Searches for resonances decaying to pairs of bosons in ATLAS

Higgs 2023, Beijing

Olof Lundberg on behalf of the ATLAS collaboration

Introduction

Several scenarios for physics beyond the Standard Model include new particles decaying into pairs of bosons

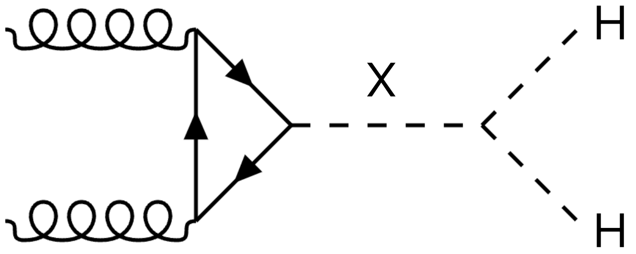
This can be due to eg. new Gauge symmetries or extensions to the Higgs sector, like the 2-Higgs Doublet Model, Supersymmetry or models introducing spin-2 gravitons.

The SM Higgs boson (in this talk denoted H) provides one (but not the only) promising potential to look for such new resonances

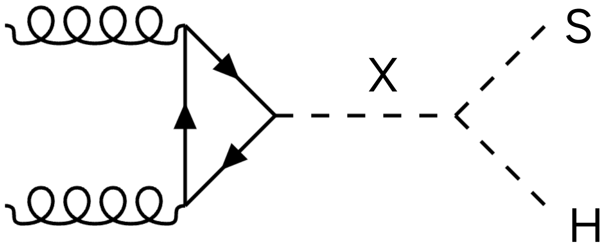
This talk looks at a set of recent searches for such resonances using the **full ATLAS Run 2 data**

A common challenge: The presence of very boosted particles in the final states – often only in parts of the searched signal parameter space

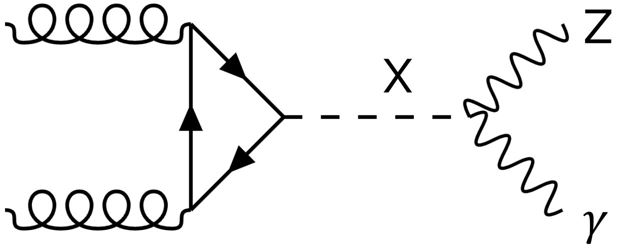
Part 1: X → HH



Part 2: X → SH



Part 3: X → Zγ



See Hartmann & Roguljic on 4b background estimates

Phys. Rev. D 105 (2022) 092002

See also VBF-targeting paper: JHEP 07 (2020) 108

Di-Higgs: $X \to HH \to b\bar{b}b\bar{b}$

2 channels spanning 251 < m_X < 5000 GeV:

- **Resolved** : Four R=0.4 *b*-tagged jets, with BDT to pair them as Higgs candidates
- **Boosted:** Two R=1.0 *b*-tagged jets, p_T>250 GeV

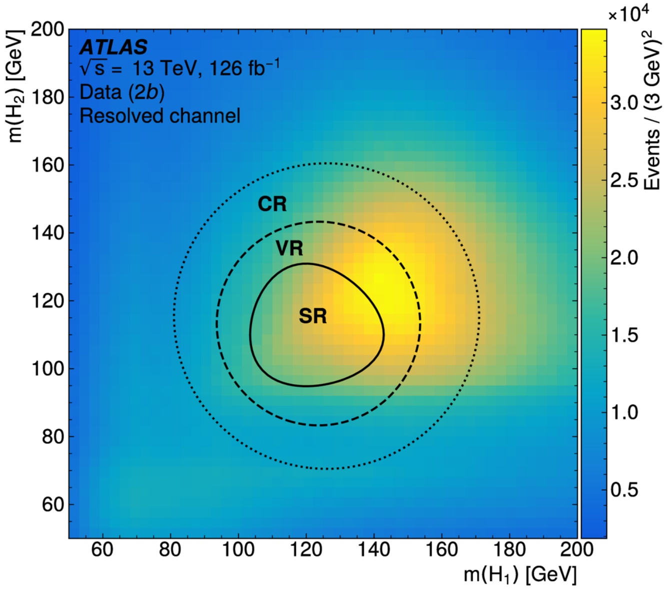
Track jets also associated to boosted jets – also *b*-tagged – split into selection with 2, 3 or 4.

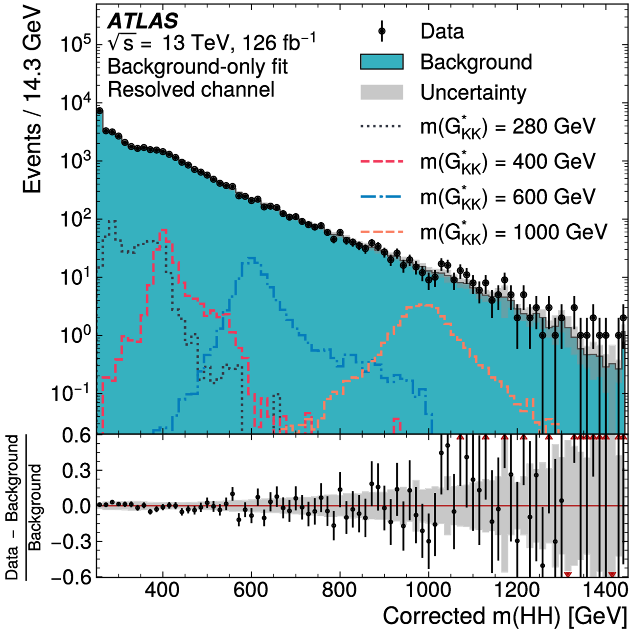
Signal region defined by invariant mass of the two Higgs candidates – background-enriched control region constrains multi-jet and top pairs

Final observable: Fit to m_{HH} spectrum.

Data agrees with SM – small excess at 1.1 TeV – 2.3σ for Spin-0 resonance, 2.5σ for Spin-2

Used to set limits on "generic" Spin-0 boson production and Spin-2 KK graviton production





For non-resonant search see talk by B. Moser

JHEP 07 (2023) 040
See also boosted analysis: JHEP 11 (2020) 163

Di-Higgs: $X \to HH \to b\bar{b}\tau^+\tau^-$

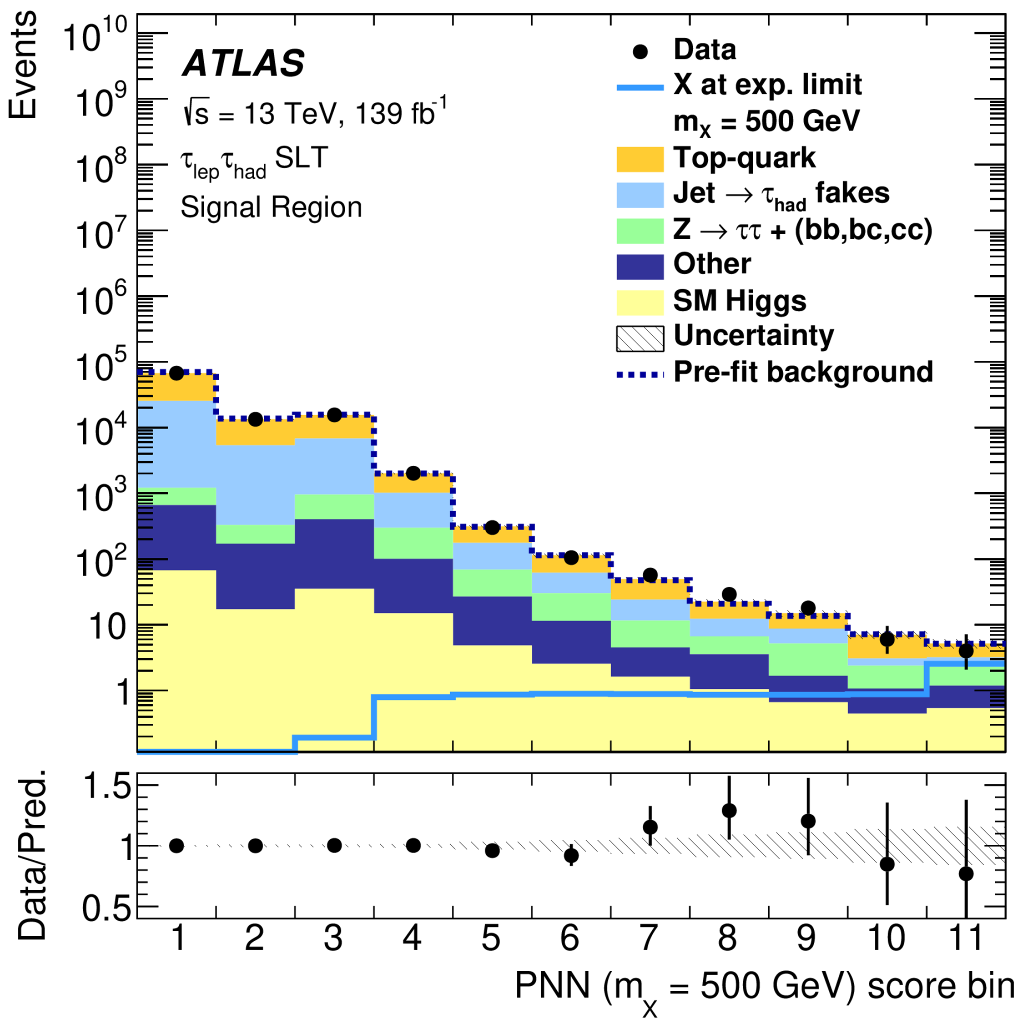
2 channels spanning 251 < m_X < 1600 GeV:

- $\tau_{had}\tau_{had}$: Two opposite-charge hadronic tau leptons, no electrons or muons – selected with trigger requiring leading τ p_T >100-180 GeV
- $\tau_{lep}\tau_{had}$: Exactly one electron or muon – one hadronic tau with opposite charge

Semileptonic channel split by trigger selection

Employs *Parameterized Neural Networks* (PNN) to discriminate signal from background : learns the m_X parametrization of signal kinematics

Final fit on PNN output – largest deviation from SM expectation a combined local (global) excess at m_X = 1 TeV, of 3.1 (2.0)σ



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Two b-jets, m_{bb} < 150 GeV

Semileptonic channel split by trigger selection

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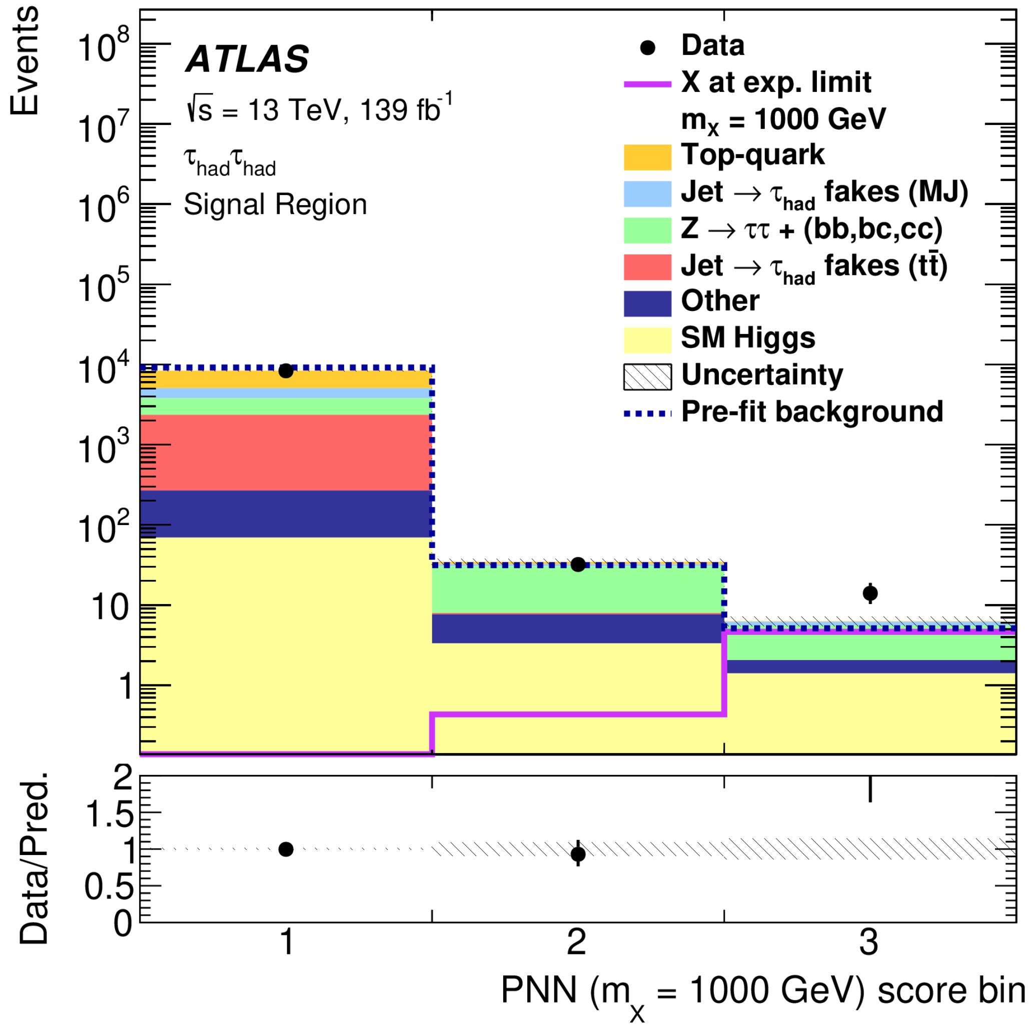


For non-resonant search see talk by E. Mazzeo

Phys. Rev. D 106 (2022) 052001

Di-Higgs: $X \rightarrow HH \rightarrow b\bar{b}\gamma\gamma$

Previous talk by E. Mazzeo covered the event selection and basic analysis strategy

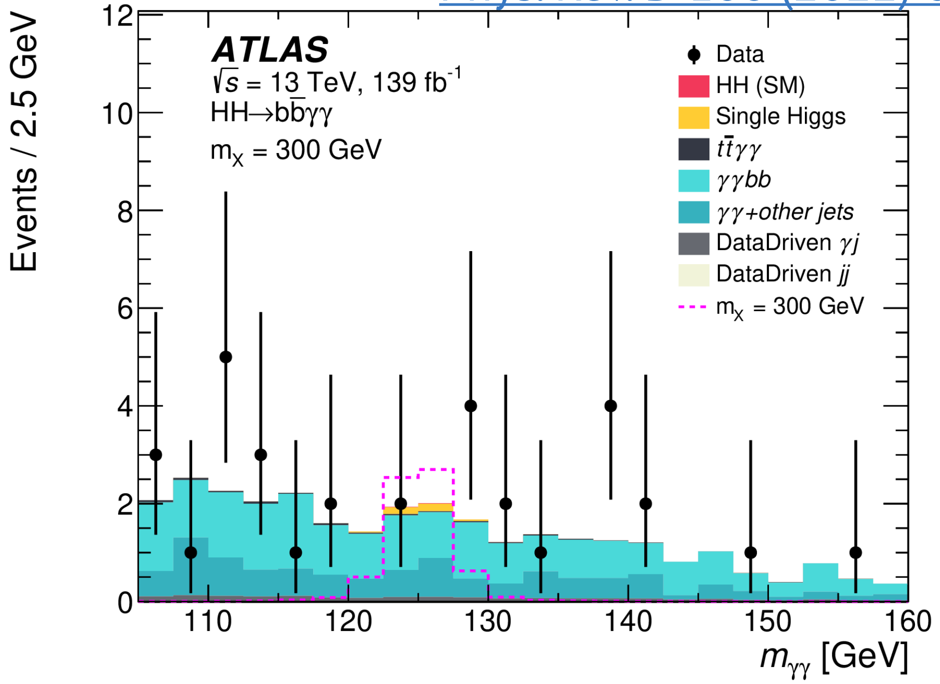
Resonant search (in 2022 paper) covers $251 < m_X < 1000$ GeV

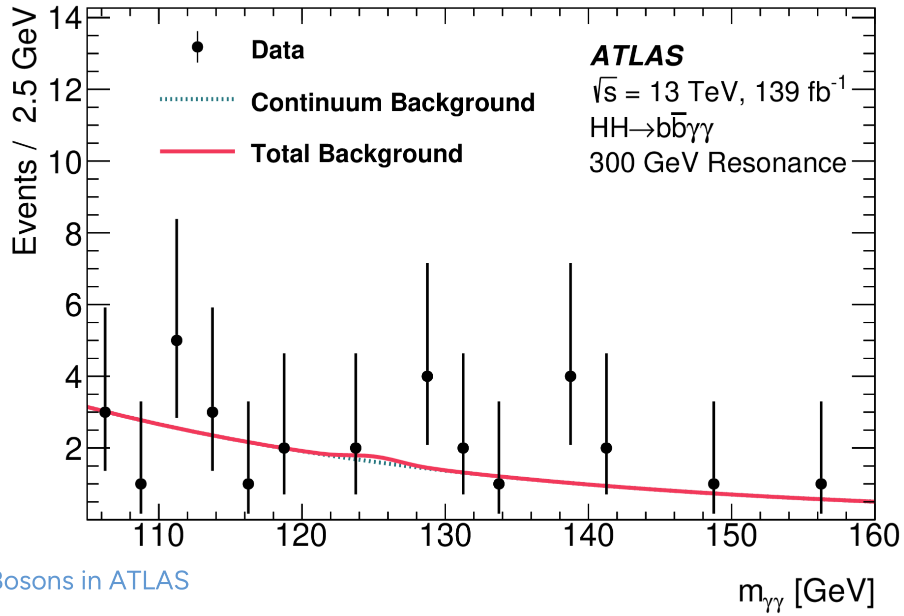
2 BDTs trained and combined to discriminate signal from non-resonant (continuum) and resonant (single Higgs) backgrounds respectively

BDTs trained jointly for all mass points to overcome the challenge with low background at higher mass

$m_{\gamma\gamma}$ fit to exponential decay (continuum) and 2-sided Crystal Ball (signal)

No significant excess observed, proceed to set limits!





