SM Higgs results from ATLAS+CMS

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on behalf of the ATLAS and CMS Collaborations

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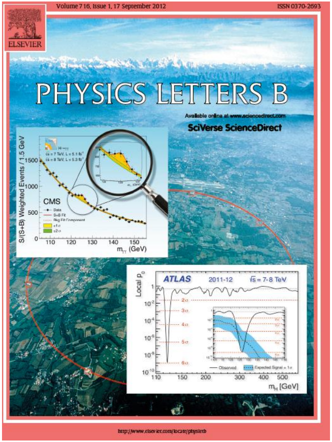
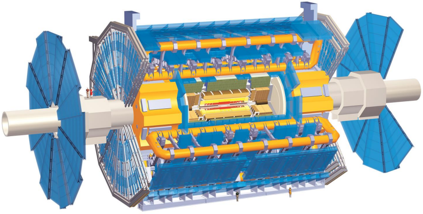
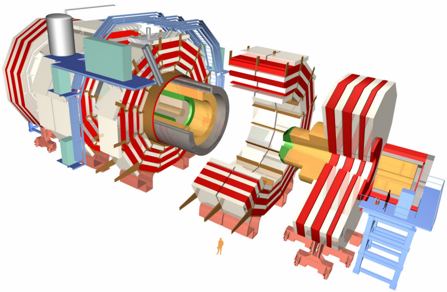
Introduction

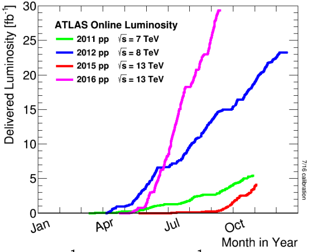


- The LHC Run I at $\sqrt{s} = 7$ and 8 TeV culminated in the discovery of the Higgs boson by the ATLAS and CMS collaborations
- So far the measurable properties accessible with the currently recorded data like mass, production and decay rates and couplings to most of the other SM particles have been determined - but still several production modes and couplings have to be measured with more data.

Higgs boson in Run I and II



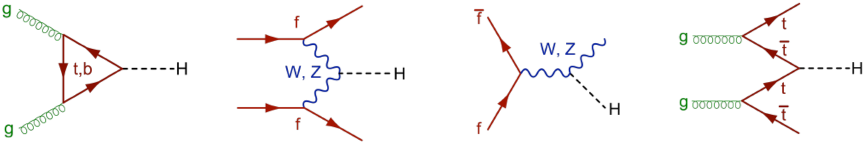




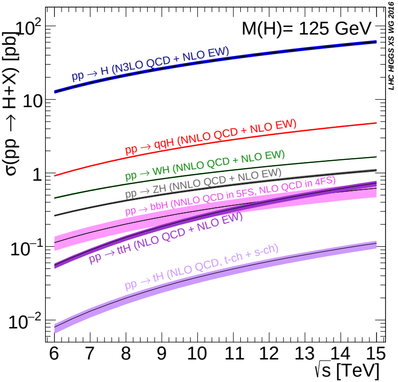
$\approx$3 fb^{-1}(2015),$\approx$13 fb^{-1}(2016 analyzed)

- During the on-going LHC Run II at $\sqrt{s} = 13$ TeV a much larger data sample has been recorded so far
- With this sample the measurement precision will be improved and it provides the possibility to study previously not accessible Higgs boson interactions
- Higher collision energy offer direct probing of BSM physics with e.g. additional Higgs bosons or non-SM Higgs boson interactions
- Already more Higgs bosons produced than in Run I

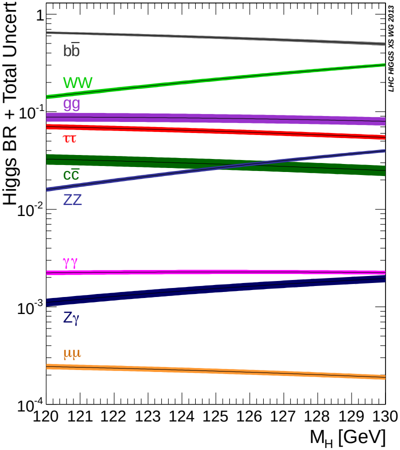
Higgs boson production at m_H=125 GeV



- Gluon gluon fusion (ggF) 87.2%
- Vector boson fusion (VBF): 6.8%
- VH: 4.1%
- ttH: 0.9%
- σ increase in range of factor 2 to 3.9(ttH) btw. Run I and II
- Observed modes: ggF, VBF

