BSM Higgs searches with ATLAS

Higgs Hunting 2016

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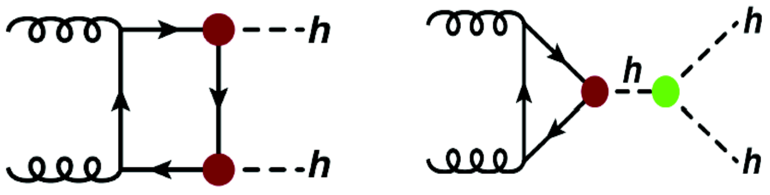
BSM Higgs Production

- 2 Higgs Doublet Models (2HDM) predict 5 physical bosons: *h*, *H* (CP=+1), *A* (CP=-1), H^+ and H^-

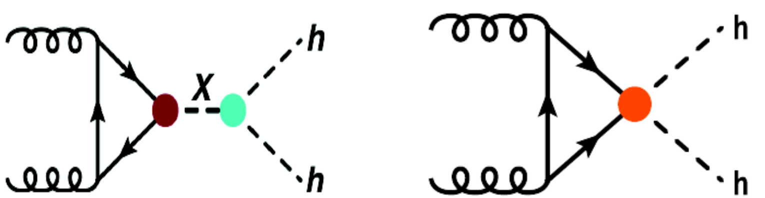
Family	Type-I	Type-II	Lepton-specific	Flipped	Type-III
u	Φ_2	Φ_2	Φ_2	Φ_1	Φ_1, Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1	Φ_1, Φ_2
e	Φ_2	Φ_2	Φ_1	Φ_2	Φ_1, Φ_2

- MSSM is a special case of type-II 2HDM, often used as benchmark. It can be described by two parameters at tree-level:
  - **tanβ**=$<\Phi_2>/<\Phi_1>$
  - **m_A** : mass of the CP-odd Higgs boson
- MSSM scenarios commonly used:
  - **m_h^{max}** (stop mixing yielding maximum m_h)
  - **$m_h^{mod\pm}$** (modified stop mixing)
  - **hMSSM**: m_h=125 GeV used as input to generate the rest of the phenomenology.

- **Di-higgs** production is very small in SM due to destructive interference:
  - 33.7 fb@pp,√s=13 TeV, non resonant

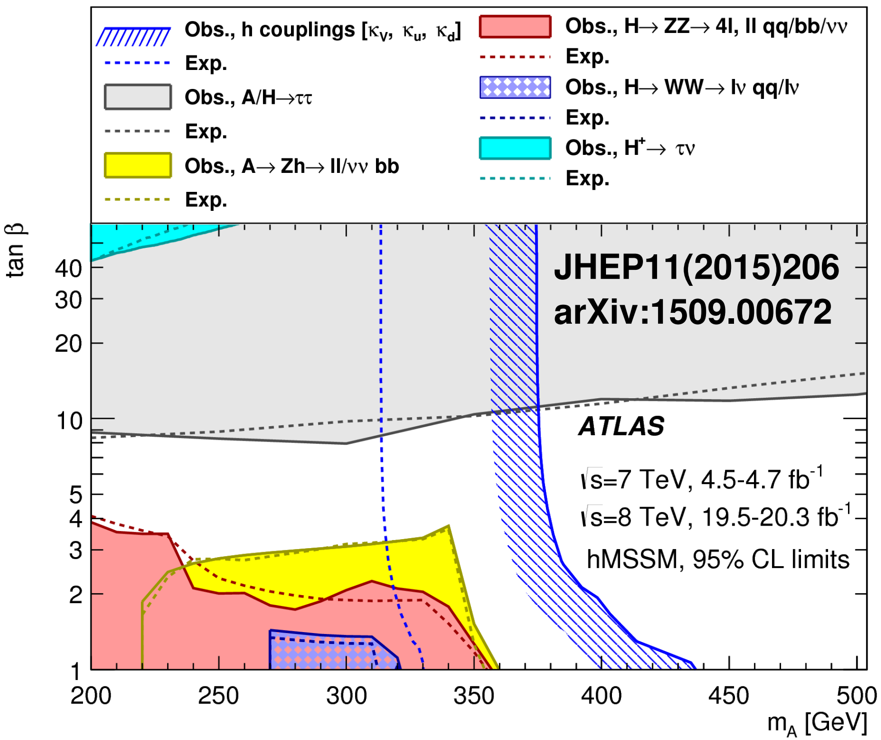


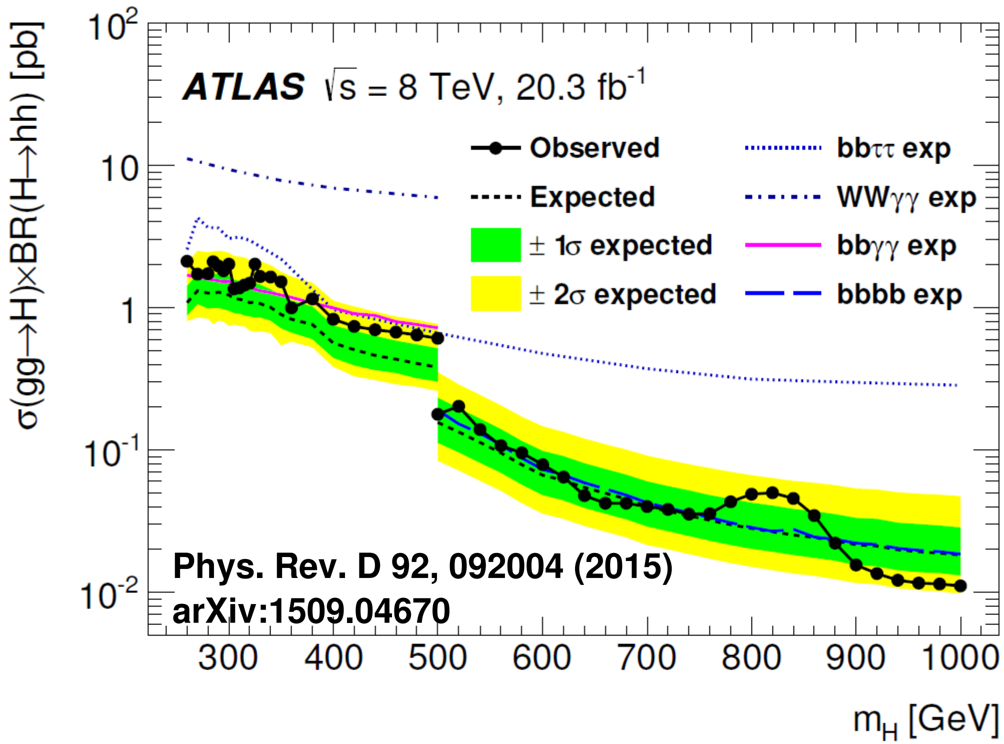
- In BSM, can be enhanced by:
  - Modified top Yukawa coupling or λ_{hhh} (**non-resonant production**).
  - **Resonant** production: 2HDM H→ hh, KK gravitons,....



Run-1 Results Summary

- Panorama at Higgs Hunting 2015
- MSSM: couplings to down-type fermions dominate for high tanβ, couplings to bosons and up-type fermions more important for low tanβ.
- di-Higgs: combined result of bbbb, bbγγ, bbττ and γγWW



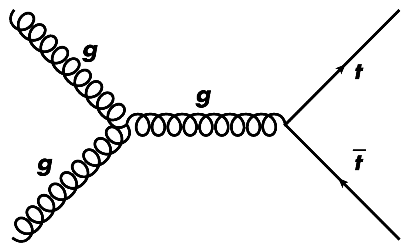


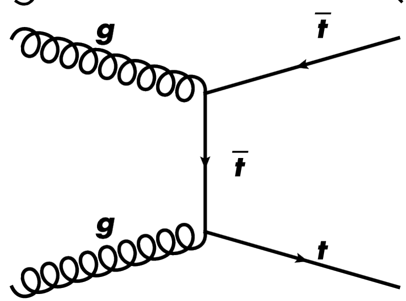
$H/A \rightarrow$ Fermions Search

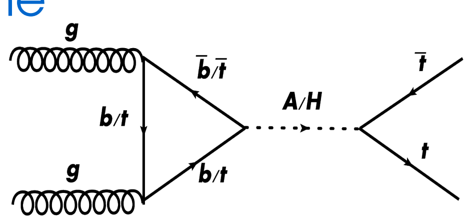
H/A → ttbar:

• Branching ratio is larger for low tanβ

• Interference between the signal and ttbar background production modes taken into account.







• Signal+Interference obtained from "**diagram subtraction**" and from "**diagram removal**" schemes (Madgraph modified to remove ttbar background diagrams).

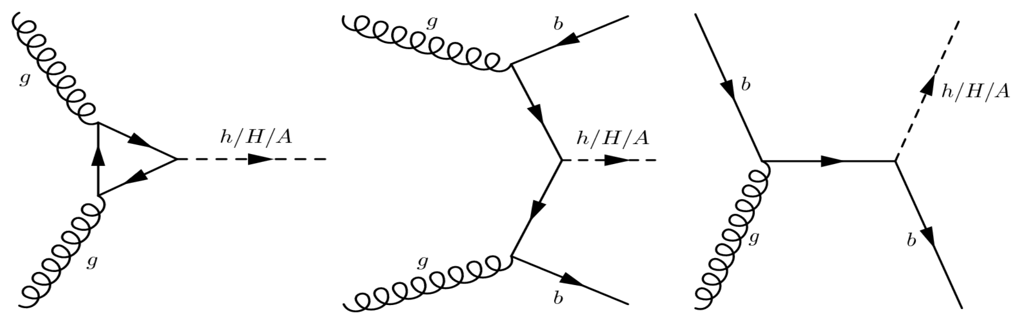
• Difference between the approaches taken as systematics: 0.4%

H/A → ττ:

• For $m_A >> m_Z$ (decoupling limit) the lightest scalar h has SM-like couplings;

• The heavier H/A bosons are almost degenerate in mass and coupling to *b* and τ is enhanced for high tanβ

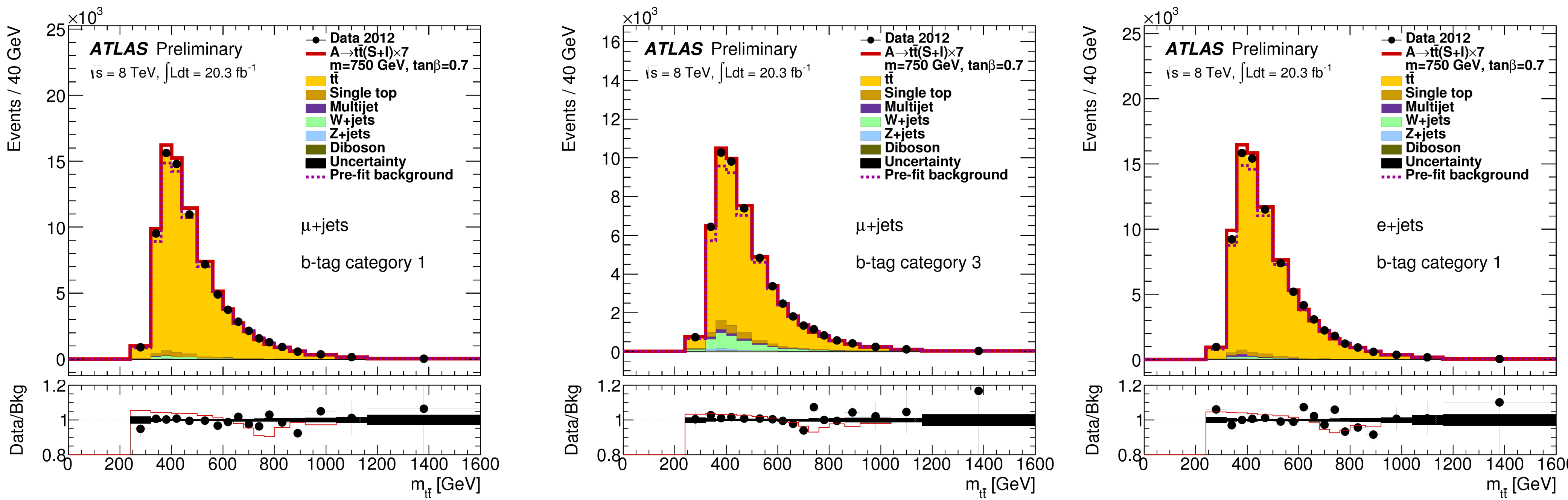
→ exploit *b*-tag and *b*-veto categories



