Overview of recent ATLAS Higgs Physics Results

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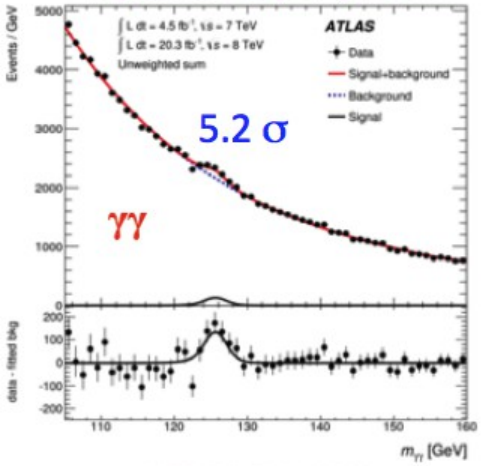
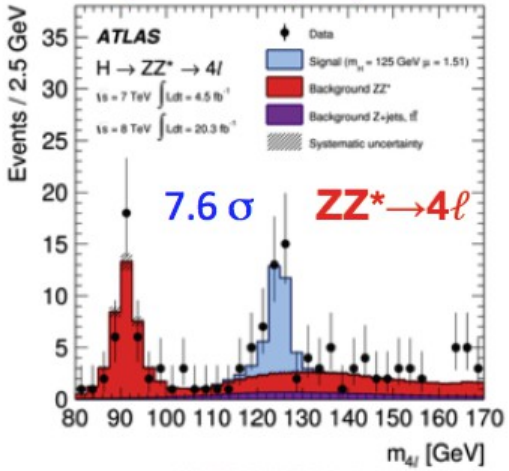
Workshop on Multi-Higgs Models (5-9 Sept 2016)

Summary of Run 1 results

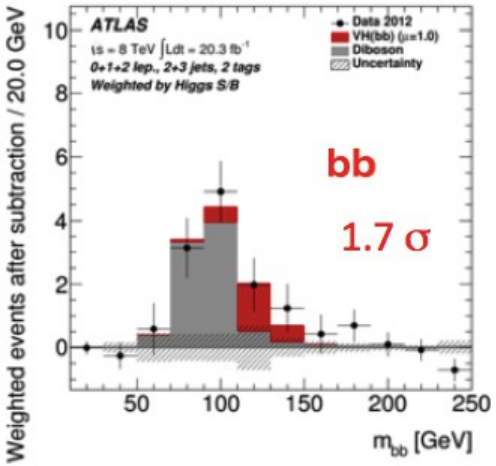
Phys. Rev. D90 (2014) 112015



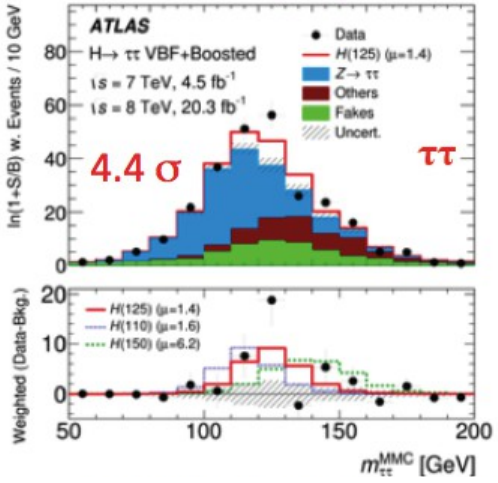
Phys. Rev. D91 (2015) 012006



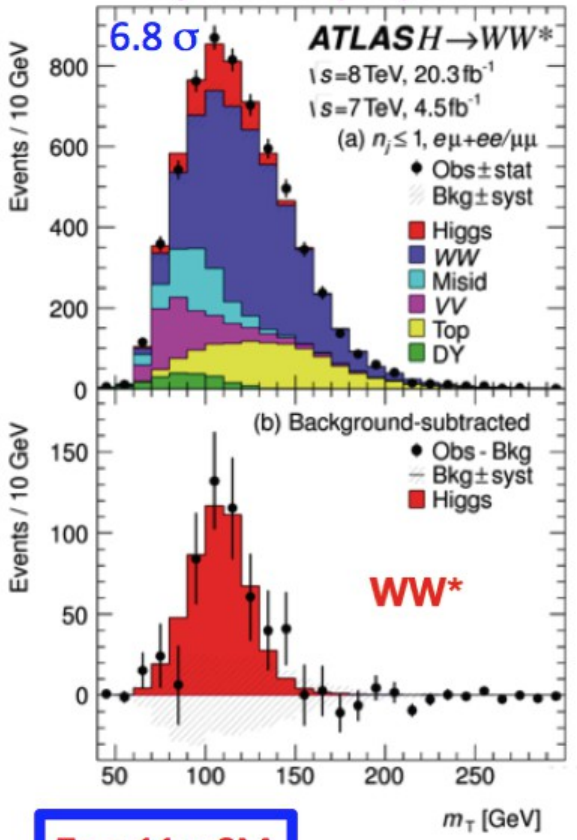
JHEP 01 (2015) 069



JHEP 04 (2015) 117



Phys. Rev. D92 (2015) 012006

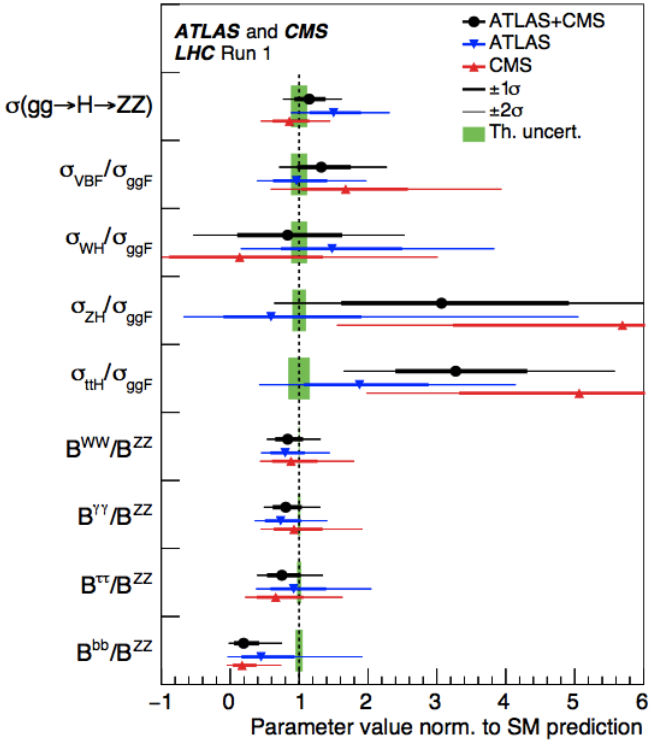


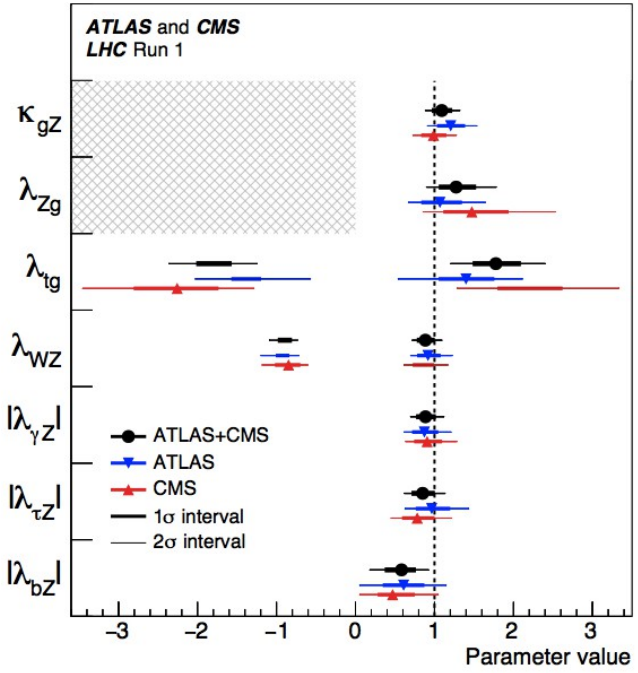
Zγ < 11 x SM

μμ < 7 x SM

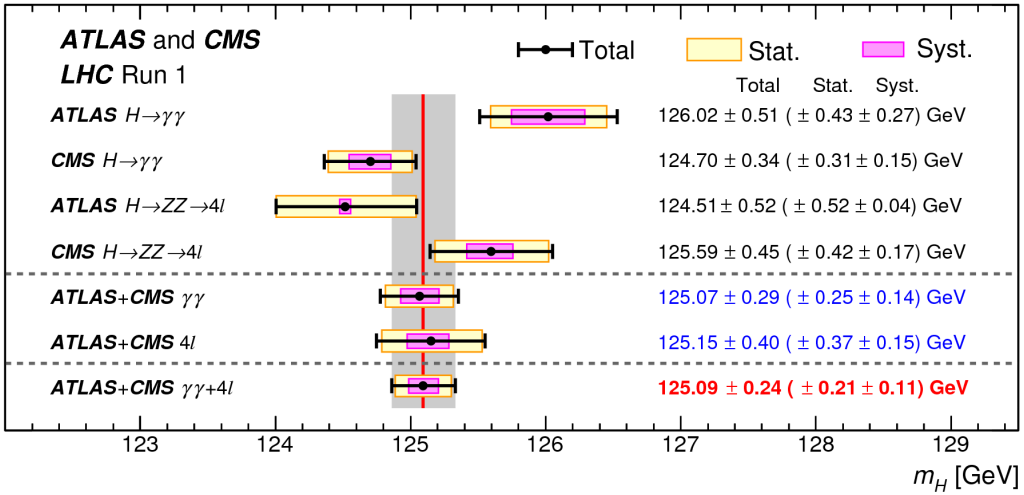
Run 1 couplings combination

- Best ATLAS+CMS fit for the ratio of production modes and BR
  - Cancellation of inclusive production theoretical uncertainties
  - Reference channel: smallest systematics and overall uncertainty: $H \rightarrow ZZ$





Run 1: Spin, Parity and mass



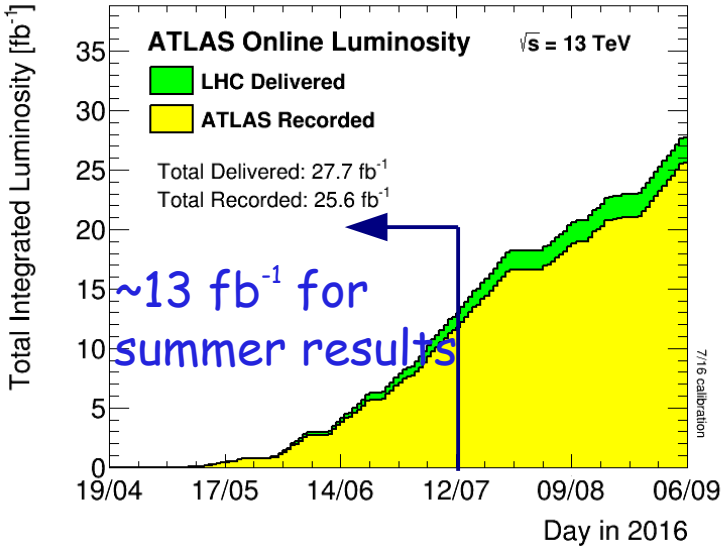
- J^P SM assignment tested versus alternative hypothesis combining angular observables from H→γγ, H→WW, H→ZZ channels

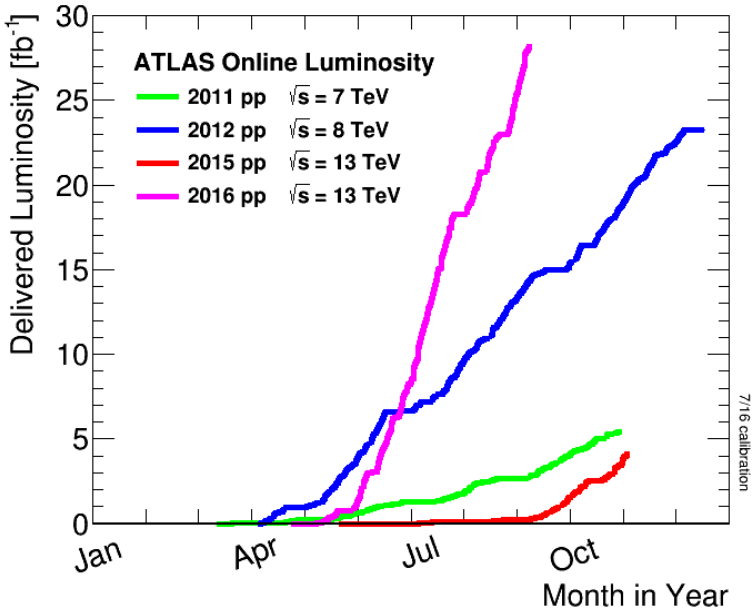
  Alternative hypothesis rejected at 99% CLs limit in favour of SM one

Tested Hypothesis	$p^{\text{alt}}_{\text{exp},\mu=1}$	$p^{\text{alt}}_{\text{exp},\mu=\hat{\mu}}$	$p^{\text{SM}}_{\text{obs}}$	$p^{\text{alt}}_{\text{obs}}$	Obs. CL_s (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300\ \text{GeV})$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125\ \text{GeV})$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300\ \text{GeV})$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125\ \text{GeV})$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

The LHC at 13 TeV

- Spectacular performance of the LHC this year





ATLAS pp 25ns run: April-July 2016										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
98.9	99.9	100	99.8	100	99.6	99.8	99.8	99.8	99.7	93.5
Good for physics: 91-98% (10.1-10.7 fb^{-1})										

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at √s=13 TeV between 28th April and 10th July 2016, corresponding to an integrated luminosity of 11.0 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1}. Analyses that don't require the toroid magnet can use that data.

27.7 fb^{-1} delivered luminosity

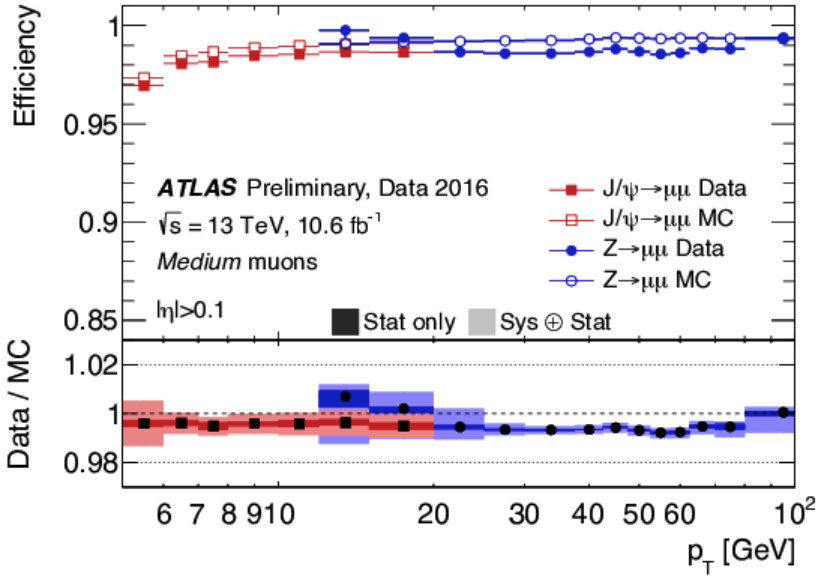
25.6 fb^{-1} recorded at ATLAS

Newest results use at most 13 fb^{-1}

91-98% of the collected data with good quality for physics analysis

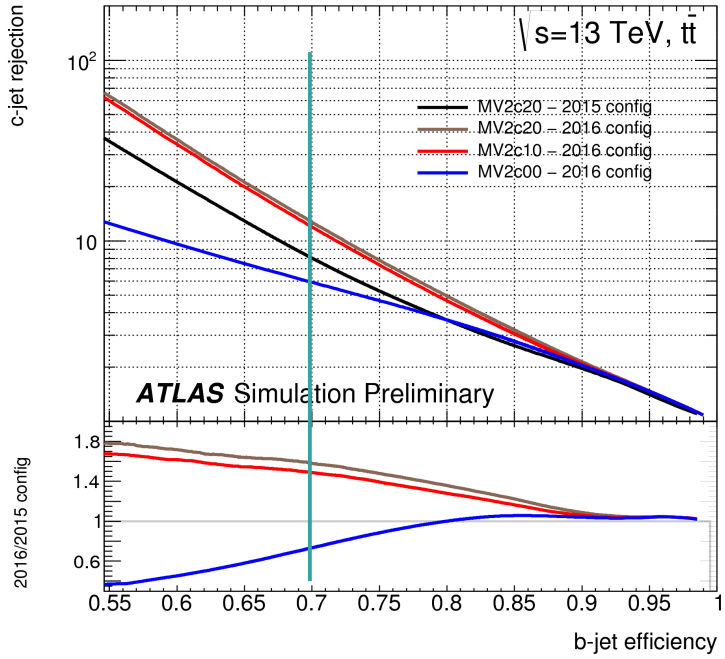
ATLAS Run 2 Performance highlights

- Strong effort to understand the detector performance
- Some examples:
  - Electron/muon reconstruction, trigger and identification efficiencies studied with data
    - Differences data/MC corrected at analysis level



