Higgs(general) at ATLAS

Wei-Ming Yao (LBNL)
On behalf of the ATLAS Collaboration

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Outline

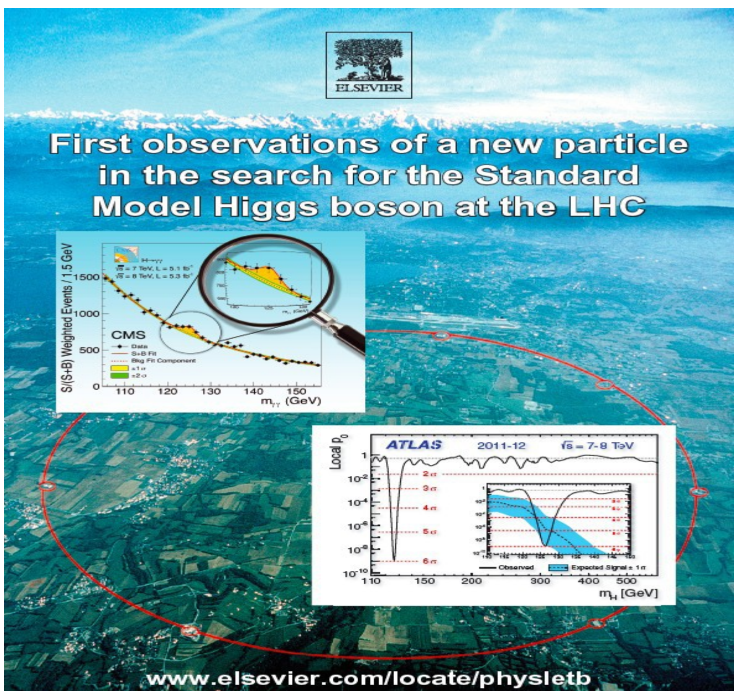
- Introduction
- ATLAS Higgs program
- Highlights of recent Higgs results using up to 79.8 fb^{-1}:
  - Higgs bosonic decays: $H \rightarrow \gamma\gamma, WW^*, ZZ^*$
  - Higgs fermionic decays: $H \rightarrow \tau\tau$, bb, $\mu\mu$.
  - Combination of Higgs production and coupling
  - Search for additional Higgs-like bosons
  - Di-Higgs production for probing Higgs self-coupling
- Conclusion

* I apologize if I have left out your results in the talk.

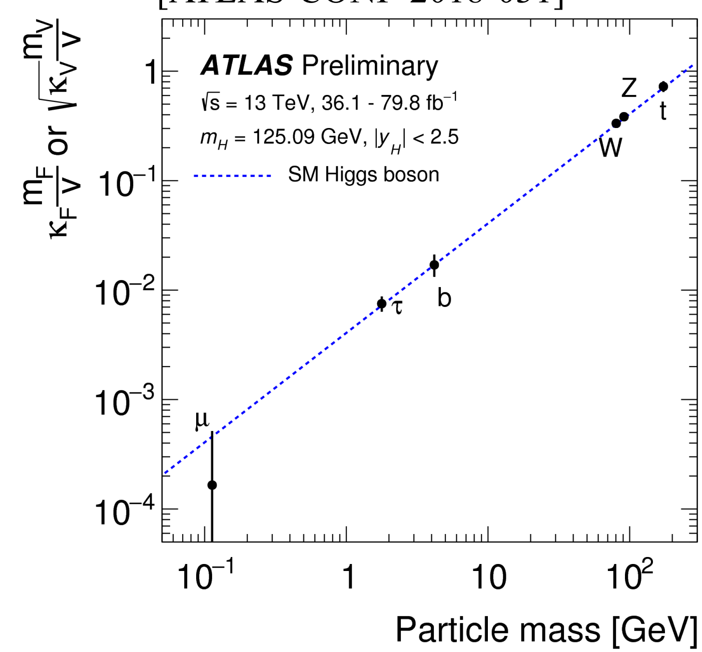
Introduction

- Observation of Higgs boson at LHC in 2012
- Marked completeness of the standard model (SM) and opened way to explore the Higgs sector that is responsible for EWSB.
- Data so far are consistent with SM predictions.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L Y \Phi \Psi_R + h.c.$$



[ATLAS-CONF-2018-031]



ATLAS Higgs Program toward HL-LHC era

- Extremely rich and exploring in multiple-fronts:

- Precision measurements:
  - Mass, width
  - Spin, CP
  - Coupling on-/off-shell
  - Differential xsec
  - ...

H^0 $J = 0$

Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.10 \pm 0.11$
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma <$ 6.6, CL = 95%
$t\bar{t}H^0$ Production $= 2.3^{+0.7}_{-0.6}$

PDG

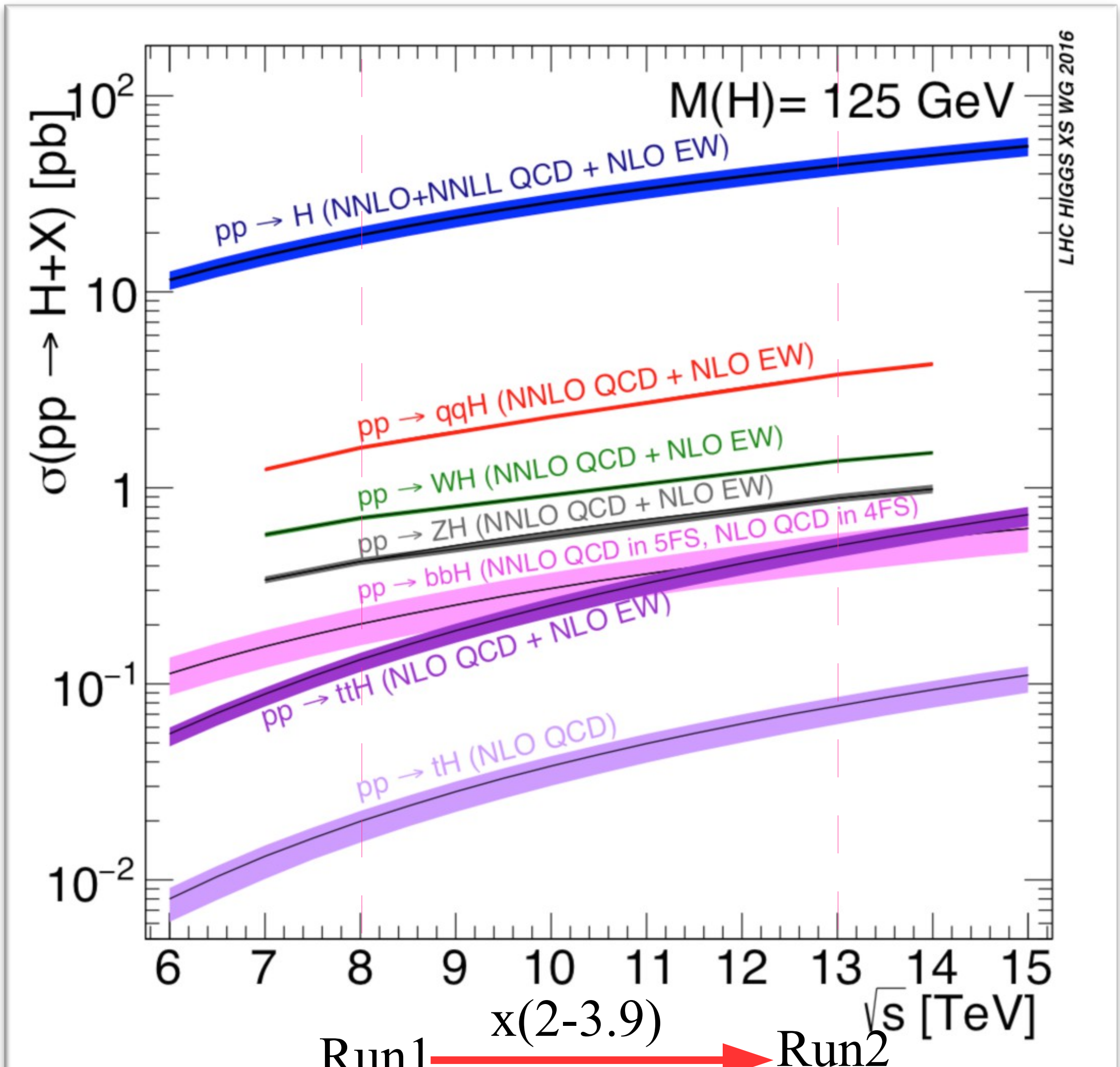
- Rare/BSM decays:
  - $H \to Z\gamma$
  - $H \to \mu\mu$
  - $H \to cc$
  - $H \to \tau\mu$, τe, μe
  - $H \to$ invisible
  - ...