In slightly different context see talk by TJ Khoo

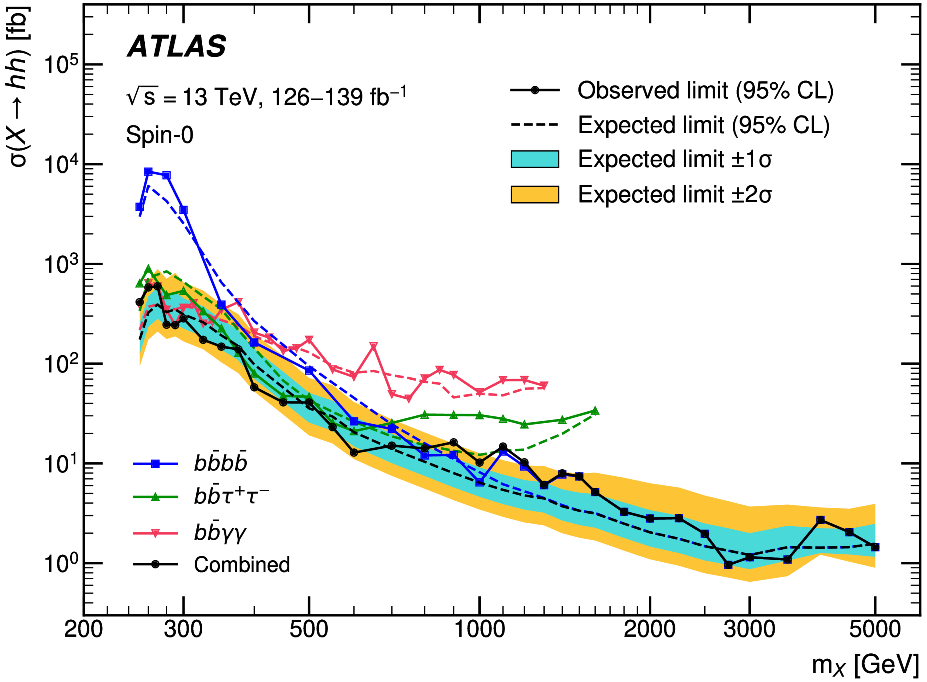
arXiv:2311.15956

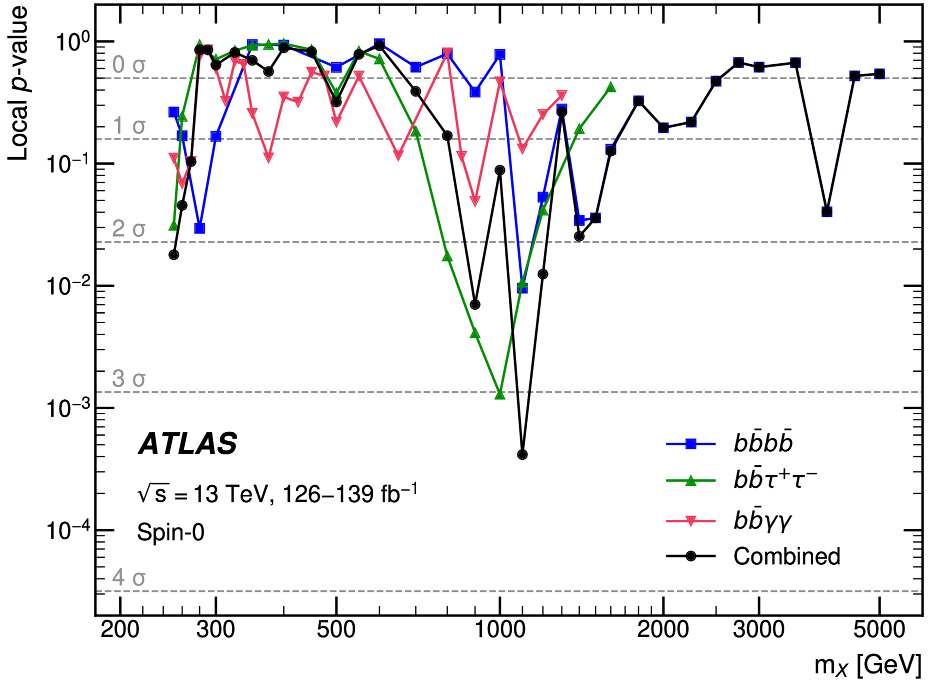
Di-Higgs: Combination

A combined likelihood calculated by combining the likelihoods of all three analyses – the individual signal regions have negligible overlap, and thus are statistically independent

No significant excess! Limits set! Largest combined deviation of 3.3 (2.1)σ at 1.1 TeV

$b\bar{b}\gamma\gamma$ strongest at low, $b\bar{b}\tau^+\tau^-$ at intermediate and $b\bar{b}b\bar{b}$ at high m$_X$





Di-Higgs: Combination

Interpretation:
Type-I Two-Higgs Doublet Model

Extension of SM with three neutral Higgs bosons

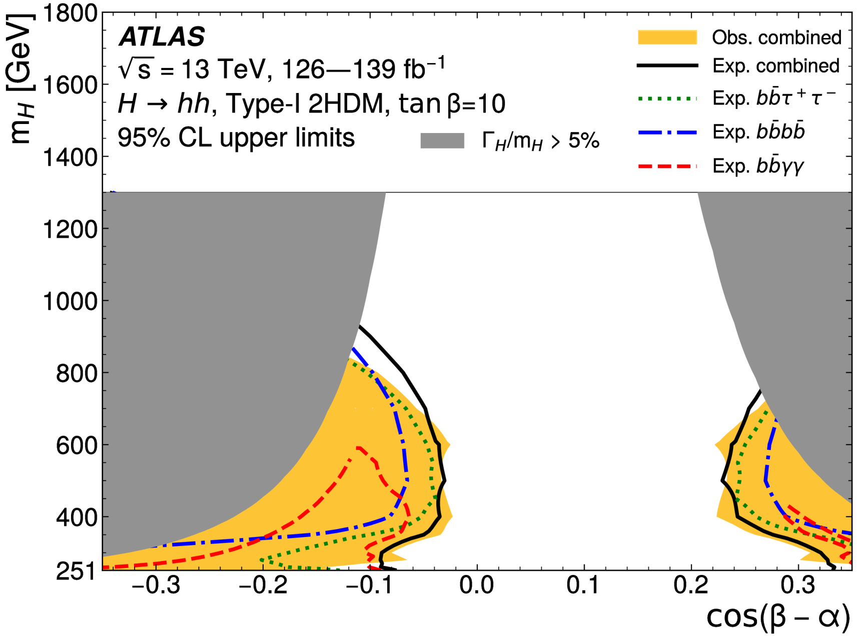
In this context assumed:

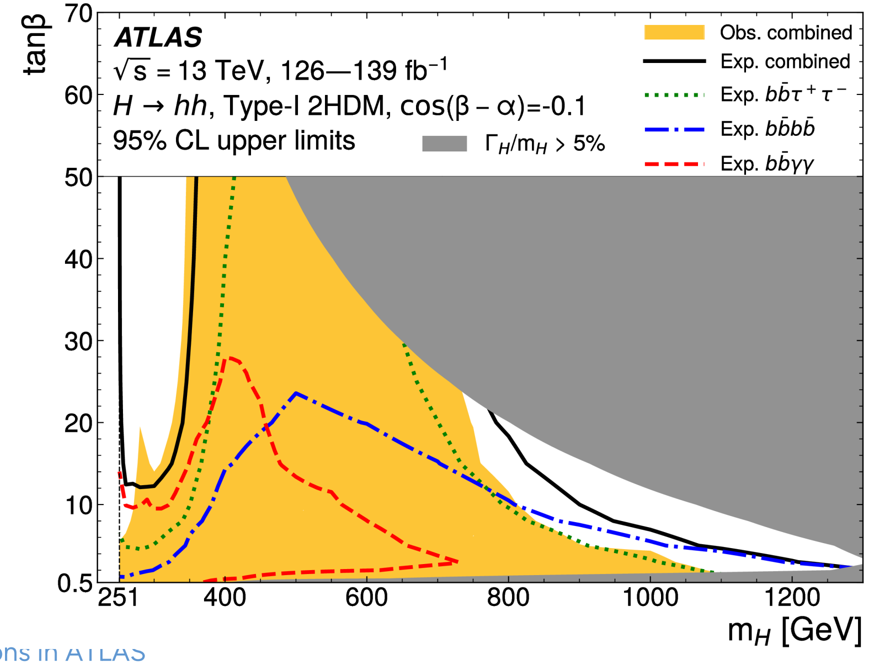
- The resonance decaying to Higgs pair corresponds to heavy CP-even *H* decaying to two light CP-even *h*
- All parameters assumed fixed except cos(β-α), m_H and tan(β)

The non-fixed parameter form planes in which we can set exclusion limits

Exludes certain regions still allowed by Higgs boson coupling measurements

MSSM interpretation in backup!





SH: $X \to SH \to VV\tau^+\tau^-$

Scans a window of 500 < m_X < 1500 GeV,
200 < m_S < 500 GeV (assuming $m_X > m_S + m_H$)

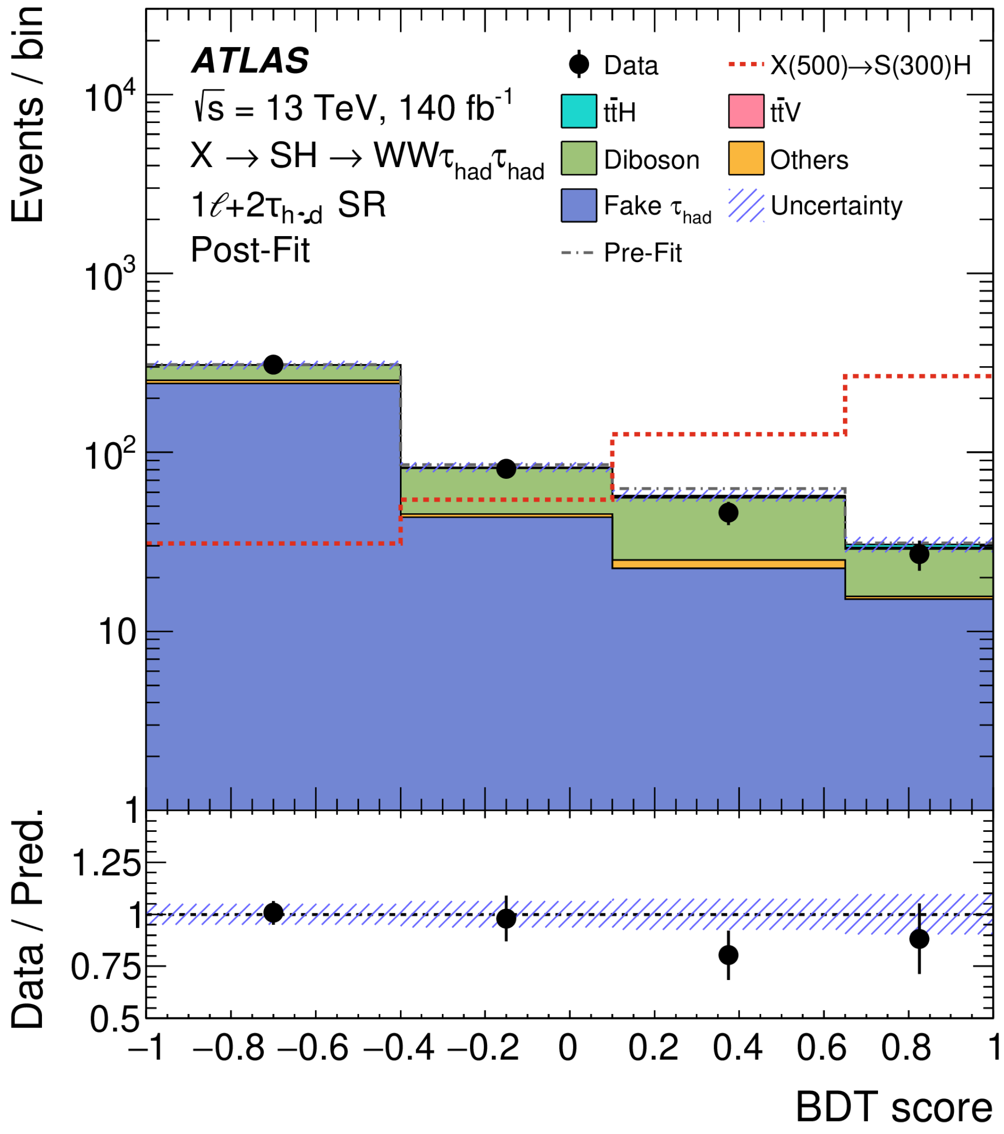
Select two opposite-sign τ_{had} (p_T>25 GeV, ΔR<2)

Three signal regions:

- **WW1ℓ**: Exactly one light lepton
- **ZZ2ℓ**: same-flavour opposite-sign leptons with m_{ll} in Z window
- **WW2ℓ**: opposite-sign leptons, vetoed if same-flavour leptons in Z window

Signal-to background (dibosons, ttV, fake τ) discrimination using ***parameterized* BDT** – one per signal region and m_S hypothesis – 12 in total

Simultaneous binned fits to all BDT bins, jointly analysed to test for signal presence



See also J. Stegemann's talk for NMSSM context plots

JHEP 10 (2023) 009

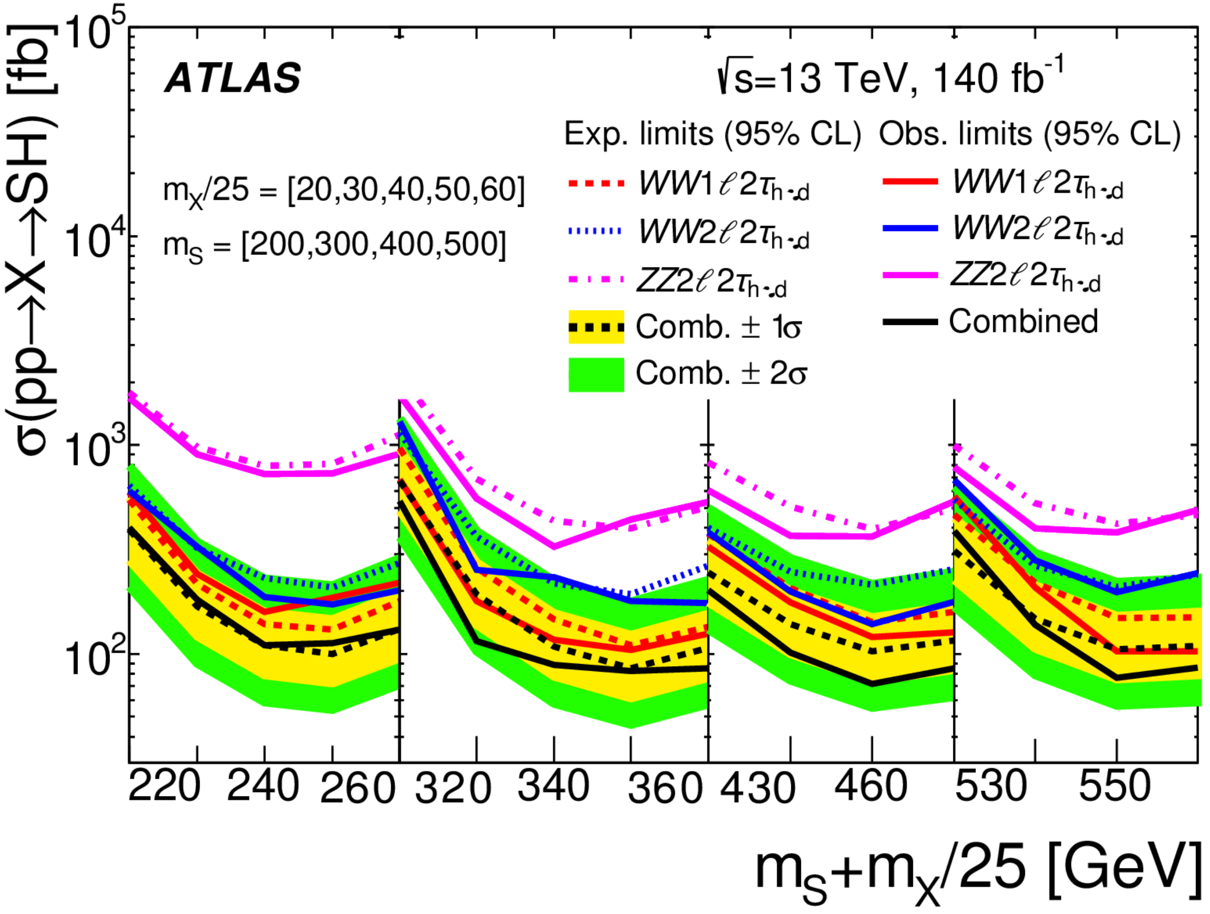
SH: $X \rightarrow SH \rightarrow VV\tau^+\tau^-$