Improved b-tagging efficiency

For 70% eff: ~400(10) rejection on light (c) jets

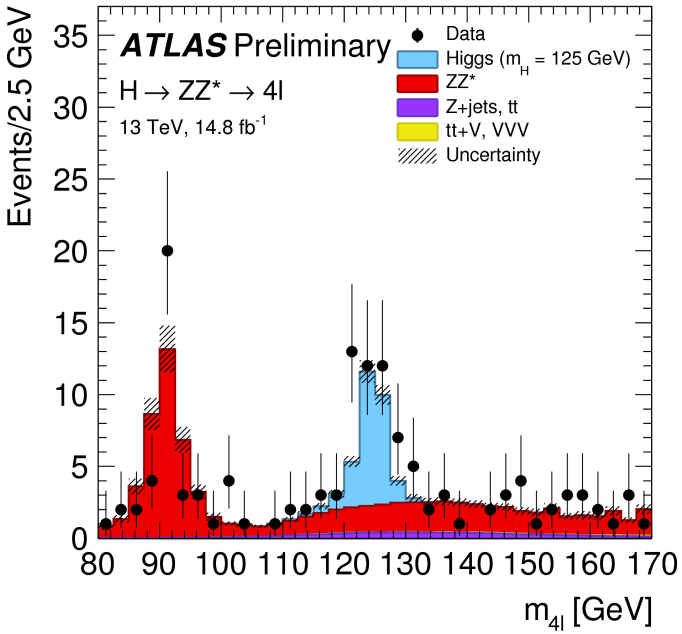


Higgs re-discovery at 13 TeV

ATLAS-CONF-2016-079

- $H \rightarrow ZZ \rightarrow 4\ell$

14.8 fb^{-1} pp collisions @ 13 TeV

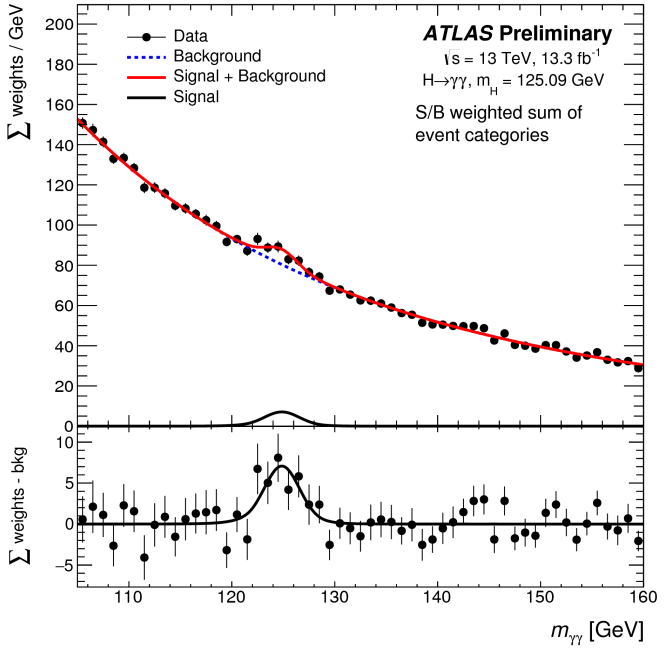


$$\sigma_{\text{tot,SM}} = 55.5^{+3.8}_{-4.4}\ \text{pb.}$$
$$\sigma_{\text{tot}} = 81^{+18}_{-16}\ \text{pb}$$

ATLAS-CONF-2016-067

- $H \rightarrow \gamma\gamma$

13.3 fb^{-1} pp collisions @ 13 TeV



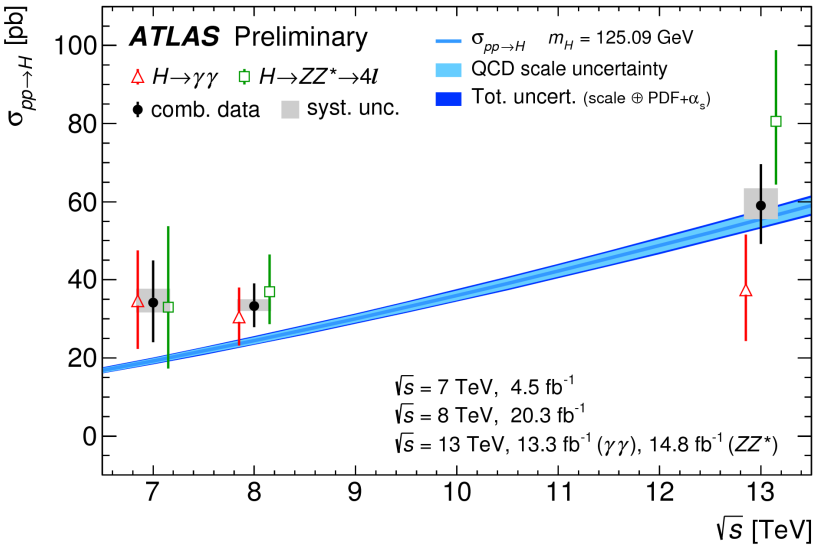
$$\sigma_{\text{fid}} = 47.0 \pm 13.9\,(\text{stat.}) \pm 5.4\,(\text{syst.})\ \text{fb}$$

SM prediction $62.8^{+3.4}_{-4.4}$ fb

Cross sections in H → γγ & H → 4ℓ

ATLAS-CONF-2016-081

- Cross section as a function of the pp center of mass energy



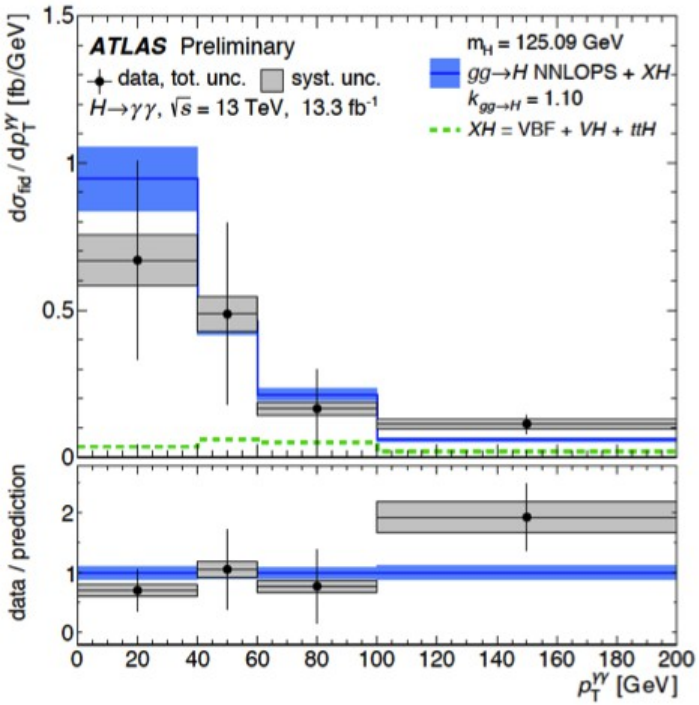
	Measurement at 13 TeV	SM prediction at 13 TeV
σ (pb)	$59.0^{+9.7}_{-9.2}(\text{stat})^{+4.4}_{-3.5}(\text{syst})$	$55.5^{+2.4}_{-3.4}$
μ	$1.13^{+0.18}_{-0.17}$	1

ATLAS-CONF-2016-067

- H → γγ differential cross section as a funtion of $p_T^{\gamma\gamma}$

Agreement with theory

Slightly harder pT in data



H→γγ & H→4ℓ combination @ 13TeV

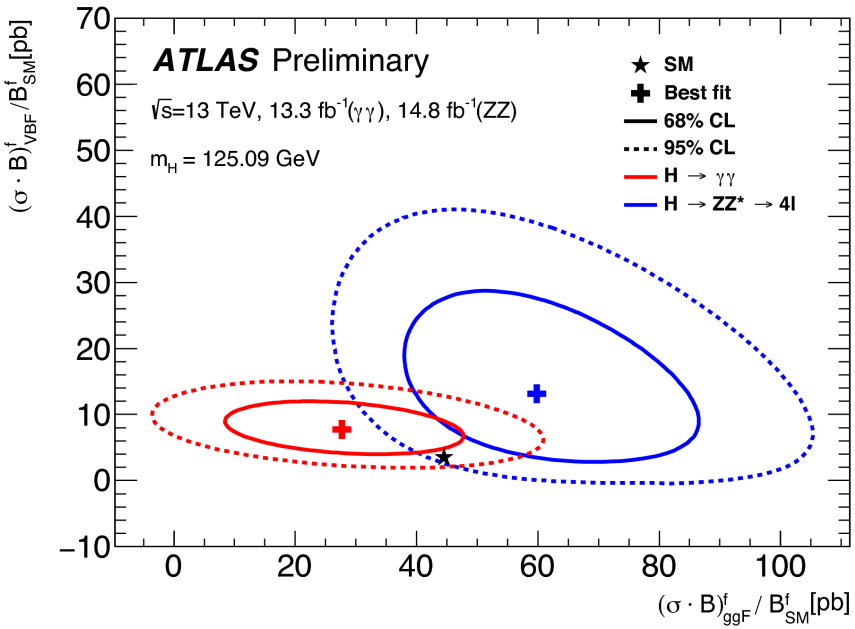
ATLAS-CONF-2016-081

- Fitted VBF and ggF contours

  Dominant systematics:

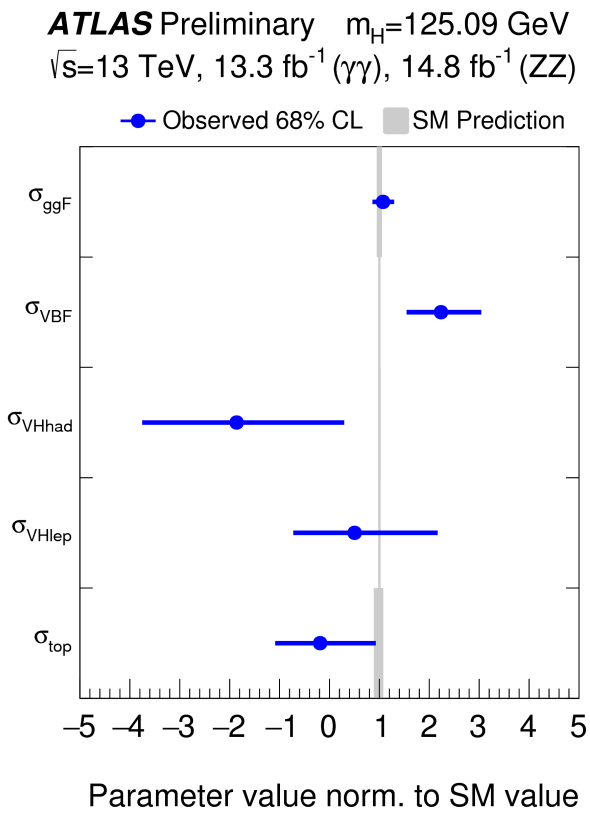
  e/γ energy resolution, γ identification efficiency

  Theory: ggF acceptance in events with fixed number of jets



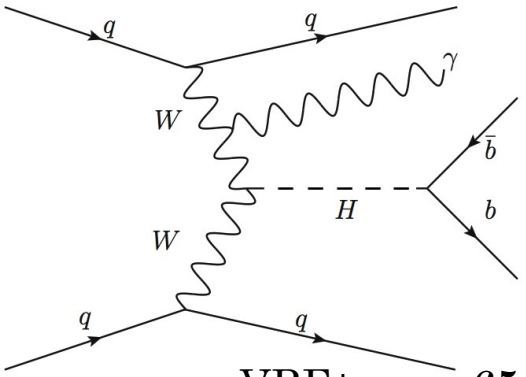
- Production cross sections assuming SM BR:

  Compatibility with SM: p_{SM} = 21%

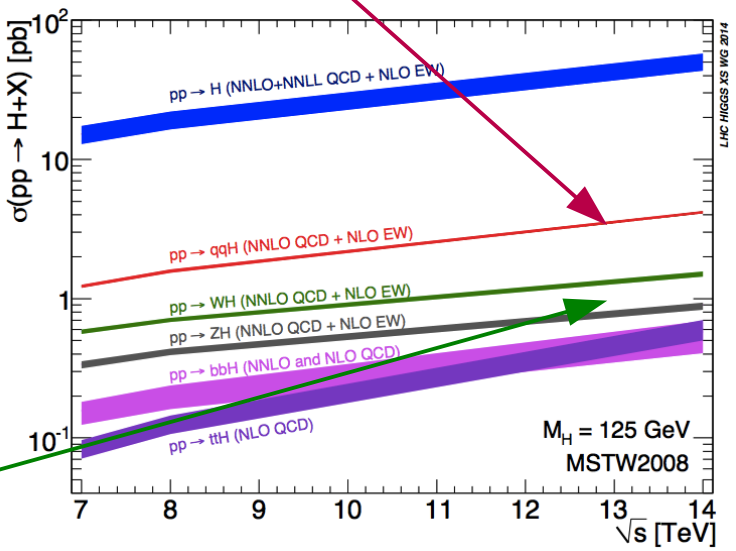


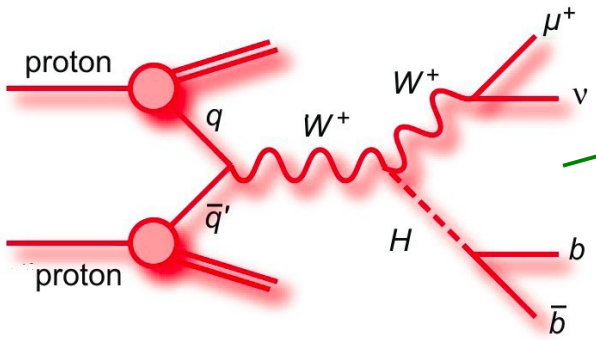
H → bb searches

- Explore non-dominant production modes
- Vector boson fusion + photon (VBF search)
  - Use photon to trigger
  - bbγjj non-resonant bckg. suppressed by ~10×
- Previous inclusive VBF (H→bb) limits:
  - ATLAS: obs/expect. upper limit : 4.4/5.4 × SM
  - CMS Run 1 obs/expect. upper limit: 5.5/2.5 × SM
  - CMS Run 2 (2015)
    - obs/expect. upper limit: 3.0/5.0 × SM
- Associated production with W or Z (VH search)
  - Trigger on e/μ from W/Z decay



VBF+γ: σ = 65.98 fb





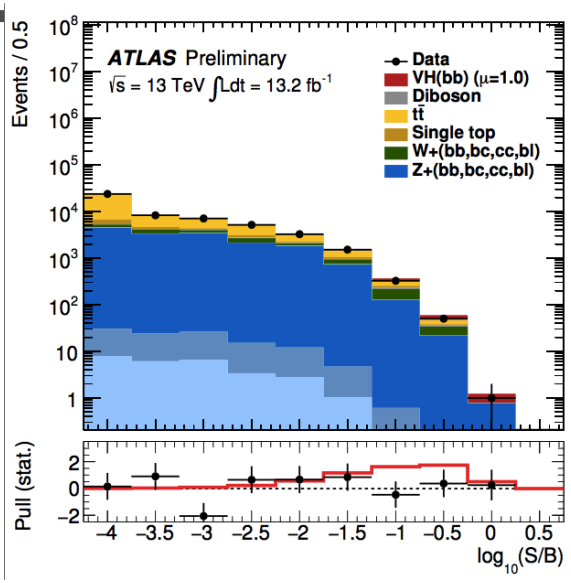
WH: σ = 1.373 pb
ZH: σ = 0.884 pb

WH and ZH with H → bb

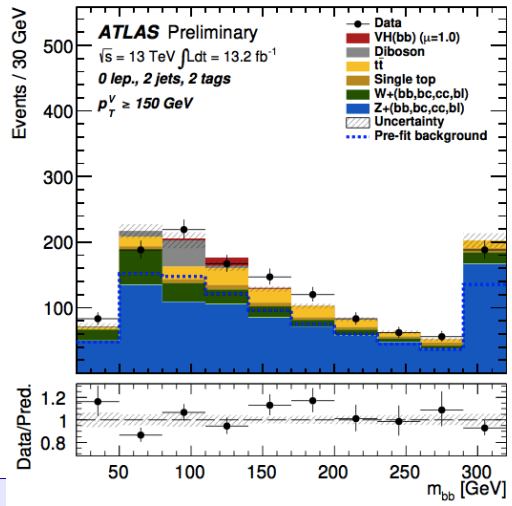
- 3 channels: 0, 1, 2 leptons
- 8 event categories

  0/1/2 leptons, 2/3 (or ≥3) jets, p_T^V >/< 150 GeV
- BDT discriminant
- Profiled likelihood fit to measure signal strength

