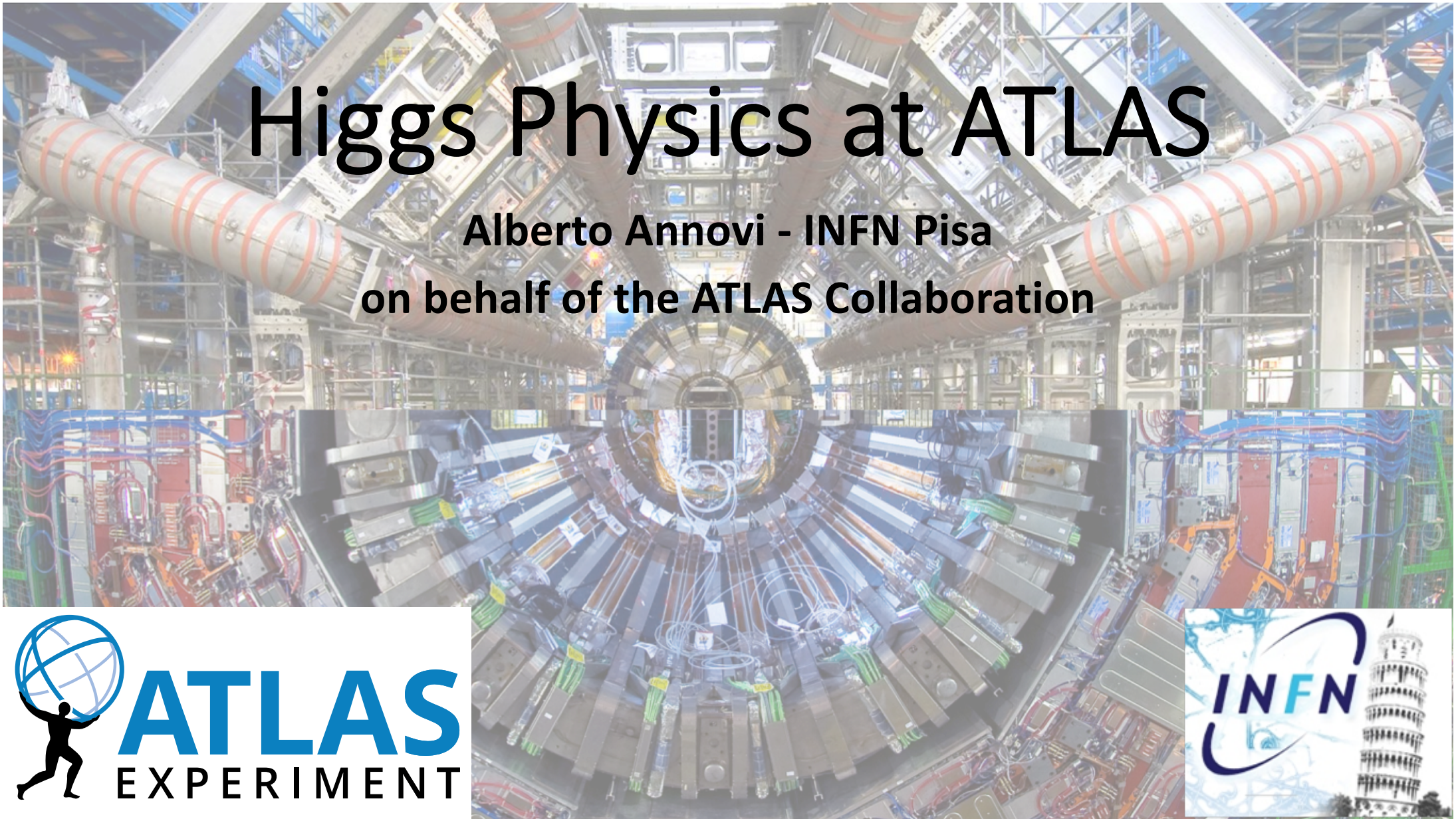
Higgs Physics at ATLAS

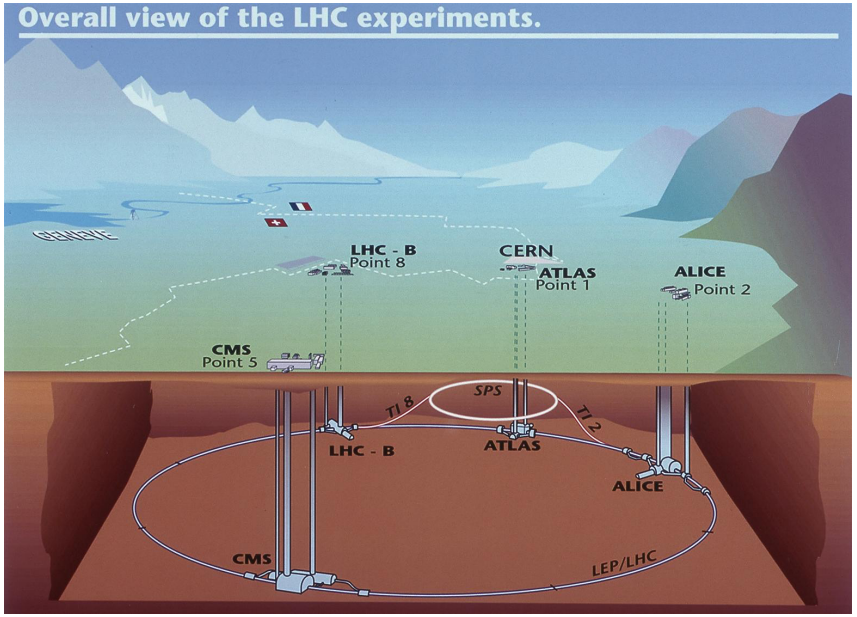
Alberto Annovi - INFN Pisa

on behalf of the ATLAS Collaboration

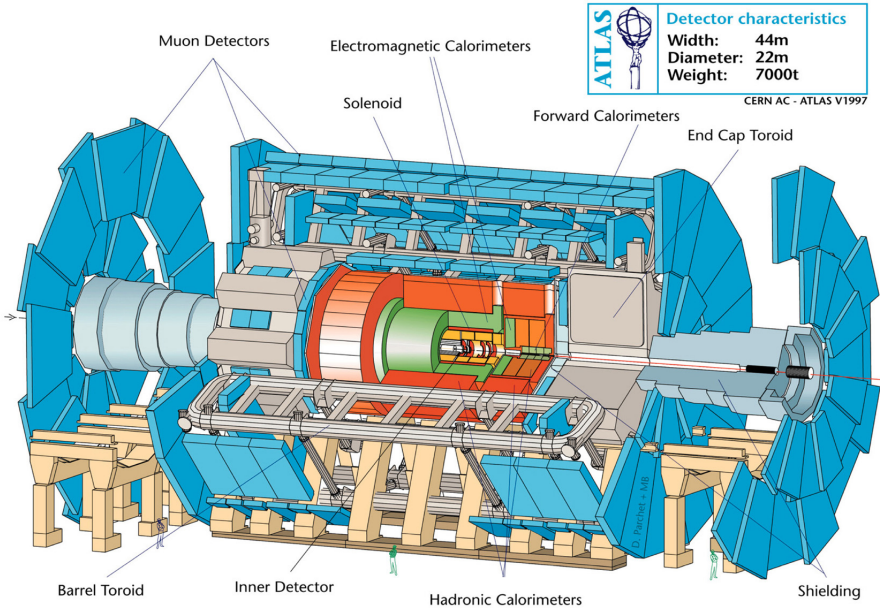


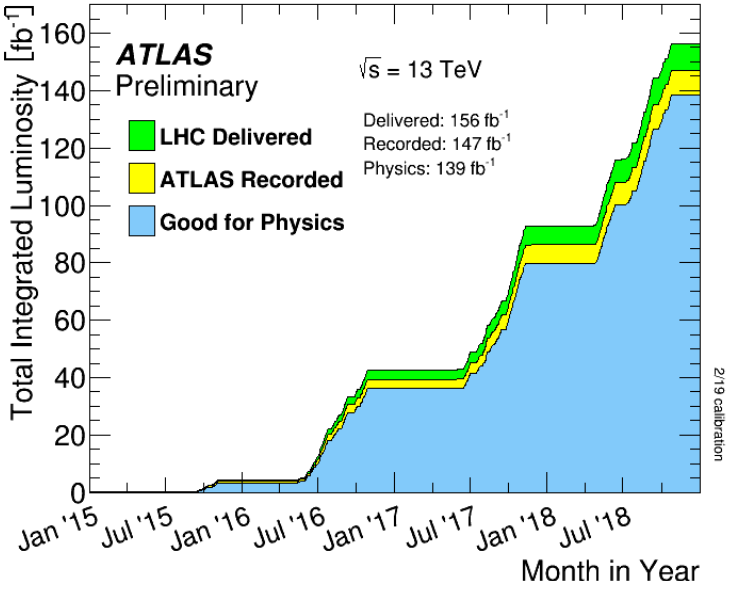
ATLAS EXPERIMENT

INFN



The LHC & the ATLAS experiment

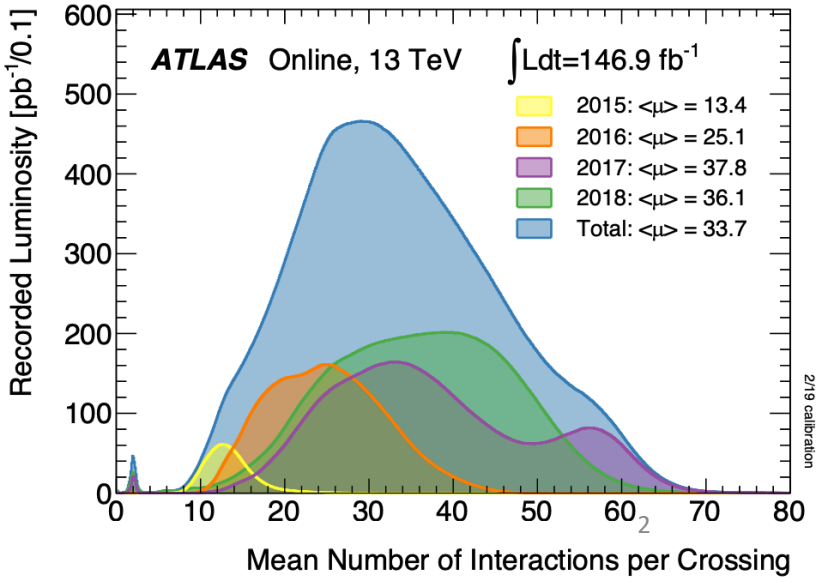




Run2 collected almost 140fb^{-1} good for physics at 13 TeV

Average number of pp interactions per crossing ~34

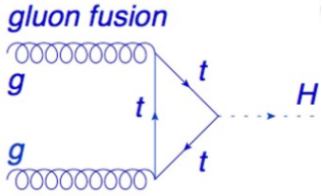
~8M Higgs produced



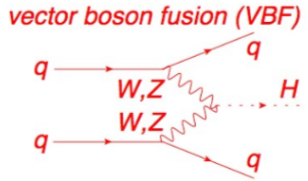
Higgs production modes

Dominant production without distinctive features

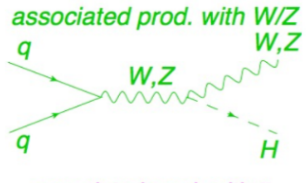
[Phys. Rev. D **98**, 030001 (2018)]



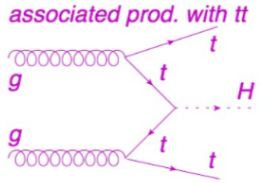
σ(13 Tev) = 49pb



σ(13 Tev) = 3.8pb

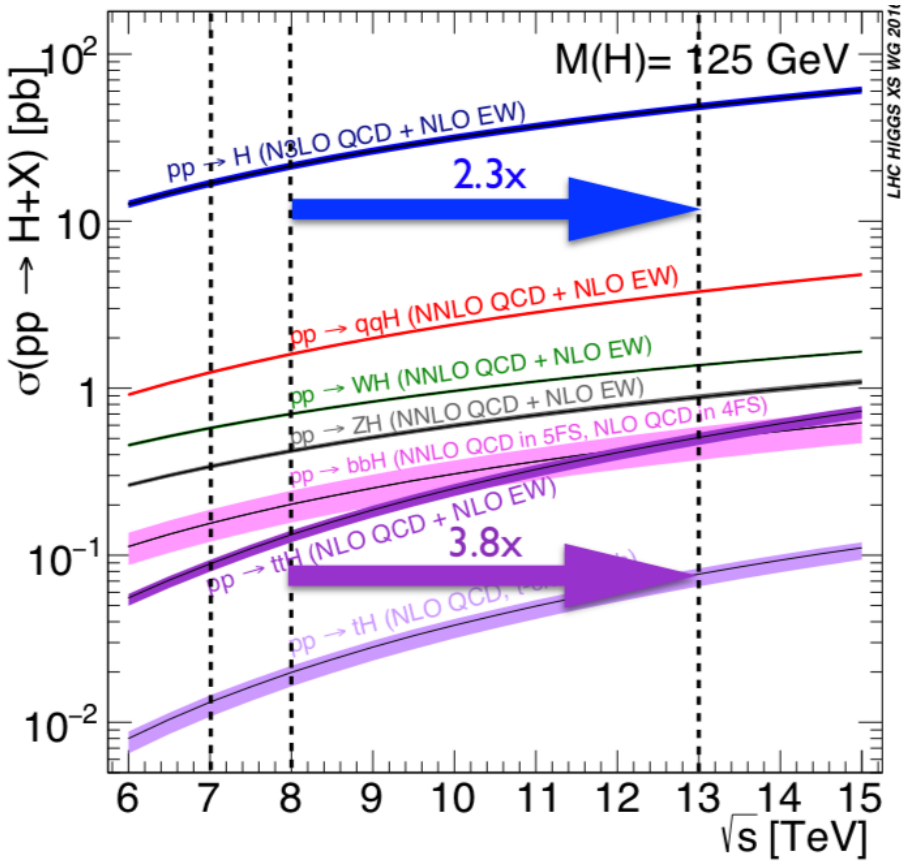


σ(13 Tev) = 2.3pb



σ(13 Tev) = 0.6 pb

[LHC Higgs X-sec WG]



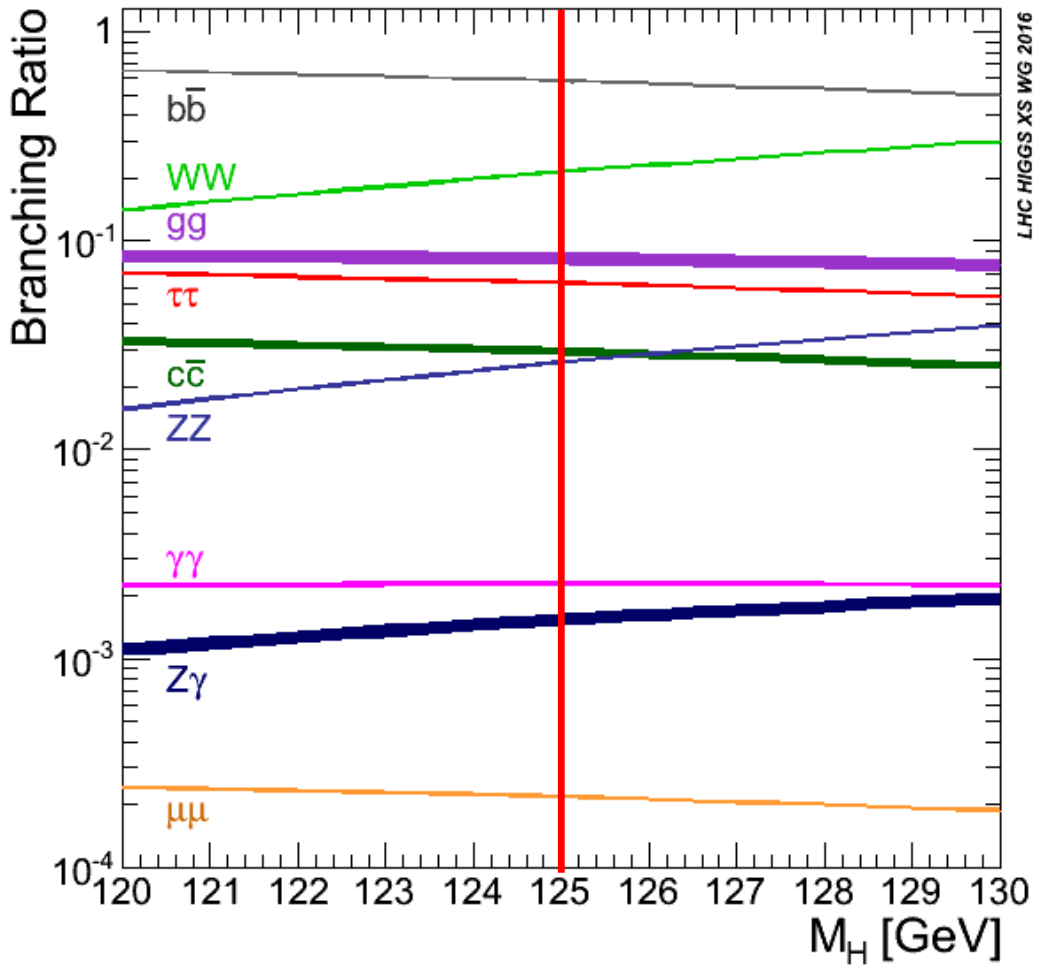
Non-inclusive channels have lower σ while providing additional signatures to reject background

Higgs decay channels

- $b\bar{b}$ dominant BR (58.4%)
- $\tau\tau$ complex final state BR (6.3%)
- WW* 2nd largest and clean BR (21.4%)
- ZZ* clean fully reconstructed BR (2.6%)
- $\gamma\gamma$ clean with high sensitivity BR (0.23%)
- $\mu\mu$ clean, very low BR (0.022%)

