ATLAS + CMS Searches for DiHiggs

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Introduction

Di-Higgs production is a key process for Standard Model and Beyond-the-SM physics

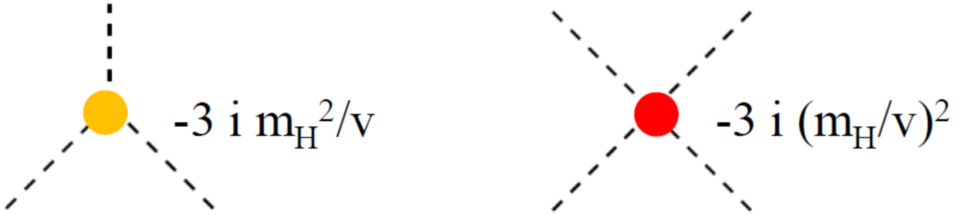
Discovery of **non-resonant HH production** would establish the shape of the Higgs potential and tests an important prediction of the SM by measuring λ_{HHH}

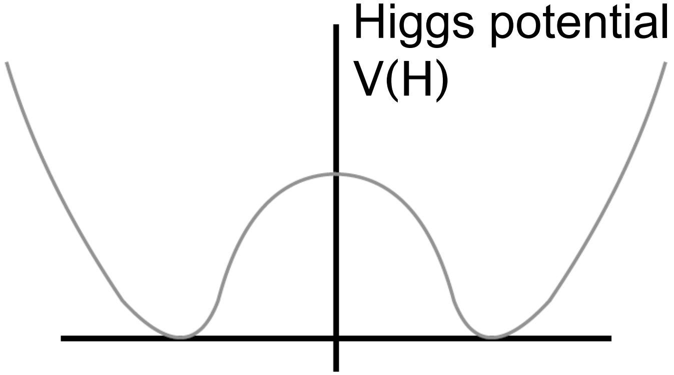
$$V(H) = \lambda v^2 H^2 + \lambda v H^3 + (1/4)\lambda H^4$$

$\lambda v^2 H^2$ → related to Higgs mass

$\lambda v H^3$ → trilinear self-coupling

$(1/4)\lambda H^4$ → quartic self-coupling





$$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$$

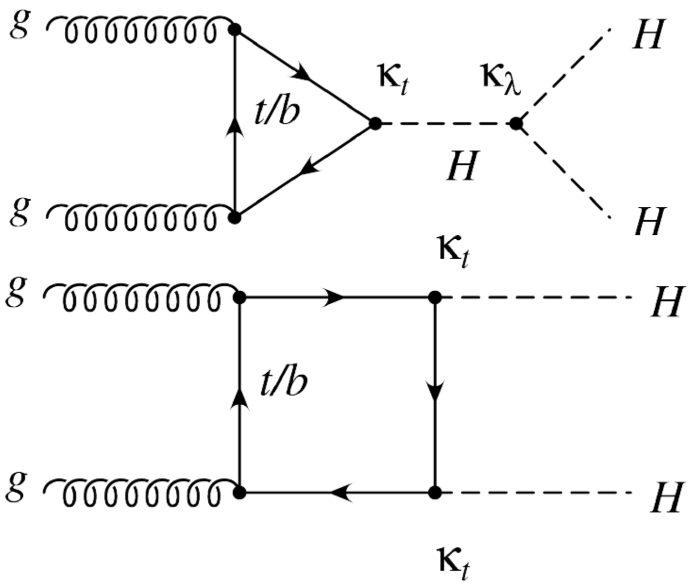
SM predicts $\kappa_\lambda = 1$

Gluon fusion:

The Box and Triangle diagrams interfere destructively.
SM HH cross section at 13 TeV is tiny: $\sigma(gg\rightarrow HH)$ = 31.1 **fb**
For comparison: $\sigma(gg\rightarrow H)$ = 48.68 **pb**

In case of deviations from the SM (κ_λ = 1), the HH cross section increases considerably (also m_{HH} shape changes).

→ Can already now establish constraints on that parameter κ_λ



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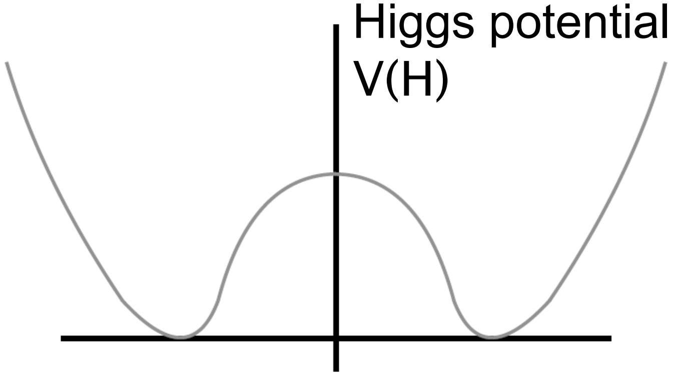

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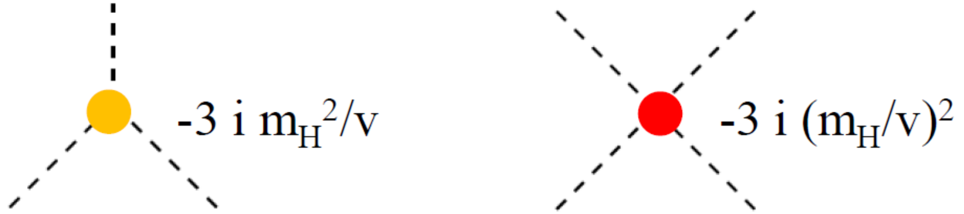
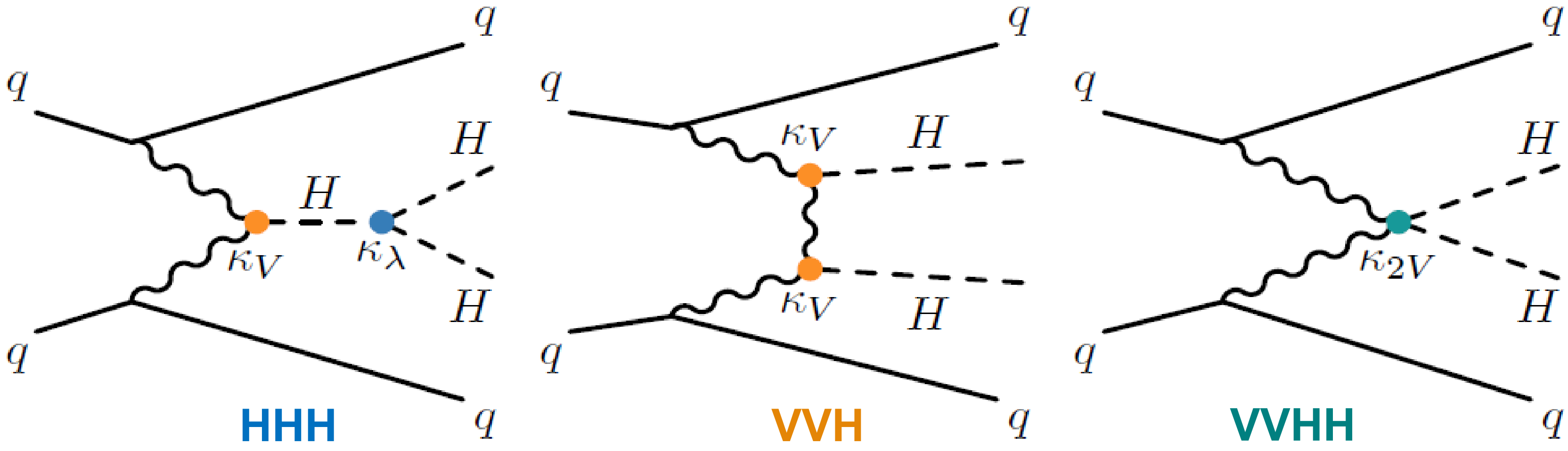


Vector boson fusion:



Cross section for non-resonant VBF (13 TeV): 1.73 fb

VBF production is sensitive to κ_{2V} coupling

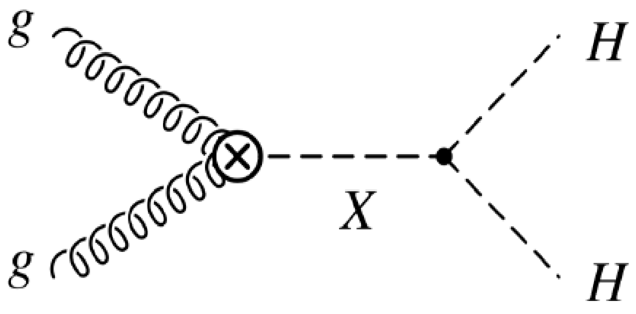
$$\kappa_{2V} = g_{HHVV} / g_{HHVV}^{SM}$$

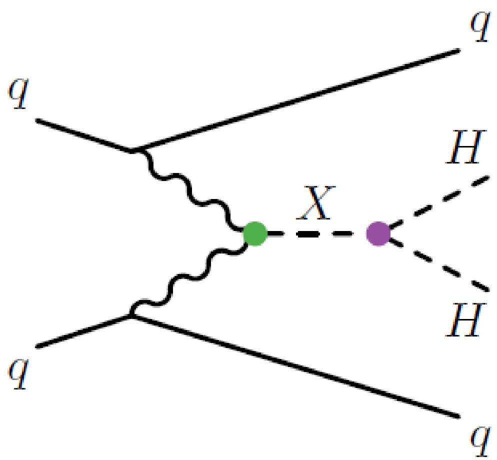
SM: $\kappa_{2V} = 1$

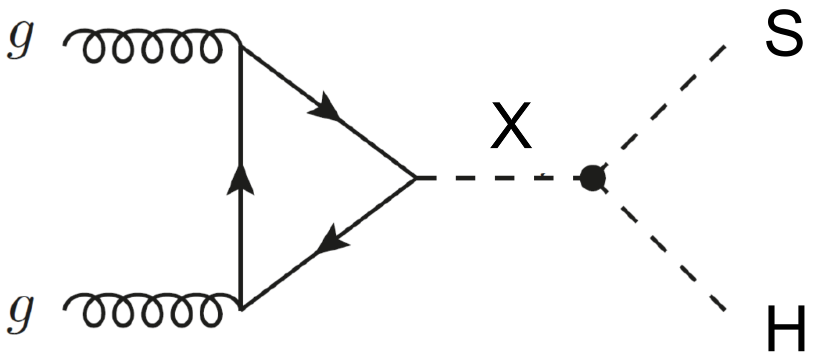
Introduction

Searches for **resonant production** of Di-Higgs could establish the presence of new particles

Limits on the production of these resonances can be used to constrain BSM model parameters







Benchmark signal models:

Heavy scalar X → HH, with a negligible decay width, could e.g. be a heavy Higgs in the MSSM

Spin-2 gravitons G → HH, as predicted by the bulkRandall-Sundrum model (with k/M_{Pl}=1)

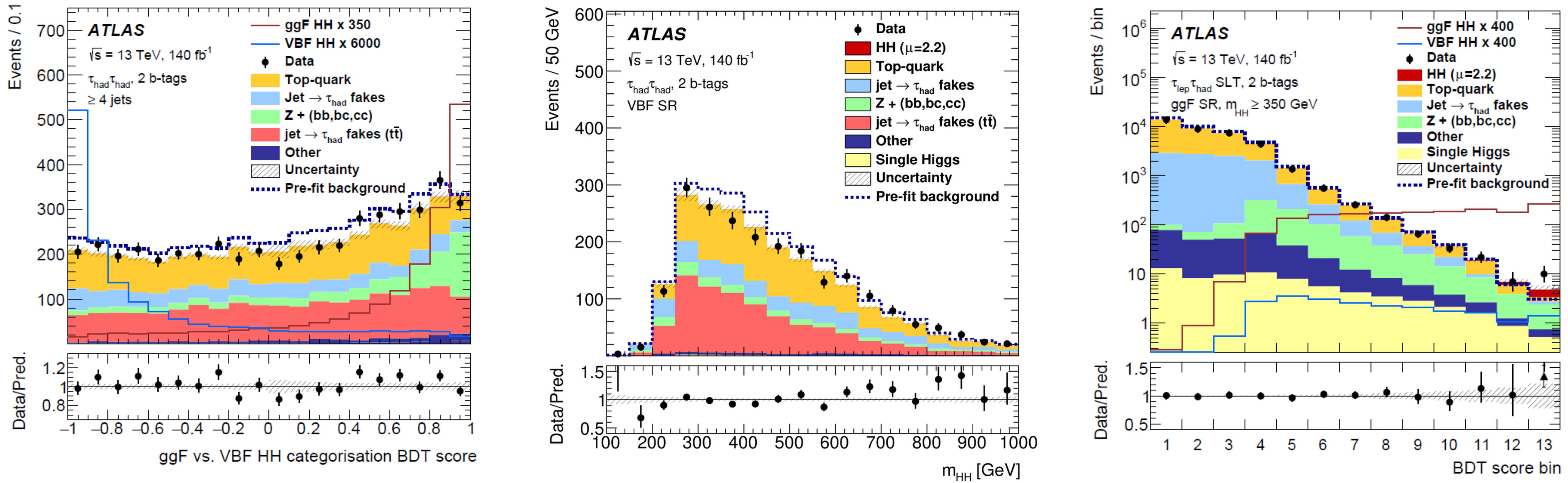
New: Narrow width scalar X → SH
Can have larger rates than X → HH in some models, e.g. TRSM, 2HDM+S, NMSSM, … for some parameter values.

Non-resonant HH → bbττ

New!

2404.12660

- Best non-resonant limit in previous round of publications (4.7xSM obs, 3.7 exp) 2209.10910
- New: **Better MVA classifier** and considering **VBF production** (in addition to ggF)
- Channels: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ **(single lepton triger)**, $\tau_{lep}\tau_{had}$ **(lepton+tau trigger)**
- In each channel: BDTs to split into three categories: **VBF**, **low-mHH**, **high-mHH** (>350 GeV)
- Another BDTs then trained in each category to discriminate signal and background (trained on κ_λ=10 for the low-mHH cateorgy, κ_λ =1 elsewhere)



Non-resonant HH → bbττ

New!

