Searches for extended Higgs sectors

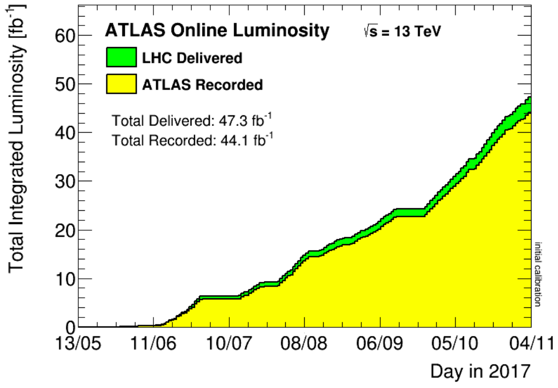
XIFENG RUAN (UNIVERSITY OF THE WITWATERSRAND)

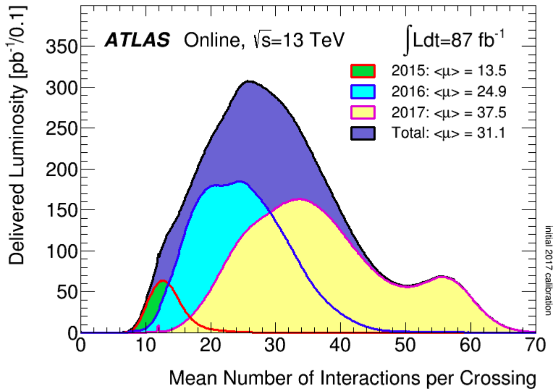
ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

Higgs Couplings, 7th November, 2017, Heidelberg, Germany

Introduction

The LHC has delivered so far 47 fb^{-1} in 2017





This presentation will summarize the 13 TeV results from both ATLAS and CMS with data up to 36 fb^{-1} of integrated luminosity collected in 2015 and 2016 with the following final states:

- Searches for heavy CP even and/or CP odd scalar bosons with the following decays: $\gamma\gamma$, $Z\gamma$, ZZ, WW→lνqq, top pair, Zh, $\tau\tau$
- Charged scalars: $H^{\pm}\to\tau\nu$, $H^{++}/H^{--}\to ll$

2HDM, extension of the Higgs sector:

5 particles: h, H, $H^{\pm}$, A(CP odd)

7 free parameters:

m_h, m_H, m_A, m_{H+}, α, tanβ, m_{12}

2HDM with MSSM:

2 free parameters at the tree level:

m_A, tanβ

Higgs triplet:

H^{++}, H^{--}

Heavy resonance searches with diphoton channel (ATLAS)

arXiv:1707.04147

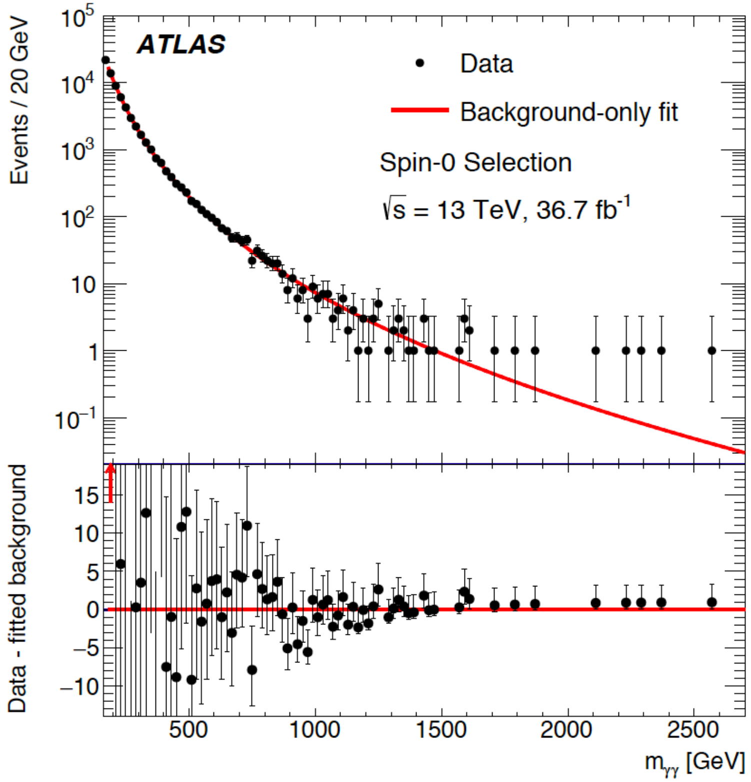
ATLAS reported new results using 36.7 fb^{-1} of 13 TeV data

Improved photon reconstruction and calibration

Search for the diphoton resonance with various models

Tested models:

- Spin-0: 200-2400 GeV with width up to 10% of the mass
- Spin-2: Randall-Sundrum model with 1 wrapped dimension, m_{G*} varies from 500-5000 GeV, with coupling $k/\overline{M}_{Pl}$=0.01 to 0.3
- Arkani-Hamed, Dimopoulos and Dvali (ADD) model, testing ultraviolet cutoff M_S in the range 3500-6000 GeV. Count events with mass greater than 2240 GeV



Selection:

- Spin 0: $p_{T\gamma}^{1}>0.4m_{\gamma\gamma}$, $p_{T\gamma}^{2}>0.3m_{\gamma\gamma}$
- Spin 2: $p_{T\gamma}>$ 55 GeV
- Well identified and isolated photons
- Fit the mass spectrum with signal plus continuous background parametrizations

Heavy resonance searches with diphoton channel (ATLAS)

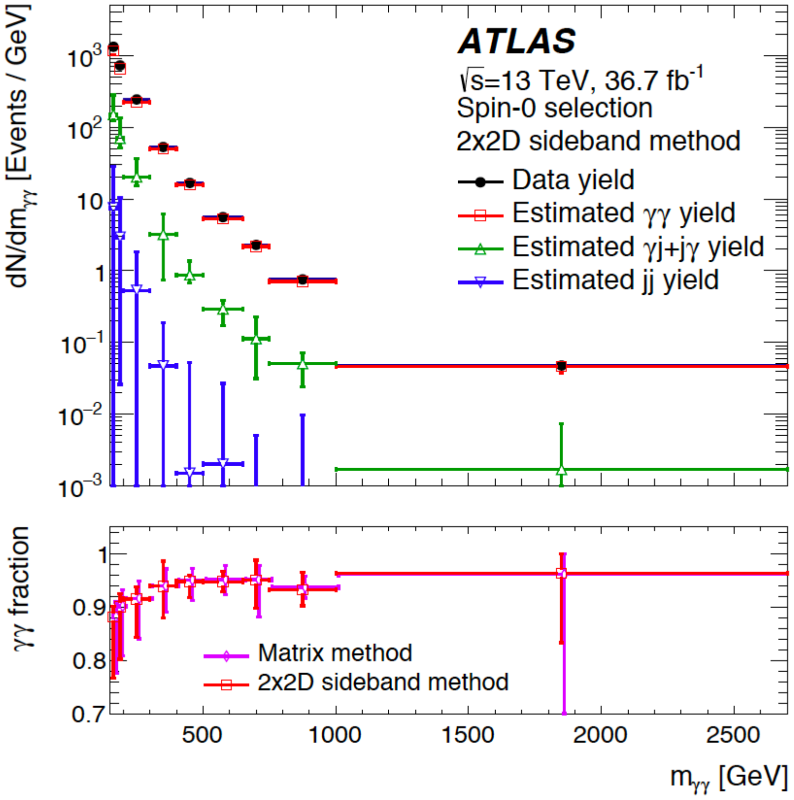
Background modelling and photon energy resolution are critical

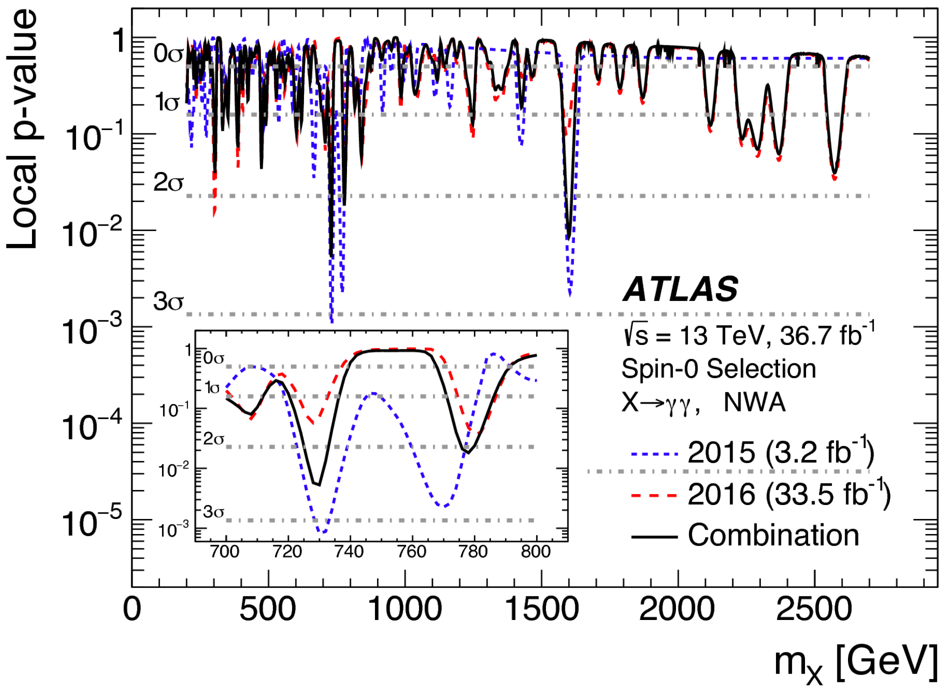
Using 2 photons x 2D (photon-ID, photon-Iso) method to decompose the continuum background into $\gamma\gamma$, γj and jj.

Potential bias by choosing different function forms are estimated for spin 0 analysis,

DIPHOX is used to generate high mass side band for spin 2 and ADD analyses

Uncertainty source	Spin-0 resonance [%]	Spin-2 resonance [%]	Spin-2 non-resonant [%]
Signal mass resolution	17–38	28–36	–
Signal photon identification efficiency	1.3–3.0	2.6–3.1	3.2
Signal photon isolation efficiency	1.1–1.3	1.2–1.4	1.4
Signal width dependence	2.8	2.9	–
Trigger efficiency		0.4	
Luminosity		2.1 (2015), 3.4 (2016)	
Total uncertainty in signal yield	4.6–5.4	5.3–5.5	4.8





Results:

Largest fluctuations at:

730 GeV: 2.6 σ (Spin 0, local)

708 GeV: 3.0 σ (Spin 2 $k/\overline{M}_{Pl}$ 0.3, local)

ADD: 5.7-8.6 TeV on M_S, depending on theoretical assumptions

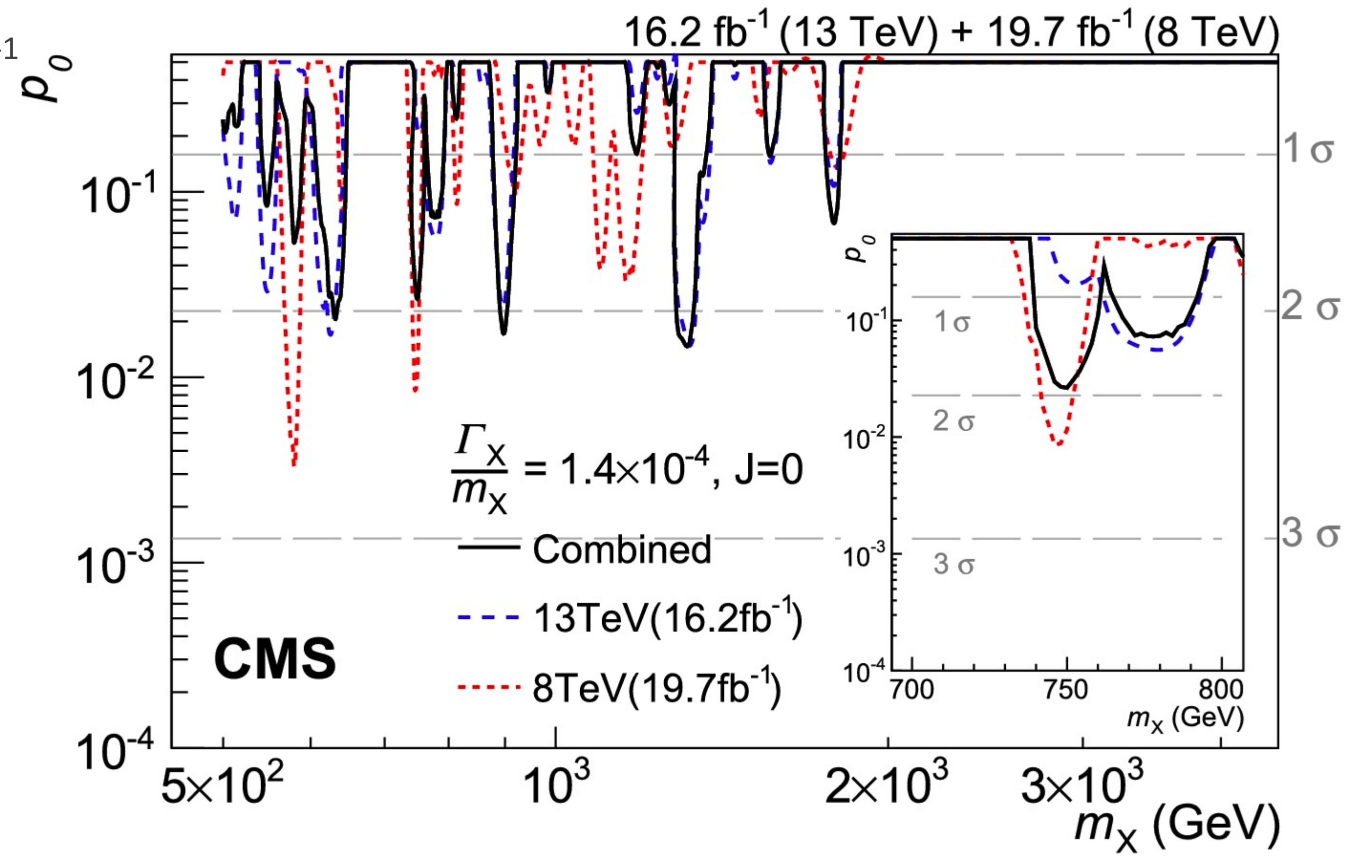
Diphoton results in CMS

Physics Letters B Volume 767, 10 April 2017, Pages 147-170

- CMS combines 16.2 fb^{-1} of 13 TeV data with 19.7 fb^{-1} of 8 TeV data for ggF process
- Photon p^T >75 GeV
- Drop end-cap end-cap events due to increasing slightly the signal efficiency with large background
- Background shape:

$$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\ \log(m_{\gamma\gamma})}.$$

- Using pseudo experiments to quantify background uncertainties



Testing models:

Scalar and spin 2 RS models

500 GeV to 4500 GeV

Width: spin 0 : Γ_X/m_X $1.4\times10^{-4}, 1.4\times10^{-2}$, and 5.6×10^{-2}

Spin 2: $\Gamma_X/m_X = 1.4\,\tilde{k}^2$ $\tilde{k} = 0.01, 0.1$, and 0.2

Systematics: luminosity 6.2%, selection 6.0%, PDFs 6.0%, resolution 6.0%

$X \to Z\gamma$ search

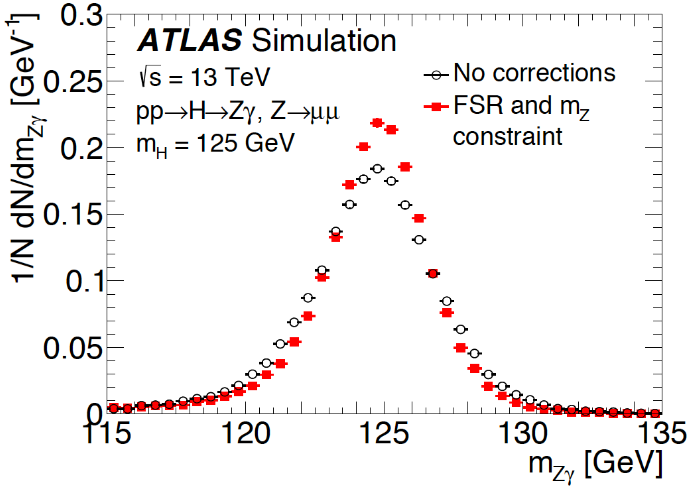
ATLAS: arXiv:1708.00212

CMS leptonic: arxiv: 1610.02960

CMS hadronic (PhysicsLettersB772(2017)363–387)

ATLAS updated the search with 36.1 fb^{-1}, leptonic channel only

CMS uses 8 TeV of 19.7 fb^{-1} and of 13 TeV 2.7 fb^{-1} data, combining leptonic and hadronic channels



(a)

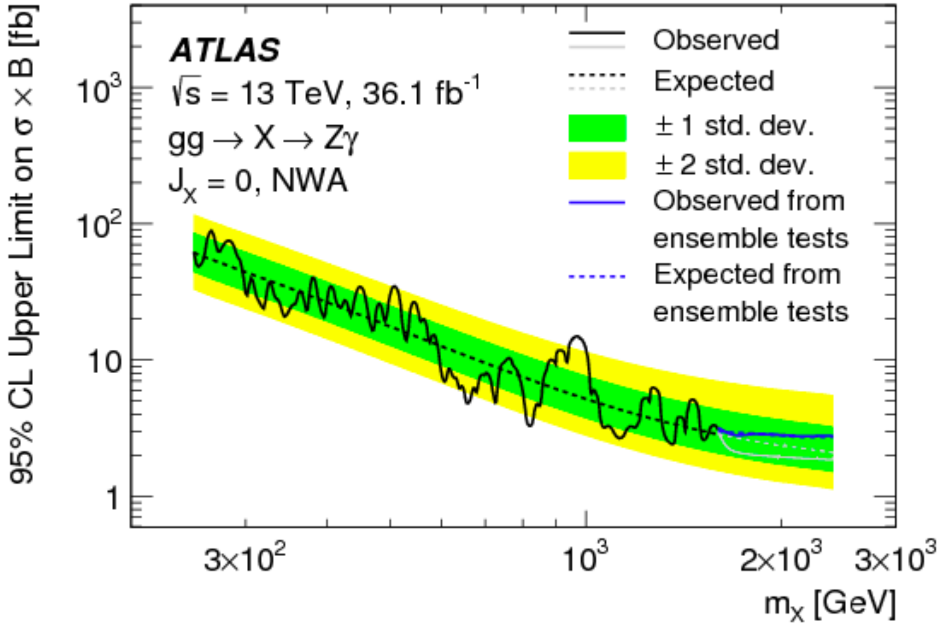
ATLAS leptonic selection:

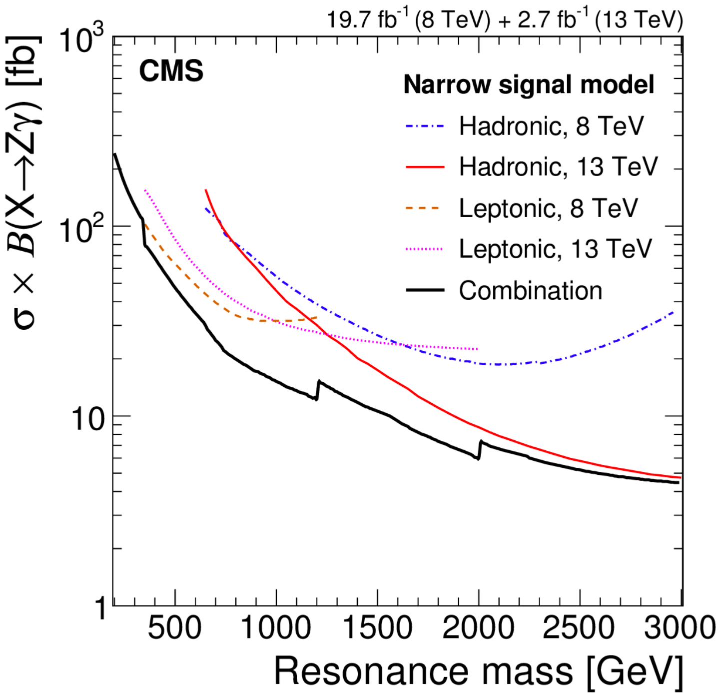
ll γ, well identified and isolated

FSR correction, Z mass constraint

$$p_{\mathrm{T}t} = 2|p_x^Z p_y^\gamma - p_x^\gamma p_y^Z| / p_{\mathrm{T}}^{Z\gamma}$$

Category
VBF-enriched
High relative p_{T}
ee high $p_{\mathrm{T}t}$
ee low $p_{\mathrm{T}t}$
$\mu\mu$ high $p_{\mathrm{T}t}$
$\mu\mu$ low $p_{\mathrm{T}t}$





CMS hadronic selection:

Large p^{T} photon, large-cone jet with mass around Z mass, with or without b-tagged subjet

The ZZ final states (ATLAS)

ATLAS-CONF-2017-058

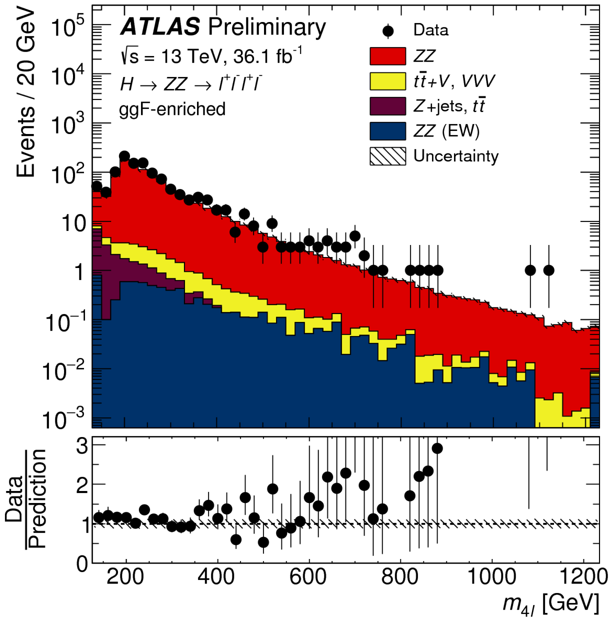
4l together with ll$\nu\nu$ final states in ATLAS result

