Heavy neutral scalar searches at the LHC

Lailin Xu（徐来林）

Higgs potential and BSM opportunity 希格斯物理研讨会

Nanjing Uni., Aug 27-31, 2021 (Online)

Introduction

- Is the Higgs boson *solely* responsible for the EWSB?
- Many BSM theories predict new particles that decay into SM particles
- Search for resonances is one of the most straightforward ways to probe BSM

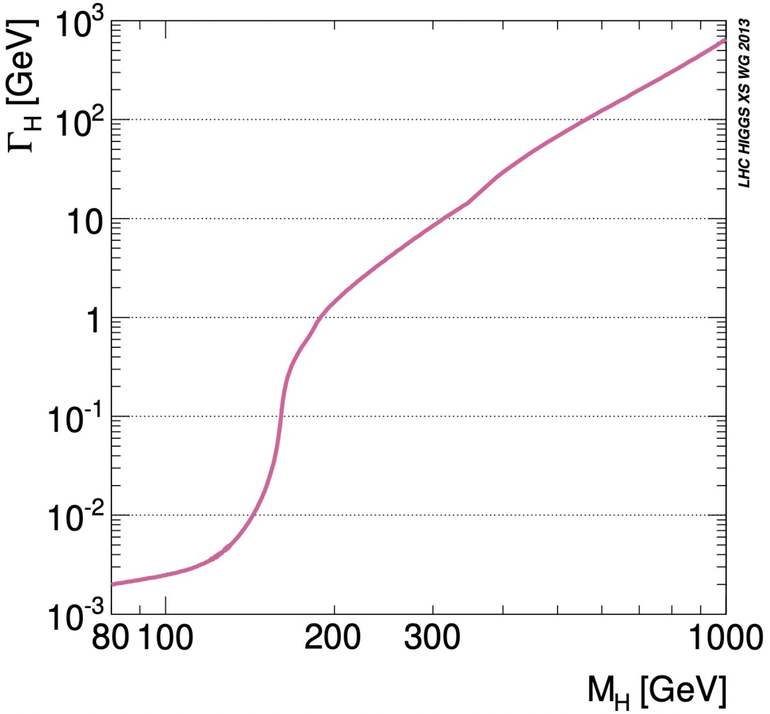
- Overview of heavy neutral (pseudo)scalar searches
  - Experimental signatures
    - Dilepton
    - Dijet
    - Multiboson
  - Benchmark models
    - Heavy Higgs: CP-even (h), CP-odd (A)
    - Radions
    - Dark sector: dark Higgs (*not covered*)
    - Axion-like particles

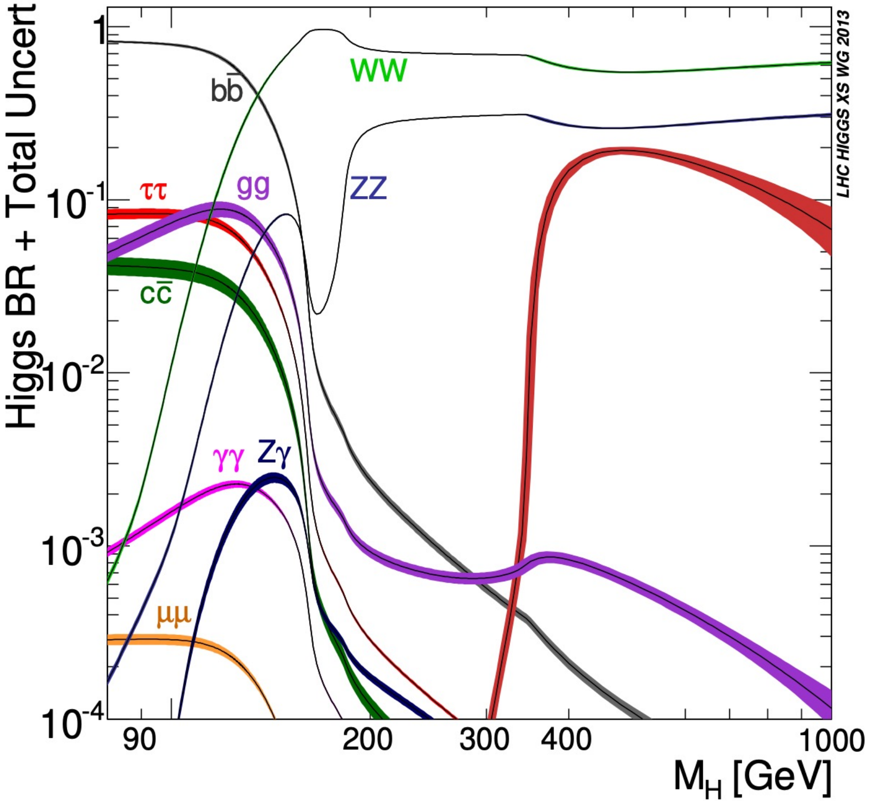
For light scalar or charged scalar searches, see talks by Hanlin Xu, Jin Wang

For DiHiggs resonance searches, see talks in Sunday (Zihang Jia, Bowen Zhang, Bruce Mellado, …)

Heavy Higgs-like scalars

- Quite generic (less model-dependent) resonance searches
  - Properties similar to the SM Higgs with couplings to SM particles
- Width assumption:
  - Narrow width: intrinsic width ≪ detector resolution → interference with the SM can be safely ignored
  - Large width: scan different values of $\frac{\Gamma_H}{m_H}$





LHC Higgs WG

Extended Higgs sector

- Electroweak singlet: simplest extension
  - Either a real or complex scalar singlet
  - Can provide a strong first order electroweak phase transition → electroweak baryogenesis
- Extension of the SM Higgs sector to 2 Higgs doublets: 2HDM
  - Lead to 5 Higgs bosons: CP-even h, **H**, CP-odd: **A**, charged: $\boldsymbol{H^{\pm}}$
  - Benchmark coupling structures: type-I/II/III/IV

See theory talks by Wei Liu, Mengchao Zhang

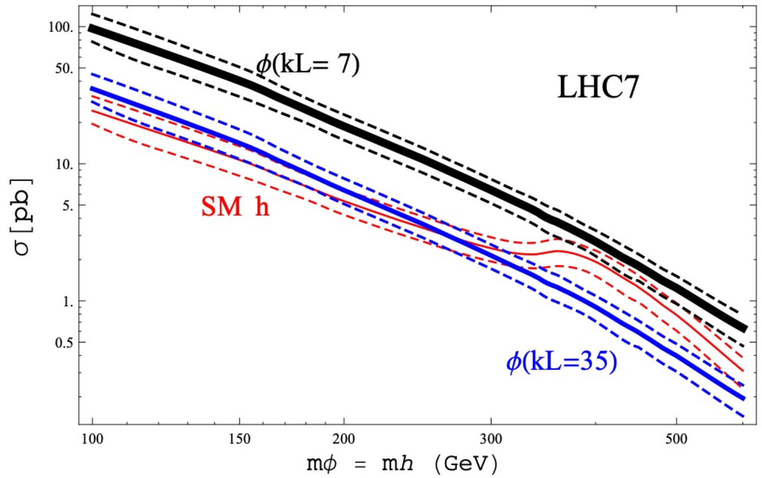
	I	II	Lepton Specific	Flipped
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$g_{ht\bar{t}}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$g_{hb\bar{b}}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$g_{h\tau^+\tau^-}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

- MSSM: the same structure of the Higgs sector as for 2HDM-II
  - Only two basic inputs for the Higgs sector at tree level: $\mathbf{m_A}$**, tanβ**
  - Some variants:
    - hMSSM, M_h^{125} scenarios, etc

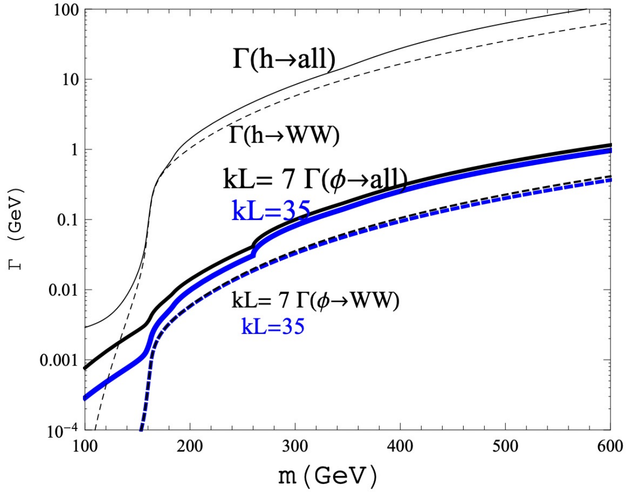
Radion

- A scalar predicted by the bulk Randall-Sundrum model
  - can address both the hierarchy problem and fermion mass hierarchies
- LHC phenomenology: similar to heavy Higgs
  - Radions can be produced via both ggF and VBF processes
  - Decay to WW/ZZ/$\gamma\gamma$/hh/tt

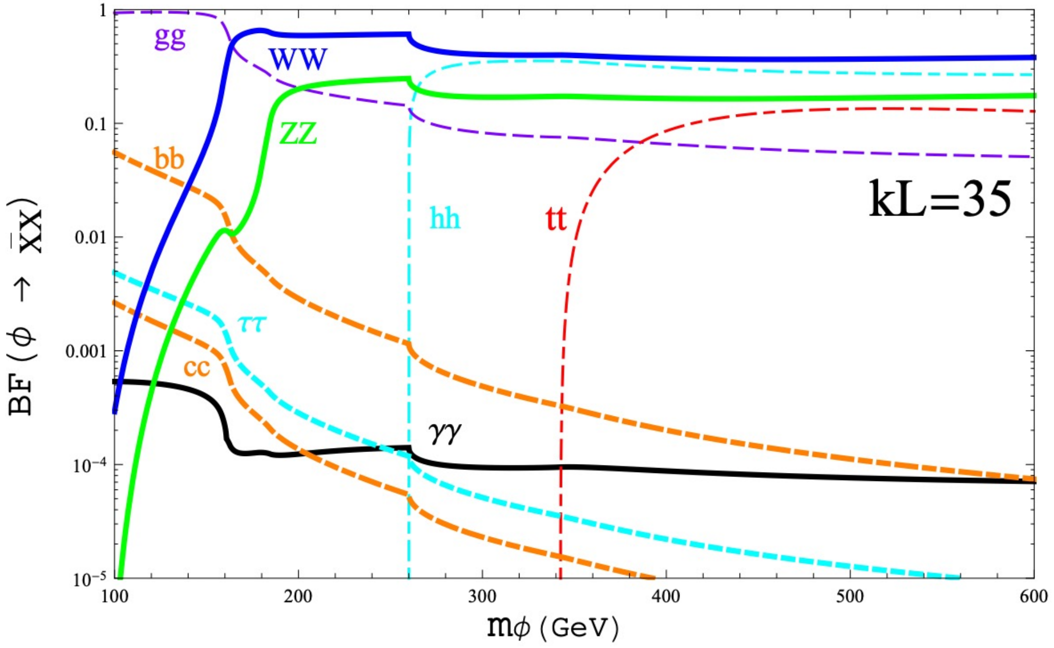
ggF production



Total width



Decay branching ratios



V. Barger, M. Ishida, PLB 709 (2012) 185-191

Axion-like particles

- The QCD axion: a pseudo-scalar and originally proposed to solve the strong-CP problem
  - Couplings to SM particles proportional to its mass
- ALPs: an extension to QCD axions with two free parameters (m_a, f_a)
  - f_a : the scale of symmetry breaking of the new field (couplings $\sim \frac{1}{f_a}$)
- Constraints from ALPs are mainly from astrophysical observations
  - Through $a\gamma\gamma$ interactions for very low m_a ($\sim 10^{-10}$eV)
- ALPs can also be probed at the LHC
  - eg. as an off-shell mediator in the s-channel 2 → 2 scattering processes

M.B. Gavela et al, PRL 124, 051802 (2020)

$$\delta\mathcal{L}_{\rm eff} \supset c_{\tilde{G}}\,\mathcal{O}_{\tilde{G}} + c_{\tilde{B}}\,\mathcal{O}_{\tilde{B}} + c_{\tilde{W}}\,\mathcal{O}_{\tilde{W}} + c_{a\Phi}\,\mathcal{O}_{a\Phi}\,,$$
$$\mathcal{O}_{\tilde{G}} \equiv -\frac{a}{f_a}G_{\mu\nu}\widetilde{G}^{\mu\nu}\,, \quad \mathcal{O}_{\tilde{W}} \equiv -\frac{a}{f_a}W^a_{\mu\nu}\widetilde{W}^{\mu\nu}_a\,,$$
$$\mathcal{O}_{\tilde{B}} \equiv -\frac{a}{f_a}B_{\mu\nu}\widetilde{B}^{\mu\nu}\,, \quad \mathcal{O}_{a\Phi} \equiv i\frac{\partial^\mu a}{f_a}\,\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\,.$$

$\Rightarrow$

$$g_{agg} = \frac{4}{f_a}c_{\tilde{G}}\,, \quad g_{a\gamma\gamma} = \frac{4}{f_a}\left(s_w^2\,c_{\tilde{W}} + c_w^2\,c_{\tilde{B}}\right)$$
$$g_{aWW} = \frac{4}{f_a}c_{\tilde{W}}\,, \quad g_{aZZ} = \frac{4}{f_a}\left(c_w^2\,c_{\tilde{W}} + s_w^2\,c_{\tilde{B}}\right)$$
$$g_{a\gamma Z} = \frac{8}{f_a}s_w c_w (c_{\tilde{W}} - c_{\tilde{B}})\,,$$

Gives non-resonant diboson production

Dilepton searches

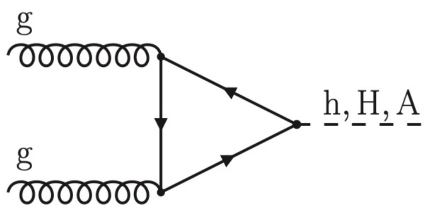
A/H→$\mu\mu$

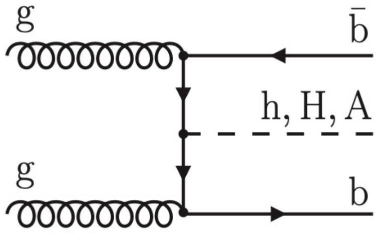
A/H→$\tau\tau$: see Hanfei's talk

A/H→μμ

PLB 798 (2019) 134992

- Search of MSSM A/H
- Has small branching ration but excellent mass resolution
  - $\lambda_f = \sqrt{2}\frac{m_f}{v}$, $\Gamma(\mathrm{H} \to \mathrm{ff}) \propto \lambda_f^2$

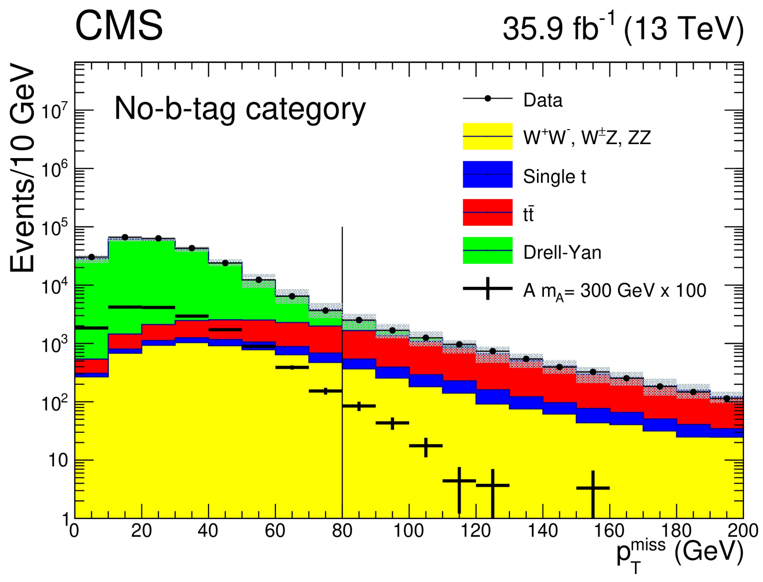




- Overview:
  - Events split into b-tag and no-b-tag categories to target for gg- and bb-initiated productions
  - Dominant background: Drell-Yan
  - Discriminant: $m_{\mu\mu}$
    - Background shape parametrized as a functional form
  - Signal modelling considered all dimuon events from h/H/A decays

$$\boxed{F_{\mathrm{sig}} = w_{\mathrm{h}} F_{\mathrm{h}} + w_{\mathrm{H}} F_{\mathrm{H}} + w_{\mathrm{A}} F_{\mathrm{A}}}$$

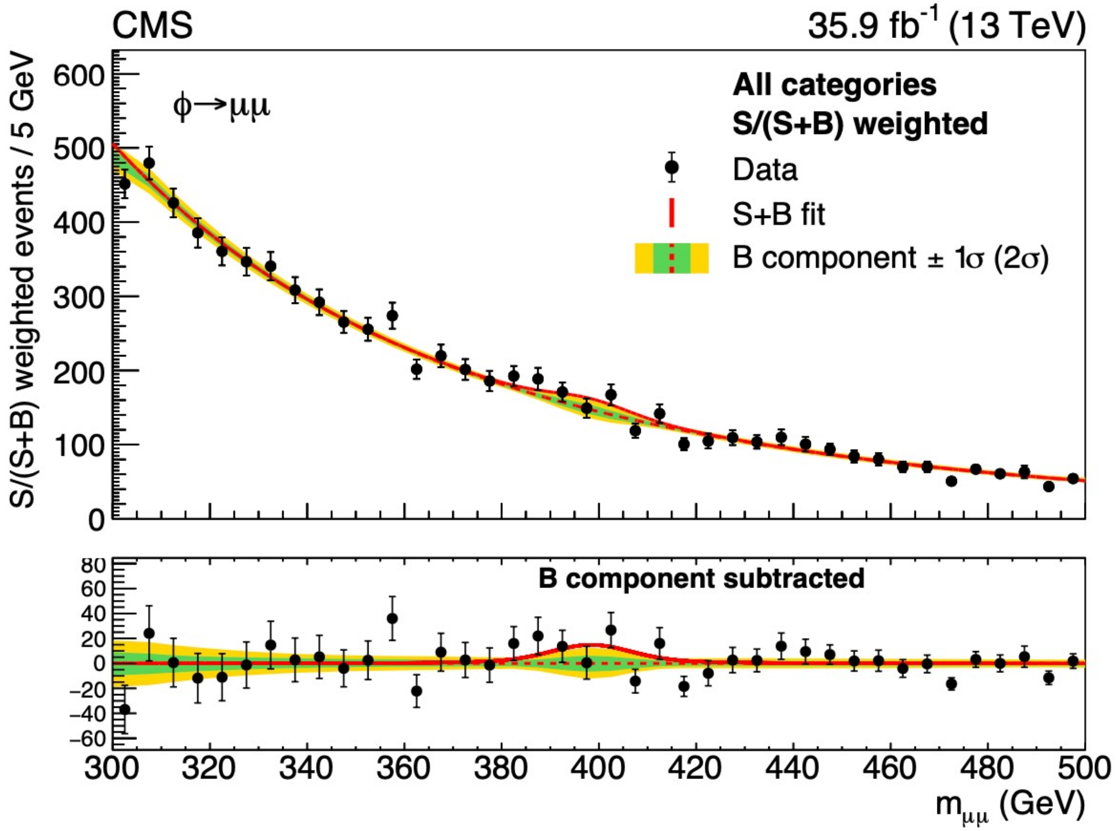
    - For each m_A, tanβ pair



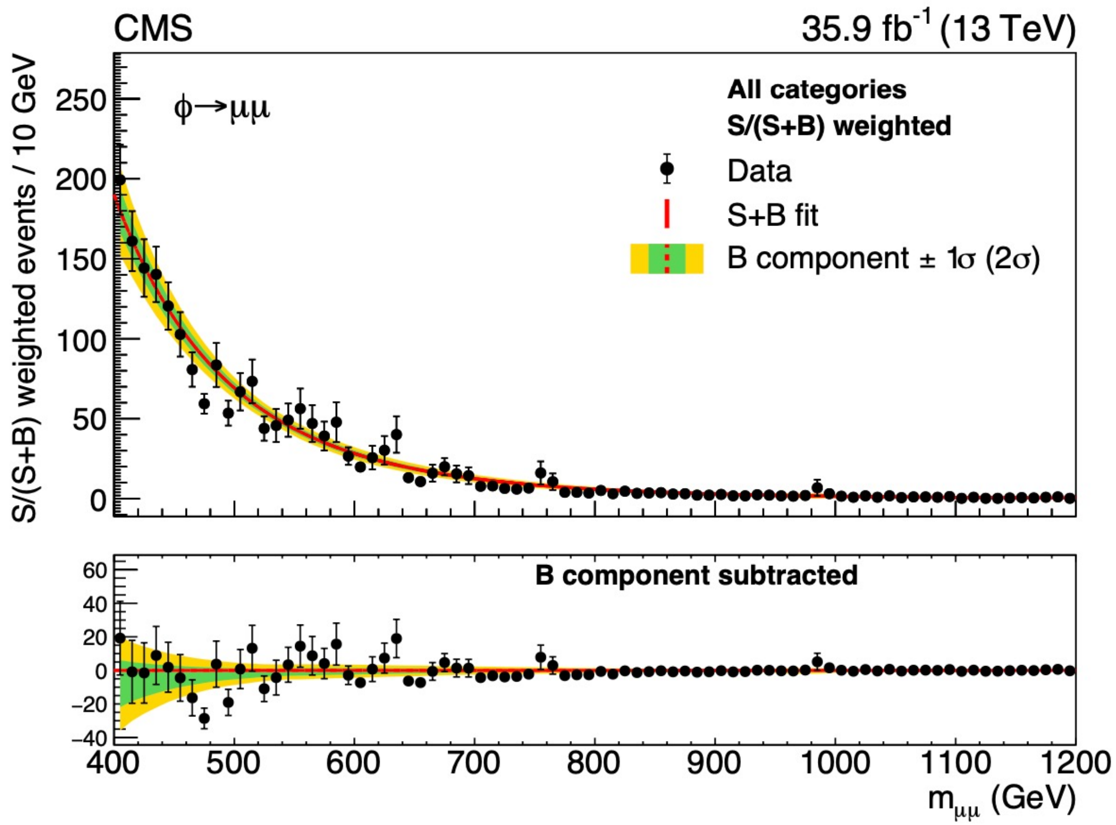
A/H→μμ

PLB 798 (2019) 134992

- Dimuon mass



Signal + bkg fit with signal mass of **400** GeV

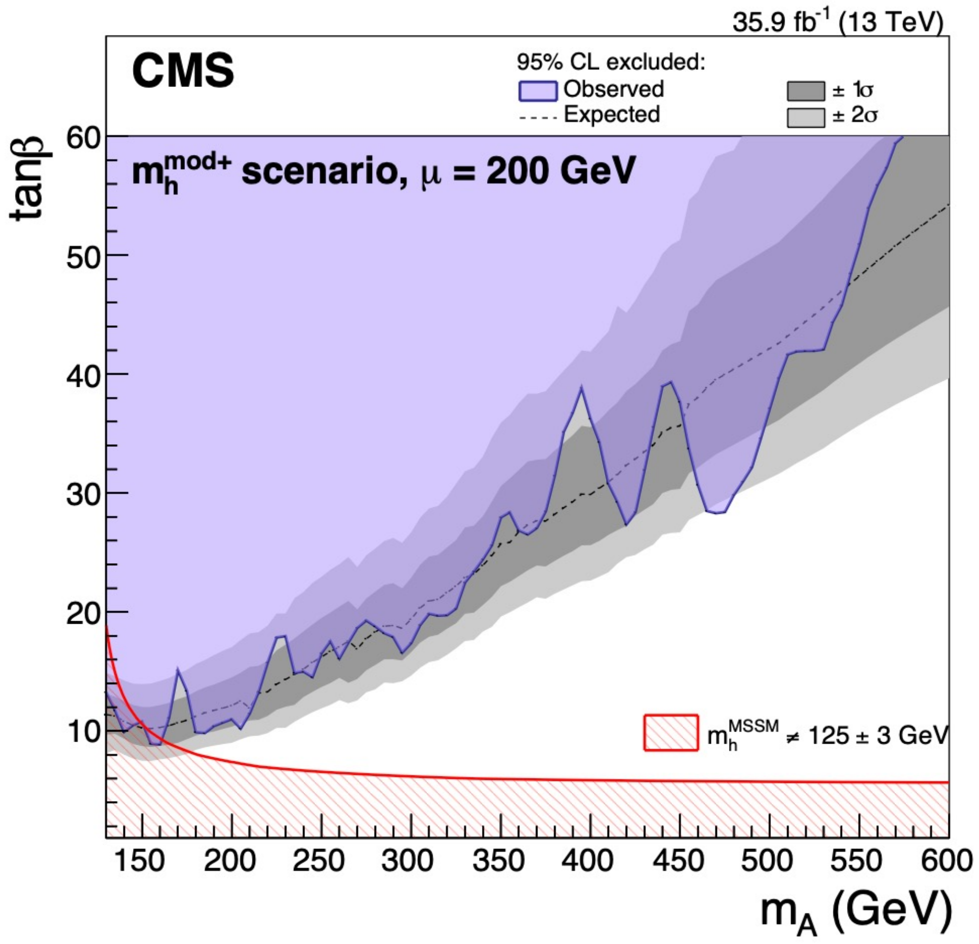


Signal + bkg fit with signal mass of **980** GeV

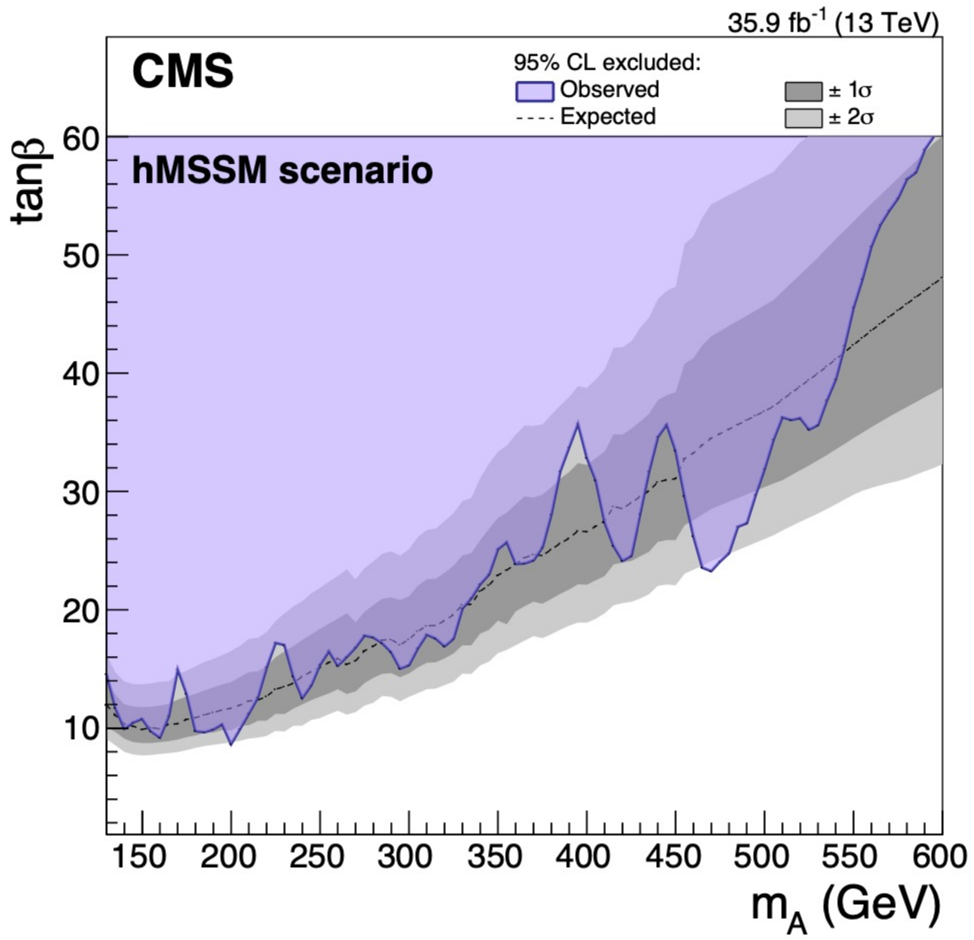
A/H→μμ

PLB 798 (2019) 134992

- Exclusion limits



m_h^{mod+} scenario



hMSSM scenario

Dijet searches

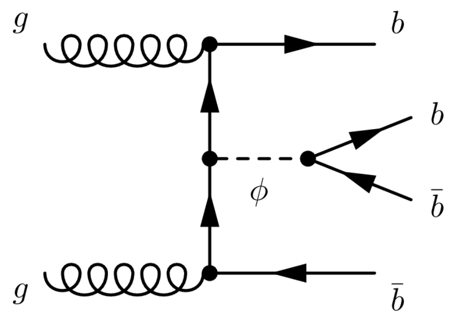
A/H→bb

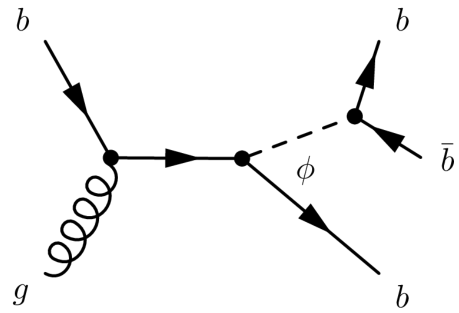
Top-quark final states: see Nicola's talk