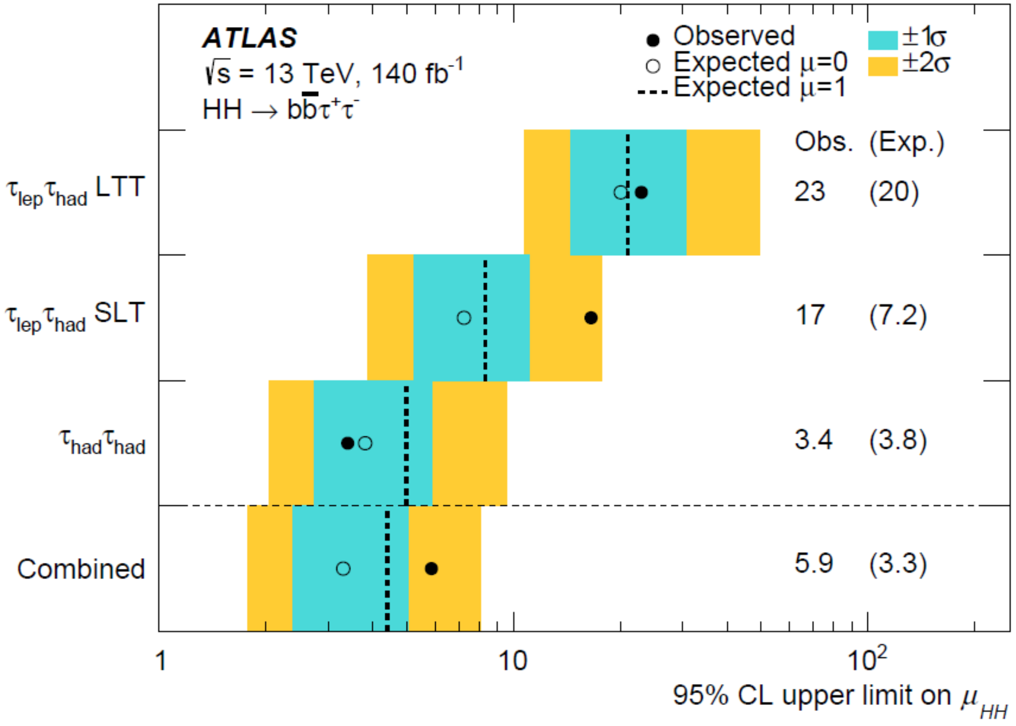
2404.12660

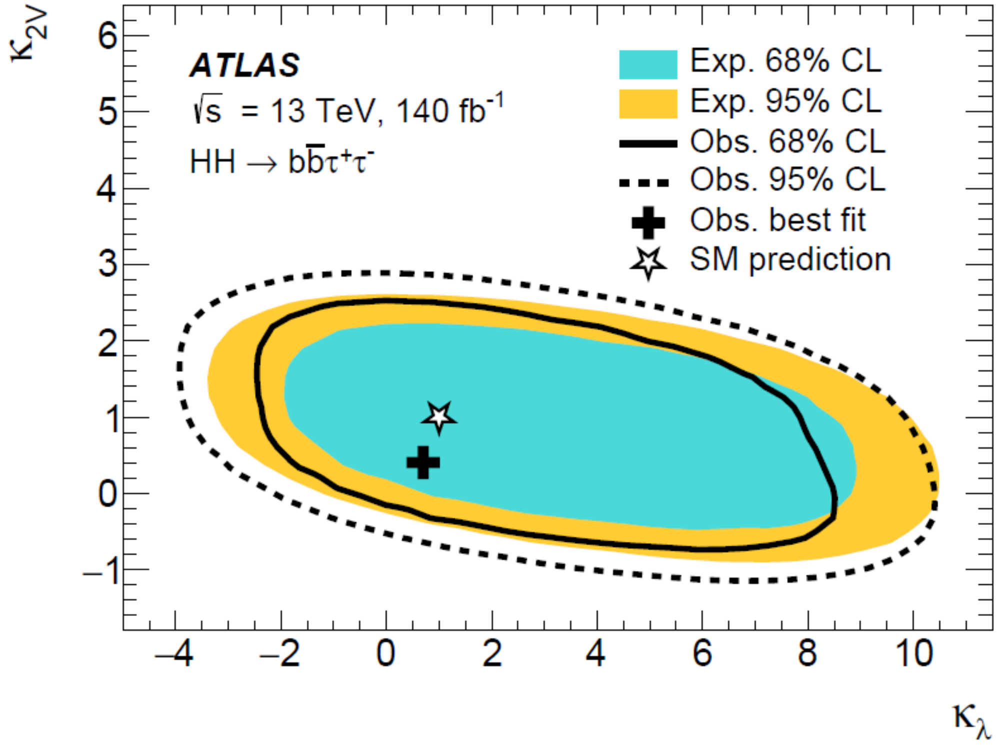
95% CL limit on μ_{HH} = 5.9 (observed) and **3.3 (expected)** (ggF and VBF combined)

Best fit: $\hat{\mu}$ = 2.2 ± 1.7

Limit on ggF: 5.8 (observed) and **3.4 (expected)**, **VBF: 91 (observed)** and **73 (expected)**

Sensitivity is most-limited by data statistics.
Largest systematics: QCD scales and top-quark mass scheme, MC statistical uncertainties.





Observed:
$-3.1 < \kappa_\lambda < 9.0$
Expected:
$-2.5 < \kappa_\lambda < 9.3$

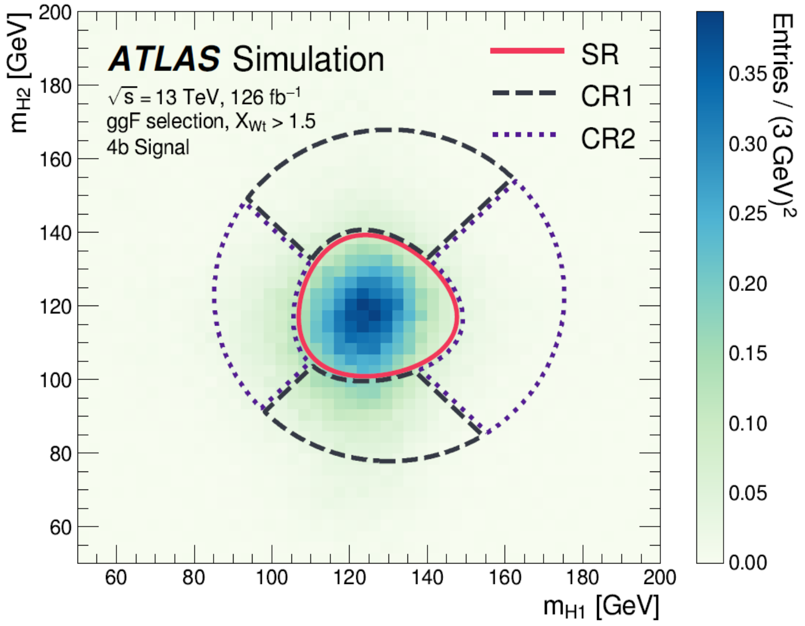
Observed:
$-0.5 < \kappa_{2V} < 2.7$
Expected:
$-0.2 < \kappa_{2V} < 2.4$

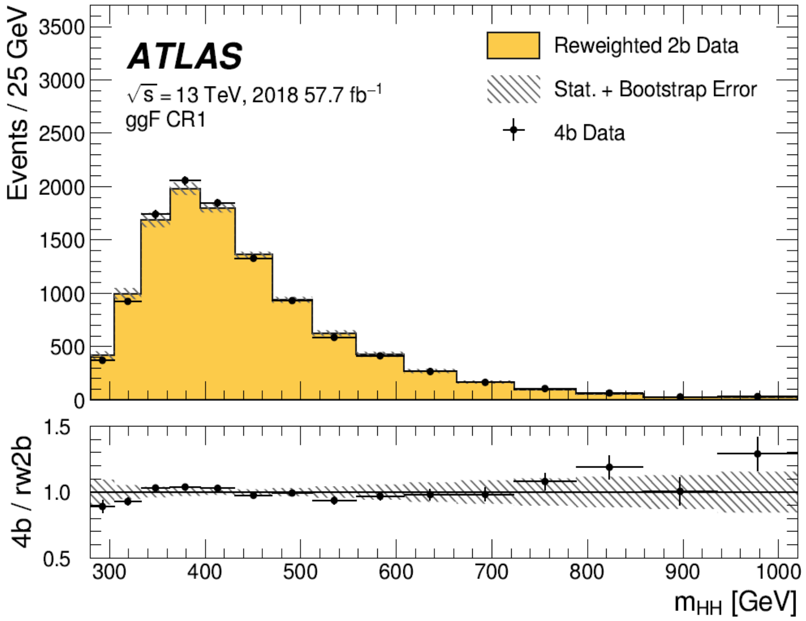
Non-resonant HH → bbbb

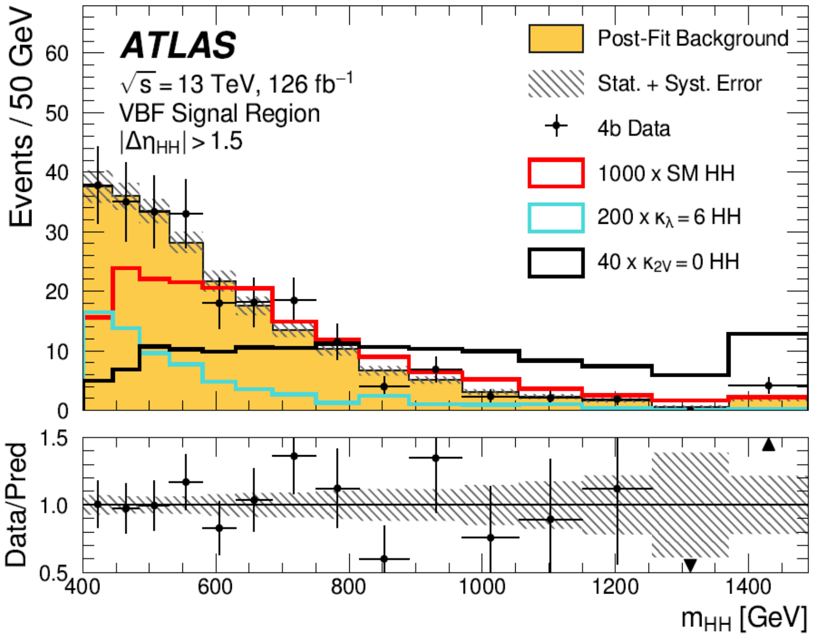
2301.03212

- Largest BR (~0.3) of all DiHiggs channels, but large backgrounds that are difficult to estimate
- Triggers: **2b+1j** (b-jet E_T>55 GeV, extra jet E_T>100-150 GeV) or **2b+2j** (jet E_T > 35 GeV)
- **4 resolved b-jets** → 3 ways to pair them to two Higgs boson candidates. Simple solution gave best efficiency: Highest pT-pair must have lowest ΔR_{bb} separation
- VBF selection: Two additional foward jets and m_{jj} > 1 TeV and $|\Delta\eta_{jj}|$ > 3
- Background (~90% multijet) estimated from 2b data (signal-depleted), reweighted to resemble 4b data using two control regions

m_{4b} is the final discriminant:





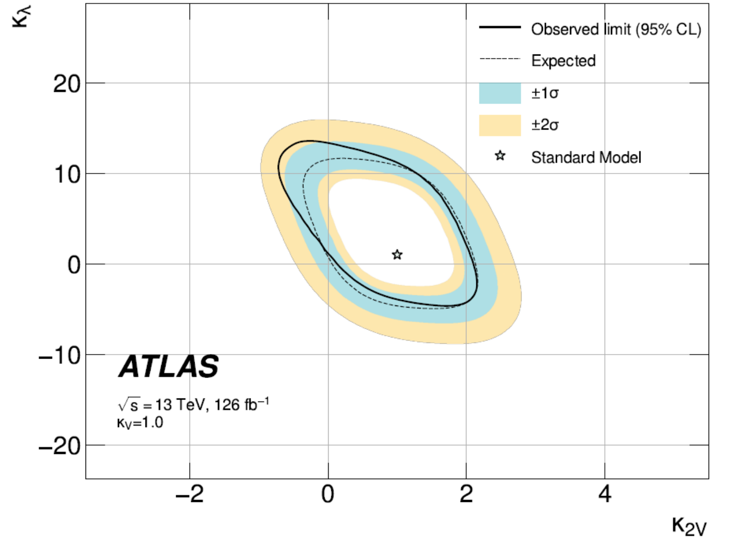


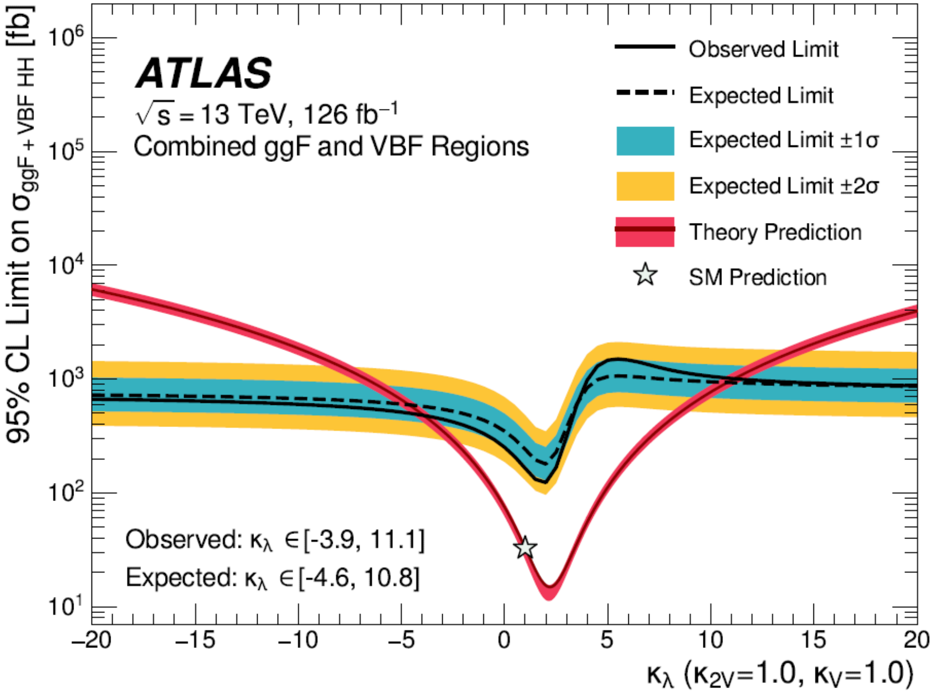
Non-resonant HH → bbbb

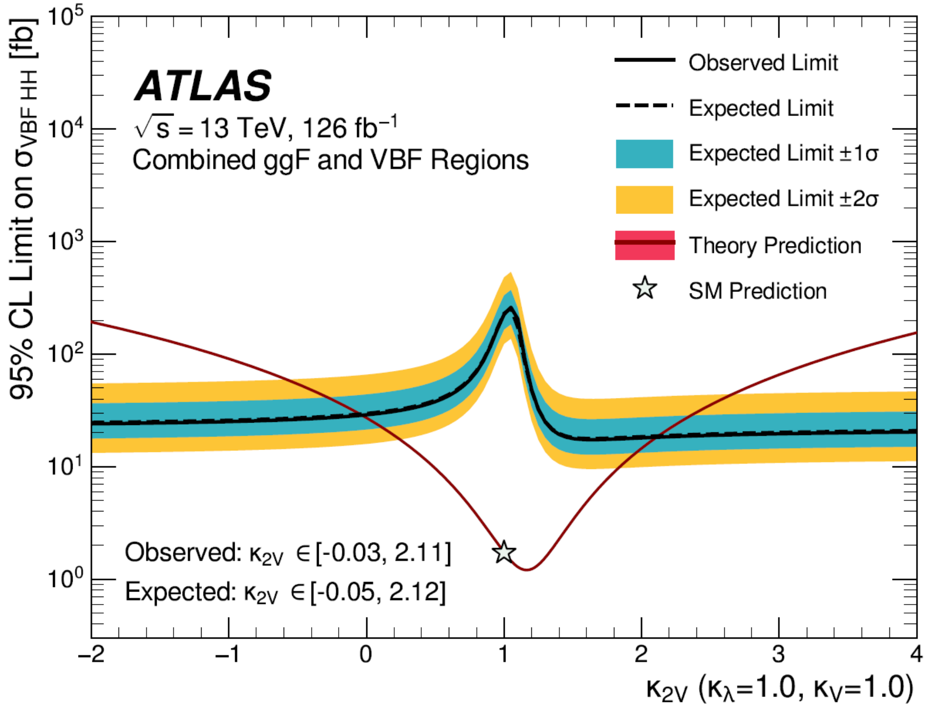
2301.03212

95% CL limits on SM HH:

	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
μ_{ggF}	5.5	4.4	5.9	8.2	12.4	19.6
μ_{VBF}	130	70	100	130	190	280
$\mu_{ggF+VBF}$	5.4	4.3	5.8	8.1	12.2	19.1







Observed:
$-3.5 < \kappa_{\lambda} < 11.3$
Expected:
$-5.4 < \kappa_{\lambda} < 11.4$

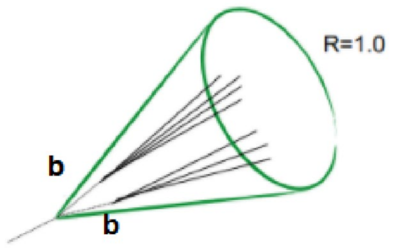
Observed:
$0.0 < \kappa_{2V} < 2.1$
Expected:
$-0.1 < \kappa_{2V} < 2.1$

Better than bbττ for κ_{2V}
But, can do even better…

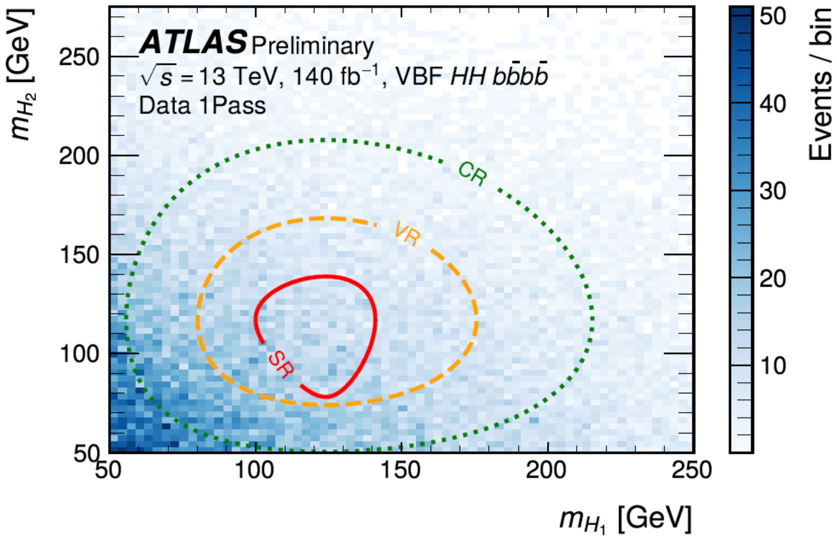
Boosted VBF HH → bbbb

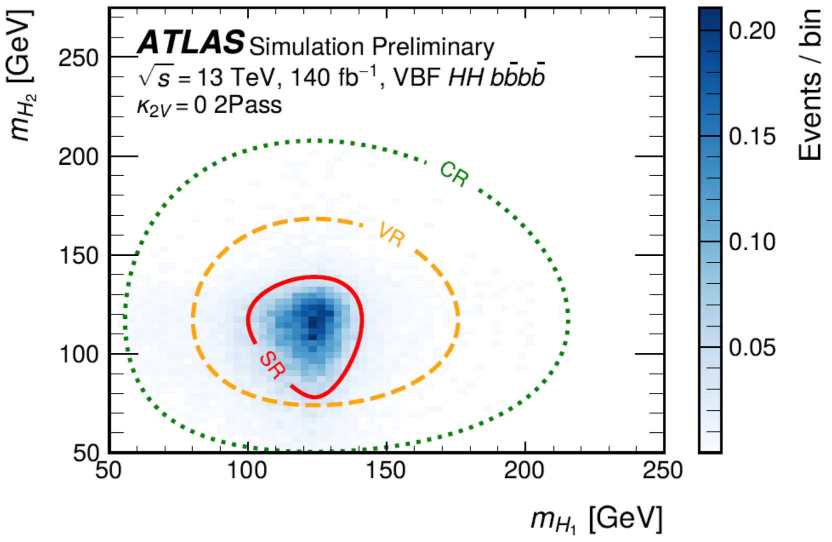
New!

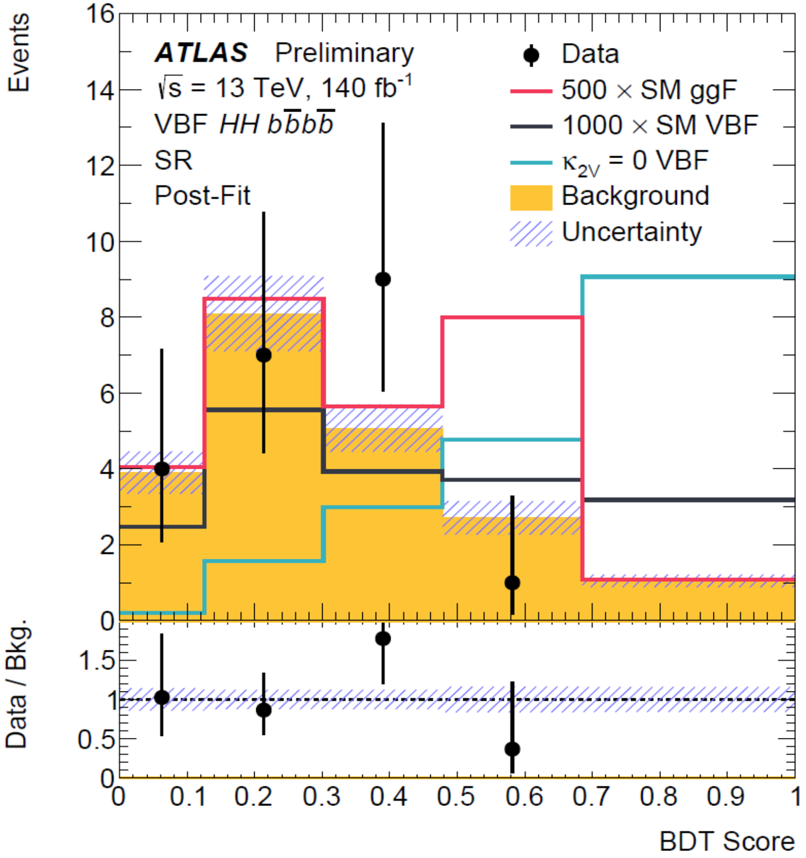
ATLAS-CONF-2024-003



- VBF events with non-SM couplings tend to produce energetic boosted HH
- Each Higgs boson is reconstructed as a **single large radius jet**
- Leading jet pT > 450 GeV (sub-leading > 250 GeV)
- Double b-tagger based on deep neural network (60% efficiency working point)
- Background estimated from events where only one large-radius jets is double b-tagged („1Pass“)
- BDT trained to discriminate κ_{2V}=0 signal vs. background





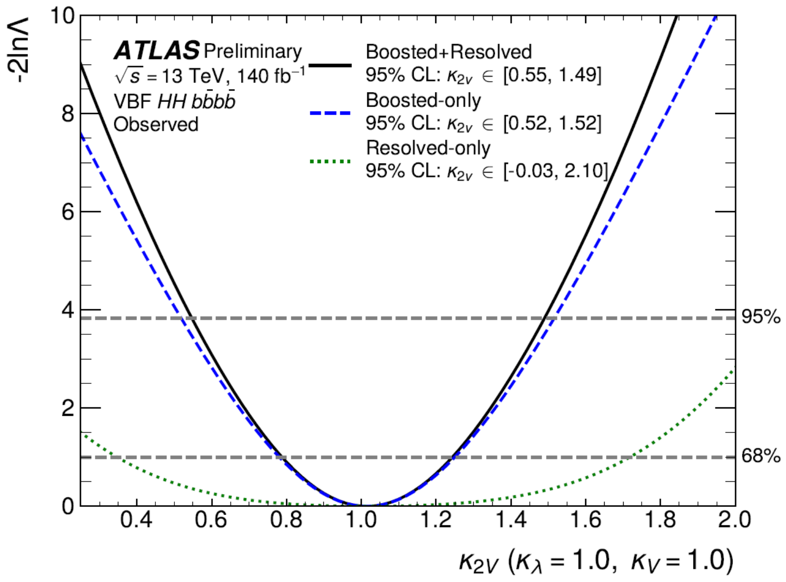


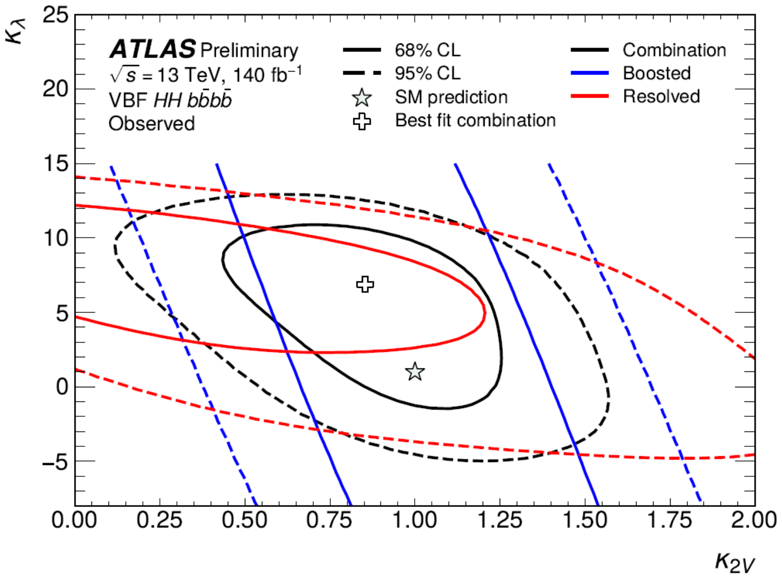
Boosted VBF HH → bbbb

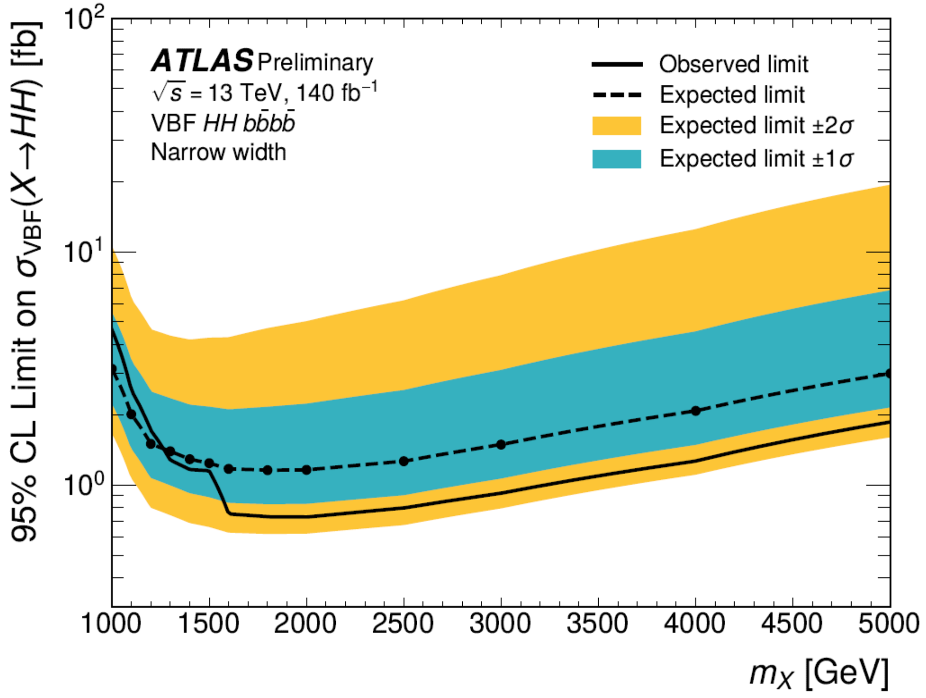
New!

ATLAS-CONF-2024-003

- Boosted analysis is combined with the resolved one to maximize the sensitivity
- Allowed parameter ranges: **Observed: 0.55 < κ_{2V} < 1.49. Expected: 0.37 < κ_{2V} < 1.67**
- **κ_{2V}=0 excluded with 3.8σ. Best fit** (κ_λ=1 fixed): **κ_{2V} = 1.01+ 0.23 – 0.22**
- Analysis also used to set limits on resonant signals VBF X → HH → 4b