Events categorized in ggF and VBF enriched categories

Using transverse mass m_T in the ll$\nu\nu$ channel

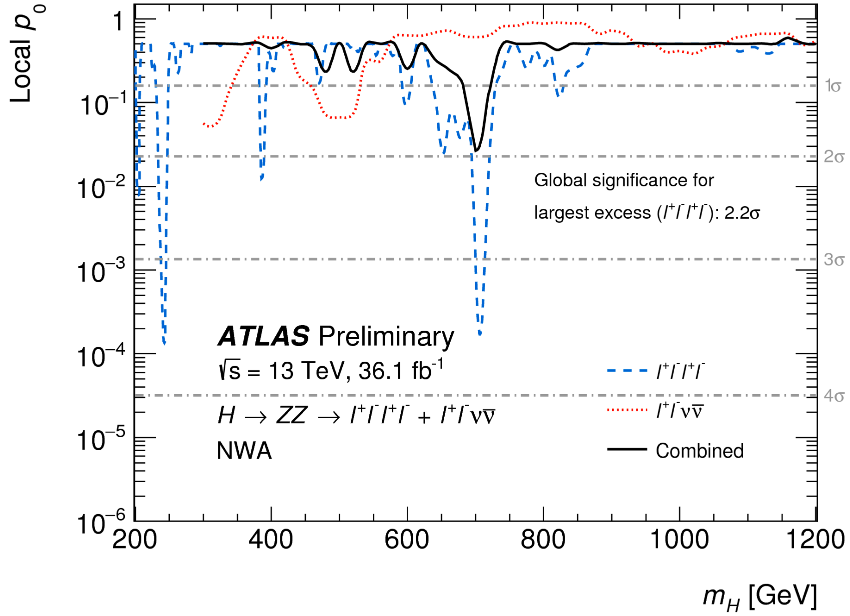
$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{miss}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2}$$

Interpretation in terms of NWA, LWA, spin0, spin2 and 2HDM



Event selection (4l):

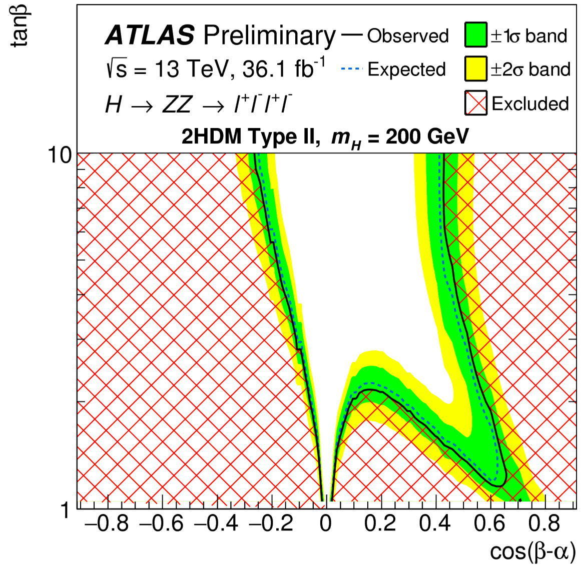
- 4 leptons, with 20,15,10, 7 (5 for muon) GeV p_T threshold
- Leptons categorized into same flavor and opposite sign pairs
- Reconstruct the invariant mass using 4l



Background estimation:
Continuous 4l background taken from MC simulation, the relative contributions of gg/qq processes are parameterized with an empirical function

Excess found at 242 GeV in 4l (3.6 σ local, 2.2 σ global, driven by 4e events)

Excess around 700 GeV in 4l is excluded in ll$\nu\nu$



The ZZ final states (CMS)

arxiv: 1706.09936

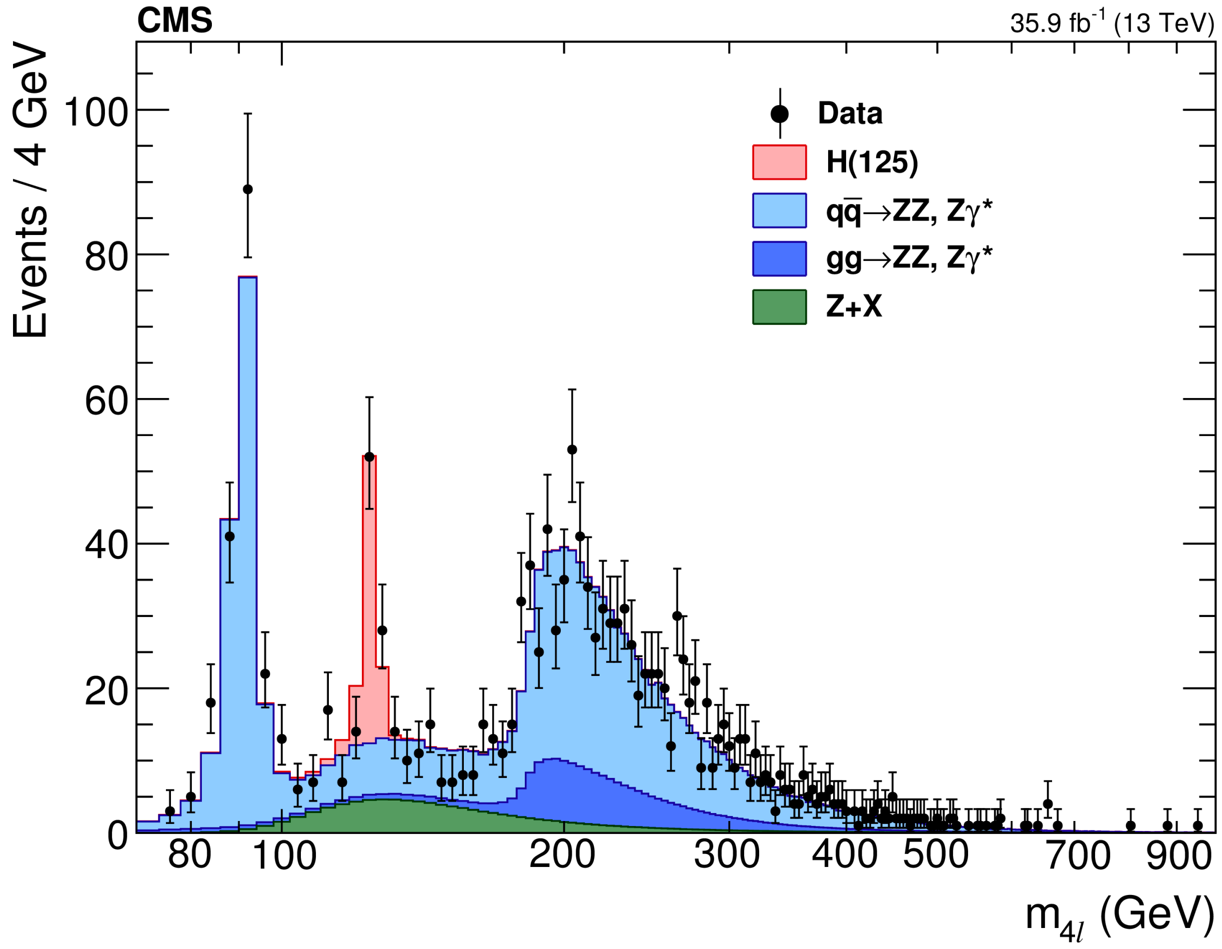
Study covered by the SM Higgs measurement

4 well isolated, identified leptons with FSR correction

Two pairs of same flavor, opposite sign leptons

For Z_1Z_2 candidates composed of four same flavor leptons, an alternative pairing Z_aZ_b can be formed out of the same four leptons. Discard the Z_1Z_2 candidate if $m(Z_a)$ is closer to m_Z than $m(Z_1)$ and $m(Z_b) < 12$ GeV.

Dominant irreducible background obtained from MC simulation



H → WW→ lνqq (ATLAS)

arxiv 1710.07235

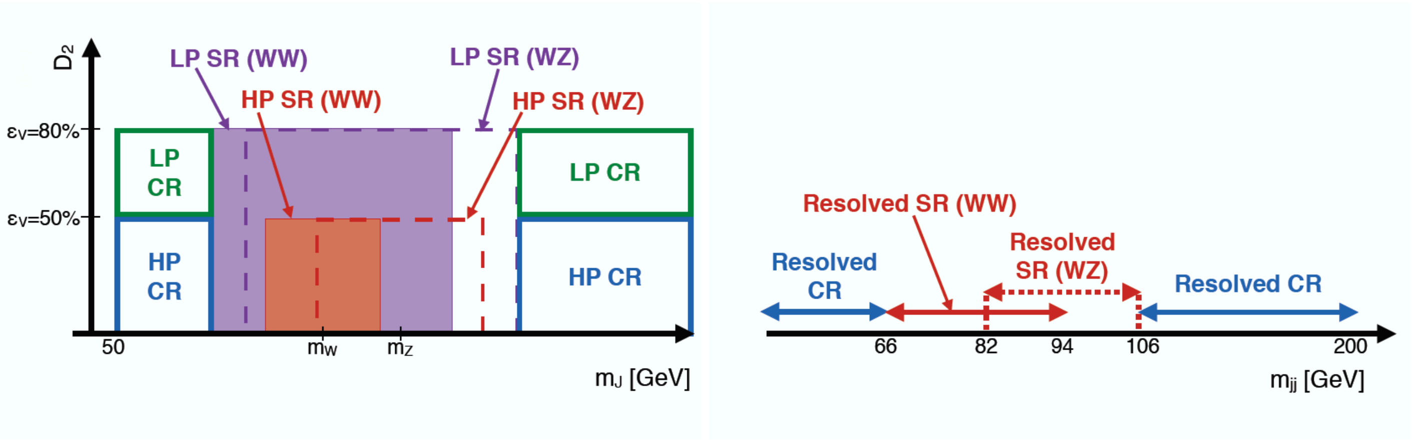
Search for a neutral heavy resonance
Decaying into WW, with lνqq or lνJ final states

Large-R jet analysis:
V-tagging, using D_2 variable and m_J

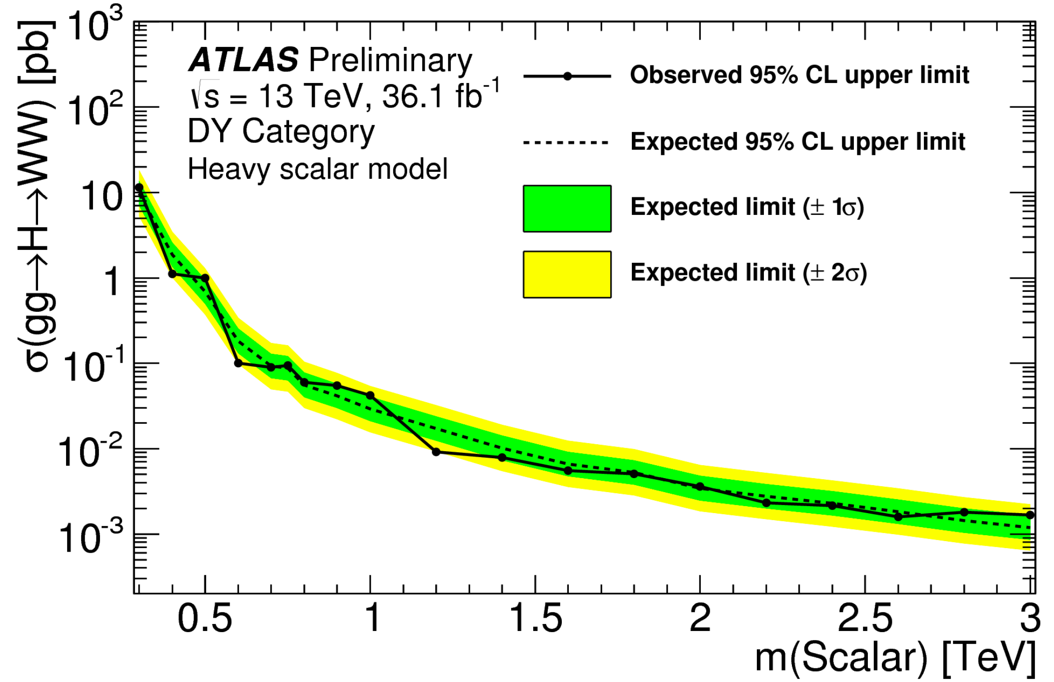
D_2 is defined as a ratio of two- and three-point energy correlation functions, which are based on the energies and pairwise angular distances of particles within a jet.

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k\in J} p_{T i}\, p_{T j}\, p_{T k} \left(R_{ij} R_{ik} R_{jk}\right)^{\beta},$$

Small R jet analysis: cut on m_{jj}
W+jet and tt background, controlled by CR

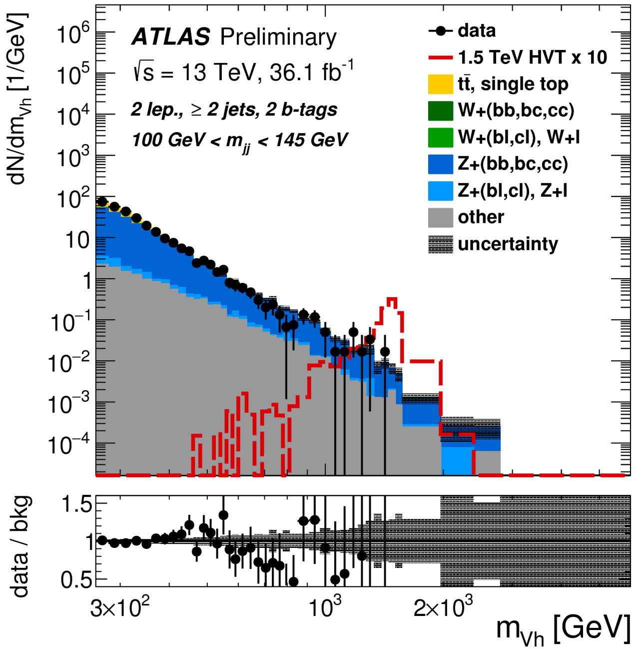


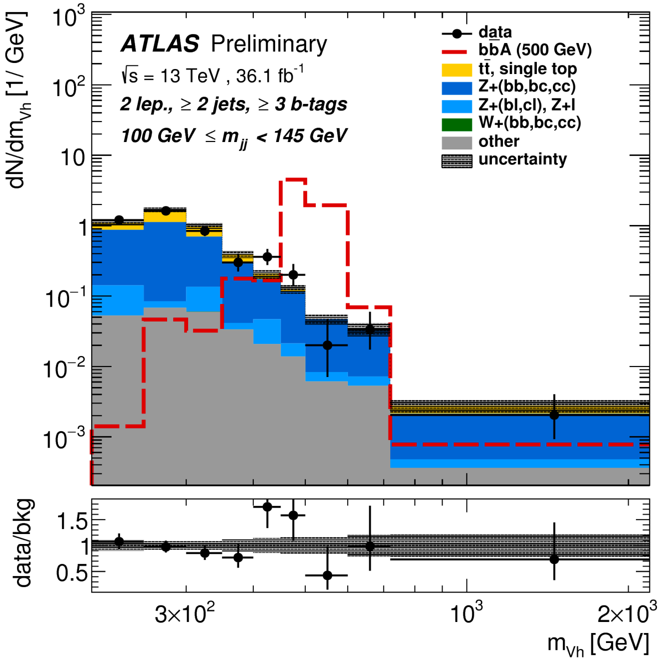
Selection		SR: HP (LP)	W CR: HP (LP)	$t\bar{t}$ CR: HP (LP)
Production category	VBF	$m^{tag}(j,j) > 770$ GeV and $\lvert\Delta\eta^{tag}(j,j)\rvert > 4.7$		
	ggF/$q\bar{q}$	Fails VBF selection		
$W \to \ell\nu$ selection	Num. of signal leptons	1		
	Num. of veto leptons	0		
	E_T^{miss}	> 100 GeV		
	$p_T(\ell\nu)$	> 200 GeV		
	$E_T^{miss}/p_T(e\nu)$	> 0.2		
$V \to J$ selection	Num. of large-R jets	≥ 1		
	D_2 eff. working point (%)	Pass 50 (80)	Pass 50 (80)	Pass 50 (80)
	Mass window Eff. working point (%)	Pass 50 (80)	Fail 80 (80)	Pass 50 (80)
Topology criteria	$p_T(\ell\nu)/m(WV)$ $p_T(J)/m(WV)$	> 0.3 for VBF and > 0.4 for ggF/$q\bar{q}$ category		
Num. of b-tagged jet	excluding b-tagged jets with $\Delta R(J,b) \leq 1.0$	0		≥ 1

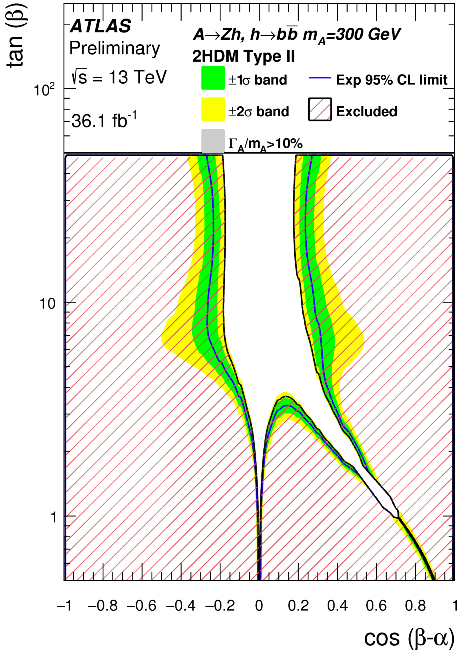


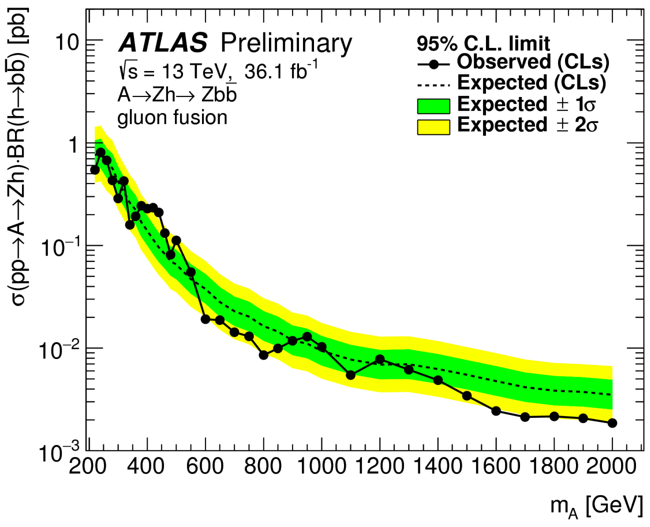
WZ final states were also searched in the same analysis

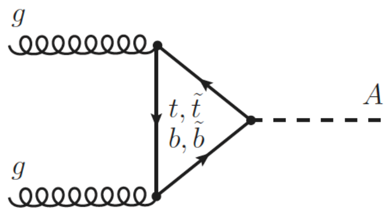
A → Zh (ATLAS)



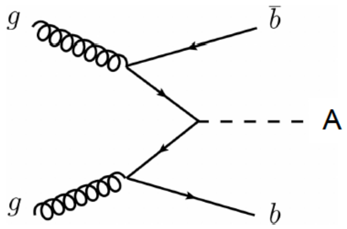


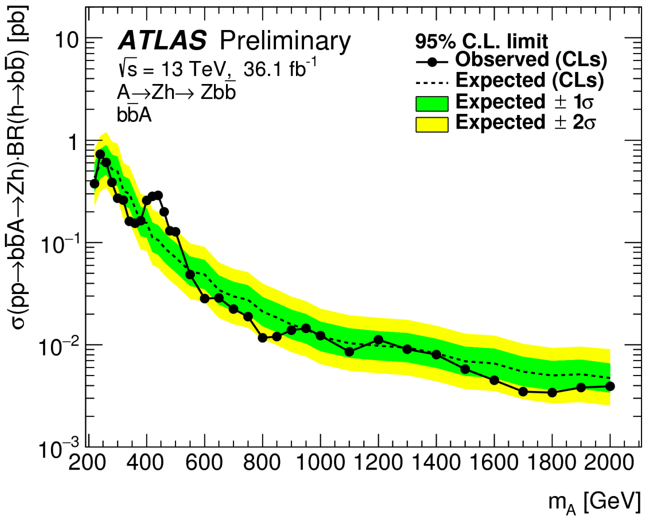






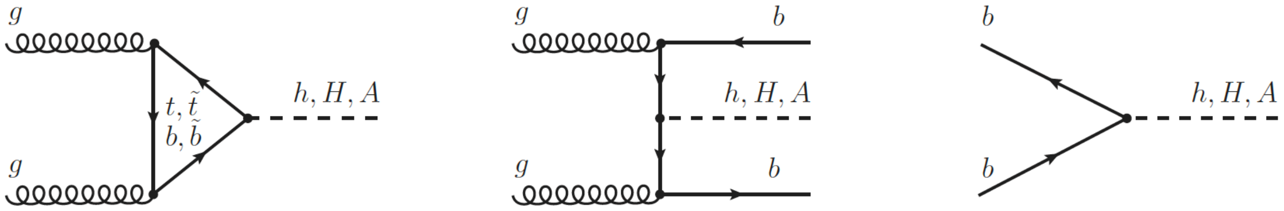
- A → Zh (125), h → bb, Z → $\nu\,\nu$ / ll,
- Gluon fusion or b associated production
- 0, 2 leptons, 1-3 b-tagged region
- Merged and resolved h→bb topologies
- Strong limits at low tan(β)
- Local (global) significance 3.6(2.4) σ excess at 440 GeV
- Excess is driven by di-muon channel with extra b-tags

