SM Higgs boson measurements with fermionic final states in ATLAS

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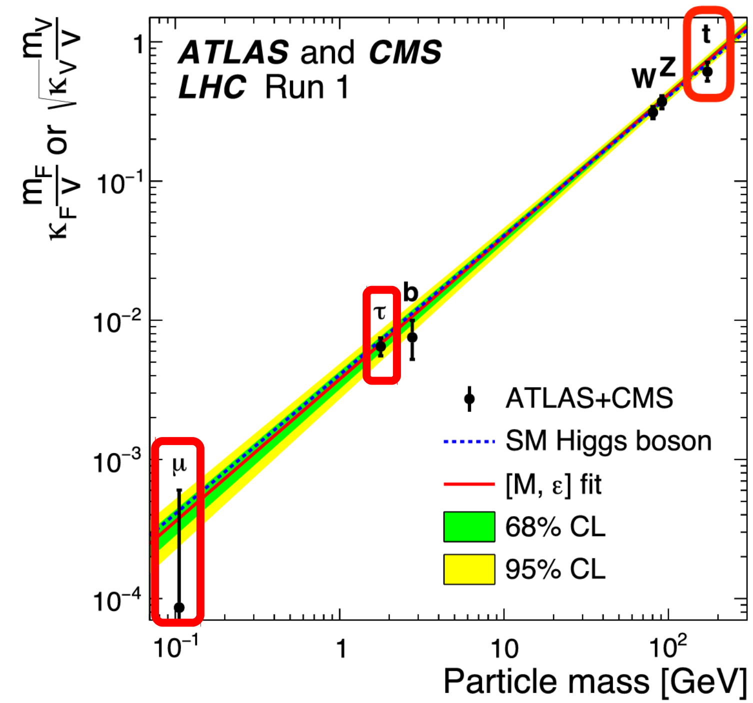
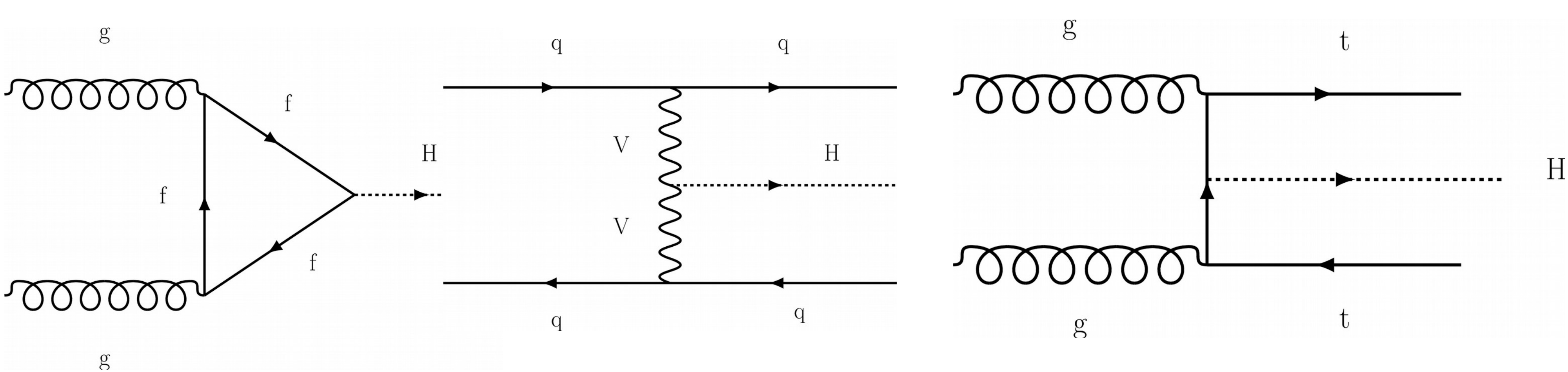
Introduction

ATLAS measurements of the Higgs interactions with fermions are presented

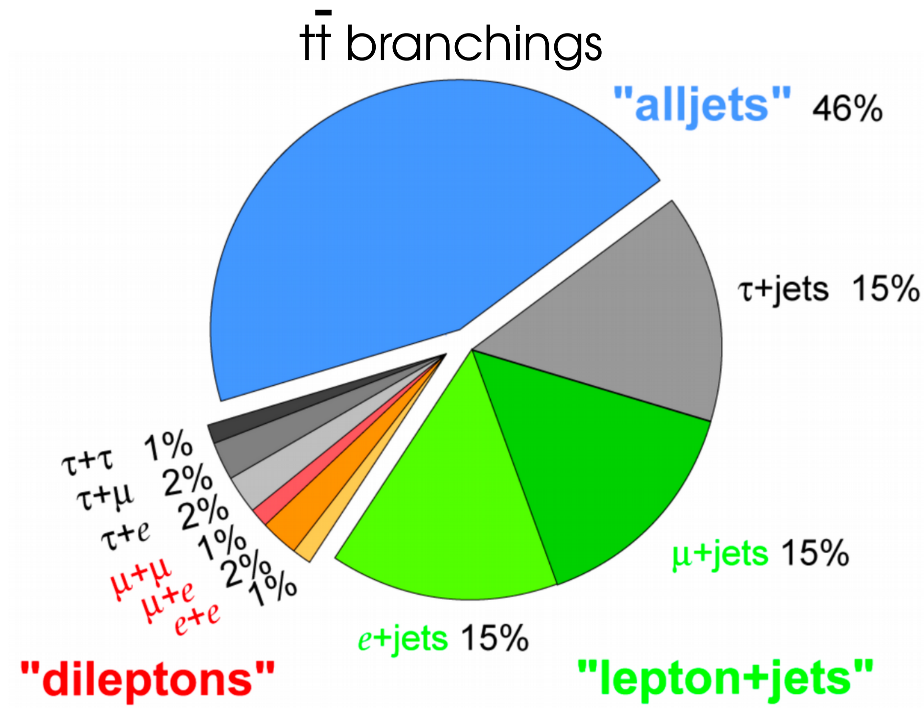
- Establish Higgs affinity to fermionic masses
- Probe Yukawa interactions of leptons and quarks with Higgs
- Final states $\mu^+\mu^-$, $\tau^+\tau^-$, $c\bar{c}$, $J/\psi\gamma$ for all accessible production modes (mainly ggF and VBF) and ttH production for all accessible final states
- Study of H interaction with b-quark is in the separate talk by Louis





ttH, General overview

- Direct measurement of top Yukawa coupling which also contributes to ggF H production and $H \to \gamma\gamma$ decay through loops
- Experimental signature depends on $t\bar{t}$ and H decays
- Four analyses combined:
  - ttH, $H \to bb$ (0, 1 or 2 e/μ)
  - ttH to multilepton ($H \to WW^*, \tau\tau, ZZ^*$)
  - ttH, $H \to \gamma\gamma$ (0 or ≥ 1 e/μ)
  - ttH, $H \to ZZ^* \to 4$ e/μ
- Challenges: $\sigma_{ttH} = 0.5$ pb, $\sigma_{tt} = 830$ pb at 13 TeV, combinatorics of leptons and jets from top decays

