August 28 - September 8 2022

Workshop on the Standard Model and Beyond

Searches for additional Higgs bosons in ATLAS

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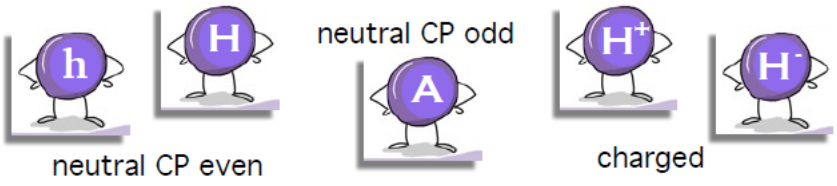
On behalf of the ATLAS collaboration

Introduction

- Is **h(125 GeV) THE Higgs** boson or **A Higgs** boson?
- Extended Higgs sectors common to many Beyond-the-Standard-Model (BSM) theories
  - E.g. SUSY, dark matter, axions, baryogenesis models …
  - Searches often interpreted in the context of **2HDMs**, but always also have **model-independent limits**

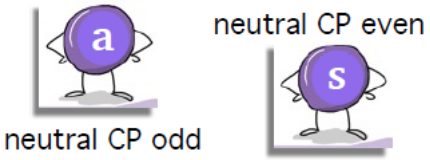
2HDM = 2 Higgs Doublets Model
- add another SU(2) Higgs doublet to the SM

5 physical states:
(CP conserving case)

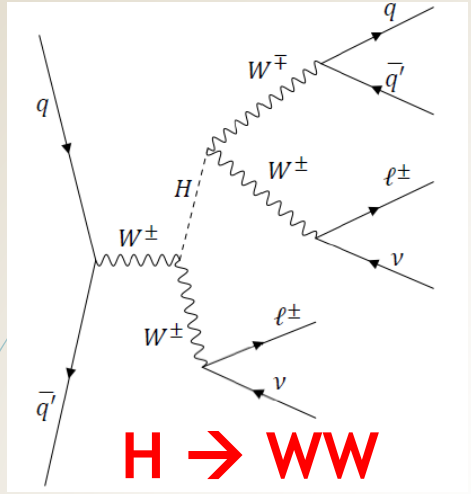


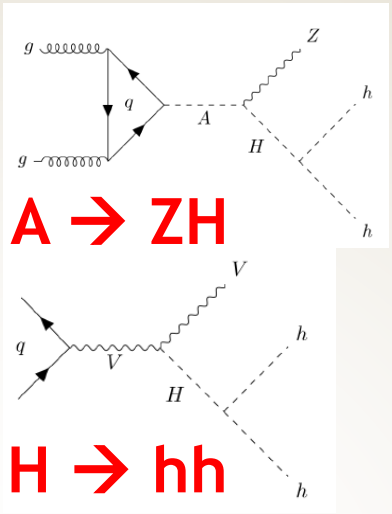
2HDM + S (singlet)

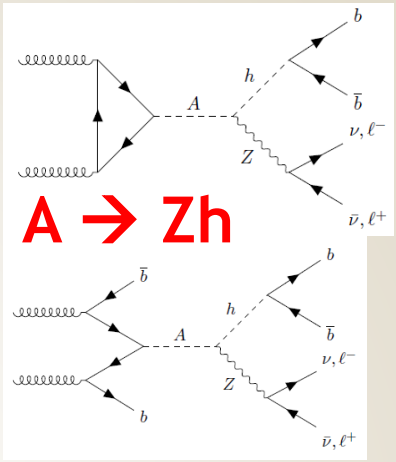
- 2 additional physical states
  - ➡ Possibly light ($m < m_h$)
  - ➡ e.g. NMSSM



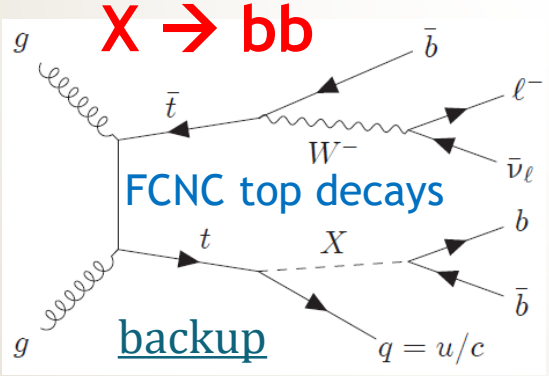
- **Will show some of the most recent ATLAS results with the full Run 2 dataset corresponding to 139 fb^{-1}**

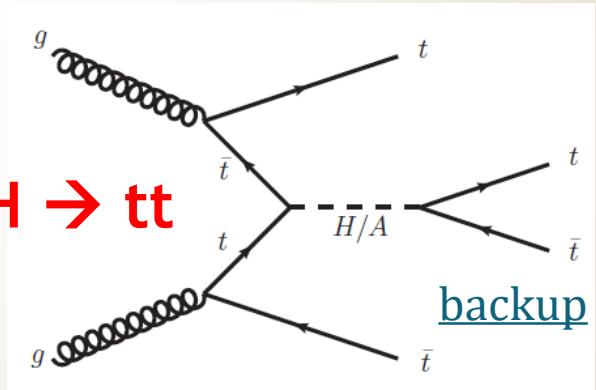


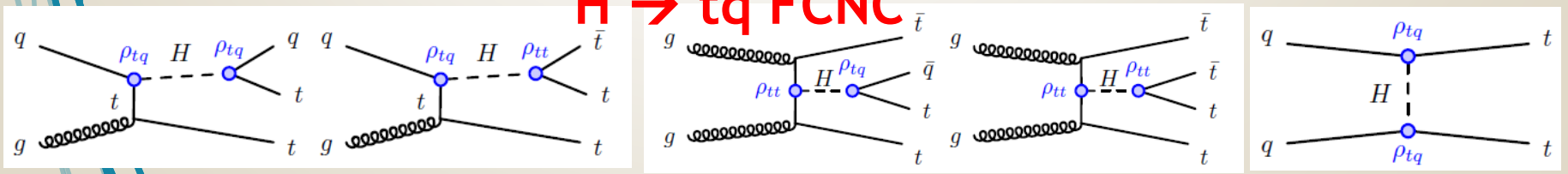




Heavy Neutral Higgs







WH(→WW)

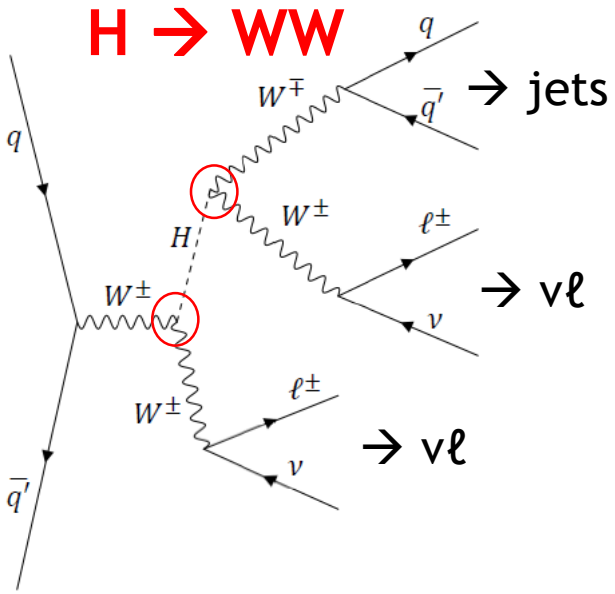
ATLAS-CONF-2022-033

- **Production in association with W-boson**
  - Interesting in scenarios with reduced fermionic couplings
  - Effective 2HDM Langrangian terms with heavy H couplings to SM W-bosons:

$$\mathcal{L}^{(4)}_{HWW} = \rho_H g m_W H W^\mu W_\mu$$

$$\mathcal{L}^{(6)}_{HWW} = \rho_H g m_W \frac{f_W}{2\Lambda^2}\left(W^+_{\mu\nu}W^{-\mu}\partial^\nu H + h.c.\right) - \rho_H g m_W \frac{f_{WW}}{\Lambda^2} W^+_{\mu\nu}W^{-\mu\nu}H$$

- Select events with:
  - **2 same-sign (SS) leptons (e,μ)**
  - $\boldsymbol{E_T^{miss}}$
  - Either 2 small radius **jets** (**resolved**) or 1 large-radius (**merged**) jet, consistent with W mass



ρ_H = sin(β-α) in 2HDM models
f_W, f_{ww} = anomalous coupling to W

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ATLAS-CONF-2022-033

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  - **2 same-sign (SS) leptons (e,μ)**
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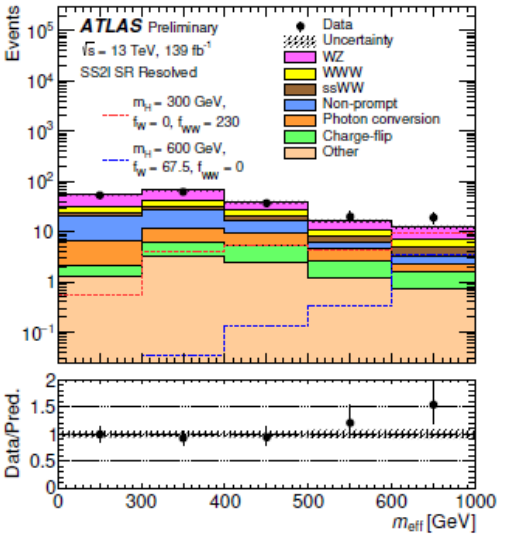
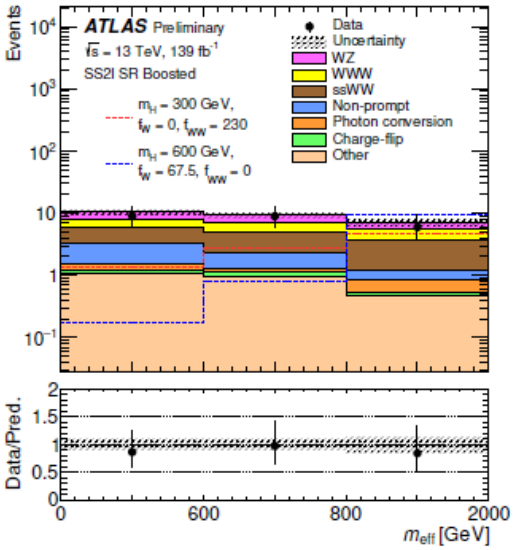
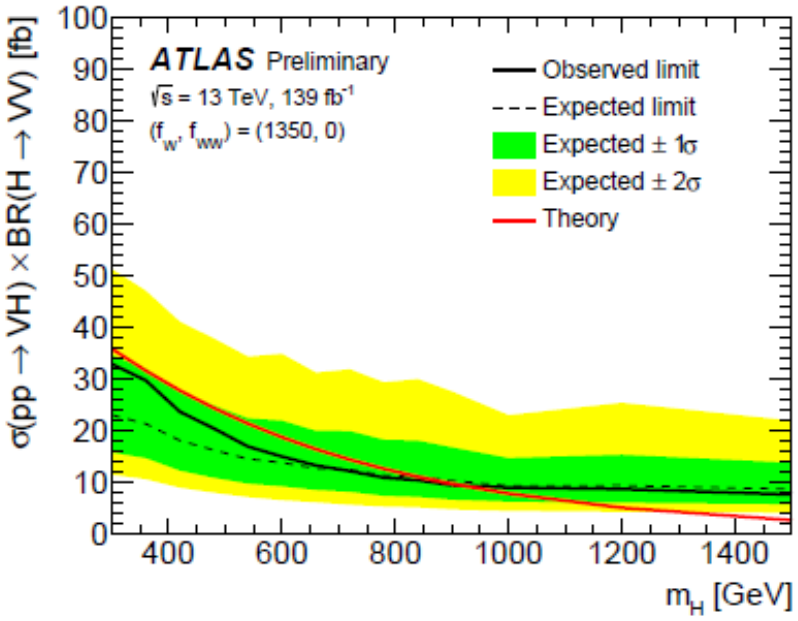
  - Either 2 small radius **jets** (**resolved**) or 1 large-radius (**merged**) jet, consistent with W mass
- Main discriminant: **effective mass (m_{eff})** = scalar sum of p_Ts of all the objects in the event

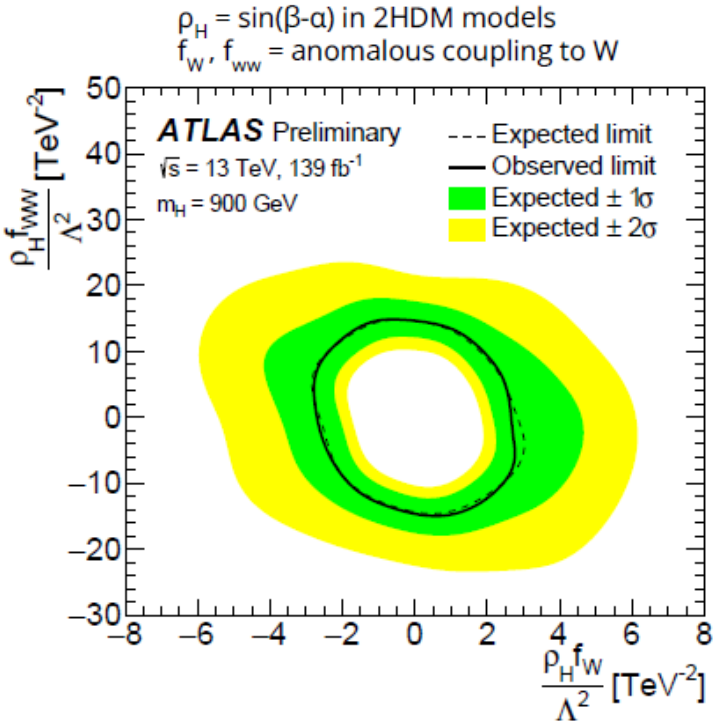




WH(→WW)

- Simultaneous binned maximum-likelihood (ML) fit in m_{eff} in SRs and in total yield in CRs
  - Normalization of dominant backgrounds (WZ+jets & WW+jets) constrained in CRs
- **No significant excess observed**
- **Interpretation in terms of BSM HVV couplings** of the effective 2HDM Langrangian

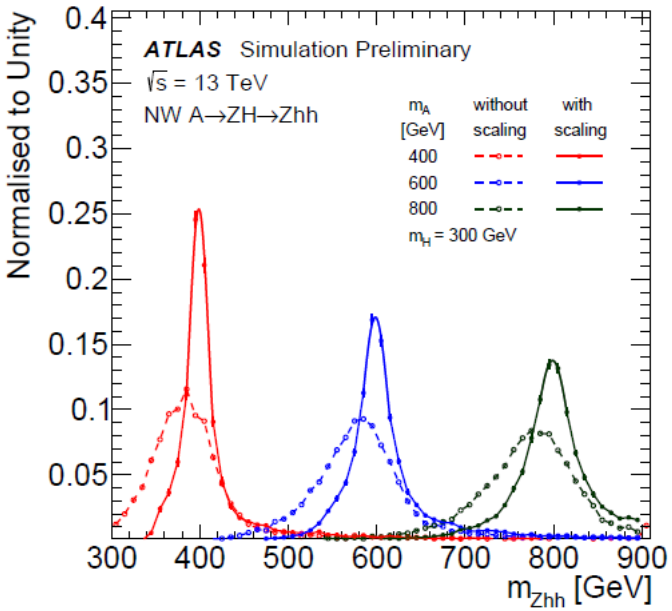


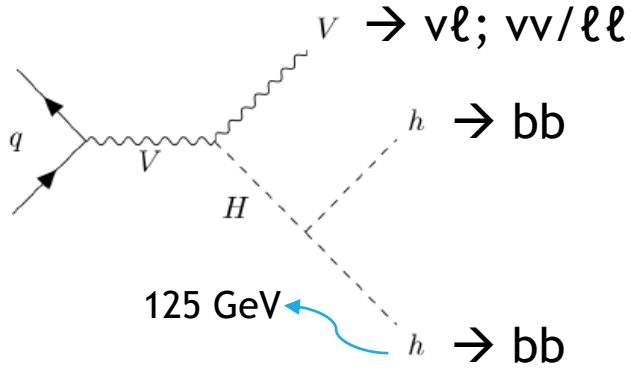


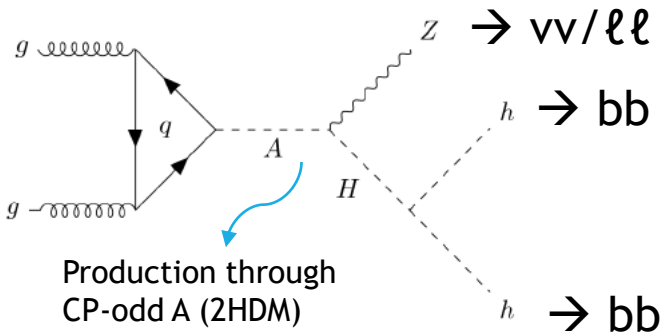
V H(→hh)

- Heavy H decaying to 2 SM-like h decaying to bb
- Three channels (**0L, 1L, 2L**), depending on the W/Z decay mode

- Discriminant: m_{hh} / m_{Zhh}
  - **mass resolution improved** (up to factor 4) **by scaling the b-jet momenta** for each h with the measured m_{bb}/125 GeV







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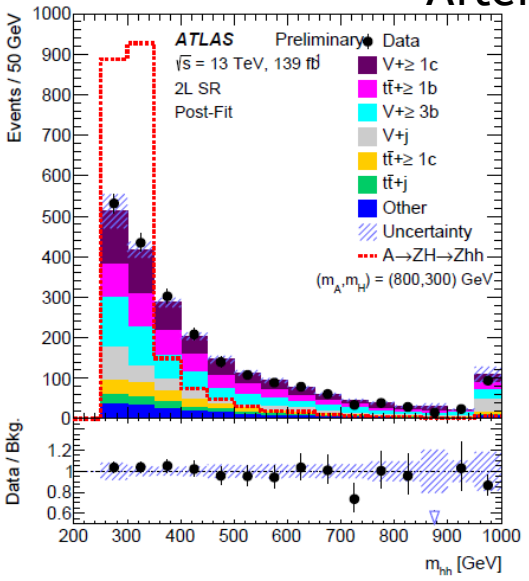
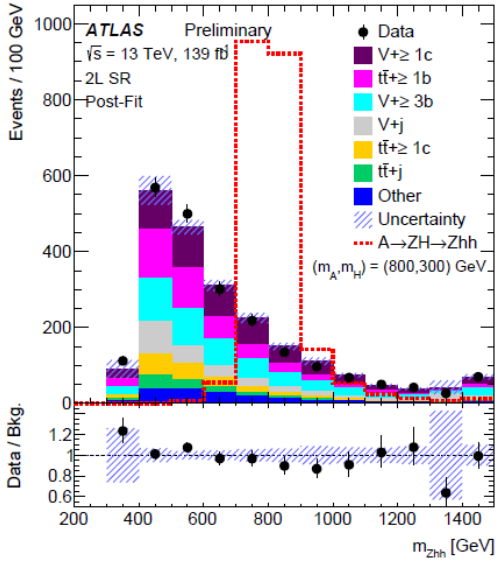
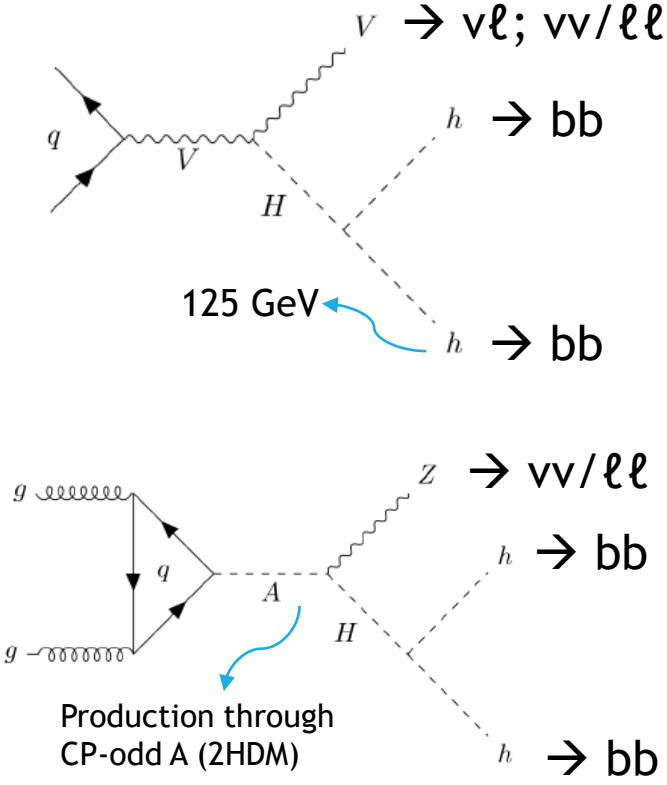
After rescaling

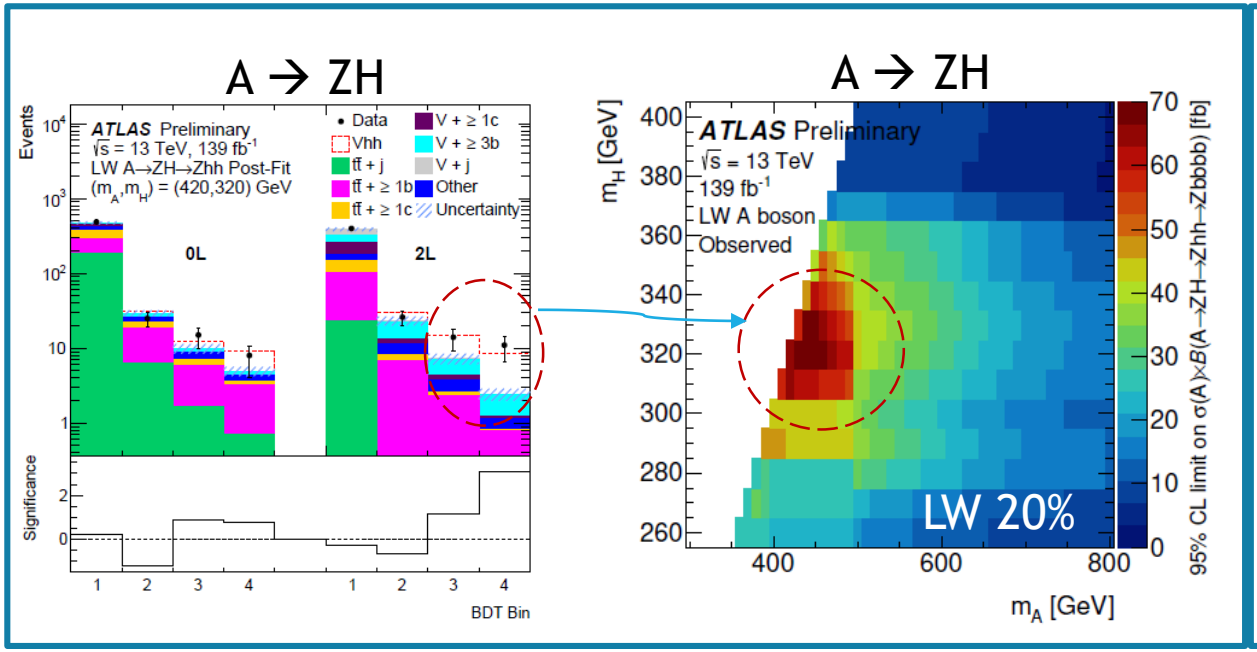


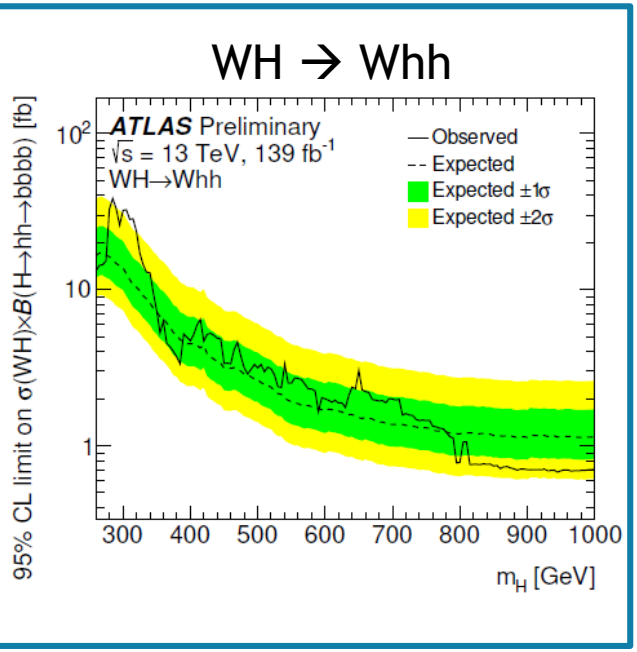




V H(→hh)