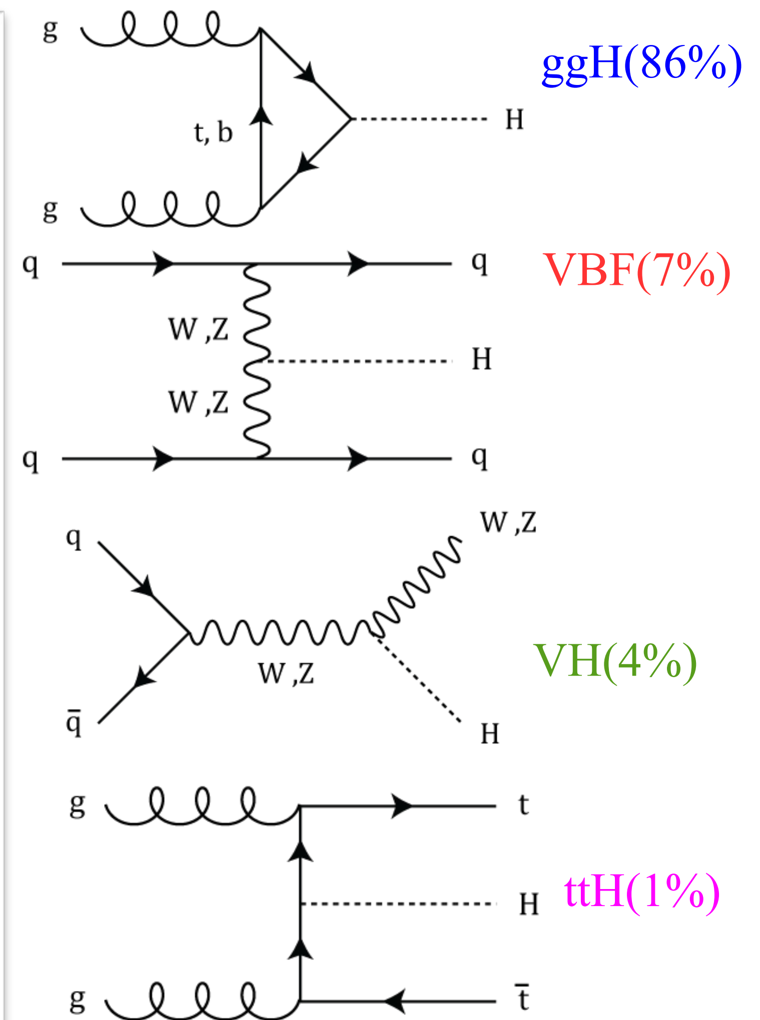
- Discovery tools:
  - Higgs potential
  - Di-Higgs
  - FCNC
  - ...

- Extended Higgs sector:
  - Extra Higgs
  - 2HDM
  - H+
  - H++
  - ...

Higgs Production at LHC

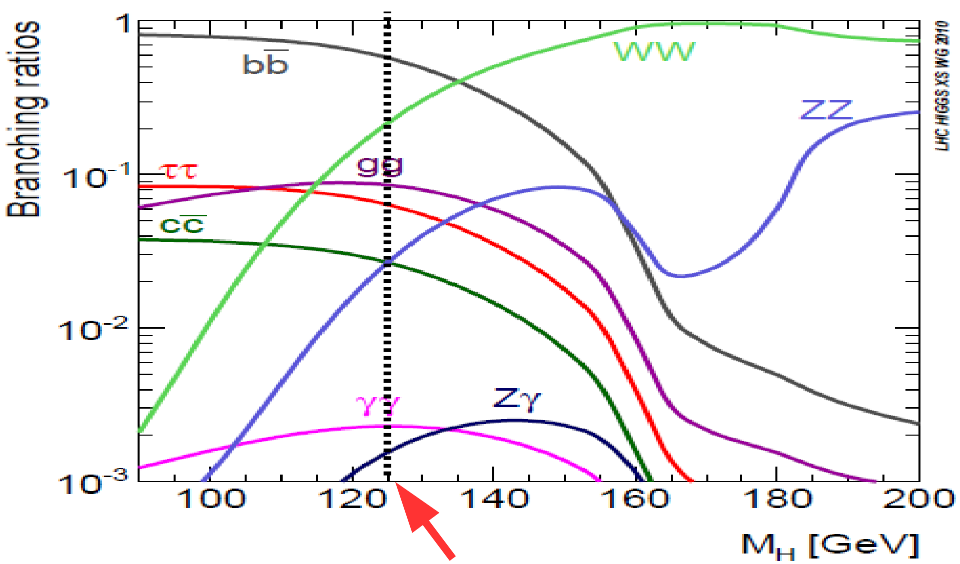
- Higgs predominantly produced via ggF, VBF, VH, and ttH.





Standard Model Higgs Decays

- For m_H=125 GeV, there are five main observable decay modes available:
  - bb(58%)
  - WW*(21%), WW*→lνlν(1.0%)
  - ττ(6.3%)
  - ZZ*(2.6%), ZZ*→4l(1.2E-4)
  - γγ(0.2%).



M_H=125 GeV

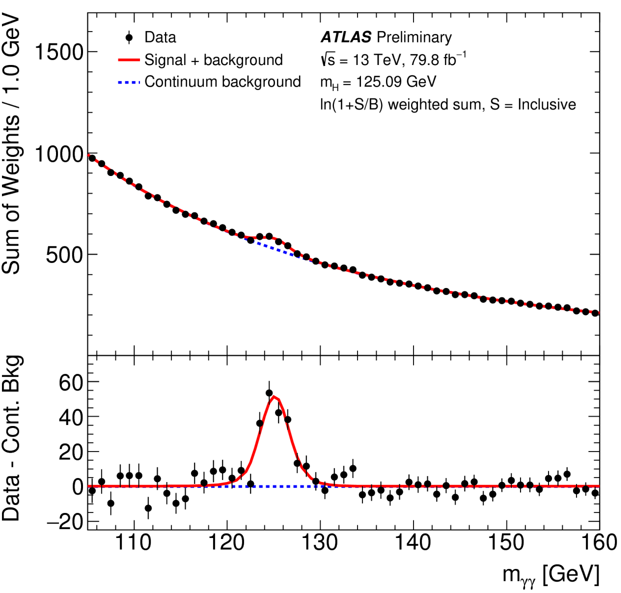
- H→γγ, ZZ→4l: excellent mass res.
  - Mass and differential xsec.
- H→WW→lνlν: sizable BR, but poor mass resolution.
- H→bb, ττ: large BR, but low S/B, probe b, τ Yukawa coupling directly.
- H→μμ, Zγ decays: small BR, requiring more data.
- Other H→cc, gg decays, are challenge, requiring new ideas.

Probing Higgs Bosonic Decays

- Signal strength as $\mu = (\sigma x B)^{Data}/(\sigma x B)^{SM}$

$H \rightarrow \gamma\gamma$ (80 fb^{-1})

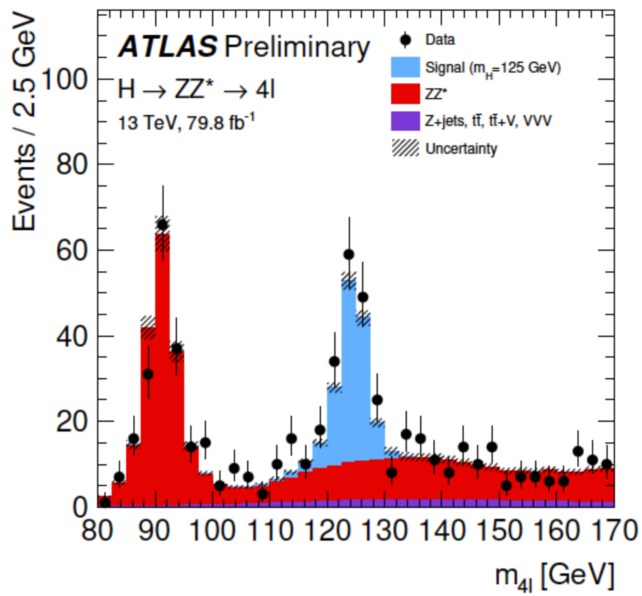
[ATLAS-CONF-2018-028]



$\mu=1.06 \pm 0.08 ^{+0.11}_{-0.09}$

$H \rightarrow ZZ^* \rightarrow 4l$ (80 fb^{-1})