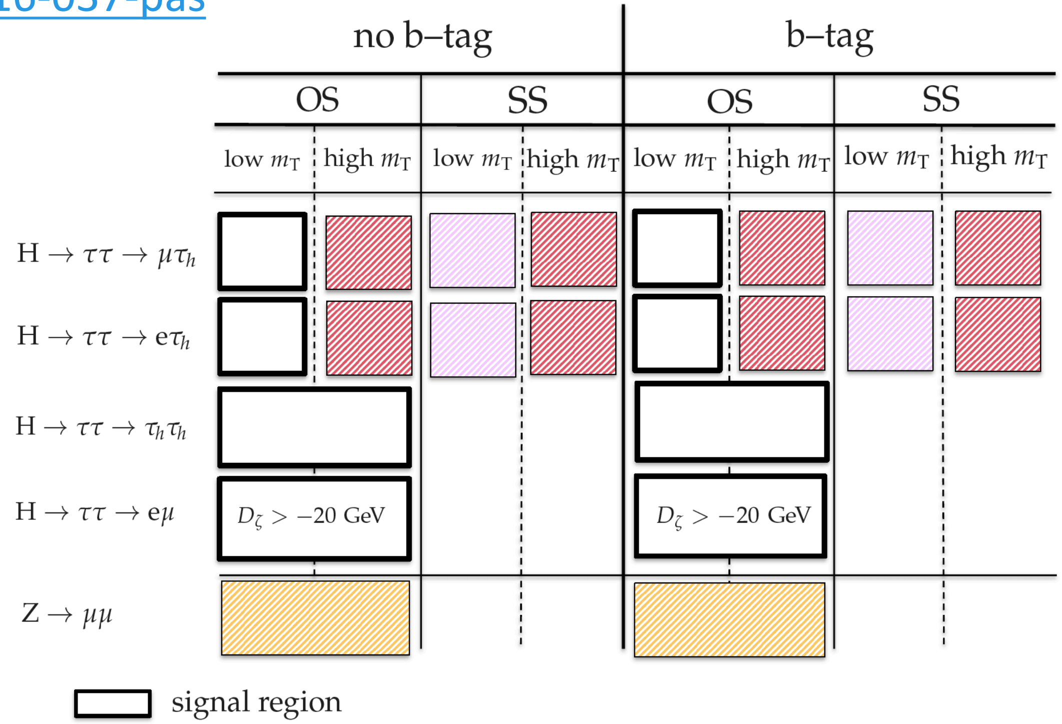




$\tau\tau$ searches(CMS)

HIG-16-037-pas





Analysis in $e\tau_{had}$, $\mu\tau_{had}$, $\tau_{had}\tau_{had}$ and eμ channel

Additional leptons are vetoed

Select low transverse mass to reject W+jets background

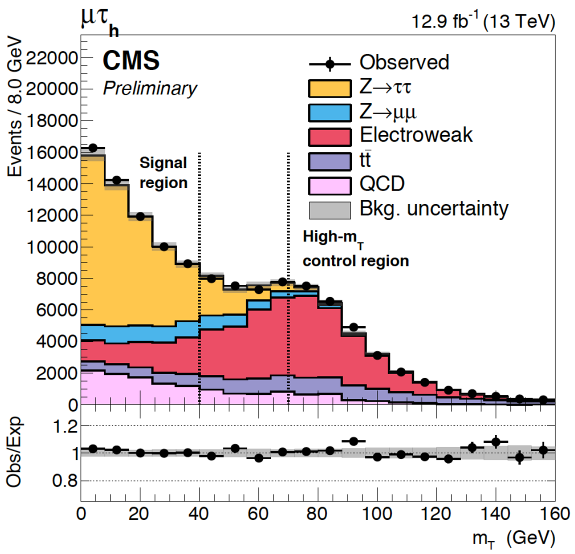
$$m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{miss}) \equiv \sqrt{2 p_T^\ell E_T^{miss} \left[1 - \cos\Delta\phi(\mathbf{p}_T^\ell, \mathbf{E}_T^{miss})\right]},$$

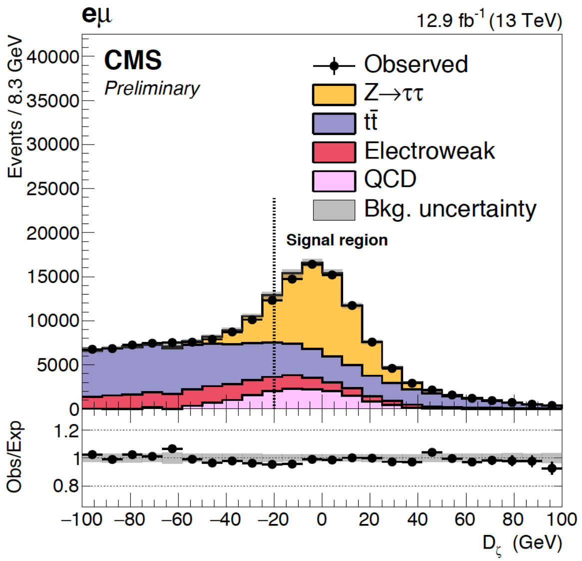
Topological discriminator along the eμ direction to reject tt background:

$$P_\zeta = (\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{p}_T^{\,miss}) \cdot \frac{\vec{\zeta}}{|\vec{\zeta}|} \quad \text{and} \quad P_\zeta^{vis} = (\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu}) \cdot \frac{\vec{\zeta}}{|\vec{\zeta}|}$$

$$D_\zeta = P_\zeta - 1.85 \cdot P_\zeta^{vis} > -20 \text{ GeV}$$

Events are categorized into b-tagged and no b-tagged region





$\tau\tau$ searches (CMS)

Background estimation:

Using $Z \rightarrow \mu\mu$ to calibrate the $Z/\gamma^* \rightarrow \tau\tau$ MC simulation

For the $e\tau_{had}$ and $\mu\tau_{had}$ channel, using same-sign lepton-τ_{had} and high m_T region to estimate the fake τ from the W+jets and the multi-jets background.

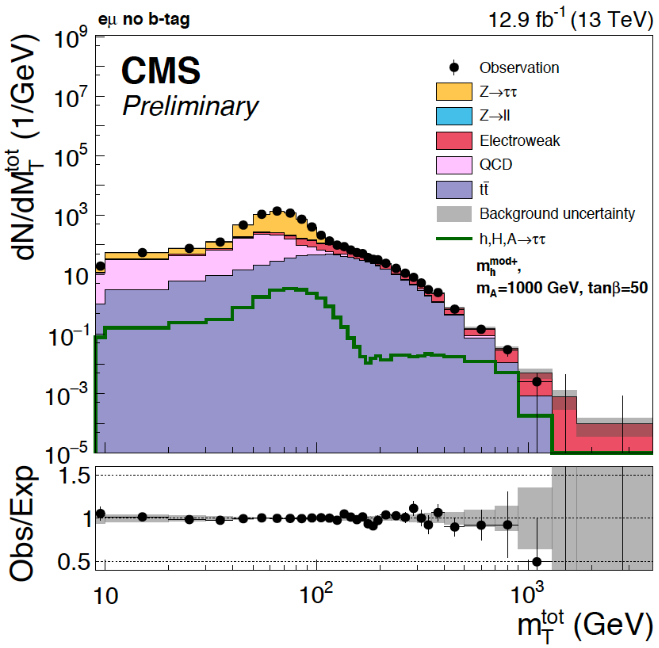
For the $\tau_{had}\,\tau_{had}$ channel, the QCD background is estimated by loosening the subleading τ_{had} isolation criteria

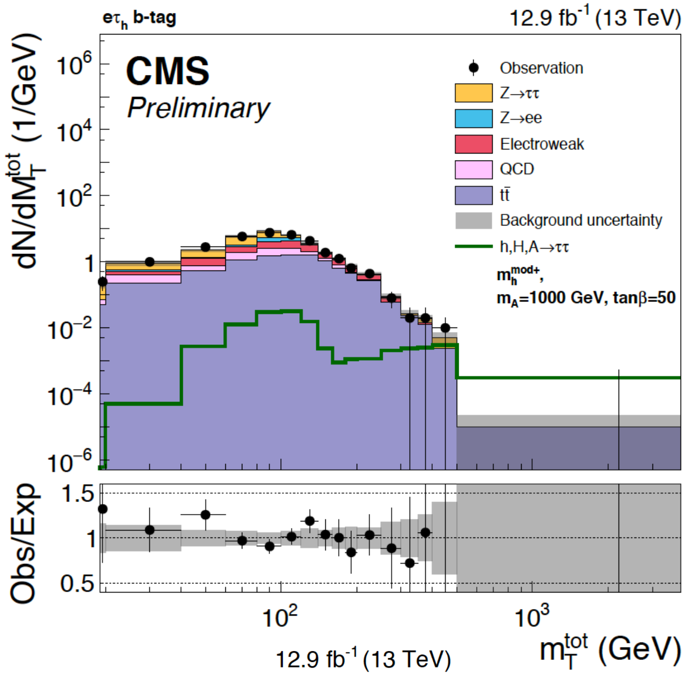
For the eμ channel, the QCD background is estimated in the same sign lepton region, the tt background is estimated from the MC simulation

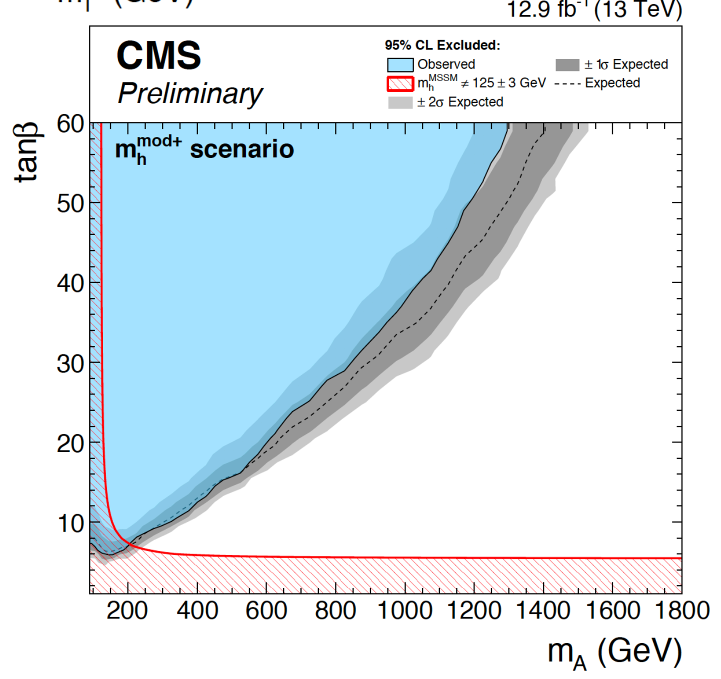
m_T^{tot} is the final discriminating variable:

$$m_T^{tot} = \sqrt{m_T(E_T^{miss}, \tau_1^{vis})^2 + m_T(E_T^{miss}, \tau_2^{vis})^2 + m_T(\tau_1^{vis}, \tau_2^{vis})^2}.$$

HIG-16-037-pas







$\tau\tau$ searches (ATLAS) arXiv:1709.07242

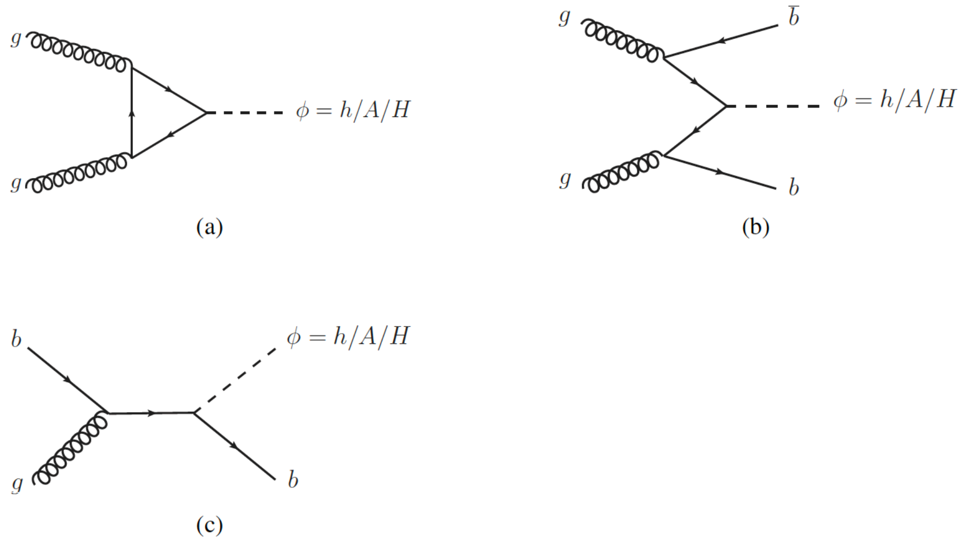
Heavy neutral Higgs like boson decay to τ leptons,

Semi leptonic decay and full hadronic final states

MSSM interpretation, enhanced coupling to τ and b at large tan(β)

$\tau_{\text{lep}}\ \tau_{\text{had}}$ and $\tau_{\text{had}}\ \tau_{\text{had}}$ channels, with b veto or b tagged region

τ_{had} decays are composed of a neutrino and a set of visible decay products $\tau_{\text{had-vis}}$, typically one or three charged pions and up to two neutral pions.



Leptonic selection:

$$|\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\ell}, \mathbf{p}_{\mathrm{T}}^{\tau_{\text{had-vis}}})| > 2.4\,\mathrm{rad}$$

m_T<40 GeV to reject W+jets

Invariant mass of $\tau_{\text{lep}}\ \tau_{\text{had}}$ outside of Z mass window for the electron channel

Overall 1%-7% signal efficiency

Full hadronic selection:

Requires single τ p^T >85, 130, 165 GeV according to the fired trigger

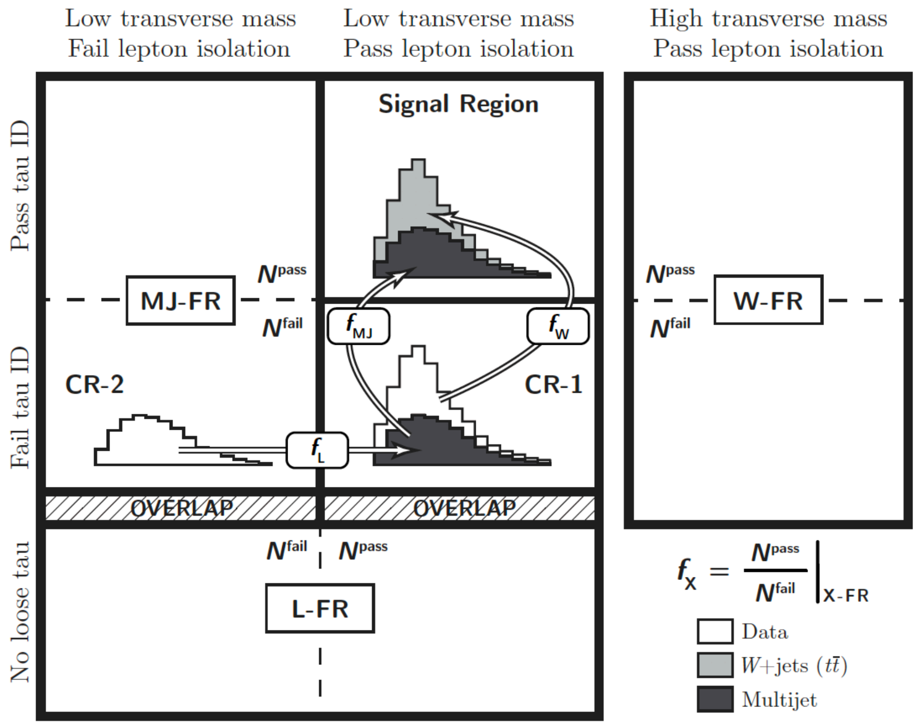
All τ p^T should be at least 65 GeV

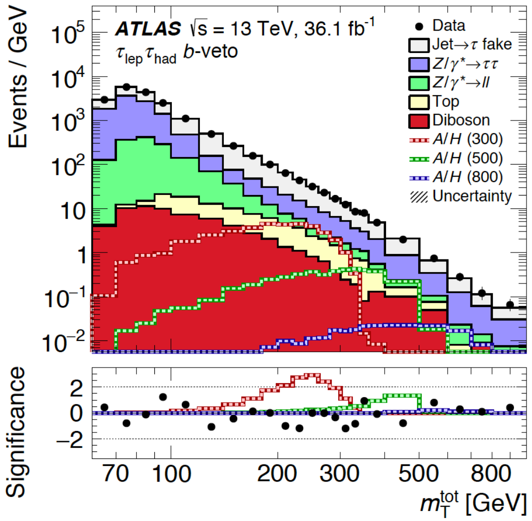
$$|\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_1}, \mathbf{p}_{\mathrm{T}}^{\tau_2})| > 2.7\,\mathrm{rad}$$

$m_{\mathrm{T}}^{\mathrm{tot}}$ is the final discriminating variable

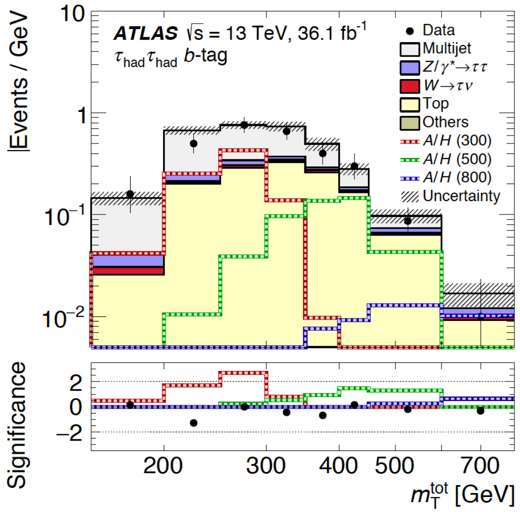
$\tau\tau$ searches (ATLAS)

- Leptonic:
  - Multi-jets and W+jets backgrounds due to jet faking τ_{had} and jet faking lepton are estimated by using control regions with the correction of fake factors.
  - The control regions are defined by failing the τ_{had} ID or failing both the τ_{had} ID and the lepton isolation.
  - The jet-lepton fake factor is obtained in the region with 1 lepton, 0 loose τ_{had} and at least 1 jet.
  - The jet-τ_{had} fake factor is obtained in the region with very loose τ_{had} and 1 lepton failing the isolation.
- Full hadronic:
  - The jet faking τ_{had} rate is estimated from the two-τ_{had} region without the τ_{had} identification.

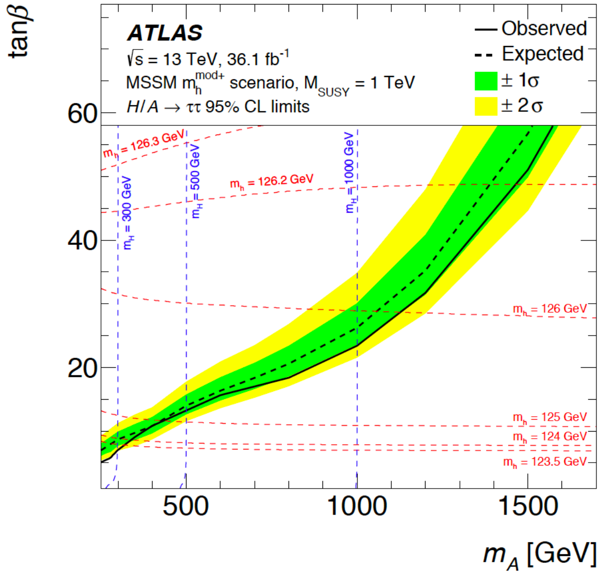




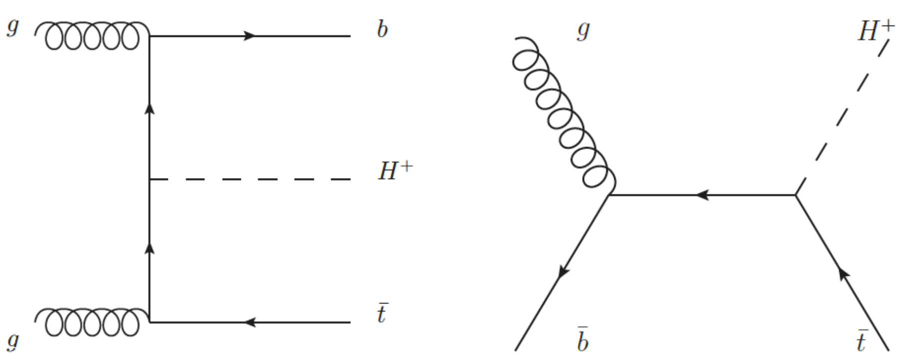
(a) $\tau_{lep}\tau_{had}$ *b*-veto category

