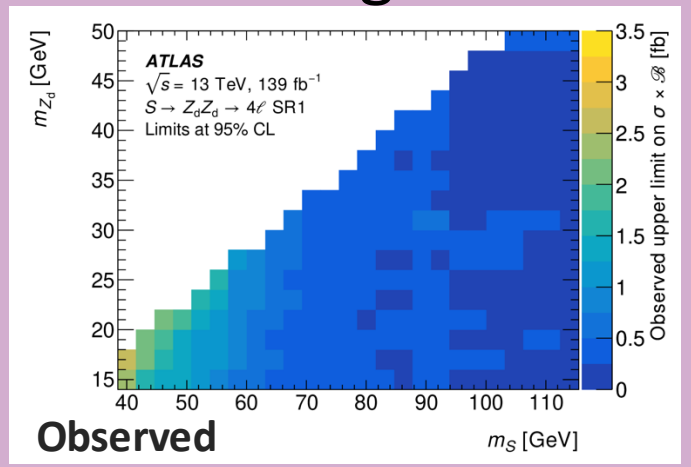


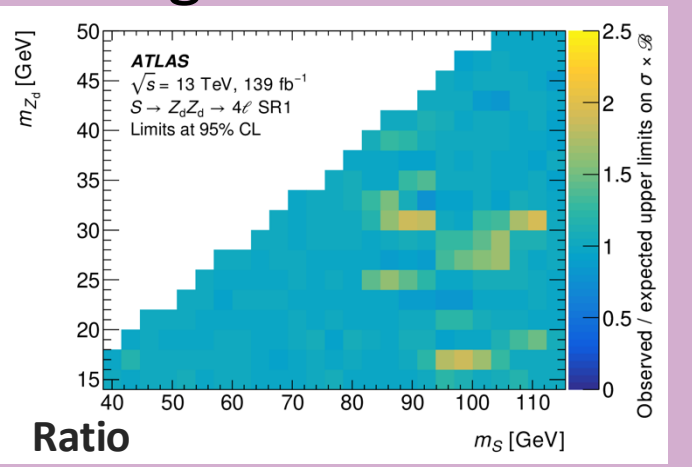
$S \to Z_d Z_d \to 4l$ Results

arXiv: 2410.16781
Submitted to: Phys. Lett. B

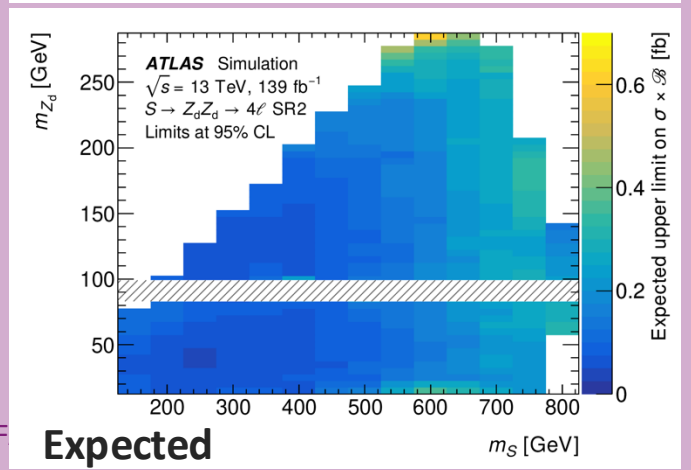
- No significant excess observed
- 95% upper CL on σ × branching ratio set for range of masses

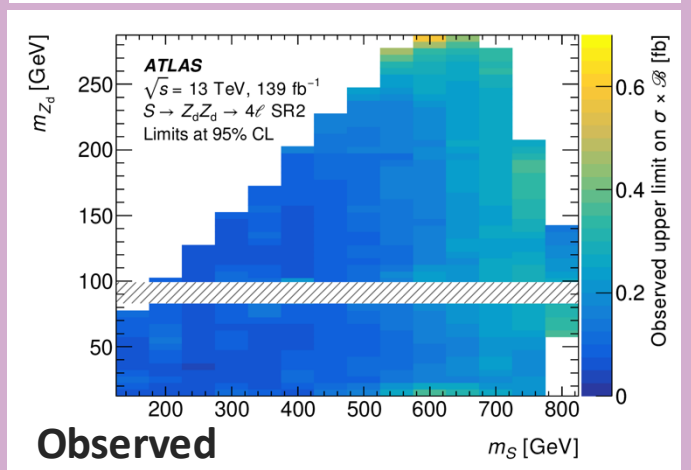


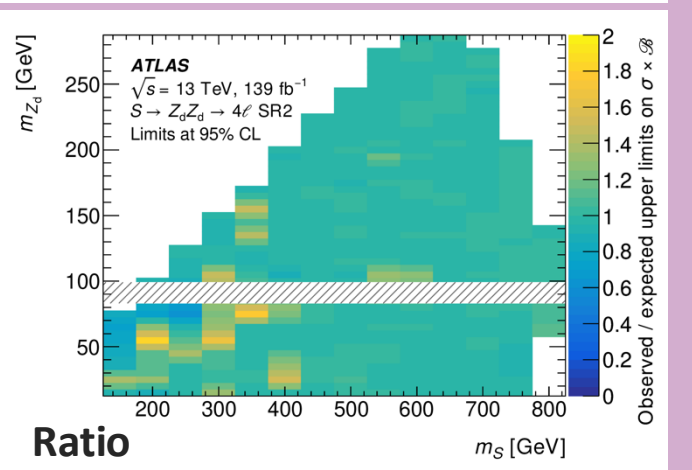




SR1







SR2

$H^{\pm} \rightarrow W^{\pm}h \rightarrow (l\nu/qq)bb$

Motivation & strategy

arXiv: 2411.03969
Submitted to: JHEP

- N2HDM, 3HDM, Georgi-Machacek model
  - $H^{\pm} \rightarrow W^{\pm}h$ decay mode becomes important
- Single-lepton, multi-jet (including b-jets) final state
- Backgrounds: $t\bar{t}$, W+jets, Z+jets
  - Modelled using MC (data-driven corrections to $t\bar{t}$)
- Split based on $h \rightarrow bb$: resolved or merged