No significant excess observed in data to SM background expectation

Limits set through combining the three channels, range from 538 to 72 fb for $\sigma(X \rightarrow SH)$ under assumption that branching ratios of S equal to those of SM Higgs

The single-lepton W SR main contributor

Limits also set individually on $\sigma(X \rightarrow S(\rightarrow W^+W^-)H(\rightarrow \tau^+\tau^-))$ and $\sigma(X \rightarrow S(\rightarrow ZZ)H(\rightarrow \tau^+\tau^-))$ (in backup)



$Z\gamma$: X → $Z\gamma$; leptonic

Targets 220 < m_X < 3400 GeV

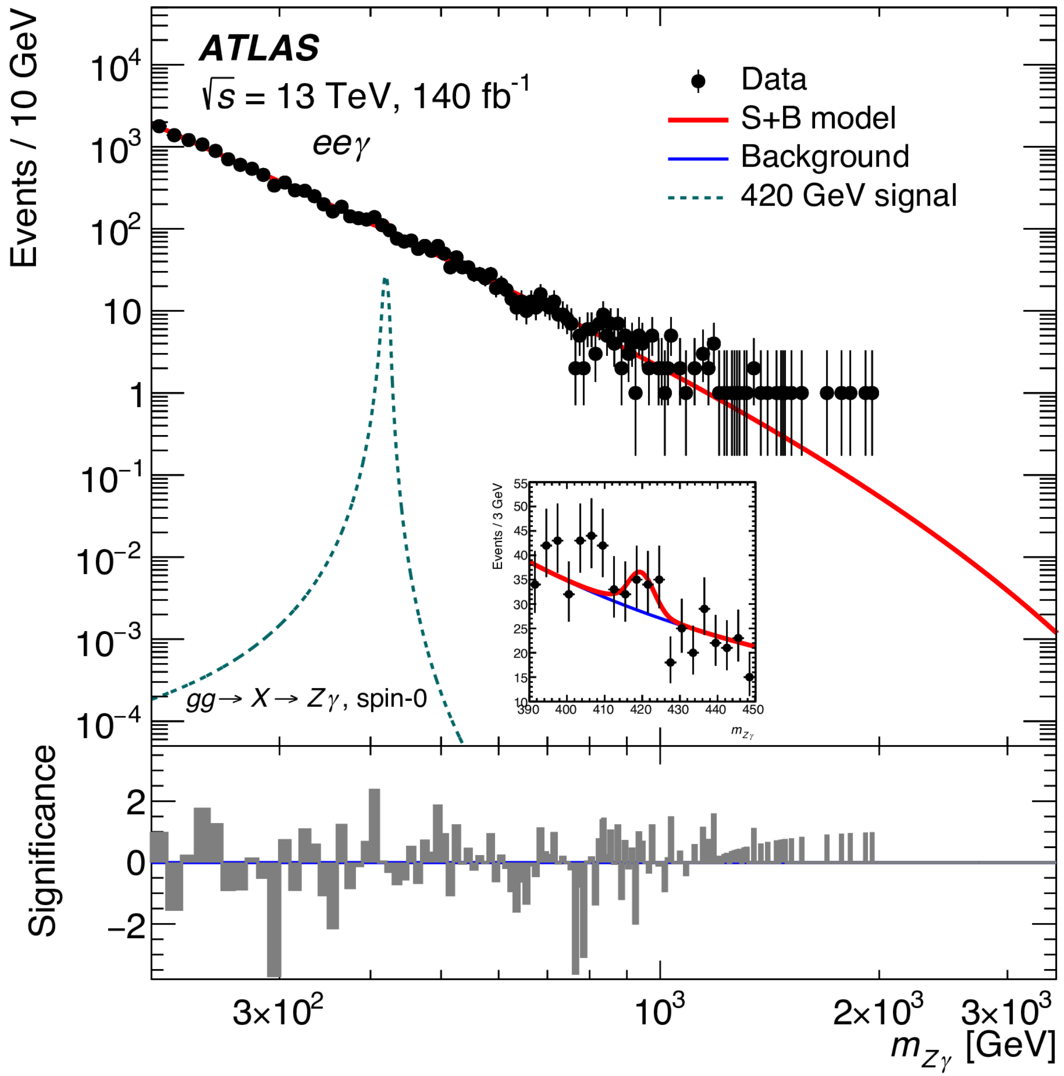
Two channels: $\mu\mu\gamma$ and eeγ, selecting a photon and opposite-sign leptons, $p_T^\gamma / m_{Z\gamma}$ > 0.2

Boost means degradation of *e* ID performance:

- Dedicated *MVA-based* ID criterion developed; combined with *Loose* → *Mixed ID*. Increases overall ID efficiency by 6.2-12.7% and allows higher mass range than previous search
- Also selection to mis-identified as photons to selection

Functional form in $m_{Z\gamma}$ to minimize bias from spurious signal, signal modelled with 2-Sided CB

No significant deviation from SM – largest local combined excess at m_X = 420 GeV of 2.3σ



Zγ: X → Zγ; hadronic

Targets 1 < m_X < 6.8 TeV resonances to Zγ and Wγ

Select **high-p_T (> 200 GeV), large-radius jet** (assuming highly boosted di-quark system) + **photon with E_T > 200 GeV** (increases with $m_{j\gamma}$)

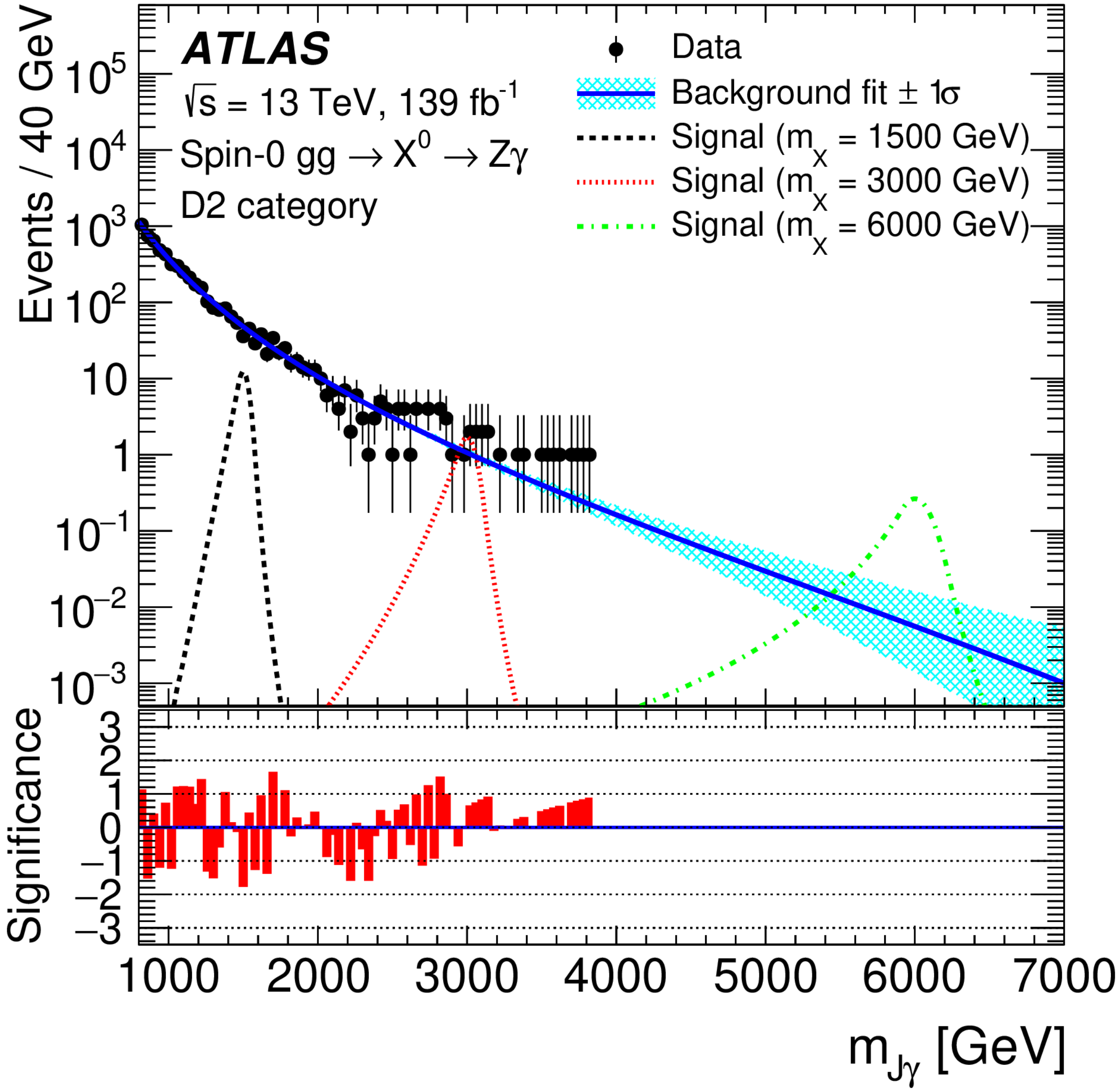
Jet substructure (energy and inter-cluster distance in large-R jet) and mass cuts enhance signal purity

Three categories:

- **2 b-tagged sub-jet** selection (Z only)
- Not 2 b-tags but **2-pronged substructure**
- Neither, but jet **mass consistent with W/Z**

Background (γ+jet) described by "best" functional form in $m_{j\gamma}$, signal parameterized as 2-sided CB

No significant excess, largest local deviation at m_X = 3640 GeV with a 2.5σ local significance.



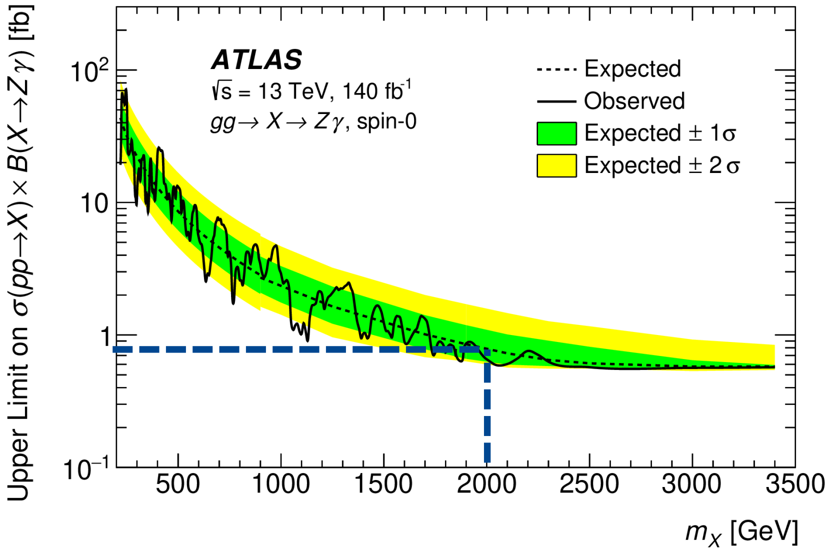
Zγ: X → Zγ limits

Limits from both papers set on $\sigma(pp \to X) \times B(X \to Z\gamma)$, for Spin-0 and Spin-2 (gg as well as qq production) resonances.

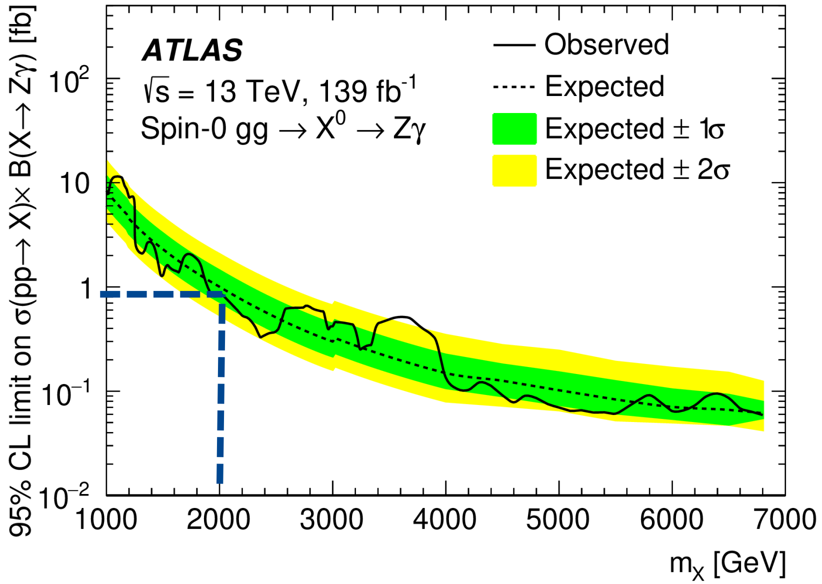
Up to ~2 TeV the leptonic final state limits typically lower, above that hadronic final state typically lower

Observed limits in range 65.5 fb to 0.6 fb (leptonic), and 10 to 0.05 fb for hadronic; *NB ranges not the same*

Leptons



Hadrons



Summary

A set of searches for resonances decaying to pairs of bosons in ATLAS has been presented

The resonance masses in these searches span from $220 < m_X < 6800$ GeV, and final states with photons, light leptons, τ leptons and jets (large- and small-radius, *b*-tagged and not) have been investigated.

So far no significant excesses in data to SM expectation found, and we proceed to set limits on potential new physics beyond the Standard Model

These resonances remain a promising potential for future analyses of LHC Run 2 and Run 3 data

Backup

Boosted topologies

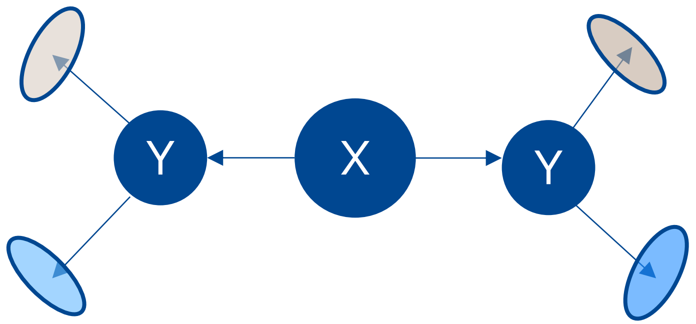
How to make consistent analysis strategies spanning very large mass ranges (with sometimes very different kinematics)?

-> In the scope of this talk we span resonances from 220 GeV to 6.8 TeV

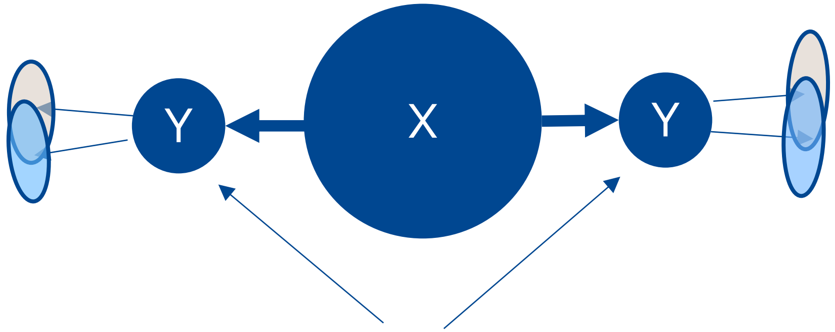
How to handle very heavy resonances leading to very boosted final states?