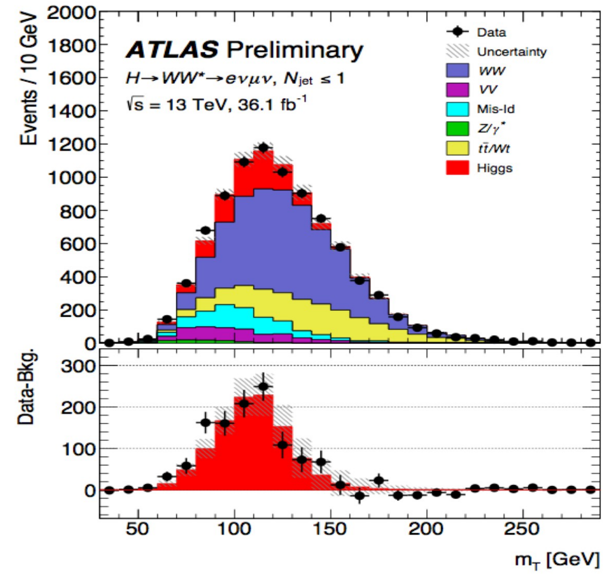
[ATLAS-CONF-2018-018]



$\mu=1.19 \pm 0.12 ^{+0.10}_{-0.09}$

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ (36.1fb^{-1})

[arXiv:1808.09054]



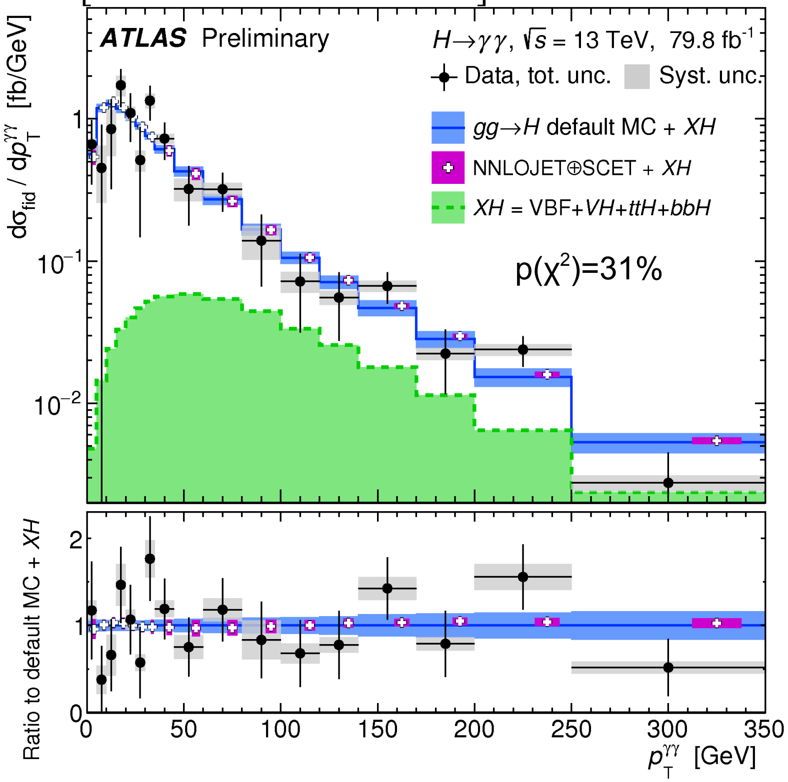
$\mu_{ggF}=1.21 \pm 0.10 ^{+0.20}_{-0.19}$

$\mu_{VBF}=0.62 ^{+0.30}_{-0.28} \pm 0.21$

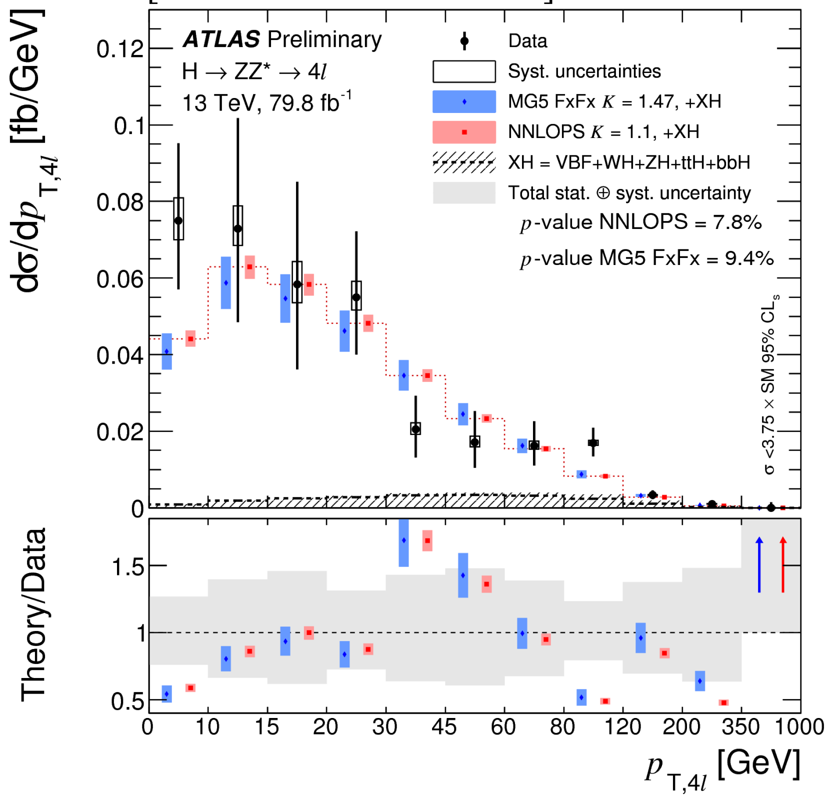
Fiducial and Differential cross sections

- Higgs pT provides a precision test of QCD and is sensitive to high mass scale.
- Higgs dσ/dpT are shown for H→γγ, 4l using 80 fb^{-1} of run2 data.
- Many differential distributions measured and consistent with expectations.
- Interpreted σ·B using simplified template xsec(STXS) to probe BSM coupling.

[ATLAS-CONF-2018-028]

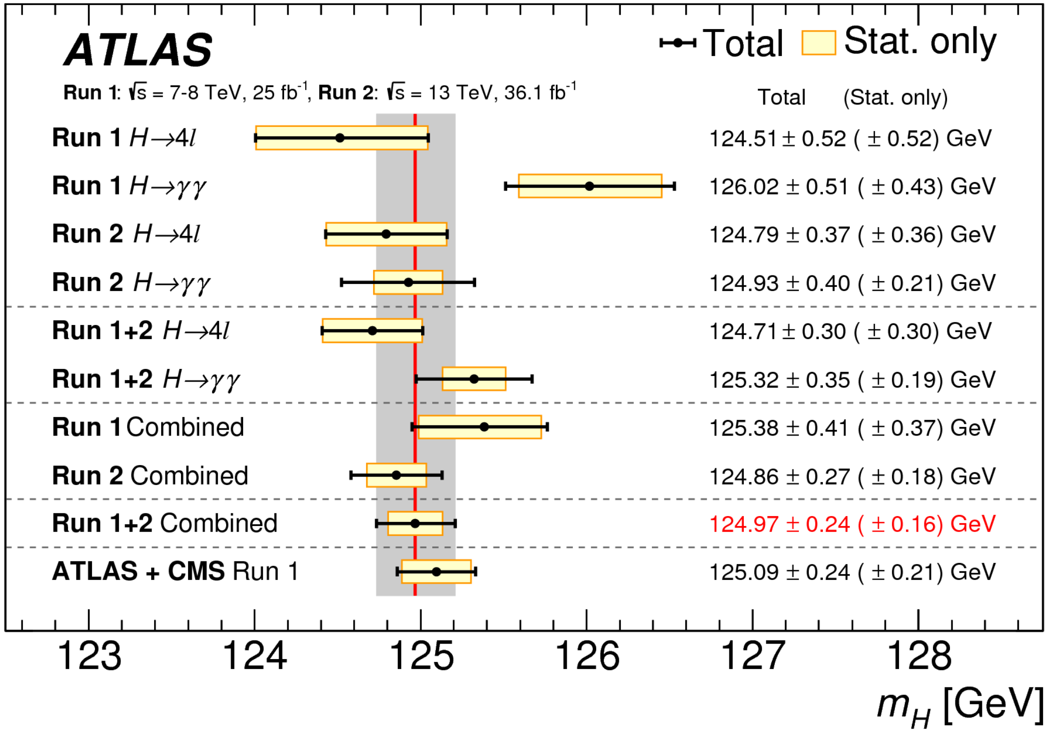


[ATLAS-CONF-2018-018]