- Boosted decision trees (BDT) discriminant trained for each channel & each signal model
  - Mass requirement on m_{hh} (30-220 GeV wide) before the fit to BDT distributions
  - ML fit to BDT distributions in the SRs to extract the results
- Most significant excess in **A→ ZH channel (m_A, m_H) = (420, 320) GeV local** (global) **3.8σ** (2.8σ) for large-width (LW) A
  - For NW: 3.6 (11.6)σ local (global) at (m_A, m_H)= (800, 300) GeV

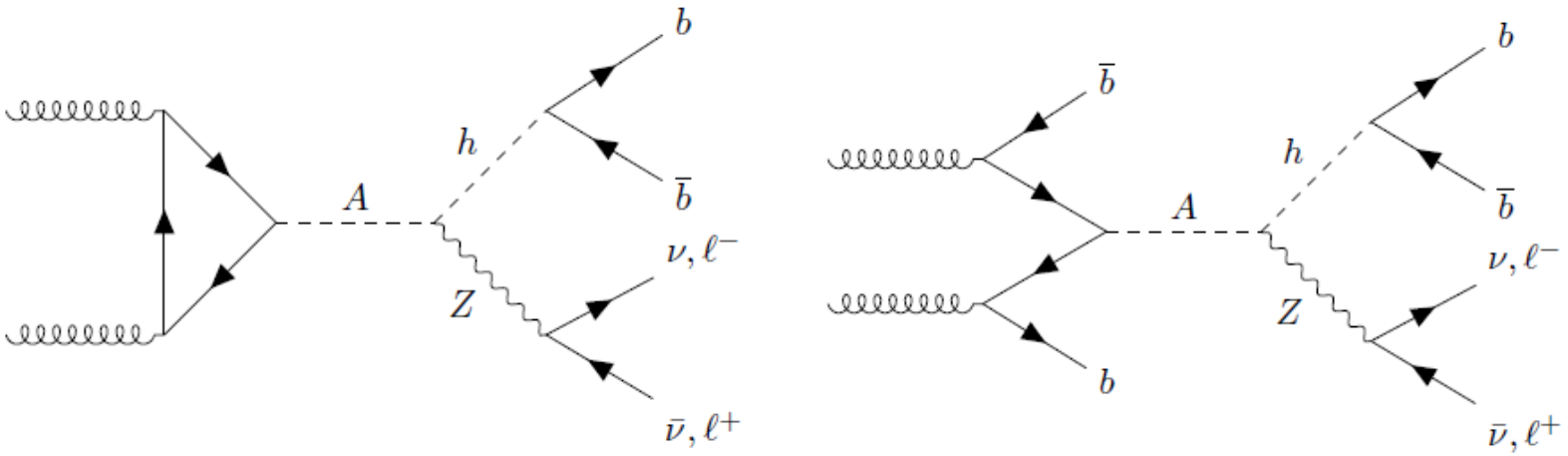




A → Z(ℓℓ/νν)h(bb)

2207.00230

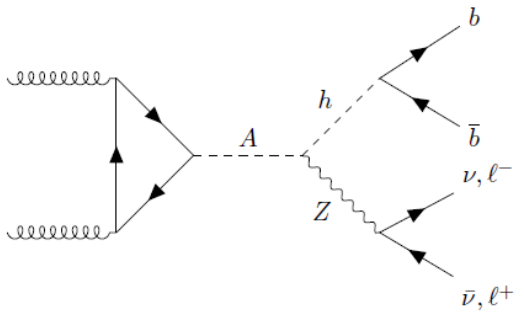
- Look for gluon-gluon fusion (**ggA**) and bb associated (**bbA**) A-boson production
- SRs categorised according to the number of leptons (**0ℓ or 2ℓ**) and b-jets (**1b, 2b or ≥3b**)
  - Both **resolved and merged h→bb decays** considered



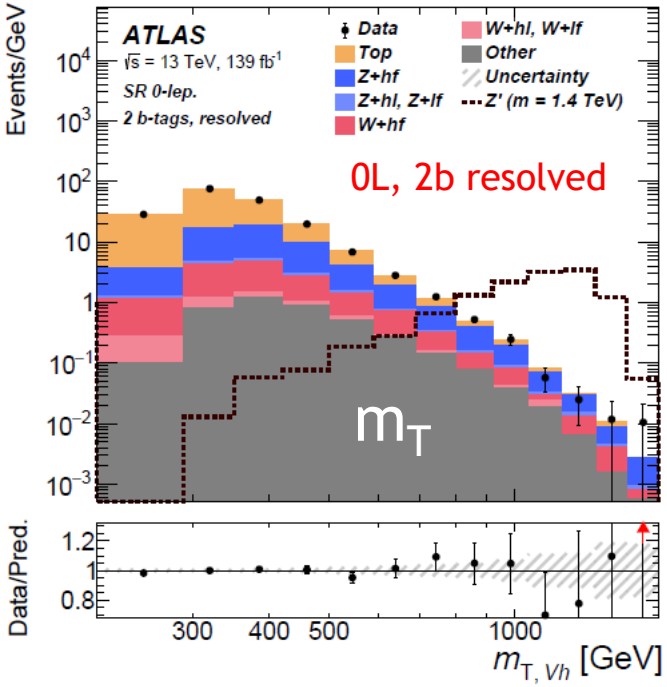
A → Z(ℓℓ/νν)h(bb)

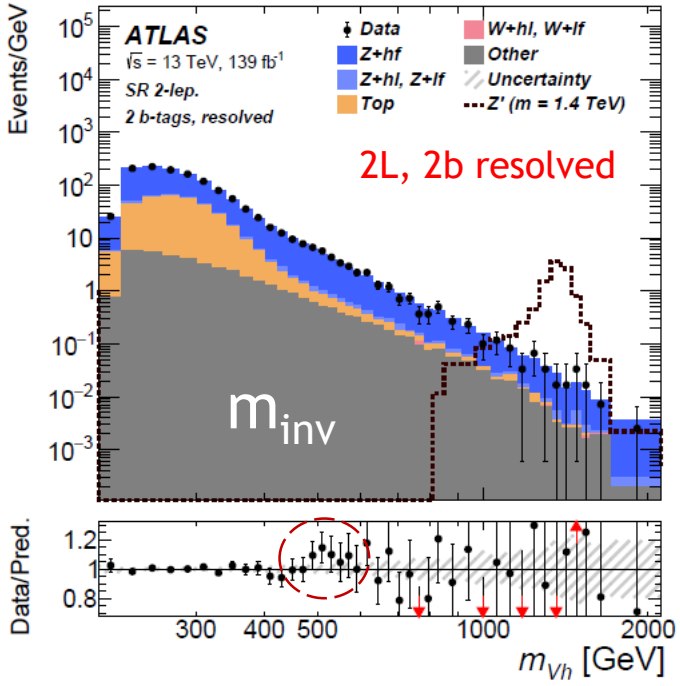
2207.00230

- Discriminating variables:
  - $m_{T,Zh}$ **in 0ℓ** channel $m_{\mathrm{T},Vh} = \sqrt{\left(E_{\mathrm{T},h} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{\mathrm{T},h} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2}$
  - m_{Zh} **in 2ℓ** channel
  - p_{bb} rescaled by $m_{bb}/125$ GeV to improve the resolution



- Binned ML fits on $m_{T,Zh}/m_{Zh}$ performed over SRs & CRs



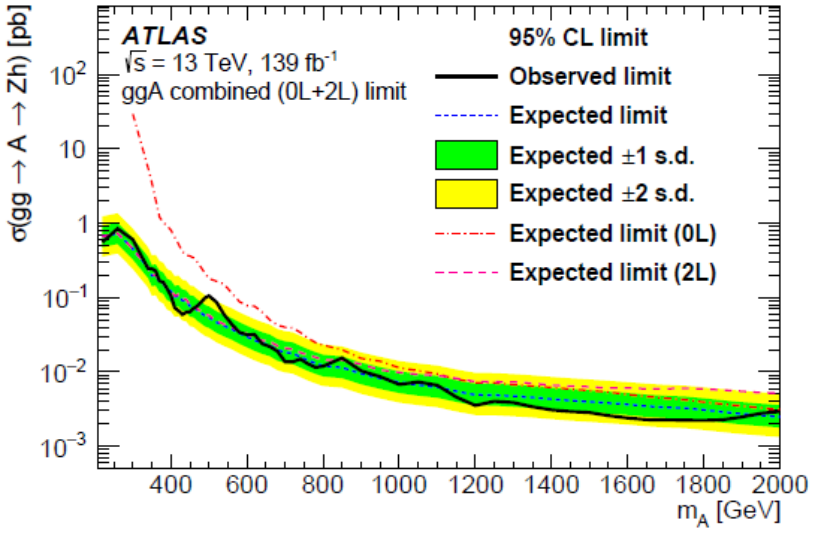


A → Z(ℓℓ/νν)h(bb)

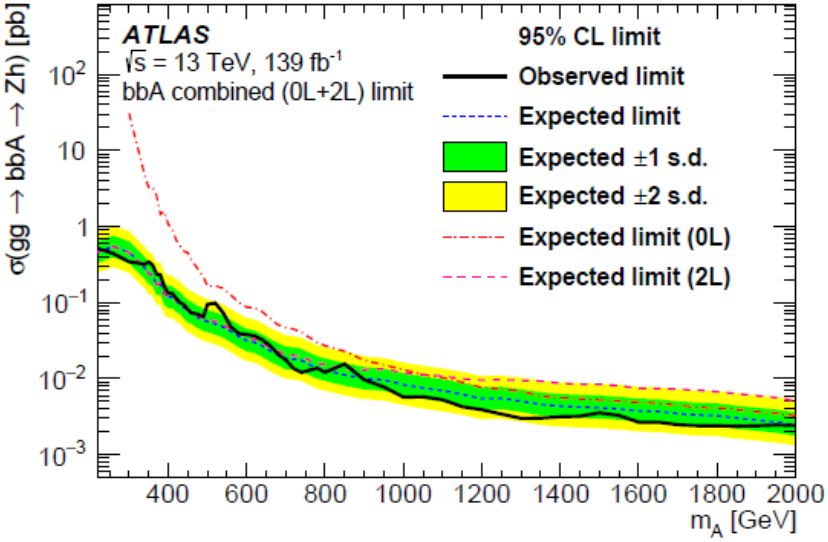
2207.00230

- **Model-independent limits** on σ x Br (combined 0ℓ+2ℓ)
  - The largest deviation from the SM expectation found at **500 GeV in ggA** search corresponding to a significance of **2.1σ** (1.1 σ) **local** (global) (1.6σ local for bbA)

ggA 0L+2L



bbA 0L+2L



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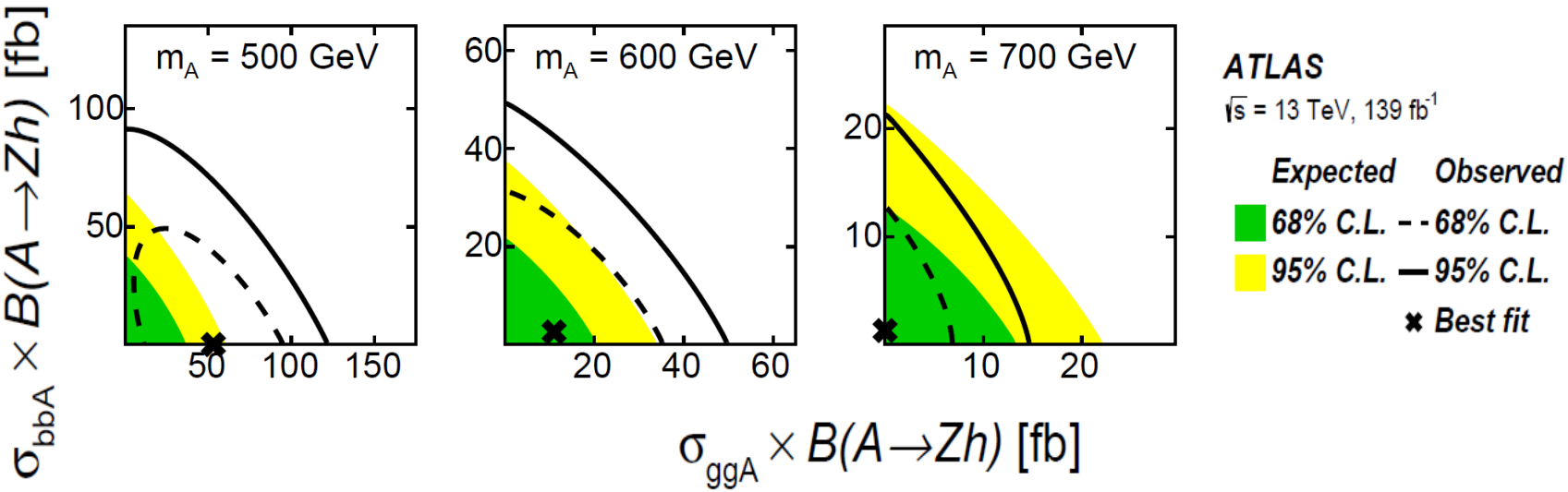
  - The largest deviation from the SM expectation found at **500 GeV in ggA** search corresponding to a significance of **2.1σ** (1.1 σ) **local** (global) (1.6 σ for bbA)
- **2D likelihood scan** for various m_A to determine the compatibility for **different σ_{bbA} & σ_{ggA} contributions**



A → Z(ℓℓ/νν)h(bb)

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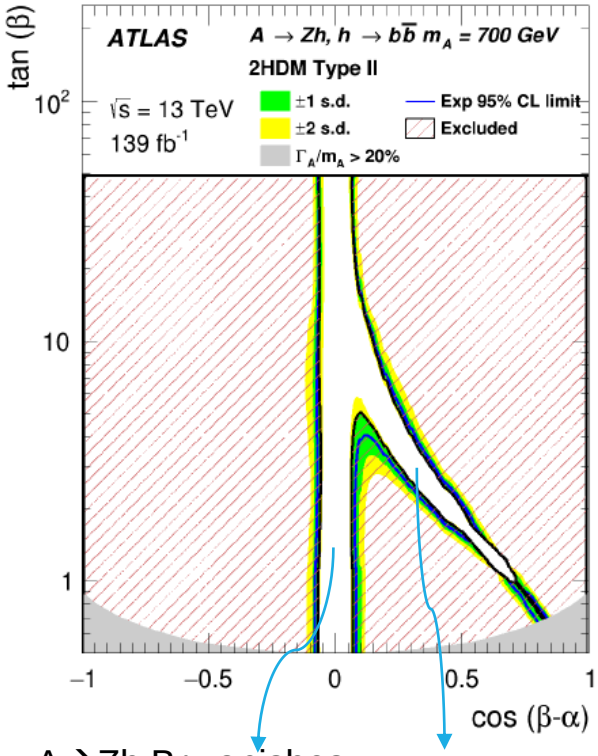
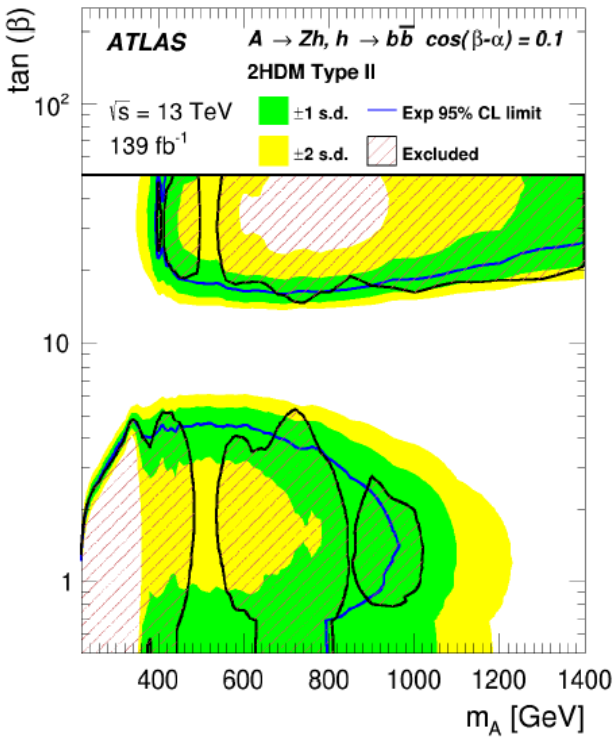
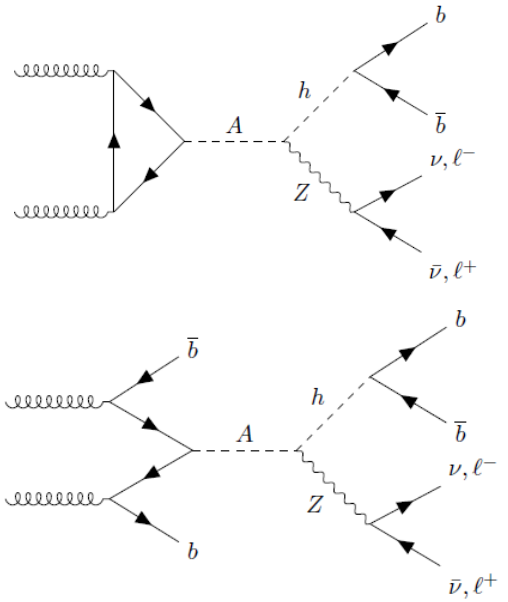
- Interpretation for various 2HDM types
  - tanβ controls ggA vs bbA contributions
  - Limits vary along m_A depending the cross section and the preferred A-decay mode





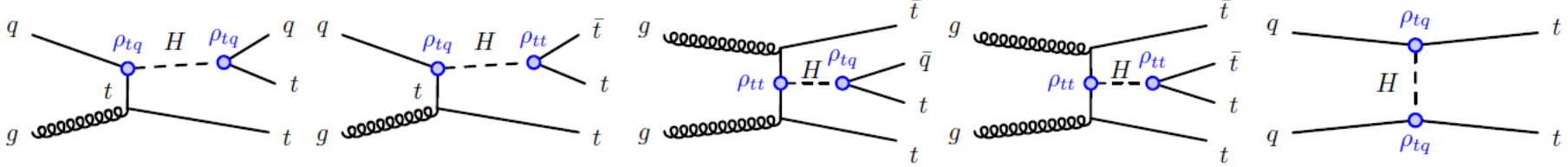


A→Zh Br vanishes

h→bb Br vanishes

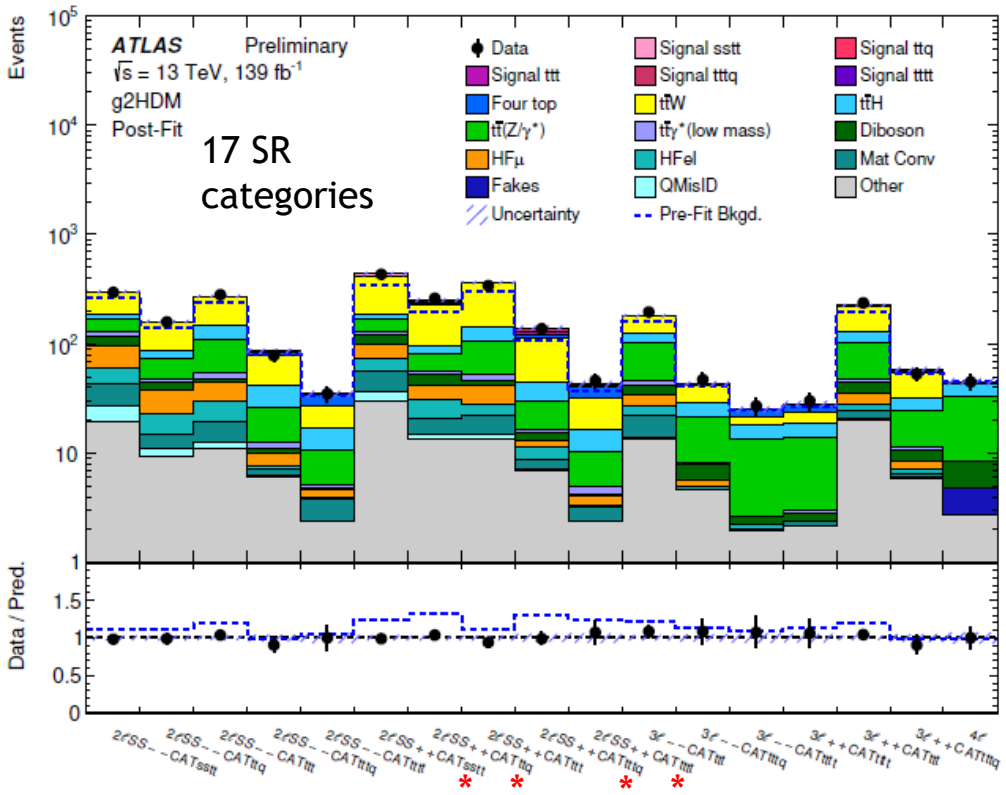
H → leptons + b-jets

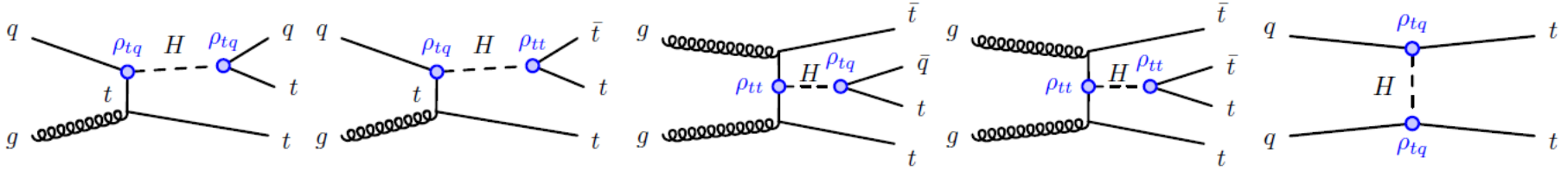
- **General 2HDM (g2HDM) featuring a heavy scalar with flavor-changing decays (FCNH)**
  - Consider tt, tc & tu couplings
- Giving rise to interesting topologies sensitive to new physics
  - **3-top signature**
  - **Same-sign (SS) top production (t^+t^+)**
- First to target BSM production leading to three-top final states and the first to probe the g2HDM
- **Multiple leptons (e & μ) and b-jets in the final state + charge asymmetry**



H → leptons + b-jets

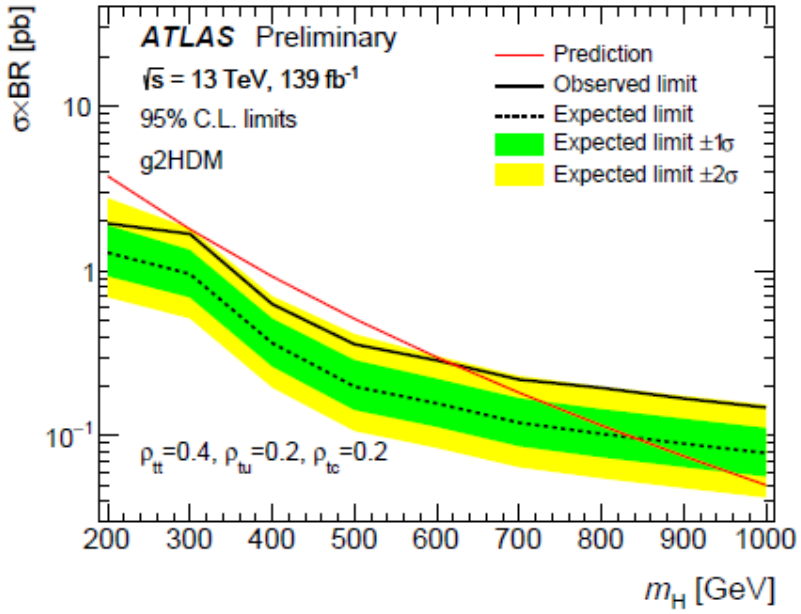
- Events separated into 3 SR categories depending on the number of leptons:
  - **SS2ℓ**
  - **3ℓ**
  - **4ℓ**
- Further split based on **ℓ** charge **(++ or --)**
- **Categorized into 5** possible **g2HDM** production and decay **modes** based on the Deep Neural Network (DNN) output