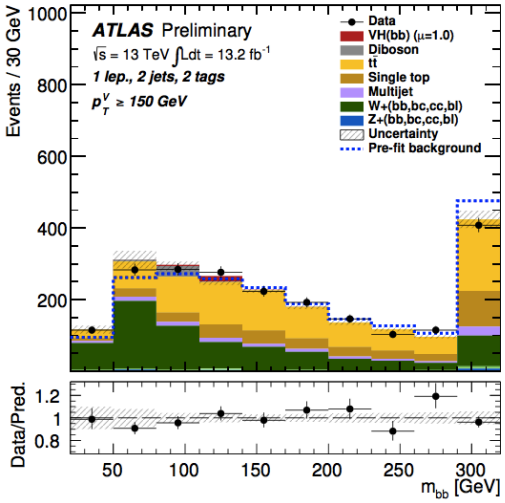
  Constraint main backgrounds



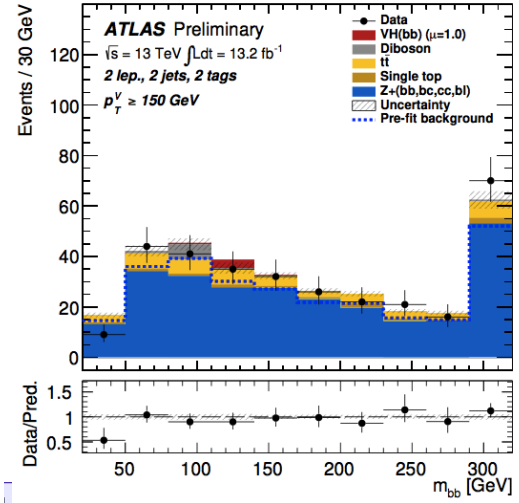
0 lepton



1 lepton



2 leptons



Results H→bb in association with a W or Z

- Combined signal strength with 13.2 fb^{-1} of pp collisions at √s= 13 TeV

$$\mu_{VH,\,H\to bb} = 0.21^{+0.51}_{-0.50}$$

Systematic and statistical uncertainties of the same size

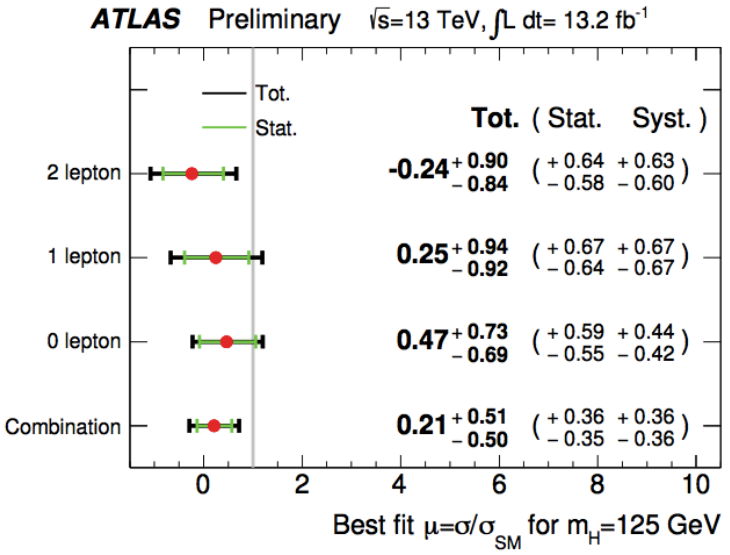
Dominant systematics from b-tagging and background normalization & modelling (W+jets, Z+jets, top)

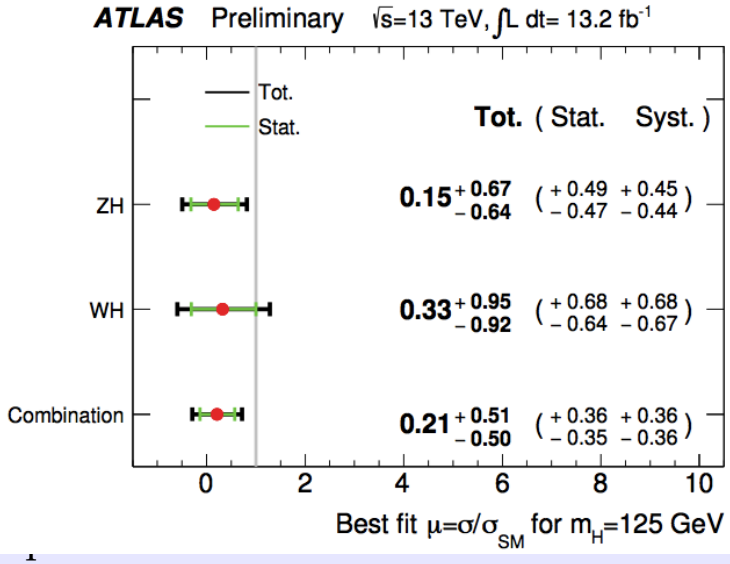
- Fit cross checked with di-boson signal (WZ+ZZ with Z→bb)

Observed significance: 3.2σ

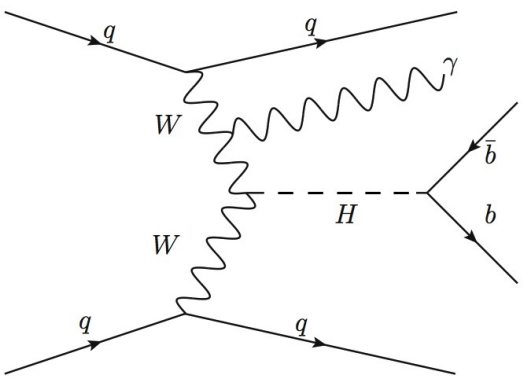
$$\mu_{VZ} = 0.91 \pm 0.17\,(stat)^{+0.32}_{-0.23}\,(sys)$$

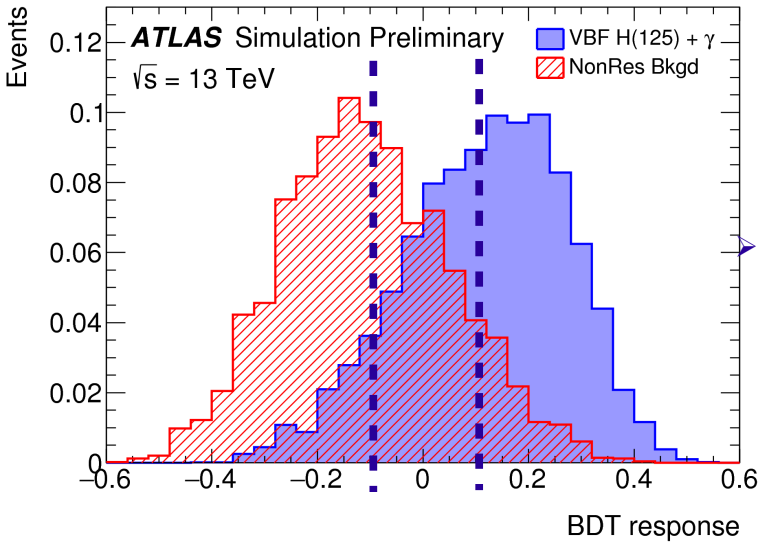
ATLAS-CONF-2016-091





Search for H → bb in VBF+γ production





- Trigger:
  - L1 trigger: single photon (p_T > 25 GeV)
  - High level trigger: 4 jets p_T > 35 GeV, m_{jj} > 700 GeV
- Selection:
  - Tight ID photon, p_T > 30 GeV
  - 4 jets with p_T > 40 GeV
    - 2 central (|η|<2.5) b-tagged jets
    - p_T(bb system) > 80 GeV
    - Non b-tagged jets: m_{jj} > 800 GeV
- BDT discriminant
  - Built with variables uncorrelated to m_{bb}

$$\Delta R(jet, \gamma),\ m_{jj},\ \Delta\eta_{jj},\ H_T^{soft},\ jet\ width,\ \gamma\ centrality,\ p_T^{balance}$$

  - Define 3 regions with different S/B
  - Fit m_{bb} in these 3 regions

H→bb VBF+γ results

ATLAS-CONF-2016-063

- Use a profile likelihood fit
- Non resonant background estimated with 2nd order polinomial fit in m_{bb} sideband
- Fit tested searching for Z→bb + γ production:

  Expected 95% CL limit: $1.8^{+0.7}_{-0.5}$

  Observed: 2.0

- Observed signal strength in the Higgs search:

  $\mu_{H,VBF+\gamma} = -3.9^{+2.8}_{-2.7}$

- Expected 95% CL limit:

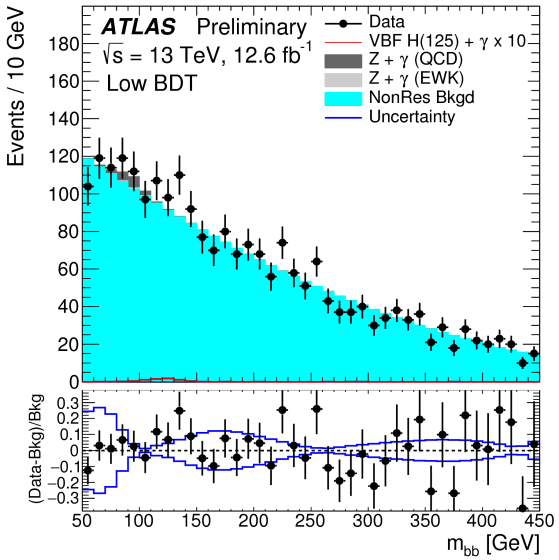
  $6.0^{+2.3}_{-1.7}$

- Observed 95% CL limit:

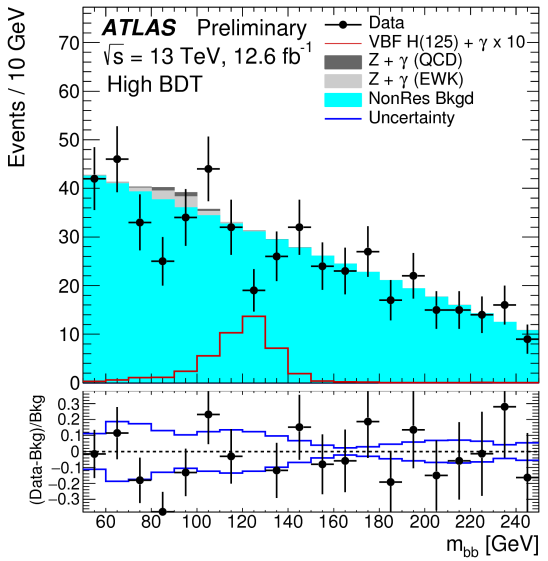
  $4\times(\sigma\times BR)^{SM}$

Result	$H(\to b\bar{b})+\gamma jj$	$Z(\to b\bar{b})+\gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0^{+2.3}_{-1.7}$	$1.8^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9^{+2.8}_{-2.7}$	0.3 ± 0.8

- Low BDT score region:



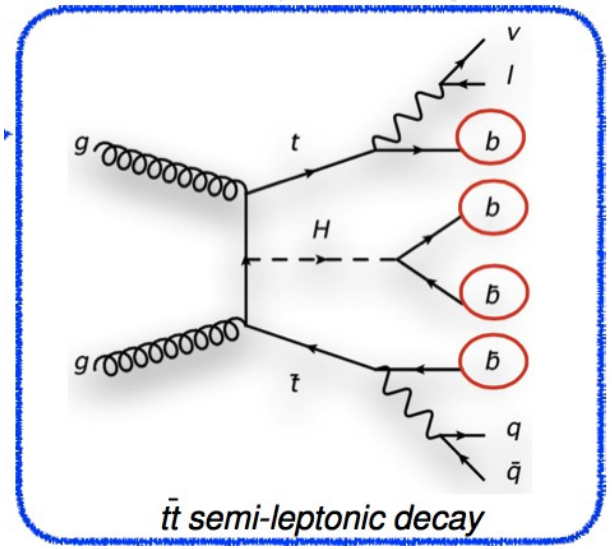
- High BDT score region



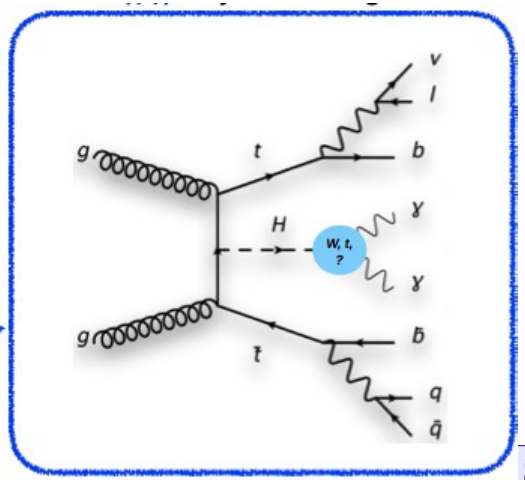
Search for Higgs boson in ttH production

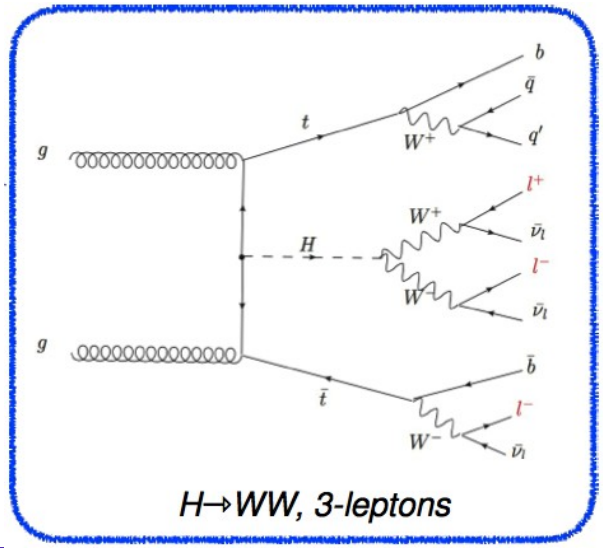
- Many possible final states

Higgs decay mode	Branching ratio [%]
H→ bb	58.1
H→ WW	21.5
H→ ττ	6.3
H→ ZZ	2.6
H→ γγ	0.23



$t\bar{t}$ semi-leptonic decay

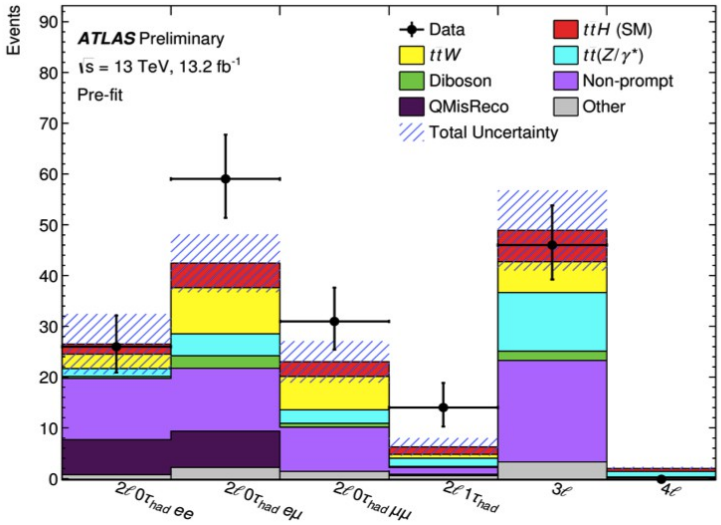




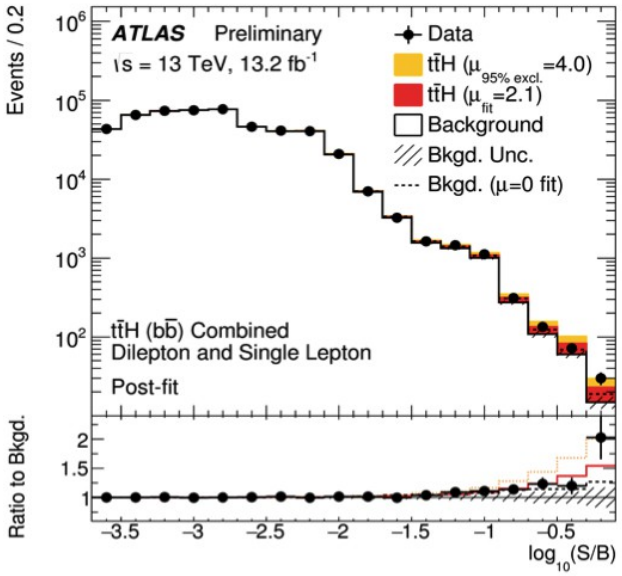
H→WW, 3-leptons

Search for Higgs boson in ttH production

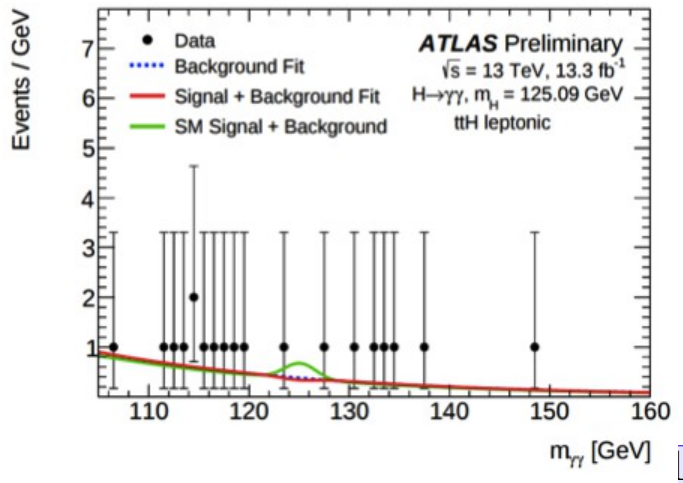
- Multi-leptons: cut and count in different event categories