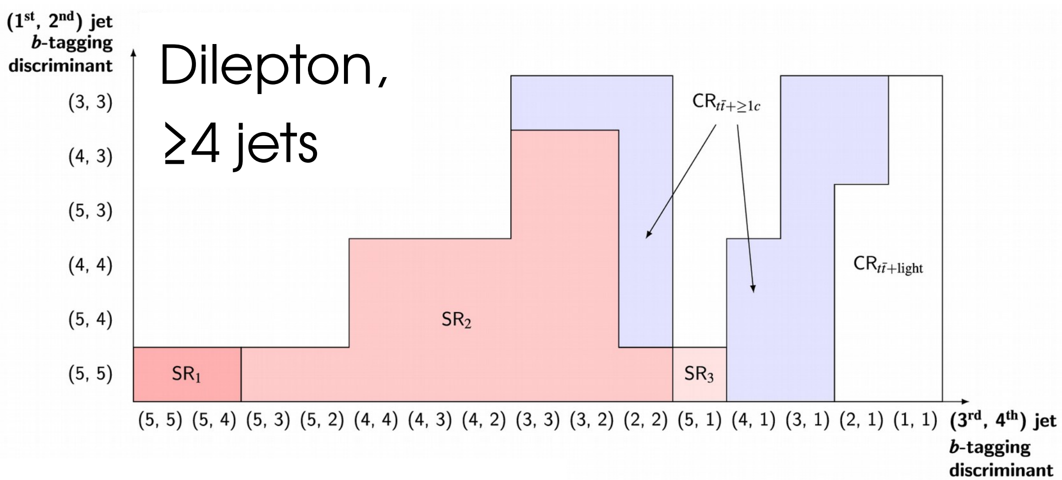


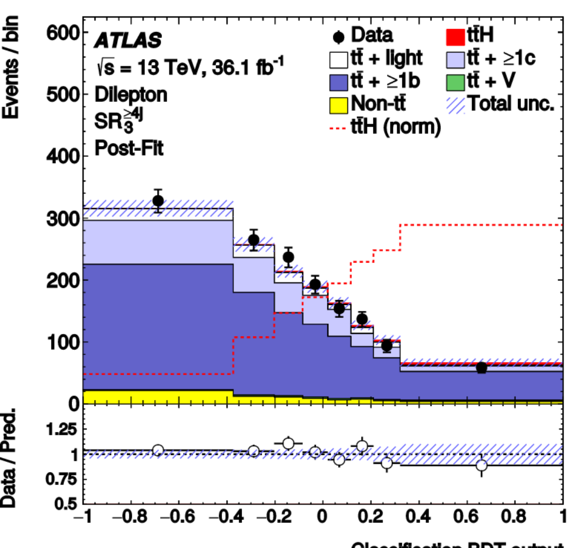
ATLAS history of the analysis:
- Slight excess in Run-1 with μ=1.7±0.8 (JHEP05(2016)160); combination with CMS gave 2.3σ deviation from SM (ATLAS-CONF-2015-044)
- ttH cross-section increased by a factor of 4 in Run-2. Results with 36.1 fb^{-1} of 13 TeV data gave μ=1.2±0.3 (consistent with SM) and brought evidence for ttH with significance: 4.2σ obs. (3.8σ exp.) (Phys. Rev. D 97, 072003)
- Results with update of some channels to 80 fb^{-1} are presented here

Phys. Rev. D 97, 072016

$t\bar{t}H$, H → bb, 36.1 fb^{-1}

- Largest H branching ratio, but huge background from tt+heavy flavor jets
- 1- and 2-lepton channels split into 9 signal and 10 control regions based on jet and b-jet multiplicity and quality



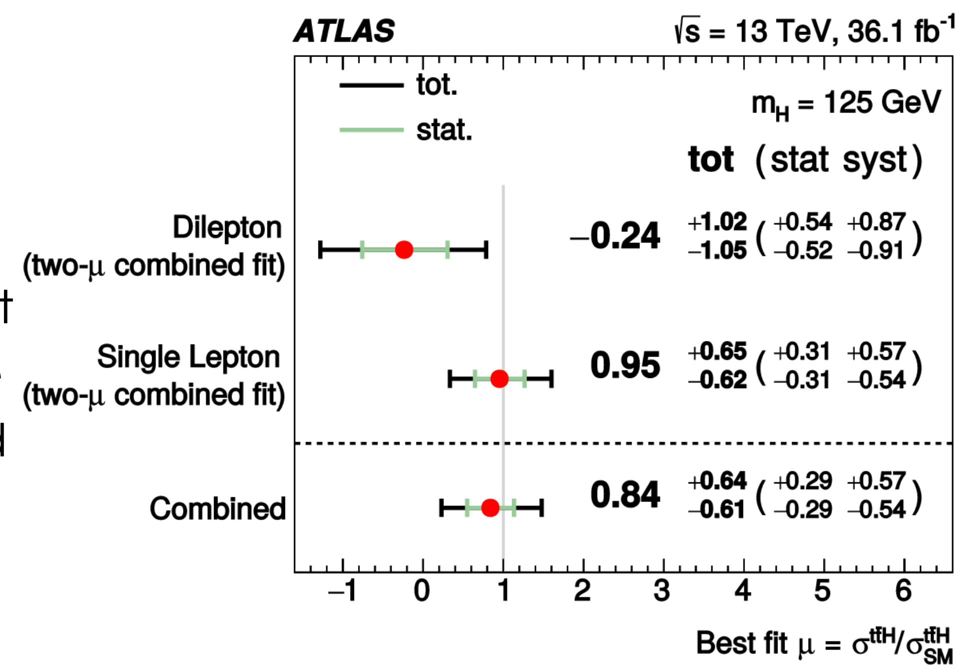


- Different ttH vs. tt discriminants and event kinematic variables are combined into Boosted Decision Tree (BDT) in each signal region

- Signal extracted with binned profile likelihood fit to all SRs and CRs.
- Main systematics:
  - tt + ≥ 1b background modelling (generator comparison): **±0.46 – Main limitation for this analysis!**
  - Background model stat. unc.: +0.29, -0.31

$$\mu = 0.84 \pm 0.29\,(\text{stat.})\ ^{+0.57}_{-0.54}\,(\text{syst.}) = 0.84^{+0.64}_{-0.61}$$

Significance: 1.4σ (1.6σ expected)

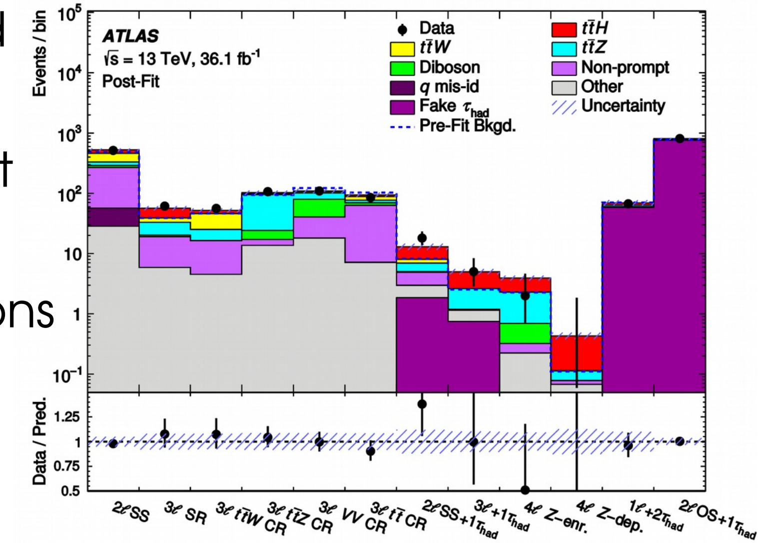


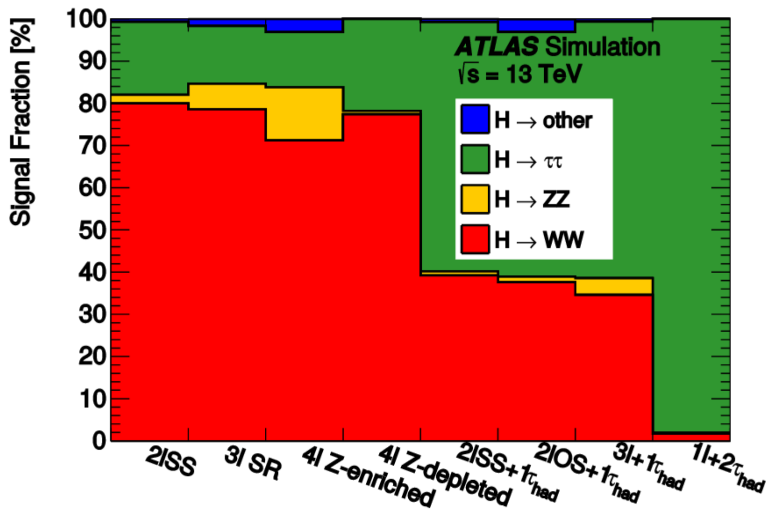
Phys. Rev. D 97, 072003

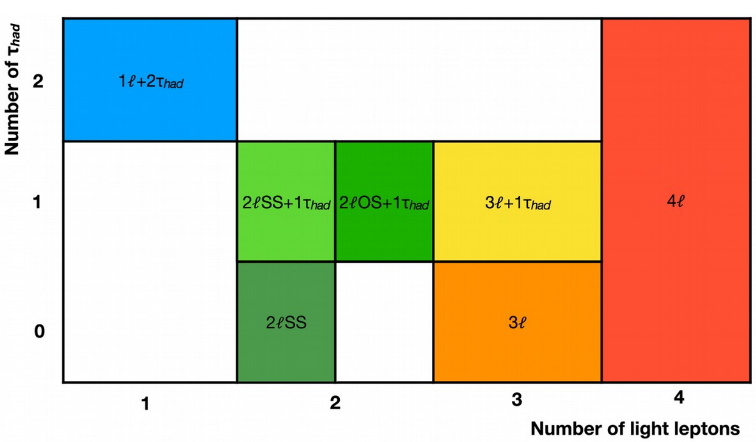
ttH, Multilepton, 36.1 fb^{-1}

- Combination of seven channels with different e/μ and τ multiplicities
- Irreducible backgrounds (ttW, ttZ) estimated from MC and validated in data
- Reducible backgrounds (non-prompt e/μ and fake hadronic τ) estimated from data