-> ”Standard” object reconstruction fail to resolve physical objects – sometimes only in part of the search space

Resolved final state



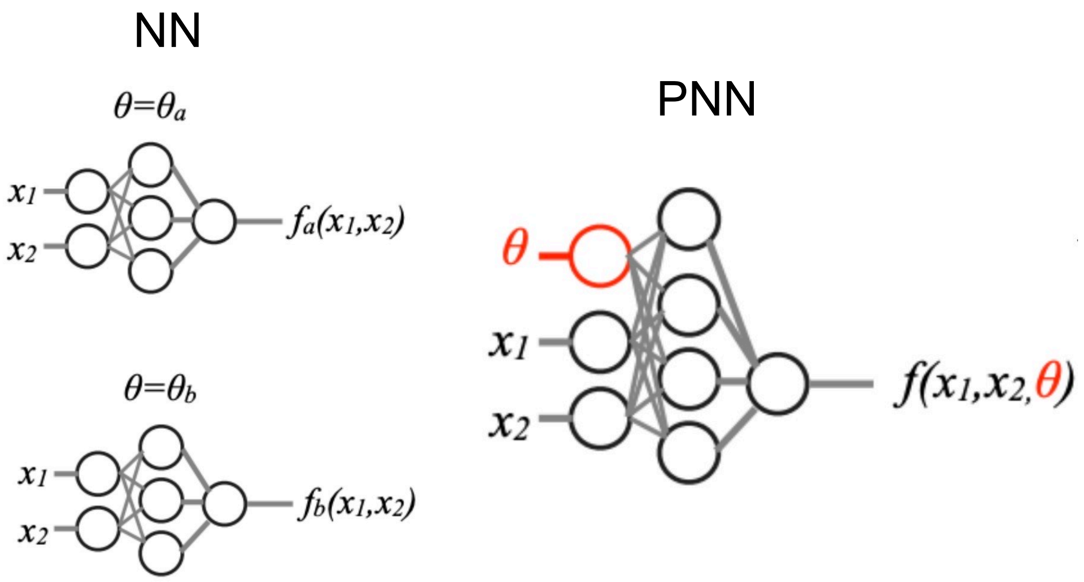
Boosted final state

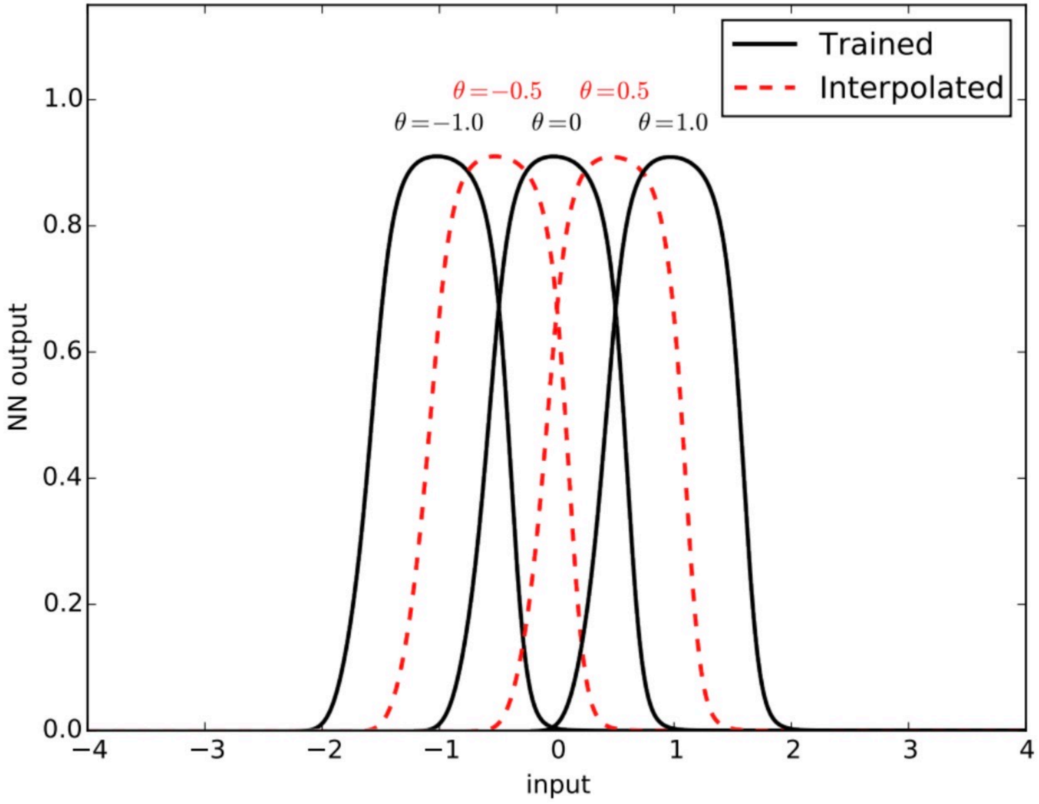


High p_T bosons

Parameterized MVA

PNN -> Output parameterized, allows smooth interpolation of the output discriminant and limits



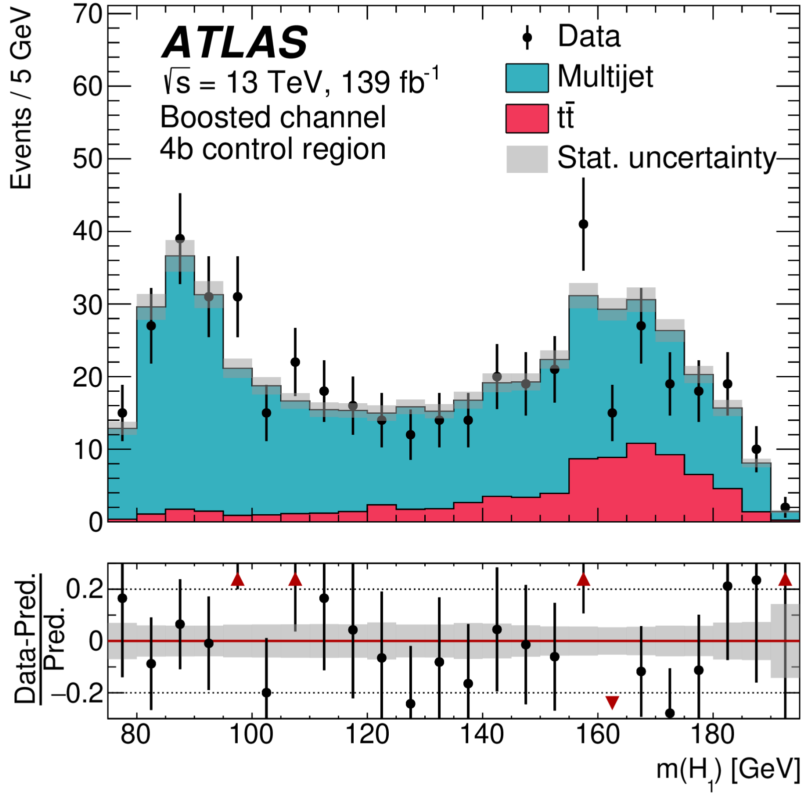


Phys. Rev. D 105 (2022) 092002
See also VBF-targeting paper: JHEP 07 (2020) 108

Di-Higgs: $X \to HH \to b\bar{b}b\bar{b}$

4b control region

$m(G^*_{KK})$ [GeV]	Corrected $m(HH)$ range [GeV]	Data	Background model	Spin-2 signal model
260	[250, 393]	26 775	26 650 ± 130	368 ± 25
500	[464, 636]	4655	4719 ± 37	138.6 ± 5.7
800	[707, 950]	795	811 ± 13	52.1 ± 1.9
1200	[993, 1279]	146	120.6 ± 2.8	14.45 ± 0.67



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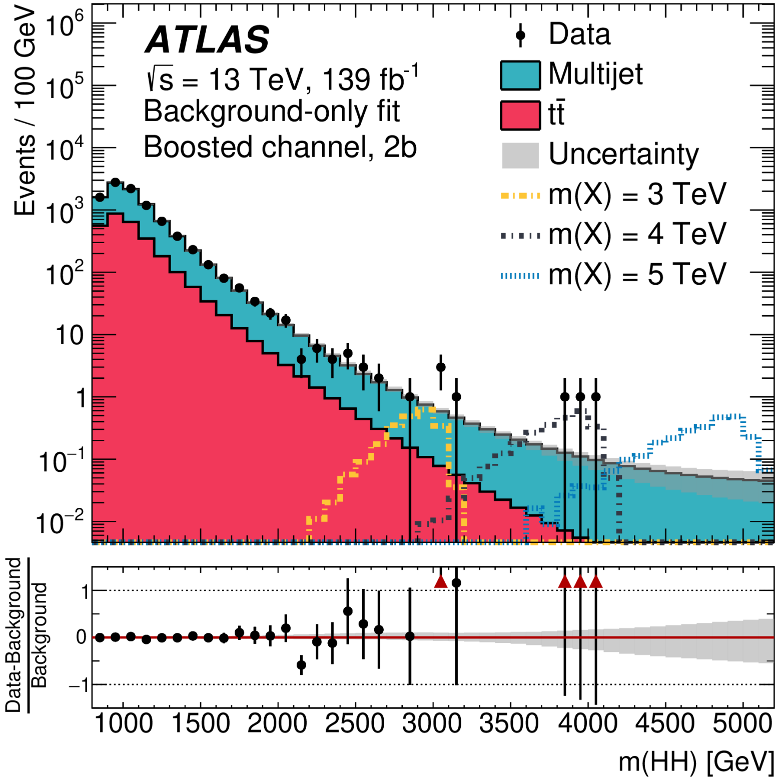

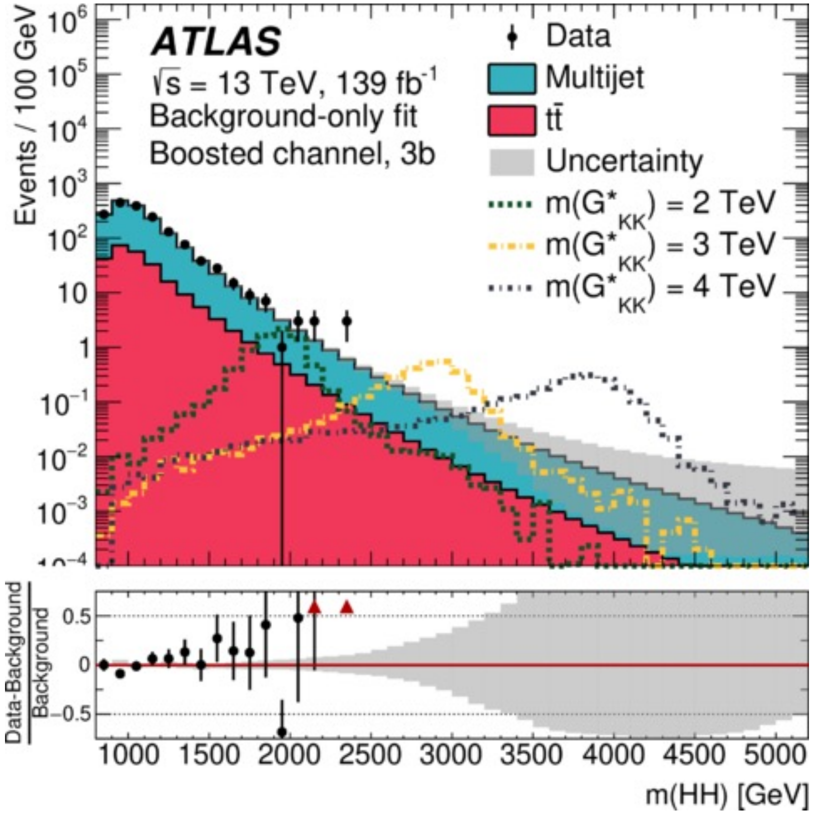

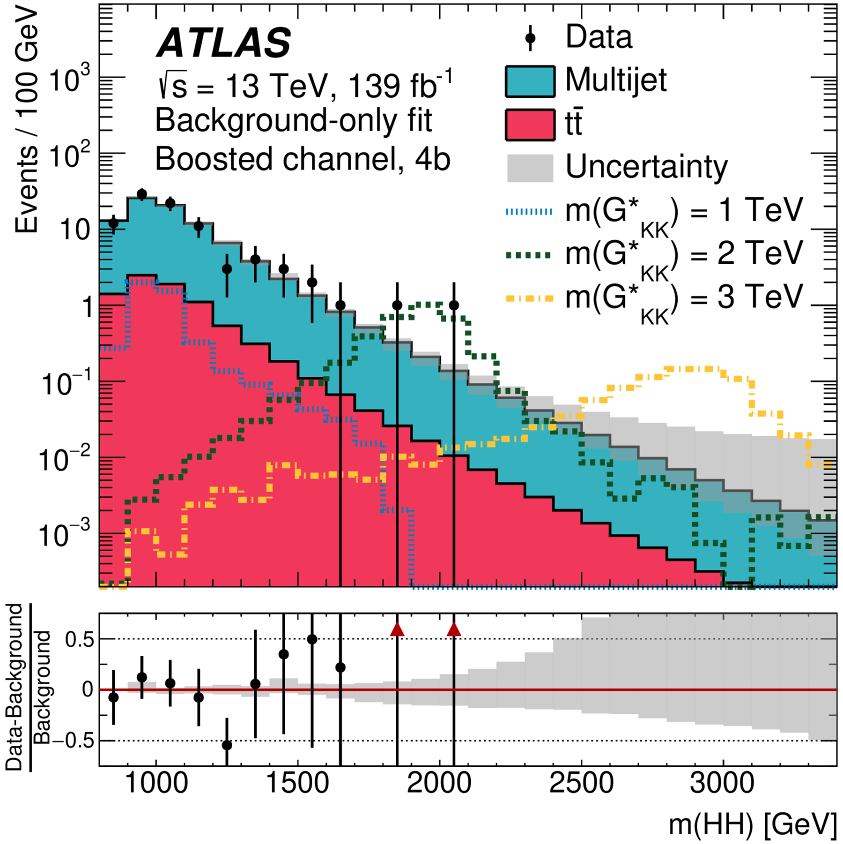

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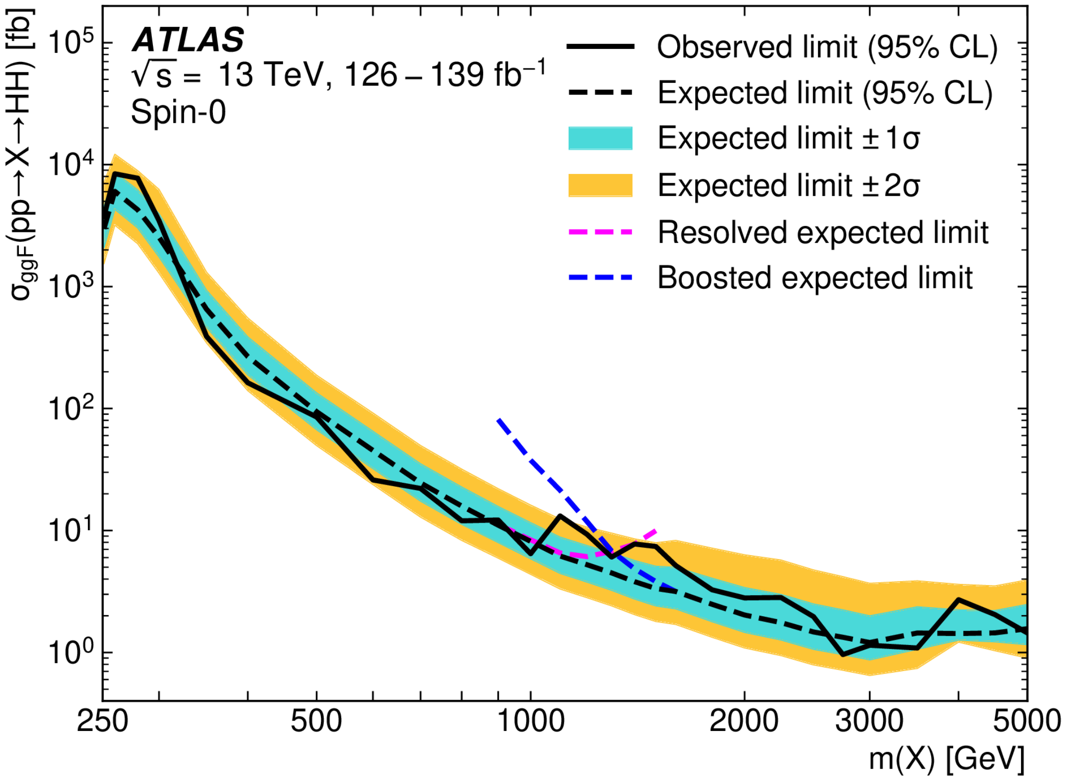

