HH/HY and VH Resonant Searches in ATLAS and CMS

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SEZIONE DI ROMA TRE

Physics Motivations

Disclaimer: covering only a limited set of analyses, focussing on the most recent ATLAS and CMS results, for more details refer to ATLAS and CMS public pages

- The non-resonant HH analyses covered in the presentation by ***Jason***, ***Nicola***, and resonant HH (ATLAS) by ***Bill***

HH Gluon-gluon fusion (*ggF*) resonant mode allows to probe heavy resonances produced through quark and gluon interactions

- Production of a heavy ***spin 0*** resonance X:
  - Can be e.g. a Randall-Sundrum radion or the 2HDM heavy CP-even Higgs boson
  - Narrow width (compared to experimental resolution) assumed as a signal benchmark
- Production of a heavy ***spin 2*** resonance G^*_{KK} (or X in CMS convention)
  - Spin-2 Kaluza-Klein gravitons with model-dependent width (3%-20% of m_X)

Resonant production of HH in association with a vector boson

VH New heavy resonances decaying into SM Higgs boson and a vector boson

- These resonances are assumed to be either a new heavy vector boson (*Z'/W'*), or a heavy CP-odd scalar boson *A*
  - A generic two-Higgs-doublet model (2HDM)
  - Heavy Vector Triplet (*HVT*) *arXiv:1402.4431*

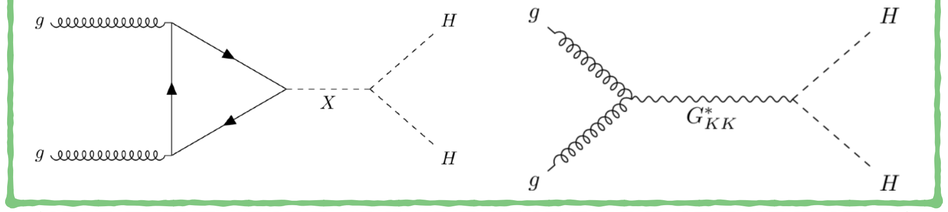
HY X heavy particle decaying to the SM Higgs boson and a scalar particle (Y in CMS convention or S in ATLAS convention)

- Results are interpreted in the context of the next-to-minimal supersymmetric standard model (*NMSSM*) and also in an extension of the SM with two additional singlet scalar fields (*TRSM*)

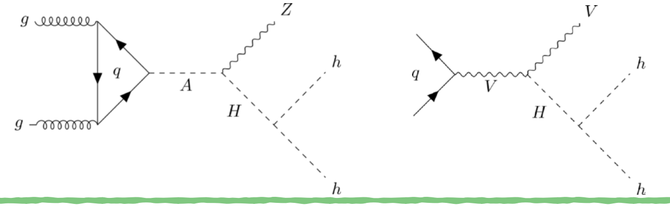
VBF VBF HH resonant production not covered in this talk, bonus ***reference***

*Signal benchmarks targeted by **ATLAS** and **CMS** searches*

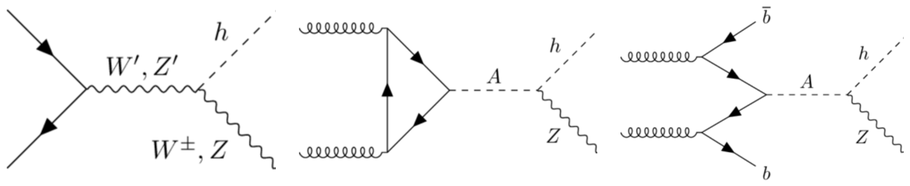
***ggF* Resonant Production of HH**



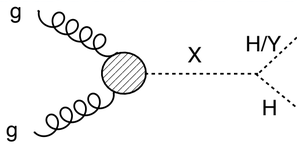
Resonant Production of HH in association with a vector boson



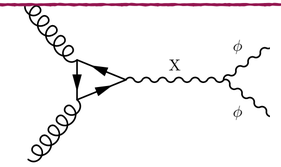
Resonant Production of VH



Resonant Production of HY

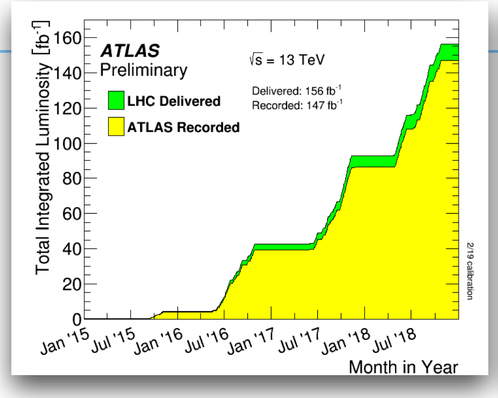


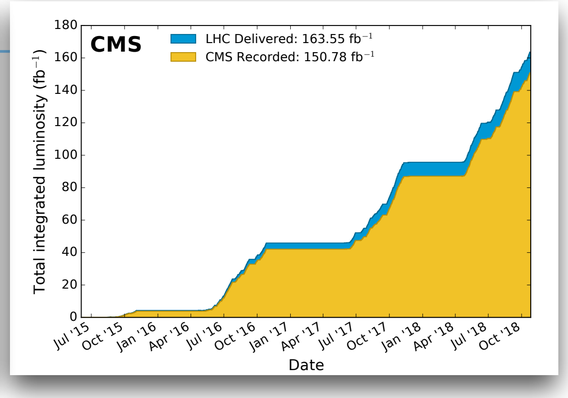
Extended Higgs sector



Experimental Overview

Run 2 data





HH decay modes | **HY decay modes**

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Rarer

Rarer

ATLAS
- HH to *bbγγ* final state: *Phys. Rev. D 106 (2022) 052001*
- HH to *bbττ* final state: *arXiv:2209.10910*
- HH to *bbbb* final state: *Phys. Rev. D 105 (2022) 092002*
- Combination: *ATLAS-CONF-2021-052*

CMS
- HH to *multilepton* final state: *arXiv:2206.10268*
- HH/HY to *bbγγ* final state: *CMS-PAS-HIG-21-011*

ATLAS
- V*hh* search: *arXiv:2210.05415*
- Generic search for Y to XH: *ATLAS-CONF-2022-045*

CMS
- HY to *bbbb* final state: *arXiv:2204.12413*

VH decay modes

	Z(νν)	Z(ee/μμ)	Z(had)
H(bb)	12%	2%	41%

	W(*l*ν)	W(had)
H(bb)	6%	40%

ATLAS
- Semi-leptonic VH search: *arXiv:2207.00230*

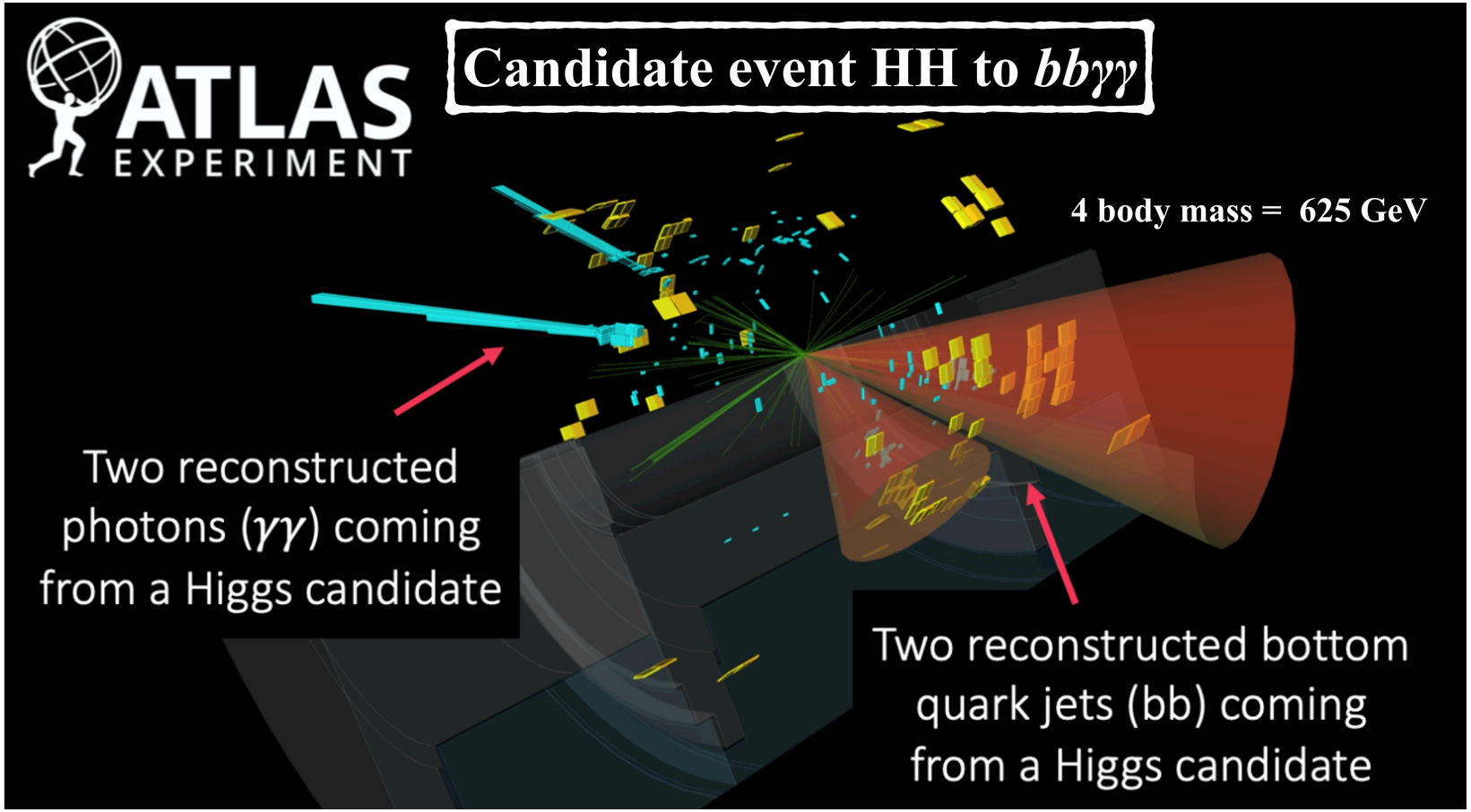
CMS
- All hadronic VH search: *arXiv:2210.00043*

Extended Higgs sector

CMS
- Search for new particles in an extended Higgs sector with four b quarks in the final state: *arXiv:2203.00480*

HH to *bbγγ* search - *ATLAS*

Phys. Rev. D 106 (2022) 052001

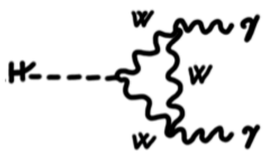


Fully reconstructable final state

HH to *bbγγ* search - *ATLAS*

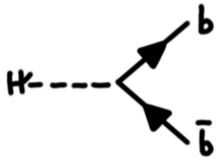
Phys. Rev. D 106 (2022) 052001

- Di-photon triggers used to allow to probe low m_X values, lepton veto



Excellent $m_{\gamma\gamma}$ resolution

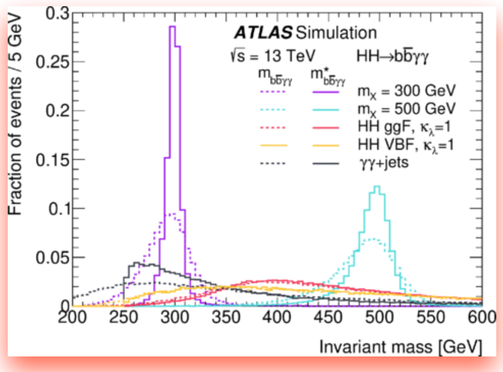
Tight and isolated, $m_{\gamma\gamma}$ in [105-160] GeV



Large BR

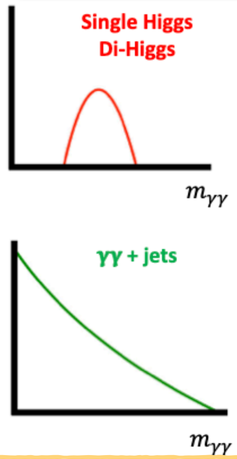
2 b-jets, b-jets corrections applied
Muon in jet + BCal

Object Selection



$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250 \text{ GeV}$$

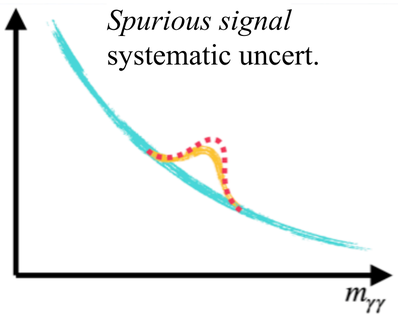
Modelling discriminating variable

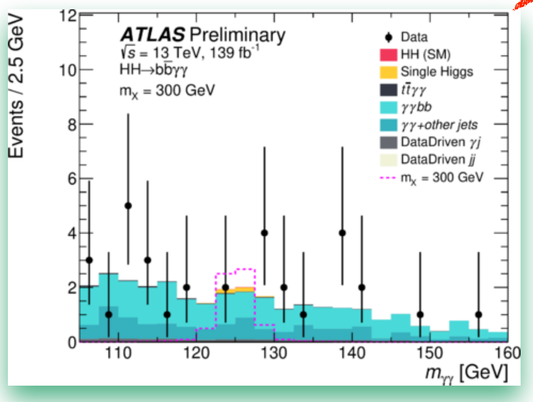


Simultaneous likelihood fit to all categories

σ vs m_X

Statistically limited with the current dataset

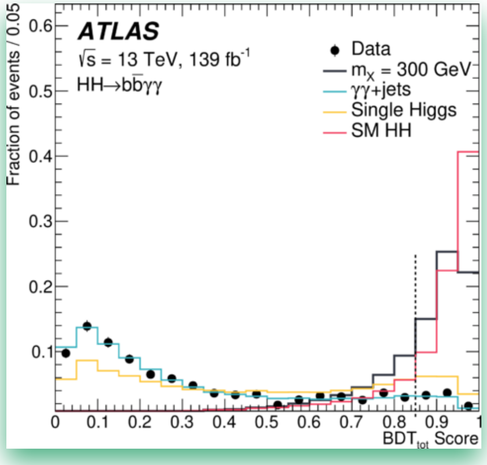


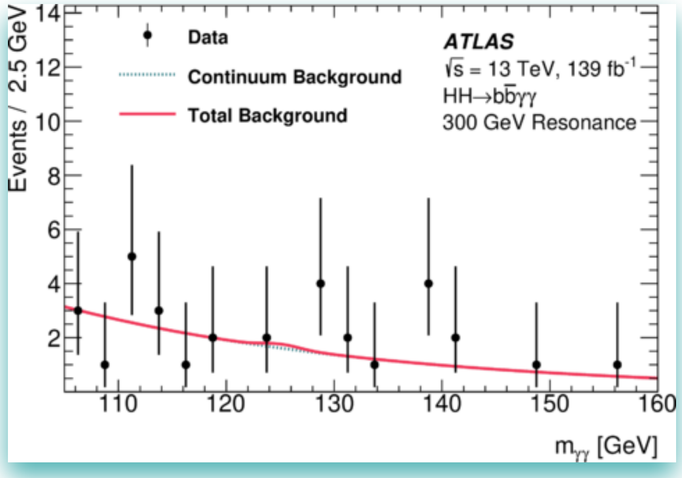


MVA approach

Single BDT for all signal hypotheses (mass dependent cut)

Event Categorisation

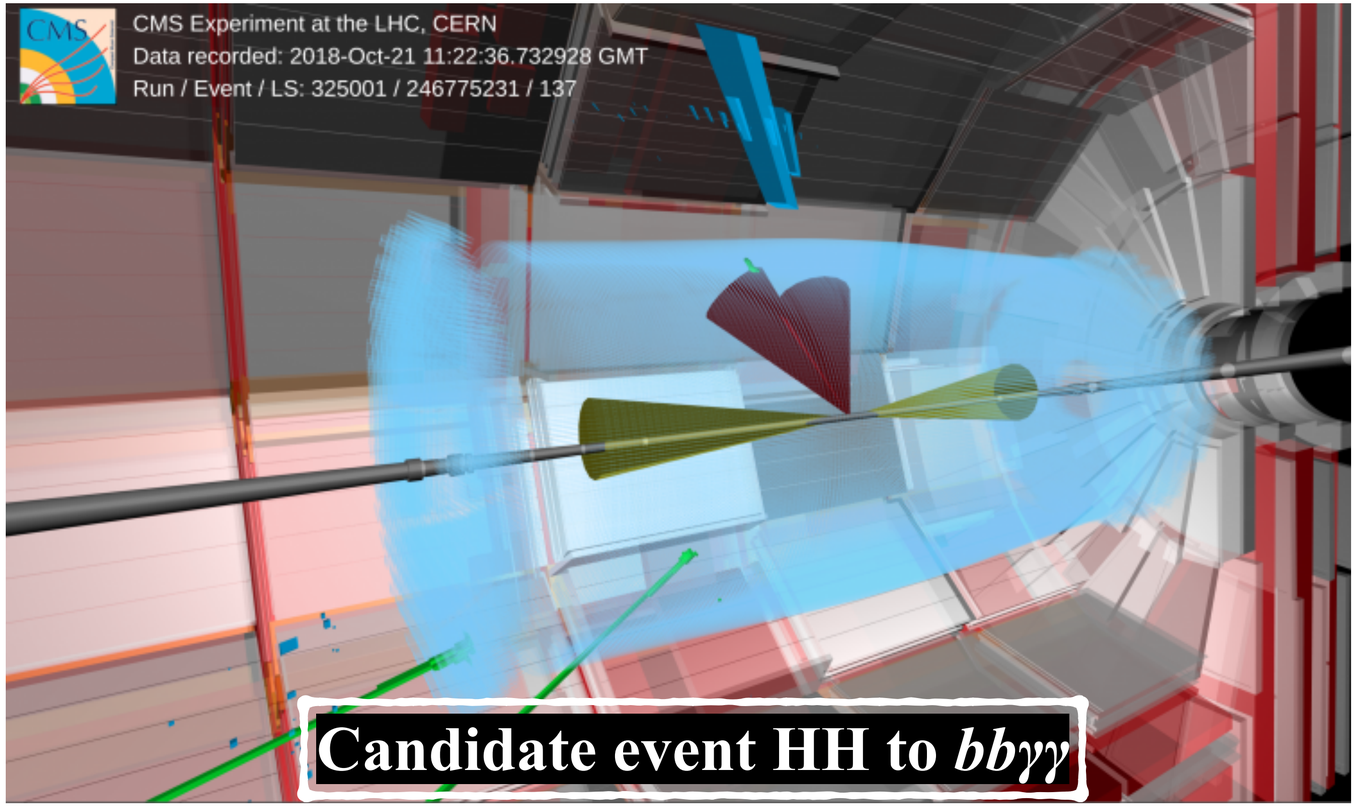




- Potential bias coming from the choice of the background modelling accounted for in systematic uncertainties

