Searches for new physics in the Higgs sector with the ATLAS detector

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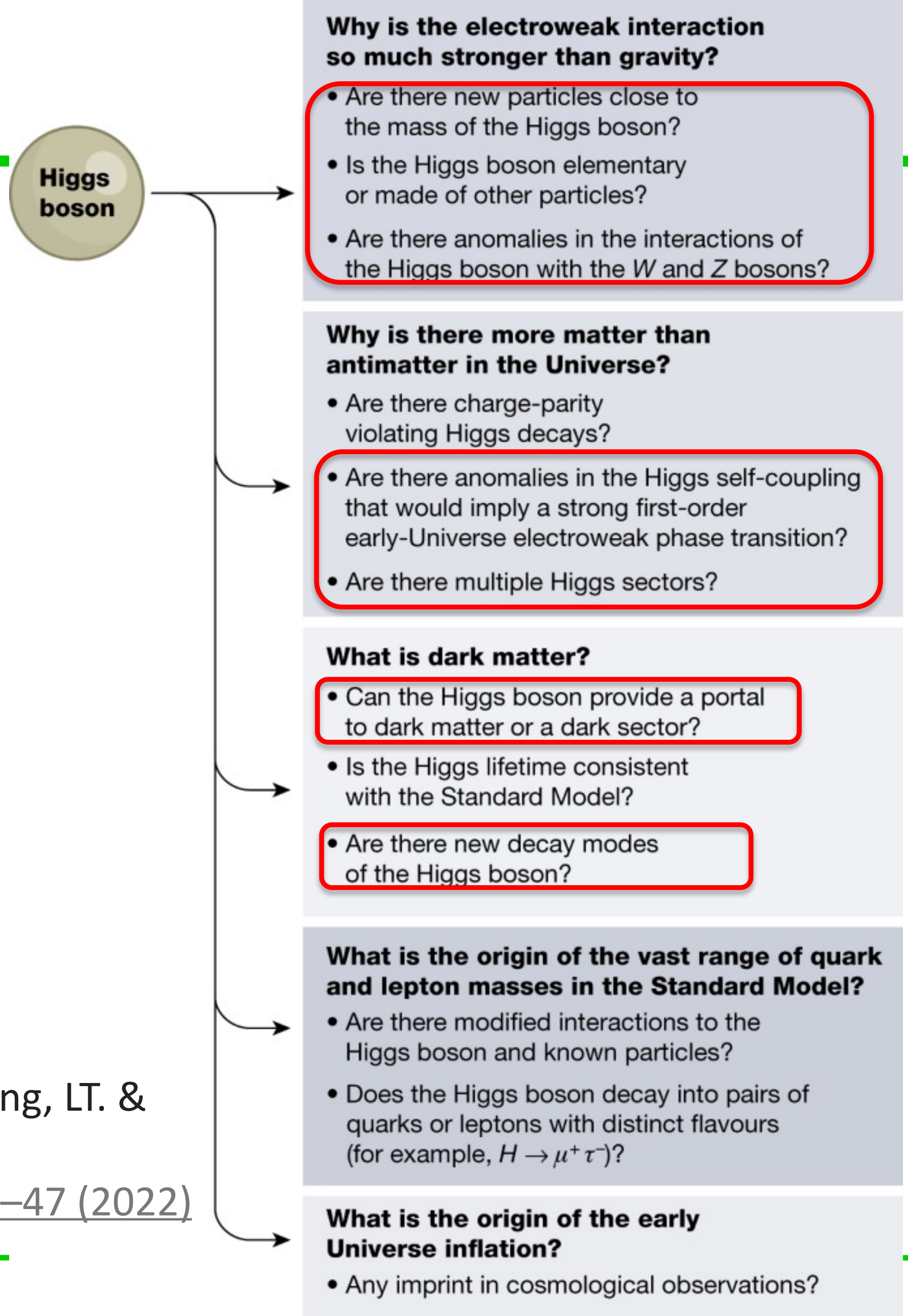
Introduction

- The SM Higgs boson opens a new window for new physics beyond the SM
- Possible connections between Higgs and major open questions of particle physics and cosmology
  - The hierarchy problem
  - Matter and antimatter asymmetry
  - Dark matter
  - …



Salam, G.P., Wang, LT. & Zanderighi, G. *Nature* **607**, 41–47 (2022)

Outline

- Recent searches for new physics in the Higgs sector with full LHC Run2 data
  - Search for additional Higgs bosons ($m_H \neq 125$ GeV)
  - Search invisible Higgs decays
  - Search for HH production

Search for additional Higgs bosons
$(m_H \neq 125\ \text{GeV})$

Additional Higgs boson

- Why there should be only one (h_{125})?
- Many extensions of the SM predict additional Higgs bosons
  - Electroweak singlets — H
  - Two-Higgs-Doublet-Models (2HDM)
  - Minimal Supersysmmetric Standard Model (MSSM)
    - (2HDM, MSSM): H (CP-even), A(CP-odd), $H^{\pm}$,
  - Georgi-Machacek model (GM) — Quintet($H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--}$), triplet($H_3^{+}, H_4^{0}, H_3^{-}$), H

Generic searches:
- New scalars
- New pseudo-scalars
  - Eg. Axions

Benchmark model searches:
- 2HDM
- GM

Additional Higgs boson

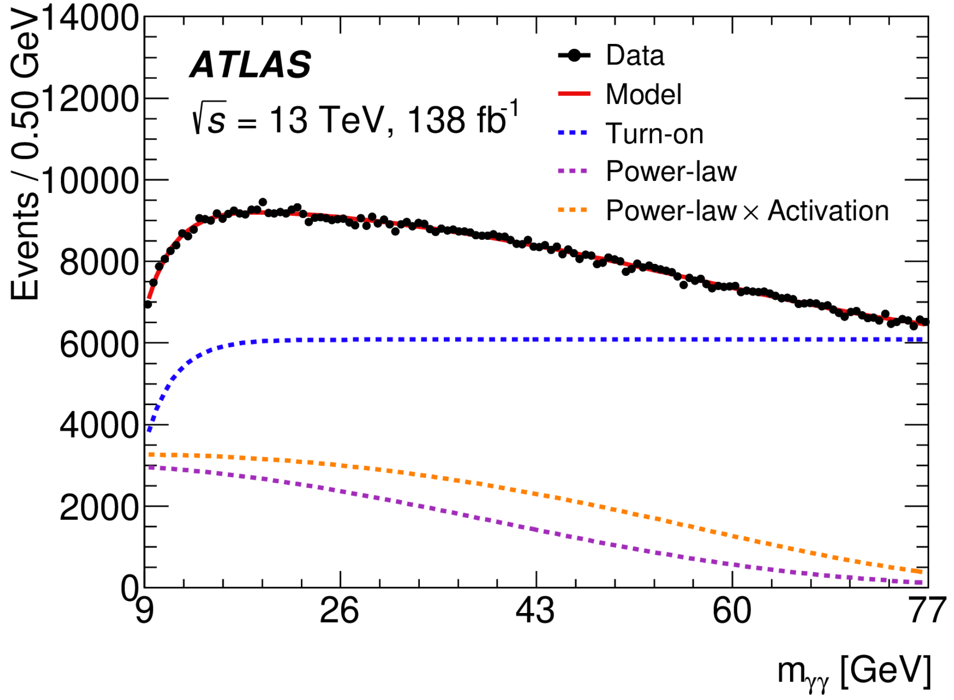
Searches	Ref.	Searches	Ref.
Boosted $a \rightarrow \gamma\gamma$ ($10\ \mathrm{GeV} < m_X < 70\ \mathrm{GeV}$)	arXiv:2211.04172	$t \rightarrow H^{\pm}b, H^{\pm} \rightarrow cb$	arXiv:2302.11739
Low-mass resonance $X \rightarrow \gamma\gamma$ ($66 < m_X < 110$ GeV)	ATLAS-CONF-2023-035	$H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$	arXiv:2211.07505
$tta, a \rightarrow \mu\mu$	arXiv:2304.14247	$ttH/A \rightarrow tttt$	arXiv:2211.01136
$X \rightarrow Z\gamma$	ATLAS-CONF-2023-030	$A \rightarrow ZH \rightarrow lltt + \nu\nu bb$	ATLAS-CONF-2023-034
$X \rightarrow WW$	ATLAS-CONF-2022-066	**FCNC** $t \rightarrow qX, X \rightarrow bb$	arXiv:2301.03902

Not able to cover all of them or in very detail

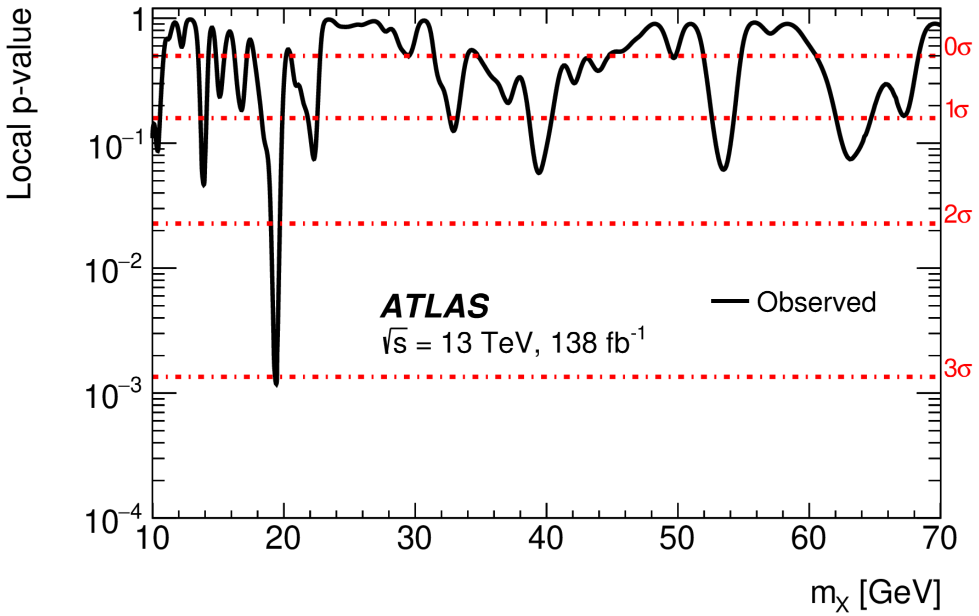
Boosted $a \to \gamma\gamma$

arXiv:2211.04172

- Search for narrow resonances (X) in $10\ \mathrm{GeV} < m_X < 70\ \mathrm{GeV}$
  - $p_T^{\gamma\gamma} > 50$ GeV → motivated by the boosted signal and to reduce background
- Background shape parameterized with analytical functions
  - Background modelling uncertainties reduced with Gaussian Processes



Largest deviation observed at 19.4 GeV with **3.1σ** of local significance (Global **1.5σ**)

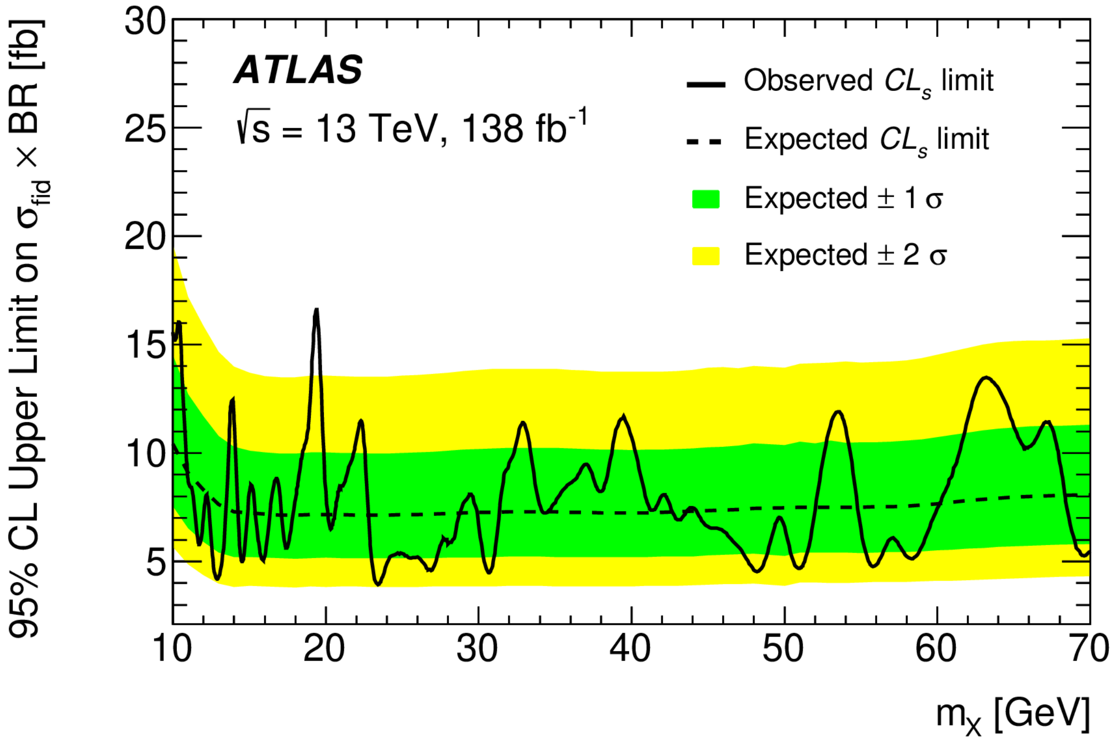


Boosted $a \to \gamma\gamma$

arXiv:2211.04172

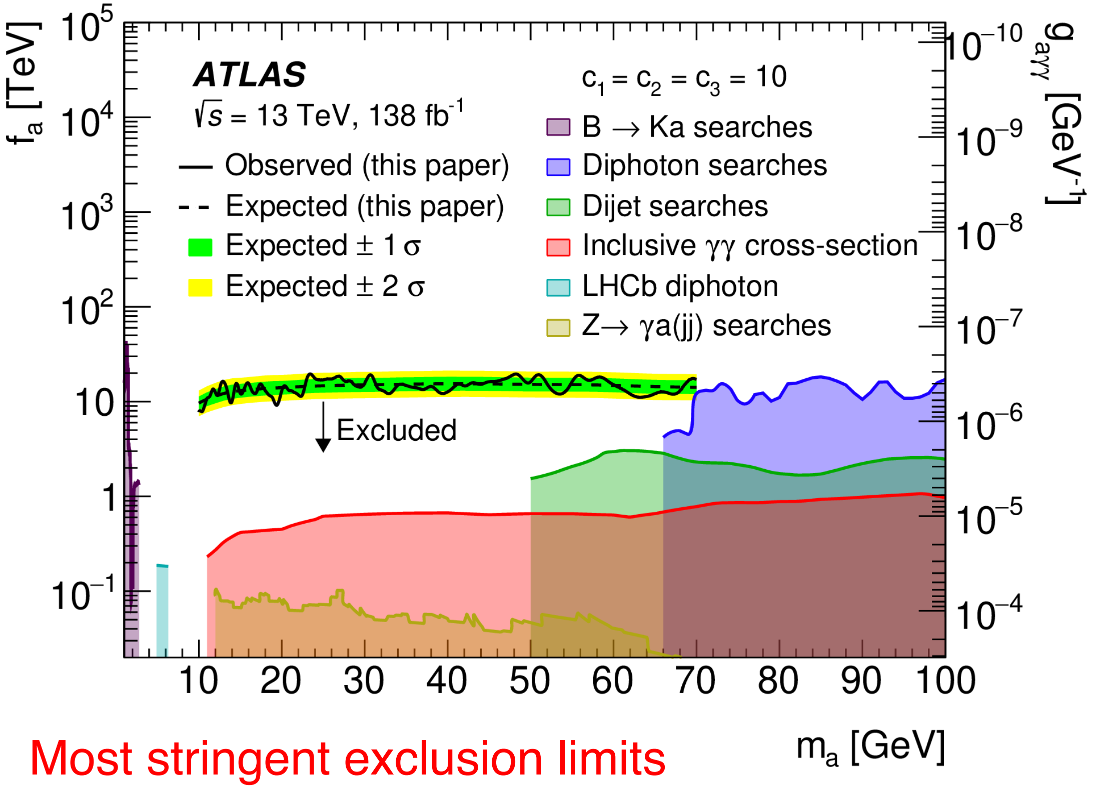
- Results

Model-independent limits (fiducial cross-sections)



Limits interpreted into the KSVZ-ALP parameter space

$$\frac{a}{4\pi f_a}\left[\alpha_3 c_3 G^a \tilde{G}^a + \alpha_2 c_2 W^i \tilde{W}^i + \alpha_1 c_1 B\tilde{B}\right] + \frac{1}{2}m_a^2 a^2$$



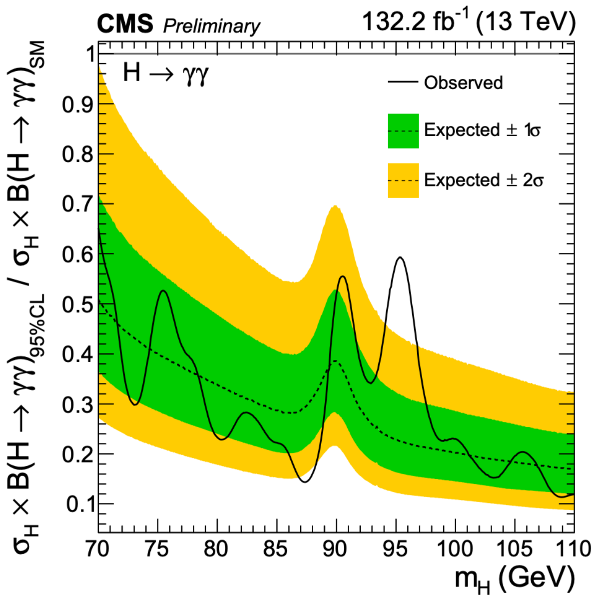
Most stringent exclusion limits

Covers a longstanding gap in diphoton resonance searches

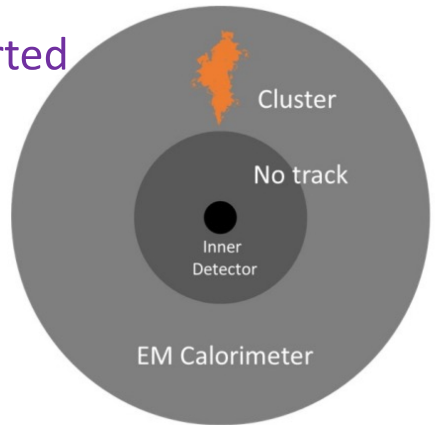
Low-mass resonance $X \rightarrow \gamma\gamma$

ATLAS-CONF-2023-035

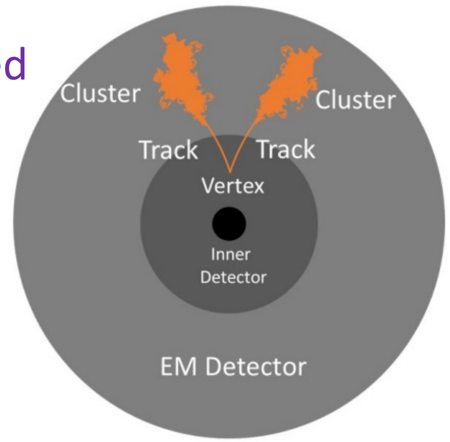
- Search for light scalar $X \rightarrow \gamma\gamma$ with $66 < m_X < 110$ GeV
  - CMS sees a 2.9σ excess at 95 GeV   CMS PAS HIG-20-002
- Model-independent search with 3 categories:
  - **CC**: two converted photons
  - **UU**: no conversion
  - **UC**: one converted photon
- Model-dependent search (to be compared with CMS):
  - Additional BDT used to separate the signal from background

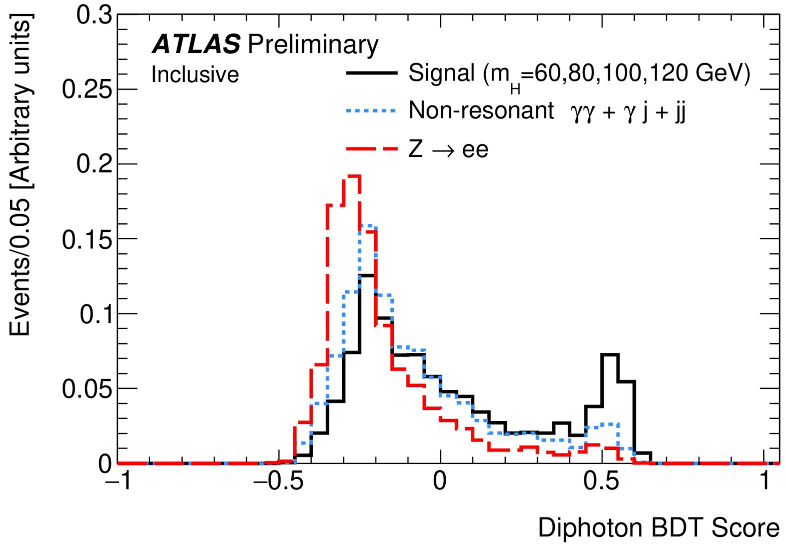


Un-converted photon



Converted photon

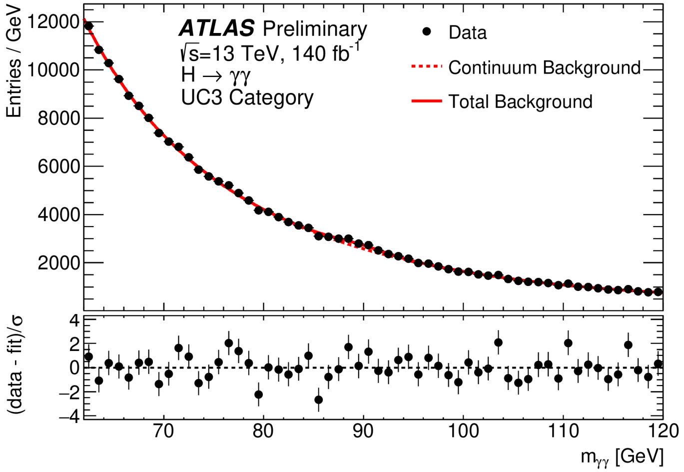


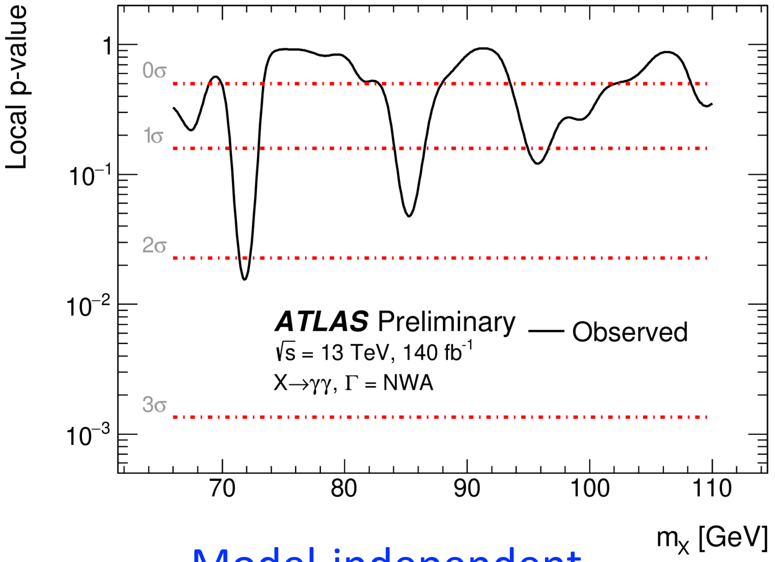


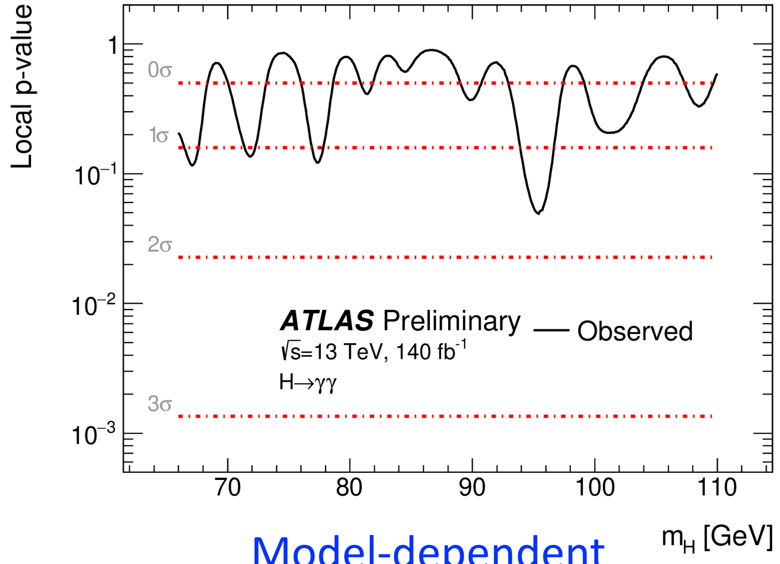
Low-mass resonance $X \rightarrow \gamma\gamma$