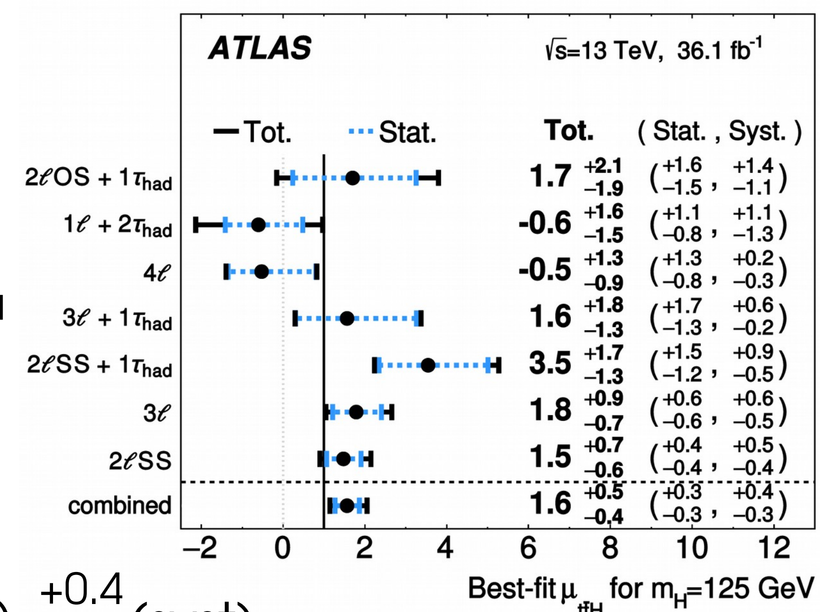
- Signal is extracted with a binned profile likelihood fit to all signal and background regions







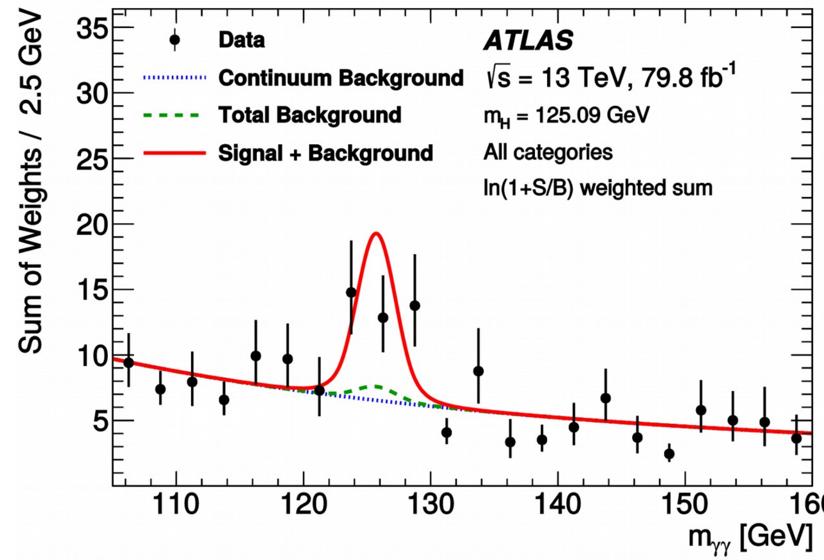
- Main systematics:
  - ⋆ Jet energy scale/resolution: +0.18/-0.15
  - ⋆ Non-prompt e/μ estimates: +0.15/-0.13

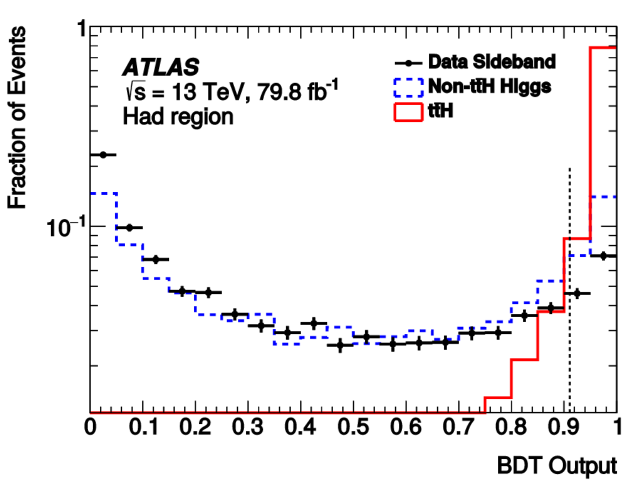


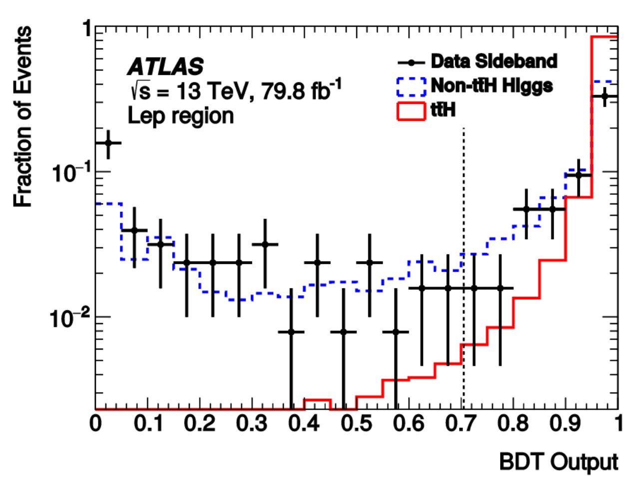
- $\mu = 1.6 \pm 0.3\ (\text{stat})\ ^{+0.4}_{-0.3}\ (\text{syst})$
- Significance: 4.1σ (2.8σ expected)

ttH, H → γγ, 79.8 fb^{-1}

- 50% improvement in the sensitivity w.r.t. the previous analysis: introduction of BDT and new reconstruction algorithms
- Categories: 0 lepton (hadronic) and ≥1 lepton (leptonic)
- Further categorisation with XGBoost BDT:
  - Inputs: 4-vector information of photons (pt, $m_{\gamma\gamma}$), jets, Etmiss, lepton and b-tag
  - Training: ttH MC vs main background (γγ and ttγγ data-driven) and other background (from MC)
  - 4 hadronic and 3 leptonic categories





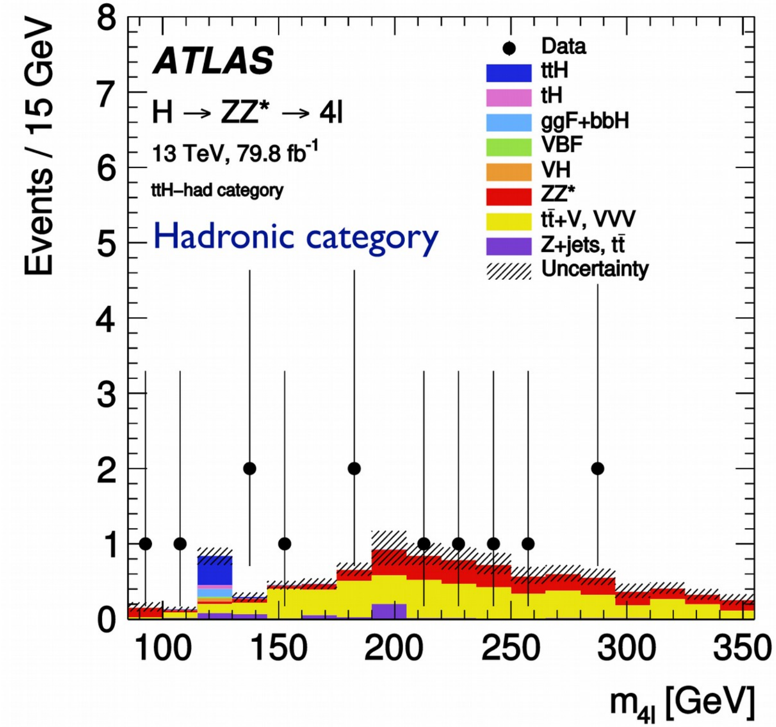


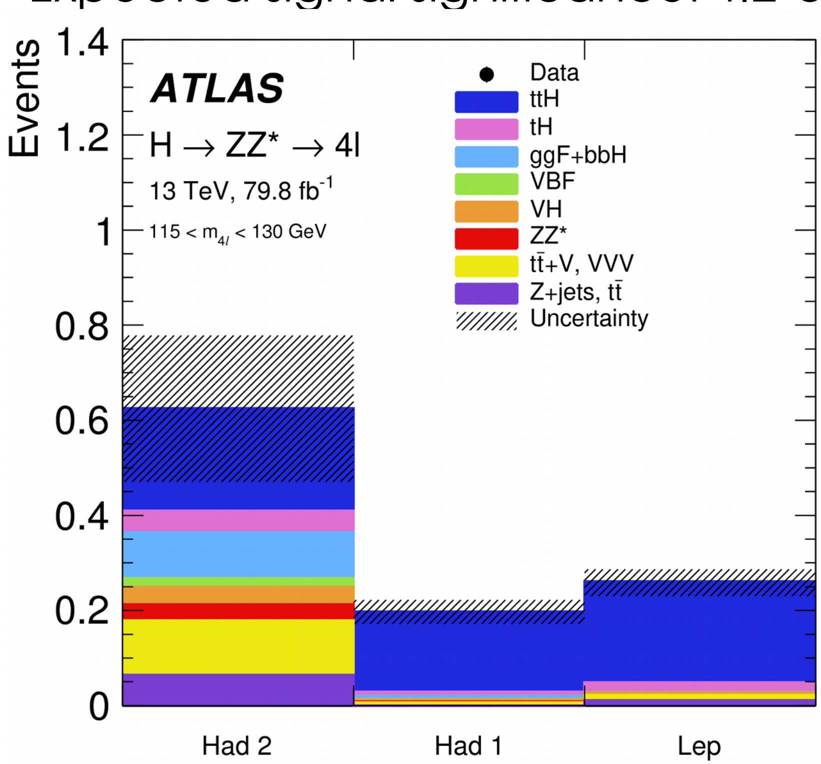
- Combined unbinned fit to 7 $m_{\gamma\gamma}$ with double-sided Crystal-Ball for signal and exponential or power law for bkg
- Significance = 4.1σ (3.7σ expected)
- $\mu = 1.6 \,^{+0.42}_{-0.38}\,\text{(stat)}\,^{+0.23}_{-0.17}\,\text{(syst)}$
- Main systematics:
  - ttH parton shower 8%
  - photon energy resolution 6%