HH/HY to *bbγγ* search - *CMS*

CMS-PAS-HIG-21-011

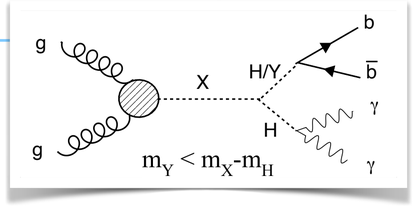


Candidate event HH to *bbγγ*

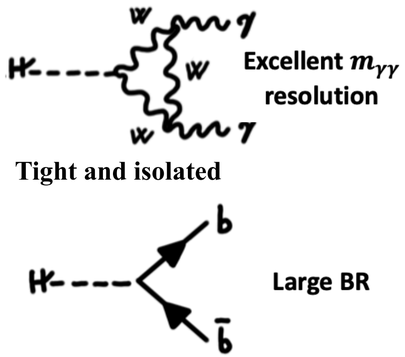
Fully reconstructable final state

HH/HY to *bbγγ* search - *CMS*

CMS-PAS-HIG-21-011

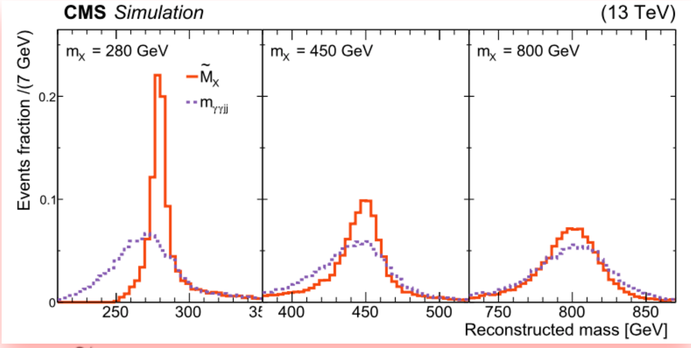


- Di-photon triggers used to allow to probe low m_X values, lepton veto



b-jets corrections applied
Energy regression

Object Selection



$$\tilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$$

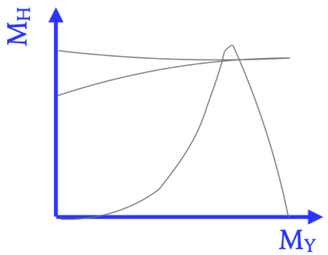
70 < m_{jj} < 190 (1200) GeV

MVA approach

Using b-jet ID, photon ID and kinematic variables

Event Categorisation

Modelling discriminating variable



Extract signal from 2D fit: m_Y vs m_H, in windows of m_X

Statistical analysis

σ vs m_X - m_Y

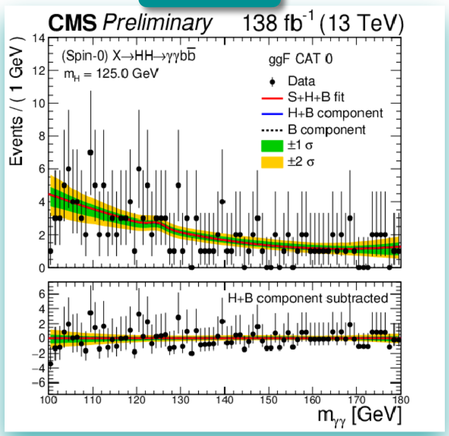
Statistically limited with the current dataset

Resonant m_X and m_Y hypotheses differ in kinematics

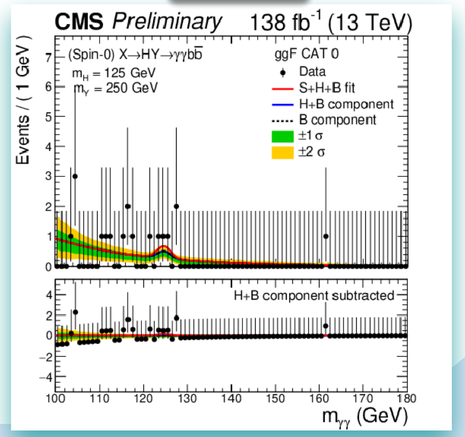
BDT is trained for six different mass ranges, based on boost factor $m_X/(m_H + m_Y)$:

- 3 ranges in m_X (m_X < 500 GeV, 500 < m_X < 700 GeV and m_X > 700 GeV)
- 3 ranges in m_Y (m_Y < 300 GeV, 300 < m_Y < 500 GeV, and m_Y > 500 GeV)

HH



YH

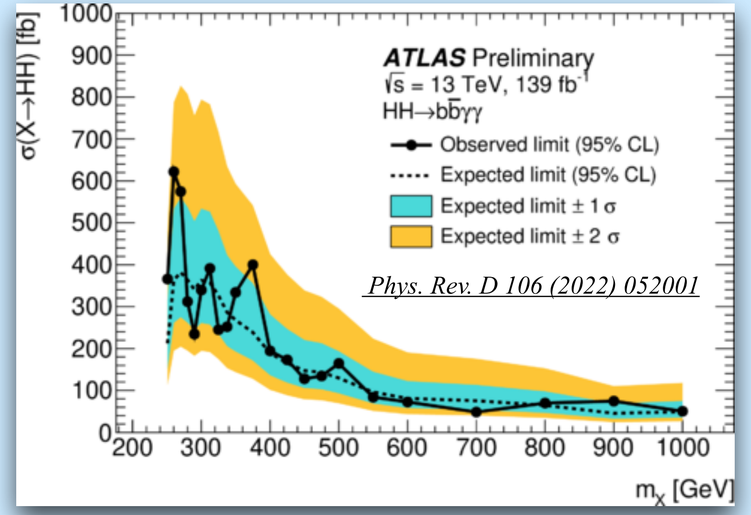


Results: HH to *bbγγ* final state

ATLAS

- X resonance decaying to HH
- Narrow width approximation
- Spin 0 hypothesis

Upper limit on σ(pp→X→HH)



The expected limit on the cross section improves overall by a factor of 2-3 wrt the partial Run 2 analysis

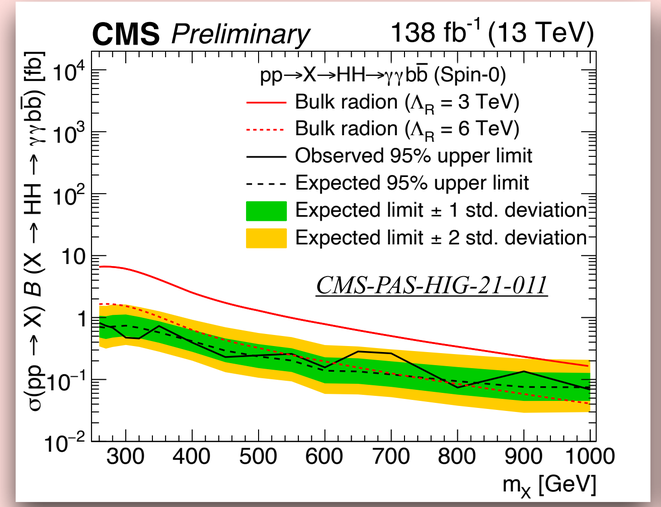
25 mass hypothesis for $251 < m_X < 1000$ GeV

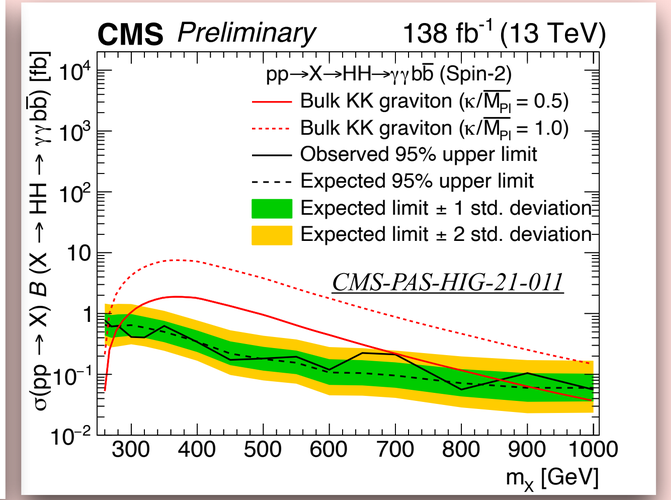
	Observed	Expected
Max	640 fb	391 fb
Min	44 fb	46 fb

CMS

- X resonance decaying to HH or SH (results in the next slide)
- Spin 0 (narrow width approximation) and spin 2 hypotheses

Upper limit on σ(pp→X→HH) x BR (HH→ *bbγγ*)



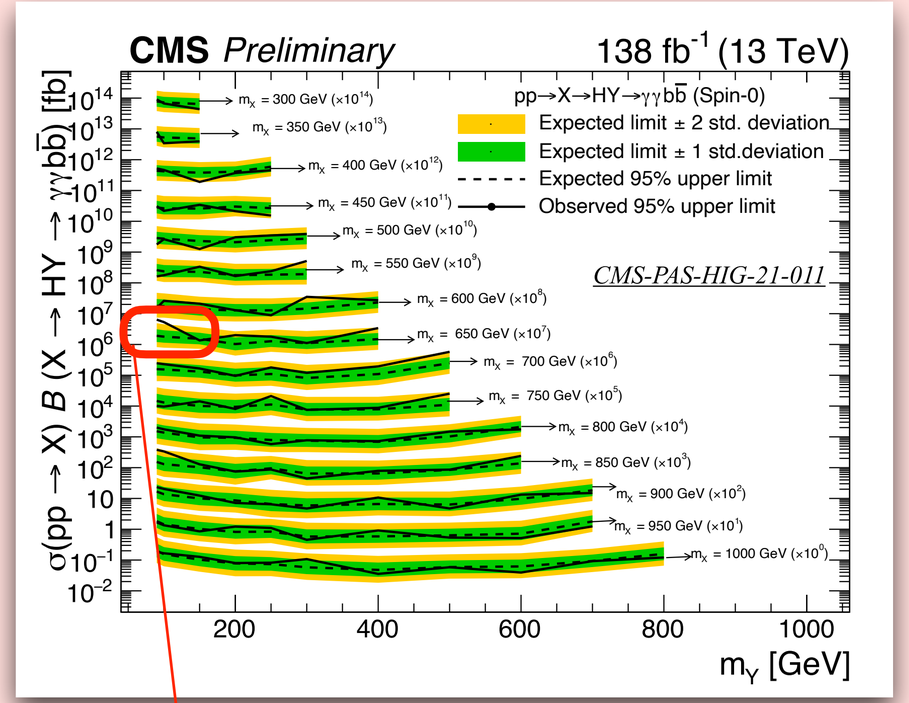


Spin 0	Observed	Expected
Max	0.07 fb	0.08 fb
Min	0.82 fb	0.74 fb

Spin 2	Observed	Expected
Max	0.06 fb	0.06 fb
Min	0.78 fb	0.65 fb

These results exclude masses up to 600 GeV for spin 0 bulk radion signal at $\Lambda_R = 6$ TeV and up to 850 GeV for spin 2 bulk KK graviton signal with coupling factor $\kappa/M_{pl}=0.5$

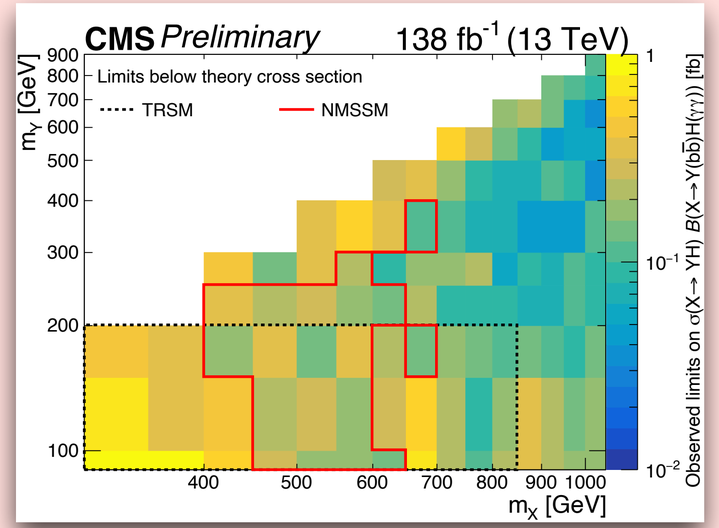
Results: HY to *bbγγ* final state - *CMS*

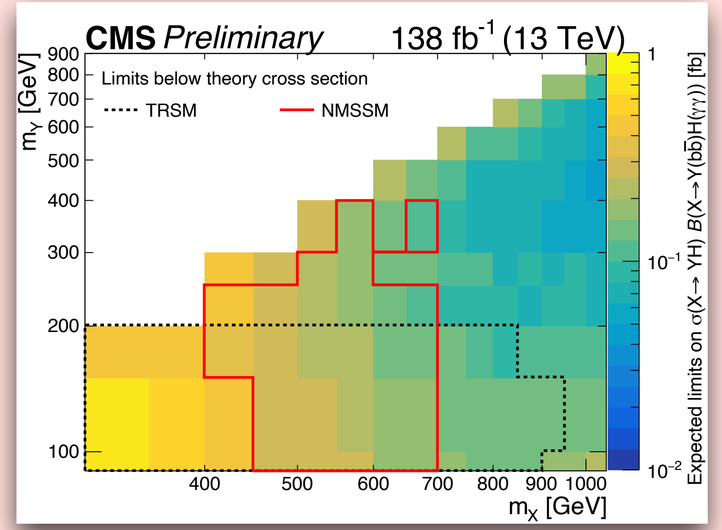


Excess observed:

M_X= 650 GeV M_Y=90 GeV

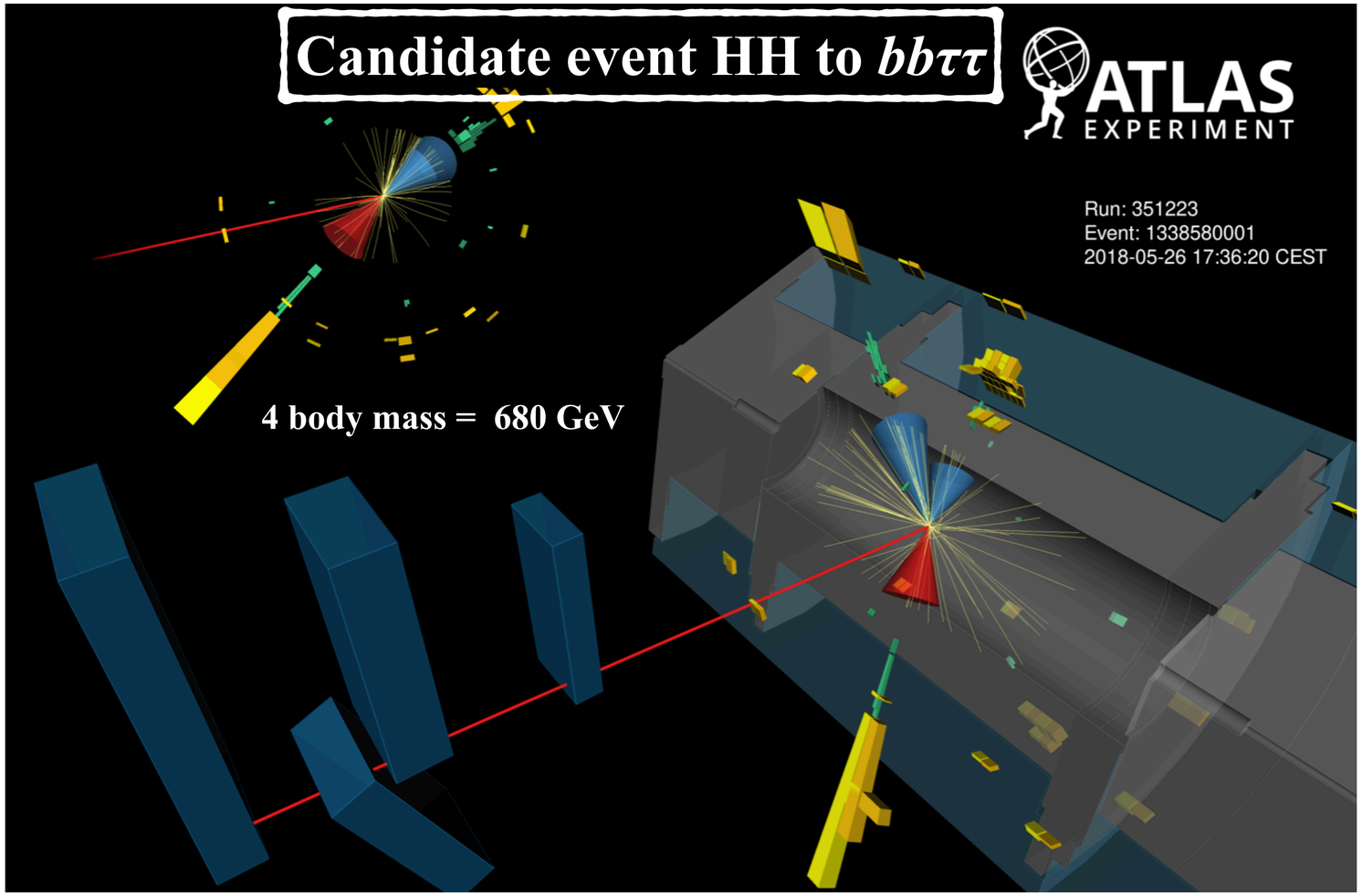
3.8σ local 2.6σ global





HH to *bbττ* search - *ATLAS*

arXiv:2209.10910

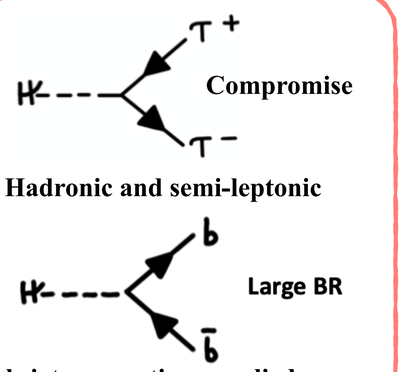


Good compromise between BR and clean final state

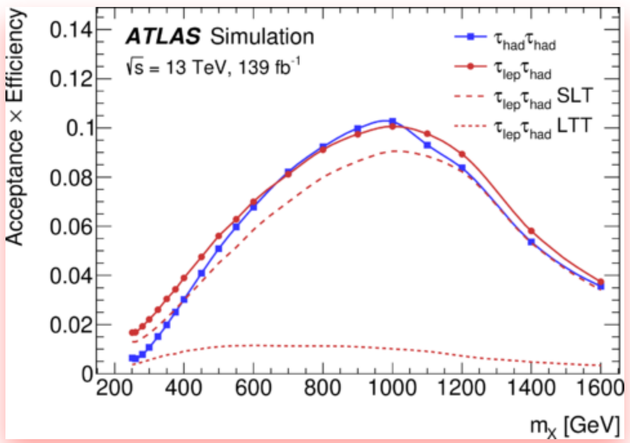
HH to $bb\tau\tau$ search - *ATLAS*

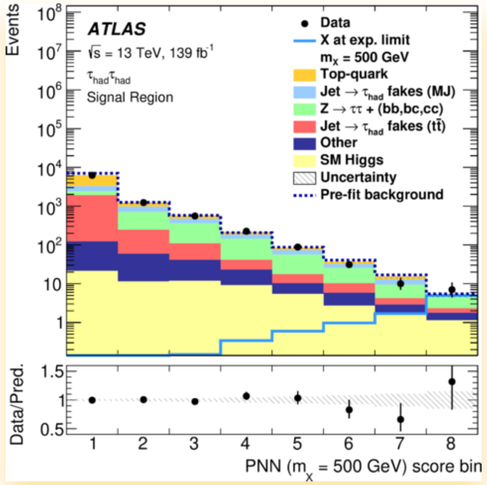
arXiv:2209.10910

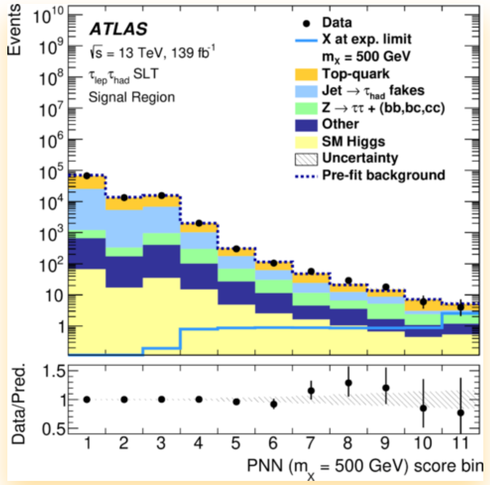
- Complex trigger strategy using a mixture of hadronic single-/di-τ triggers and lepton/lepton+τ triggers
  - **Single Tau** Trigger & **Di-Tau** Trigger **for** $\tau_{had}\,\tau_{had}$ **Single Lepton** Trigger (SLT) and **Lepton+Tau Trigger** (LTT) **in** $\tau_{lep}\,\tau_{had}$

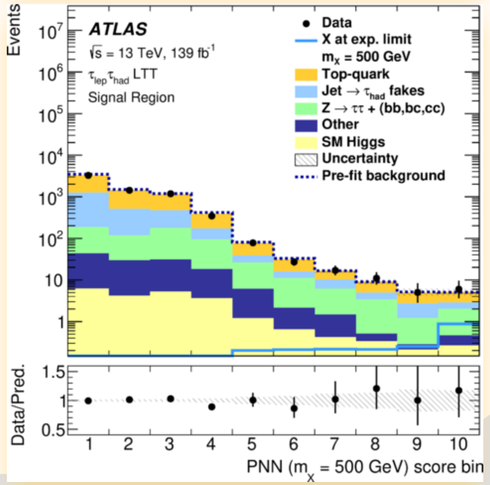


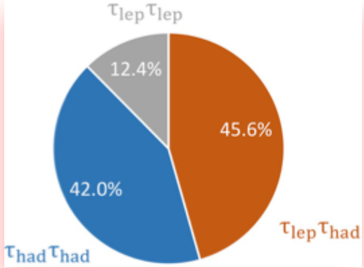
Object Selection











MVA in 3 categories:

1. $\tau_{had}\,\tau_{had}$
2. $\tau_{lep}\,\tau_{had}$ (e/μ & opp. charged τ) **LTT SLT**
3. Control region for Z+HF (m_{ll})

Event Categorisation

NN signal extraction

Neural Network (NN) to construct a discriminant, which is then fitted

- NN is parameterized on m_{HH} for optimal performance across the whole range

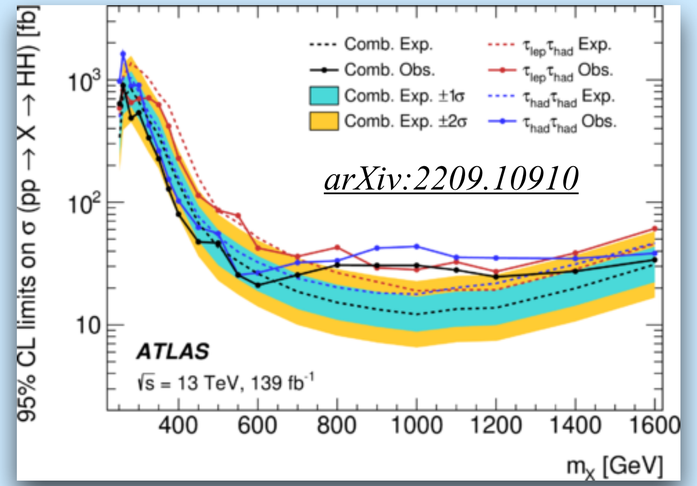
- Backgrounds are estimated using a mix of simulation and control samples in data

Results: HH to *bbττ* final state

ATLAS

- X resonance decaying to HH
- Narrow width approximation
- Spin 0 hypothesis

Upper limit on σ(pp→X→HH)



Mass hypothesis for 251 < m_X < 1600GeV

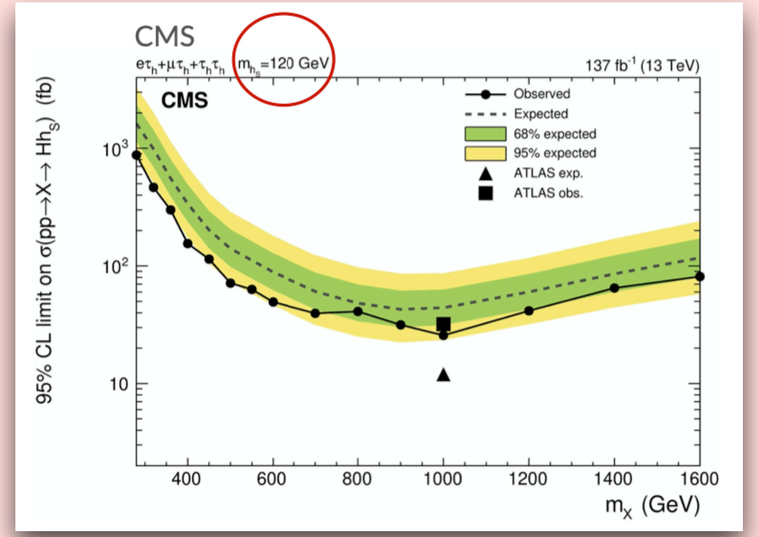
The largest (very broad) excess is observed at a resonance mass of 1 TeV, with a local (global) significance of 3.1*σ* (2.0*σ*)

	Observed	Expected
Max	900 fb	840 fb
Min	21 fb	12 fb

CMS

- (Not covered here) Semi-boosted analysis: JHEP11(2021)057
- NMSSM framework

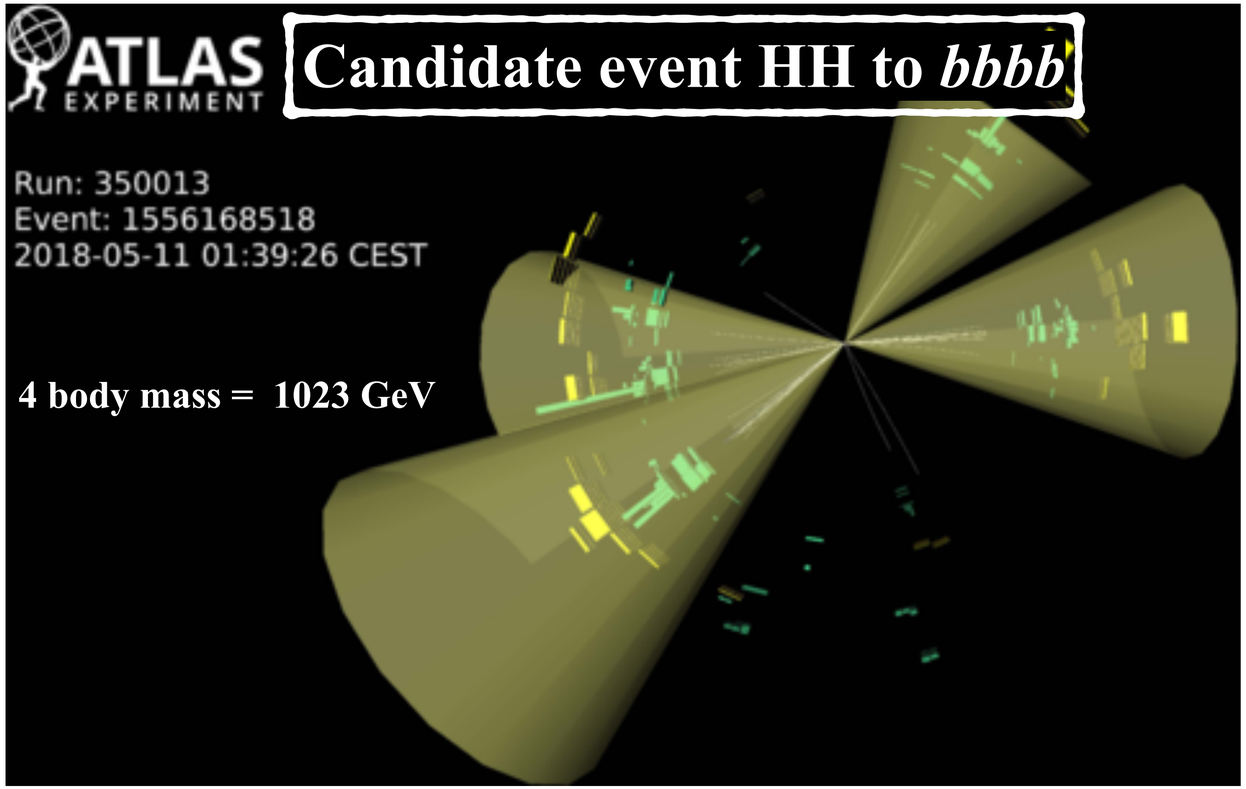
Upper limit on σ(pp→X→Hh_s)



- CL_{exp} (m(X)=320 GeV) = 986 fb
- CL_{exp} (m(X)=1000 GeV) = 44 fb
- CL_{exp} (m(X)=1600 GeV) = 117 fb

HH to *bbbb* search - *ATLAS*

Phys. Rev. D 105 (2022) 092002



Highest BR but challenging backgrounds in the final state

HH to *bbbb* search - *ATLAS*

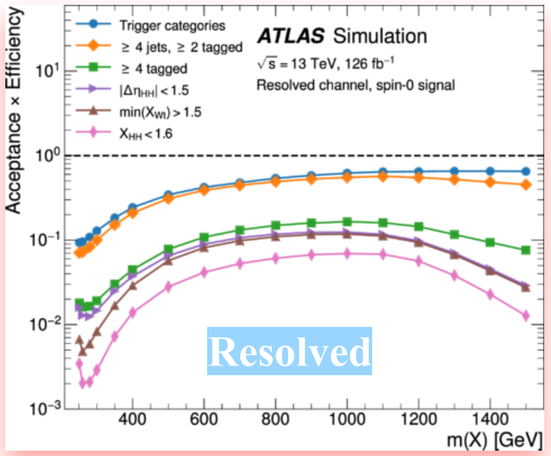
Phys. Rev. D 105 (2022) 092002

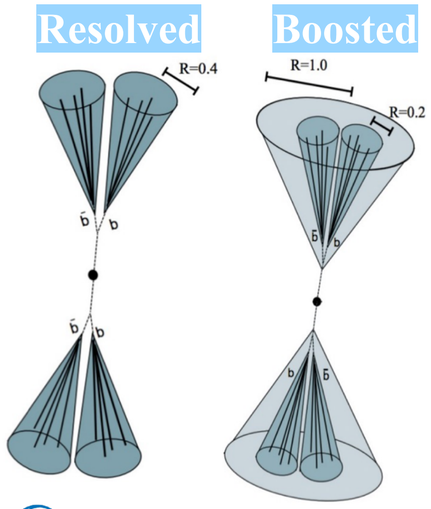
- Largest BR, but large multi-jet backgrounds and challenging combinatorics
- 12 different b-jet & jet triggers for *resolved* (eff up to 80%), single jet trigger for *boosted* (eff ~80%)
- Resolved and boosted analyses, combined in the overlap region

Resolved
(251 GeV – 1.5 TeV) 4 b-tagged ΔR=0.4 jets
Boosted
(900 GeV – 3 TeV) VR track-jets for b-tagging, topo cluster jets for large R jets with ΔR=1.0

b-jets corrections applied

Object Selection





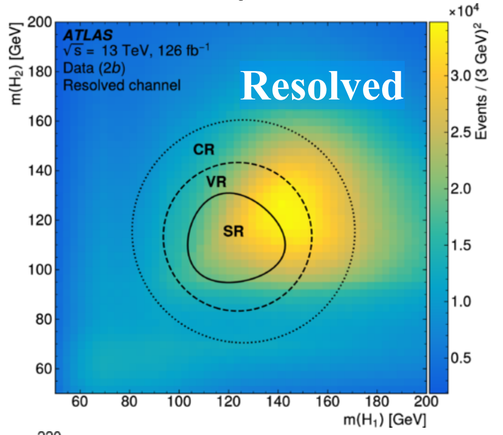
BDT to pair jets from Higgs (65-100% eff)

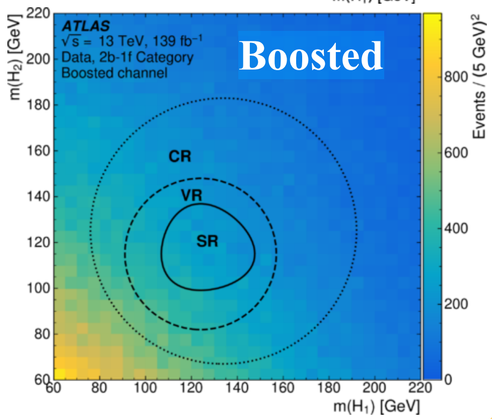
- 4*b* category is used for signal hypotheses with $m(X/G^*_{KK}) \leq 3$ TeV
- 2*b* category is used for signal hypotheses with $m(X/G^*_{KK}) \geq 2$ TeV
- For resonance masses in the range 900 GeV–1.5 TeV, the resolved and boosted channels are fitted simultaneously

Event Categorisation

Background Modelling

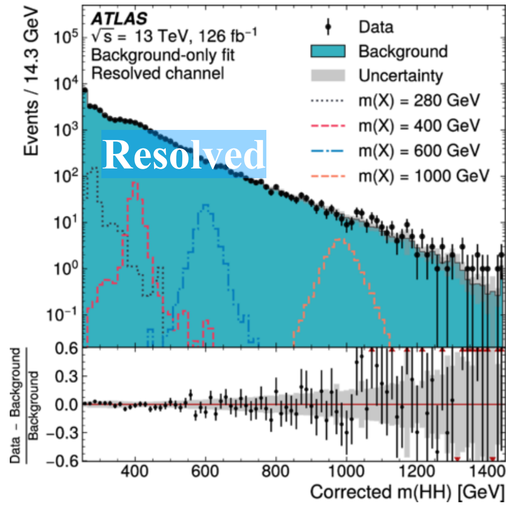
Dominated by multi-jet + $t\bar{t}$
Data-driven multi-jet & MC-driven $t\bar{t}$