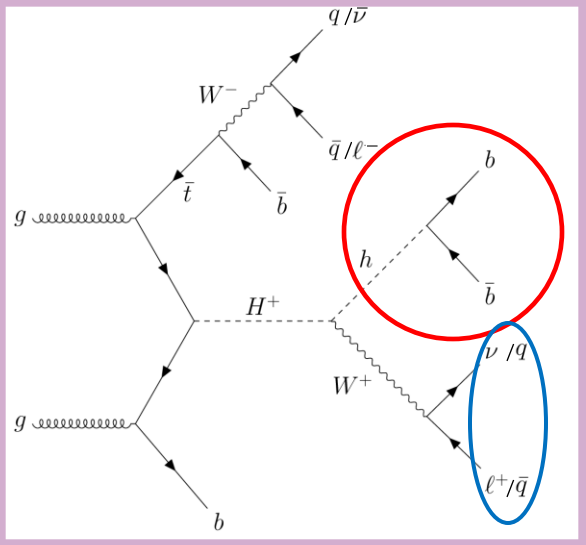
Resolved

- h expected as 2 b-jets
- Use m_t to **split** $l\nu bb$ vs. $qqbb$
- Use BDT to reconstruct event
- Use (same) BDT reconstruction score to define regions

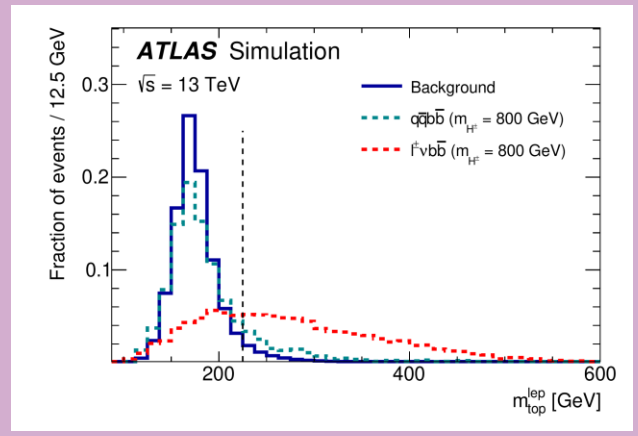
Merged

- h expected as 1 large-R ‘boosted $h \rightarrow bb$’-tagged jet
- **Split** $l\nu bb$ vs. $qqbb$ by number/masses of large-R jets
- Reconstruct event by hand
- Train NN to define regions

- Fit on $m_{W^{\pm}h}$ (30 channels!)
  - Combine CLs: resolved $m_{H^{\pm}} \leq 900$GeV, merged $m_{H^{\pm}} \geq 900$GeV



Representative Feynman diagram of signal

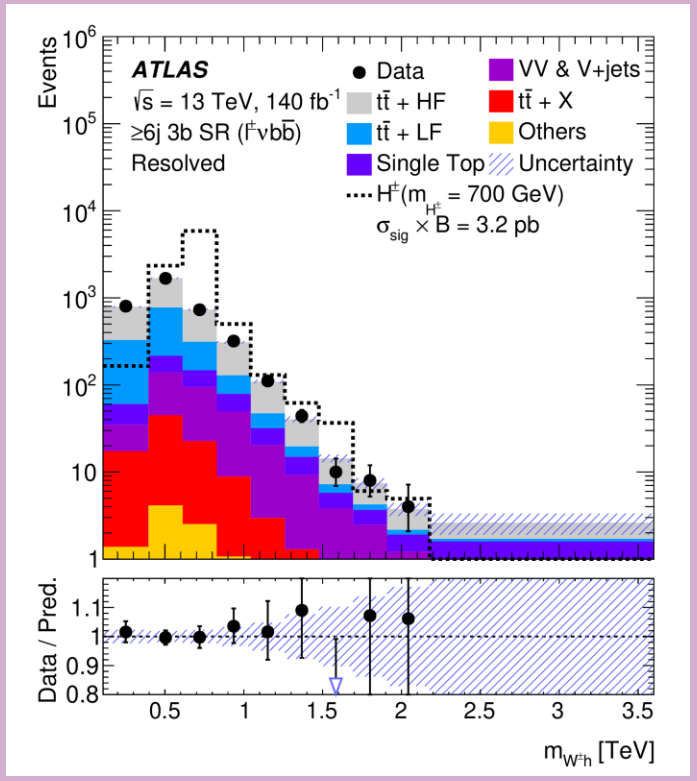


Reconstructed top mass m_t for resolved channel

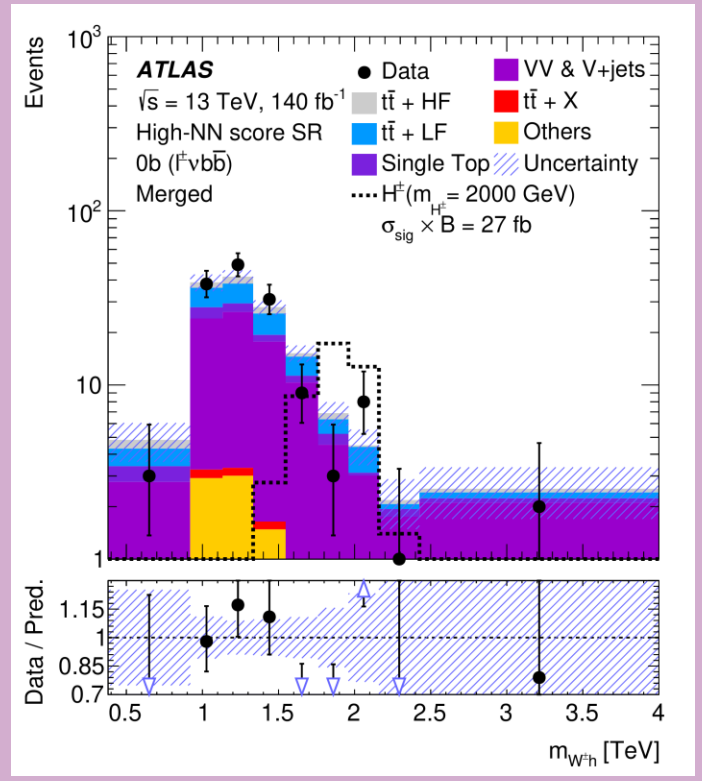
$H^{\pm} \rightarrow W^{\pm}h \rightarrow (l\nu/qq)bb$ Results