arXiv:1806.00425

ttH, H → ZZ* → 4 e/μ, 79.8 fb^{-1}

- Very small branching ratio, but clean final state
- Categories to select ttH:
  - ≥1 b-tagged jet
  - ≥ 4 jets (hadronic tt) or 1 lepton + ≥ 2 jets (leptonic tt)
- BDT in hadronic category using as inputs: kinematic variables, matrix element discriminant (ttH vs ttV)
- Expected signal significance: 1.2 σ



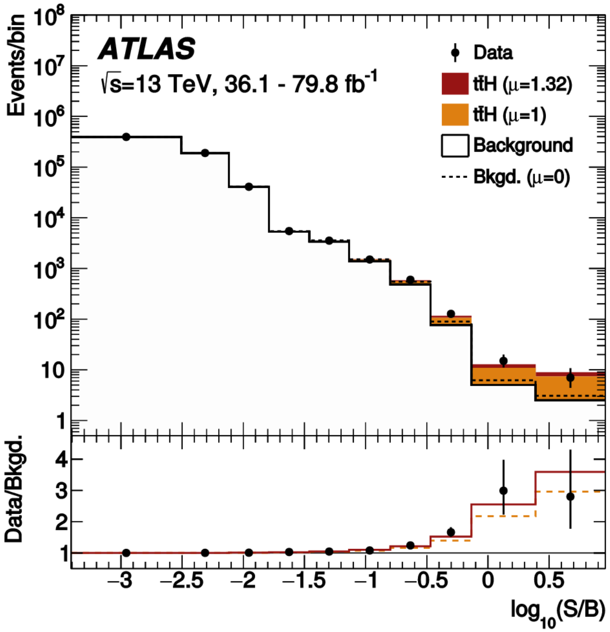


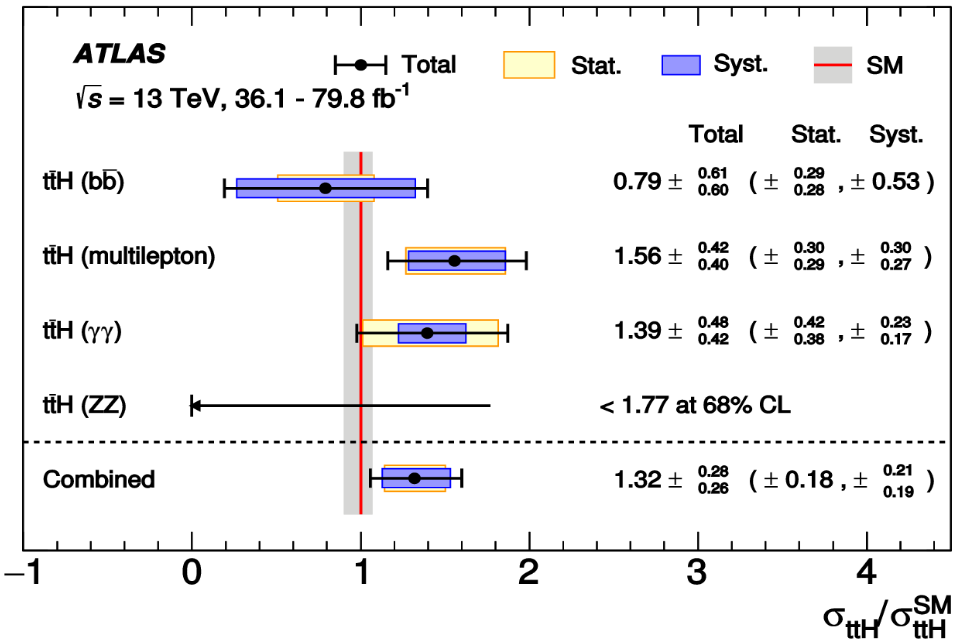
- No events observed in signal region 115 GeV < m4l < 130 GeV
- Expected 0.6 events

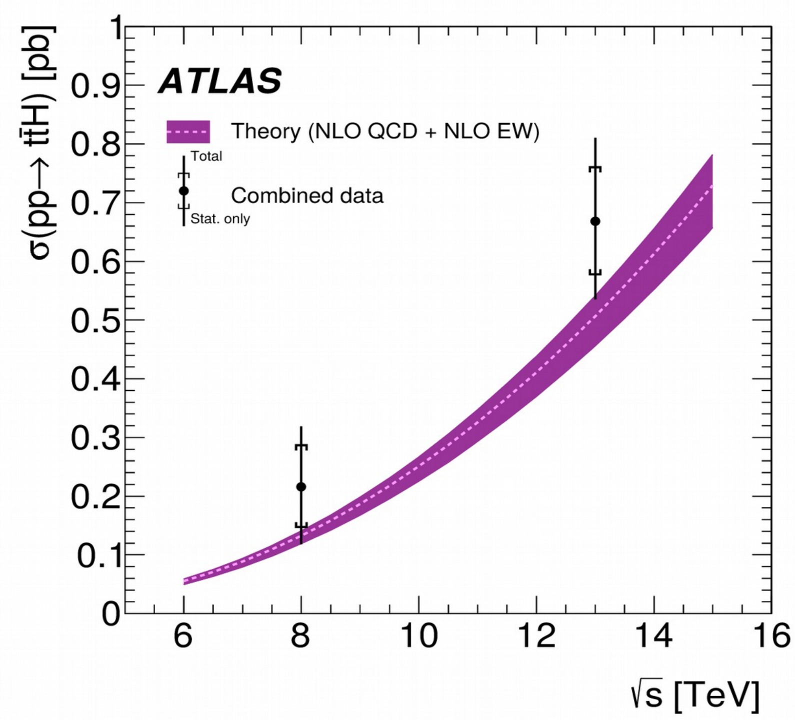
arXiv:1806.00425

ttH, Combination, 36.1 – 79.8 fb^{-1}

- Simultaneous fit to signal and control regions of individual analyses
- Contribution from non-ttH Higgs fixed to SM
- Cross-section for pp → ttH extracted assuming SM branching ratios
- Significance is 5.8σ (4.9σ) observed (expected)
  with Run-1: 6.3σ (5.1σ) observed (expected)
- Measured: σ(pp→ttH) = 670 ± 90 (stat) +110/-100 (syst) fb
  Standard Model: 507 +35/-50 fb





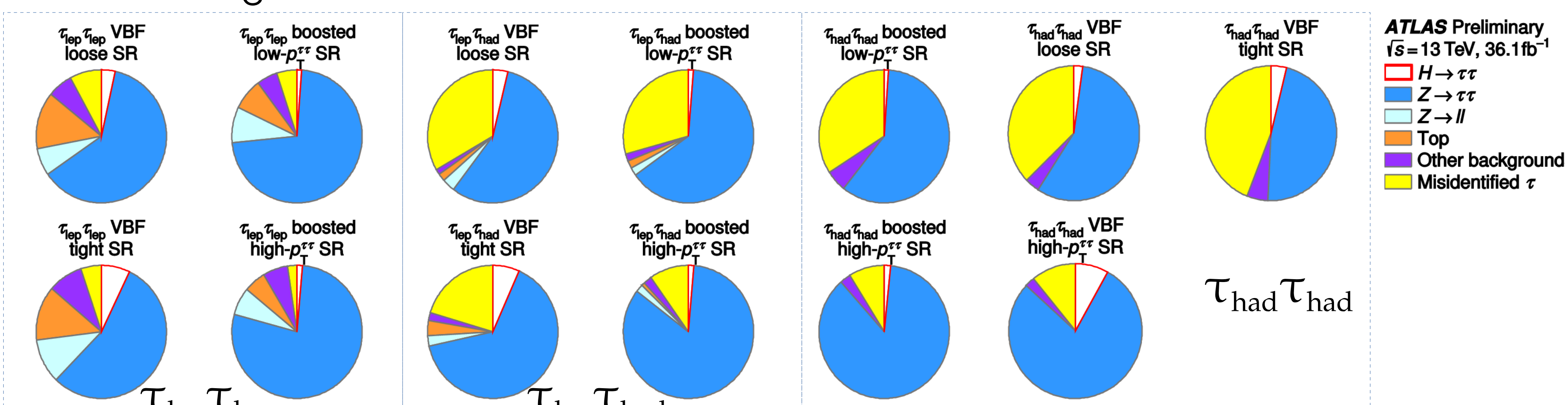


$H \rightarrow \tau^+\tau^-$, Signal and Background

To enhance signal sensitivity several regions are defined

- 5 categories based on production mode: VBF (splits into loose, tight, high-pt), boosted (‘low’ pt, high pt)
- 3 categories based on final state: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$.
- Overall (3 x 5) – 2(high pt VBF only for $\tau_{had}\tau_{had}$) = 13 Signal regions
- Main backgrounds: $Z\tau\tau$, jet-faking-τ, Zll, top
- 6 Control regions to constrain normalization of Zll and top backgrounds
- Dominant irreducible background $Z\tau\tau$ accounts for 50 – 90% of total background and is estimated from MC