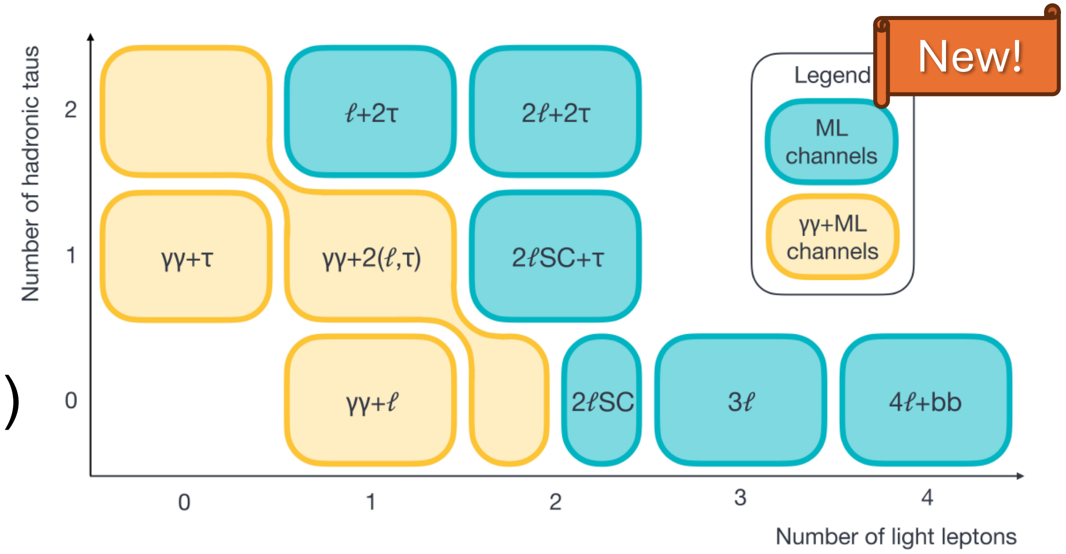


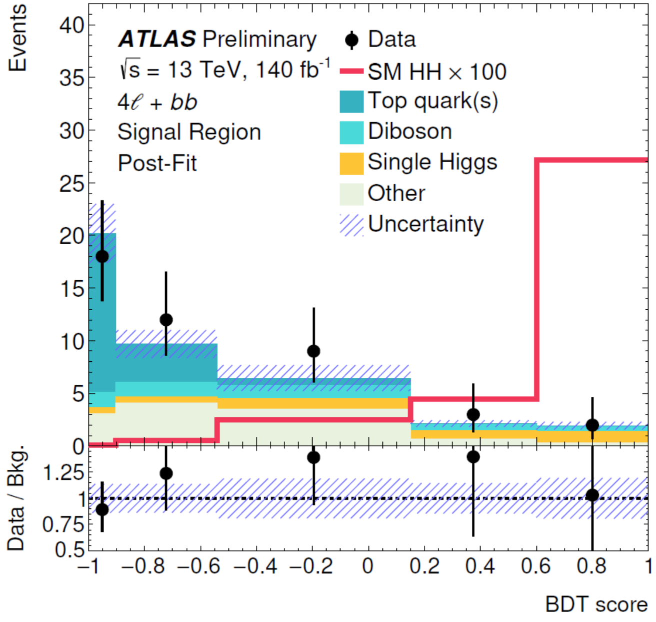


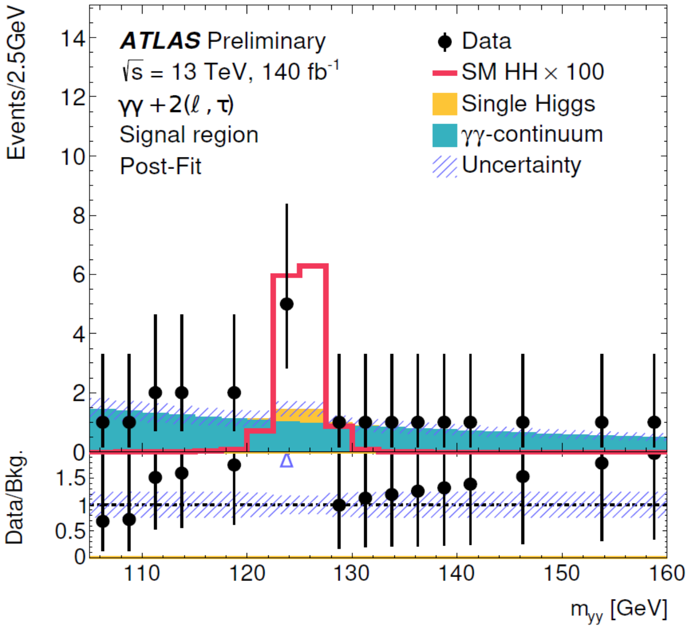
Non-resonant HH → Multileptons

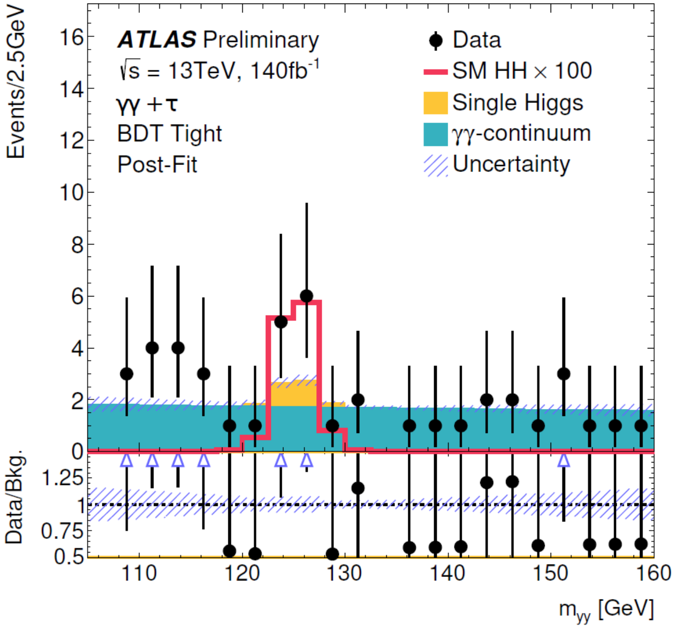
ATLAS-CONF-2024-005

- Combining several subleading channels with small BR: **bbZZ**, **4V**, **VVττ**, **γγVV**, **γγττ** (V=W/Z)
- **ggF and VBF** both considered (but not separated)
- **Nine categories** based on number of light leptons (e/μ), hadronic taus and photons
- **BDTs** in 8 categories used to discriminate SM HH from the backgrounds (γγ+2(l,τ) has too little statistics)
- Final discriminant is **BDT score** or **$m_{\gamma\gamma}$ distribution**









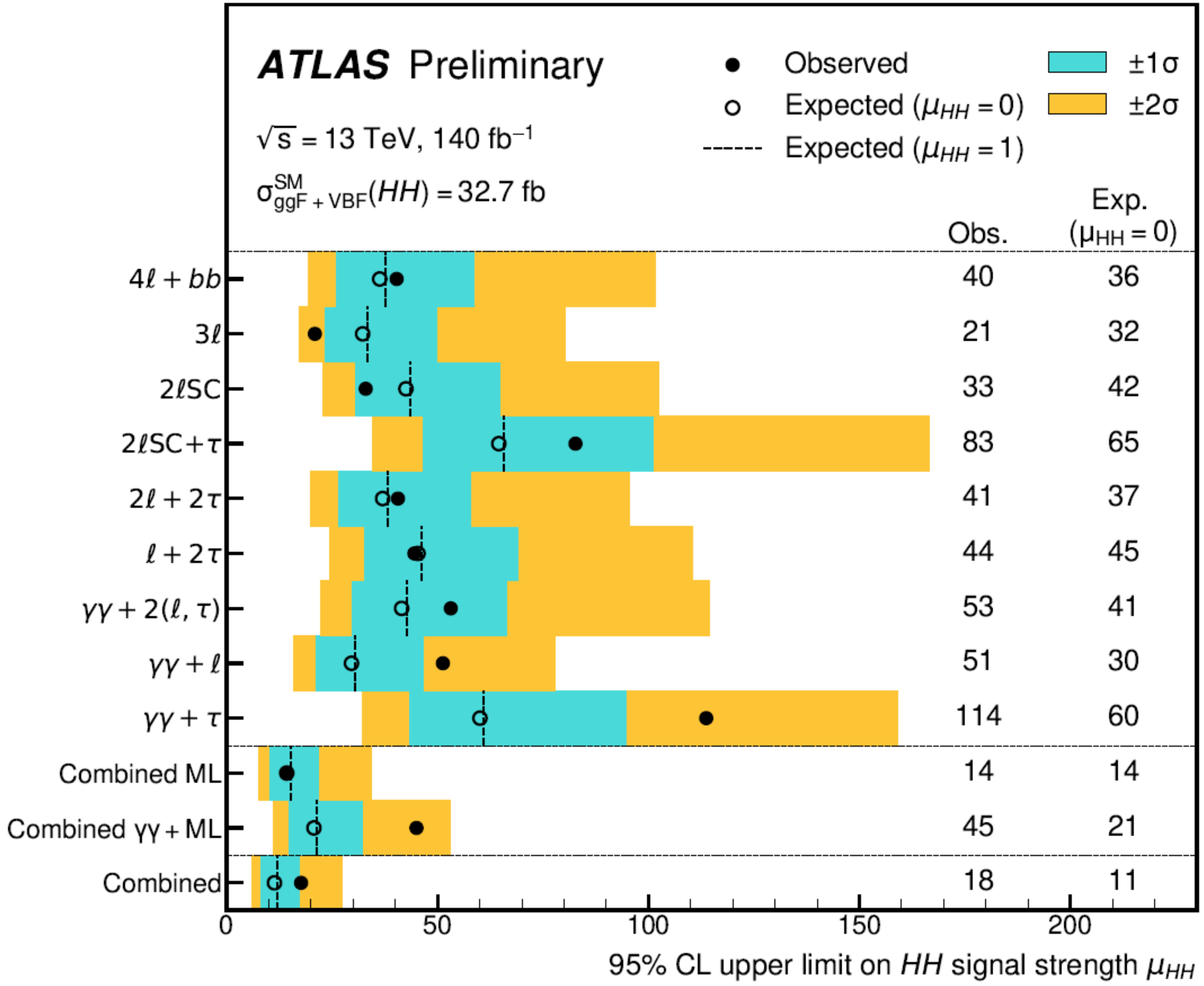
Non-resonant HH → Multileptons

ATLAS-CONF-2024-005

New!

Combined limit on SM HH production: 18 (observed), 11 (expected)

Sensitivity limited by data statistics

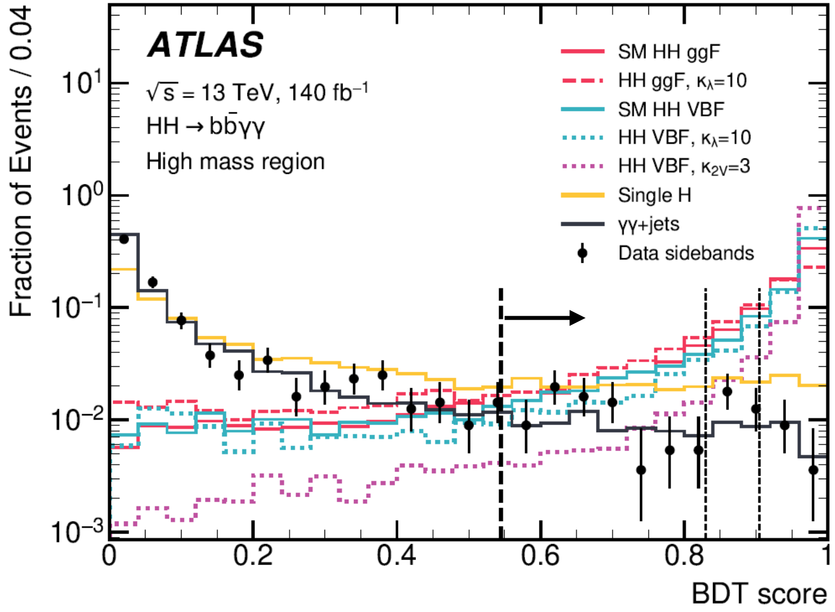


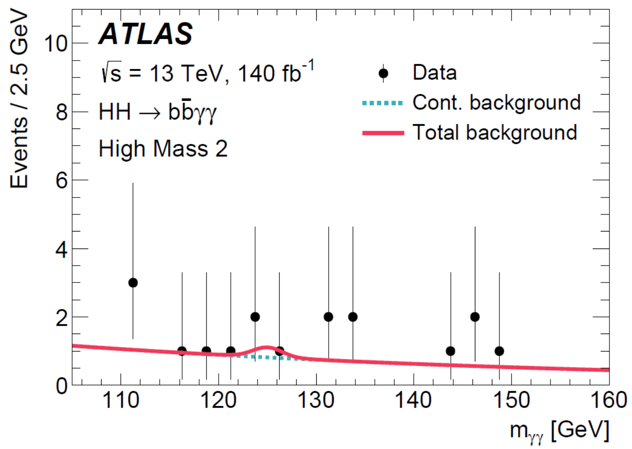
Non-resonant HH → $bb\gamma\gamma$

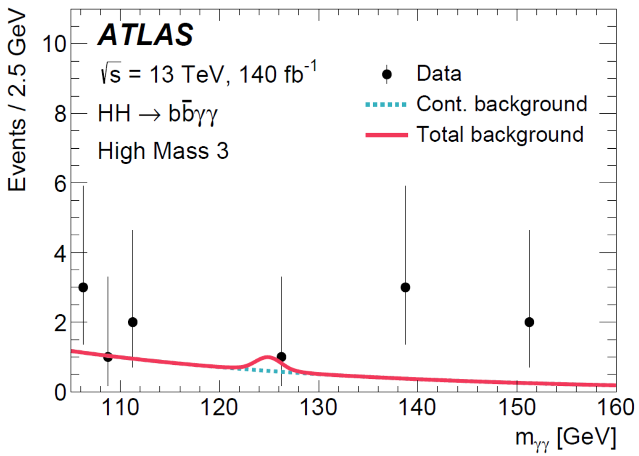
2310.12301

New!

- Re-analysis of Run 2 dataset. ggF and VBF both considered.
- Better classification of events, higher sensitivity to κ_λ and κ_{2V}
- Events split into high-m_{HH} and low-m_{HH}
- In each category, BDTs trained to classify events into 3 or 4 regions with different S/B values
- Final discriminant: Diphoton mass. No excess found!
- **Limit on SM HH** (VBF+ggF)**: 4 (observed), 5.0 (expected)** (previously: 4.2 (obs), 5.7 (exp) 2112.11876)



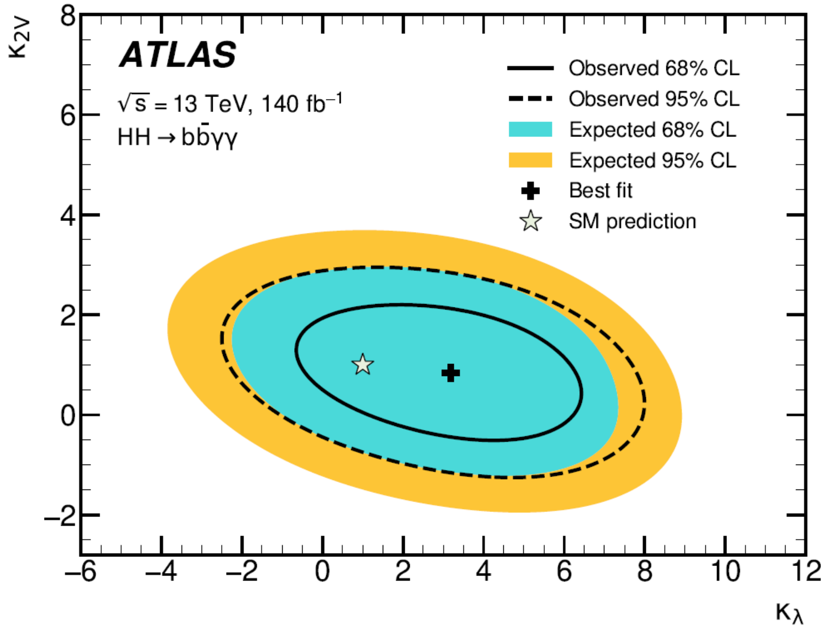




Statistics limited!