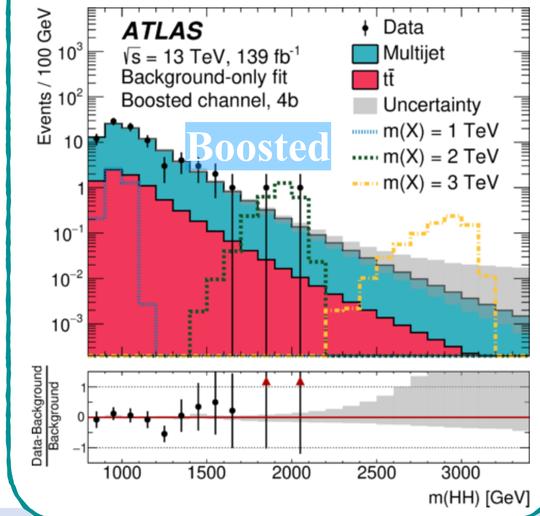




Statistical analysis

fit m_{HH} spectrum to search for a resonant bump



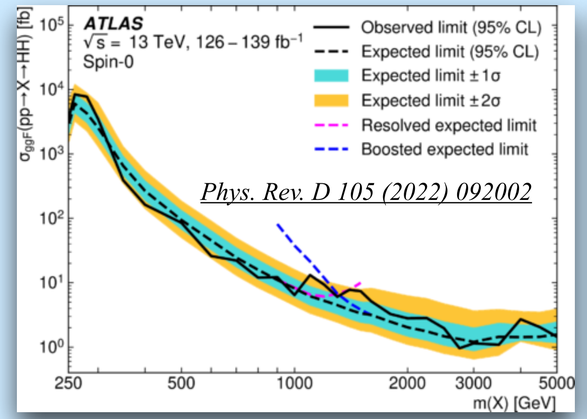


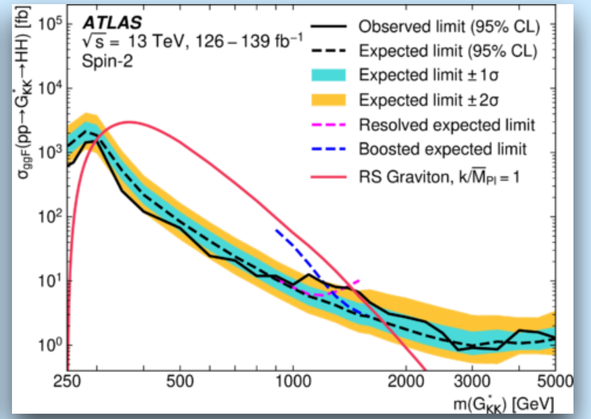
Results: HH to *bbbb* final state

ATLAS

- Narrow width approximation for spin 0 search
- Widths ranging from 3% to 20% spin 2 hypothesis

Upper limit on σ(pp→X→HH)





Mass hypothesis for 251 < m_X < 5000 GeV

- For signal masses up to 3 TeV, the limits are computed using asymptotic formulae
- At higher masses the limits are computed by sampling pseudo-experiments

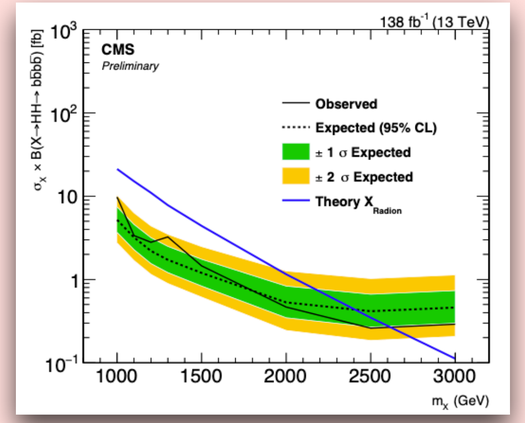
The largest excess is observed at a resonance mass of 1.1 TeV, with a local (global) significance of 2.3*σ* (0.4*σ*) for spin 0 signal and with a local (global) significance of 2.5*σ* (0.8*σ*) for spin 2 signal

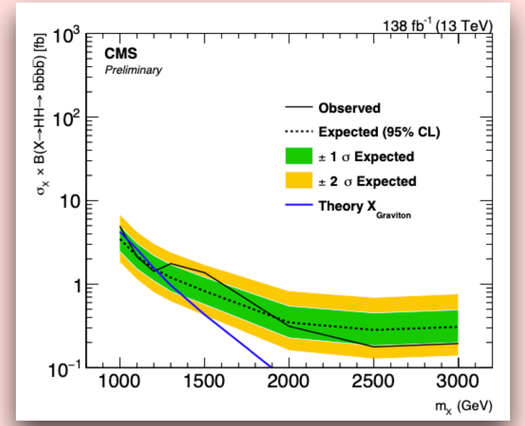
	Excl. up to - Observed	**Excl. up to - Expected**
bulk RS model	298 < mass < 1460 GeV	304 < mass < 1740 GeV

CMS

- (Not covered here) Semi-boosted analysis: CMS-B2G-20-004
- Narrow width approximation for spin 0 search
- Spin 2 hypothesis

Upper limit on σ(pp→X→HH) x BR (HH→ *bbbb*)





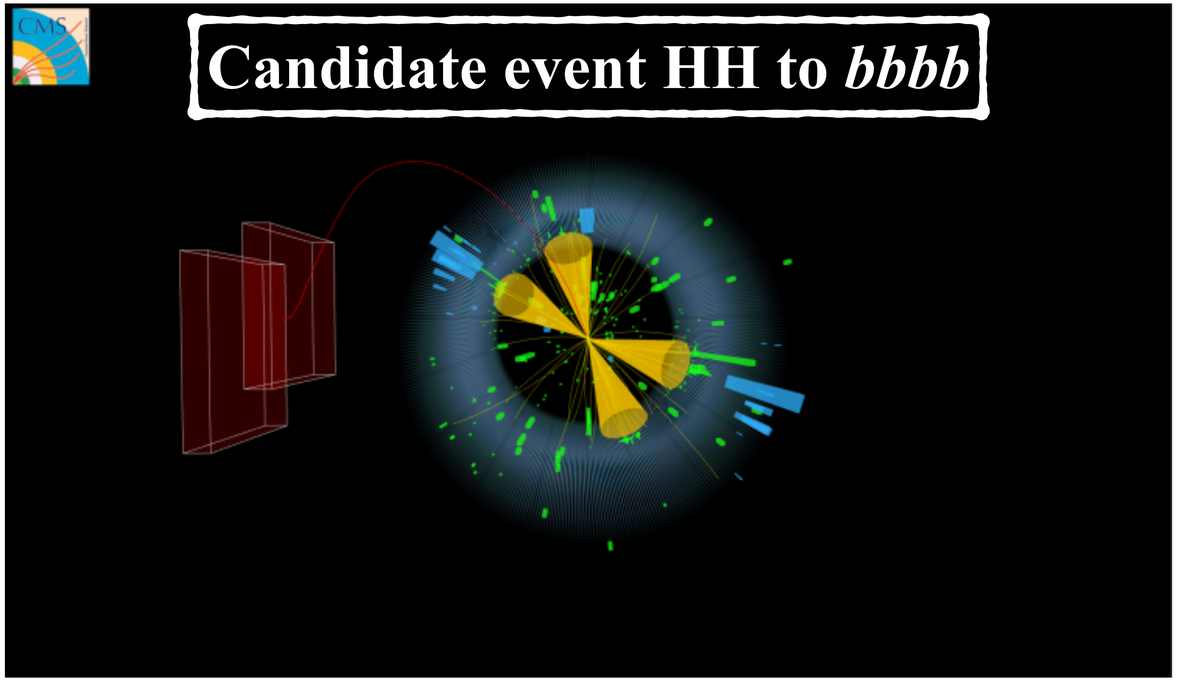
Mass hypothesis for 1000 < m_X < 3000 GeV

Mass (GeV)	Obs. (fb)	Exp. lim. (fb)
1000	9.74	5.12
1100	3.37	3.20
1200	2.80	2.20
1300	3.24	1.72
1500	1.46	1.10
2000	0.47	0.53
2500	0.26	0.42
3000	0.29	0.46

Mass (GeV)	Obs. (fb)	Exp. lim. (fb)
1000	4.94	3.47
1100	2.13	2.12
1200	1.42	1.54
1300	1.76	1.20
1500	1.37	0.83
2000	0.31	0.35
2500	0.18	0.28
3000	0.19	0.31

HY to *bbbb* search - *CMS*

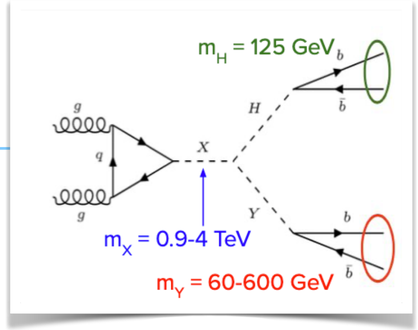
arXiv:2204.12413



Highest BR but challenging backgrounds in the final state

HY to *bbbb* search - *CMS*

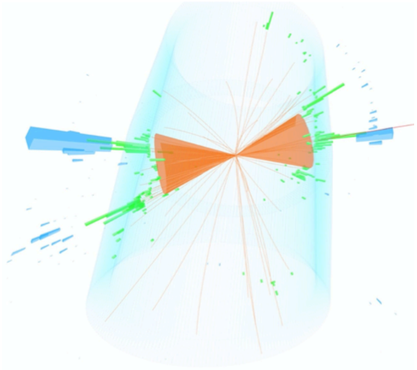
arXiv:2204.12413



- Large BR, but large multi-jet backgrounds and challenging combinatorics
- Hadronic triggers

Boosted event topology: X and Y reconstructed as large-radius jets (R=0.8)

Object Selection



1. ParticleNet convolutional graph neural network for H/Y→bb vs. QCD jet classification for large-R jets
2. Mass de-correlation with dedicated training techniques → no mass sculpting

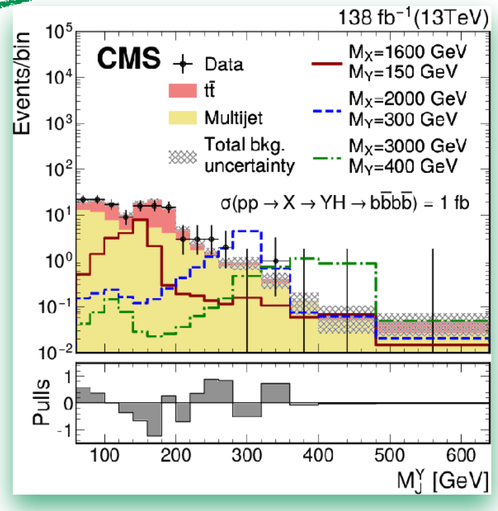
Event Categorisation

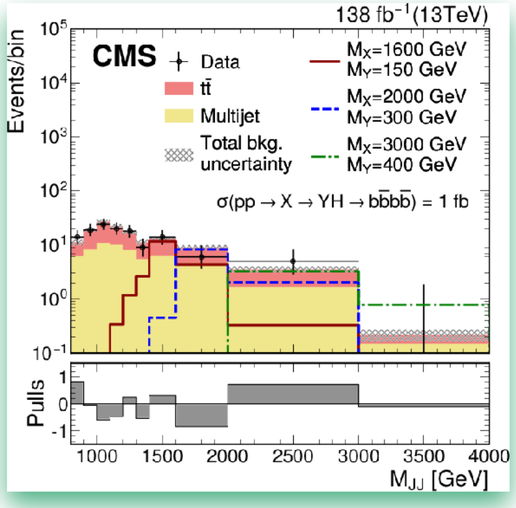
Background Modelling

Background dominated by multi-jet and < 10% $t\bar{t}$

Modeling of QCD bkg from data and of $t\bar{t}$ from simulation

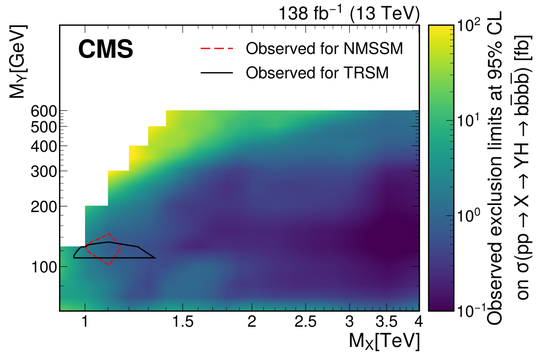
- Data control regions for validation & to improve data/MC agreement

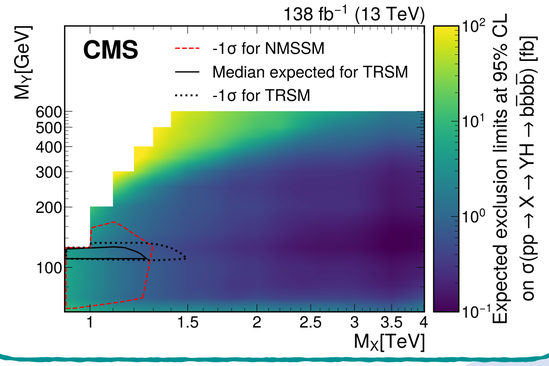




Statistical analysis & Results

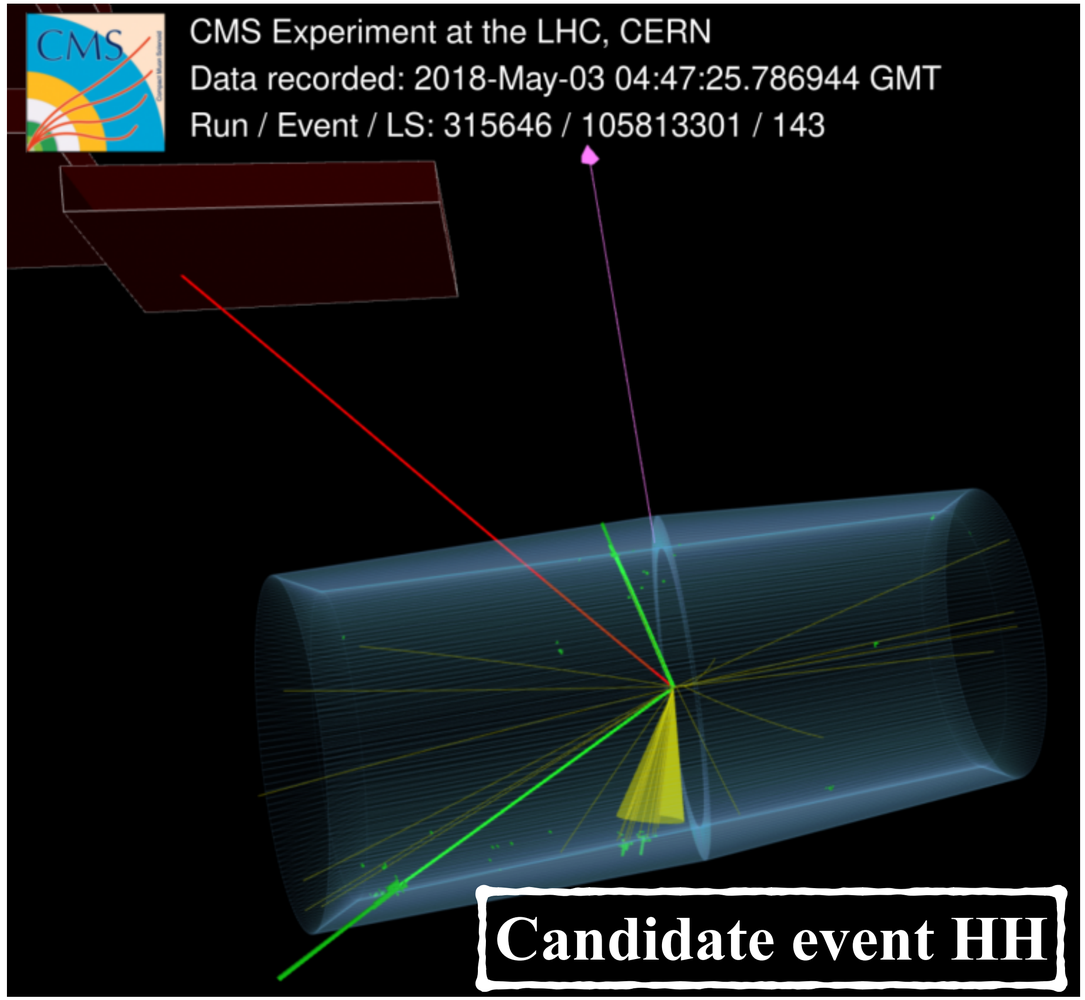
2D fit to reconstruct m_X and m_Y of signal candidates





HH to multi lepton search - *CMS*

arXiv:2206.10268

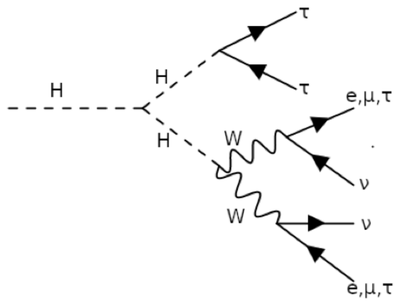


HH to multi lepton search - *CMS*

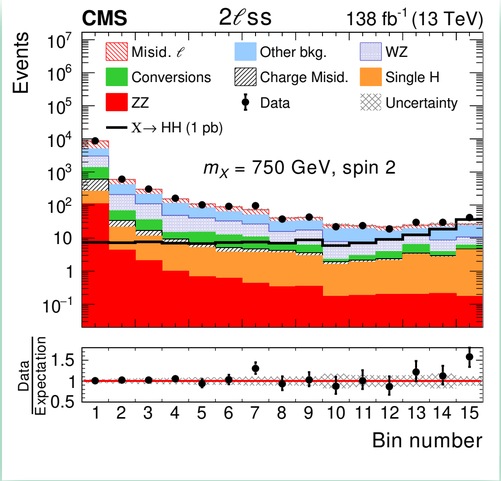
arXiv:2206.10268

- Reasonable BR, very good at low mass
- Combination of lepton and tau triggers

HH → VVVV, HH → VVττ and HH → ττττ final states



Object Selection

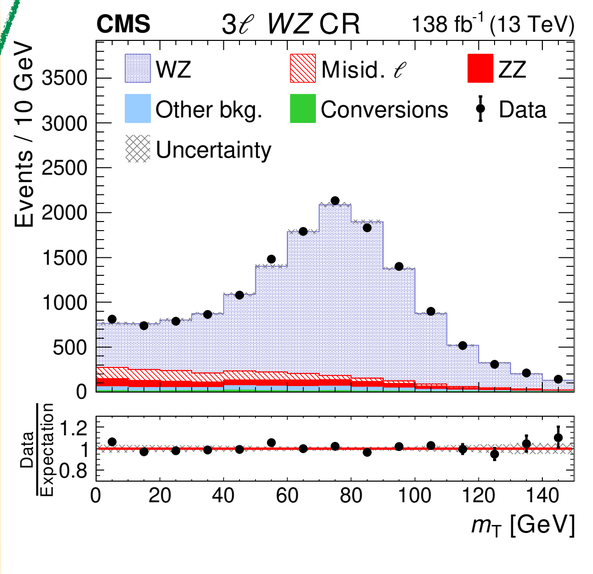


1. Seven channels with multiple l = e, μ/τ_h
2. Signal extraction on BDT classifier output:
   - Parametrized BDT on resonant mass for spin 0/spin 2 scenarios
   - 19 resonant masses in range 250 − 1000 GeV