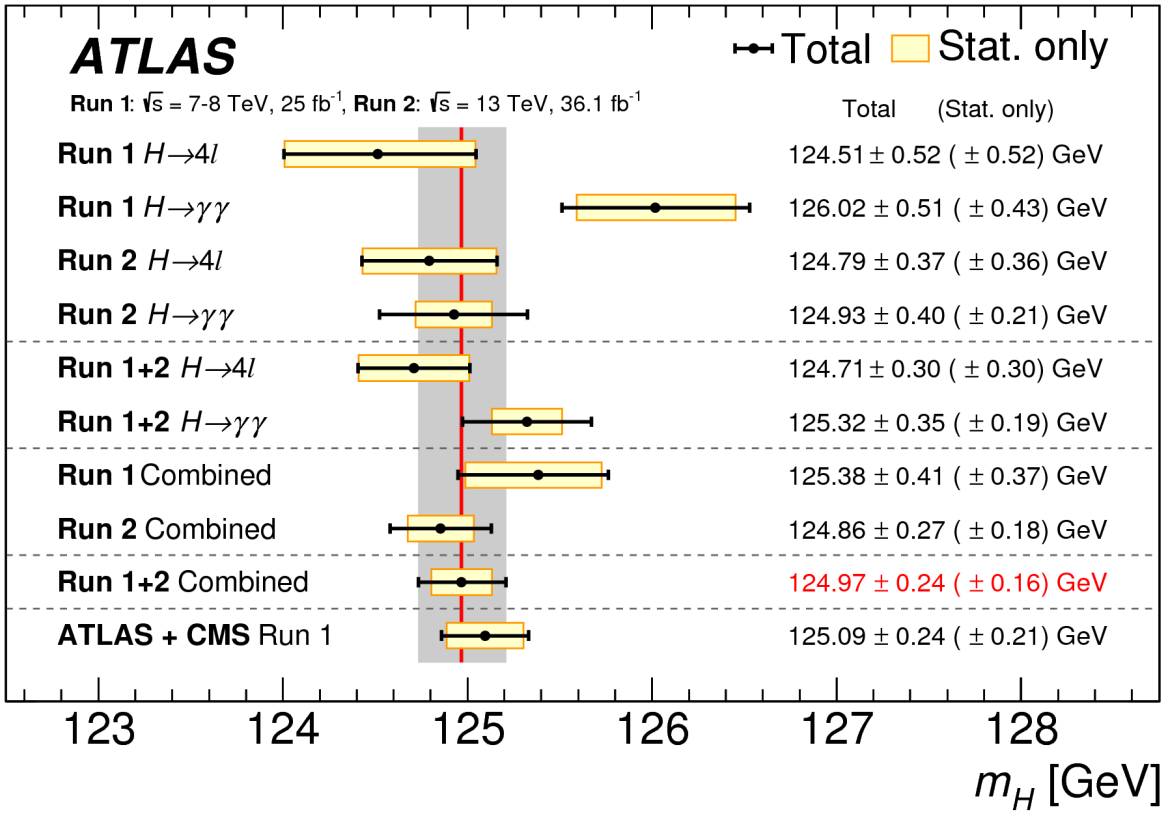
[Phys. Rev. D **98**, 030001 (2018)]

[LHC Higgs X-sec WG]



Higgs Mass in $\gamma\gamma$ and ZZ*→4l final states

$m_H = 124.97 \pm 0.24\ (\pm 0.16)$ GeV



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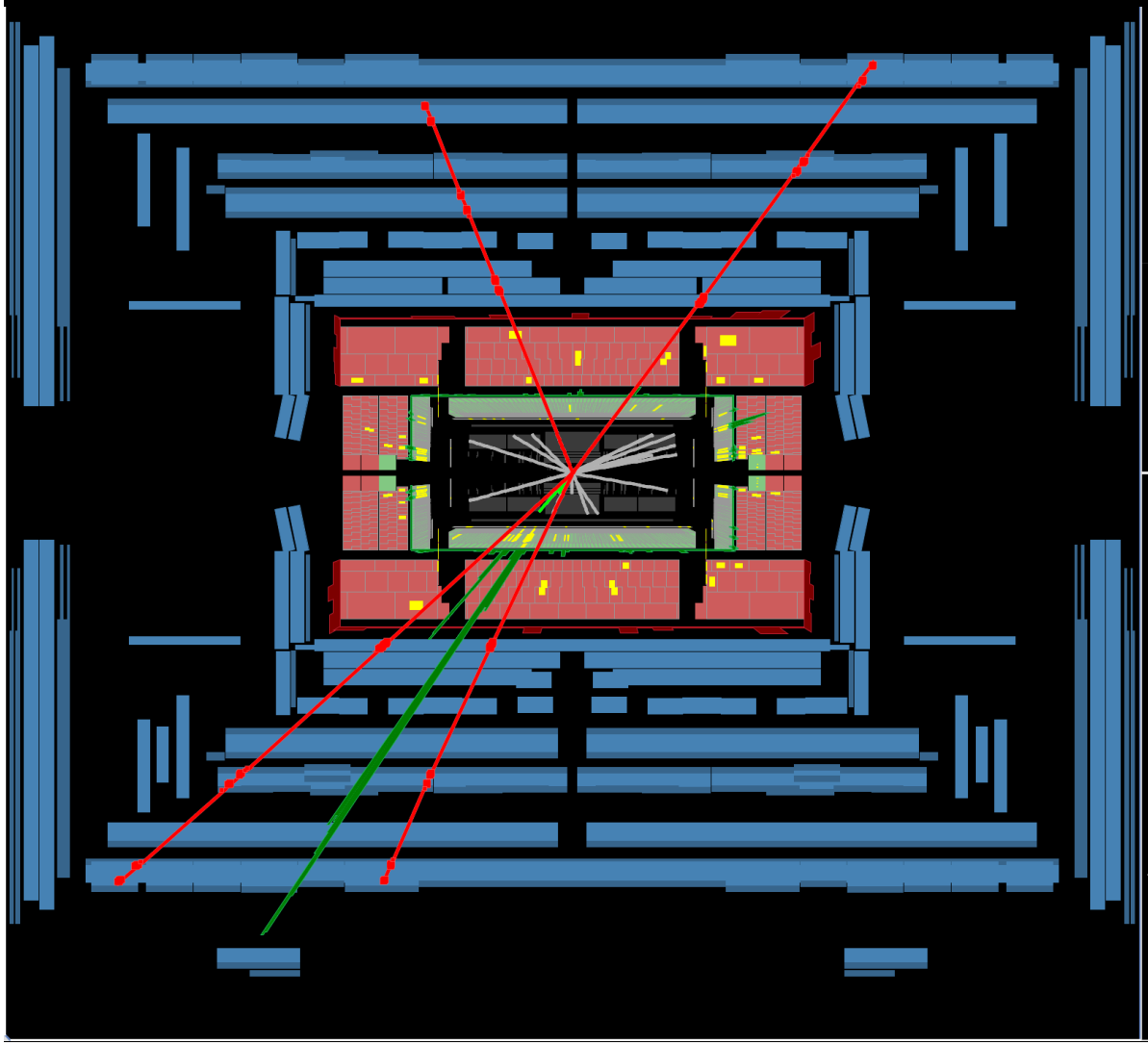
- For H->$\gamma\gamma$ systematic uncertainties are important (photon energy calibration)
- H->4l is still dominated by statistical uncertainties (36 fb^{-1})
- The current combination (with 36 fb^{-1}) has comparable statistical and systematic uncertainties
- 0.2% precision

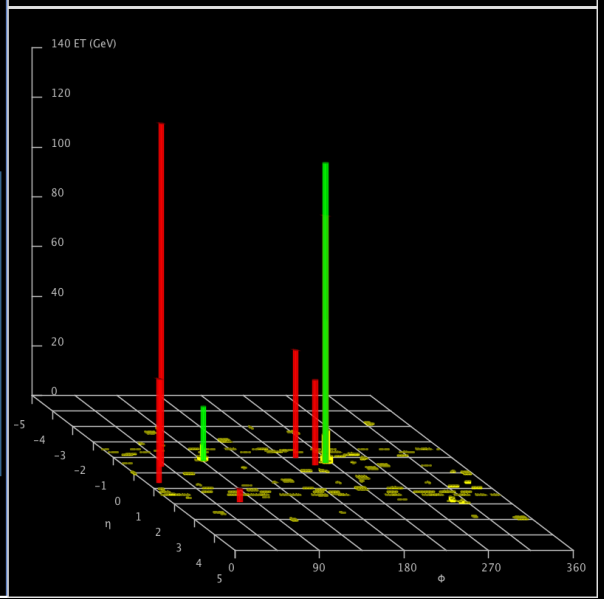
Higgs decays to Bosons



ATLAS EXPERIMENT

Run Number: 359058, Event Number: 2965933740

Date: 2018-08-25 02:51:44 CEST



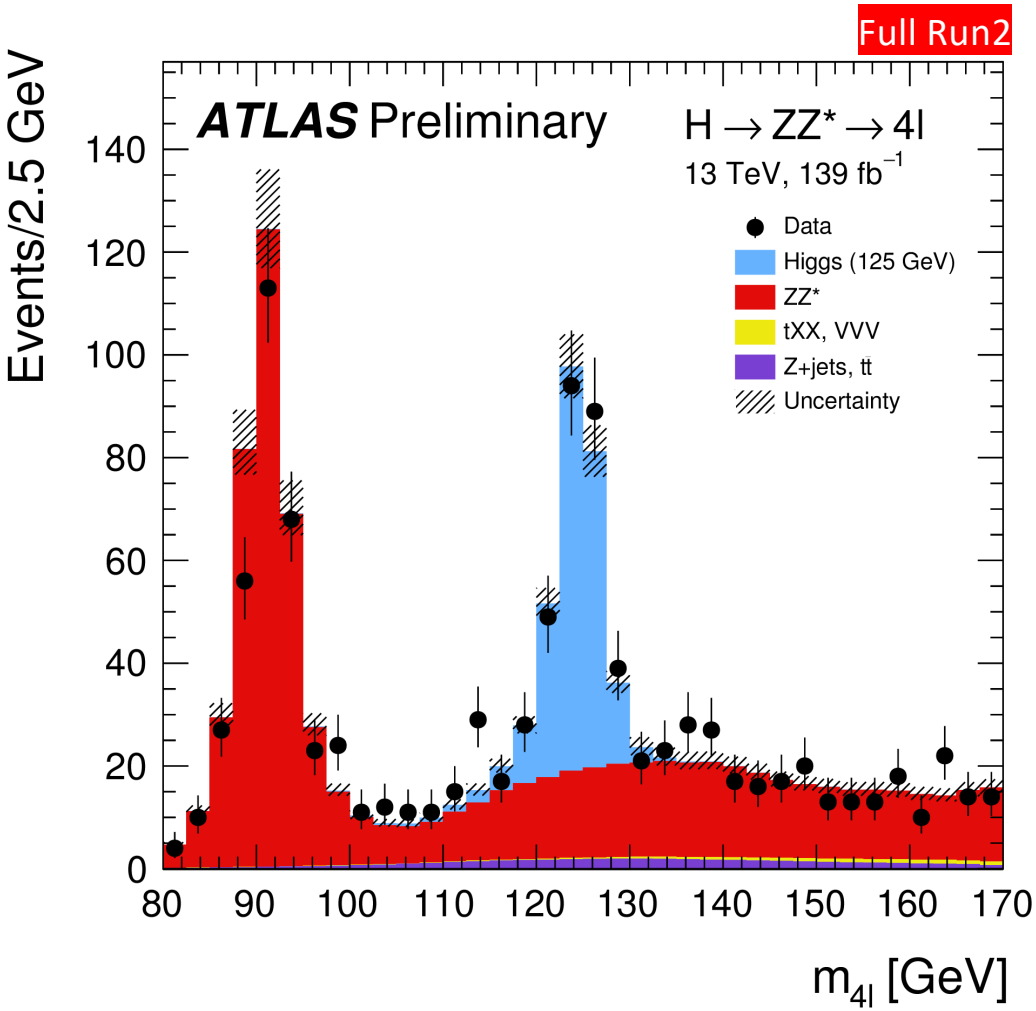
Z(→μμ)+ H(→μμee) candidate in 2018 data

NEW

Higgs to ZZ*

- Select two pairs of same-flavor opposite-sign leptons
- Require one pair to be compatible with the Z mass
- Main background ZZ*
- ZZ* background normalization is constrained from data new for this measurement
- Run2 sample of ~200 signal events
- Fiducial σ*BR (H→ZZ*→4l) measured is 3.35 ± 0.32 fb (cfr SM 3.41 ± 0.18 fb)

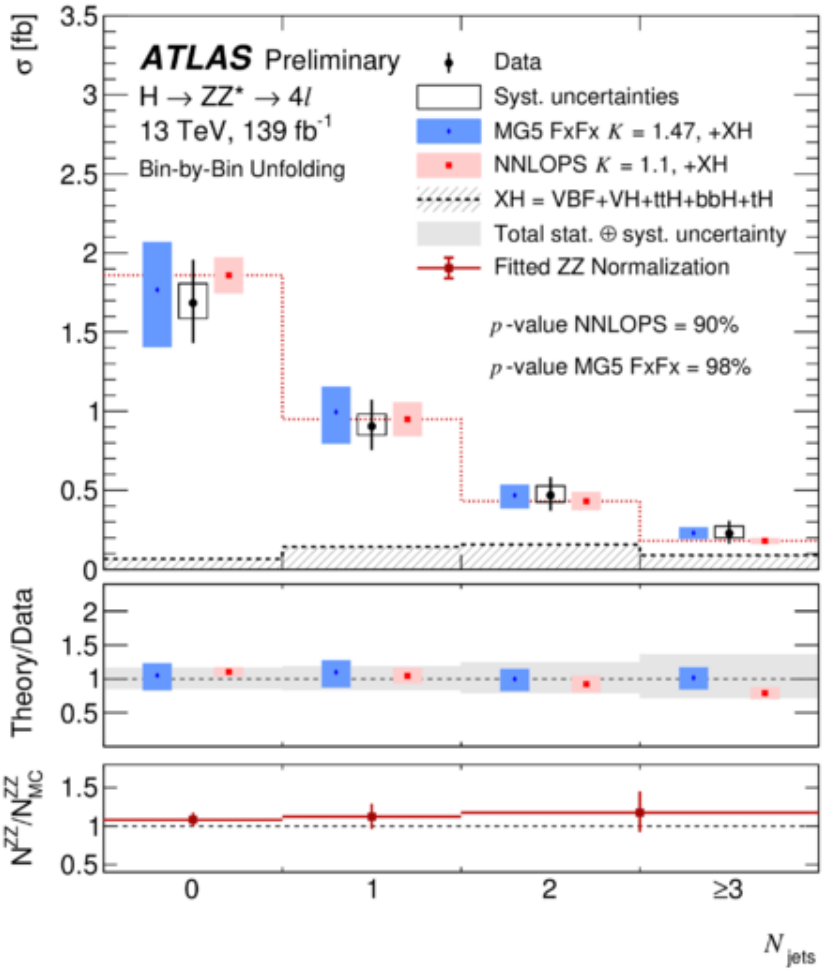
ATLAS-CONF-2019-025



NEW

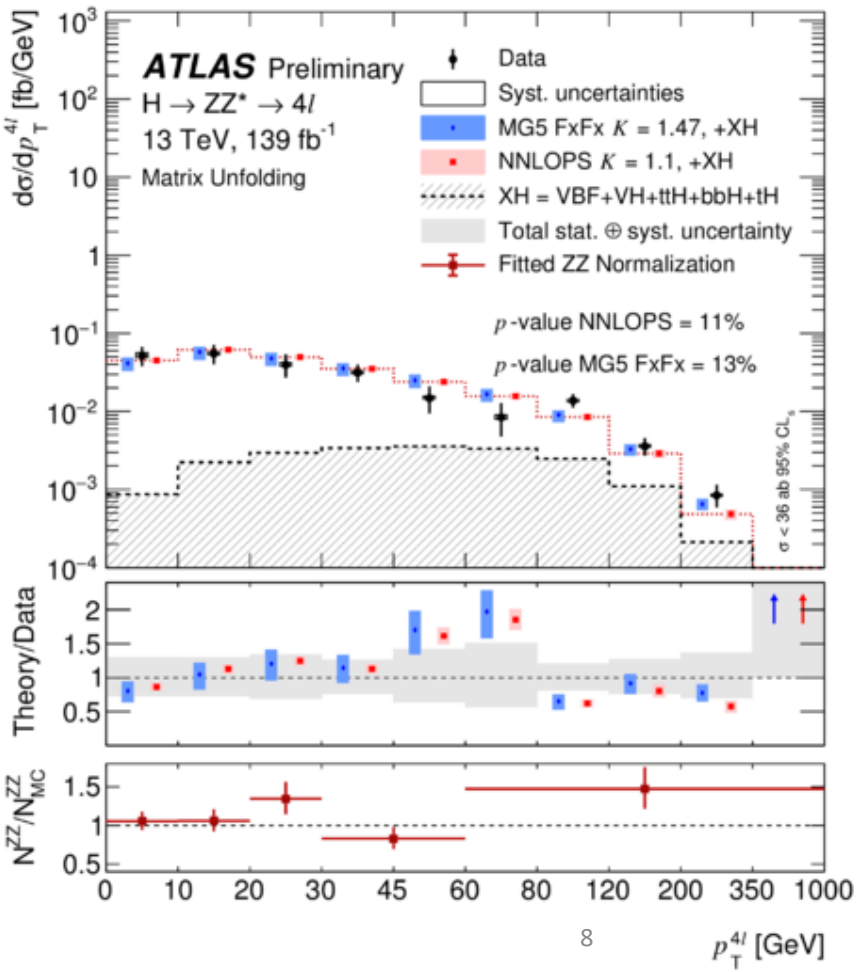
Higgs to ZZ* differential cross-sections