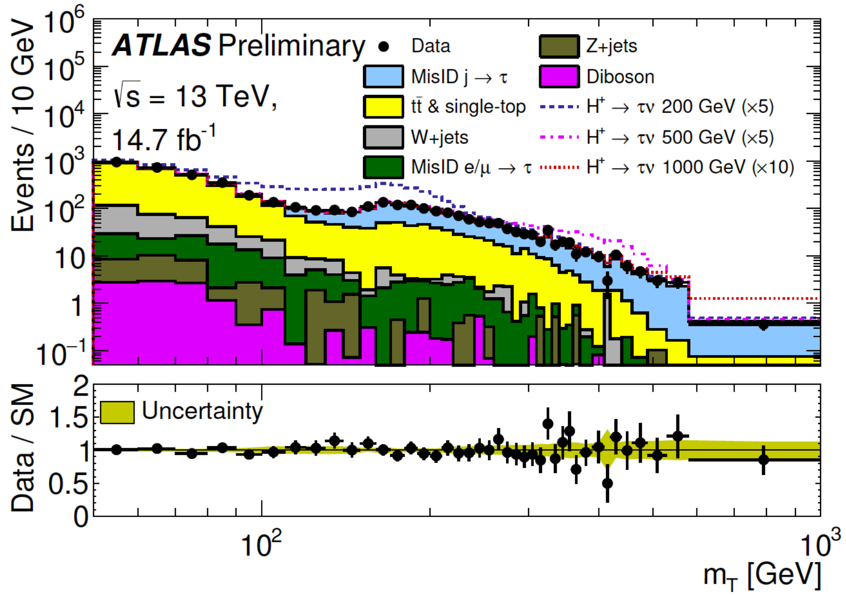


(d) $\tau_{had}\tau_{had}$ *b*-tag category



$H^{\pm} \to \tau\nu$ (ATLAS) ATLAS-CONF-2016-088





Full hadronic channel, with (b)t$H^{\pm} \to$(b)(jjb) $\tau_{had}\nu$

One visible τ_{had} jet

Lepton rejection, transverse missing energy greater than 150 GeV

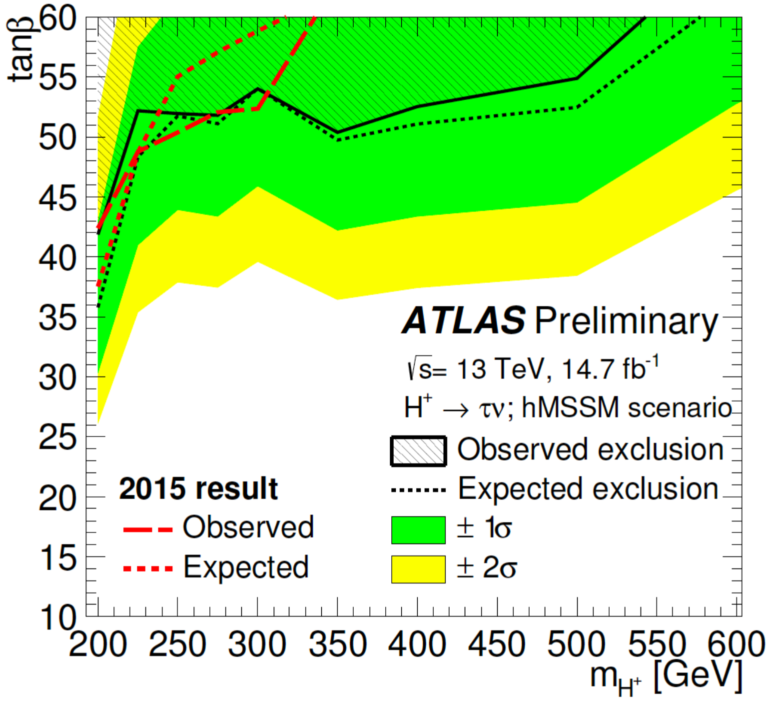
Three or more jets

At least one b-tagged jet

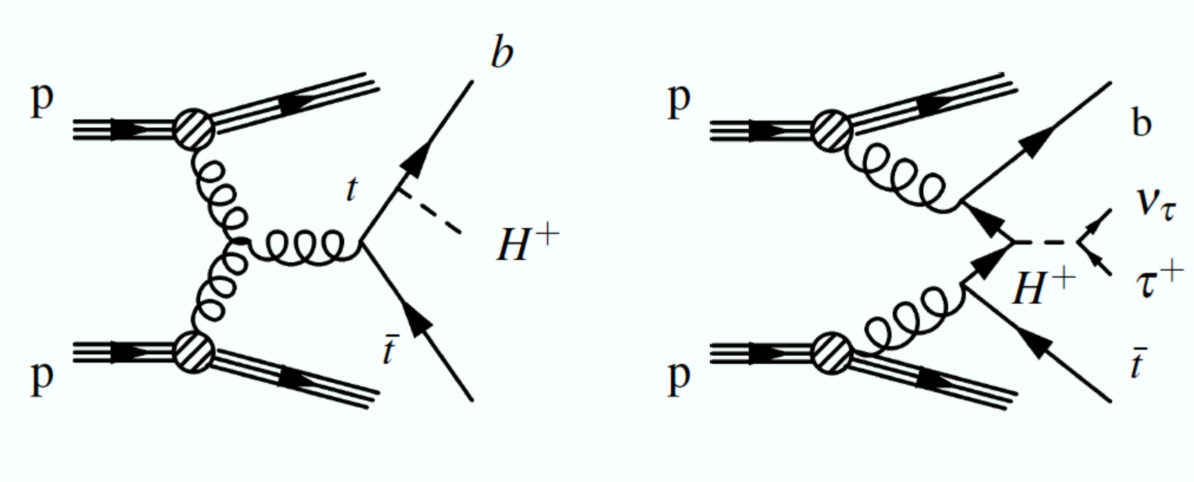
Main backgrounds are top and misidentification of light jet to τ_{had}

Use m_T as the discriminator

$$m_T = \sqrt{2p_T^{\tau}E_T^{\text{miss}}(1 - \cos\Delta\phi_{\tau,\text{miss}})},$$



$H^{\pm} \rightarrow \tau\nu$ (CMS) HIG-16-031



Search for the presence of hadronic τ and large missing transverse energy

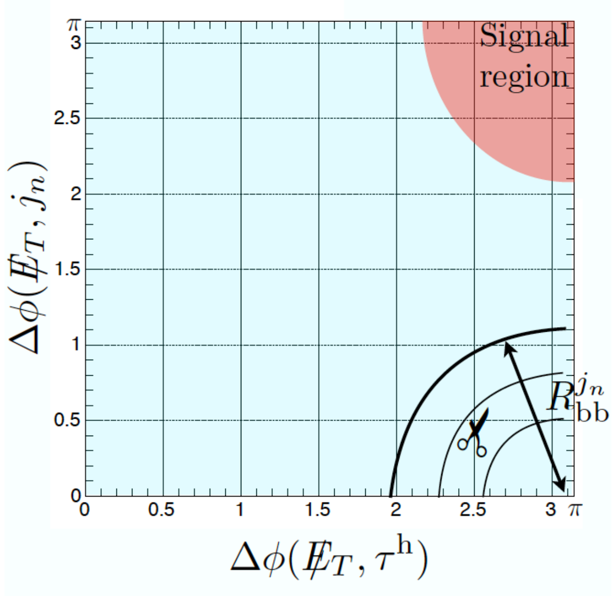
Veto on electrons and muons

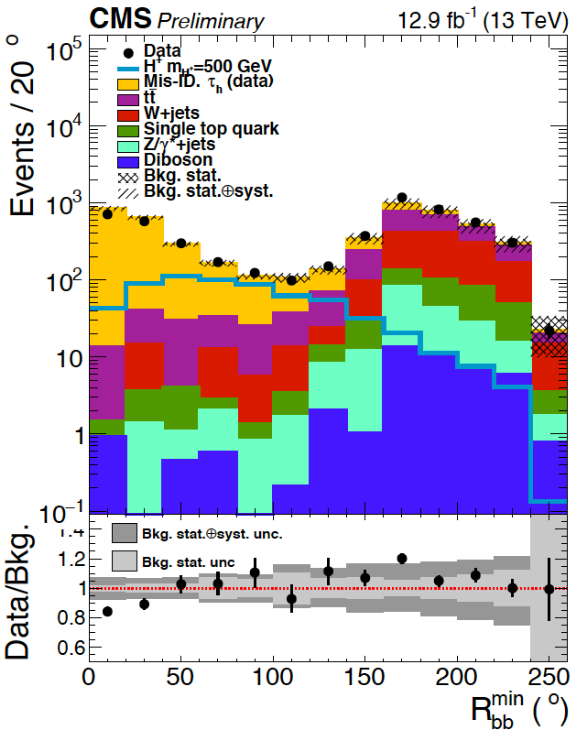
At least three jets and 1 b-tagged jet

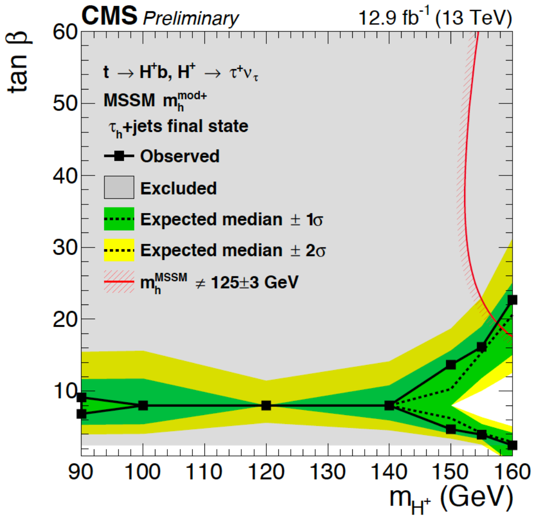
R_{bb}^{min} >40° $R^{\rm min}_{\rm bb} = \min_{j \in j_1..j_3} \sqrt{\Delta\phi(\not{E}_T, j)^2 + (\pi - \Delta\phi(\tau^{\rm h}, \not{E}_T))^2}$

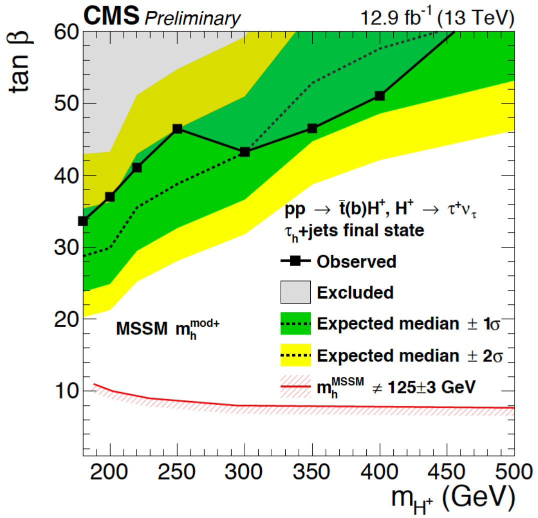
Final discriminating variable, transverse mass m_T

Search range 80 GeV-160 GeV, 180 GeV-3 TeV

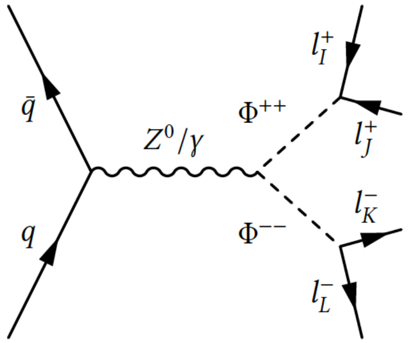




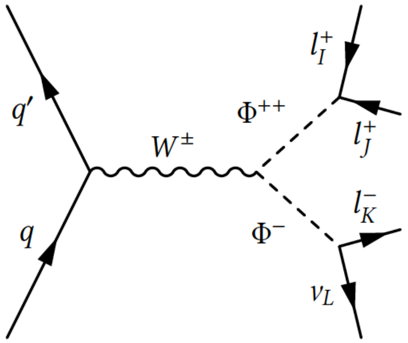




Doubly charged Higgs (CMS) CMS-PAS-HIG-16-036



(a) 4ℓ

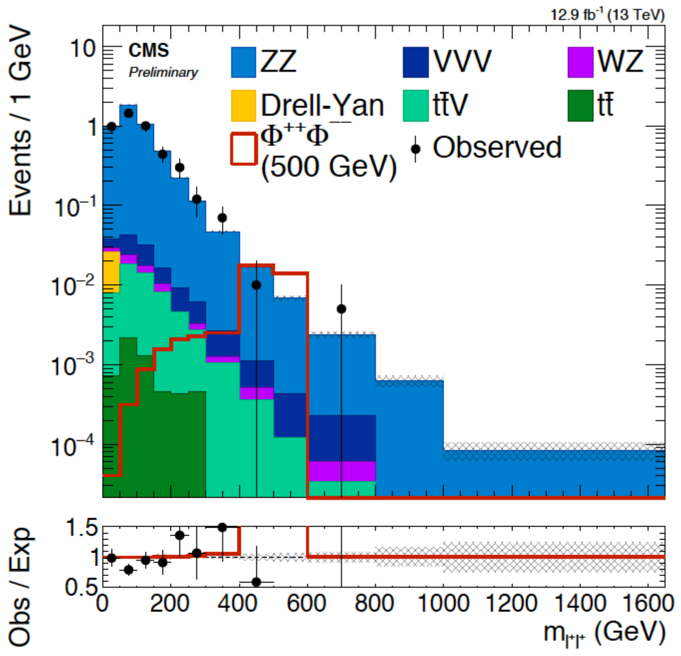


(b) 3ℓ

The minimal Type II seesaw mechanism extends the SM particle spectrum with a scalar triplet

Using 3 lepton and 4 lepton final states for the associated and pair production

Event selection: using scalar sum of lepton p^T (S_T), Z veto, isolation of leptons and missing energy



(a) $\ell^+\ell^+\ell^-\ell^-$

Table 2: Selections made on three lepton final states to define the final signal region.

Variable	ee, $e\mu$, $\mu\mu$	$e\tau$, $\mu\tau$	$\tau\tau$
S_T	$> 0.99 \cdot m_{\Phi^{++}} - 35$ GeV	$> 1.15 \cdot m_{\Phi^{++}} + 2$ GeV	$> 0.98 \cdot m_{\Phi^{++}} + 91$ GeV
$\|m_{\ell^+\ell^-} - m_Z\|$	> 10 GeV	> 20 GeV	> 25 GeV
E_T^{miss}	–	> 20 GeV	> 50 GeV
$\Delta R(\ell^\pm\ell'^\pm)$	–	< 3.2	$< m_{\Phi^{++}}/380 + 1.86$ ($m_{\Phi^{++}} \leq 400$) $< m_{\Phi^{++}}/750 + 2.37$ ($m_{\Phi^{++}} > 400$)
Mass window	$[0.9 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}]$ GeV	$[0.4 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}]$ GeV	$[0.3 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}]$ GeV

Table 3: Selections made on four lepton final states to define the final signal region.

Variable	ee, $e\mu$, $\mu\mu$	$e\tau$, $\mu\tau$	$\tau\tau$
S_T	$> 1.23 \cdot m_{\Phi^{++}} + 54$ GeV	$> 0.88 \cdot m_{\Phi^{++}} + 73$ GeV	$> 0.46 \cdot m_{\Phi^{++}} + 108$ GeV
$\|m_{\ell^+\ell^-} - m_Z\|$	–	> 10 GeV	> 25 GeV
$\Delta R(\ell^\pm\ell'^\pm)$	–	–	$< m_{\Phi^{++}}/1400 + 2.43$
Mass window	$[0.9 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}]$ GeV	$[0.4 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}]$ GeV	$[0.3 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}]$ GeV

Doubly charged Higgs (CMS)

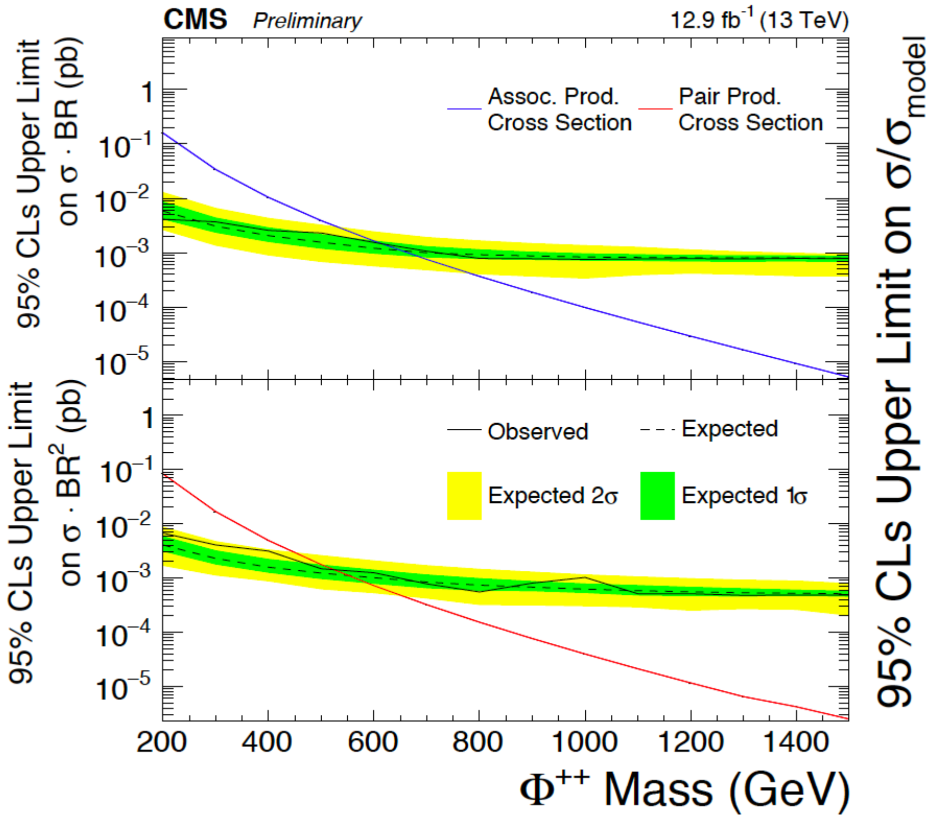
Limits on associated and pair production for different benchmarks

Benchmark	AP [GeV]	PP [GeV]	Combined [GeV]
100% $\Phi^{\pm\pm} \to ee$	734 (720)	652 (639)	800 (785)
100% $\Phi^{\pm\pm} \to e\mu$	750 (729)	665 (660)	820 (810)
100% $\Phi^{\pm\pm} \to \mu\mu$	746 (774)	712 (712)	816 (843)
100% $\Phi^{\pm\pm} \to e\tau$	568 (582)	481 (543)	714 (658)
100% $\Phi^{\pm\pm} \to \mu\tau$	518 (613)	537 (591)	643 (708)
100% $\Phi^{\pm\pm} \to \tau\tau$	479 (483)	396 (419)	535 (544)
Benchmark 1	613 (649)	519 (548)	723 (715)
Benchmark 2	670 (671)	465 (554)	716 (723)
Benchmark 3	706 (682)	531 (562)	761 (732)
Benchmark 4	639 (639)	496 (539)	722 (704)

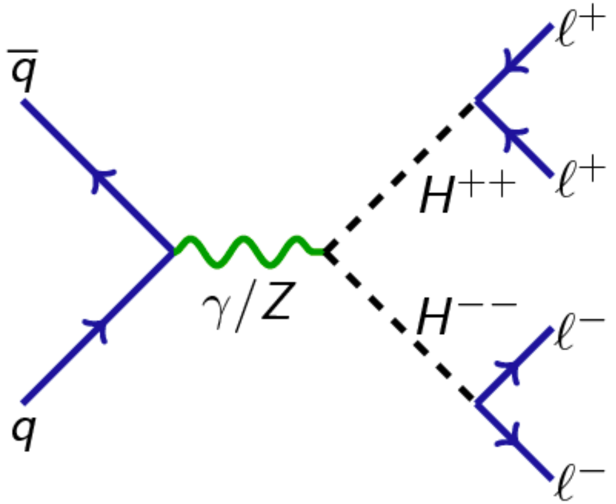
Table 1: Branching fraction scenarios for the decays of $\Phi^{\pm\pm}$.

Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

Benchmark 1



Doubly charged Higgs (ATLAS) arxiv:1710.09748



Doubly charged Higgs decays into two same sign leptons

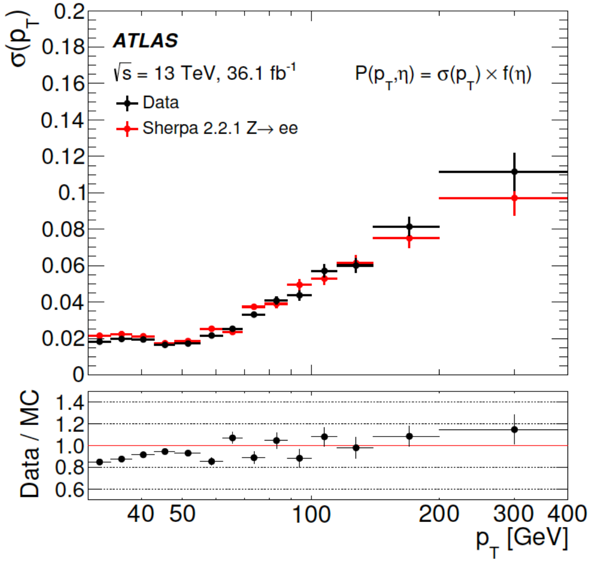
Considering 2, 3 and 4 leptons final states, e and μ final states only

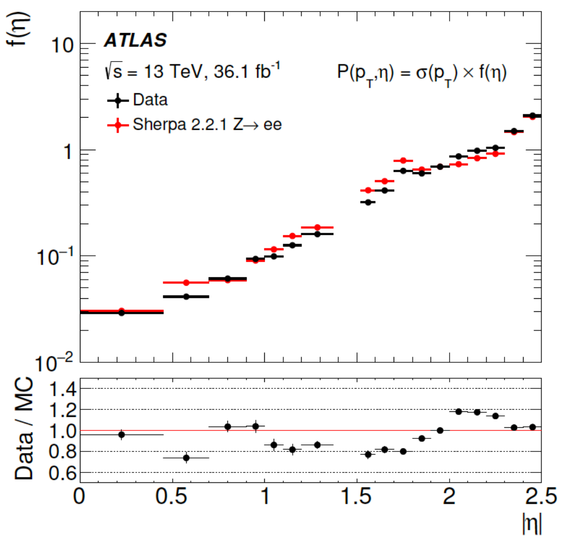
H^{++} decay to WW is assumed to be negligible

Decay width is assumed to be small

Data driven method to estimate the charge mis-ID and fake leptons

Region / Channel	Control Regions			Validation Regions			Signal Regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
electron ch.	$e^\pm e^\mp$	$e^\pm e^\pm e^\mp$		$e^\pm e^\mp$	$e^\pm e^\pm e^\mp$		$e^\pm e^\pm$	$e^\pm e^\pm e^\mp$	
mixed ch.	-	$e^\pm \mu^\pm \ell^\mp$	$4\ell^\pm$	$\ell^\pm \ell'^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$4\ell^\pm$	$\ell^\pm \ell'^\pm$	$e^\pm \mu^\pm \ell^\mp$ $\ell^\pm \ell^\pm \ell'^\mp$	$4\ell^\pm$
muon ch.	-	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$		$\mu^\pm \mu^\pm$	$\mu^\pm \mu^\pm \mu^\mp$	
mass range [GeV]									
$m(\ell^\pm \ell^\pm)$ electron ch.	[130, 2000]	[90, 200)		[130, 200)	[90, 200)		[200, ∞)	[200, ∞)	
$m(\ell^\pm \ell^\pm)$ mixed ch.	-	[90, 200)	[150, 200)	[130, 200)	[90, 200)	[60, 150)	[200, ∞)	[200, ∞)	[200, ∞)
$m(\ell^\pm \ell^\pm)$ muon ch.	-	[60, 200)		[60, 200)	[60, 200)		[200, ∞)	[200, ∞)	
selection									
b-jet veto	✓	✓	✓	✓	✓	✓	✓	✓	✓
Z veto	-	inv.	-	-	✓	-	-	✓	✓
$\Delta R(\ell^\pm \ell^\pm) < 3.5$	-	-	-	-	-	-	✓	✓	-
$p_T(\ell^\pm \ell^\pm) > 100$ GeV	-	-	-	-	-	-	✓	✓	-
$\sum \lvert p_T(\ell) \rvert > 300$ GeV	-	-	-	-	-	-	✓	✓	-
$\Delta M/\bar{M}$ cut	-	-	-	-	-	-	-	-	✓





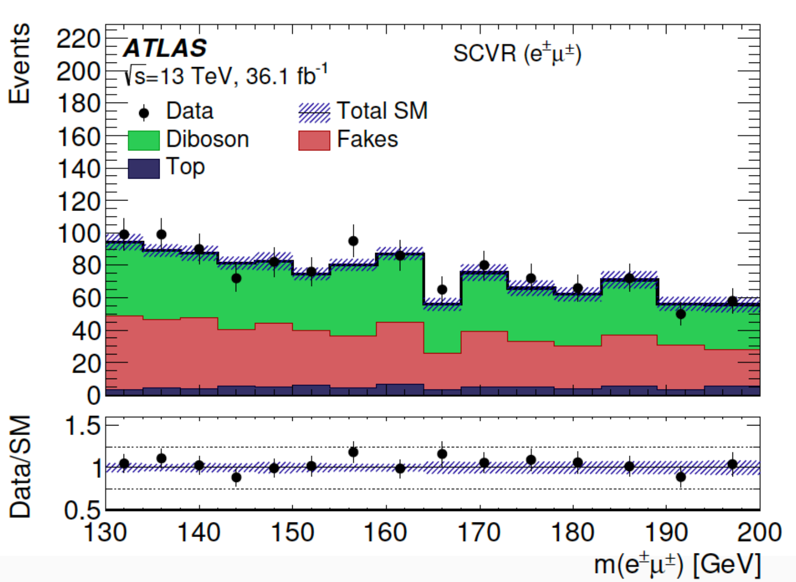
Doubly charged Higgs (ATLAS)

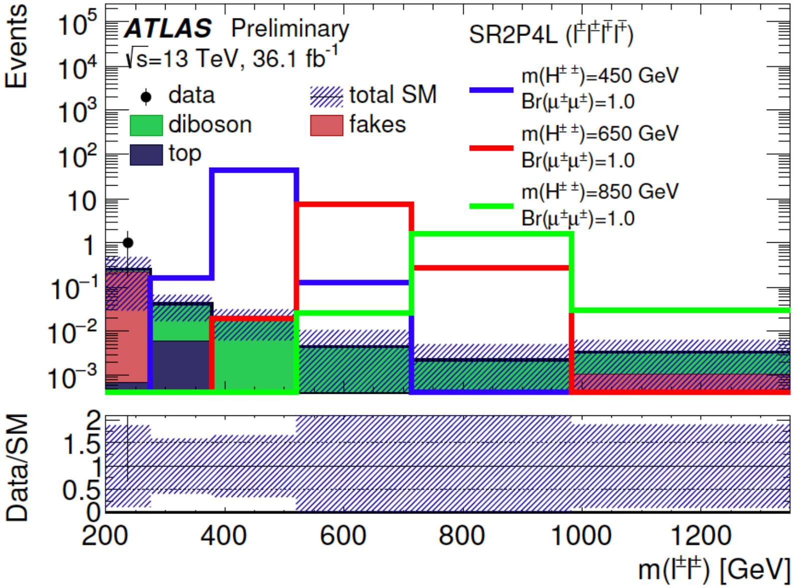
The charge misidentification is measured in the Z→ee regions with same/opposite charge

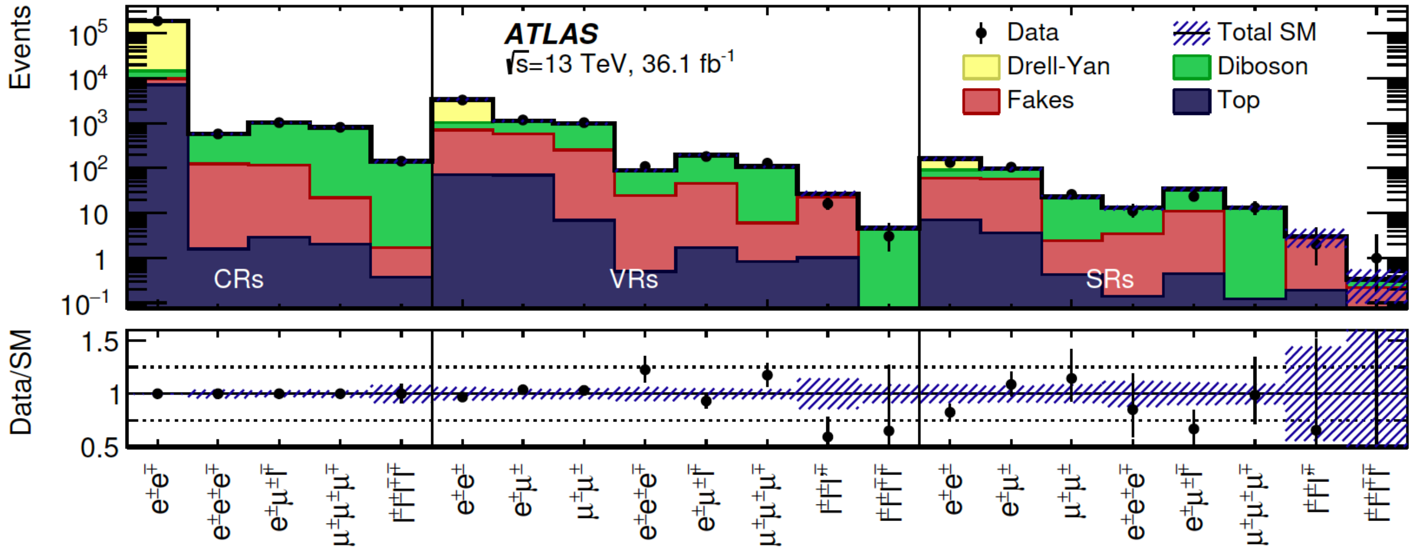
The fake lepton background is measured in the control region where at least one lepton fails the tight identification criteria

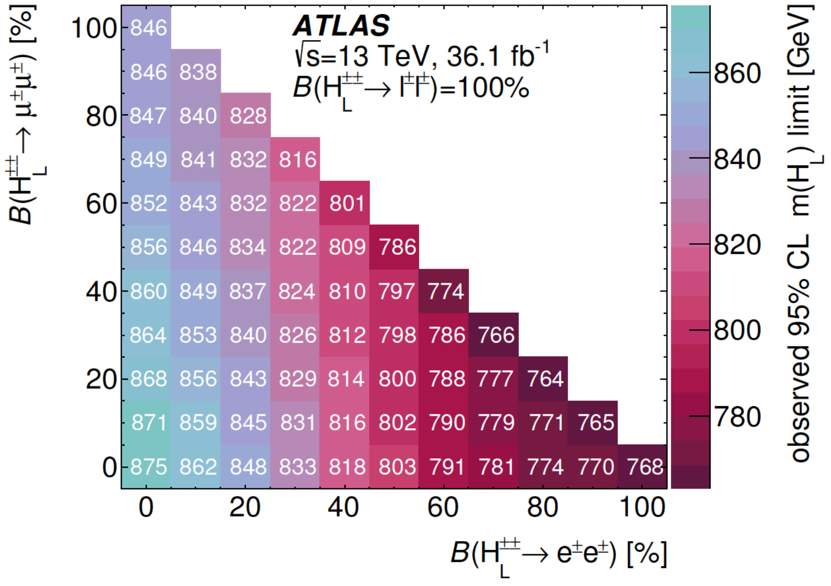
Validate the charge misidentification and fake background prediction in the same-charge two-lepton regions

Validate the diboson modelling in the 3 and 4 lepton validation regions



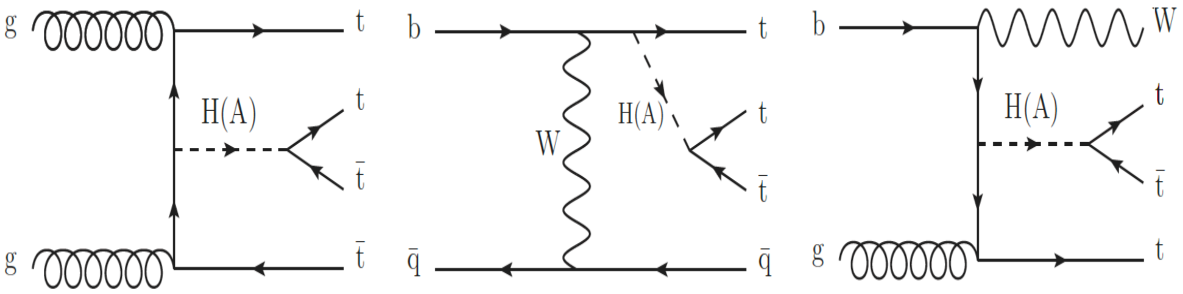






Top quark final states (CMS)

arxiv: 1704.07323



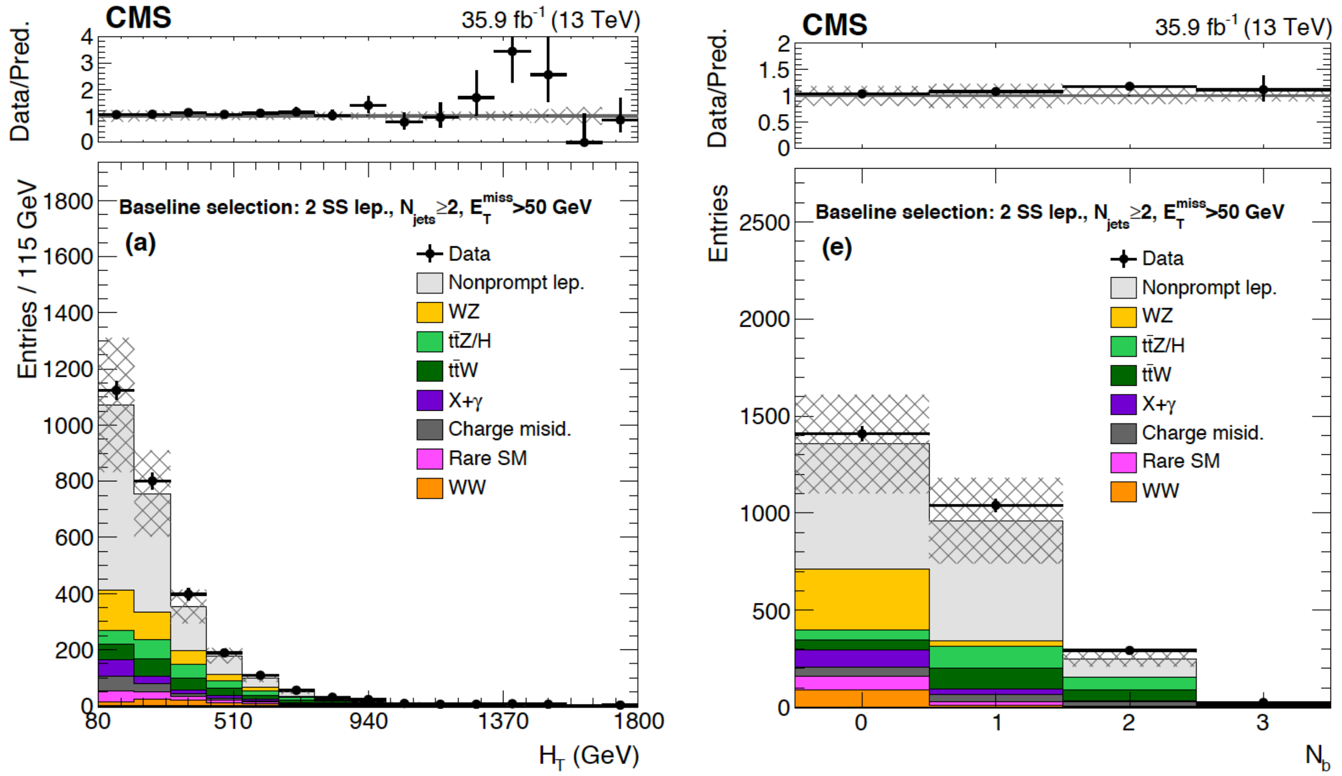
Object	p_T (GeV)	$\lvert\eta\rvert$
Electrons	>15	< 2.5
Muons	>10	< 2.4
Jets	>40	< 2.4
b-tagged jets	>25	< 2.4

Study the two same sign leptons final states

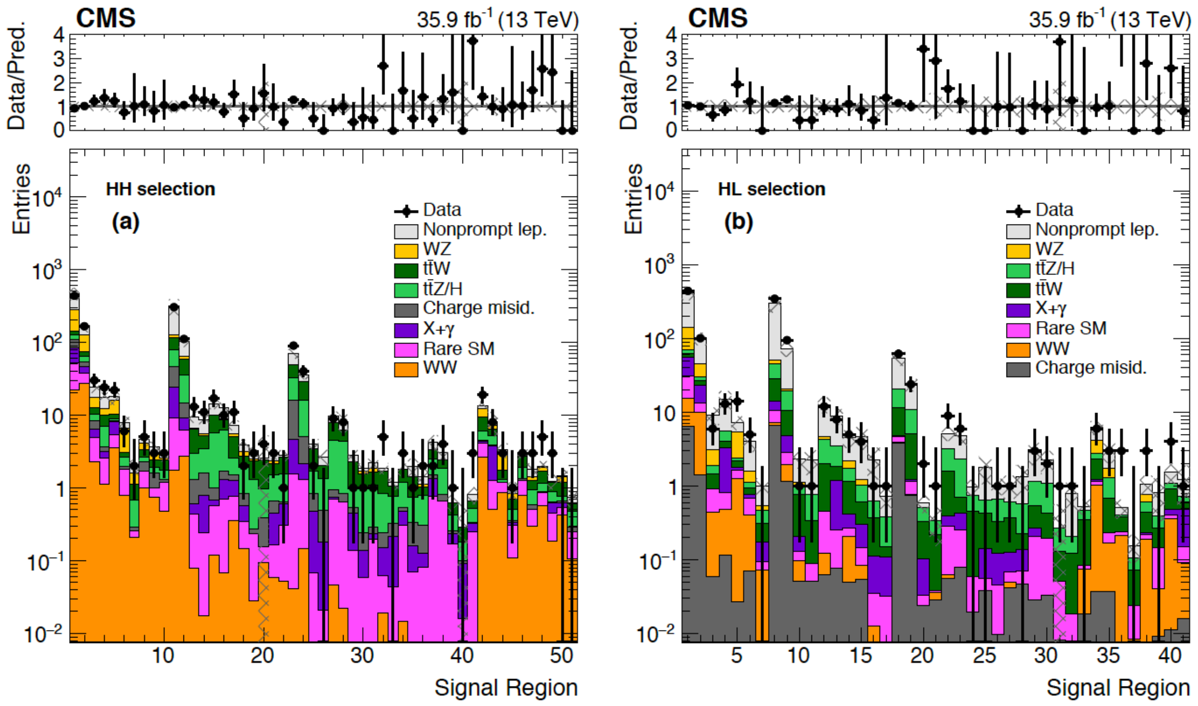
Interpret with heavy (pseudo) scalar model

Events selected with at least 2 jets and moderate missing energy

Categorization depending on lepton p_T, transverse mass, missing energy, H_T and number of jets and b-tagged jets



Top quark final states (CMS) arxiv: 1704.07323



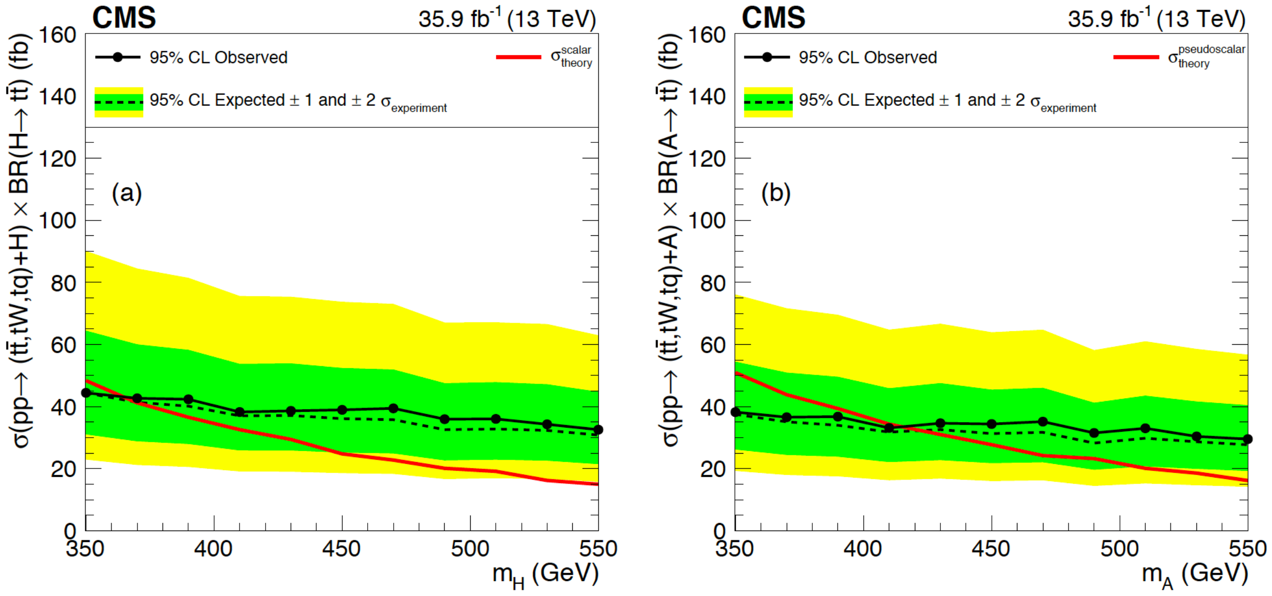
Source	Typical uncertainty (%)
Integrated luminosity	2.5
Lepton selection	4 – 10
Trigger efficiency	2 – 7
Pileup	0 – 6
Jet energy scale	1 – 15
b tagging	1 – 15
Simulated sample size	1 – 10
Scale and PDF variations	10 – 20
WZ (normalization)	12
$t\bar{t}Z$ (normalization)	30
Nonprompt leptons	30 – 60
Charge misidentification	20

Main backgrounds:

Prompt SS dileptons

Events with a non-prompt lepton

Opposite-sign dilepton events with a charge-misidentified lepton



Summary and other results

Channel	ATLAS	2016 Lumi	CMS	2016 lumi
Diphoton	arXiv:1707.04147	36.7	PLB. 767, 147-170	16.2
$Z\gamma$	arXiv:1708.00212	36.1	CMS leptonic, CMS hadronic	2.7
4l	ATLAS-CONF-2017-058	36.1	arxiv: 1706.09936	35.9
tt	ATLAS-CONF-2016-104	13.2	arxiv: 1704.07323	35.9
A→Zh	ATLAS-CONF-2017-055	36.1		
$H^{\pm}\rightarrow\tau\nu$	ATLAS-CONF-2016-088	14.7	HIG-16-031	12.9
Doubly charged Higgs →2/3/4 l	arxiv:1710.09748	36.1	CMS-PAS-HIG-16-036	12.9
WW (ll$\nu\nu$)	arXiv:1710.01123	36.1		
H→WW/ZZ($\nu\nu$qq, llqq, qqqq)	arXiv:1708.09638	36.1		
H→WW(lνqq)	arxiv 1710.07235	36.1		
H/Z→$\tau\tau$	arXiv:1709.07242	36.1	HIG-16-037-pas	12.9
$H^{\pm}\rightarrow W^{\pm}Z$			arXiv:1705.02942	15.2
$H^{\pm}\rightarrow$tb	ATLAS-CONF-2016-089	13.2		

Conclusion

The ATLAS and CMS experiments are actively pursuing the search for additional bosons