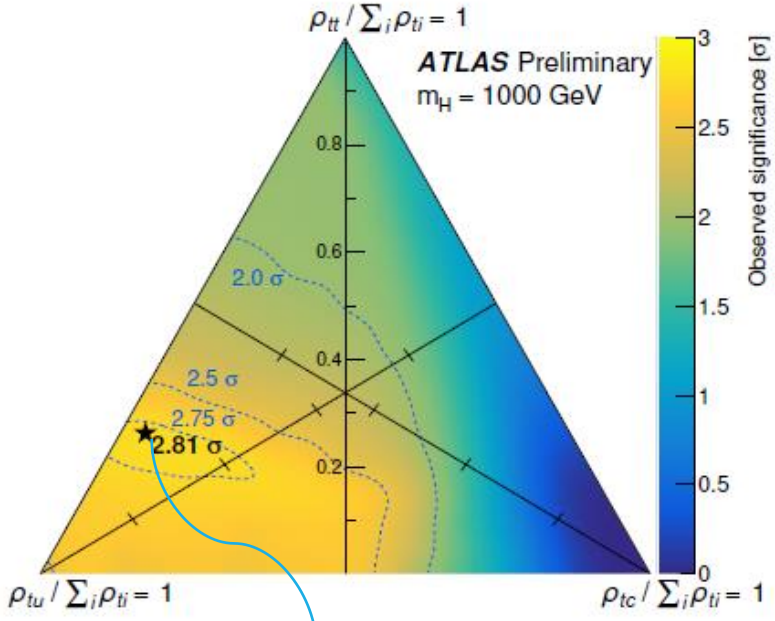




H → leptons + b-jets

- ML fit performed across all the SRs & CRs categories
- Signal summed into 1 template and limits set for different coupling choices
- Mild excess observed corresponding to a **local significance of 2.81 σ for m_H=1 TeV**

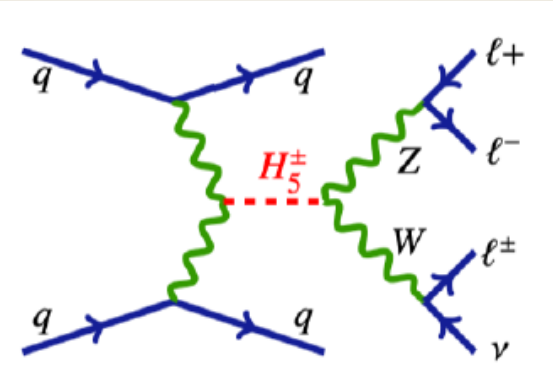




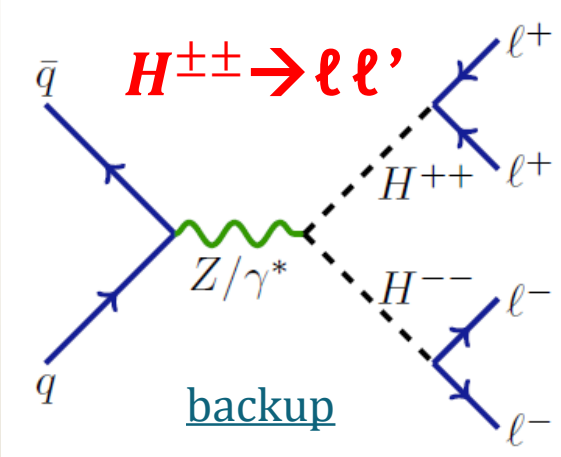
ρ_{tt}=0.32, ρ_{tc}=0.05, and ρ_{tu}=0.85

71% ttq, 20% sstt, and 9% ttt

H → ZW



Charged Higgs

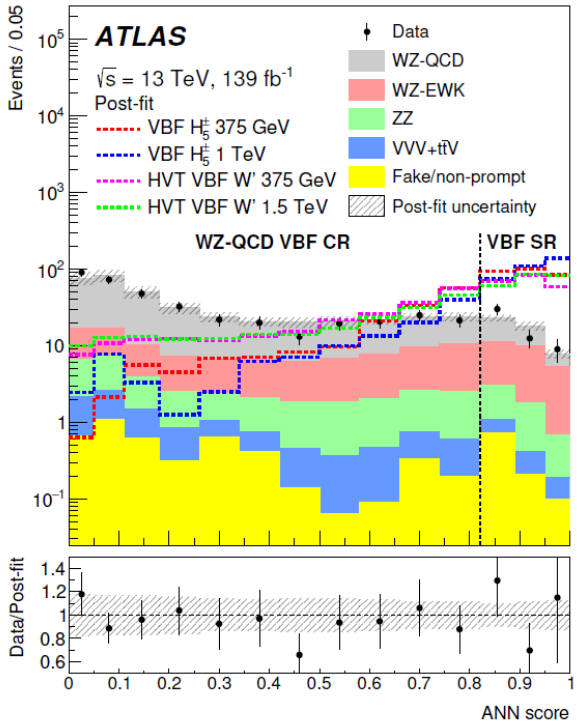


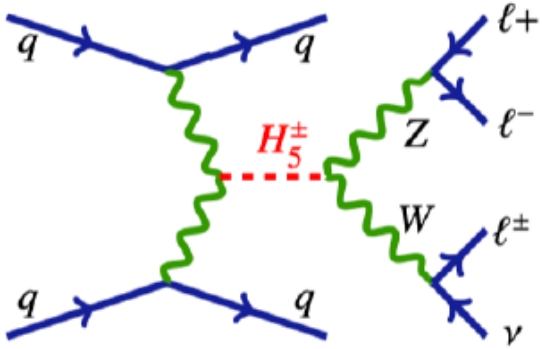
backup

$H^{\pm} \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$

arXiv:2207.03925

- **Fermiophobic heavy H from Georgi-Machacek model** that couples to W & Z bosons
  - Produced in VBF
  - Fully leptonic channel sensitive in spite of low Br due to lower SM backgrounds
- Use artificial neural networks (ANN) to select signal-enriched regions



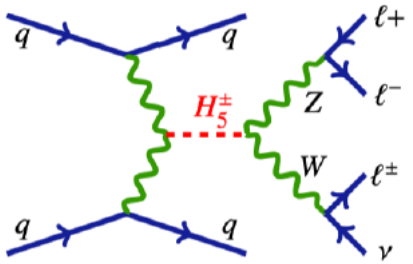


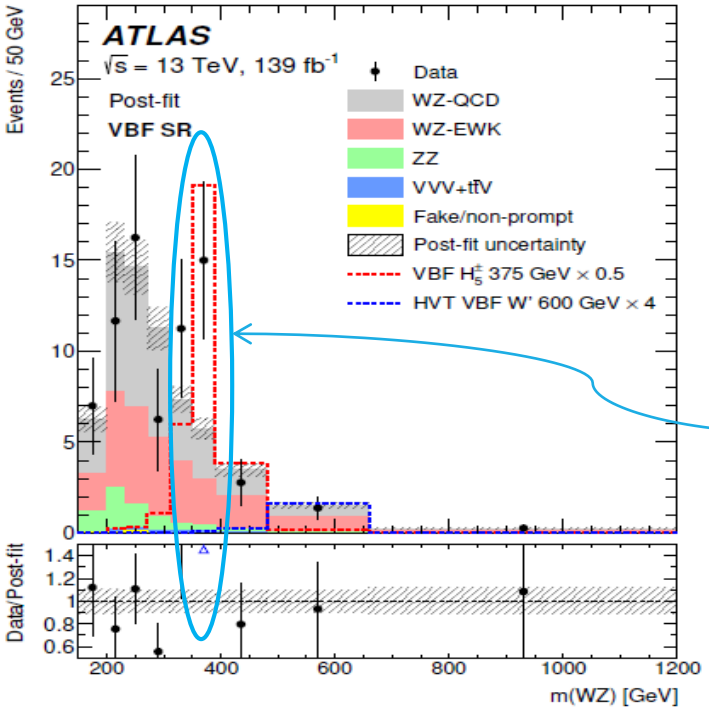
At least 2 *VBF jets*
$m_{jj} > 100$ GeV
Veto events with *b*-tagged jets
ANN Output > 0.82
Exactly 3 *Loose* leptons

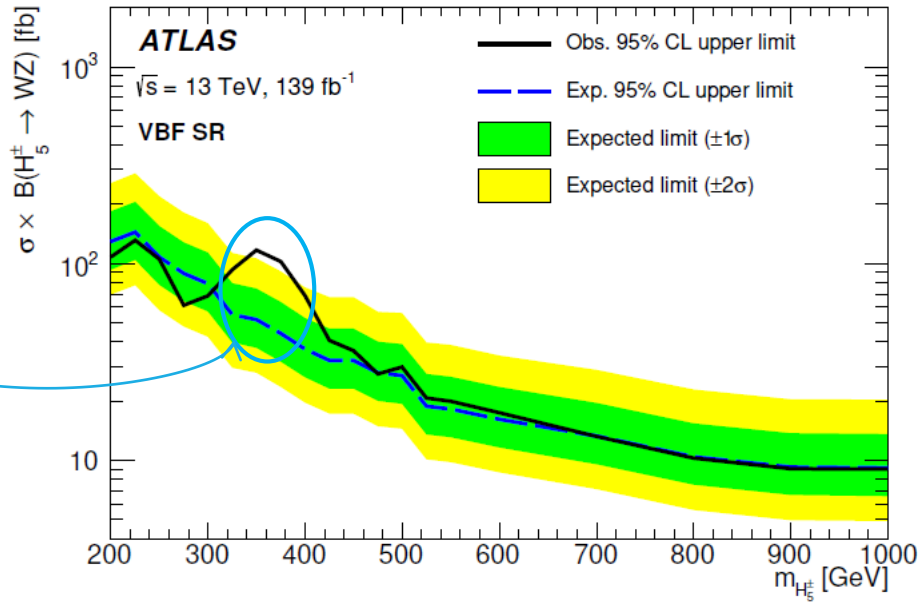
$H^{\pm} \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$

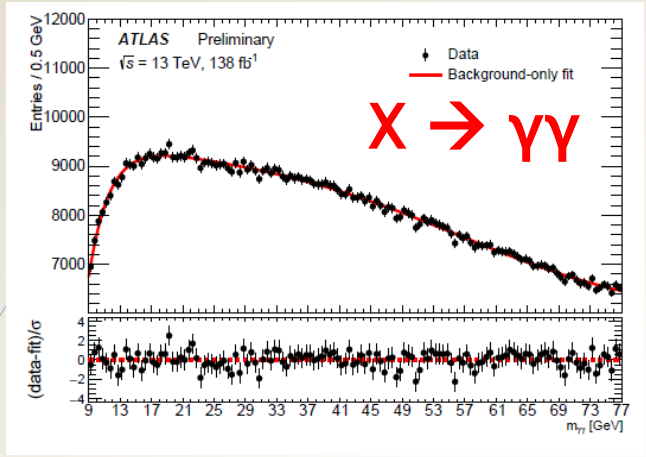
arXiv:2207.03925

- **WZ invariant mass (m_{WZ}) as discriminating variable**
  - The longitudinal $p_z(\nu)$ estimated by constraining $\nu\ell$ system to m_W
  - Simultaneous ML fit of binned m_{WZ} in SR & CRs
- **Local** (global) significance of **2.8σ** (1.6σ) at **375 GeV**

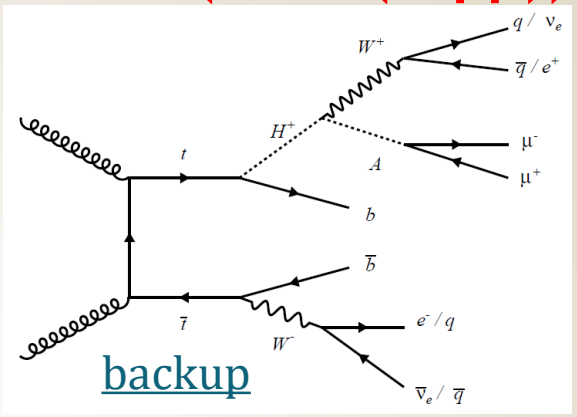






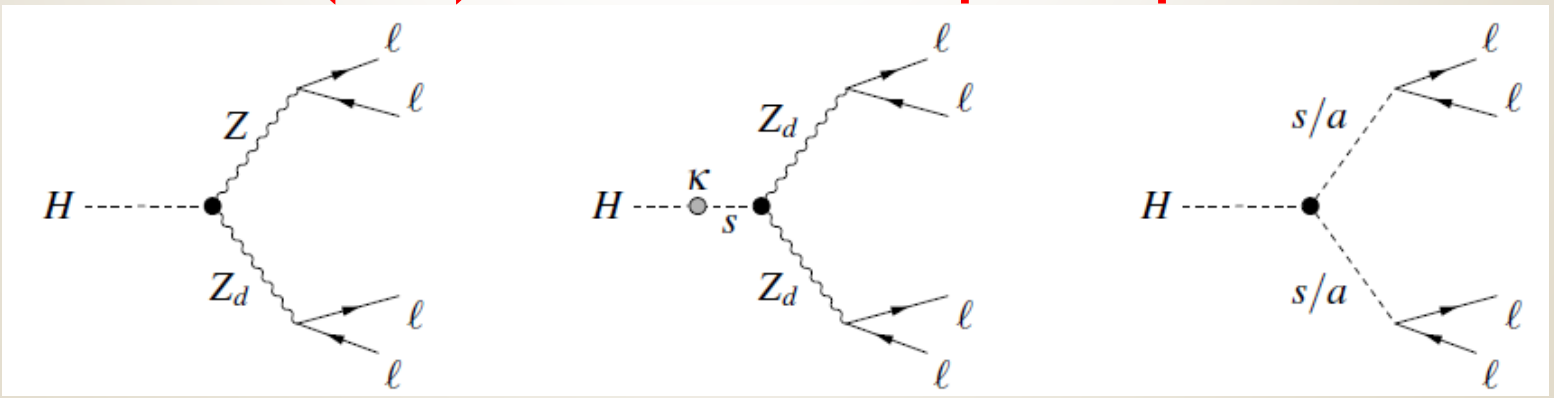


t→bH⁺(→Wa(→μμ))



Low-mass Higgs = m(X)<125 GeV

h(125) → aa → 4ℓ/2b2μ/4b/2μ2τ….

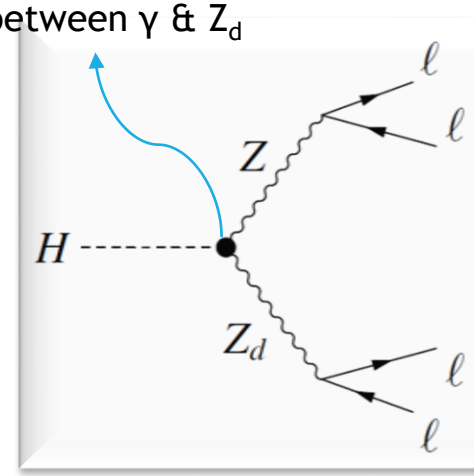


H(125) → XX/ZX→4ℓ

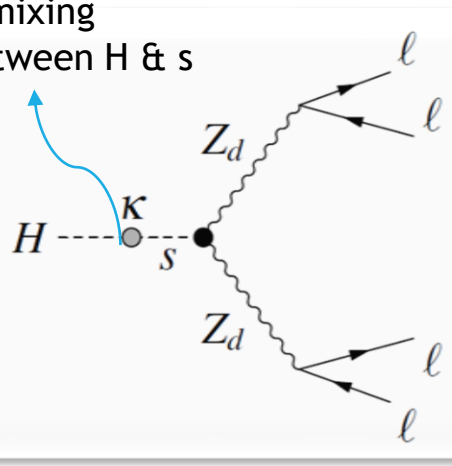
- **Br(H→BSM) up to 12% allowed** based on current measurements (Nature (2022))
- Hidden sector particles could couple preferentially (only?) to the SM H
  - **Exotic Higgs decays could be a portal to new physics!**
- 2 benchmark models
  - Dark photons Z_d - $U(1)_d$ spontaneously broken by **dark Higgs *s***
  - **Singlet scalar from 2HDM+S**

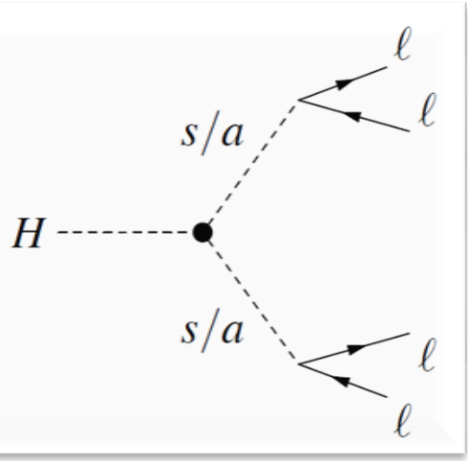
- High-mass (HM): $H \to XX \to 4\ell$ ($15\,\text{GeV} < m_X < 60\,\text{GeV}$).
- Low-mass (LM): $H \to XX \to 4\mu$ ($1\,\text{GeV} < m_X < 15\,\text{GeV}$).
- Single Z boson (ZX): $H \to ZX \to 4\ell$ ($15\,\text{GeV} < m_X < 55\,\text{GeV}$)

Kinetic mixing **ε** between γ & Z_d



κ mixing between H & s





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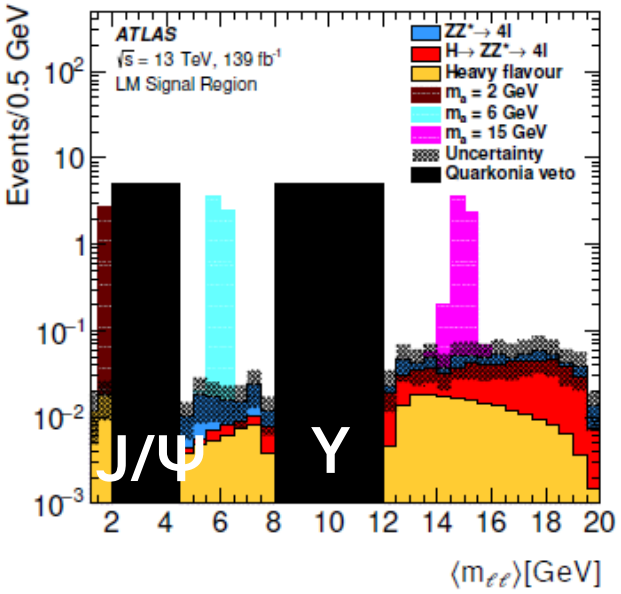
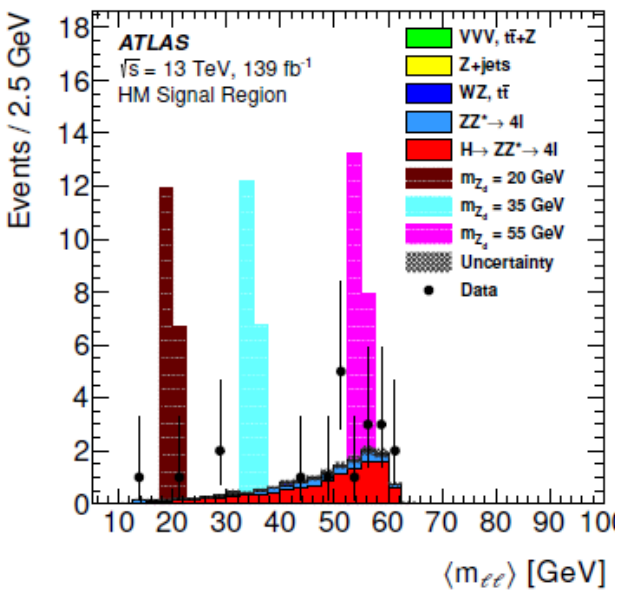
H(125) → ZX/XX→4ℓ

- Main discriminant: **dilepton invariant mass**
- Dominant backgrounds (H→ZZ* & ZZ*) estimated from the simulation and validated in the CRs
- No events observed in the 1-15 GeV mass range, consistent with the background prediction

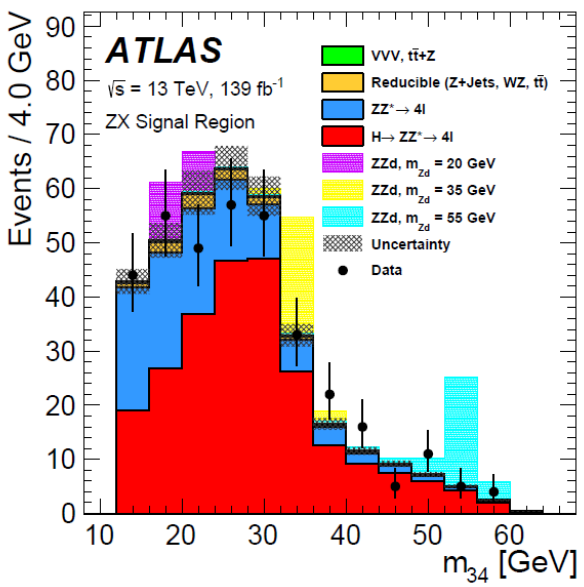
$H \to XX \to 4\mu$ (1 GeV < m_X < 15 GeV)



$H \to XX \to 4\ell$ (15 GeV < m_X < 60 GeV)



$H \to ZX \to 4\ell$ (15 GeV < m_X < 55 GeV).



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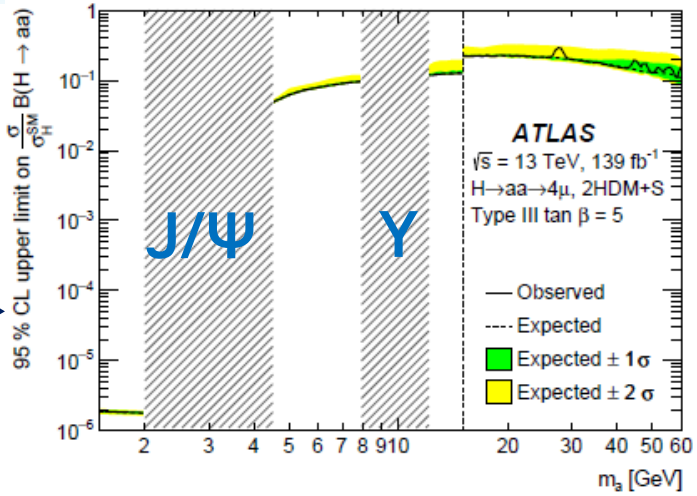
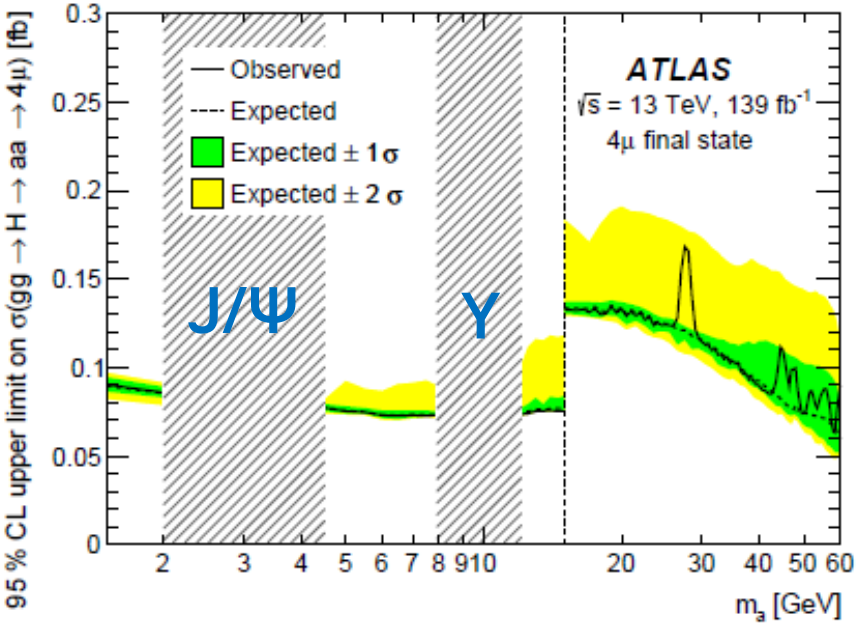
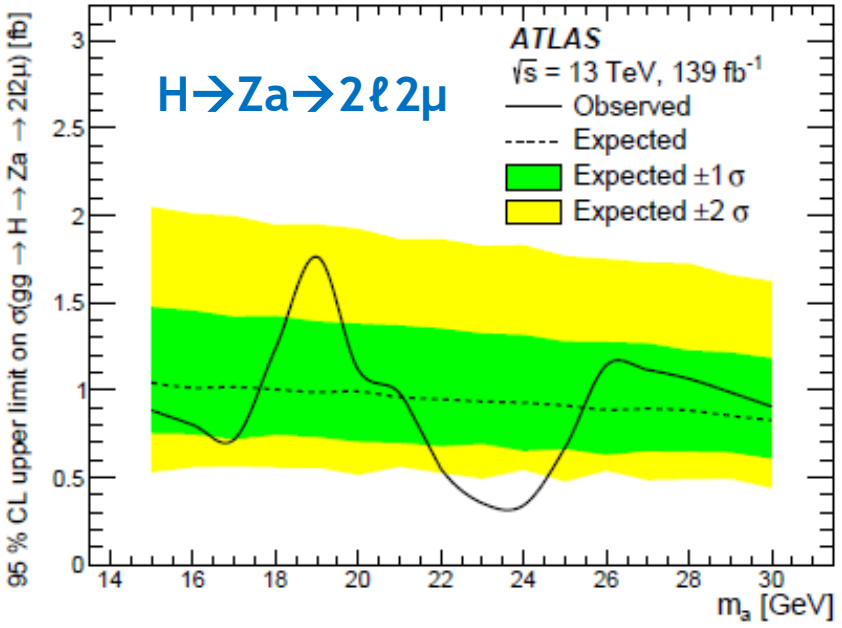
H(125) → ZX/XX→4ℓ