Full Run2



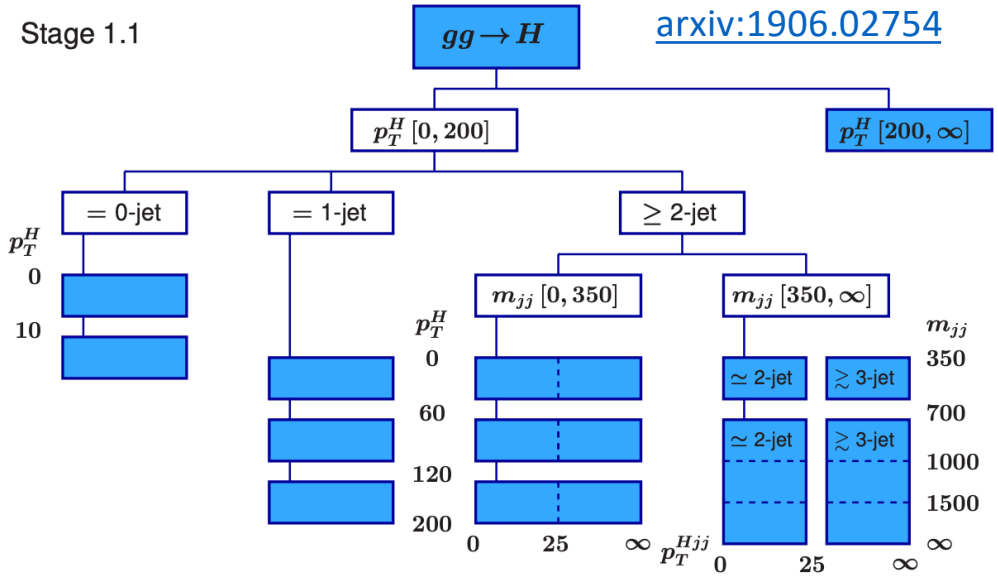
ATLAS-CONF-2019-025

Full Run2



Simplified Template cross-section (STXS)

- Define regions within the phase space of each production process, and fit for the cross-section in each region
- Reduce model dependence and maximize sensitivity to BSM
- Increasing level of detail stage 0, stage 1, stage 1.1



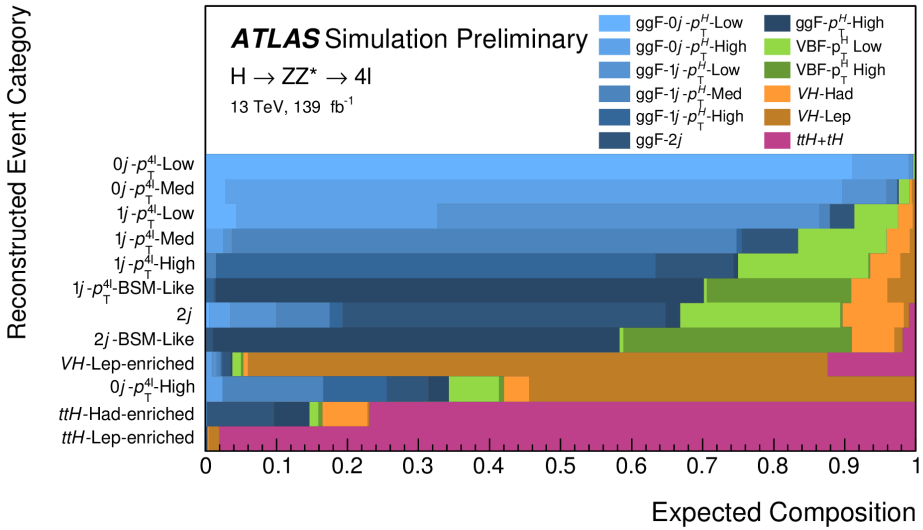
arxiv:1906.02754

- In the following STXS results are shown for H→ZZ*→4l and for the combined analysis
- STXS results available for many more single channels

NEW

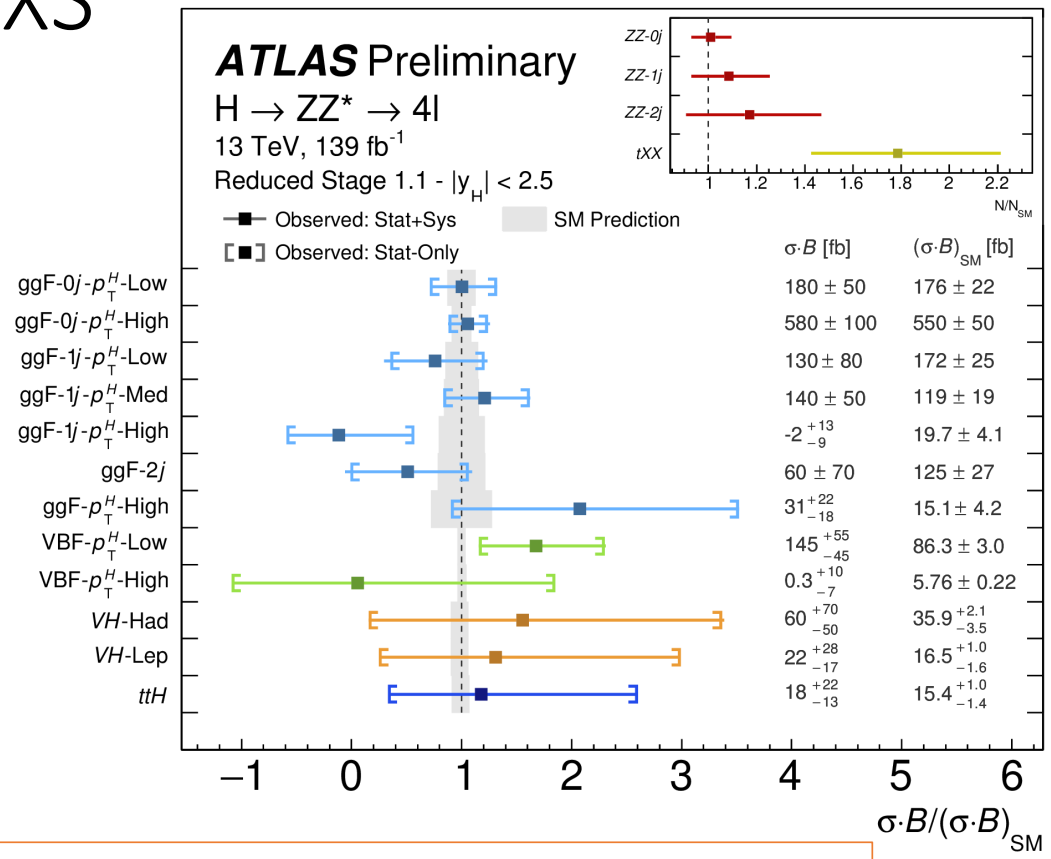
Higgs to ZZ* with STXS

- Simplified Template cross-section (STXS) to probe various regions of the phase space (reduced stage 1.1)
  - 12 reconstruction categories
- Good agreement with SM



ATLAS-CONF-2019-025

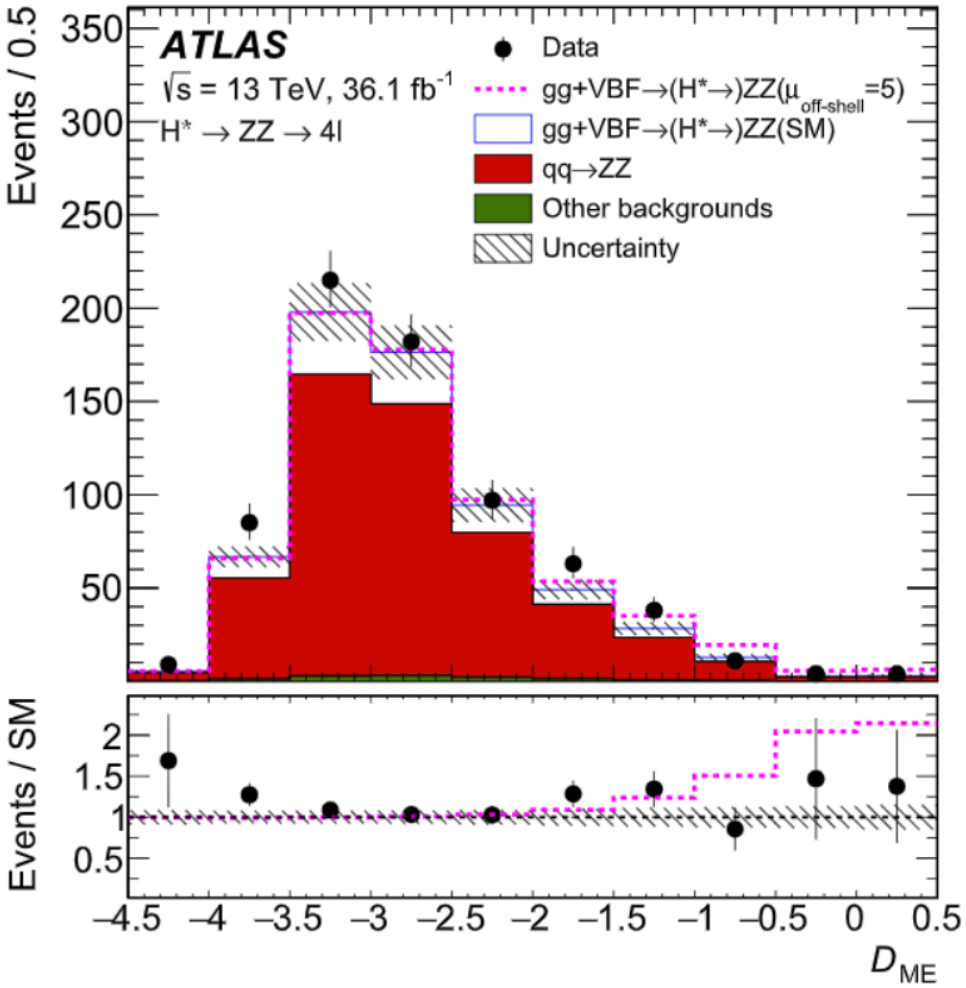
Full Run2



σ_{ggF} * BR(H→ZZ*) = 1.14 ± 0.13 pb with $|y_H|$< 2.5
(cfr SM 1.17 ± 0.08)

σ_{VBF} * BR (H→ZZ*)= 0.13 ± 0.04 pb with $|y_H|$< 2.5
(cfr SM 0.0920 ± 0.0031)

Off-shell Higgs boson production



- Two final states ZZ→4l and ZZ→2l2ν
- ZZ→4l uses ME discriminant to separate signal from ZZ production
  - Inputs are masses and angles
- ZZ→2l2ν discriminant is the transverse mass

- The ratio of off/on shell signal strength is measured and interpreted as

$$\mu_{\text{off-shell}}/\mu_{\text{on-shell}} = \Gamma_H/\Gamma_H^{\text{SM}}$$

  - Assumes off- and on-shell coupling modifiers are the same for both ggF and VBF production
  - See *Phys. Lett. B 786 (2018) 223*

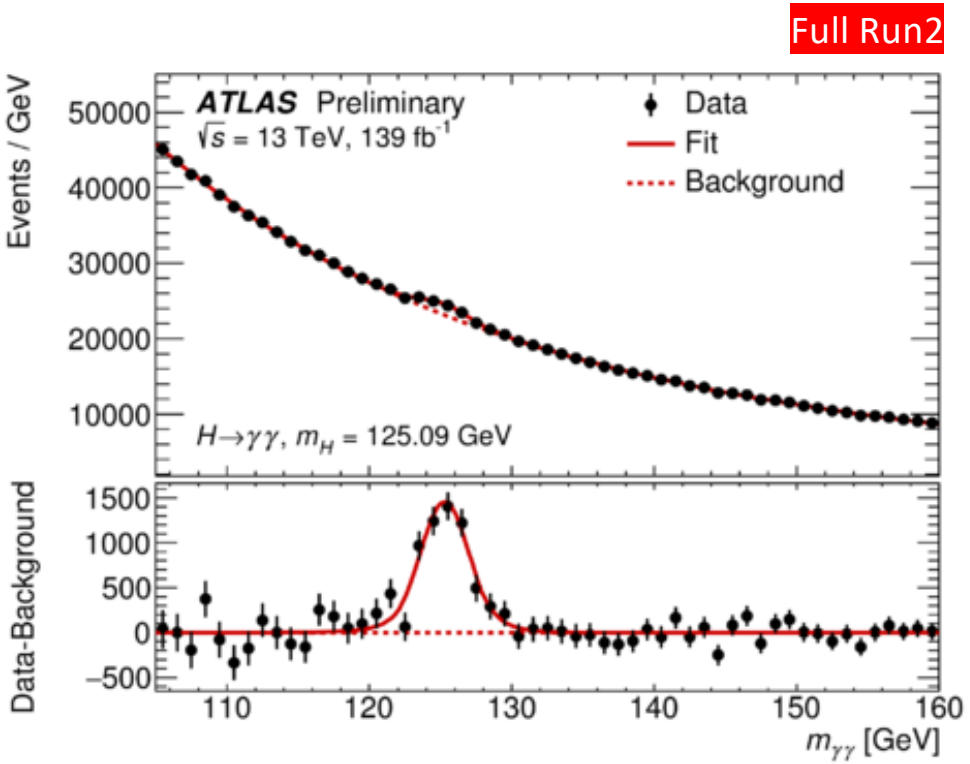
- $\Gamma_H / \Gamma_H^{SM} < 3.5$ (3.7 exp.)
- $\Gamma_H < 14.4$ MeV (15.2 exp.) @ 95% CL

NEW

Higgs to $\gamma\gamma$

ATLAS-CONF-2019-029

- Select two high p_T isolated photons
- Main back ground is irreducible $\gamma\gamma$
- Background parametrized with analytic function
  - Limit potential bias on the extracted signal
- Run2 sample of ~6500 signal events
- Fiducial σ * BR is measured: 65.2 ± 7.1 fb
  - cfr SM 63.6 ± 3.3 fb

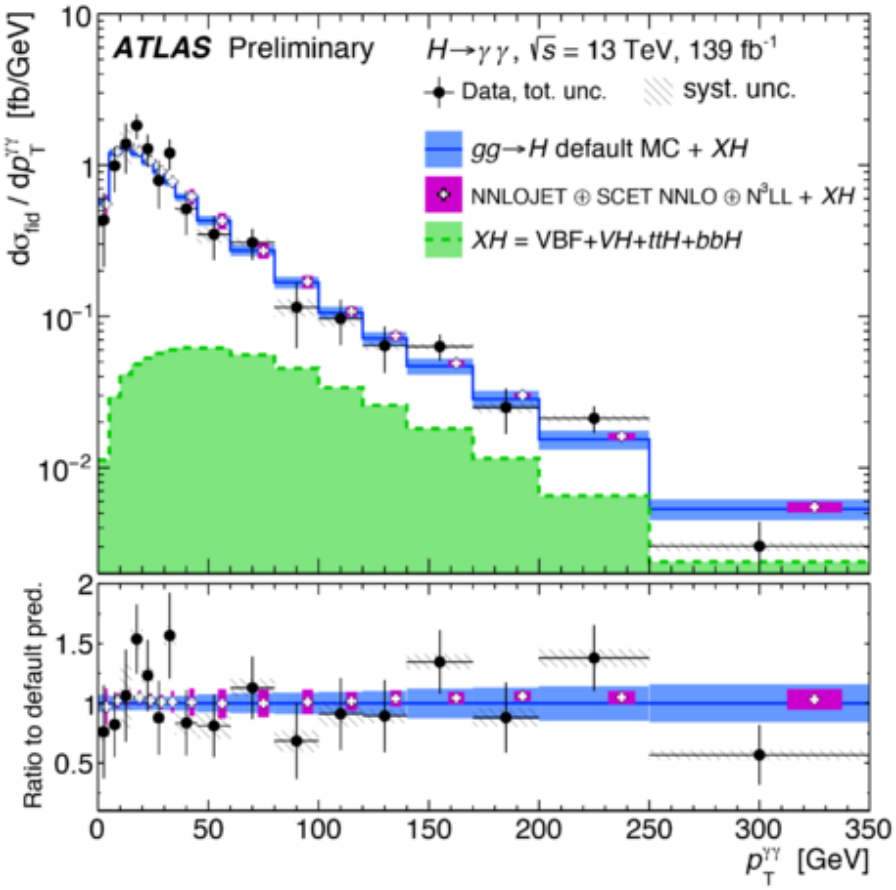


NEW

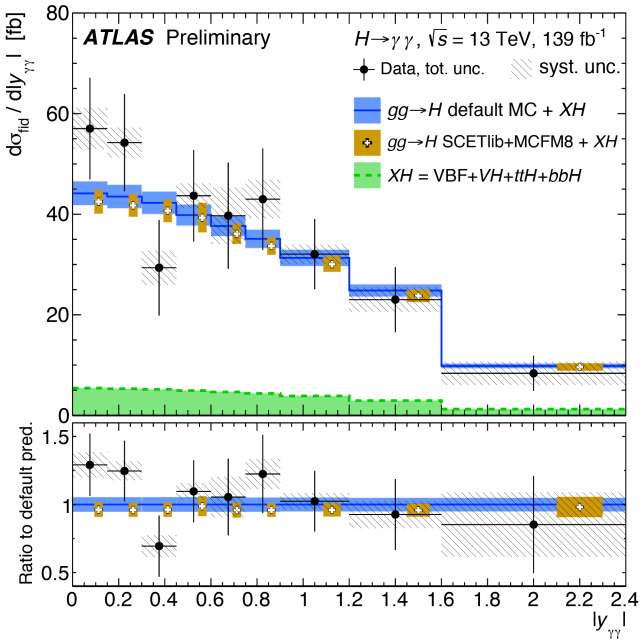
Higgs to $\gamma\gamma$

ATLAS-CONF-2019-029

Full Run2



- Measure p_T differential cross-section
  - Sensitive to charm quark Yukawa coupling via cc→H production and interference of c- and t-mediated contributions to the gg fusion loop
  - Limits on κ_c are set [−19, 24] at 95% CL