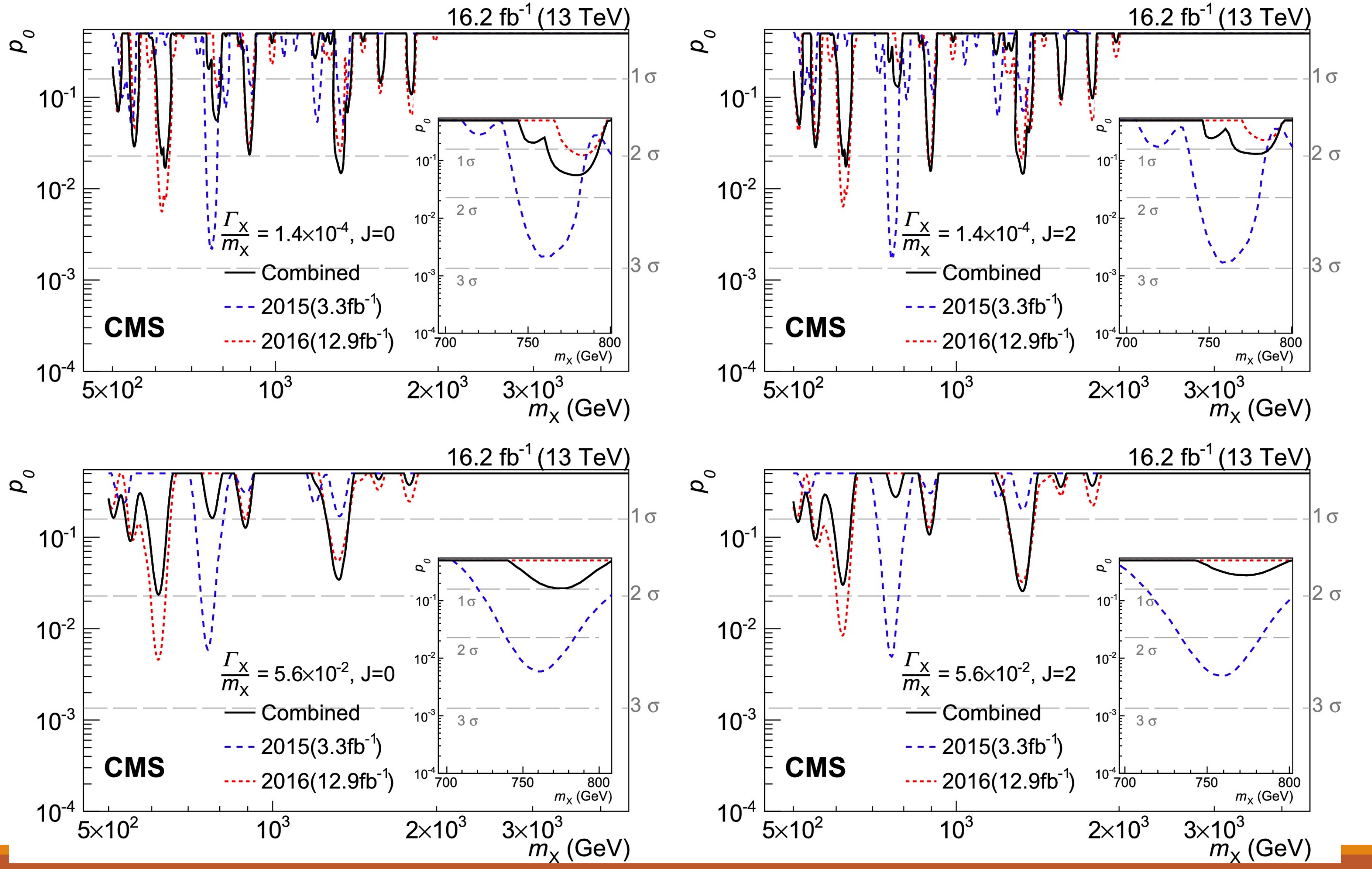
This includes the searches for CP even, CP odd spin 0 bosons and charged bosons

Significant improvement of sensitivity with full 2015+2016 datasets compared to run I

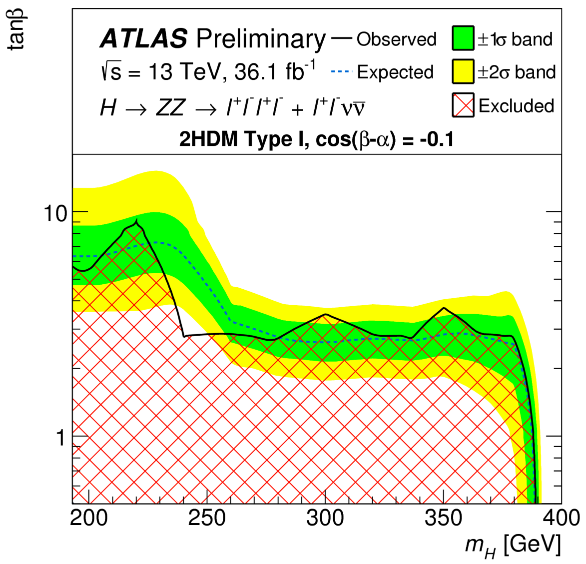
A lot of new data will be available by the end of 2018, stay tuned.

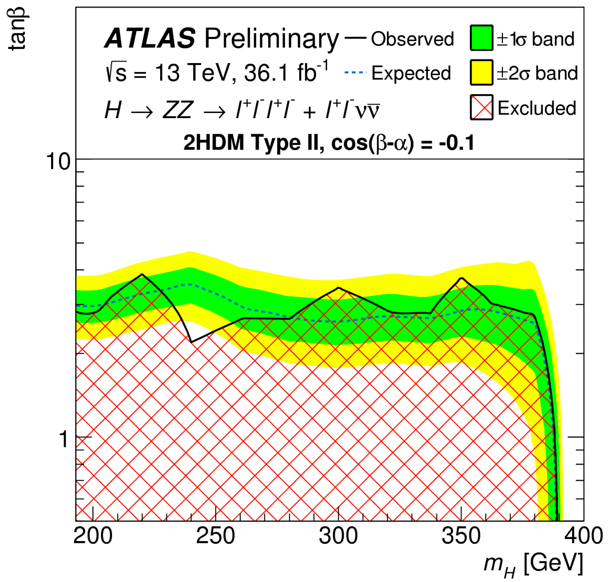
Back up

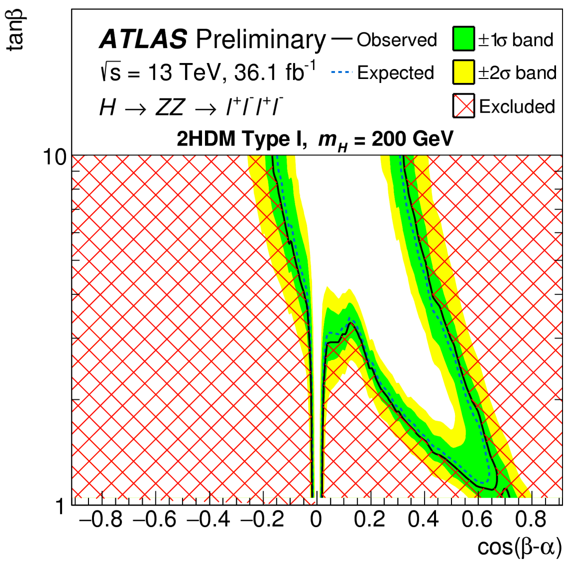
CMS Diphoton scan

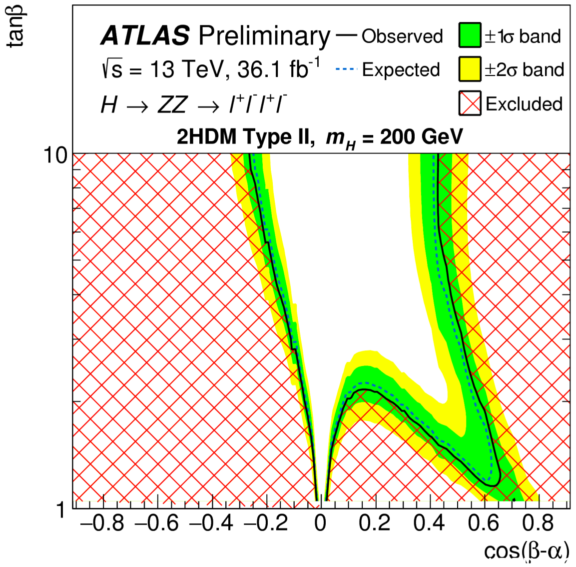


ATLAS 4l constraint on the 2HDM model









H → WW→ lνqq (ATLAS)

MC details:

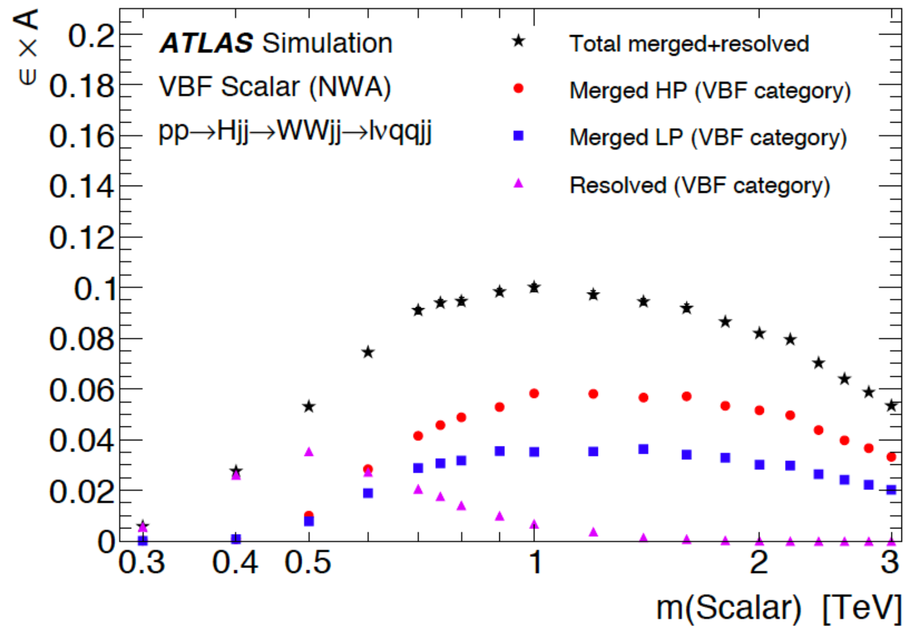
Powheg-Box_v1, NLO, for ggH and VBF

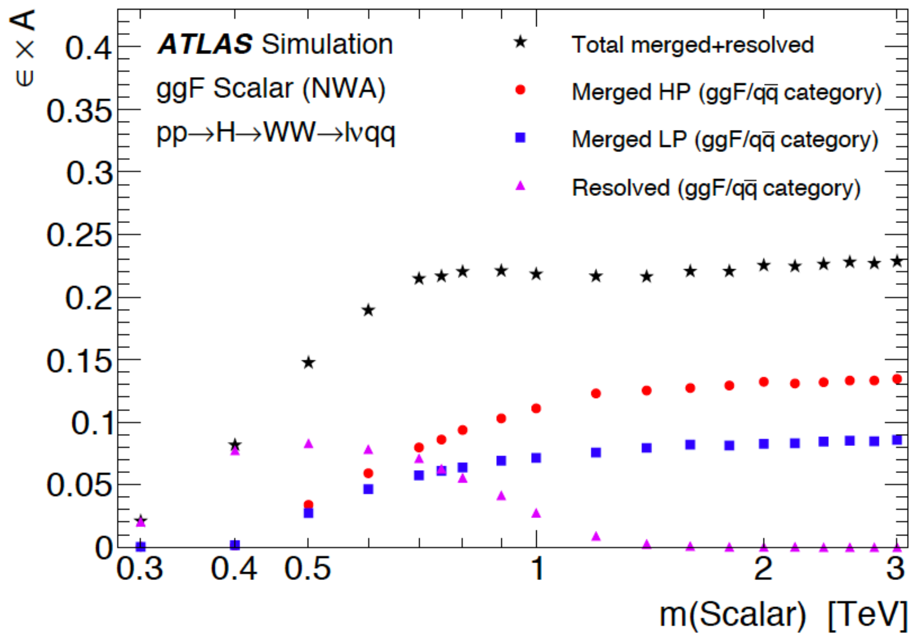
Neglect interference and with narrow width

Leading systematics:

VBF Category			
$m(Z') = 1200$ GeV		$m(W') = 500$ GeV	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
MC statistical uncertainty	15	MC statistical uncertainty	16
Large-R jets mass resolution	5	W+jets: cross section	10
W+jets: PDF choice	5	Multijet E_T^{miss} modelling	10
$t\bar{t}$: alternative generator	5	Small-R jets energy resolution	9
W+jets: cross section	5	SM diboson cross section	8
$t\bar{t}$: scales	4	$t\bar{t}$: cross section	7
Total systematic uncertainty	24	Total systematic uncertainty	40
Statistical uncertainty	52	Statistical uncertainty	30

ggF/$q\bar{q}$ Category			
$m(W') = 2000$ GeV		$m(Z') = 500$ GeV	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
MC statistical uncertainty	12	Large-R jets kinematics	17
W+jets: generator choice	8	MC statistical uncertainty	12
W+jets: scale	5	$t\bar{t}$: scale	11
SM diboson normalization	4	SM diboson cross section	10
Large-R jets mass resolution	4	W+jets: alternative generator	10
Large-R jets D_2 resolution	4	W+jets: scale	9
Total systematic uncertainty	20	Total systematic uncertainty	42
Statistical uncertainty	50	Statistical uncertainty	18





A → Zh (ATLAS)

Modelling:

ggF MadGraph5_aMC@NLO 2.2.2 at LO accuracy, NWA

bbA MadGraph5_aMC@NLO 2.2.3 using NLO matrix elements with massive b-quarks, NWA

The cross-sections are calculated using up to NNLO QCD corrections for gluon fusion and b-quark associated production in the five-flavour scheme as implemented in Sushi. For the b-quark associated production a cross-section in the four-flavour scheme is also calculated and combined with the five-flavour scheme calculation.

$m(H^{\pm})=m(H)=m(A)$

A → Zh (ATLAS)

variable	Resolved	Merged
Common selections		
number of jets	≥2 small-R jets (==2 or 3 1-lep.)	≥1 large-R jet
leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_J [GeV]	110–140 (0,1-lep.), 100–145 (2-lep.)	75–145
0-lepton selection		
E_T^{miss} [GeV]	> 150	> 200
$\sum p_T^{jet_i}$ [GeV]	> 150 $(120^{(*)})$	–
$\Delta\phi(j, j)$	$< 7\pi/9$	–
p_T^{miss} [GeV]	> 30	
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss})$	$< \pi/2$	
$\Delta\phi(\vec{E}_T^{miss}, h)$	$> 2\pi/3$	
min[$\Delta\phi(\vec{E}_T^{miss}$, small-$R$ jet)]	$> \pi/9$ (2 or 3 jets) , $> \pi/6$ (≥ 4 jets)	
$N_{\tau_{had}}$	0 **	
1-lepton selection		
leading lepton p_T [GeV]	> 27	> 27
E_T^{miss} [GeV]	$> 40(80^{(\ddagger)})$	> 100
p_T^W [GeV]	$> \max[150,\ 710 - 3.3 \cdot 10^5\ \text{GeV}/m_{Vh}]$	$> \max[150,\ 394 \cdot \ln(m_{Vh}/1\ \text{GeV}) - 2350]$
$m_T(W)$ [GeV]	<300	
2-lepton selection		
leading lepton p_T [GeV]	> 27	> 27
sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss}/\sqrt{H_T}$ [$\sqrt{\text{GeV}}$]	$< 1.15 + 8 \cdot 10^{-3}\ m_{Vh}/1\ \text{GeV}$	
$p_{T,\ell\ell}$ [GeV]	$> 20 + 9 \cdot \sqrt{m_{Vh}/1\text{GeV} - 320}^{\ddagger\ddagger}$	
$m_{\ell\ell}$ [GeV]	[87 - 0.030 · m_{Vh}/1 GeV, 97 + 0.013 · m_{Vh}/1 GeV]	

W, Z + jets are separated by different flavor for fitting

2-lepton: tt control region, eμ channel

Process	quantity/source	value
signal	acceptance	3-7%
SM Vh, $t\bar{t}V$, $t\bar{t}h$	norm.	50%
diboson	norm.	11%
multijet (1-lep.)	norm.	50%
	template method	S
single top	norm.	19%
	resolved / merged	24%
	m_{jj} SR / m_{jj} CR (1-lep.)	7%
$t\bar{t}$	resolved / merged	15-45%
	m_{jj} SR / m_{jj} CR (1-lep.)	7%
	SR / $e\mu$ CR (2-lep.)	2%
	PS, ISR/FSR, ME	S
	p_T reweight	S
Z+(bb, bc, cc)	resolved / merged	19%
	0-lep. / 2-lep.	15%
	generator, PDF, scale	S
Z+(bl, cl)	resolved / merged	28%
	0-lep. / 2-lep.	12%
	generator, PDF, scale	S

Process	quantity/source	value
Z+l	norm.	19%
	resolved / merged	23%
	0-lep. / 2-lep.	8%
	generator, PDF, scale	S
W+(bb, bc, cc)	norm. (A,Z')	26%
	resolved / merged	18-43%
	m_{jj} SR / m_{jj} CR (1-lep.)	6%
	0-lep. / 1-lep.	26%
	generator, PDF, scale	S
W+(bl, cl)	norm. (A,Z')	23%
	resolved / merged	15-35%
	m_{jj} SR / m_{jj} CR (1-lep.)	5%
	0-lep. / 1-lep.	22%
	generator, PDF, scale	S
W+l	norm.	20-30%
	resolved / merged	16-20%
	m_{jj} SR / m_{jj} CR (1-lep.)	2%
	0-lep. / 1-lep.	19%
	generator, PDF, scale	S

$\tau\tau$ searches (CMS)

Systematics:

Luminosity 6.2%

2%-7% for trigger and lepton/tau ID

JES 1%-10%

B tagging 1%-5%

MET: 1%-3%

Background MC normalization, 4%-6%

Mis-ID among leptons: 10%-30%

OS/SS ratio of QCD, 4%, 12% for muon/electron, non-b-tagged region, 60% in b-tagged region

OS/SS ratio of W+jets, 8%-10%

High m_T to low m_T: 2% (non-b tagged) to 14%-17% (b tagged)

Full hadronic channel: QCD uncertainty 12%-20%

Full leptonic channel: QCD uncertainty 23%-34%

Factorization and renormalization scales: 15%-25%

SM Higgs and shape uncertainties

$\tau\tau$ searches (ATLAS)

Systematics:

Luminosity 3.2%

Tau ID 6%, trigger 3%-14%, ES: 2%-3%, e→tau 3%-14%

Background MC normalization, 5%-10%

Signal: 1%-4%

W jet-tau fake factor : 10% $|\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_{\text{had-vis}}}, \mathbf{E}_{\mathrm{T}}^{\text{miss}})|$ correction: 30%

MJ tau fake factor: 20% $|\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_{\text{had-vis}}}, \mathbf{E}_{\mathrm{T}}^{\text{miss}})|$ correction: 50%

Lepton fake factor: 5%-50%

Full hadronic channel MJ tau fake factor: 10%-50%

Full hadronic channel non MJ tau fake factor: 40%

H$^{\pm} \rightarrow \tau\nu$ (ATLAS)

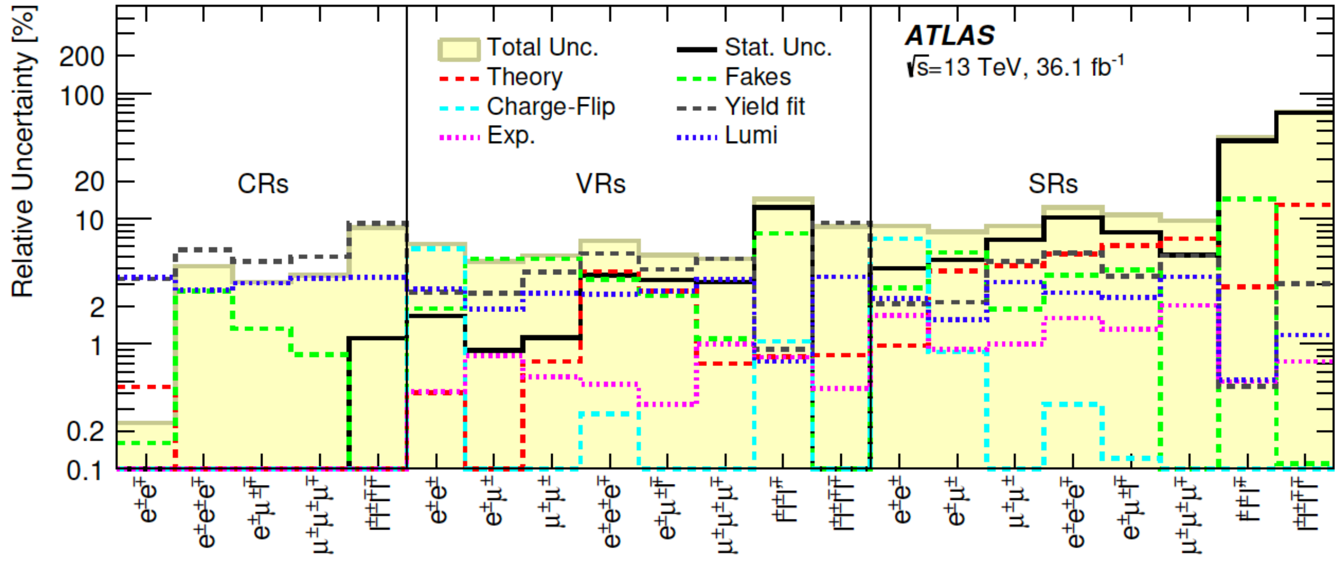
Source of systematic uncertainty	Impact on the expected limit (in %) $m_{H^+} = 200$ GeV	$m_{H^+} = 1000$ GeV
Experimental		
luminosity	1.5	0.9
trigger	< 0.1	< 0.1
$\tau_{\text{had-vis}}$	1.0	1.4
jet	3.0	0.2
$E_{\text{T}}^{\text{miss}}$	< 0.1	< 0.1
Fake factors	0.8	4.7
Signal and background models		
$t\bar{t}$ modelling	13.2	3.5
H^+ signal modelling	1.4	1.4

Doubly charged Higgs systematic uncertainties

CMS

Uncertainty source	Uncertainty
Luminosity	0.6-6.2%
Trigger	0.5%
Pileup	$< 0.1\%$
Electron identification	0.1-3.3%
Muon identification	0.1-1.7%
Tau identification	0.5-4.6%
Charge identification	0.4-6.5%
Signal cross section	3-14%
Background estimation method	10-100%

ATLAS



CMS tt heavy Higgs categories (HH)