ATLAS-CONF-2023-035

Model-dependent

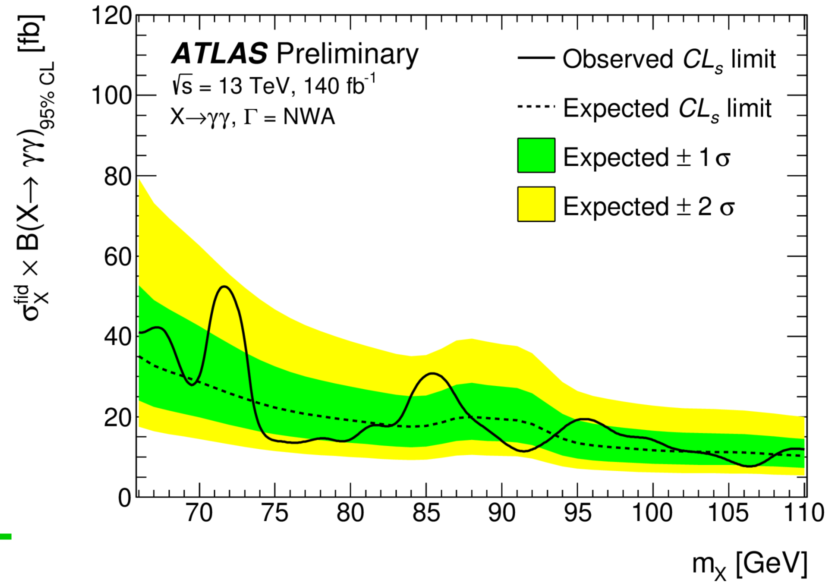


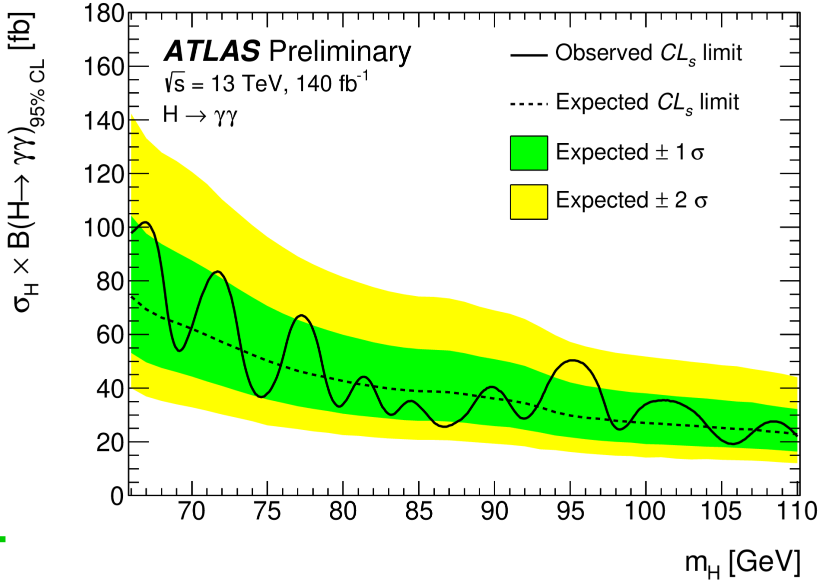




Model-independent

Model-dependent



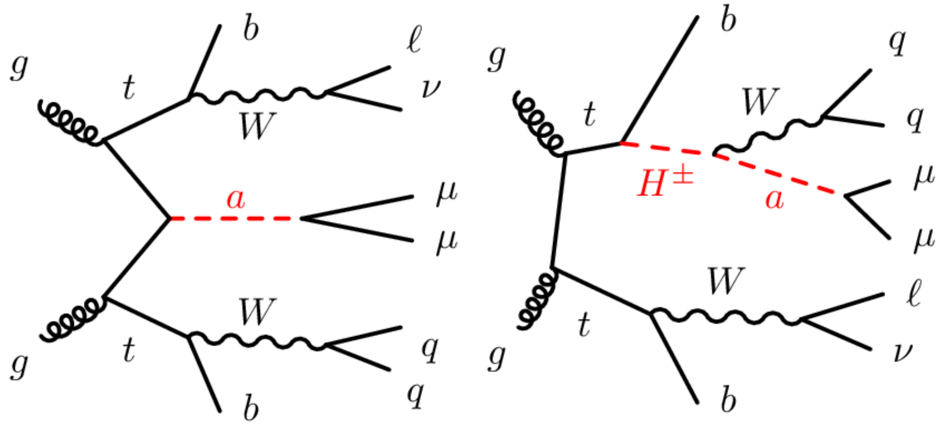


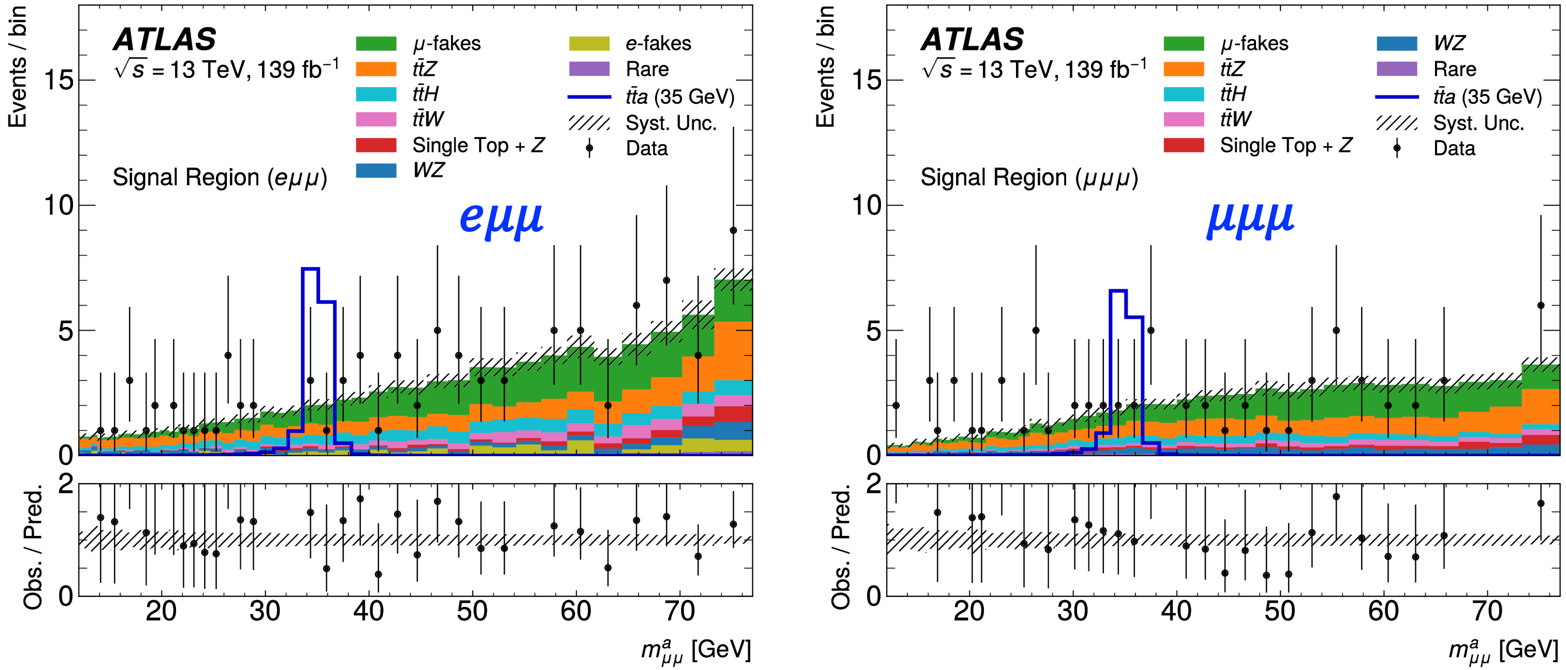
The 95 GeV excess
is not confirmed

$tta, a \to \mu\mu$

arXiv:2304.14247

- Search for a light pseudoscalar produced with a top-quark pair, $15 < m_a < 72$ GeV
- Two signal processes:
  - $tta, a \to \mu\mu$
  - $t \to H^+b, H^+ \to W^+a, a \to \mu\mu$: $120 < m_{H^\pm} < 160$ GeV
- Semileptonic tt decays with $e\mu\mu$ and $\mu\mu\mu$





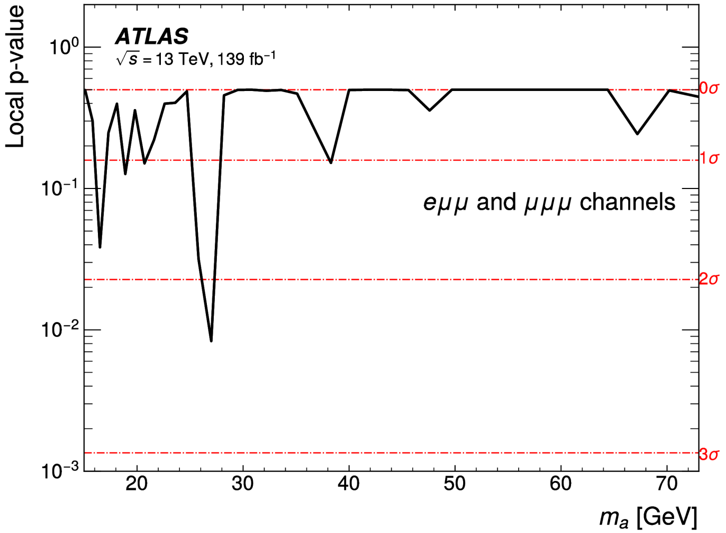
Use dimuon mass $m_{\mu\mu}$ to search for signals

$tta, a \to \mu\mu$

arXiv:2304.14247

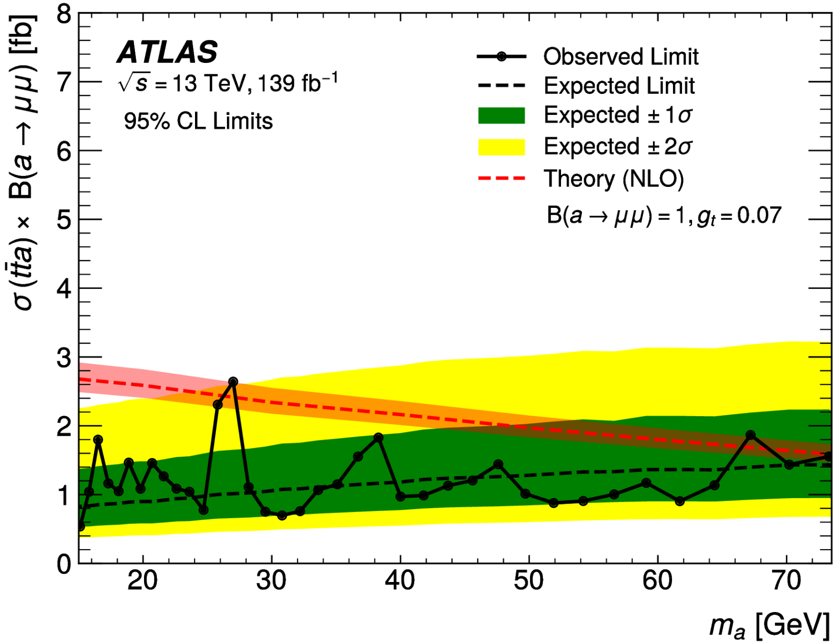
- Results

Upper limits on $\sigma \times Br$



Lagest excess: 27 GeV with a local significance of 2.4σ

tta

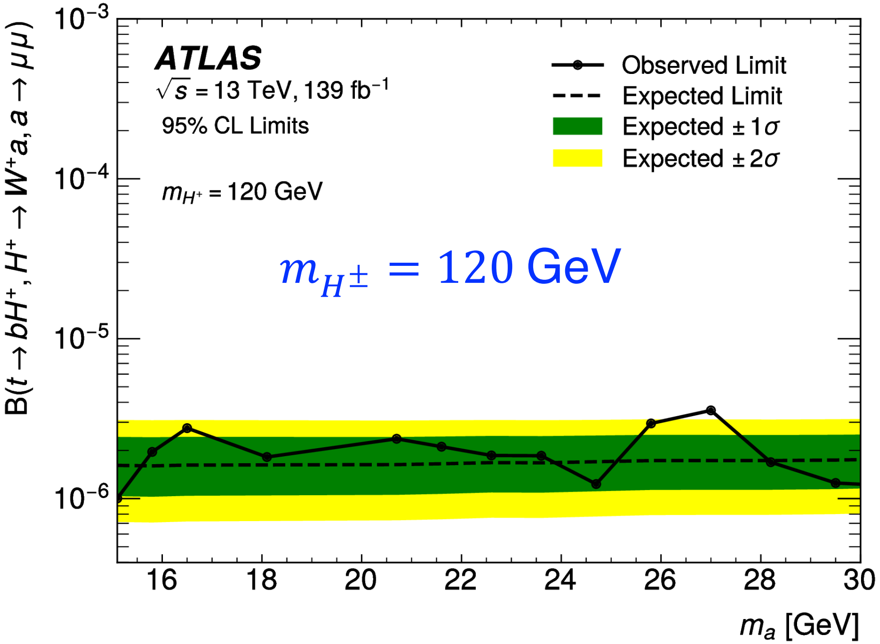


First limit on tta

Compared with a theory prediction

$$-iy_t g_t a(\bar{t}\gamma_5 t)/\sqrt{2}$$

$t \to H^+ b, H^+ \to W^+ a$



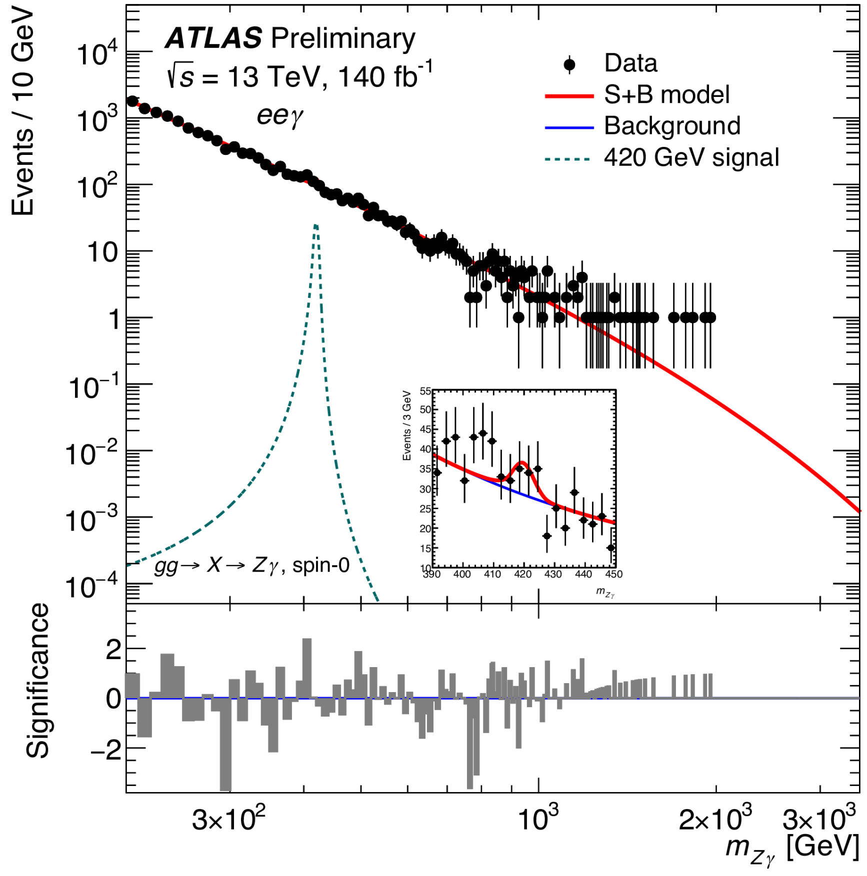
$m_{H^\pm} = 120$ GeV

Limits presented for $m_{H^\pm} = 120, 140, 160$ GeV respectively

Heavy resonances, $X \to Z\gamma$

ATLAS-CONF-2023-030

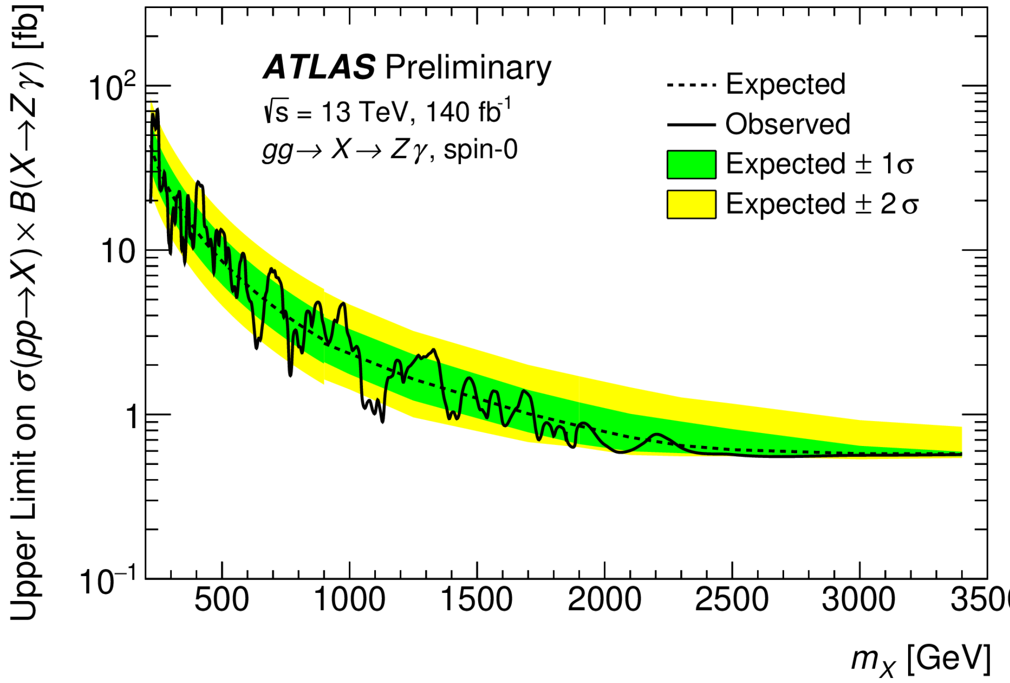
- Search for heavy narrow resonances in $X \to Z\gamma, Z \to ee/\mu\mu$, $220\ \mathrm{GeV} < m_X < 3.4\ \mathrm{TeV}$
  - Spin-0: ggF
  - Spin-2: ggF and qq→X



A dedicated electron identification is developed for boosted $Z \to ee$

Background shape parameterized using analytical functions

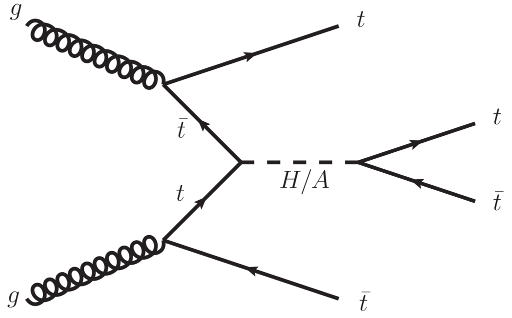
Upper limits on $\sigma \times Br$ (Spin-0)



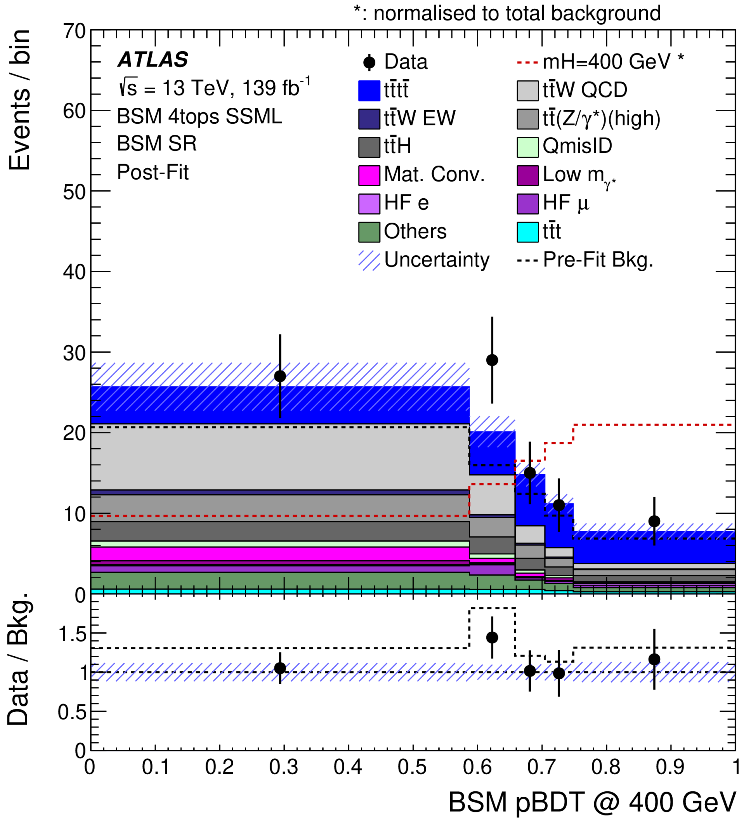
$ttH/A \rightarrow tttt$

arXiv:2211.01136

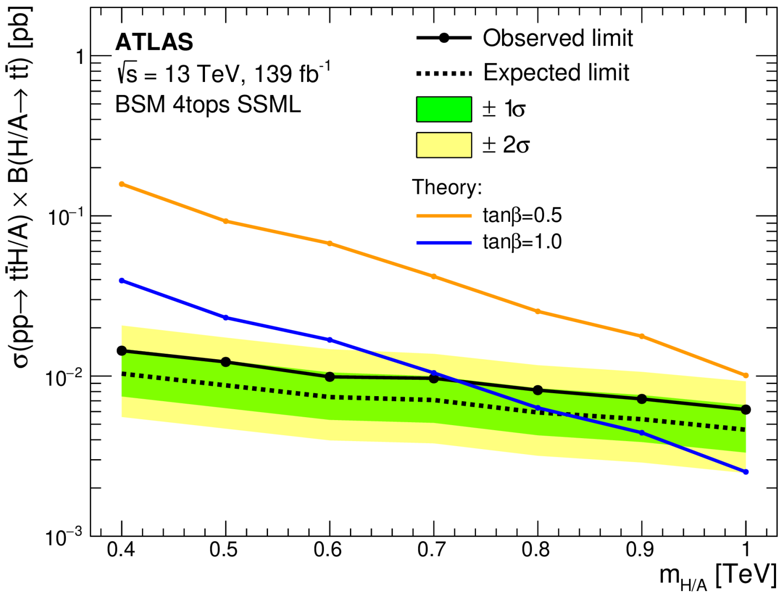
- Search for a new heavy scalar/pseudo-scalar ($H/A \rightarrow t\bar{t}$) produced in association with $t\bar{t}$
  - Signal model: type-II 2HDM, $400 < m_{H,A} < 1000$ GeV



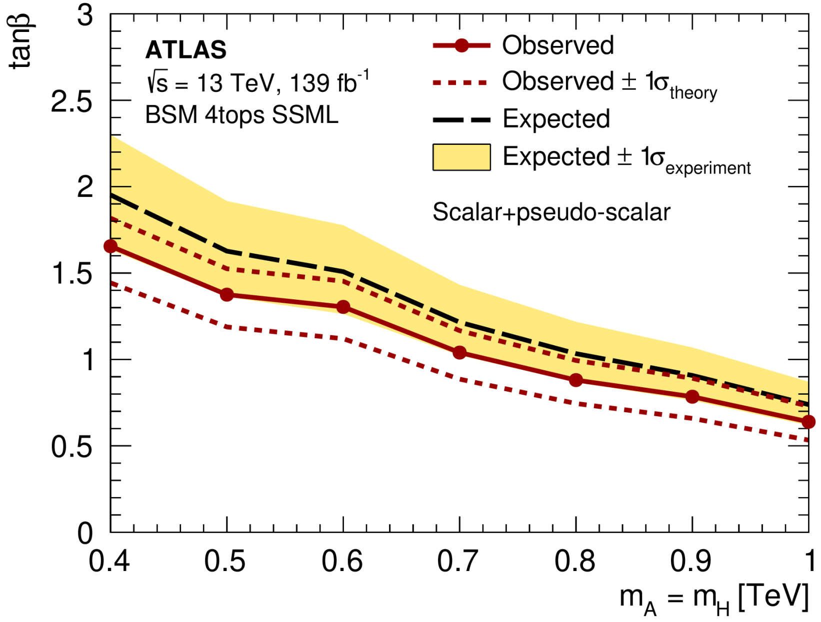
- SR: 2l same-sign ($l^{\pm}l^{\pm}$) or 3l with ≥ 6 jets and ≥ 2 b-jets
- Mass-parametrized BDT to separate BSM from the SM