H/A→bb

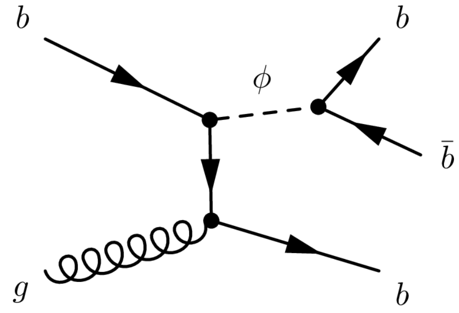
JHEP 08 (2018) 113

- Search for H/A→bb in association with b-quarks
  - Targeted for several MSSM and 2HDM scenarios
- Overview
  - Events are selected with >= 3 b-jets
    - Benefited from dedicated b-jet triggers
    - Two leading b-jets (M_{12}) to reconstruct H/A
  - Dominant background: QCD jets
  - Discriminant: M_{12}
    - Parametrized with functional forms
    - Divided into the three overlapping subranges, to avoid bias
      - [200, 650] GeV → for signal mass points $m_{A/H}$ in [300, 500] GeV
      - [350, 1190] GeV → for $m_{A/H}$ in [500, 1100] GeV
      - [500, 1700] GeV → for $m_{A/H}$ in [1100, 1500] GeV
    - Validated in a b-tag veto CR





FSR

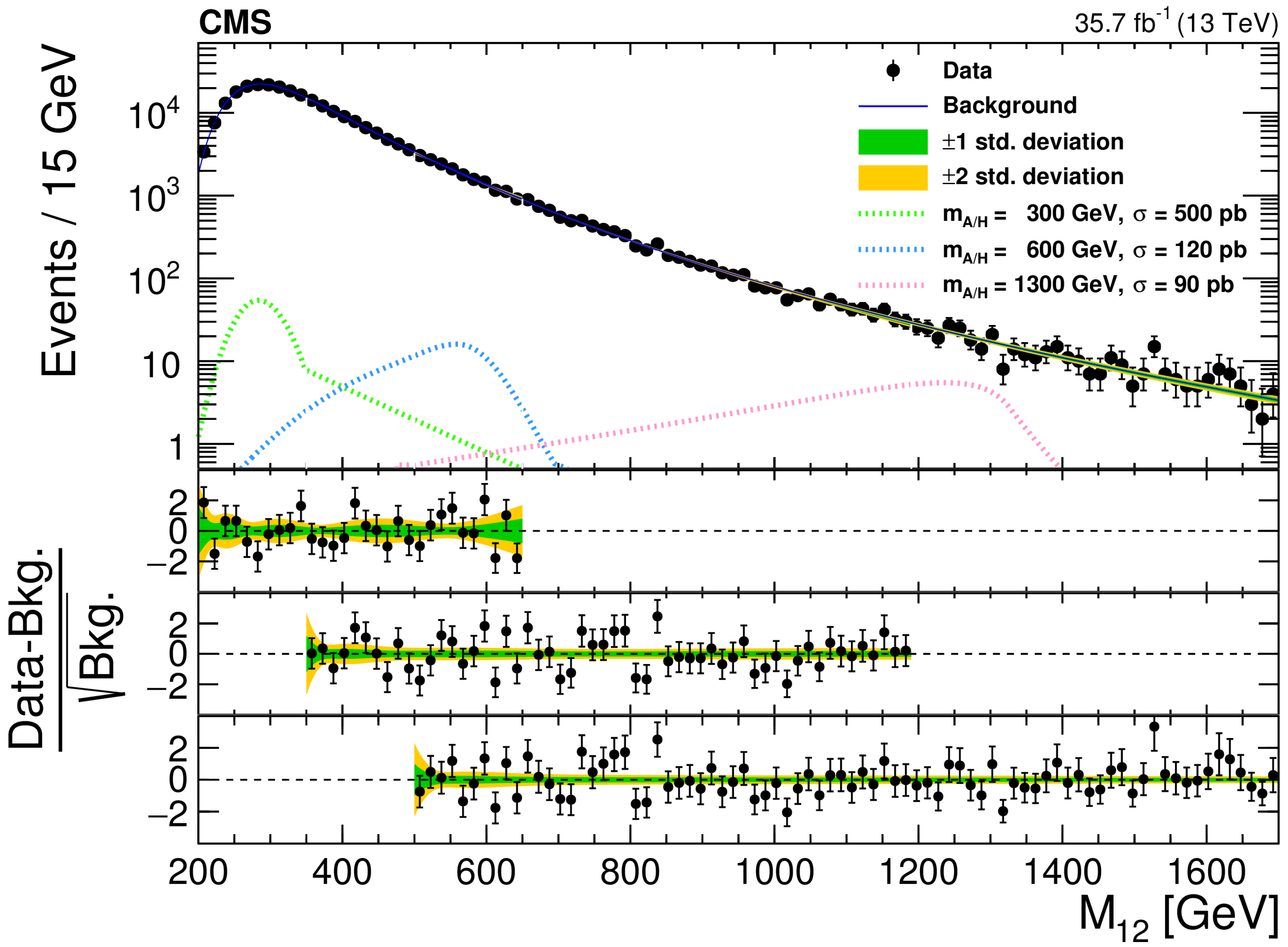


ISR

H/A→bb

JHEP 08 (2018) 113

- Mass spectrum



Signal + bkg fit in three sub-ranges

← [200, 650] GeV

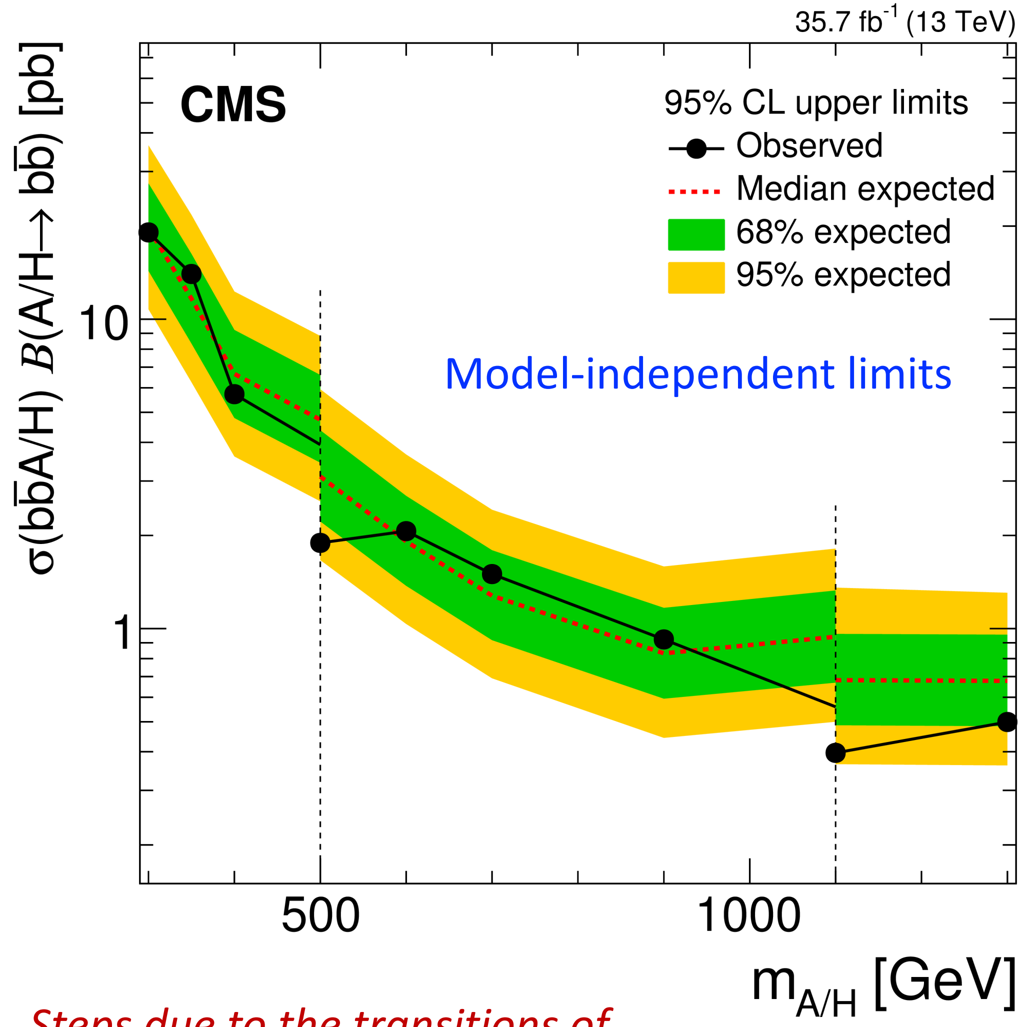
← [350, 1190] GeV

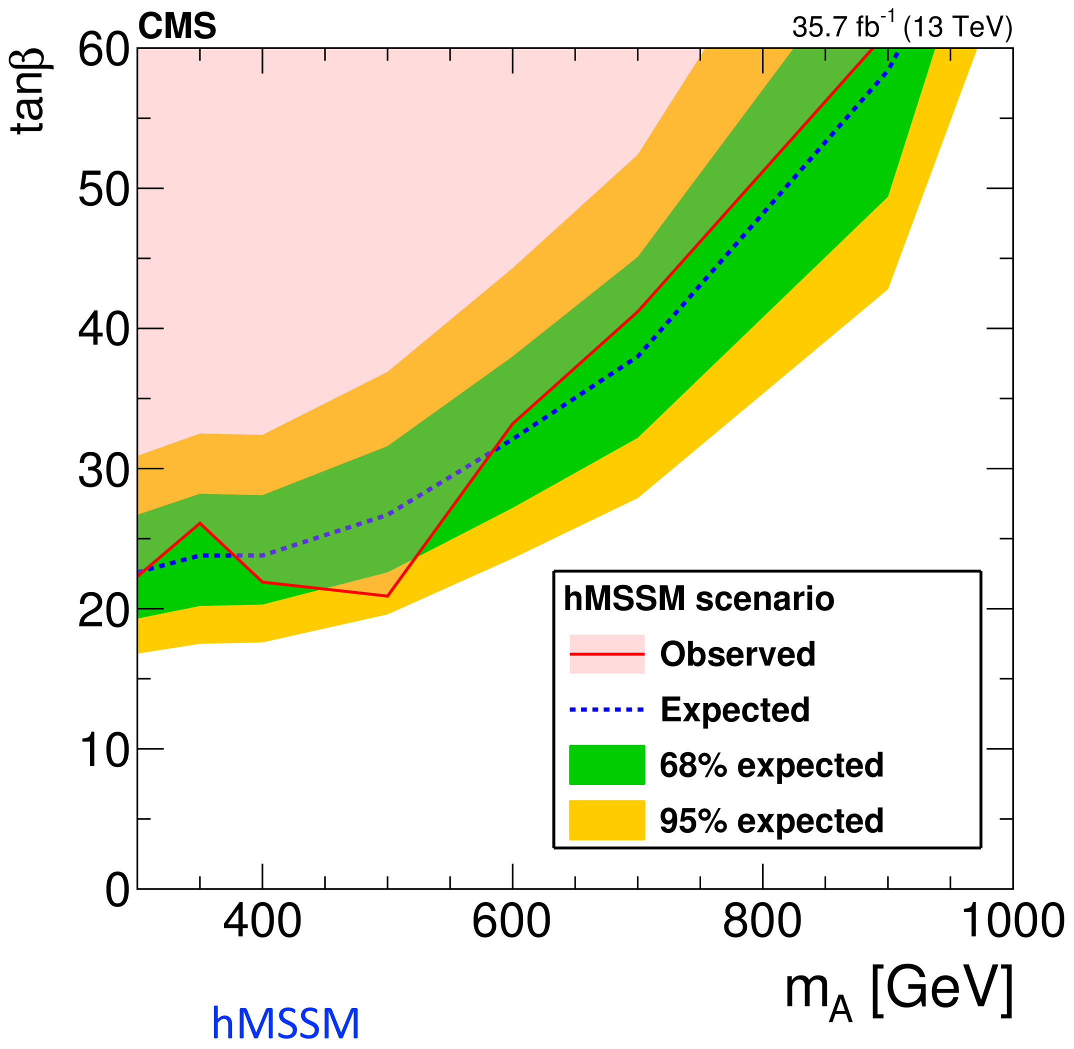
← [500, 1700] GeV

H/A→bb

JHEP 08 (2018) 113

- Exclusion limits





Steps due to the transitions of the mass sub-ranges

Diboson searches

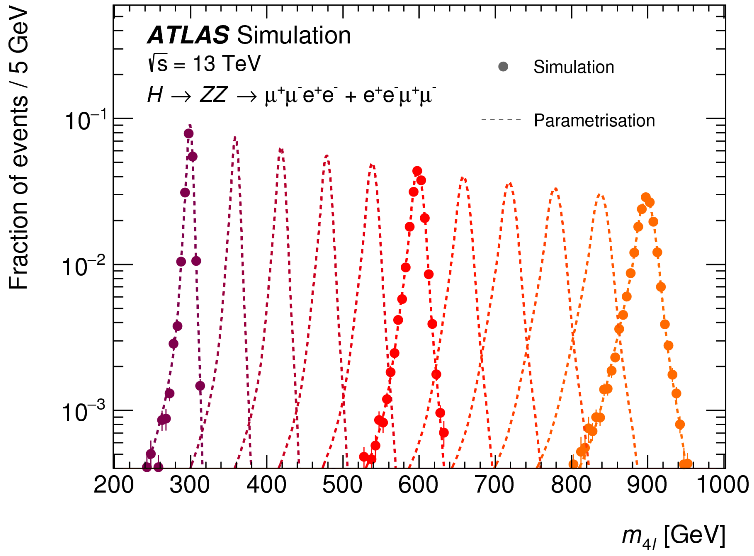
$X^0 \rightarrow ZZ$, WW, ZH, $Z\gamma$, $\gamma\gamma$

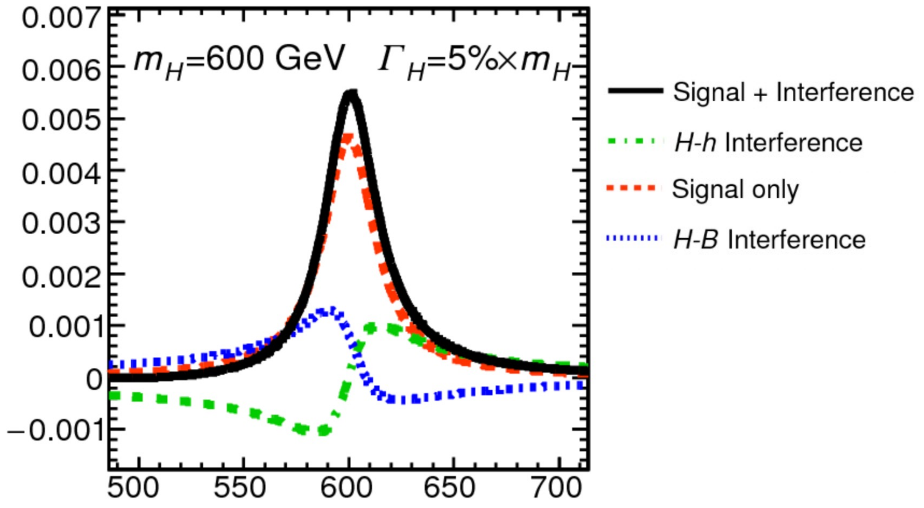
$X^0 \rightarrow HH$, see talks from the DiHiggs session

ZZ→4l, 2l2v

ATLAS EXPERIMENT [EPJC 81 (2021) 332]

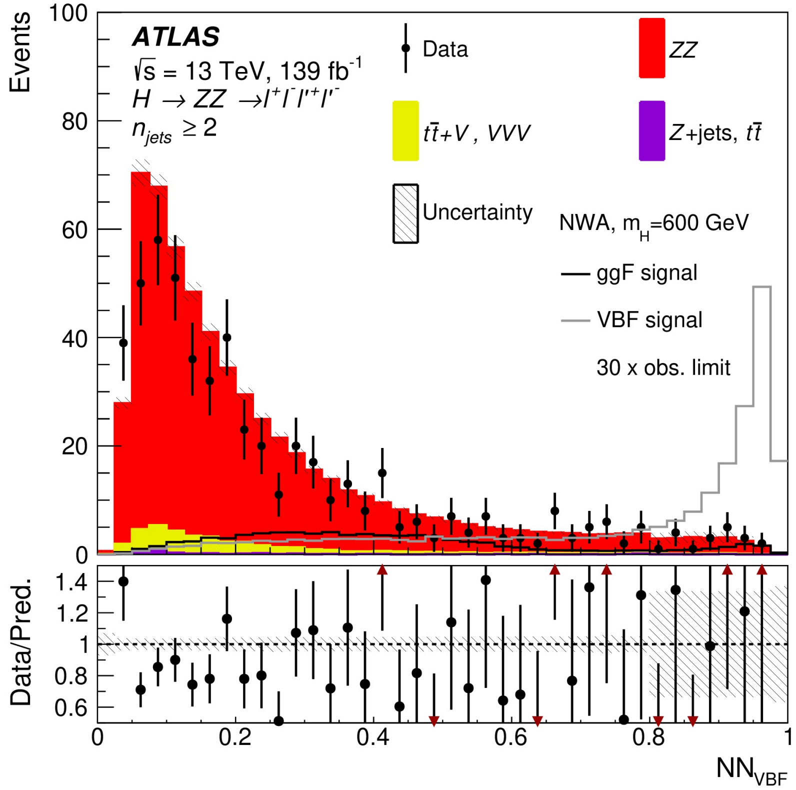
- Combination of 4l and 2l2v channels
  - benefit from mass resolution of 4l and larger branching ratio of 2l2v
- Overview:
  - Events are split into ggF-like and VBF-like categories to search for different signal productions
  - Discriminant: m_{4l}, $m_T(ll + E_T^{miss})$
  - Dominant SM background: ZZ, WZ (for 2l2v)
    - Normalization constrained from data
  - Interpretations: consider different signal width assumptions
    - narrow-width
    - large-width: $\frac{\Gamma_H}{m_H}$ = 1%, 5%, 10%, 15%, interference with the SM background considered