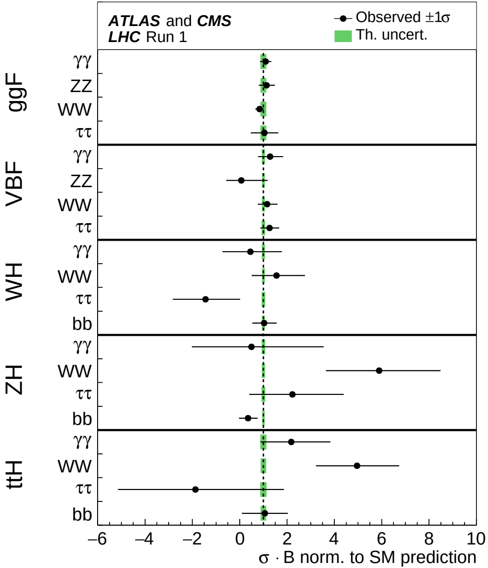


Higgs boson decays



- $\gamma\gamma$, ZZ: best mass resolution
- bb: huge BG but some potential in VH production
- $\tau\tau$: VBF to reduce BG
- WW: high rate but poorer mass resolution in $\ell\nu\ell\nu$ decays
- $\mu\mu$: very small BR
- Observed decay modes: $\gamma\gamma$, ZZ, WW, $\tau\tau$

Higgs boson production and decays in Run I



- $m_H = 125.09 \pm 0.24$ GeV
- Consistent with Spin 0 and even parity
- All couplings consistent with SM
- ggF precision in reach of theoretical uncertainties

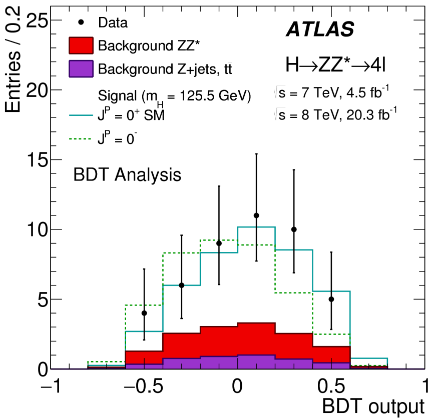
ATLAS and CMS Run I combination papers:

Mass: Phys. Rev. Lett. 114, 191803

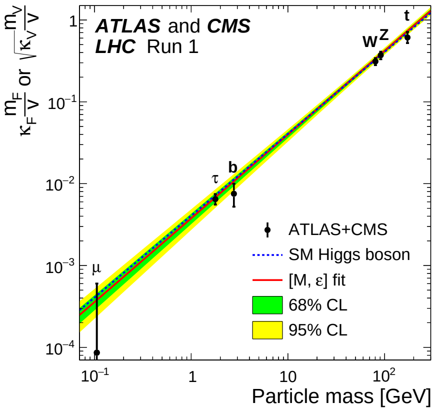
Rate, Couplings: JHEP08 (2016) 045

Higgs boson production and decays in Run I

Phys. Lett. B 726 (2013)
Rate, Couplings: JHEP08 (2016) 045



BDT output for Spin/Parity determination in $H \to ZZ^*$ decays

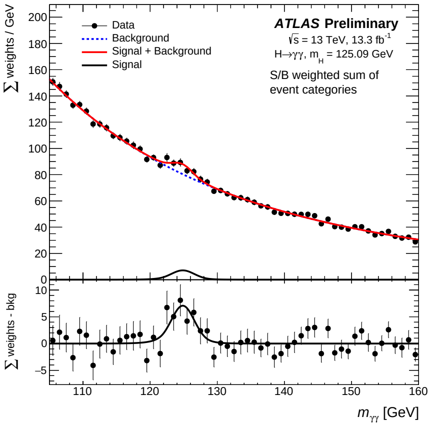


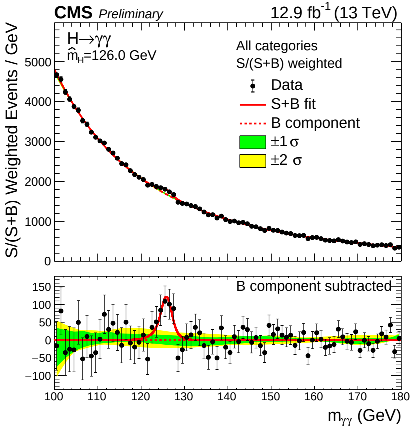
Relation btw. fitted coupling modifiers (dependent on masses) and SM predictions

$H \to \gamma\gamma$ I

ATLAS-CONF-2016-067
CMS-PAS-HIG-16-020

- Signature: 2 isolated γ, small peak on falling BG
- Categorize in production modes, extract signal by fit of $m_{\gamma\gamma}$
- Main BG: $\gamma\gamma$, γ-jet continuum production
- Dominant Systematic Uncert.: γ energy scale and resolution, choice of BG and photon ID uncertainty (smaller than stat. uncert.)