- BDT discriminant in ttH (H→bb)

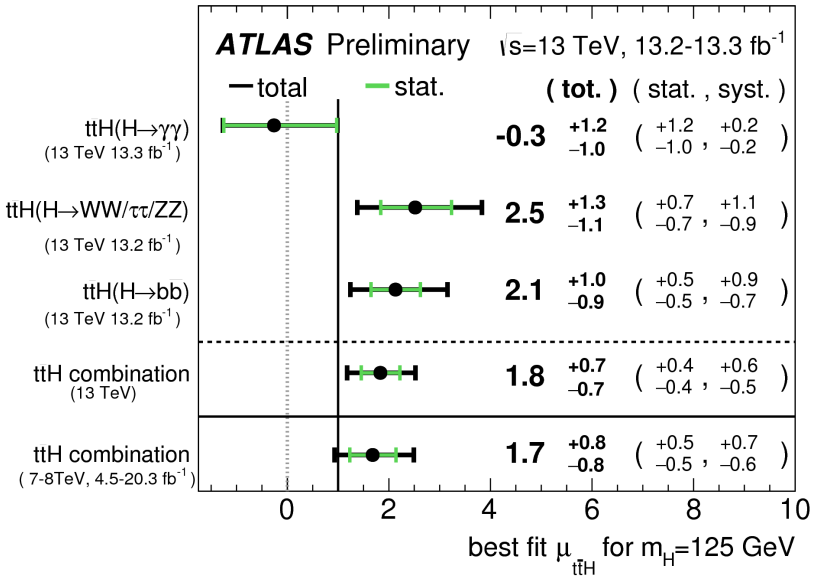


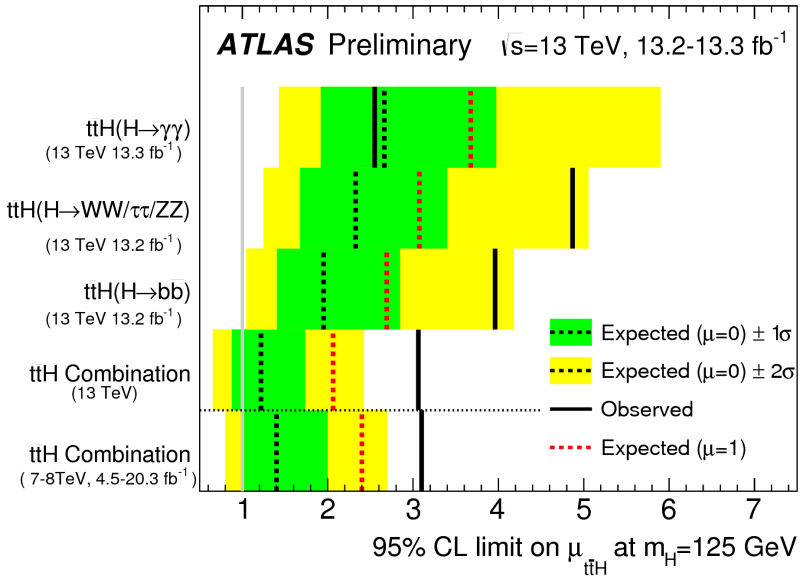
- $m_{\gamma\gamma}$ in ttH (H→γγ) leptonic events



Results on ttH Higgs searches

- Combined signal strength: $\mu = 1.7^{+0.5}_{-0.5}(stat)^{+0.7}_{-0.6}(sys)$





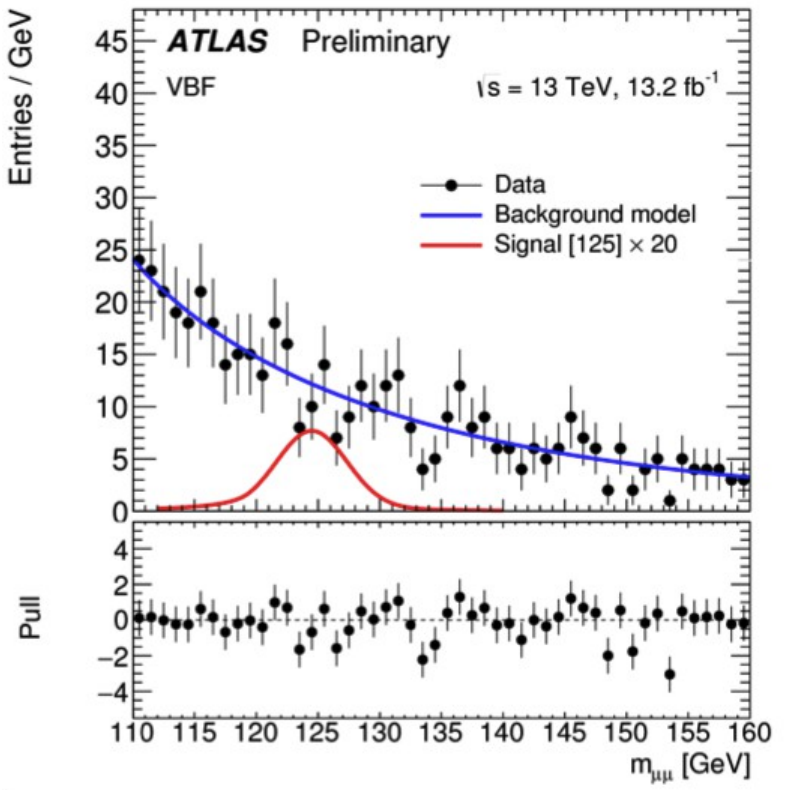
- Expected and observed significance:

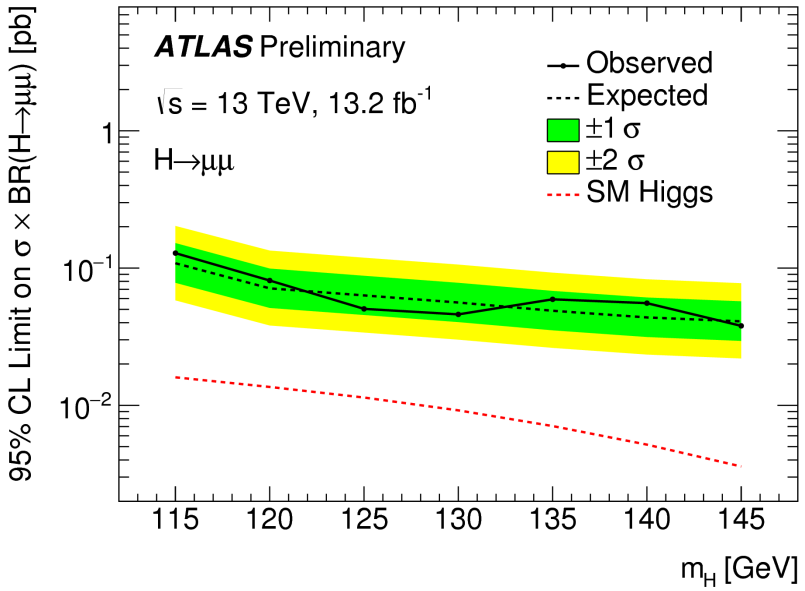
Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H, H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H, H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H, H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

Search for the Higgs decays to muons

ATLAS-CONF-2016-041

- Very rare decay in the SM but important to probe Yukawa coupling to second generation fermions





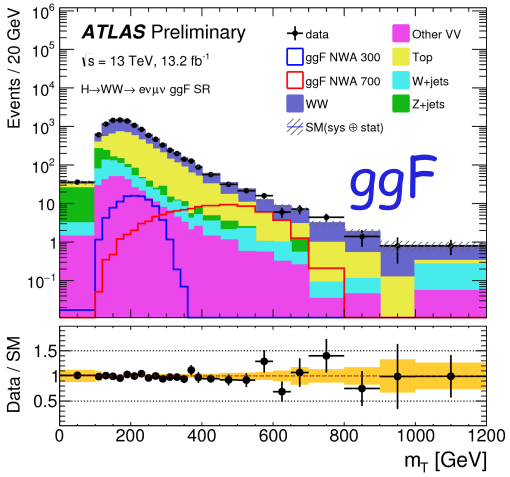
ATLAS	Upper limit x SM (expected)
Run 1	7.1 (7.2)
Run 2	4.4 (5.5)
Combined Run 1 and Run 2	3.5 (4.5)

Beyond the Standard Model Searches

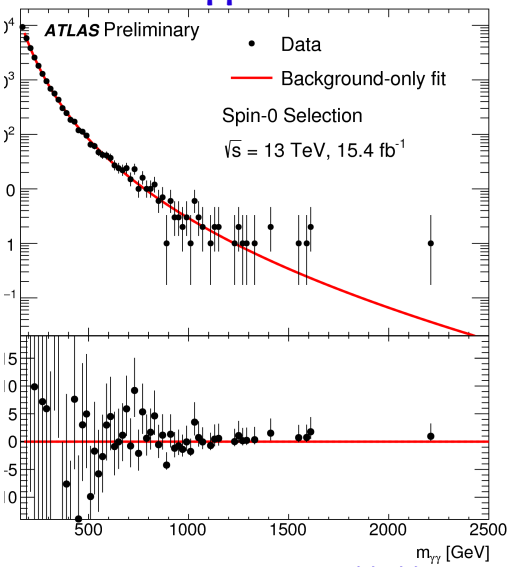
- High mass resonnances
- CP odd Higgs: $A \rightarrow Zh \rightarrow \ell\ell bb$
- Charged Higgs: $H^{+} \rightarrow \tau\nu$, $H^{+} \rightarrow tb$