- **No significant deviation from the SM**
- Showing limits for the pseudoscalar case, H→aa
- Limits on Br(H→aa) in Type III 2HDM+S



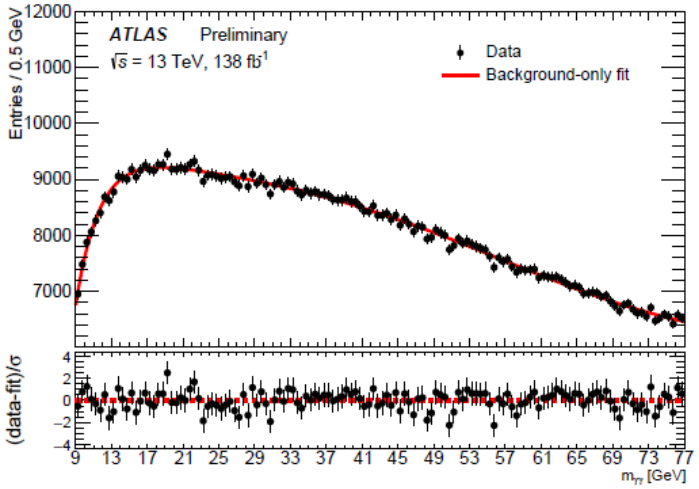
H→aa→μμ

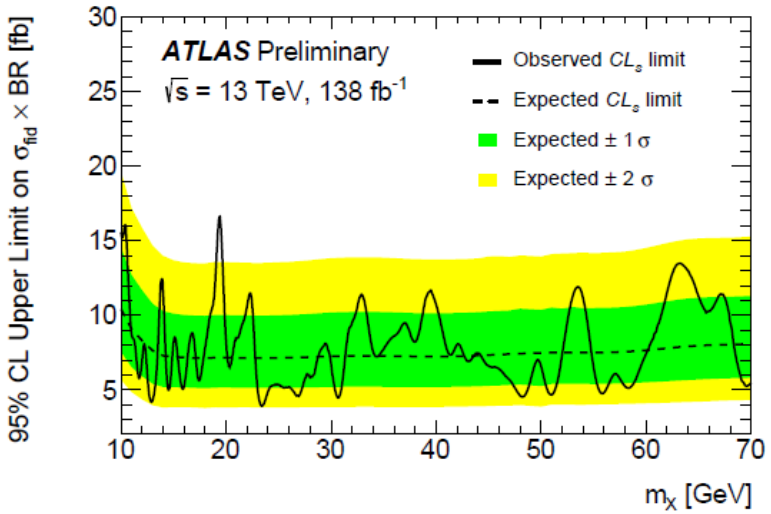




Low mass X → γγ

- Search for a generic resonance in γγ spectrum 10-70 GeV
- Challenges at low mass:
  - Need to **cover the mass region below the trigger energy threshold of 22 GeV**
    - Select close-by γγ pairs (boosted against a jet): $p_T^{\gamma\gamma}$ **>50 GeV**
  - More complex background fit around the turn-on region at 20 GeV
- Most significant deviation from the background observed at **19.4 GeV**
  - **Local** (global) significance **3.05σ** (1.48σ)

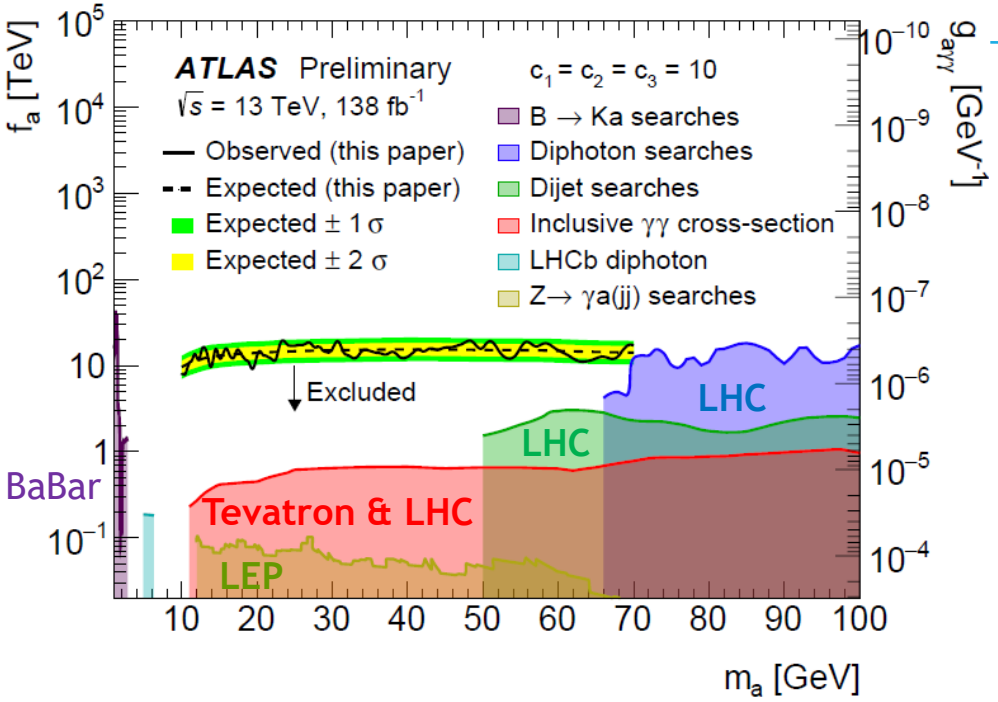




Low mass X → γγ

- **Interpretation for axion-like particles (ALPs)**
  - Heavy-colored states generating ALP-gauge bosons coupling are multi-TeV & inaccessible at the LHC
  - Lower limit on the ALP decay constant f_a (σ*Br ~ $1/f_a^2$)
  - **Covers previously unexplored phase space!**

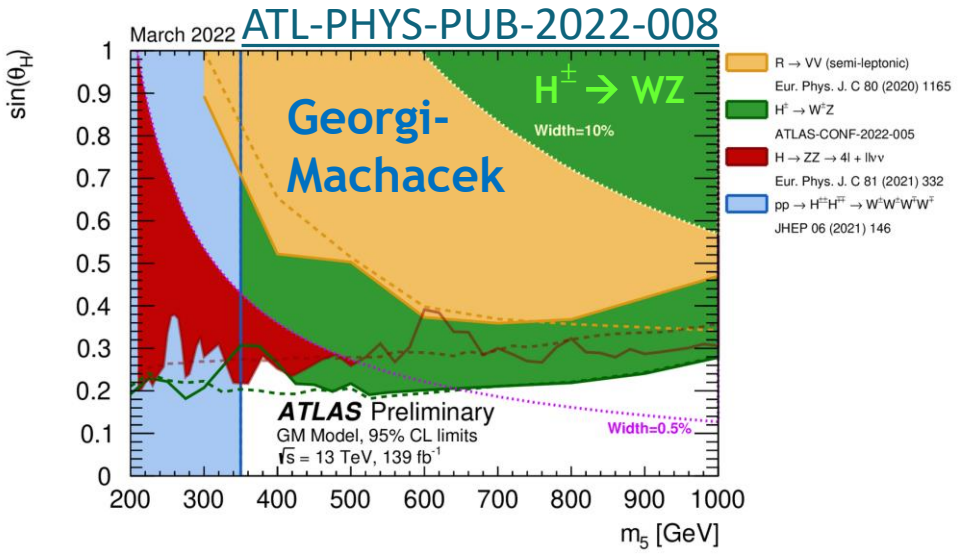
Lower limit on ALP decay constant

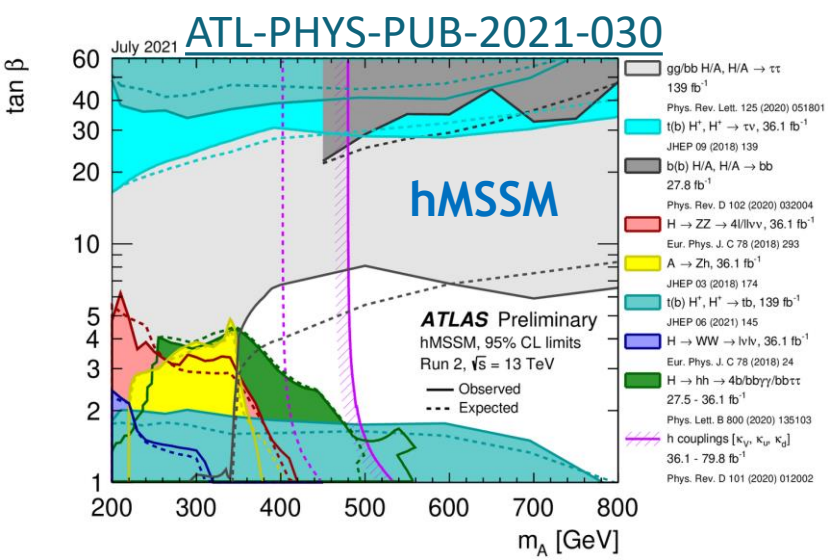


Upper limit on ALP-γγ coupling

Summary

- Looking for **additional Higgs bosons** (or more generally additional scalars) in many different final states/production mechanisms
  - **Probing so-far unconstrained phase space**
- Many searches performed in an **model-independent way**
  - Can be easily re-interpreted
- **No significant deviations** from the SM prediction observed
- **More results with the full 139 fb^{-1} of Run 2 in preparation**

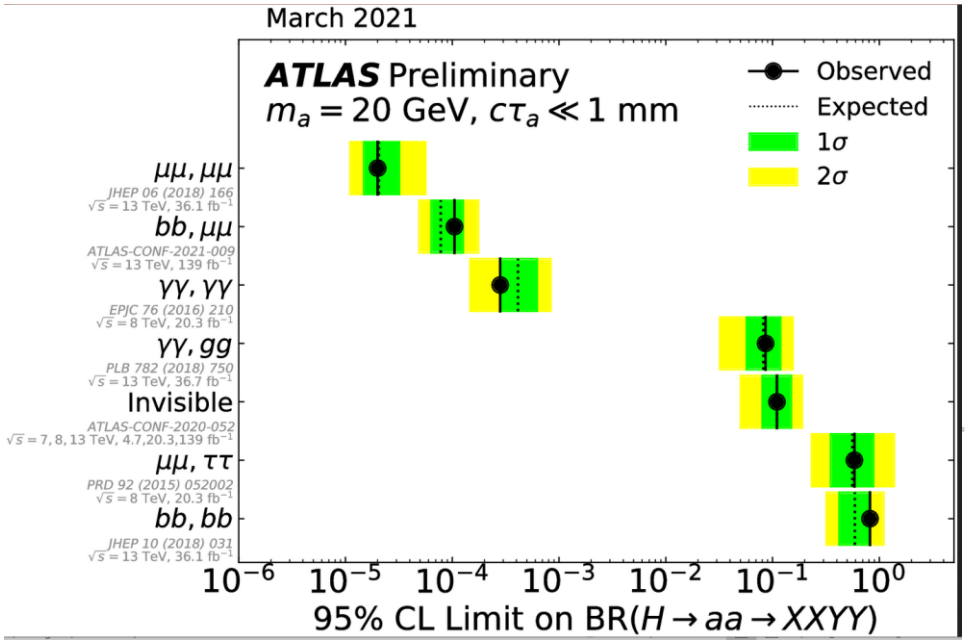


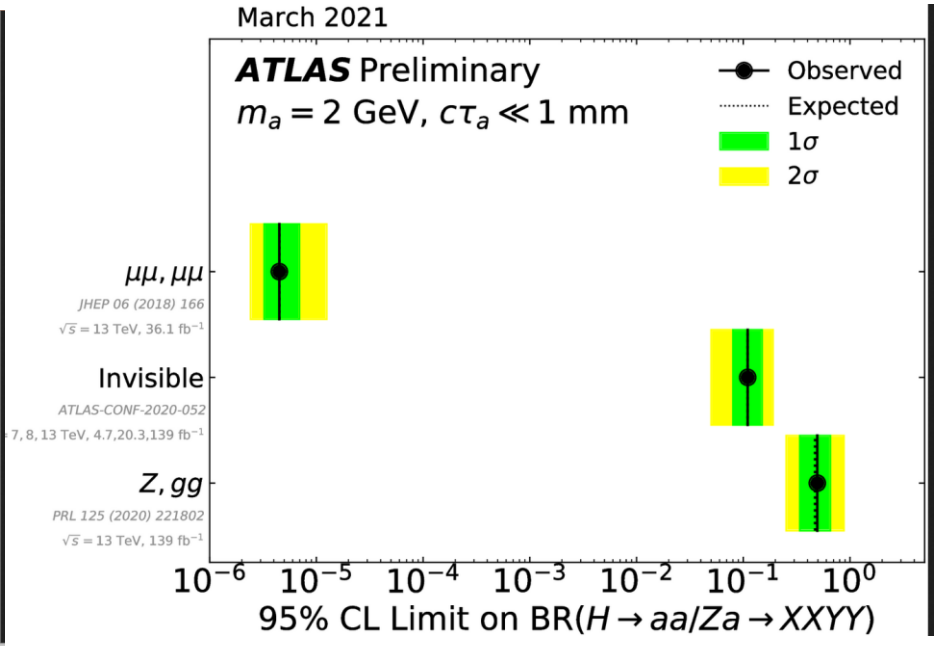


Backup

Exotic h(125) decays summary

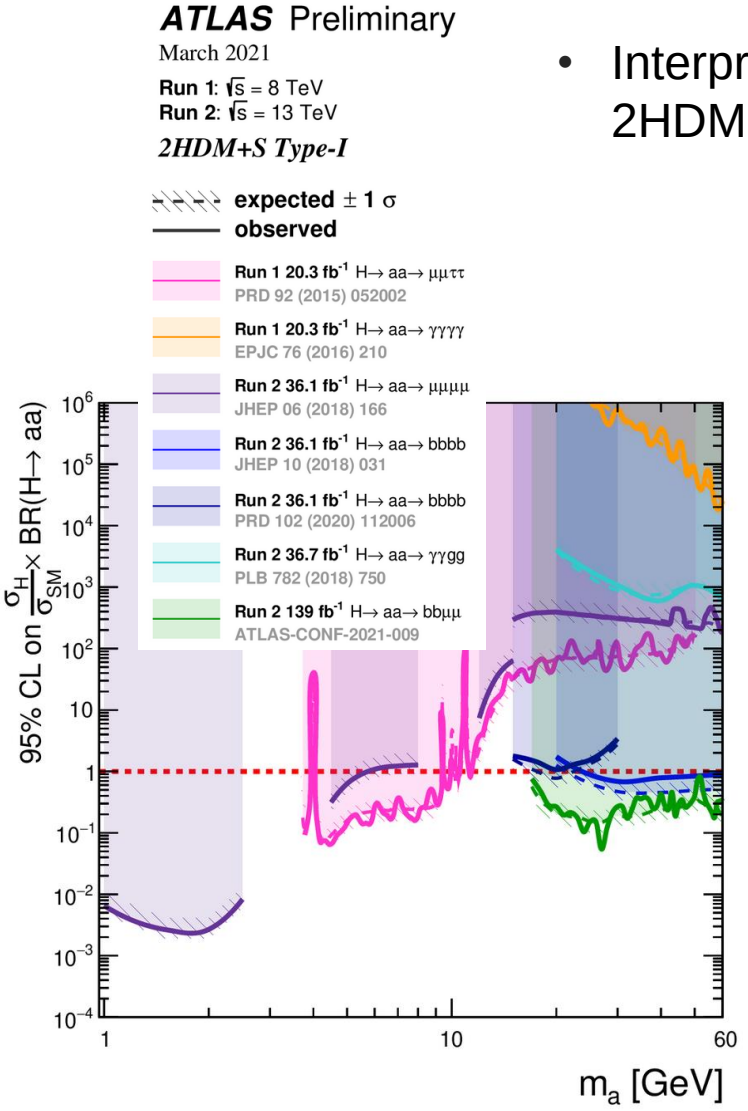
- Model independent limits on Br(H→aa/Za→XXYY)