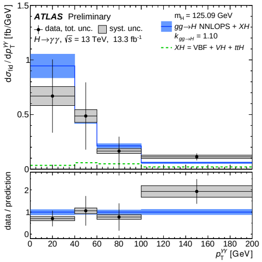
$H \to \gamma\gamma$ II

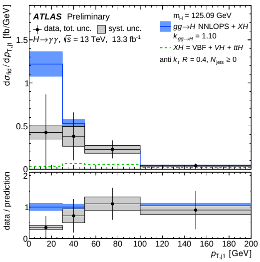
Fiducial cross sections:

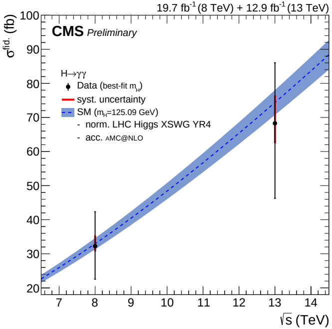
	$\sigma_{Fiducial}$ [fb]	SM pred. [fb]
ATLAS (13.3 fb^{-1})	$43.2 \pm 14.9(\text{stat}) \pm 4.9(\text{syst})$	$62.8^{+3.4}_{-4.4}$ (N3LO+XH)
CMS (12.9 fb^{-1})	$69^{+16}_{-22}(\text{stat})^{+8}_{-6}(\text{syst})$	73.8 ± 3.8

$\sigma_{Fiducial}$ uses event yields corrected for detector inefficiency and resolution for minimal theoretical modeling, different acceptance btw. ATLAS and CMS

Differential cross sections:

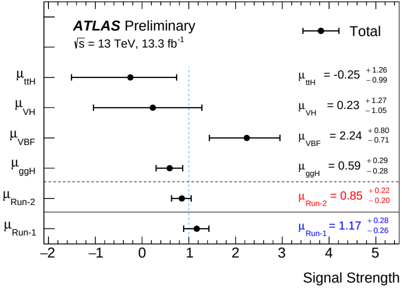






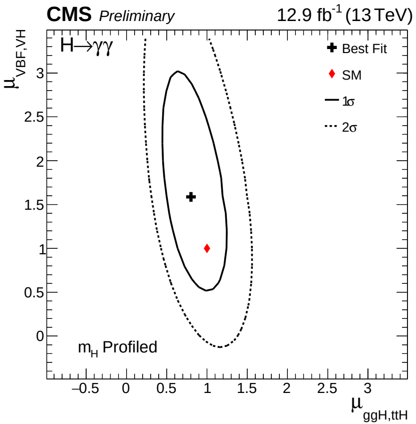
$H \to \gamma\gamma$ III

Production σ and signal strength μ:



$\mu = 0.85^{+0.22}_{-0.20}$ for m_H=125.09 GeV

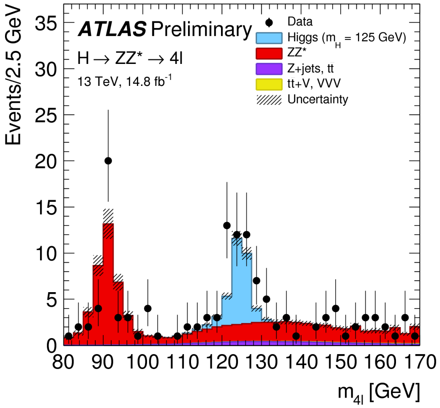
Also a 2-parameter fit:

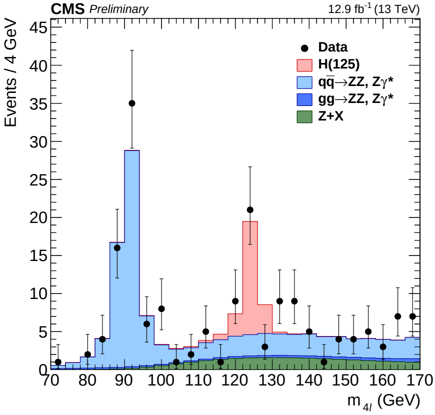


$\mu = 0.91 \pm 0.20$ for m_H=125.09 GeV

$H \to ZZ^*$ I

- Signature: 2 pairs of isolated, oppositely charged, same flavour leptons (e,μ), narrow peak, flat BG
- All production modes
- Signal from fit in $m_{4\ell}$ distribution, enhance purity by additional kinematic discriminants
- Dominant Systematic Uncert: Luminosity and lepton SF (smaller than statistical uncertainty)