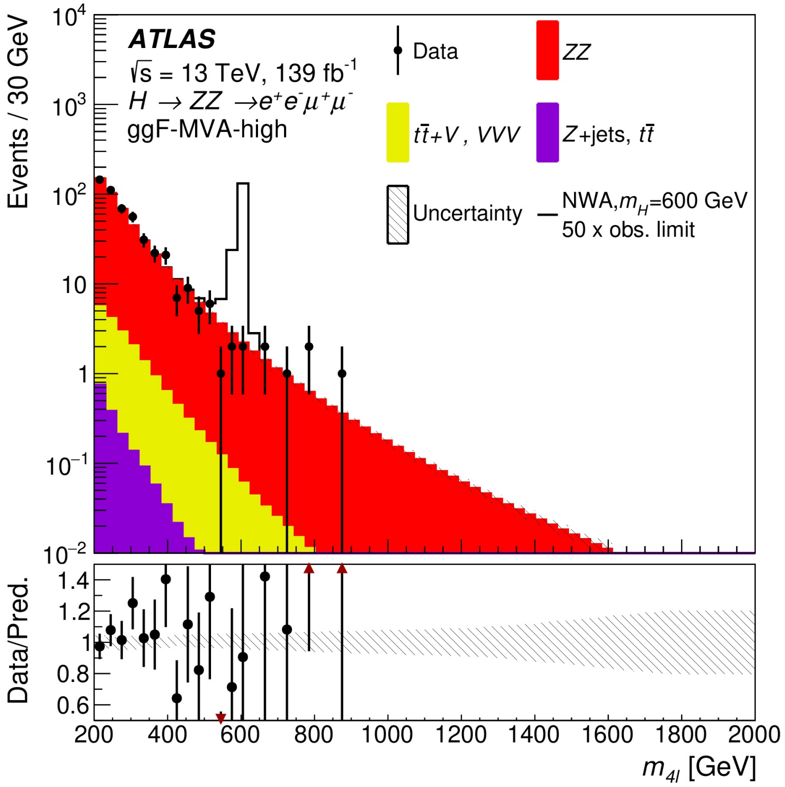


ZZ→4l, 2l2ν

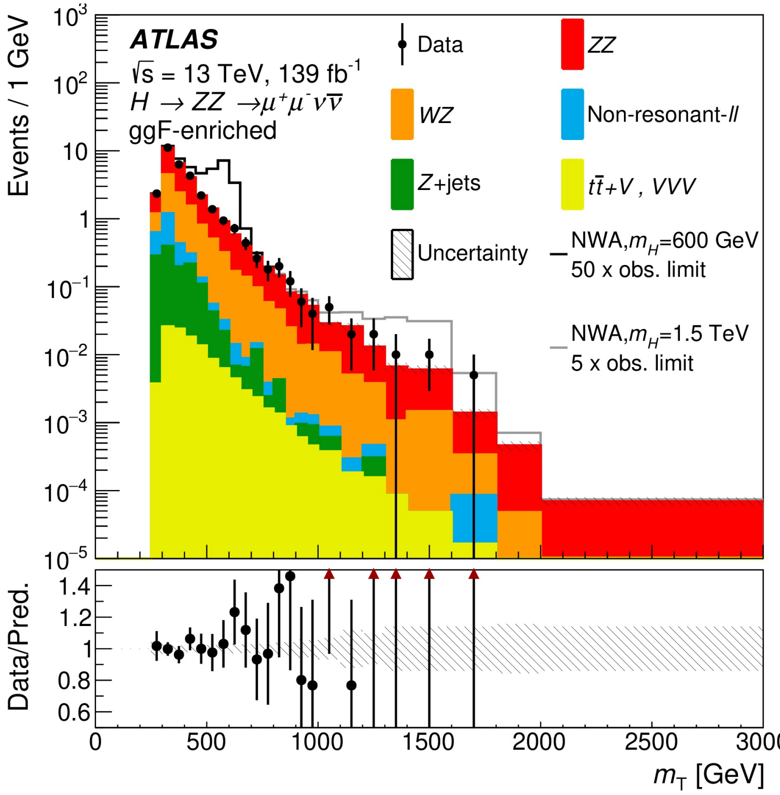
EPJC 81 (2021) 332



Neural Network Discriminant



Invariant mass m_{4l}

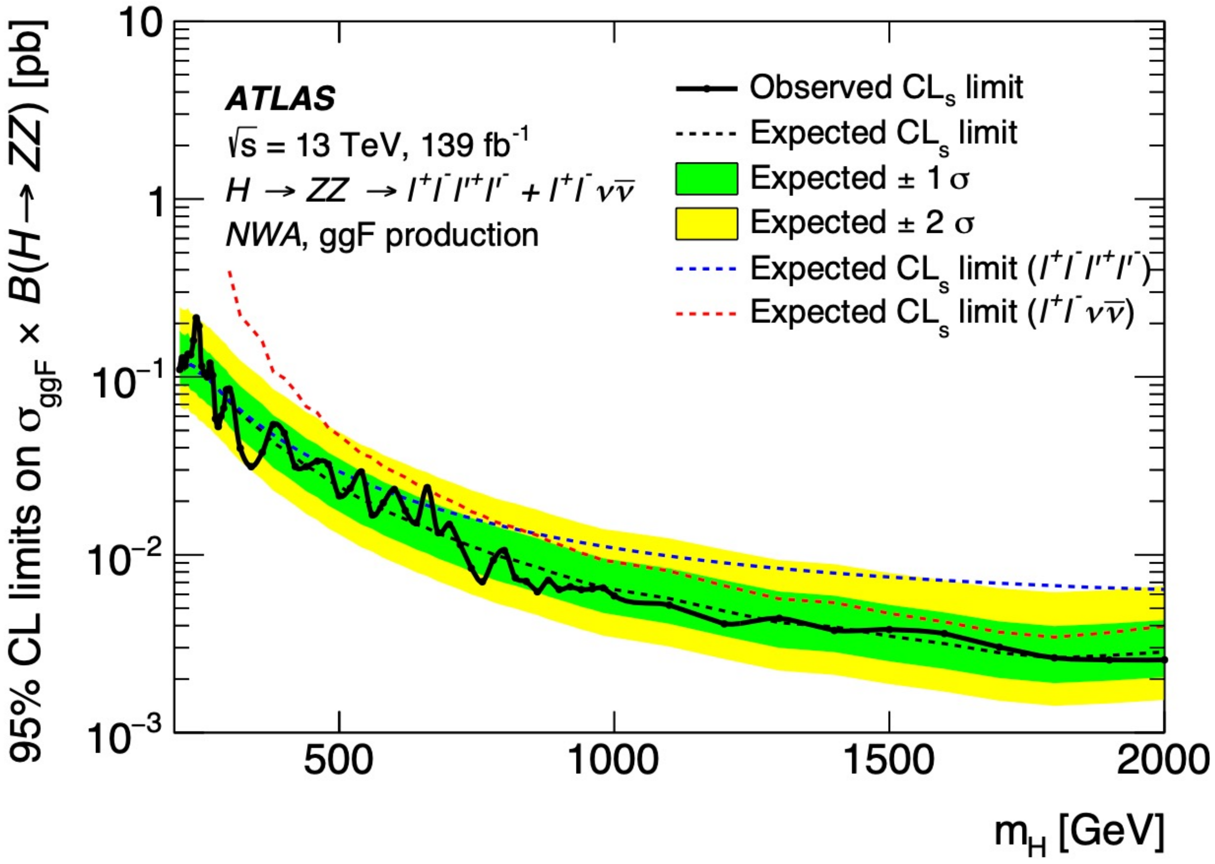


Transverse mass $m_T(ll + E_T^{miss})$

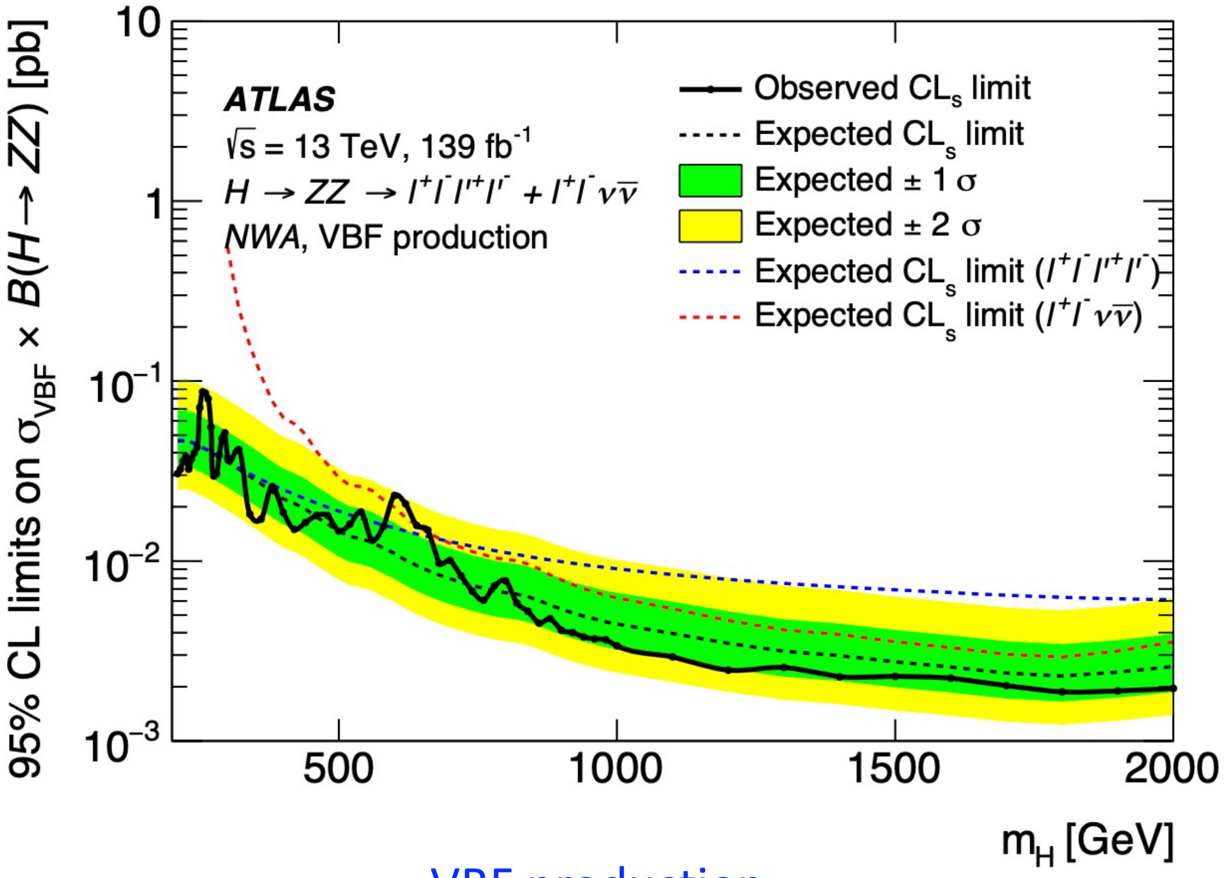
ZZ→4l, 2l2ν

EPJC 81 (2021) 332

- Exclusion limits: narrow width scalars



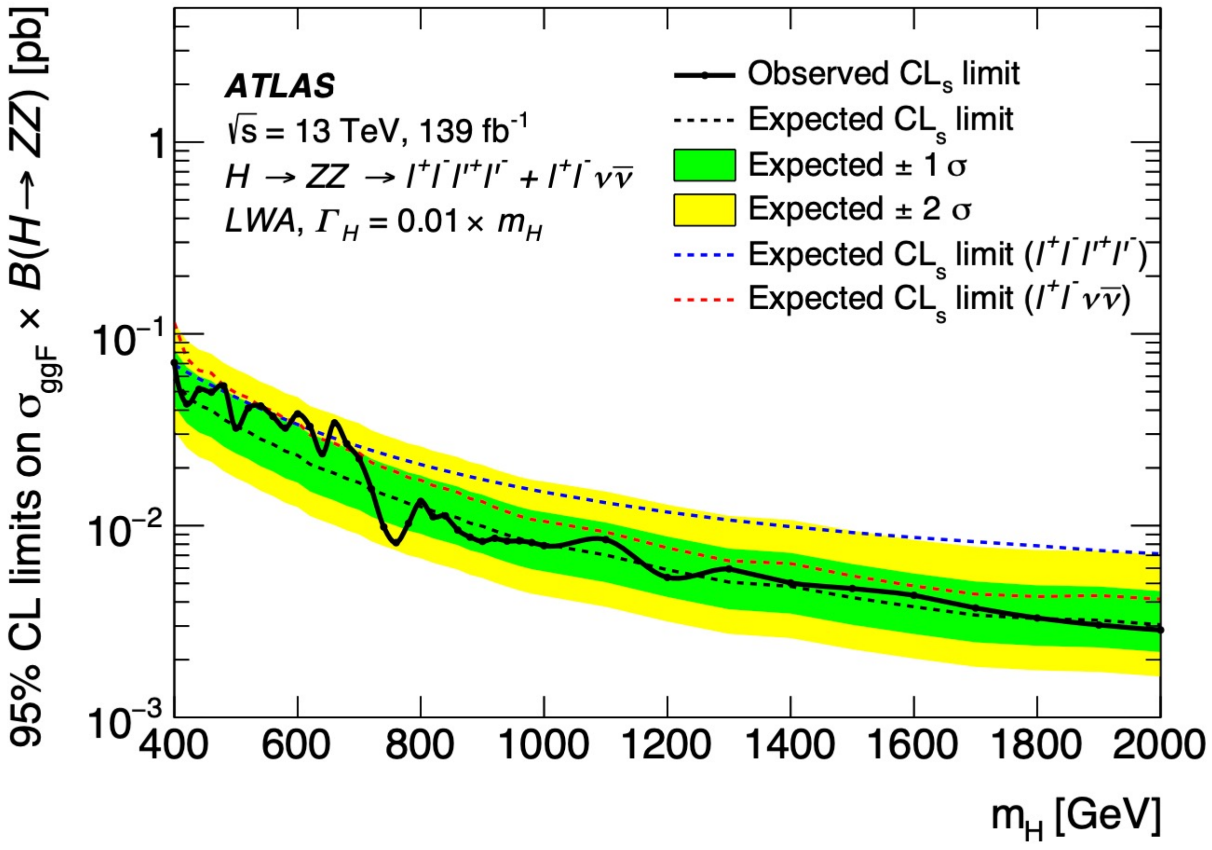
ggF production



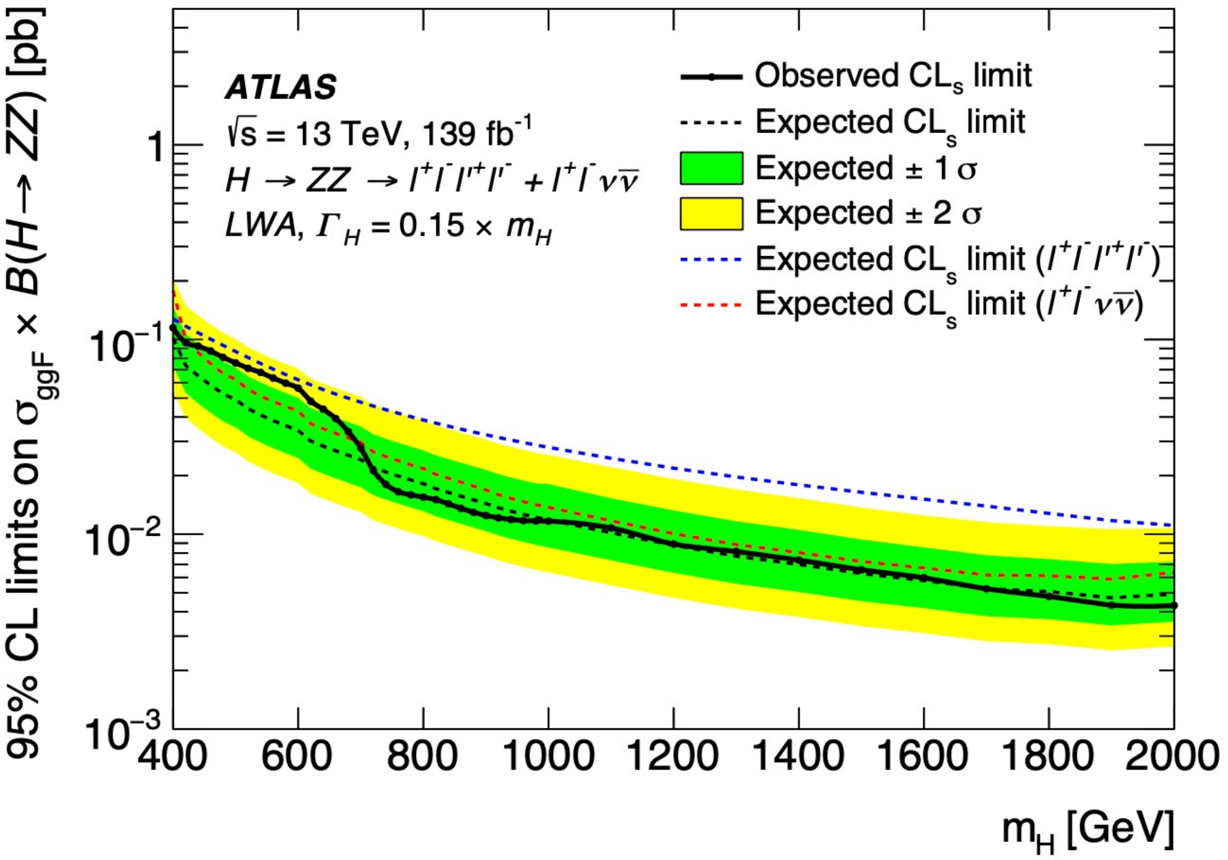
VBF production

EPJC 81 (2021) 332

- Exclusion limits: large width scalars



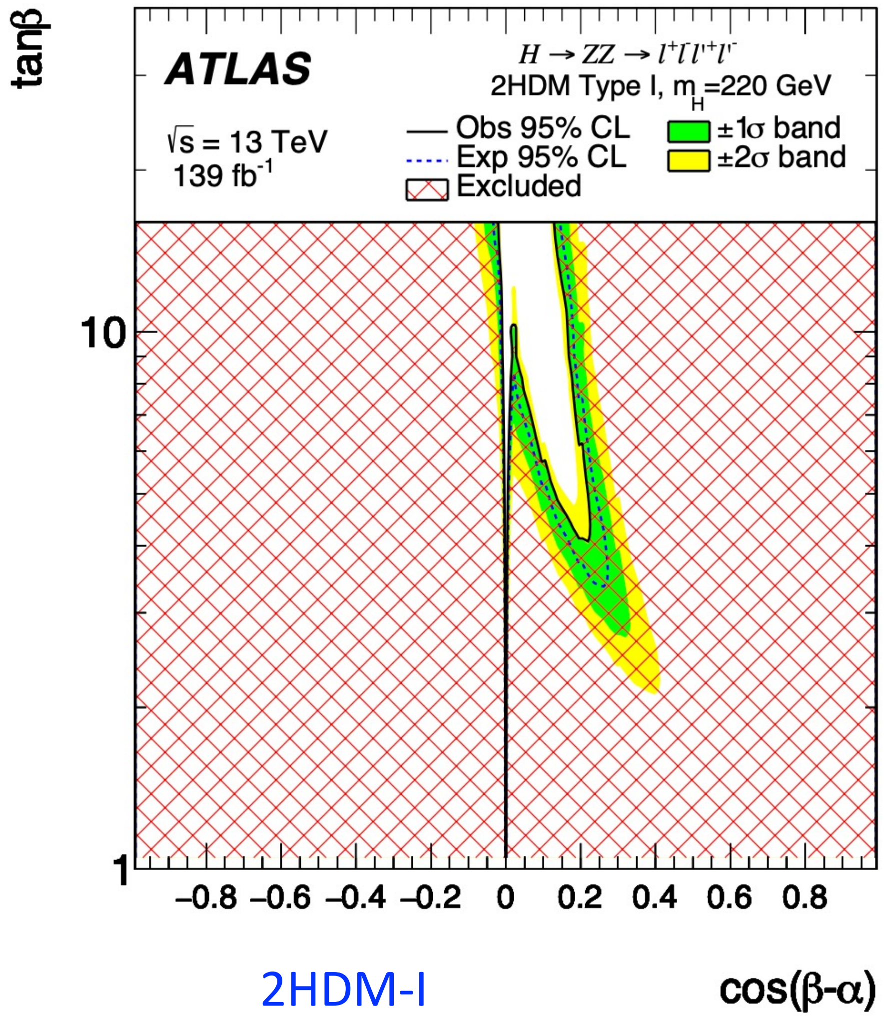
ggF production



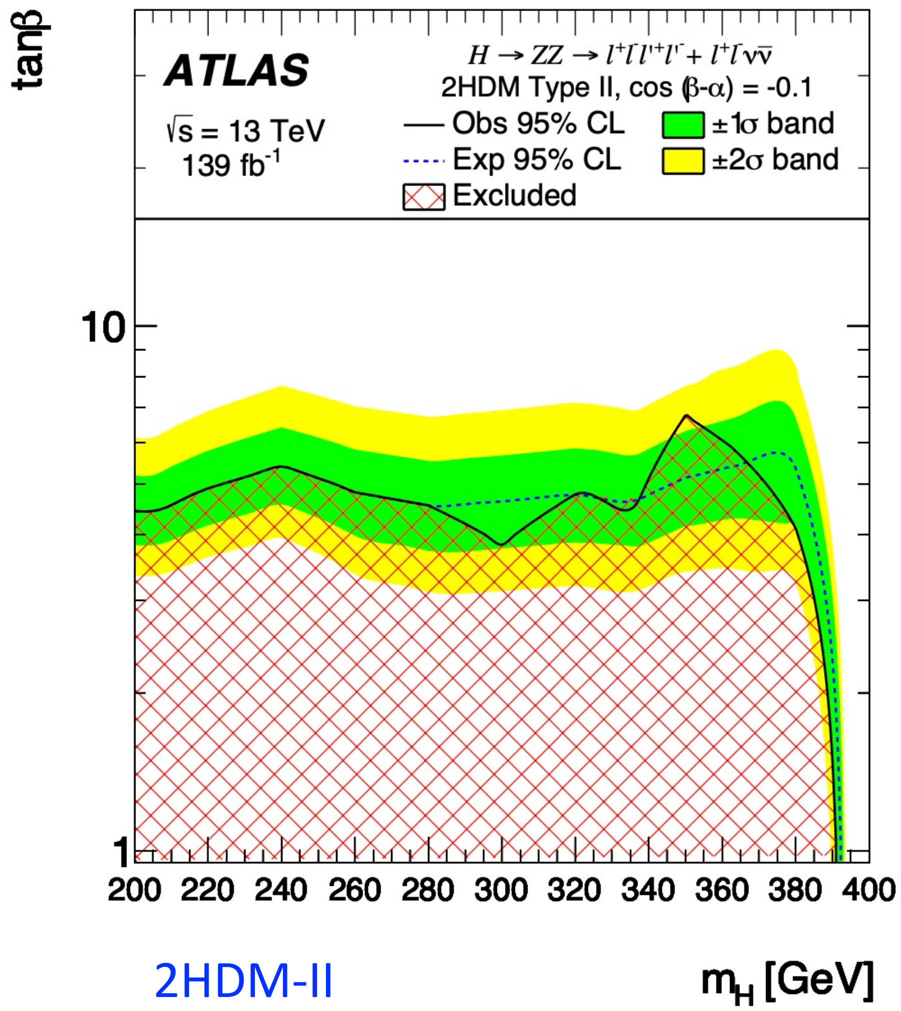
VBF production

EPJC 81 (2021) 332

- 2HDM interpretations



2HDM-I

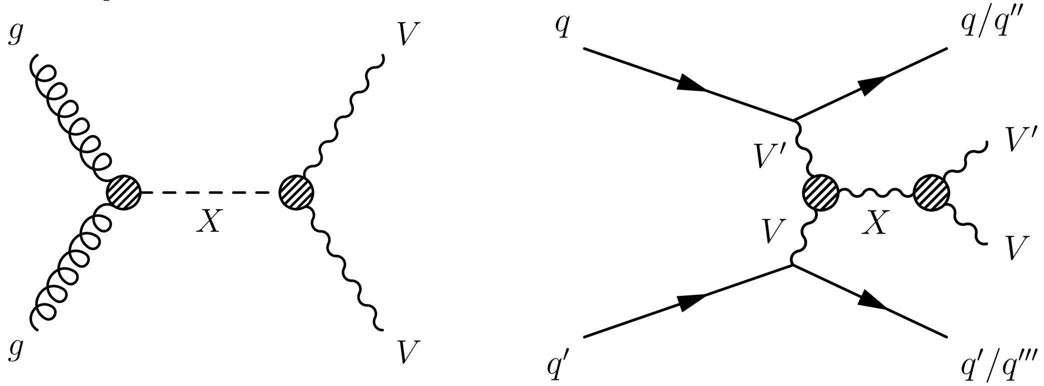


2HDM-II

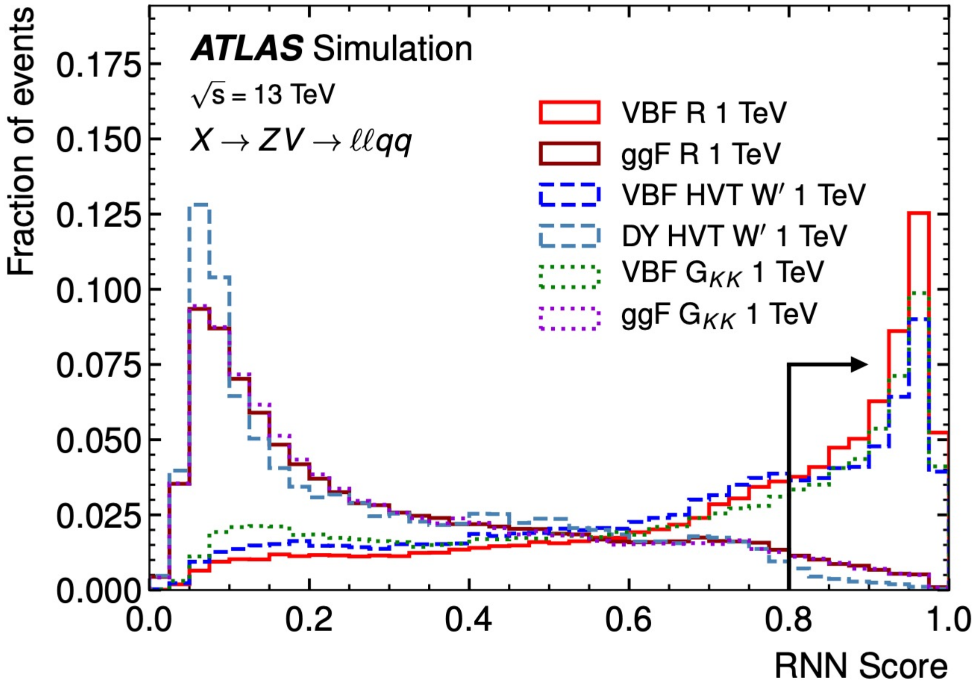
VV semileptonic

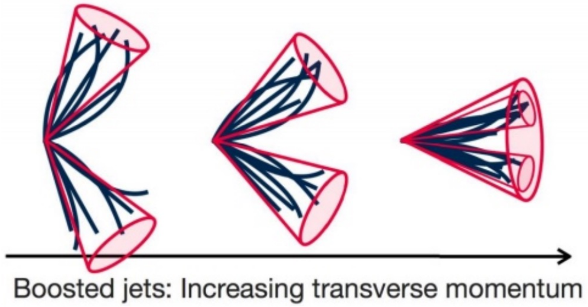
EPJC 80 (2020) 1165

- Systematically search for resonances in VV semileptonic final states
  - Leptonic V: W→lv, Z→ll, Z→vv
  - Hadronic V: W→qq, Z→qq



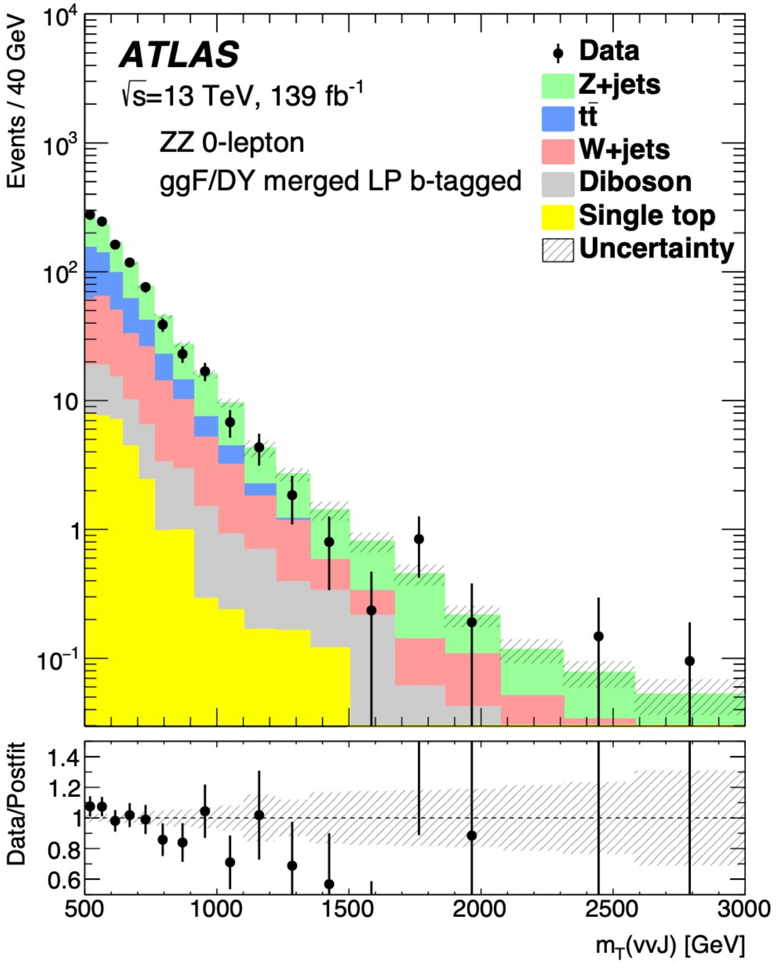
- Overview
  - 3 lepton channels: 0-lep, 1-lep, 2-lep
  - Both resolved (V→jj) and boosted (V→J)
  - Events split into ggF and VBF categories
    - Based on a recurrent neural network (RNN) discriminant
  - Dominant backgrounds: V+jets, ttbar
    - Constrained with dedicated data control regions



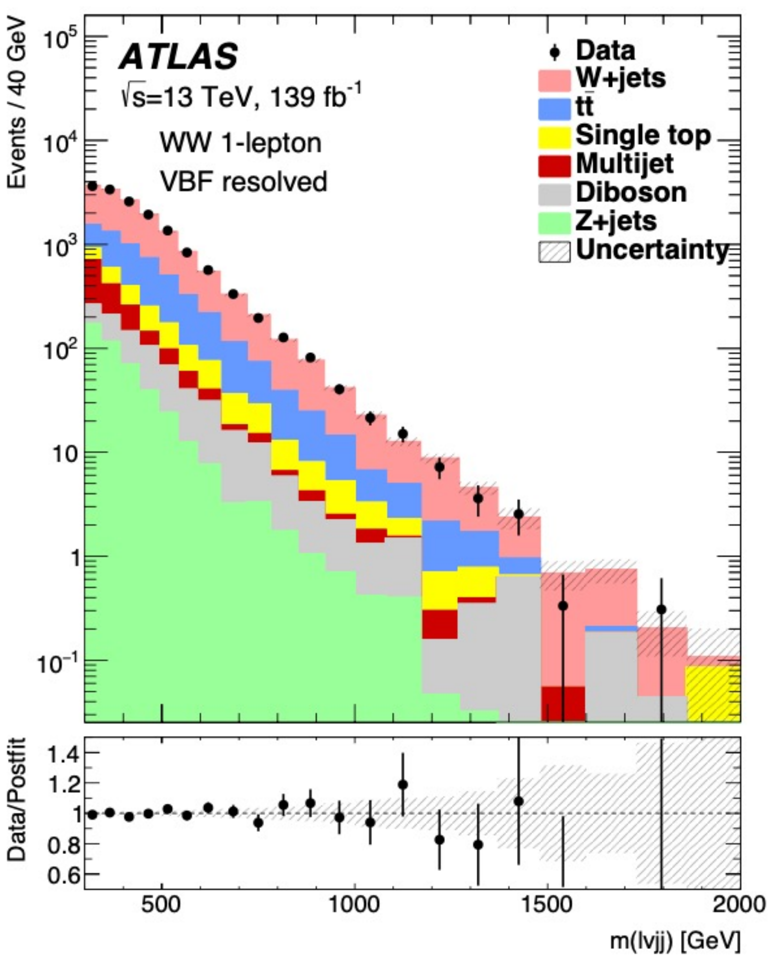


EPJC 80 (2020) 1165

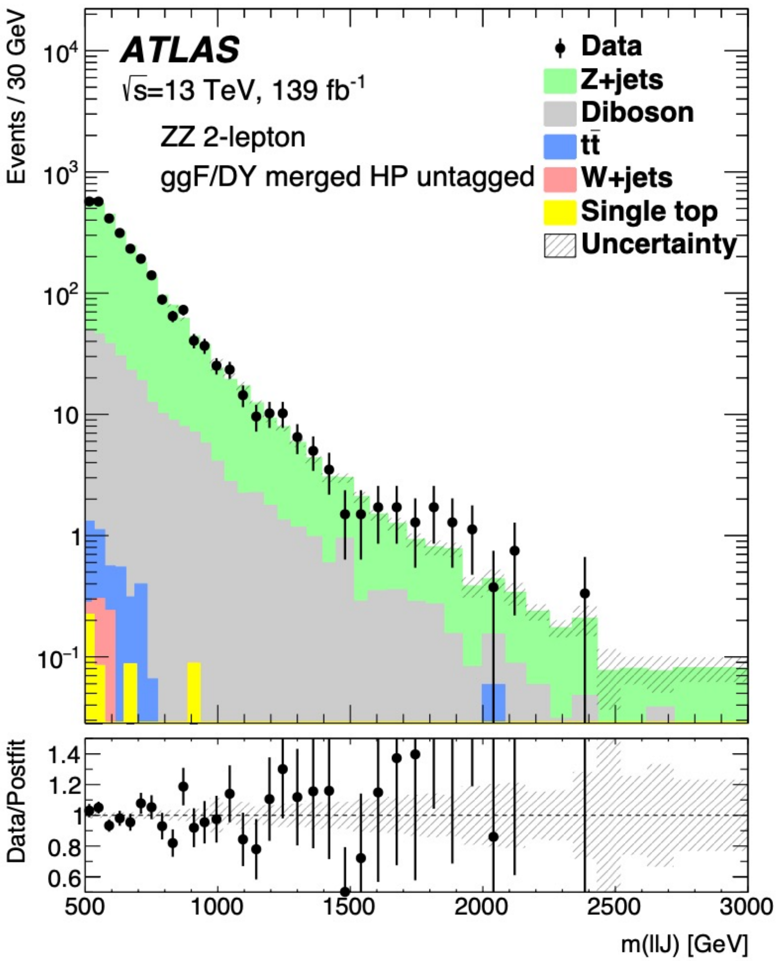
- Mass spectrum



0-lep, ggF, boosted



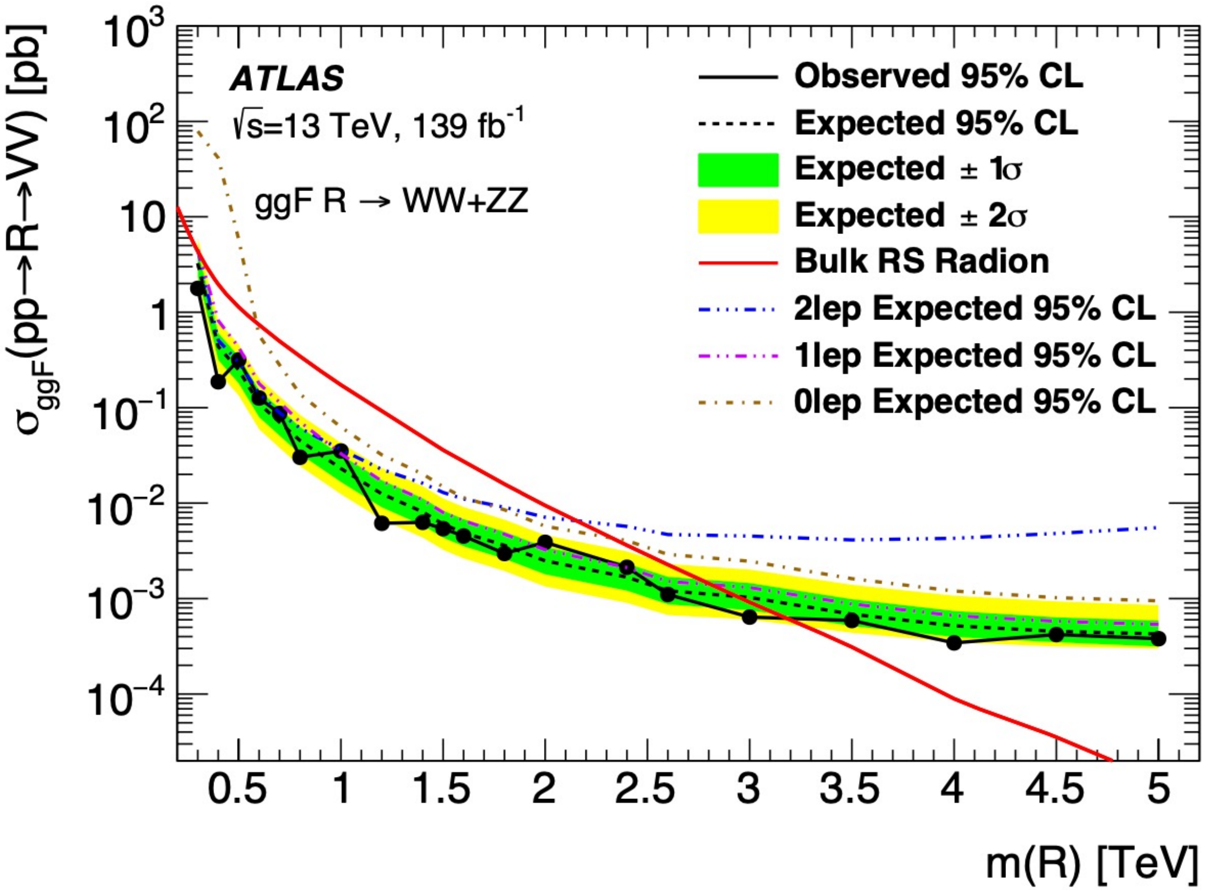
1-lep, VBF, resolved



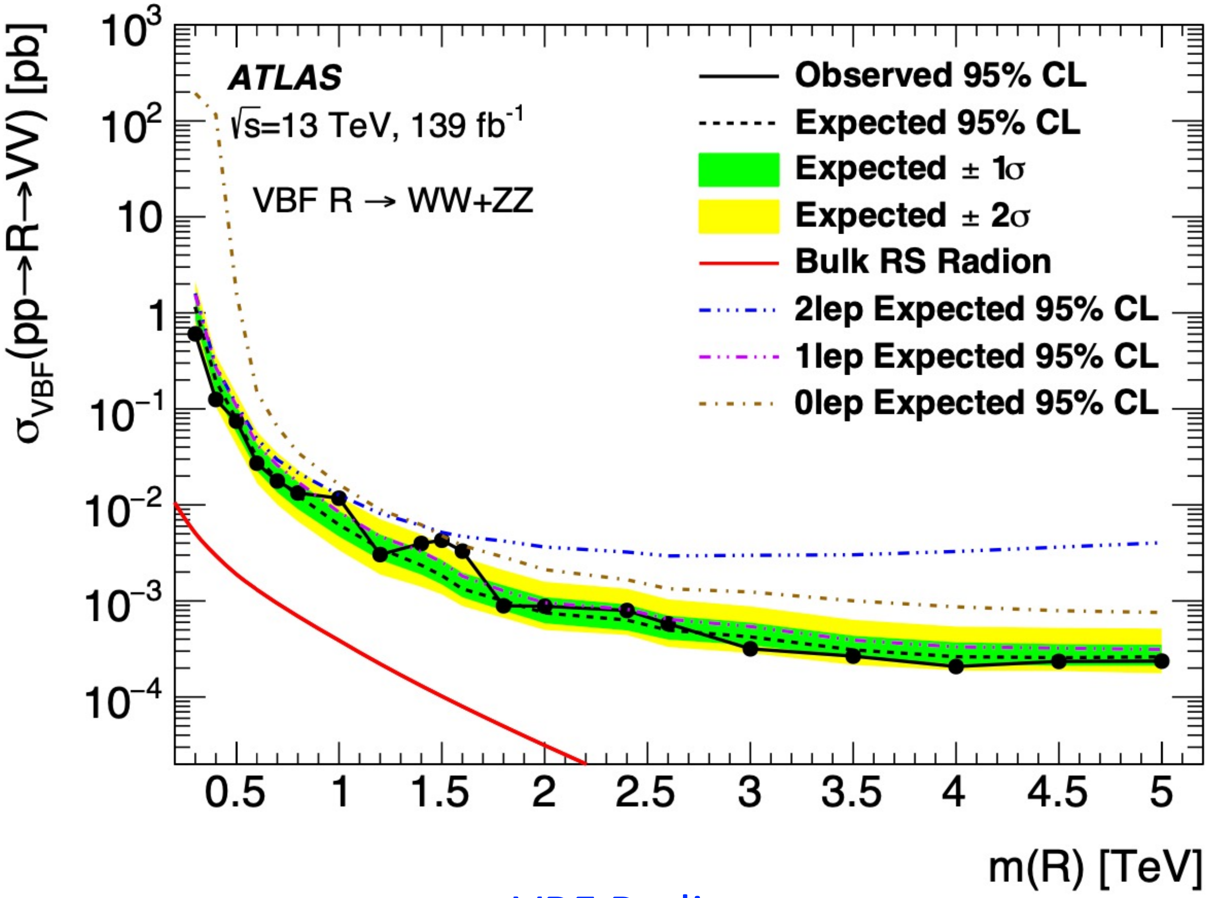
2-lep, ggF, boosted

VV semileptonic

- Exclusion limits: bulk RS Radion, R→WW, ZZ



ggF Radion

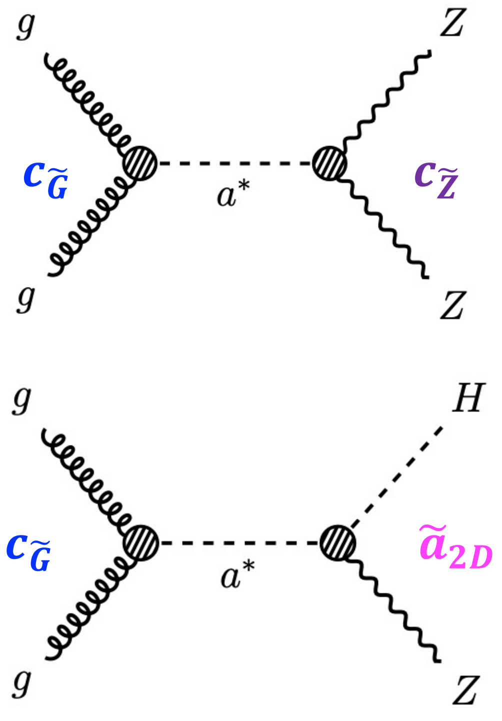


VBF Radion

ZZ/Zh→llqq

[CMS-PAS-B2G-20-013]