Upper limits on $\sigma \times Br$



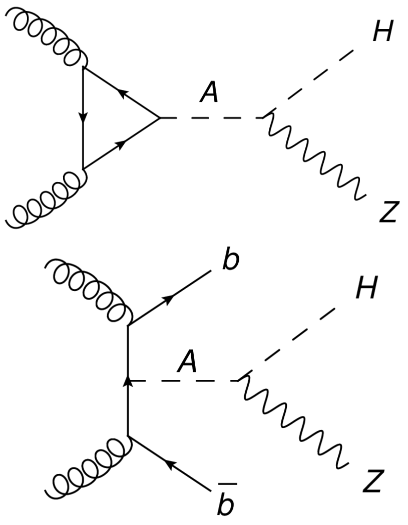
$\tan\beta$ vs m_A

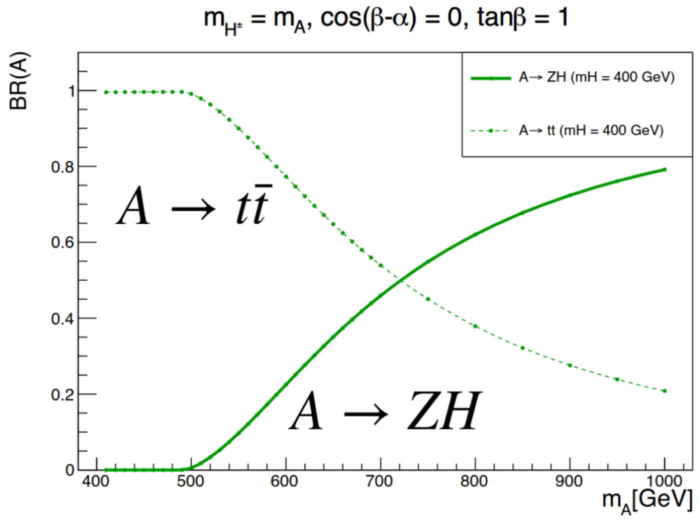


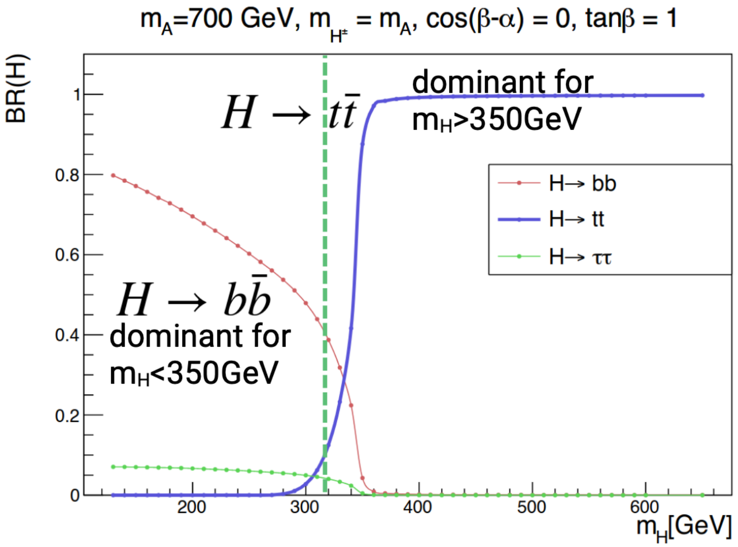
$A \rightarrow ZH \rightarrow lltt + vvbb$

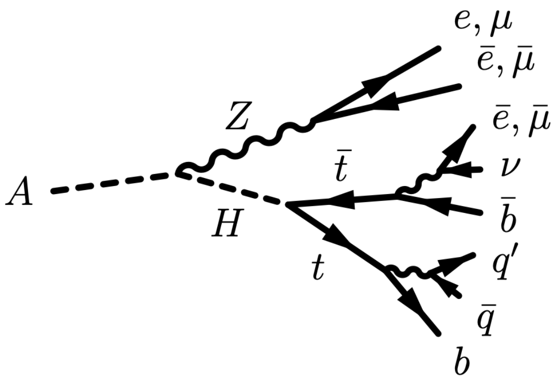
ATLAS-CONF-2023-034

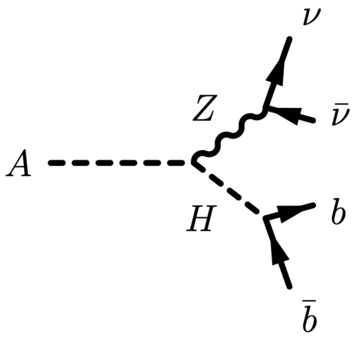
- In 2HDM, $m_A > m_H$ is favored by electroweak baryogenesis and strong first-order phase transition
  - $A \rightarrow ZH$ decay dominates
- $lltt$ channel: sensitive to $m_H > 350$ GeV
  - 3 lep, $\geq$ 4-jets, 2 b-jets
  - Main bkg: ttZ
- $vvbb$ channel: sensitive to $m_H < 350$ GeV
  - $E_T^{miss} > 150$ GeV, $\geq$ 2 b-jets
  - Main bkg: tt and Z+heavy flavor









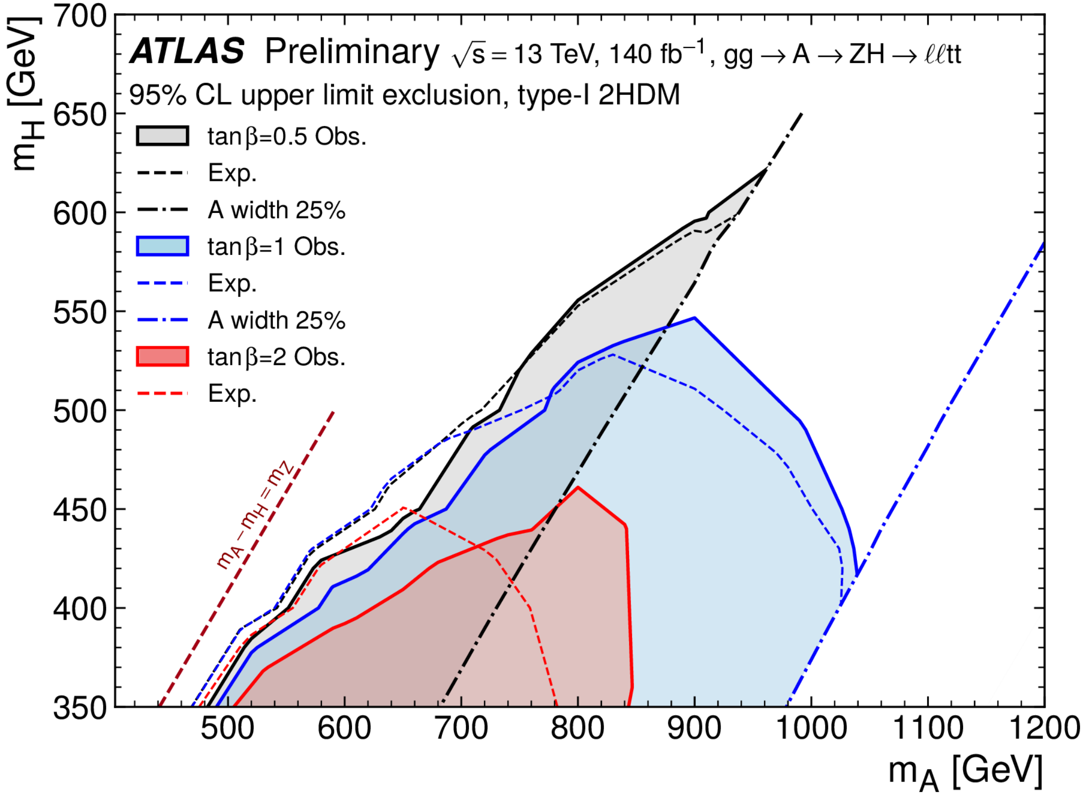


These channels have not been previously explored at the LHC

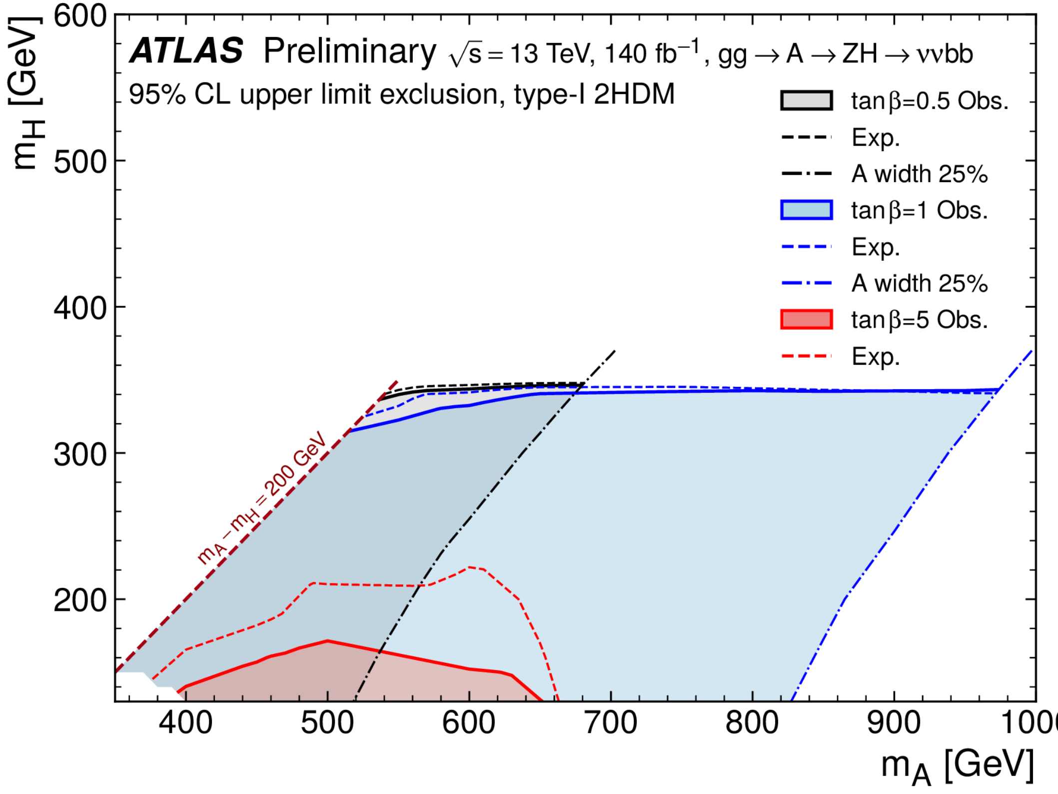
$A \to ZH \to lltt + \nu\nu bb$

Exclusion limits in the $m_A - m_H$ plane
in both type-I and type-II 2HDM (only type-I shown here)

$gg \to A \to ZH \to lltt$



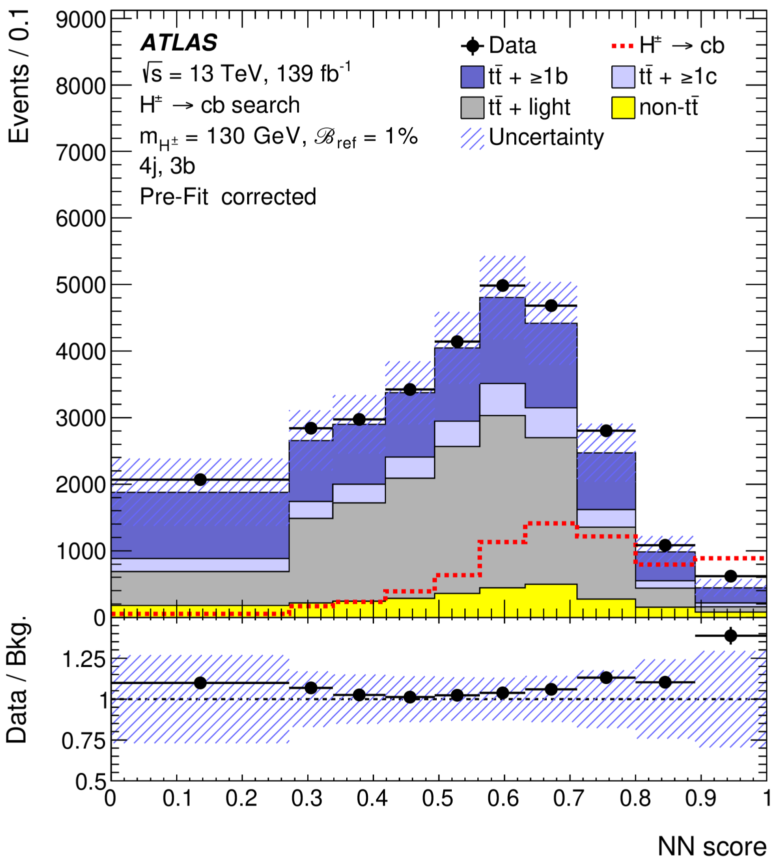
$gg \to A \to ZH \to \nu\nu bb$



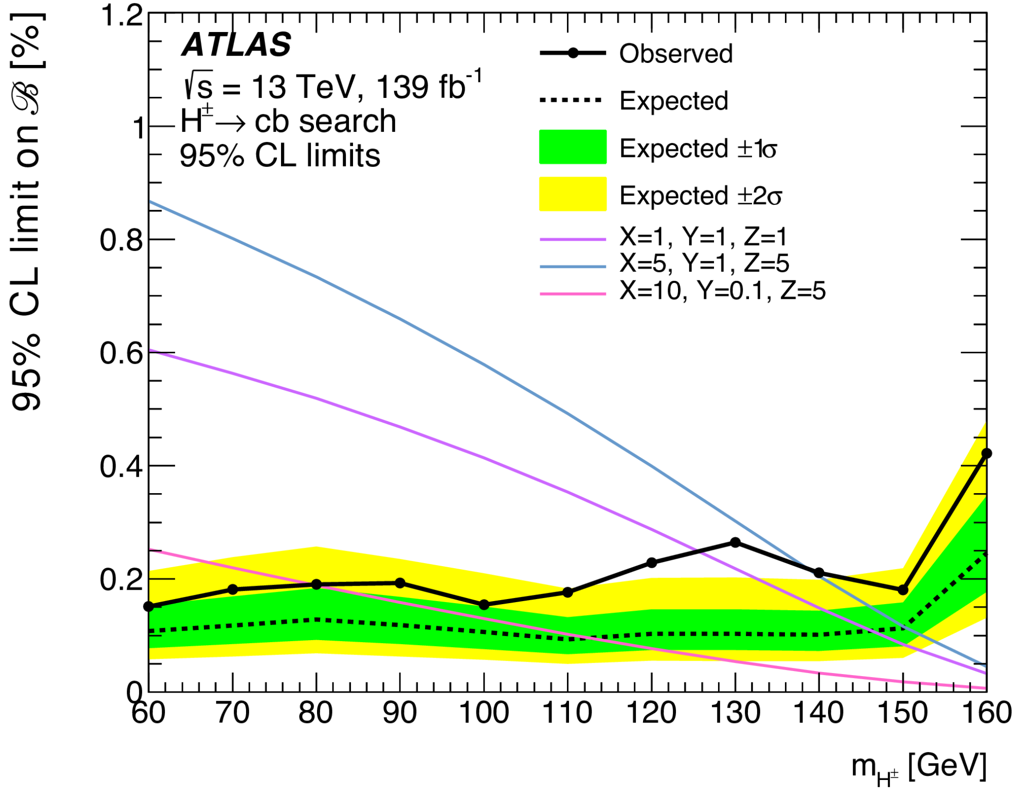
$t \to H^{\pm}b, H^{\pm} \to cb$

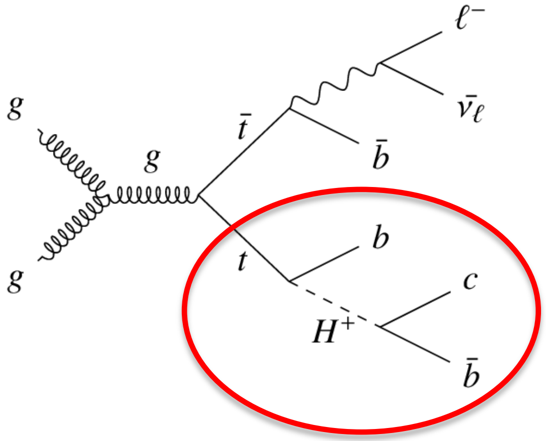
arXiv:2302.11739

- Search for a charged Higgs boson produced in top-quark decays, $60 < m_{H^{\pm}} < 160$ GeV
- Mass parametrized Neural Network discriminant



Upper limits on $B(t \to H^{\pm}b) \times B(H^{\pm} \to cb)$





Largest excess: $\mathbf{3\sigma @ m_{H^{\pm}} = 130}$ GeV (Global significance: 2.5σ)

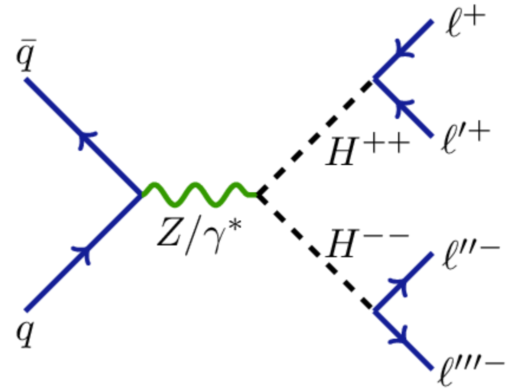
A factor 5 improvement compared to previous CMS search (JHEP11(2018)115) and with extended mass range

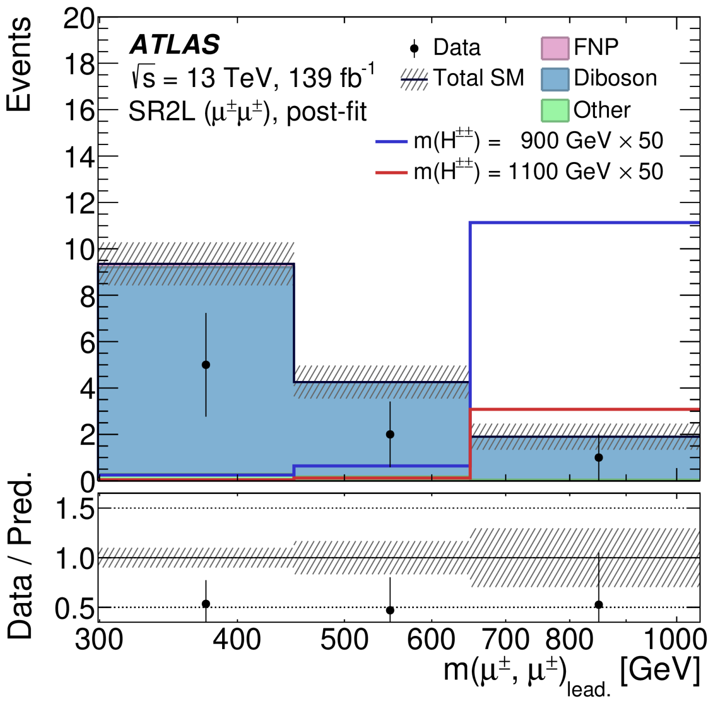
Compared with predictions from the 3HDM

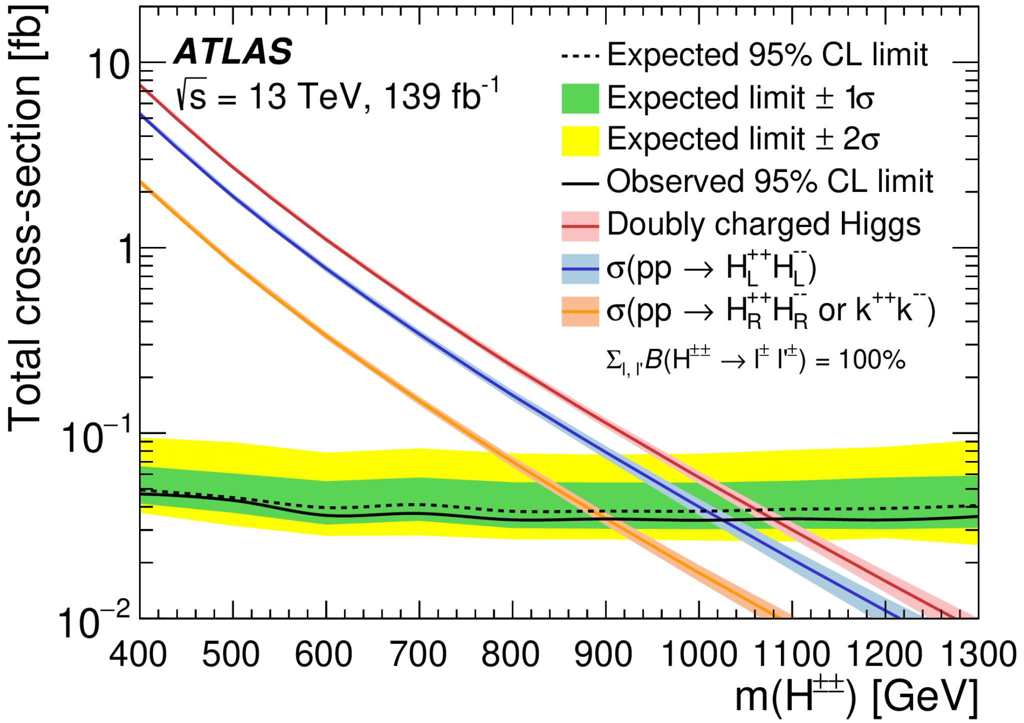
$H^{\pm\pm}, H^{\pm\pm} \to l^{\pm}l^{\pm}$

arXiv:2211.07505

- Search for pair production of doubly charged Higgs bosons $H^{\pm\pm}$, $300 < m_{H^{\pm\pm}} < 1300$ GeV
  - $H^{\pm\pm} \to l^{\pm}l^{\pm}, l = e, \mu, \tau$ with electrons and muons in the final state
  - Assuming the same Br of $H^{\pm\pm} \to ee, e\mu, \mu\mu, e\tau, \mu\tau, \tau\tau$ final states
  - Benchmark signal model: left-right symmetric type-II seesaw and Zee–Babu
- Signal regions: $l^{\pm}l^{\pm}$, $l^{\pm}l^{\pm}l^{\mp}$, $l^{+}l^{+}l^{-}l^{-}$







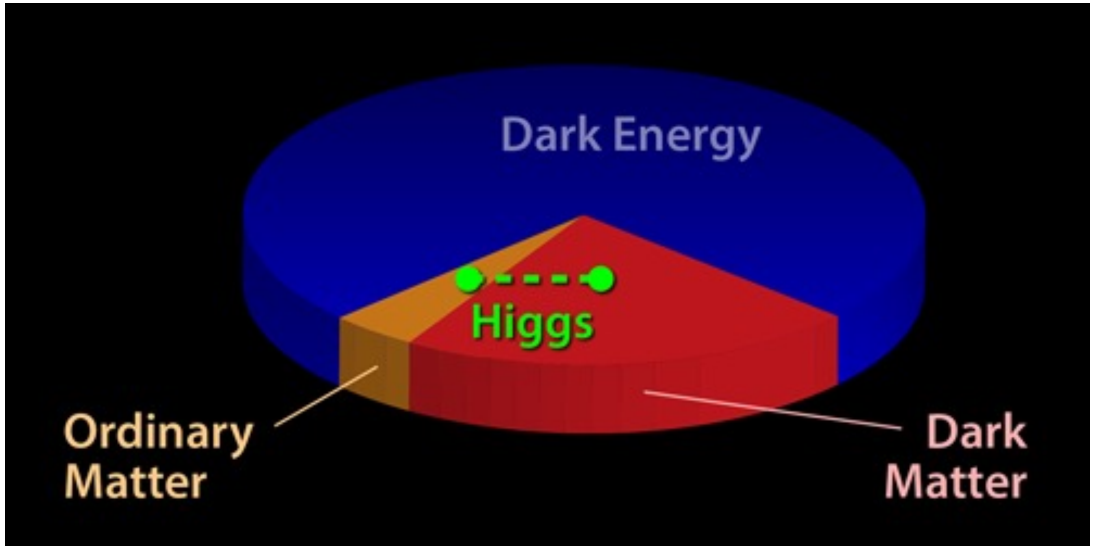
$m_{H^{\pm\pm}} < 1080\ (900)$ GeV excluded for the LRSM (Zee-Babu) model