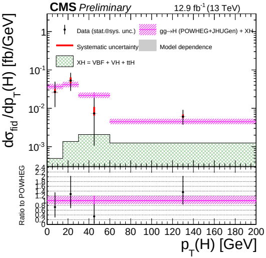


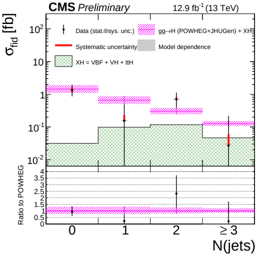
$H \to ZZ^*$ II

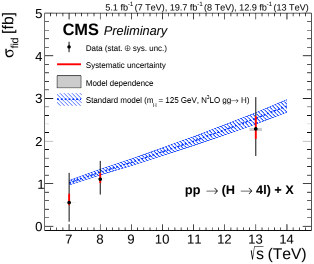
Fiducial cross sections:

	$\sigma_{Fiducial}$ [fb]	SM pred. [fb]
ATLAS (14.8 fb^{-1})	$4.54^{+1.02}_{-0.90}$	$3.07^{+0.21}_{-0.25}$
CMS (12.9 fb^{-1})	$2.29^{+0.74}_{-0.64}(\text{stat})^{+0.30}_{-0.23}(\text{syst})$	2.53 ± 0.13

Differential cross sections:



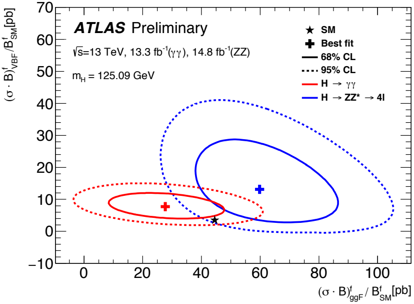


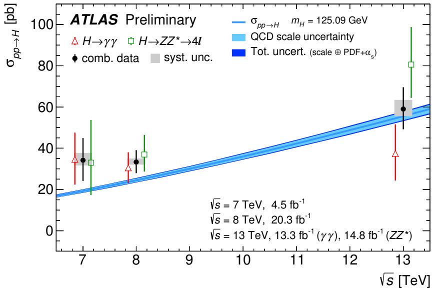


Combination of $H \to \gamma\gamma$ and $H \to ZZ^*$

ATLAS-CONF-2016-081

- Combination of $H \to \gamma\gamma$ and $H \to ZZ$
- $\sigma_{obs} = 59.0^{+9.7}_{-9.2}$ (stat) $^{+4.4}_{-3.5}$ (syst) pb ($\sigma_{SM} = 55.5^{+2.4}_{-3.4}$ pb)
  (inclusive signal yields, no categorization)
- $\mu_{obs} = 1.13^{+0.18}_{-0.17}$



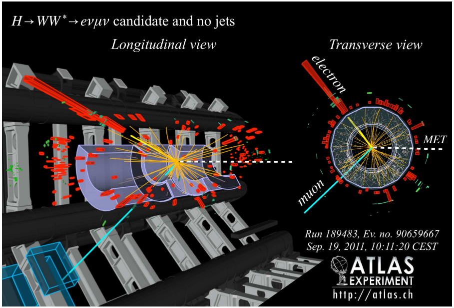


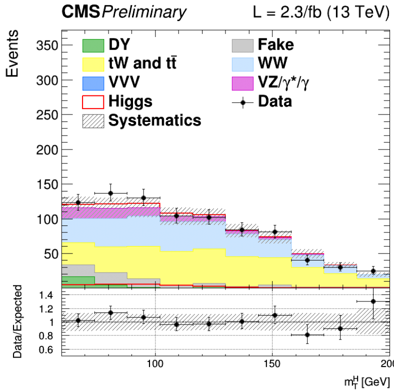
$H \to WW^*$

Rate, Couplings: JHEP08 (2016) 045
CMS-PAS-HIG-15-003

Run I results ($m_H = 125.09 \pm 0.24$ GeV) :

	Signal strength μ	Signal significance σ obs. (exp.)
ATLAS	$1.22^{+0.23}_{-0.21}$	6.8 (5.8)
CMS	$0.9^{+0.23}_{-0.21}$	4.8 (5.6)





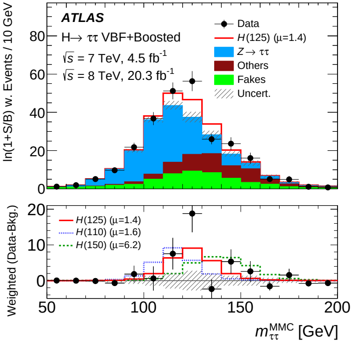
Obs. (exp.) significance: 0.7σ (2.0σ)