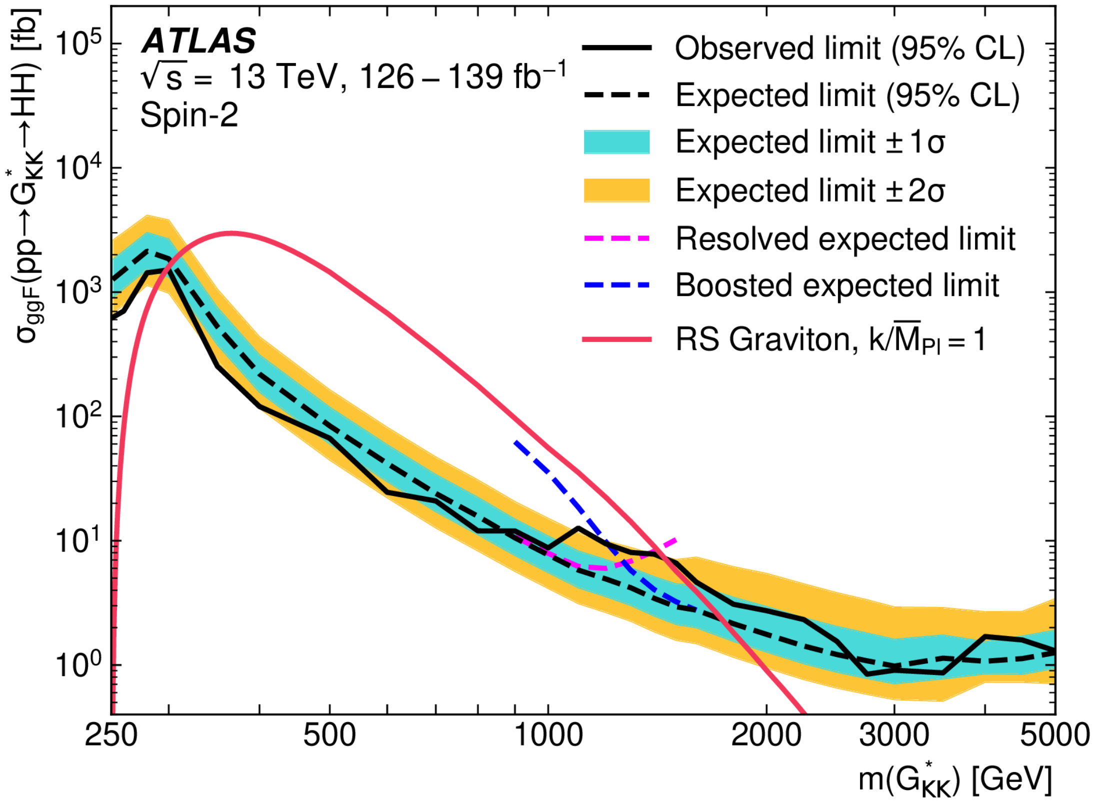

JHEP 07 (2023) 040
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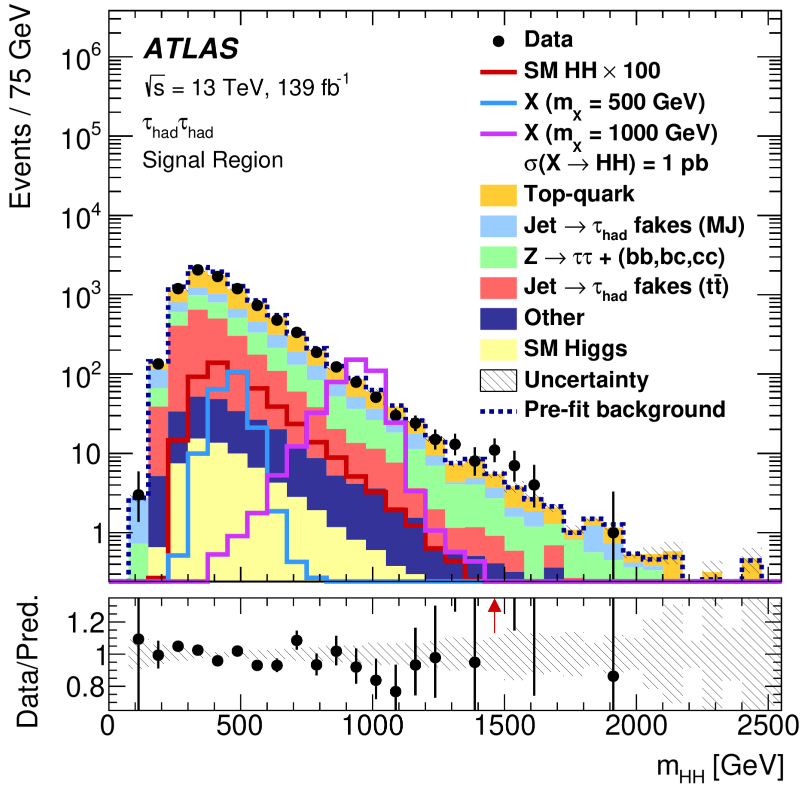

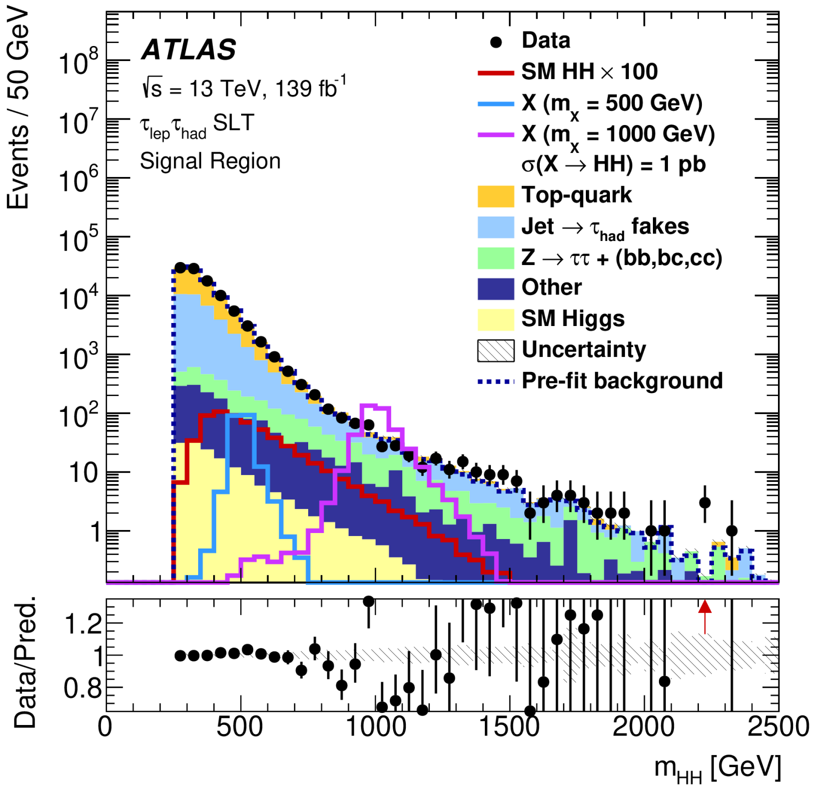

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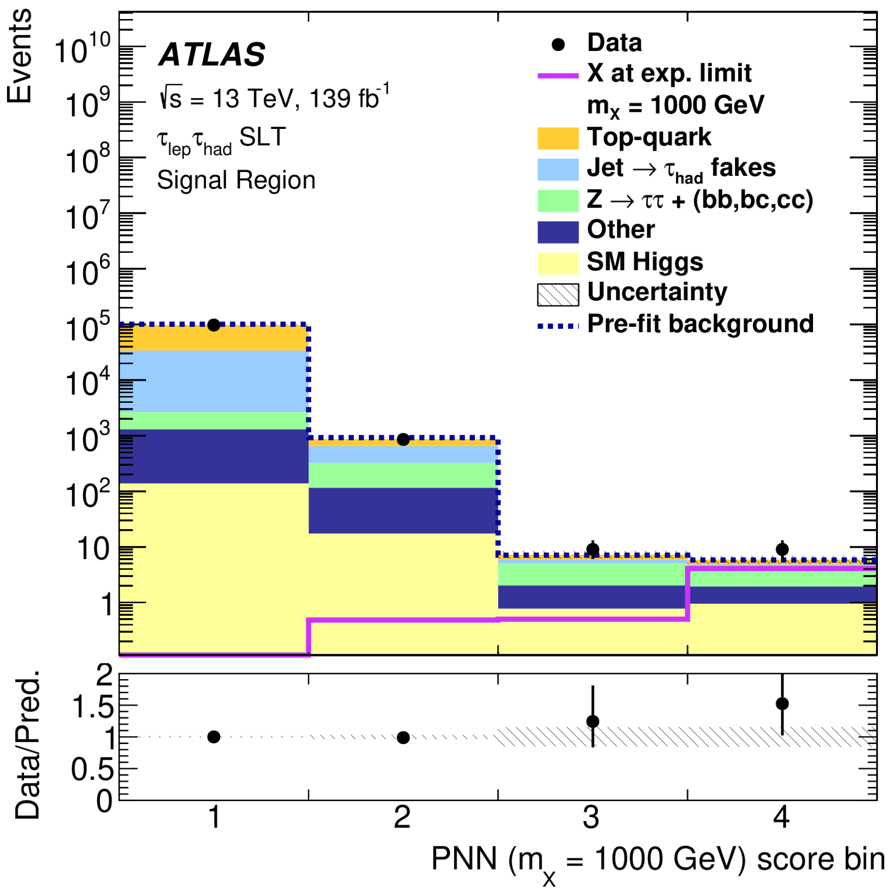

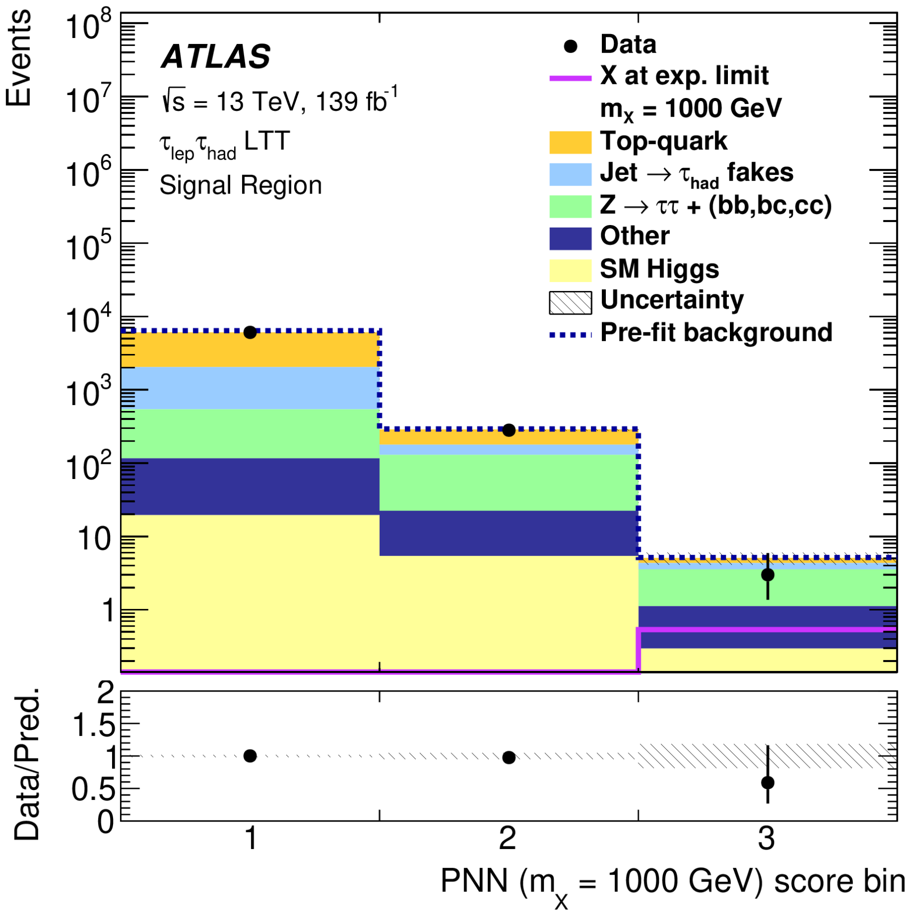

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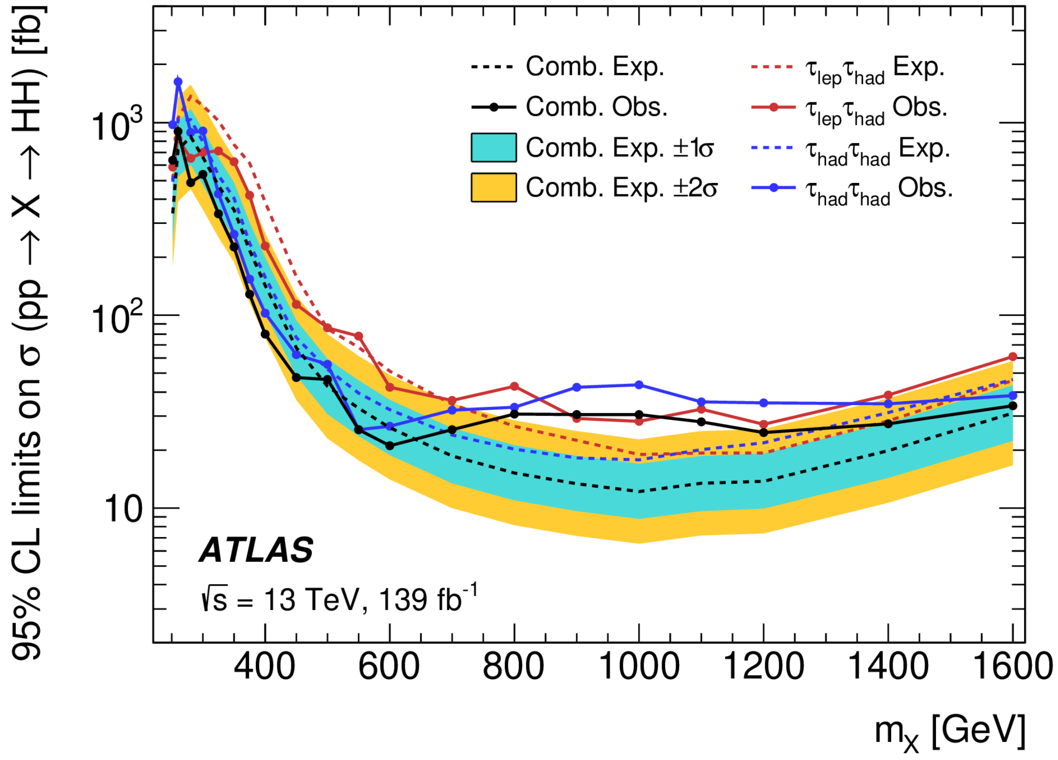
Di-Higgs: $X \to HH \to b\bar{b}\tau^{+}\tau^{-}$

	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT
Data	8	7	7
Non-resonant ggF HH	1.58 ± 0.27	0.77 ± 0.13	0.25 ± 0.05
Non-resonant VBF HH	0.0227 ± 0.0019	0.0075 ± 0.0007	0.00455 ± 0.00035
$t\bar{t}$	0.5 ± 0.1	0.44 ± 0.12	1.76 ± 0.32
Single top-quark	0.47 ± 0.20	1.2 ± 0.7	0.61 ± 0.35
Z + HF	2.3 ± 0.4	1.55 ± 0.33	1.7 ± 0.4
Combined fakes	–	1.09 ± 0.22	0.8 ± 0.5
Multi-jet fakes	0.47 ± 0.17	–	–
$t\bar{t}$ fakes	0.29 ± 0.07	–	–
Single Higgs boson	1.7 ± 0.5	1.10 ± 0.28	0.4 ± 0.1
Other backgrounds	0.4 ± 0.1	0.48 ± 0.09	0.33 ± 0.07
Total background	6.1 ± 0.8	6 ± 1	6 ± 1