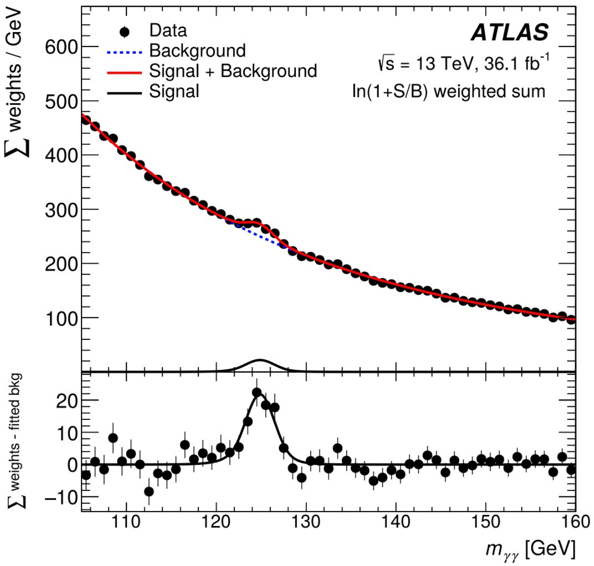


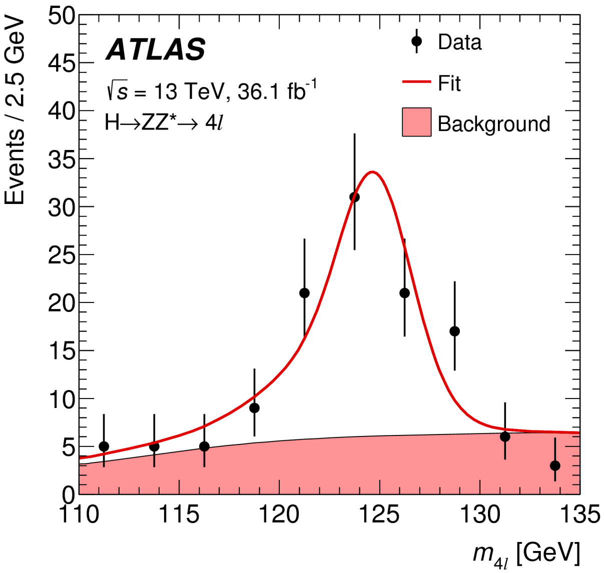
Higgs Mass Measurement

- Higgs mass is updated from $H\to\gamma\gamma$ and $H\to ZZ^*\to 4l$ final states with 36.1 fb^{-1}.
  - Run2 Combined: m_H=124.86 ± 0.18 ± 0.20 (GeV)
  - Combining with Run1: m_H=124.97±0.24 (GeV)
  - LHC Run-I: m_H=125.09 ± 0.24 (GeV)



[PLB 784(2018)345]





Higgs boson width

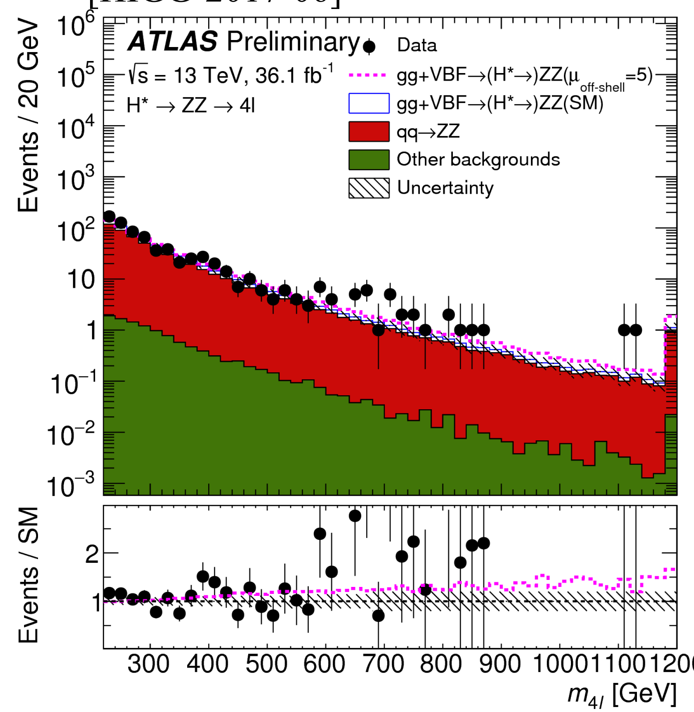
- Higgs width sensitive to new unknown decays while expected SM value of 4 MeV is too small to be measured directly at LHC.
- $(\mu_{\text{off-shell}}/\mu_{\text{on-shell}})^{gg\to H\to ZZ^*} = \Gamma_H/\Gamma_H^{SM}$ by assuming same Higgs Kappa coupling modifiers.

$$\mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}}$$

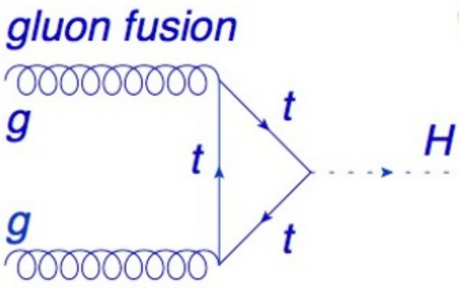
$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}},$$

- Set limit for $H\to ZZ^*\to 4l/2l2v$ with 36.1 fb^{-1}:
  - Obs. $\mu_{\text{off-shell}}^{gg\to H\to ZZ^*} < 3.8$ (3.4 exp.) @95%CL
  - $\Gamma_H < 14.4$ MeV(15.2 MeV exp.) @95%CL
- Uses NLO K factors for $gg\to H^*\to ZZ^*$ as function of m(ZZ*) [Caola et al,Phys. ReV D92(2015) 094028]
- Improved on Run-1 ATLAS and CMS expected limits by a factor of 2.

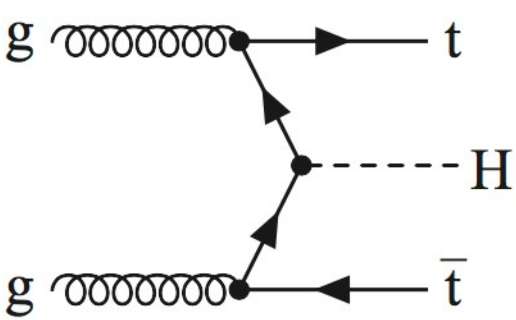
[HIGG-2017-06]



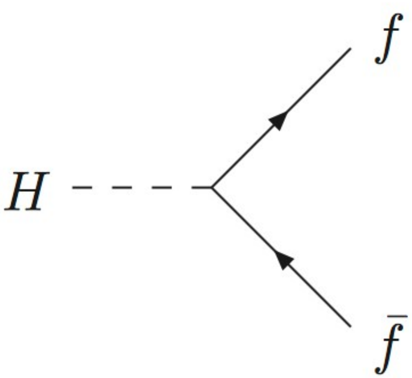
Probing Higgs coupling to fermions



- Probing Higgs Yukawa coupling indirectly at loop level via ggF production.
- Probing Yukawa coupling directly at tree-level via productions (VBF, ttH) or decay BR in kappa modifiers.



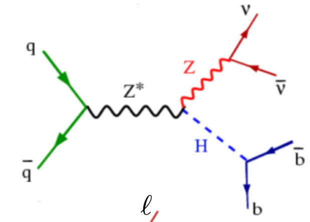
- Any deviation could be a sign of new physics.
- Observed so far:
  - $H \rightarrow bb$ for k_b [arXiv:1808.08238]
  - $H \rightarrow \tau\tau$ for k_τ [ATLAS-CONF-2018-021]
  - ttH for k_t [PLB 784(2018) 173, See talk by Fabrice Hubaut]

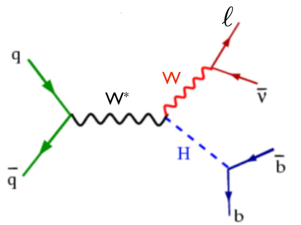


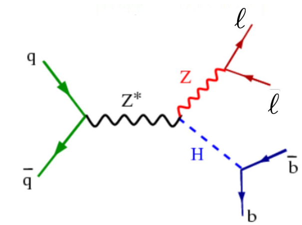
- Probing 2nd – generation coupling:
  - $H \rightarrow \mu\mu$ for k_μ [ATLAS-CONF-2018-026]
  - $H \rightarrow cc$ for k_c [PRL 120 (2018) 211802]

Observations of H→bb and VH

- gg→H→bb is dominant decay, limited by large background.
- VH most sensitive, leptonic W/Z provides trigger & QCD rejection.
- Dividing into 0-, 1-, 2-charged leptons based on W/Z decays.
- Requiring 2 b-tagged jets and pT(V)>75 or 150 GeV.
- BDT trained using m(bb), pT(V),ΔR(bb) +... as inputs.