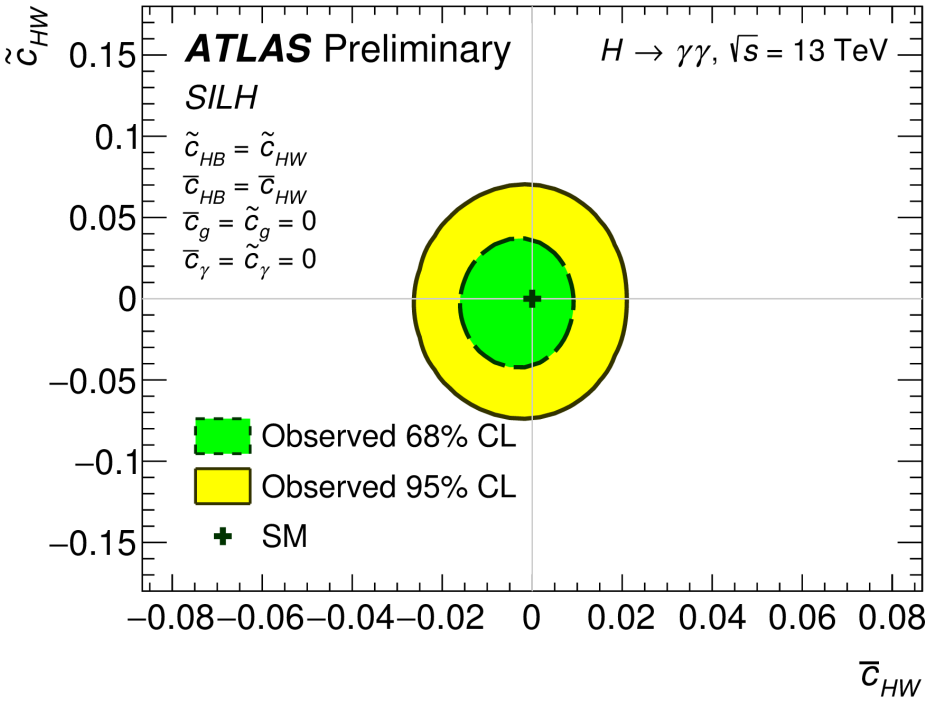
NEW

Higgs to $\gamma\gamma$

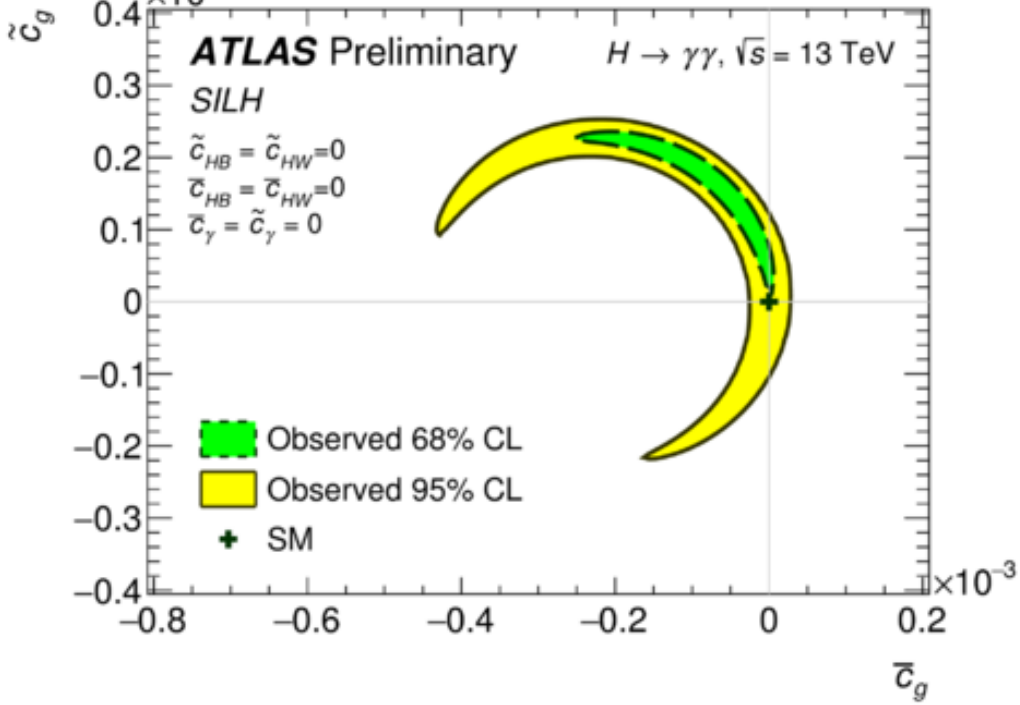
- Probe for new physics with differential cross section
- Limits on dimension-6 operators Wilson coefficients describing couplings with W and gluons

ATLAS-CONF-2019-029

Full Run2



Full Run2



Higgs to WW*→e$\nu\mu\nu$

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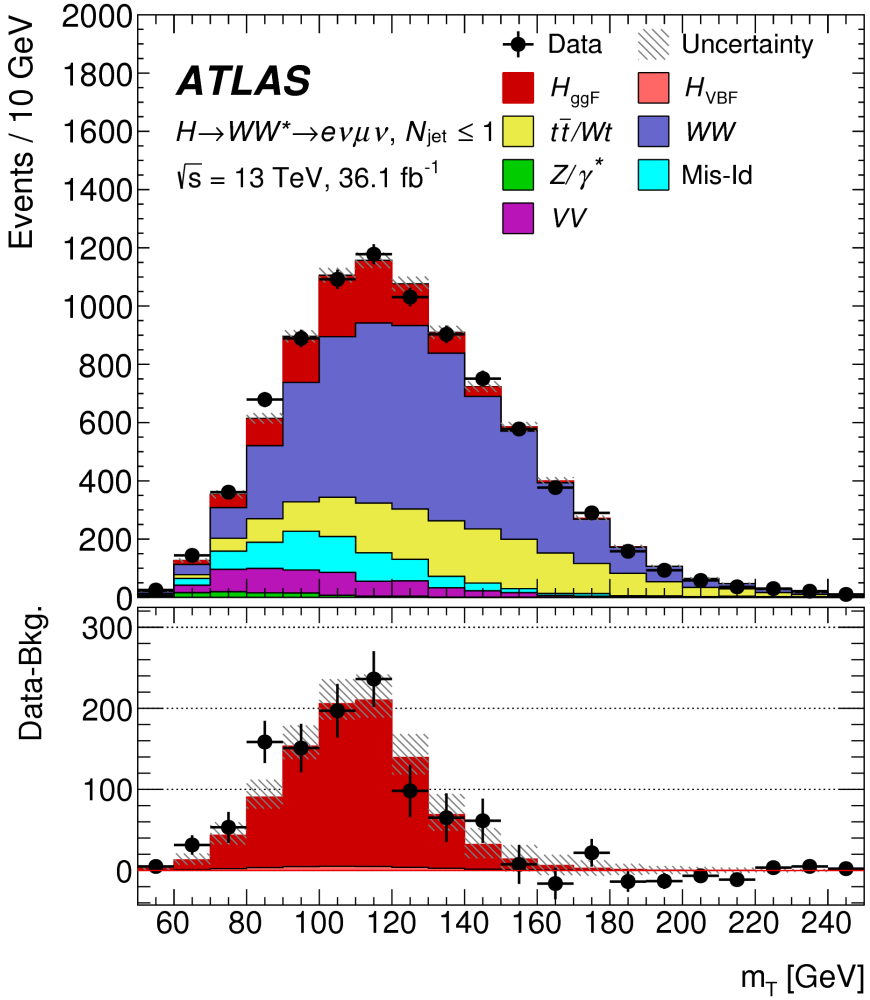
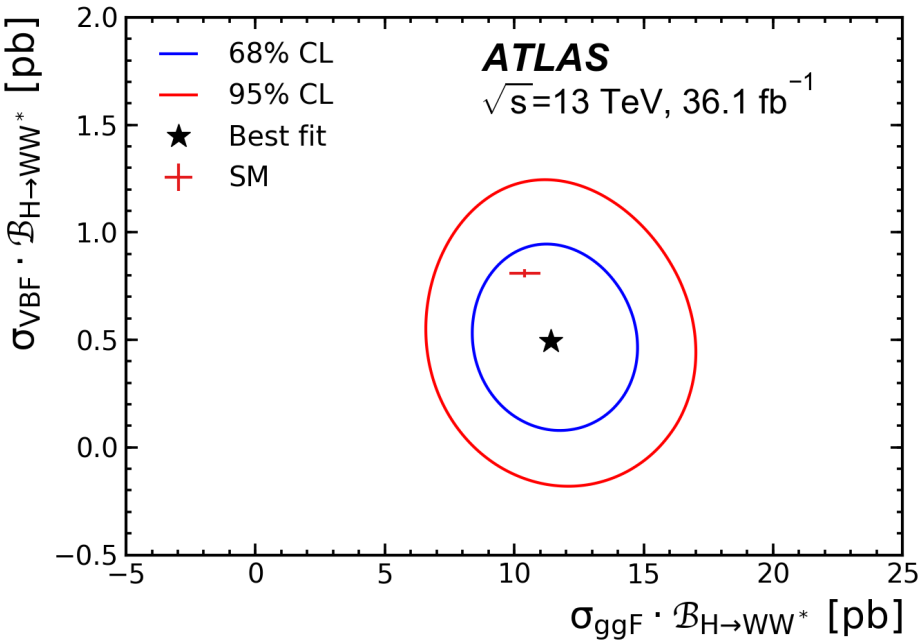
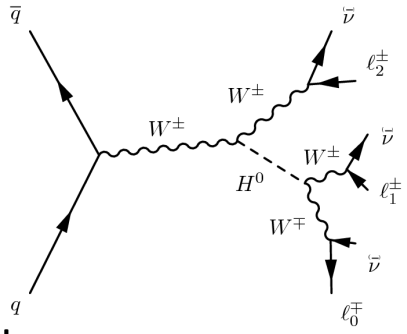


- Two different-flavor OS leptons selected
- Main backgr. are WW, top, diboson and Z→$\tau\tau$
- σ_{ggF}*BR(H→WW*) = $11.4^{+2.2}_{-2.1}$pb
- σ_{VBF}*BR(H→WW*) = $0.5^{+0.29}_{-0.28}$pb



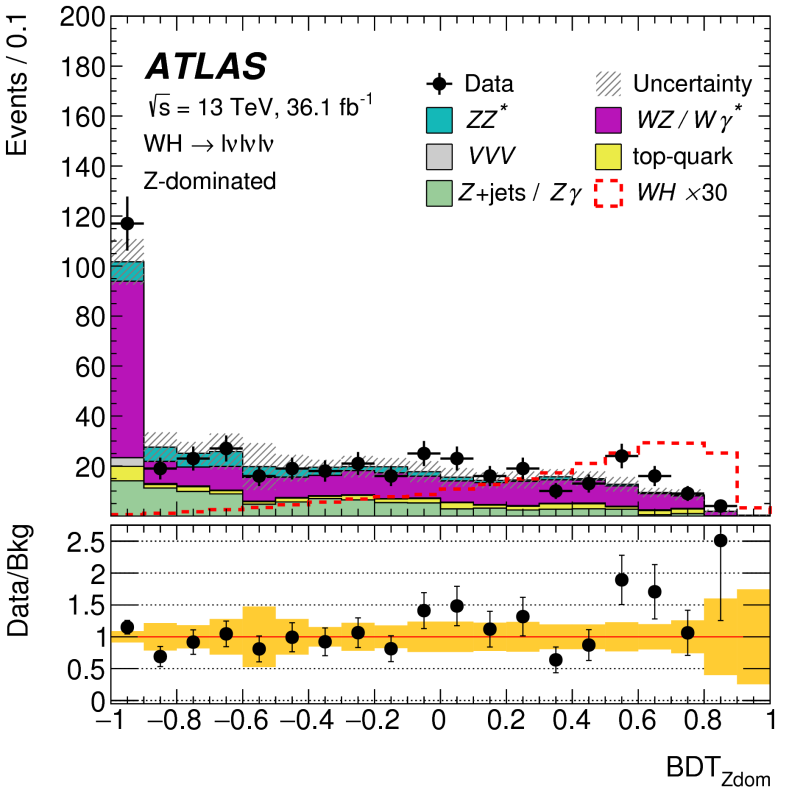
VH with H→WW*→lνlν

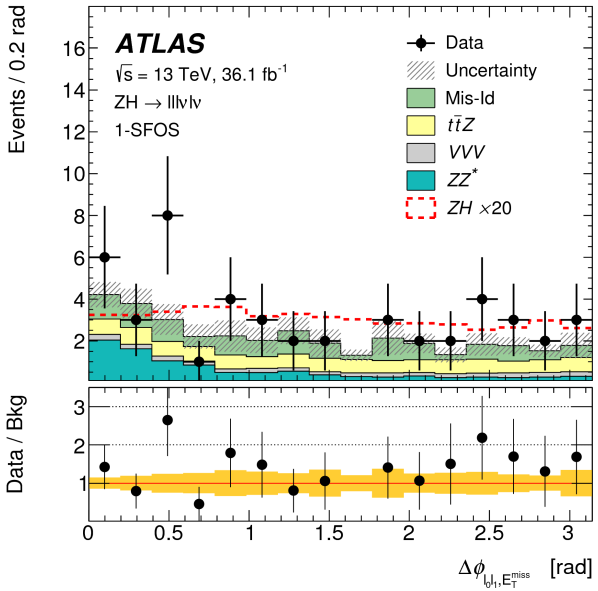
arxiv:1903.10052



WH

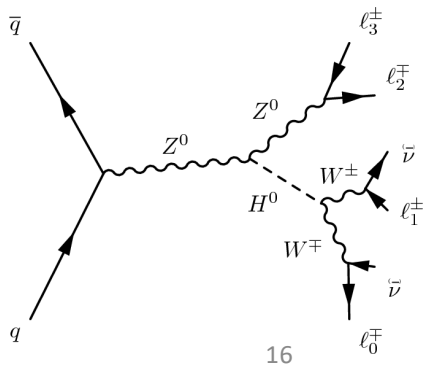
- Events are selected with exactly 3 isolated leptons with p_T>15 GeV
- The total charge is required to be ± 1
- The main WH backgrounds are WZ/Wγ * and top processes
- BDT discriminants are used to extract the signal





ZH

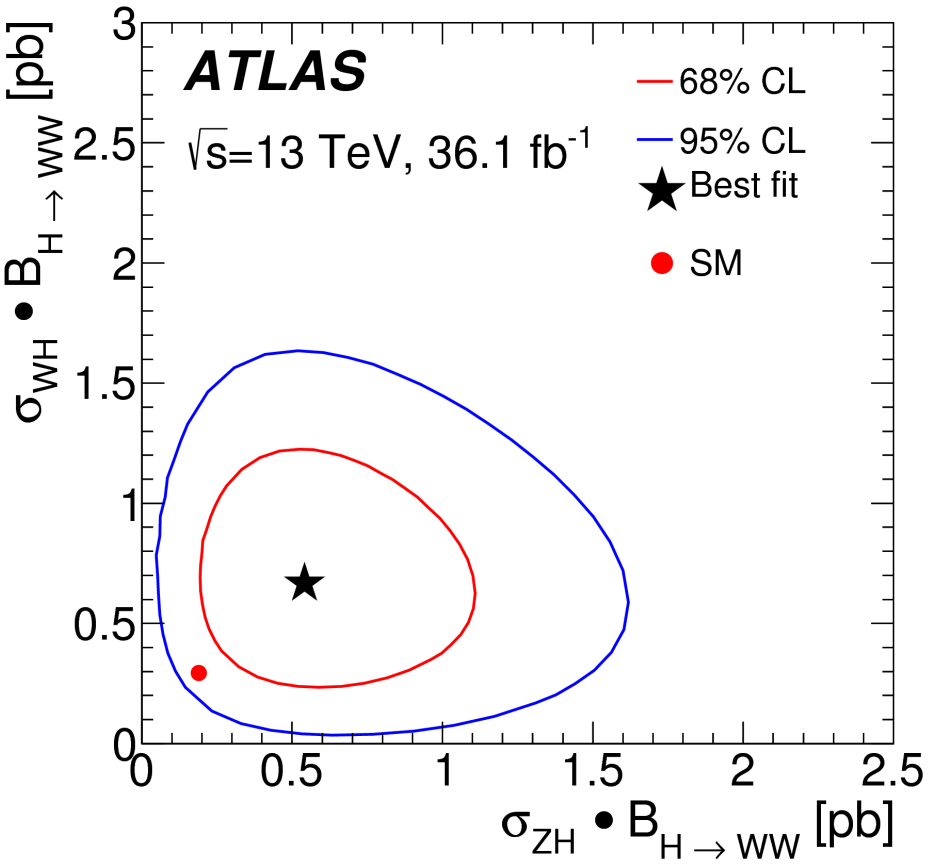
- Events are selected with 4 leptons p_T>10 GeV with a total charge of 0
- Only events with 1 or 2 same flavor opposite sign (SFOS) leptons are kept