- First LHC search for ALPs, using ZZ/Zh→llqq final states
- Overview
  - Select a leptonic Z(→ee/mm) candidate and a hadronic Z/H candidate
    - Boosted: one large-R jet
    - Resolved: two small-R jets
  - Two signal regions based on the hadronic boson mass
    - SR1: for Z→jj/J
    - SR2: for H→jj/J
  - Dominant background: Z+jets
    - Normalization constrained from data side-band regions
  - Discriminant: m_{lljj}, m_{llJ}
    - Look for deviations in the high mass tail



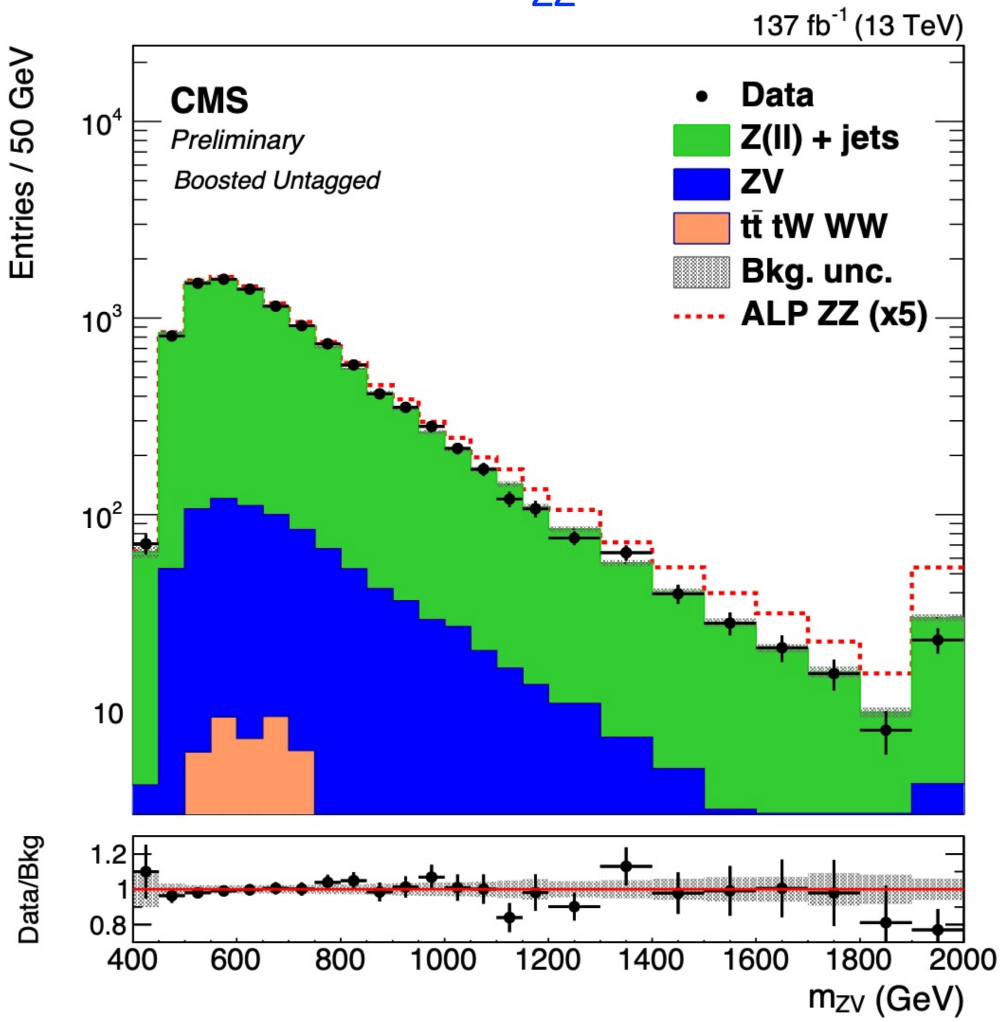
$$\sigma(gg \to ZZ) \sim \frac{c_{\tilde{G}} * c_{\tilde{Z}}}{f_a^2}$$

$$\sigma(gg \to ZH) \sim \frac{c_{\tilde{G}} * \tilde{a}_{2D}}{f_a^2}$$

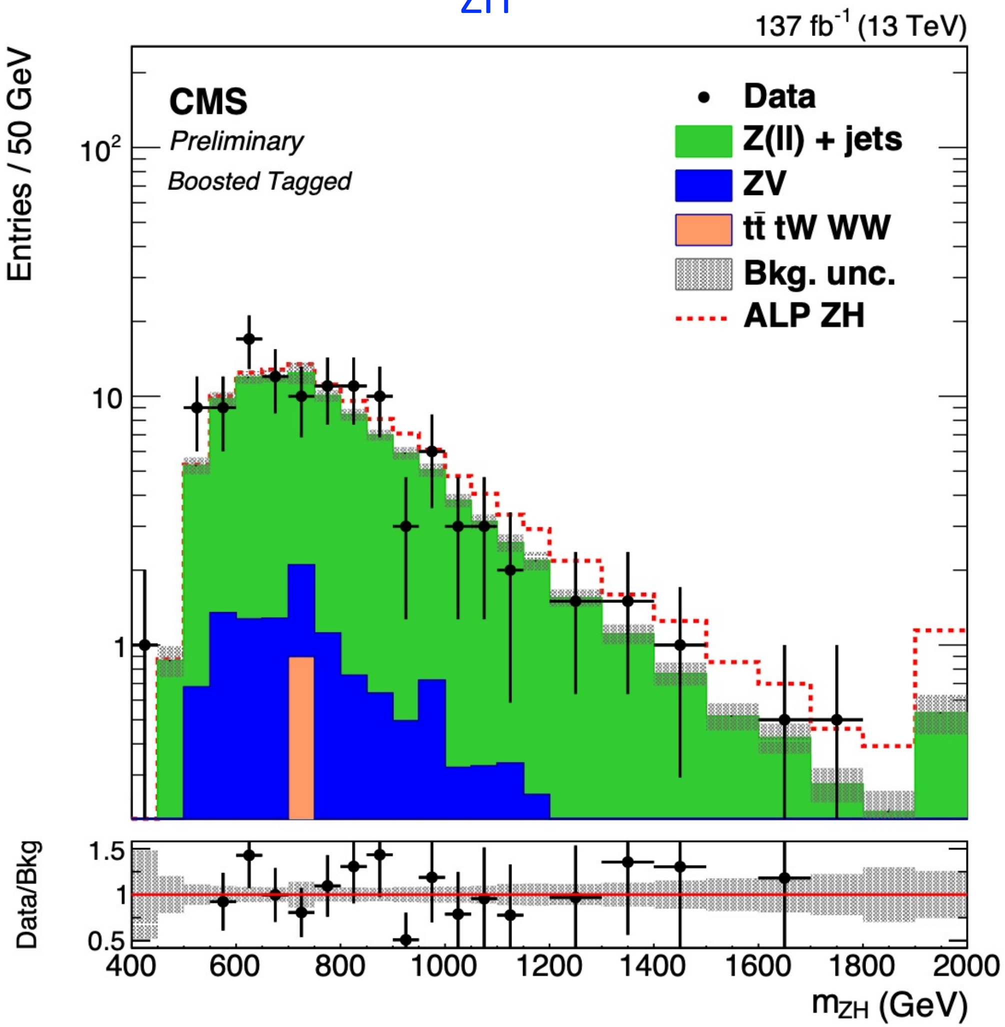
[CMS-PAS-B2G-20-013]

- Mass spectrum

ZZ



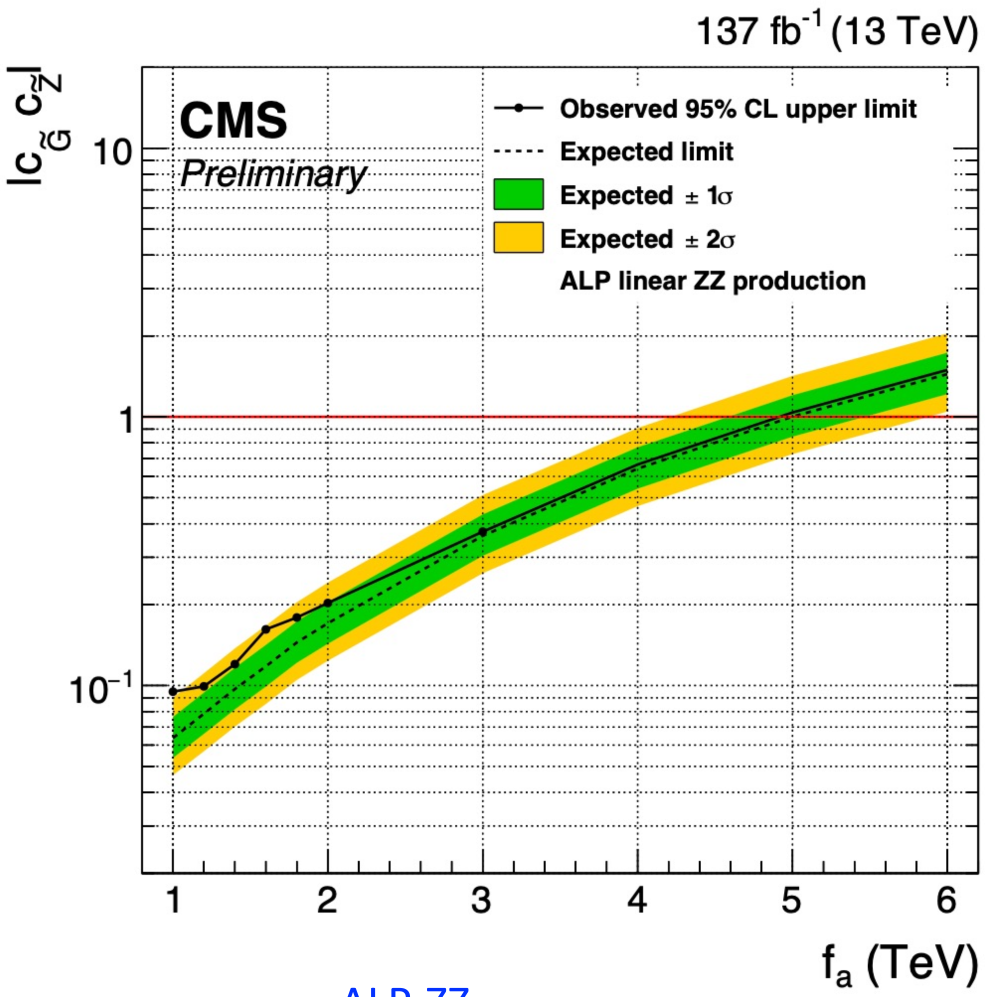
ZH



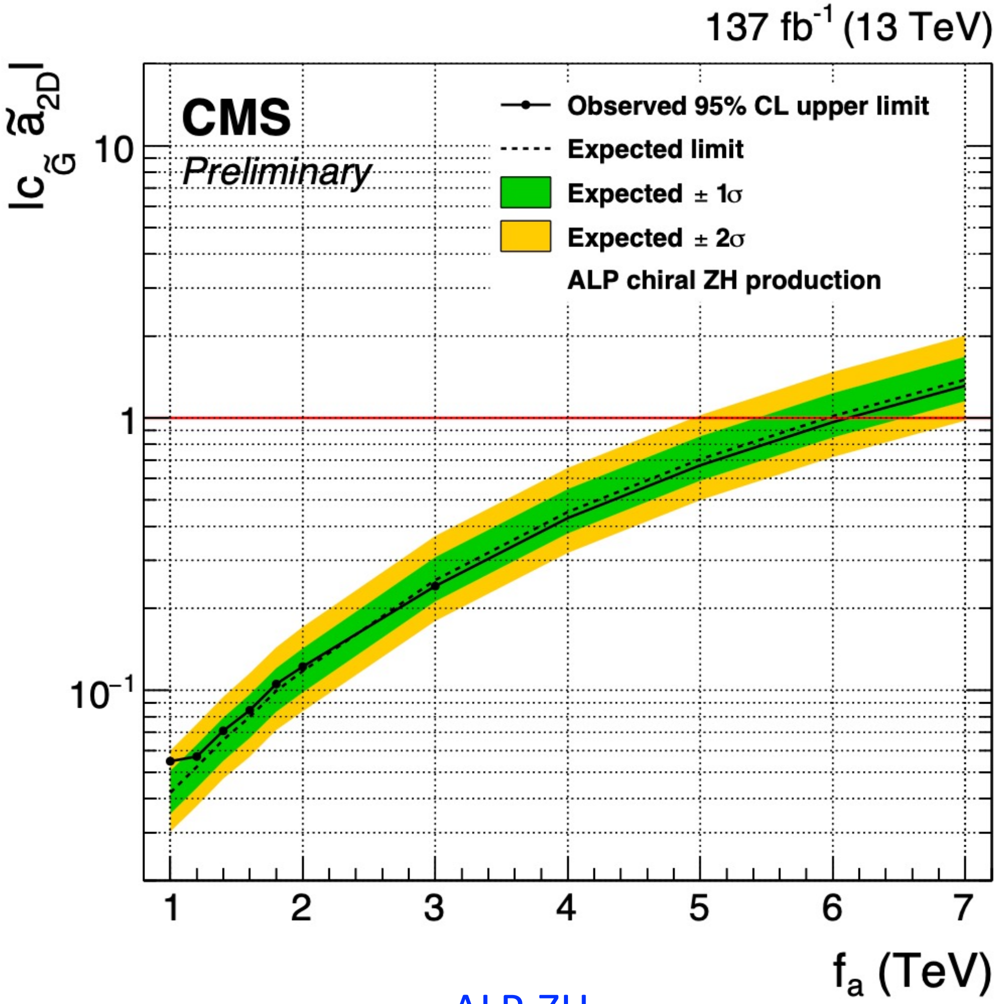
ZZ/Zh→llqq

CMS-PAS-B2G-20-013

- Exclusion limits



ALP-ZZ

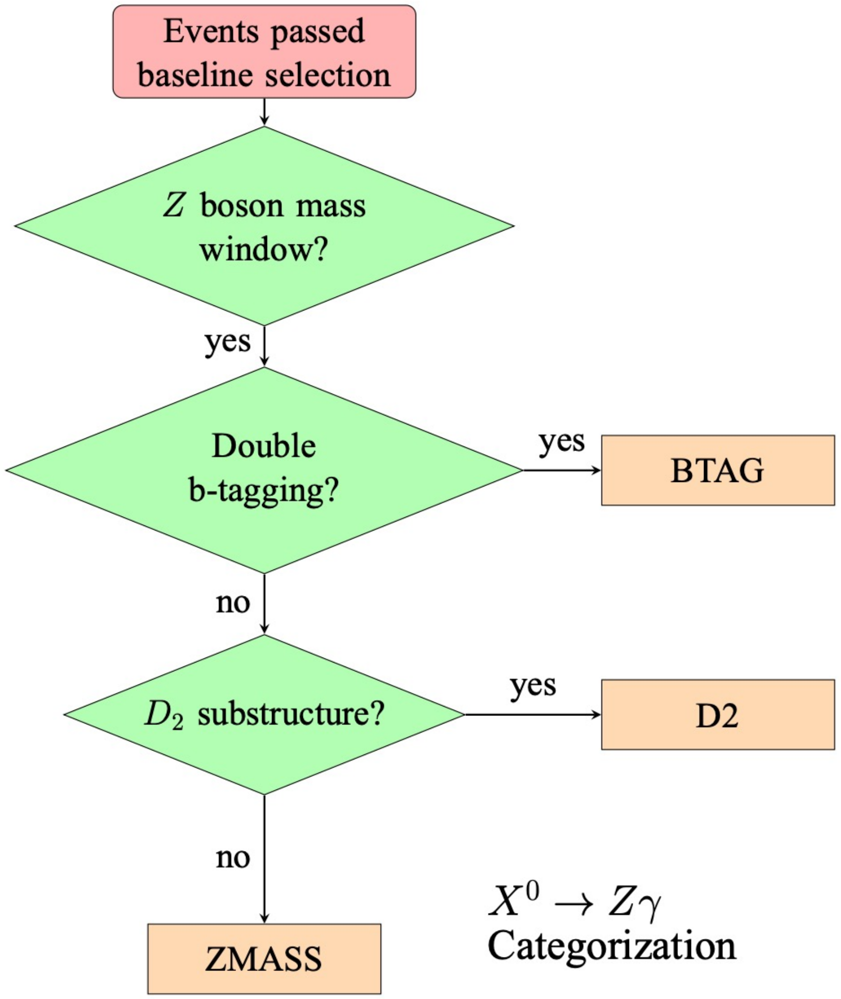


ALP-ZH

$Z\gamma$ hadronic

ATLAS-CONF-2021-041

- Very clean final states: an energetic photon + a large-R jet
- Overview:
  - Objects:
    - $E_T^\gamma > 200$ GeV and $|\eta_\gamma| < 1.37$
    - $p_T^J > 200$ GeV and $|\eta_J| < 2.0$
  - Discriminant: $m_{J\gamma}$ (1.0, 6.8) TeV
  - Background: γ+jets, $Z\gamma$
    - Shape parametrized with a function
    - Normalization constrained from data



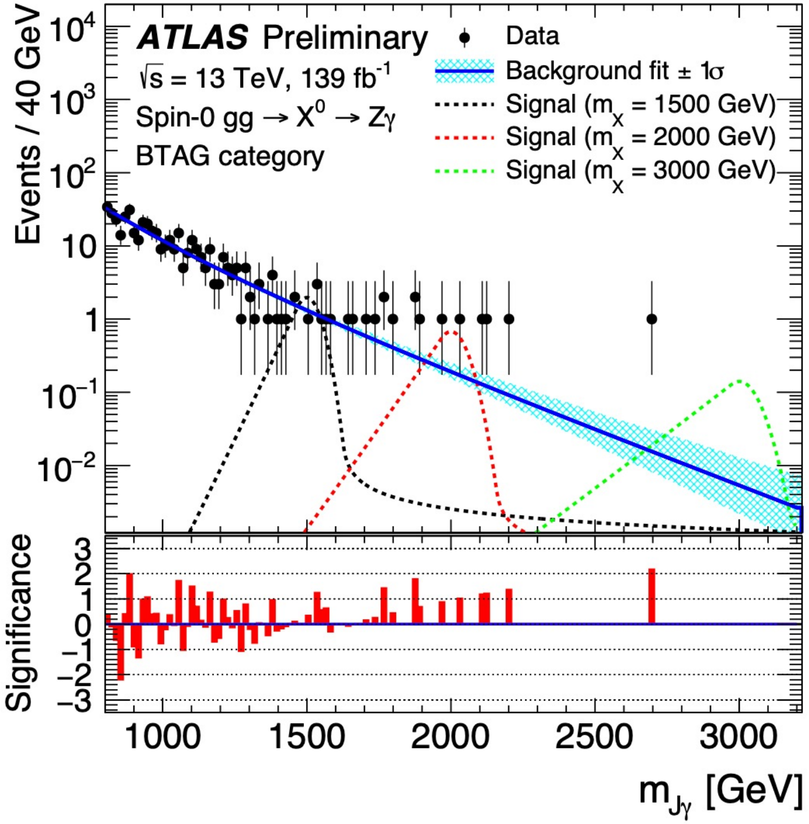
Zγ hadronic

ATLAS EXPERIMENT [ATLAS-CONF-2021-041]