$H,A \rightarrow$ ttbar Search

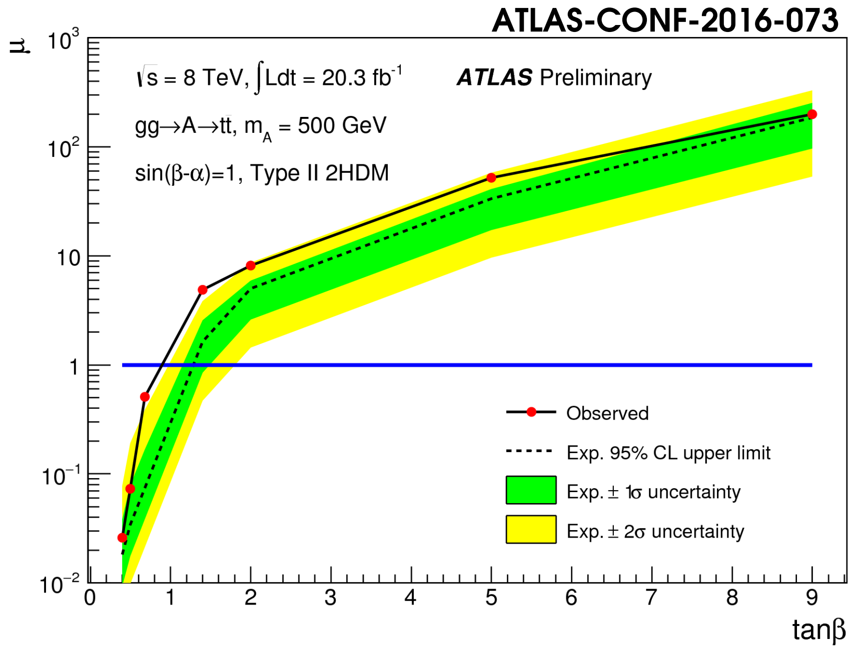
- **ATLAS-CONF-2016-073, 20.3 fb^{-1} of 8 TeV data**
- Revisit ATLAS Run-1 ttbar resonance search: JHEP 08 (2015) 148
- e,μ +jets final states, 3 *b*-tag categories for each final state.
- 4 jets, >= 1 b-tag jet, E_T^{miss} > 20 GeV, $E_T^{miss}+m_T$ > 60 GeV $\quad m_T^W = \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss} \cdot (1-\cos\phi_{\ell\nu})}$,
- Kinematic fit (χ^2) of the event (constraints on top and W masses)

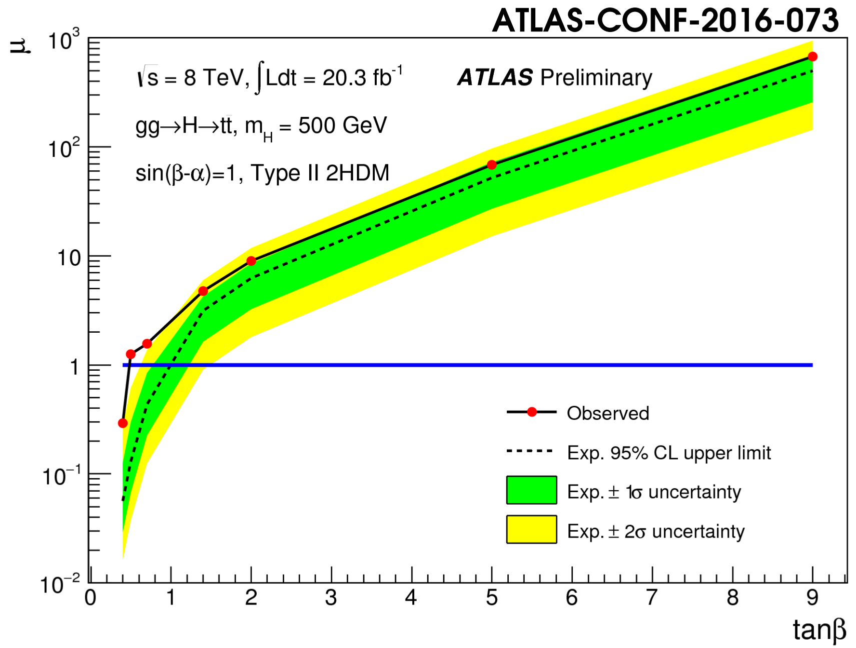
- **Main backgrounds**: ttbar and W+jets (the latter estimated from data).



$H,A \rightarrow$ ttbar Results

- Upper limits as a function of the parameter tanβ are set for a neutral scalar H and pseudoscalar A with benchmark masses of 500 GeV and 750 GeV.
- μ=1 corresponds to the signal strength in a Type-II 2HDM with sin(β–α)=1 and m_h= 125 GeV.

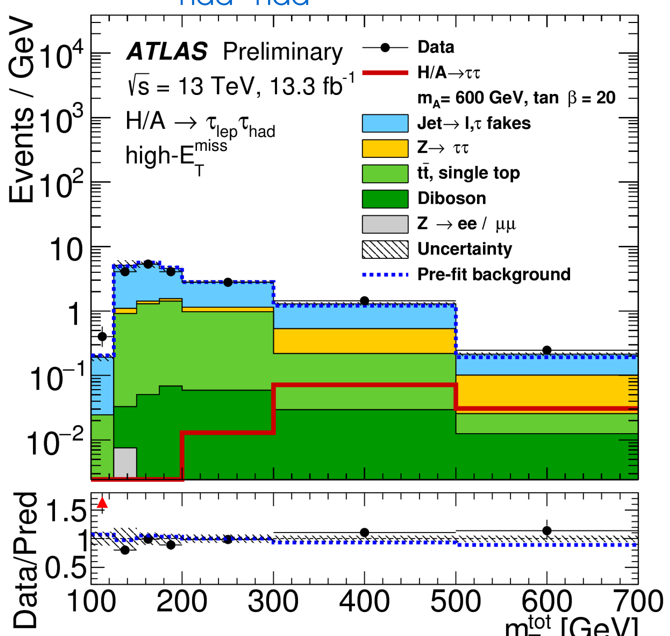


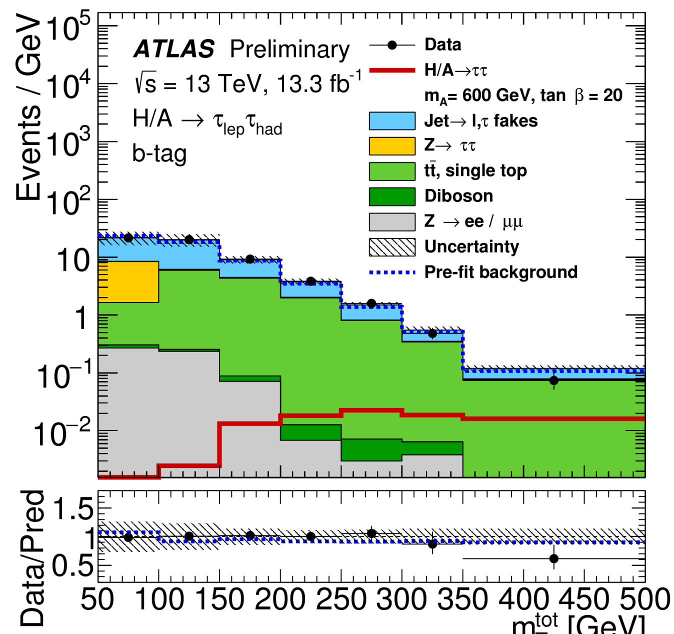


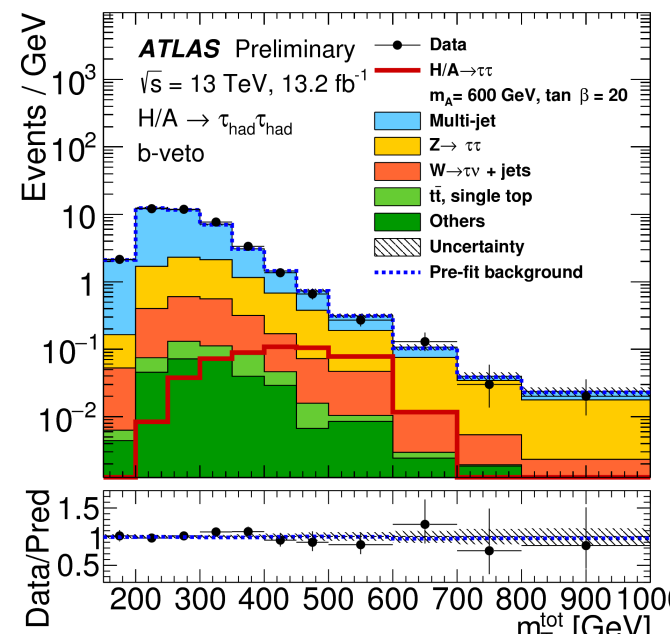
- tanβ < 0.85 and < 0.45 are excluded for m_A=500 GeV and m_H=500 GeV at 95% CL
- No tanβ values can be excluded for the higher mass point of 750 GeV.

$H/A \to \tau\tau$ Search

- **ATLAS-CONF-2016-085, <=13.3 fb^{-1} of 13 TeV data**
- $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels (they dominate the sensitivity at high mass)
- *b*-tag and *b*-veto categories. High-E_T^{miss} category also used for $\tau_{lep}\tau_{had}$
- m_T^{tot} variable used in both channels $m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_T^2(E_{\mathrm{T}}^{\mathrm{miss}},\tau_1) + m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}},\tau_2) + m_{\mathrm{T}}^2(\tau_1,\tau_2)},$
- **Backgrounds:**
  - $\tau_{lep}\tau_{had}$: multi-jet and W-jets/top estimated with data-driven methods.
  - $\tau_{had}\tau_{had}$: multi-jet and fake taus in other backgrounds: data-driven methods







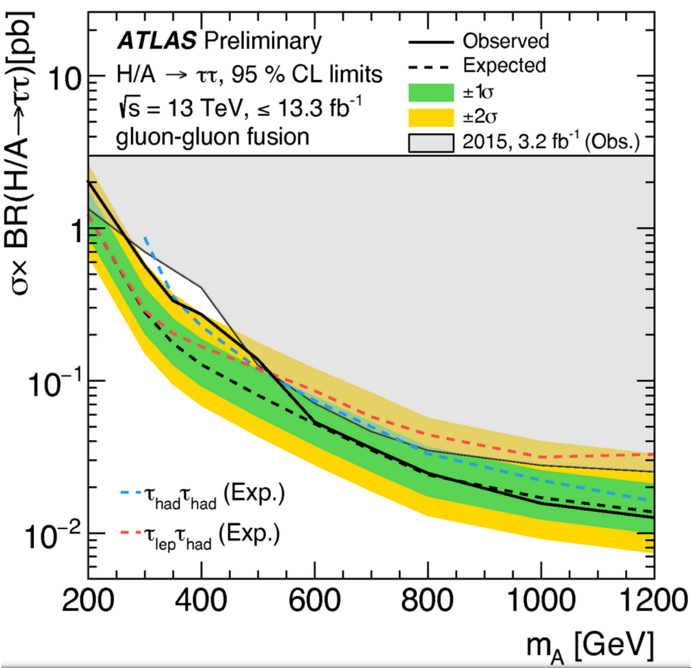
$H/A \to \tau\tau$ Results

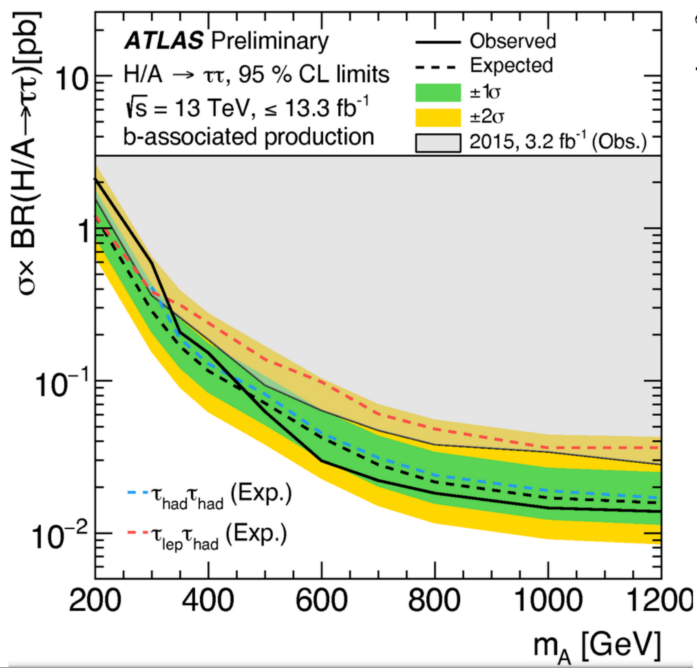
ATLAS-CONF-2016-085 results: both model independent and MSSM scenarios:

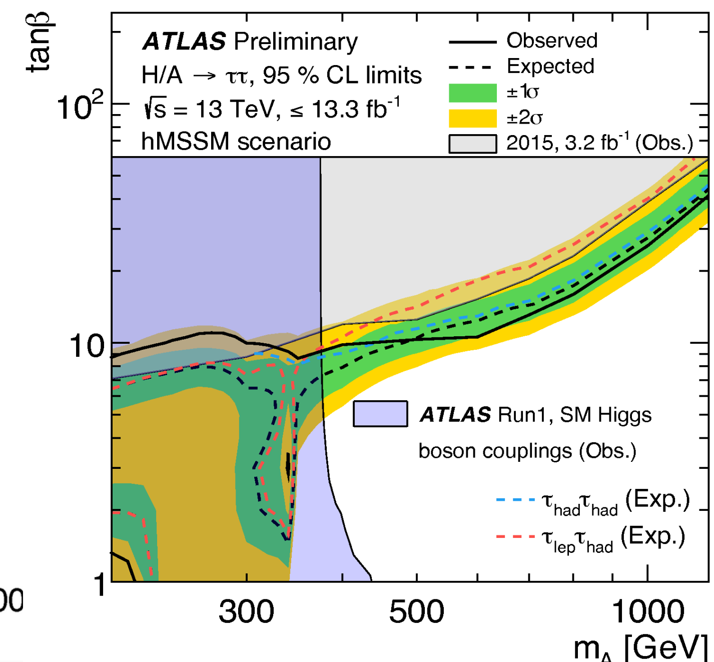
- ggH limits: 2.0-0.013 pb for m_A=200-1200 GeV
- bbH limits: 2.1-0.014 pb for m_A=200-1200 GeV

→ *More details in P. De Bruin talk this afternoon!*

- Check out also the recently submitted ATLAS paper searching for $H/A \to \tau\tau$ and $Z' \to \tau\tau$ with 3.2 fb^{-1}: arXiv.org:1608.00890





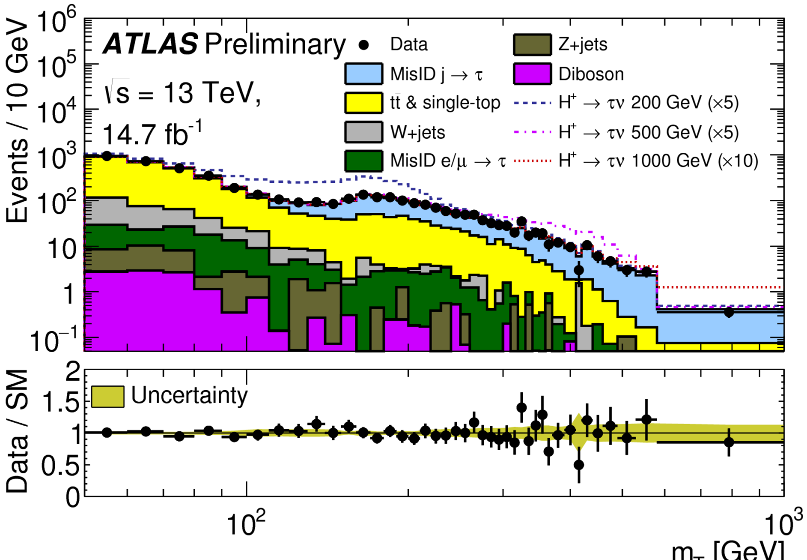


Charged Higgs $H^{\pm} \rightarrow \tau\nu$ Search

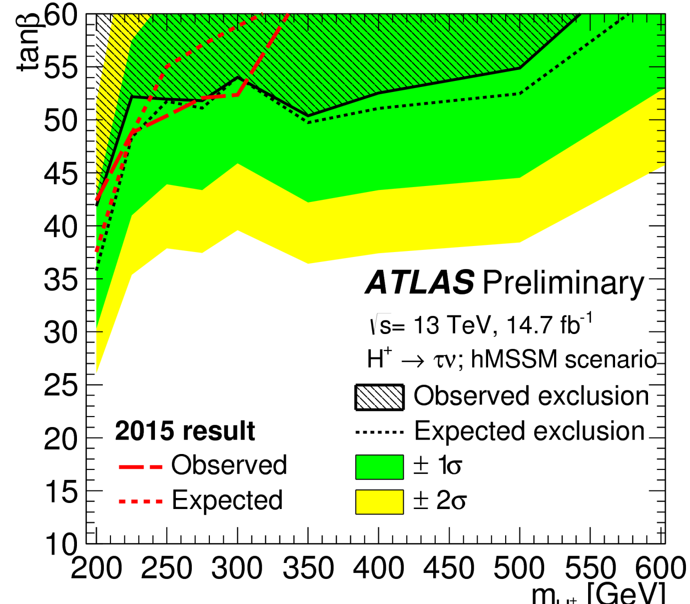
- For $m_{H^{\pm}} > m_t$, production in association with top-quark is dominant
- **$H^{\pm} \rightarrow \tau\nu$ search: ATLAS-CONF-2016-088**
- Discriminant variable is m_T:

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

- **Backgrounds:**
  - True τ_{had}: MC normalised/checked in CRs with low m_T
  - Jet $\rightarrow \tau_{had}$ fakes: Fake Factor (FF)



- **Signal Region:**
  - 1 τ_{had} p_T>40 GeV
  - 3 jets p_T>25 GeV (>=1 *b*-tagged jet)
  - E_T^{miss} > 150 GeV

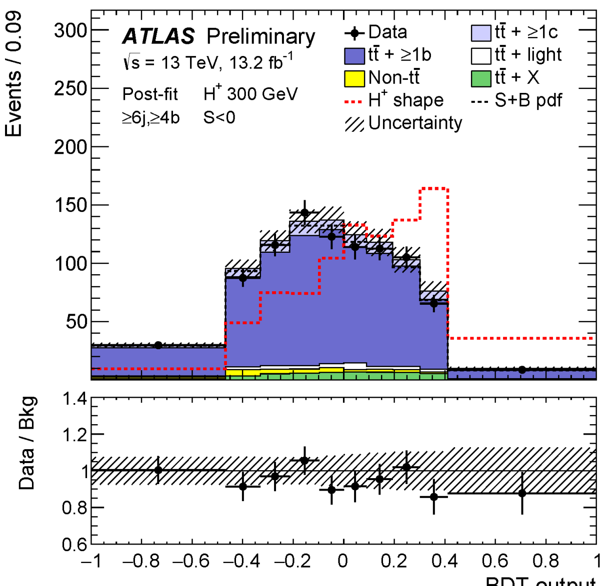


Observed hMSSM exclusion:
tanβ>42-60 @ $m_{H^{\pm}}$ = 200-540 GeV

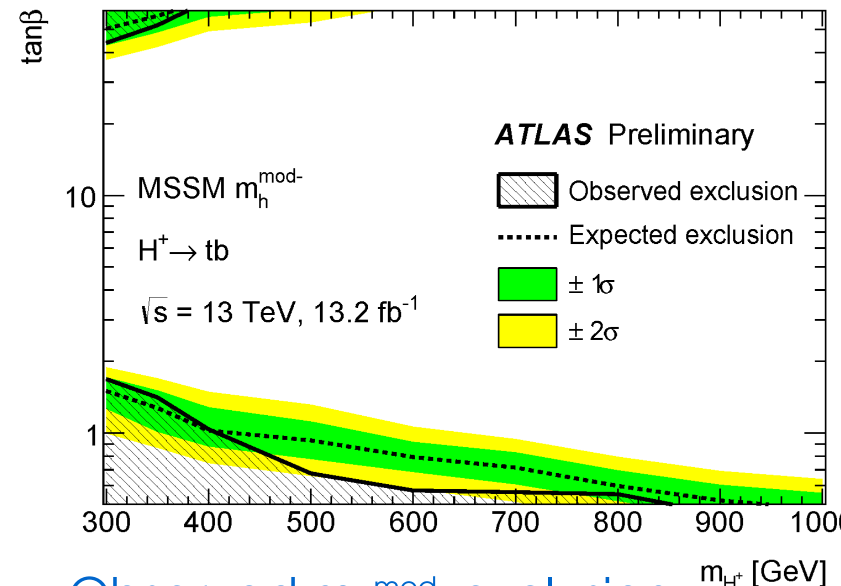
Charged Higgs $H^{\pm} \to tb$ search

- For $m_{H^{\pm}} > m_t$, production in association with top-quark is dominant

- **$H^{\pm} \to tb$ search: ATLAS-CONF-2016-089**
- **lepton+jets final state (lep=e,μ)**
- Discriminant variable is a BDT-score calculated from 12 input variables
- Signal Regions:
  - 1 lepton with p_T > 25 GeV
  - 5j3b, 5j≥4b, ≥6j3b and ≥6j≥4b



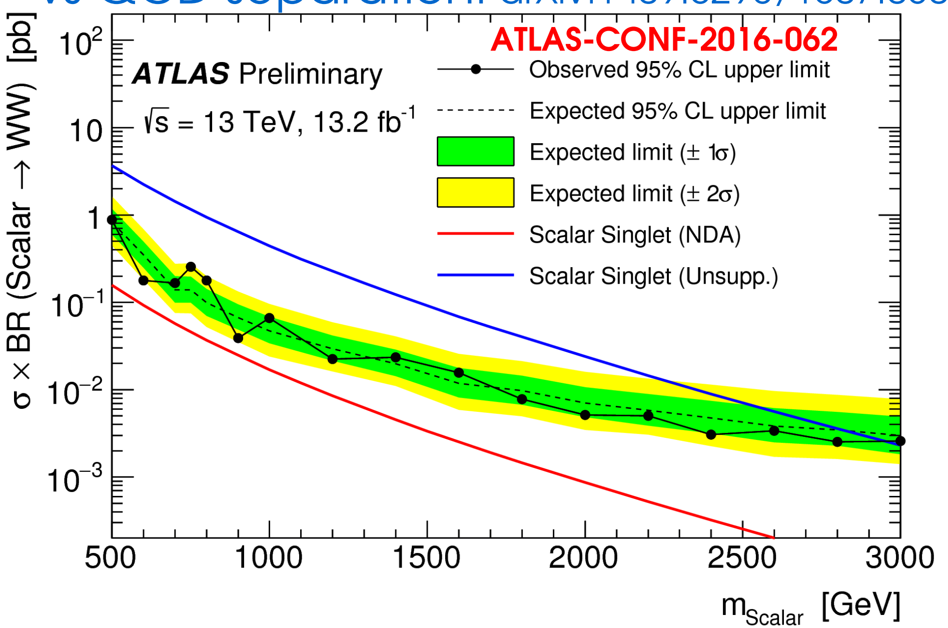
- **Backgrounds:**
- ttbar+jets production dominates, modelled using Powheg + Pythia6: reweight ttbar+light and ttbar+≥1c to NNLO and ttbar+≥1b to NLO
- Control Regions: 4j2b, 4j≥3b, 5j2b and ≥6j2b
- H_T^{had} (Sum of p_T of selected jets) used for CR



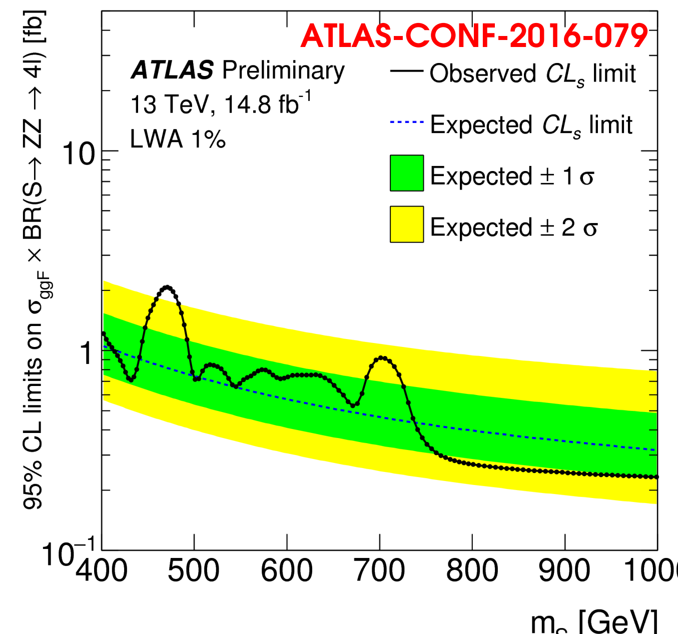
Observed m_h^{mod-} exclusion:
tanβ<1.7-0.5 @ $m_{H^{\pm}}$ = 300-855 GeV