High mass neutral Higgs boson searches

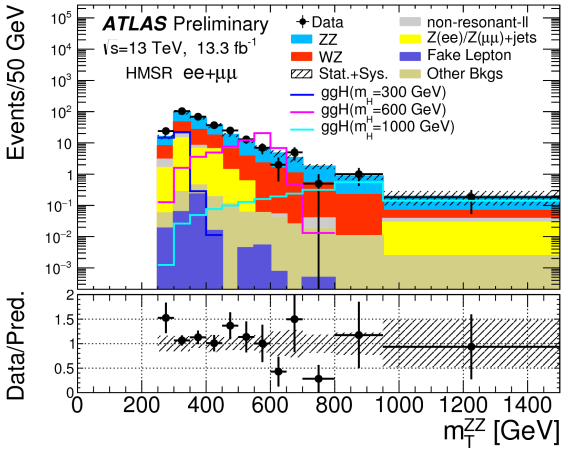
- $X \to WW \to \ell\nu\,\ell\nu$



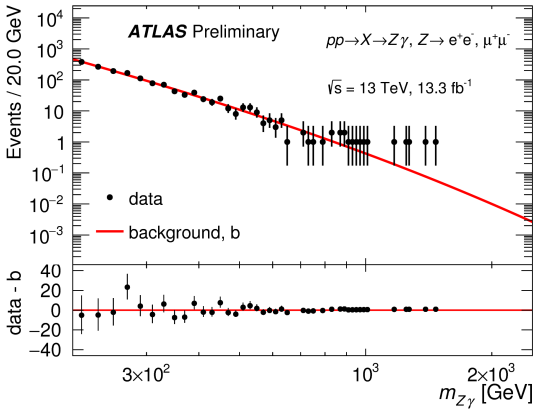
- $X \to \gamma\gamma$



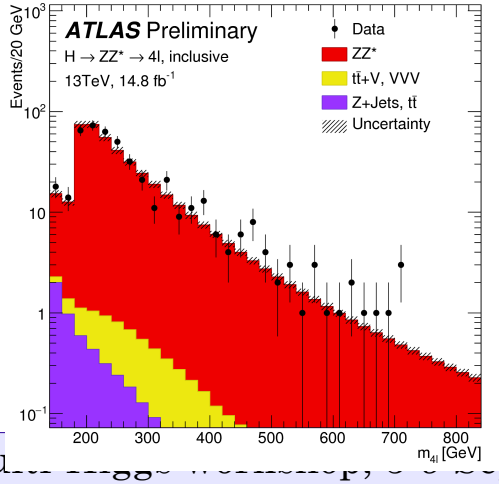
- $X \to ZZ \to \ell\ell\nu\nu$



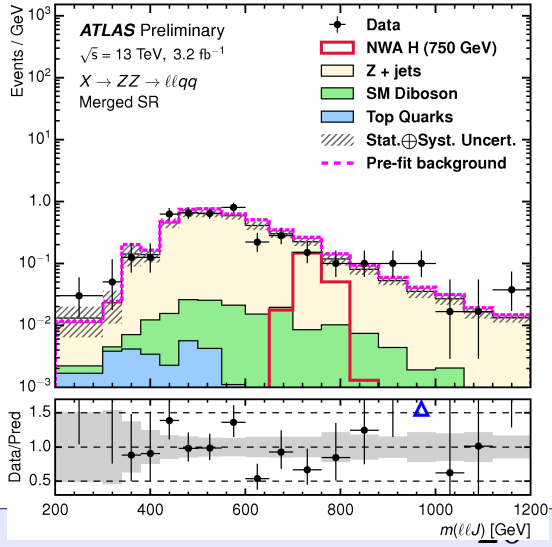
- $X \to Z\gamma$



- $X \to ZZ \to \ell\ell\,\ell\ell$

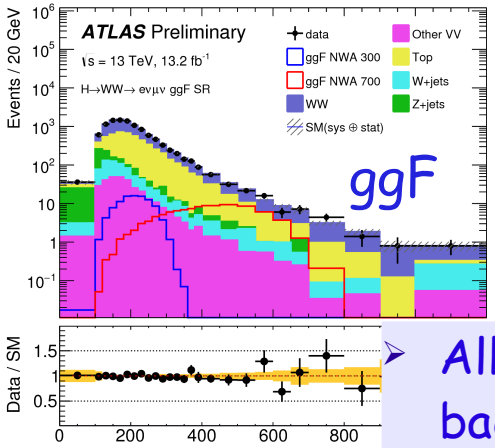


- $X \to ZZ \to \ell\ell qq$

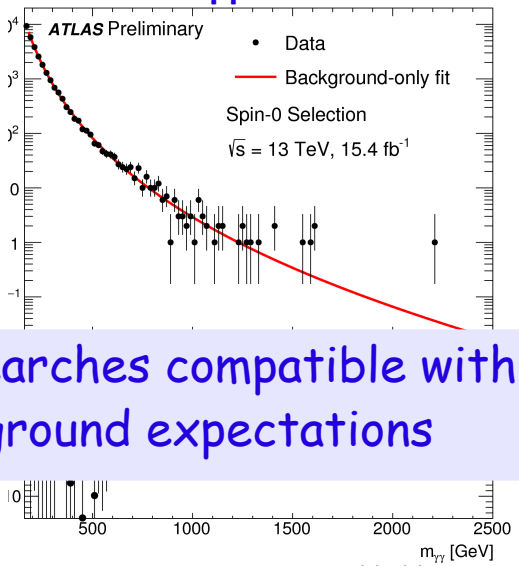


High mass neutral Higgs boson searches

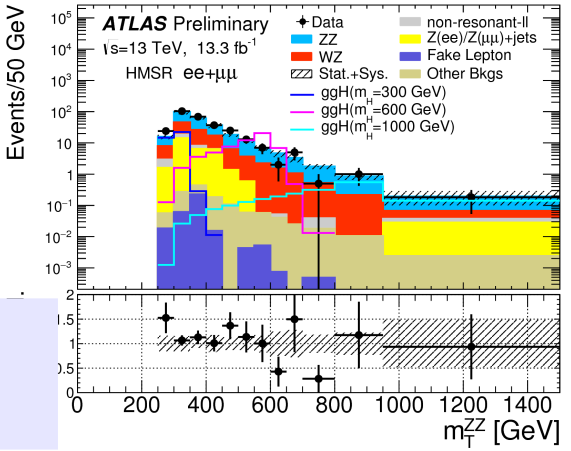
- $X \to WW \to \ell\nu\,\ell\nu$



- $X \to \gamma\gamma$

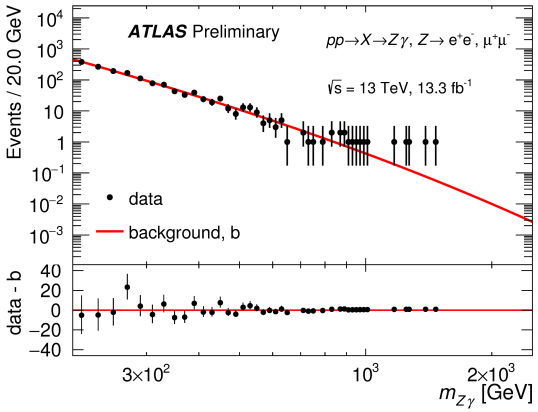


- $X \to ZZ \to \ell\ell\nu\nu$

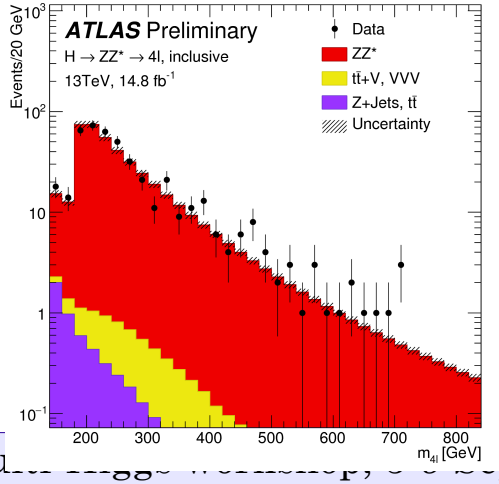


- All searches compatible with SM background expectations

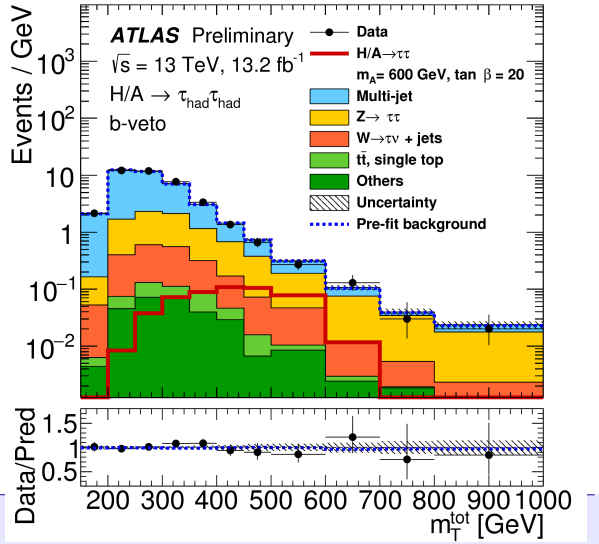
- $X \to Z\gamma$



- $X \to ZZ \to \ell\ell\,\ell\ell$



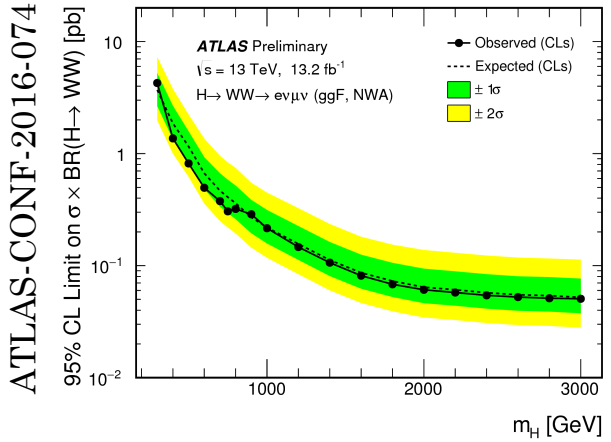
- $X \to \tau\tau$



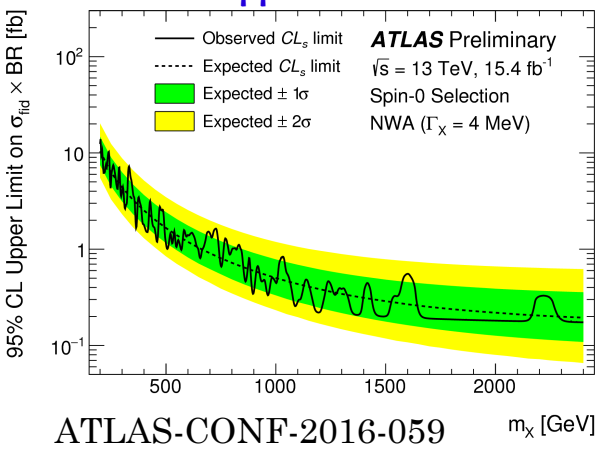
Limits on neutral high mass Higgs bosons

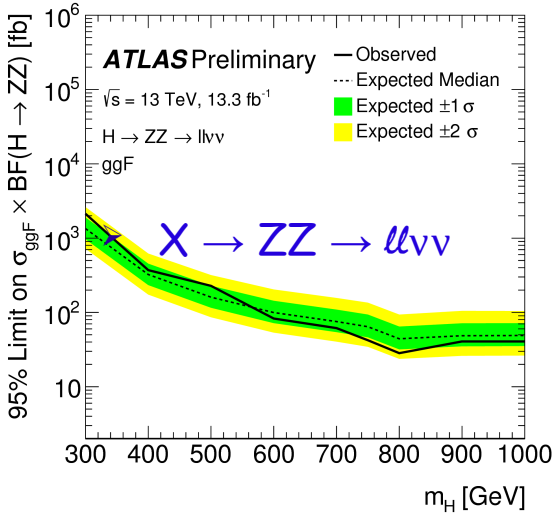
- Limits defined for different production modes in most cases

- $X \to WW \to \ell\nu\,\ell\nu$

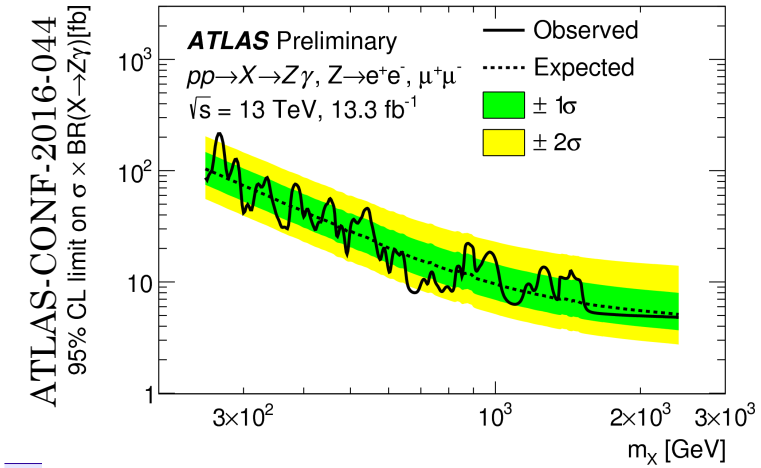


- $X \to \gamma\gamma$

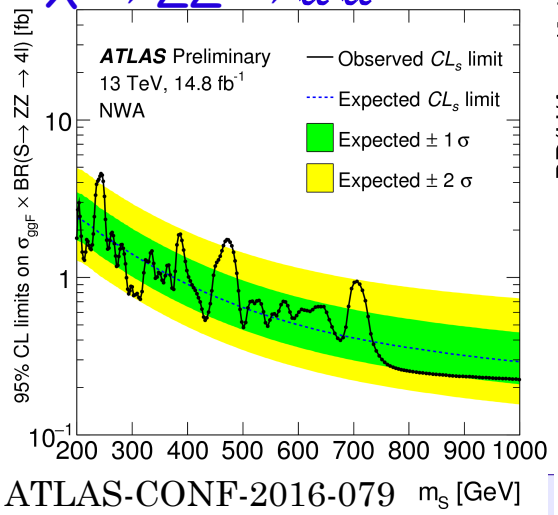


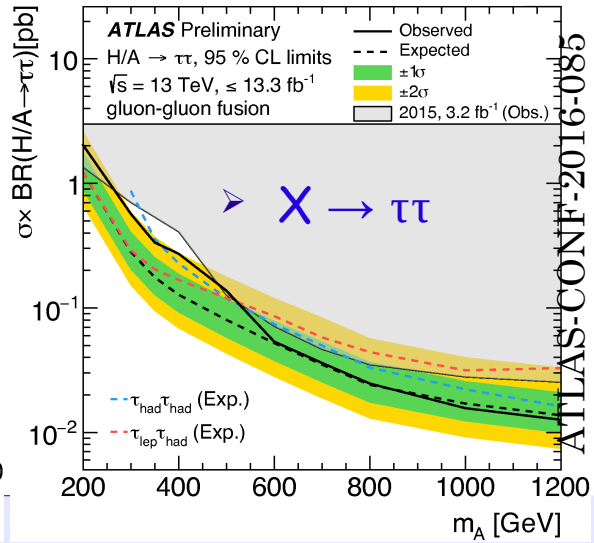


- $X \to Z\gamma$



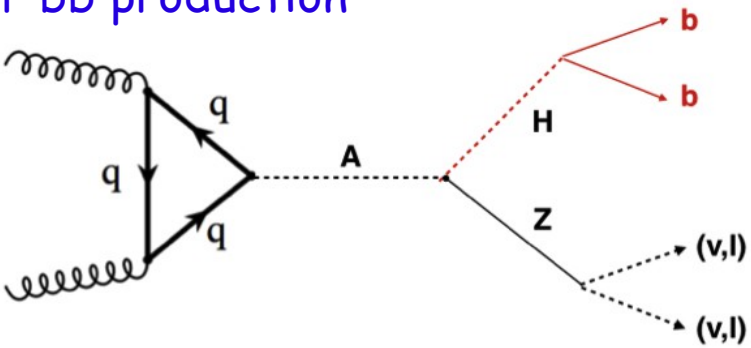
- $X \to ZZ \to \ell\ell\,\ell\ell$



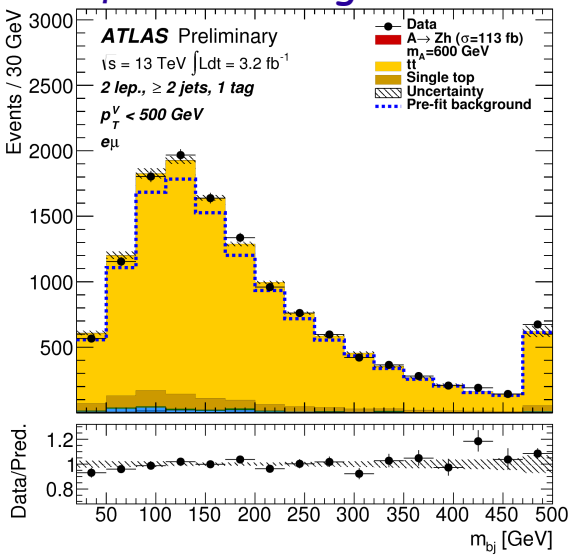


Search for a CP-odd Higgs A→Zh with h→bb

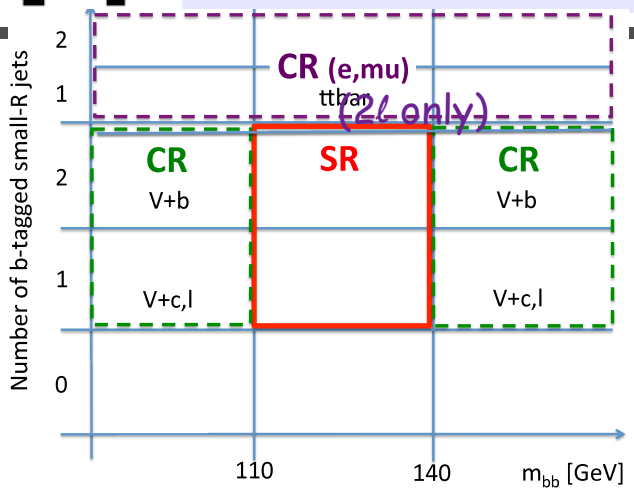
- Search for a CP-odd Higgs in gg fusion or bb production
  - Predicted by two Higgs doublet models
  - 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV
- Two channels:
  - 2 leptons: A→Zh→ ℓℓbb
  - 0 leptons: A→Zh→νν̄bb
- h→bb reconstruction:
  - p_T^Z < 500 GeV: Two calorimeter jets R=0.4
  - p_T^Z > 500 GeV: boosted regime
    - calorimeter jet R=1.0, trimmed
    - b-tagging on track-jets R=0.2
- Search for a resonance in the invariant mass
- Use dedicated control regions for background modelling



eμ control region

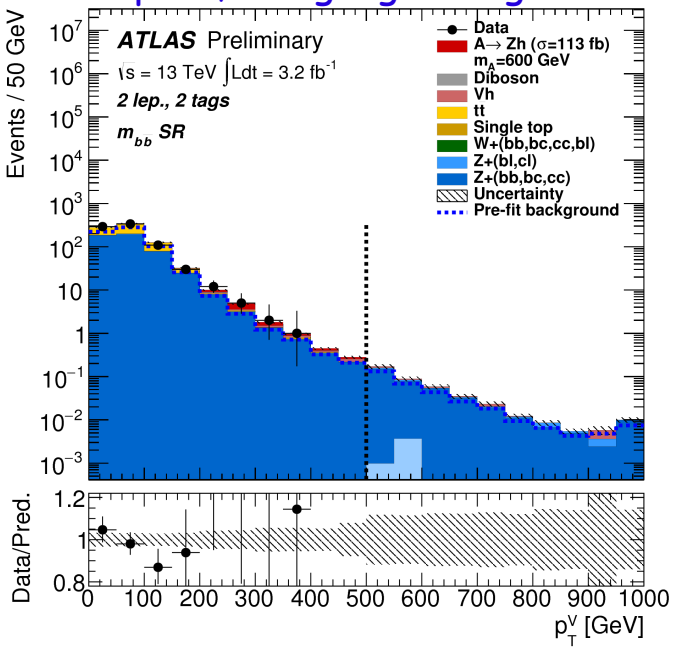


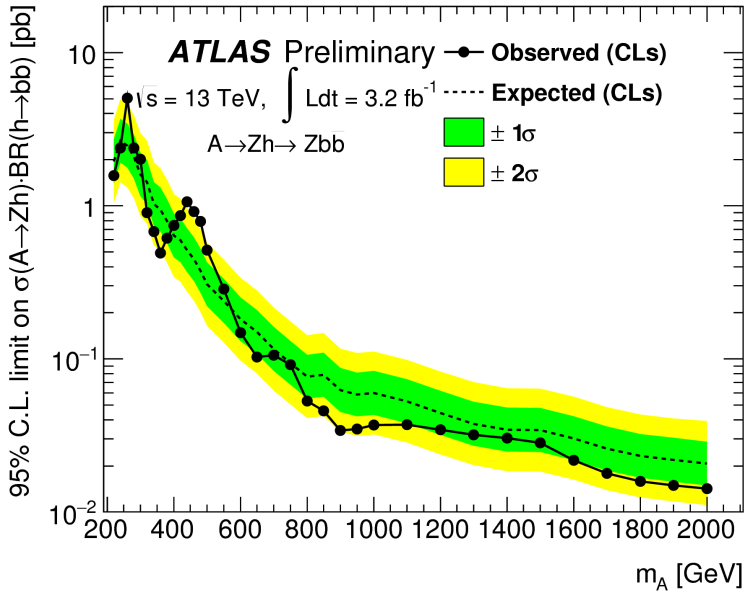
Results of the search for A→Zh with h→bb



- Profiled likelihood fit considering signal and control regions
- Dominant systematic uncertainties:
  - calibration/resolution of small-R and large-R jets energy, large-R jets mass (high p_T^Z), b-tagging efficiency and mistag rate

- 2lepton, 2 tag signal region





Charged Higgs search channels

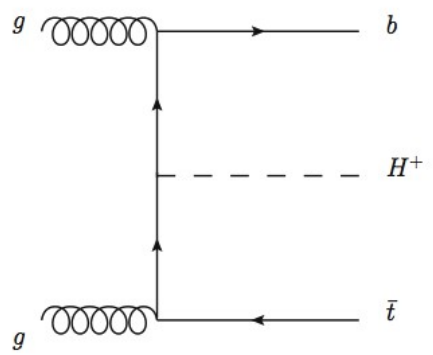
- Decay channels

  For $m_{H+} > 200$ GeV: tb final state dominate

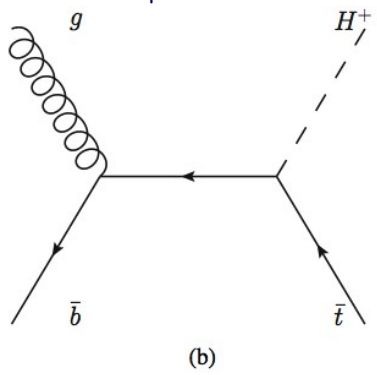
  For $m_{H+} < 200$ GeV: $\tau\nu$ decay dominates