ATLAS history of the analysis:
- Evidence in Run-1 with 4.5 (3.4) obs (exp) σ (JHEP04(2015)117)
- Observation on Run-1 dataset in combination with CMS: 5.5 (5.0) σ (JHEP08(2016)045)
- Now observation with combination of Run-1 and 36.1 fb^{-1} of Run-2 ATLAS only dataset: 6.4 (5.4) σ

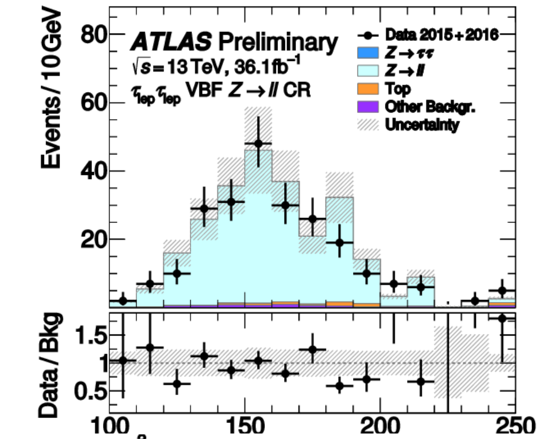


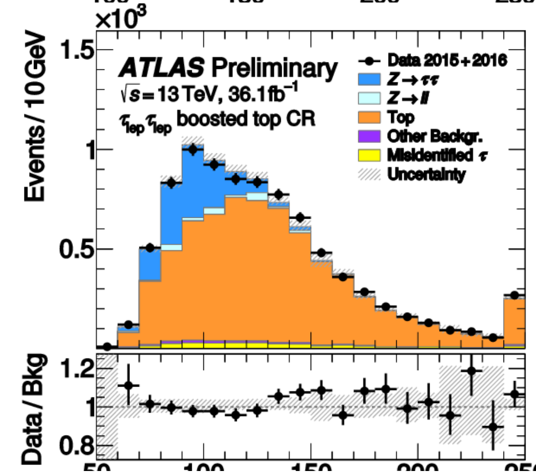
36.1 fb^{-1}

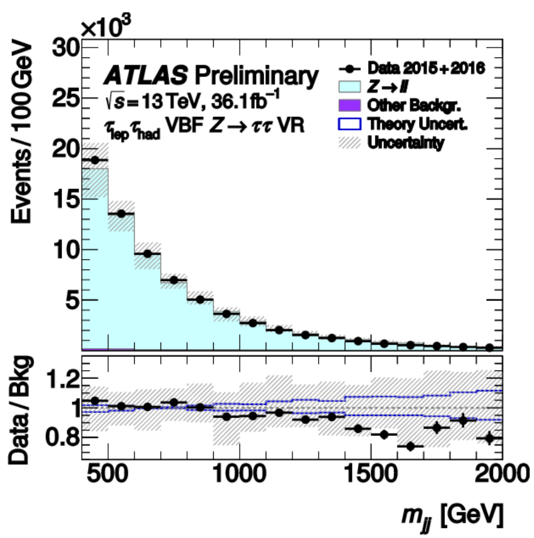
ATLAS-CONF-2018-021

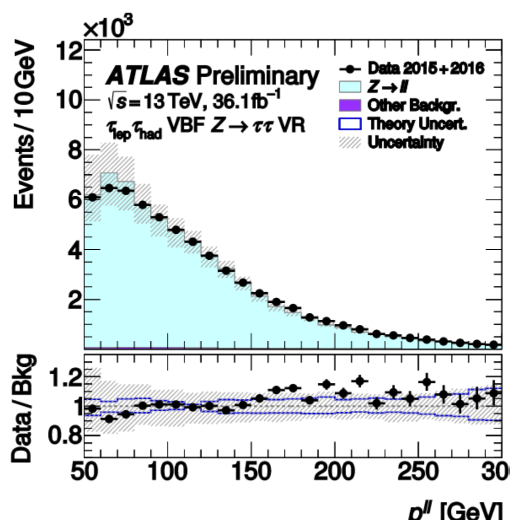
$H \rightarrow \tau^+\tau^-$, Background estimation

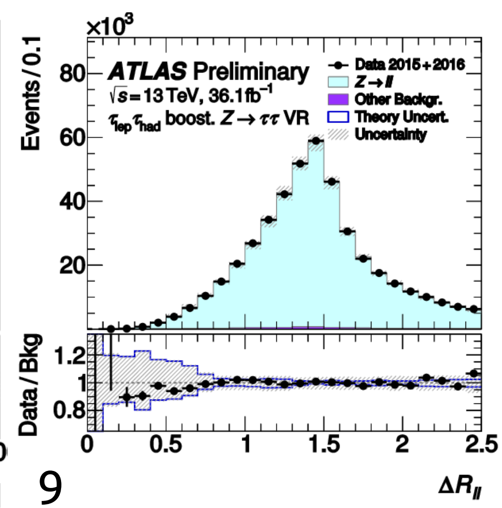
- <u>$Z\tau\tau$</u> is estimated from MC, validated in special $Z\tau\tau$ validation regions
- Separation from signal is limited by $m_{\tau\tau}$ reconstruction
- $Z\tau\tau$ normalization factor is correlated across channels and constrained by $m_{\tau\tau}$ at Z peak.
- <u>Zll</u> and <u>top</u> shapes are taken from MC, normalization is constrained from 6 control regions
- <u>Fake τ</u> are estimated using data-driven techniques.
  ⋆ W+jets and QCD multijet contributing to this bkg in $\tau_{lep}\tau_{had}$ are estimated using fake factors F = N(pass ID τ_{had})/N(fail ID τ_{had})
  ⋆ QCD multijet contributes to fakes in $\tau_{had}\tau_{had}$ and is modeled with template extracted from data by inverting opposite charges requirement and allowing relaxed N(tracks).