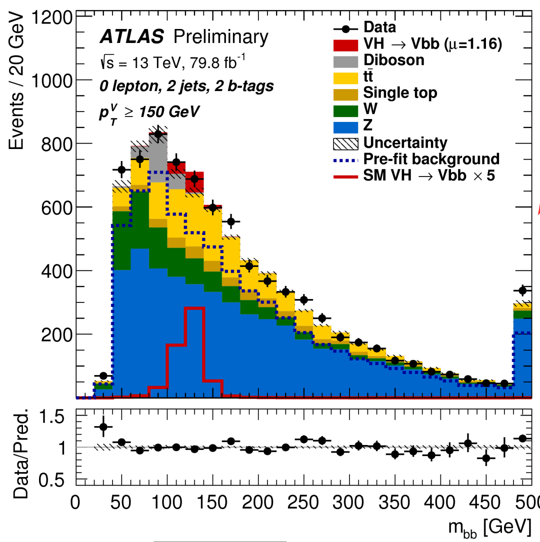




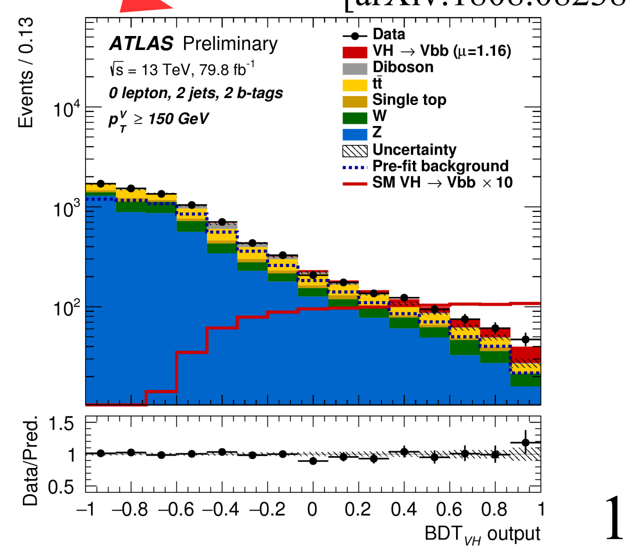


- Main backgrounds:
  - ttbar(NLO Powheg)
  - single top(NLO Powheg)
  - W+jets(Sherpa 2.2.1)
  - Z+jets(Sherpa 2.2.1)
  - Diboson(Sherpa 2.2.1)
- Normalization from data and shape from MC.

0-lepton(met) is most sensitive:



BDT

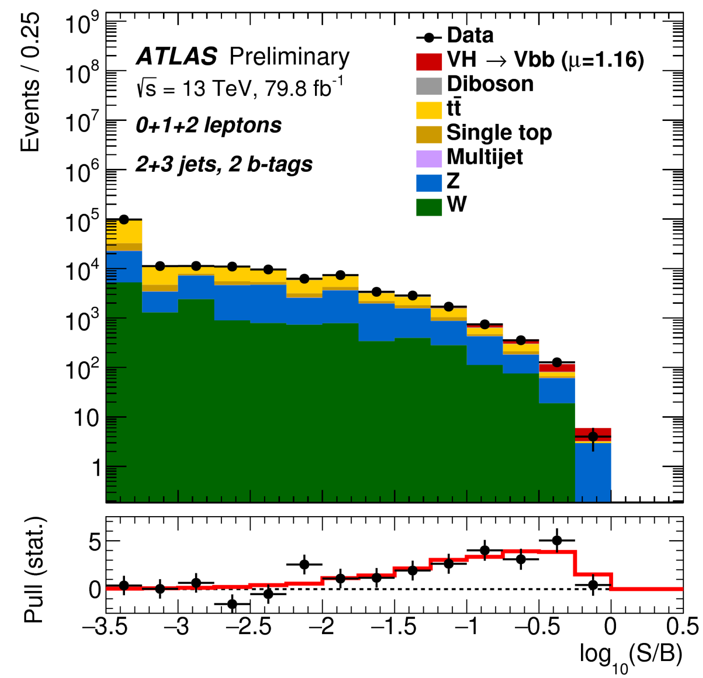


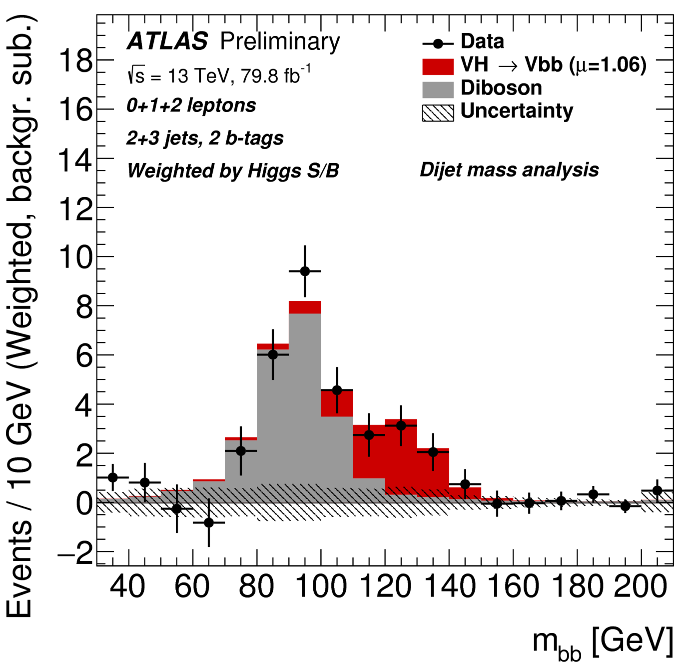
[arXiv:1808.08238]

Run2 VH, H→bb results

- Fit result with 79.8 fb^{-1} of Run-2 data:
  - Obs. $\mu=\sigma_{obs}/\sigma_{SM}=1.16 \pm 0.16 ^{+0.21}_{-0.19}$
  - Obs. significance of 4.9σ(4.3σ exp.)
- Combination with Run-1:
  - Obs. $\mu=0.98 \pm 0.14 ^{+0.17}_{-0.16}$
  - Obs. Significance of 4.9σ(5.1σ exp.)

- Cumulative log(S/B) from all chan.