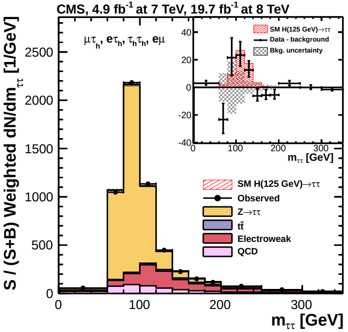
$H \to \tau\tau$

JHEP 08 (2016) 045
JHEP 04 (2015) 117
JHEP 05 (2014) 104

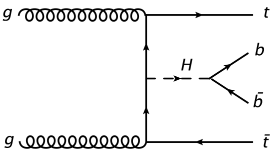
Run I results ($m_H = 125.09 \pm 0.24$ GeV):

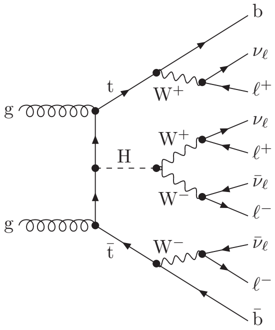
	Signal strength μ	Signal significance σ obs. (exp.)
ATLAS	$1.41^{+0.40}_{-0.36}$	4.4 (3.3)
CMS	$0.88^{+0.30}_{-0.28}$	3.4 (3.7)





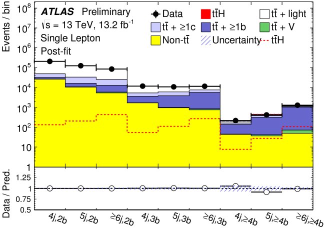
ttH Production I

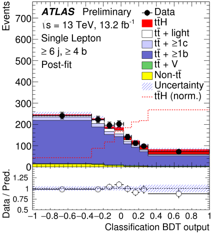


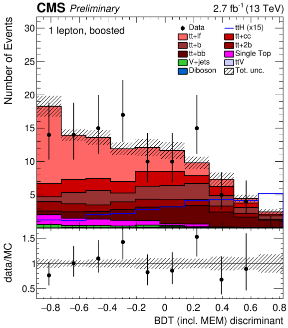


- Probe top-Quark Higgs Yukawa coupling either in ggF(assuming no BSM particle in the loop) or directly in top-associated production
- ttH (bb)
- ttH (multileptons)
- ttH $(\gamma\gamma)$ (in $H \to \gamma\gamma$ analysis)

- Categorize event based on number of leptons, (b-)jets
- Main BG: *tt*+heavy flavour - difficult theoretical description
- Dominant Systematic Uncert.: Signal and BG modelling/normalisation (larger than statistical uncertainty)





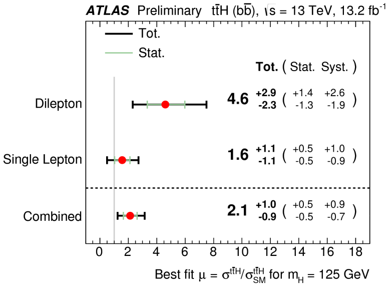


Uses BDT for Signal/BG separation in different categories

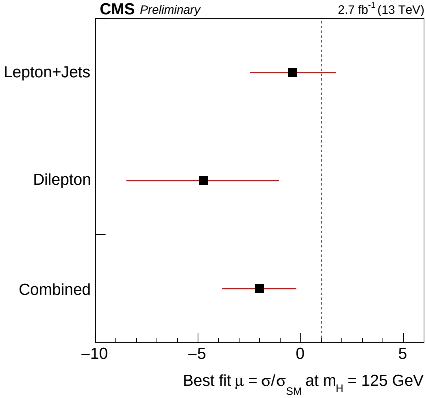
Uses 2D matrix element and BDT

ttH Production, ttH (bb) II

Results:



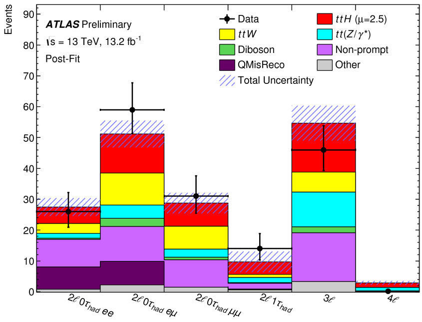
$$\mu = 2.1^{+1.0}_{-0.9}$$

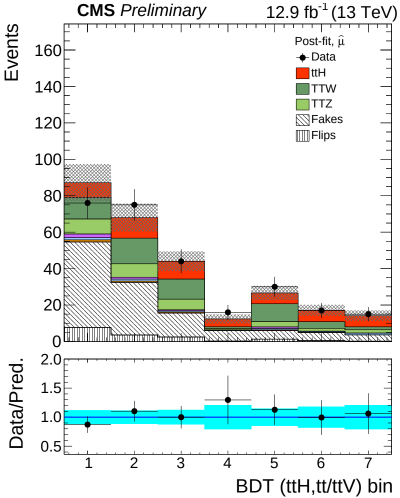


$$\mu = -2.0^{+1.8}_{-1.8}$$

ttH Production, *ttH* (multileptons)