arXiv: 2411.03969
Submitted to: JHEP

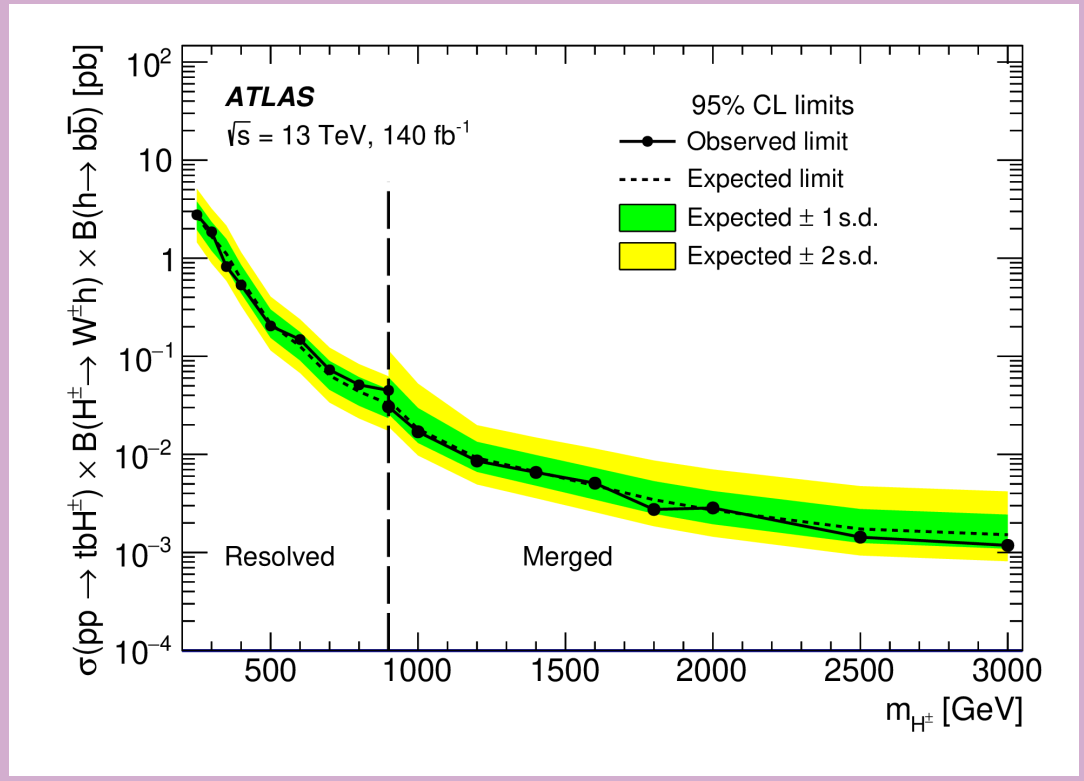
- No significant excess observed



Post-fit $m_{W^{\pm}h}$ distribution for example resolved signal region



Post-fit $m_{W^{\pm}h}$ distribution for example merged signal region



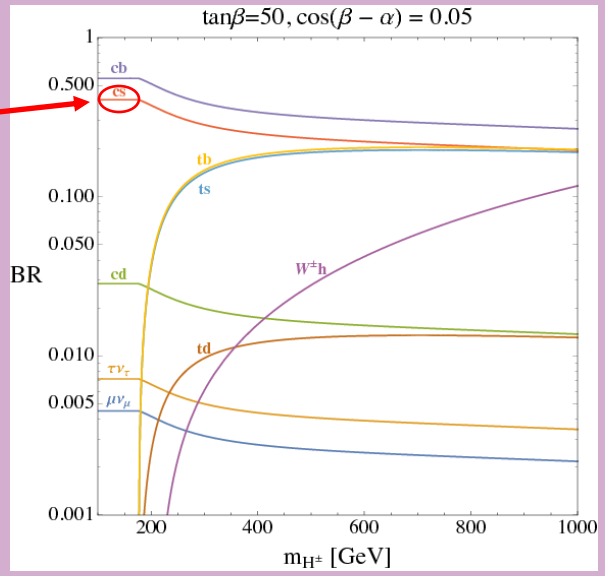
95% confidence limits on cross section times branching ratio

$t \to H^{\pm} b \to cs\ b$

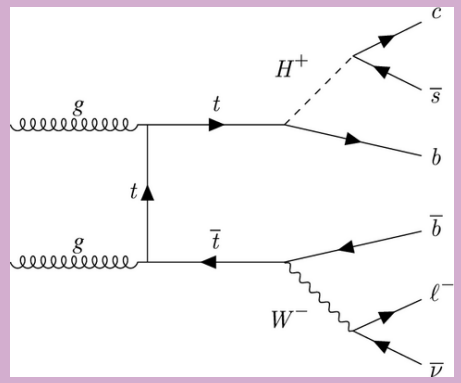
Motivation & strategy

arXiv: 2407.10096
Submitted to: EPJ C

- BSM Higgs extensions (eg. 2HDM with $\tan\beta < 1$)
- Large branching ratio at $H^{\pm}$ masses below m_t
  - Covers 60 GeV$< m_{H^{\pm}} <$ 168 GeV
- Previous CMS result* with less data & smaller mass range
- Main background: $t\bar{t}$
- Strategy:
  - Single lepton + multi-jet final-state event selection
  - Pseudo-continuous b/c jet-tagging using DL1r tagger
  - Reconstruct $t\bar{t}$ system fully
  - Background modelling: MC simulation + data-driven corrections
  - Use Boosted Decision Tree (BDT) to classify events
  - Binned maximum-likelihood fit on BDT score



Branching ratios of charged Higgs [Phys Rev D 94 (2016) 115032]