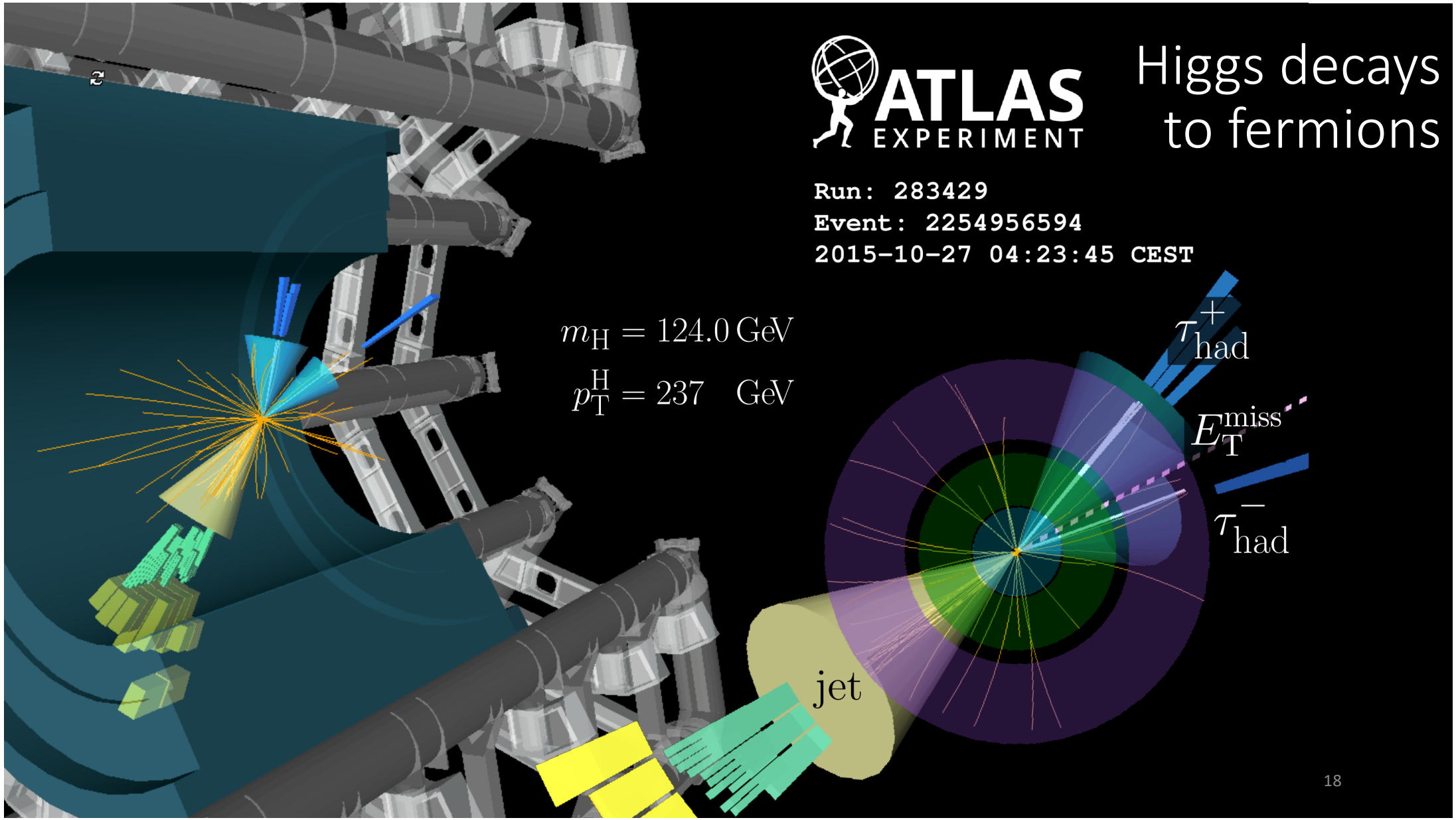
VH with H→WW*→lνlν

arxiv:1903.10052

- σ(WH)*BR(H→WW*) is measured to be $0.67^{+0.31}_{-0.27}(\text{stat.})^{+0.18}_{-0.14}(\text{syst.})$ pb
- σ(ZH)*BR(H→WW*) is measured to be $0.54^{+0.31}_{-0.24}(\text{stat.})^{+0.15}_{-0.07}(\text{syst.})$ pb
- The WH and ZH combined significance is 4.1σ (1.9 exp.)

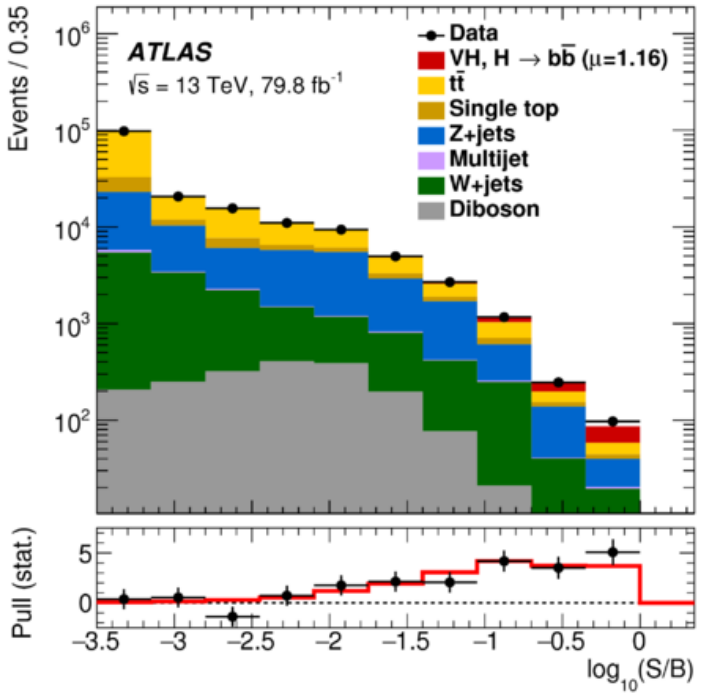


Higgs decays to fermions



VH with H→$b\bar{b}$

- H→$b\bar{b}$ hidden by large $b\bar{b}$ background
- VH prod. improves S/B and provides best sensitivity
- Signal includes ZH→$\nu\nu b\bar{b}$, WH→$l\nu b\bar{b}$, ZH→$ll b\bar{b}$ corresponding to 0, 1 and 2 charged leptons



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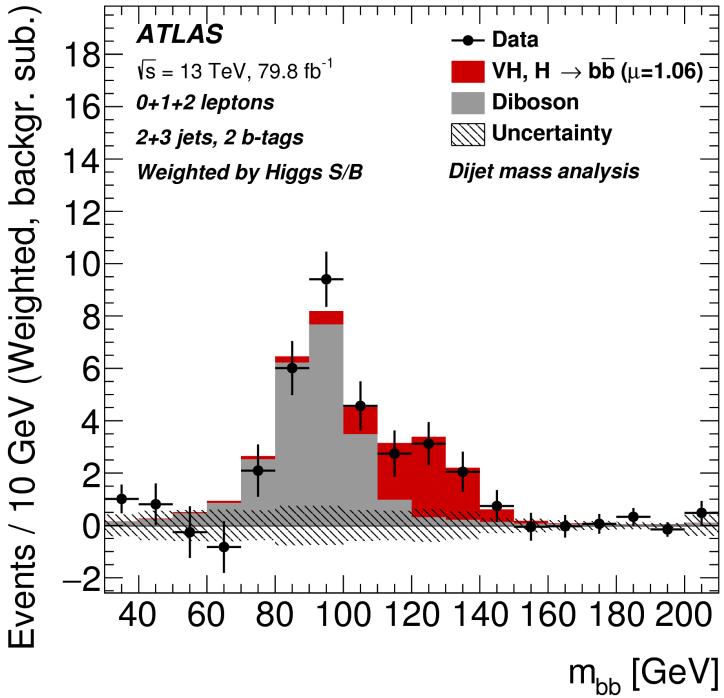


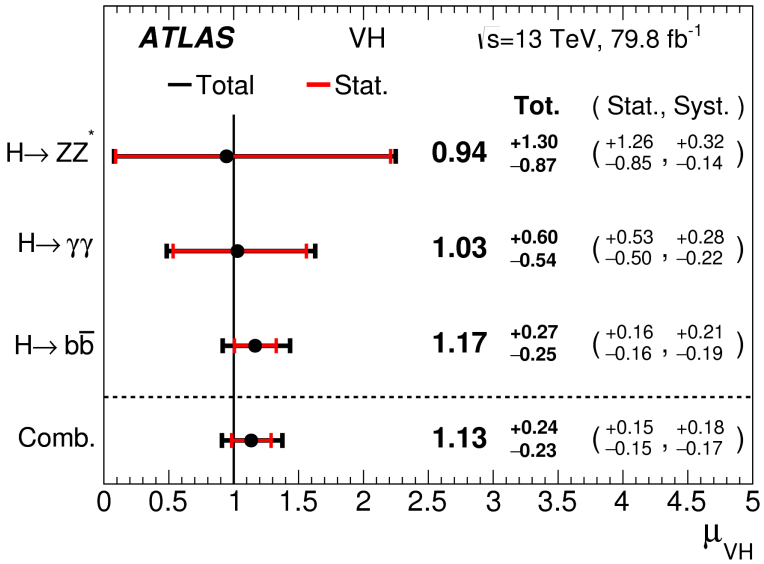
- Events selected with exactly 2 b-tagged jets that form the Higgs candidate, with one b-jet having p_T>45 GeV
- 8 event categories based on 2 or 3 jets, number of leptons and Higgs p_T
- BDT analysis is performed in each region

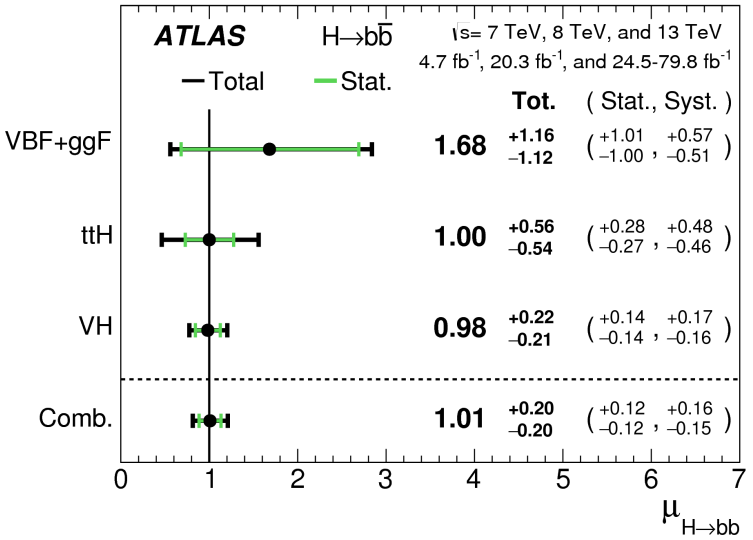
Combination with H→$b\bar{b}$ and VH channels

- The VH (H→$b\bar{b}$) result is combined with the $b\bar{b}$ analysis of ttH and VBF+ggF production modes Run1 and Run2
- The measured combined signal strength relative to SM is

$$\mu_{H\to bb} = 1.01 \pm 0.20 = 1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.}).$$

- The H→$b\bar{b}$ combined significance is 5.4σ (5.5σ exp.).
  - VH (H→$b\bar{b}$) alone has 4.9σ significance (Run2 only)





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- The Run2 VH (H→$b\bar{b}$) result is combined with VH in the decay channels H→ZZ*→4l and H→$\gamma\gamma$
- The VH comb. has a significance of 5.3σ (4.8σ exp.)
- The signal strength is 1.13 ± 0.15 (stat.) ± 0.18 (syst.)

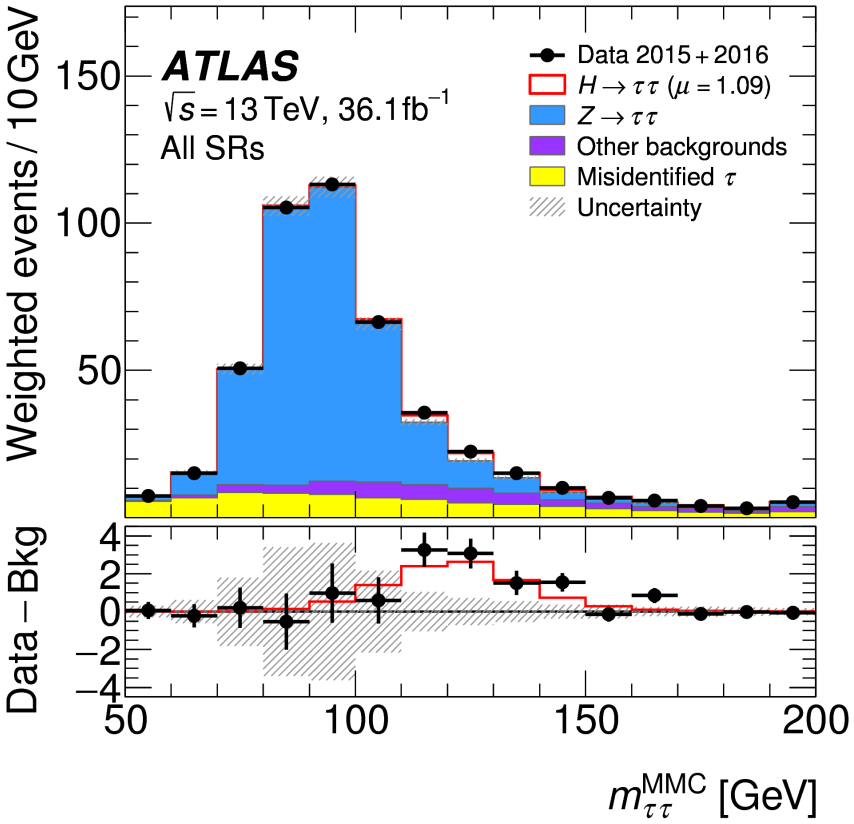
Higgs to $\tau\tau$

- Select all of pairs of $\tau \rightarrow e\nu\nu$, $\tau \rightarrow \mu\nu\nu$, $\tau \rightarrow \nu$ hadrons
- Main backgrounds Z→$\tau\tau$, Z→ll, top, misidentified τ
- Dominant Z→$\tau\tau$ is normalized to data via Z→ll validation regions
- Require a jet with p_T>40 GeV to suppress Z→$\tau\tau$
  - Jet p_T>70 GeV for $\tau_{had}\tau_{had}$ channel
- Two categories to improve S/B and disentangle the production modes
  - VBF : Jet2 p_T>30GeV, $|\Delta\eta_{jj}|$>3, m_{jj}>400GeV
  - Boosted : not VBF and $p_T^{\tau\tau}$ > 100 GeV
- The total σ * BR(H→$\tau\tau$) is measured to be

$$3.77^{+0.60}_{-0.59}(\text{stat.})^{+0.87}_{-0.74}(\text{syst.})\text{pb}$$

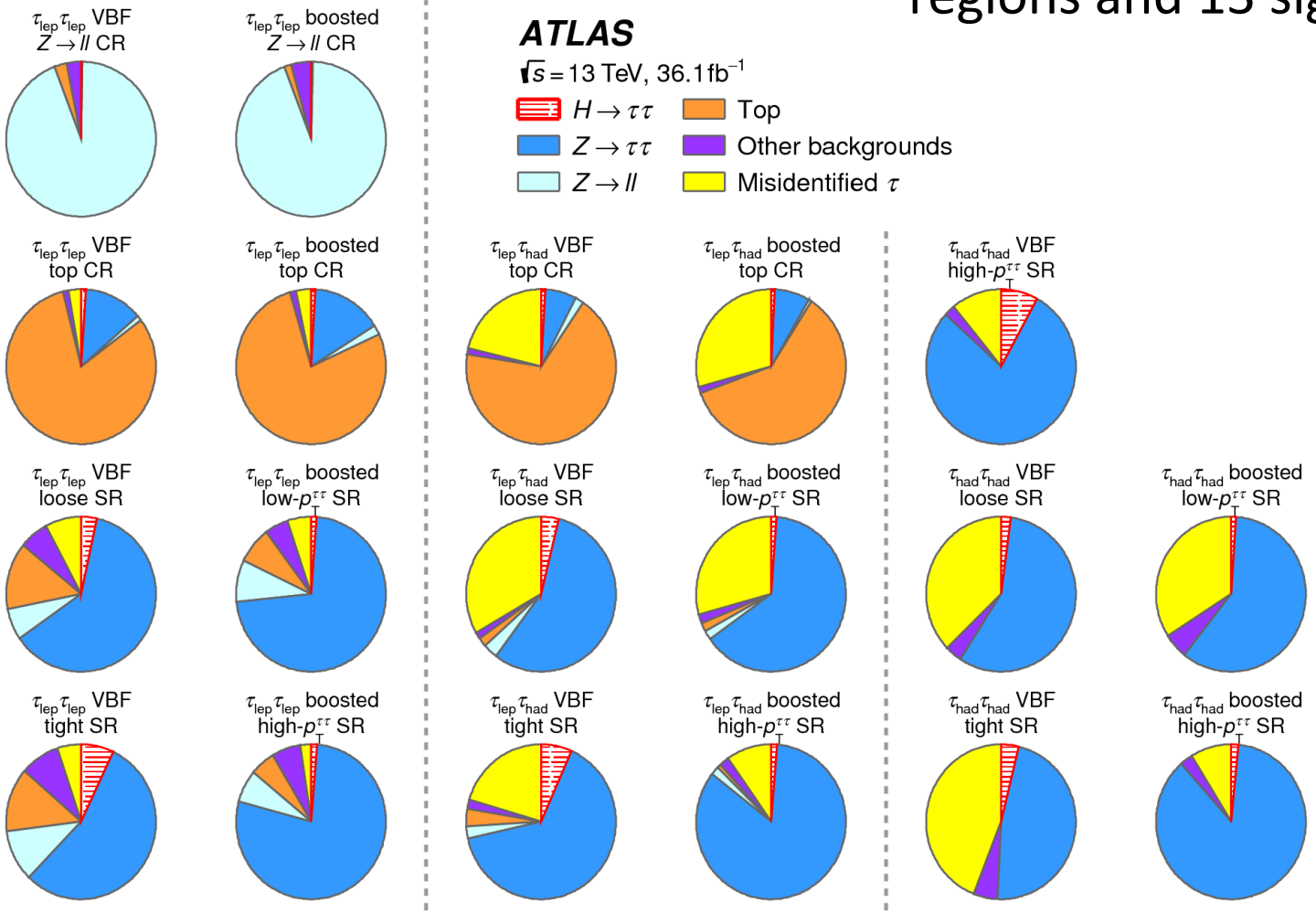
- In combination with run 1 data, H→ $\tau\tau$ has been observed with a significance of 6.4 σ (5.4 exp)