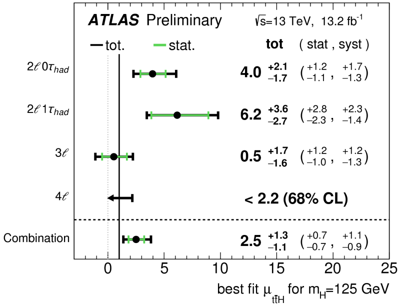
- Signature: 2-4 leptons, >=2 jets, >=1 b-jet (allows also τ_{Had})
- Dominant Systematic Uncert.: fake lepton determination and non-prompt BG



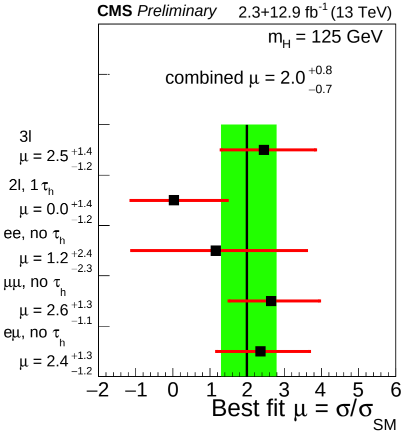


ttH Production, ttH (multileptons)

Results:



$\mu = 2.5^{+1.3}_{-1.1}$



$\mu = 2.0^{+0.8}_{-0.7}$

ATLAS-CONF-2016-068

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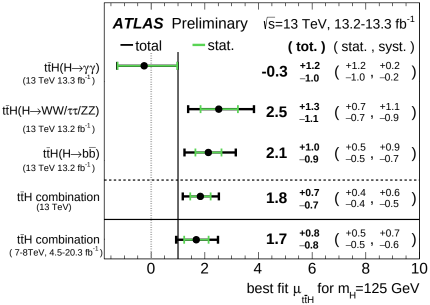
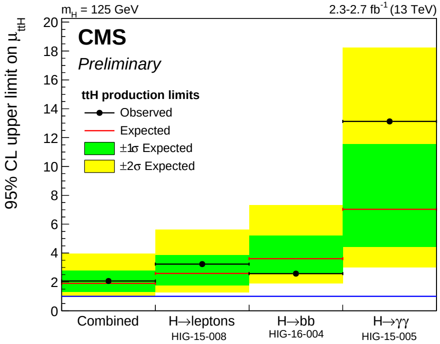
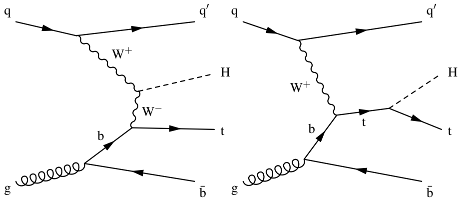


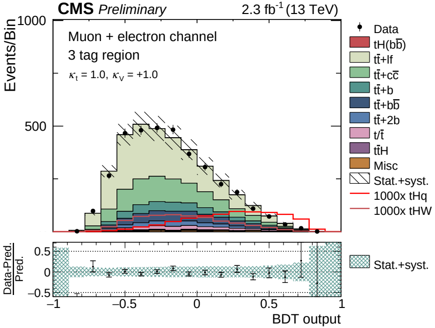


- $\mu = 1.8^{+0.7}_{-0.7}$
- Obs. (exp.) significance : 2.8 (1.8) σ
- Exceeds Run I expected significance of 1.5 σ

- Obs. (exp.) limit on μ_{ttH} is 2.1 (1.8)

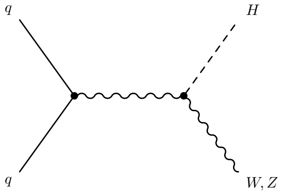
$tH \to b\bar{b}$

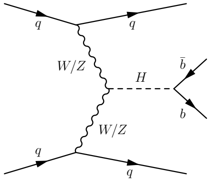




- Smallest production cross section
- Selection: e/μ decays of W + 4 b-tagged jets
- Use BDT to suppress overwhelming BG
- Exp. (obs.) limits: 113.7 $\times\sigma_{SM}$ (98.6 $\times\sigma_{SM}$)