$H \to WW \to l\nu qq$ and $H \to ZZ \to 4l$ searches

- **$H \to WW \to l\nu qq'$ ($l=e,\mu$):** 13.2 fb^{-1}@13 TeV
- **Selection**: e,μ + E_T^{miss} > 100 GeV, ≥1 R=1 jet
- Likelihood fit with dedicated control regions for ttbar and W+jets
- Signal Regions:
  - High/Low-purity: pass/fail $D_2^{\beta=1}$ selection
  - $D_{2,\beta=1}$ jet substructure variable for boostV vs QCD separation: arXiv:1409.6298, 1507.03018



- **$H \to ZZ \to 4l$ ($l=e,\mu$):** 14.8 fb^{-1}@13 TeV
- Same selection as SM, but requires both Z on-shell
- **VBF-enriched category**: mjj > 400 GeV and Δηjj > 3.3
- **ggH-enriched category**: the rest
- Limits set for VBF and ggH production and 4.07 MeV, 1%, 5% and 10% widths

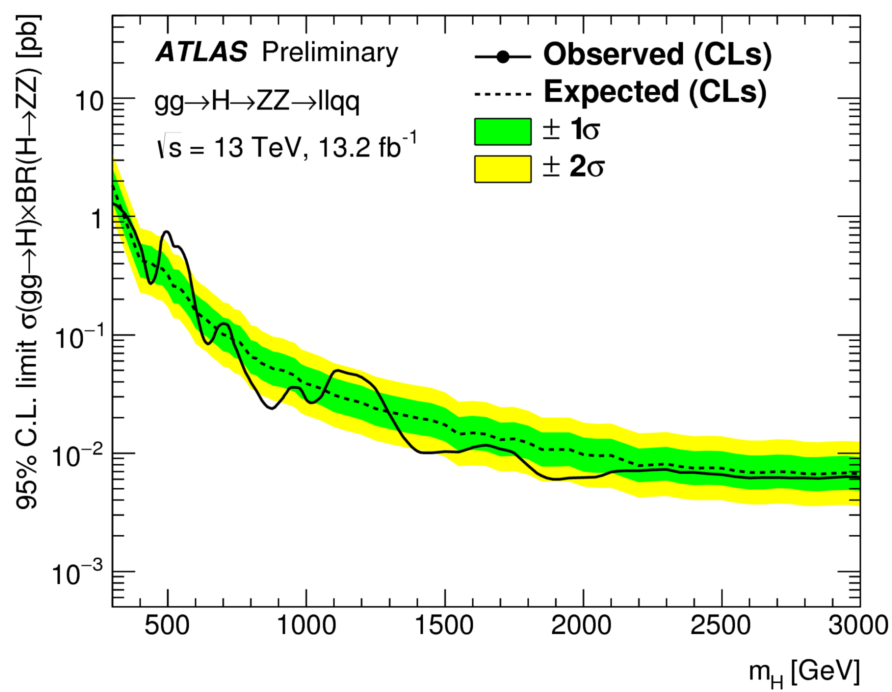


H→ZZ→llqq and νvqq Searches

- **ATLAS-CONF-2016-082, 13.2 fb^{-1}@13 TeV**
- Searches for a heavy H and a W' of heavy vector triplet (HVT) model

H→ZZ→llqq and W'→ZW→llqq searches:

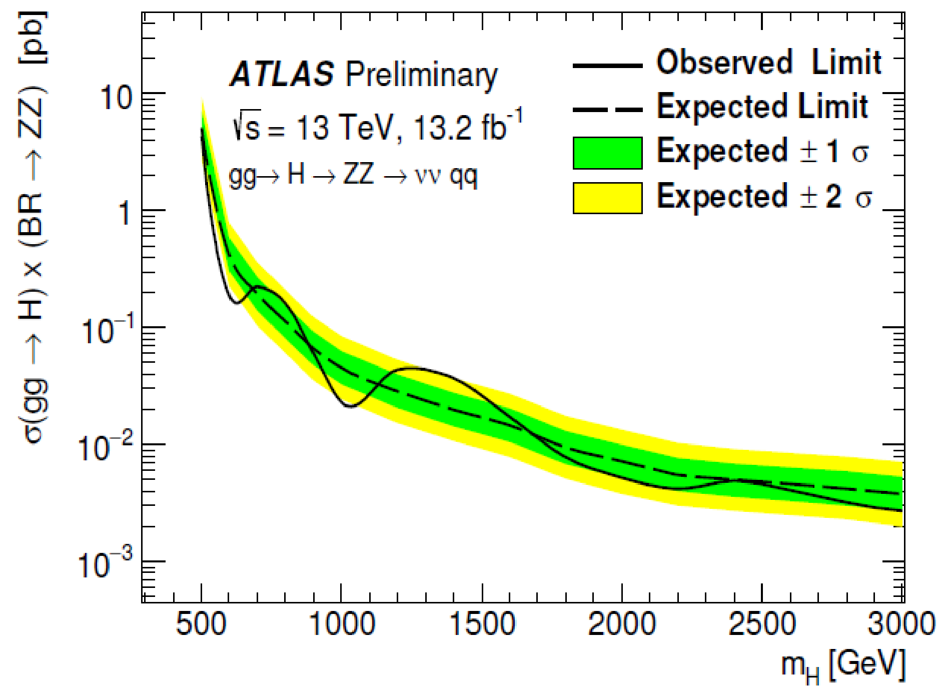
- merged and resolved (2 *b*-tag and rest) jets final states.
- VBF- and ggF-enriched categories
- Discriminant variables are m(llJ) and m(lljj)



H→ZZ→ννqq and W'→ZW→ννqq searches:

- E_T^{miss} >250 GeV and >=1 R=1 jet
- Two categories (pass/fail $D_2^{\beta=1}$ selection)
- Discriminant variable is $m_T(\nu\nu J)$:

$$m_T = \sqrt{(E_{T,J} + E_T^{miss})^2 - (\vec{p}_{T,J} + \vec{E}_T^{miss})^2}$$



$hh \to bbbb$ Search

- **ATLAS-CONF-2016-049**, 13.3 fb^{-1} of 13 TeV data.
- **Resolved search**: optimized for low mass and non-resonant regimes
  - 4 *b*-tagged jets (R=0.4), jet pairing using ΔR_{jj} and m_h constraints.
- **Boosted search**: optimized for high mass resonances, where the two *b*-jets of the Higgs boson decay cannot be resolved.
  - 2 R=1 jets, each of them containing at least 1 R=0.2 track jet
  - Events split in 2,3,4 tag categories, based on the number of track jets.

- **Main backgrounds**: multi-jet and ttbar for both searches

- **Resolved Analysis:**
  - multi-jet: data-driven
  - ttbar: modelled with MC
- **Boosted Analysis:**
  - multi-jet: data-driven
  - ttbar: data-driven normalization, shape from MC

- **Systematic Uncertainties:**
  - *b*-tagging is the main systematic uncertainty for both analyses.

$hh \rightarrow bbbb$ Results, ATLAS-CONF-2016-049

- **Results:**
- 95% CL limit is (pp → hh → bbbb) < 330 fb

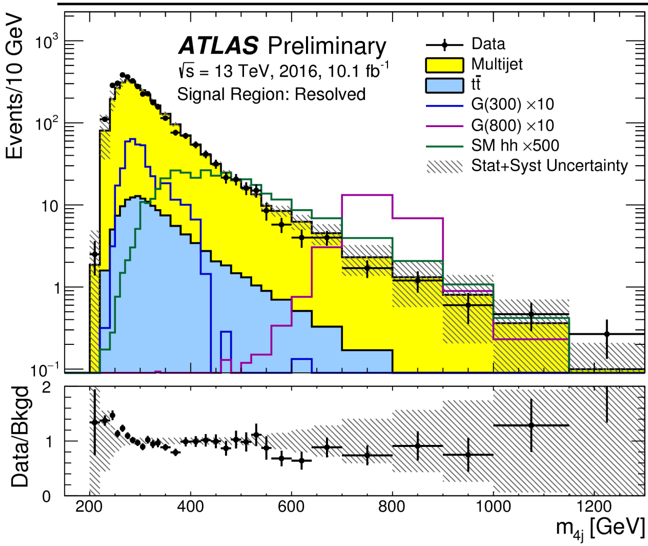
- **Excluded mass range:**
- observed: 360 GeV < m(G_{KK})< 860 GeV
  (expected: 380 GeV < m(G_{KK})< 910 GeV)

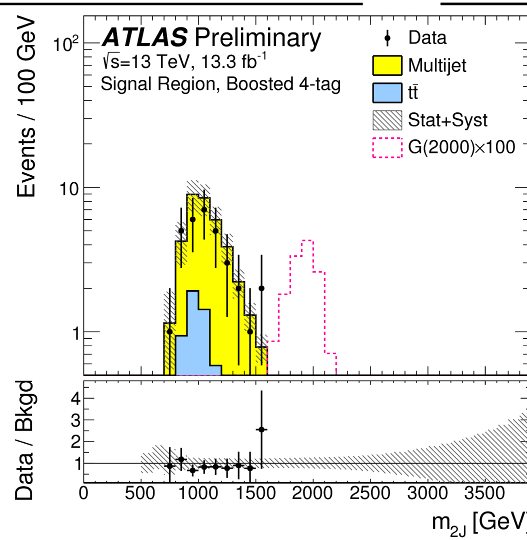
Resolved

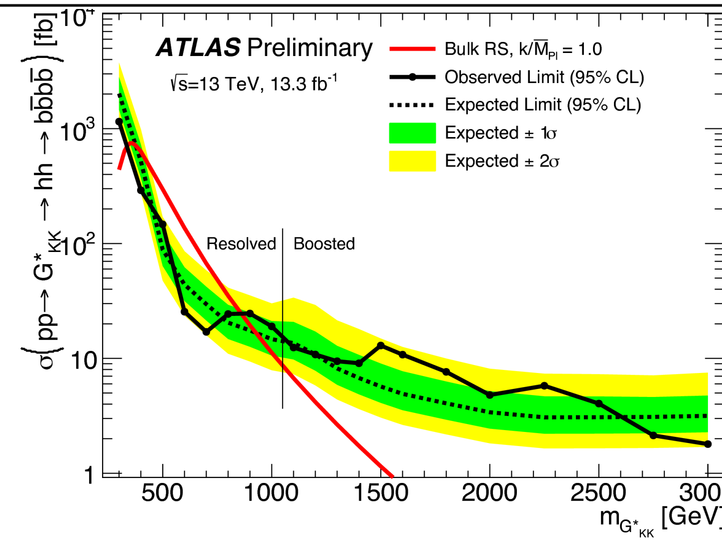
Sample	2015 Signal Region	2016 Signal Region
Multijet	$1\,131 \pm 68$	$3\,670 \pm 200$
$t\bar{t}$	57 ± 34	190 ± 110
Total	$1\,189 \pm 76$	$3\,860 \pm 230$
Data	$1\,231$	$3\,990$
SM hh	0.47 ± 0.12	1.5 ± 0.4
G^*_{KK} (800 GeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	8 ± 3	24 ± 8

Boosted

Sample	2-tag-split	3-tag	4-tag
Multijet	$2\,310 \pm 240$	515 ± 41	32.6 ± 7.6
$t\bar{t}$	460 ± 170	81 ± 37	5.7 ± 5.2
Total	$2\,770 \pm 130$	596 ± 39	38.3 ± 9.0
Data	$2\,813$	671	32
G^*_{KK} (2 TeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	0.17 ± 0.10	0.31 ± 0.06	0.15 ± 0.06







Check also arXiv:1606.04782 with L=3.2 fb^{-1} for H → hh specific interpretation.

Summary

- Several new searches with 13 TeV have been recently released for charged and neutral Higgs bosons, investigating both fermionic and bosonic final states.
- Impressive performance of the LHC machine during the last months allowed to significantly improve limits on $\sigma\times$BR set over wider mass-ranges and final states, but no significant excess was observed.
- We are still at the beginning of Run-2 in terms of delivered luminosity, exciting times ahead of us!

- Additional 13 TeV results with >13 fb^{-1} data recently released by ATLAS, apologies if your favorite search was not shown in this talk!