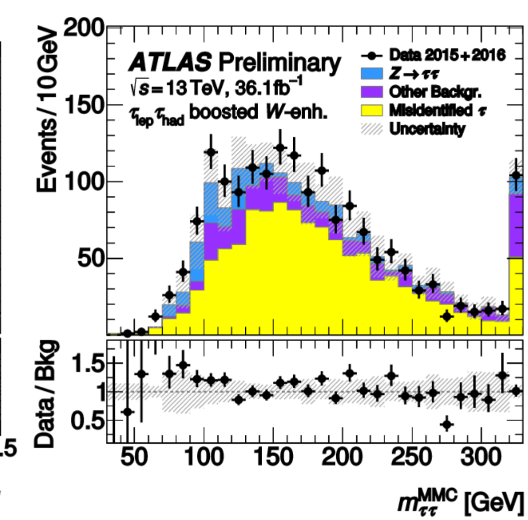






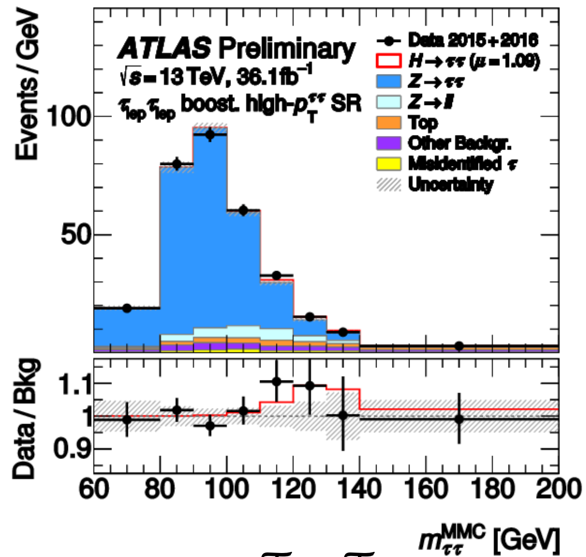




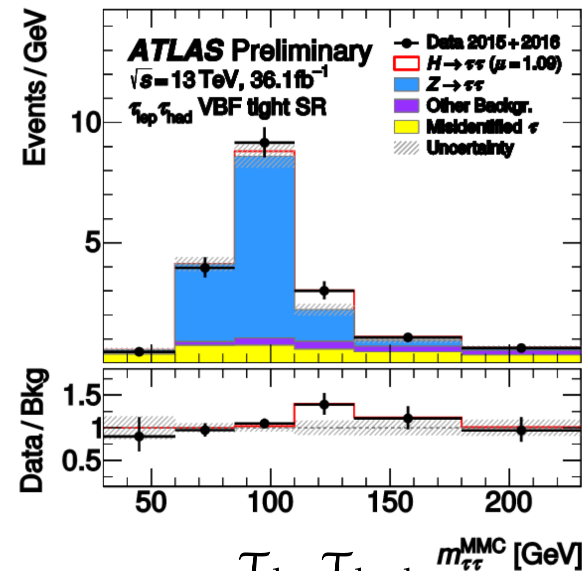


$H \rightarrow \tau^+\tau^-$, Statistical Procedure

- Simultaneous maximum likelihood fit of $m_{\tau\tau}$ to 13 signal and 6 control regions
- Parameter of interest is $\sigma_H * B(H \rightarrow \tau^+\tau^-)$, systematics are taken into account with nuisance parameters
- Significance of signal excess around 125 GeV is tested against SM background only hypothesis



$\tau_{lep}\tau_{lep}$



$\tau_{lep}\tau_{had}$

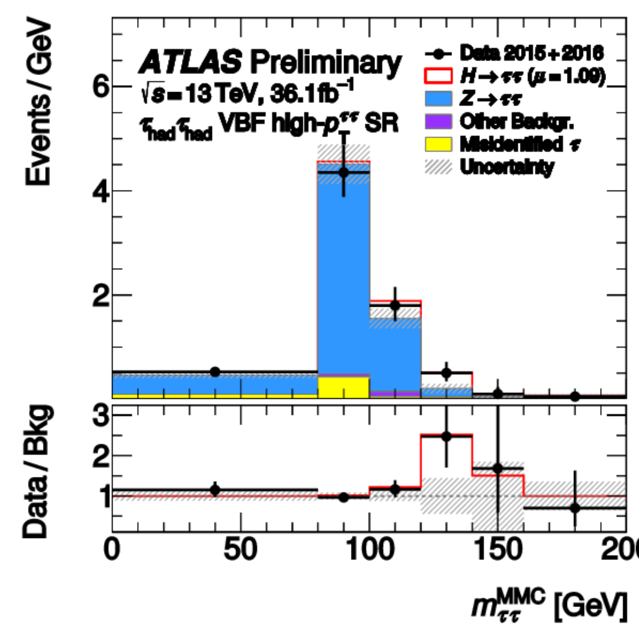
$$\mu = 1.09 \,^{+0.18}_{-0.17}\,(\text{stat.})\,^{+0.27}_{-0.22}\,(\text{syst.})\,^{+0.16}_{-0.11}\,(\text{theory syst.})$$

$$\sigma_{H\rightarrow\tau\tau} \text{ is } 3.71 \pm 0.59\,(\text{stat.})\,^{+0.87}_{-0.74}\,(\text{syst.})\,\text{pb}$$

$$\sigma^{SM}_{H\rightarrow\tau\tau} = 3.43 \pm 0.13\,\text{pb}$$

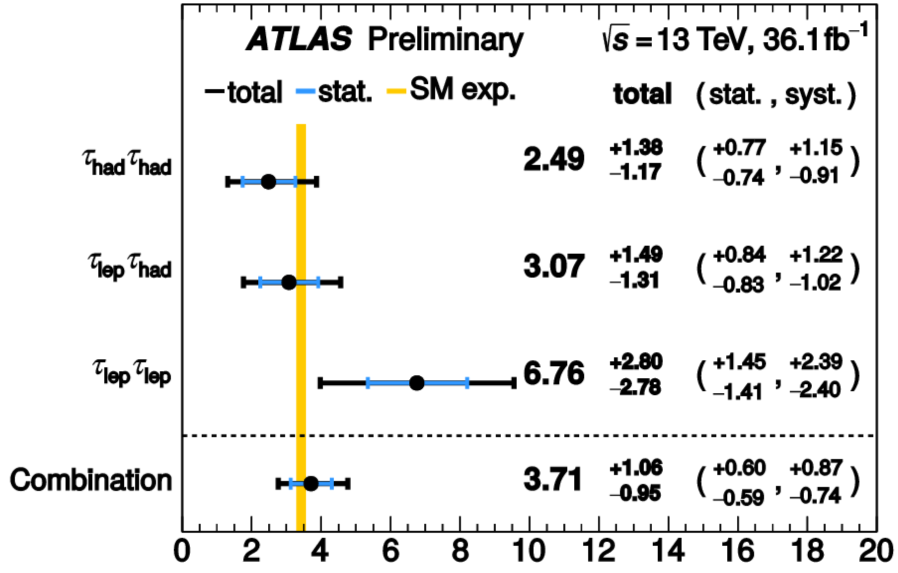
√s (TeV)	7, 8	13	Combined
Observed (σ)	4.5	4.4	6.4
Expected (σ)	3.4	4.1	5.4

$\tau_{had}\tau_{had}$

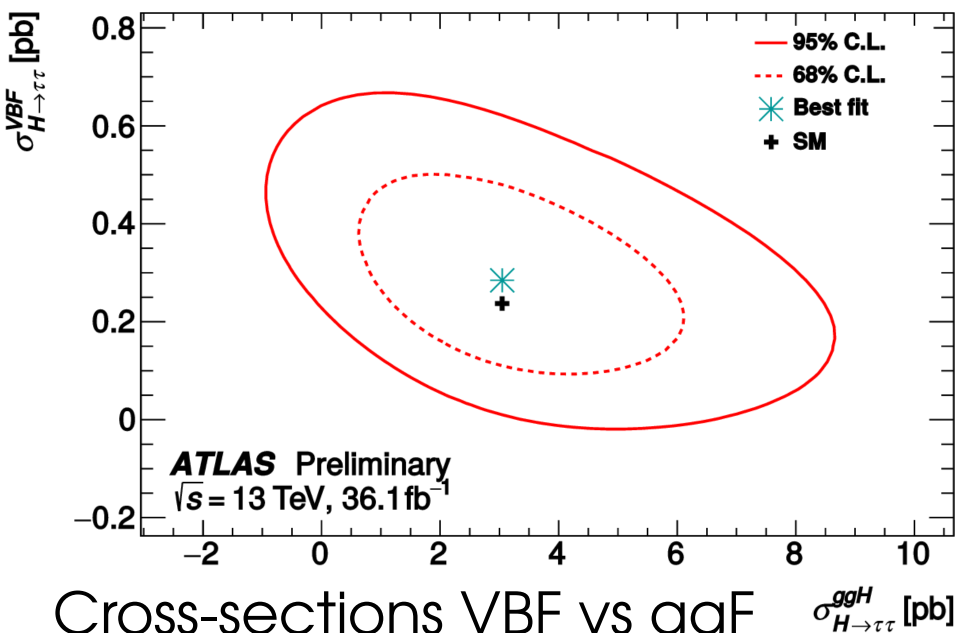


$H \rightarrow \tau^+\tau^-$, Cross-section results

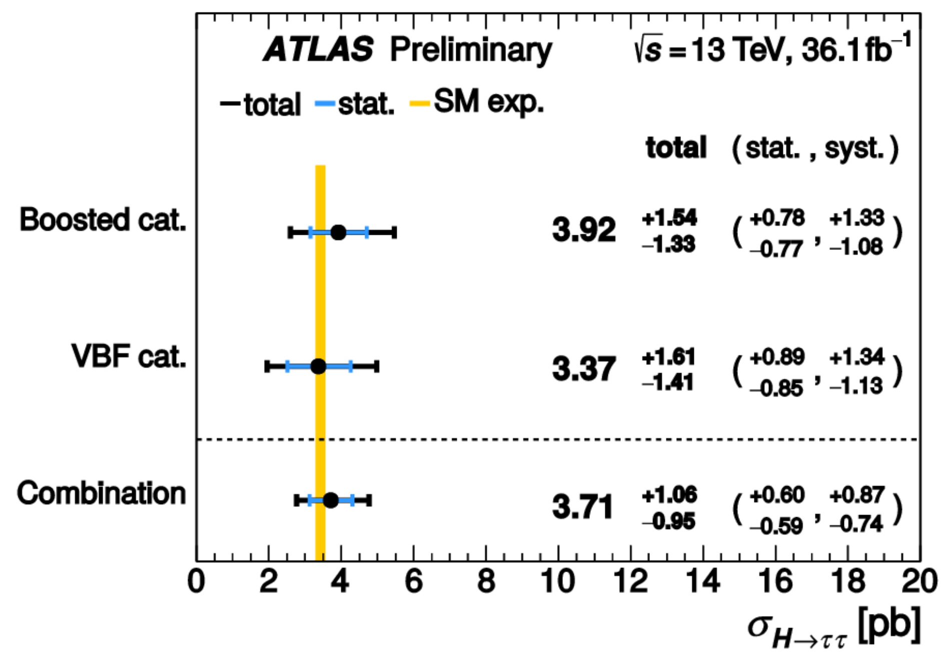
- VBF category is sensitive to VBF production and boosted is to ggF
- Results are consistent with SM
- 2d likelihood contour for the combination of all channels as a result of a two-cross-section-parameter fit
- Strongly anti-correlated results for ggF and VBF cross-sections (ρ = -52%)