$H \to b\bar{b}$

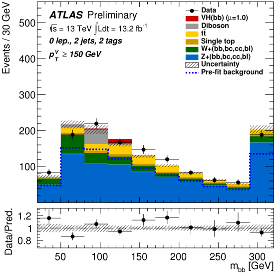




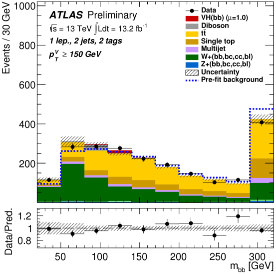
- Use this decay to establish Higgs to b-quark Yukawa coupling
- Extremely difficult because of the overwhelming QCD multi-jet production BG
- Use associated production channels for additional BG suppression:
  - VH: additional lepton and $\not{E}_T$
  - *ttH*: see before
  - VBF: 2 foward jets for event tagging

$VH \to b\bar{b}$

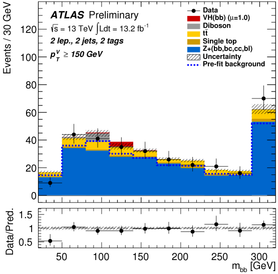
- Use additional lepton from W/Z decays ($Z \to \nu\nu$, $W \to \ell\nu$, $Z \to \ell\ell$)
- Multivariant analysis to improve S/B
- Dominant BG: Z+b-jets, $t\bar{t}$
- Use m_{bb} and $\Delta R(b_1, b_2)$
- Dominant Systematic Uncert.: b-jet tagging eff., BG normalisation



0-lepton



1-lepton



2-lepton

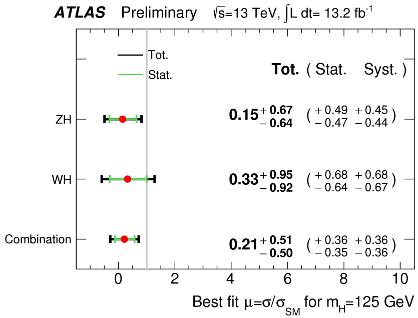
$VH \to b\bar{b}$ II

Significance obs. (exp.):

- ATLAS (13 TeV): 0.4σ (1.9σ)
- ATLAS+CMS (8 TeV): 2.6σ (3.7σ)

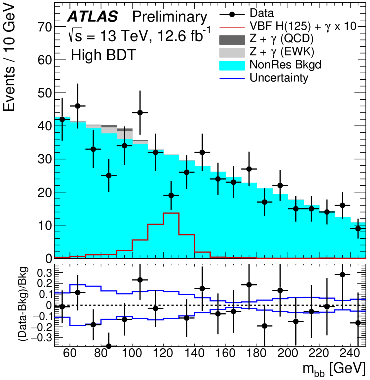
Diboson validation:

- Extract diboson $W(Z)Z$ signal strength as signal
- $\mu = 0.91 \pm 0.17$ (stat.) ${}^{+0.32}_{-0.27}$(syst.)



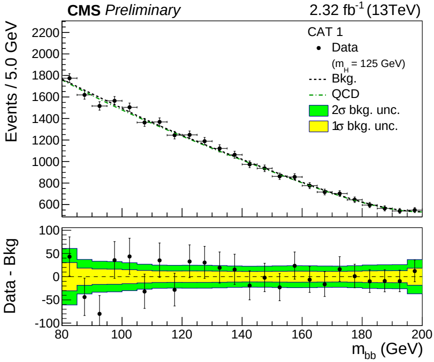
VBF $H \to b\bar{b}$

- Larger cross section for VBF vs. VH
- Use VBF signature to discriminate multi-jet BG
- Fit in m_{bb} distribution



Require additional γ for trigger

Obs. (exp.) limit: 4.0 (6.0) $\times \sigma_{SM}$

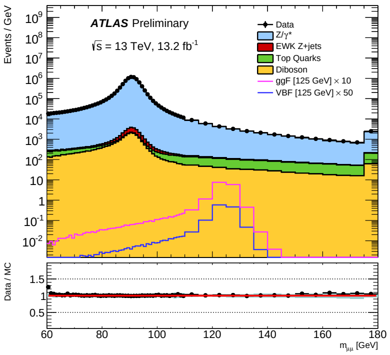


Obs. (exp.) limit : 3.4 (2.3) $\times \sigma_{SM}$

$H \to \mu\mu$ I

ATLAS-CONF-2016-041

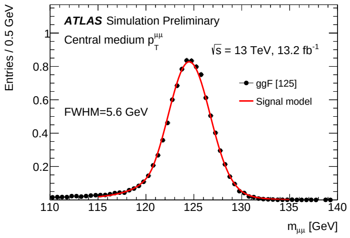
- Very rare Higgs decay: $B(H[125] \to \mu^+\mu^-) = 2.2 \times 10^{-4}$
- Strategy: Look for a narrow bump on top of continuous $m_{\mu\mu}$ background distribution
- Challenges: Irreducible background from $Z/\gamma^* \to \mu\mu$
- $\Gamma(H[125]) = 4.1$ MeV - signal width is dominated by detector resolution
- Categorize: ggF and VBF