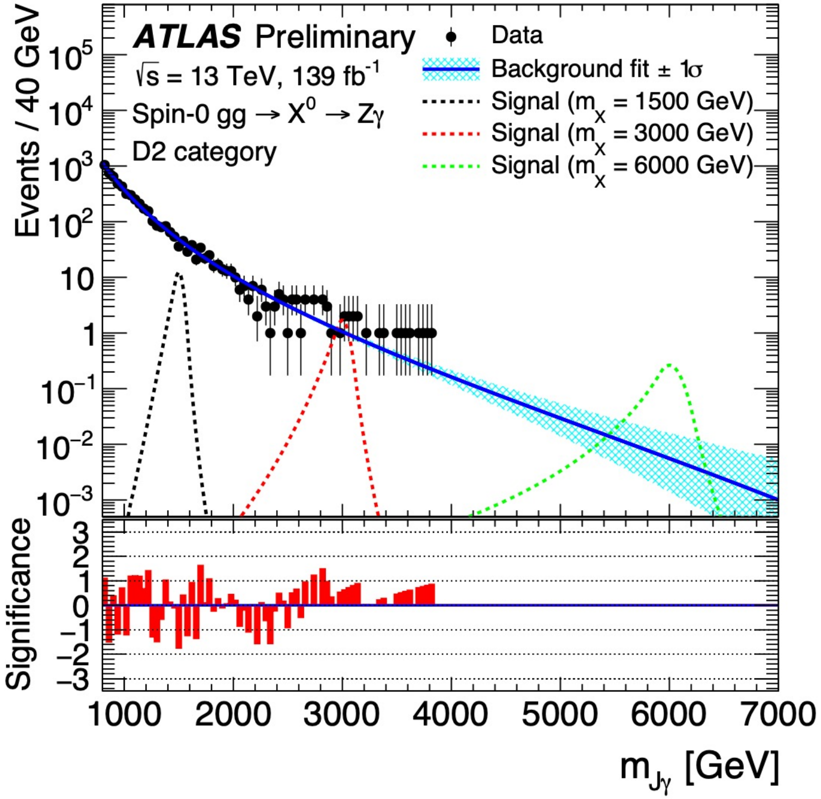
- $m_{J\gamma}$ in 3 categories

$$\mathcal{B}(m_{J\gamma};\boldsymbol{p}) = (1-x)^{p_1} x^{p_2+p_3\log(x)}$$

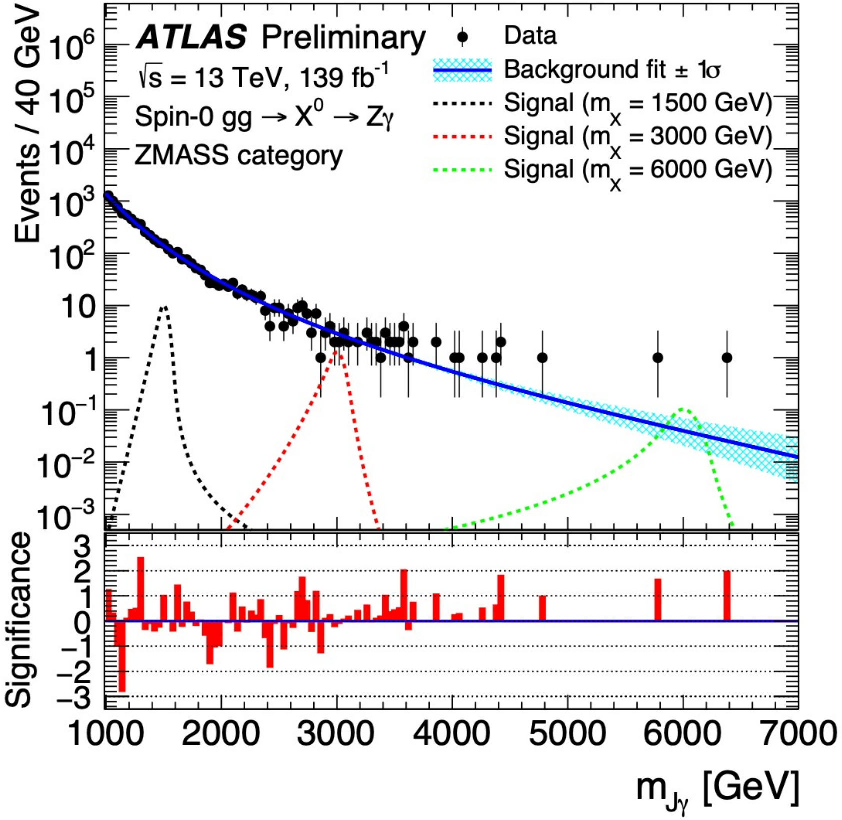
$$x = m_{J\gamma}/\sqrt{s}\,,$$



BTAG category



D2 category

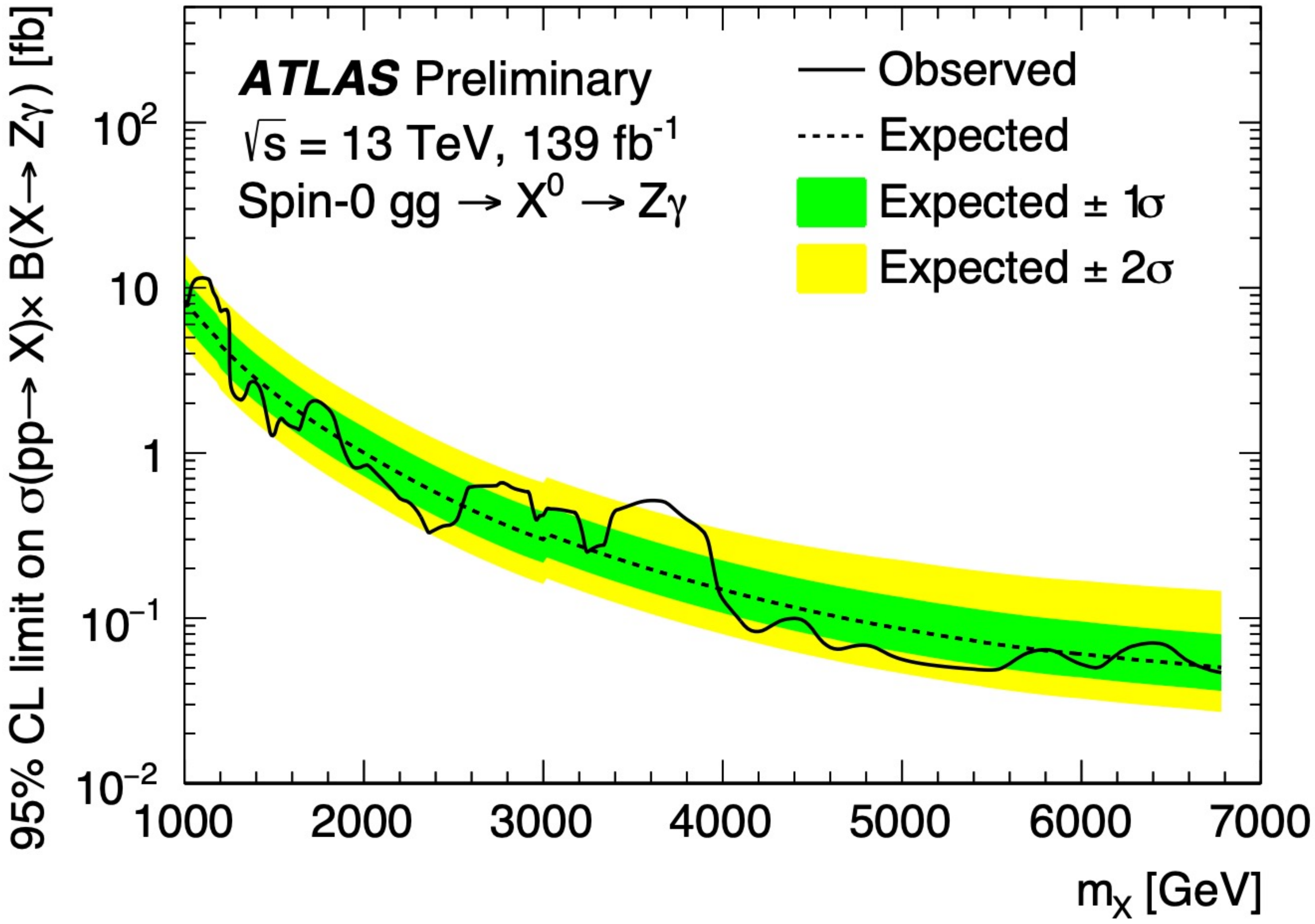


ZMass category

Zγ hadronic

ATLAS-CONF-2021-041

- Exclusion limits: narrow width scalars

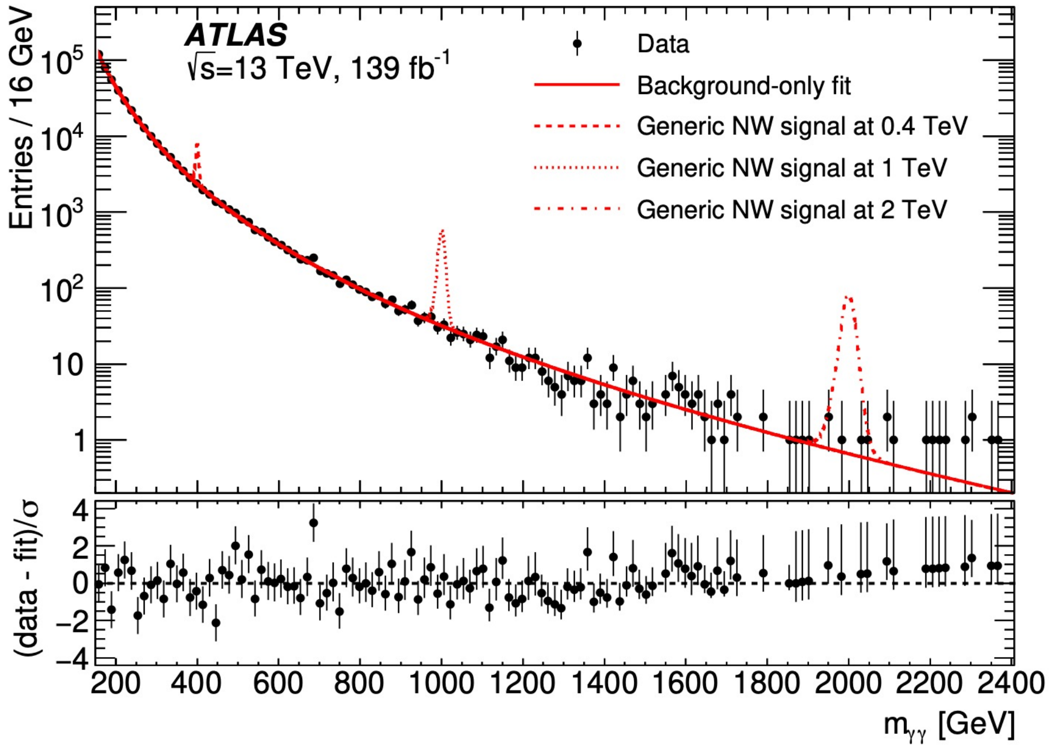


$\gamma\gamma$

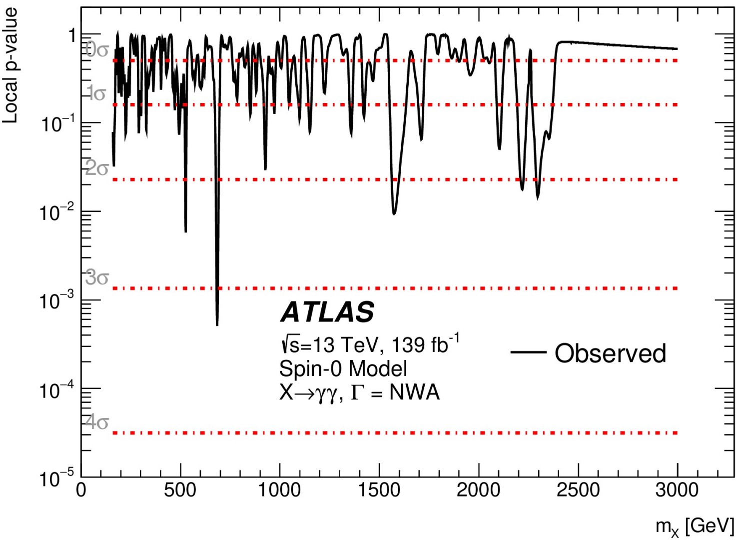
arXiv:2102.13405

- One of the discovery channels of the SM Higgs
  - Very clean final states and excellent mass resolution
- Overview
  - Background: $\gamma\gamma$, γ+jets
    - Analytical function built from simulated $\gamma\gamma$ events, and from a data control region for γ +jet events
    - Smoothed using the functional decomposition (FD) method to suppress statistical fluctuation

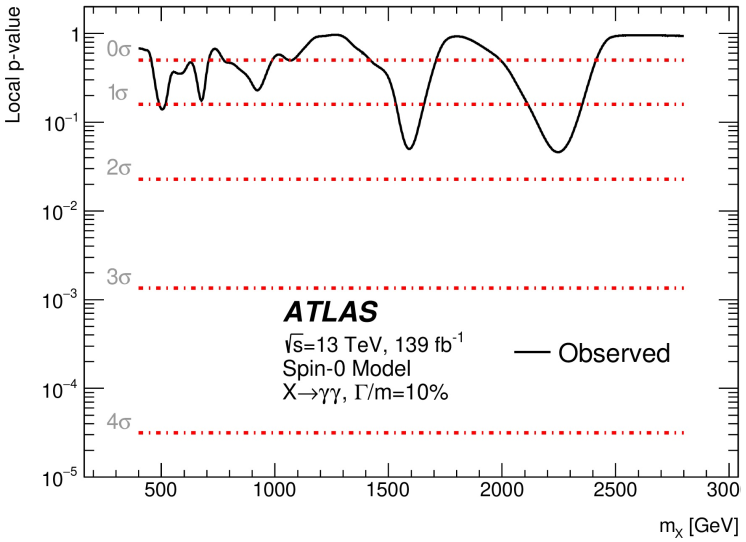
$$f(x; b, a_0, a_1) = N(1 - x^{1/3})^b x^{a_0 + a_1 \log(x)}$$



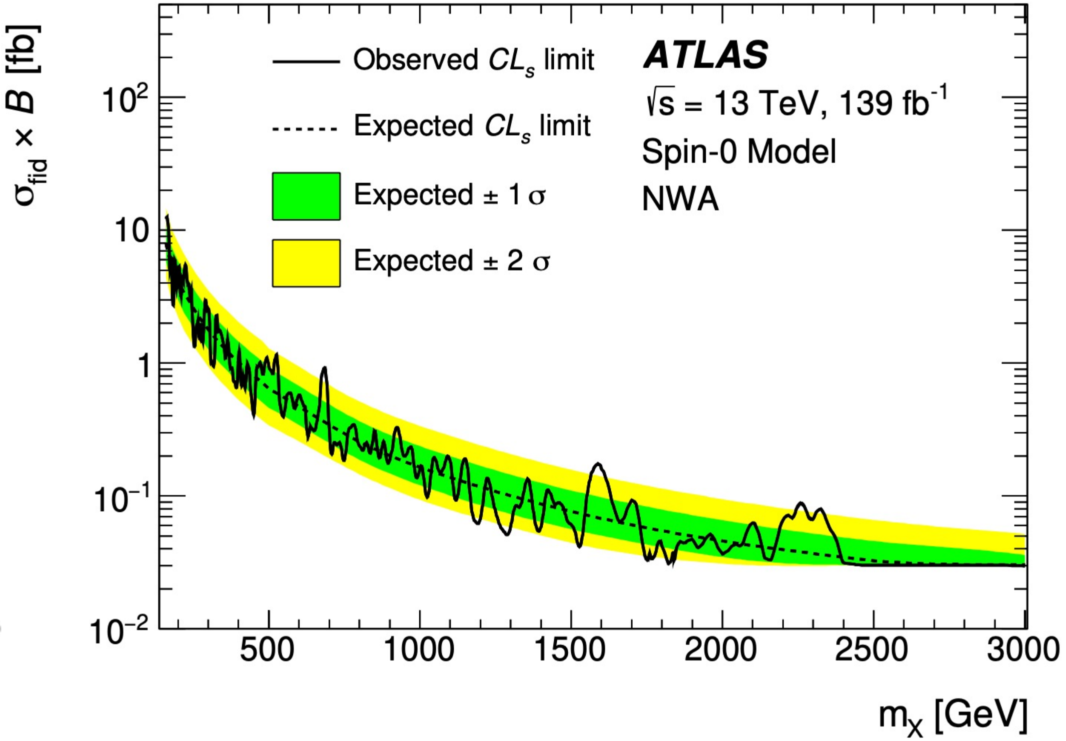
- Results: scalars



Local p_0 scan, narrow width



Local p_0 scan, $\frac{\Gamma_H}{m_H} = 10\%$



Exclusion limits, narrow width

Triboson searches

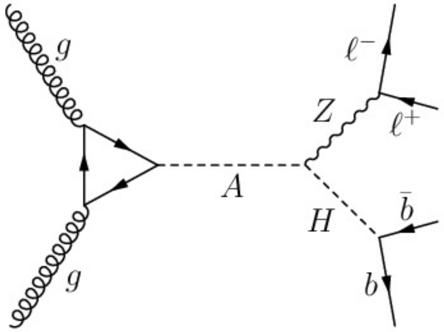
$A \rightarrow ZH(\rightarrow WW)$

$W_{kk} \rightarrow R(\rightarrow WW)W$ searches, see Qiang Li's talk

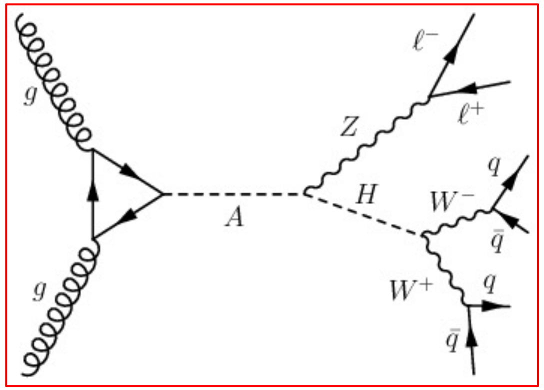
A→ZH, H→WW

EPJC. 81 (2021) 396

- Search for heavy pseudo-scalar (A) and heavy scalar (H) in 2HDM
  - Z→ll, with two decay channels for H
    - H→bb: high branching ratio in the weak decoupling limit ($\cos(\beta - \alpha) = 0$)
    - H→WW→qqqq: dominant when **away** the weak decoupling limit



- Overview
  - Select at least 4 small-R jets
  - Both m_A and m_H are unknown: sliding m_{4q} window cuts
    - eg: $m_H - 53$ GeV $< m_{4q} < 0.97 m_H + 54$ GeV.
  - Discriminants: m_{2l4q}
  - Backgrounds: Z+jets, top-quarks
    - Normalizations constrained with data CRs

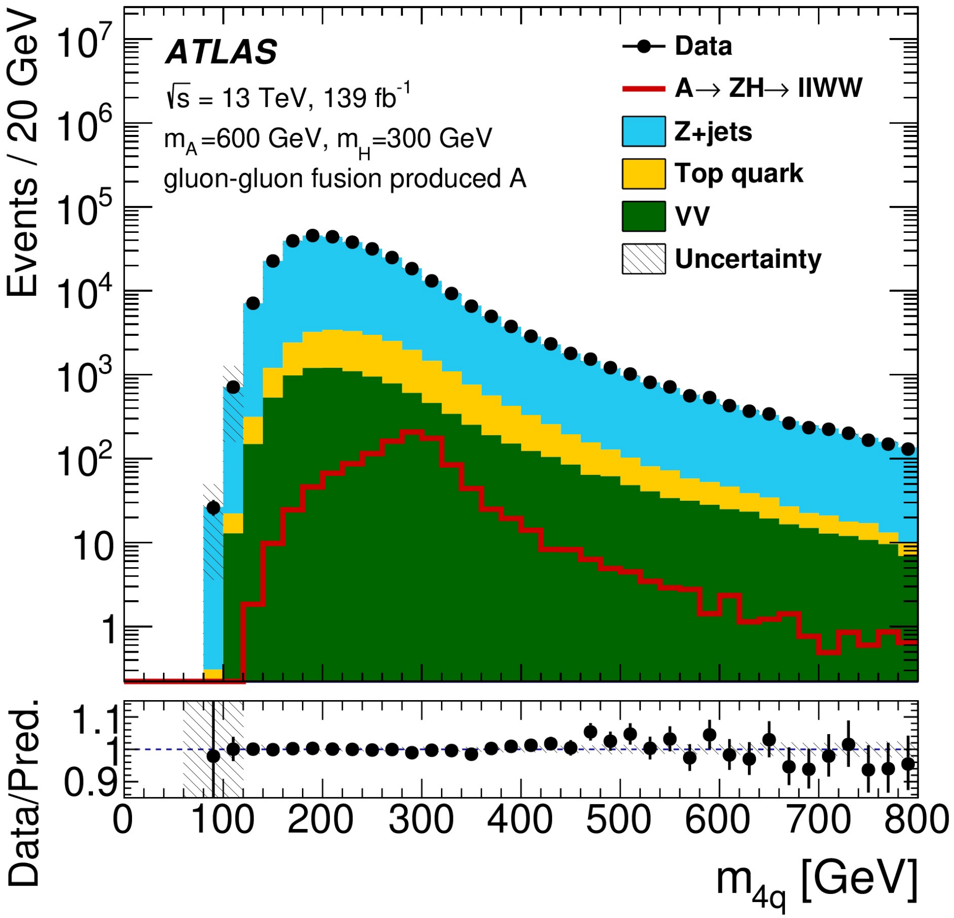


A→ZH(→WW→4q)

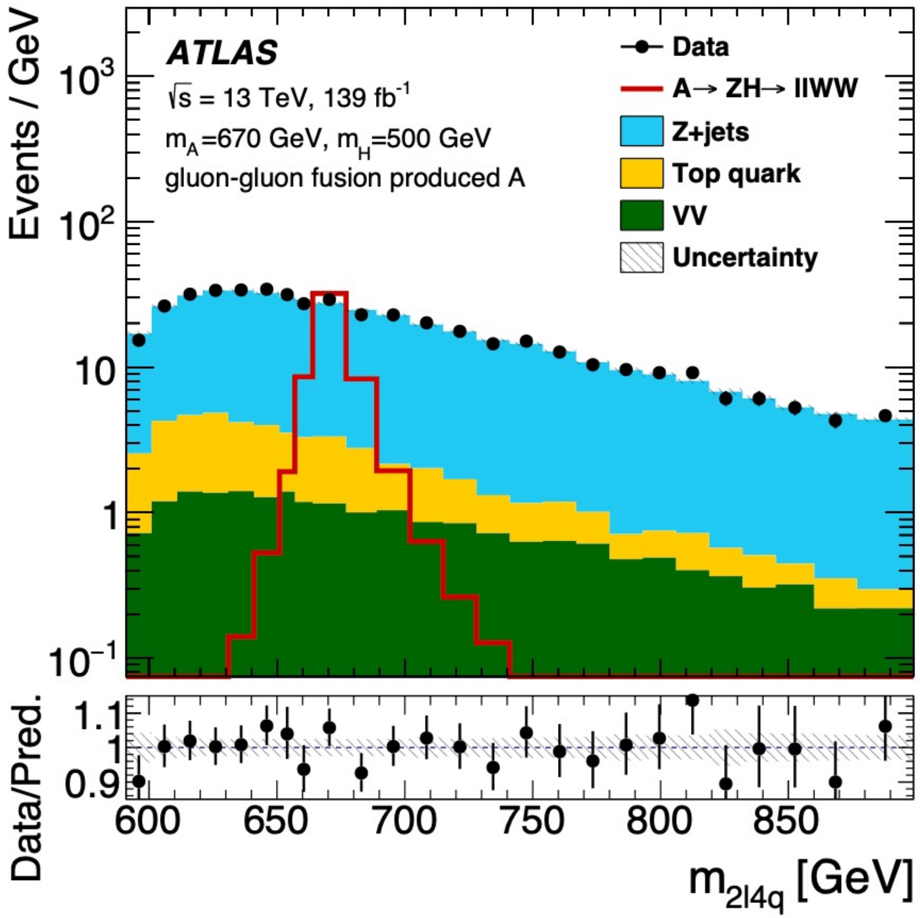
[EPJC. 81 (2021) 396](#)

- Mass spectrum

H→WW→4q



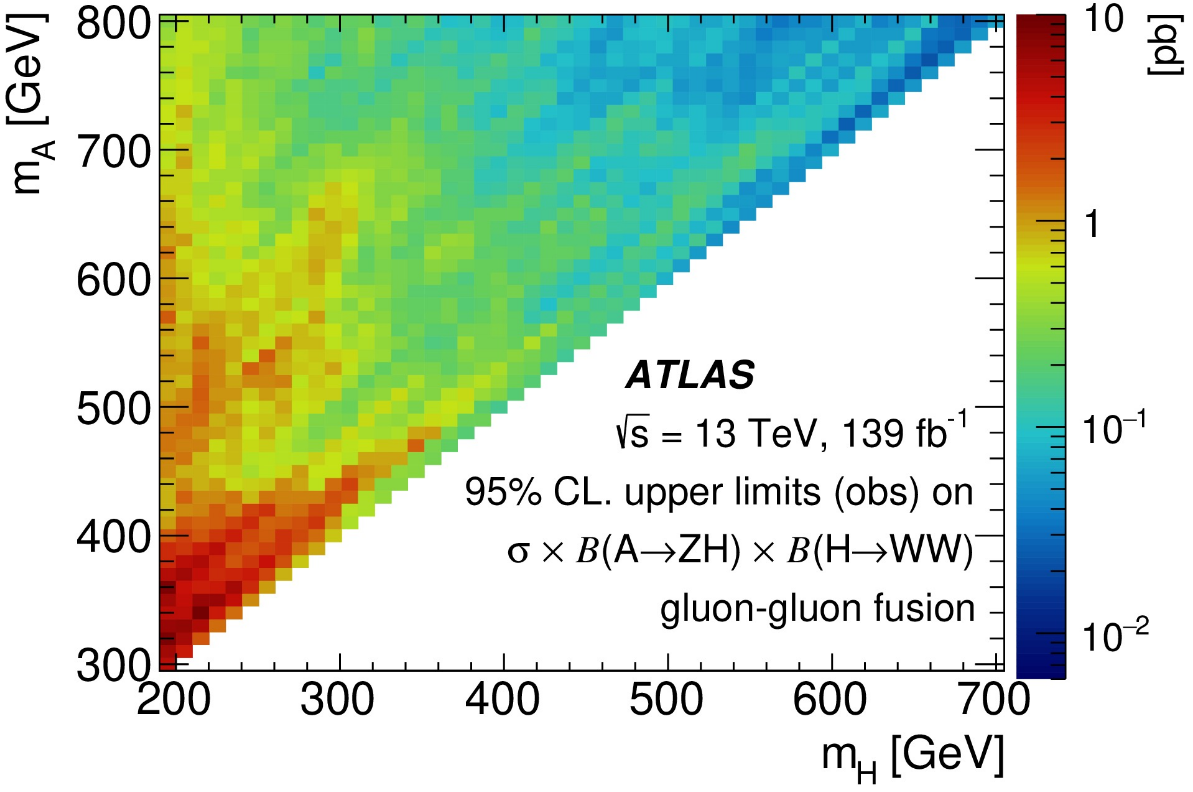
A→ZH



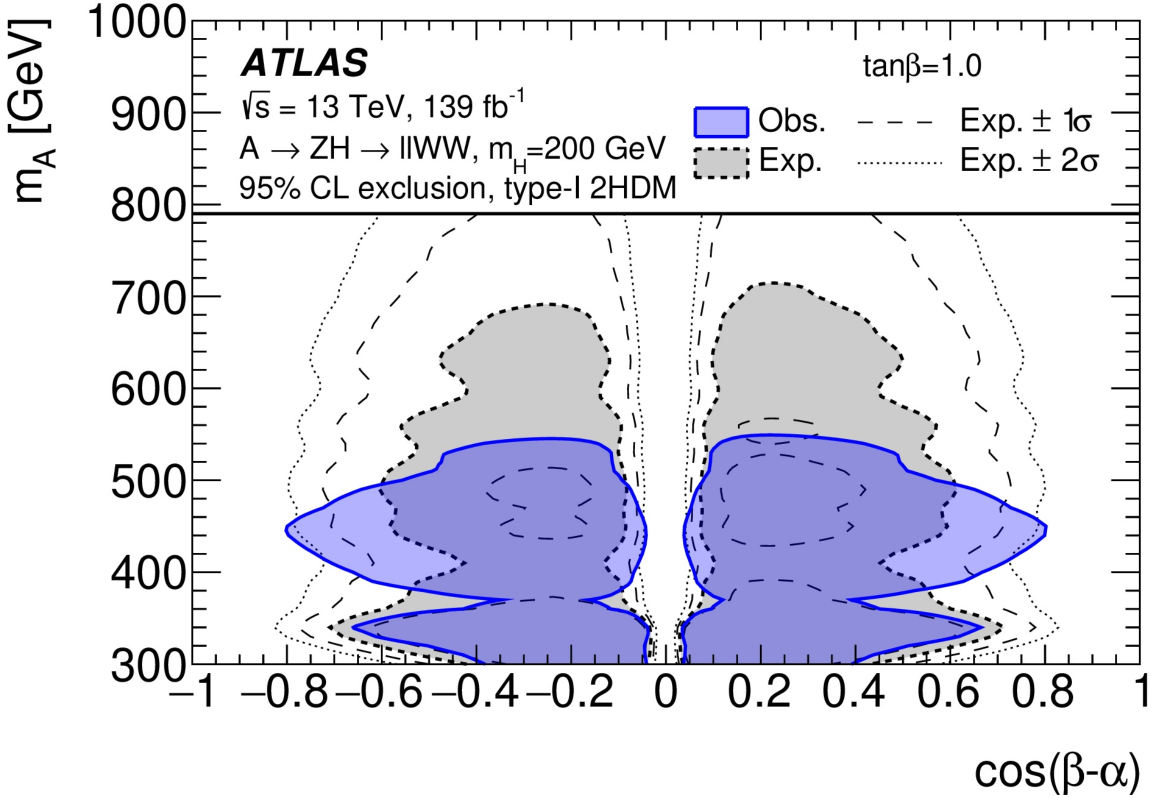
A→ZH(→WW→4q)

EPJC. 81 (2021) 396

- Exclusion limits: 2D scan (m_A, m_H)