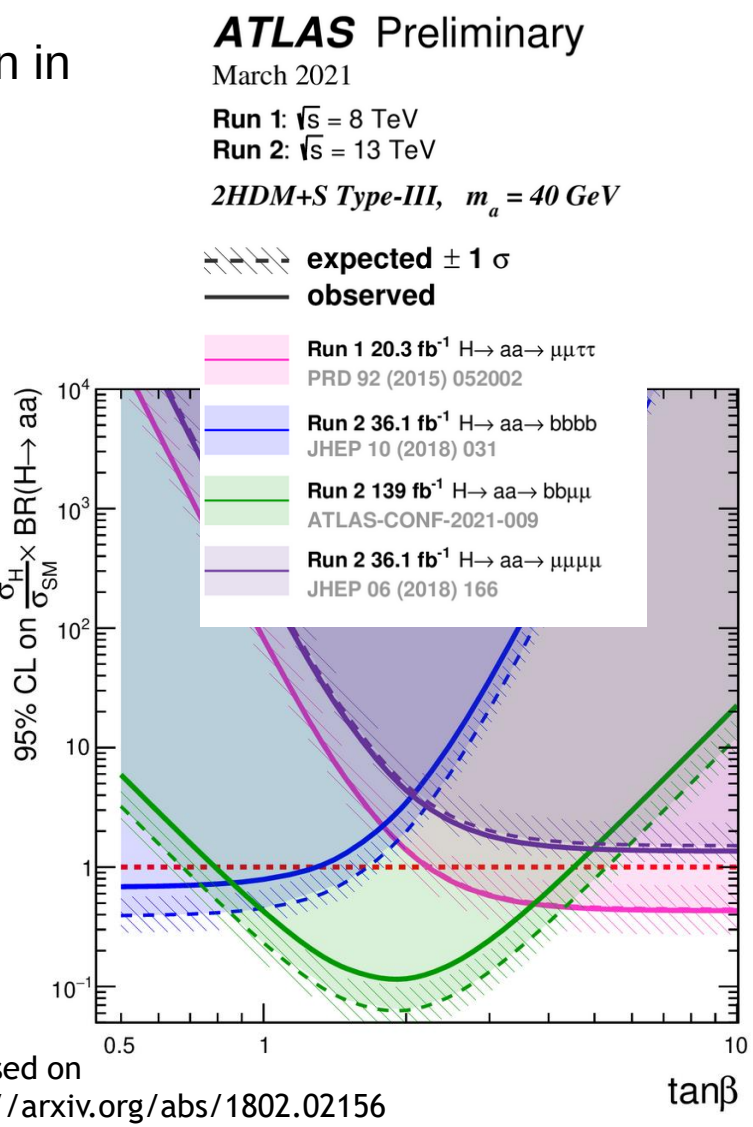




Exotic h(125) decays summary

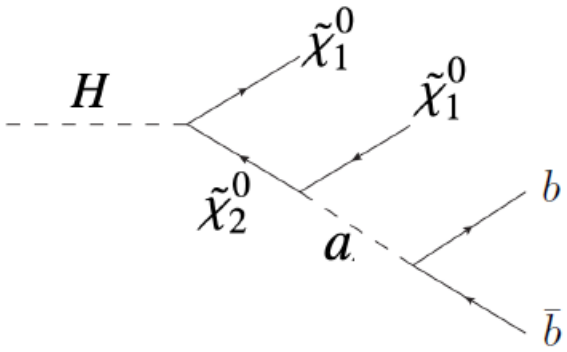
- Interpretation in 2HDM+S



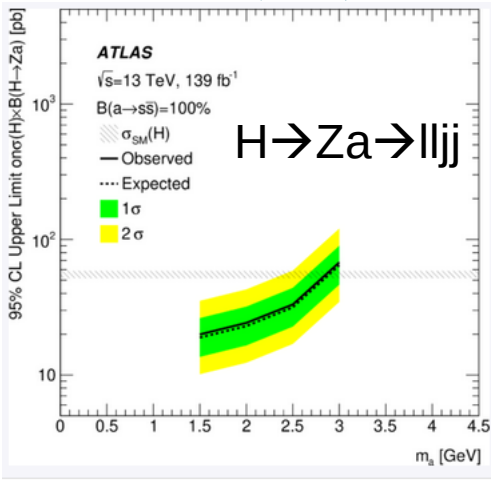


Brs based on https://arxiv.org/abs/1802.02156

h→bb+MET, h→Za→lljj



Phys. Rev. Lett. 125 (2020) 221802



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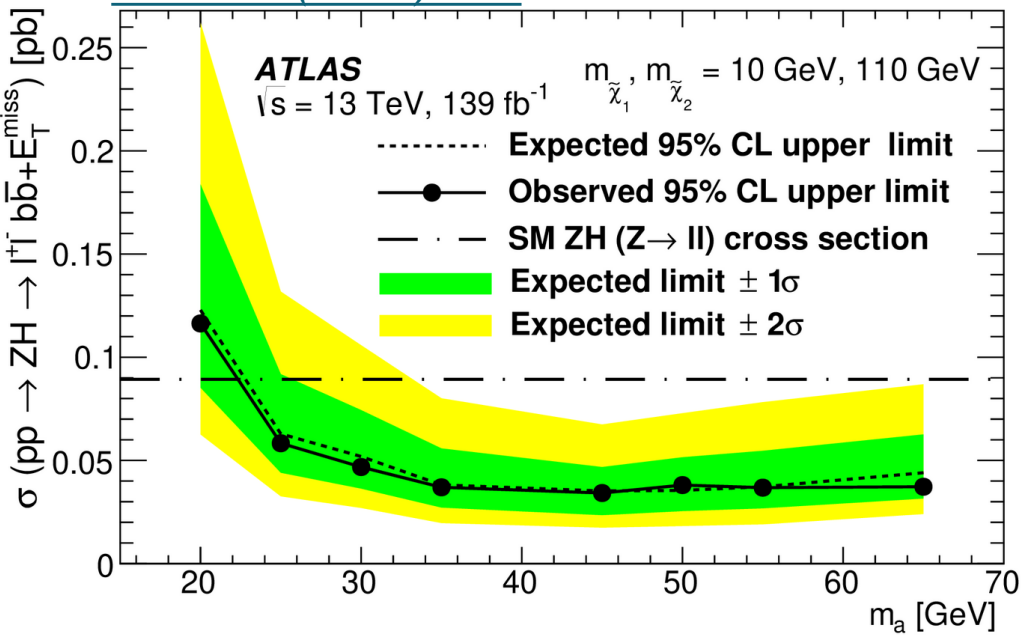
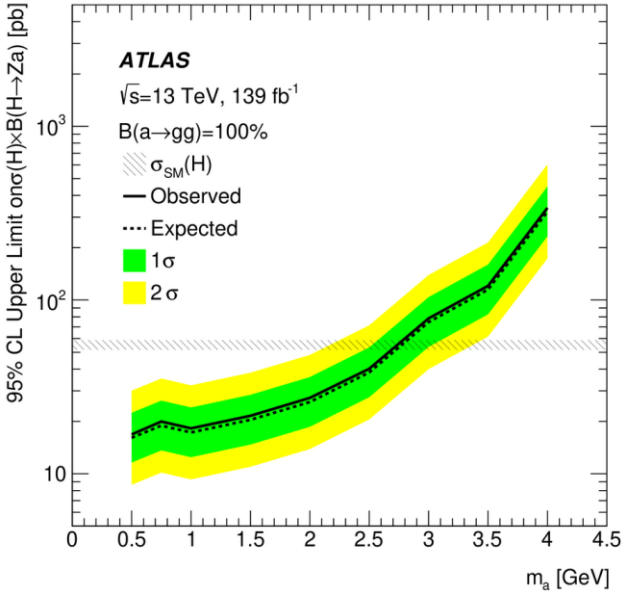
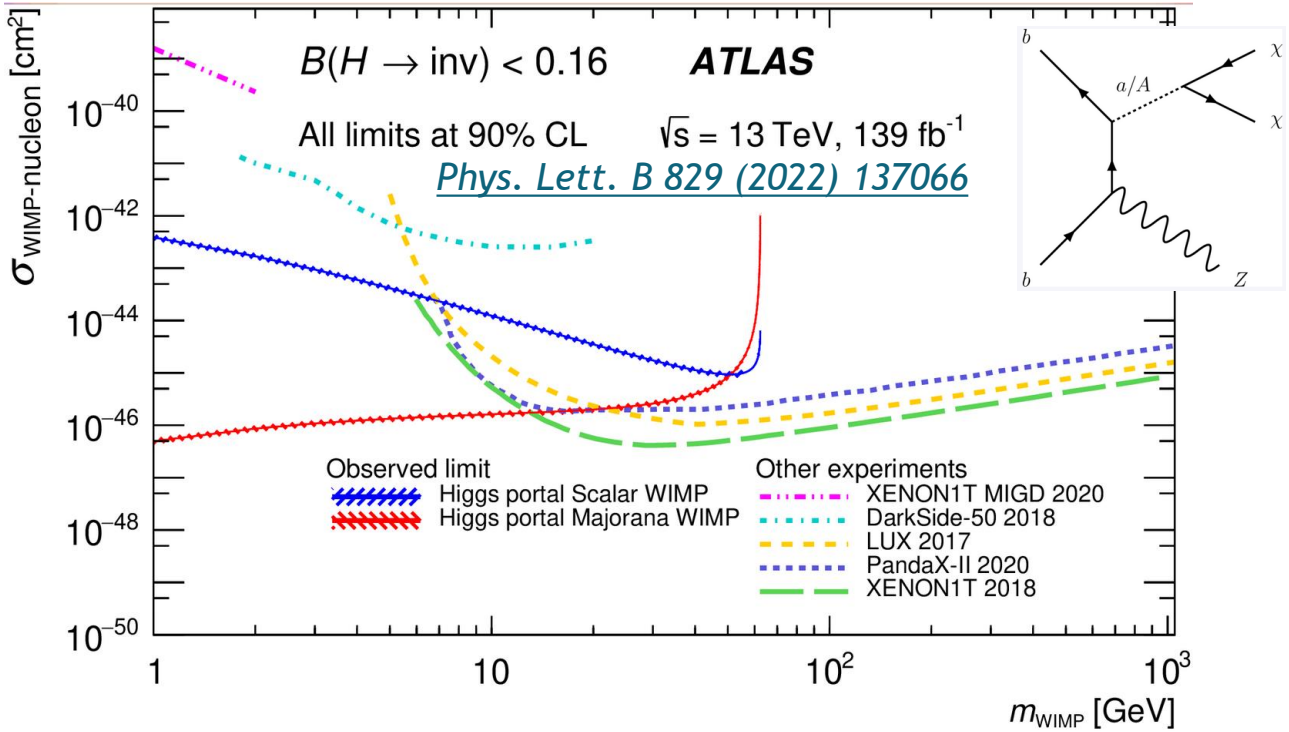
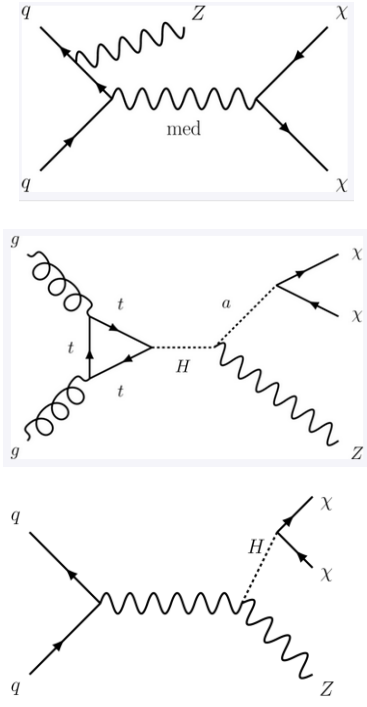




h(125) → invisible

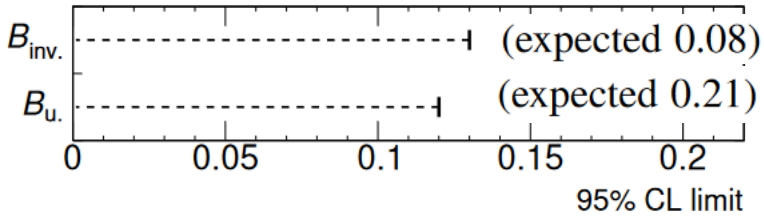




Phys. Rev. Lett. 122 (2019) 231801

Analysis	$\sqrt{s}$	Int. luminosity	Observed	Expected
Run 2 VBF	13 TeV	36.1 fb^{-1}	0.37	$0.28^{+0.11}_{-0.08}$
Run 2 Z(lep)H	13 TeV	36.1 fb^{-1}	0.67	$0.39^{+0.17}_{-0.11}$
Run 2 V(had)H	13 TeV	36.1 fb^{-1}	0.83	$0.58^{+0.23}_{-0.16}$
Run 2 Comb.	13 TeV	36.1 fb^{-1}	0.38	$0.21^{+0.08}_{-0.06}$
Run 1 Comb.	7, 8 TeV	4.7, 20.3 fb^{-1}	0.25	$0.27^{+0.10}_{-0.08}$
Run 1+2 Comb.	7, 8, 13 TeV	4.7, 20.3, 36.1 fb^{-1}	0.26	$0.17^{+0.07}_{-0.05}$

Nature (2022)



V H(→hh)

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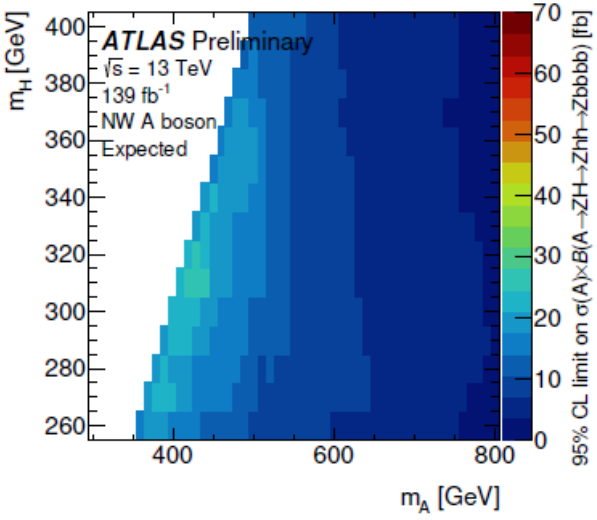
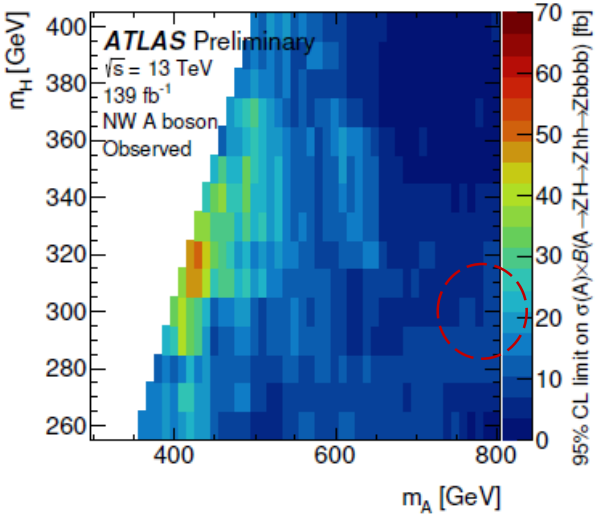
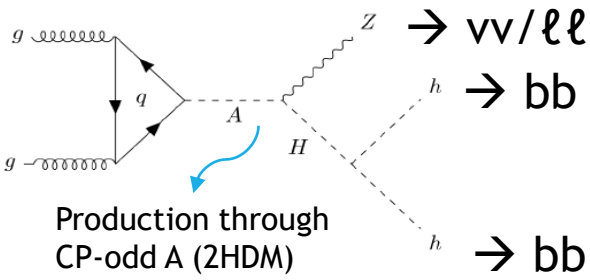
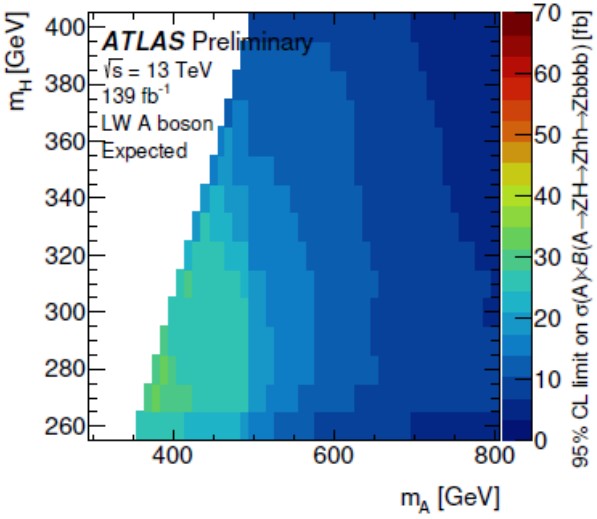


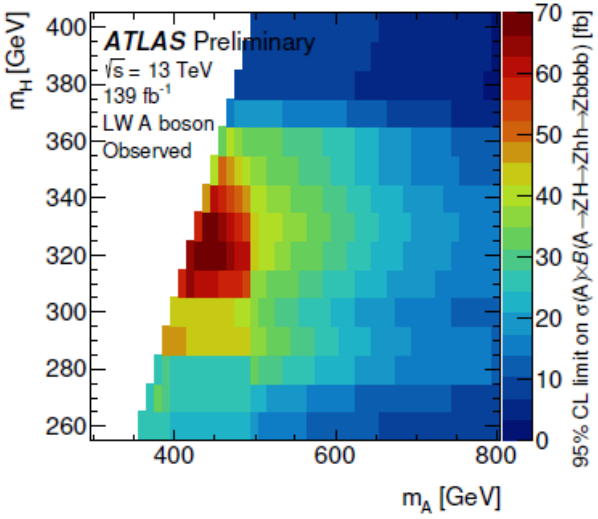
(a)



(b)

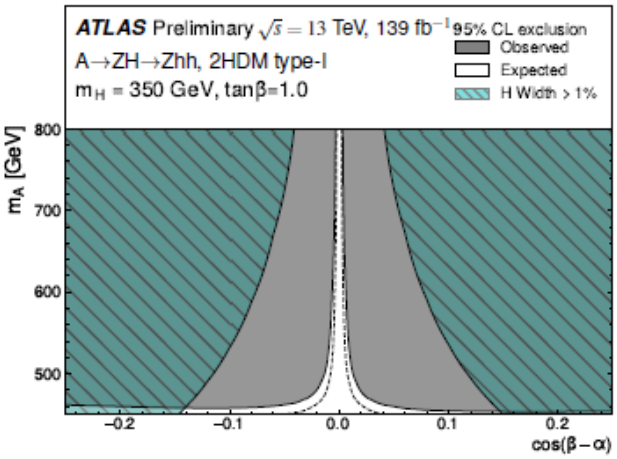


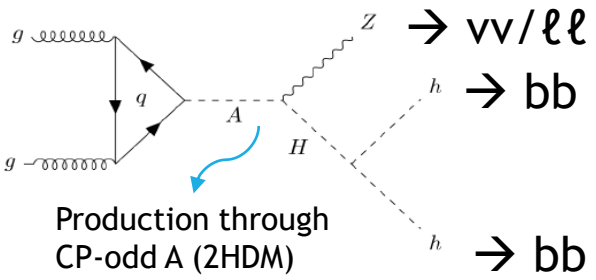




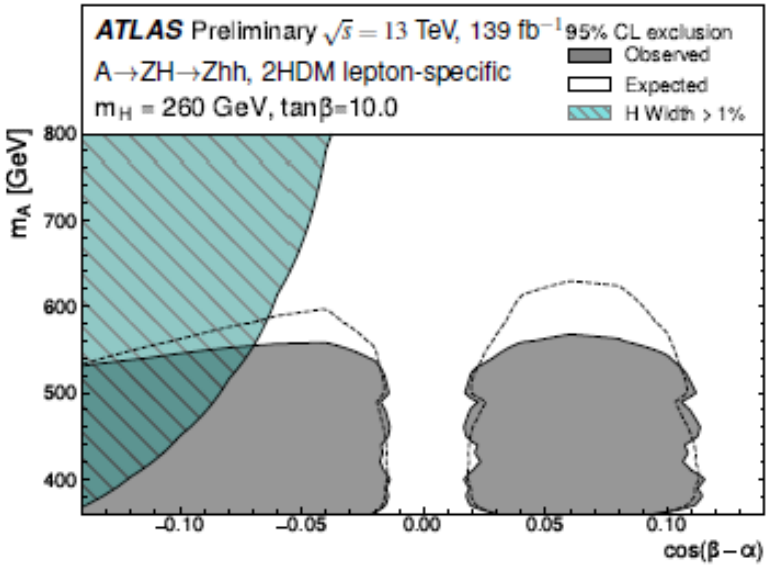
Finding a relatively high significance NW result at m_A. m_H = (1800, 300) GeV is not inconsistent with the excess at (m_A. m_H)= (420, 320) GeV in the LW scenario.

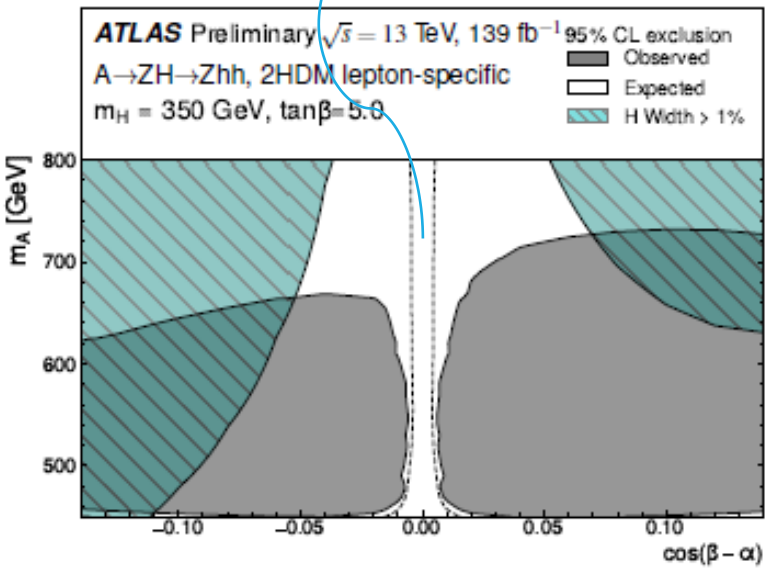
V H(→hh)



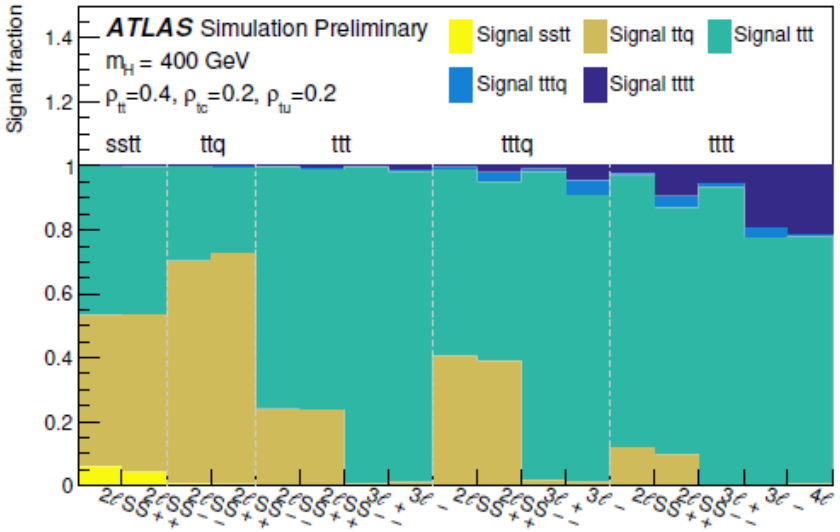


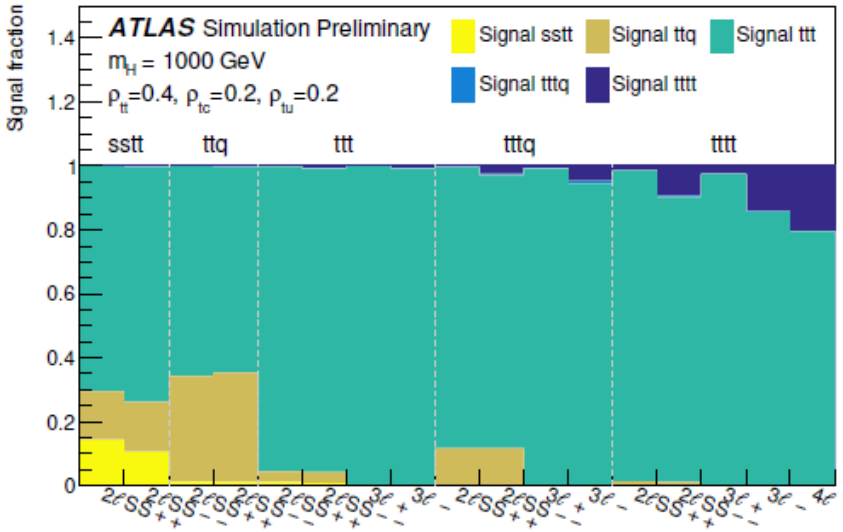
Hhh coupling vanishes

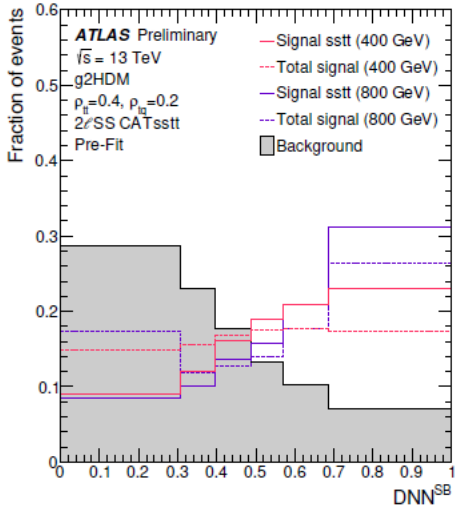


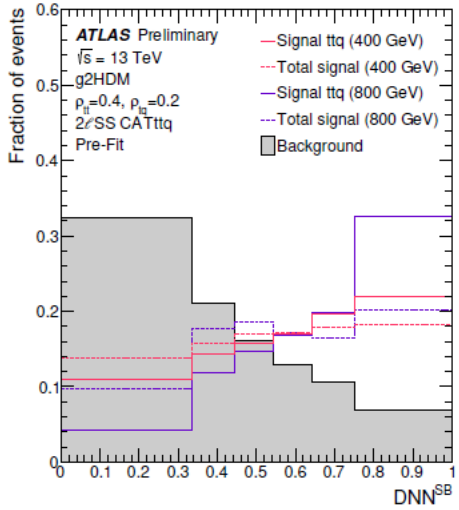


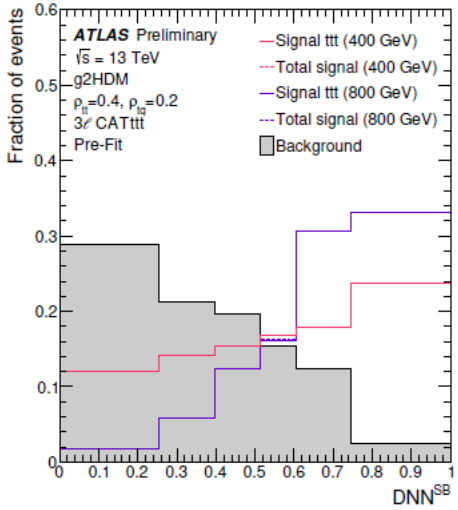
H → leptons + b-jets











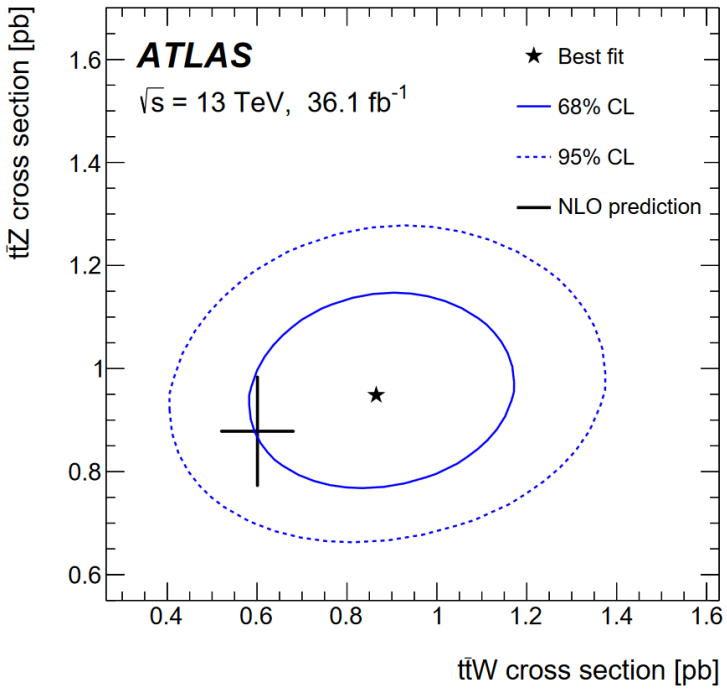
H → leptons + b-jets

- Benchmark couplings for optimization chosen so that they could be responsible for higher observed ttW & 4t yields
- Measured ttW normalization factor consistent with previous ttW & 4t measurements

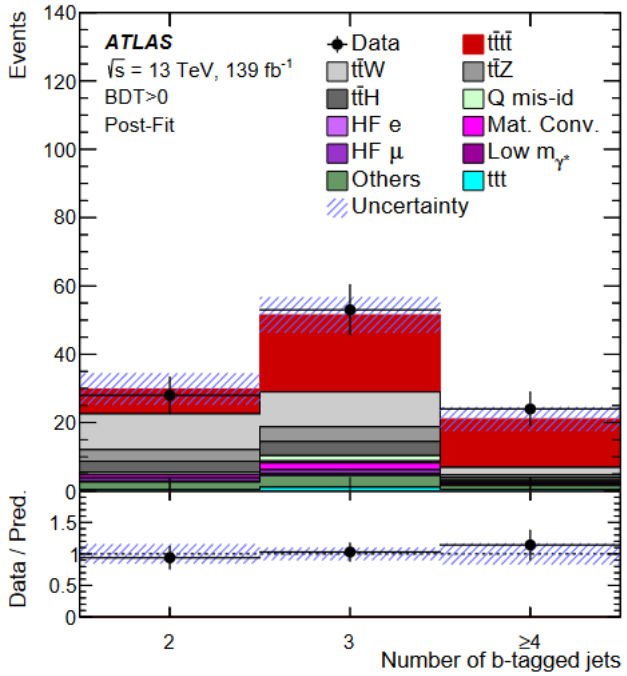
$$\rho_{tt} = 0.4 \text{ and } \rho_{tq} = 0.2$$

$$\hat{\lambda}_{t\bar{t}W} = 1.50 \pm 0.14$$

https://arxiv.org/pdf/1901.03584.pdf



https://arxiv.org/pdf/2007.14858.pdf



$$\mu = 2.0 \pm 0.4(\text{stat}) \,^{+0.7}_{-0.4}(\text{syst}) = 2.0 \,^{+0.8}_{-0.6}$$

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5(\text{stat}) \,^{+5}_{-4}(\text{syst}) \text{ fb} = 24 \,^{+7}_{-6} \text{ fb}.$$