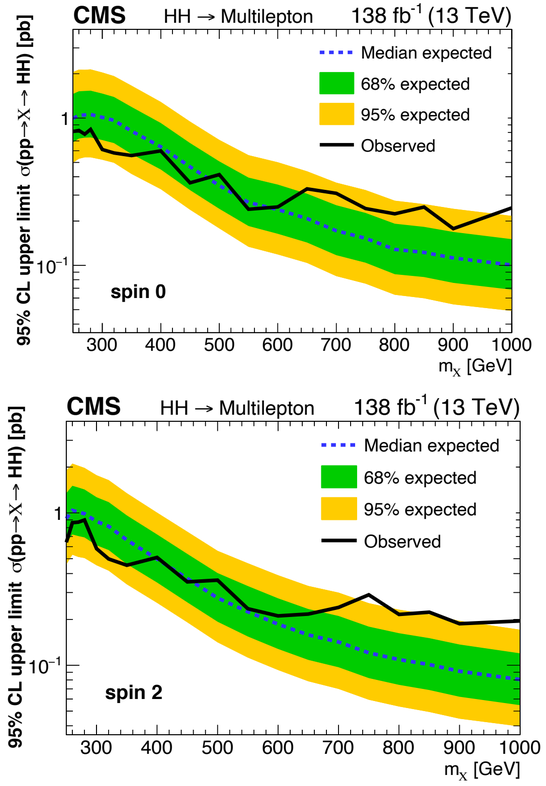
Event Categorisation

Signal extraction

- Fit to 7 BDT outputs/year for given mass
- Two control regions/year for WZ/ZZ backgrounds included
- No signal yet → Asymptotic limits



Results

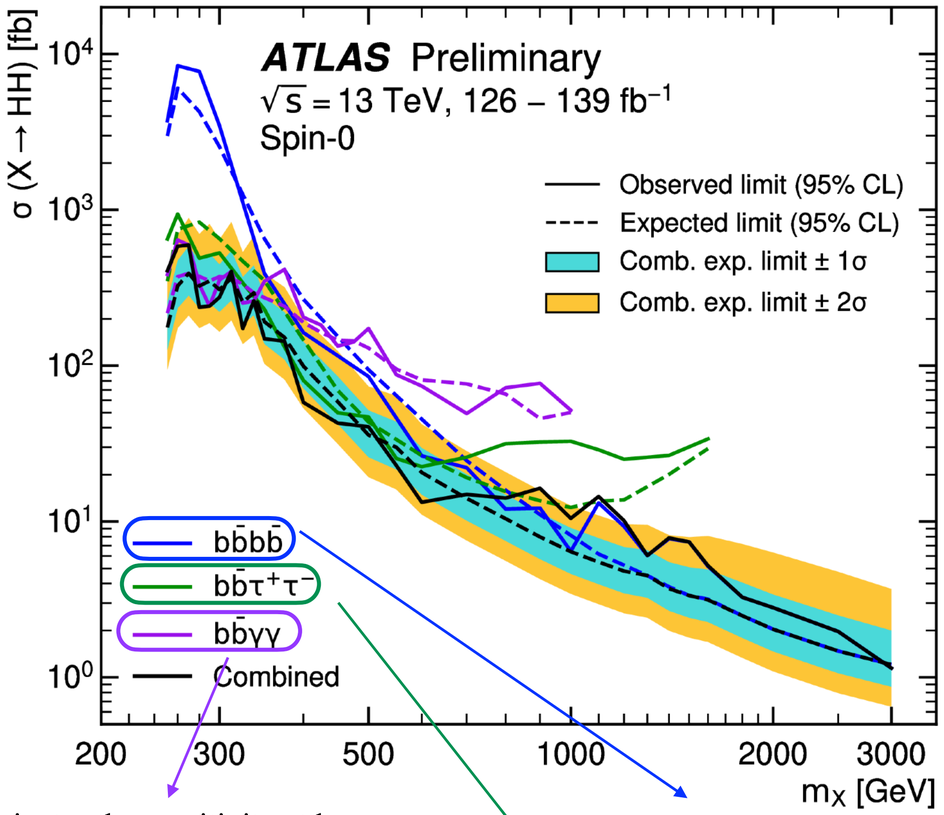


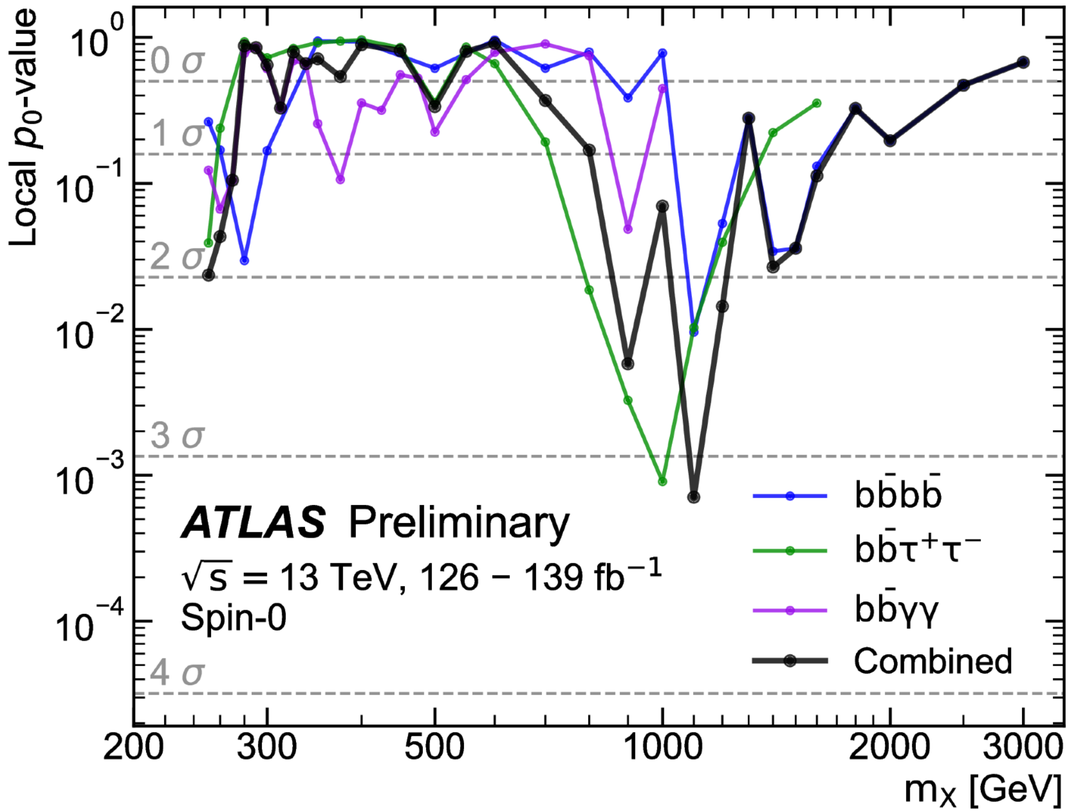
Observed (expected) limits on σ(pp → X → HH): 0.18 to 0.90 (0.08 to 1.07) pb

X to HH search - Summary - *ATLAS*

ATLAS-CONF-2021-052

Upper limit on σ(pp→X→HH)





bbγγ dominates the sensitivity at low m_X

bbbb dominates the sensitivity for high values of m_X

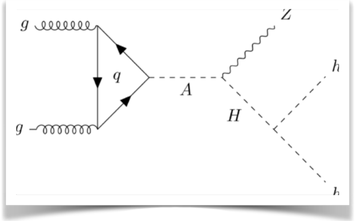
bbττ dominates the sensitivity for medium values of m_X

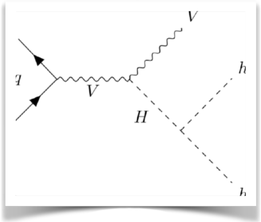
V*hh* & VH searches

V*hh* search - *ATLAS*

arXiv:2210.05415

- First analysis targeting Vhh final state. Two signal scenarios are considered:



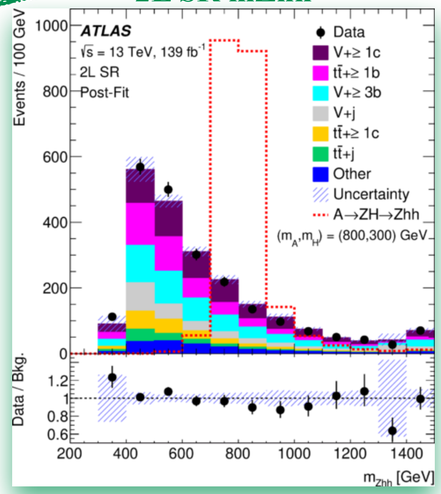


H – heavy scalar Higgs
h – standard model Higgs
A – neutral, heavy, CP-odd pseudo-scalar

1. BDT categorisation
2. Fit on BDT output

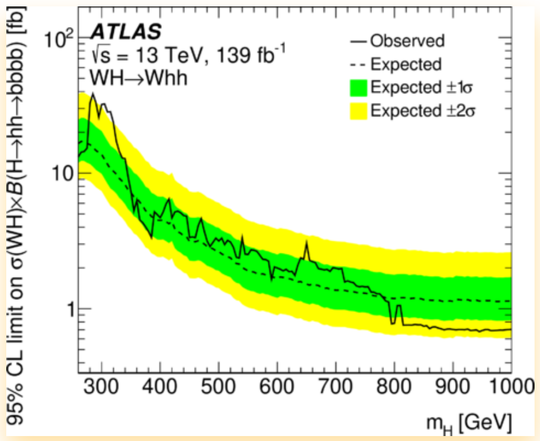
Event Categorisation & Fit strategy

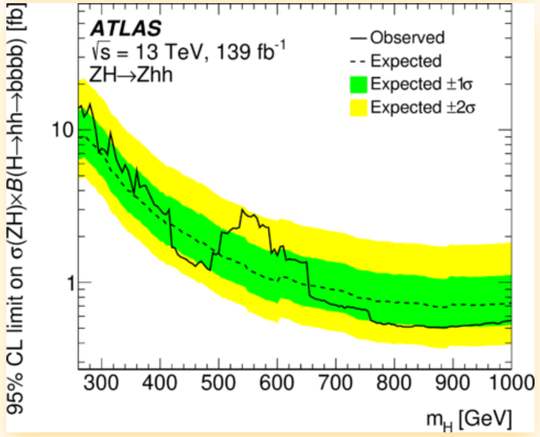
2L SR mZhh

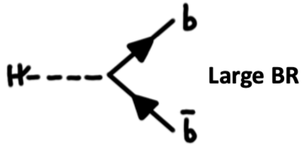


Results & Interpretations

1. VH, H—>hh results
   - No significant excess.
   - Largest deviation:
     - WH at 315 GeV: local (global) significance 2.5 (1.3) σ.
     - ZH at 550 GeV: local (global) significance 2.7 (1.3) σ





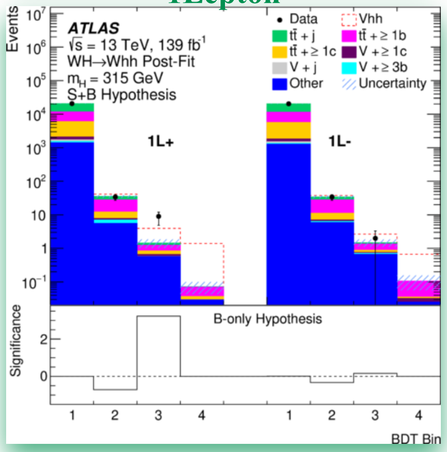


0L, 1L, 2L channels targeting vvbbbb, lvbbbb, llbbbb final states

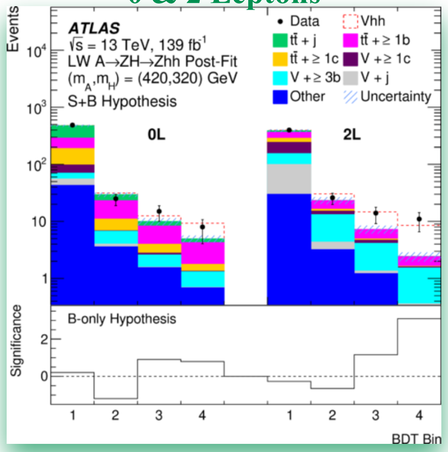
Lepton triggers

Object Selection

1Lepton



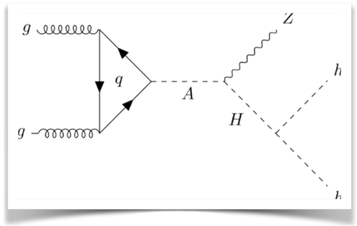
0 & 2 Leptons

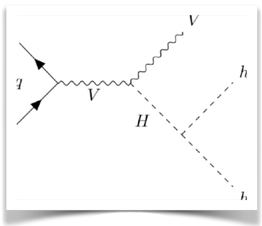


V*hh* search - *ATLAS*

arXiv:2210.05415

- First analysis targeting Vhh final state. Two signal scenarios are considered:

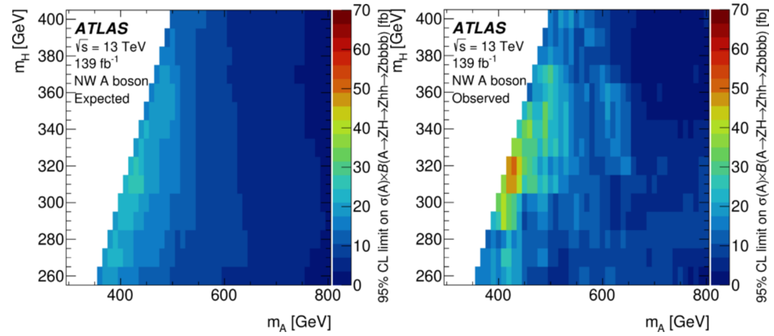




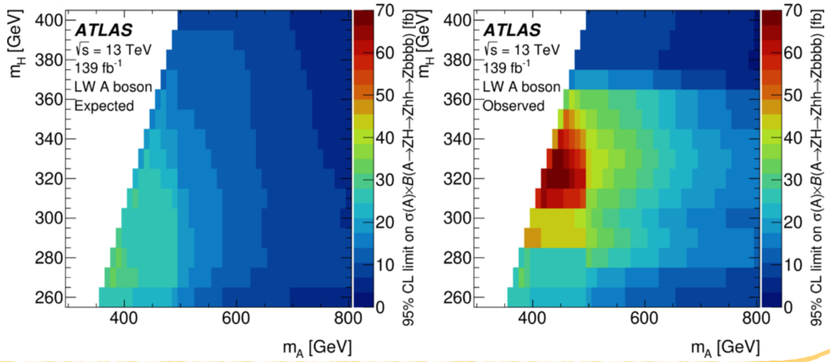
H – heavy scalar Higgs
h – standard model Higgs
A – neutral, heavy, CP-odd pseudo-scalar

Results & Interpretations

2. A to ZH, H—>hh
   - Narrow width A boson
     Largest deviation: (m_A, m_H) = (800, 300) Local: 3.6 σ Global: 1.6 σ



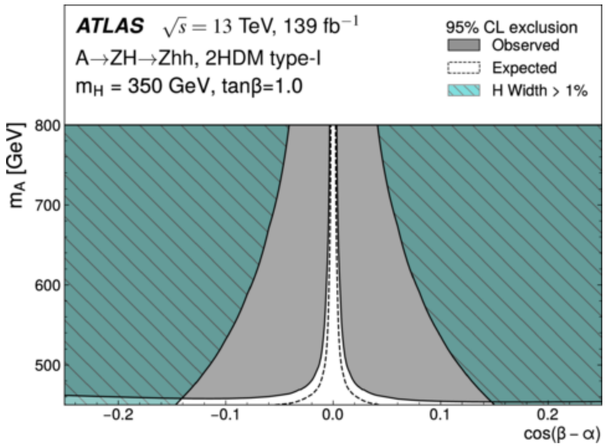
   - Large-width (20%) A boson
     Largest deviation: (m_A, m_H) = (420, 320) Local: 3.8 σ Global: 2.8 σ



Results & Interpretations

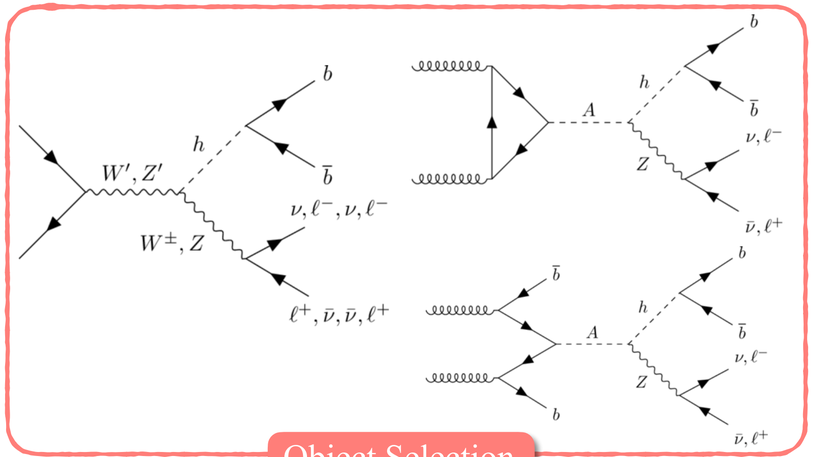
3. A to ZH results are interpreted as constraints in the 2HDM parameter space

- m_A – mass of the A boson.
- m_H–mass of the heavy H boson.
- tanβ – ratio of the vacuum expectation values of the two doublets.
- cos(β−α) – with α as the mixing angle of H and h.