Phys. Rev. D 99 (2019) 072001

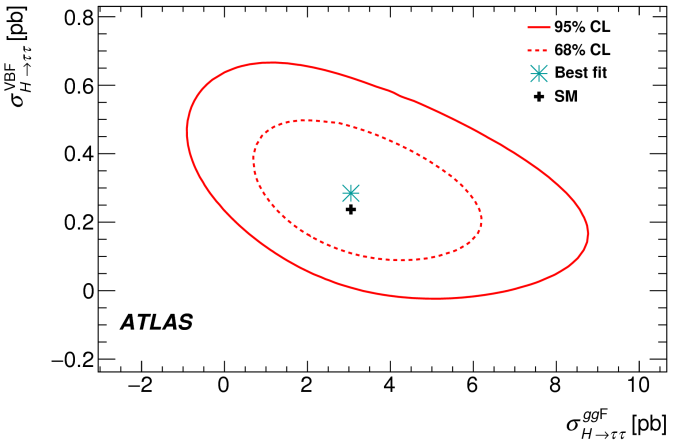


Higgs to $\tau\,\tau$

Background (and signal) composition for the 6 control regions and 13 signal regions



σ^{VBF} vs σ^{ggF}



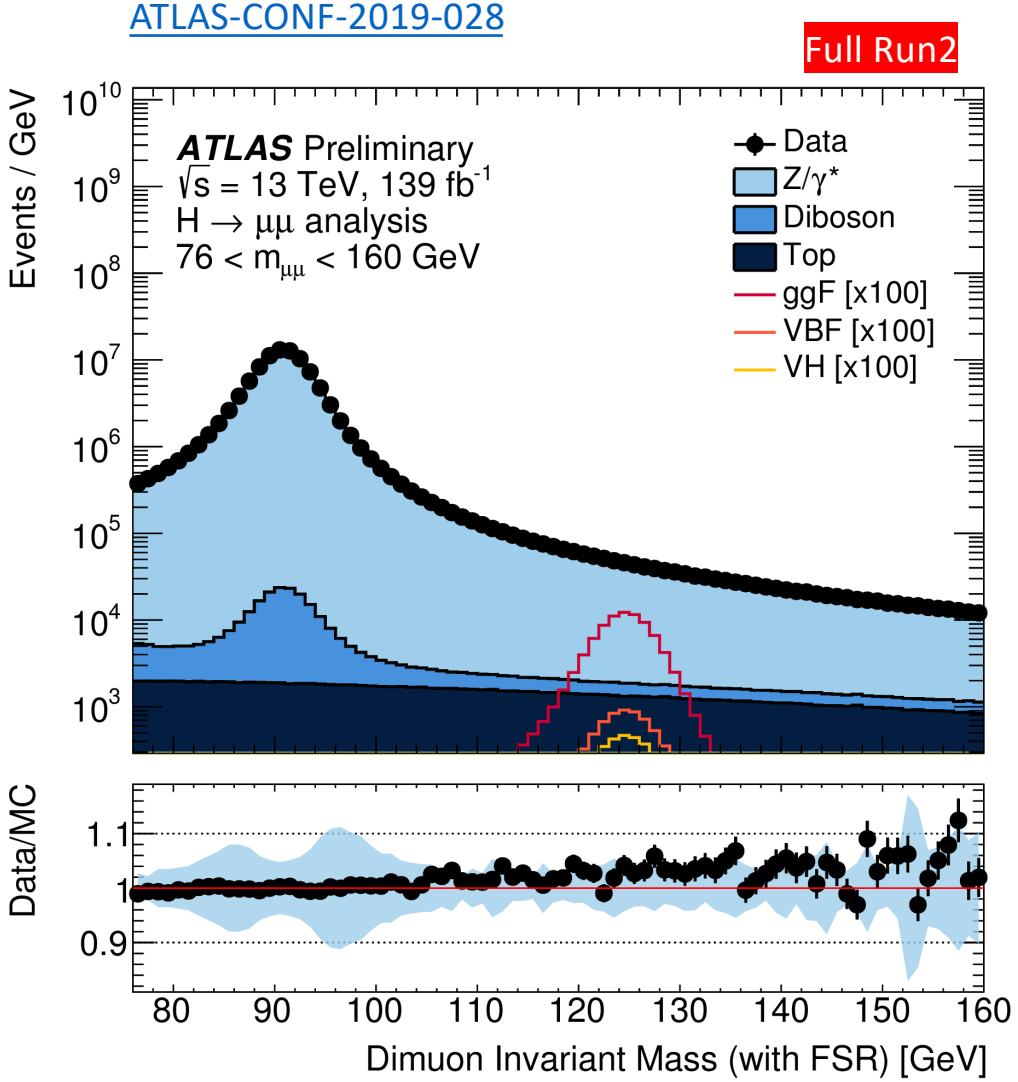
Phys. Rev. D 99 (2019) 072001

NEW

Higgs to $\mu\mu$

- With its low BR (0.022%), the Higgs $\rightarrow \mu\mu$ signal hasn't been observed yet
- Select two opposite sign isolated muons
- Main backgrounds Z/γ*, top, diboson
- Inclusive selection has a challenging S/B = 0.2%
- Background is modeled with an analytical function to avoid bias

ATLAS-CONF-2019-028



NEW

Higgs to $\mu\mu$

- Improve sensitivity with BDT
- BDT trained with background from side bands and simulated signal
- BDT inputs
  - Dimuon system variables
  - Jet(s) p_T and η (for events with 1 or 2+ jets)
  - Angles among jet(s) and dimuon system (for events with 1 or 2+ jets)
- Set limits on σ*BR(H→$\mu\mu$) / SM < 1.74 (1.33 exp)

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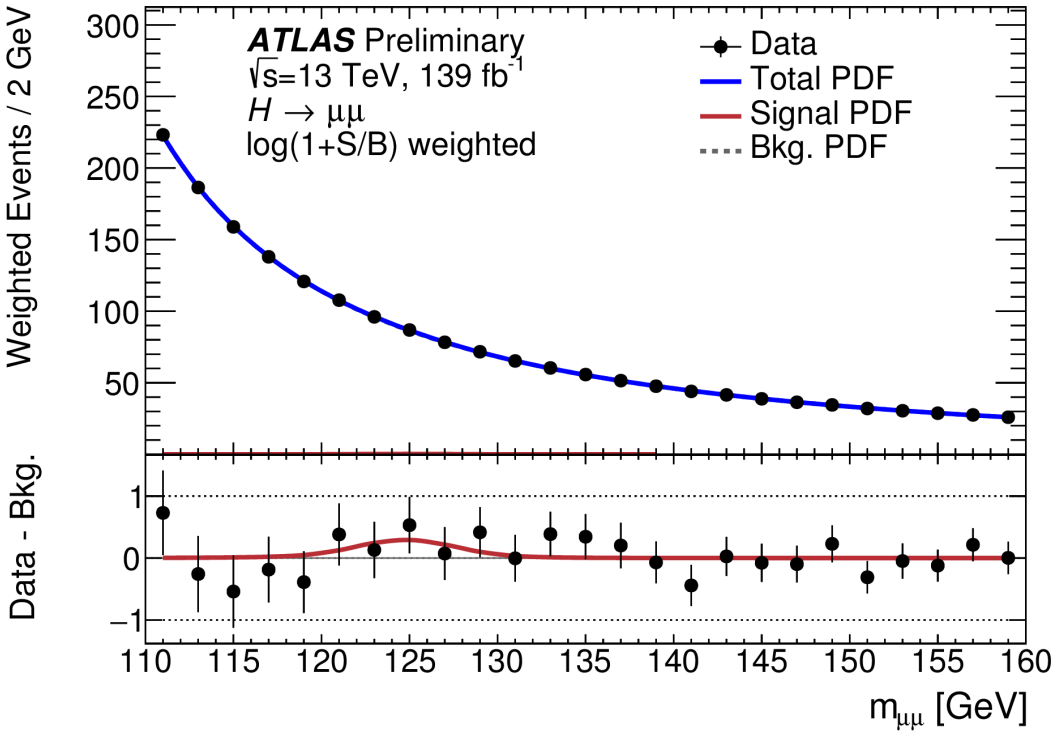
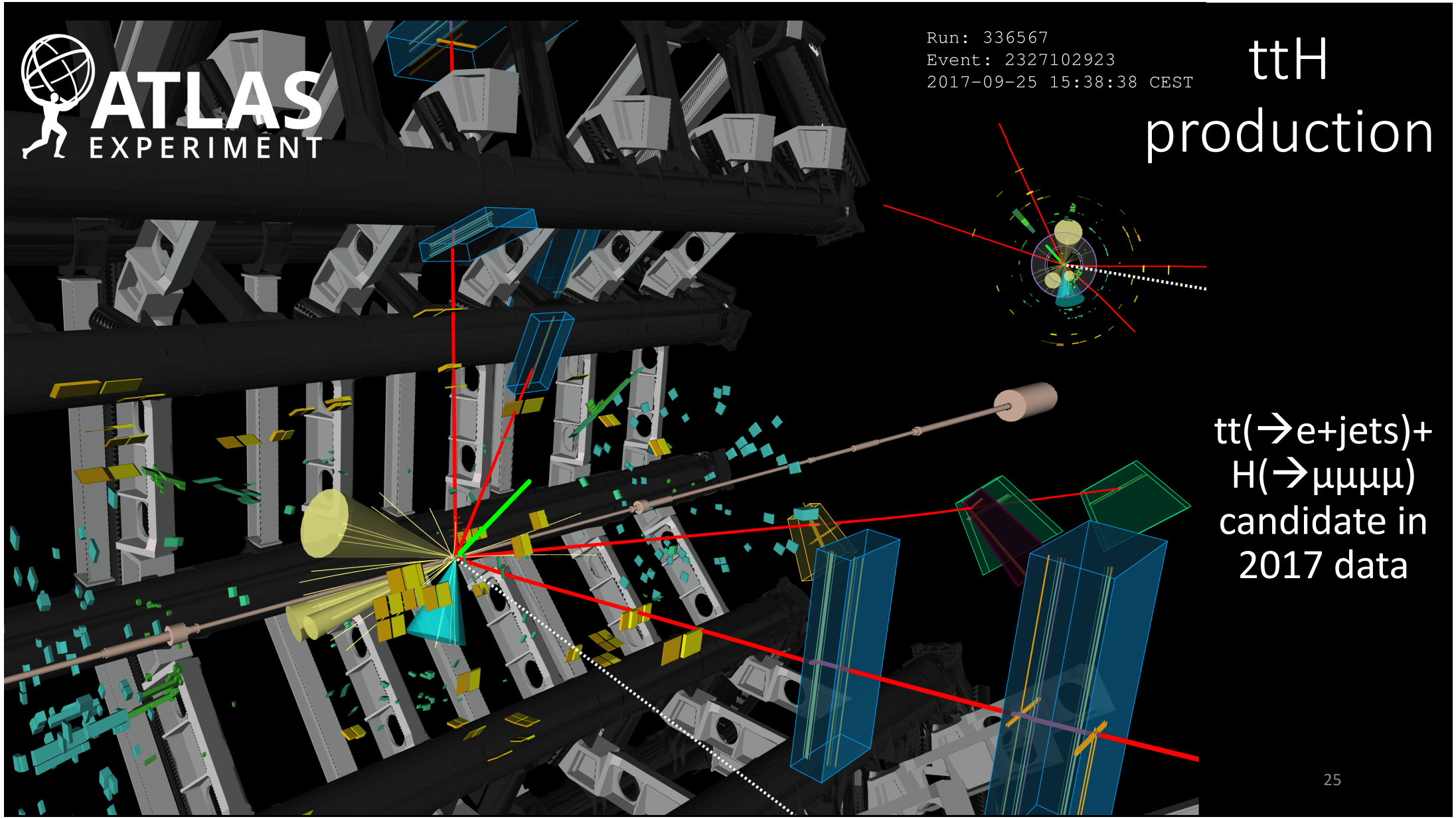
Full Run2





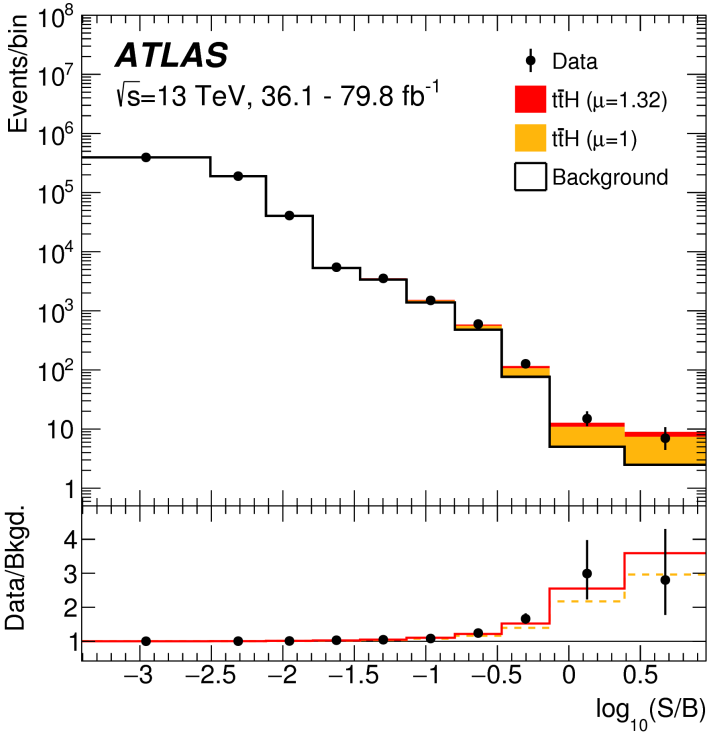
ttH production

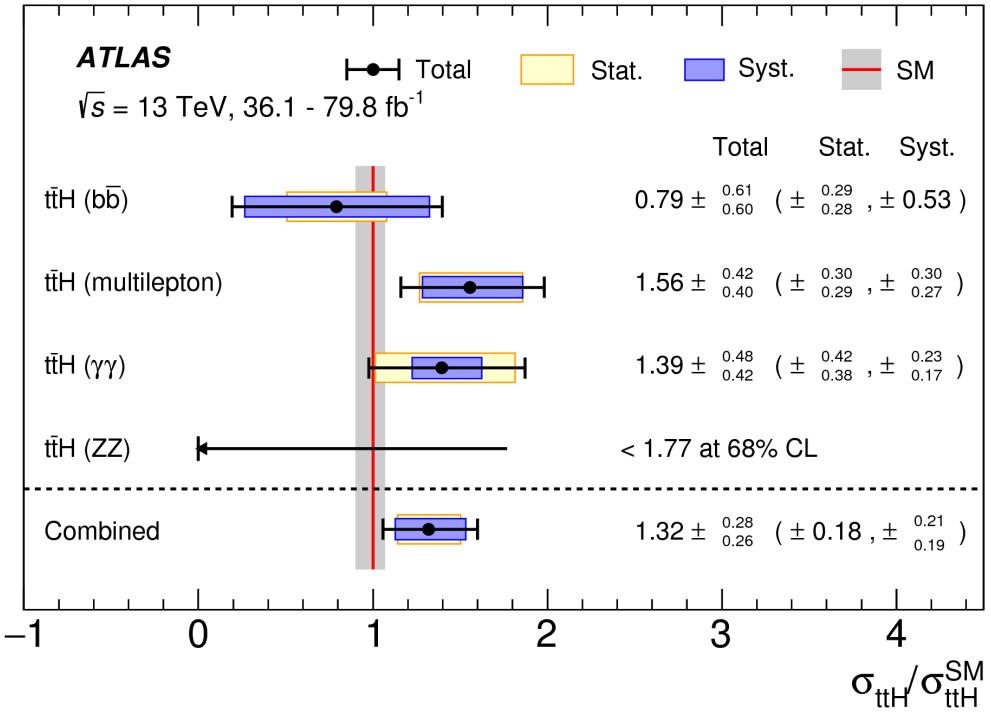
tt(→e+jets)+ H(→μμμμ) candidate in 2017 data

Observation of ttH production

Phys. Lett. B 784 (2018) 173

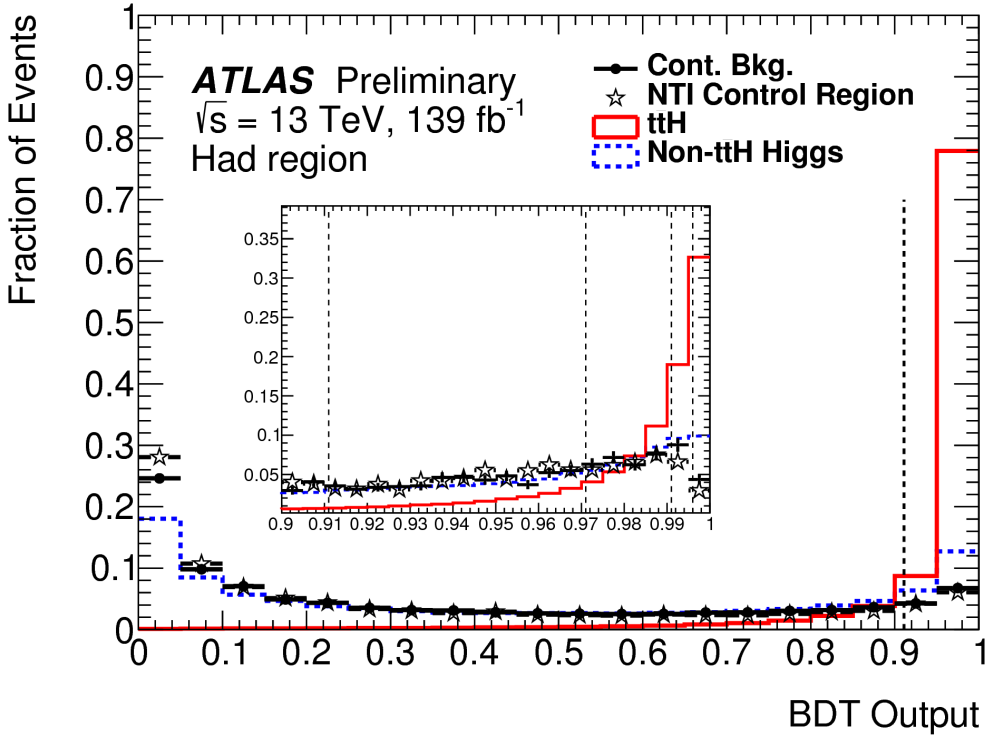
- Combination of ttH searches in $\gamma\gamma$, ZZ*→4l, multilepton, and $b\bar{b}$ (data at 7, 8 and 13 TeV)
- ttH production observed with a significance of 6.3σ (5.1 exp.)
- At 13 TeV σ_{ttH} is measured to be $670 \pm 90\ (stat.)\ ^{+110}_{-100}(syst.)$fb (cfr SM 507^{+35}_{-50}fb)