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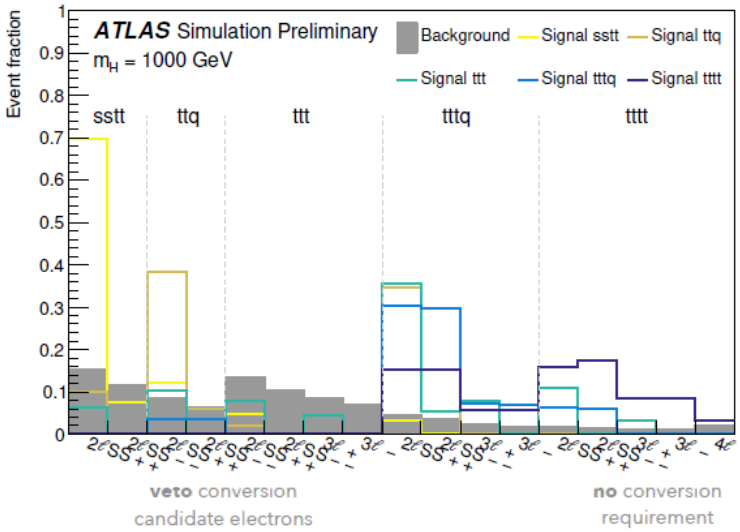
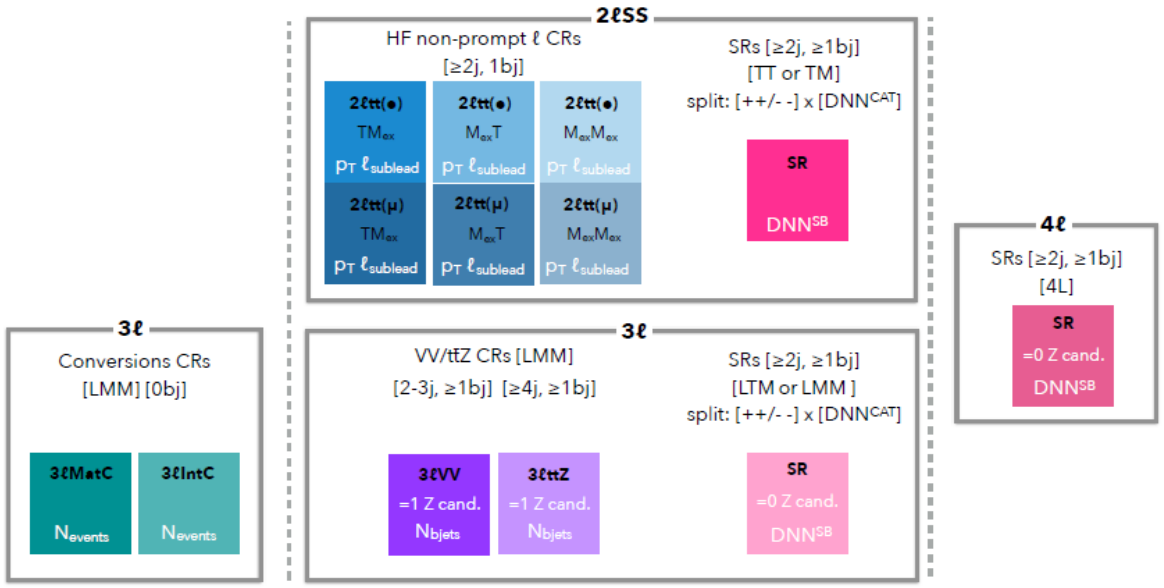
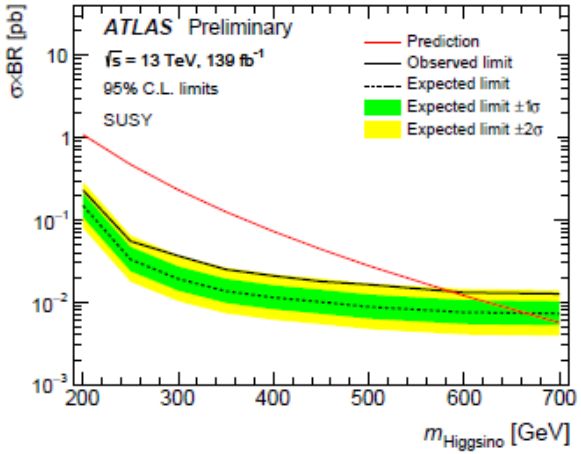
H → leptons + b-jets

- Limits set on H mass and couplings and R-parity violating SUSY models motivated by flavor anomalies and $(g-2)_\mu$



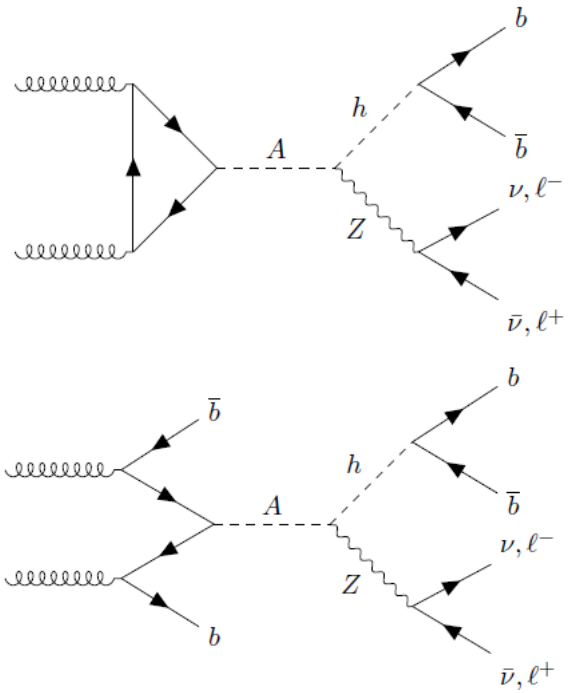




A → Z(ℓℓ/νν)h(bb)

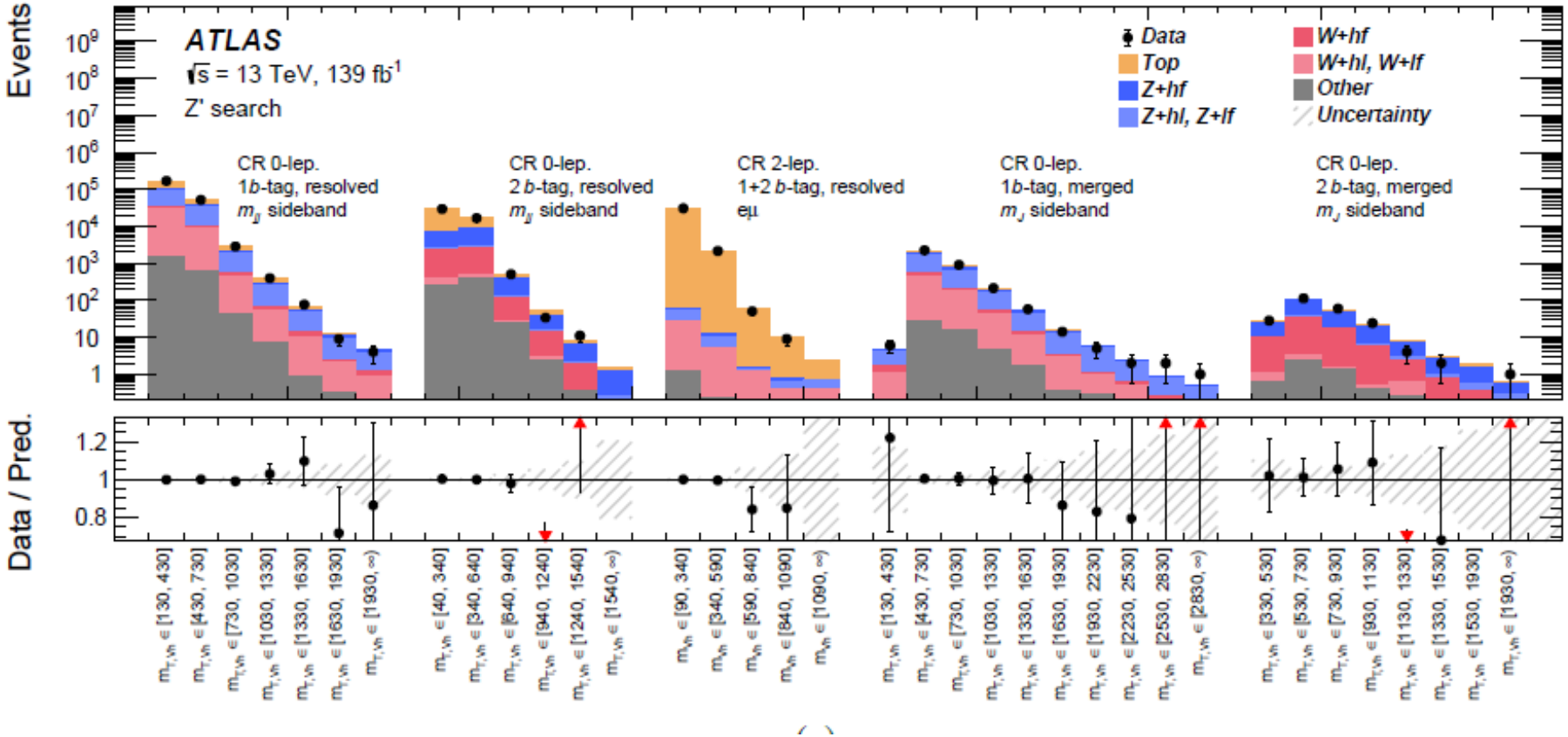
2207.00230

Variable	Resolved	Merged
	Common selection	
Number of jets	≥2 small-R jets (0, 2-lep.) 2 or 3 small-R jets (1-lep.)	≥1 large-R jet ≥ 1 VR track-jets (matched to leading large-R jet)‡‡
Leading jet p_{T} [GeV]	> 45	> 250
m_h [GeV]	110–140 (0,1-lep.), 100–145 (2-lep.)	75–145
	0-lepton selection	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 200
S_{T} [GeV]	> 150 (120*)	–
$\Delta\phi_{jj}$	$< 7\pi/9$	–
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 60	
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< \pi/2$	
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, h)$	$> 2\pi/3$	
$\min\left[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{small-}R\text{ jet})\right]$	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)	
$N_{\tau_{\mathrm{had}}}$	0 (≤ 1**)	
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\mathcal{S}$	$\begin{cases} > 9 & \text{if } m_{Vh} < 240\,\text{GeV}, \\ > 6.6 + 0.01 \cdot m_{Vh} & \text{if } 240\,\text{GeV} \le m_{Vh} < 700\,\text{GeV}, \\ > 13.6 & \text{if } m_{Vh} > 700\,\text{GeV}, \end{cases}$	
	1-lepton selection	
Leading lepton p_{T} [GeV]	> 27	> 27
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 40 (80†)	> 100
$p_{\mathrm{T},W}$ [GeV]	$> \max\left[150,\ 710 - (3.3 \cdot 10^5\,\text{GeV})/m_{Vh}\right]$	$> \max\left[150,\ 394 \cdot \log(m_{Vh}/(1\,\text{GeV})) - 2350\right]$
$m_{\mathrm{T},W}$ [GeV]	< 300	
$\Delta R(\ell, h)$	> 2.0	
	2-lepton selection	
Leading lepton p_{T} [GeV]	> 27	> 27
Subleading lepton p_{T} [GeV]	> 20	> 25
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [$\sqrt{\text{GeV}}$]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}/(1\,\text{GeV})$	
$p_{\mathrm{T},\ell\ell}$ [GeV]	$> 20 + 9 \cdot \sqrt{m_{Vh}/(1\,\text{GeV}) - 320}$††	
$m_{\ell\ell}$ [GeV]	$\in \left[\max\left[40,\ 87 - 0.030 \cdot m_{Vh}/(1\,\text{GeV})\right], 97 + 0.013 \cdot m_{Vh}/(1\,\text{GeV})\right]$	



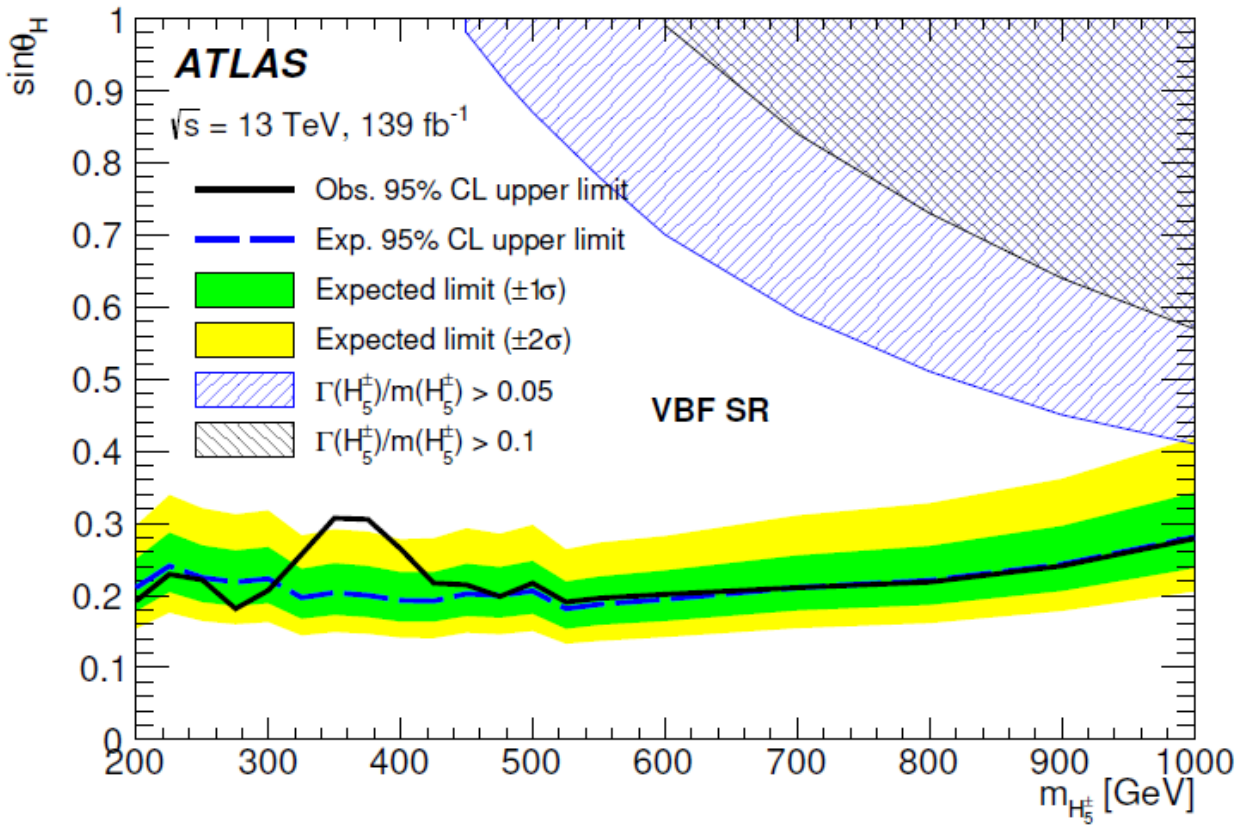
A → Z(ℓℓ/νν)h(bb)

2207.00230

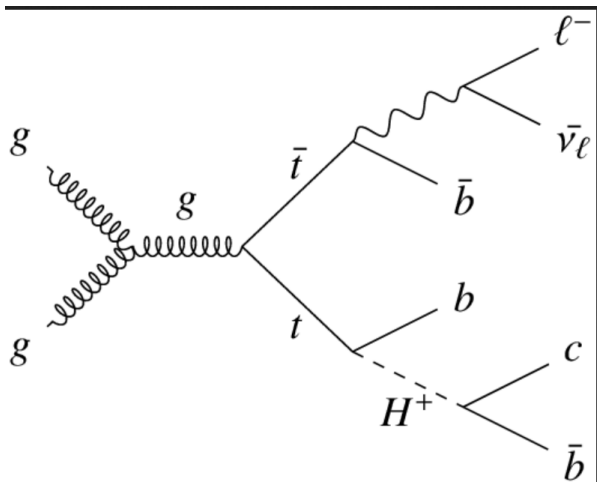


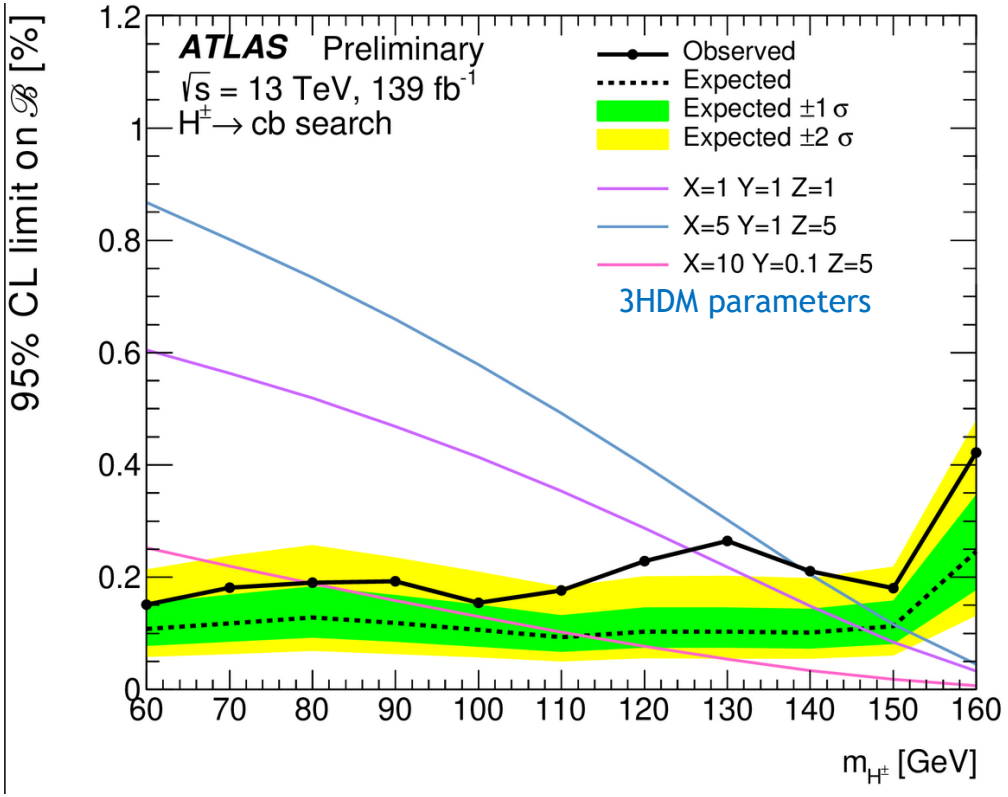
$H^{\pm} \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$

arXiv:2207.03925



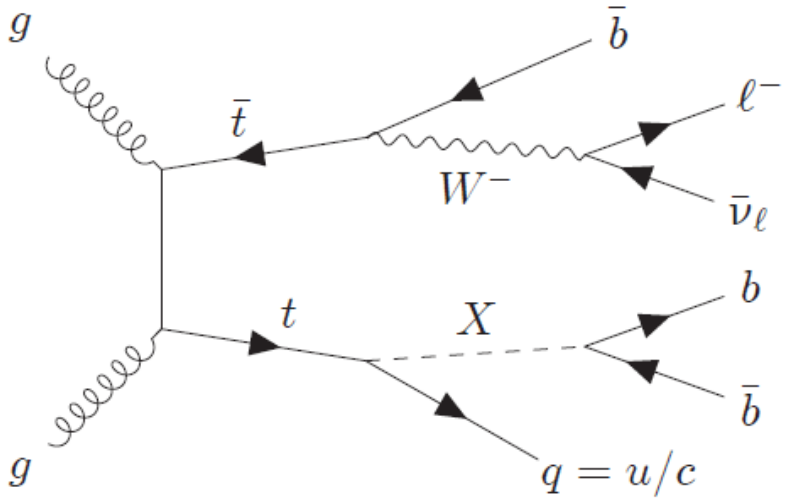
$t \rightarrow bH^{+}(\rightarrow cb)$





FCNC t → qX(→bb)

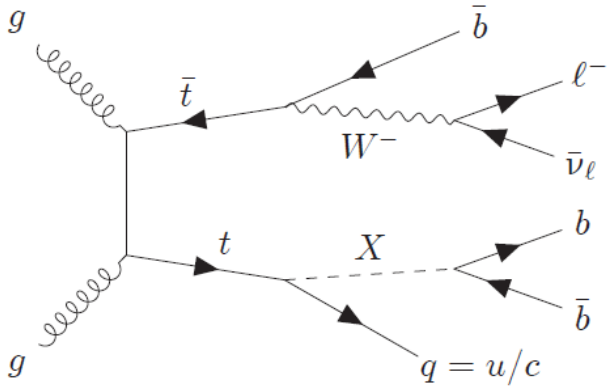
- BSM Higgs called "**flavon**" with flavor charge inducing FCNC top decays
- Dominant decay <200 GeV: **X→bb**
- Events separated into signal and control regions based on number of (b)-jets
  - SR: **4j3b, 5j3b, 6j3b**
  - CR: 4j4b, 5j ≥ 4b, 6j ≥ 4b

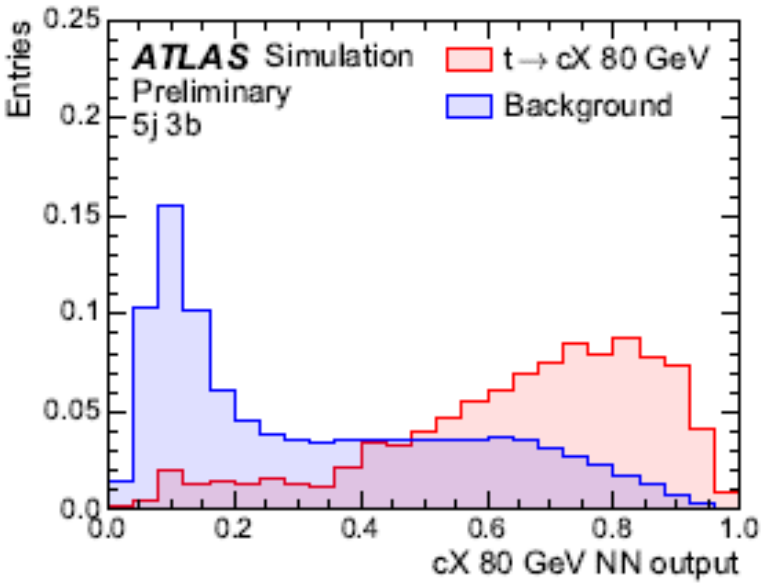


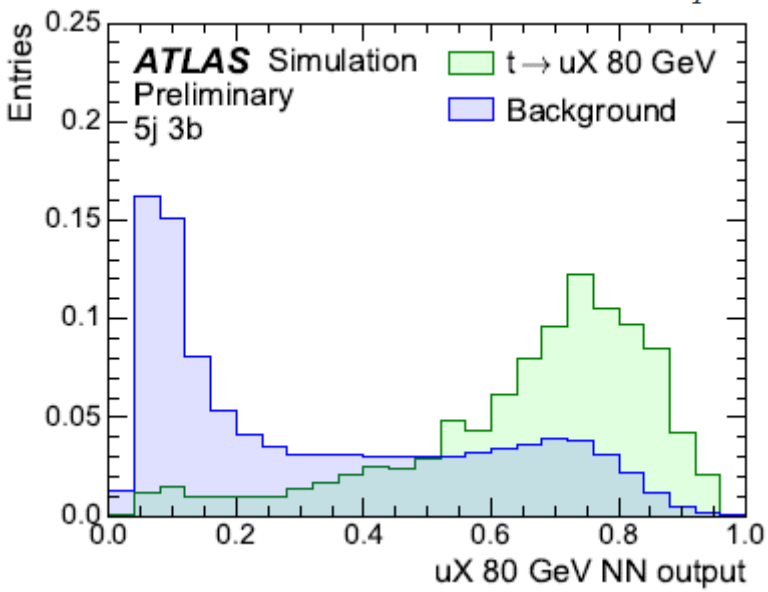
FCNC t → qX(→bb)

- Discriminating variable based on NN defined in each SR for each signal mass and separately for t→uX and t→cX
  - Simultaneous fit over SRs/CRs in binned NN discriminants

SR: 4j3b, 5j3b, 6j3b



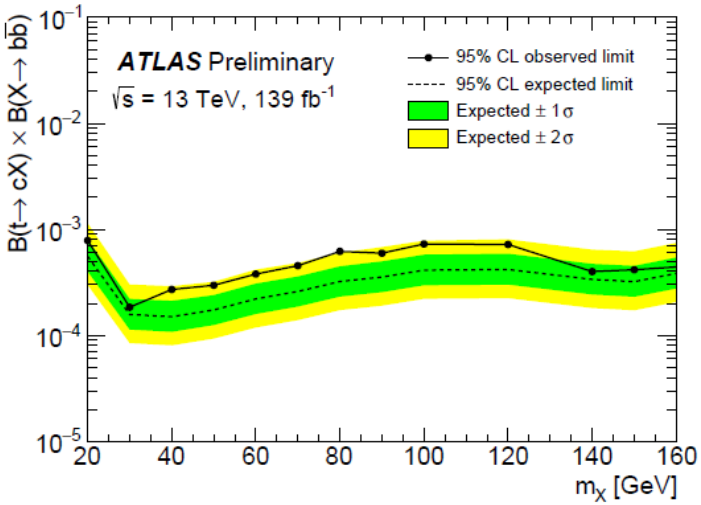


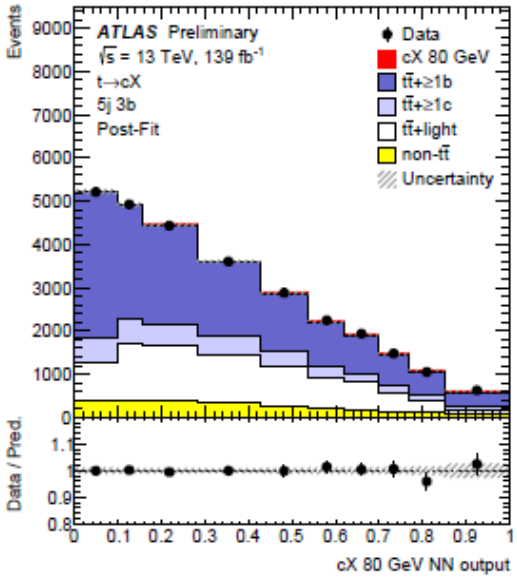


- Additional jets from PS Simulation corrected to the data for W→cb and each jet multiplicity (Nj+2b+1bl) and as a function of HT