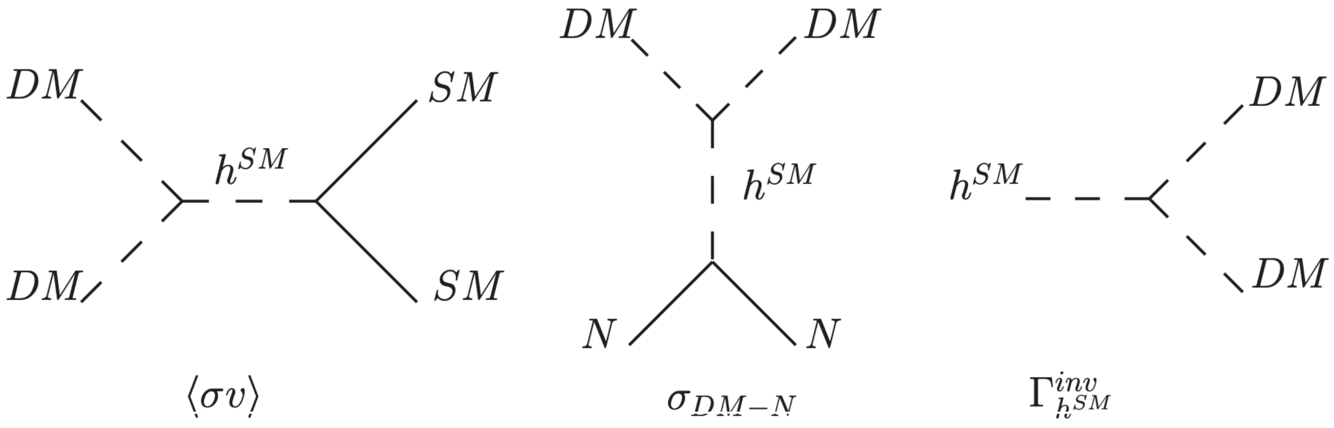
Provides a first direct test of the Zee–Babu model ($k^{++}k^{--}$) at the LHC

Search invisible Higgs decays

Invisible Higgs decay

- In the SM, Br(H→inv) = 0.1% ($H \rightarrow ZZ^* \rightarrow 4v$)
- Higgs portal is a benchmark Dark Matter model

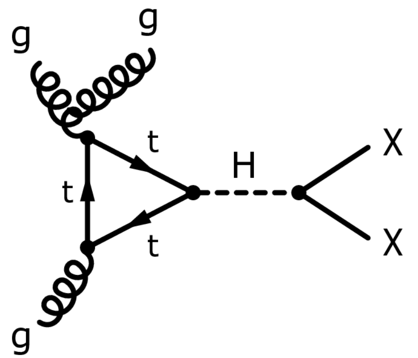


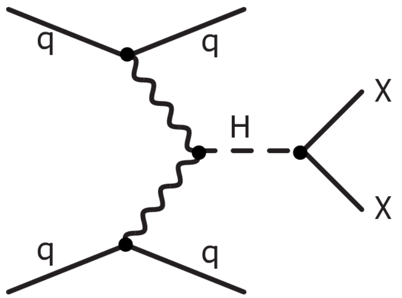


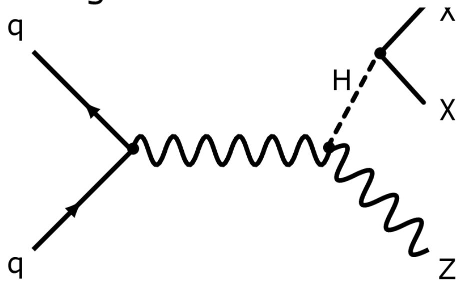
Combination of invisible Higgs searches

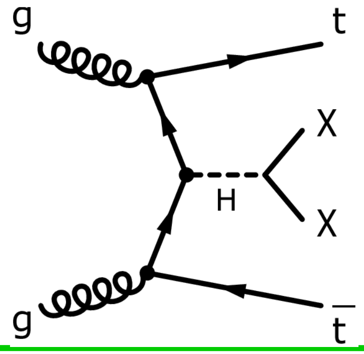
- Channels entering the conbintion:
  - **ggF**: $jet + E_T^{miss}$ PRD 103 (2021) 112006
  - **VBF**: VBF + E_T^{miss} JHEP 08 (2022) 104
  - **ZH**: Z(→ll) + E_T^{miss} PLB 829 (2022) 137066
  - **ttH**: tt + E_T^{miss} EPJC 83 (2023) 503

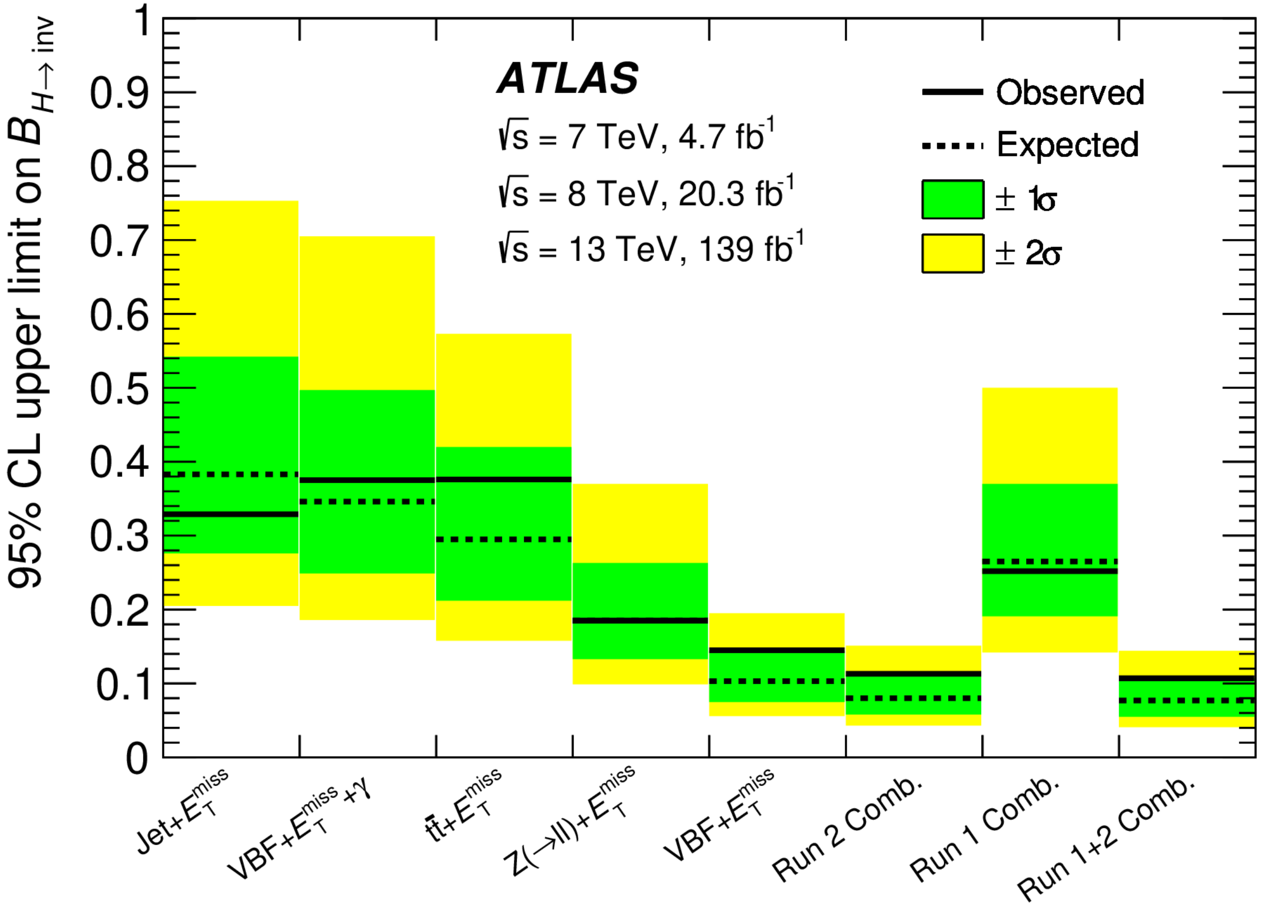
Phys. Lett. B 842 (2023) 137963







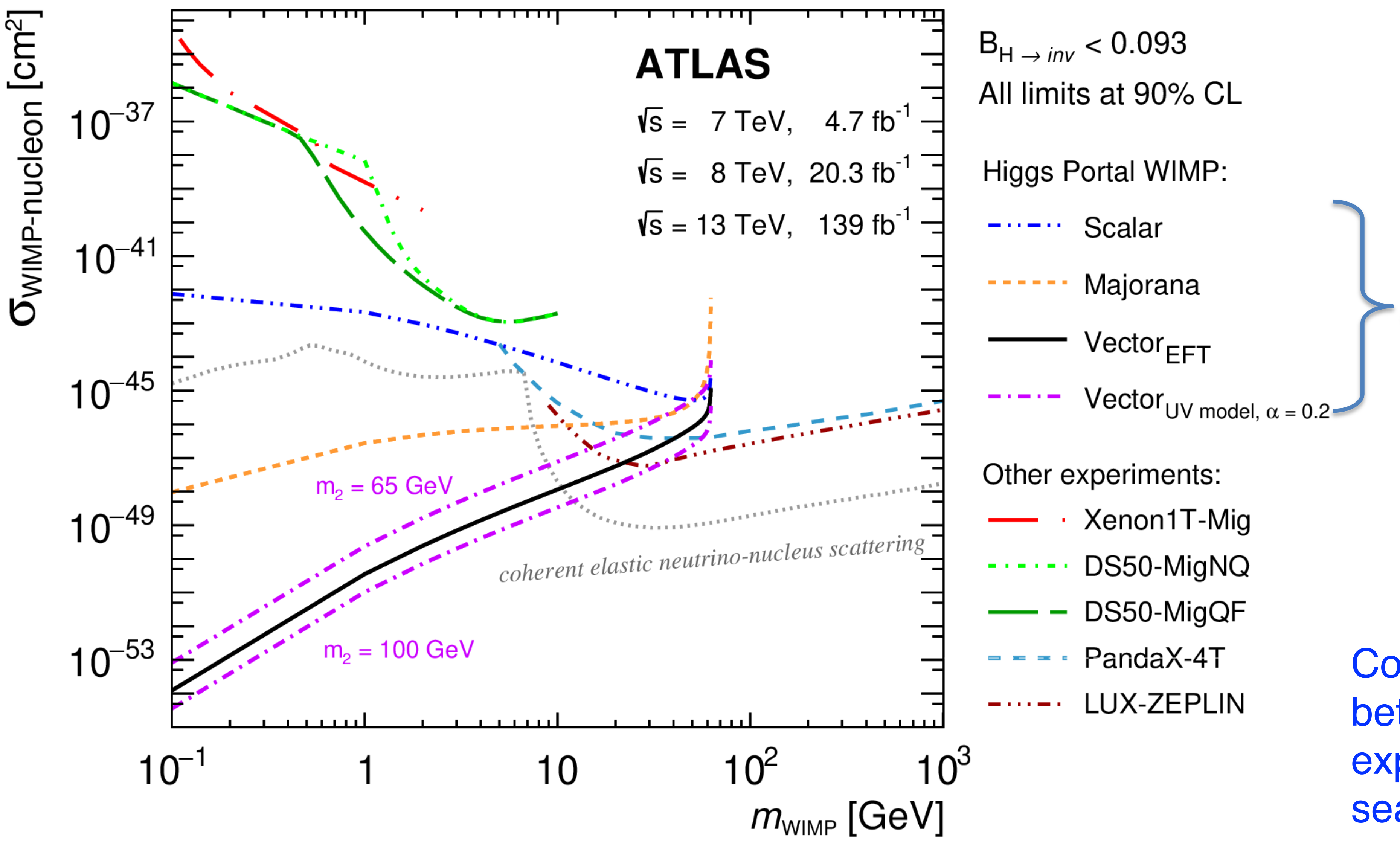


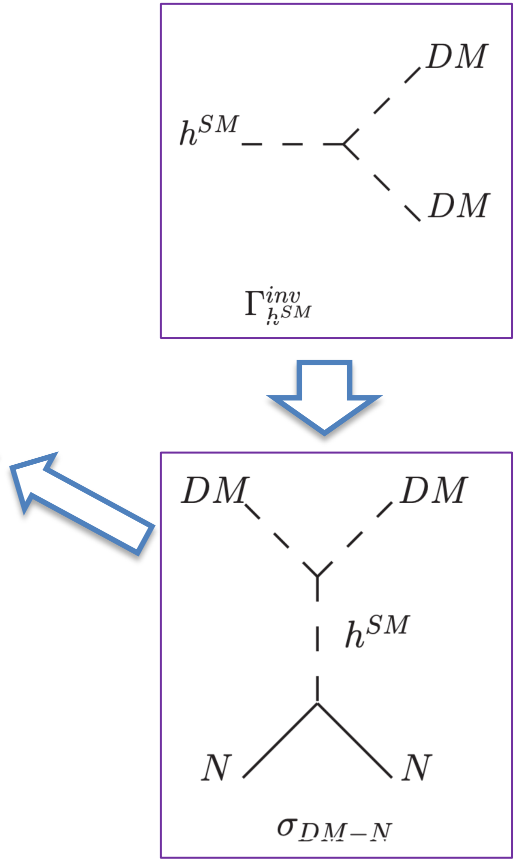


Observed (expected) 95% CL limit:

Br(H→inv) < 10.7 (7.7)%

Higgs portal Dark Matter





Complementary sensitivity between direct-detection experiments and collider searches

Search for HH production

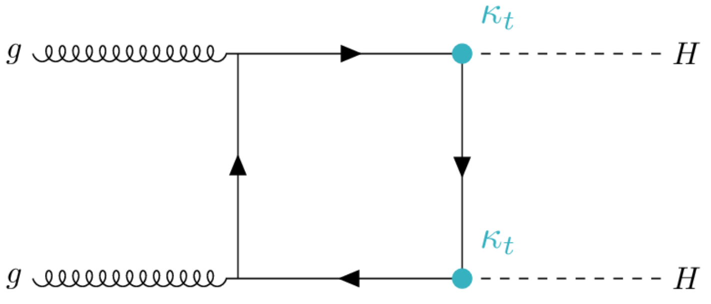
DiHiggs production

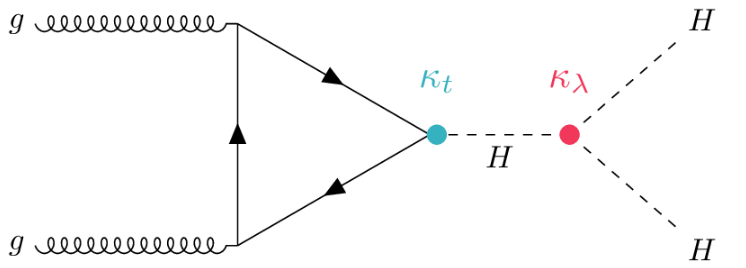
- Non-resonant hh：
  - Direct probe of the trilinear Higgs self-coupling κ_λ
  - Main production processes: ggF and VBF

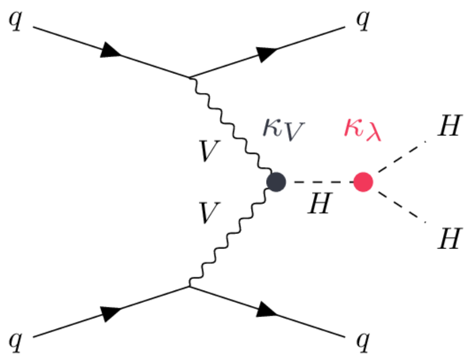
$$\sigma_{HH}^{GGF} = 31.05\ \mathrm{fb}\ \pm 3\%(\mathrm{PDF}+\alpha_S)\ ^{+2.2\%}_{-5\%}\ (\mathrm{scale})\ \pm 2.6\%(m_t)\ @\ 13\ TeV$$

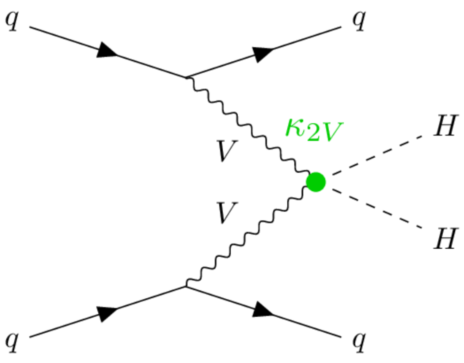
$$\sigma_{HH}^{VBF} = 1.73\ \mathrm{fb}\ \pm 2.1\%(\mathrm{PDF}+\alpha_S)\ ^{+0.03\%}_{-0.04\%}\ (\mathrm{scale})\ @\ 13\ TeV$$

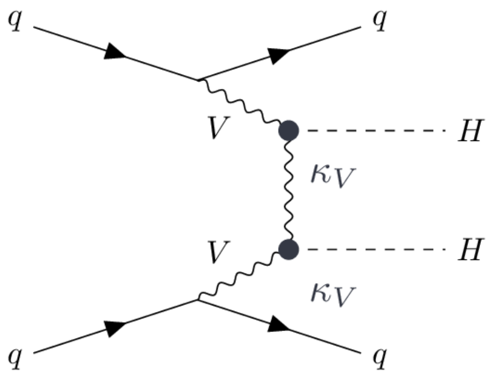
~2000 times smaller than that for the single Higgs production







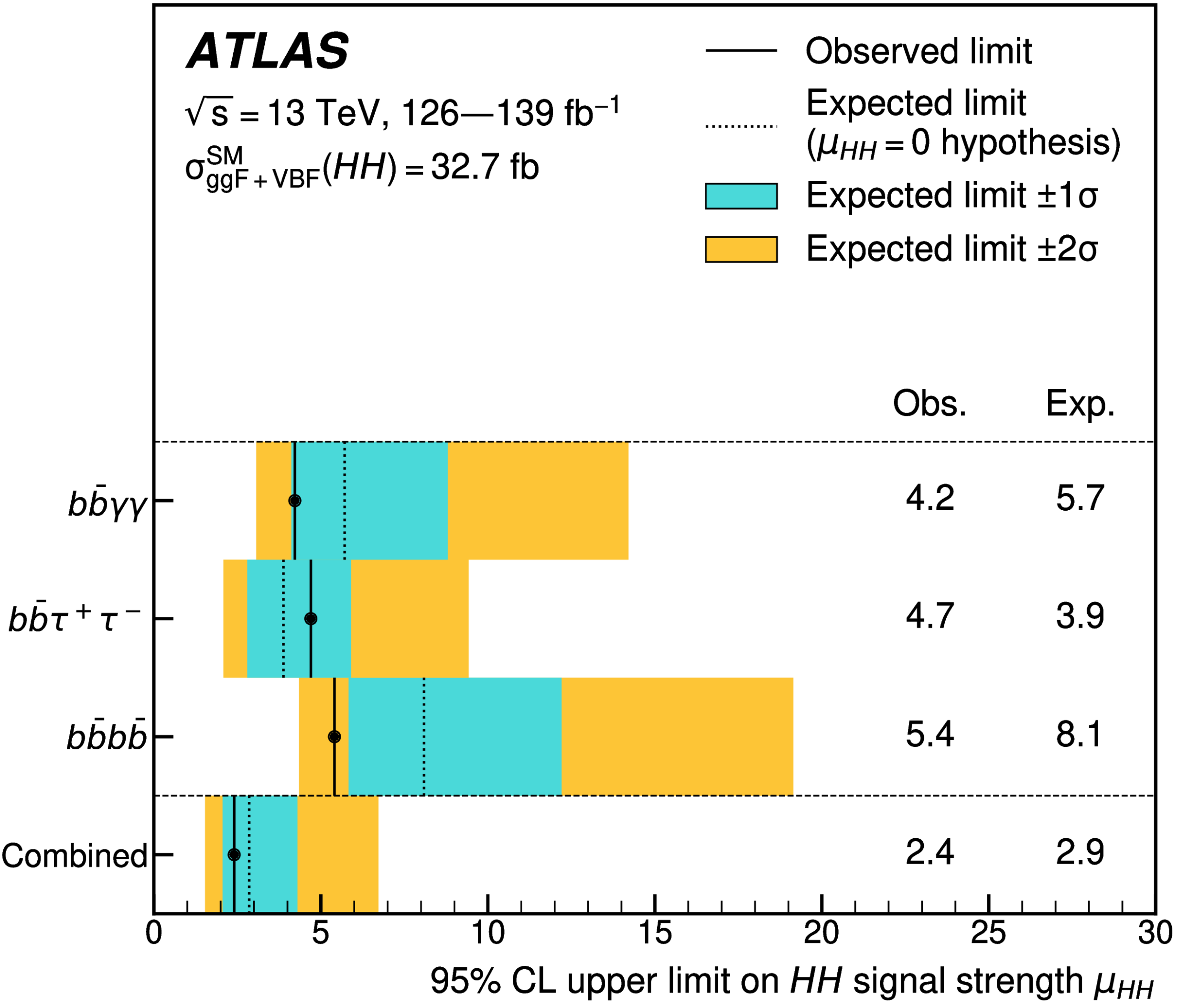


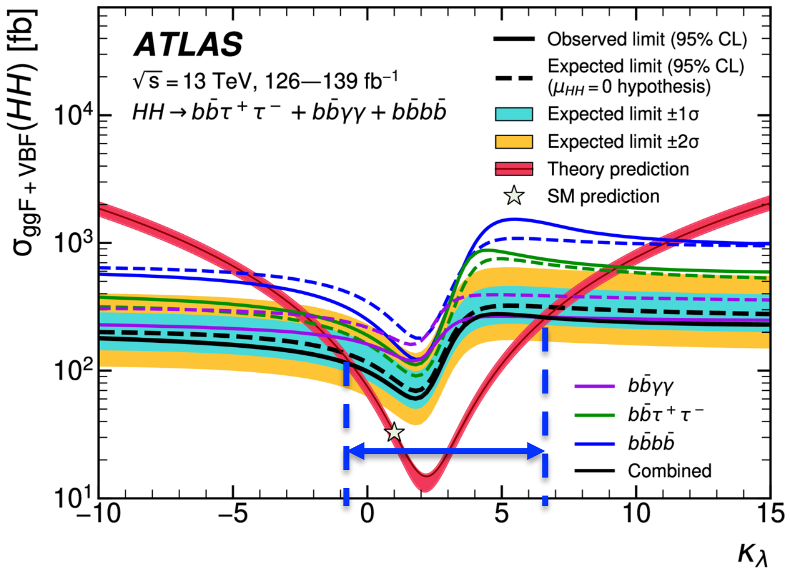


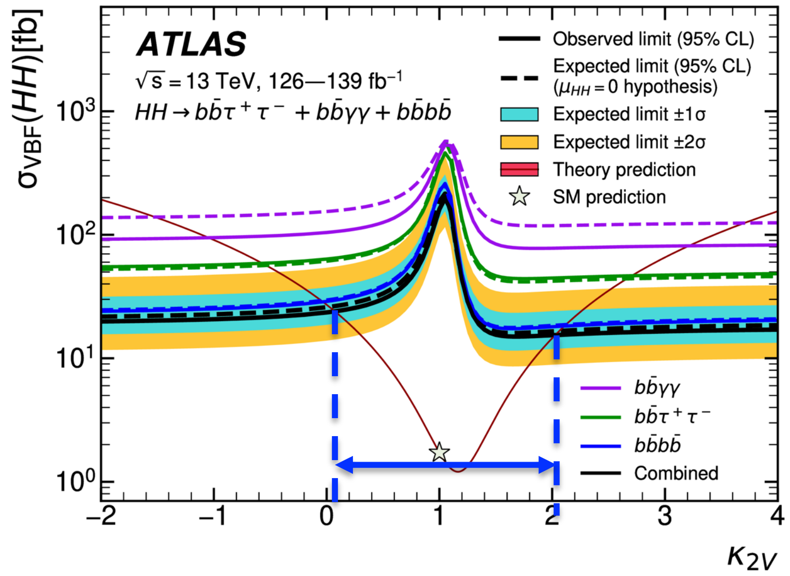
- Resonant hh production: BSM
  - $X \to hh$

hh combination

Phys.Lett.B 843 (2023) 137745





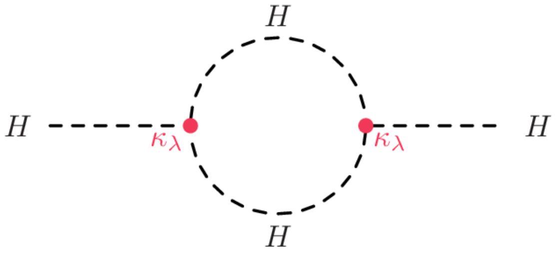


h + hh combination

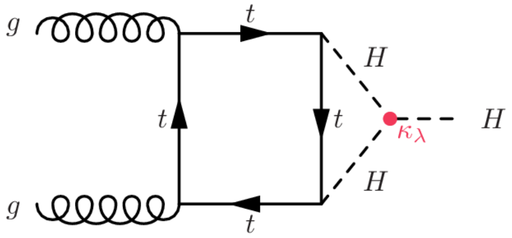
Phys.Lett.B 843 (2023) 137745

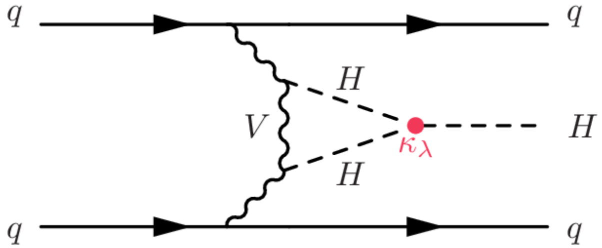
- Single-Higgs processes are indirectly sensitive to κ_λ via NLO EW corrections:

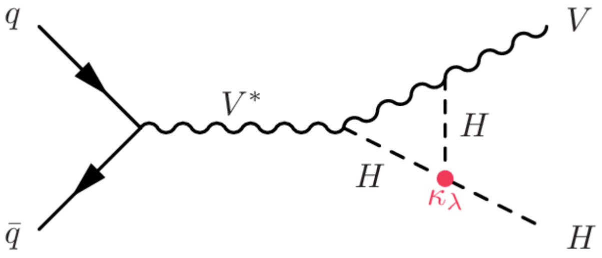
Universal correction $\boldsymbol{O}(\kappa_\lambda^2)$: Higgs loops

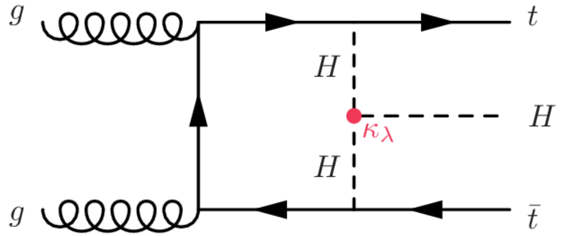


Linear correction $\boldsymbol{O}(\kappa_\lambda)$: both process and kinematics dependent









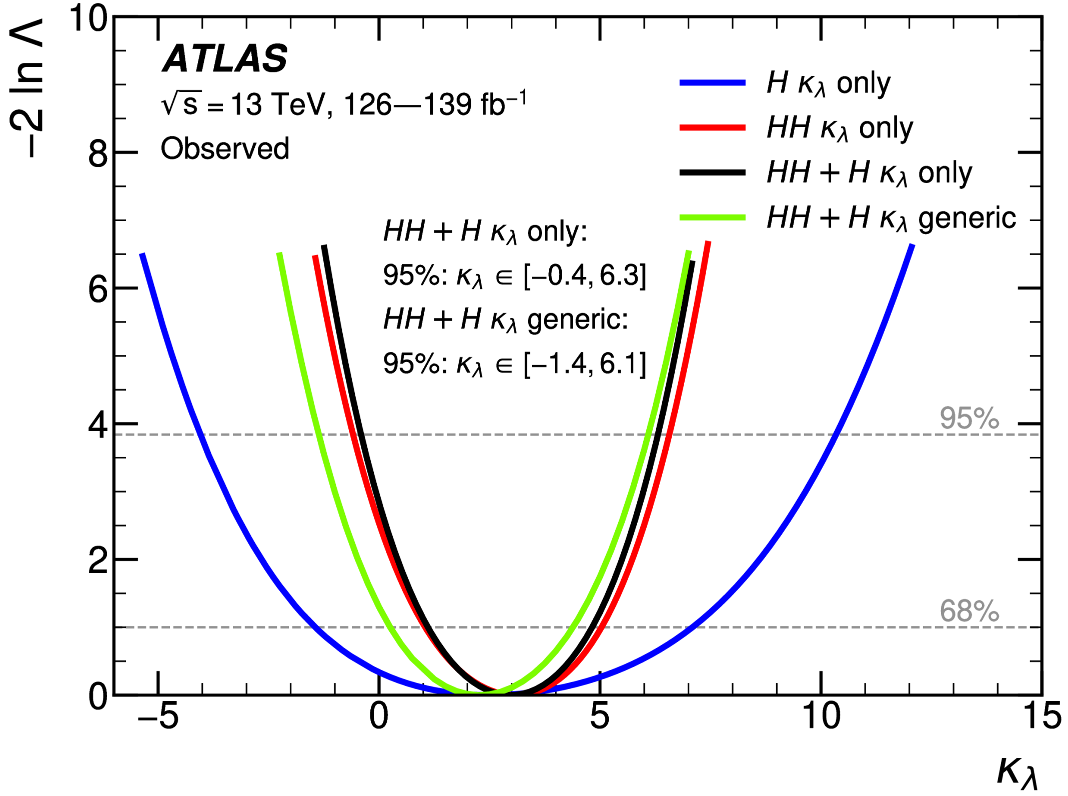
- Simplified template cross-section (STXS) results are parametrized as a function of $(\kappa_\lambda, \kappa_m)$ κ_m: the other couplings modifier $(\kappa_V, \kappa_t, \kappa_b, \kappa_\tau)$

$$n_{i,f}^{\text{signal}}(\kappa_\lambda, \kappa_m) \propto \mu_i(\kappa_\lambda, \kappa_m) \times \mu_f(\kappa_\lambda, \kappa_m) \times \sigma_{\text{SM},i} \times \text{BR}_{\text{SM},f} \times (\epsilon \times A)_{if}$$

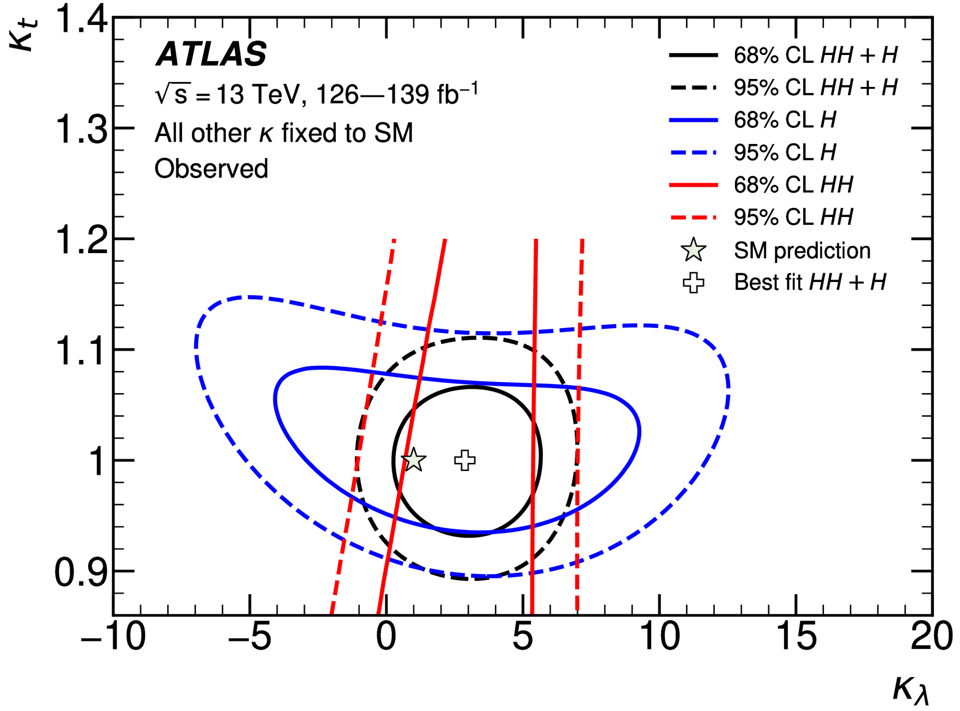
production | decay

h + hh combination

Phys.Lett.B 843 (2023) 137745



Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$



Provides the most stringent constraints on Higgs boson self-interactions to date

Great advantage of combination

Summary

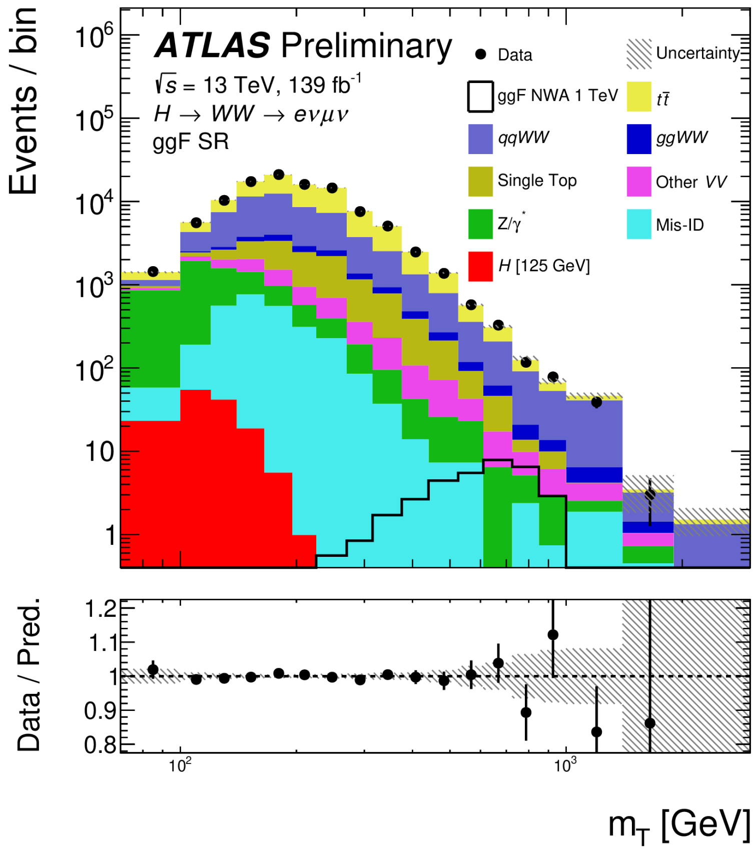
- Diverse program in the Higgs sector to probe BSM physics
  - Direct searches for Higgs-like new scalar or pseudo-scalars
    - Produced in pp collisions or exotic Higgs decays
  - Charged or doubly charged scalars
  - Invisible Higgs decays
  - DiHiggs production: resonance and non-resonance
  - …
- Covers many event topologies and BSM models
- No significant deviation from the SM yet, but Run3 data taking is on-going … and the HL-LHC …

Backup

Heavy resonances, $X \to WW$

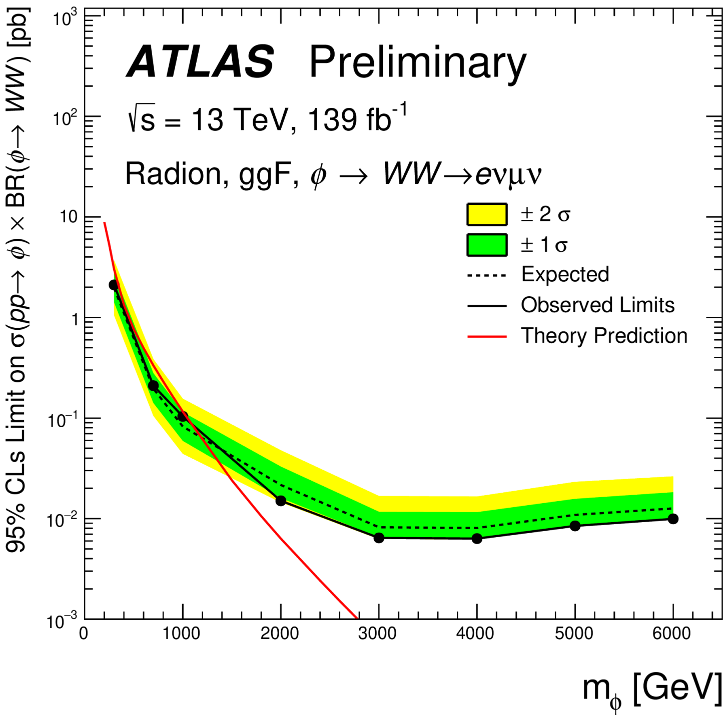
ATLAS-CONF-2022-066

- Search for heavy narrow resonances in $X \to WW \to e\nu\mu\nu$

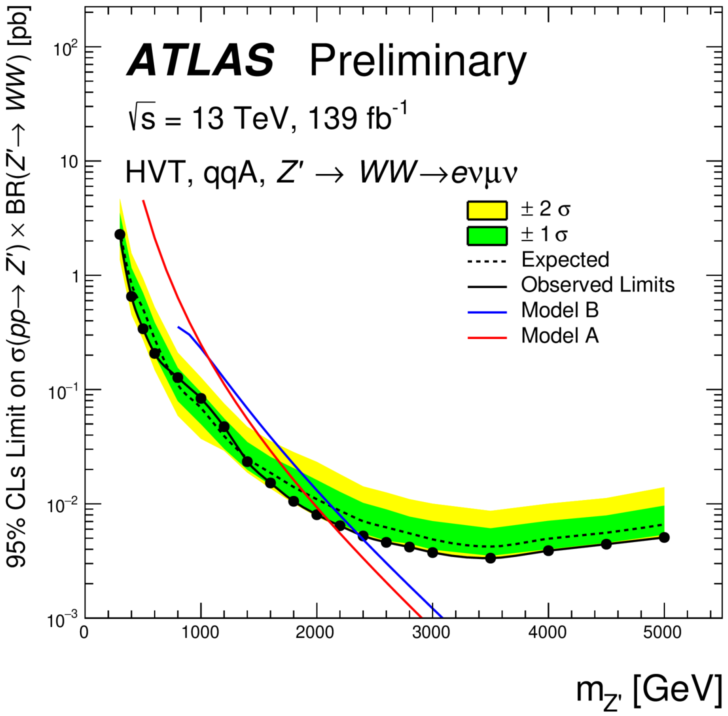


Results are interpreted in 5 signal models

bulk Randall-Sundrum radion



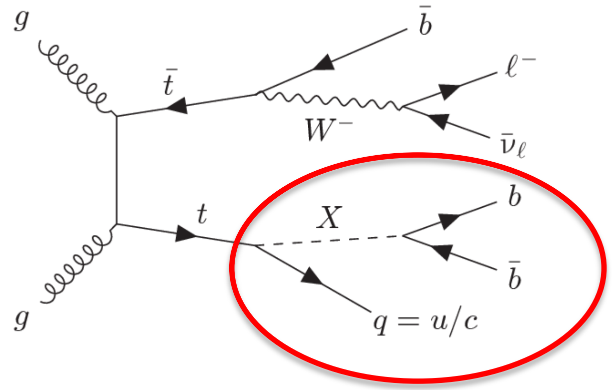
spin-1 heavy vector triplet (HVT)

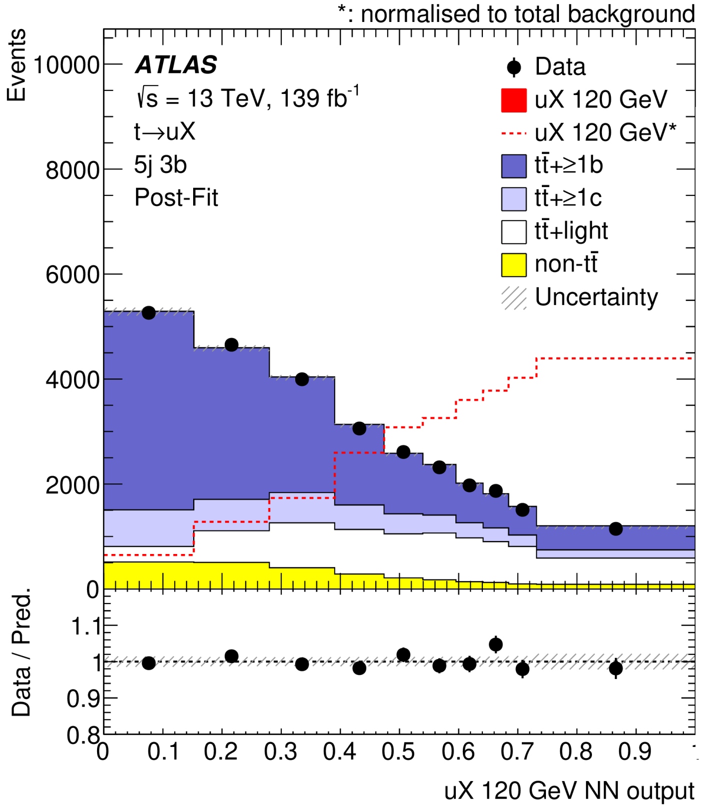


FCNC $t \to qX, X \to bb$

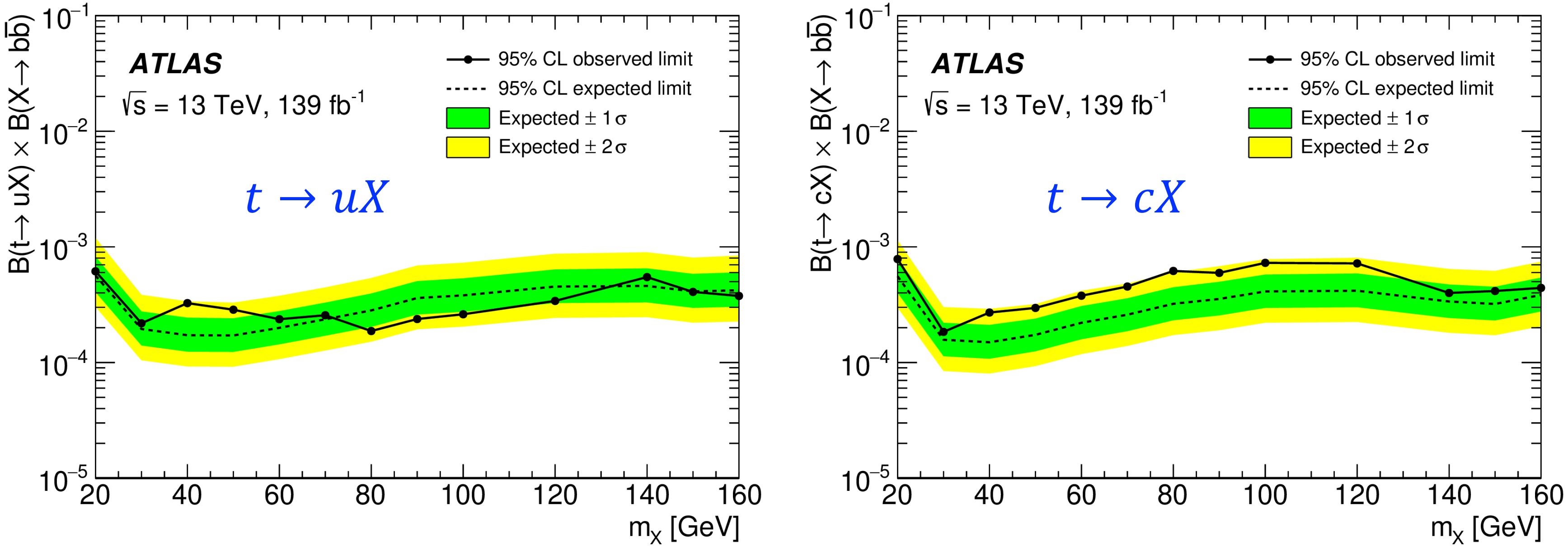
arXiv:2301.03902

- lepton+jets $tt \to (qX)(b\ell\nu)$ with scalar $X \to bb$ and $q = u/c$
  - Light scalar $m_X < m_t$ (uncovered search at the LHC)
- A mass-parameterized neural network to separate S/B
- Main bkg normalization from control regions





Exclusion limits on Br($t \to qX$) for $20 < m_X < 160$ GeV



A factor of 3 improvement in sensitivity for $m_X = 125$ GeV ($t \to qH$)

Axions

- PQ mechanism [Peccei, Quinn PRL 38 (1977), PRD 16 (1997)]
  - assume a global $U(1)_{PQ}$: i) QCD anomalous and ii) spontaneously broken
  - axion: PGB of $U(1)_{PQ}$ breaking [Weinberg PRL 40 (1978), Wilczek PRL 40 (1978)]

$$a(x) \to a(x) + \delta\alpha\, f_a$$

$$\mathcal{L}_{\rm eff} = \underbrace{\left(\bar{\theta} + \frac{a}{f_a}\right)} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{1}{2}\partial^\mu a \partial_\mu a + \mathcal{L}(\partial_\mu a, \psi)$$

$\langle \theta_{\rm eff}(x) \rangle \to 0$ (dynamically, via a QCD-induced axion potential)

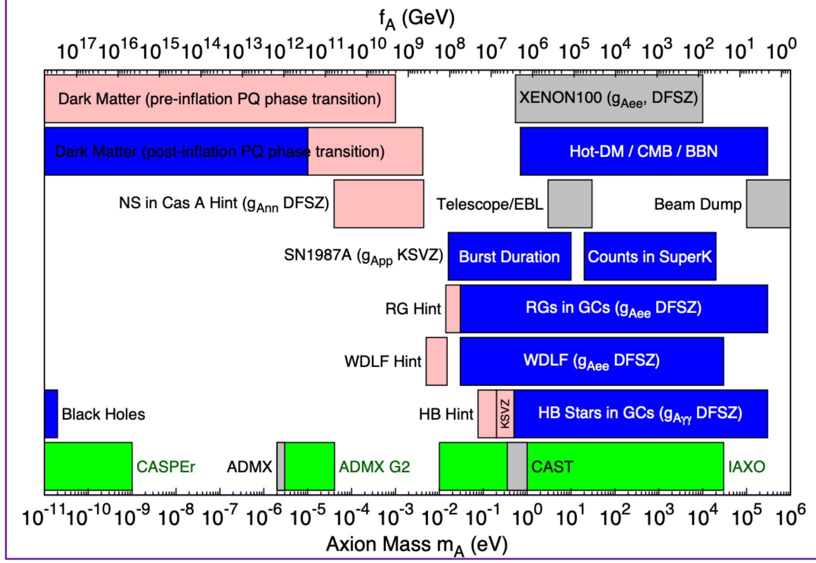
- PQWW axion
  - axion identified with the phase of the Higgs in a 2HDM ($f_a \sim v$, ruled out long ago)
- Needs $f_a \gg v$ → invisible axion (phase of a SM singlet)
  - DFSZ axion: [Zhitnitsky SJNP 31 (1980), Dine, Fischler, Srednicki PLB 104 (1981)]

    SM quarks charged under PQ (requires 2HDM)
  - KSVZ axion: [Kim PRL 43 (1979), Shifman, Vainshtein, Zakharov NPB 166 (1980)]

    new vector-like quarks charged under PQ

L. Di Luzio

- axion mass $m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6\ \mathrm{meV}\, \frac{10^9\ \mathrm{GeV}}{f_a}$
- axion couplings $\sim 1/f_a$



[Ringwald, Rosenberg, Rybka, Particle Data Group (2016)]

Astro/cosmo exclusions

Lab exclusions

Exp. sensitivities

DM explained / Astro Hints

2HDM

- Two complex scalar SU(2) doublets

P. M. Ferreira et al. arXiv:1106.0034

$$V = m_{11}^2\,\Phi_1^\dagger\Phi_1 + m_{22}^2\,\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\,\Phi_1^\dagger\Phi_1\,\Phi_2^\dagger\Phi_2 + \lambda_4\,\Phi_1^\dagger\Phi_2\,\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right],$$

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2$$

$$\langle\Phi_1\rangle_0 = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}, \quad \langle\Phi_2\rangle_0 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

$$\tan\beta \equiv \frac{v_2}{v_1}$$

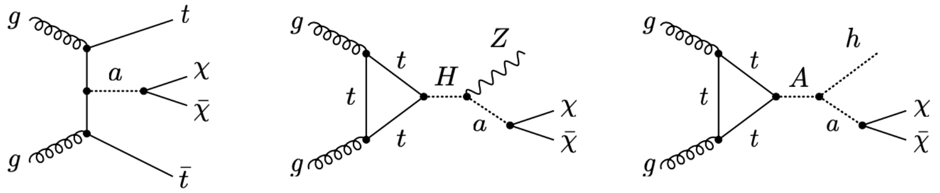
Yukawa couplings of u, d, l to the neutral Higgs bosons h, H, A in the four different models

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

2HDM+a

- A simplified Dark Matter model for spin-0 mediators based on 2HDM
  - Gauge invariant and renormalisable
  - Pseudoscalar mediators: advantage of avoiding constraints from DM direct detection experiments
  - Recommended by the LHC DM WG (arXiv:1810.09420)