Phys. Rev. D 106 (2022) 052001

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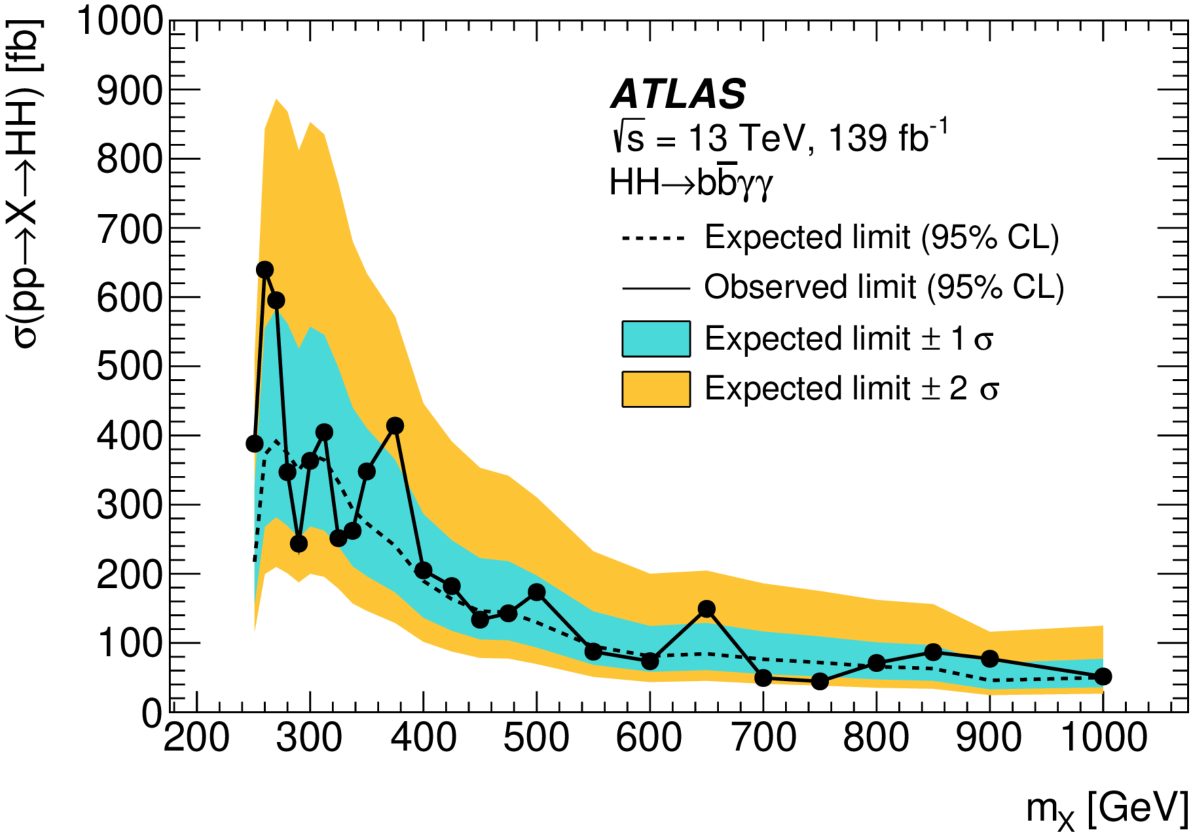


m_X [GeV]	BDT threshold	Efficiency [%]
251	0.70	6.6
260	0.75	5.7
270	0.80	5.1
280	0.85	4.5
290	0.85	4.7
300	0.85	4.9
312.5	0.85	5.2
325	0.85	5.2
337.5	0.85	5.5
350	0.85	5.8
375	0.90	5.5
400	0.80	7.6
425	0.85	7.6
450	0.85	8.1
475	0.80	9.1
500	0.75	9.9
550	0.60	11.6
600	0.45	12.9
700	0.20	14.9
800	0.10	16.2
900	0.20	19.4
1000	0.05	20.0

Di-Higgs: Combination

Interpretation:
Type-I Two-Higgs Doublet Model

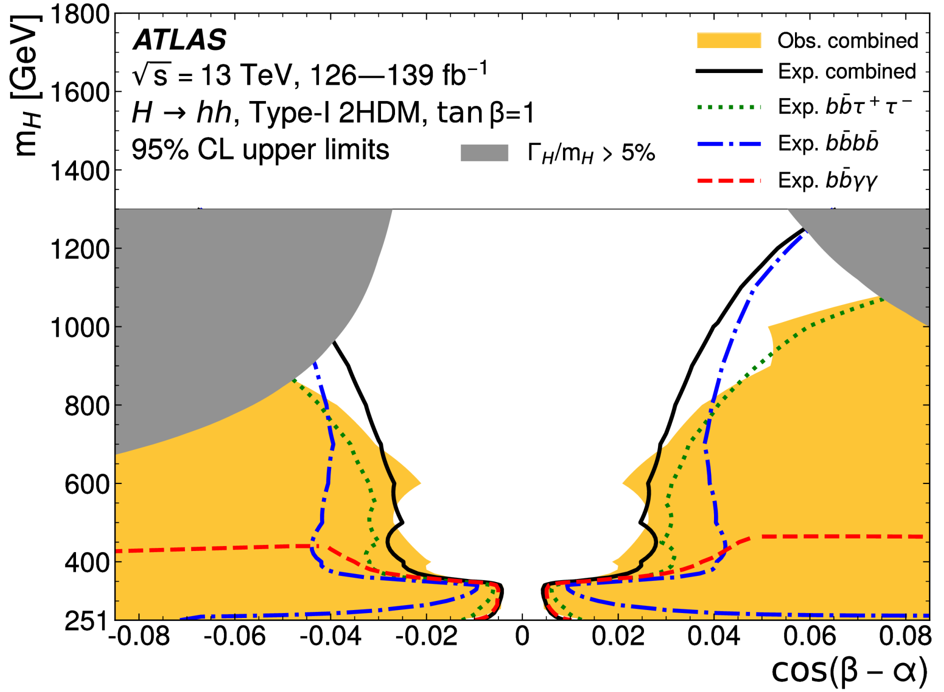
Extension of SM with three neutral Higgs bosons

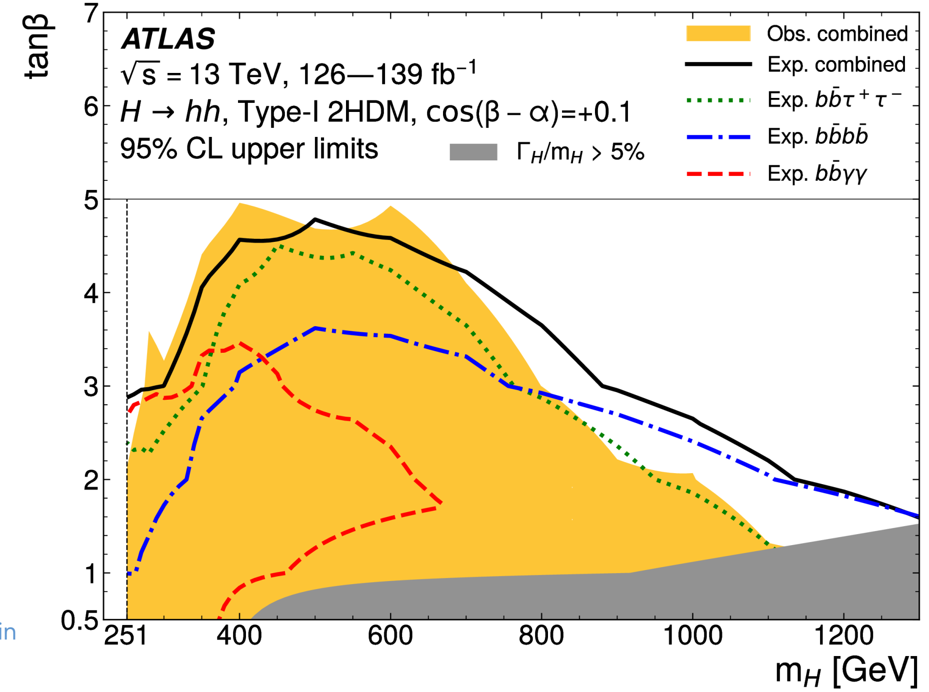
In this context assumed:

- The resonance decaying to Higgs pair corresponds to heavy CP-even H decaying to two light CP-even h
- All parameters assumed fixed except $\cos(\beta\text{-}\alpha)$, m_H and $\tan(\beta)$

The non-fixed parameter form planes in which we can set exclusion limits

Stronger limits in certain regions of $\cos(\beta\text{-}\alpha)$ than provided by Higgs boson coupling measurements





Di-Higgs: Combination

Interpretation:
Minimal Supersymmetric Standard Model

Has Higgs sector of Type-II 2HDM – includes same parameters as previous interpretation

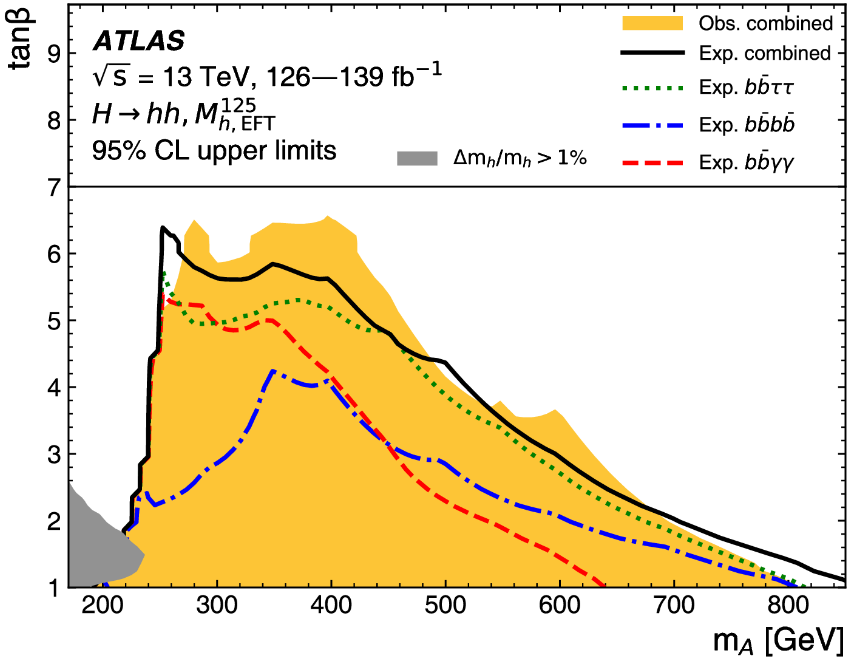
Supersymmetry constrains free Higgs sector parameters to only m_H and $\tan(\beta)$ – plane in which limits are set

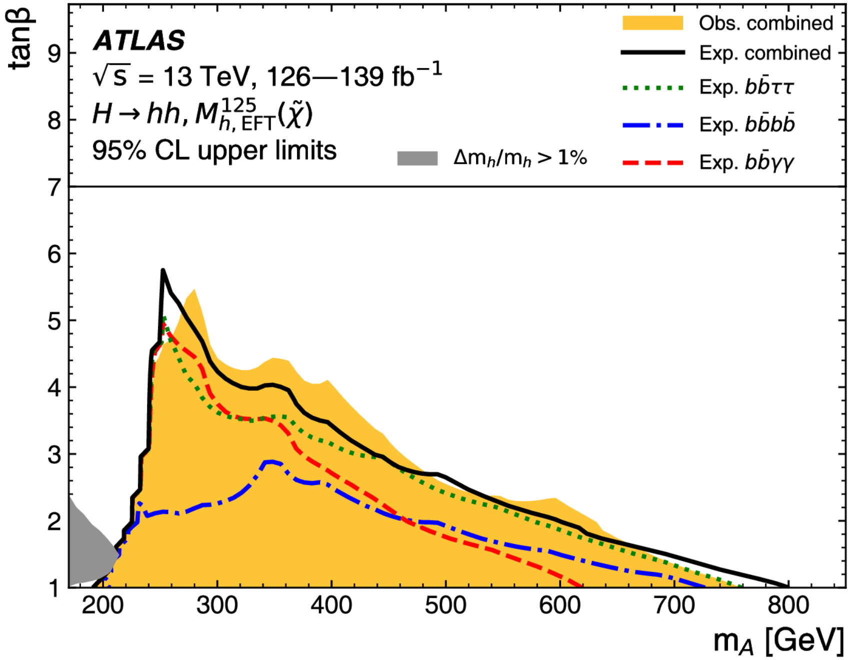
2 scenarios:

(i) Mass scales very high

(ii) Neutralinos and charginos are accessible

Excludes region around $\tan(\beta)$ ~2 and ~5 not probed by otherwise sensitive probes to this parameter space





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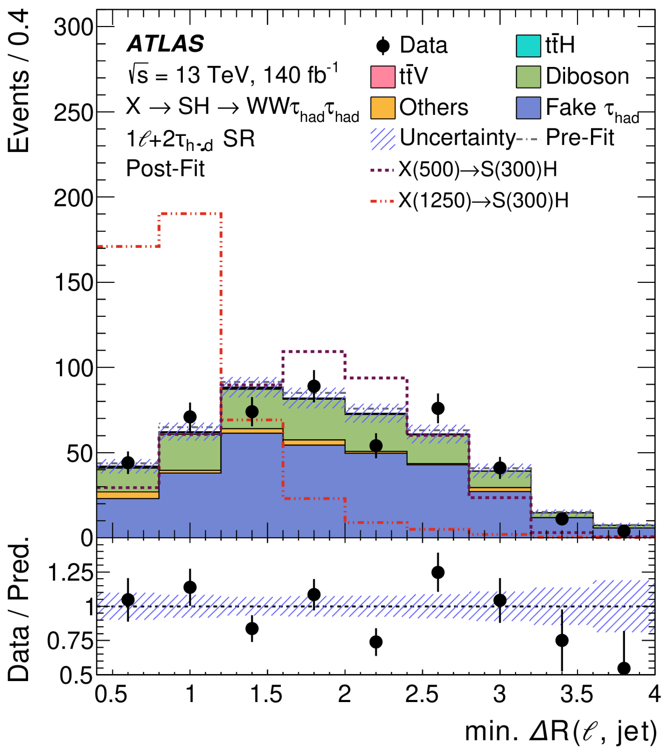
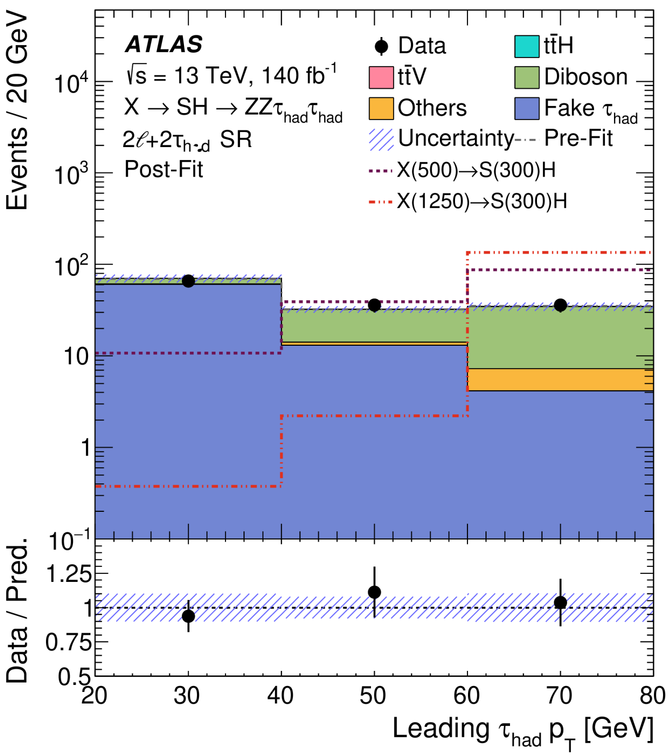
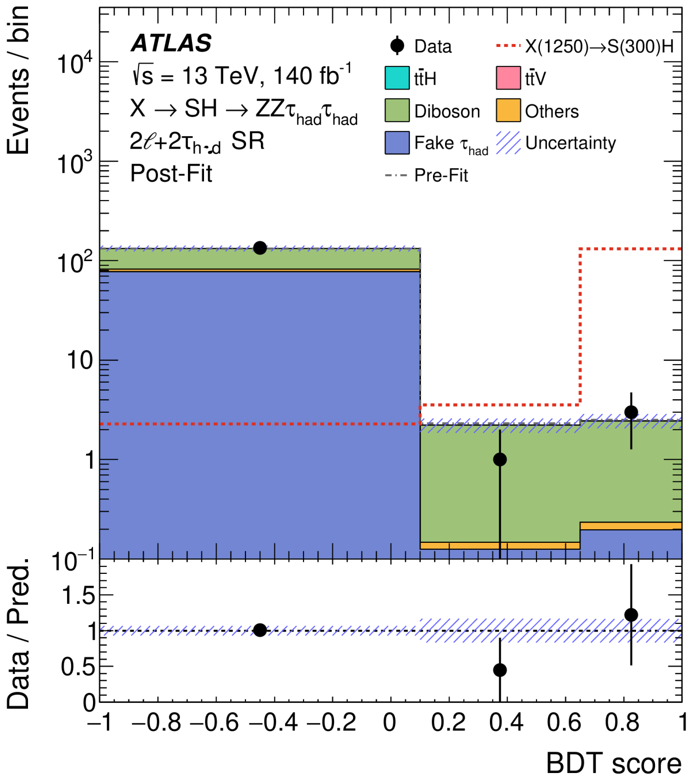
SH: → $VV\tau^+\tau^-$