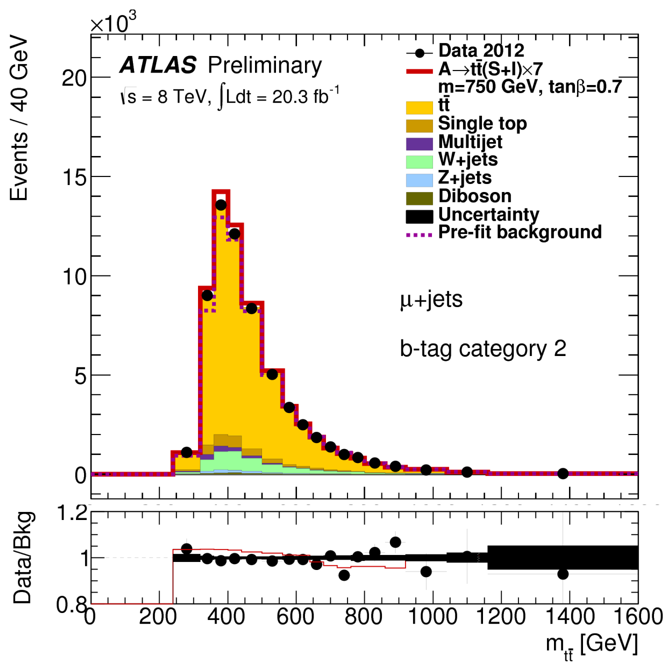
- $H \rightarrow WW \rightarrow l\nu l\nu$: ATLAS-CONF-2016-074 → *shown by P. Rados yesterday*
- $H \rightarrow ZZ \rightarrow ll\nu\nu$: ATLAS-CONF-2016-056
- $X \rightarrow H(\gamma\gamma)+E_T^{miss}$: ATLAS-CONF-2016-087
- $hh \rightarrow WW\gamma\gamma$: ATLAS-CONF-2016-071
- $X \rightarrow Z/Wh \rightarrow qqbb$: ATLAS-CONF-2016-083
- $X \rightarrow VV$: ATLAS-CONF-2016-055
- $H^{\pm\pm} \rightarrow e^{\pm}e^{\pm}$: ATLAS-CONF-2016-051

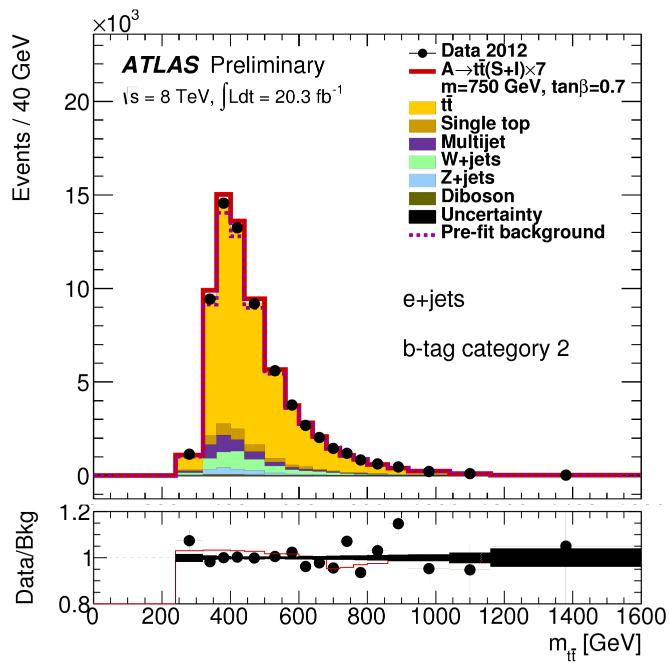
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

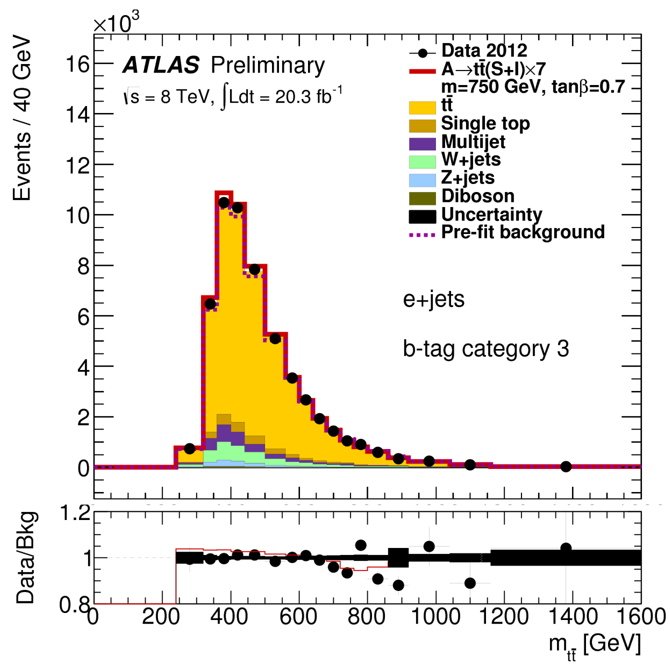
Backup

H,A→ ttbar Search

- **ATLAS-CONF-2016-073, 20.3 fb^{-1} of 8 TeV data**
- *b*-tag categories:
  - category 1: *b*-tagged jet assigned to each of the hadronically and semileptonically decaying top-quark candidates by the χ^2 algorithm.
  - category 2: *b*-tagged jet assigned only to the hadronically
  - category 3: *b*-tagged jet assigned only to the semileptonically decaying top quark







H,A→ ttbar Search (2)

- Main systematics are:
  - jet energy scale (JES), 4% (1%) for central jets with a transverse momentum of 20 GeV (1 TeV)
  - jet reconstruction efficiency
  - jet energy resolution (JER).
  - The combined impact of the JES and JER uncertainties on the event yields is 6% for the total background, 4% for the pure resonant signal S of a pseudoscalar resonance with a mass of mA = 500 GeV and tan = 0:68, and 8% for the corresponding S+I component.

Type	e+jets		μ+jets		Sum	
$t\bar{t}$	95,000	± 11,000	93,000	± 11,000	188,000	± 22,000
Single top quark	3,900	± 500	3,800	± 500	7,700	± 1,000
$t\bar{t}V$	290	± 40	280	± 40	560	± 80
W+jets	6,600	± 2,100	7,200	± 2,300	13,800	± 4,300
Z+jets	1,400	± 620	650	± 250	2,100	± 900
Diboson	320	± 120	310	± 120	630	± 240
Multijet e	5,300	± 1,100	-		5,300	± 1,100
Multijet μ	-		1,060	± 230	1,060	± 30
Total	112,000	± 13,000	106,000	± 12,000	219,000	± 25,000
Data	115,785		110,218		226,003	

Table 2: Data and expected background event yields after the resolved-topology selection. The uncertainty on the expected background yields is derived by summing all systematic uncertainties and the MC statistical uncertainty in quadrature. The expected yields and uncertainties are shown before the profile likelihood fit (described in the text) to the full dataset.

$H/A \to \tau\tau$ Signal and Control Regions

$\tau_{lep}\tau_{had}$ signal region	$\Delta\phi(\tau_{\text{had-vis}}, \ell) > 2.4$, $m_T(\ell, E_T^{miss}) < 40$ *GeV*, Veto $80 < m_{e,\tau} < 110$ *GeV* for $\tau_e\tau_{had}$,
high-E_T^{miss} category:	E_T^{miss} ($\lvert\vec{p_T}(\mu) + \vec{E}_T^{miss}\rvert$)$> 150$ *GeV* for $\tau_e\tau_{had}$ ($\tau_\mu\tau_{had}$),
b-tag/b-veto categories:	fail high-E_T^{miss} category requirements, $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
b-veto/$t\bar{t}$ fake-factor control region	$m_T(\ell, E_T^{miss}) > 70$ (60) GeV for $\tau_e\tau_{had}$ ($\tau_\mu\tau_{had}$), $N_{b\text{-tag}} = 0$ different $\tau_{\text{had-vis}}$ identification for the anti-τ_{had} region
b-tag control region	$N_{b\text{-tag}} \geq 1$, $m_T(\ell, E_T^{miss}) > 100$ *GeV*
Multi-jet fake-factor control region	invert e, μ isolation requirement, $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto and high-E_T^{miss} categories) different $\tau_{\text{had-vis}}$ identification for the anti-τ_{had} multi-jet control region
Multi-jet control region for r_{MJ} estimation	$m_T(\ell, E_T^{miss}) < 30$ GeV, no e, μ isolation requirement, no $\tau_{\text{had-vis}}$ passing loose identification, $N_{jet} \geq 1$ and $N_{b\text{-tag}} = 0$ (b-veto category), $N_{jet} \geq 2$ and $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{jet} \geq 1$, $N_{b\text{-tag}} = 0$ and E_T^{miss} ($\lvert\vec{p_T}(\mu) + \vec{E}_T^{miss}\rvert$)$> 150$ *GeV* for $\tau_e\tau_{had}$ ($\tau_\mu\tau_{had}$) (high-E_T^{miss} category)

$\tau_{had}\tau_{had}$ signal region	$\Delta\phi(\tau_{\text{had-vis},1}, \tau_{\text{had-vis},2}) > 2.7$, $N_{b\text{-tag}} \geq 1$ and $p_T > 65$ *GeV* for the sub-leading $\tau_{\text{had-vis}}$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
Multi-jet fake-factor control region	pass single-jet trigger, leading $\tau_{\text{had-vis}}$ with $p_T > 100$ *GeV* that fails medium identification, no charge requirements and for leading $\tau_{\text{had-vis}}$ $n_{tracks} \leq 7$ (b-tag category), $n_{tracks} = 1, 3$ (b-veto category), $\frac{p_T^{\tau_{\text{had-vis},2}}}{p_T^{\tau_{\text{had-vis},1}}} > 0.3$
Fake rate control region	pass single-muon trigger, isolated muon with $p_T > 55$ *GeV*, $\tau_{\text{had-vis}}$ with $p_T > 50$ *GeV*, $\Delta\phi(\mu, \tau_{\text{had-vis}}) > 2.4$, $m_T(\mu, E_T^{miss}) > 40$ *GeV* $\%\sum_{L=\mu,\tau} \cos\Delta\phi(L, E_T^{miss}) < 0$ (for b-veto category only) $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
Same-sign validation region	The two $\tau_{\text{had-vis}}$ objects are required to have the same electric charge

$H/A \to \tau\tau$ Systematics

Source of uncertainty	F_- (%)	F_+ (%)
$t\bar{t}$ background parton shower model	-21	$+39$
$\tau_{\text{had-vis}}$ energy scale, detector modelling	-10	$+12$
r_{MJ} estimation b-veto region ($\tau_\mu\tau_{\text{had}}$)	$-\ 5$	$+\ 6$
r_{MJ} estimation b-veto region ($\tau_e\tau_{\text{had}}$)	$-\ 2.3$	$+\ 3.0$
bbH signal cross-section uncertainty	$-\ 3.8$	$+\ 1.6$
Multi-jet background ($\tau_{\text{had}}\tau_{\text{had}}$)	$-\ 2.2$	$+\ 2.6$
Jet-to-$\tau_{\text{had-vis}}$ fake rate b-veto region ($\tau_{\text{lep}}\tau_{\text{had}}$)	$-\ 1.3$	$+\ 2.9$
$\tau_{\text{had-vis}}$ energy scale, in-situ calibration	$-\ 1.4$	$+\ 1.1$
r_{MJ} estimation high-$E_{\text{T}}^{\text{miss}}$ region ($\tau_\mu\tau_{\text{had}}$)	$-\ 1.4$	$+\ 1.0$
τ trigger (2016)	$-\ 0.5$	$+\ 1.3$
Statistics (data and simulation)	-48	$+25$

$H^{\pm} \rightarrow \tau\nu$ Systematics

Sample	Event yield
True τ_{had}	
$t\bar{t}$ & single-top-quark	$2880 \pm 770 \pm 25$
$W \rightarrow \tau\nu$	$265 \pm 51 \pm 18$
$Z \rightarrow \tau\tau$	$43 \pm 6.8 \pm 7.6$
diboson (WW, WZ, ZZ)	$13.8 \pm 2.2 \pm 1.7$
Misidentified $e, \mu \rightarrow \tau_{\text{had-vis}}$	$126 \pm 24 \pm 6.5$
Misidentified jet $\rightarrow \tau_{\text{had-vis}}$	$1170 \pm 110 \pm 16$
All backgrounds	$4500 \pm 800 \pm 36$
H^+ (200 GeV), hMSSM $\tan\beta = 60$	$523 \pm 86 \pm 4$
H^+ (1000 GeV), hMSSM $\tan\beta = 60$	$7.5 \pm 0.6 \pm 0.05$
Data	4645

Table 1: Expected event yields for the backgrounds and a hypothetical H^+ signal after all selection criteria, and comparison with 14.7 fb^{-1} of data. The values shown for the signal assume a charged Higgs boson mass of 200 or 1000 GeV, with a cross section times branching fraction $\sigma(pp \rightarrow [b]tH^{\pm}) \times \text{BR}(H^{\pm} \rightarrow \tau\nu)$ corresponding to $\tan\beta = 60$ in the hMSSM benchmark scenario. The sytematic and statistical uncertainties are given, respectively. Sources of systematic uncertainty are correlated amongst backgrounds when evaluating the uncertainty on the total background.