U. Haisch et al JHEP05(2017)138



- Model parameters
  - 14 in total,
    - 2HDM parameters: $m_h, m_H, m_{H^\pm}, m_A, \lambda_3, VEV, \tan\beta, \cos(\beta-\alpha)$
    - Additional parameters on the pseudoscalar:
      - m_a: mass of the pseudoscalar
      - Quartic couplings with a: λP1, λP2
      - θ: mixing between a and A
    - Additional parameters on DM: m_χ, y_χ (the coupling between a and the DM)
  - reduced to 5 with some assumptions
    - $m_a, m_A, m_\chi, \tan\beta, \sin\theta$

3HDM

- X, Y , and Z are coupling functions of four parameters of a unitary matrix U

$$\begin{pmatrix} G^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \\ \phi_3^+ \end{pmatrix} \qquad X = \frac{U_{d2}^\dagger}{U_{d1}^\dagger}, \qquad Y = -\frac{U_{u2}^\dagger}{U_{u1}^\dagger}, \qquad Z = \frac{U_{\ell 2}^\dagger}{U_{\ell 1}^\dagger}.$$

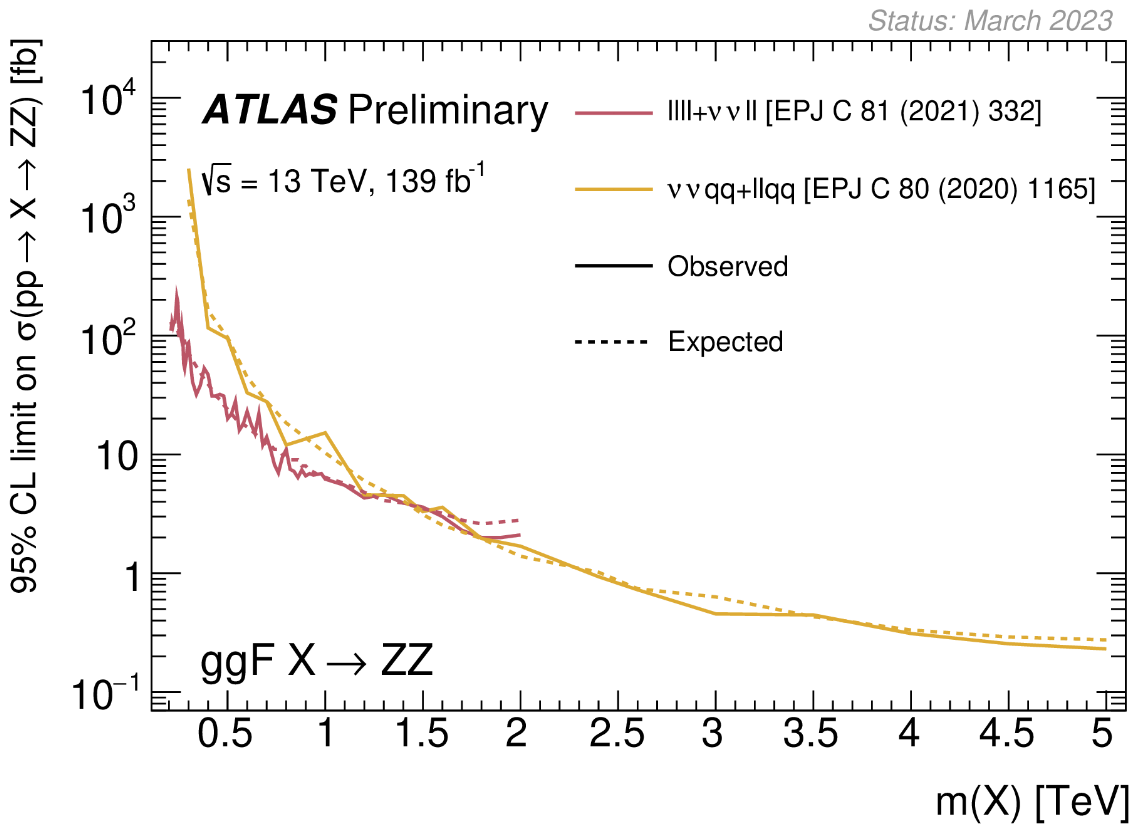
The values of d, u, and l in these matrix elements depend on which of the five distinct 3HDMs is under consideration

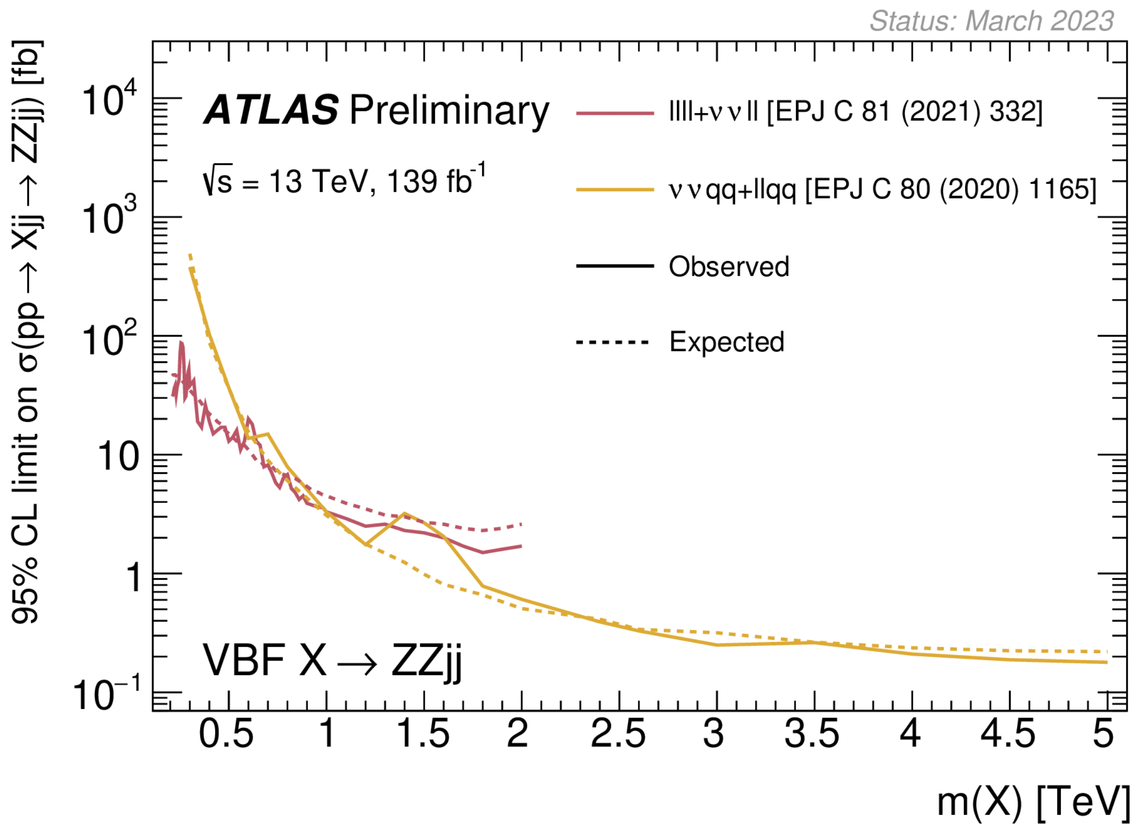
	u	d	ℓ
3HDM (Type I)	2	2	2
3HDM (Type II)	2	1	1
3HDM (Lepton-specific)	2	2	1
3HDM (Flipped)	2	1	2
3HDM (Democratic)	2	1	3

A.G. Akeroyd, Stefano Moretti, Muyuan Song,
arXiv:1810.05403

Summary plots: generic (narrow width) neutral scalars

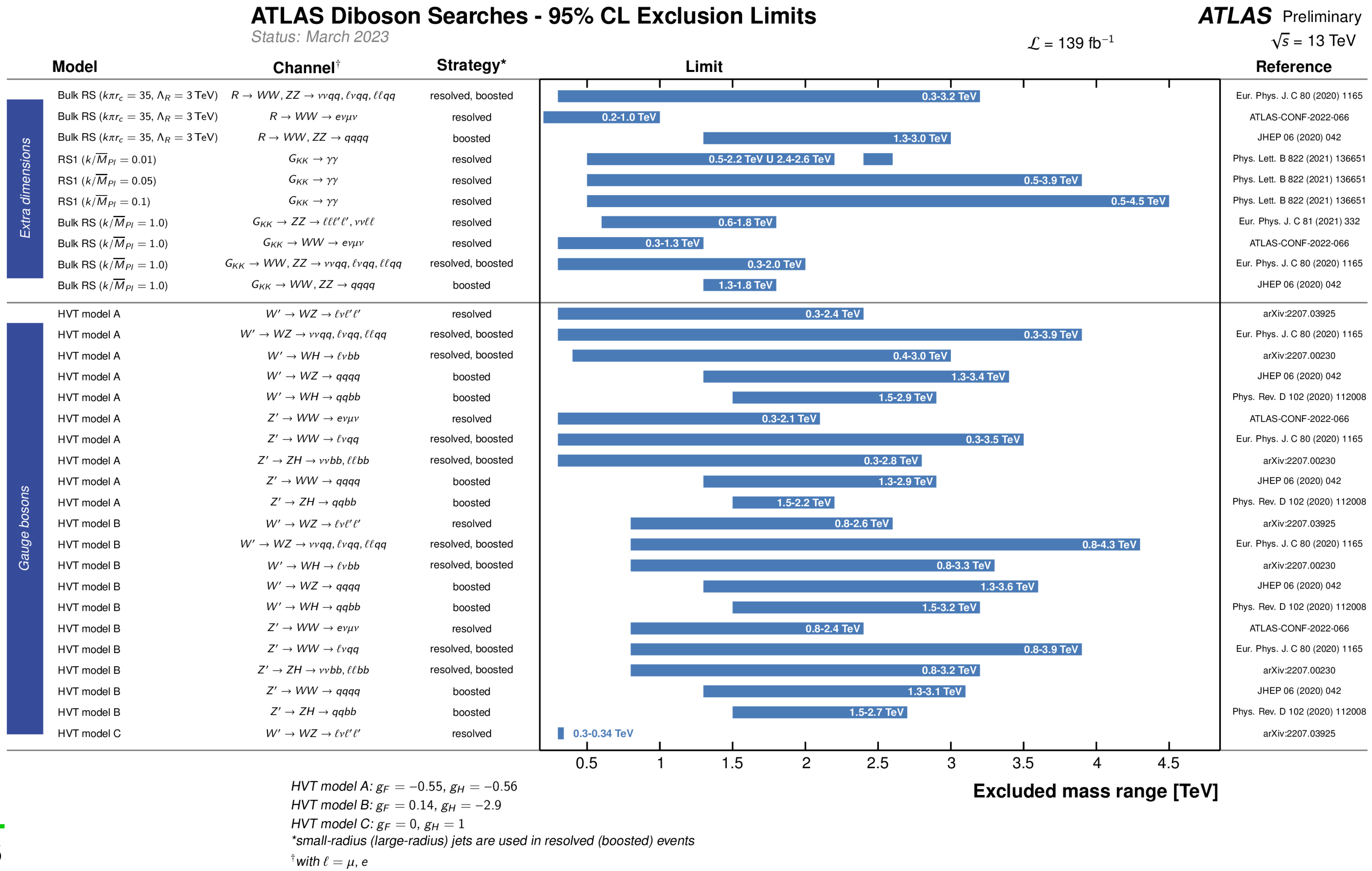
ATL-PHYS-PUB-2023-007





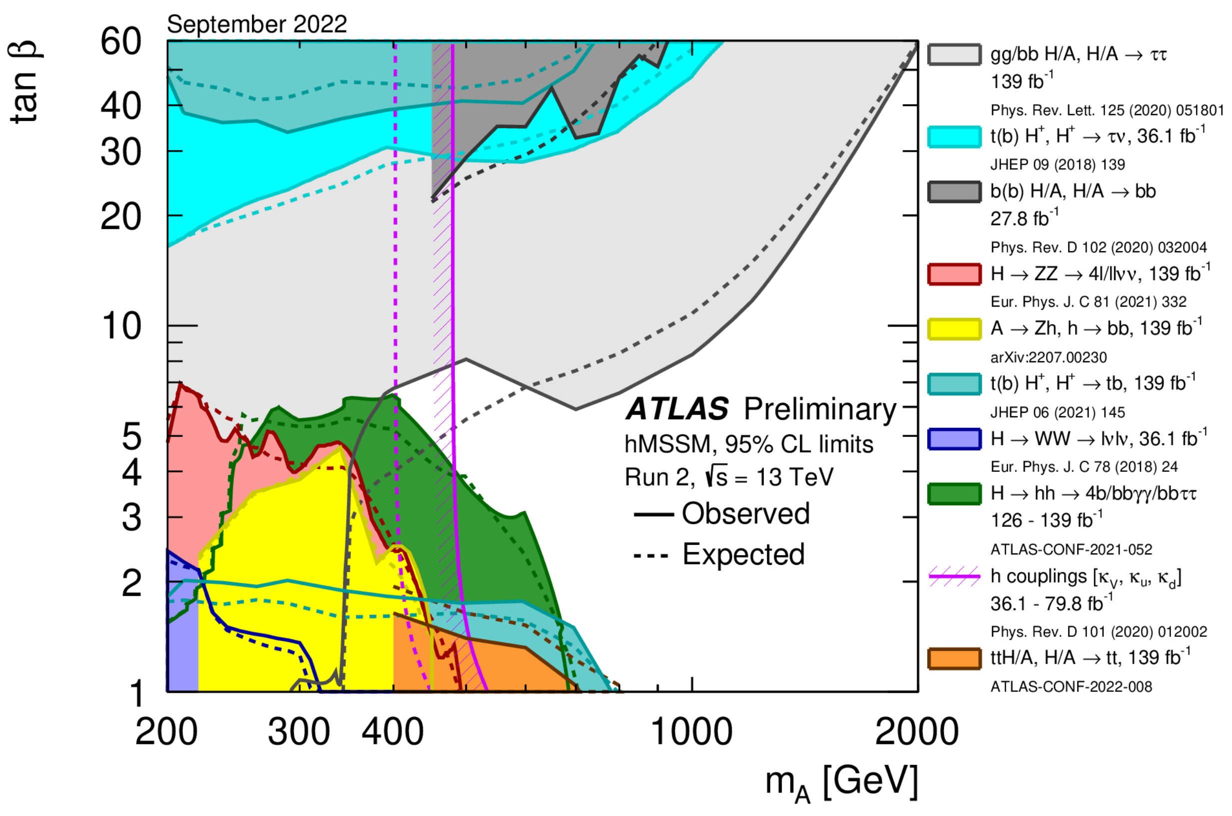
Summary plots: diboson resonances

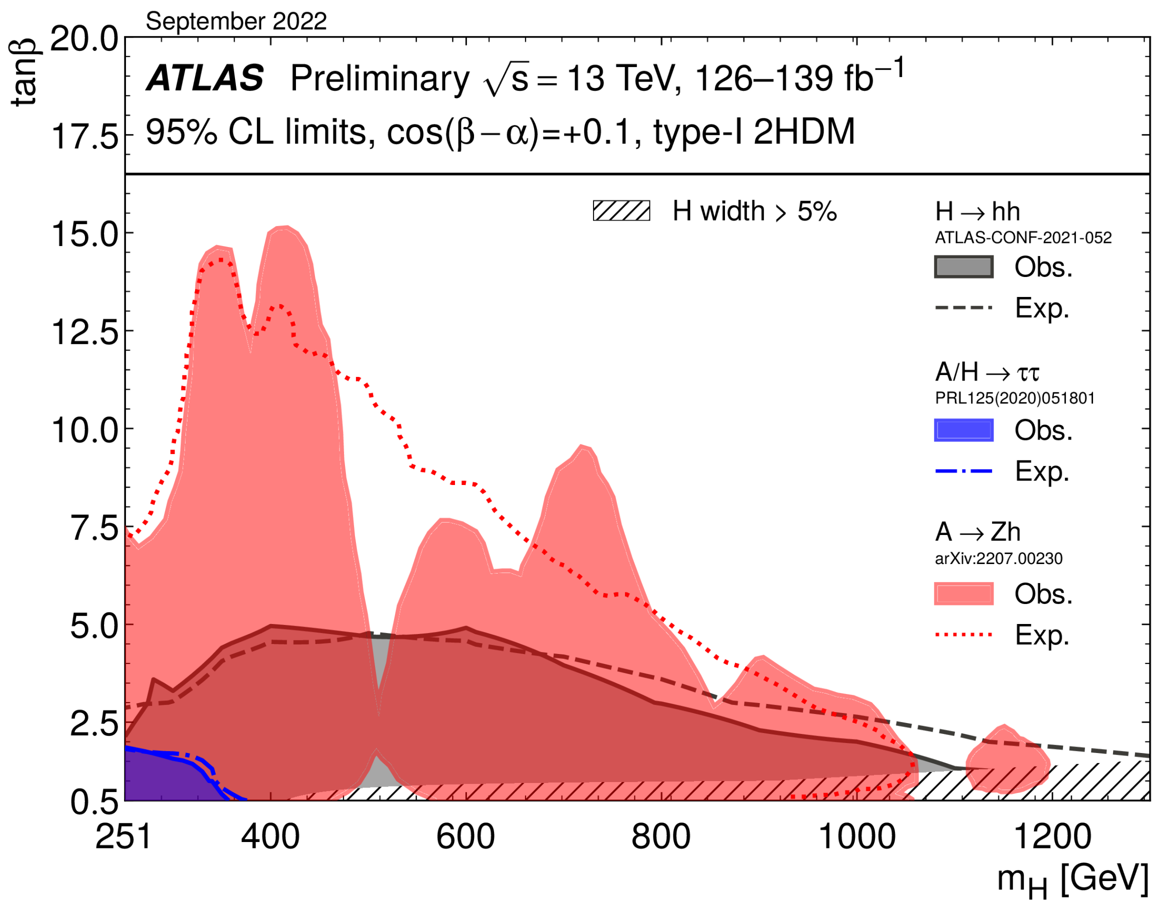
ATL-PHYS-PUB-2023-007



Summary plots: hMSSM and 2HDM

ATL-PHYS-PUB-2022-043

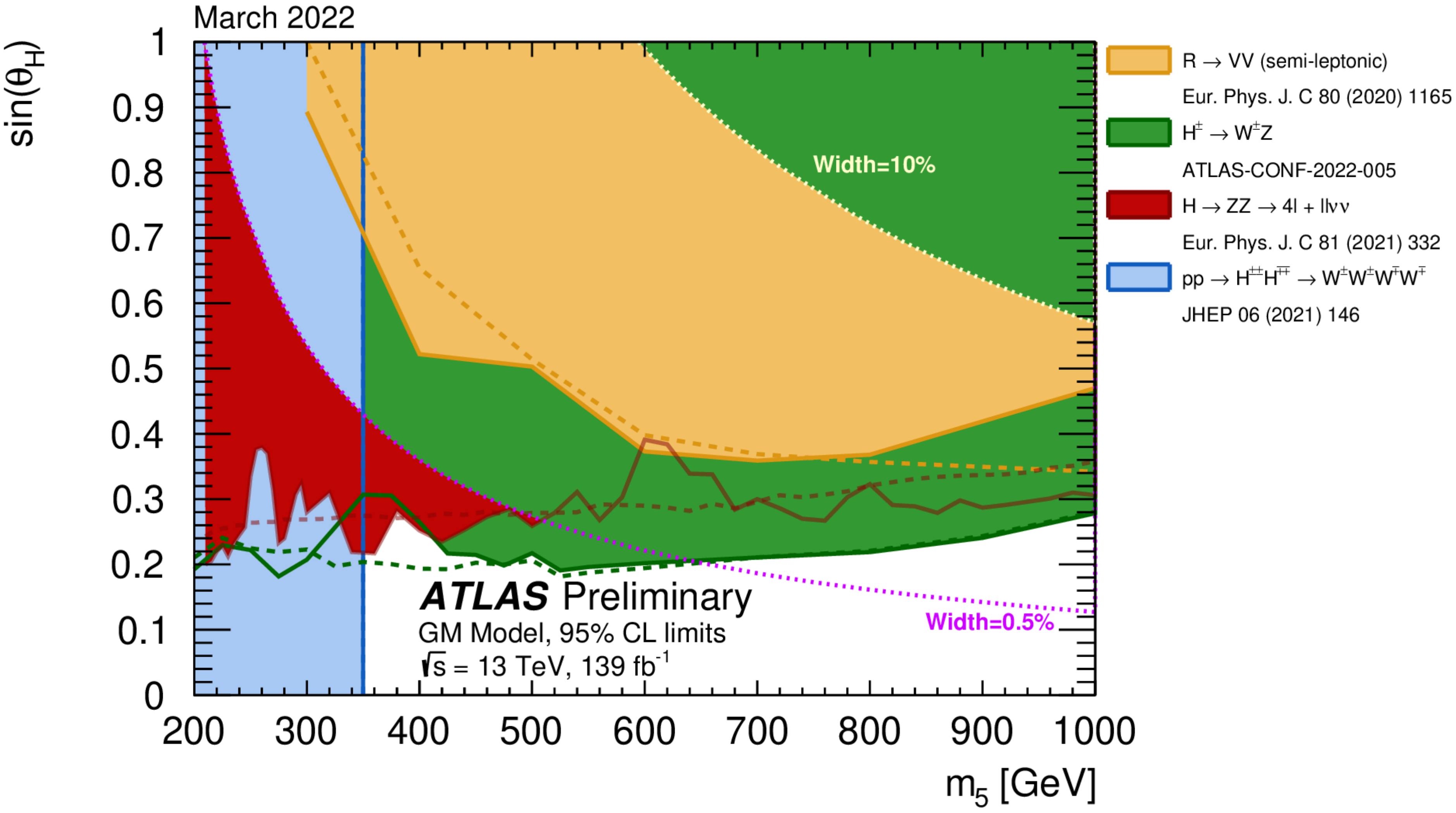




Summary plots: Georgi-Machacek

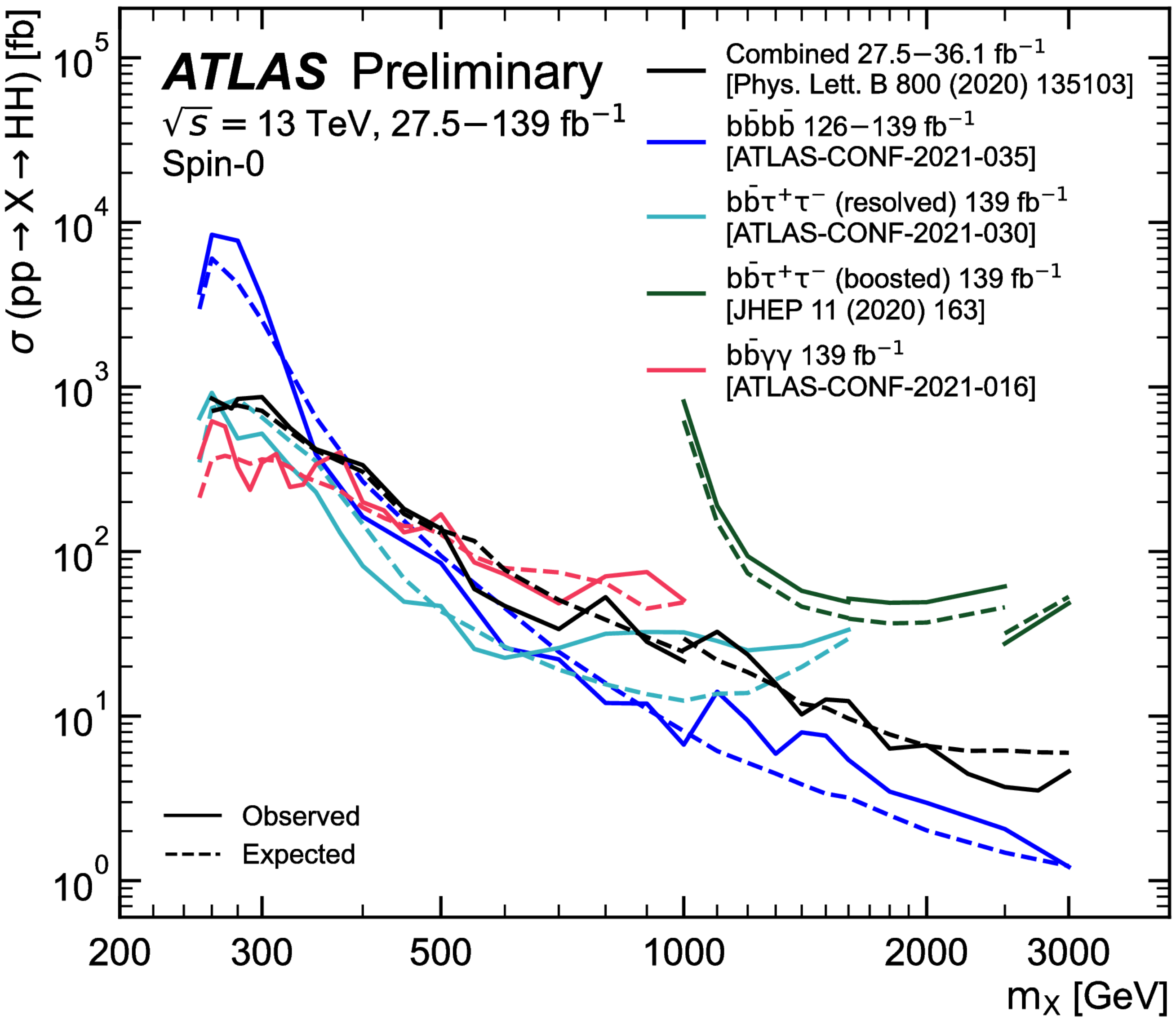
H5 plane benchmark of the Georgi-Machacek model