Cross-sections by final states

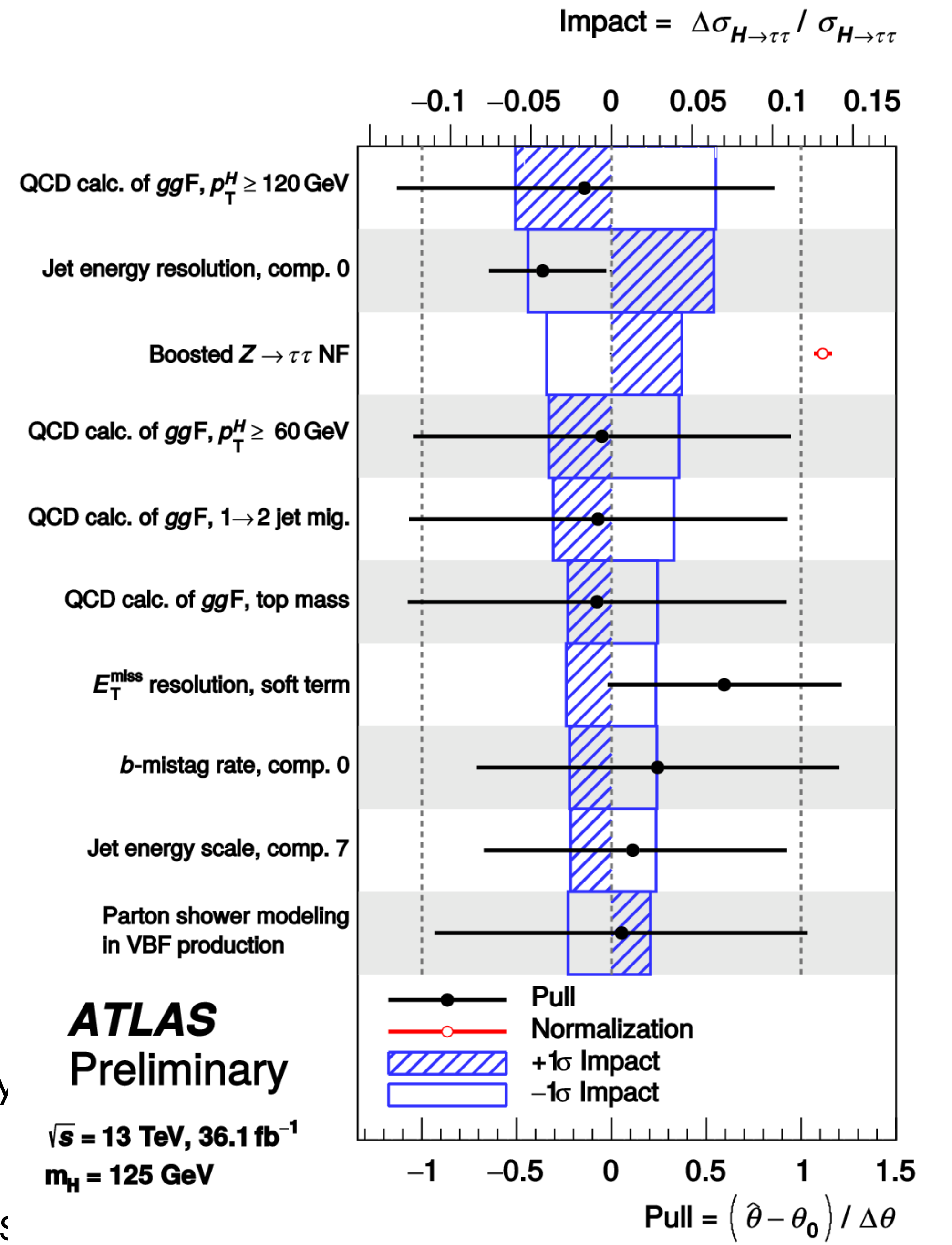


Cross-sections VBF vs ggF



$H \to \tau^+\tau^-$, Systematic uncertainties

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ (%) Observed	Expected
Theoretical uncert. on signal	+13.5 / −8.7	+11.9 / −7.7
Background statistics	+11 / −10	+10.2 / −9.8
Jets and E_T^{miss}	+11.5 / −9.3	+10.5 / −8.6
Background normalization	+6.8 / −4.8	+6.6 / −4.6
Misidentified τ	+4.5 / −4.2	+3.7 / −3.4
Theoretical uncert. on background	+4.6 / −3.6	+5.1 / −4.2
Hadronic taus	+4.7 / −3.0	+5.8 / −4.2
Flavour tagging	+3.3 / −2.4	+2.9 / −2.2
Luminosity	+3.3 / −2.3	+3.1 / −2.2
Electrons and muons	+1.2 / −1.0	+1.1 / −0.9
Total systematic uncert.	+24 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −26	+27 / −25

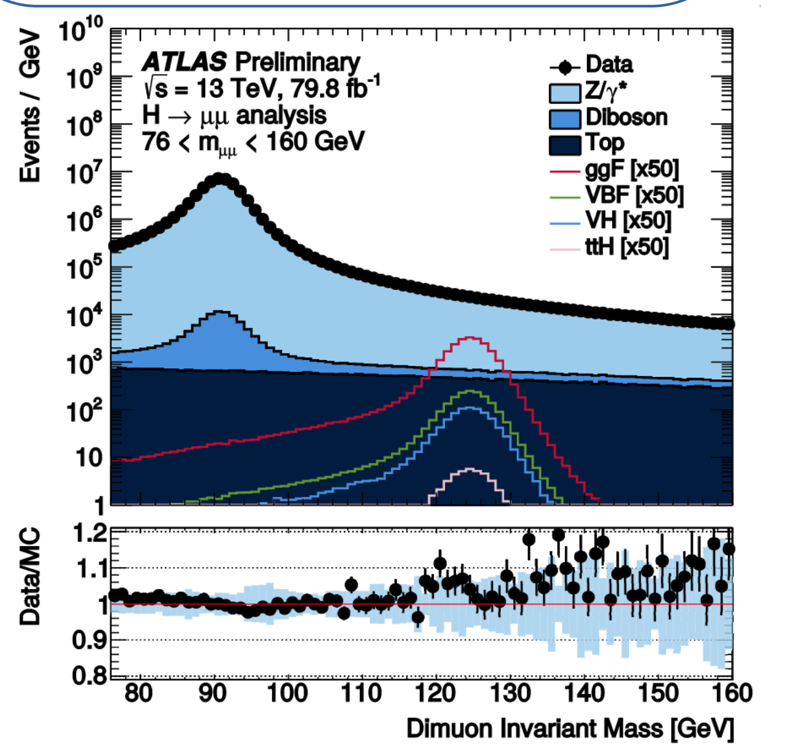


- 9 sources of theoretical unc. on signal:
  - 2 for yield due to factorization (μF) and renormalization (μR) scale variations;
  - 2 for events migration between Njets
  - 2 for migration between „low" & high pt
  - 1 for loop corrections due top mass unc.
  - 2 for acceptance unc. of ggF into VBF category
- Background statistics unc. is mainly due to the low MC statistics available for Z+jets sample in SRs phase space.