Feynman diagram of signal process

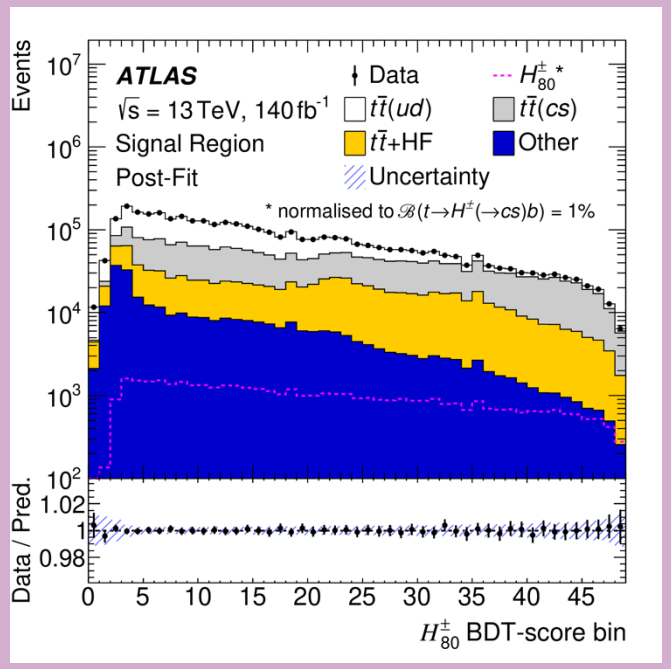
* [arXiv:2005.08900]

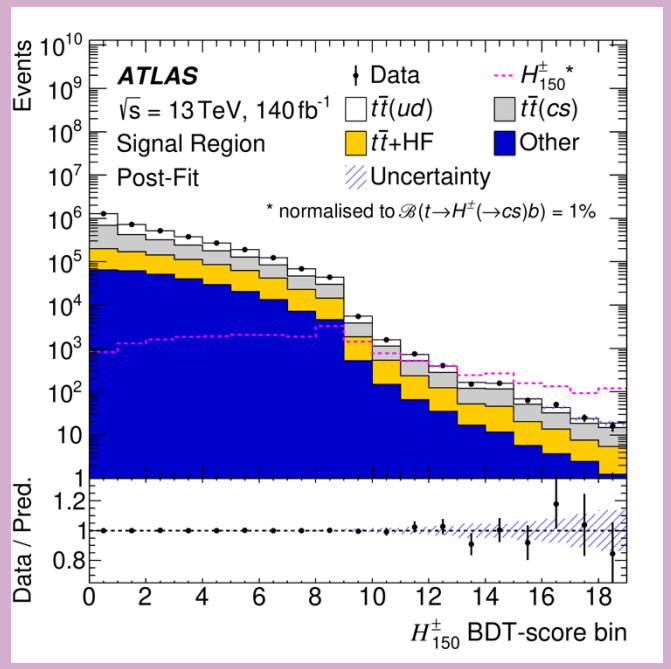
$t \to H^{\pm} b \to cs\ b$

Results

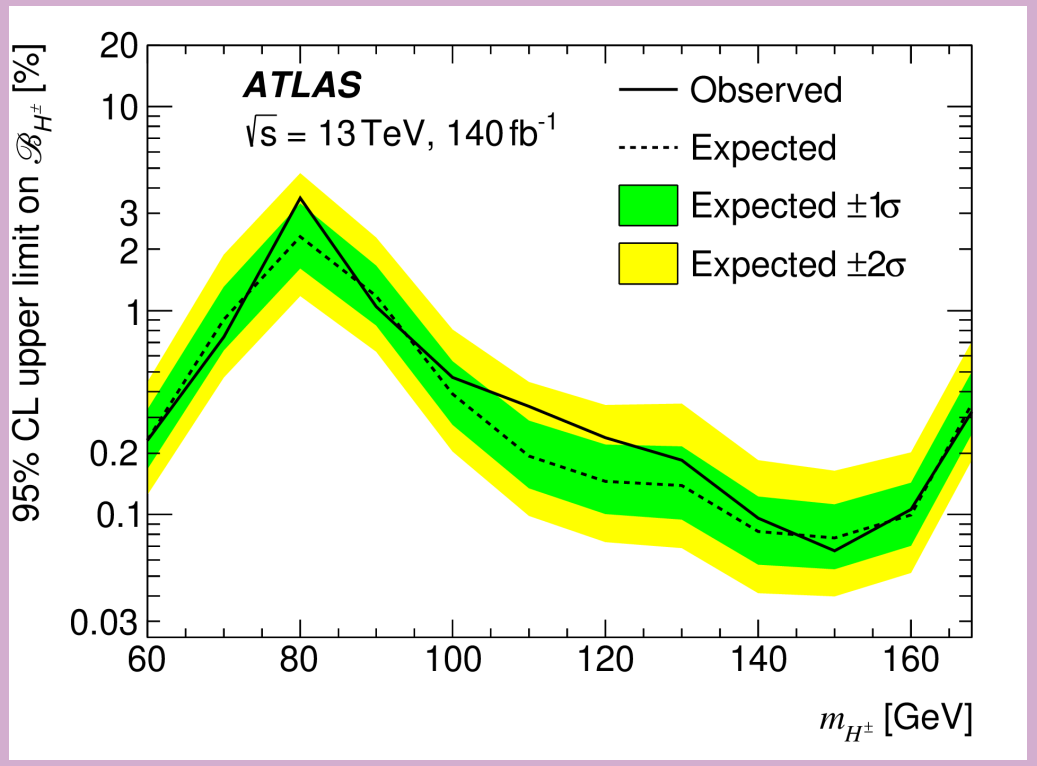
arXiv: 2407.10096
Submitted to: EPJ C

- No significant excess found





80GeV (left) and 150GeV (right) BDT score distributions



95% Confidence limits on branching ratio
[assumes B(t → Wb) + B(t → H±(→ cs)b) = 1.0]

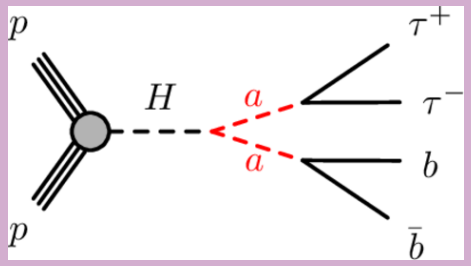
$H \to aa \to bb\tau\tau$

Motivation & strategy

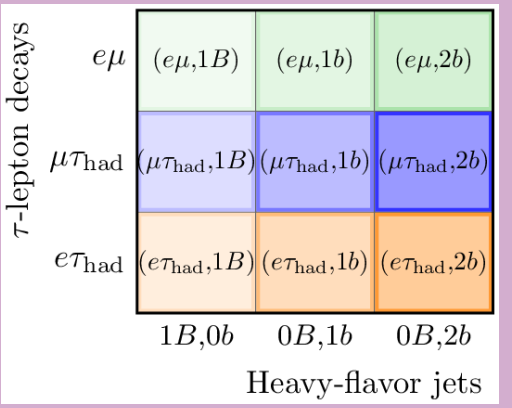
arXiv: 2407.01335
Accepted by: Phys. Rev. D
DOI: 110.052013