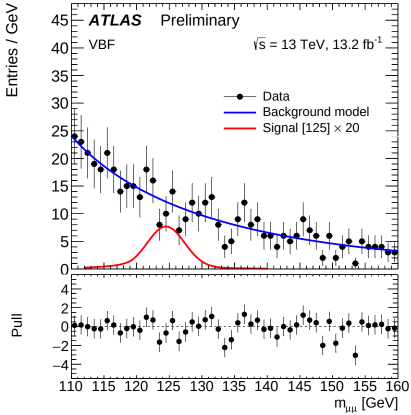


$H \rightarrow \mu\mu$ II

Obs. (exp.) upper limits:

- Run I: 7.1 (7.2) $\times \sigma_{SM}$
- Run II: 4.4 (5.5) $\times \sigma_{SM}$
- Combination: 3.5 (4.5) $\times \sigma_{SM}$

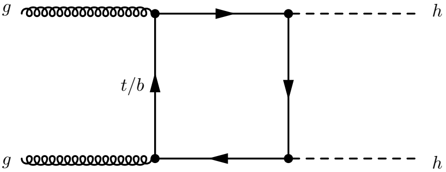




Mass resolution for $\mu^+\mu^-$ wider than for $\gamma\gamma$

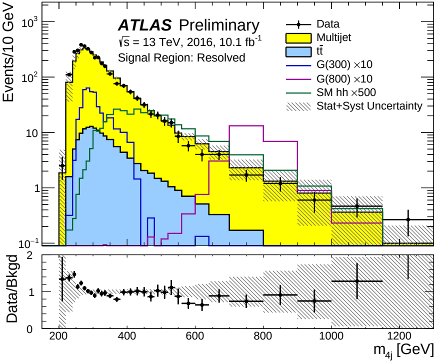
DI-HIGGS BOSON PRODUCTION I

ATLAS-CONF-2016-049

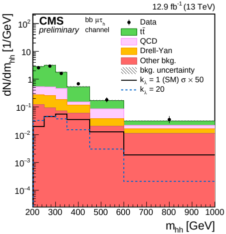


SM example I:

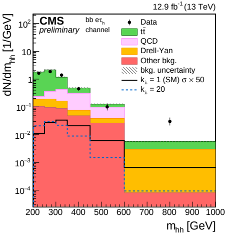
- $hh \to b\bar{b}b\bar{b}$



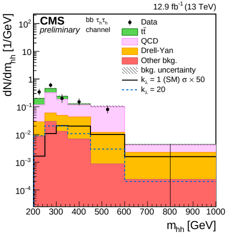
- Select 4 b-tagged jets
- Dominant Systematic uncert.: BG modelling and b-tagging
- Limit $\sigma <$330 fb, compared to SM prediction of 11.3±0.9 fb (29 times SM)



(a) $bb\mu\tau_h$



(b) $bbe\tau_h$



(c) $bb\tau_h\tau_h$

SM example II:

- $hh \rightarrow b\bar{b}\tau^+\tau^-$
- Select 2 b-tagged jets and 3 $\tau\tau$ final states: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Dominant Systematic uncert.: BG modelling
- Obs. (exp.) limit $\sigma <$508 (420) fb which is about 200 (170) times SM prediction

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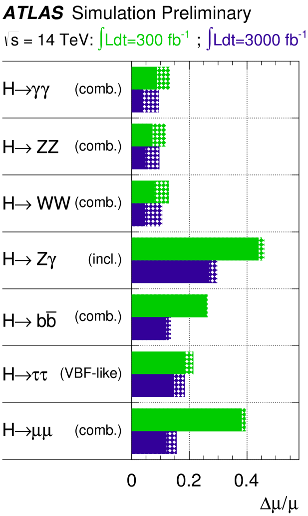

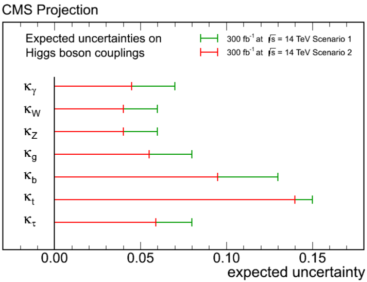

- ECFA workshop on-going this week 3-6 October 2016
- Several updates of projections for HL-LHC luminosity compared to here shown numbers

Summary and Conclusions

- LHC Run I brought the discovery of the Higgs boson with $m_H = 125.09 \pm 0.24$ GeV , consistent with Spin 0 and even parity and couplings consistent with SM
- Dataset from LHC Run II with even more Higgs bosons already recorded
- Analysis of Run II data at full swing - expect higher precision

- Looking forward to exciting new results !