- Production modes

$m_{H+} \leq m_{top}$



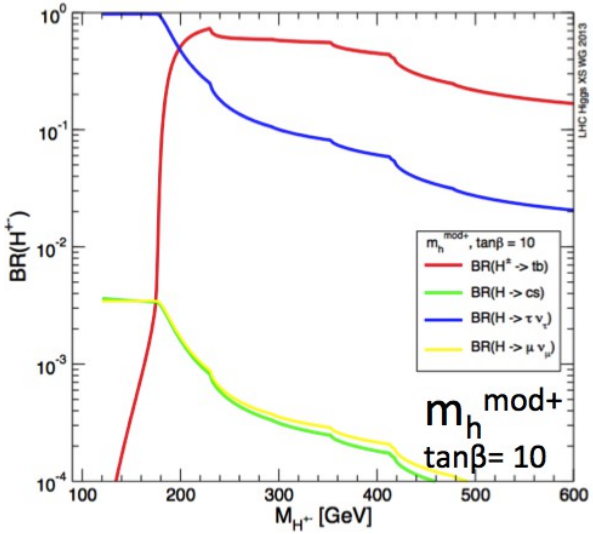
$m_{H+} > m_{top}$

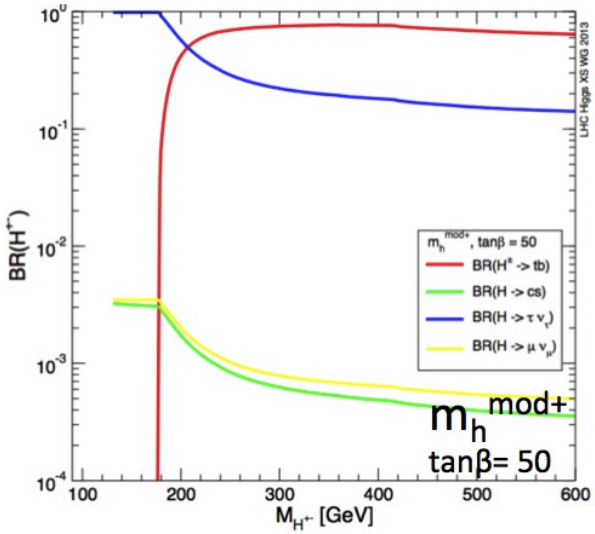


- Search channels

  $H^+ \rightarrow$ tb: 1 lepton, ≥4 jets (≥ 2 b-tags)

  $H^+ \rightarrow \tau\nu$: tau+ hadronic top decay

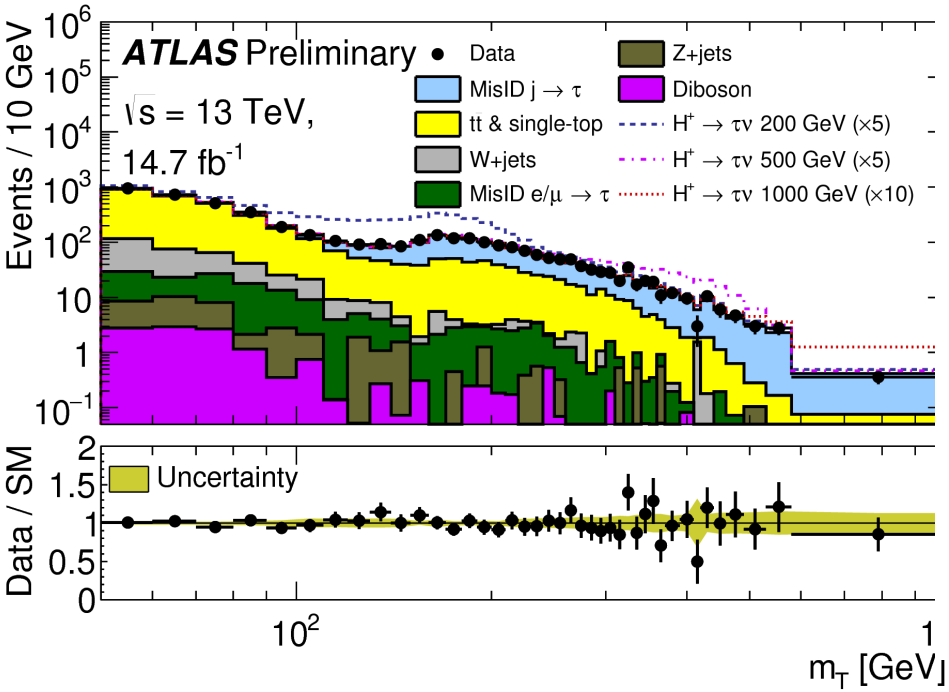




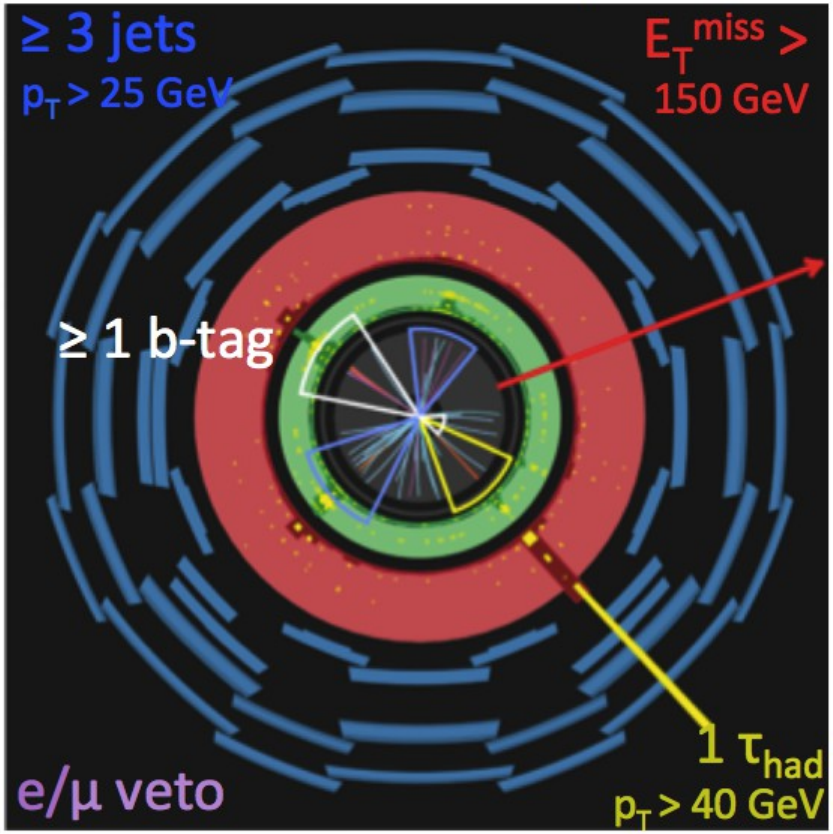
$H^+ \rightarrow \tau\nu$ Search

- Discriminant: transverse mass

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



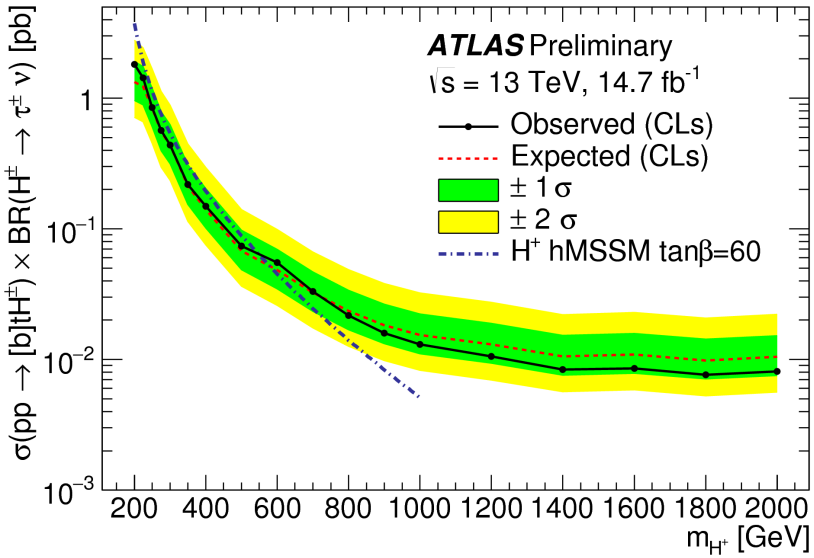
- Hadronic τ + hadronic top decay



$H^+ \rightarrow \tau\nu$ Search

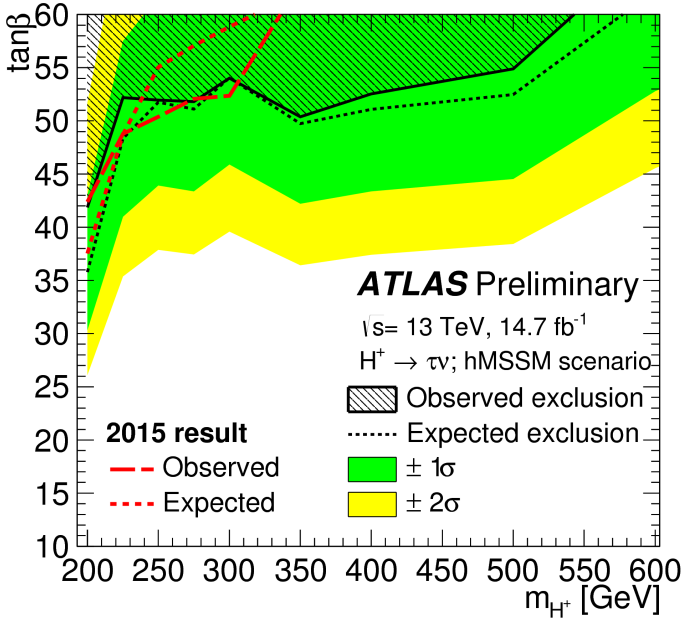
- Observed 95% Cls limits on σ×BR:

  2. pb- 8 fb



- Exclusion in the hMSSM scenario

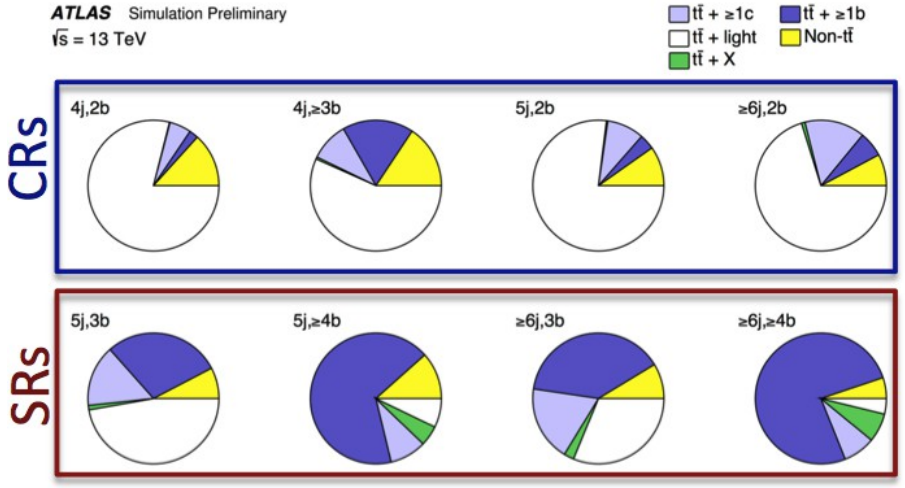
  Significant improvements over 2015 results

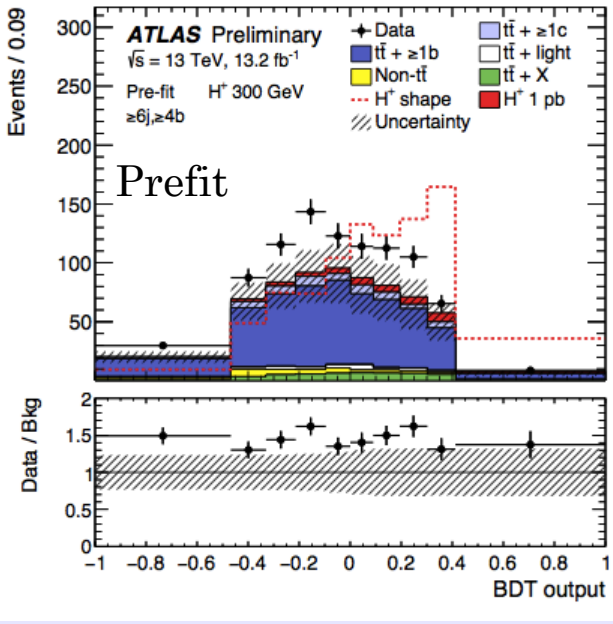


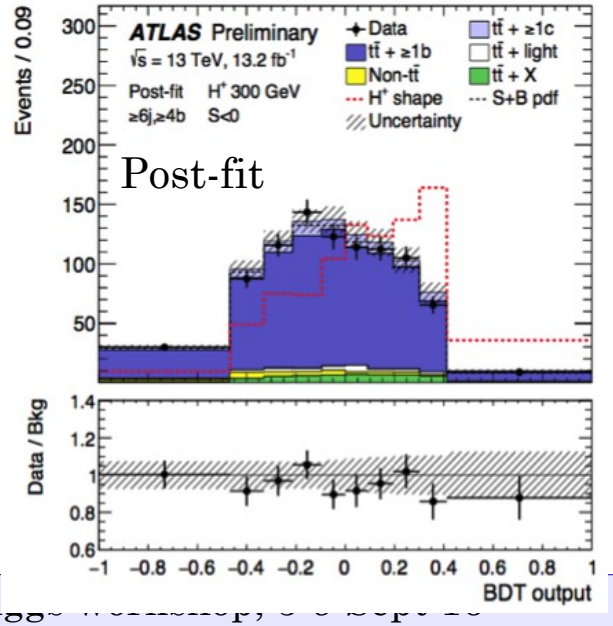
$H^+ \rightarrow bt$

- Isolated lepton with p_T > 25 GeV, ≥4 jets (≥2 b-tags)
- 4 signal and 4 control regions
- BDT discriminant
- Combined likelihood fit

  Constraint the backgrounds

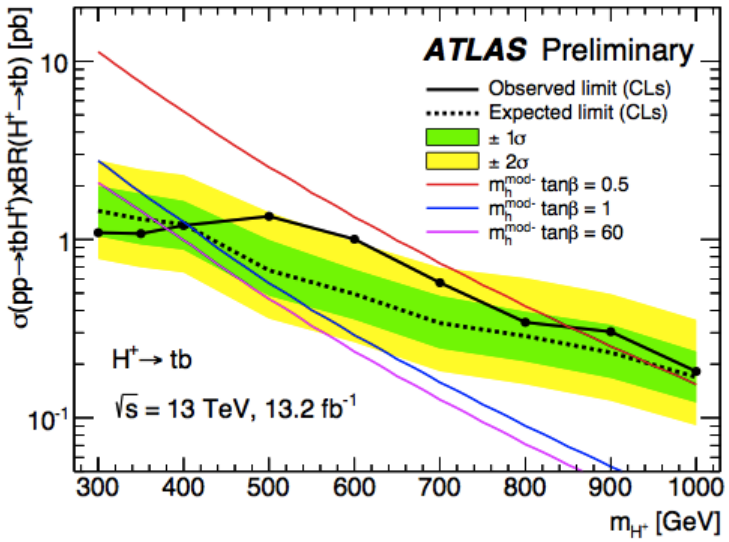




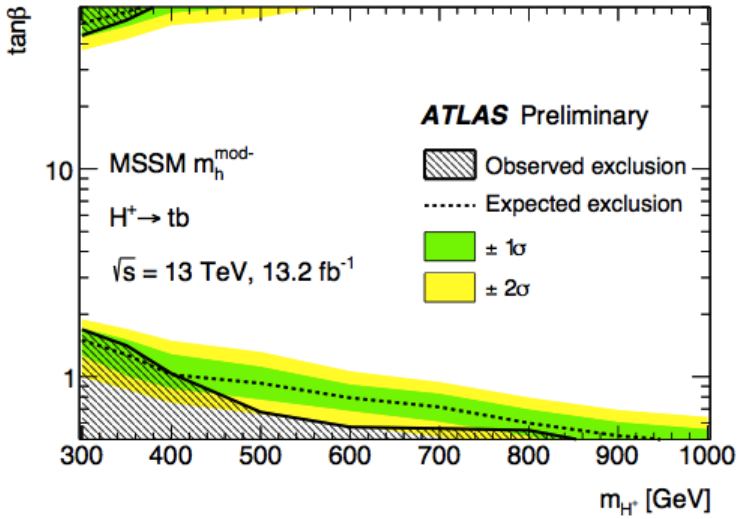


$H^+ \rightarrow bt$ results

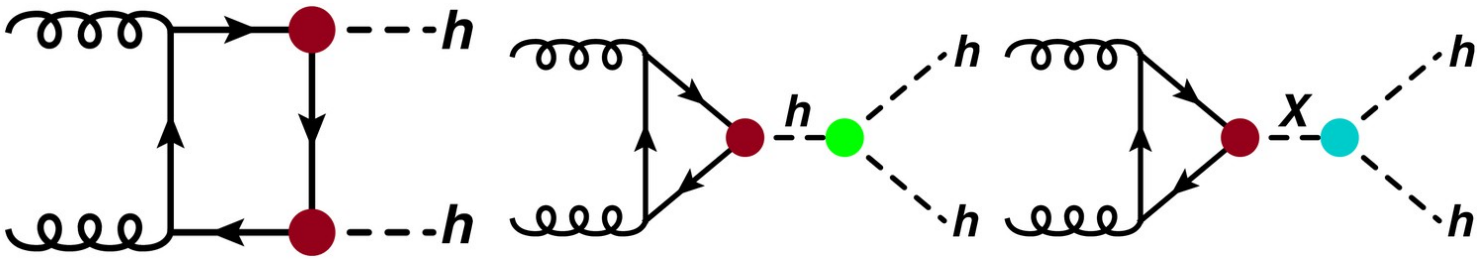
- Observed 95% Cls limits on σ×BR:
  1.1 pb- 0.18 pb