N_b	m_T^{min} (GeV)	E_T^{miss} (GeV)	N_{jets}	$H_T < 300$ GeV	$H_T \in [300, 1125]$ GeV	$H_T \in [1125, 1300]$ GeV	$H_T \in [1300, 1600]$ GeV	$H_T > 1600$ GeV
0	<120	50 – 200	2-4	SR1	SR2	SR46 (++) / SR47 (−−)	SR48 (++) / SR49 (−−)	SR50 (++) / SR51 (−−)
			≥5	SR3	SR4			
		200 – 300	2-4		SR5 (++) / SR6 (−−)			
			≥5		SR7			
	>120	50 – 200	2-4		SR8 (++) / SR9 (−−)			
			≥5		SR10			
		200 – 300	2-4					
			≥5					
1	<120	50 – 200	2-4	SR11	SR12			
			≥5	SR13 (++) / SR14 (−−)	SR15 (++) / SR16 (−−)			
		200 – 300	2-4		SR17 (++) / SR18 (−−)			
			≥5		SR19			
	>120	50 – 200	2-4		SR20 (++) / SR21 (−−)			
			≥5		SR22			
		200 – 300	2-4					
			≥5					
2	<120	50 – 200	2-4	SR23	SR24			
			≥5	SR25 (++) / SR26 (−−)	SR27 (++) / SR28 (−−)			
		200 – 300	2-4		SR29 (++) / SR30 (−−)			
			≥5		SR31			
	>120	50 – 200	2-4		SR32 (++) / SR33 (−−)			
			≥5		SR34			
		200 – 300	2-4					
			≥5					
≥3	<120	50 – 200	≥2	SR35 (++) / SR36 (−−)	SR37 (++) / SR38 (−−)			
		200 – 300			SR39			
	>120	50 – 300	≥2	SR40	SR41			
inclusive	inclusive	300 – 500	≥2	—	SR42 (++) / SR43 (−−)			
		>500		—	SR44 (++) / SR45 (−−)			

CMS tt background estimation

3 leptons control region to fit the N b-tagged jets distribution

Non-prompt leptons: tight-to-loose method, using single non-prompt lepton region suppressing W+jets to get the extrapolation factor and applied on loose-non-tight control region

Charge mis-ID: OS region apply the SS/OS ratio from the simulation

H→WW→eνμν arXiv:1710.01123

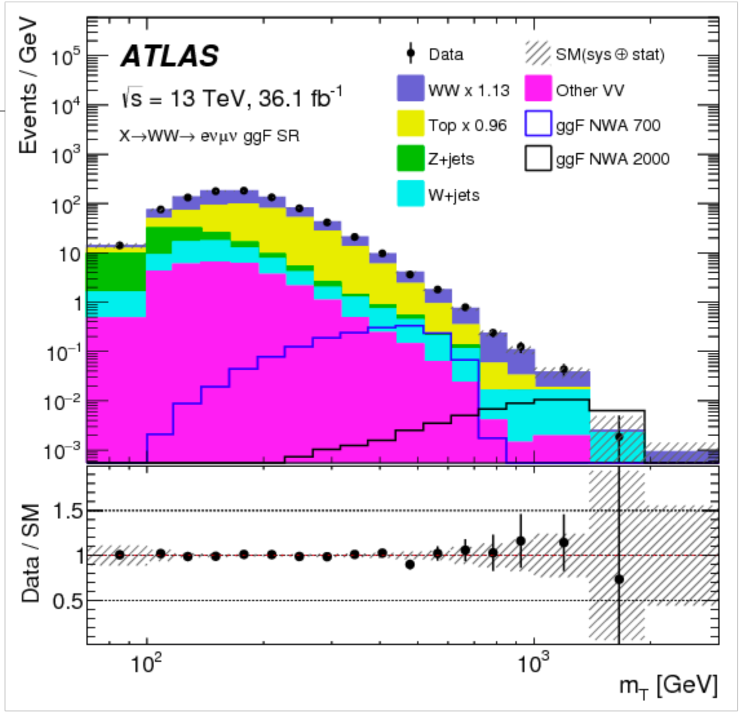
ATLAS 36.1fb^{-1}

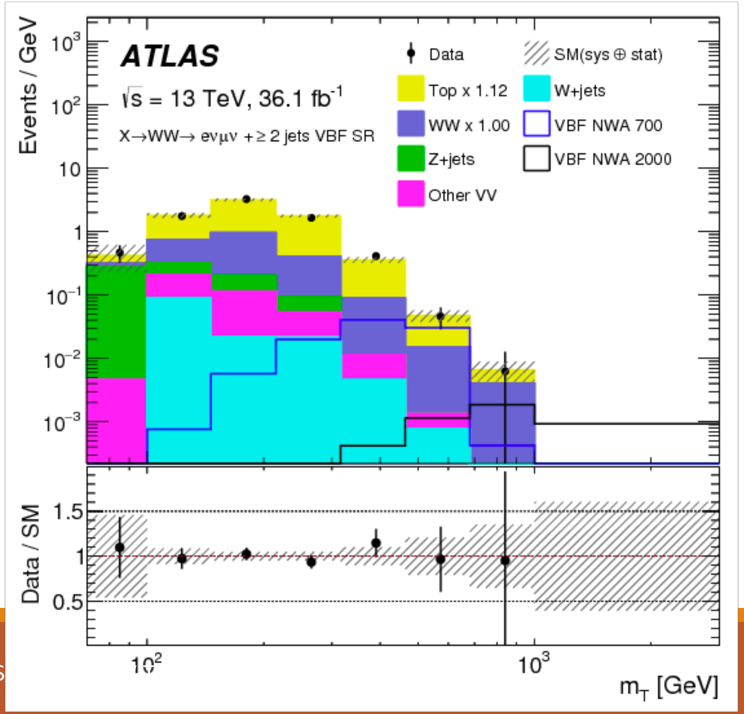
WW to opposite sign opposite flavor dilepton channel

Testing NWA, LWA, Spin 2 and 2HDM models

Model	Resonance spin	Production mode ggF	Production mode qqA	Production mode VBF
NWA	Spin-0	x		x
2HDM		x		x
LWA		x		x
GM				x
HVT	Spin-1		x	x
Bulk RS	Spin-2	x		
ELM				x

$\mathrm{SR_{ggF}}$	$\mathrm{SR_{VBF1J}}$	$\mathrm{SR_{VBF2J}}$
Common selections		
$N_{b\text{-tag}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ $m_{\ell\ell} > 55$ GeV $p_{\mathrm{T}}^{\ell,\mathrm{lead}} > 45$ GeV $p_{\mathrm{T}}^{\ell,\mathrm{sublead}} > 30$ GeV veto if $p_{\mathrm{T}}^{\ell,\mathrm{other}} > 15$ GeV $\max(m_{\mathrm{T}}^{W}) > 50$ GeV		
ggF phase space	VBF1J phase space	VBF2J phase space
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{\mathrm{jet}} = 1$ and $\lvert\eta_j\rvert > 2.4$, $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{\mathrm{jet}} \geq 2$ and $m_{jj} > 500$ GeV, $\lvert\Delta y_{jj}\rvert > 4$