Model-independent limits

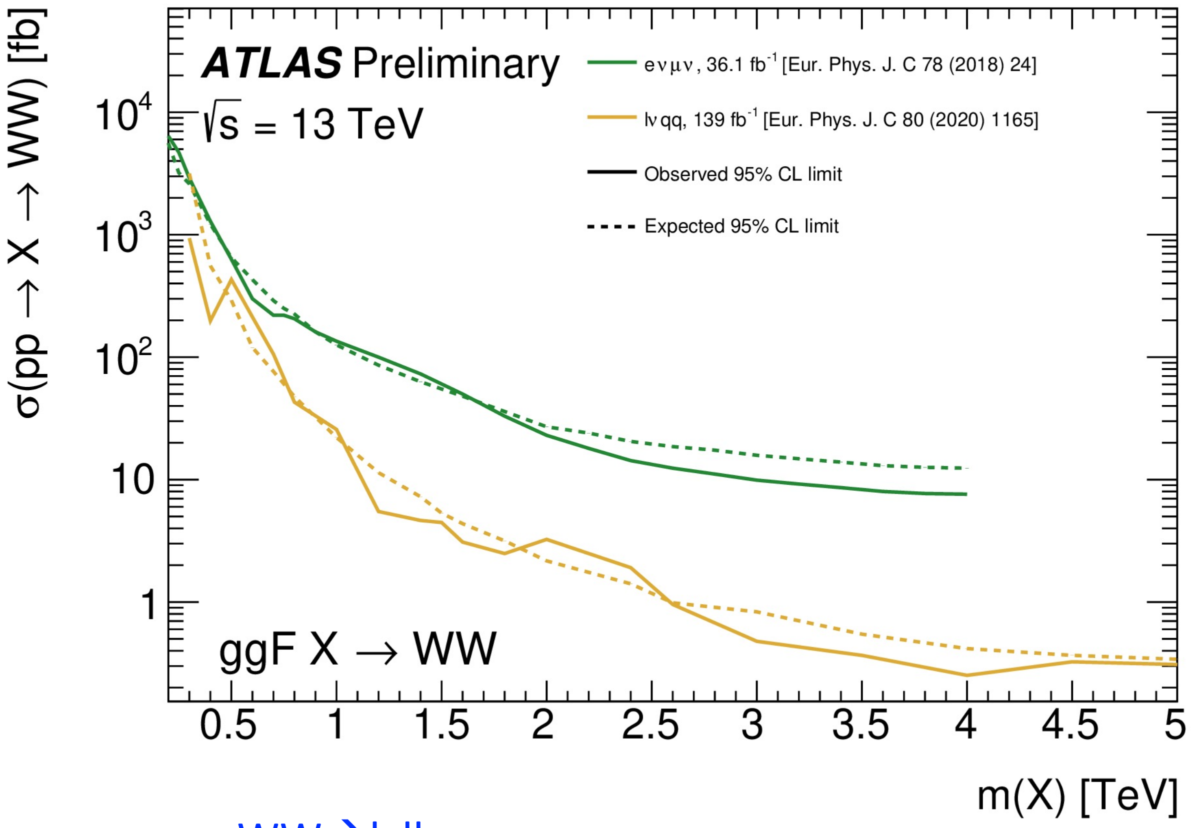


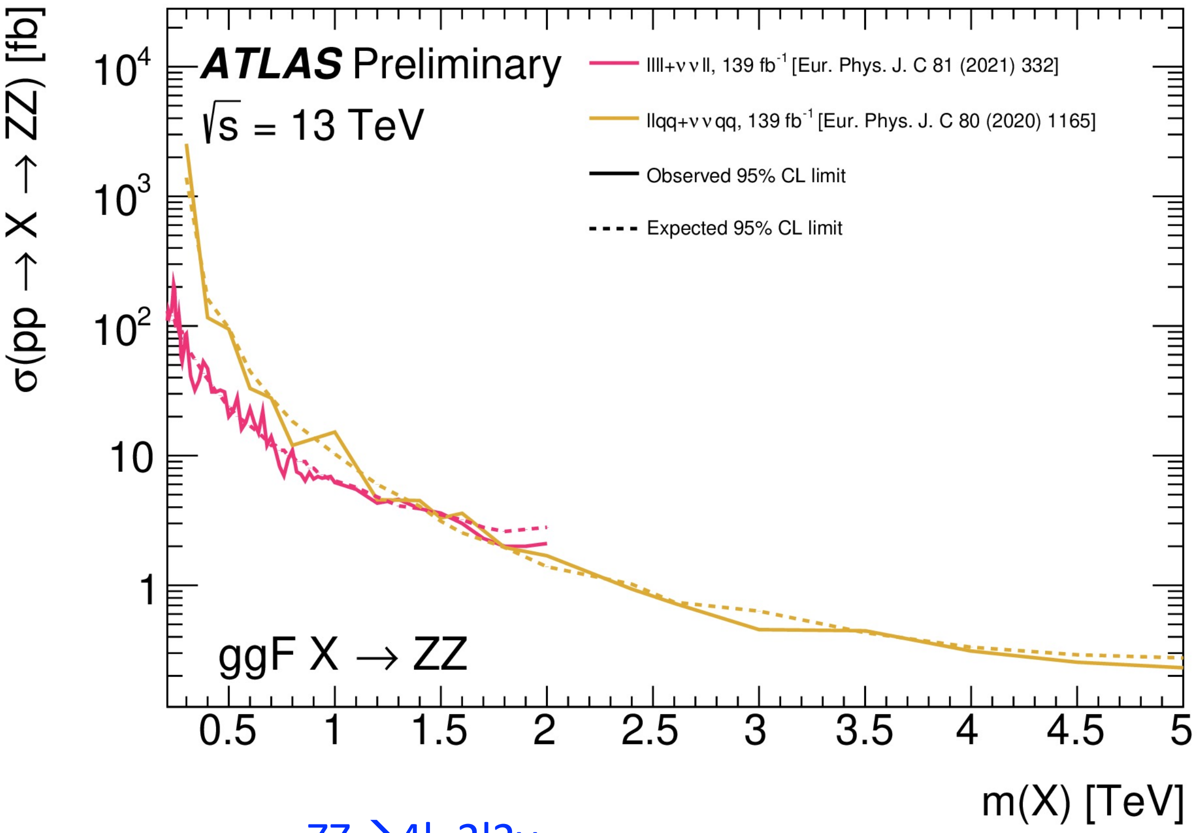
2HDM-I contours

Summary

Generic scalar summary: ggF X→VV

ATL-PHYS-PUB-2021-018



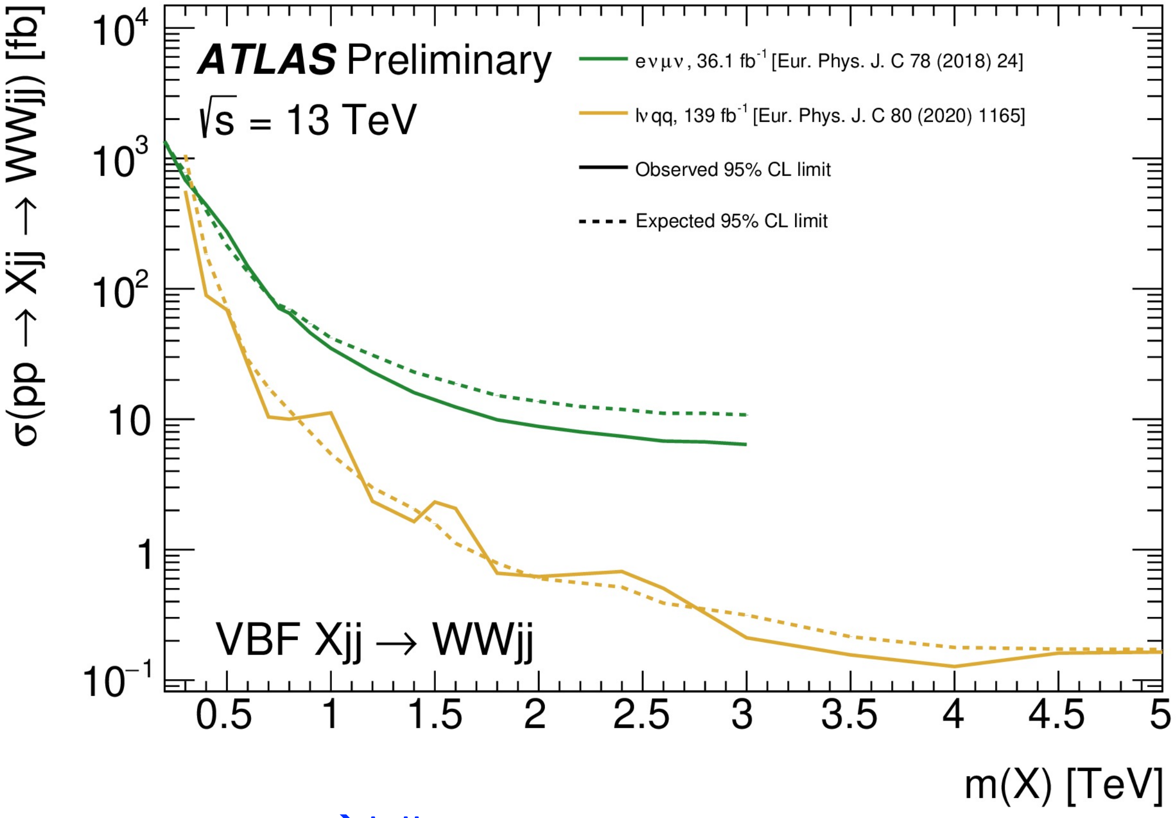


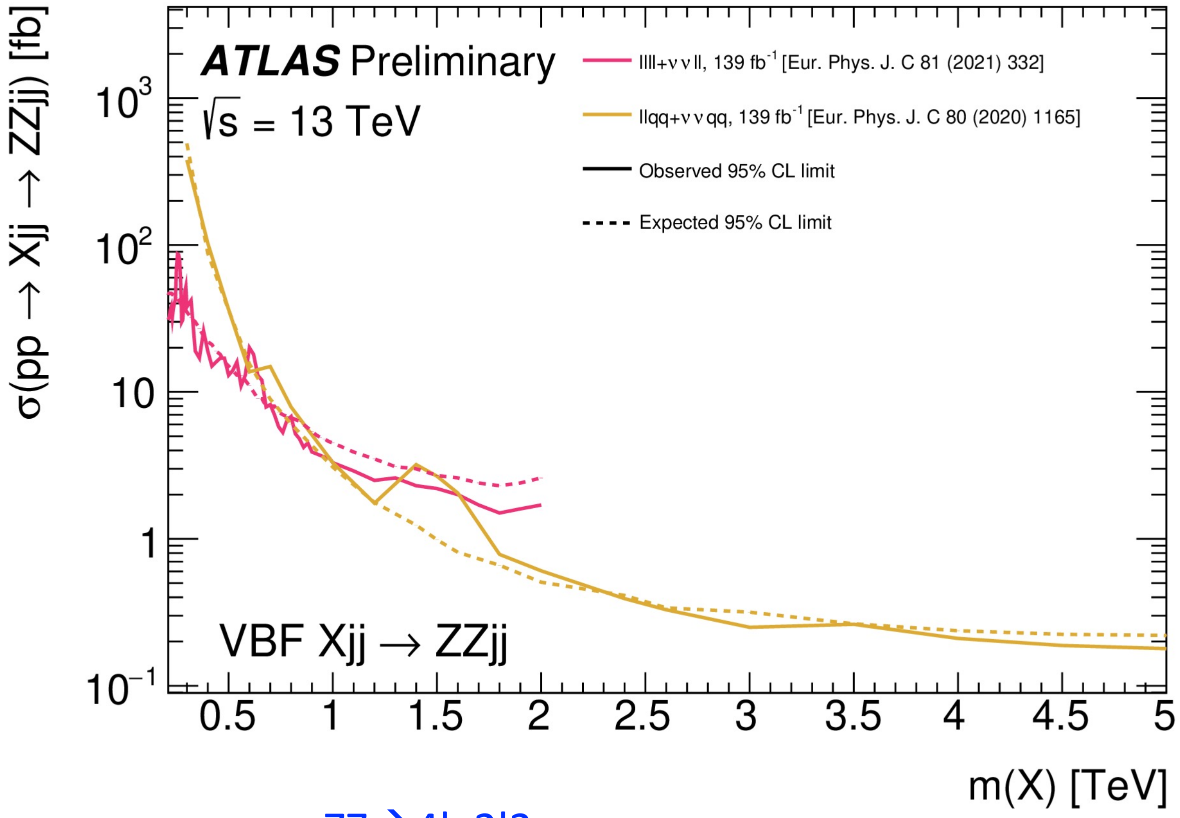
WW→lvll
WW→lvqq

ZZ→4l, 2l2v
ZZ→llqq, vvqq

Generic scalar summary: VBF X→VV

ATL-PHYS-PUB-2021-018

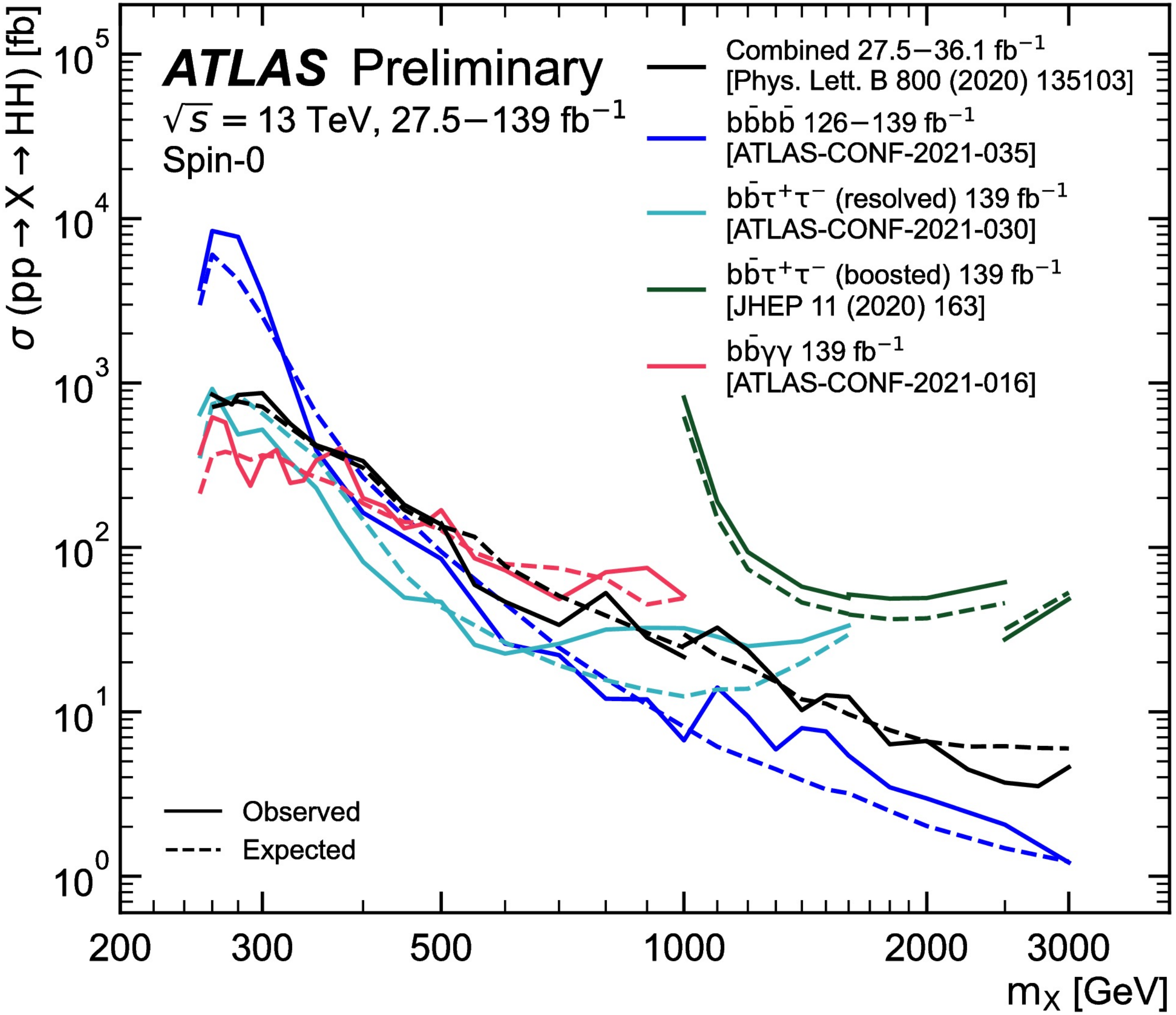




WW→lνll
WW→lνqq

ZZ→4l, 2l2ν
ZZ→llqq, ννqq

Generic scalar summary: X→HH



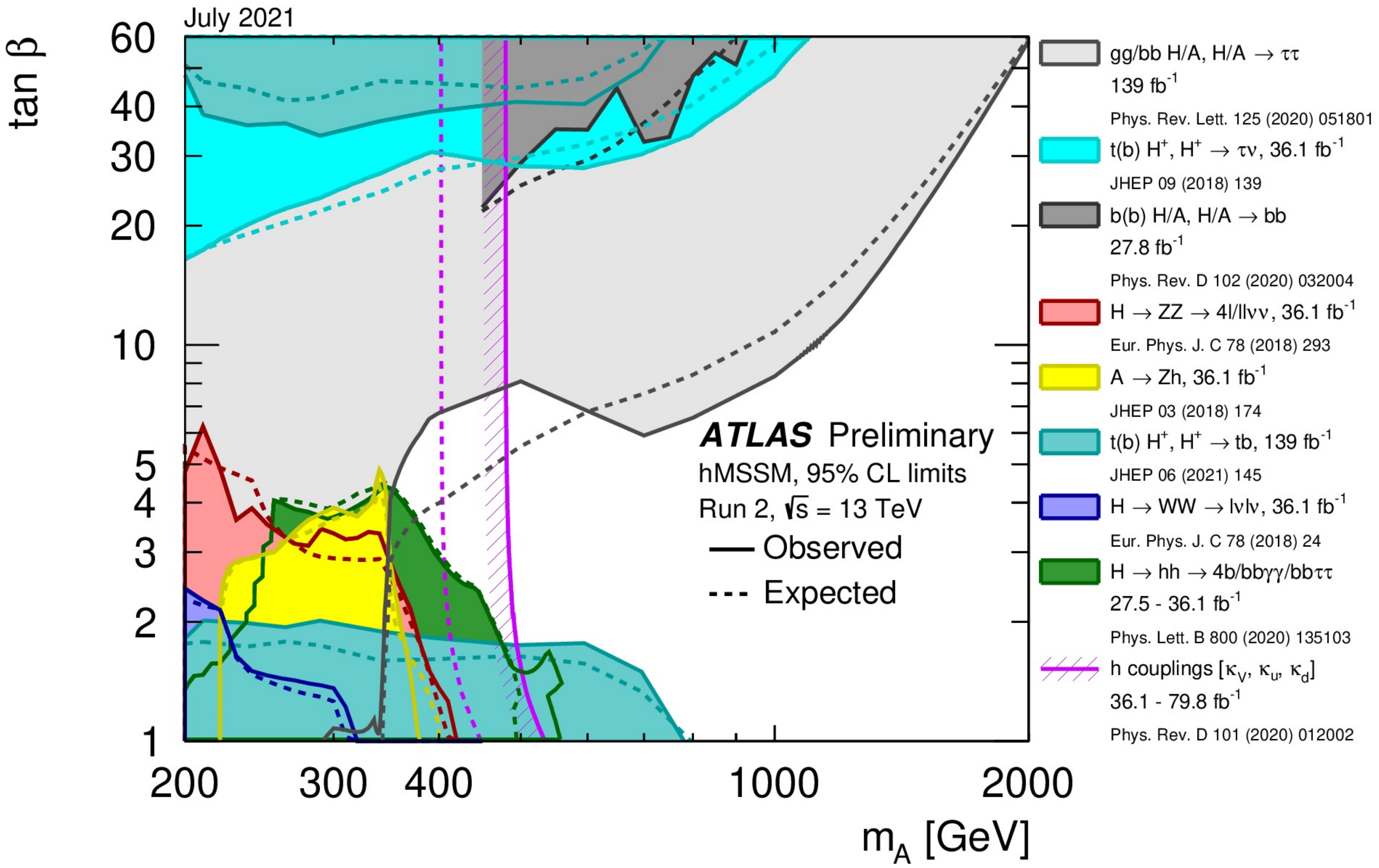
ATL-PHYS-PUB-2021-031

HH→4b
HH→$bb\tau\tau$
HH→$bb\gamma\gamma$

hMSSM summary

ATL-PHYS-PUB-2021-030

- Overlay of direct searches and indirect Higgs measurements



Summary

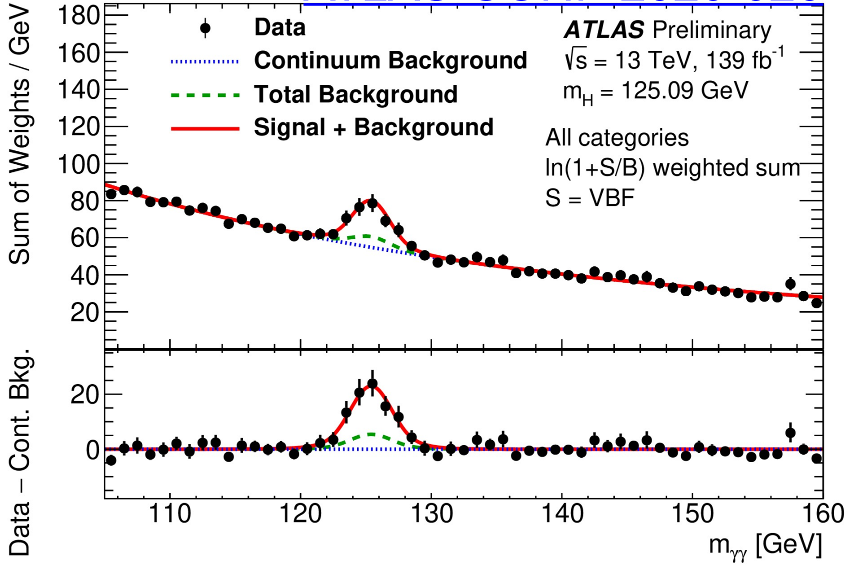
- Search for heavy neutral scalars is well motivated by several benchmark BSM models
  - Bulk RS radion, heavy Higgs (H/A) in 2HDM, MSSM, Axion-like particles, etc
- Very dynamic experimental program at the LHC
  - Exploit various experimental signatures
    - Dileptons, dijets, dibosons, multibosons, etc
  - Interpretated in a few BSM models
- Novel experimental techniques being explored
  - Deep neutral network based discriminants
  - Jet substructure and boosted boson tagging
  - Cascade decays
  - Functional forms for signal/background parametrization (eg. functional decomposition methods)
- Looking forward for new results with full Run-2 LHC data and beyond
  - More data, new experimental methods
  - New motivated models from the theory community

Backup

Search strategies

- Resonant search strategy
  - Bump hunting:
    - Search for new resonances in the smoothly falling SM background
    - The SM background is usually taken from SM predictions or empirical functions/fits
  - Experimental signatures
    - Leptonic final states have lower backgrounds that can be triggered on efficiently
    - Hadronic decays can have larger branching ratios but with higher backgrounds

ATLAS-CONF-2020-026



- Non-resonant search strategy
  - Look for deviations from precision measurements
    - *not covered*

M_h^{125} scenarios

- MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios for Run 2 and Beyond

arXiv:1808.07542

LHC Higgs WG, MSSM

- ▶ M_h^{125} scenario → all SUSY particles at the TeV scale
- ▶ $M_h^{125}(\tilde{\tau})$ scenario → light Stau, Bino and Winos
- ▶ $M_h^{125}(\tilde{\chi})$ scenario → light Bino, Winos and Higgsinos
- ▶ M_h^{125}(alignment) scenario → alignment without decoupling
- ▶ M_H^{125} scenario → heavy $\mathcal{CP}$-even Higgs is SM-like
- ▶ $M_{h_1}^{125}$(CPV) scenario → $\mathcal{CP}$-violation in the Higgs sector

Typical resonances

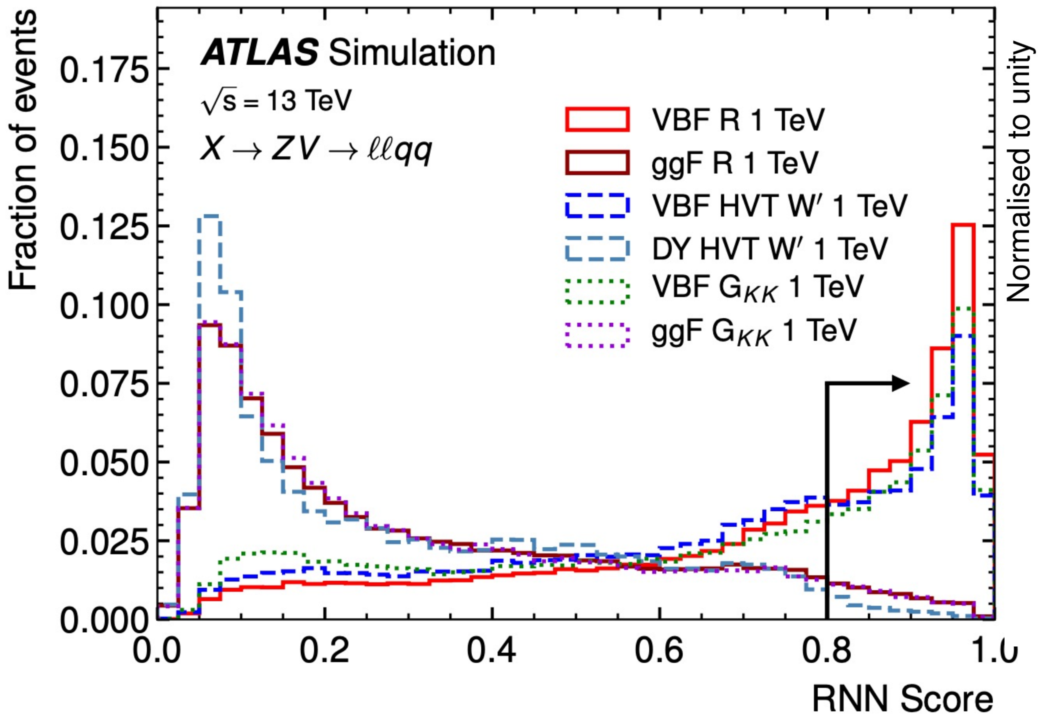
EPJC 80 (2020) 1165

Table 1: List of benchmark signal models. Predictions of cross-section σ, branching ratio $\mathcal{B}$ into WW, WZ, or ZZ, and intrinsic width divided by the resonance mass Γ/m, for the given hypothetical new particle at $m = 800$ GeV and 3 TeV are summarised.

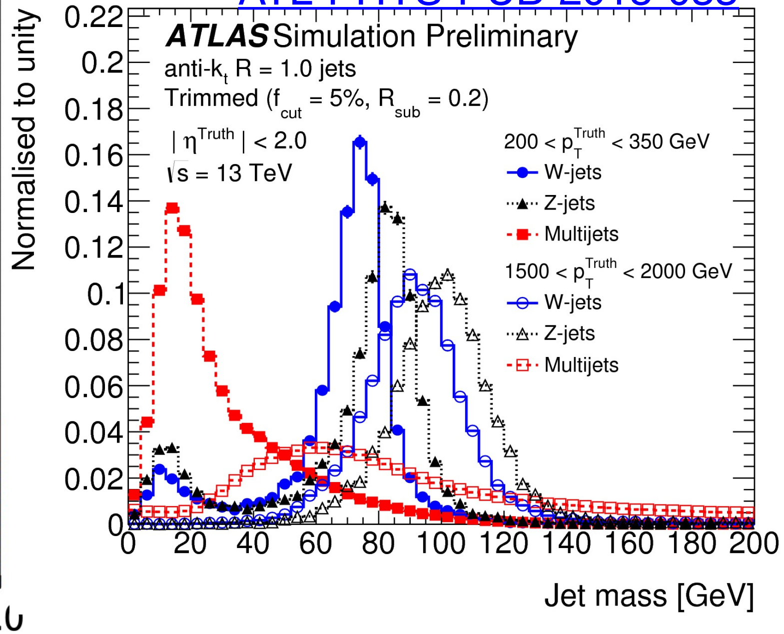
Model			Spin	$m = 800$ GeV			$m = 3$ TeV		
				σ [pb]	$\mathcal{B}$	Γ/m	σ [fb]	$\mathcal{B}$	Γ/m
RS radion ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)		$R \to WW$ $R \to ZZ$	0	0.54 (ggF) 1.1×10^{-3} (VBF)	0.43 0.21	2.6×10^{-3}	1.38 (ggF) 5.5×10^{-3} (VBF)	0.44 0.22	0.032
HVT	Model A	$W' \to WZ$ $Z' \to WW$	1	53 26	0.024 0.023	0.026	79 36	0.020	0.025
	Model B	$W' \to WZ$ $Z' \to WW$		1.6 0.86	0.43 0.41	0.040	5.5 2.5	0.47	0.031
	Model C (VBF)	$W' \to WZ$ $Z' \to WW$		4.0×10^{-3} 2.7×10^{-3}	0.50 0.49	3.5×10^{-3}	1.6×10^{-3} 1.0×10^{-3}	0.50	3.3×10^{-3}
Bulk RS G_{KK} ($k/\overline{M}_{Pl} = 1.0$)		$G_{KK} \to WW$ $G_{KK} \to ZZ$	2	1.9 (ggF) 0.050 (VBF)	0.28 0.14	0.051	0.47 (ggF) 1.6×10^{-2} (VBF)	0.20 0.10	0.062