ATLAS EXPERIMENT

- Decay of SM 125 GeV Higgs boson into 2 light pseudoscalars a
  - $12\ \text{GeV} < m_a < 62\ \text{GeV}$
- Backgrounds: τ_{had}-fakes, e/μ-fakes, tt+jets, Z+jets
- Event selection:
  - e/μ ($p_T > 27\text{GeV}$) **or** $e\mu$ triggers
  - small-radius b jet(s) **or** large-radius B jet
    - b-jet originates from 1 b-hadron, B-jet originates from $a \to bb$ pair
- Dedicated B-tagger used since others struggle for low-mass parents [see ATL-PHYS-PUB-2022-042]
- Parametrised neural network (pNN) trained using heavy-flavour jet + tau-lepton variables



Feynman diagram of signal process



Event selection categories

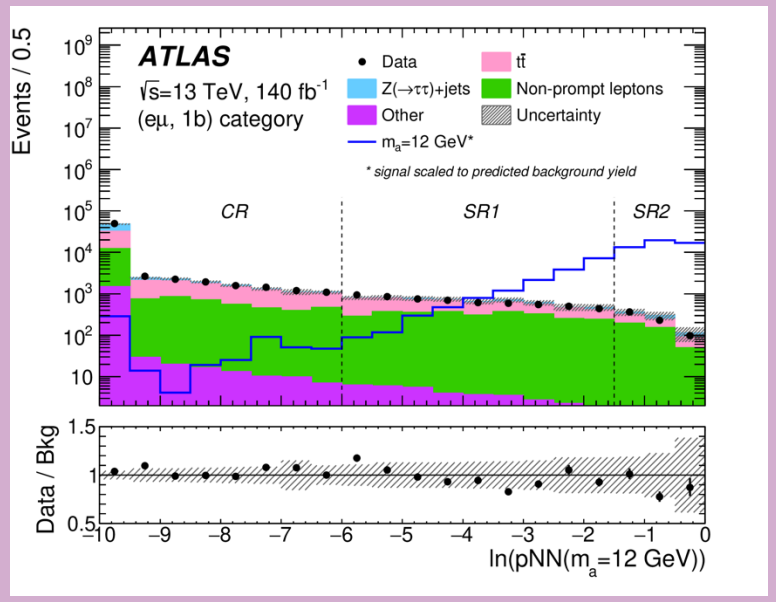
$H \to aa \to bb\tau\tau$

Results

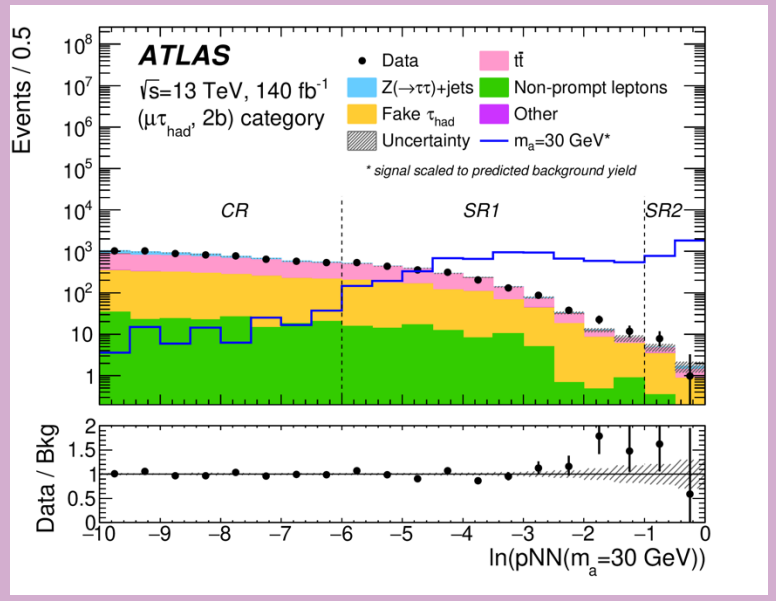
arXiv: 2407.01335
Accepted by: Phys. Rev. D
DOI: 110.052013