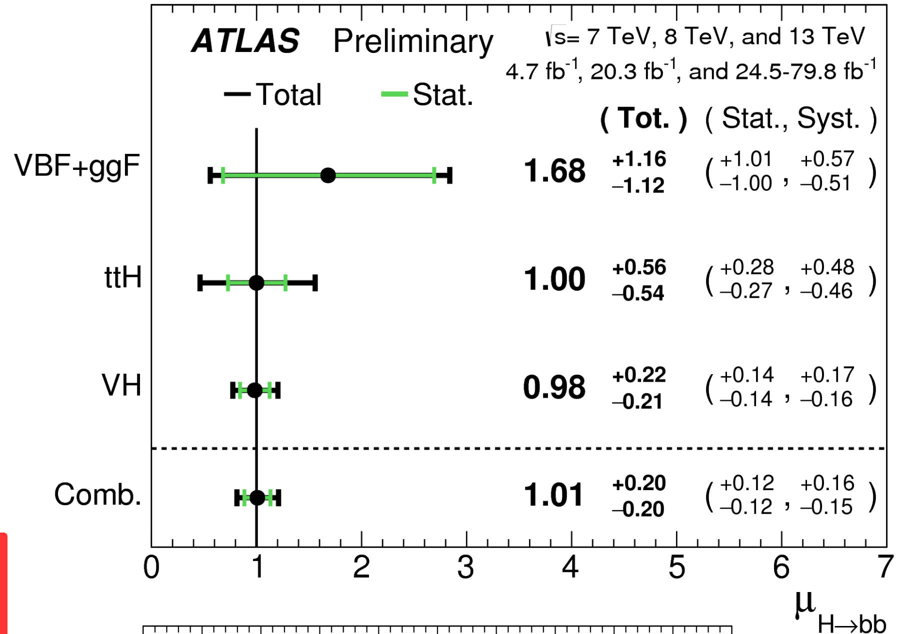




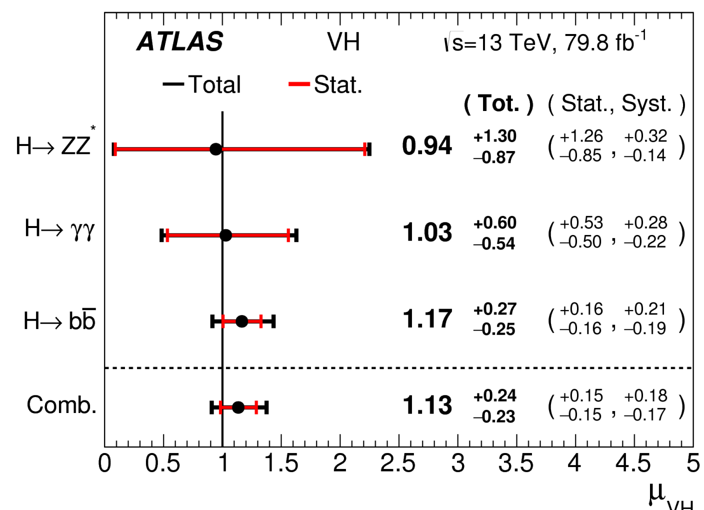
- Validation of analysis strategies:
  - Fit to diboson VZ, Z→bb:
    - Obs. $\mu=1.2 \pm 0.20$
  - m(bb) fit for VH, H→bb:
    - Obs. $\mu=1.06 \pm 0.20 ^{+0.30}_{-0.26}$ (3.6σ)

Combined H→bb and VH

- Run-1 + Run-2 H→bb combination:
  - VH, H→bb
  - VBF(+ggF), H→bb
  - ttH, H→bb
  - Combined: $\mu=1.01 \pm 0.12\ ^{+0.16}_{-0.15}$
- Obs. significance: 5.4σ (5.5σ exp.)



- Combination of VH production:
  - VH, H→bb
  - VH, H→γγ
  - VH, H→ZZ*
  - Combined: $\mu=1.13 \pm 0.15\ ^{+0.18}_{-0.17}$
- Obs. significance: 5.3σ (4.8σ exp.)

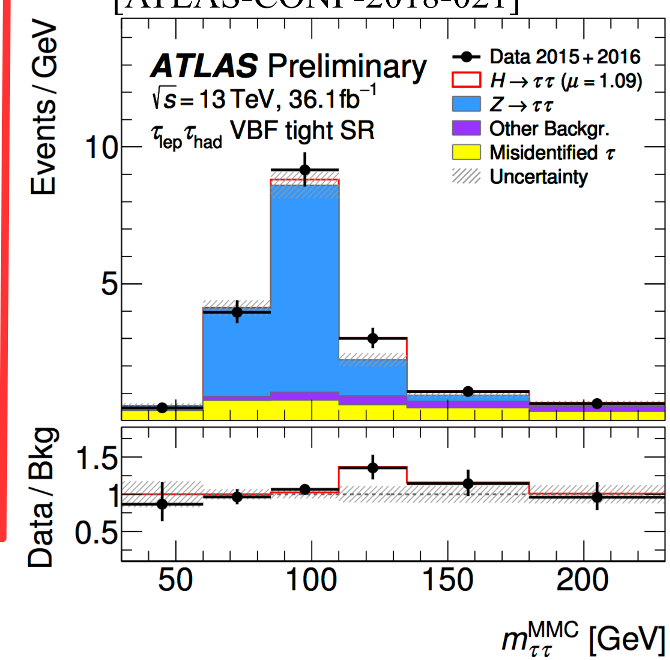


→Observations of H→bb and VH production

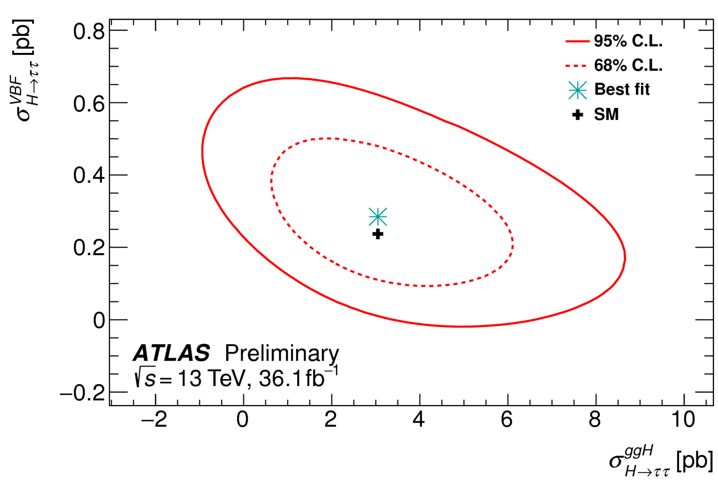
Measurement of H→ττ

- All τ leptonic and hadronic decay modes considered ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$).
- Divided into 13 categories targeting VBF and ggF in the "boosted" region.
- Main discriminant: $m_{\tau\tau}^{MMC}$ from visible+met, crucial to separate H→ττ from Z→ττ background.

[ATLAS-CONF-2018-021]



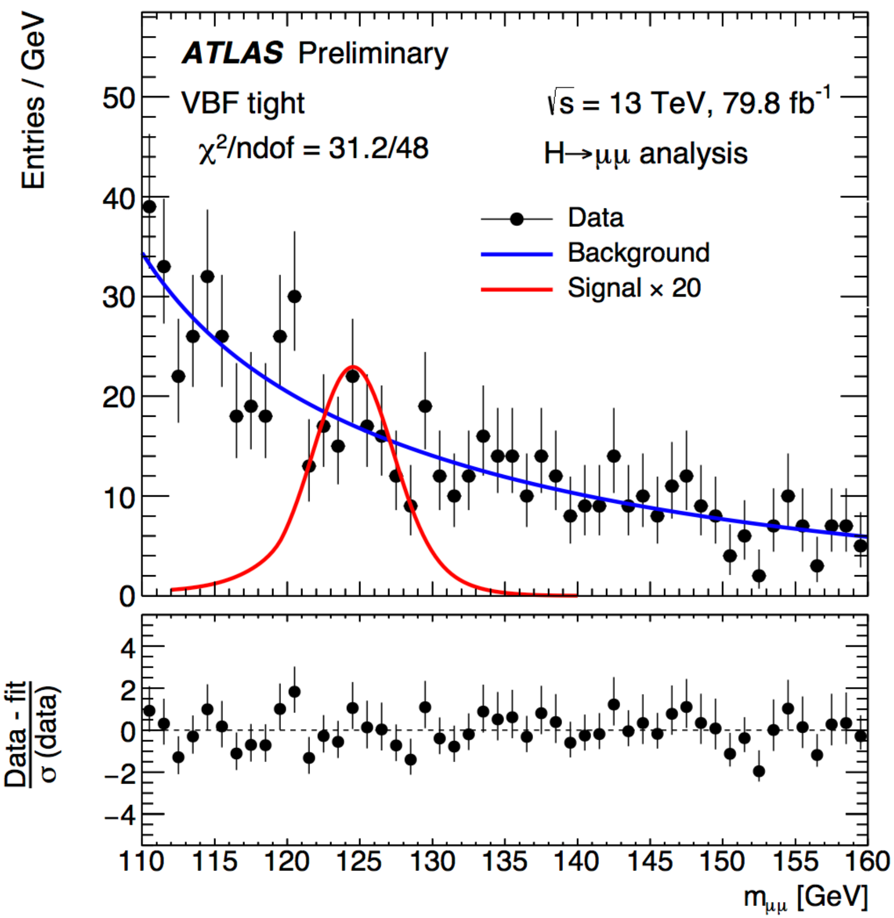
- Normalization of Z→ττ estimated from data, shapes from MC using Run2 36.1 fb^{-1}.
- Run2 obs. $\mu=1.09\,^{+0.18}_{-0.17}\,(\text{stat})\,^{+0.31}_{-0.25}\,(\text{syst})$
- Run2 obs. significance: 4.4σ (4.1σ exp.)
- Combined Run1+Run2: 6.4σ (5.4σ exp.)