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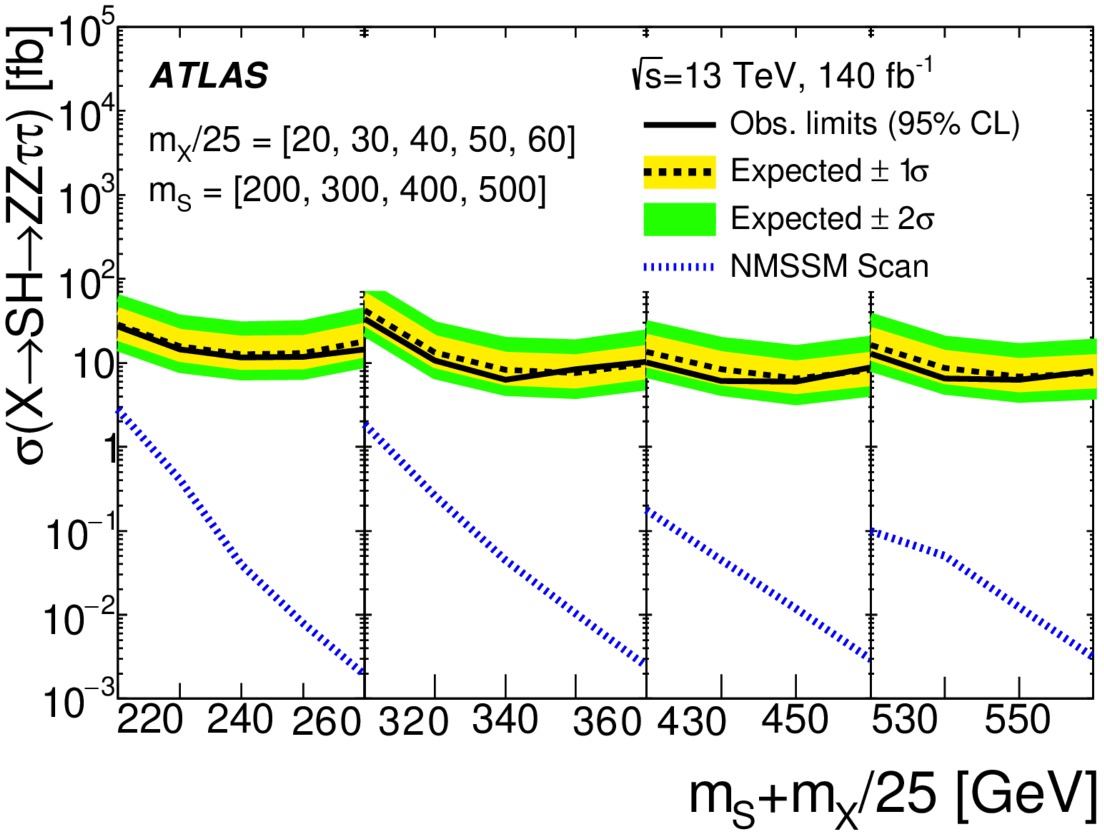
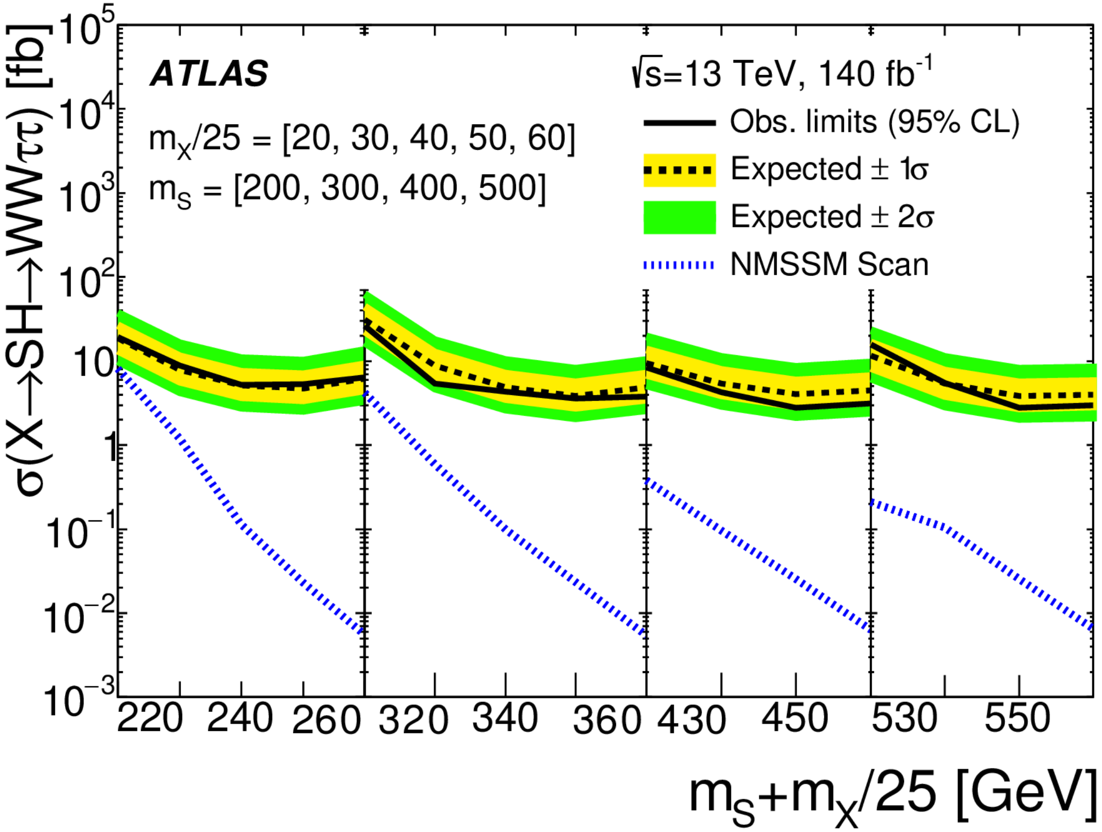
SH: $\rightarrow VV\tau^{+}\tau^{-}$





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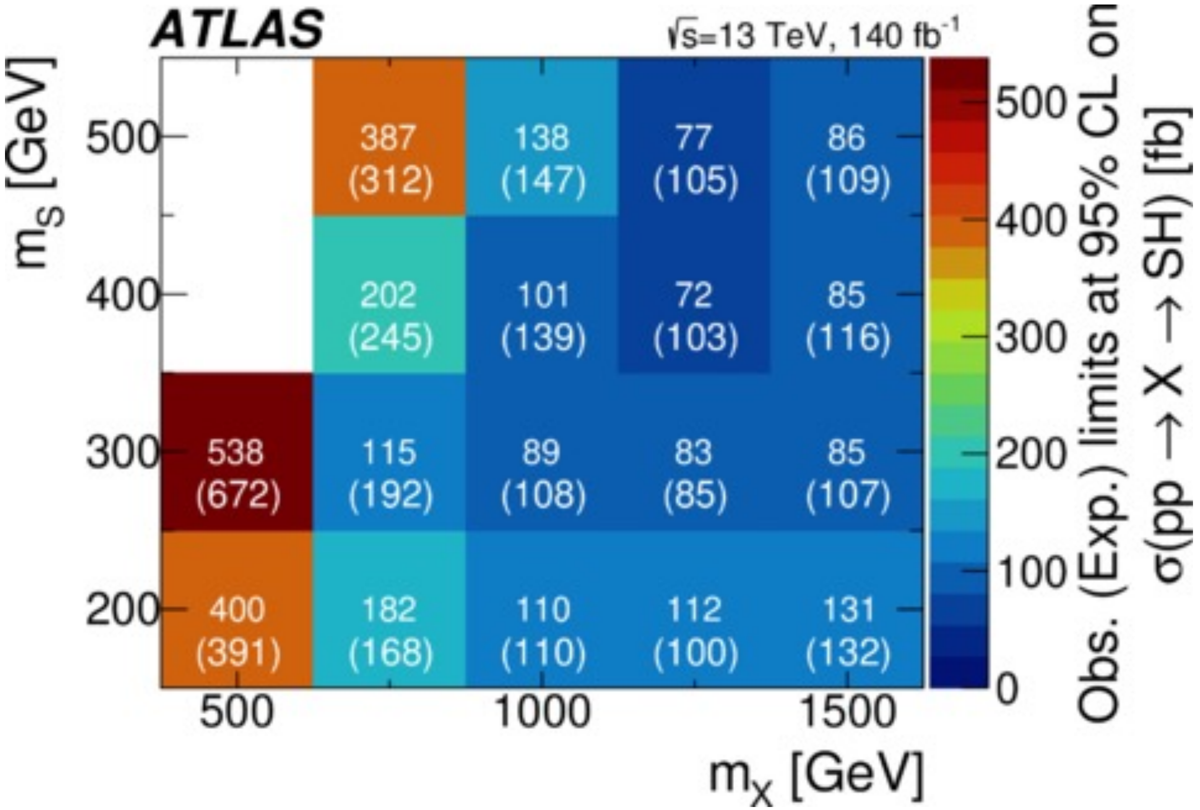
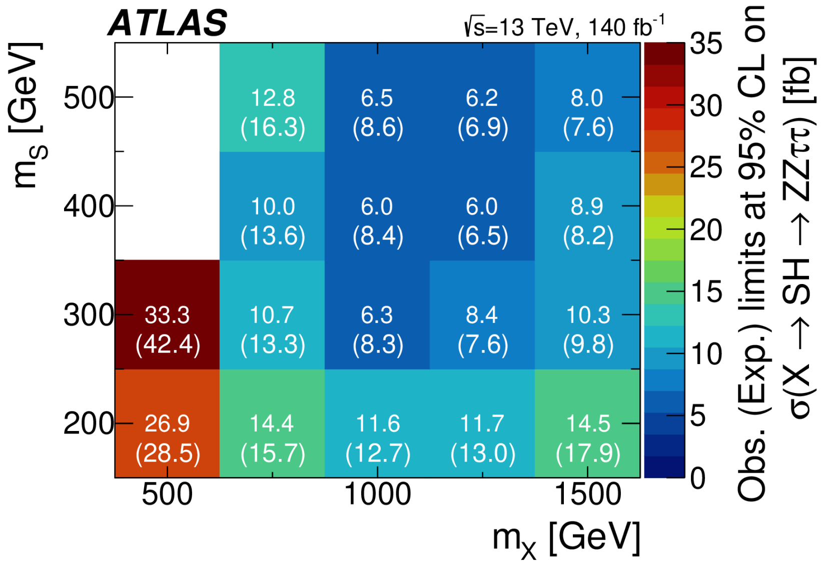
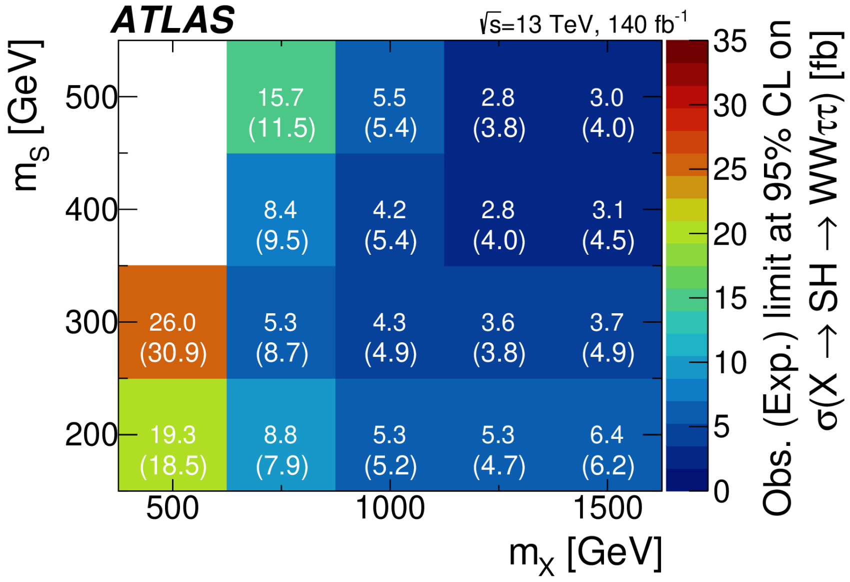
SH: $\rightarrow VV\tau^+\tau^-$