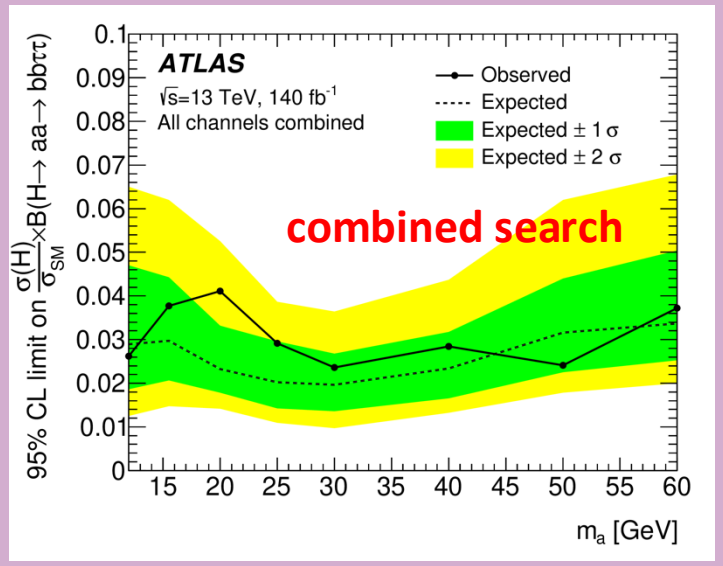
- No significant excess found

Parametrised neural network output for $e\mu - 1b$ category

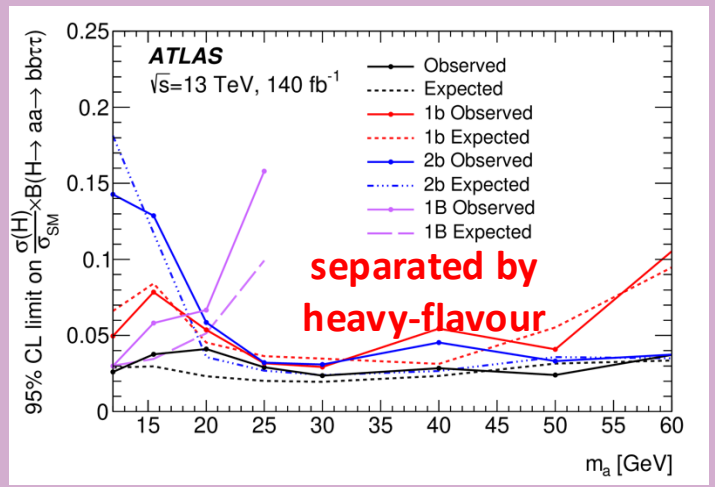


Parametrised neural network output for $\mu\tau_{\text{had}} - 2b$ category





95% confidence limits



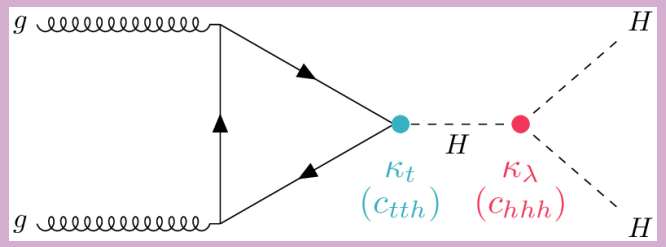
HH combination

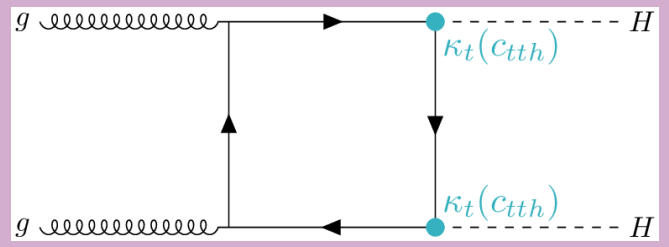
Motivation

arXiv: 2407.07546
Accepted by: PhysRevLett
DOI: 133.101801

- Di-Higgs of interest…

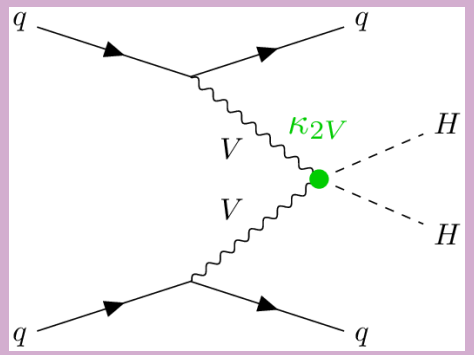
…in SM

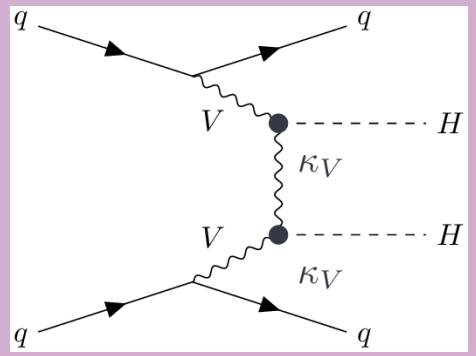


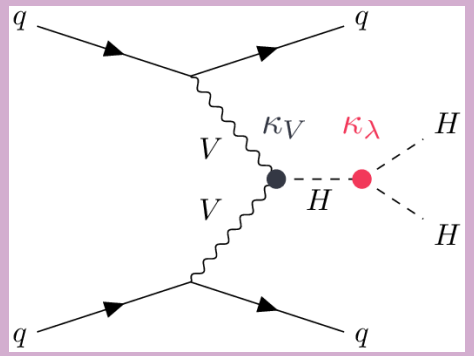


Above: SM gluon-gluon fusion production of Higgs pairs

Below: SM vector boson fusion production of Higgs pairs

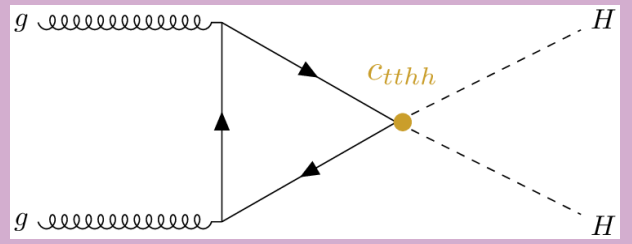


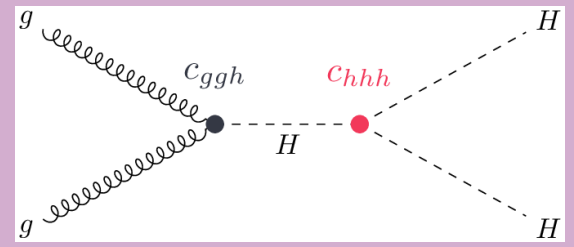


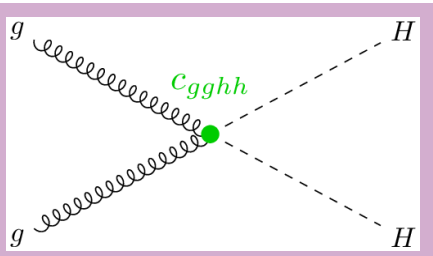


…and beyond

Non-SM gluon-gluon fusion production of Higgs pairs







HH combination

Analysis strategy

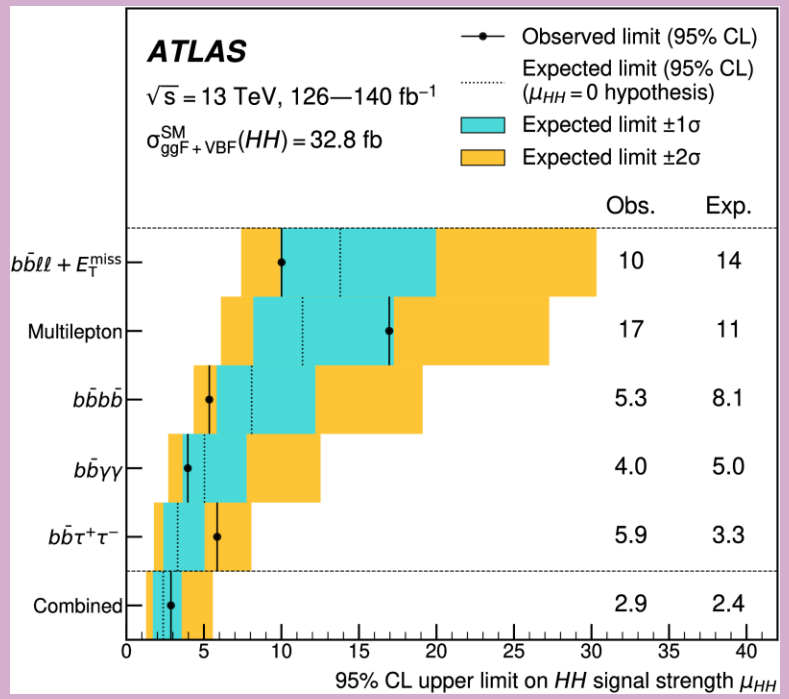
arXiv: 2407.07546
Accepted by: PhysRevLett
DOI: 133.101801

- Combined results from several decays:
  - $b\bar{b}b\bar{b}$ - now using both resolved & merged (ie boosted) topologies
  - $b\bar{b}\tau^+\tau^-$ - better classification, higher stats, better background modelling
  - $b\bar{b}\gamma\gamma$ - better classification
  - multilepton
  - $b\bar{b}ll$+ E_T^{miss}
- Fit to different variables per decay channel
- Create ‘global likelihood’ as product of individual channel likelihoods
  - Check overlaps & uncertainty correlations between channels
- Signal strength μHH defined as:
  - ratio of measured inclusive ggF and VBF HH production cross section to the SM prediction

HH combination

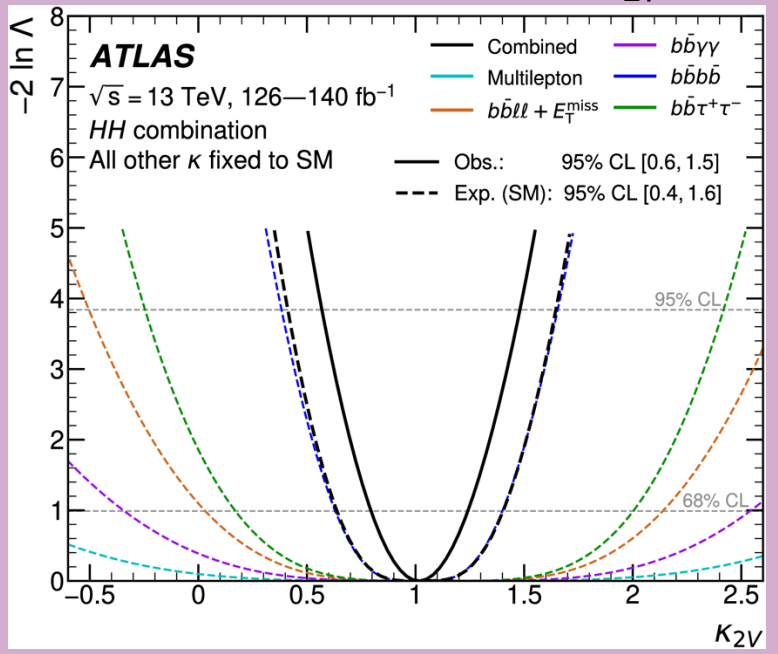
Results

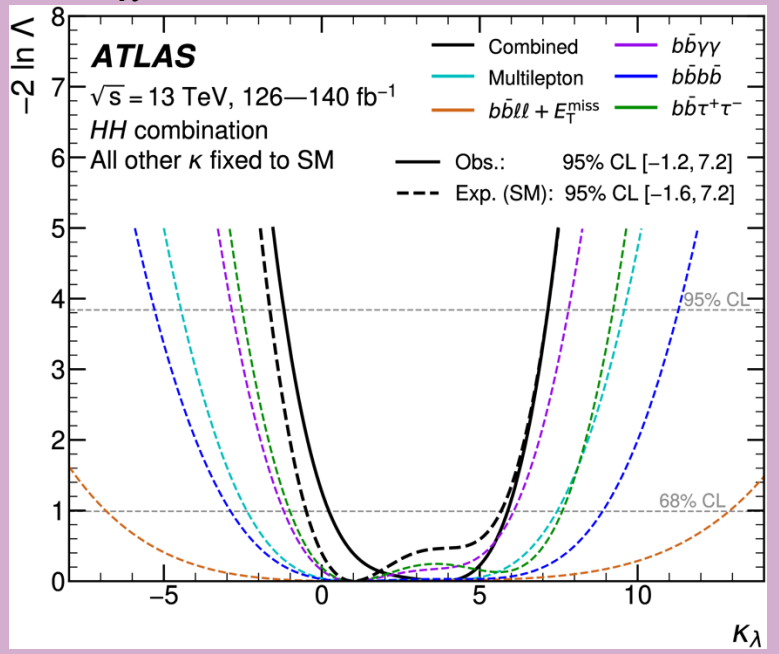
arXiv: 2407.07546
Accepted by: PhysRevLett
DOI: 133.101801



95% CL upper limits on the signal strength μHH

Expected & observed values of test statistic as functions of κ_{2V} (left) and κ_λ (right)





Observe 17% improvement in limits from previous analysis [arXiv: 2211.01216]:

- 13% from improvements to existing channels
- 4% from addition of multilepton & $b\bar{b}ll+ E_T^{\text{miss}}$

$X \to HS \to \gamma\gamma$ + lepton(s)