ATL-PHYS-PUB-2022-008



Summary plots: $X \rightarrow hh$

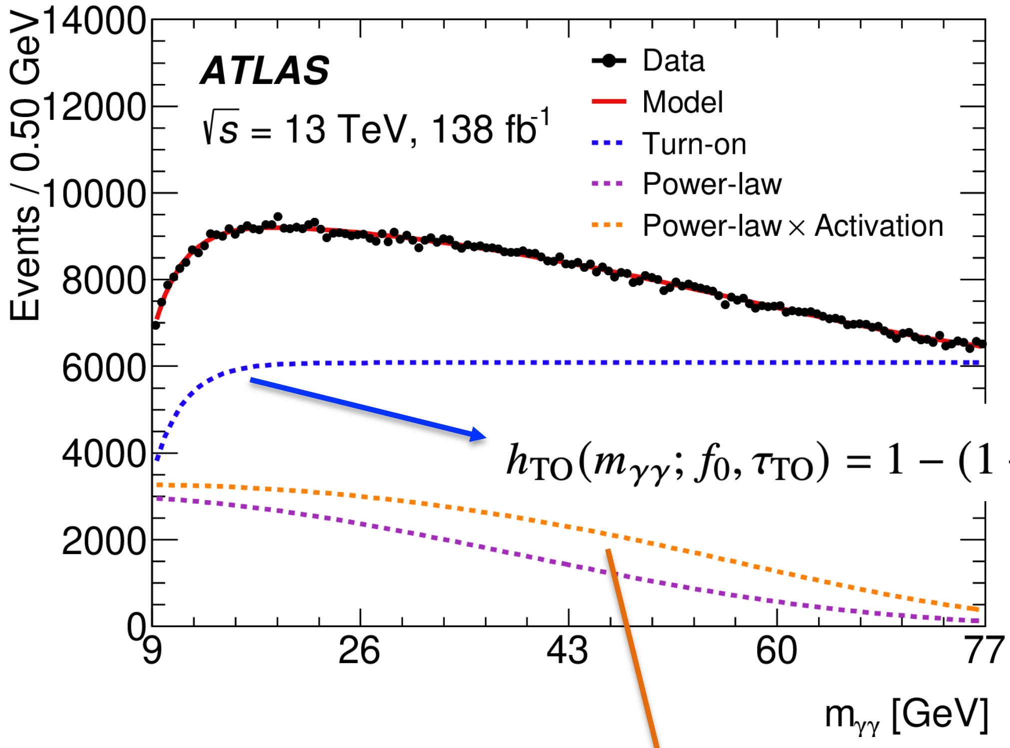
ATL-PHYS-PUB-2021-031



Boosted $a \rightarrow \gamma\gamma$

arXiv:2211.04172

- Shape parameterized with analytical functions
  - Background modelling uncertainties reduced with Gaussian Processes

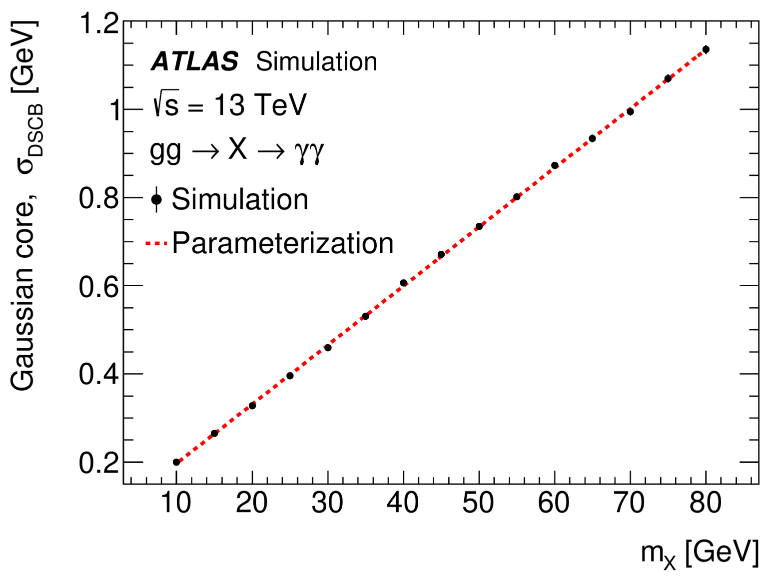


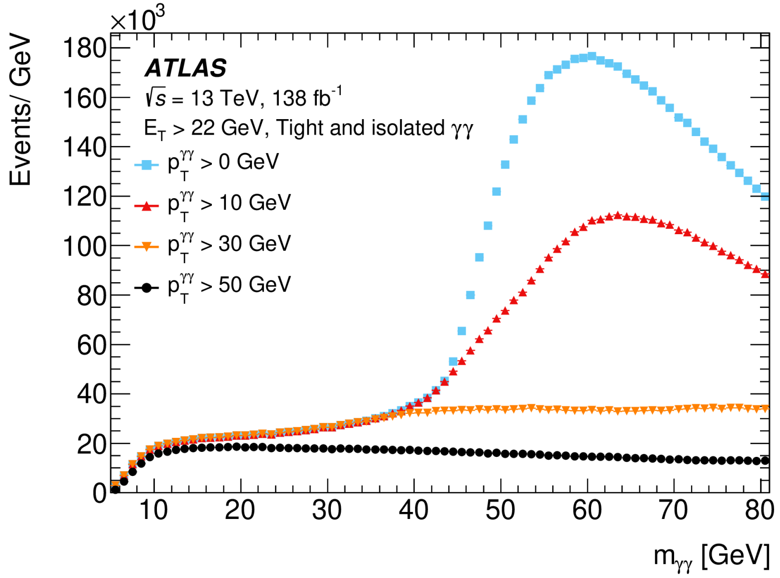
$$h_{\mathrm{TO}}(m_{\gamma\gamma}; f_0, \tau_{\mathrm{TO}}) = 1 - (1 - f_0)\, \mathrm{e}^{-\frac{m_{\gamma\gamma}}{\tau_{\mathrm{TO}}}}$$

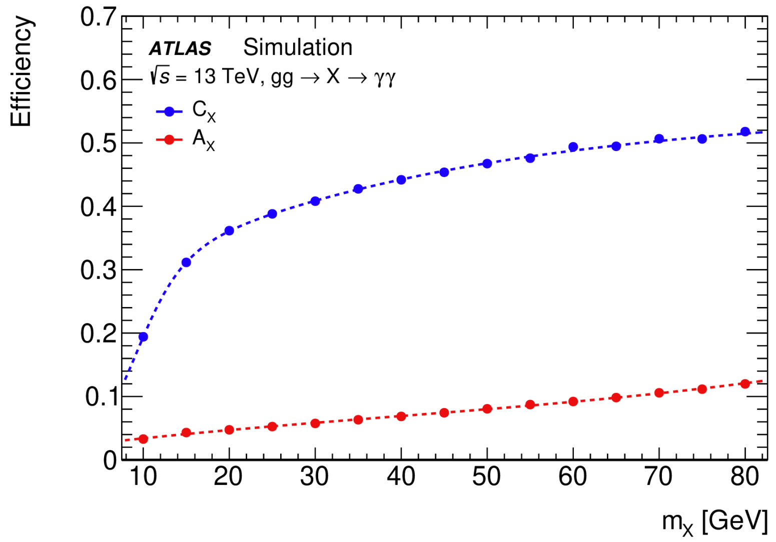
$$h_{\mathrm{High}}(m_{\gamma\gamma}; c_1, a_0, c_0, \delta_{\mathrm{tail}}, \tau_{\mathrm{tail}}, \delta_{\mathrm{thresh}}, \tau_{\mathrm{thresh}}) = \underbrace{\left(1 - \left(\frac{m_{\gamma\gamma}}{c_1}\right)^{a_0}\right)^{c_0}}_{\text{Power-law}} \underbrace{\left(1 + \frac{\mathrm{e}^{\frac{m_{\gamma\gamma}-\delta_{\mathrm{tail}}}{\tau_{\mathrm{tail}}}}}{1 + \mathrm{e}^{-\frac{m_{\gamma\gamma}-\delta_{\mathrm{thresh}}}{\tau_{\mathrm{thresh}}}}}\right)}_{\text{Activation function}}$$

Boosted $a \to \gamma\gamma$

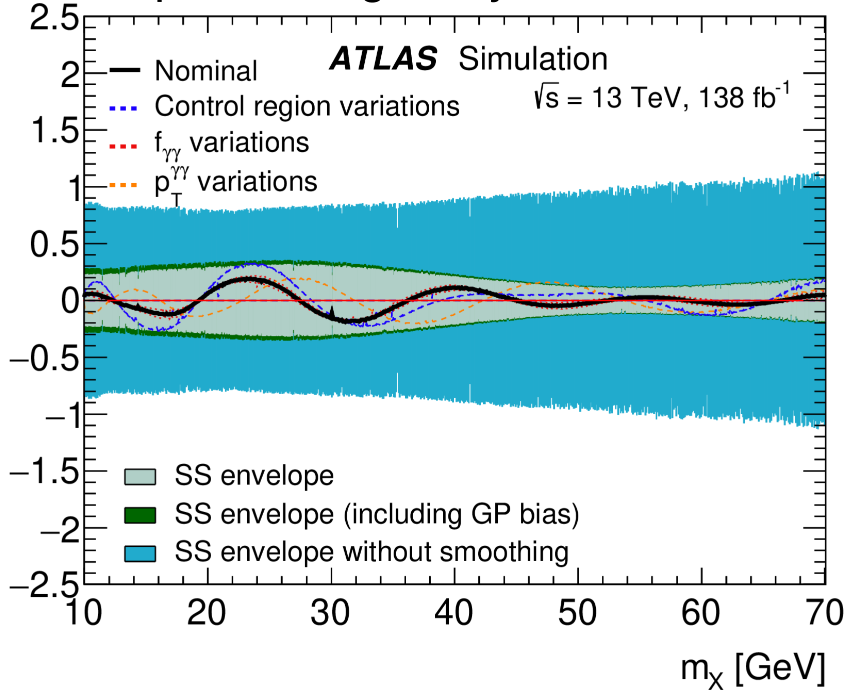
arXiv:2211.04172







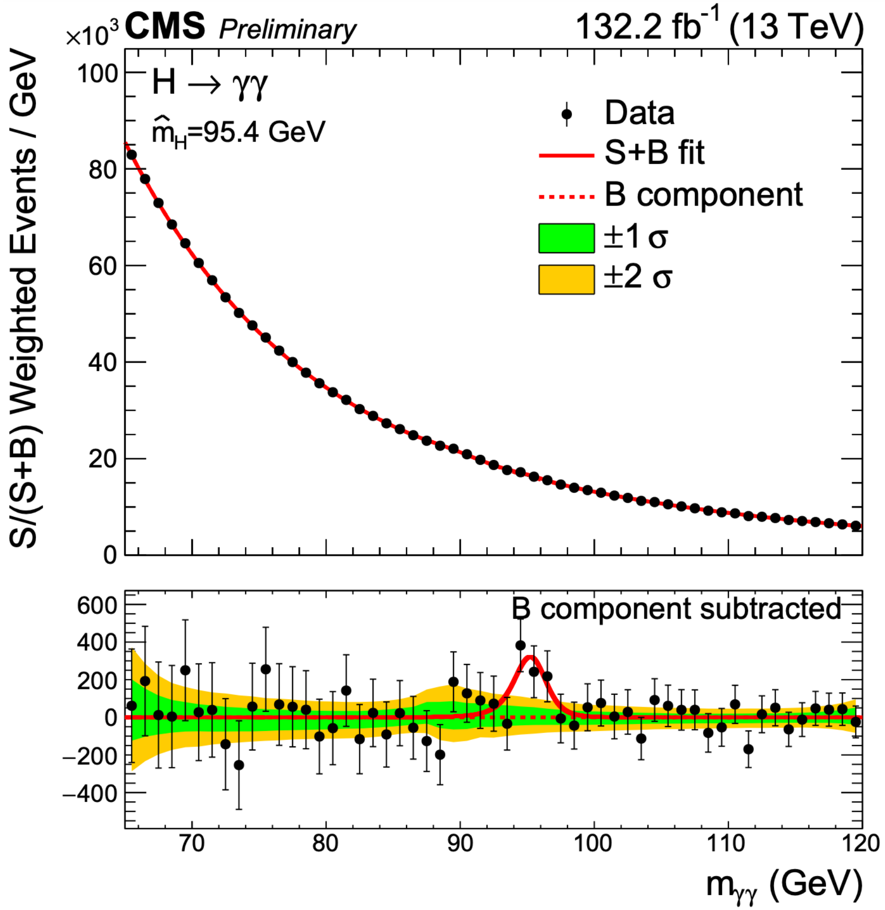
Spurious signal systematic

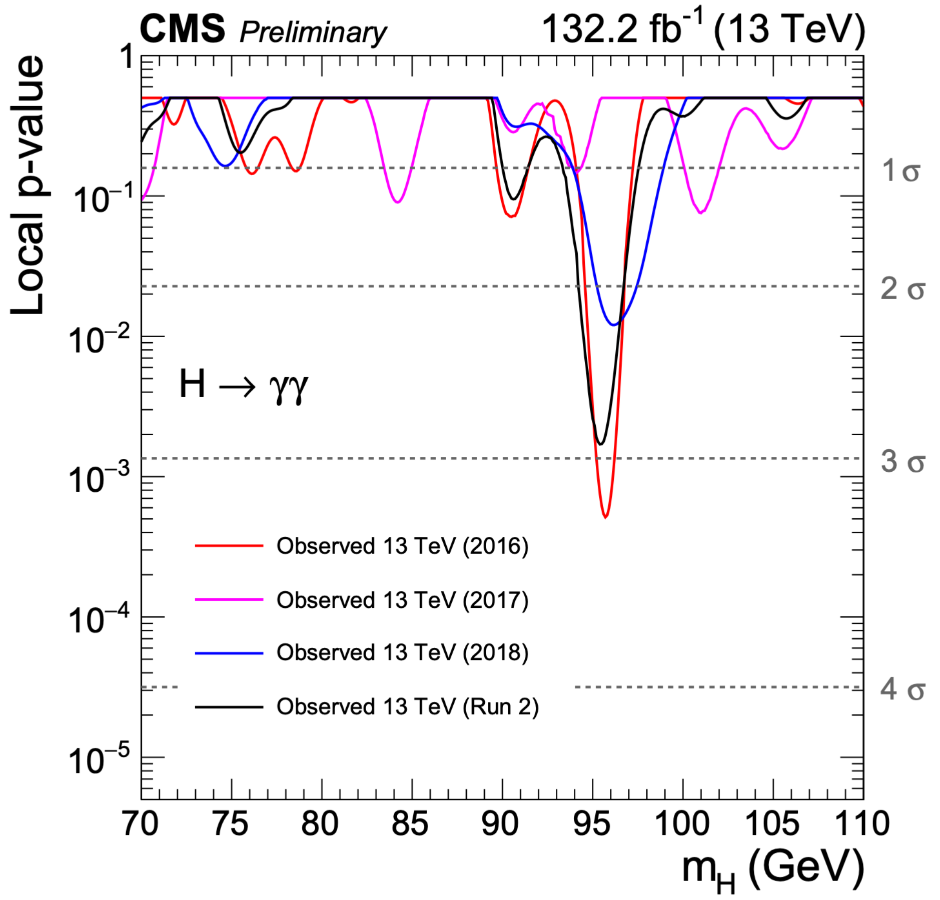


Low-mass resonance $X \rightarrow \gamma\gamma$

A diphoton BDT is used to discriminate between diphoton events from Higgs boson decays and those from the diphoton continuum

CMS PAS HIG-20-002



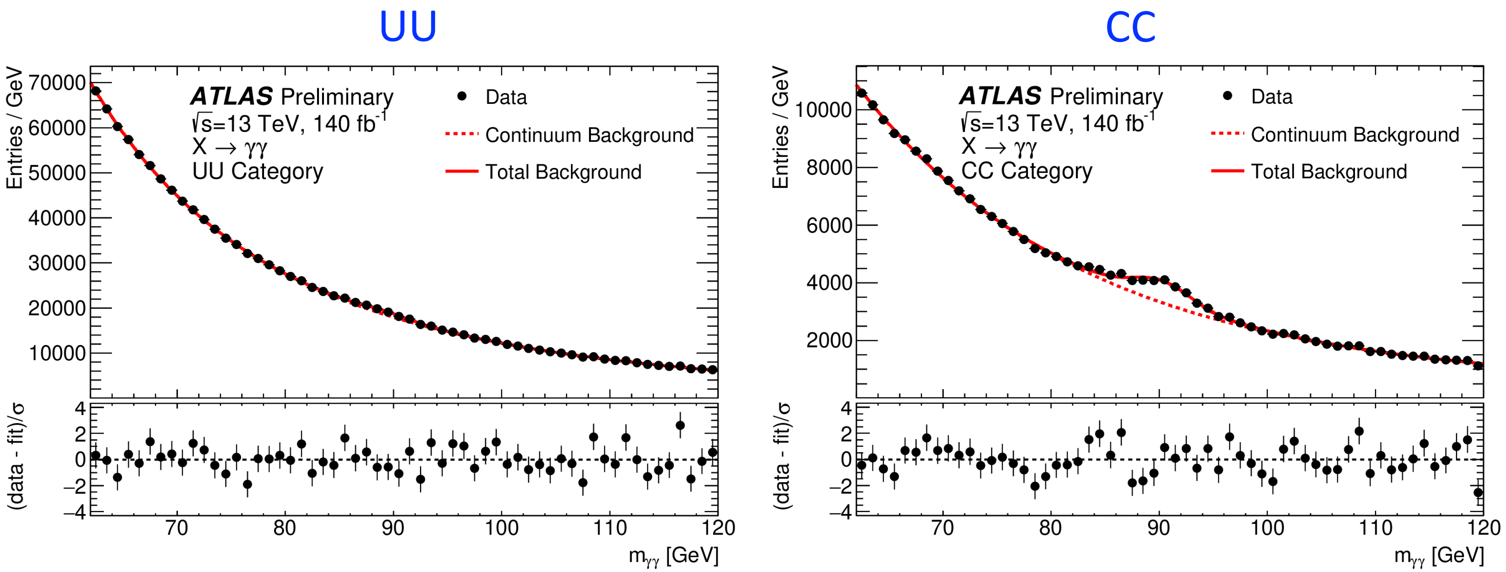


Low-mass resonance $X \to \gamma\gamma$

ATLAS-CONF-2023-035

- Background-only fits to data
  - Background modelled with analytical functions
  - Modelling systematics reduced after smoothing with a Gaussian Process regression

Model-independent



BDT Category	Component	UU Events	UU [%]	UC Events	UC [%]	CC Events	CC [%]
Bin 1	$\gamma\gamma$	423746	71.5	331118	67.0	64521	57.3
	γj	124037	20.9	118863	24.1	33610	29.9
	jj	40357	6.8	35958	7.2	9217	8.2
	DY	4263	0.7	8289	1.7	5255	4.6
Bin 2	$\gamma\gamma$	379797	74.7	279785	69.7	55632	64.5
	γj	102841	20.2	96895	24.1	23029	26.7
	jj	24437	4.8	22205	5.5	6037	7.0
	DY	1473	0.3	2761	0.7	1577	1.8
Bin 3	$\gamma\gamma$	205134	80.3	153411	73.5	30061	66.6
	γj	42662	16.7	45750	21.9	11808	26.2
	jj	6897	2.7	8395	4.0	2479	5.5
	DY	486	0.2	1160	0.6	758	1.7

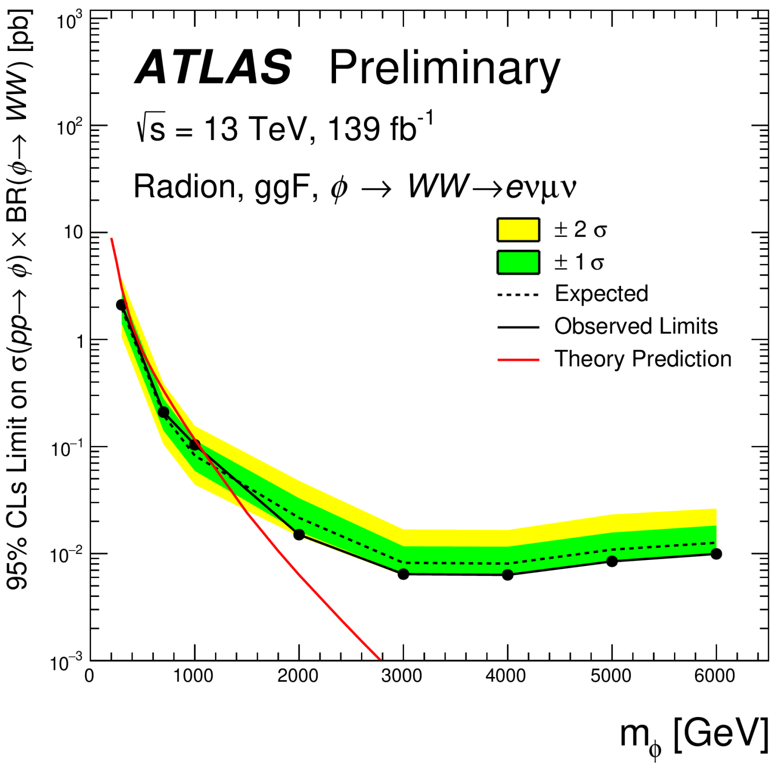
The DY background is modeled using a DSCB function

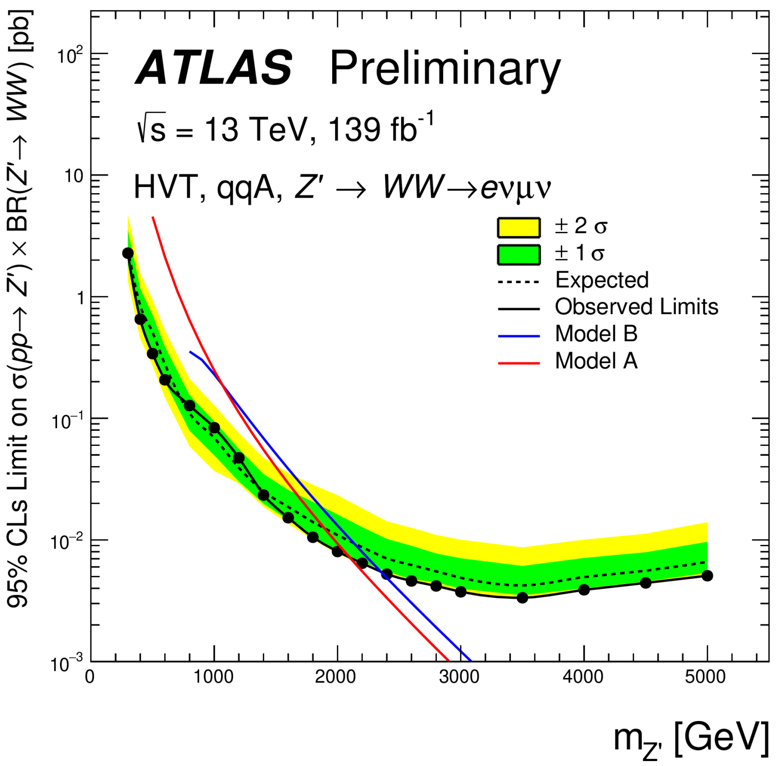
Heavy resonances, $X \rightarrow WW$

ATLAS-CONF-2022-066

- Results are interpreted in 5 signal models
  - a Higgs-like narrow width scalar
  - a Higgs boson in the Georgi–Machacek model
  - a radion particle arising in the bulk Randall-Sundrum model
  - a spin-1 heavy vector triplet
  - a spin-2 graviton