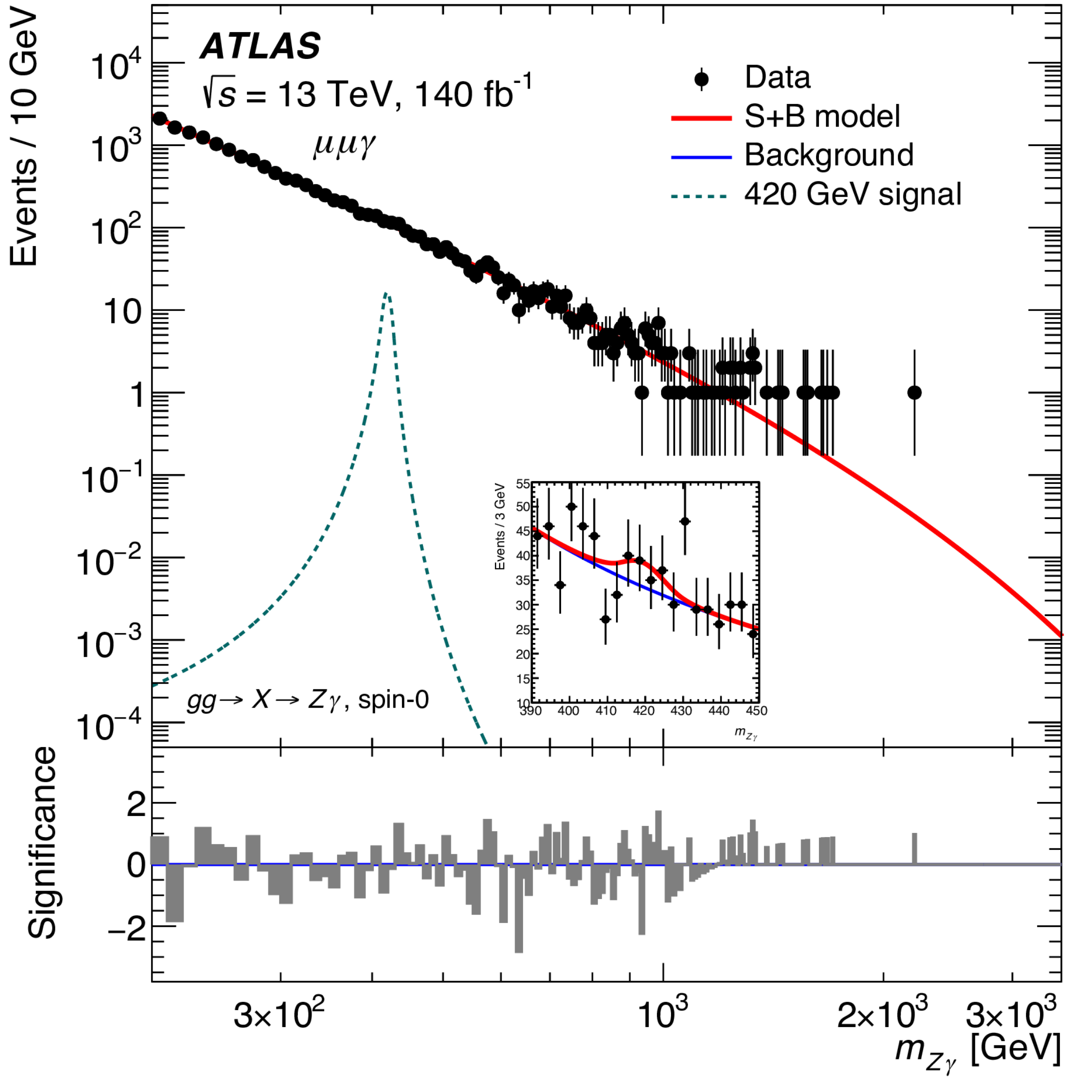




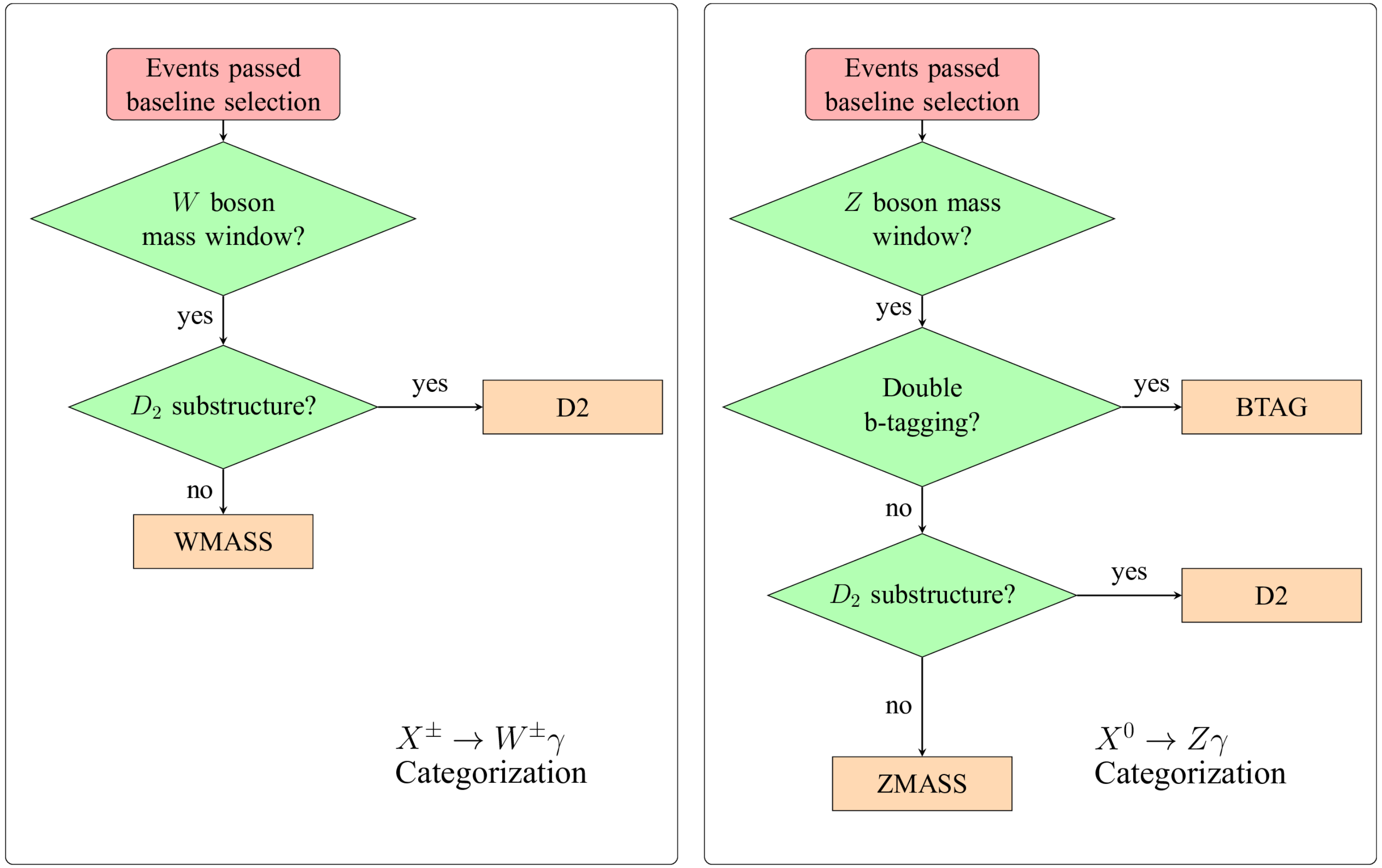


arXiv:2309.04364

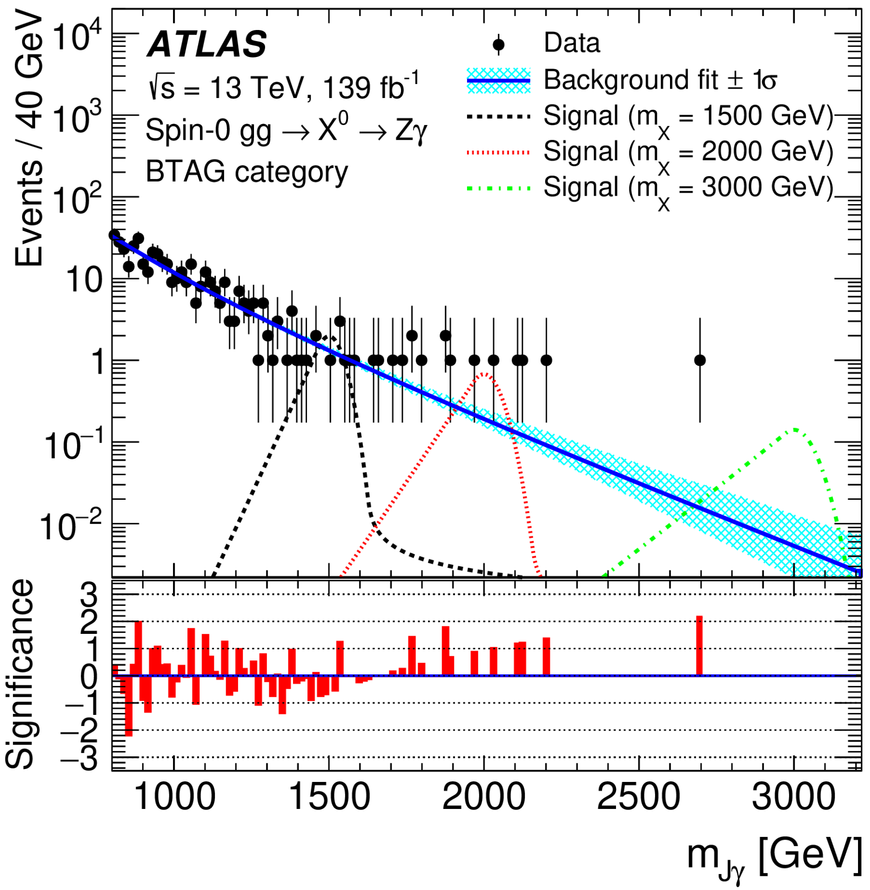
Zγ: X → Zγ; leptonic

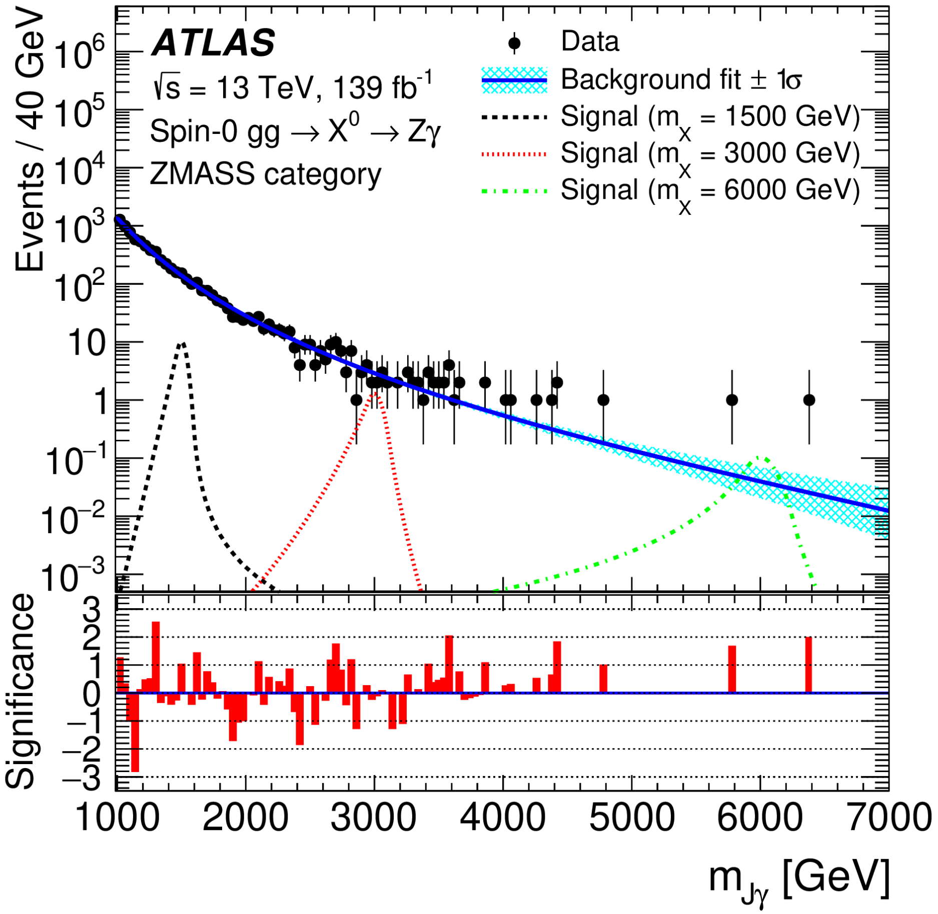


Zγ: X → Zγ; hadronic



$Z\gamma$: $X \to Z\gamma$; hadronic





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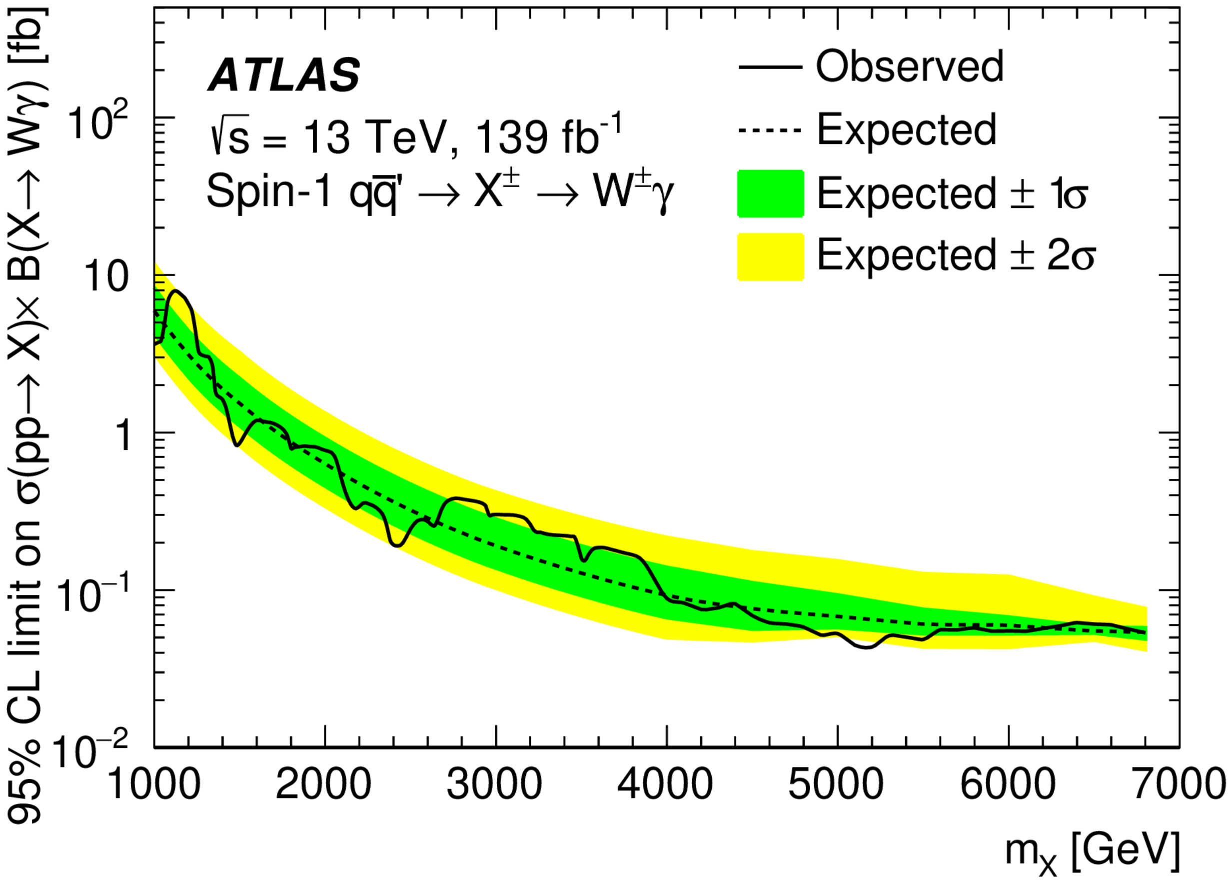
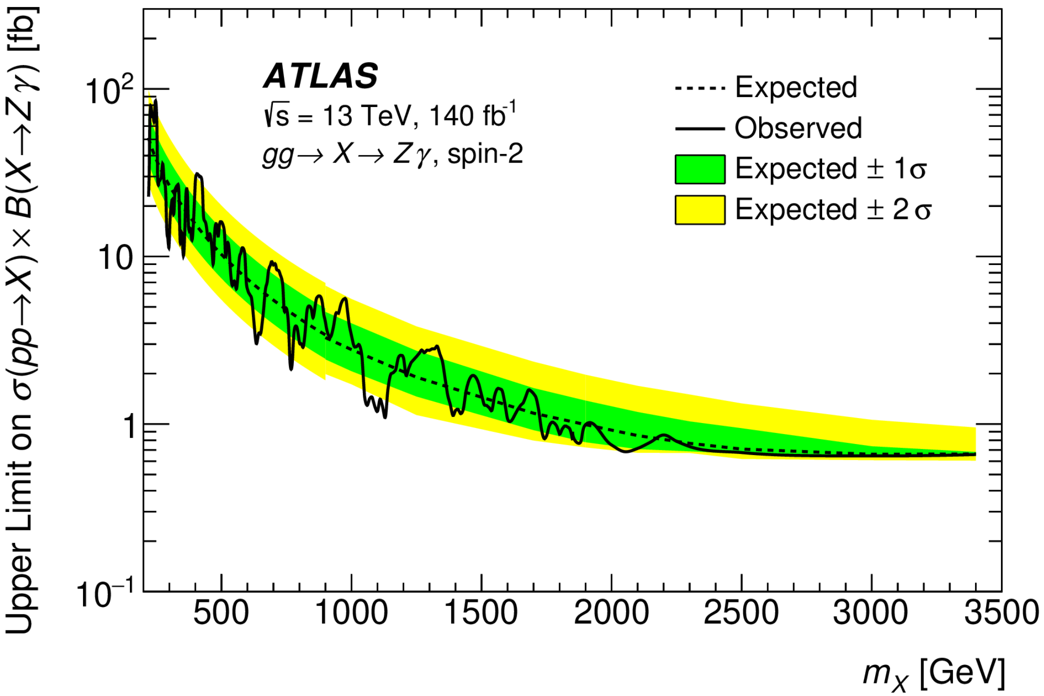
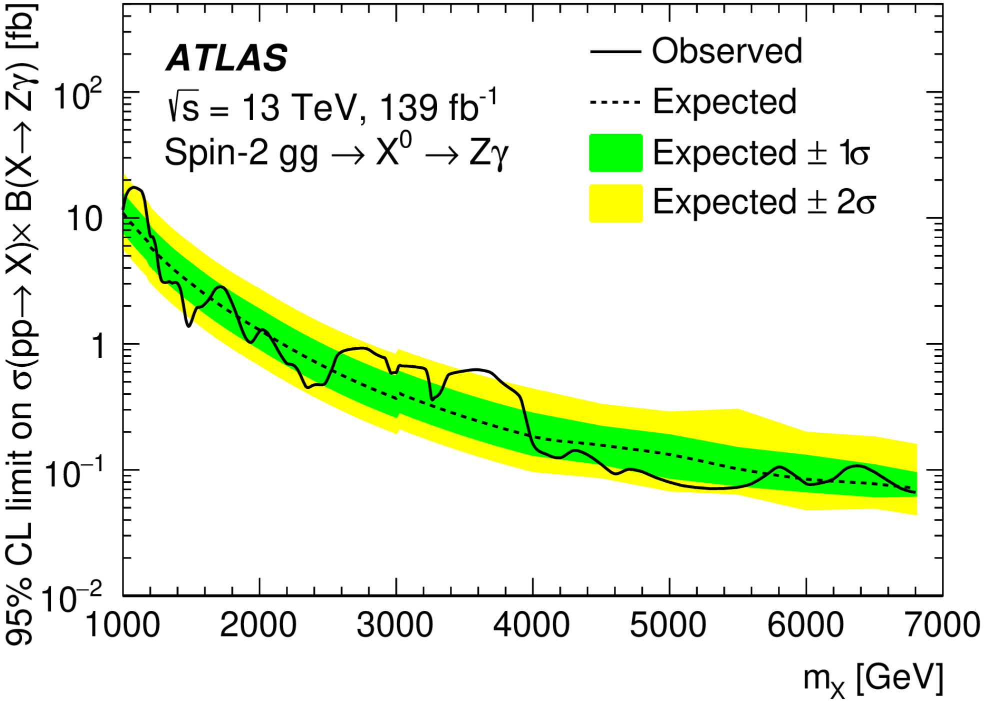
$Z\gamma$: $X \to Z\gamma$; hadronic

Channel	BTAG	D2	VMASS
Spin-0 $gg \to X^0 \to Z\gamma$	436	5 659	20 728
Spin-2 $gg \to X^0 \to Z\gamma$	436	10 772	32 281
Spin-2 $q\bar{q} \to X^0 \to Z\gamma$	436	5 618	18 264
Spin-1 $q\bar{q}' \to X^\pm \to W^\pm\gamma$	—	6 373	25 146



Spin-2 limits from $X \to Z\gamma$





Spin-2 limits from $X \to Z\gamma$