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

Charged Higgs $H^{\pm} \rightarrow tb$ search

- **BDT variables:**
- The leading jet pT.
- The mass of the bb pair with smallest DR.
- The pT of the fifth jet, with the jets ordered by transverse momentum with the b-tagged jets first and
- then the non-b-tagged jets.
- The second Fox-Wolfram moment calculated using all jets and leptons.
- The average DR of all bb pairs.
- The DR of the lepton and the bb pair with smallest DR.
- The mass of the untagged jet pair with smallest DR.
- The scalar sum of ET calculated using all jets.
- The mass of the bb pair with largest pT.
- The mass of the bb pair with largest mass.
- The mass of the jet triplet with largest pT.
- The centrality, defined as the ratio of the scalar sum of the pT of all jets and leptons over the total visible energy.

- Background Composition:

$H^{\pm} \rightarrow tb$ Systematics

Process	$4j2b$	$4j \geq 3b$	$5j2b$	$\geq 6j2b$
$t\bar{t}+ \geq 1c$	10800 ± 2300	890 ± 300	10800 ± 2000	11500 ± 3600
$t\bar{t}+ \geq 1b$	4580 ± 930	1650 ± 490	4440 ± 540	4800 ± 1200
$t\bar{t}$ + light	160000 ± 30000	5310 ± 1550	91000 ± 17000	54000 ± 24000
Fakes	9200 ± 4400	820 ± 360	3700 ± 1600	1560 ± 670
$t\bar{t} + W$	99 ± 17	4.33 ± 0.99	130 ± 22	204 ± 40
$t\bar{t} + Z$	113 ± 21	15.7 ± 4.1	147 ± 25	270 ± 46
Single top	5900 ± 1600	243 ± 84	3470 ± 1140	2060 ± 820
Other top	4330 ± 1620	157 ± 30	1480 ± 280	630 ± 160
Diboson	420 ± 220	19 ± 12	200 ± 110	164 ± 88
W + jets	5250 ± 2370	183 ± 98	2300 ± 1100	1350 ± 650
Z + jets	1210 ± 580	42 ± 23	410 ± 210	260 ± 130
ttH	63.8 ± 8.9	28.0 ± 4.9	96 ± 11	198 ± 28
tH	9.6 ± 2.8	5.2 ± 1.6	8.1 ± 2.4	9.9 ± 3.1
Total	202000 ± 36000	9300 ± 2000	118000 ± 23000	77000 ± 27000
Data	208329	11904	124688	84556
H^+_{300}	245 ± 24	124 ± 18	253 ± 20	228 ± 32
H^+_{800}	170 ± 16	80 ± 15	249 ± 19	477 ± 49
Process	$5j3b$	$5j \geq 4b$	$\geq 6j3b$	$\geq 6j \geq 4b$
$t\bar{t}+ \geq 1c$	1170 ± 330	30 ± 11	1550 ± 530	71 ± 36
$t\bar{t}+ \geq 1b$	2240 ± 460	222 ± 62	3200 ± 800	670 ± 190
$t\bar{t}$ + light	3640 ± 880	24 ± 15	2600 ± 1100	34 ± 22
Fakes	260 ± 130	19.9 ± 9.3	300 ± 130	1.2 ± 0.6
$t\bar{t} + W$	8.3 ± 1.8	0.19 ± 0.07	20.8 ± 4.6	1.24 ± 0.39
$t\bar{t} + Z$	27.1 ± 5.9	4.8 ± 1.5	66 ± 12	17.9 ± 4.2
Single top	218 ± 85	8.1 ± 5.0	210 ± 100	21 ± 14
Other top	87 ± 17	6.3 ± 2.5	66 ± 16	8.3 ± 2.3
Diboson	15.6 ± 9.6	0.39 ± 0.29	14.4 ± 8.3	2.0 ± 1.3
W + jets	165 ± 100	2.3 ± 3.1	106 ± 54	10.4 ± 7.0
Z + jets	37 ± 27	0.72 ± 0.65	14.7 ± 7.9	1.17 ± 0.74
ttH	49.7 ± 7.0	11.8 ± 2.3	119 ± 18	44.9 ± 9.2
tH	4.4 ± 1.3	1.02 ± 0.35	5.9 ± 1.9	1.92 ± 0.68
Total	7900 ± 1500	331 ± 94	8300 ± 1900	890 ± 240
Data	10755	418	11561	1285
H^+_{300}	173 ± 23	24.1 ± 4.0	201 ± 31	62 ± 12
H^+_{800}	138 ± 21	20.0 ± 4.3	366 ± 51	117 ± 24

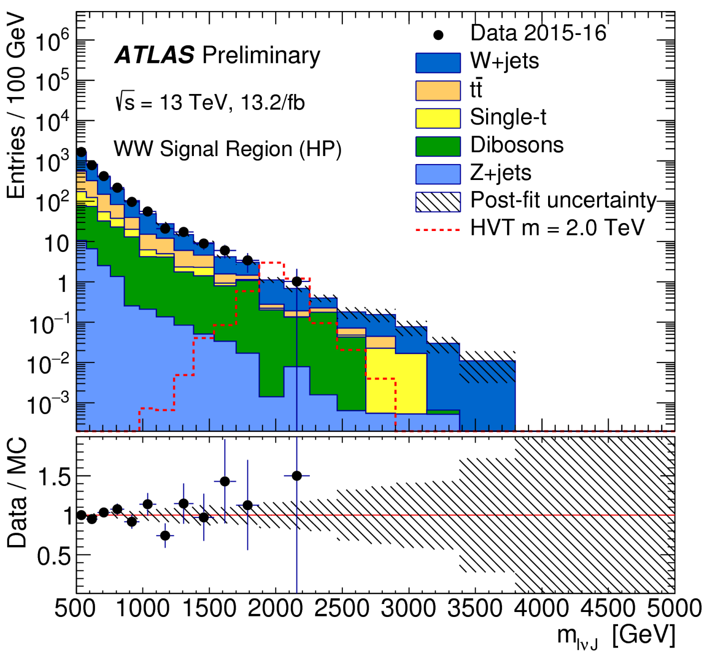
Table 1: Expected event yields of the SM background processes and observed data in all categories. The top box corresponds to the CR and the bottom one to the SR. *Single top* contribution refers to Wt production, whereas *other top* includes the Zt as well as s- and t-channel production. The quoted uncertainties include both statistical and systematical components. The prediction has not been fitted to the data. The H^+ signal yields for the 300 and 800 GeV mass hypotheses and an assumed cross section of 1 pb are also shown. A value of 13.2 fb^{-1} has been assumed for the integrated luminosity.

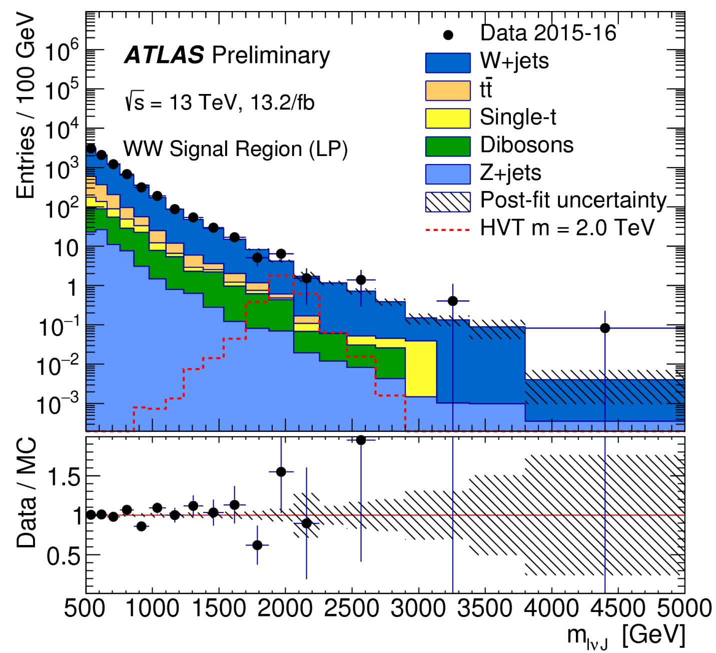
Uncertainty Source	$\Delta\mu(H^+_{300})$		$\Delta\mu(H^+_{800})$	
$t\bar{t}+ \geq 1b$ modelling	$+0.53$	-0.53	$+0.07$	-0.07
Jet flavour tagging	$+0.30$	-0.29	$+0.07$	-0.07
$t\bar{t}+ \geq 1c$ modelling	$+0.23$	-0.22	$+0.03$	-0.03
Background model statistics	$+0.19$	-0.19	$+0.05$	-0.05
Jet energy scale and resolution	$+0.18$	-0.17	$+0.03$	-0.03
$t\bar{t}$+light modelling	$+0.16$	-0.16	$+0.03$	-0.03
Other background modelling	$+0.15$	-0.14	$+0.03$	-0.03
Jet-vertex association, pileup modelling	$+0.12$	-0.11	$+0.01$	-0.01
Luminosity	$+0.12$	-0.12	$+0.01$	-0.01
Light lepton (e, μ) ID, isolation, trigger	$+0.01$	-0.01	$< +0.01$	< -0.01
Total systematic uncertainty	$+0.72$	-0.79	$+0.13$	-0.11
$t\bar{t}+ \geq 1b$ normalisation	$+0.36$	-0.36	$+0.03$	-0.03
$t\bar{t}+ \geq 1c$ normalisation	$+0.15$	-0.14	$+0.02$	-0.02
Total statistical uncertainty	$+0.44$	-0.43	$+0.08$	-0.08
Total	$+0.84$	-0.90	$+0.15$	-0.13

Table 3: Summary of the effects of the systematic uncertainties on μ for an H^+ signal with a mass of 300 GeV (left) and 800 GeV (right). Due to correlations between the different sources of uncertainties, the total systematic uncertainty can be different from the sum in quadrature of the individual sources. The normalisation factors for both $t\bar{t}+ \geq 1b$ and $t\bar{t}+ \geq 1c$ are included in the statistical component.