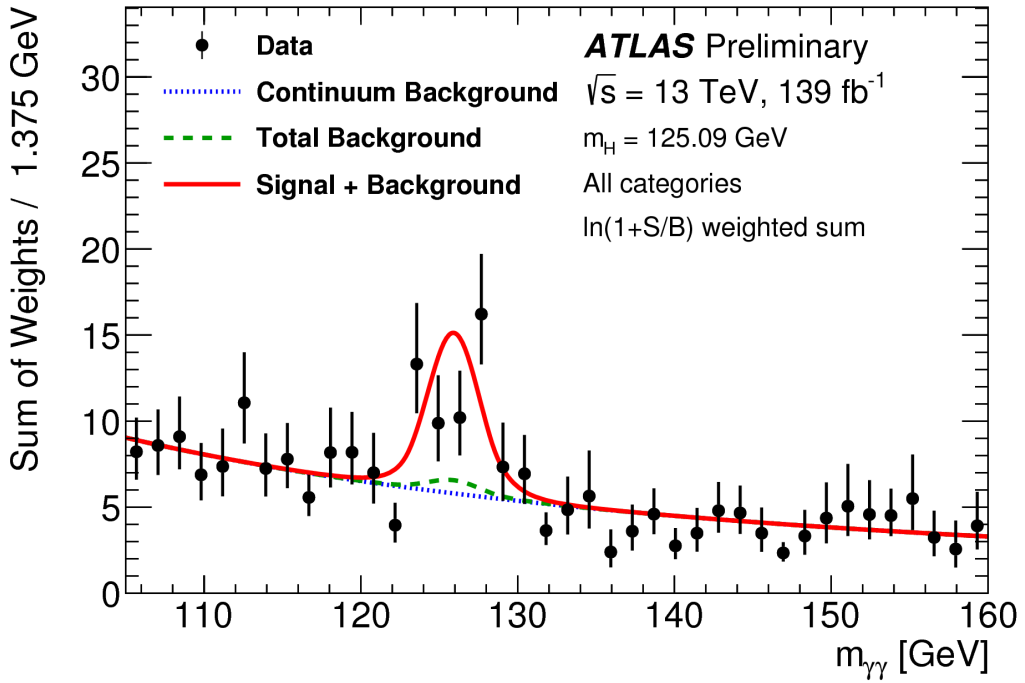


ttH production (H→$\gamma\gamma$)

- Low cross-section * BR(H→$\gamma\gamma$) low background
- Event selection based on BDT in 7 event categories
- Signal extracted fitting the $\gamma\gamma$ invariant mass
- Observed significance 4.9σ (4.2σ exp)
  - The full Run2 sample gets close observation



Full Run2



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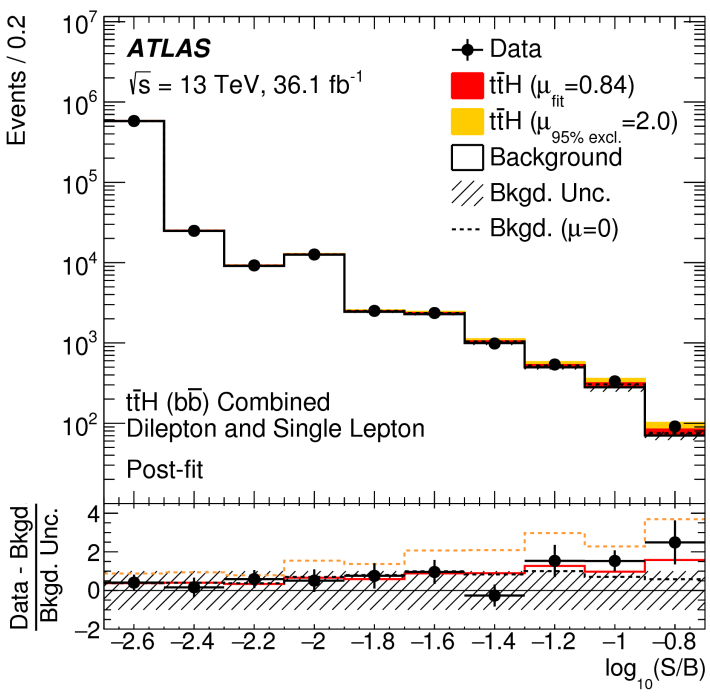
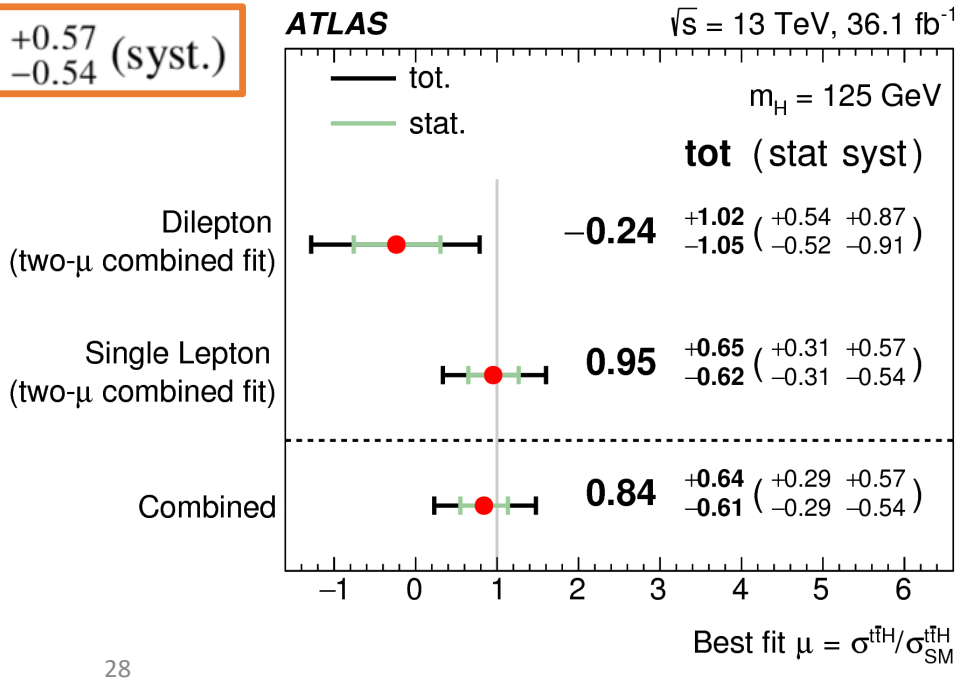
ttH production (H→$b\bar{b}$)

Phys. Rev. D 97 (2018) 072016

- Select events with 1 or 2 e or μ and with at least 3 jets of which 2 are b-tagged
- Main background is ttbar + jets
- BDT are used to classify and reconstruct the events
- Signal strength (μ) values above 2 are excluded at 95% CL

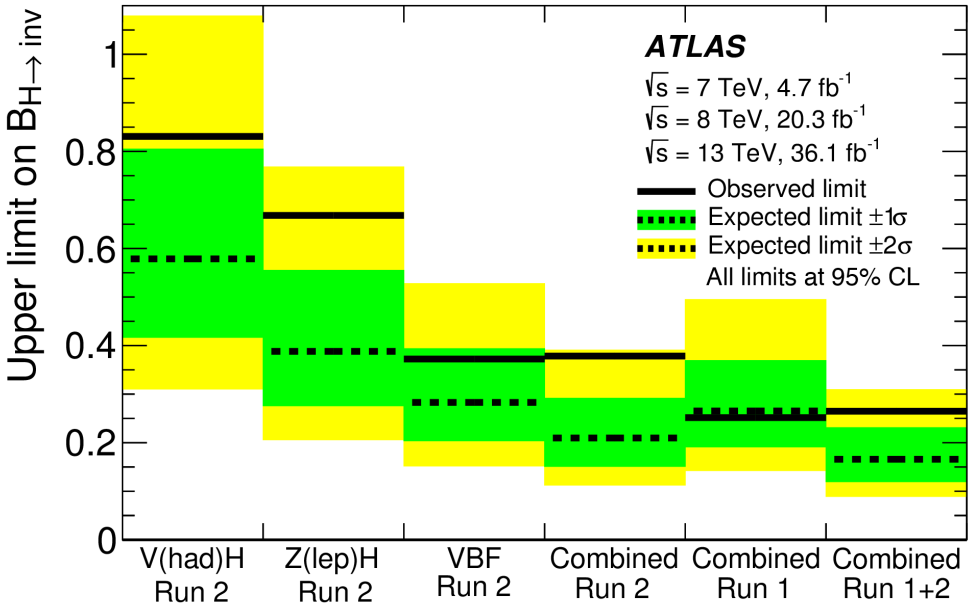


$$\mu = 0.84 \pm 0.29\ (\text{stat.})\ ^{+0.57}_{-0.54}\ (\text{syst.})$$



Invisible decays

- Dark matter particles, if sufficiently light, may be produced in decays of the Higgs boson
- Combining searches in VBF, Z(→ll)H, and V(→jj)H production modes
- BR(H→invisible) < 0.26 ($0.17^{+0.07}_{-0.05}$ exp.) at 95% CL



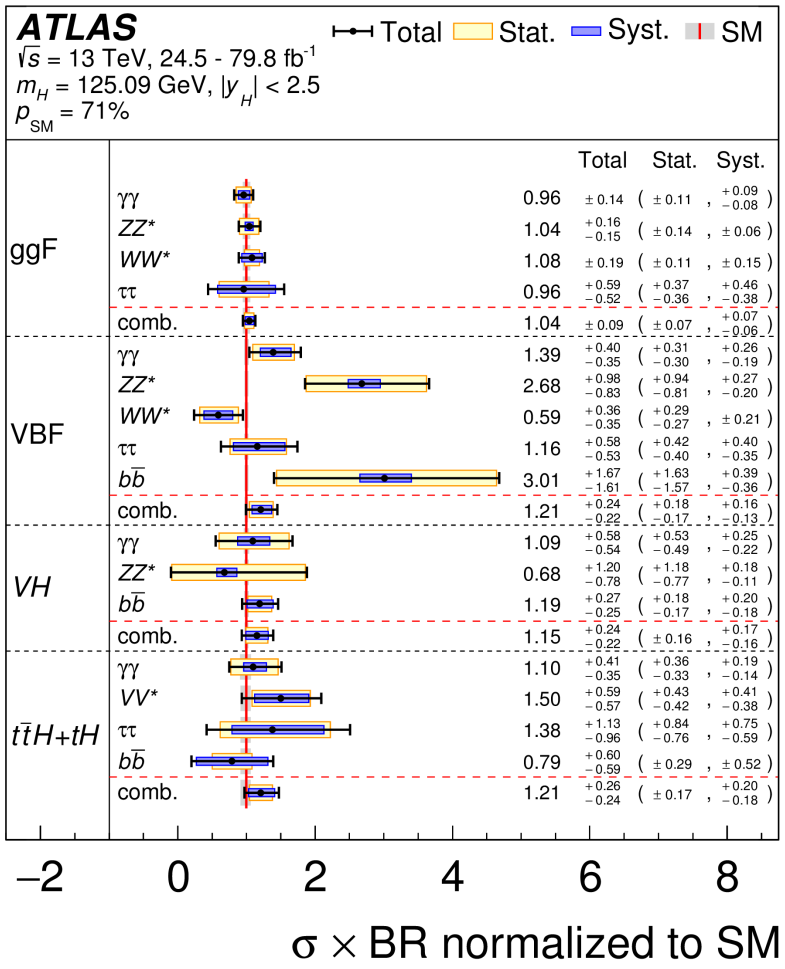
Analysis	$\sqrt{s}$	Int. luminosity	Observed	Expected	p_{SM}-value	Reference
Run 2 VBF	13 TeV	36.1 fb^{-1}	0.37	$0.28^{+0.11}_{-0.08}$	0.19	[36]
Run 2 $Z(\mathrm{lep})H$	13 TeV	36.1 fb^{-1}	0.67	$0.39^{+0.17}_{-0.11}$	0.06	[37]
Run 2 $V(\mathrm{had})H$	13 TeV	36.1 fb^{-1}	0.83	$0.58^{+0.23}_{-0.16}$	0.12	[38]
Run 2 Comb.	13 TeV	36.1 fb^{-1}	0.38	$0.21^{+0.08}_{-0.06}$	0.03	this Letter
Run 1 Comb.	7, 8 TeV	4.7, 20.3 fb^{-1}	0.25	$0.27^{+0.10}_{-0.08}$	—	[35]
Run 1+2 Comb.	7, 8, 13 TeV	4.7, 20.3, 36.1 fb^{-1}	0.26	$0.17^{+0.07}_{-0.05}$	0.10	this Letter

Phys. Rev. Lett. 122 (2019) 231801

NEW

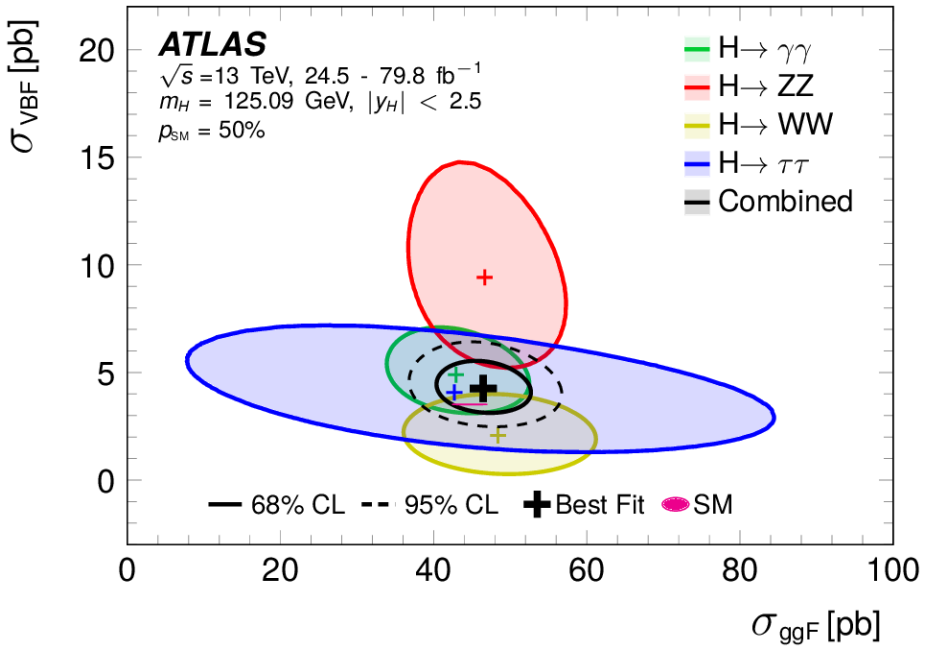
Combined Higgs cross-section

arXiv:1909.02845



- Combination of results up to 80 fb^{-1}
- Combined signal strength is determined to be