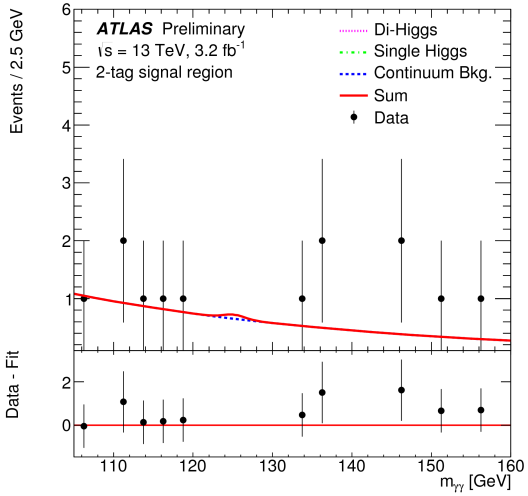
- Exclusion in the m_h^{mod-} MSSM benchmark model:
  Start to constraint high tan β



Search for HH production



- bbγγ final state



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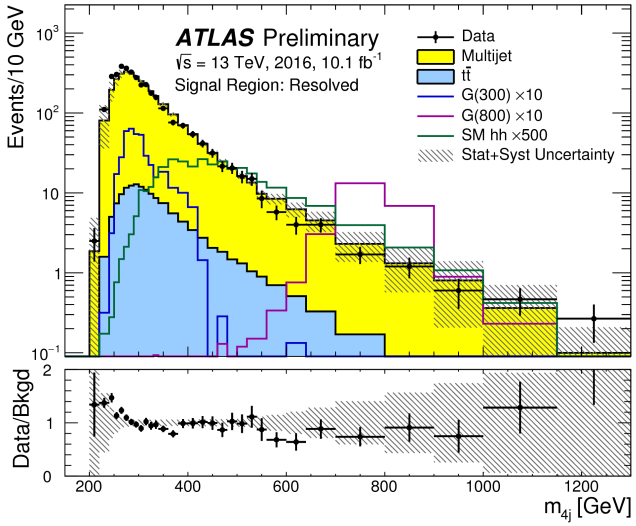
- bbbb final state



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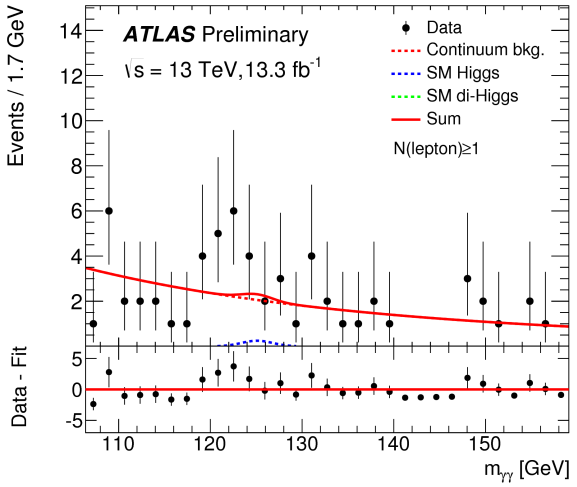
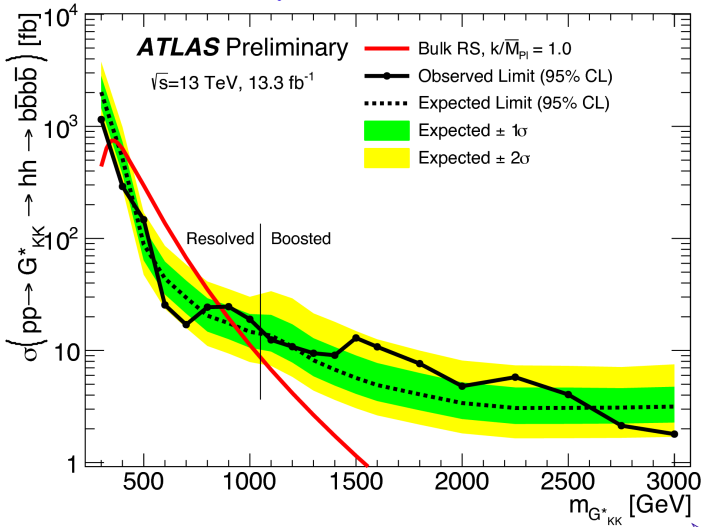
- WWγγ final state



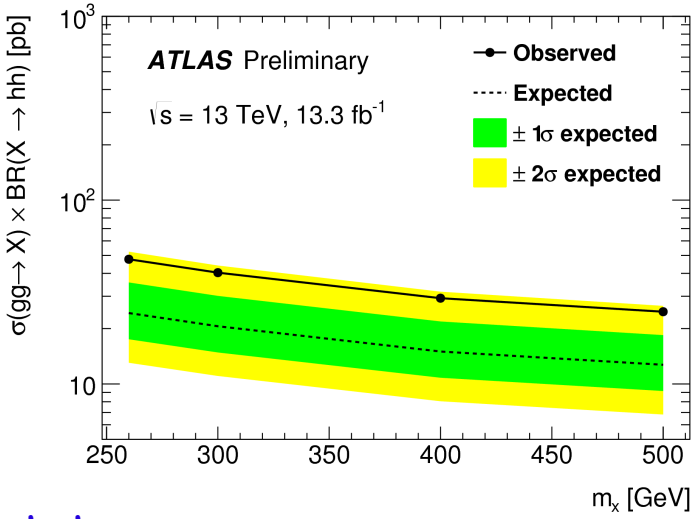
ATLAS-CONF-2016-071

Limits on HH production

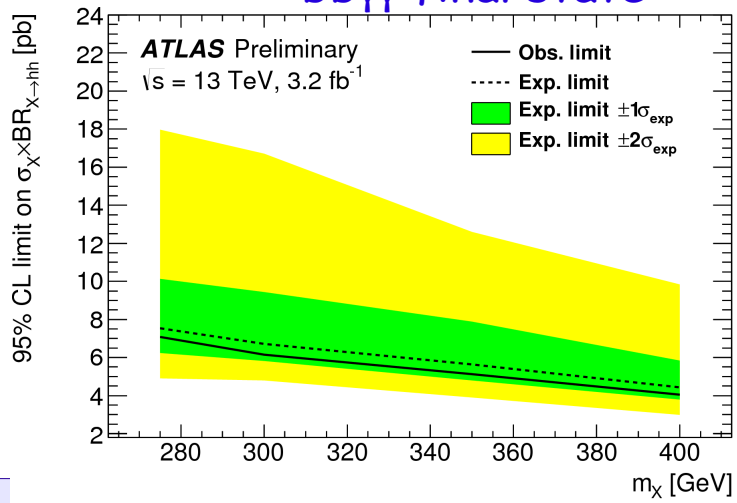
- bbbb final state



- WWγγ final state



- bbγγ final state



Summary and conclusions

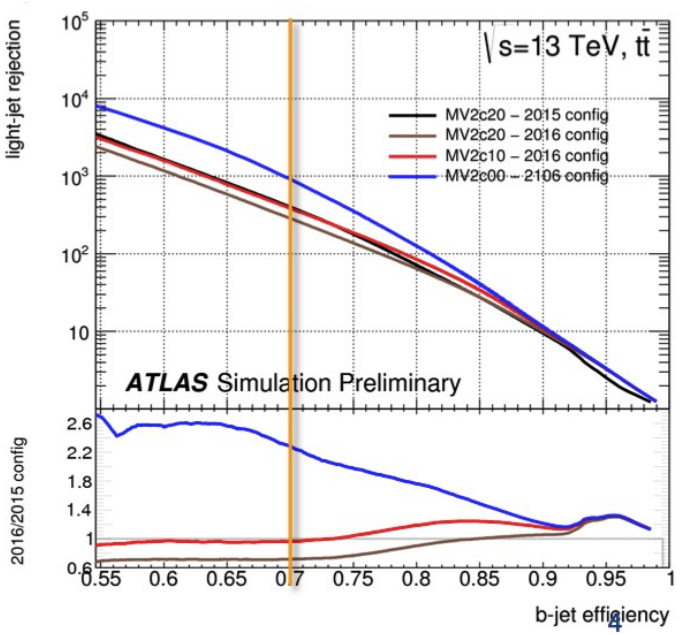
- After the discovery of the Higgs boson in 2012, the ATLAS collaboration has focused on the study of its properties
  - The Run 1 data at 7 and 8 TeV provided the first measurements, mainly in bosonic channels
  - With around 13 fb^{-1} of 13 TeV pp collisions we have
    - Re-discovered the Higgs boson in $H \rightarrow gg$ and $H \rightarrow ZZ \rightarrow 4l$ final states
    - Searched for the Higgs decaying to b-quark pairs
    - Searched for associated production with top quark pairs
    - Search for new Higgs boson in a large variety of channels
  - Reached sensitivity comparable/better than in Run 1
- Given the current performance of the LHC, we expect improved and new results in the future

Acknowledgements

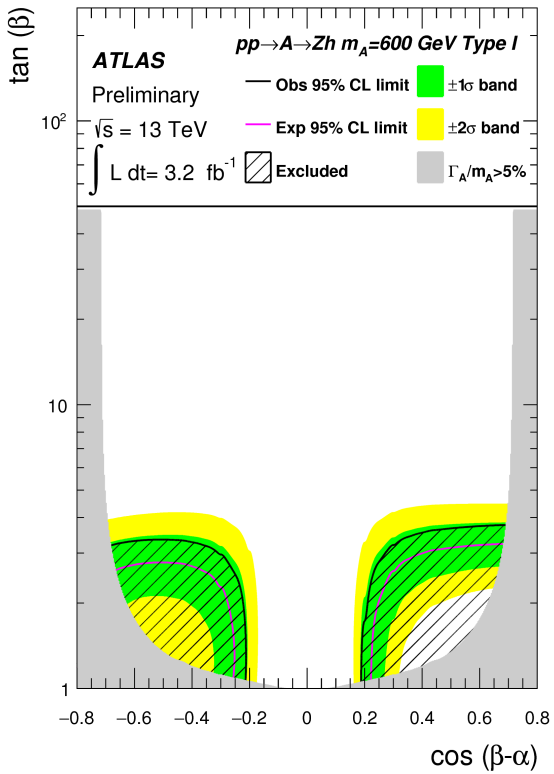
FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

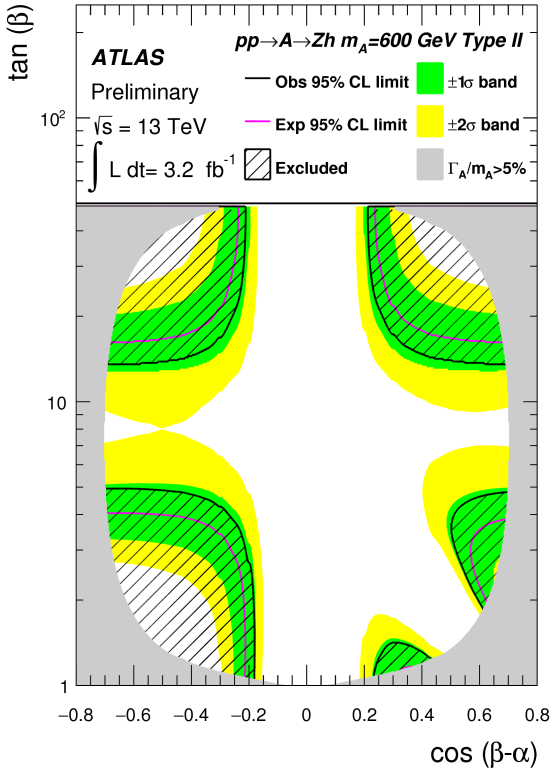
- OE, FCT-Portugal, CERN/FIS-NUC/0005/2015

Backup


light-jet rejection
10^5
10^4
10^3
10^2
10
$\sqrt{s}$=13 TeV, $t\bar{t}$
MV2c20 – 2015 config
MV2c20 – 2016 config
MV2c10 – 2016 config
MV2c00 – 2106 config
ATLAS Simulation Preliminary
2016/2015 config
2.6
2.2
1.8
1.4
1
0.6
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
b-jet efficiency

$A \rightarrow Zh$ with $h \rightarrow bb$





Search for H/A → tt

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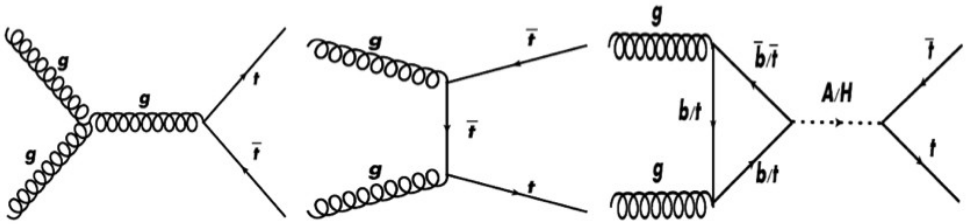
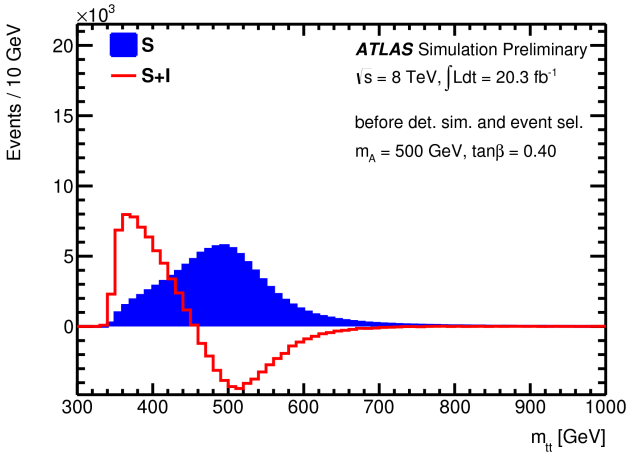
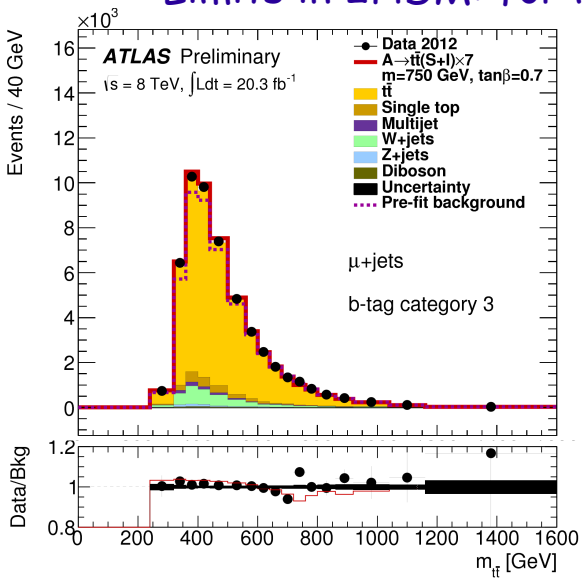
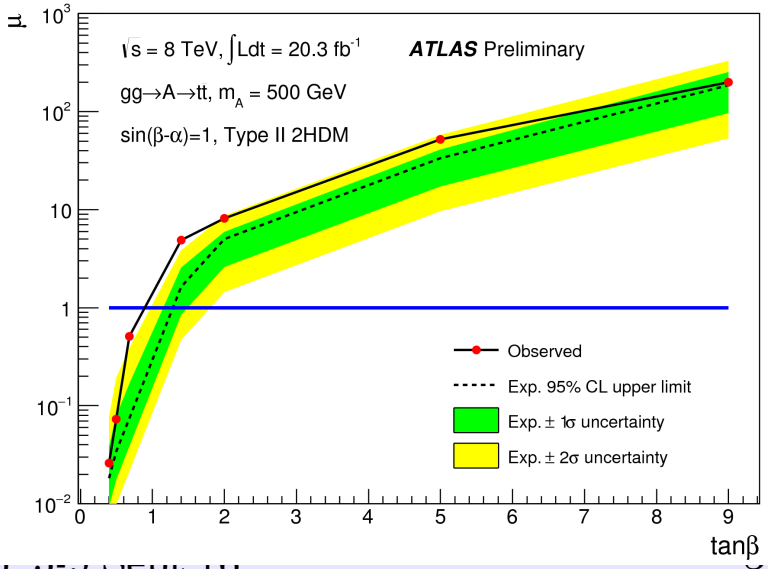