$H \to WW \to l\nu qq$ search

Selection		SR: HP (LP)	W CR: HP (LP)	$t\bar{t}$ CR: HP (LP)
$W \to \ell\nu$ selection	Number of signal leptons	1		
	Number of vetoed leptons	0		
	Number of vetoed leptons	0		
	$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 100\,GeV$		
	$p_{\mathrm{T}}(\ell\nu)$	$> 200\,GeV$		
$W/Z \to J$ selection	Number of large-R jets	≥ 1		
	Passing the $D_2^{(\beta=1)}$ cut	yes (no)	yes (no)	yes (no)
	$\lvert m_{W/Z} - m_J \rvert$	< 15 GeV	> 15 GeV	< 15 GeV
Topology cuts	$p_{\mathrm{T}}(\ell\nu)/m_{WV}$ $p_{\mathrm{T}}(J)/m_{WV}$	> 0.4		
Top-quark veto	Number of b-tagged jets	0		≥ 1





$H \to WW \to l\nu qq$ yields and Syst

	WW signal region	W+jets control region	$t\bar{t}$ control region
High-purity category			
W+jets	1810 ± 63	3182 ± 65	215 ± 12
$t\bar{t}$	654 ± 50	1020 ± 33	2940 ± 70
Single-t	163 ± 14	200 ± 15	322 ± 23
Z+jets	18.0 ± 3.8	53 ± 6	12 ± 2
Diboson	192 ± 31	70 ± 11	19.0 ± 3.8
Total SM	2830 ± 80	4530 ± 80	3500 ± 80
Data	2822 ± 53	4534 ± 67	3509 ± 59
Low-purity category			
W+jets	5630 ± 94	7320 ± 110	706 ± 37
$t\bar{t}$	730 ± 50	1410 ± 47	3100 ± 89
Single-t	178 ± 14	290 ± 22	420 ± 31
Z+jets	66.6 ± 4.8	134.1 ± 7.7	17.7 ± 2.8
Dibosons	215 ± 34	150 ± 23	22 ± 4
Total SM	6820 ± 80	9310 ± 125	4260 ± 120
Data	6849 ± 83	9276 ± 96	4270 ± 65

Postfit uncertainties

Main systematic uncertainties:

- Scale and Resolution of $D_2^{(\beta=1)}$
- Energy and mass scale of the wide-R jets
- background estimate uncertainties,

uncertainty on the shape of the W+jets background is obtained by comparing the m(lvJ) shape distribution in simulation and in data in the W+jets control region (separately for events in low and high mass sidebands)

$D_2^{(\beta=1)}$

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3} \,.$$

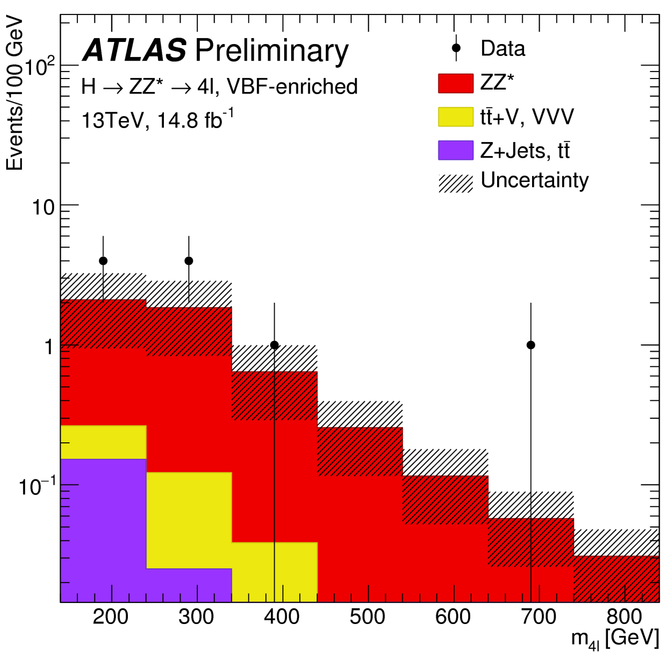
$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \leq i < j \leq n_J} p_{Ti} p_{Tj} R_{ij}^{\beta} \;,$$

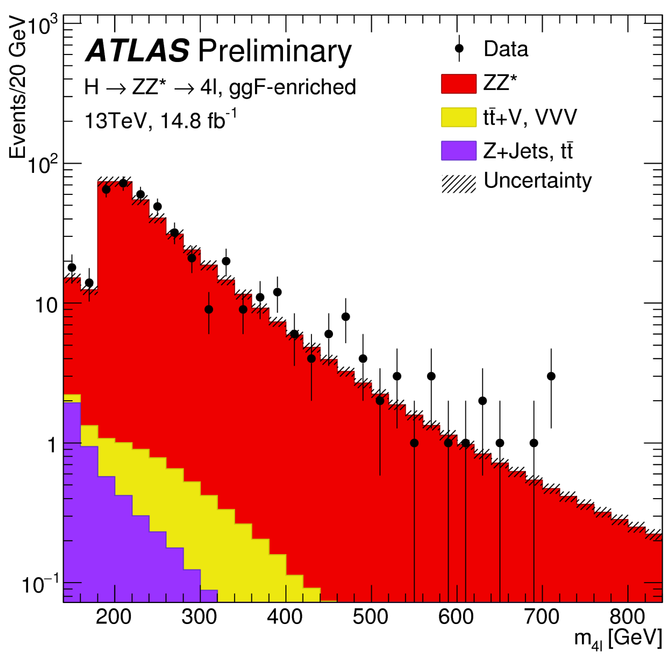
$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \leq i < j < k \leq n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta} \;,$$

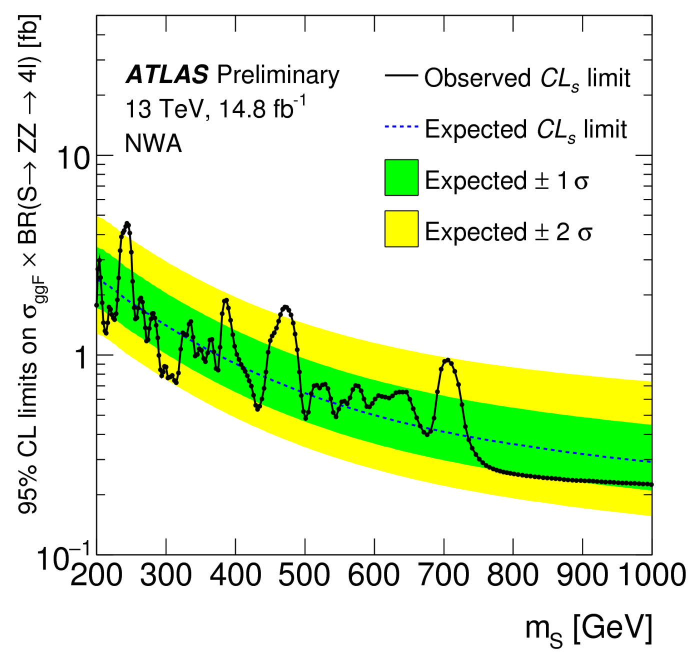
Substructure variable used to discriminate boosted W/Z decays to quarks from QCD (non top-quark) jets, based on power-counting.
Purpose is to separate 2-prong decays from 1-prong ones.

$H \to ZZ \to 4l$ search

- **ATLAS-CONF-2016-079, 14.8 fb^{-1}@13 TeV**
- Same selection as SM $H \to ZZ \to 4l$ ($l = e, \mu$), but requires both Z on-shell
- VBF-enriched category: mjj > 400 GeV and $\Delta\eta jj$ > 3.3
- ggH-enriched category: the rest
- Limits set for VBF and ggH production and 4.07 MeV, 1%, 5% and 10% widths







$H \rightarrow ZZ \rightarrow 4l$ search (2)

- **Main Systematics:**
- ZZ* background uncertainty
- uncertainty on subdominant gluon initiated ZZ production (gg → (H*) → ZZ) is also take
into account.

Final state	ZZ^*	$Z+\text{jets}$, $t\bar{t}$, WZ	$t\bar{t}V$,VVV	Expected	Observed
4μ ggF-enriched	125 ± 10	0.95 ± 0.14	1.57 ± 0.09	127 ± 10	128
$2e2\mu$ ggF-enriched	205 ± 17	2.5 ± 0.4	2.75 ± 0.17	211 ± 17	199
$4e$ ggF-enriched	83 ± 7	1.47 ± 0.22	1.28 ± 0.08	86 ± 7	111
VBF-enriched	4.6 ± 2.8	0.18 ± 0.05	0.268 ± 0.016	5.1 ± 2.8	10
Total	418 ± 35	5.1 ± 0.7	5.87 ± 0.35	429 ± 35	448

Full uncertainties are provided.

$H \rightarrow ZZ \rightarrow llqq$ and $\nu\nu qq$ Searches

H → ZZ → llqq

Process	Merged analysis		Resolved analysis	
	high purity	low purity	tagged	untagged
		Signal regions		
Z+jets	576 ± 22	1230 ± 33	409 ± 18	19900 ± 140
Diboson	49 ± 7	51 ± 5	54 ± 6	670 ± 40
Top quark	4 ± 1	5.9 ± 1.0	131 ± 6	291 ± 28
Total background	629 ± 22	1287 ± 34	594 ± 18	20861 ± 140
Data	606	1270	608	20857
H (400 GeV)	1.6 ± 0.2	4.3 ± 0.7	107 ± 6	626 ± 21
H (700 GeV)	168 ± 4	88.2 ± 2.9	20.0 ± 1.2	71.4 ± 3.3
H (1600 GeV)	35.9 ± 0.8	24.0 ± 0.6	1.00 ± 0.09	1.60 ± 0.08

H → ZZ → νν qq

Process	Merged analysis	
	high-purity	low-purity
Z+jets	1251 ± 56	3130 ± 79
W+jets	881 ± 45	2092 ± 75
Diboson	202 ± 14	227 ± 10
$t\bar{t}$ + single top	557 ± 85	610 ± 100
Total background	2891 ± 50	6059 ± 76
Data	2859	6044
H (1600 GeV)	63.7 ± 1.9	46.2 ± 1.4

The dominant uncertainties are the $D_2^{\beta=1}$ and mass scale uncertainty, which are of the order of 10%

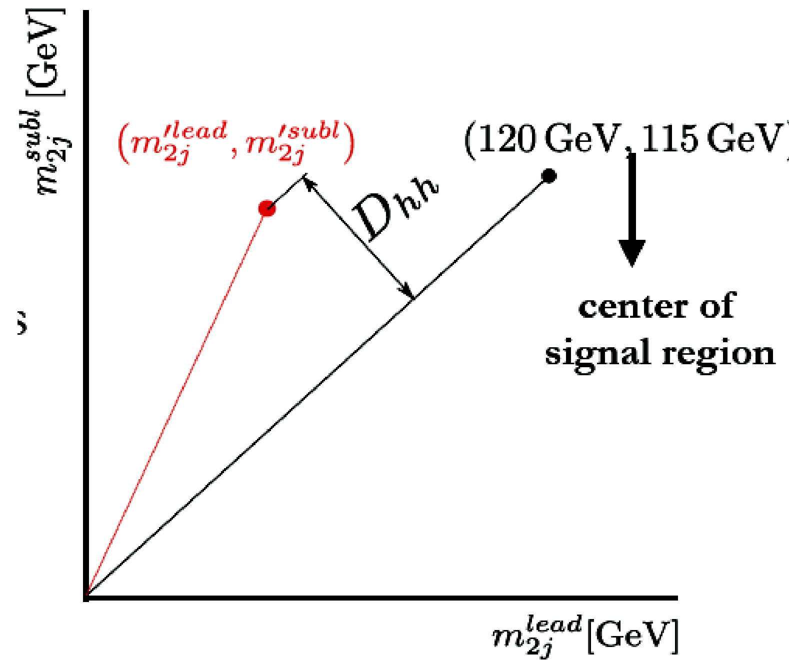
$hh \rightarrow bbbb$ Regions

Resolved Analysis:

- Pairing chosen to minimize the distance D_{hh}

- Center of the signal region is:
(120 GeV, 115 GeV) - account for energy losses through semi-leptonic decays

- The center corresponds to the median values of the narrowest intervals that contain 90% of the signal in simulation