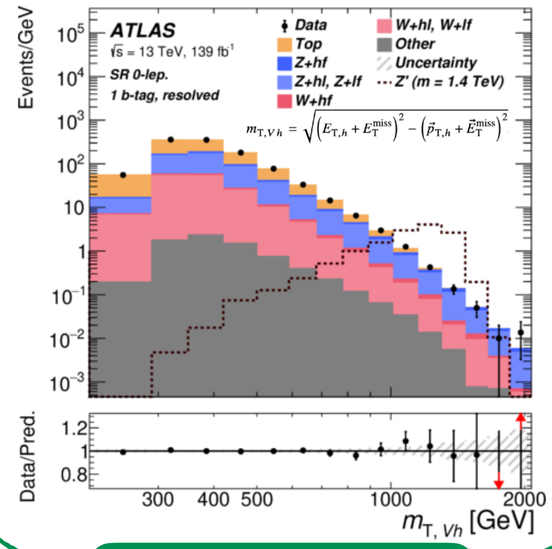
VH search - *ATLAS*

arXiv:2207.00230



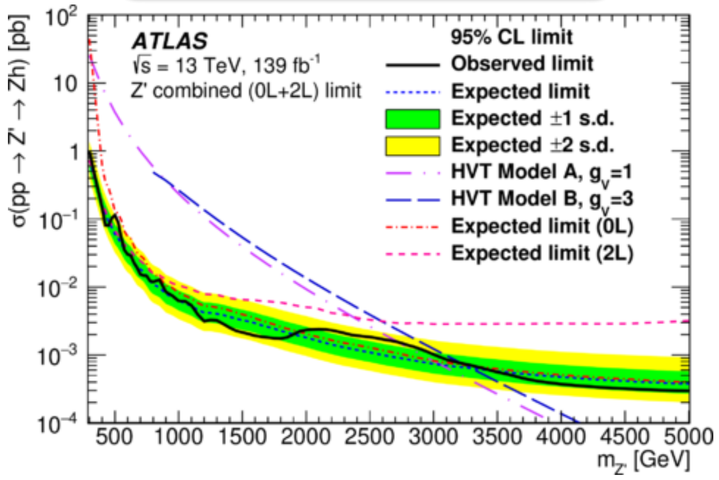
Object Selection

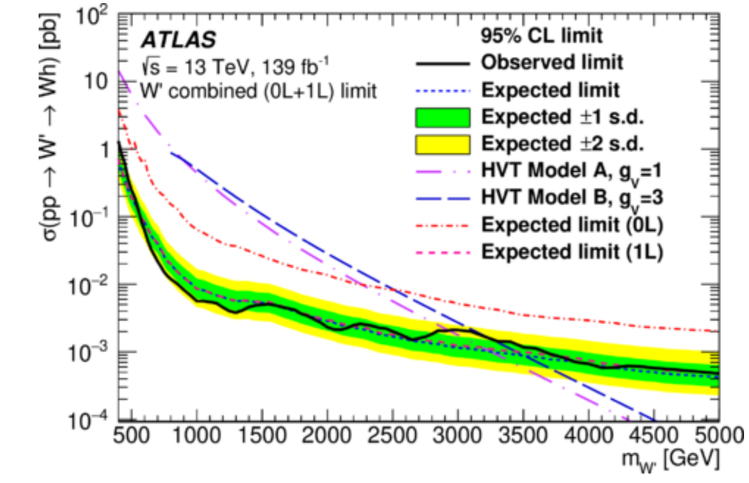
Discriminant variable



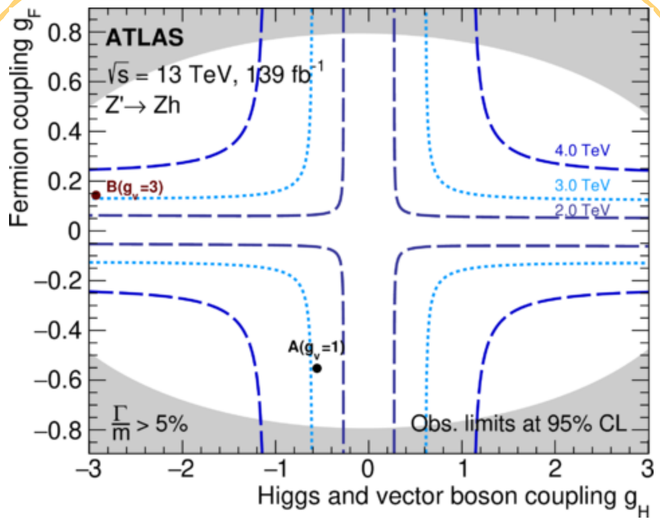
Analysis Strategy

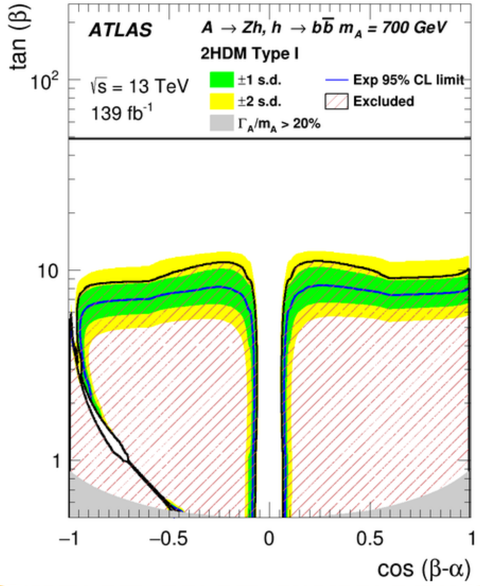
Results





HVT and 2HDM Interpretations





(All *had.*) VH search - *CMS*

arXiv:2210.00043

- This search covers also VV channels, not discussed here

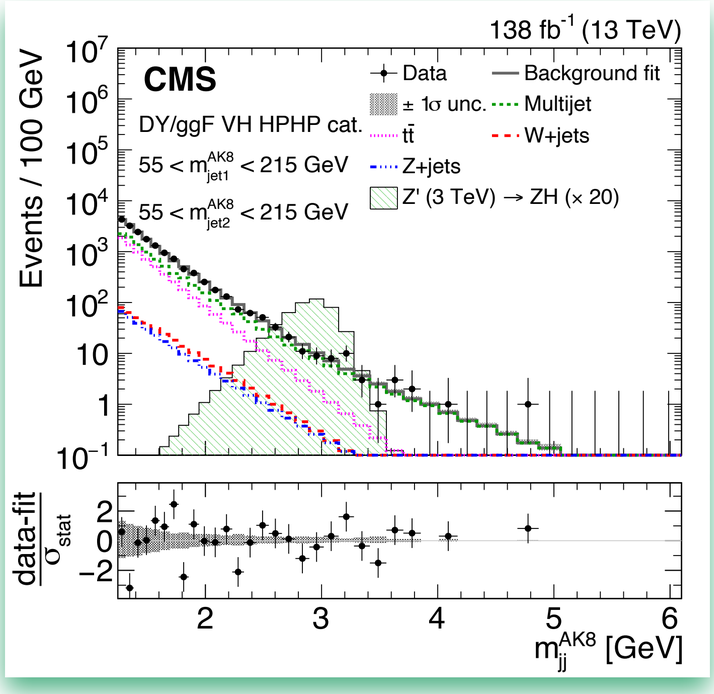
Tagging (2q) final states (w. bb category) using DeepAK8 tagger

Object Selection

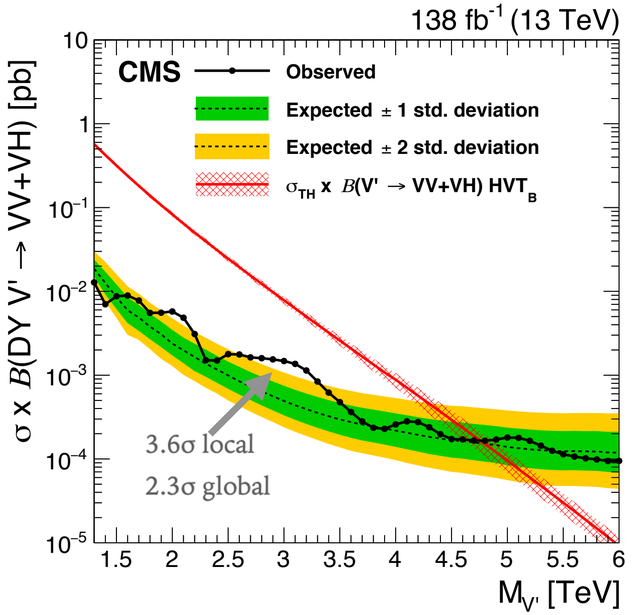
3D BUMP HUNT: $M_{JET\ 1} + M_{JET\ 2} + M_{JJ}$

Analysis Strategy

QCD model adapts to data, uses MC-based gaussian kernel templates with increased statistics



Results



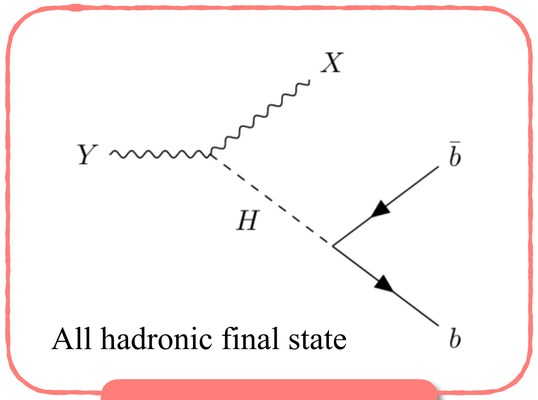
Most stringent limits on V' up to 4.8 TeV.

Also, first VBF limits (no exclusion) on all-hadronic search - see backup.

Up to 60% better sensitivity than 2016+2017 analysis

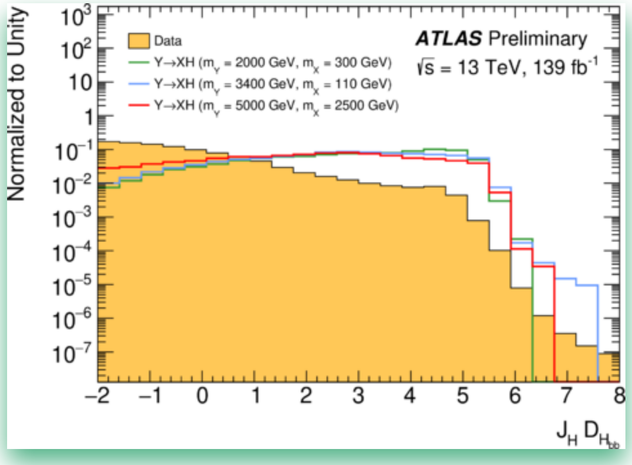
Generic search for Y to XH - *ATLAS*

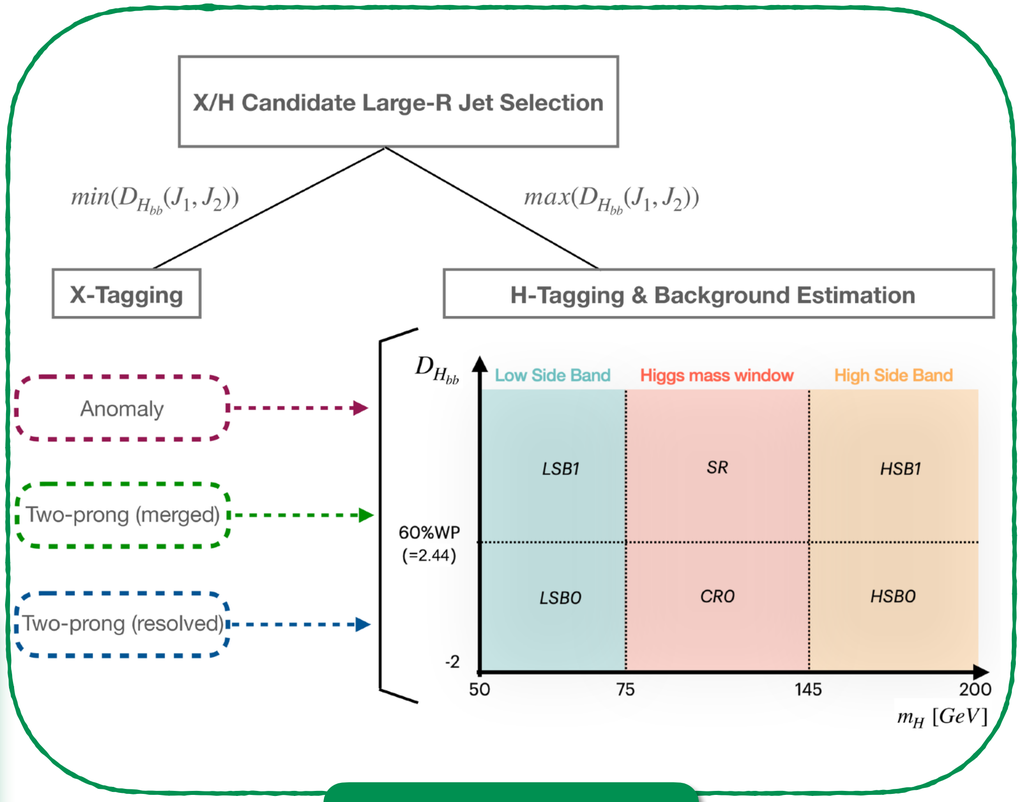
ATLAS-CONF-2022-045



Object Selection

$$D_{H_{bb}} = \ln \frac{p_{\text{Higgs}}}{f_{\text{top}} \cdot p_{\text{top}} + (1 - f_{\text{top}}) \cdot p_{\text{multijet}}}$$