Observed:
$-1.4 < \kappa_\lambda < 6.9$
Expected:
$-2.8 < \kappa_\lambda < 7.8$

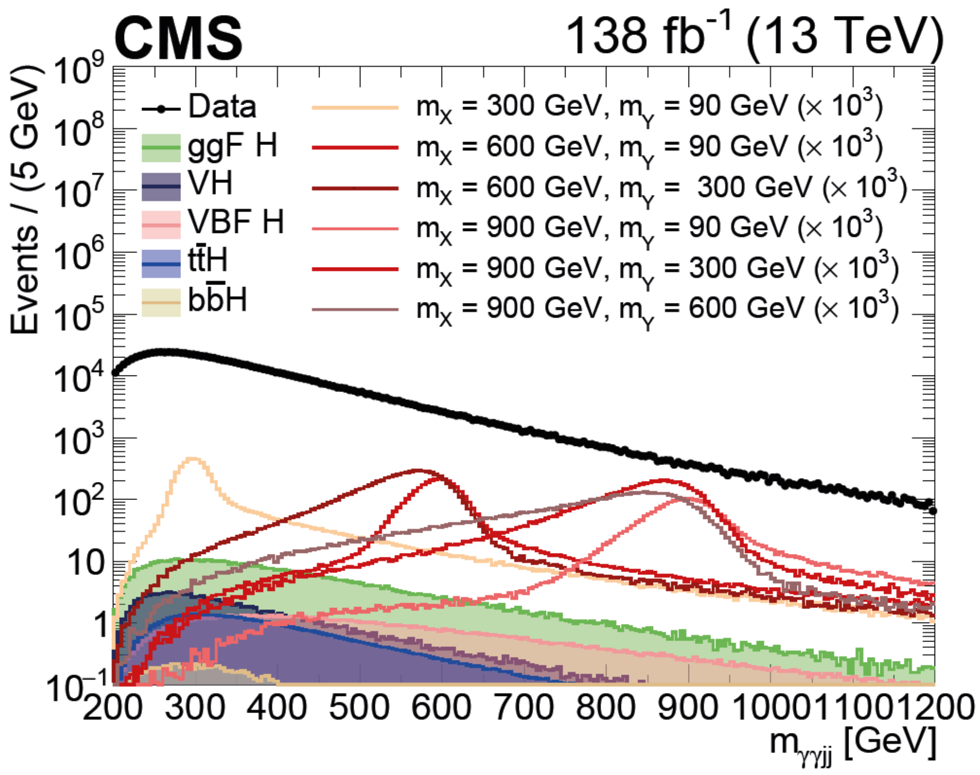
Observed:
$-0.5 < \kappa_{2V} < 2.7$
Expected:
$-1.1 < \kappa_{2V} < 3.3$

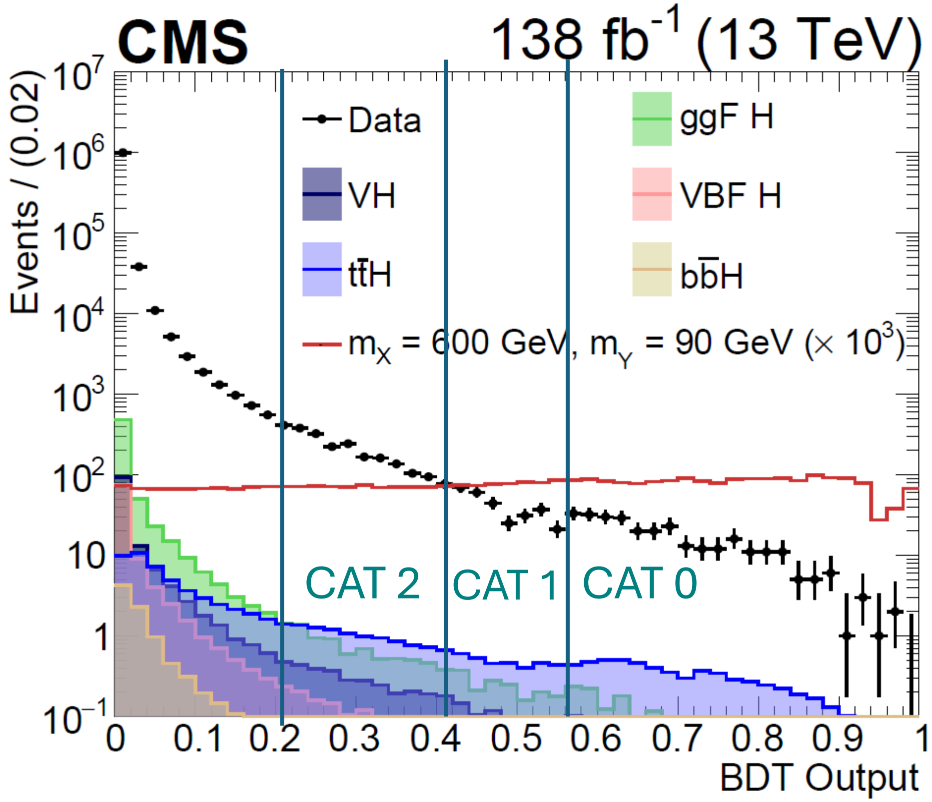


CMS Resonant X → YH → bbγγ

2310.01643

- X mass range: 300 - 1000 GeV, Y mass range: 90 – 800 GeV (with Y → bb)
- Events split into 6 m_X-m_Y domains (ensuring $m_X > m_Y$):
  mX (< 500, 500 - 700, > 700) GeV and m_Y (< 300, 300 - 500, > 500) GeV
- BDT – trained in each mass domain – used to classify events into 3 categories each to optimize S/B sensitivity → in total 18 categories.





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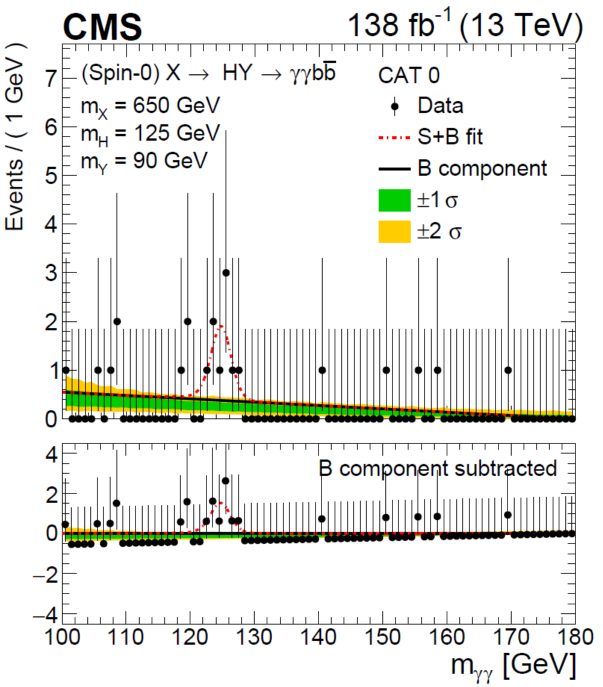
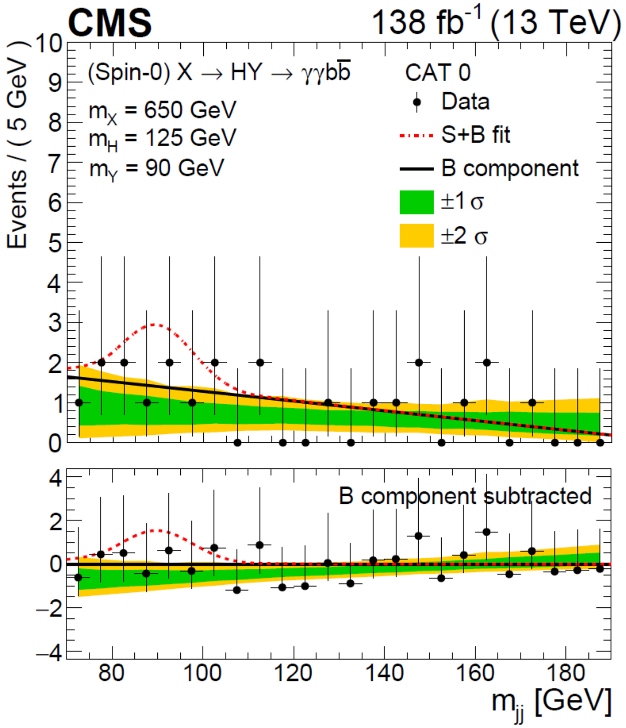
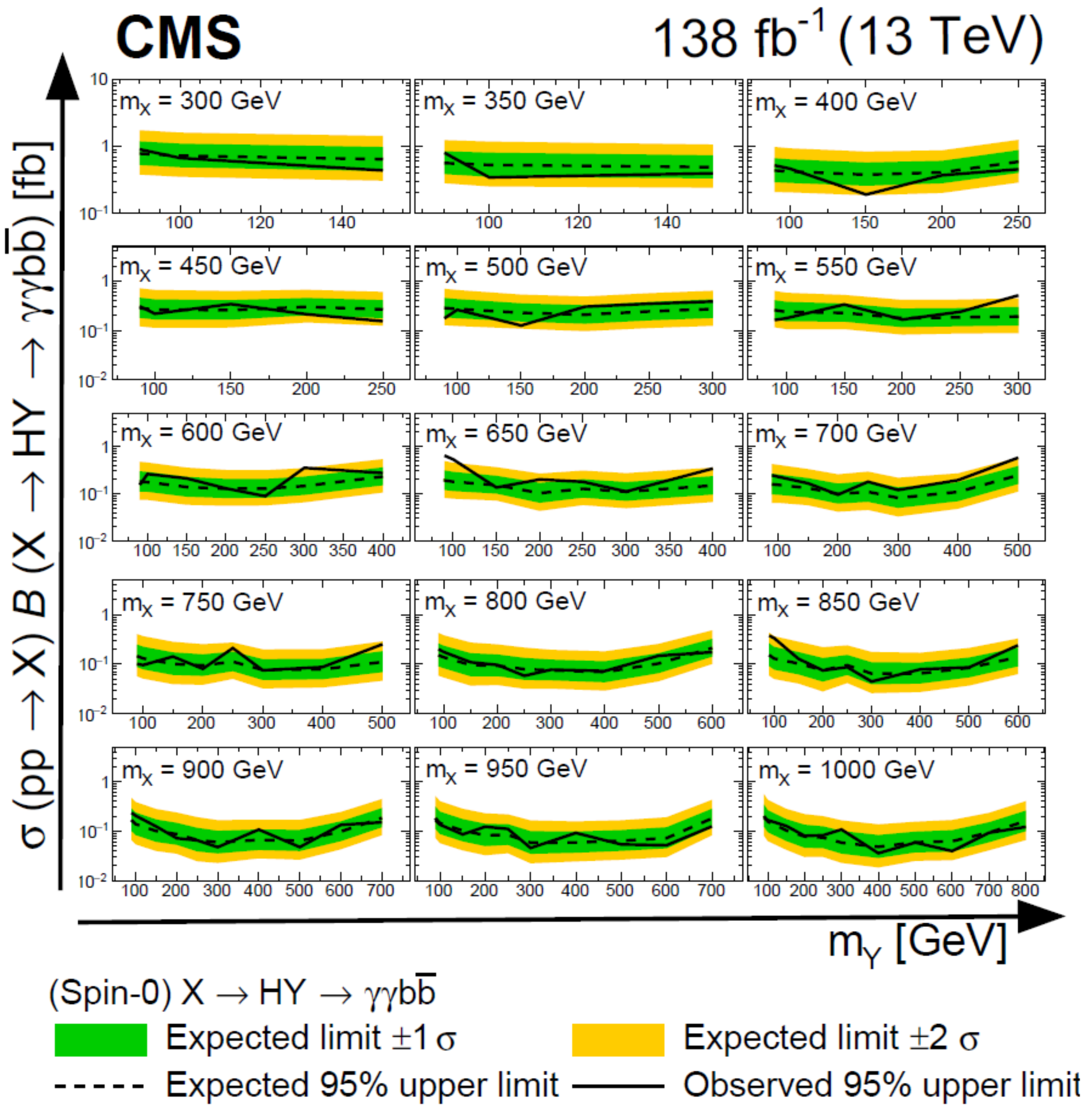






Final discriminant: 2D fit to $m_{\gamma\gamma}$ and m_{jj}

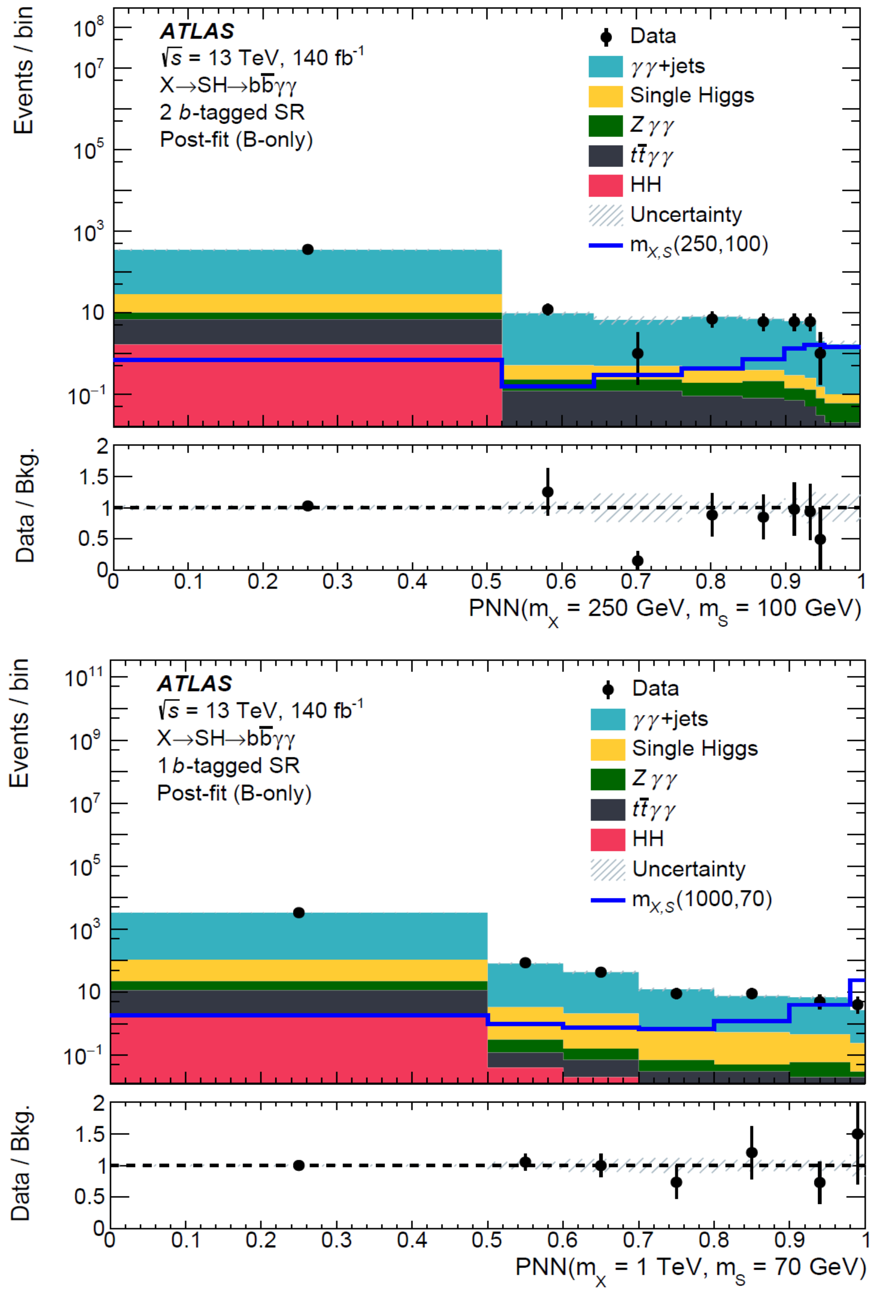
Excess at (650, 90) GeV with 3.8σ local and 2.8σ global significance

Resonant X → SH → bbγγ

2404.12915

New!