Search for H→μμ

- The rare H→μμ decay probes the Higgs coupling to 2nd – generation fermions and is sensitive to new physics.
- Select two isolated opposite-sign muon pair, triggered by pT(μ)>25 GeV.
- Categorization based on muon centrality (η), pT, BDT to enhance VBF.
- Fit to $m_{\mu\mu}$ distributions in 8 categories:
  - Obs. μ=0.1±1.1 (exp. 0.9σ)
  - Bkg. determined from sidebands.
- Set limit with 80 fb^{-1}:
  - Obs. Limit: $\mu=\sigma/\sigma_{SM}<2.1$ (2.0 exp. with absence of signal) @95%CL

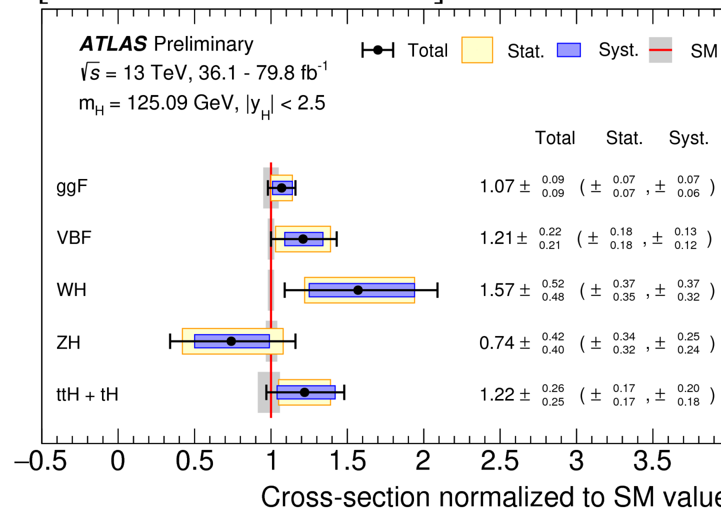
[ATLAS-CONF-2018-026]

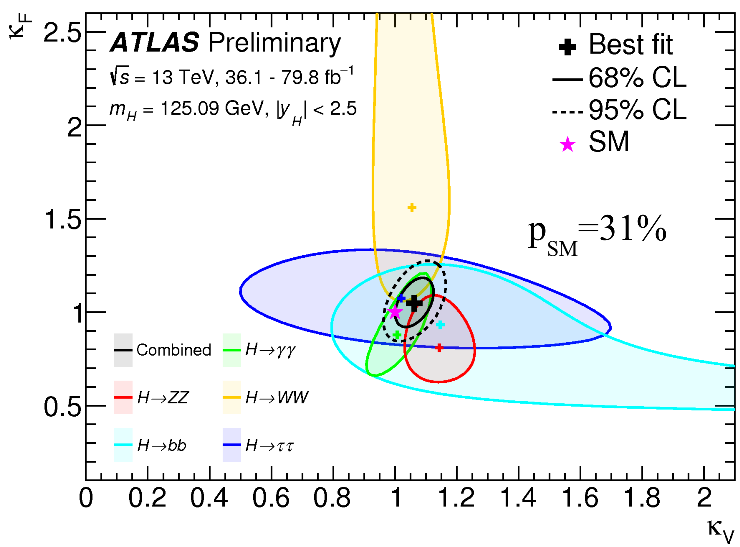


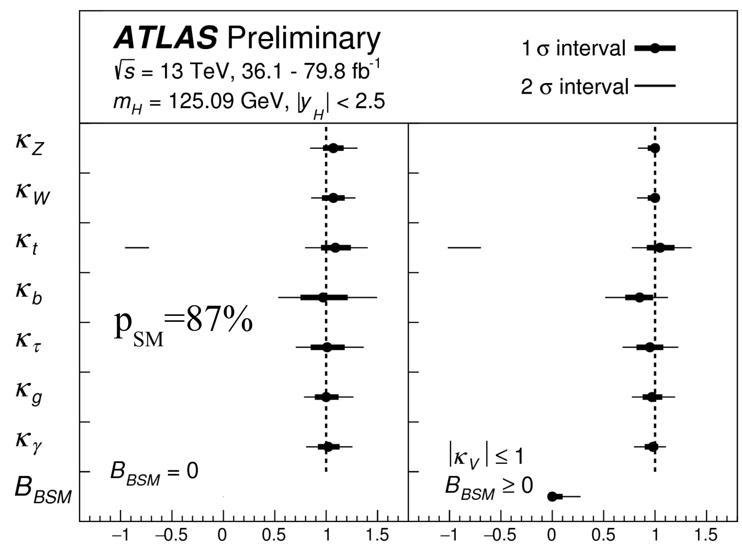
Higgs Combination

- Higgs main production modes: ggF, VBF, VH, ttH have been observed.
- Combined results to probe kappa modifiers:
  - $B_{BSM} \geq 0$: $B_{BSM} < 26\%$ (37% exp.) @95%CL
  - Comparable to H→invisible limit from VBF run1: $B_{invisible} < 28\%$ (31% exp). [JHEP 01(2016)172]
- Improved theory pred. at 5% (N3LO QCD+NLO EW, [JHEP 1605(2016) 058])

[ATLAS-CONF-2018-031]



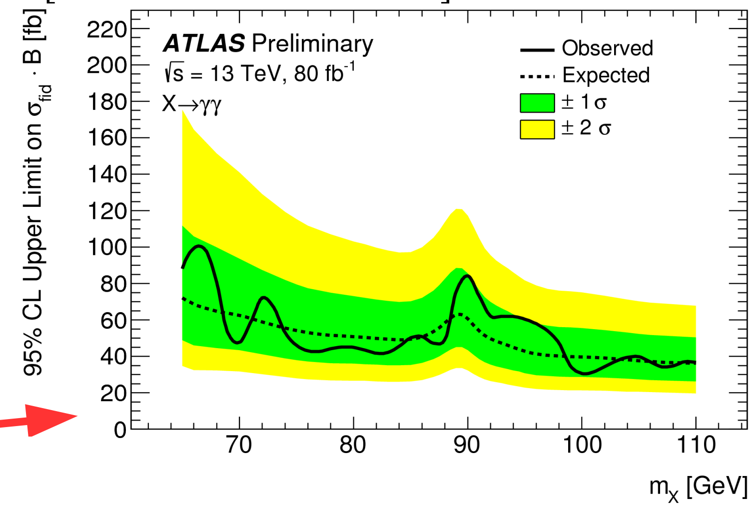


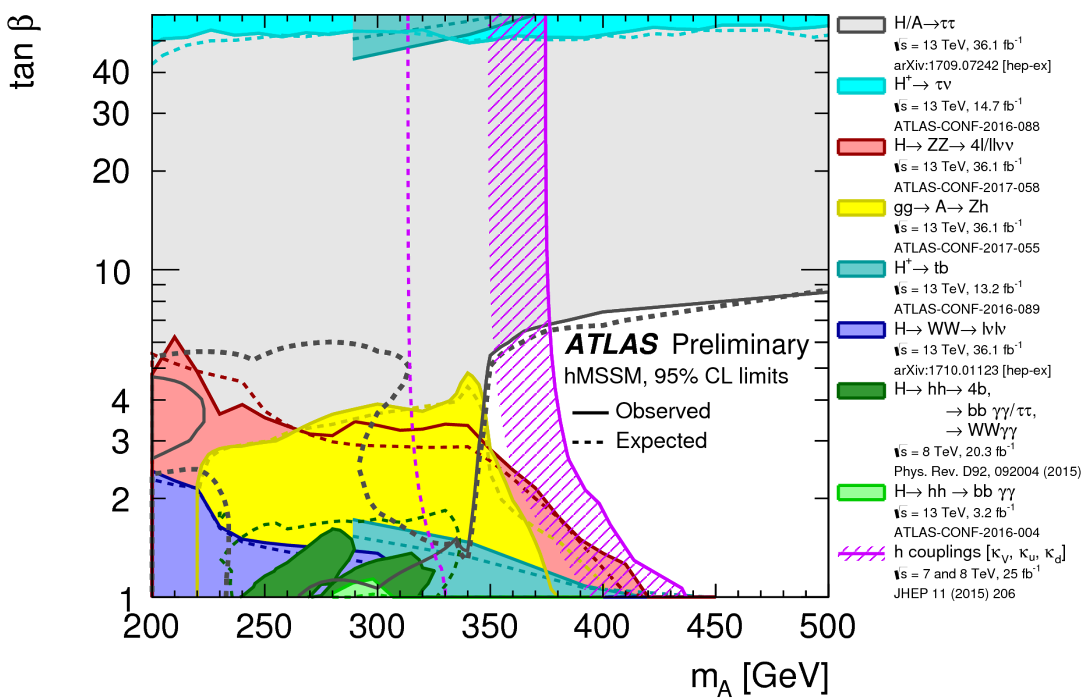


Search for Additional Higgs-like bosons

- Many BSM models predict additional Higgs-like bosons.
- Search for low mass Higgs-like boson $X\rightarrow\gamma\gamma$ search for $65<m_X<110$ GeV
- Set cross section times Br limit vs m_X.