Motivation & strategy

arXiv: 2405.20926
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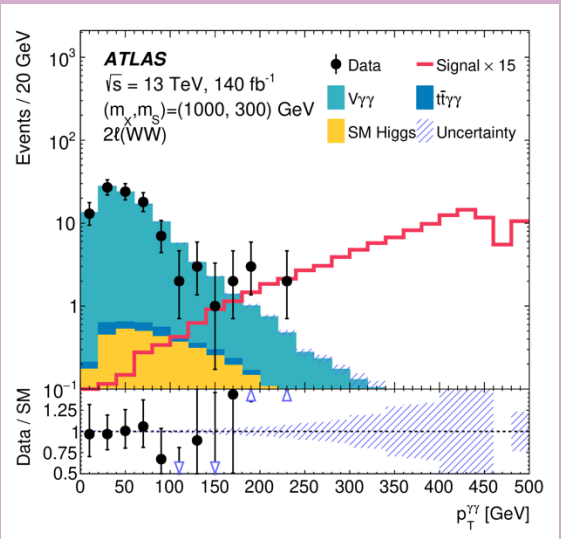
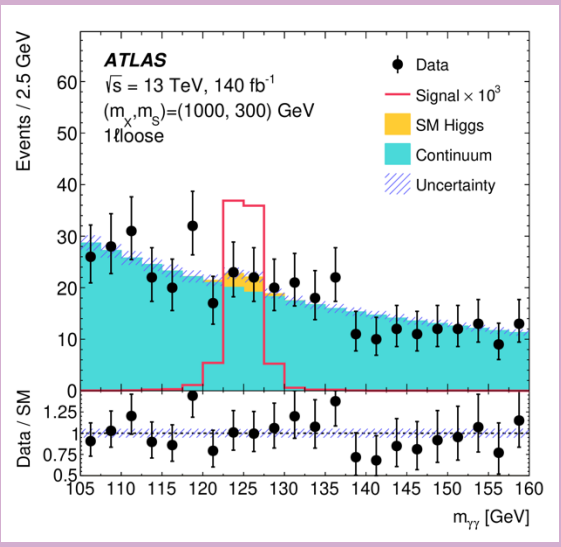
DOI: JHEP10(2024)104

- Search for $X \to Sh$ using a new final state
  - $S \to W^{\pm}W^{\mp}$ or ZZ
  - $h \to \gamma\gamma$
- Mass range
  - $m_X \in [300, 1000]$GeV
  - $m_S \in [170, 500]$GeV
- Event selection: di-photon + 1 or 2 leptons
- Background & modelling:
  - Resonant SM-Higgs uses MC-only modelling
  - Continuum ($\gamma\gamma$+jets, V+$\gamma\gamma$, $t\bar{t}\gamma\gamma$) uses MC + data-driven
- Define 6 signal regions
  - $1l$ + $2l$ ($W^{\pm}W^{\mp}$) use BDTs
    - Each split into loose & tight regions
  - $2l$ ($e\mu$) and $2l$ (ZZ) are cut-based
- Fit to $m_{\gamma\gamma}$

$p_{T_{\gamma\gamma}}$ distribution for the $2l$ ($W^{\pm}W^{\mp}$) region



$m_{\gamma\gamma}$ distribution for the $1l$ loose region



$X \to HS \to \gamma\gamma$ + lepton(s)

Results

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Accepted by: JHEP
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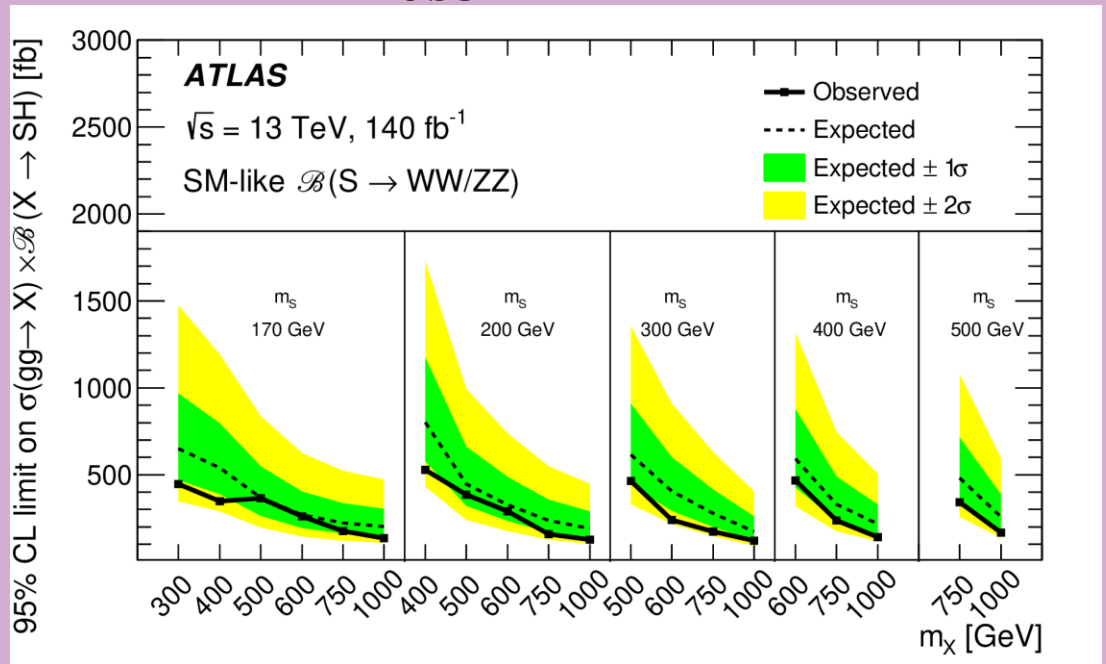
- No significant excess observed
- 95% Upper confidence limits set up to $m_X = 1\text{TeV}$, $m_S = 500\text{GeV}$
  - Including with SM-like branching ratio of S [see figure] as well as exclusively W/Z
  - With $\mathfrak{B}(S \to WW) = 100\%$: $\sigma_{\text{obs}} \in [91, 470]\text{fb}^{-1}$ $\sigma_{\text{exp}} \in [120, 610]\text{fb}^{-1}$
  - With $\mathfrak{B}(S \to ZZ) = 100\%$: $\sigma_{\text{obs}} \in [360, 1530]\text{fb}^{-1}$ $\sigma_{\text{exp}} \in [510, 2160]\text{fb}^{-1}$



Looking forward

- Lots of excellent analyses completed
  - Thanks to all collaborators!
  - Limit improvements and ‘firsts’ in several important decay channels
  - No significant excesses
- More Run 2 analyses (hopefully) soon to be published
- Also lots of exciting Run 3 analyses underway ☺