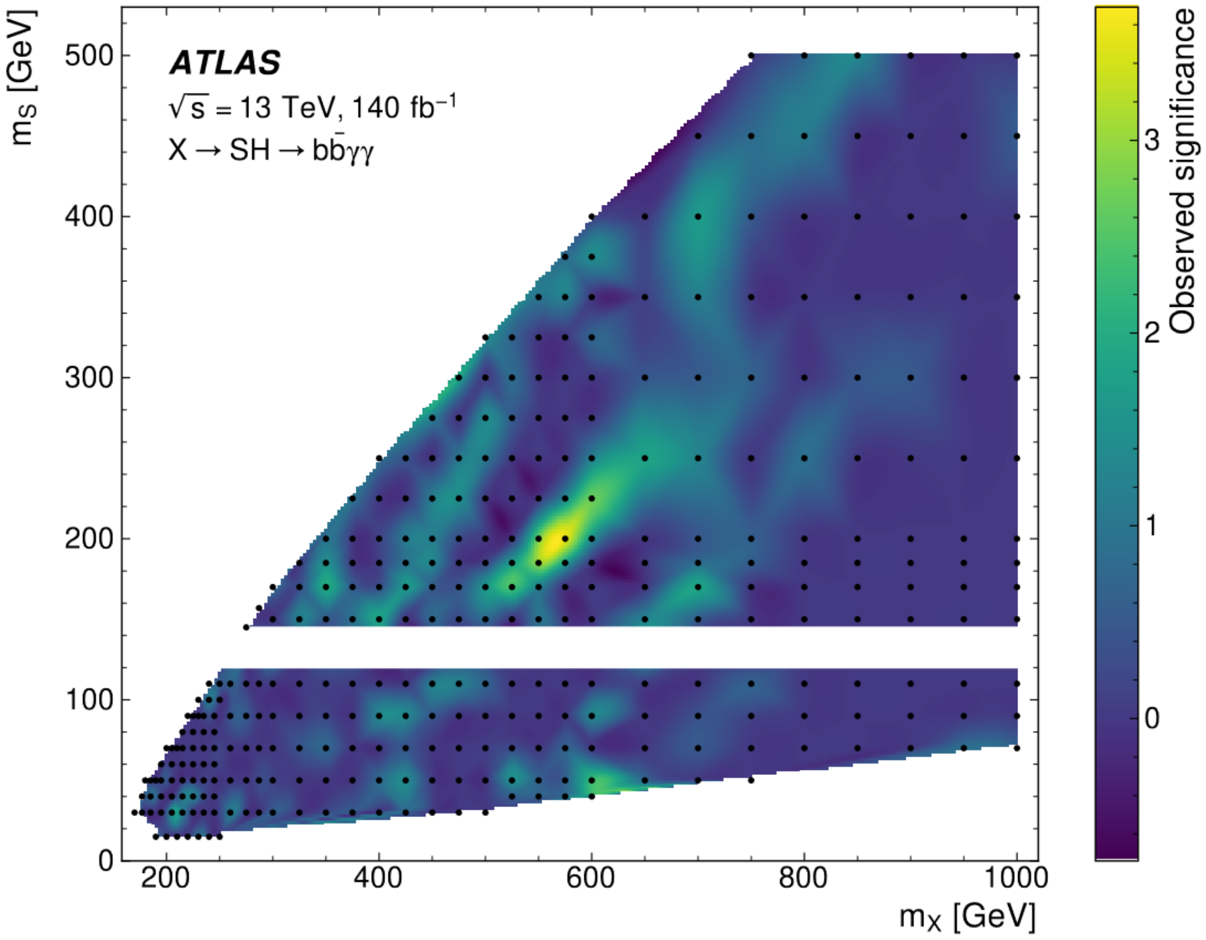
- X mass range: 170 – 1000 GeV
  S mass range: 15 – 500 GeV
- S → bb, H (125 GeV) → γγ
- If $m_X >> m_S + m_H$ → boosted regime.
  If boosted, reconstruct only 1 small-radius b-jet.
  If resolved, require two b-tagged jets.
- Parametrized neural networks (PNN) used for signal - background discrimination, trained in each SR
- PNN score is the final discriminant
- Background estimation:
  - Sherpa for γγ+jets non-resonant background shape, normalized to data sideband in $m_{\gamma\gamma}$
  - H and SM HH resonant backgrounds from MC

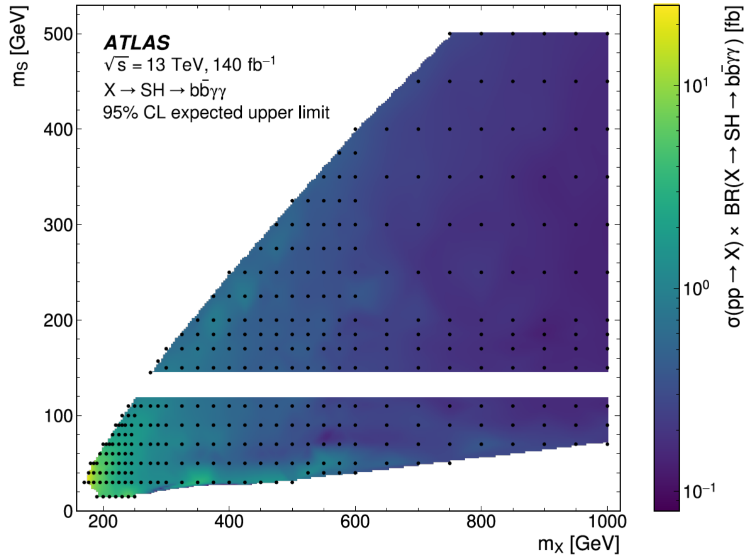


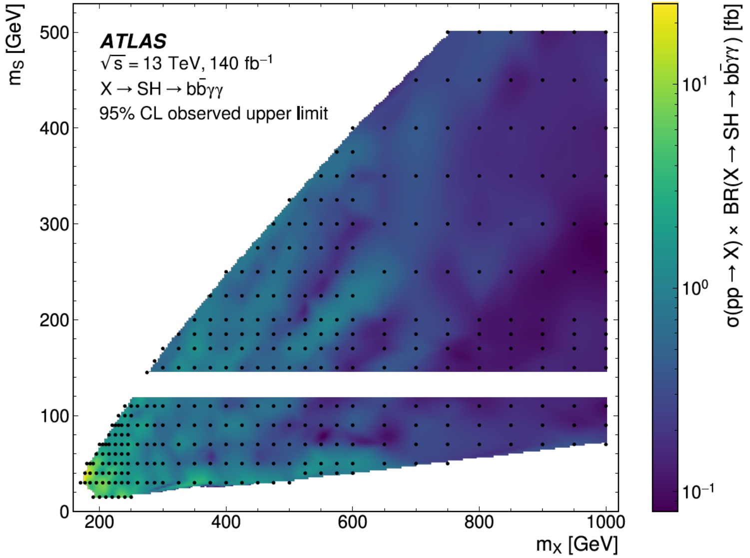
Resonant X → SH → bbγγ

2404.12915

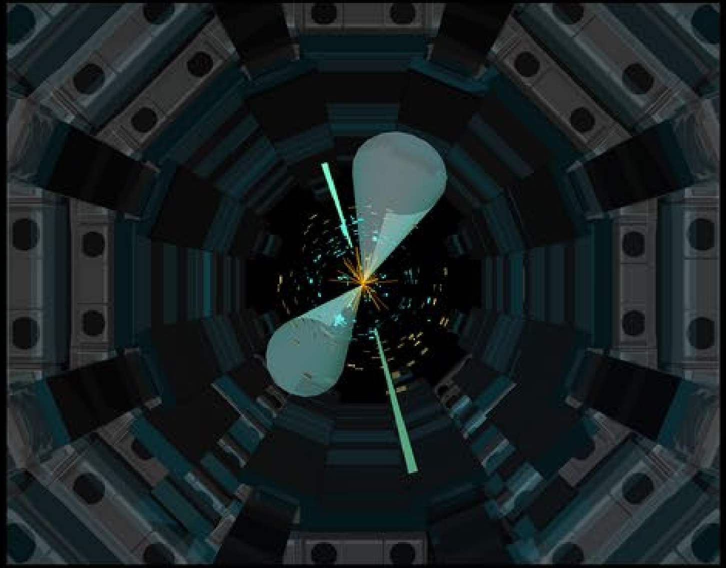
New!



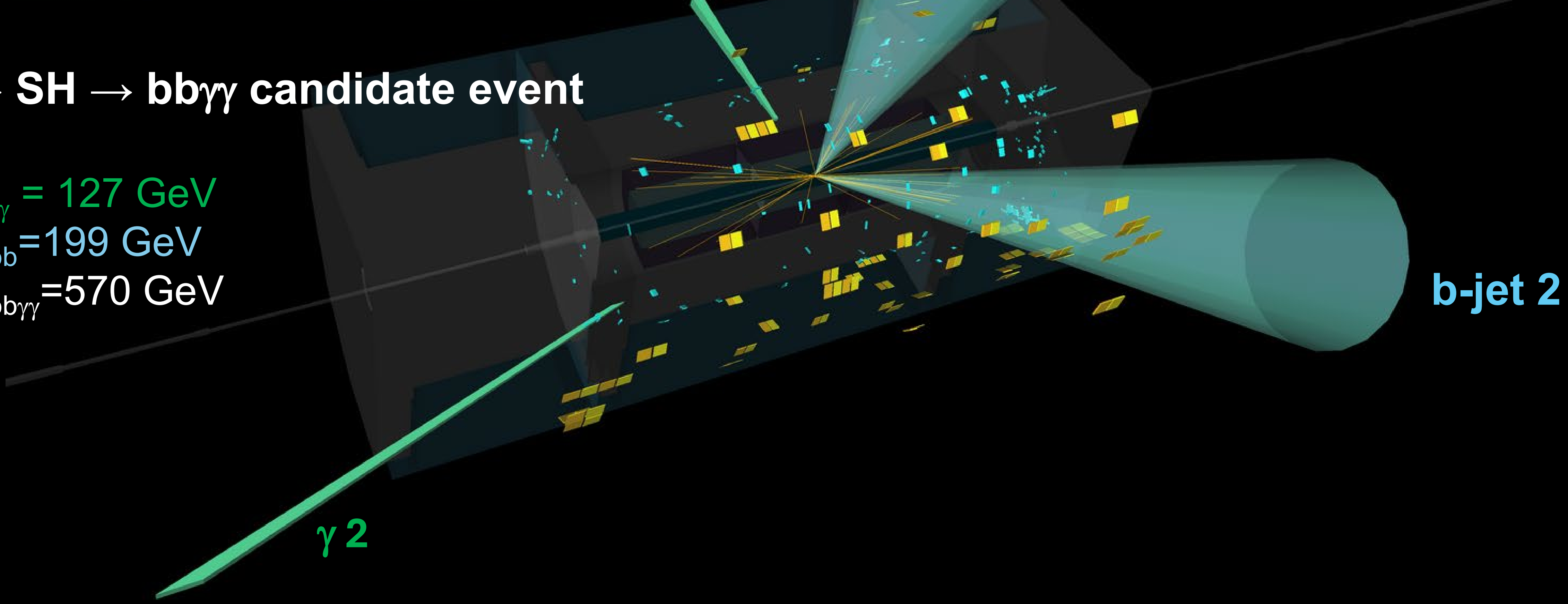




- ATLAS sees no excess at (650, 90) GeV (CMS excess)
- ATLAS would have seen this excess with 2.7σ
- Largest ATLAS excess at (575, 200) GeV, 3.5σ local, 2σ global



$X \rightarrow SH \rightarrow bb\gamma\gamma$ candidate event

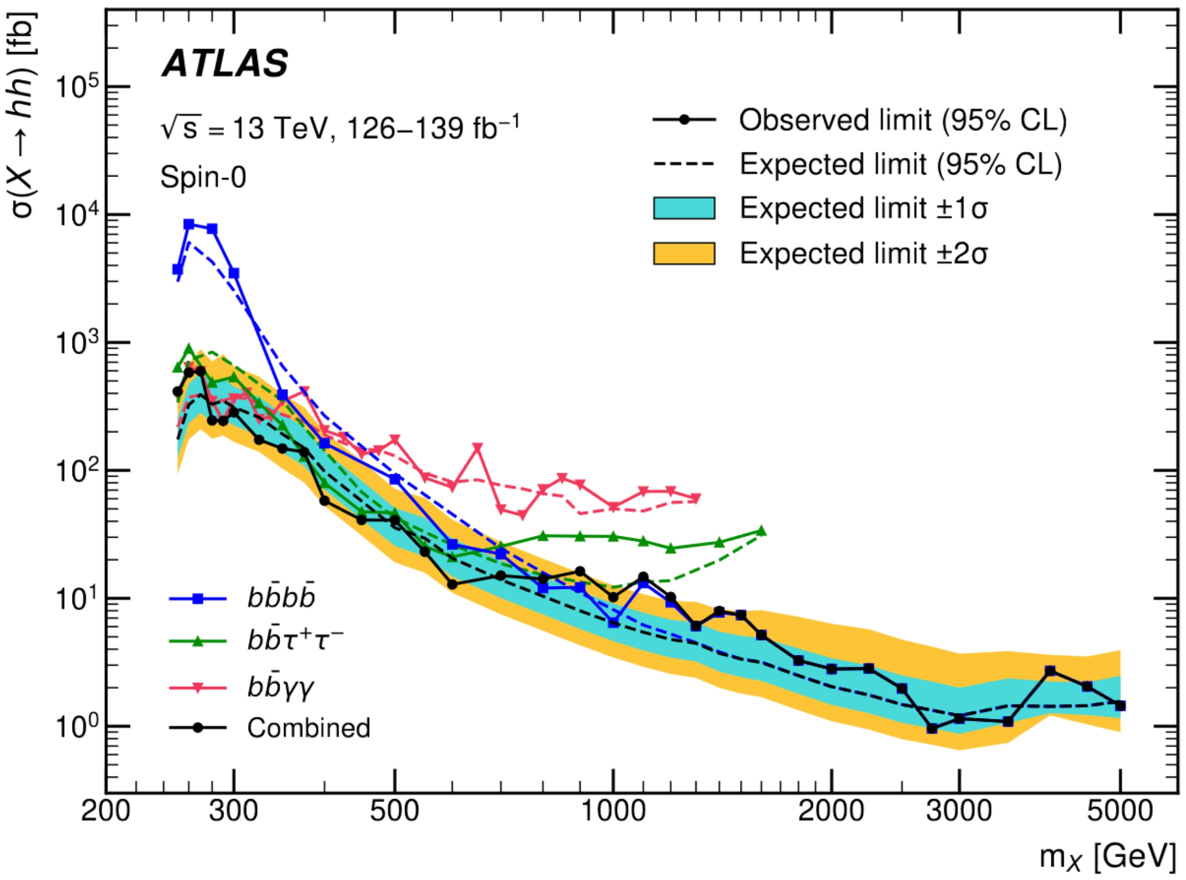


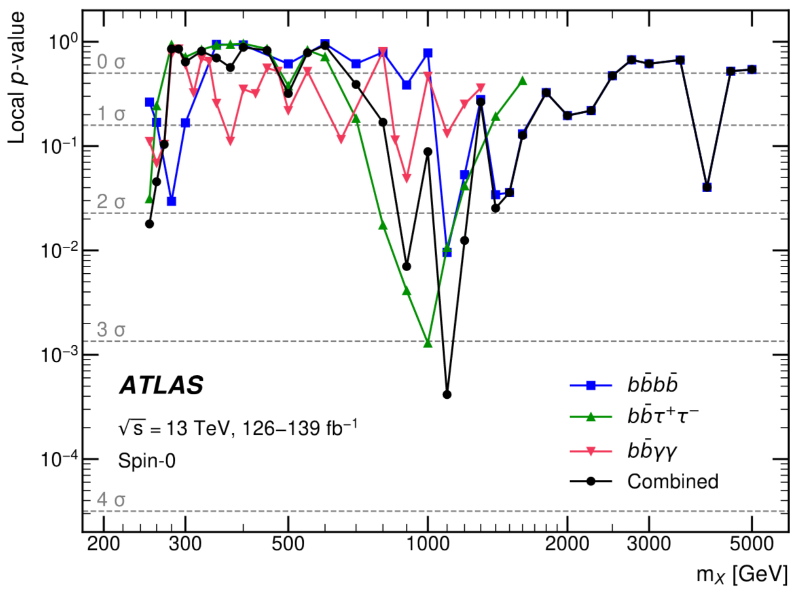
$m_{\gamma\gamma}$ = 127 GeV
m_{bb}=199 GeV
$m_{bb\gamma\gamma}$=570 GeV

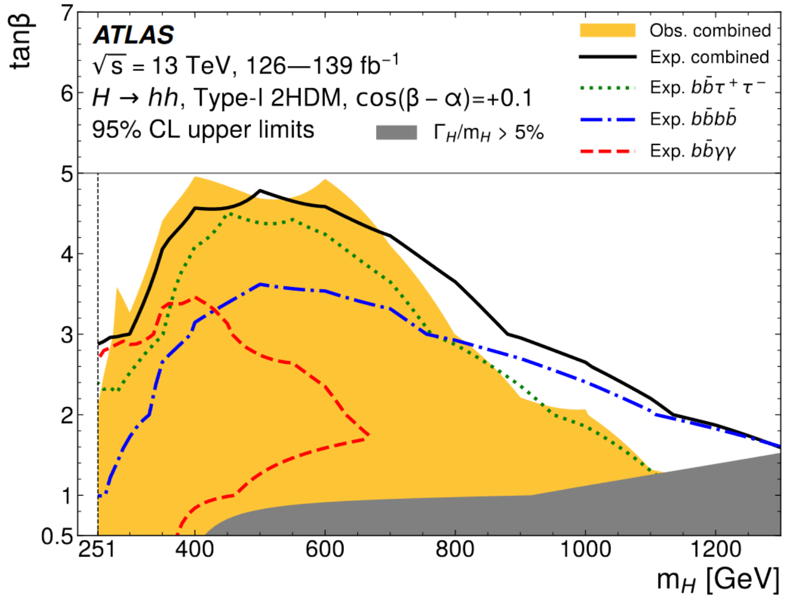
Resonant X → HH Combination

2311.15956

New!