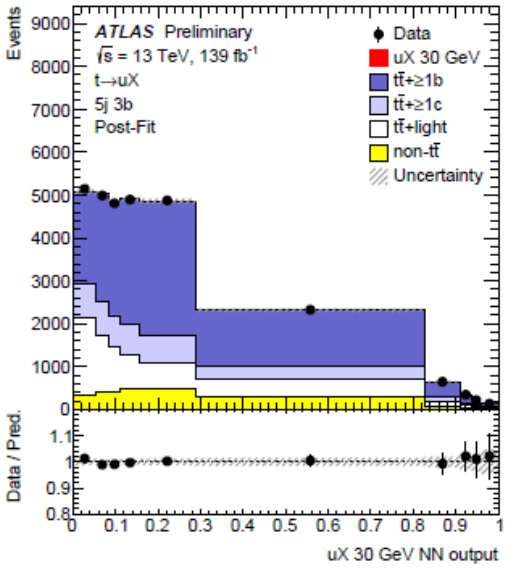
FCNC t → qX(→bb)

- Discriminating variable based on NN defined in each SR for each signal mass and separately for t→uX and t→cX
  - Simultaneous fit over SRs/CRs in binned NN discriminants
- **No significant excess observed**

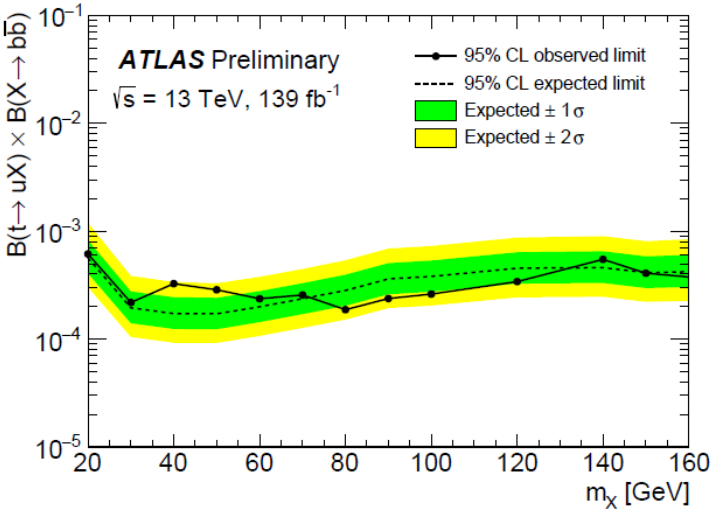




(f) $t \to cX$, 5j 3b

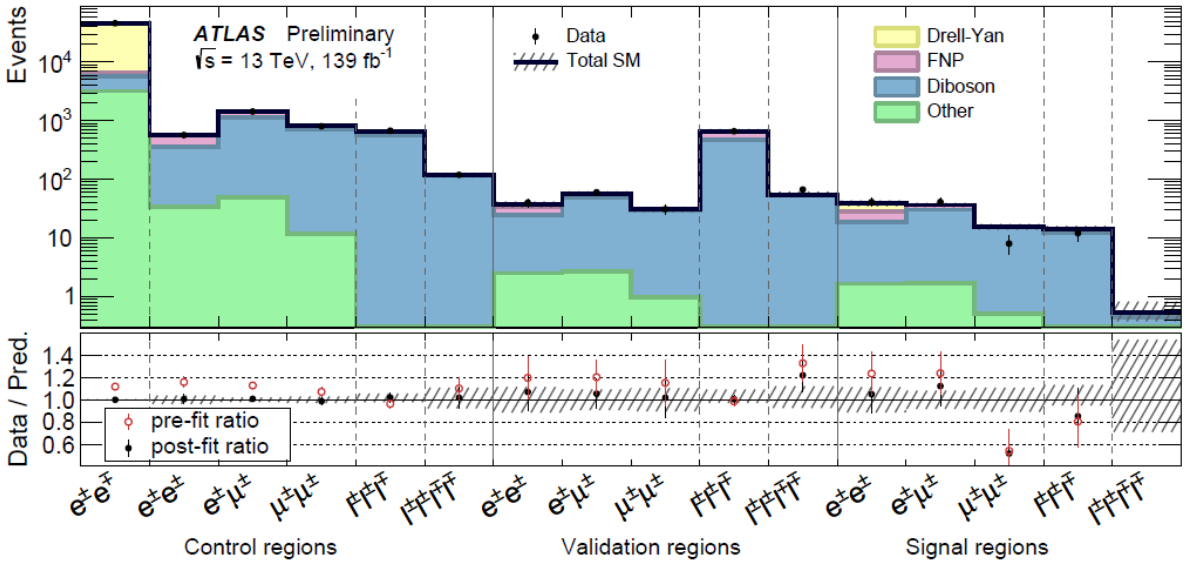


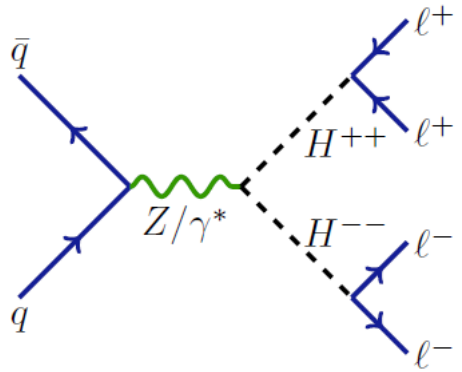
(b) $t \to uX$, 5j 3b



$H^{++}H^{--} \rightarrow 4\ell$

- Appear in e.g. left-right symmetric models, Georgi-Machacek model…
  - Depending on the parameters, can decay to WW or $\ell\ell$ - here consider $\ell\ell$ case
  - **LFV decays are allowed: $H^{\pm\pm} \rightarrow \ell\ell'$**
- **Couplings assumed to be the same for all flavor combinations** (not proportional to mass)
- Search for **SS lepton pairs in the final state**





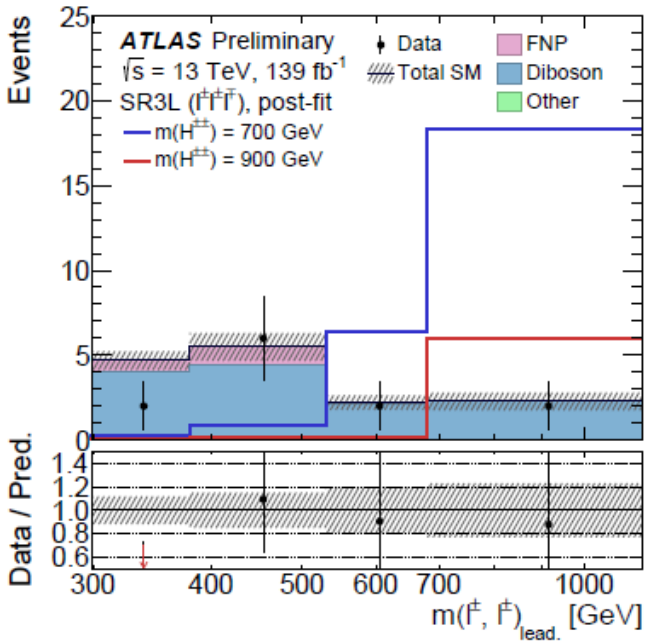
signal regions

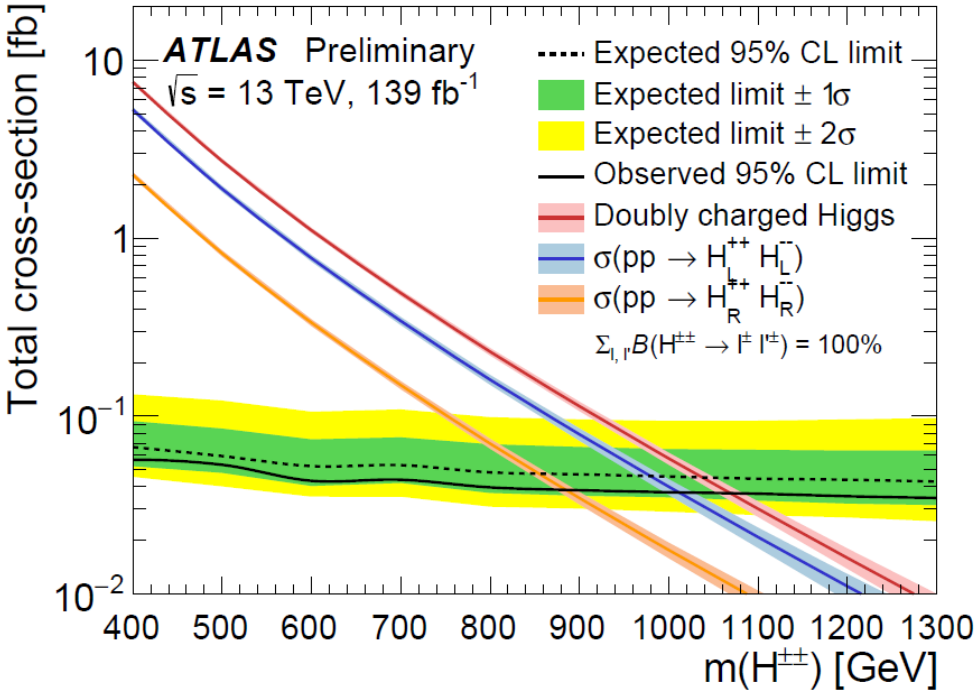
SR2L	SR3L	SR4L
$e^\pm e^\pm$ $e^\pm \mu^\pm$ $\mu^\pm \mu^\pm$	$\ell^\pm \ell^\pm \ell^\mp$	$\ell^+ \ell^+ \ell^- \ell^-$

veto events with b-jets

$H^{++}H^{--} \rightarrow 4\ell$

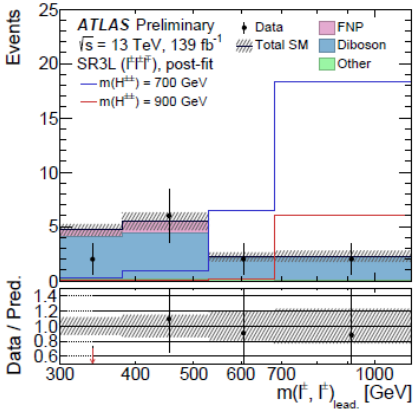
- Main discriminant: **invariant mass of the 2 leading SS leptons**
- Diboson/DY background estimated from MC scaled to the data
- Simultaneous fit over CRs & SR in the invariant mass (only 1 bin in 4ℓ case)
- **No significant excess observed**
  - 4ℓ channel most sensitive, drives the combination
  - Analysis statistically dominated

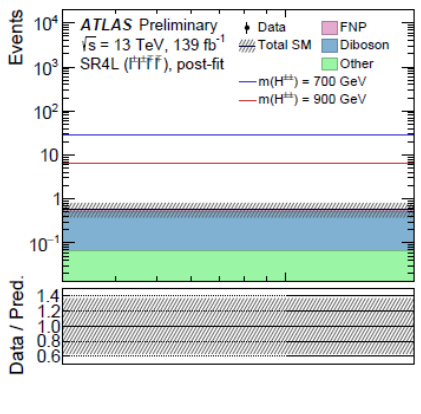


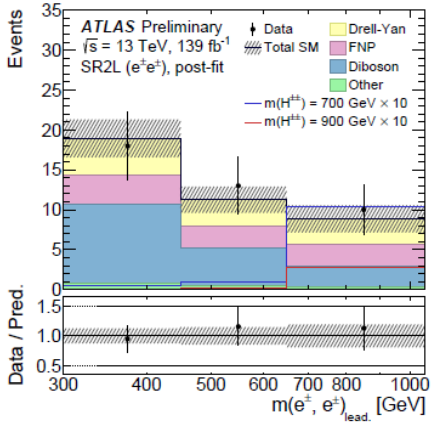


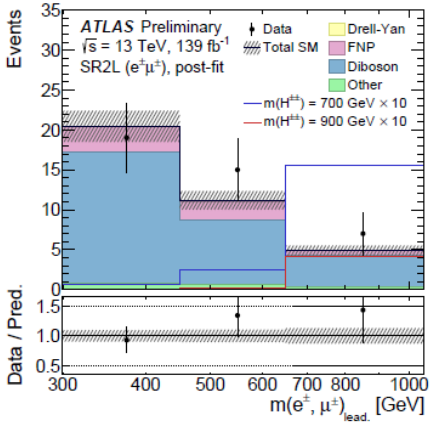
$H^{++}H^{--} \rightarrow 4\ell$

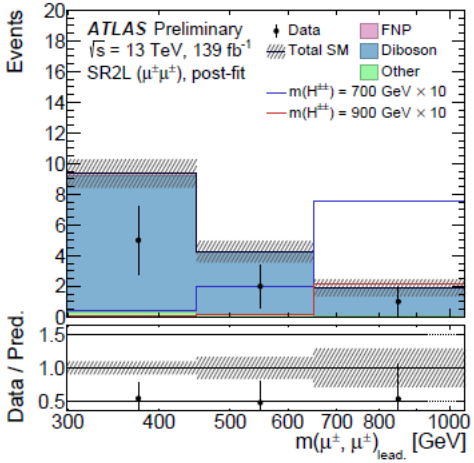
- Charge misID data driven







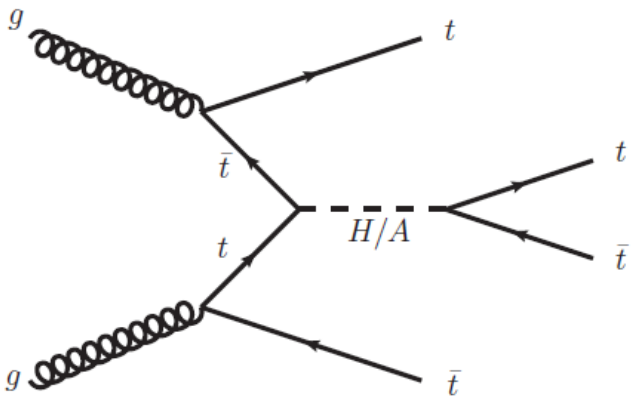




	SR2L $e^{\pm}e^{\pm}$	SR2L $e^{\pm}\mu^{\pm}$	SR2L $\mu^{\pm}\mu^{\pm}$	SR3L $\ell^{\pm}\ell^{\pm}\ell^{\mp}$	SR4L $\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$
Observed events	41	41	8	12	0
Total background	40 ± 5	37.1 ± 3.1	14.8 ± 1.6	14.6 ± 1.3	0.62 ± 0.23
Diboson	21 ± 4	30.5 ± 3.3	14.2 ± 1.6	12.7 ± 1.2	0.44 ± 0.17
FNP lep.	7.8 ± 1.1	4.8 ± 1.1	0.158 ± 0.034	1.2 ± 0.5	0.11 ± 0.05
Drell–Yan	9.7 ± 3.5	0.15 ± 0.07	–	–	–
Other	1.56 ± 0.29	1.63 ± 0.25	0.52 ± 0.05	0.58 ± 0.06	0.067 ± 0.025

tt H/A→ 4t

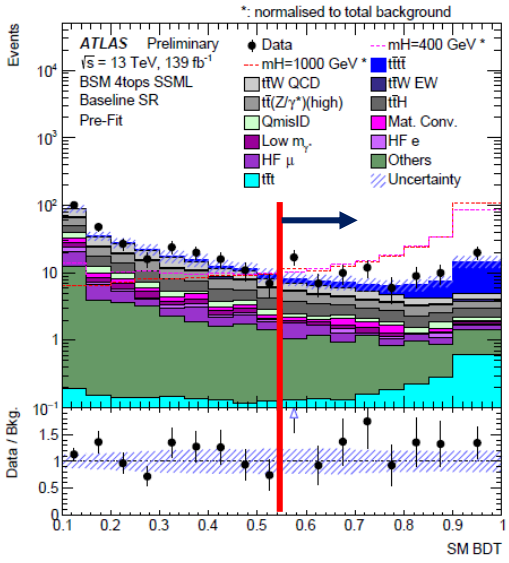
- Look for tt associated H/A (0.4 – 1 TeV) production
  - In inclusive gg→H/A resonant tt peak diluted due to negative interference effects with SM gg→tt
- Dominant decay (above 2t threshold): **H/A→ tt**
- Select events with
  - **2 SS leptons or ≥3 leptons**
  - **≥6j (≥2b)**
  - **H_T>500 GeV** (scalar sum of p_T of jets & leptons)

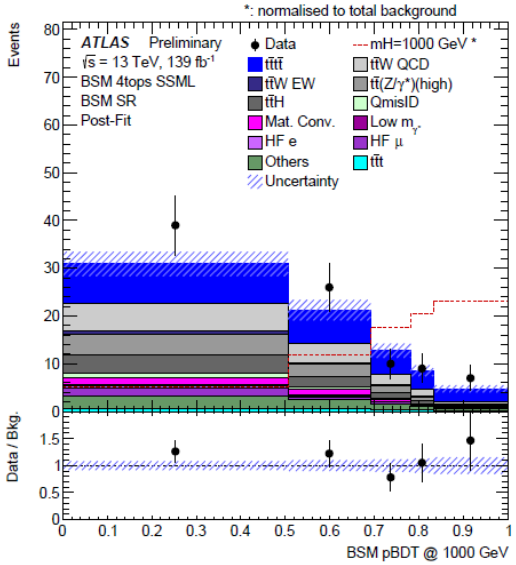


Region	Channel	N_j	N_b	Other selection cuts	Fitted variable
BSM SR	SS+3L	≥ 6	≥ 2	H_T > 500 GeV, SM BDT ≥ 0.55	BSM pBDT

tt H/A→ 4t

- Train 2 types of BDTs, sequentially:
  - ➢ **"SM BDT"** to **separate SM 4t events from other SM backgrounds**
    - Signal has similar kinematics to SM 4t
  - ➢ **"BSM pBDT"** (mass-parametrized) to **separate signal from all backgrounds**
    - SM BDT used as input

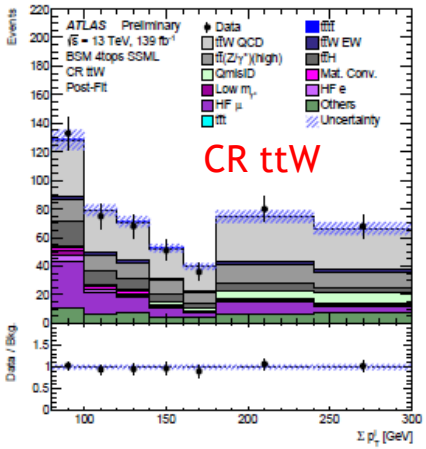


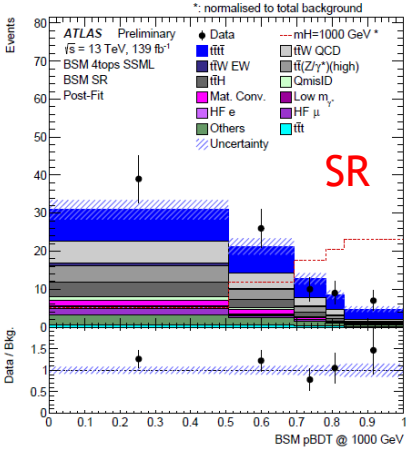


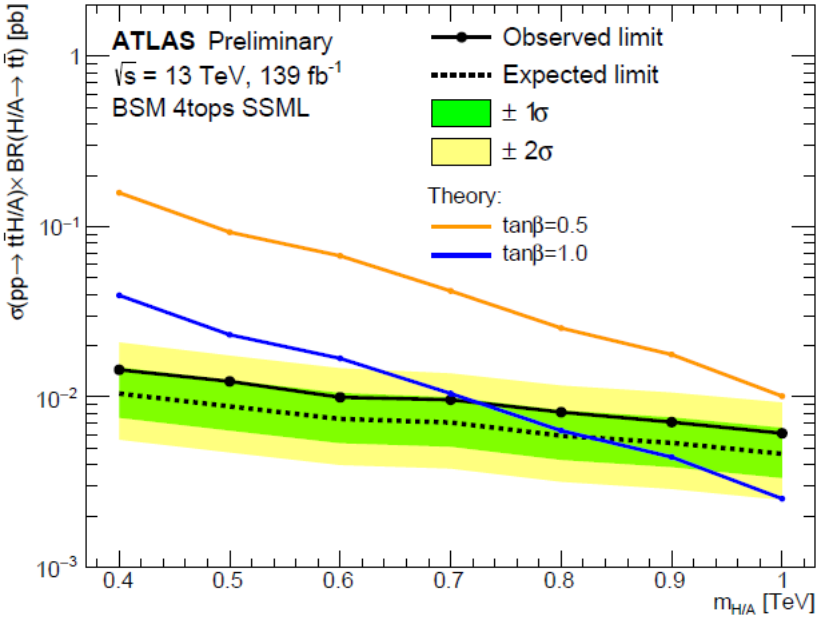
Region	Channel	N_j	N_b	Other selection cuts	Fitted variable
BSM SR	SS+3L	≥ 6	≥ 2	H_T > 500 GeV, SM BDT ≥ 0.55	BSM pBDT

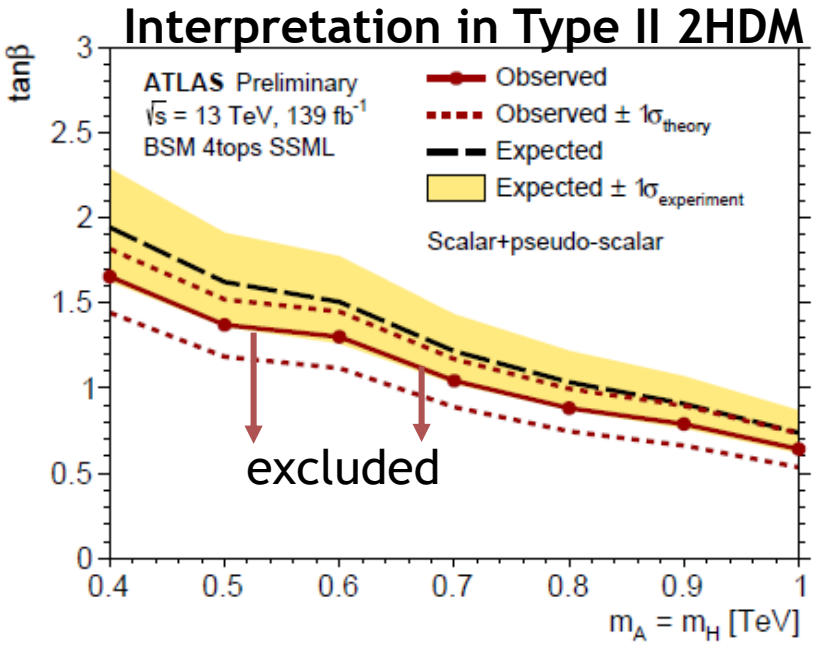
ttH/A→ 4t

- Simultaneous binned likelihood fit over various discriminating variables in CRs & SR
- **No significant deviation from SM prediction observed**