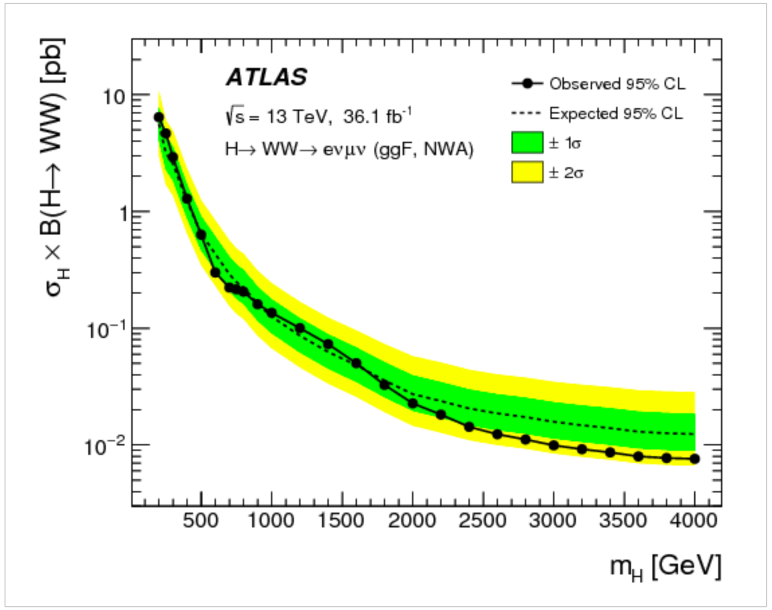


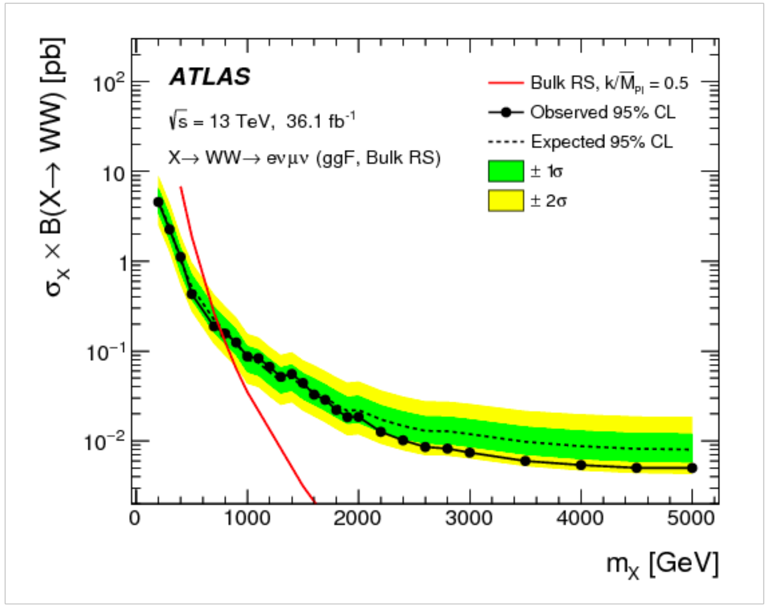


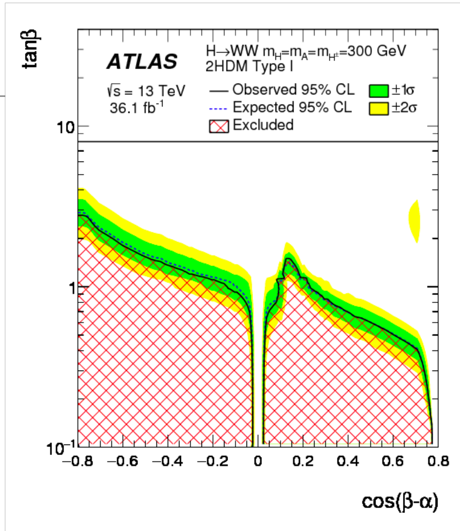
$H \to WW \to e\nu\mu\nu$

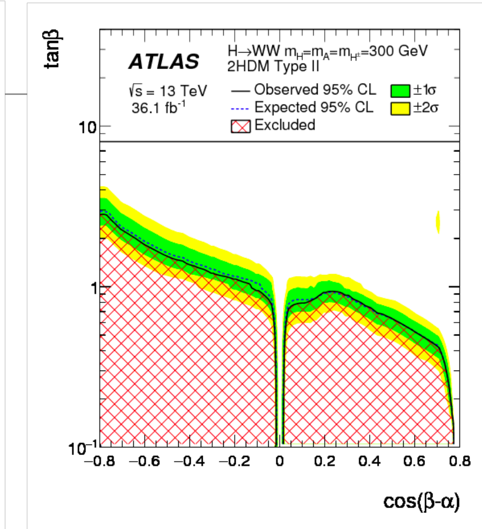
Various interpretation tested

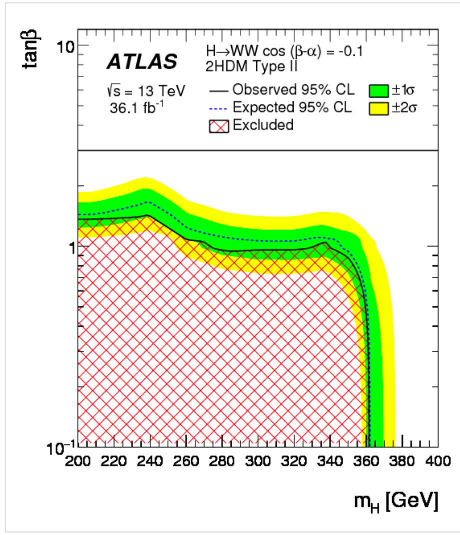
Limits set to up to 5TeV

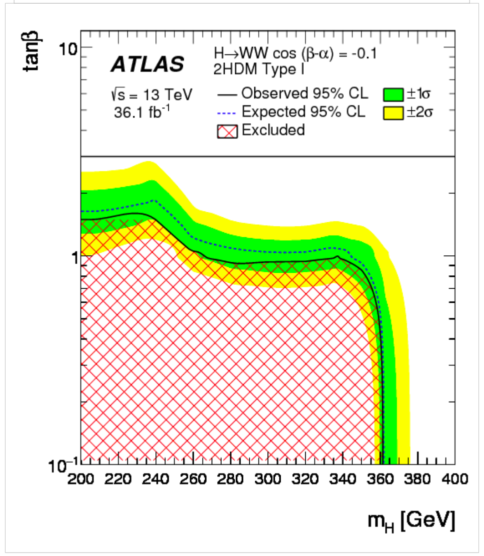




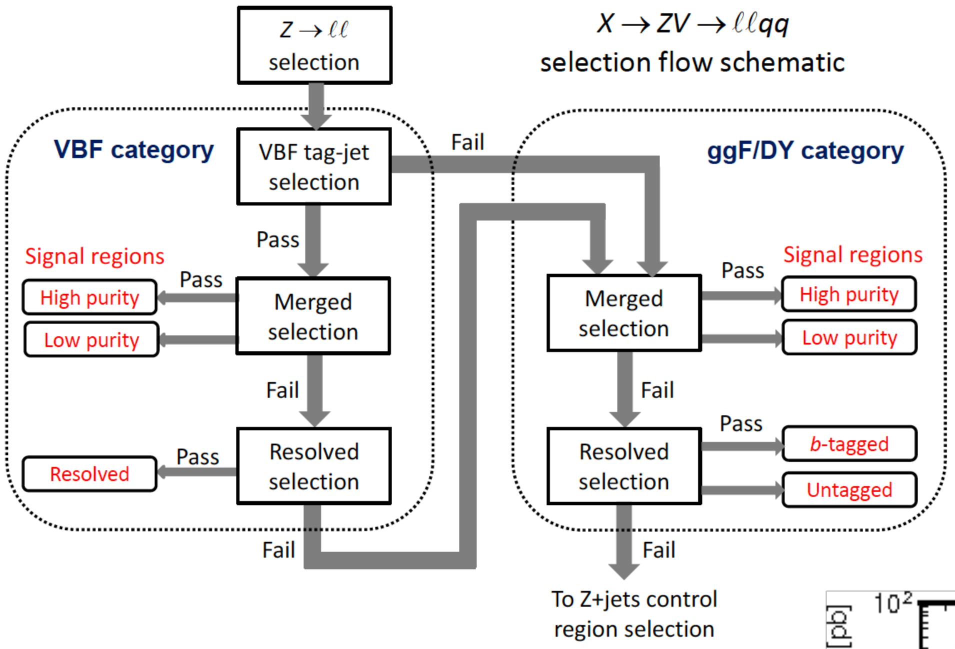


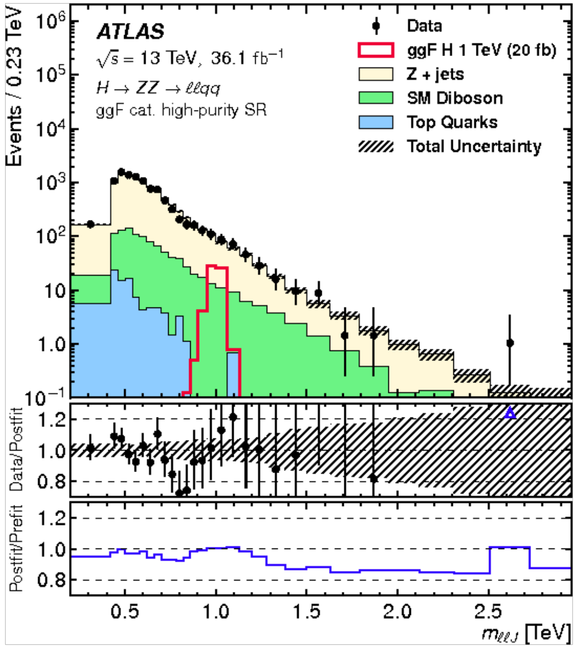


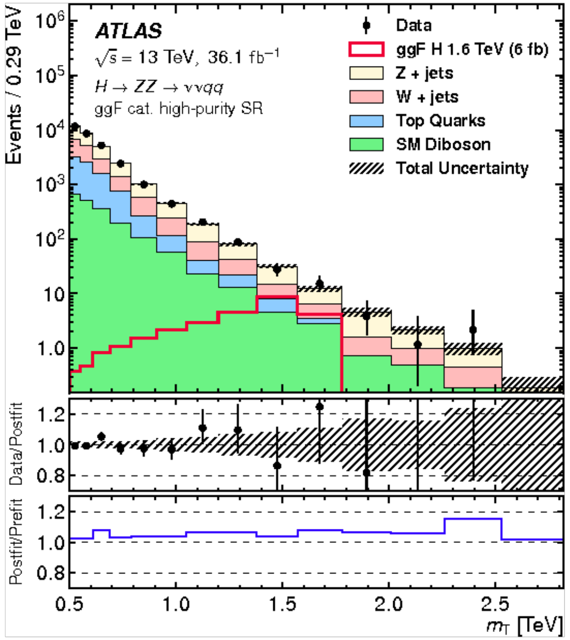




H→ZW, ZZ→$\nu\nu$qq, llqq arXiv:1708.09638





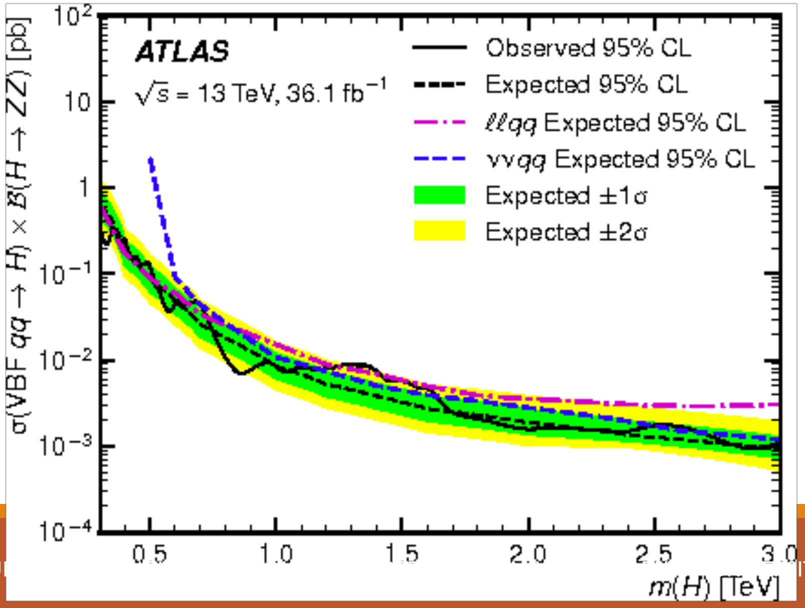


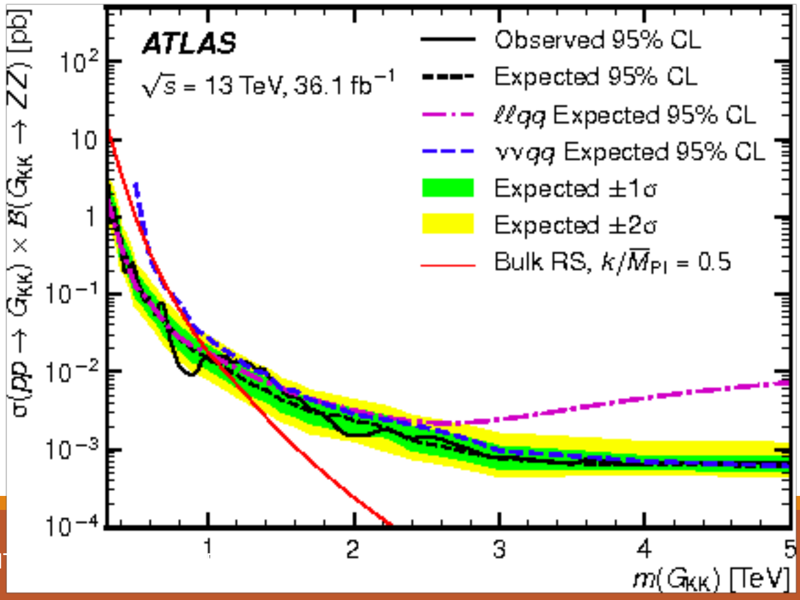
Z(ll)Z/W(jj), Z(ll)Z($\nu\nu$) channel

Spin-0 H, Spin-1 HVT, Spin-2 KK graviton model tested

Early study on more channels

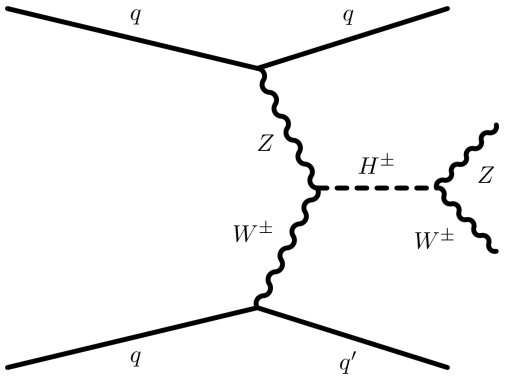
Link





Charged Higgs →3l

CMS-HIG-16-027



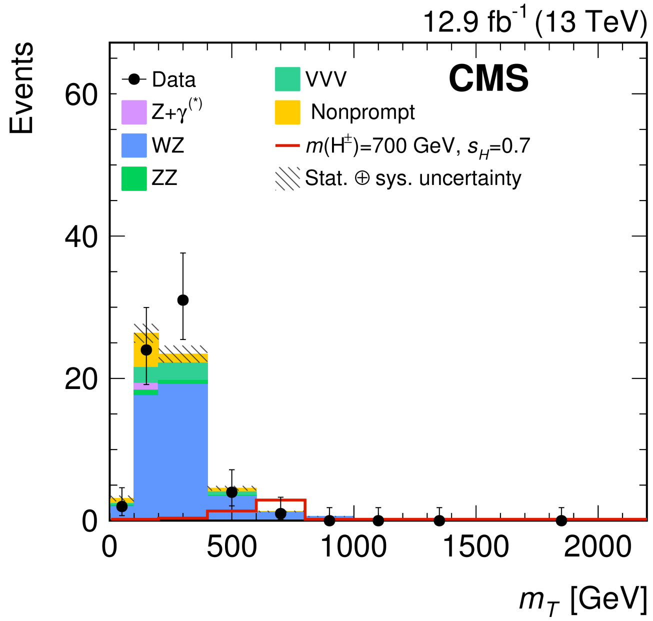
Georgi–Machacek model

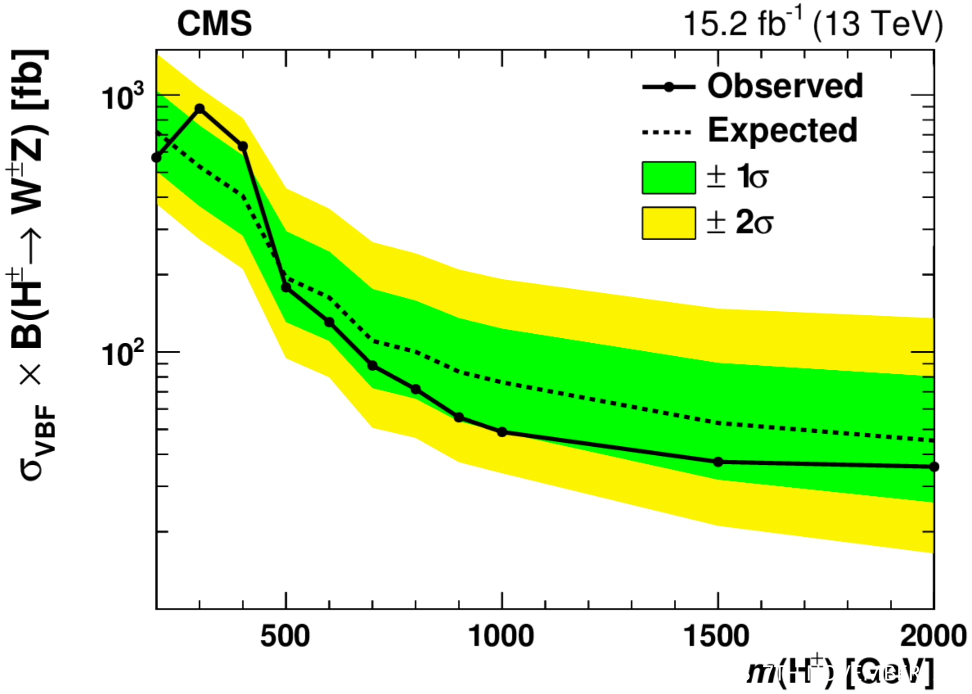
Exactly 3 leptons final states

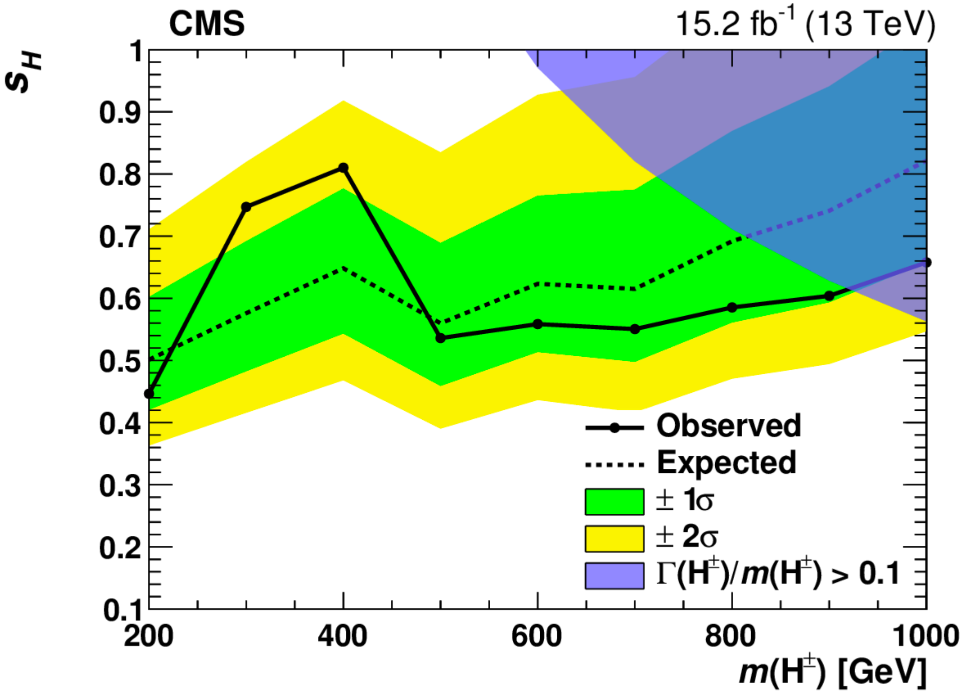
Two forward jets and VBF signature

Transverse mass as final discrimination

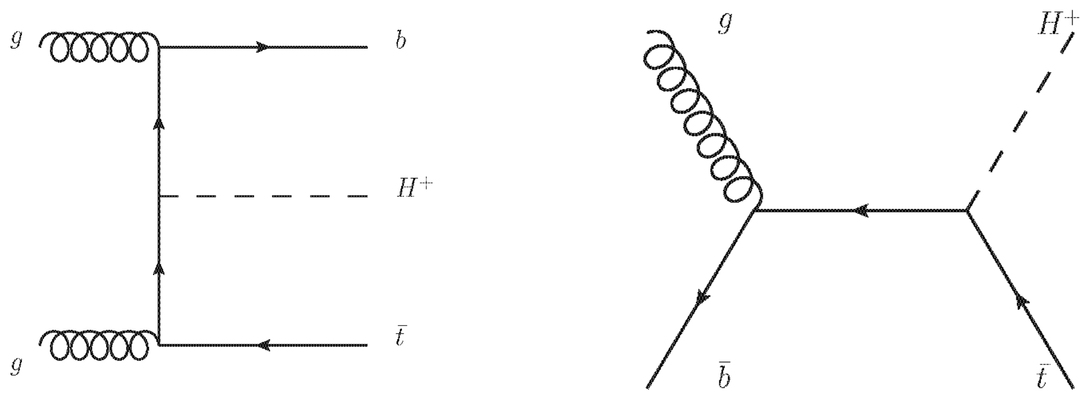
$$m_{\mathrm{T}}(\mathrm{WZ}) = \sqrt{(E_{\mathrm{T}}(\mathrm{W}) + E_{\mathrm{T}}(\mathrm{Z}))^2 - (\vec{p}_{\mathrm{T}}(\mathrm{W}) + \vec{p}_{\mathrm{T}}(\mathrm{Z}))^2},$$

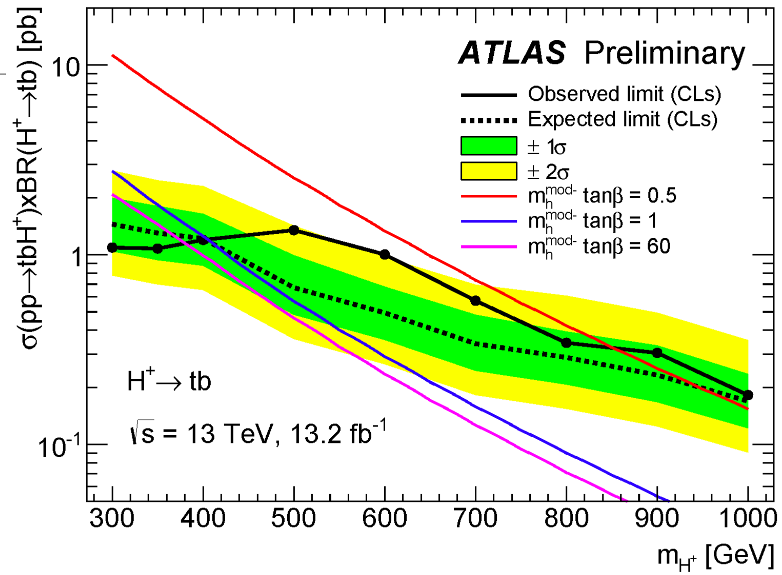






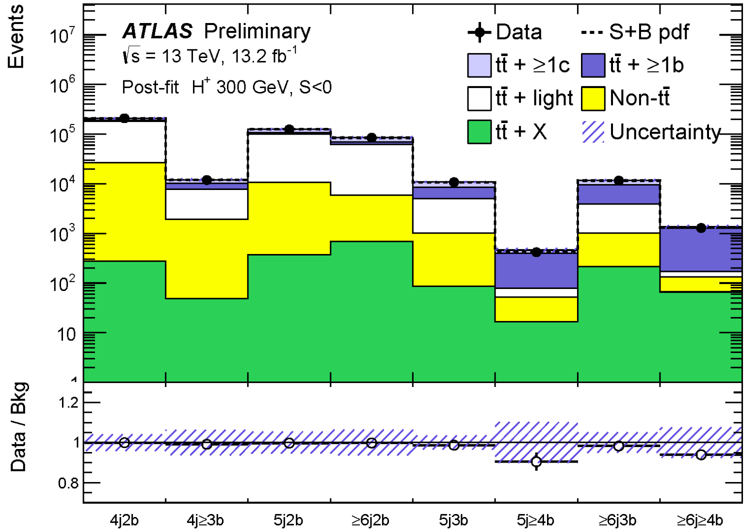
H+→tb ATLAS-CONF-2016-089

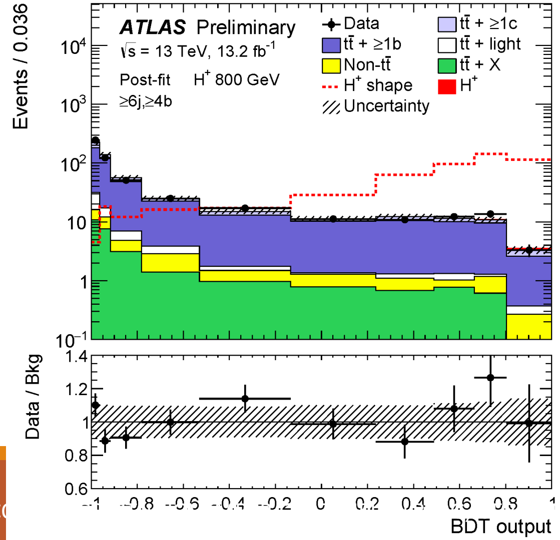


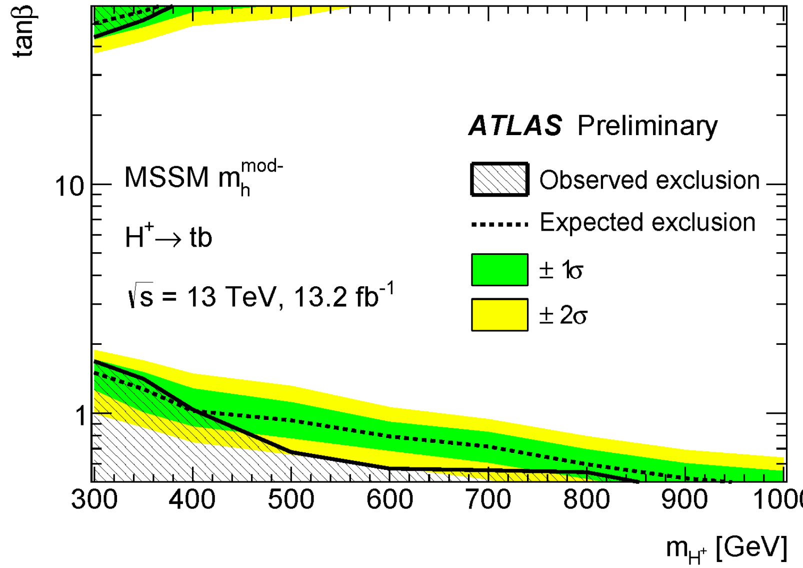


Top association production, decay to top and b quark, at least 1 lepton final state

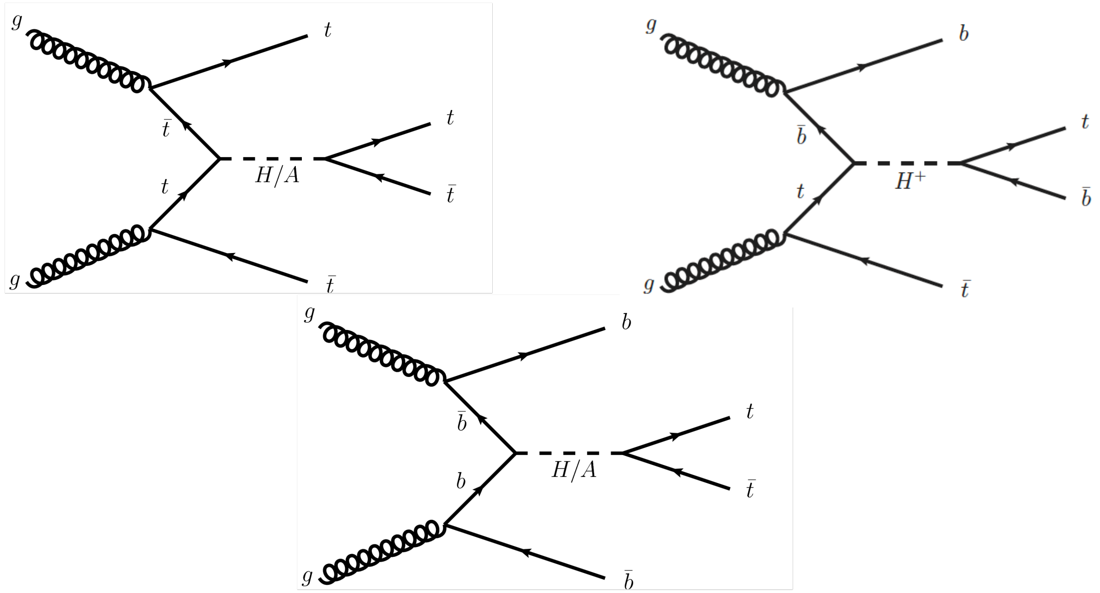
Categorized using number of jets , b jets, using MVA method

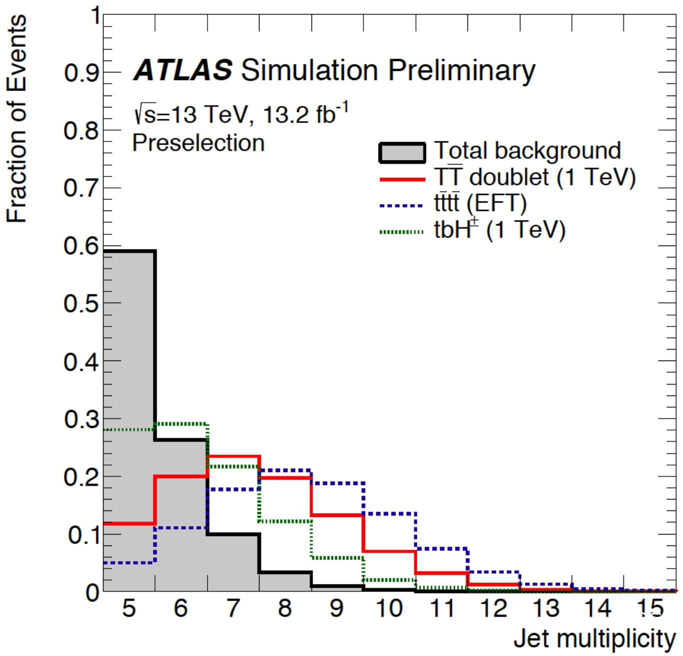






Top quark final states ATLAS-CONF-2016-104





Heavy resonance generated in association with b or t quarks, and decays to b or t quarks

Expect events with large number of jets, leptons and missing energy

Categorize events into 0 lepton and 1 lepton categories

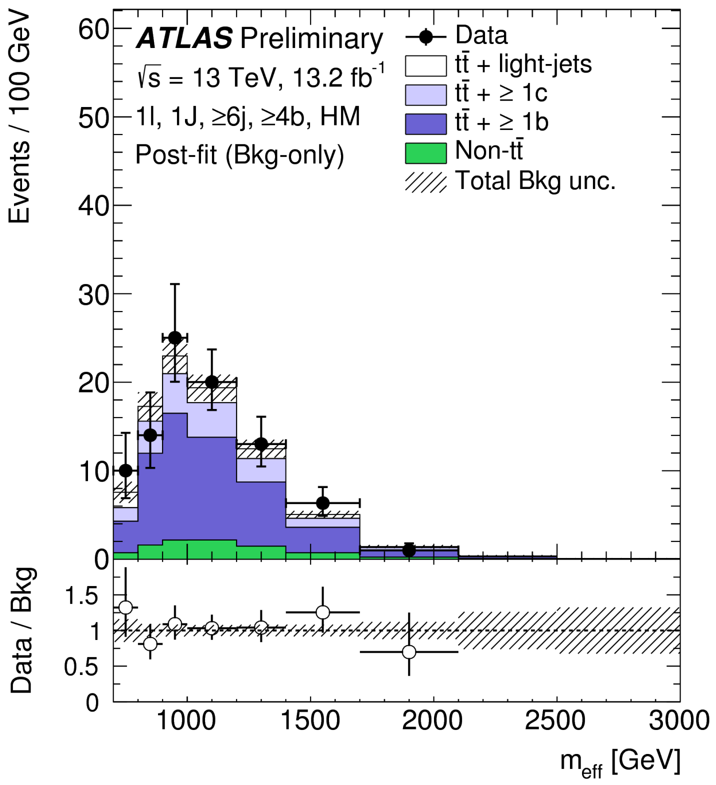
Small-R and large R jets are used, large R jets are defined:

$$p_{\mathrm{T}} > 300\ \mathrm{GeV},\ |\eta| < 2.0\ \text{and mass above } 100\ \mathrm{GeV}$$

Preselection requirements

Requirement	1-lepton channel	0-lepton channel
Trigger	Single-lepton trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
Leptons	=1 isolated e or μ	=0 isolated e or μ
Jets	≥5 jets	≥6 jets
b-tagging	≥2 b-tagged jets	≥2 b-tagged jets
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
Other $E_{\mathrm{T}}^{\mathrm{miss}}$-related	$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV	$\Delta\phi_{\mathrm{min}}^{4j} > 0.4$

Top quark final states (ATLAS)

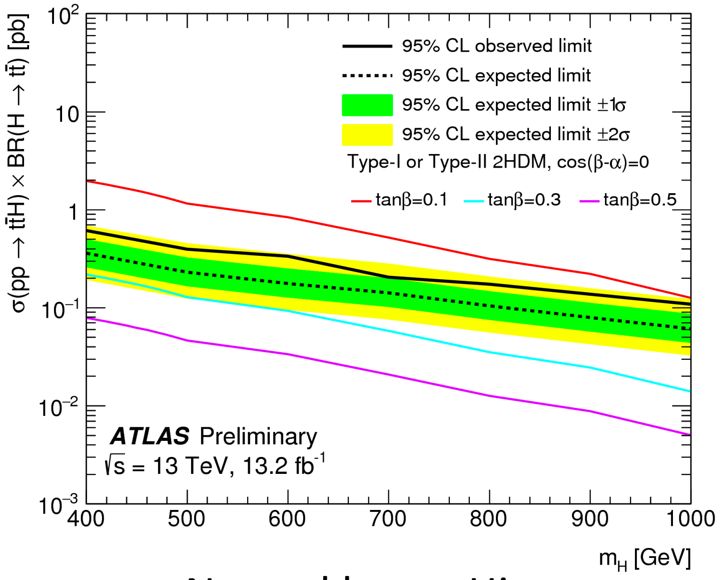


Search regions (≥6 jets)			
Mass-tagged jet multiplicity	b-jet multiplicity	$m_{bb}^{\min\Delta R}$	m_{eff}
0	3	-	> 400 GeV
0	≥4	-	> 400 GeV
1	3	< 100 GeV	> 700 GeV
1	3	> 100 GeV	> 700 GeV
1	≥4	< 100 GeV	> 700 GeV
1	≥4	> 100 GeV	> 700 GeV
≥2	3	-	-
≥2	≥4	-	-

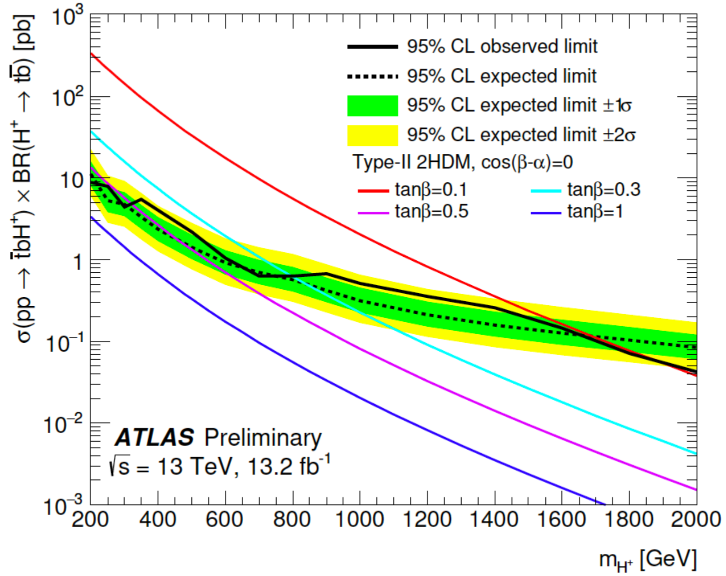
Background modelling:

- Dominant background is made of tt, single top, which are estimated from MC simulation normalized to theoretical cross-sections
- Multi jet background is estimated with a data-driven method

M_{eff} (scalar sum of hard jets, leptons, missing energy) is used as the discriminating variable



Neutral heavy Higgs



Charged heavy Higgs