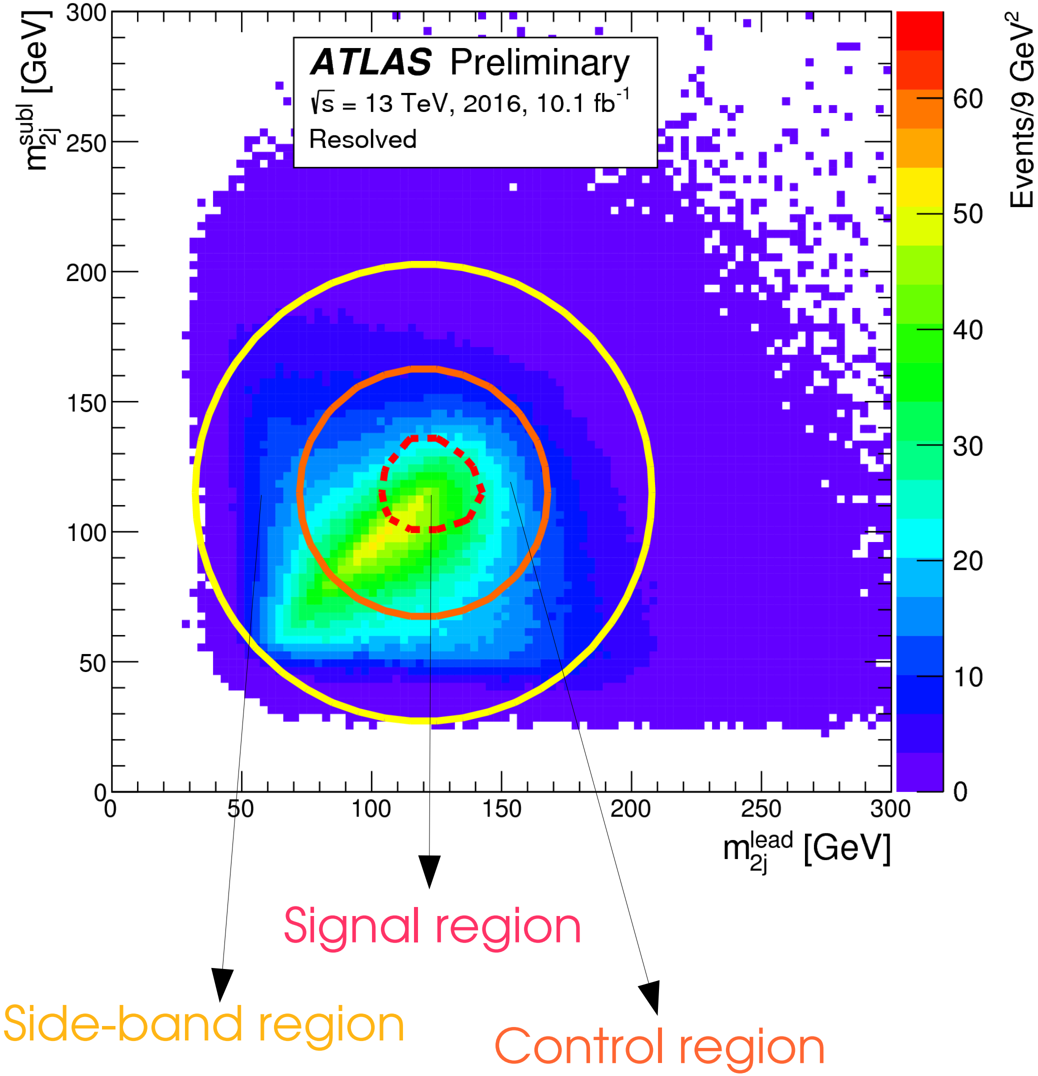


$$D_{hh} = \sqrt{\left(m_{2j}^{\text{lead}}\right)^2 + \left(m_{2j}^{\text{subl}}\right)^2} \left|\sin\left(\tan^{-1}\left(\frac{m_{2j}^{\text{subl}}}{m_{2j}^{\text{lead}}}\right) - \tan^{-1}\left(\frac{115}{120}\right)\right)\right|$$

$hh \to bbbb$ Regions

Resolved Analysis:

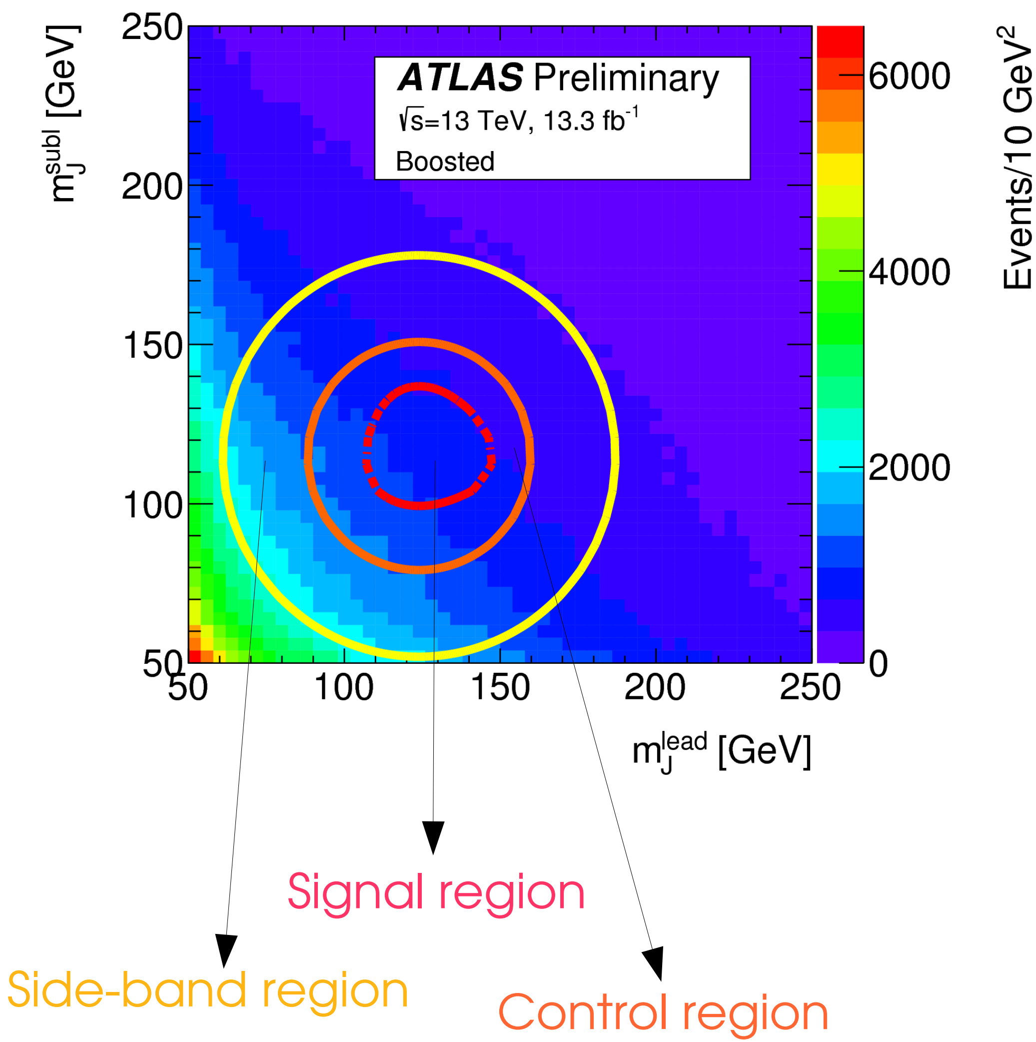
- Side-Band Region:
  - Used to extrapolate to 4-tag SR by using 2-tag events
- Control Region:
  - Verify the QCD modelling
  - Assess systematics
- Signal Region:
  - Statistical analysis



$hh \rightarrow bbbb$ Regions

Boosted Analysis:

- Side-Band Region:
  - Derive the normalisation of the multijet and ttbar backgrounds
- Control Region:
  - Verify the background models
  - Assign systematic uncertainties
- Signal Region:
  - Statistical analysis



$hh \to bbbb$ Yields and Systematics

Resolved Analysis

Sample	2015 Signal Region	2016 Signal Region
Multijet	$1\,131 \pm 68$	$3\,670 \pm 200$
$t\bar{t}$	57 ± 34	190 ± 110
Total	$1\,189 \pm 76$	$3\,860 \pm 230$
Data	$1\,231$	$3\,990$
SM hh	0.47 ± 0.12	1.5 ± 0.4
G^*_{KK} (800 GeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	8 ± 3	24 ± 8

	2015			2016		
Source	Background	SM hh	G^*_{KK} (800 GeV)	Background	SM hh	G^*_{KK} (800 GeV)
Luminosity	–	2.1	2.1	–	3.7	3.7
JER	–	5.7	3.3	–	5.4	3.5
JES	–	6.4	1.3	–	6.6	1.3
b-tagging	–	23	35	–	23	35
Theoretical	–	9.7	4.2	–	9.7	4.2
Multijet	5	–	–	5	–	–
$t\bar{t}$	58	–	–	58	–	–
Total	5.5	26	35	5.5	27	36

Boosted Analysis

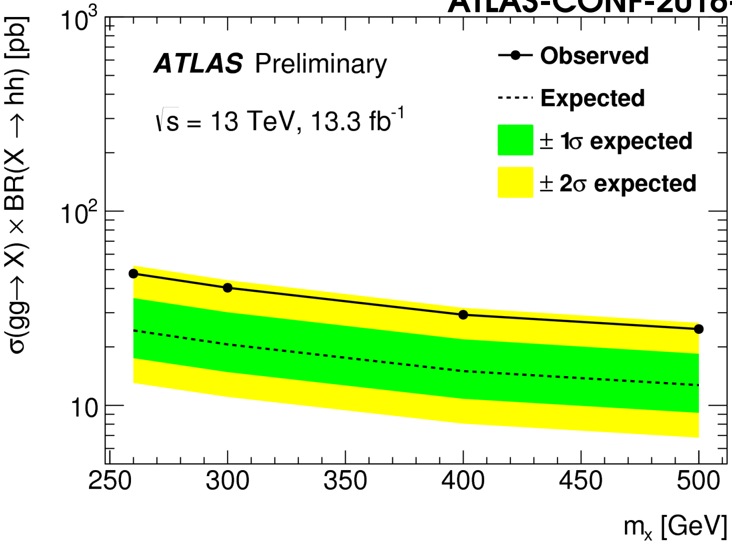
Sample	2-tag-split	3-tag	4-tag
Multijet	$2\,310 \pm 240$	515 ± 41	32.6 ± 7.6
$t\bar{t}$	460 ± 170	81 ± 37	5.7 ± 5.2
Total	$2\,770 \pm 130$	596 ± 39	38.3 ± 9.0
Data	$2\,813$	671	32
G^*_{KK} (2 TeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	0.17 ± 0.10	0.31 ± 0.06	0.15 ± 0.06

	2-tag-split		3-tag		4-tag	
Source	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)
Luminosity	-	2.9	-	2.9	-	2.9
JER	-	0.1	-	0.1	-	0.3
JMR	-	12	-	12	-	12
JES/JMS	-	4.5	-	4.2	-	3.3
b-tagging	-	58	-	15	-	38
Theoretical	-	2.7	-	2.3	-	2.4
Bkg Estimate	4.4	-	4.6	-	21	-
Statistical	0.5	1.4	1.1	1.0	1.2	1.3
$t\bar{t}$	1.6	-	4.7	-	10	-
Total Sys	4.7	59	6.6	20	24	40

$hh \rightarrow WW\gamma\gamma$ and $bb\gamma\gamma$ Searches

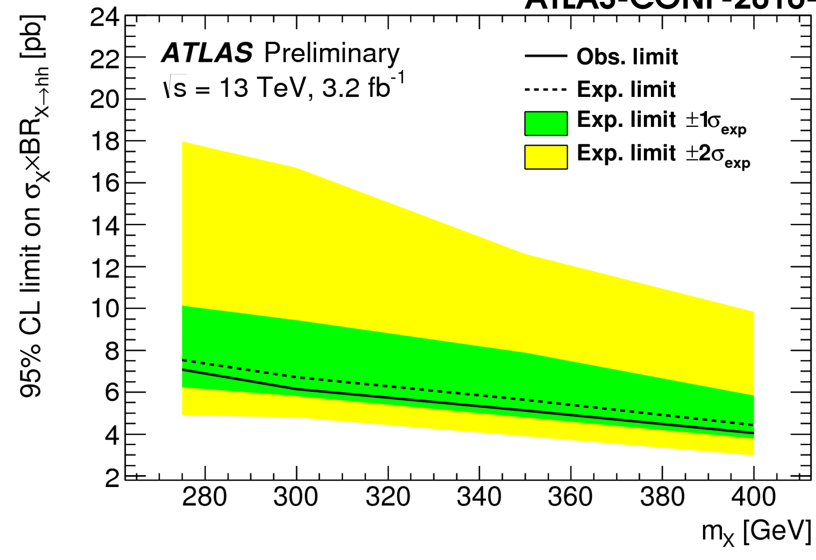
- **hh → WWγγ, 13.3 fb^{-1} :**
  - Final state $\gamma\gamma l\nu qq'$
  - 2γ, 2 non *b*-tagged jets
  - 105 GeV<$m_{\gamma\gamma}$<160 GeV
- **Results** (assuming SM Higgs BR)**:**
- Non-resonant search:
  σ(pp→hh) < 25.0 pb
- Resonant search, limits on σ(pp→X→hh):
  47.7-24.7 pb (expected 24.3-12.7 pb)
  at mX= 260-500 GeV

ATLAS-CONF-2016-071



- **hh → bbγγ, 3.2 fb^{-1} :**
  - 2γ, 2 *b*-tagged jets
  - 95 GeV < m_{bb}< 135 GeV
  - 105 GeV < $m_{\gamma\gamma}$< 160 GeV
- **Results** (assuming SM Higgs BR)**:**
- Non-resonant search:
  σ(pp→hh) < 3.9 pb
- Resonant search, limits on σ(pp→X→hh):
  7.0-4.3 pb (expected 7.8-4.5 pb)
  at mX= 270-400 GeV

ATLAS-CONF-2016-003



Fermion family	Type-I	Type-II	Lepton-specific	Flipped	Type-III
u	Φ_2	Φ_2	Φ_2	Φ_1	Φ_1 , Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1	Φ_1 , Φ_2
e	Φ_2	Φ_2	Φ_1	Φ_2	Φ_1 , Φ_2