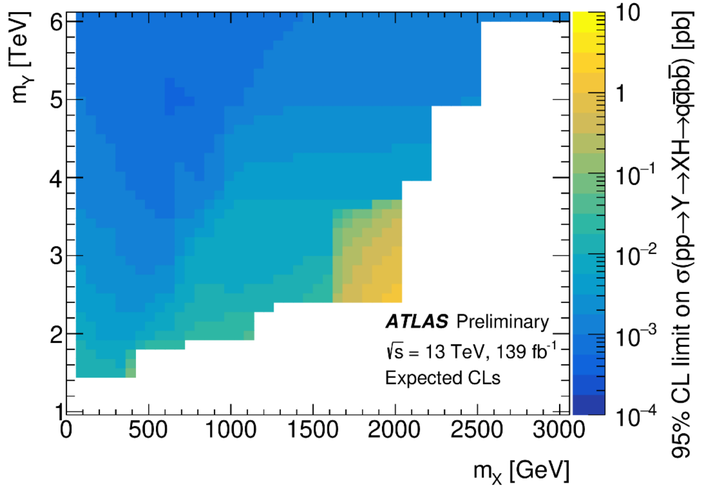


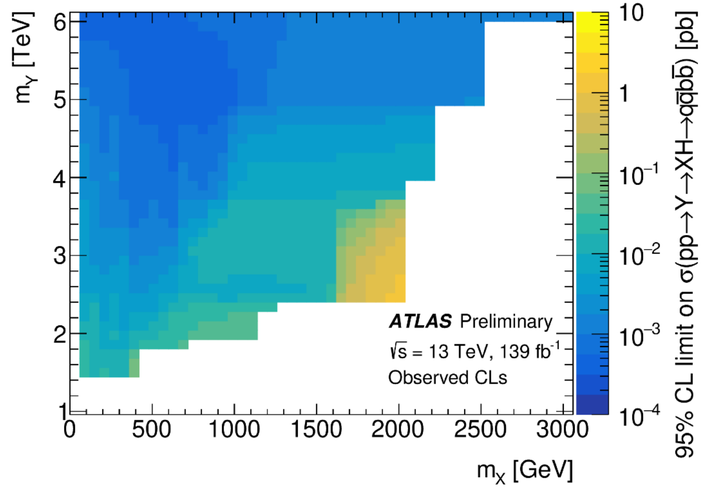


Analysis Strategy

Tested signals with m_Y between 1.5 and 6 TeV and m_X between 65 and 3000 GeV

Results

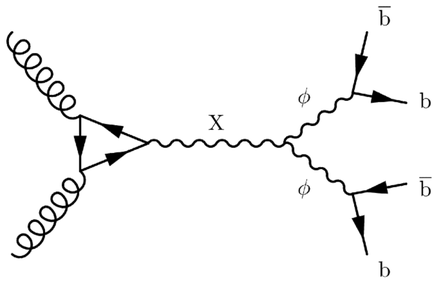


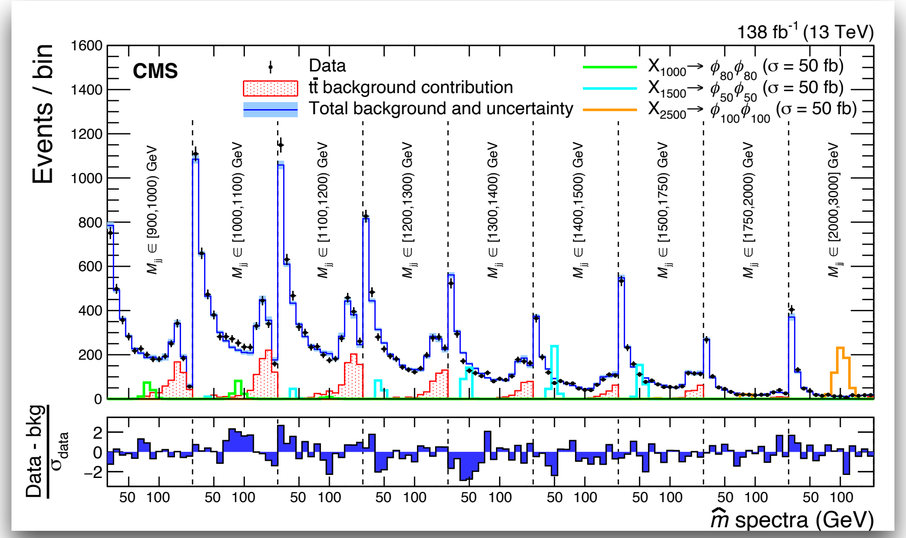


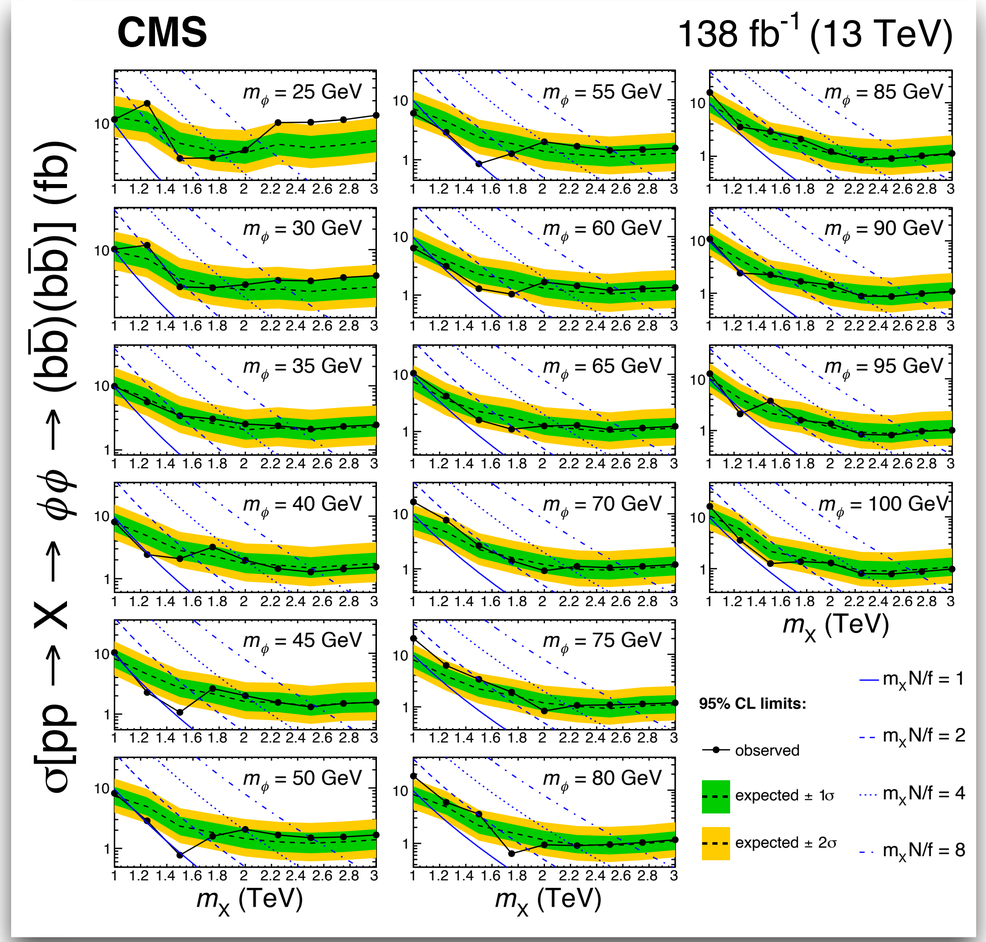
Extended Higgs sector searches *bbbb* - *CMS*

arXiv:2203.00480

The analysis is restricted to the case where the mass ratio of the resonance and the scalar bosons is such that each pair of b quarks is reconstructed as a single large-radius jet





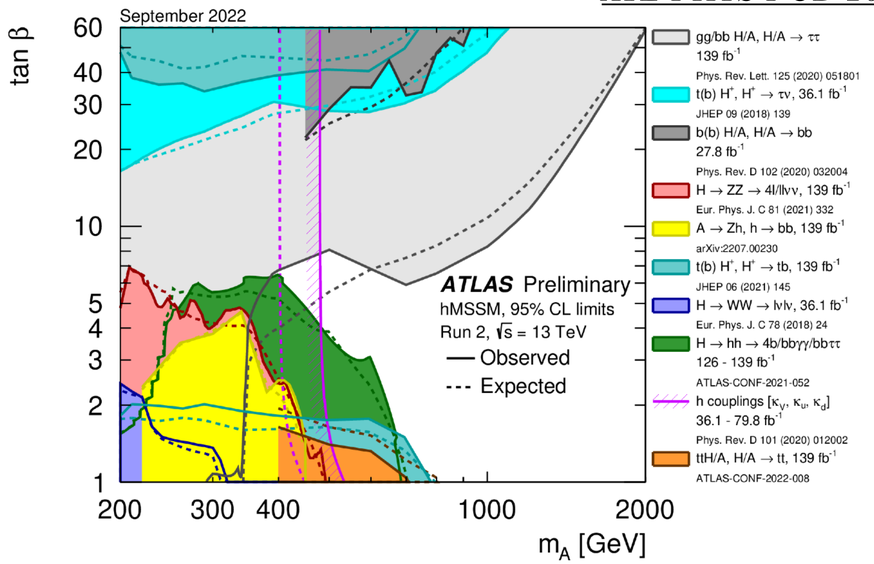


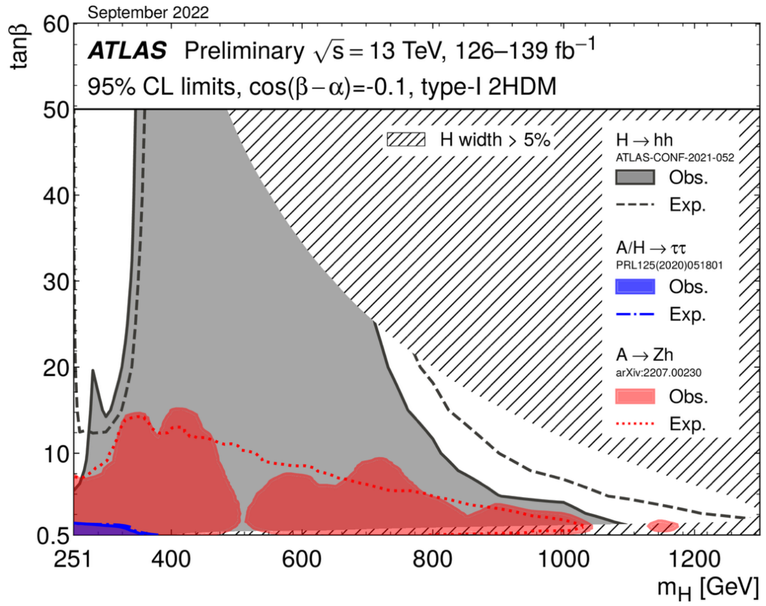
These are the first limits on this process, and range between 30 and 1 fb for a ϕ mass in the range 25-100 GeV and an X mass in the range 1-3 TeV.

Conclusions

- Full Run 2 results presented for ATLAS and CMS
- HH/HY and Vh searches presented
- Great complementarity among the channels
- No significant excess observed
- Stay tuned for Legacy Run 2 results
- **Run 3 just started!!!!**

ATL-PHYS-PUB-2022-043

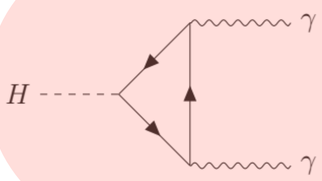




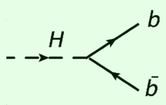
Back - up Slides

HH to *bbγγ* search - *ATLAS*

Phys. Rev. D 106 (2022) 052001



- At least **2 photons**: Identified (Tight WP)
- Calo- and Track-isolated within a cone of $\Delta R = 0.2$ $E_T^{iso} < 0.065 \cdot E_T$ and $p_T^{iso} < 0.05 \cdot E_T$
- 105 GeV < $m\gamma\gamma$ < 160 GeV
- $E_T/m\gamma\gamma$ > 0.35 and 0.25
- γγ vertex



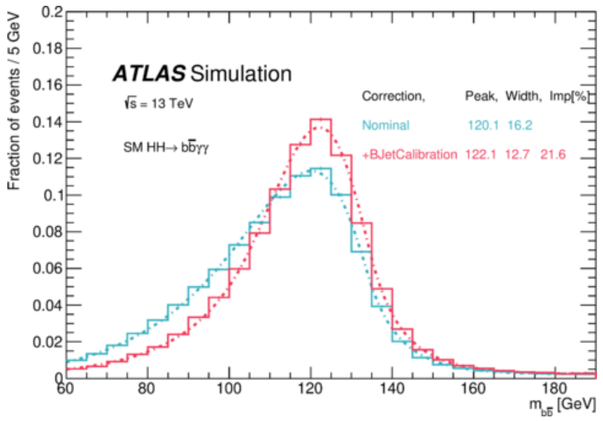
- Less than 6 central jets
- PFlow jets, anti-kt R=0.4, tight JVT applied
- Exactly **2 b-jets**
  - DL1r 77% WP, b-jet energy corrections applied

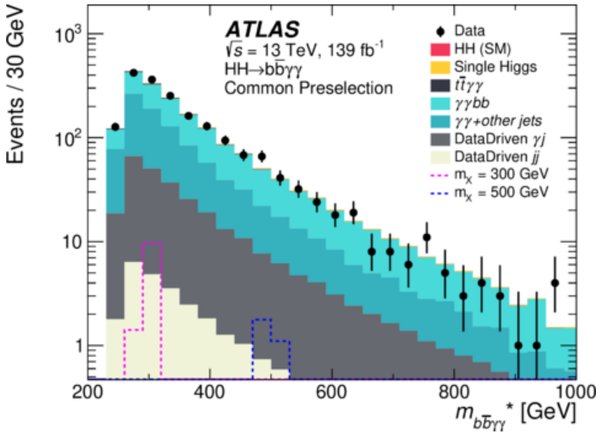
BDT Input Variables

Variable	Definition
Photon-related kinematic variables	
$p_T^{\gamma\gamma}$, $y^{\gamma\gamma}$	Transverse momentum and rapidity of the diphoton system
$\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$	Azimuthal angle and ΔR between the two photons
Jet-related kinematic variables	
$m_{b\bar{b}}$, $p_T^{b\bar{b}}$ and $y_{b\bar{b}}$	Invariant mass, transverse momentum and rapidity of the b-tagged jets system
$\Delta\phi_{b\bar{b}}$ and $\Delta R_{b\bar{b}}$	Azimuthal angle and ΔR between the two b-tagged jets
N_{jets} and $N_{b\text{-jets}}$	Number of jets and number of b-tagged jets
H_T	Scalar sum of the p_T of the jets in the event
Diphoton+dijet-related kinematic variables	
$m^*_{b\bar{b}\gamma\gamma}$	Invariant mass of the diphoton plus b-tagged jets system
$\Delta y_{\gamma\gamma,b\bar{b}}$, $\Delta\phi_{\gamma\gamma,b\bar{b}}$ and $\Delta R_{\gamma\gamma,b\bar{b}}$	Distance in rapidity, azimuthal angle and ΔR between the diphoton and the b-tagged jets system
Missing transverse momentum variables	
E_T^{miss}	Missing transverse momentum

2 BDTs to separate signal vs continuum and single Higgs backgrounds, scores combined in BDT_{tot}

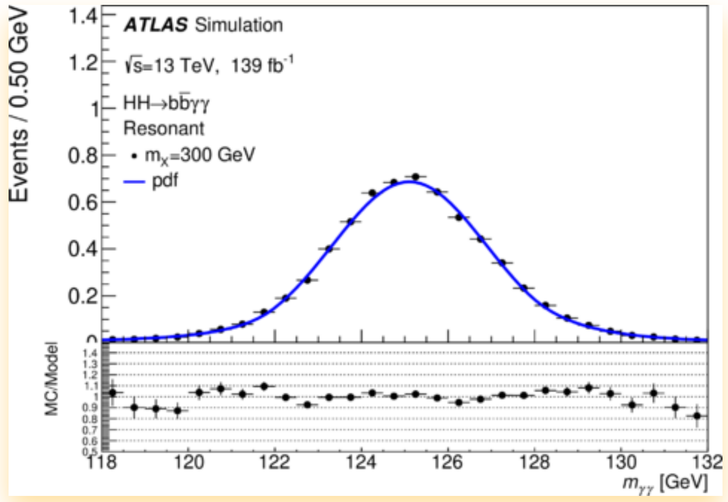
$$BDT_{tot} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \sqrt{C_1^2 \left(\frac{BDT_{\gamma\gamma} + 1}{2}\right)^2 + C_2^2 \left(\frac{BDT_{SingleH} + 1}{2}\right)^2}$$

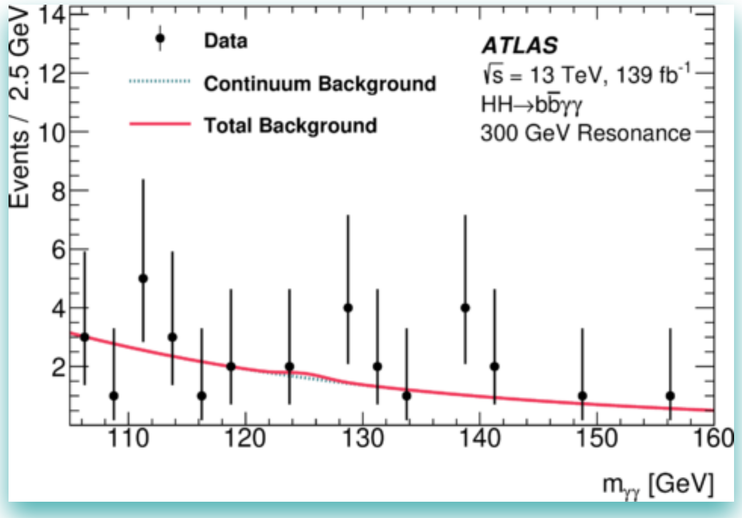


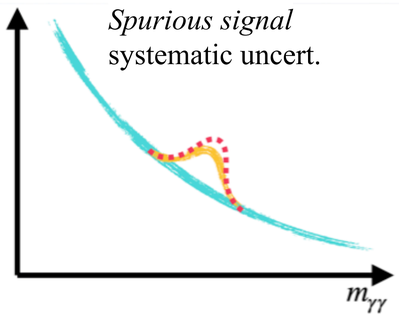


HH to *bbγγ* search - *ATLAS*

Phys. Rev. D 106 (2022) 052001





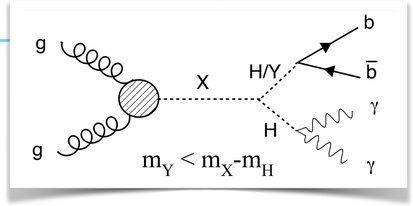


- Fit $m_{\gamma\gamma}$ distribution to a double-sided Crystal Ball (for both single Higgs backgrounds and di-Higgs signal)
- Continuum γγ background modelled as exponential function in $m_{\gamma\gamma}$
- Potential bias coming from the choice of the background modelling accounted for in systematic uncertainties

		Relative impact of the systematic uncertainties [%]	
Source	Type	Nonresonant analysis HH	Resonant analysis m_X = 300 GeV
Experimental			
Photon energy resolution	Norm. + Shape	0.4	0.6
Jet energy scale and resolution	Normalization	< 0.2	0.3
Flavor tagging	Normalization	< 0.2	0.2
Theoretical			
Factorization and renormalization scale	Normalization	0.3	< 0.2
Parton showering model	Norm. + Shape	0.6	2.6
Heavy-flavor content	Normalization	0.3	< 0.2
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	0.2	< 0.2
Spurious signal	Normalization	3.0	3.3

HH/HY to *bbγγ* search - *CMS*

CMS-PAS-HIG-21-011



Event pre-selection

Photons		Jets	
Variable	Requirement	Variable	Requirement
leading photon p_T	$> m_{\gamma\gamma}/3$	p_T	$> 25.$ GeV
subleading photon p_T	$> m_{\gamma\gamma}/4$	$\Delta R_{\gamma j}$	> 0.4
$\lvert\eta\rvert$	< 2.5	$\lvert\eta\rvert$	$< 2.4(2.5)$ for 2016 (2017–2018)
		njets	> 1
$m_{\gamma\gamma}$	100–180 GeV		70–190 GeV for HH and
		m_{jj}	70–1200 GeV for HY jet-pairs with the highest DEEPJET score sum
$t\bar{t}H$ discriminant	≥ 0.26		

Event selection

	m_Y <300 GeV	m_Y =[300–500] GeV	m_Y >500 GeV
$\tilde{M}_X$	Mass window	Mass window	Mass window
BDT categories	For m_X <500 GeV CAT 0 = 0.63–1.0 CAT 1 = 0.33–0.63 CAT 2 = 0.17–0.33 For m_X =[500–700] GeV CAT 0 = 0.55–1.0 CAT 1 = 0.40–0.55 CAT 2 = 0.21–0.40 For m_X >700 GeV CAT 0 = 0.50–1.0 CAT 1 = 0.30–0.50 CAT 2 = 0.21–0.30	For m_X =[500–700] GeV CAT 0 = 0.60–1.0 CAT 1 = 0.35–0.60 CAT 2 = 0.18–0.35 m_X >700 GeV CAT 0 = 0.35–1.0 CAT 1 = 0.24–0.35 CAT 2 = 0.18–0.24	MX>700 GeV CAT 0 = 0.40–1.0 CAT 1 = 0.29–0.40 CAT 2 = 0.13–0.29