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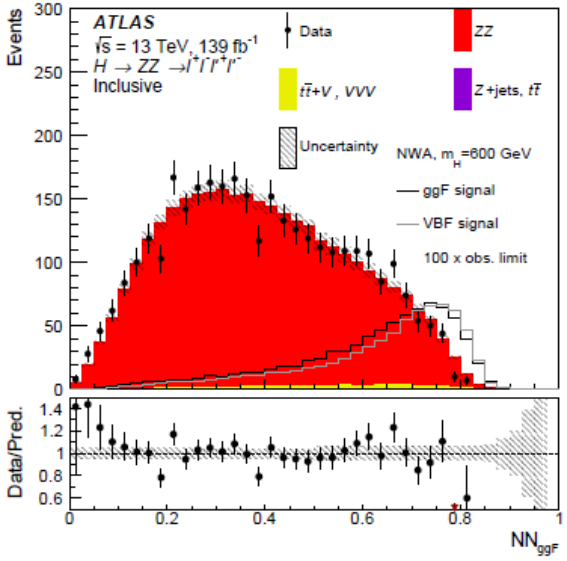
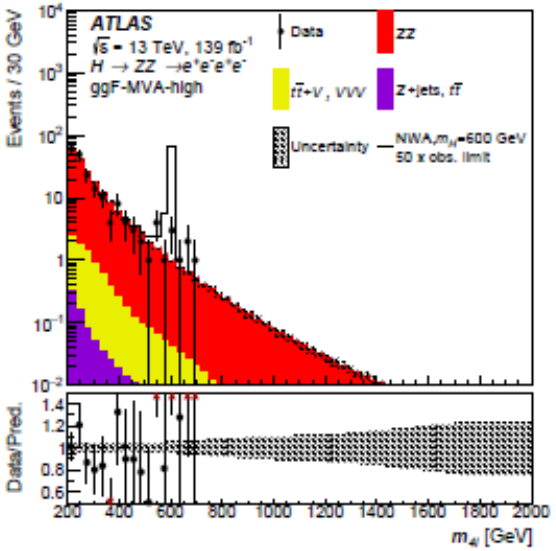
H → ZZ → 4ℓ/2ℓ2ν

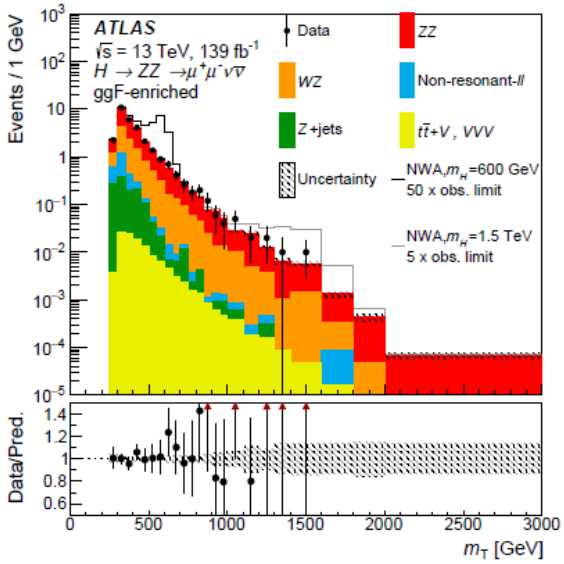
- Look for an excess in the 4ℓ invariant mass or 2ℓ2ν transverse mass
  - ggF & VBF categories considered separately for model-independent results

$$m_{\mathrm{T}} \equiv \sqrt{\left[\sqrt{m_{\mathrm{Z}}^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_{\mathrm{Z}}^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

- Consider narrow width (NWA) and large (1%-15%) width (LWA) signals
  - Interference between heavy H, SM H and ZZ continuum taken into account in the LWA case – can modify the Xsec by O(10%)
- Deep Neural networks (DNN) used to improve the sensitivity in the 4ℓ channel







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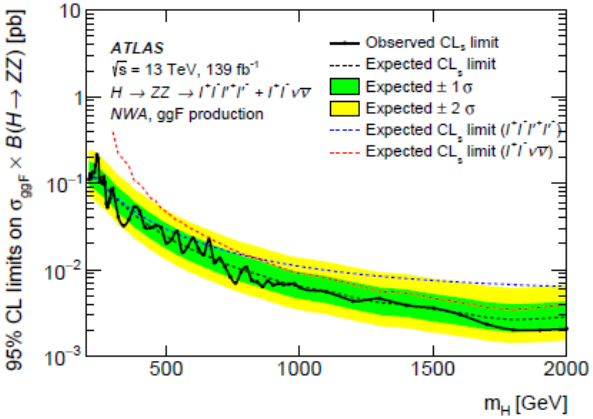
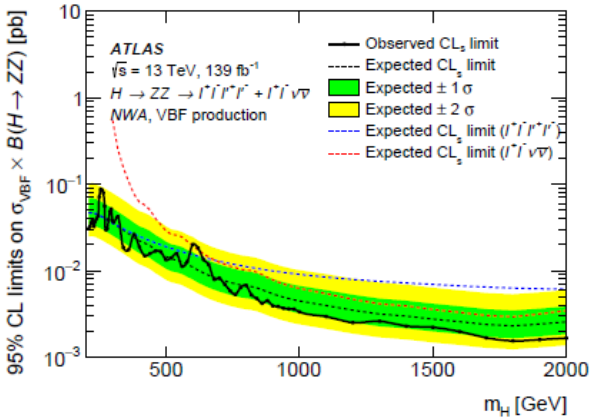
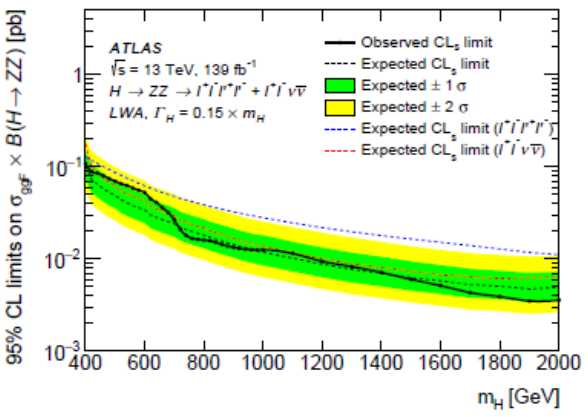
H → ZZ → 4ℓ/2ℓ2ν

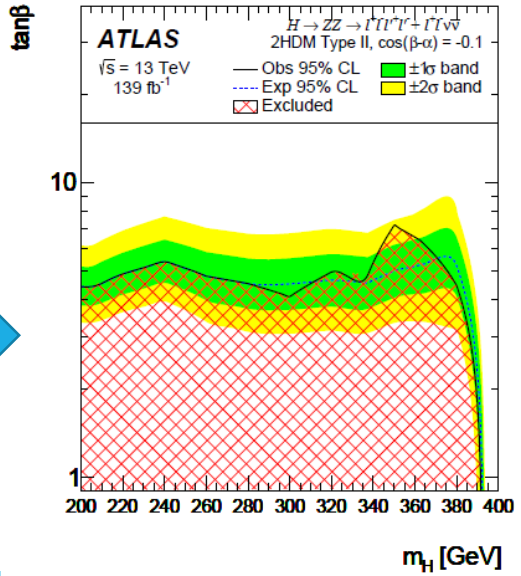
- No significant excess observed







- Interpreted in the Type I and Type II 2HDM parameter space
- The excluded region in Type II >60% larger with respect to the previous publication



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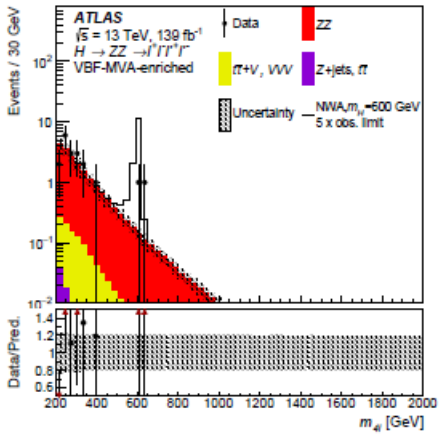
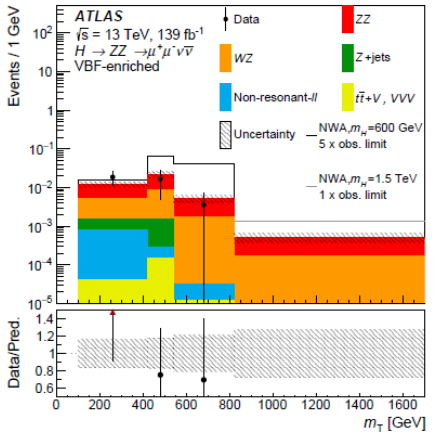
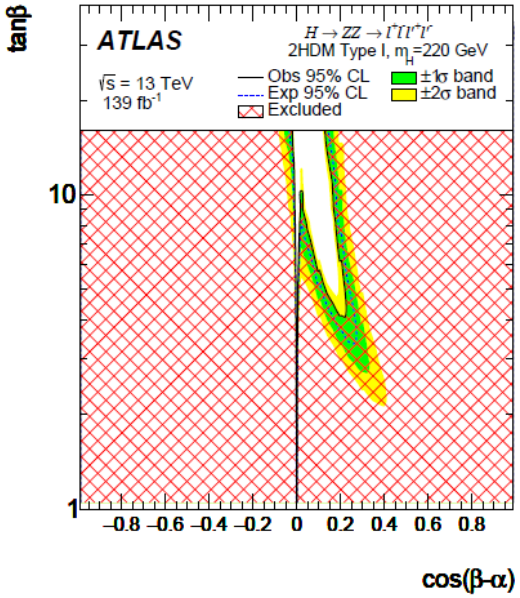
H → ZZ → 4ℓ/2ℓ2ν

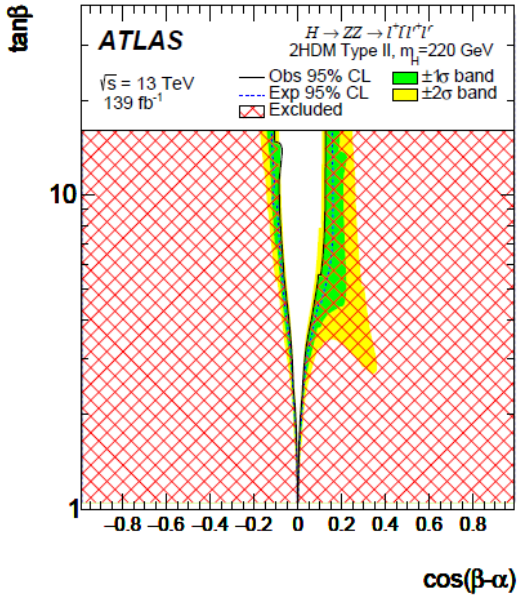
- SM ZZ normalization derived in a likelihood fit to the data
- $m_{4\ell}$ parametrized by analytic functions – combined unbinned ML fit
- Binned m_T templates based on simulation are fit to the data





- 2HDM: Coupling of the heavy H to vector bosons is proportional to cos(β-α)





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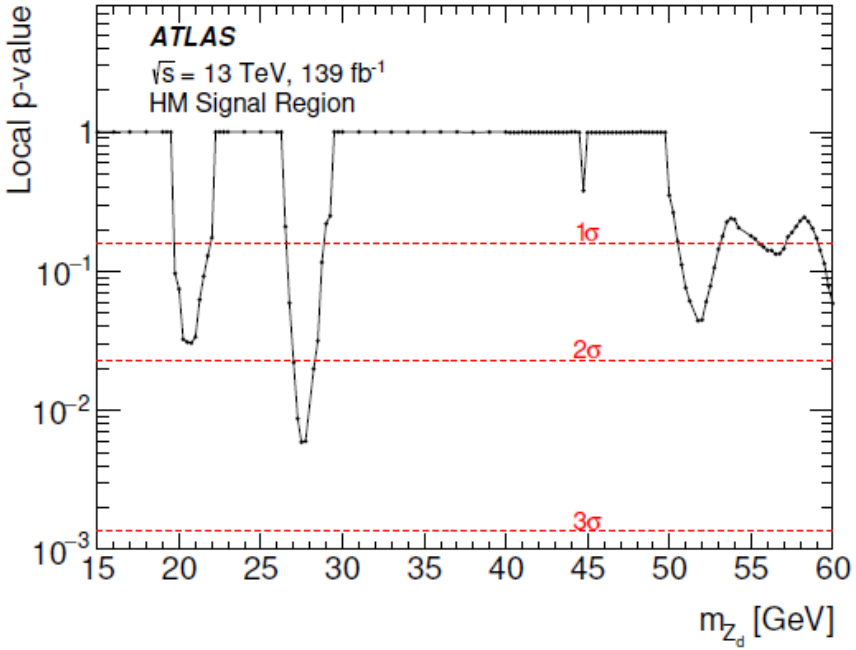
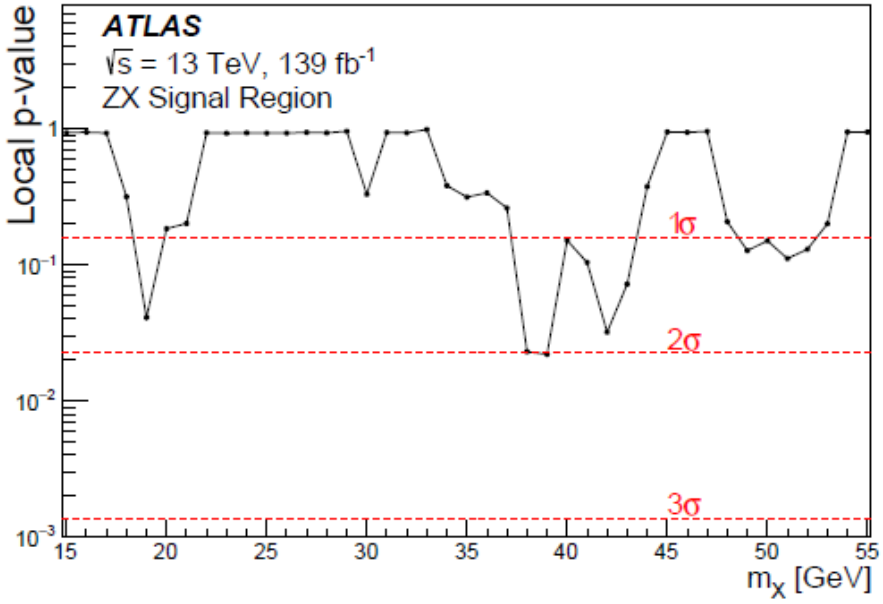
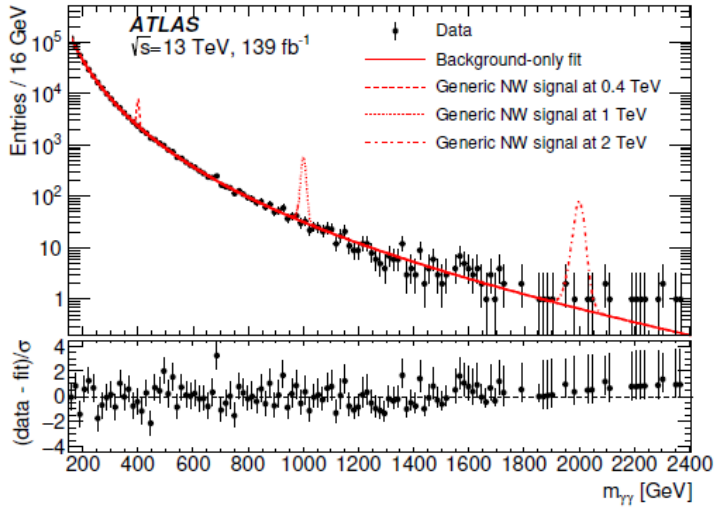
H(125) → ZX/XX→4ℓ

- Dominant bkg from simulation: H→ZZ* & ZZ*
- High-mass 4l: Largest excess found at 28 GeV with the local significance of 2.6σ





H → γγ >65 GeV



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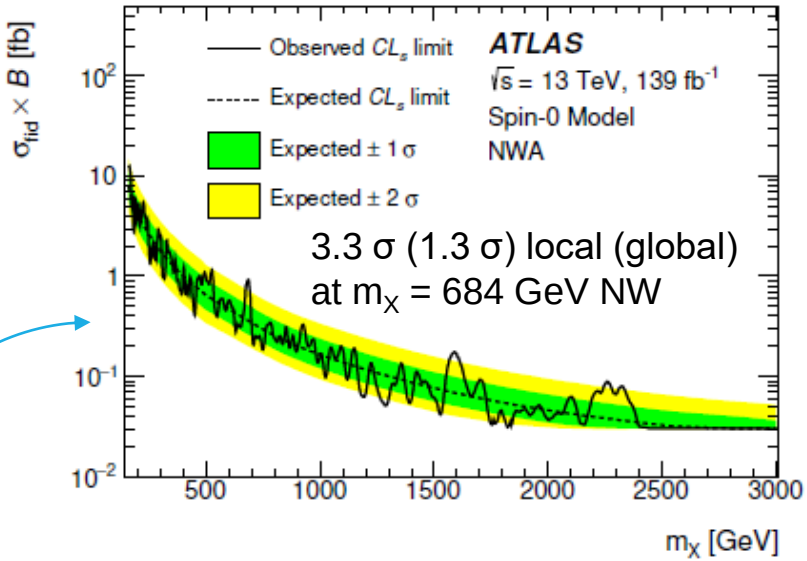

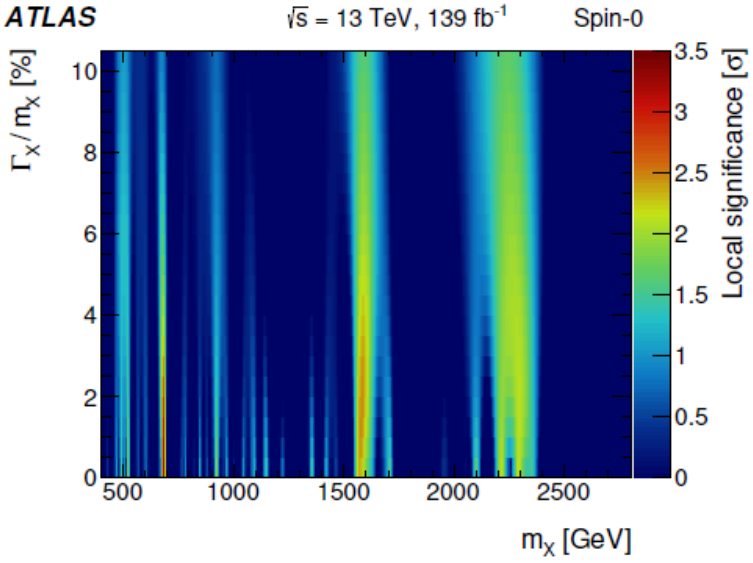

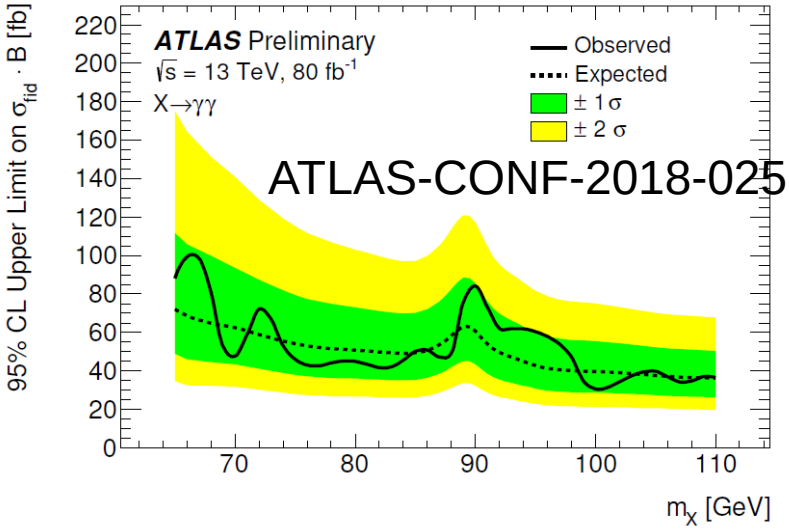

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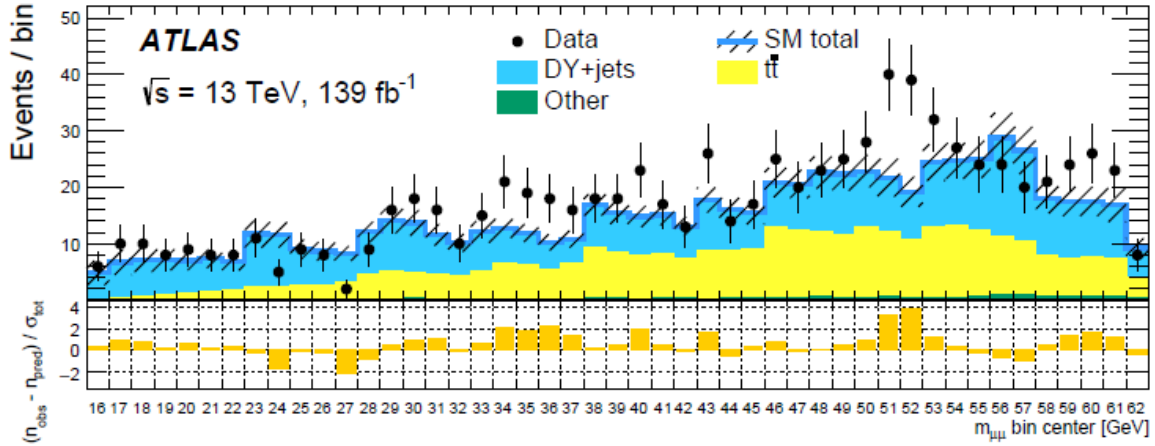
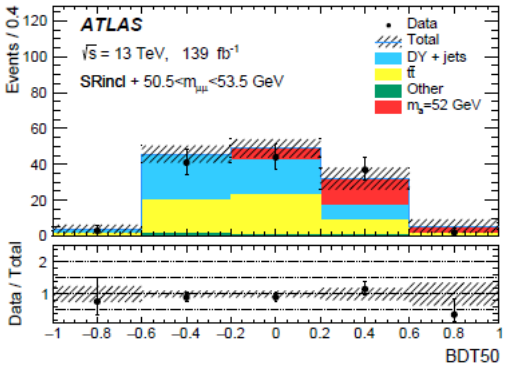
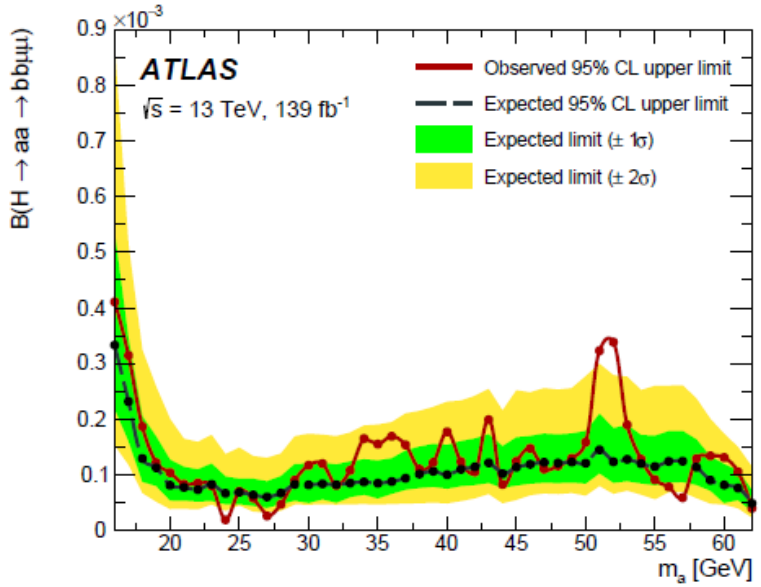
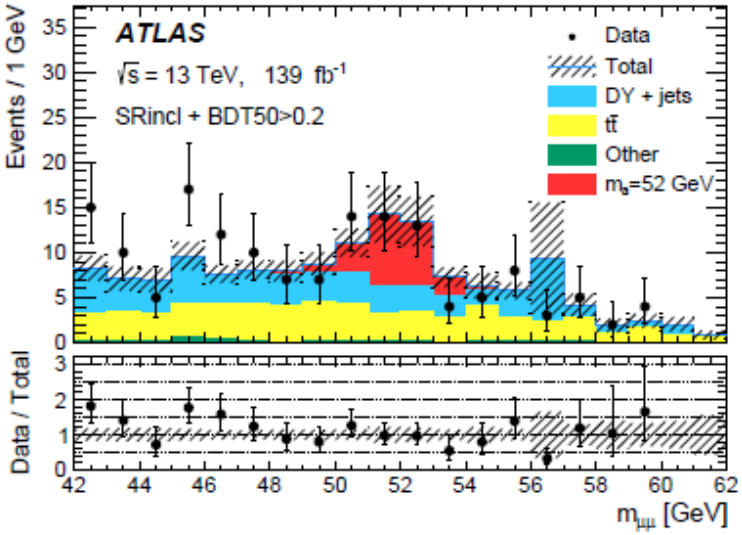
H→aa→bbμμ

- Largest excess observed at $m_{\mu\mu}$=52 GeV corresponding to the local (global) significance of 3.3σ (1.7σ)









$H^{\pm} \rightarrow W^{\pm}A(\rightarrow \mu\mu)$