Largest excess at 1.1 TeV driven by $bb\tau\tau$ (2209.10910): 3.3σ local, 2.1σ global

Low $\tan\beta$ region in 2HDM/MSSM excluded

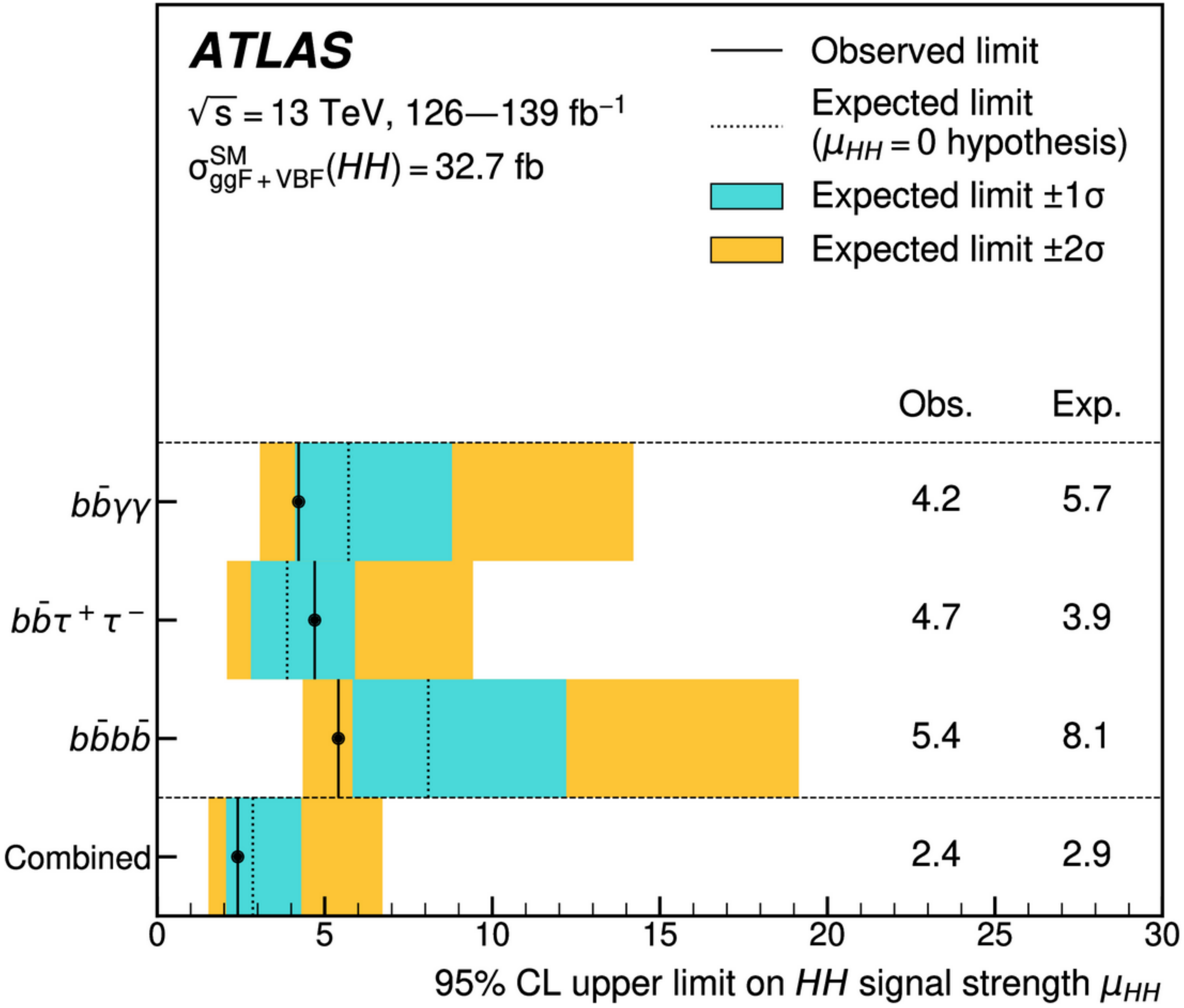
Conclusions

- Many new results based on the Run 2 dataset presented here
- κ_{2V} constrained considerably through boosted 4b channel
- CMS excess at (650, 90) GeV in $bb\gamma\gamma$ not confirmed by ATLAS
- Revisiting analysis strategies and advances in ML techniques increased the sensitivity to non-resonant HH
- All searches are limited by data statistics
- Analyses with Run 3 data are ongoing!

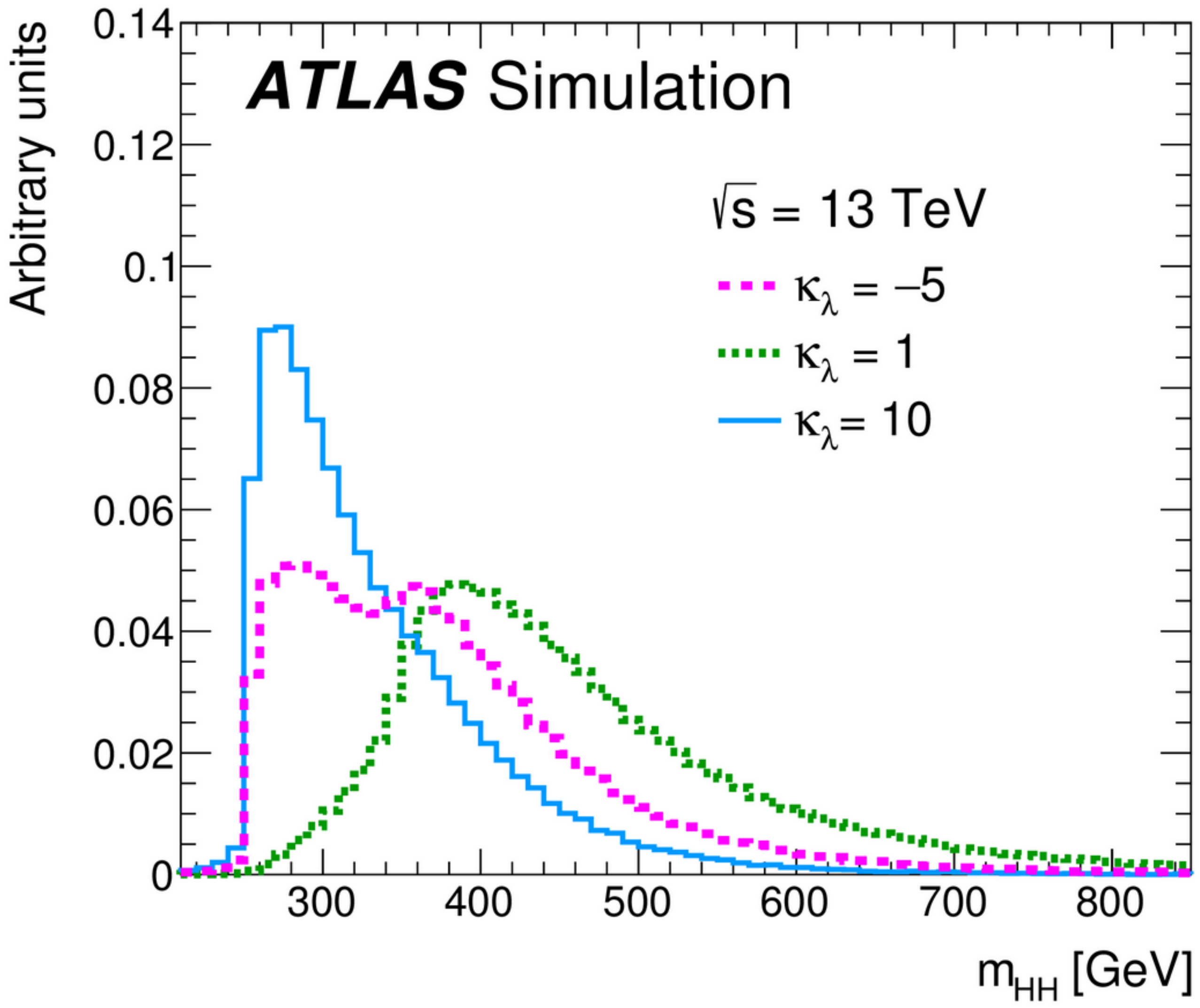
Backup

Non-resonant combination before the re-optimizations in bbττ and bbγγ

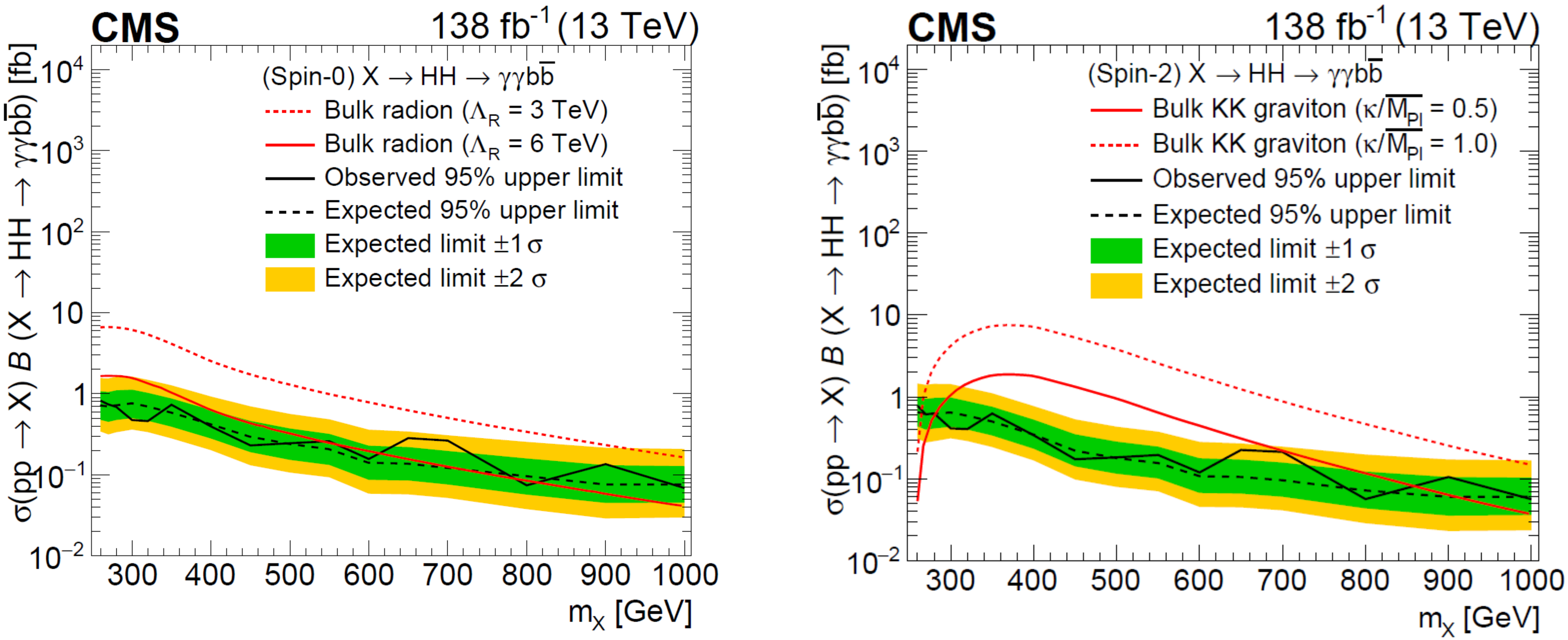
2211.01216



m_{HH} shape on truth level



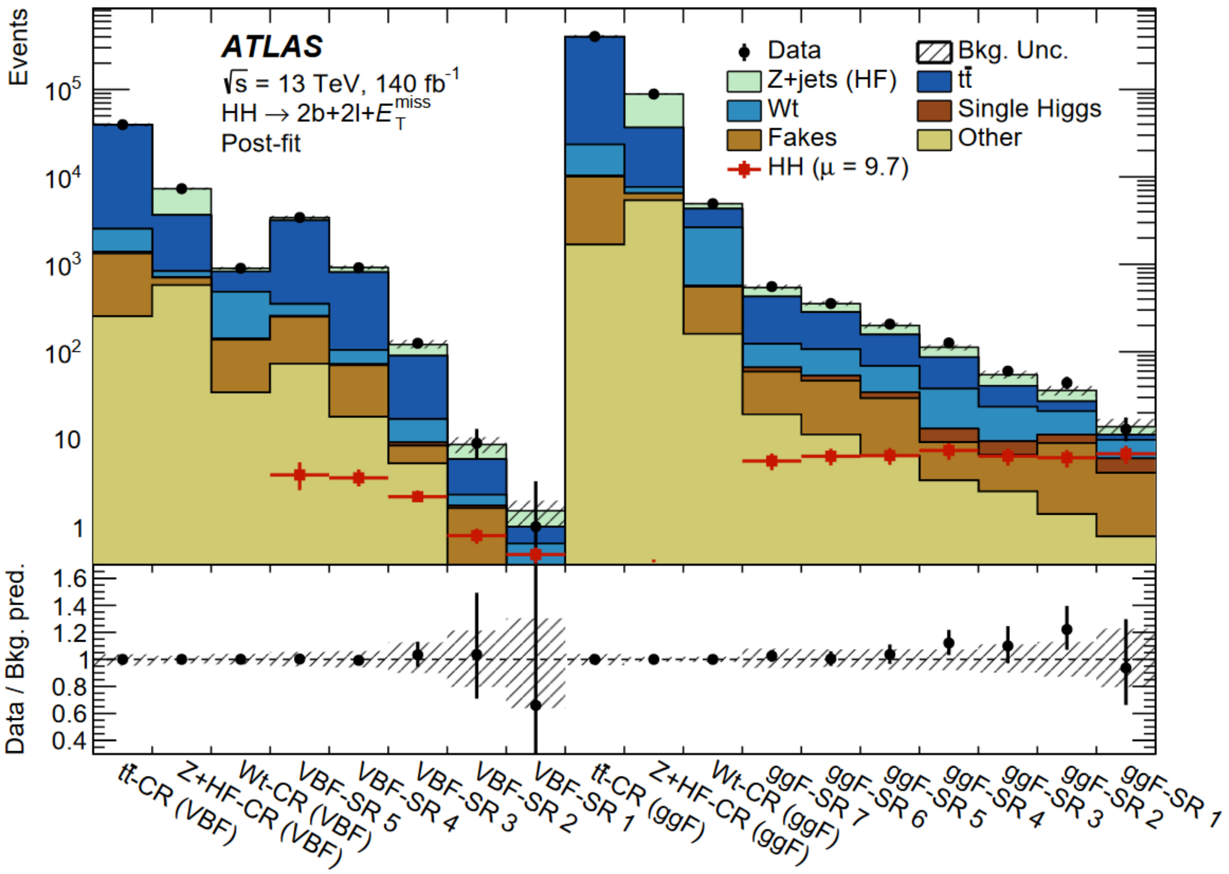
CMS $X \rightarrow HH \rightarrow bb\gamma\gamma$