Model	Resonance spin	Production mode ggF	qqA	VBF
NWA	Spin-0	x		x
GM				x
Radion		x		x
HVT	Spin-1		x	x
RS G^*_{KK}	Spin-2	x		x



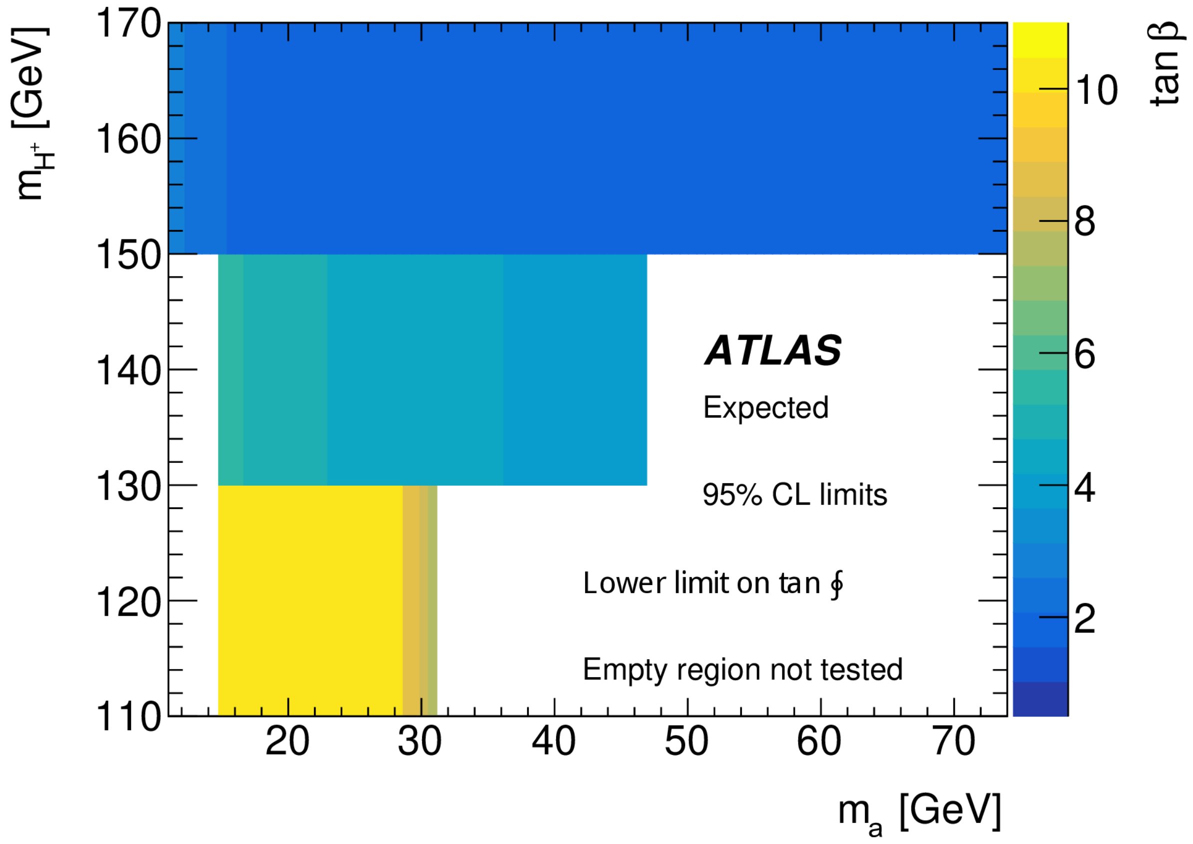


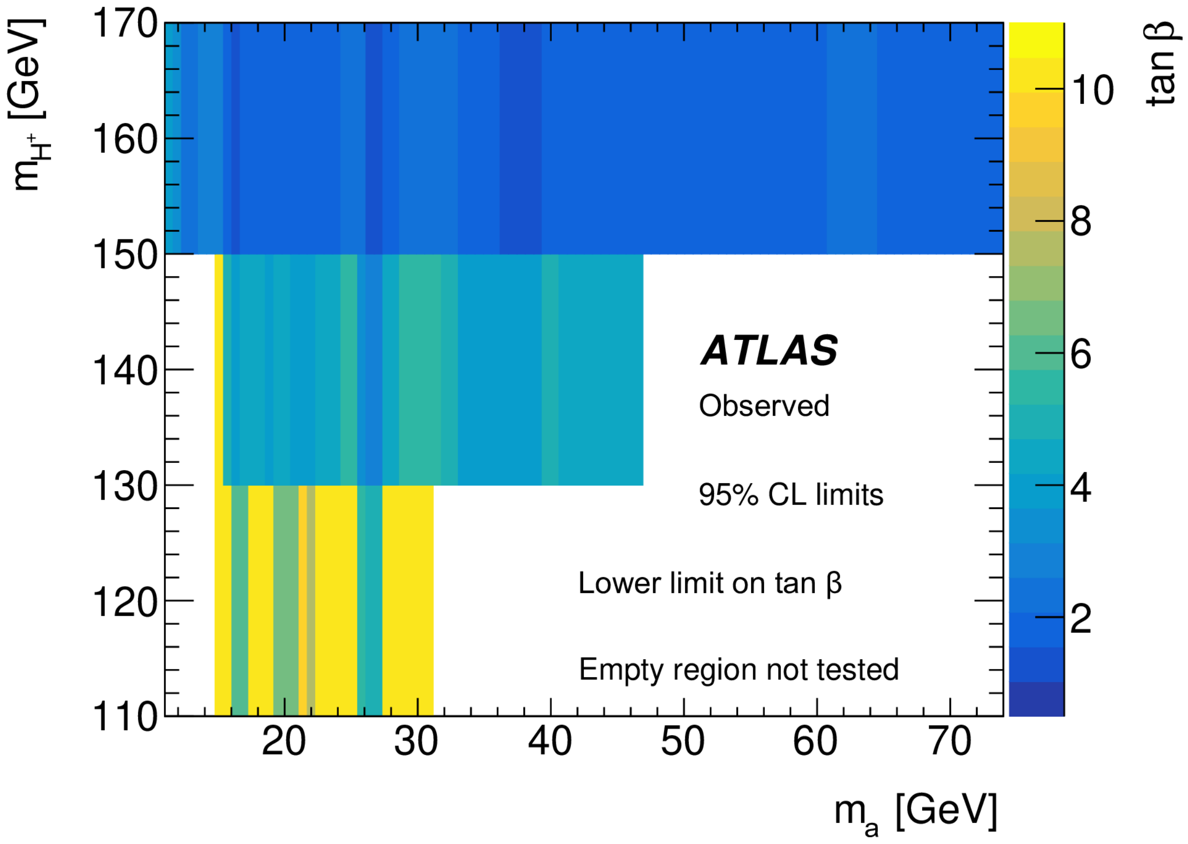
$tta, a \to \mu\mu$

arXiv:2304.14247

- 2HDM+a Results

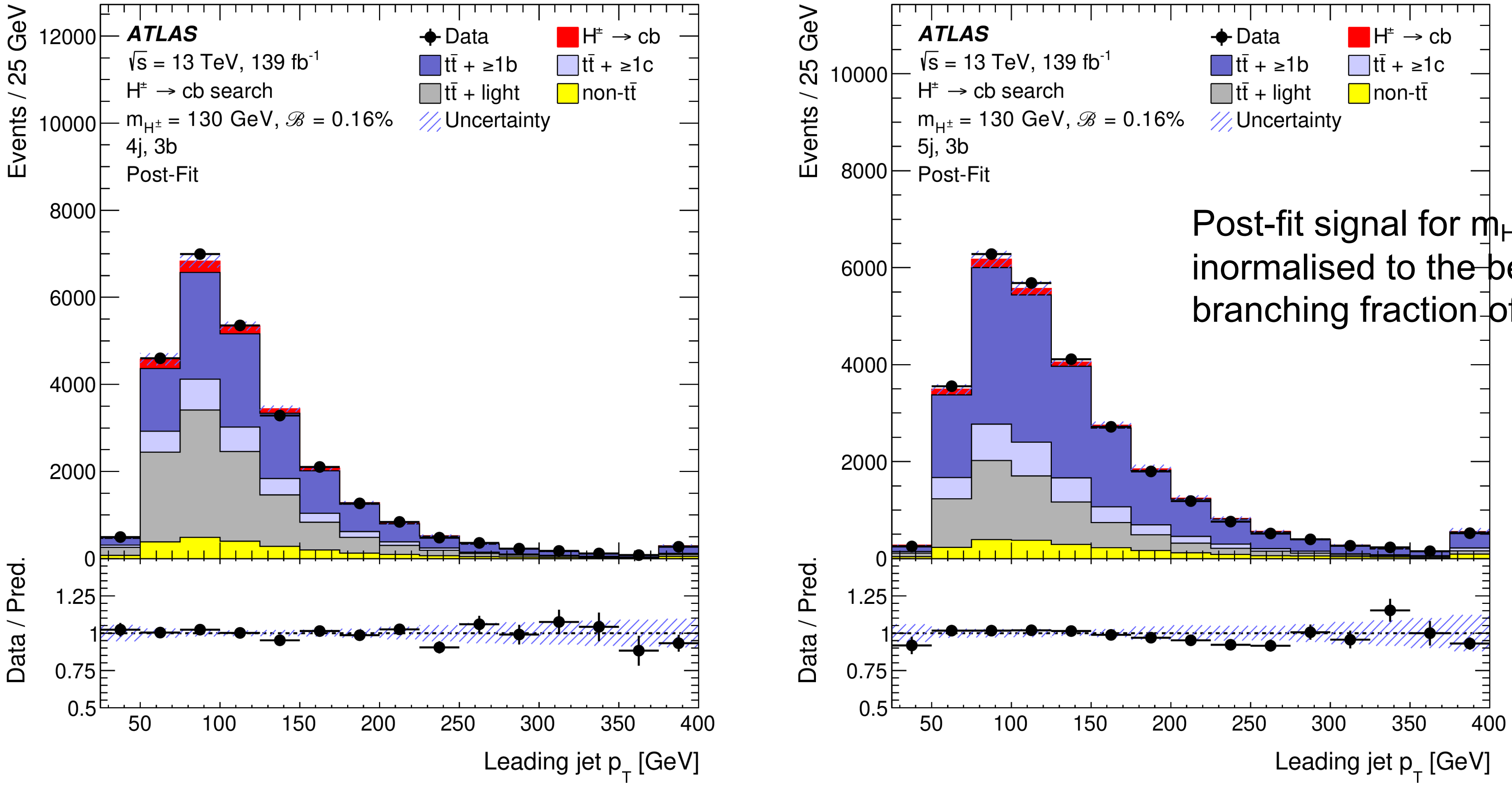
Expected and observed lower limits on $\tan\beta$





$t \to H^{\pm}b, H^{\pm} \to cb$

arXiv:2302.11739

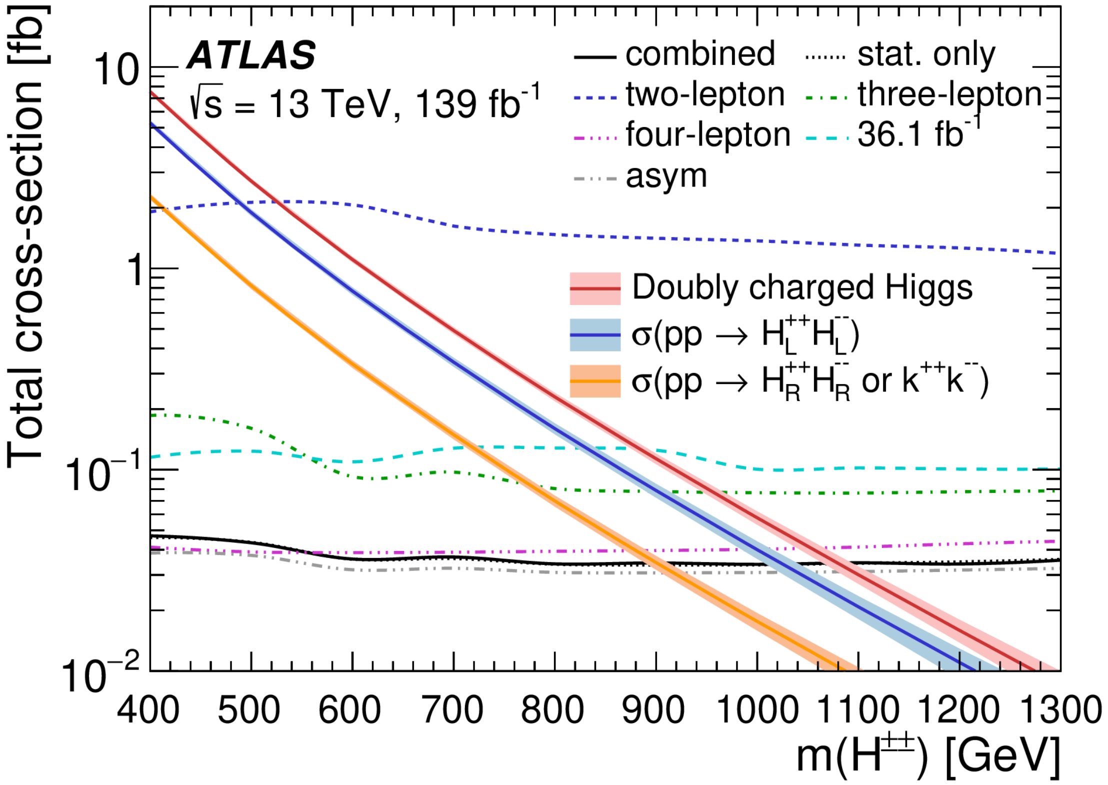


Post-fit signal for $m_{H^{\pm}}$ = 130 GeV inormalised to the best-fit branching fraction of 0.16%

$H^{\pm\pm}, H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$

- Results

Assuming the same branching ratio of $H^{\pm\pm} \rightarrow ee,\ e\mu,\ \mu\mu,\ e\tau,\ \mu\tau,\ \tau\tau$ final states



Sensitivity driven by the 4l channel

$A \rightarrow ZH \rightarrow lltt + \nu\nu bb$

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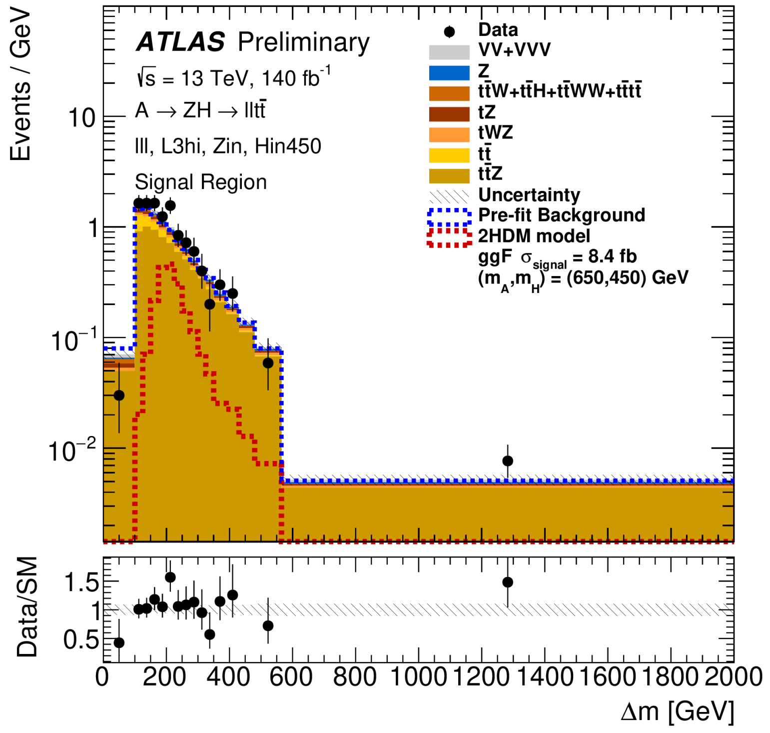
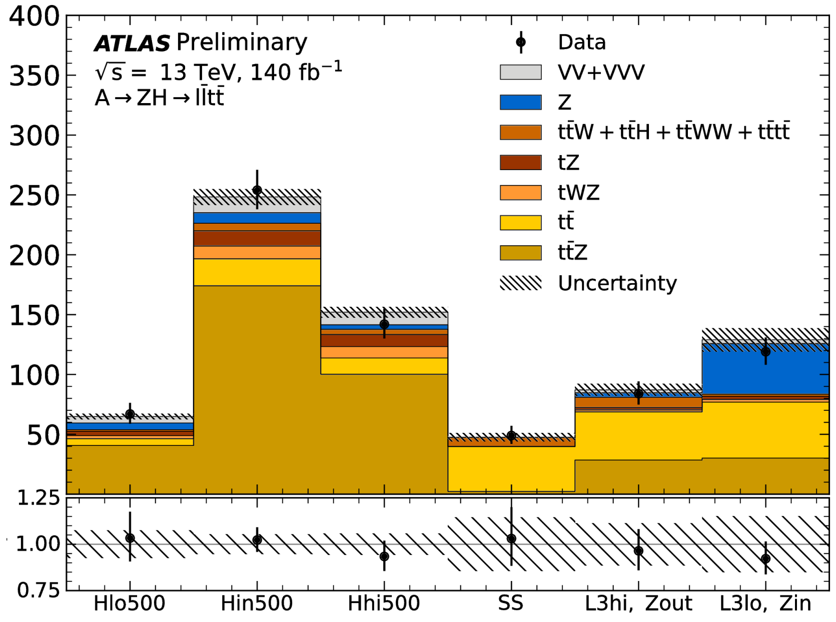
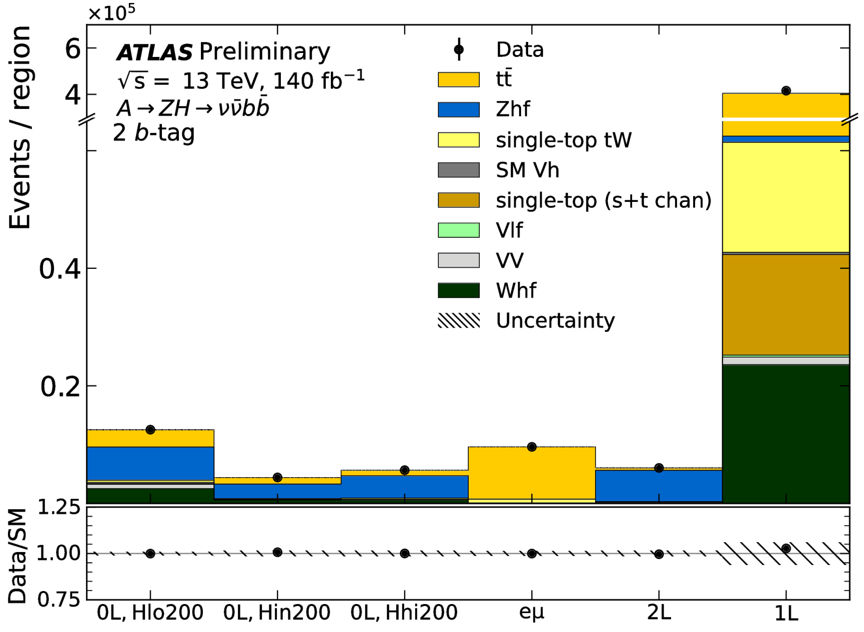
$gg \rightarrow A \rightarrow ZH \rightarrow lltt$

$$\Delta m = m_A^{cand} - m_H^{cand} \cong m_A - m_H$$

$gg \rightarrow A \rightarrow ZH \rightarrow \nu\nu bb$



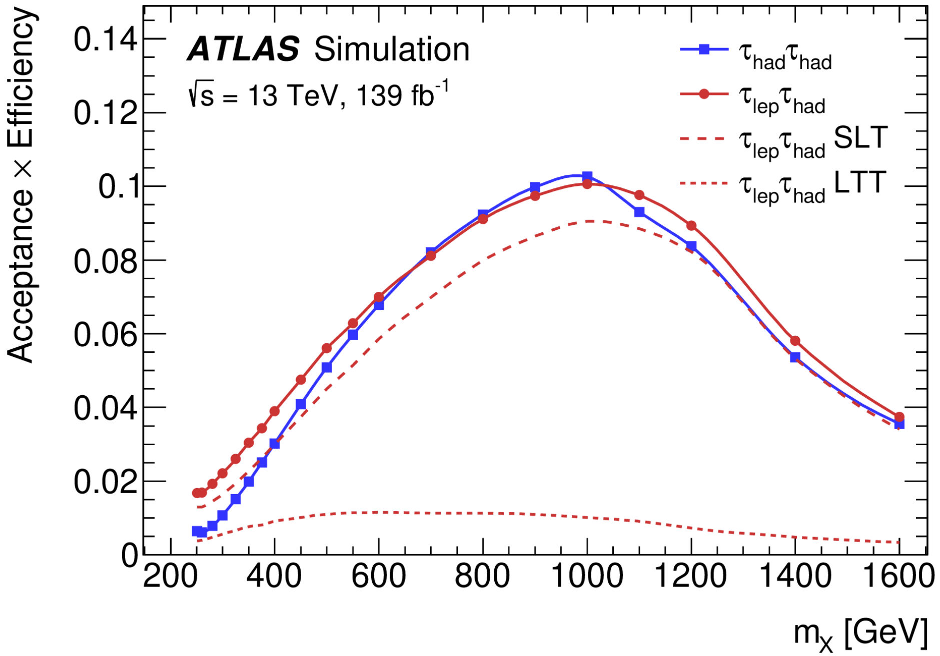


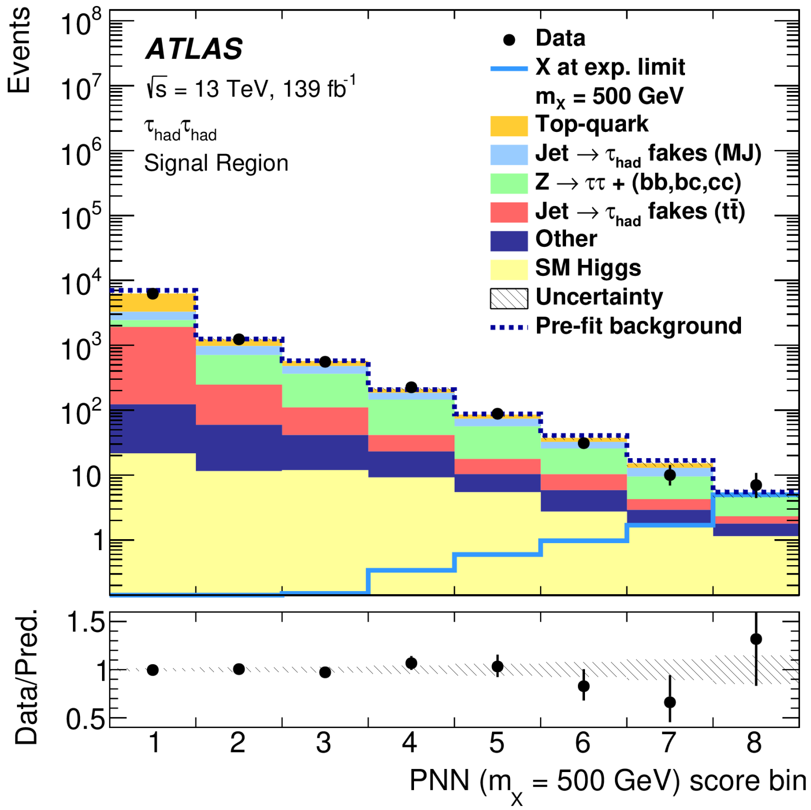


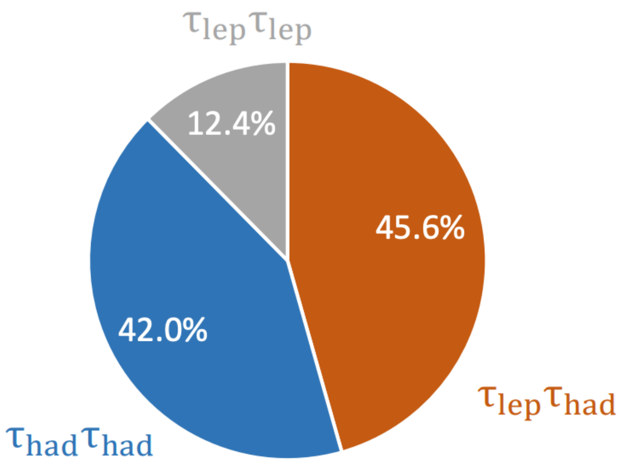
$X \to hh, hh \to bb\tau\tau$

arXiv:2209.10910

- $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ di-tau final states + 2-b jets
- pDNN to separate S/B







$X \rightarrow hh, hh \rightarrow bb\tau\tau$

arXiv:2209.10910