[ATLAS-CONF-2018-025]

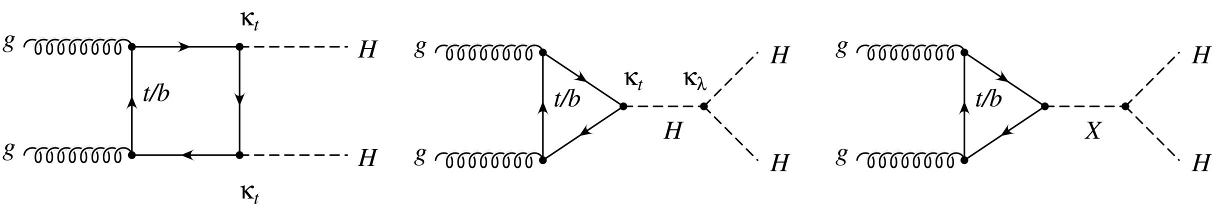


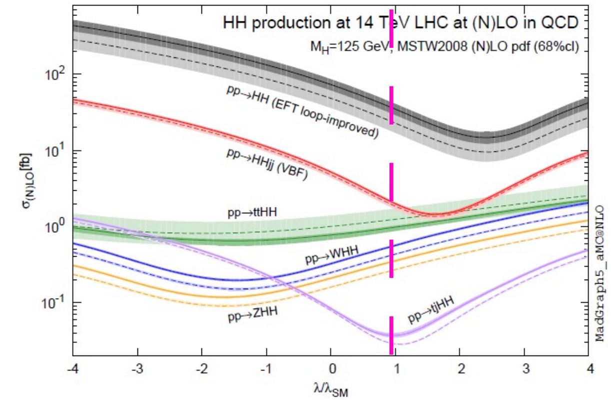


- BSM Higgs exclusion in hMSSM:
  - Direct searches for heavy Higgs
  - Set exclusions by fits to the measured rate of Higgs production and decays.

Di-Higgs production

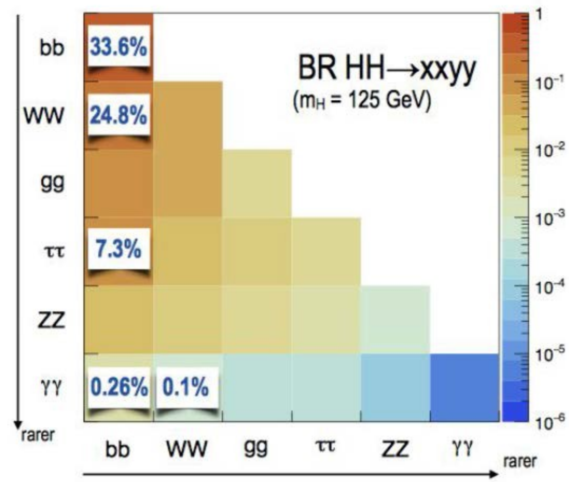
•Probing Higgs self-coupling at LHC is challenge:





•σ(gg→HH)=(33+-5.9) fb due to negative interference between first two diagrams.

•σ_{NLO}[fb] $=71.6\, y_t^4 - 46.9\, k_\lambda y_t^3 + 9.54\, k_\lambda^2 y_t^2$, sensitive to top Yukawa y_t and self-coupling $k_\lambda = \lambda/\lambda_{sm}$



•Di-Higgs enhancement via resonant X→HH production

•Results using following HH decay modes:

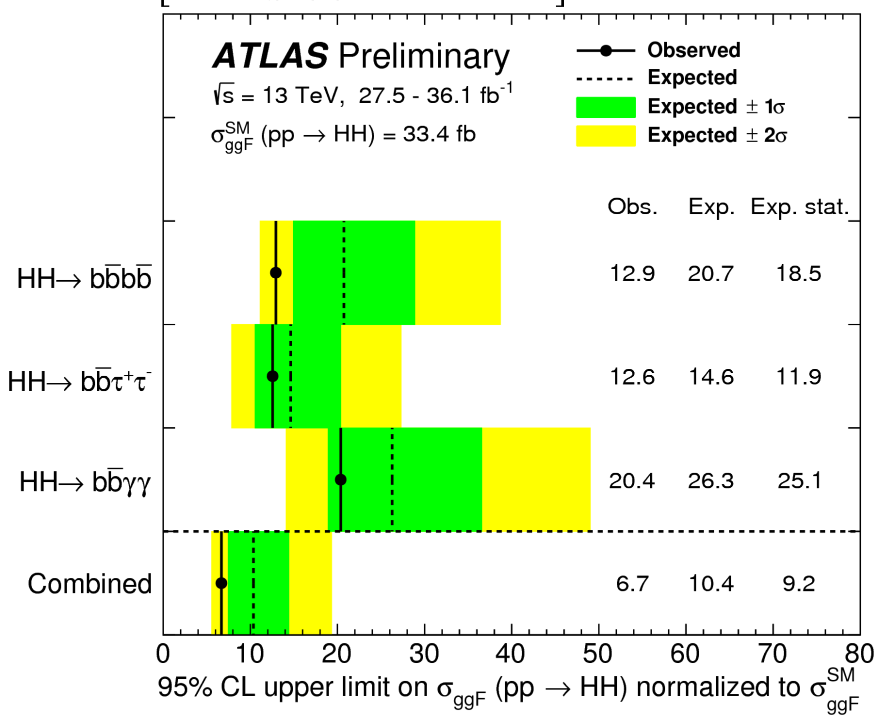
- bbbb(34%) [arXiv:1804.06174]
- bbττ(7%) [arXiv:1808.00336]]
- bbγγ(0.26%) [arXiv:1807.04873]
- WWγγ(0.1%) [arXiv:1807.08567]
- Combination [ATLAS-CONF-2018-043]

Run-2 results on di-Higgs production

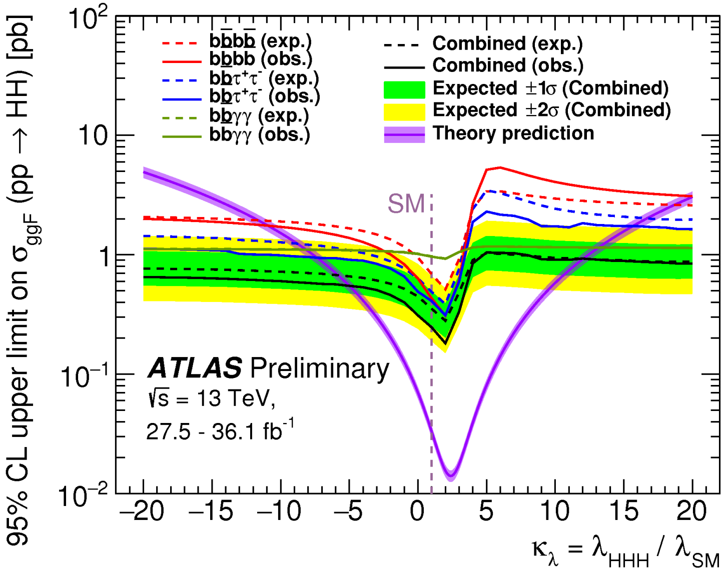
- No di-Higgs production found so far with up to 36.1 fb^{-1}
- Best single chan. limit from $HH \to bb\tau\tau$: $\mu_{HH} < 12.6$ (14.6 exp) @ 95% CL
- Combined limit: $\mu_{HH} < 6.7$ (10.4 exp.) @95% CL

- Long term goal: reach SM sensitivity by the end of HL-LHC (3000 fb^{-1}).

[ATLAS-CONF-2018-043]



- Obs. Limit $-5.0 < k_\lambda < 12.1$@95%CL.
- Exp. Limit $-5.8 < k_\lambda < 12.0$@95%CL.



Conclusion

- With more Run-2 data, Higgs physics is getting more precise.
- Observed many Higgs production and decay modes after discovery.
- The bosonic decay channels entered a precision era
- Observed all Yukawa coupling to 3rd generation fermions (t, b, τ)
- Combination with STXS will further constrain BSM couplings.
- Direct search for BSM Higgs will continue to improve.
- Sensitivity to σ_{HH} production is approaching to 6.7xSM @ 95% CL.
- Higgs provides an important probe for new physics and beyond.
- This is just at the beginning of a long journey toward the final HL-LHC luminosity! Stay tuned!