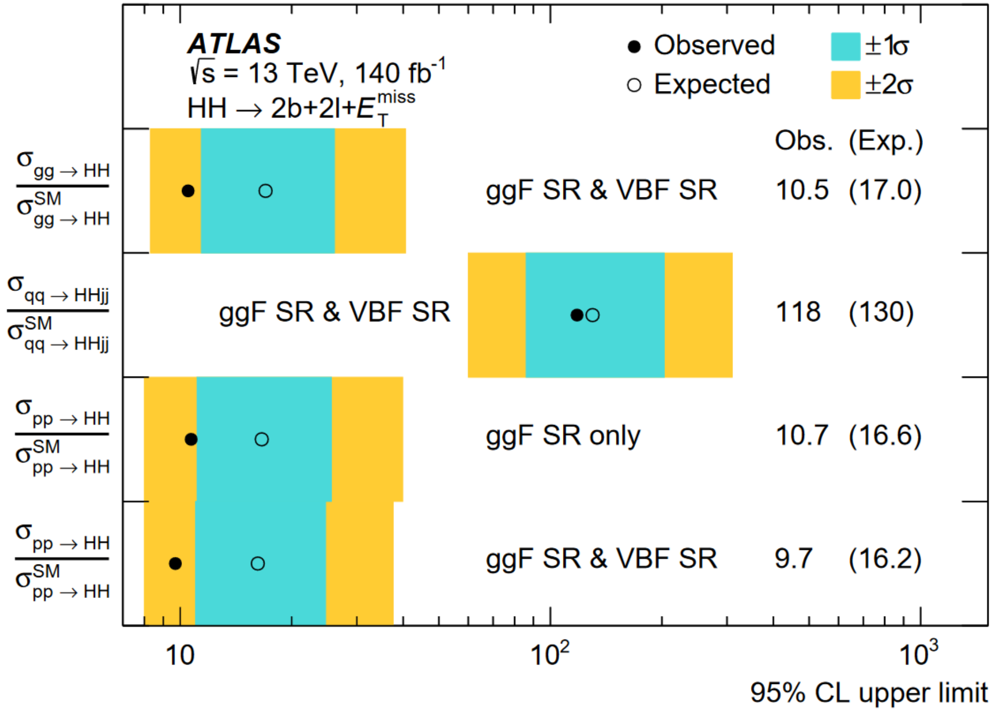
Non-resonant HH → bb+ll+MET

2310.11286

- HH → bb+WW/ZZ/ττ
- ggF and VBF considered
- Deep Neural Network for event classification, separate DNNs for ggF and VBF topologies



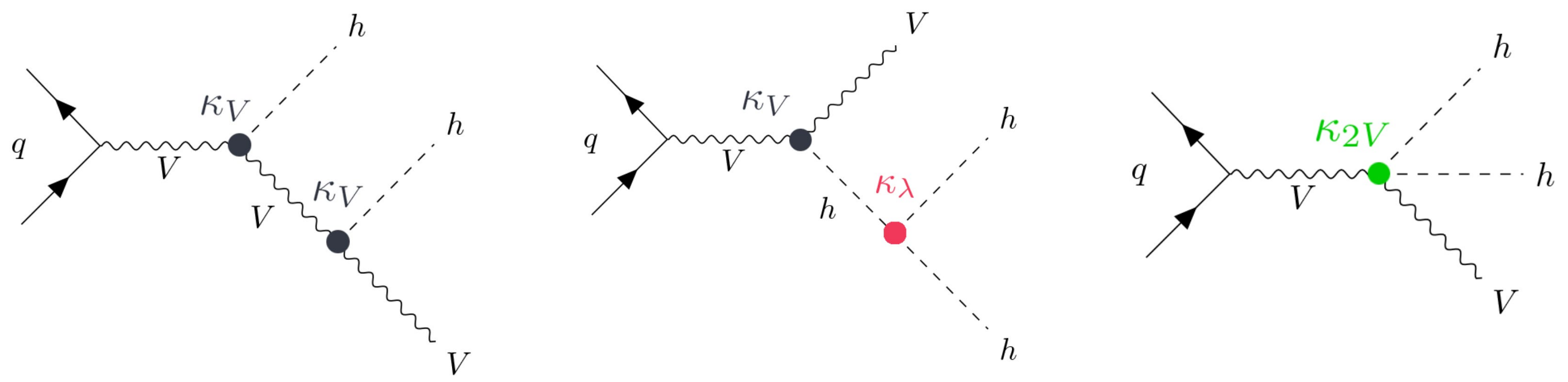
- Limit on SM HH:
  9.7 (observed), 16.2 (expected)
- κ_λ: [−6.2, 13.3] (observed), [-8.1, 15.5] (expected)
- κ_{2V}: [−0.17, 2.4] (observed) [-0.51, 2.7] (expected)

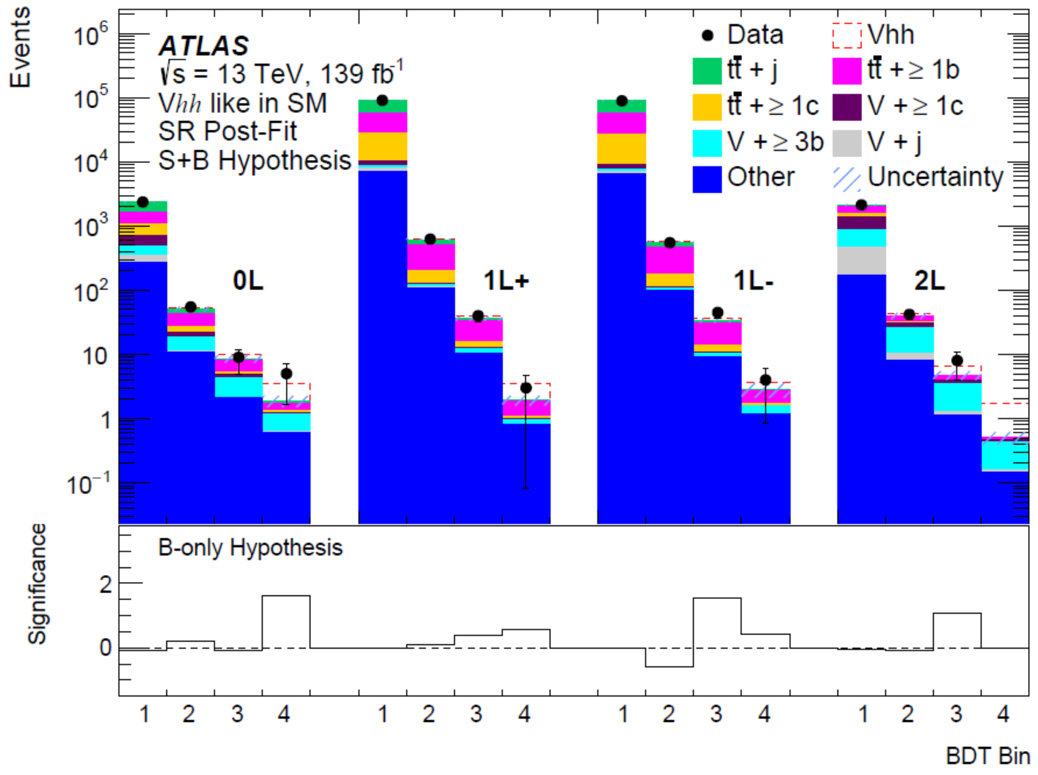


Vhh → bb+ll+MET

2210.05415

Non-Resonant:





hh → 4b

V decays leptonically (charged or neutral)

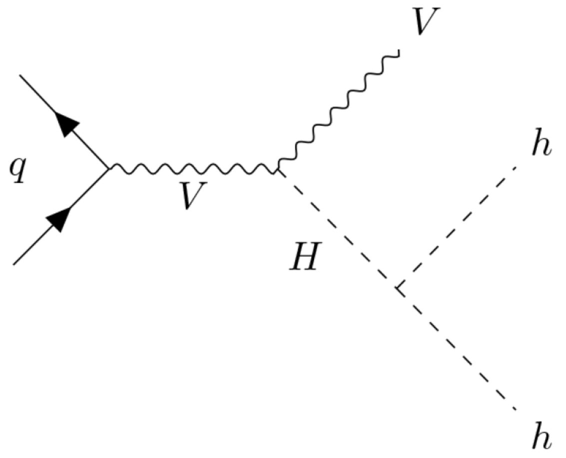
Limit on SM HH:

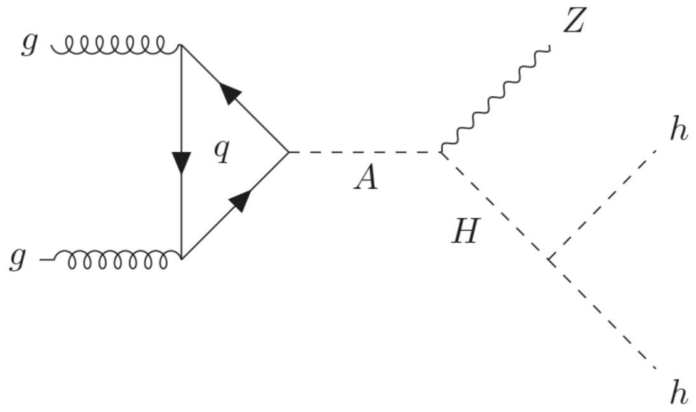
183 observed, 87 expected

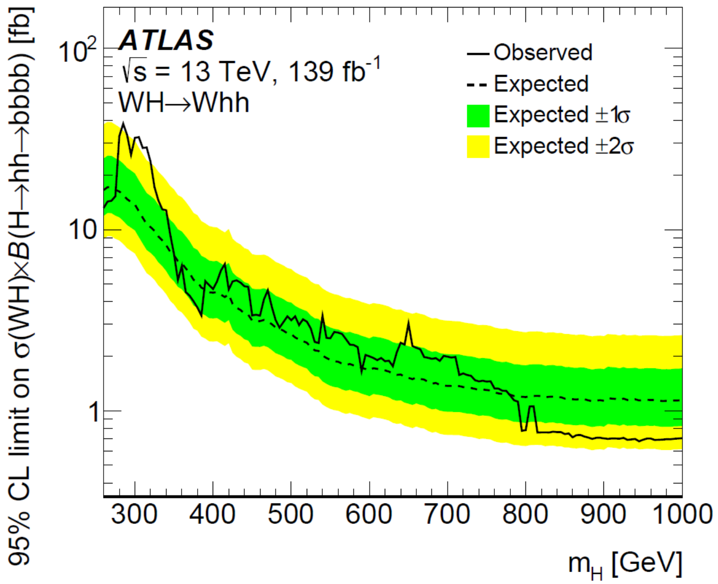
VHH → bb+ll+MET

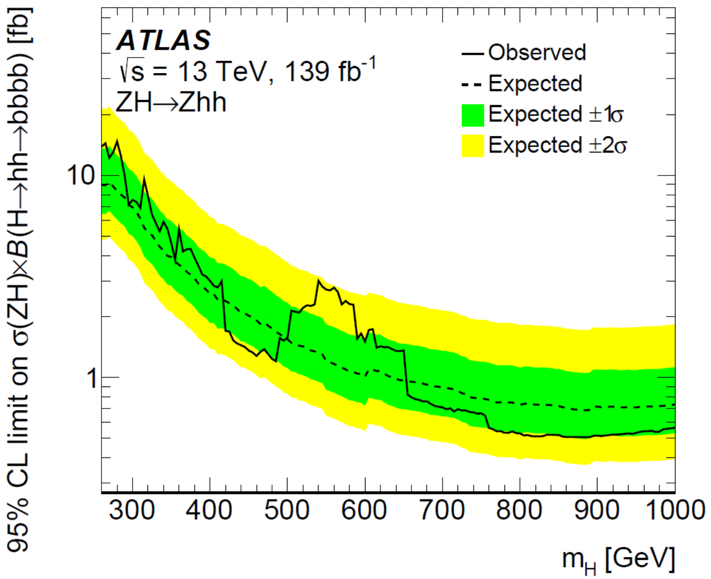
2210.05415

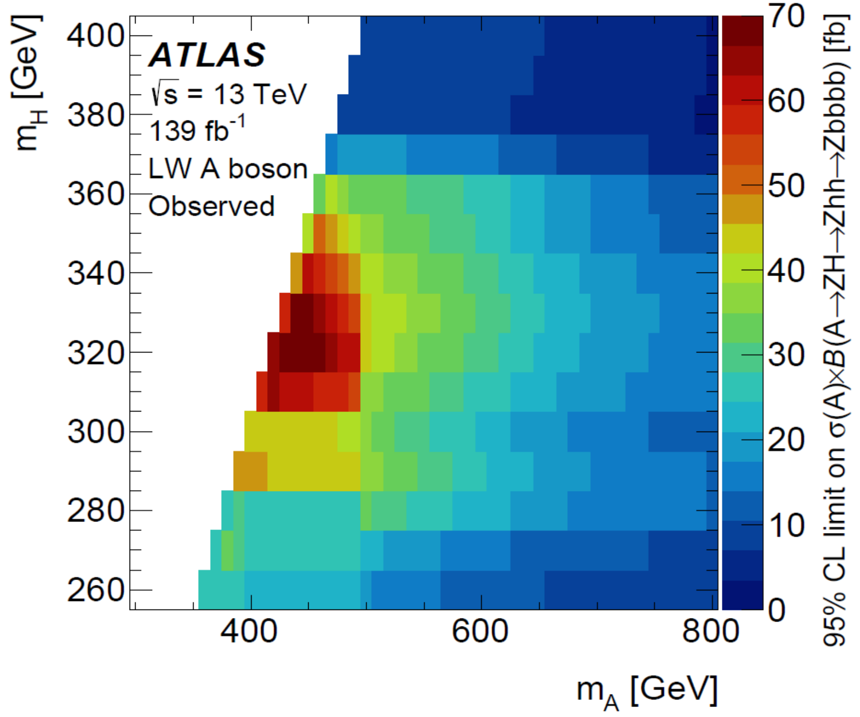
Resonant:











Excess at (420, 320) GeV
3.8σ local, 2.8σ global