VV semileptonic

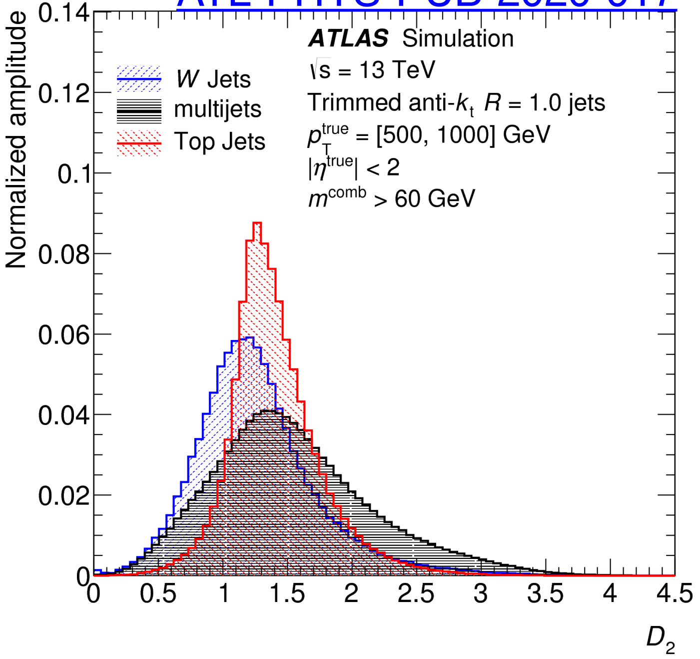
EPJC 80 (2020) 1165



ATL-PHYS-PUB-2015-033



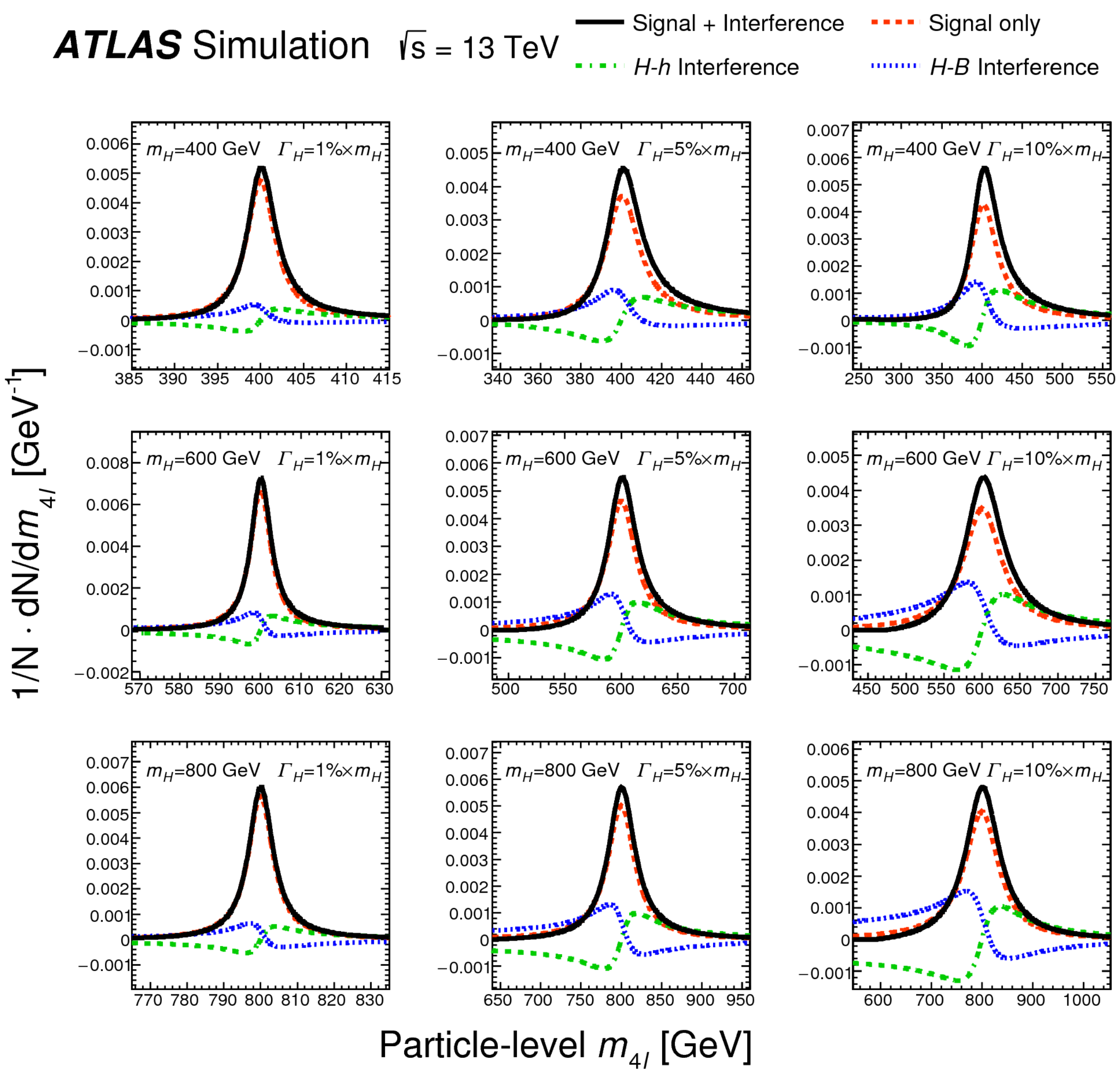
ATL-PHYS-PUB-2020-017



RNN discriminant

Boosted boson tagging

Interference



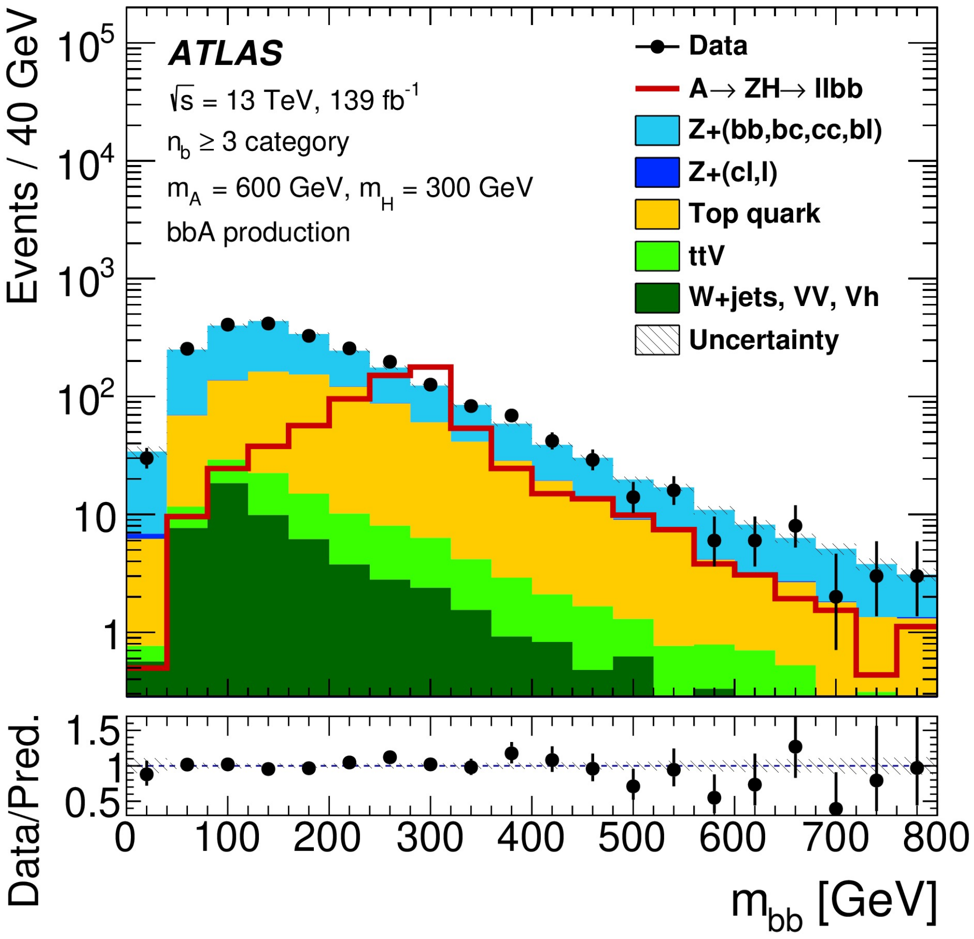
[EPJC 78 (2018) 293]

A→ZH(→bb)

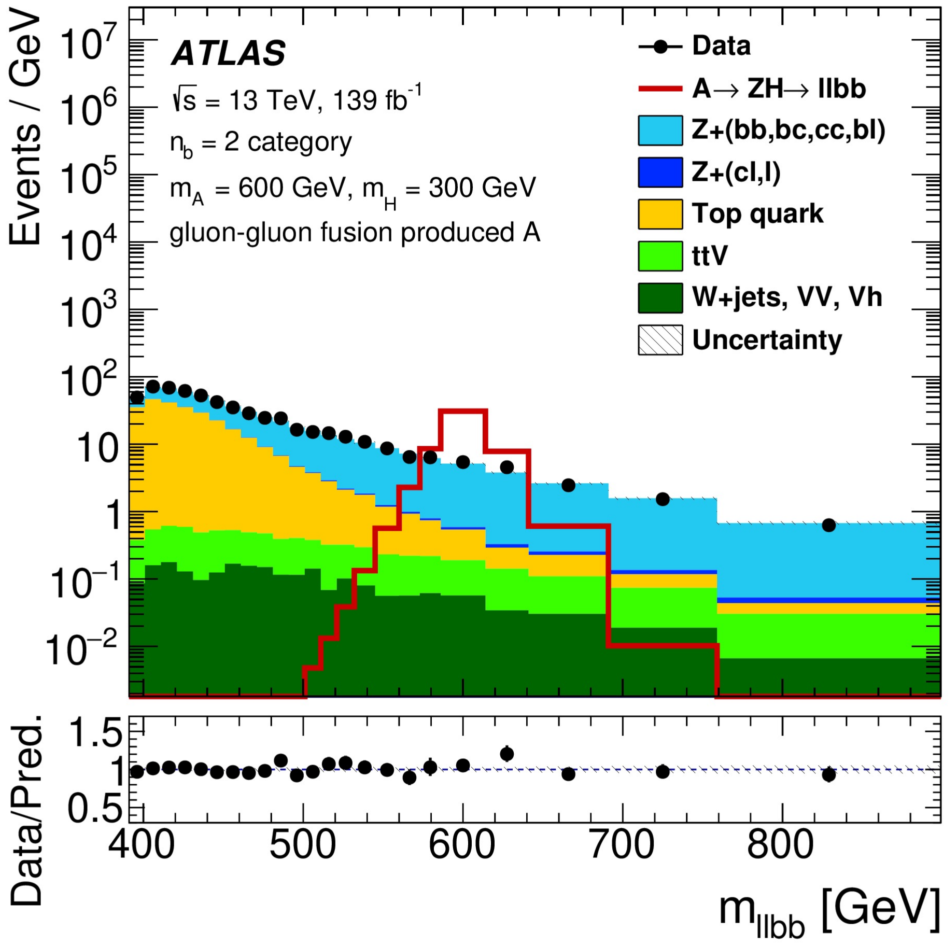
EPJC. 81 (2021) 396

- Mass spectrum

H→bb



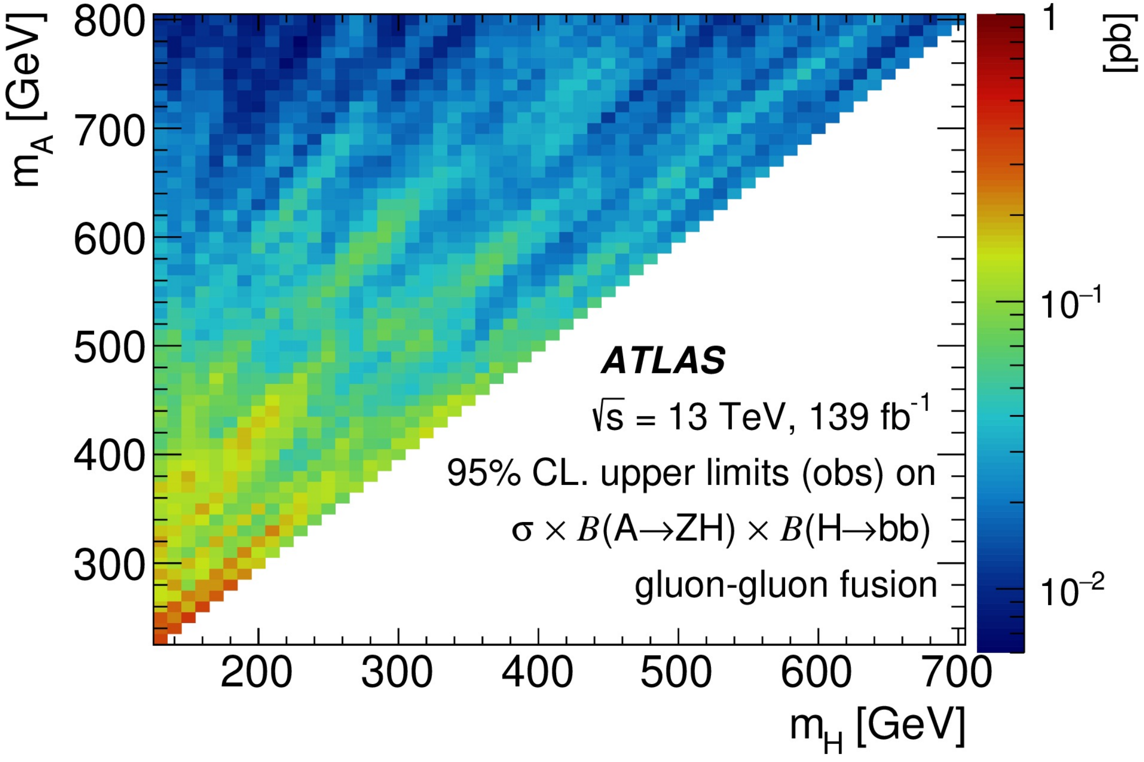
A→ZH



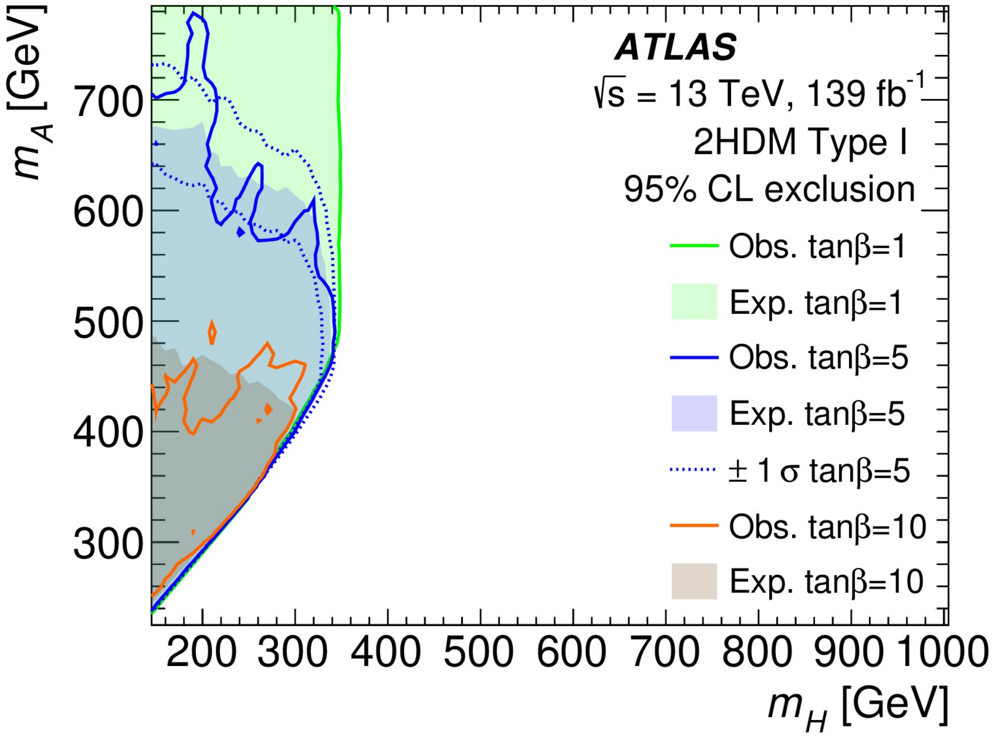
$A \to ZH(\to bb)$

EPJC. 81 (2021) 396

- Exclusion limits: 2D scan (m_A, m_H)



Model-independent limits

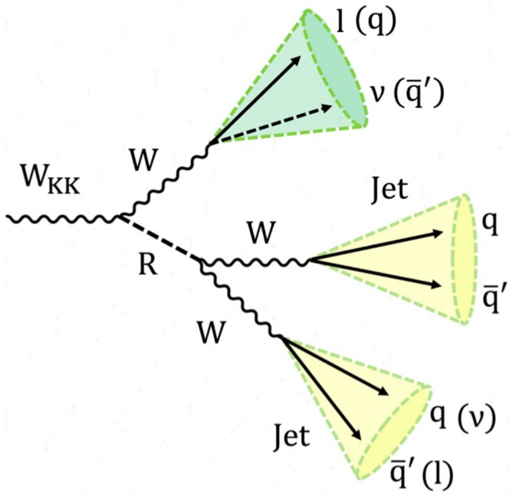


2HDM-I contours (alignment limit)

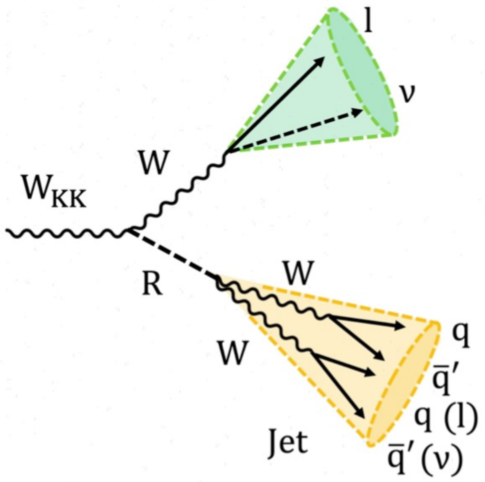
WWW: 1-lepton

CMS-PAS-B2G-20-001

- Search for heavy resonances decaying in a cascade into three W bosons
  - $W_{KK} \rightarrow WR$ and $R \rightarrow WW$
    - **Wkk**: Kaluza–Klein excited gauge boson; **R**: scalar radion

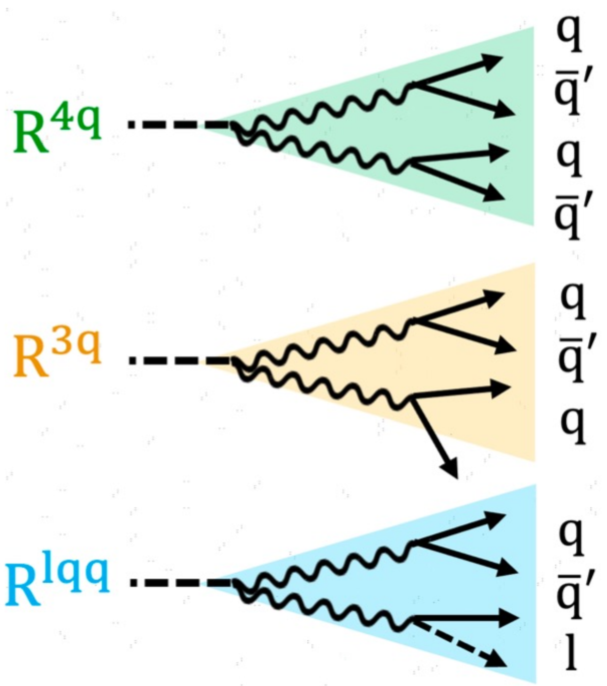


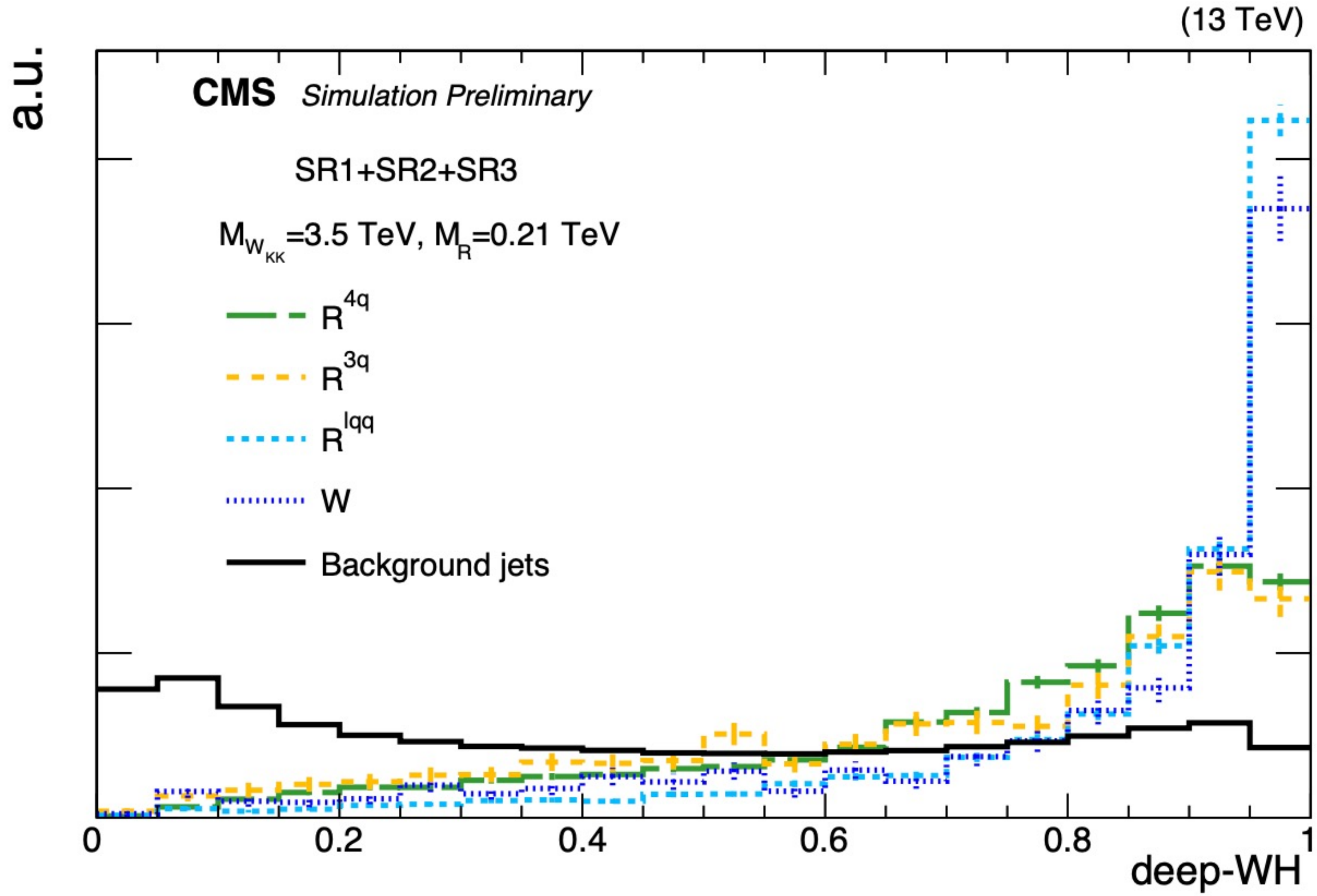
- Overview
  - Select one isolated lepton, large E_T^{miss}, one or two large-R jets
    - Boosted R: 1 large-R jet R→WW→4q or R→WW→lνqq
    - Resolved R: 2 large-R jets
  - Generative adversarial neural networks based W-tagger (deep-W) and R-tagger (deep-WH)
    - To remove mass dependence
  - Dominant background: QCD jets
    - Estimated with data control regions
  - 6 signal regions defined
    - Based on N_j, m_j window and tagger scores
  - Discriminants: $m_{l\nu jj}$, $m_{l\nu j}$



WWW: 1-lepton

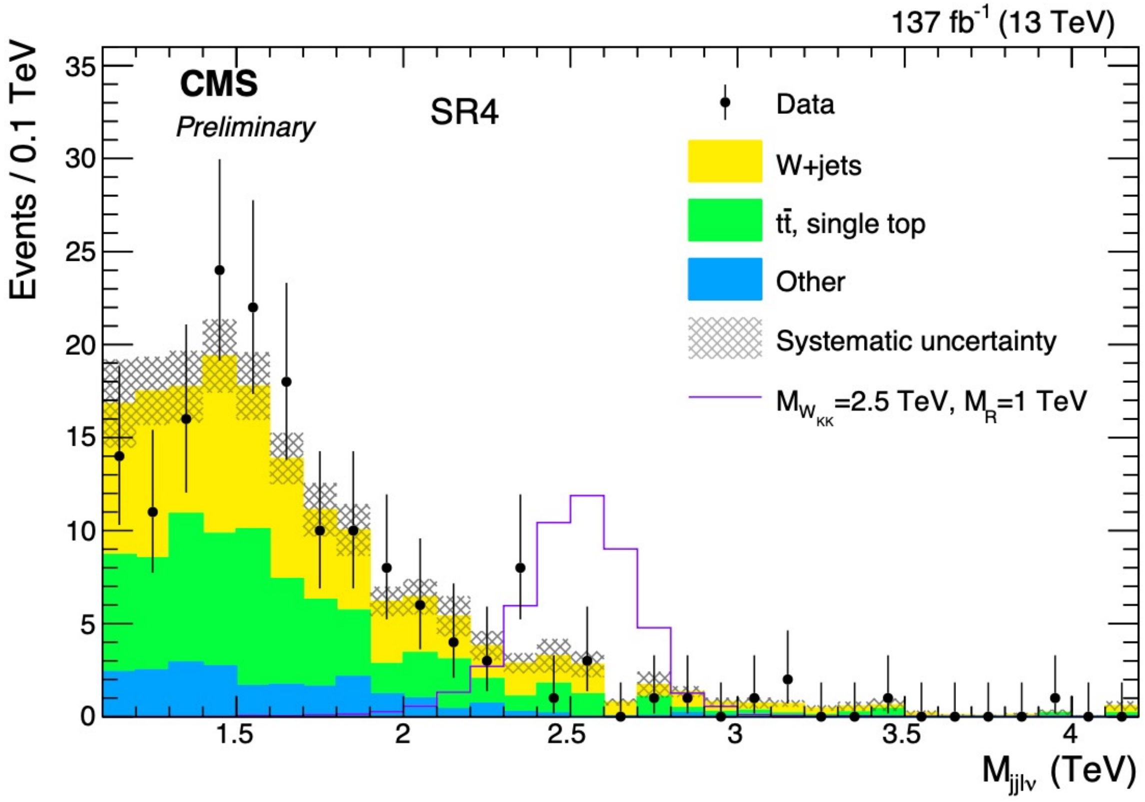
- Deep-WH discriminant
  - To discriminate W and H bosons from SM QCD jets (quarks or gluons)