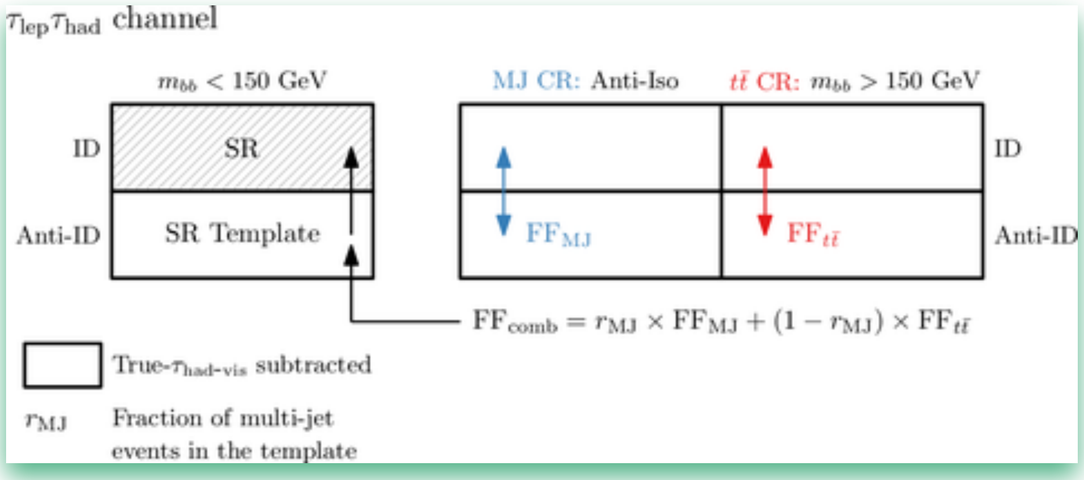
Modelling discriminating variable

- Fit $m_{\gamma\gamma}$ distribution to a double-sided Crystal Ball (for both single Higgs backgrounds and di-Higgs signal)
- Non-resonant background from envelope-method
- Resonant background from gaussian model

HH to *bbττ* search - *ATLAS*

arXiv:2209.10910

Back-ground estimation

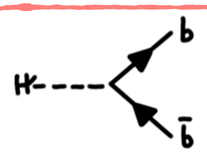


- Backgrounds are estimated using a mix of simulation and control samples in data
- Top with real τ_{had}: Use MC simulation
- Top/multijet with fake τ_{had}: Use a "fake factor" method to extrapolate from control regions
  - Inverting the τ_{ID} and/or other cuts for samples enriched in "fakes"
- Z + heavy flavor: Use MC simulation, but correct it using a data control region with Z → ll selection
- Other small backgrounds (single Higgs, diboson, etc.): Use MC simulation

HH to *bbbb* search - *ATLAS*

Phys. Rev. D 105 (2022) 092002

- Largest BR, but large multi-jet backgrounds and challenging combinatorics
- 12 different b-jet & jet triggers for *resolved,* single jet trigger for *boosted*
- Resolved and boosted analyses, combined in the overlap region



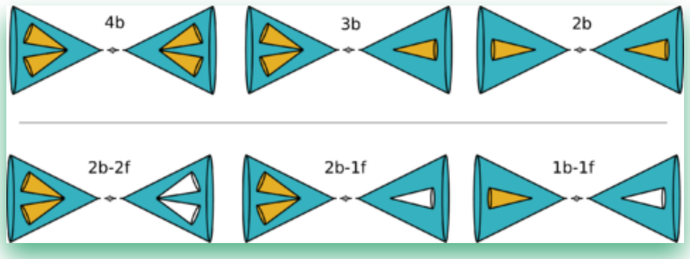
Large BR

Boosted

(900 GeV – 3 TeV) VR track-jets for b-tagging, topo cluster jets for large R jets with ΔR=1.0

b-jets corrections applied

Object Selection



→ Learn in CR

⋯▶ Predict in SR

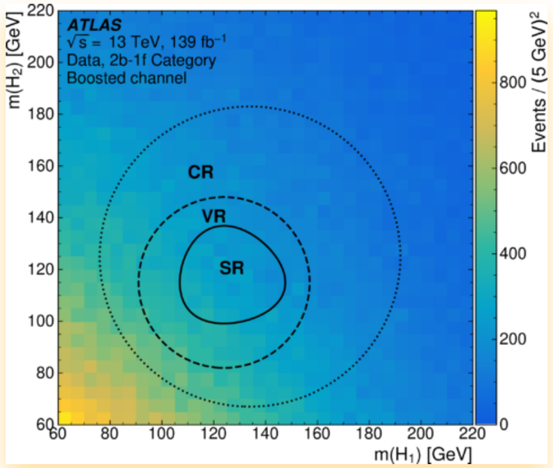
1. b-tag using variable-radius subjets constructed from their associated tracks
2. At very high resonance masses, even these get merged.
3. Most of the procedure follows the resolved strategy closely

Event Categorisation

Background Modelling

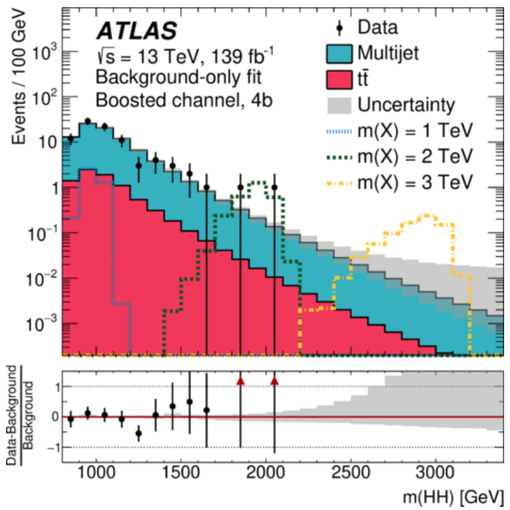
Bkg dominated by multi-jet + up to 30% $t\bar{t}$

Data-driven multi-jet & MC-driven $t\bar{t}$ (data-driven corrections in 2/3 b region)



Statistical analysis

fit m_{HH} spectrum to search for a resonant bump

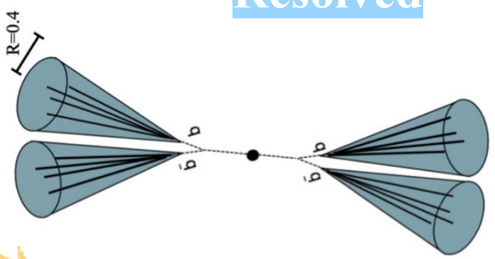


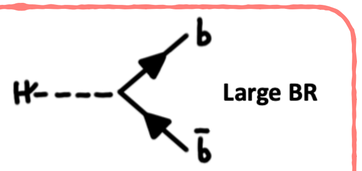
HH to *bbbb* search - *ATLAS*

Phys. Rev. D 105 (2022) 092002

Resolved

- Largest BR, but large multi-jet backgrounds and challenging combinatorics
- 12 different b-jet & jet triggers for *resolved* (eff up to 80%), single jet trigger for *boosted* (eff ~80%)
- Resolved and boosted analyses, combined in the overlap region



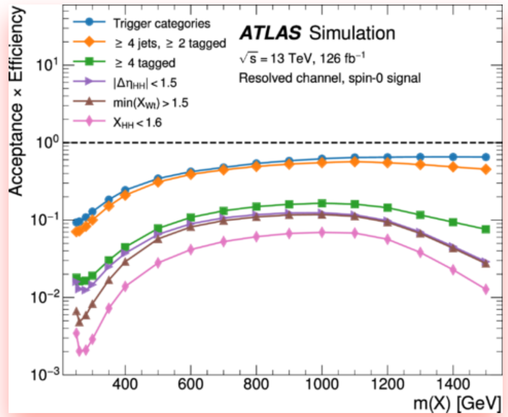


Large BR

Resolved
(251 GeV – 1.5 TeV) 4 b-tagged ΔR=0.4 jets

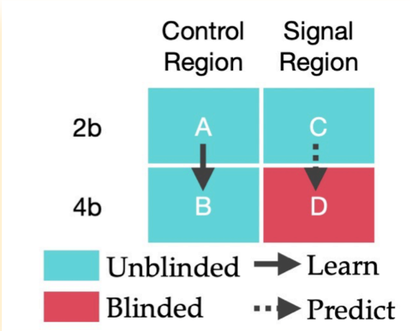
b-jets corrections applied

Object Selection

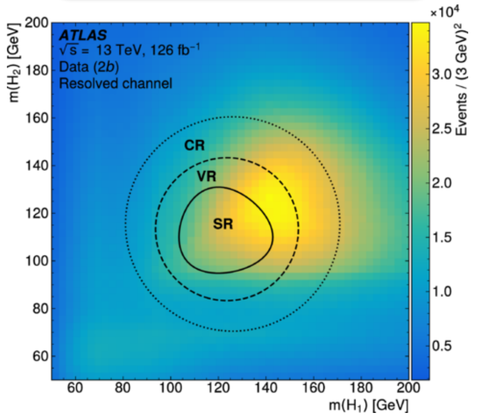


1. 4b signal region (based on the *H* candidate masses)
2. 2b category for bkg estimate
3. **BDT to pair jets from Higgs (65-100% eff)**

Event Categorisation



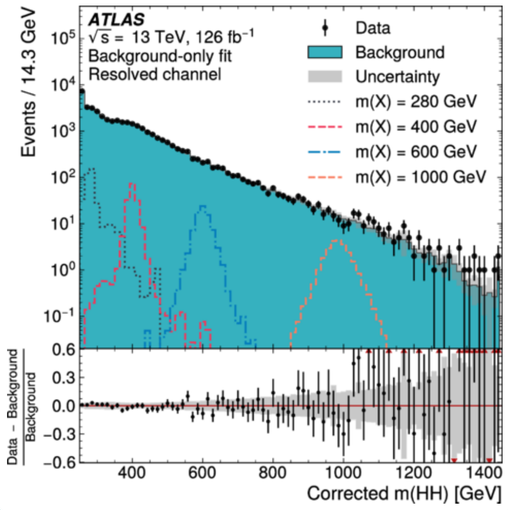
Background Modelling



dominated by multi-jet + ~5% $t\bar{t}$

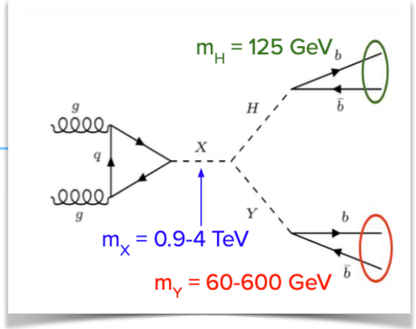
Statistical analysis

fit m_{HH} spectrum to search for a resonant bump



HY to *bbbb* search - *CMS*

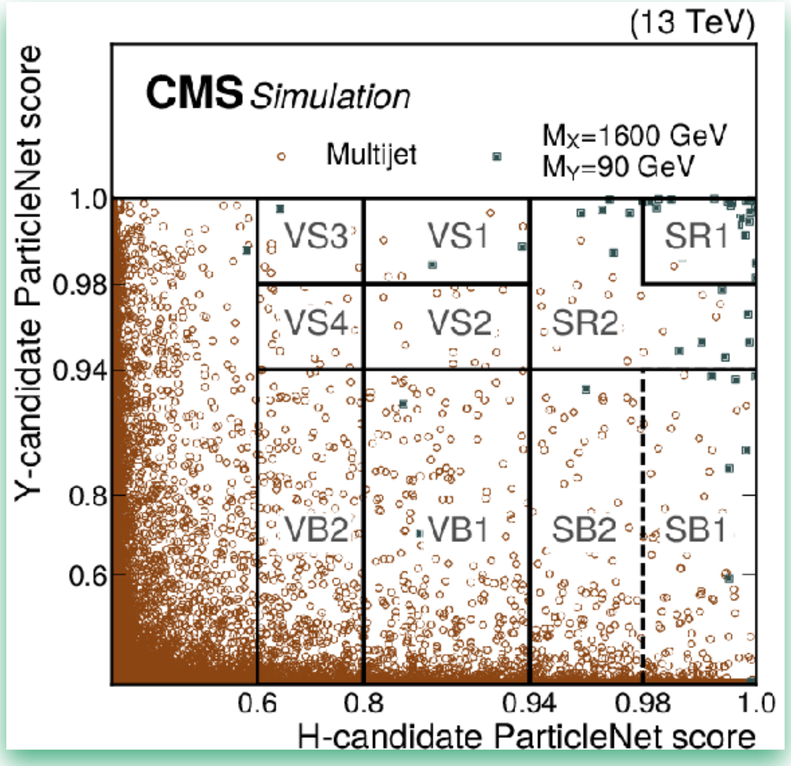
arXiv:2204.12413



- Large BR, but large multi-jet backgrounds and challenging combinatorics
- Hadronic triggers

1. ParticleNet convolutional graph neural network for H/Y→bb vs. QCD jet classification for large-R jets
2. Mass de-correlation with dedicated training techniques → no mass sculpting

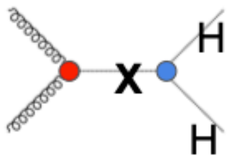
Event Categorisation



HH Combination - *CMS*

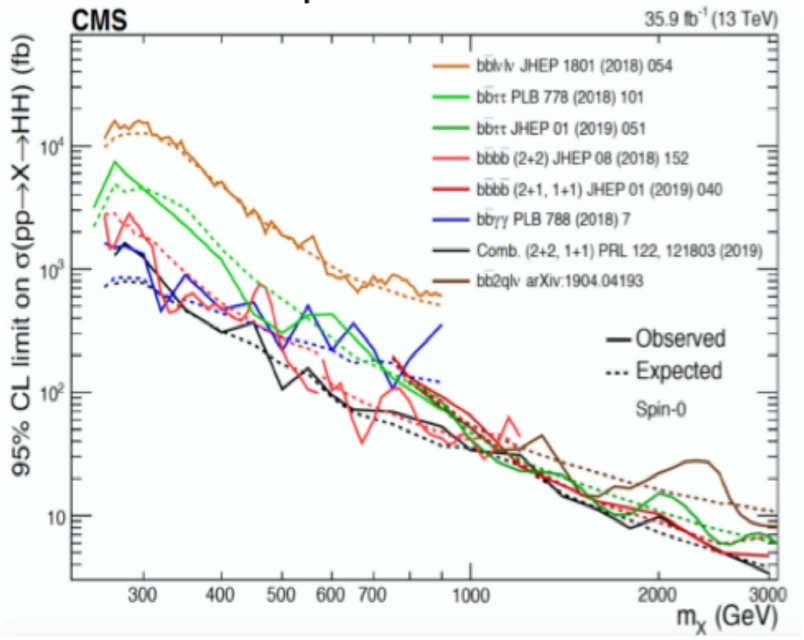
Resonant HH comb with 2016 data (~36 fb^{-1})

- No significant excess found

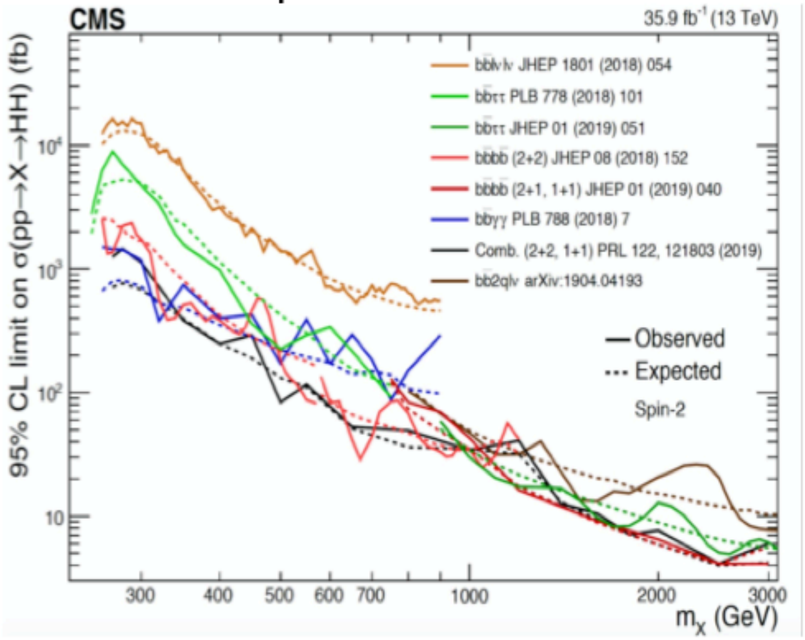


Upper limit on σ(pp→X→HH)

spin 0 resonance



spin 2 resonance



Searches in the *bbbb* final state

	Resolved (2+2 jets)	Boosted (1+1 jets)	Semi-resolved (2+1 jets)
ggF X→YH CMS	–	138 fb^{-1} **900 GeV to 4 TeV** CMS-B2G-21-003 *Submitted to Phys. Lett. B*	–
ggF X→HH ATLAS	126-139 fb^{-1} **251 GeV - 5 TeV** Phys. Rev. D 105 (2022) 092002		–
ggF X→HH CMS	36 fb^{-1} **260 GeV to 1.2 TeV** JHEP 08 (2018) 152	138 fb^{-1} **1-3 TeV** CMS-B2G-20-004	
VBF X→HH ATLAS	126 fb^{-1} **260 GeV to 1 TeV** JHEP 07 (2020) 108	–	–

HH/HY to multi lepton search - *CMS*