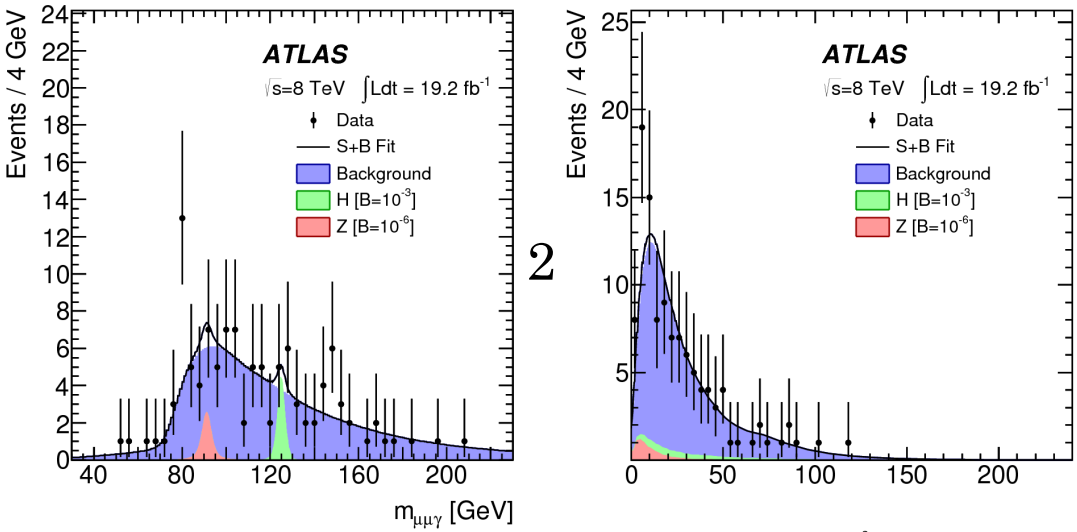


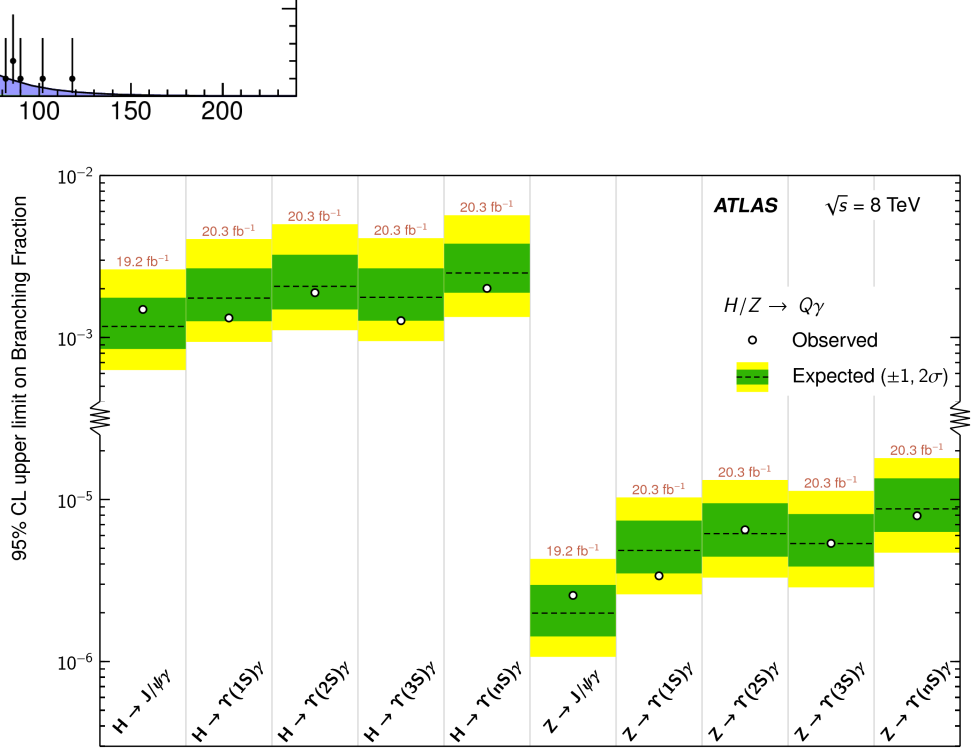
- Redone Run 1 analysis considering interference effects between signal and background
  - 6 different analysis categories
  - Limits in 2HDM: for m_A=500 GeV, tanβ<0.85 excluded



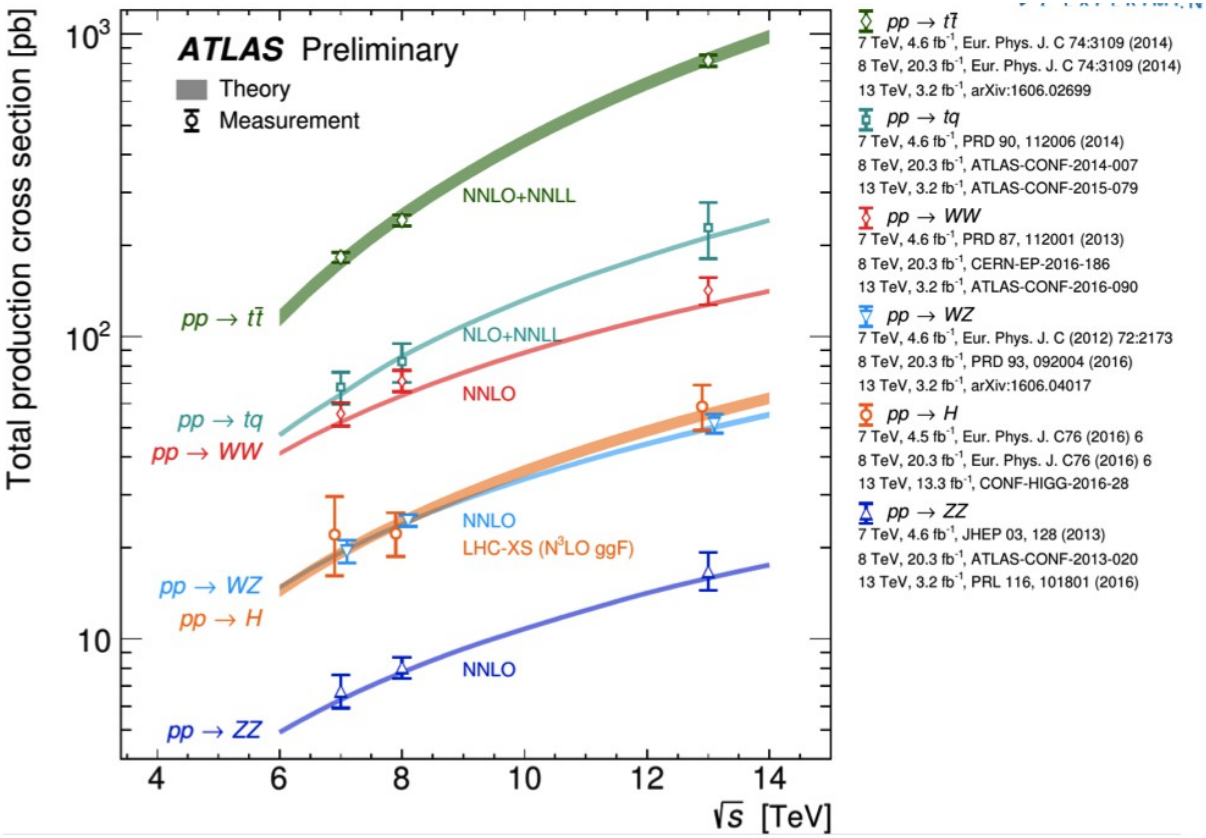


Search for H/Z decaying to J/ψ γ





Production cross sections of several processes



Search for new phenomena in $H \to \gamma\gamma + E_T^{miss}$

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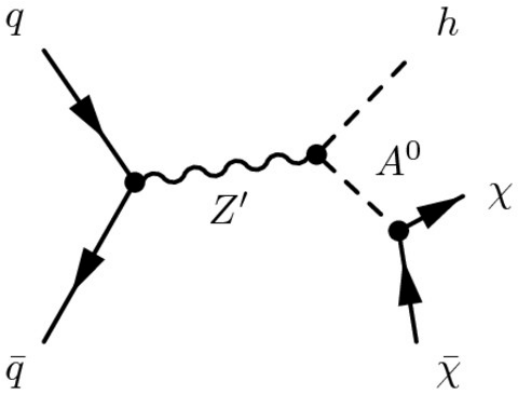
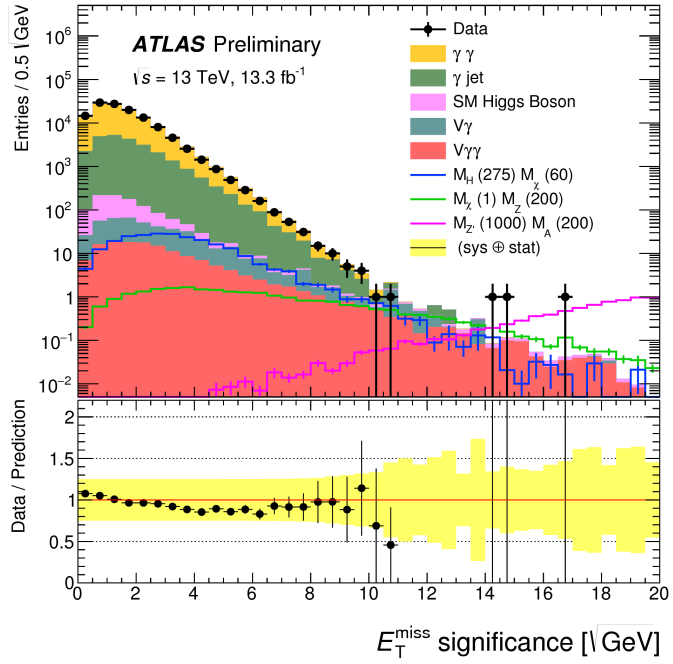
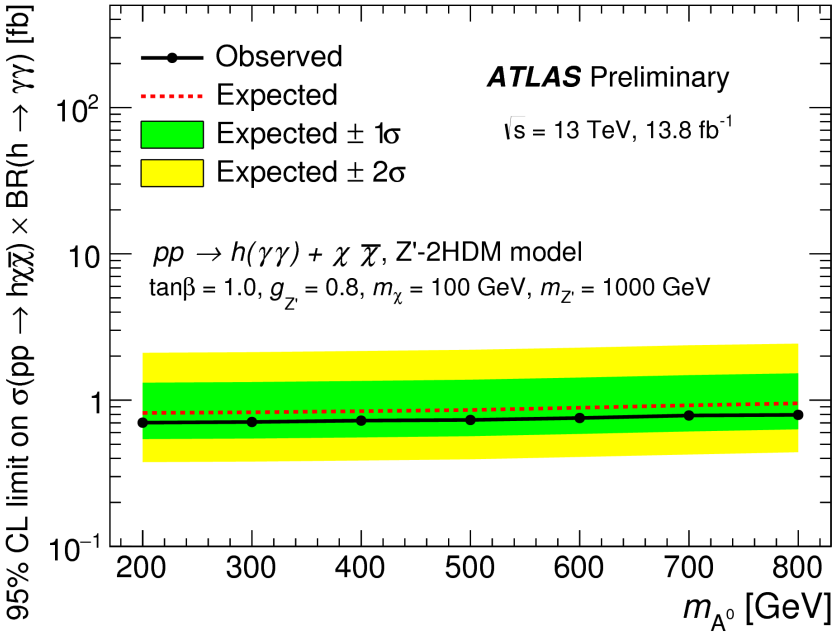


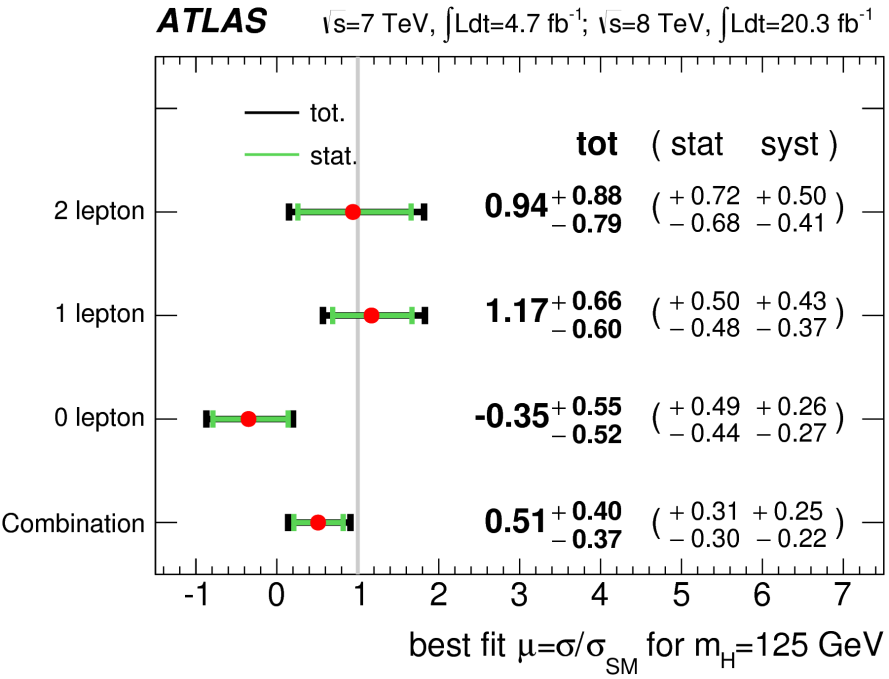


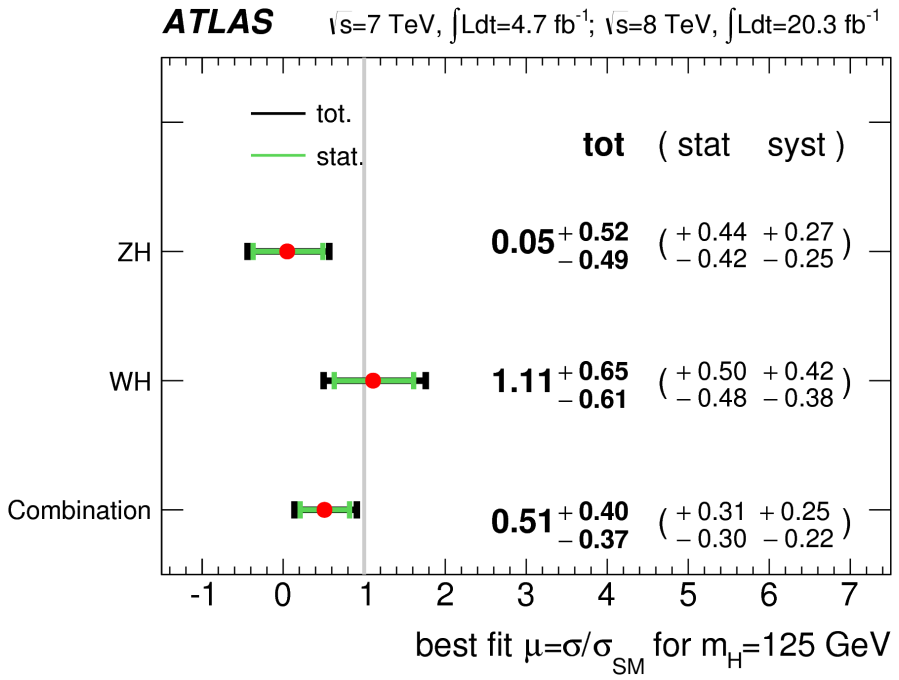


Run 1 VH (H→bb) results

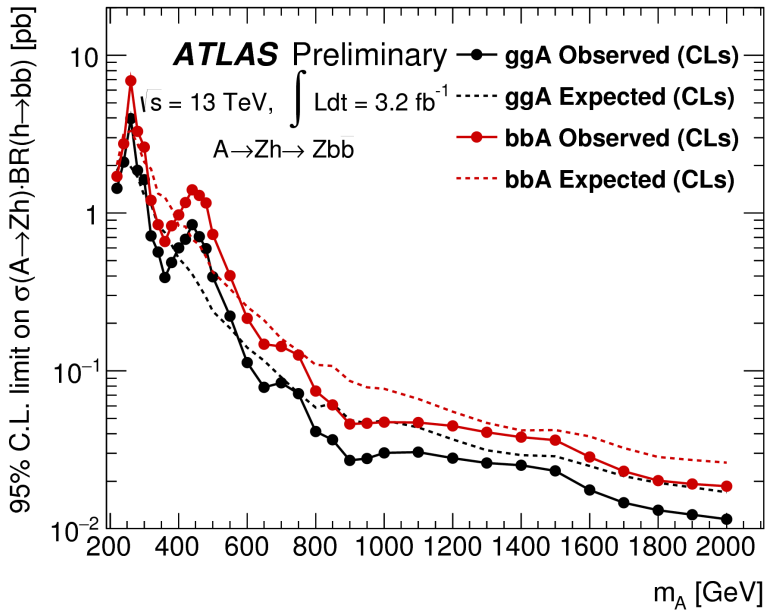
- Expected (observed) significance: 2.6 (1.6) for a mass of 125.36 GeV

$$\mu = 0.52 \pm 0.32\,(stat) \pm 0.24\,(sys)$$





- Search for a CP-odd Higgs boson $A \rightarrow Zh \rightarrow Zbb$ with 3.2 fb^{-1} of pp collisions at 13 TeV:



Di-photon resonance search