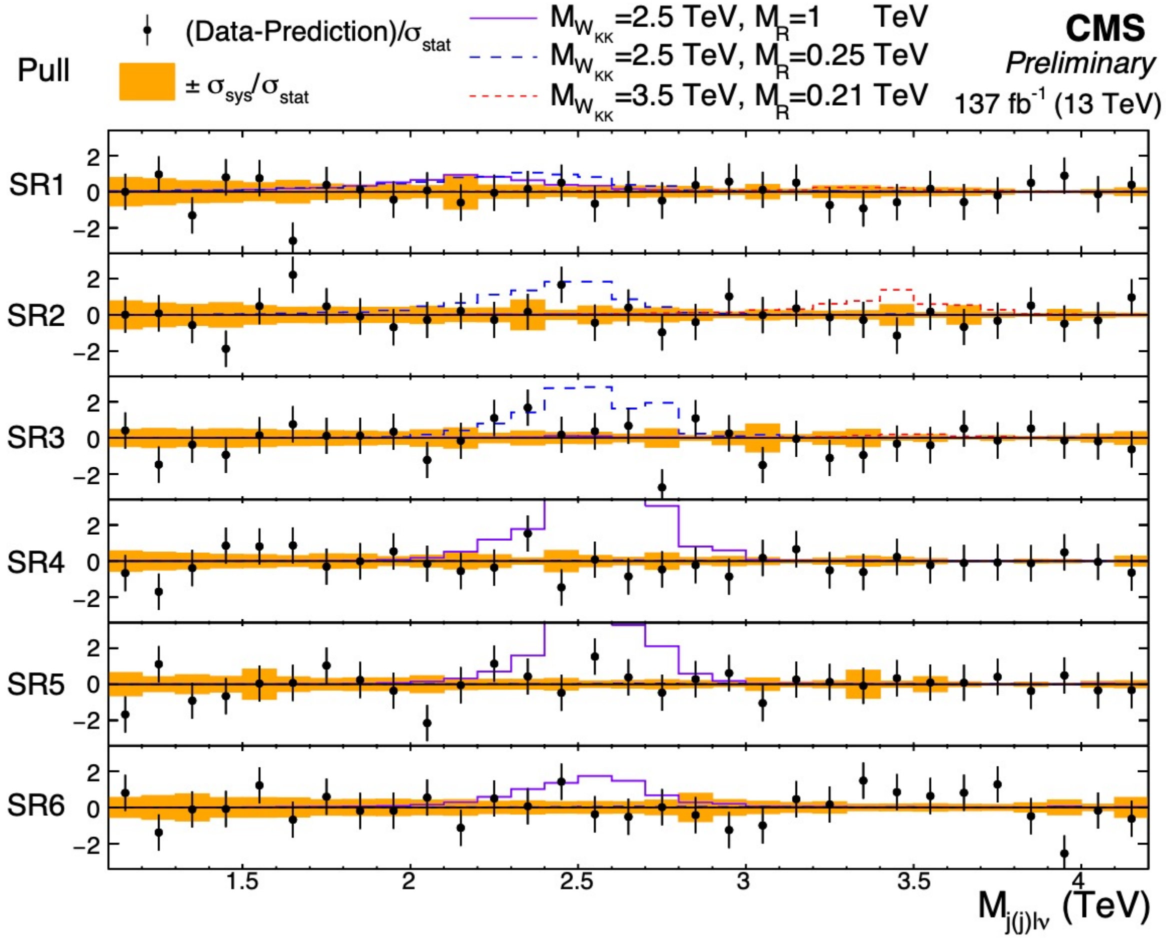




WWW: 1-lepton

CMS-PAS-B2G-20-001

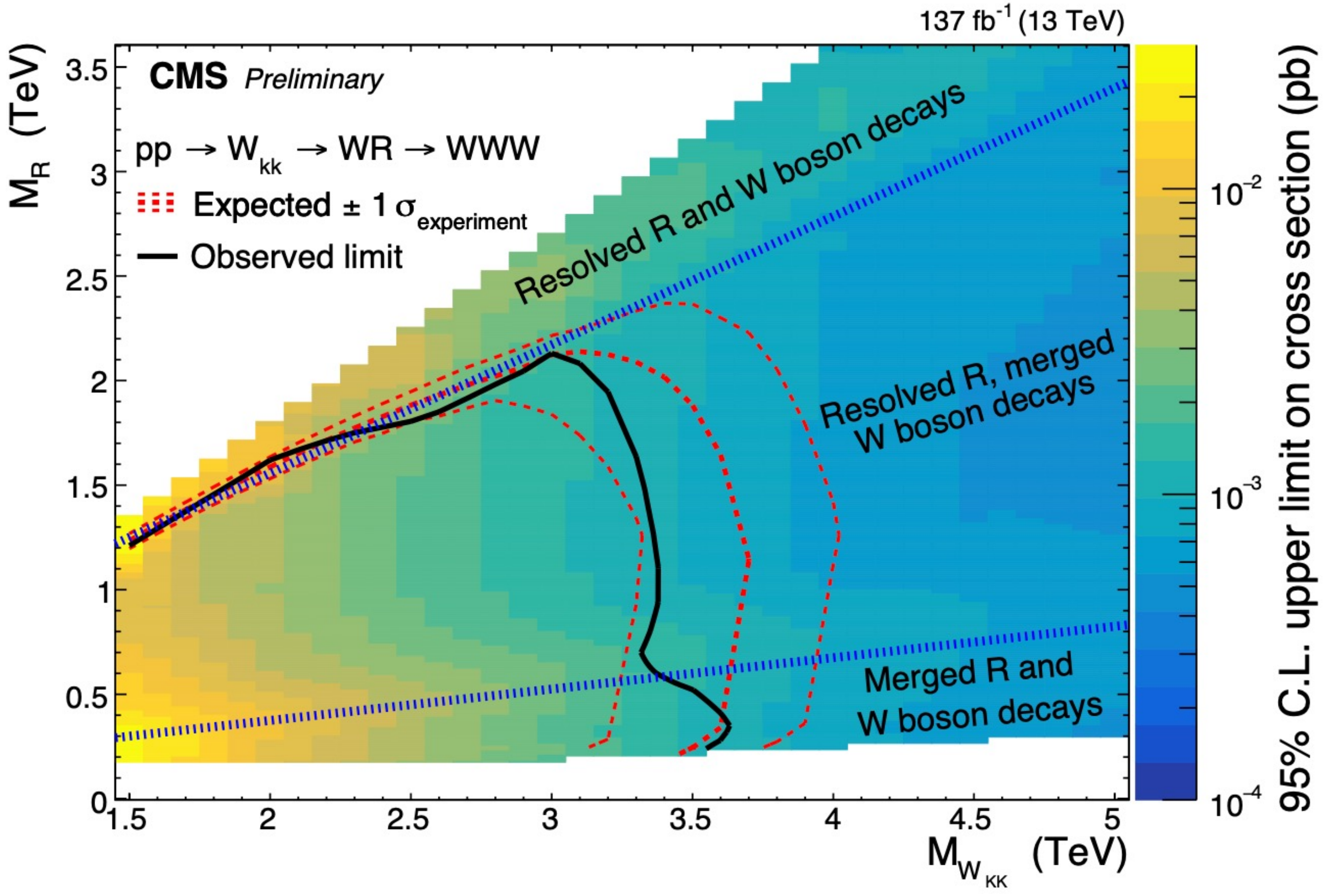




WWW: 1-lepton

CMS-PAS-B2G-20-001

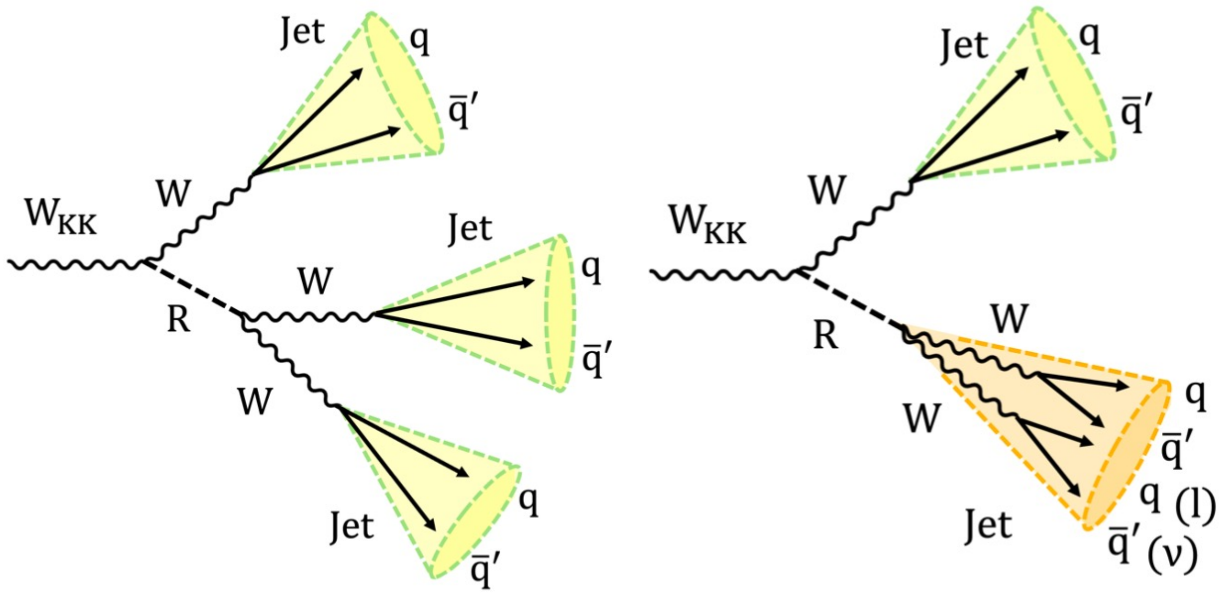
- Exclusion limits



WWW: 0-lepton

CMS-PAS-B2G-21-002

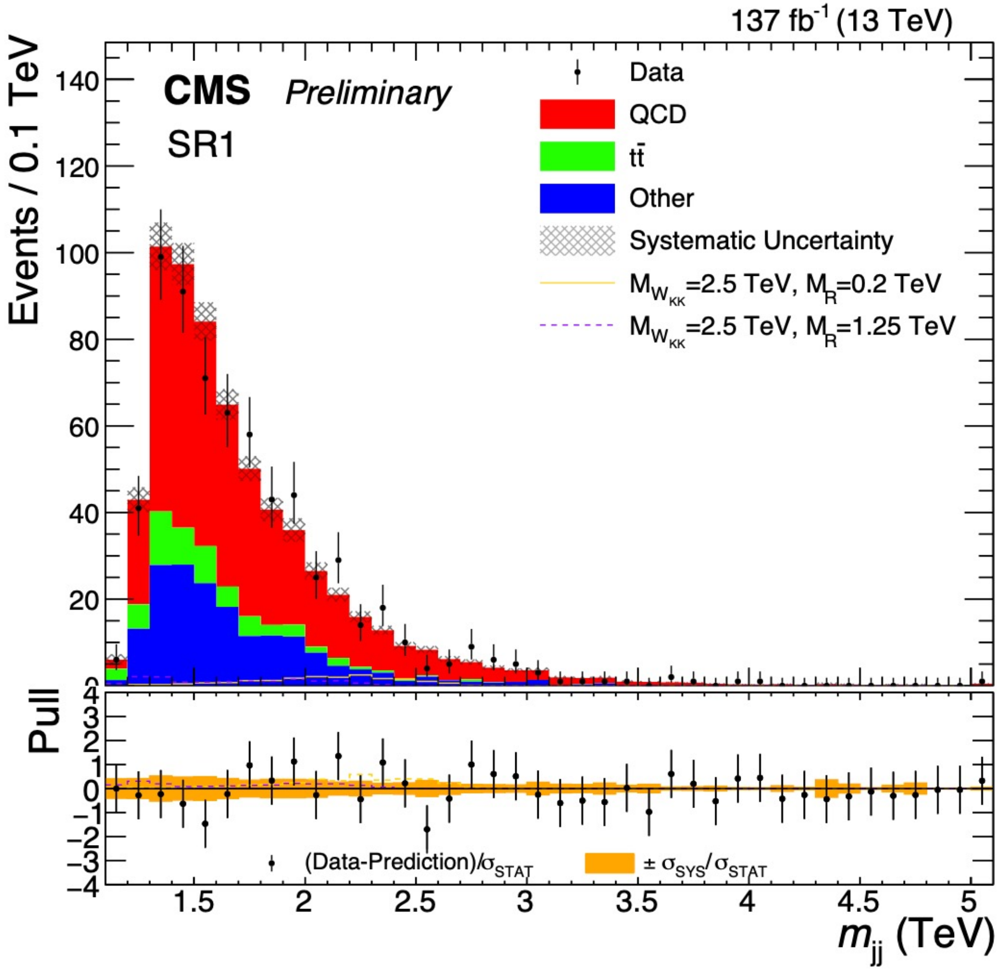
- Similar search to the 1-lep WWW search, but with 0-lep final states
- Overview
  - Select two or three large-R jets
    - Boosted R: R→WW→lvqq or R→WW→4q
    - Resolved R: R→WW, W→qq
  - Generative adversarial neural networks based W-tagger (deep-W) and R-tagger (deep-WH)
  - Dominant background: QCD jets
    - Estimated with data control regions
  - 6 signal regions defined
  - Discriminants: m_{jj} , m_{jjj}

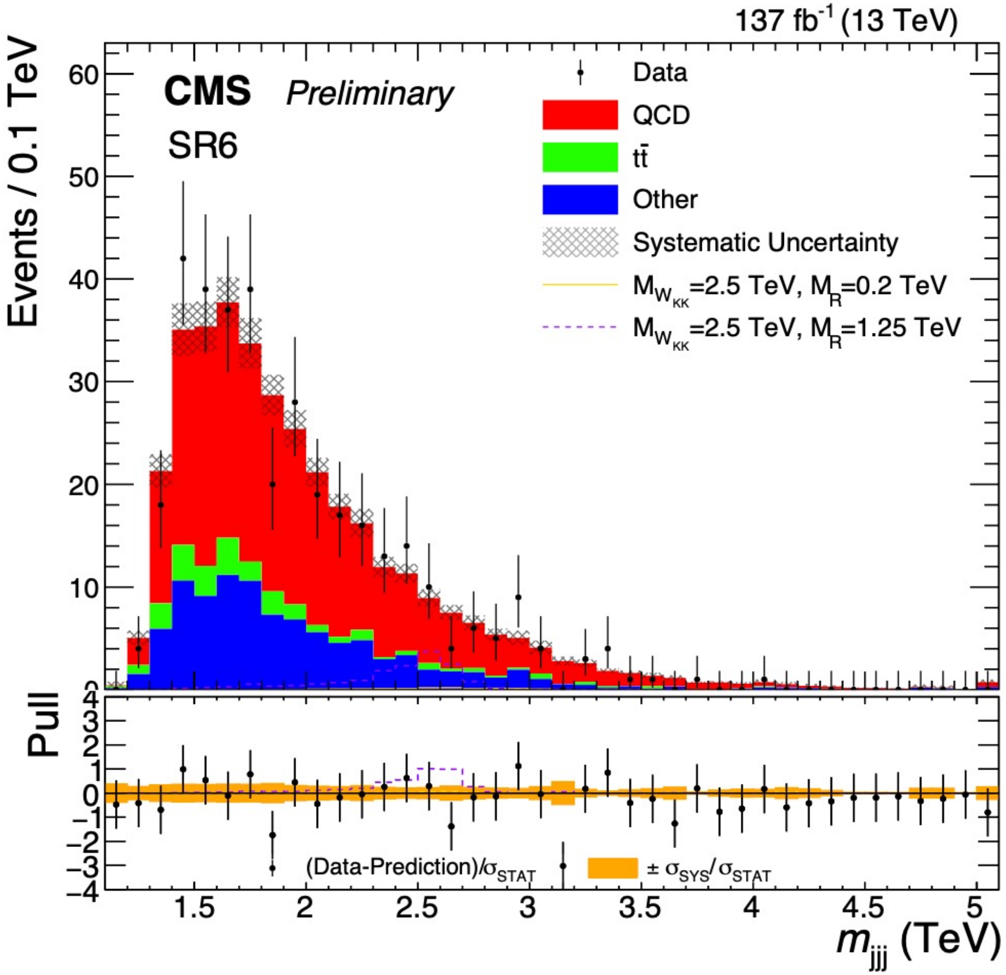


WWW: 0-lepton

CMS-PAS-B2G-21-002

- Mass spectrum

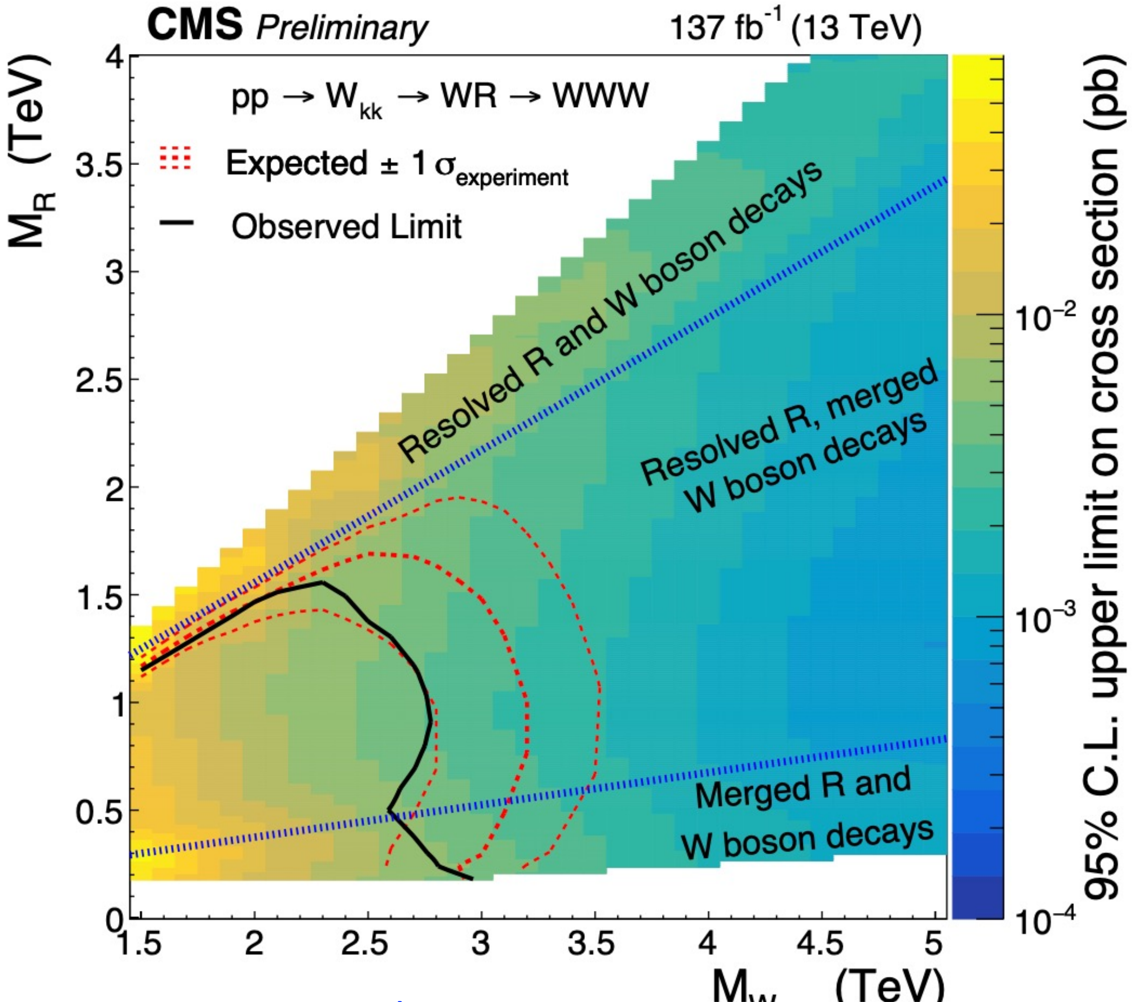




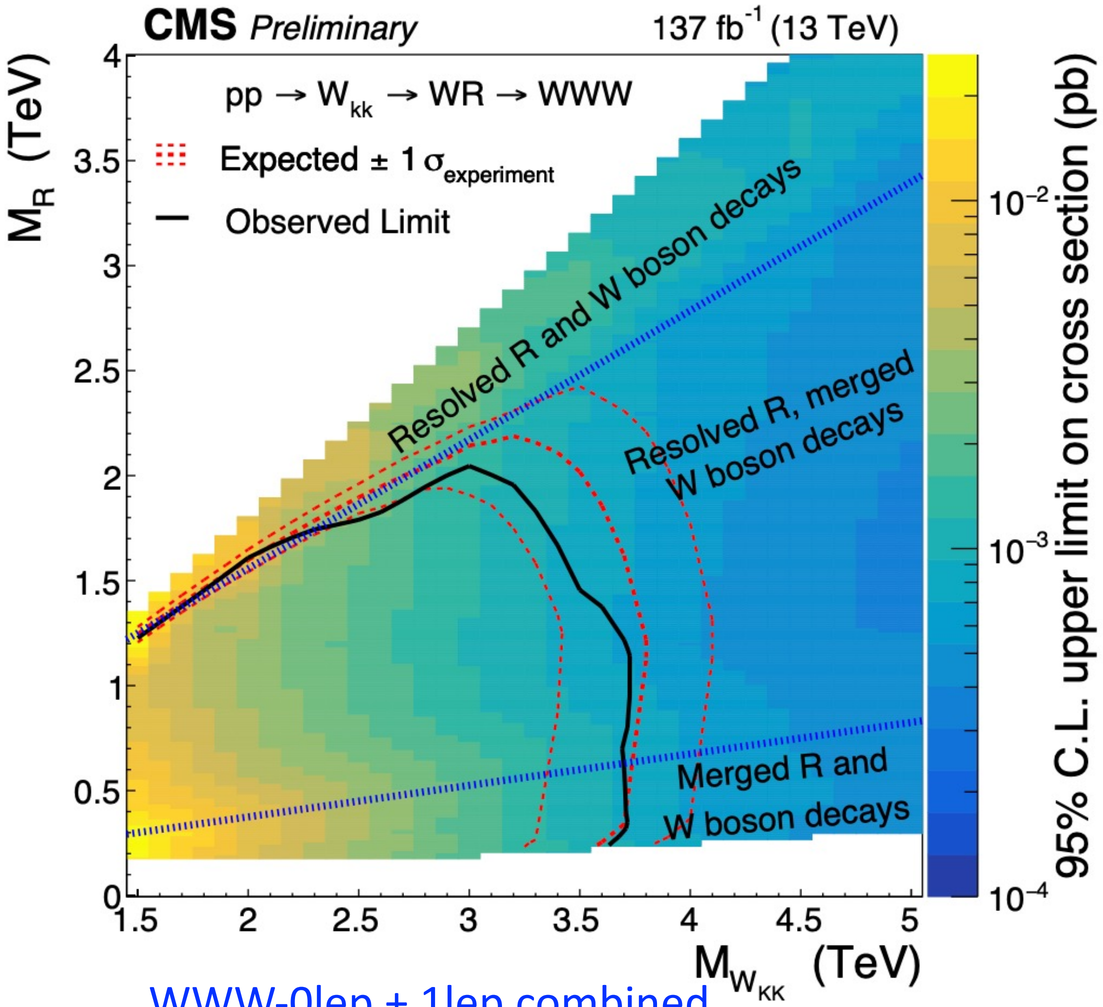
WWW: 0-lepton

CMS-PAS-B2G-21-002

- Exclusion limits



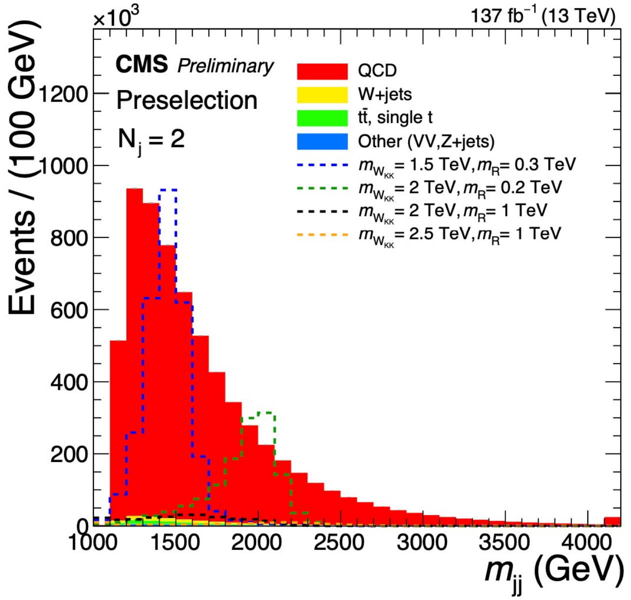
WWW-0lep



WWW-0lep + 1lep combined

WWW: DNN

CMS-PAS-B2G-21-002



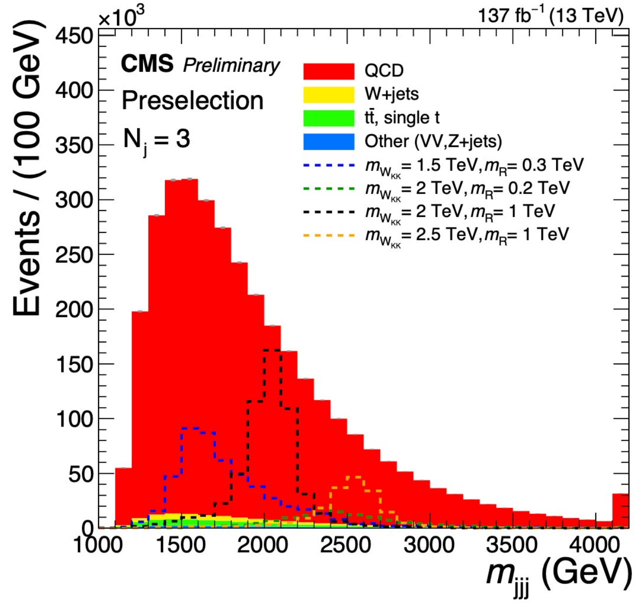
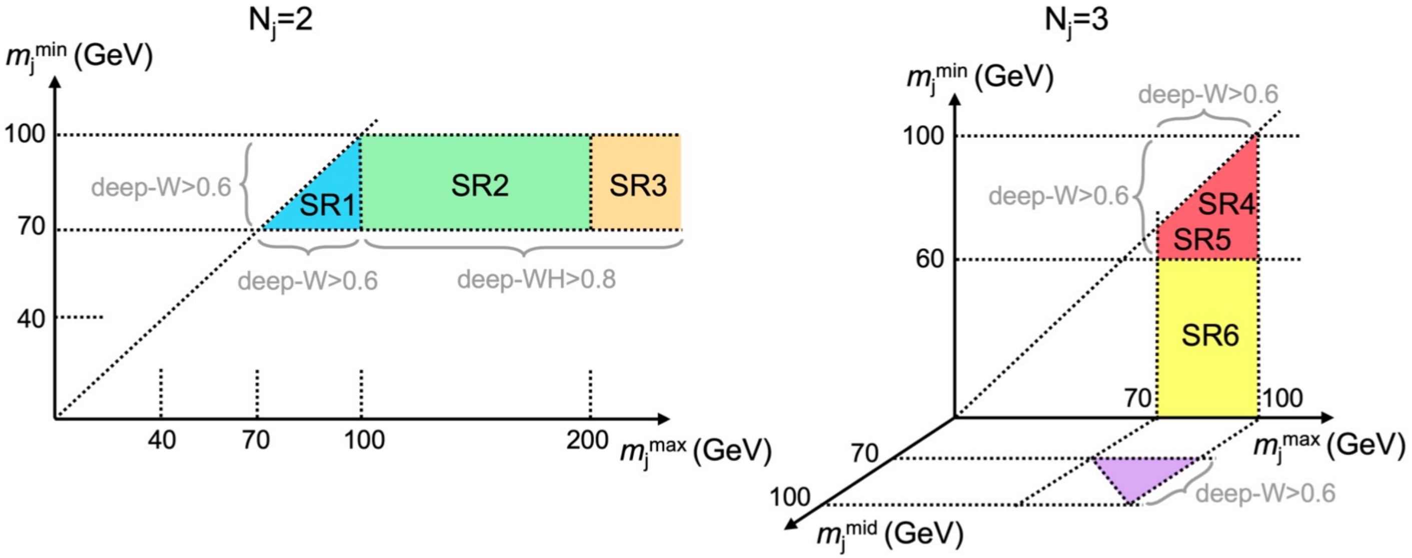


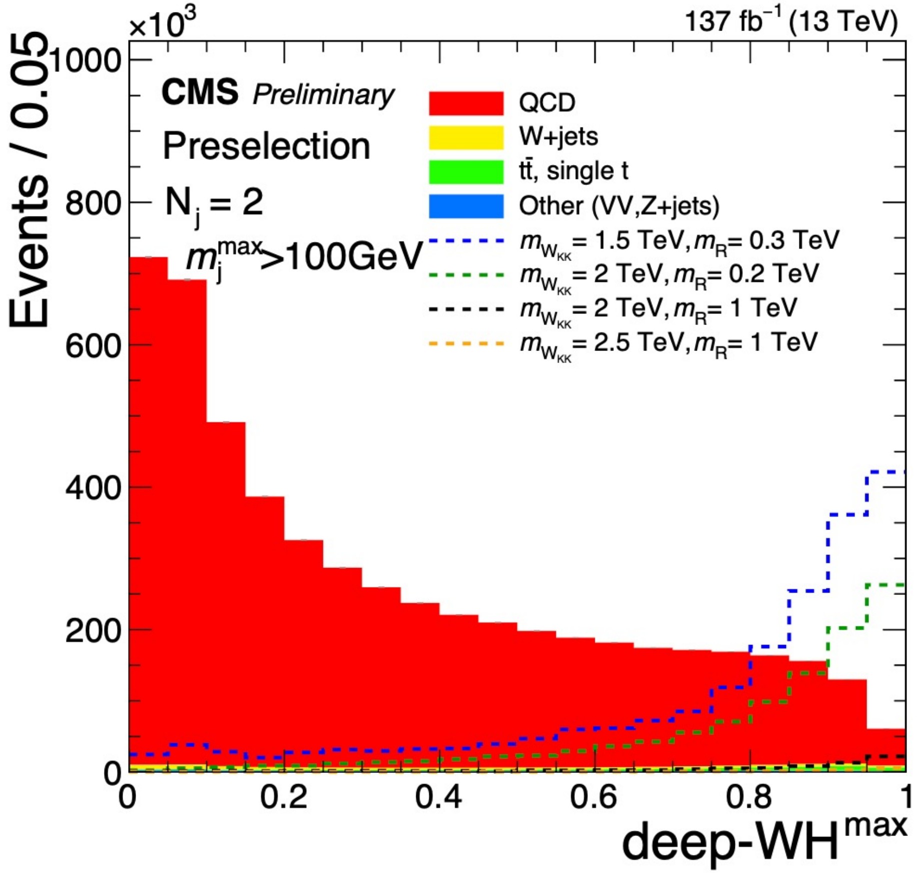
Table 1: Summary of the selection requirements for each of the signal regions.

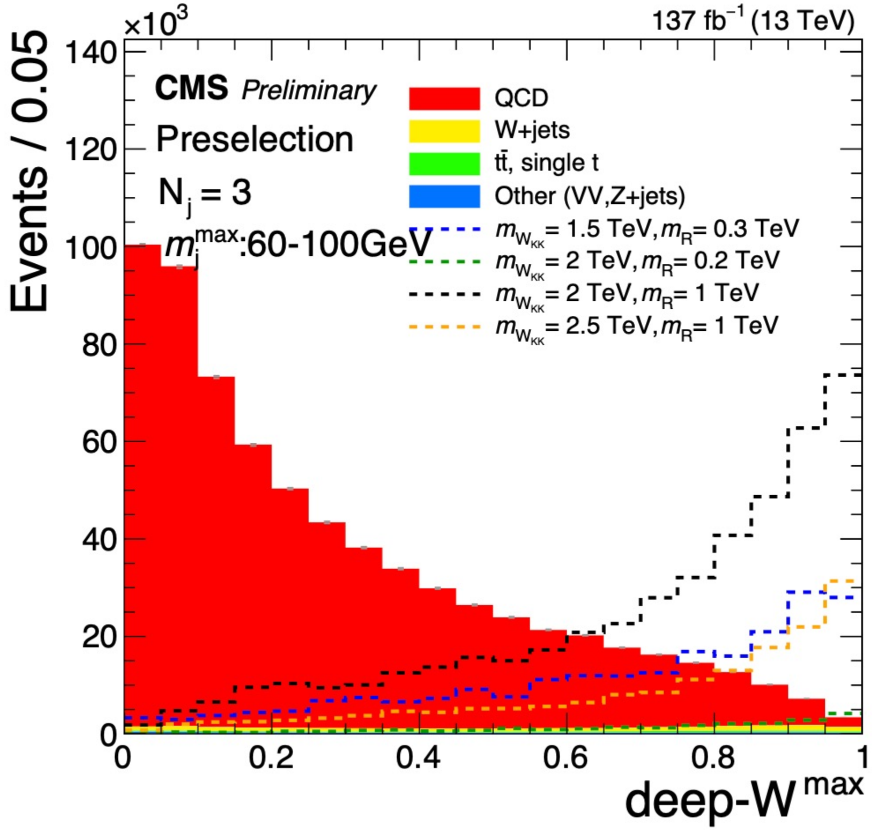
Region	N_j	m_j^{max} [GeV]	m_j^{mid} [GeV]	m_j^{min} [GeV]	Tags required
SR1	2	70–100	—	70–100	Both with deep-W > 0.8
SR2	2	100–200	—	70–100	Higher with deep-WH > 0.8, lower with deep-W > 0.8
SR3	2	>200	—	70–100	Higher with deep-WH > 0.8, lower with deep-W > 0.8
SR4	3	70–100	70–100	60–100	All three with deep-W > 0.6
SR5	3	70–100	70–100	60–100	Exactly two with deep-W > 0.6
SR6	3	70–100	70–100	0–60	Two highest with deep-W > 0.8



WWW: 0-lepton

[CMS-PAS-B2G-21-002](CMS-PAS-B2G-21-002)





WWW: DNN

CMS-PAS-B2G-21-002

- CMS uses the DEEPAK8 algorithm for boosted boson tagging
  - using PF candidates, secondary vertices, and other inputs to classify the AK8 jets into 17 categories
    - jets arising from W → qq, Z → qq, t → bqq, H → 4q, and gluon or light quark decay
- Deep-W and deep-R discriminants

  - deep-W = raw score($W \to qq$)/(raw score($W \to qq$) + raw score(QCD)), used for W boson tagging for all jet candidates with mass m_j in the range 60–100 GeV.
  - deep-WH = (raw score($W \to qq$) + raw score($H \to 4q$))/(raw score($W \to qq$) + raw score($H \to 4q$) + raw score(QCD)), used for radion tagging for all jet candidates with mass $m_j > 100$ GeV.

- Dedicated calibrations performed for the deep-W, deep-R tagger