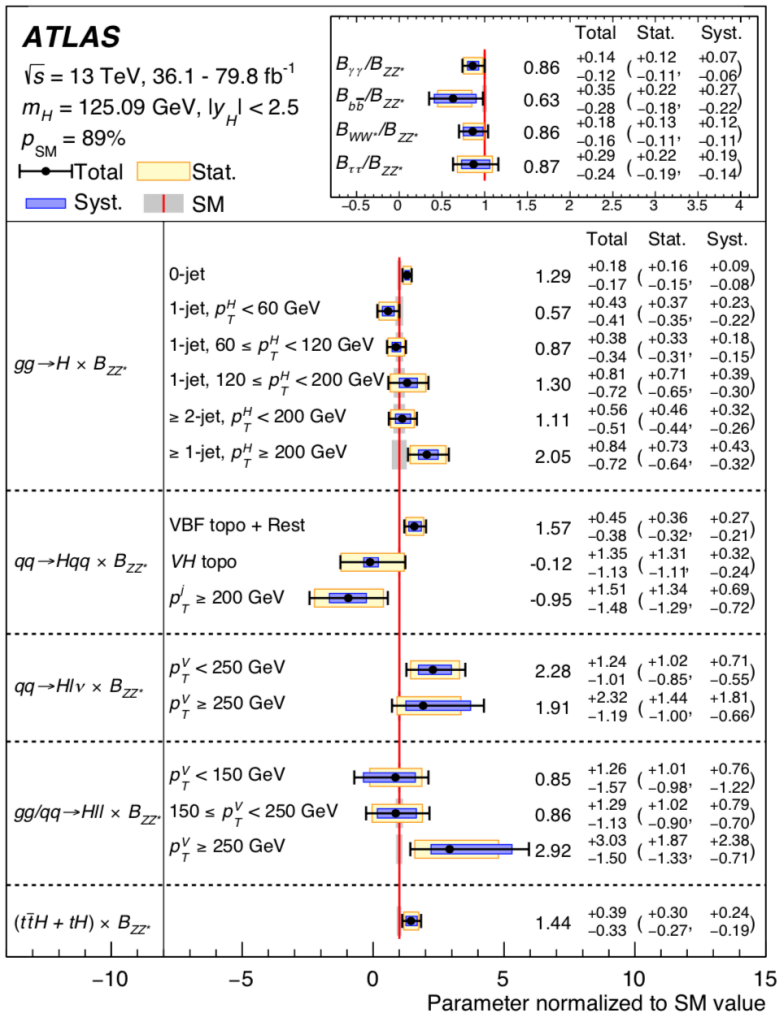
$$\mu = 1.11^{+0.09}_{-0.08}$$



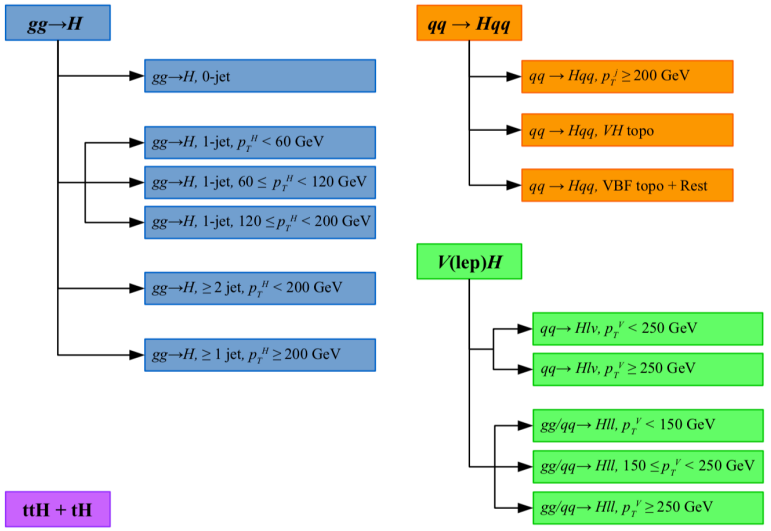
NEW

Combined Higgs cross-section

arXiv:1909.02845



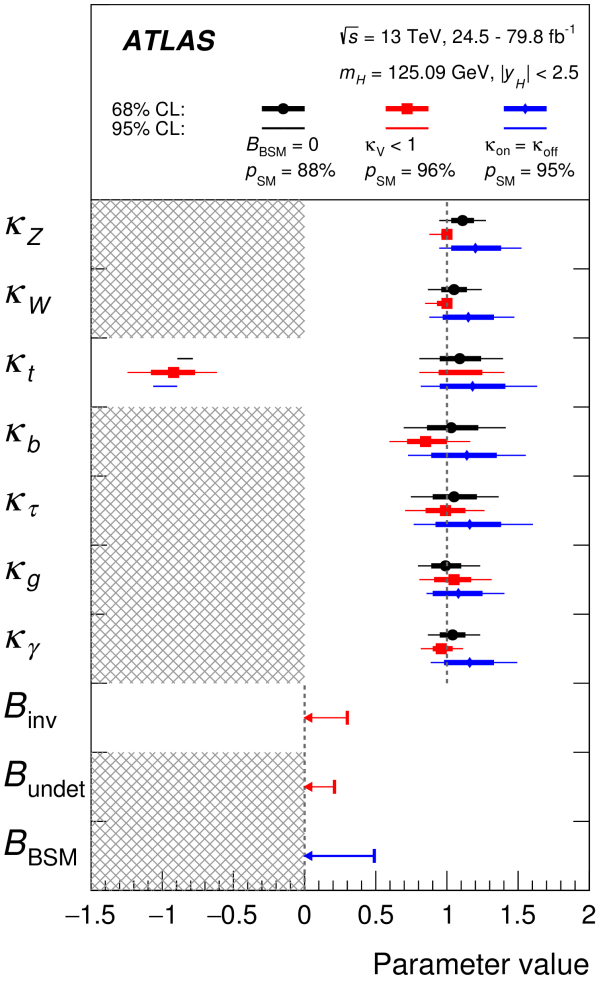
- Cross section and branching ratios with simplified template (STXS)



- Good overall agreement with SM in a range of kinematic regions of Higgs boson production processes

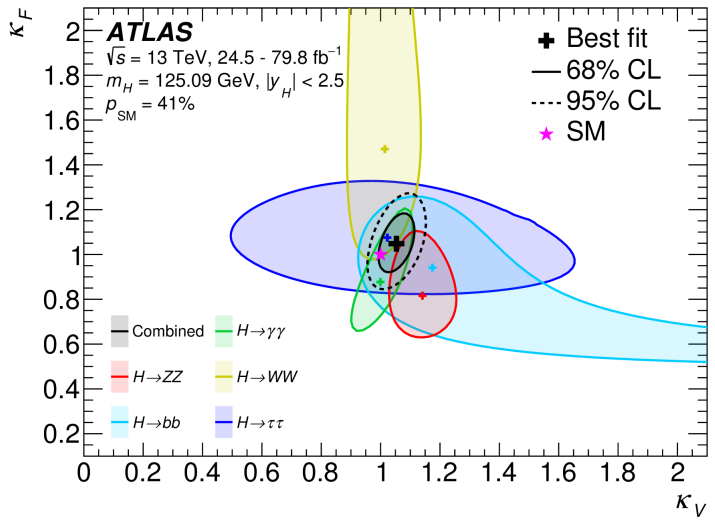
NEW

Higgs couplings from combination



- The 3 fits for the couplings assume
  - B_{BSM} = 0 : no undetected decays and SM invisible BR
  - κ_V<1 : Off-shell production doesn't depend on Γ_H^{TOT}
    - Includes H→invisible searches
  - Same on-shell and off-shell couplings
    - Includes off-shell analysis
- B_{BSM}< 47% at 95% CL

arXiv:1909.02845

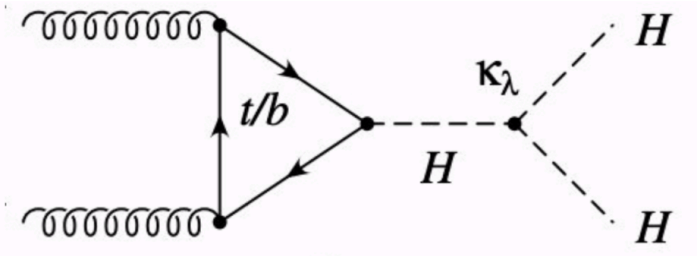


Assuming universal coupling scale factors

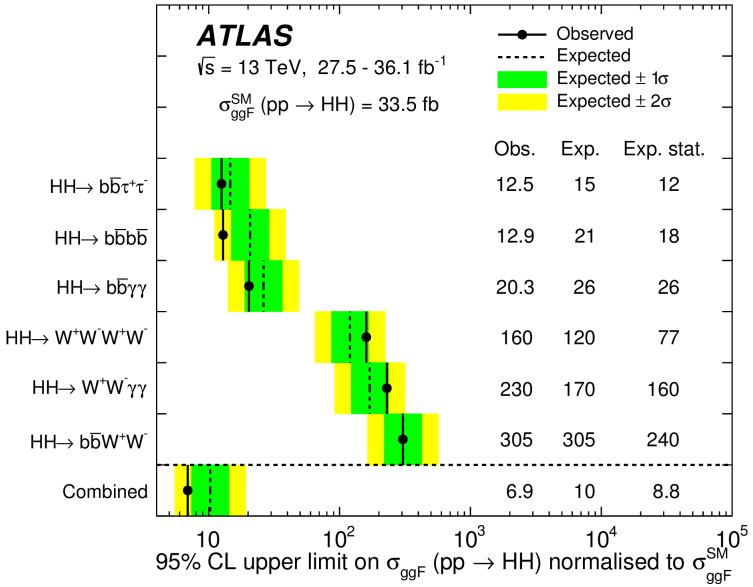
$$\kappa_V = \kappa_W = \kappa_Z$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$

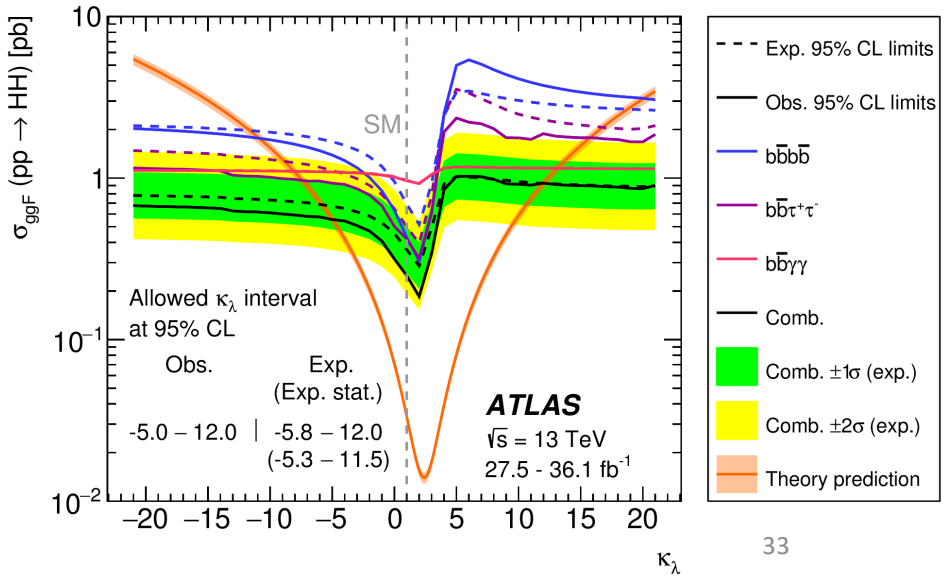
Search for Higgs pair production



- The Higgs self coupling as a further EWSB probe
- Six analyses are combined
- Limits are set on $\sigma_{HH} / \sigma_{HH}^{SM} < 6.9$ (10 exp.) at 95% CL
- Limits on Higgs self coupling modifier κ_λ are set $-5.0 < \kappa_\lambda < 12.0$ at 95% CL

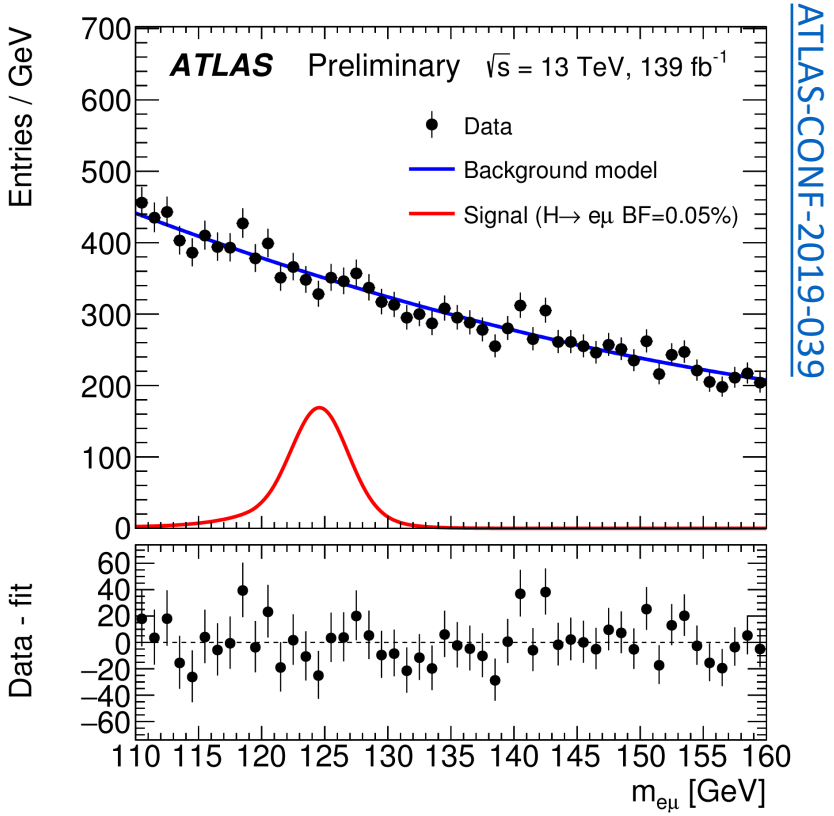


arXiv:1906.02025



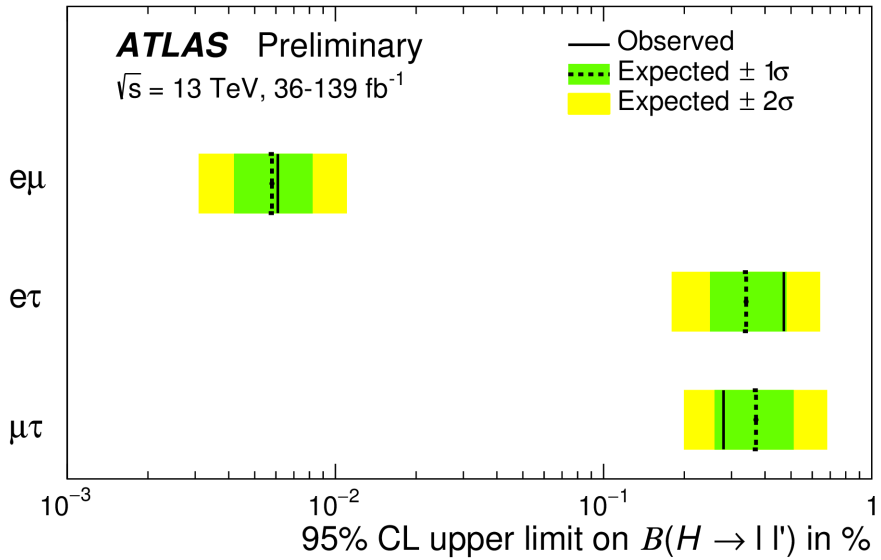
Search for LFV in Higgs decays

- Lepton flavor violation searched in the eμ, eτ, and $\mu\tau$ decays
- No significant excess observed



ATLAS-CONF-2019-039

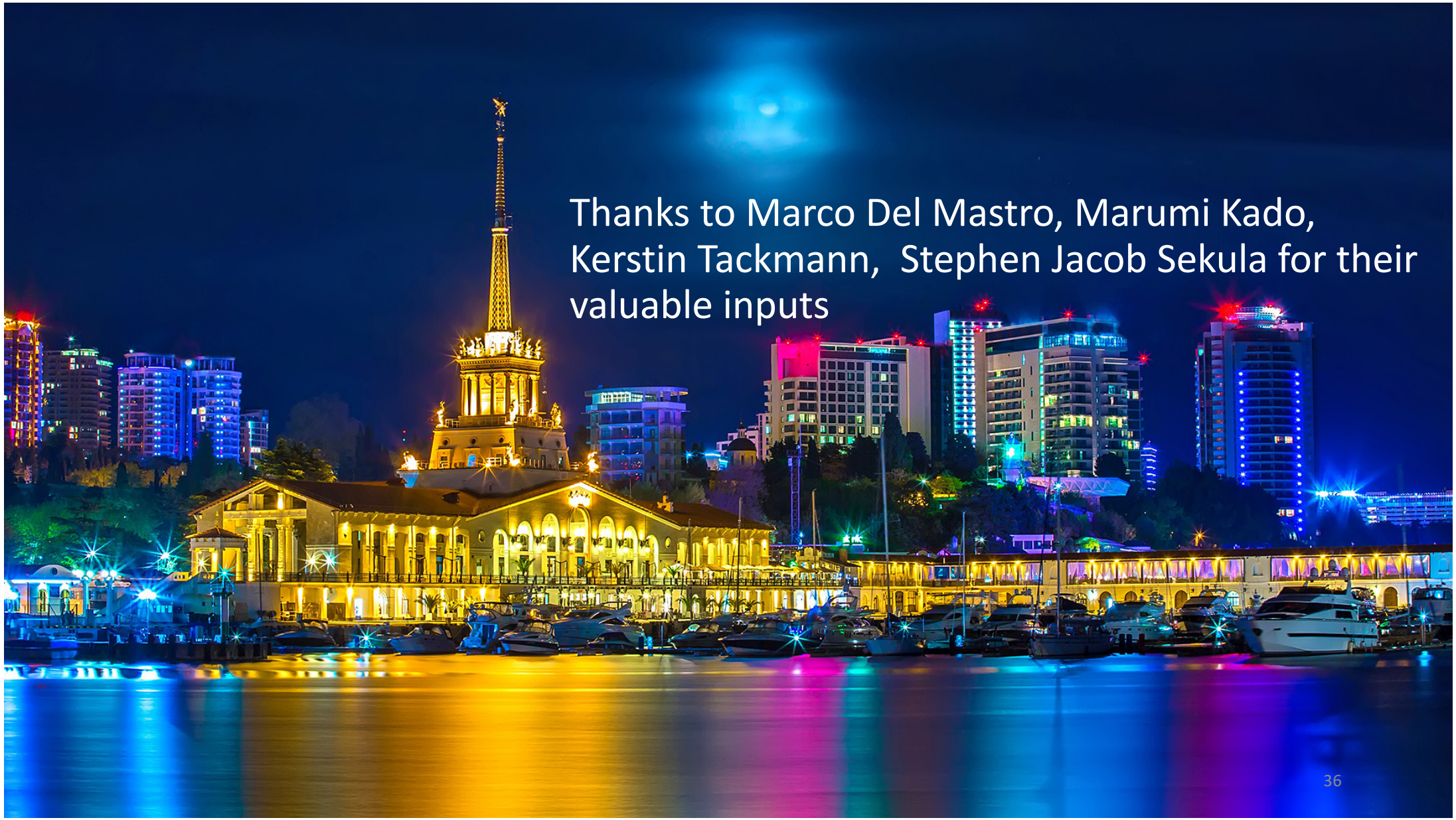
arXiv:1907.06131



- BR(H->eμ) < 6.1*10^{-5} (5.8*10^{-5} exp.)
- BR(H->eτ) < 0.47% (0.34 exp.)
- BR(H->$\mu\tau$) < 0.28% (0.37 exp.)

Summary

- Run2 provides an order of magnitude more candidate than Run1
  - More differential measurements performed
- Together with improved analysis techniques more precise Higgs measurements in an ample range of production modes and signatures
- Direct observation achieved for all main production and decay modes
  - Observation of Higgs interactions with all three third-generation fermions
- Precision probing of the SM Higgs sector on going


Thanks to Marco Del Mastro, Marumi Kado, Kerstin Tackmann, Stephen Jacob Sekula for their valuable inputs