$H \rightarrow \mu^+\mu^-$, Analysis strategy

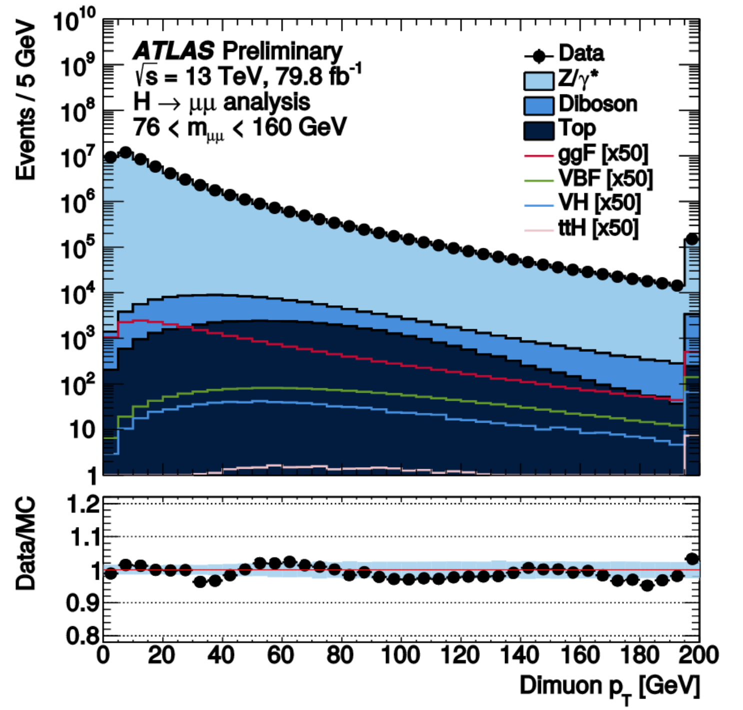
- Clean experimental signature, but very small rate compared to background
- Main background is Drell-Yan $Z/\gamma^* \rightarrow \mu\mu$
- General event selection: exactly two muons with high pt, $E_T^{miss} < 80$ GeV to suppress events with any b-jets (WZ, WW background)
- Dedicated categories for ggF and VBF to exploit kinematic differences between signal and background and increase S/B

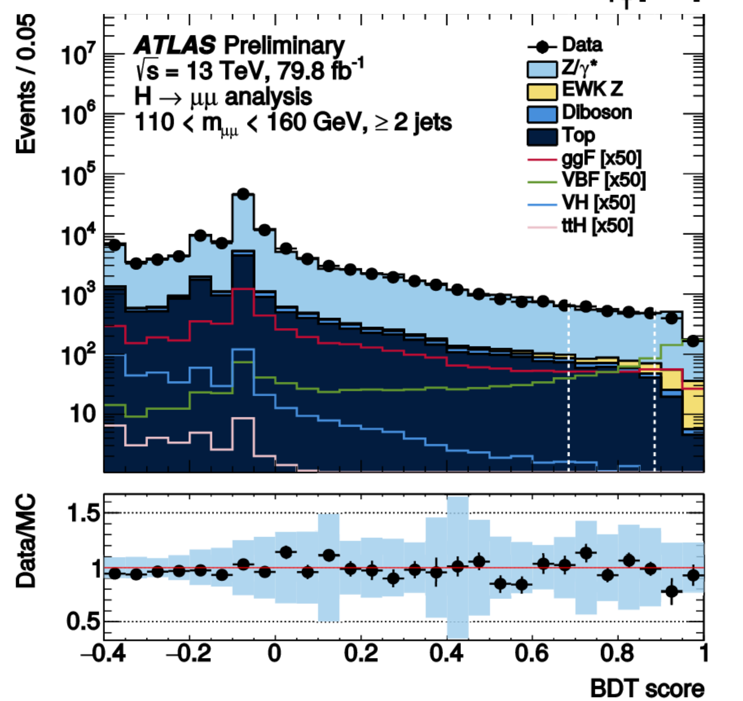
ATLAS history of the analysis:
- Run-1 analysis delivered upper limit on the signal strength: 7.1 observed (7.2 expected) for 125 GeV H. (Phys. Lett. B 738 (2014) 68)
- Corresponding result for 36.1 fb^{-1} of Run-2: $\mu < 2.8$ observed (2.9 expected) (Phys. Rev. Lett. 119 (2017) 051802)
- Results with 79.8 fb^{-1} are presented here



$H \rightarrow \mu^+\mu^-$, Categorization

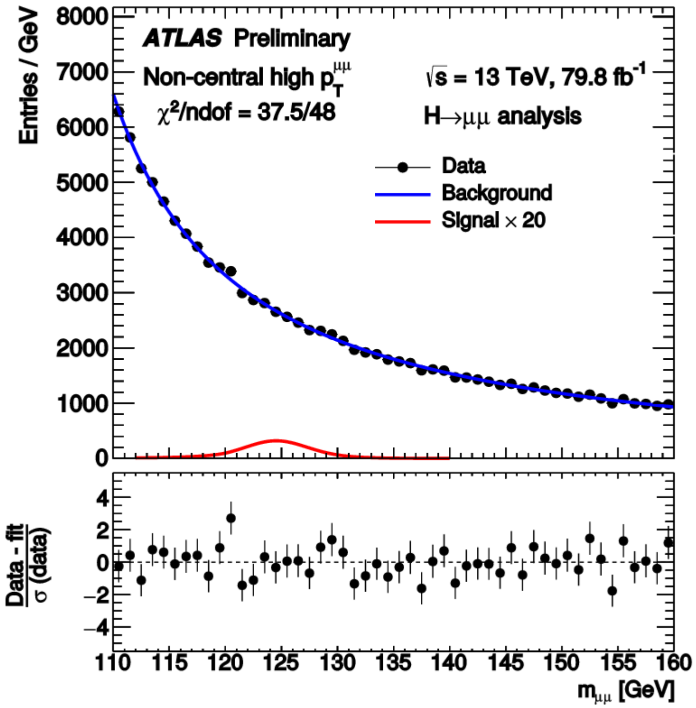
- <u>ggF</u>: signal tends to have harder pt spectrum than Drell-Yan due to QCD radiation from initial partons — events are separated into regions:
  - low pt: $pt_{\mu\mu} < 15$ GeV
  - medium pt: 15 GeV $< pt_{\mu\mu} <$ 50 GeV
  - high pt: $pt_{\mu\mu} > 50$ GeV
- <u>VBF</u>: BDT to separate signal, 14 variables (most sensitive mjj, Δηjj, ptμμ, ΔRjj).
  - BDT > 0.885 — VBF tight
  - 0.685 < BDT < 0.885 — VBF loose
  - BDT < 0.685 — ggF-like

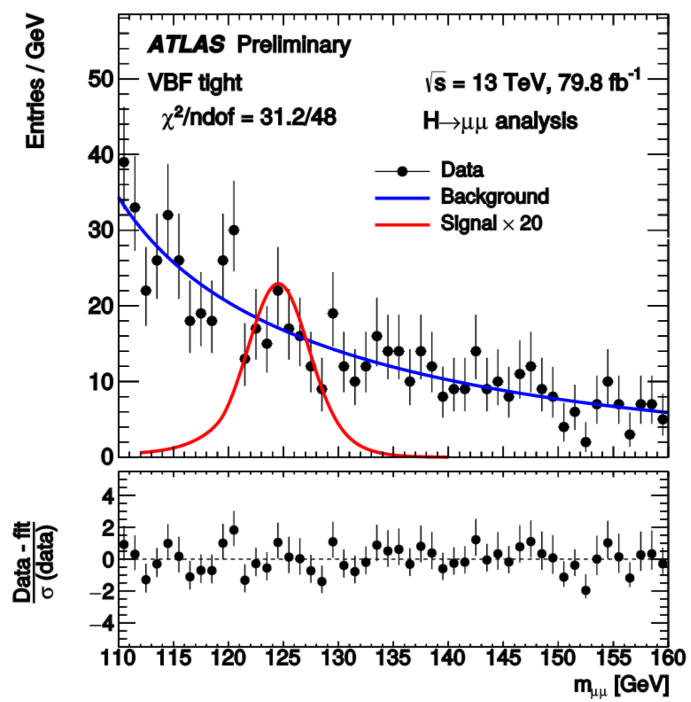




H → μ⁺μ⁻, Results

- In fit signal modelled with Crystal-Ball + Gaussian
- Background function: Breit-Wigner convolved with Gauss and exponential divided by cubic function
- No excess observed
  Expected significance: 0.9σ
  μ < 2.1 (2.0) observed (expected)





36.1 fb^{-1}

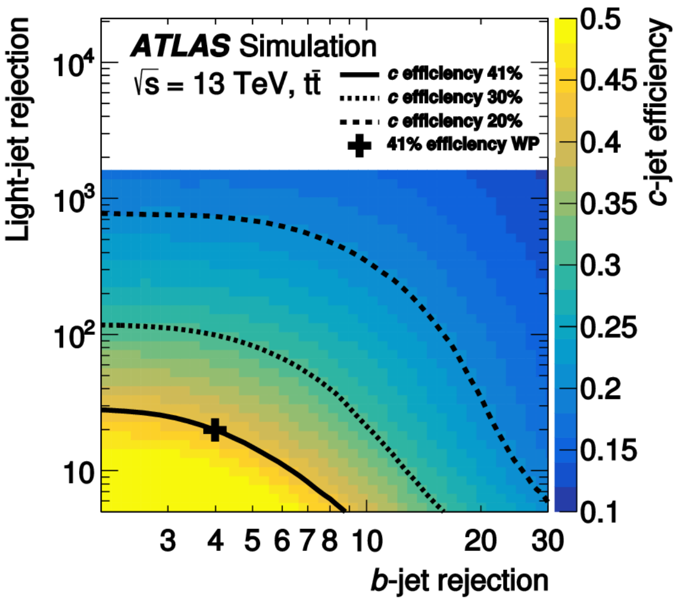
H → $c\bar{c}$

Phys. Rev. Lett. 120 (2018) 211802

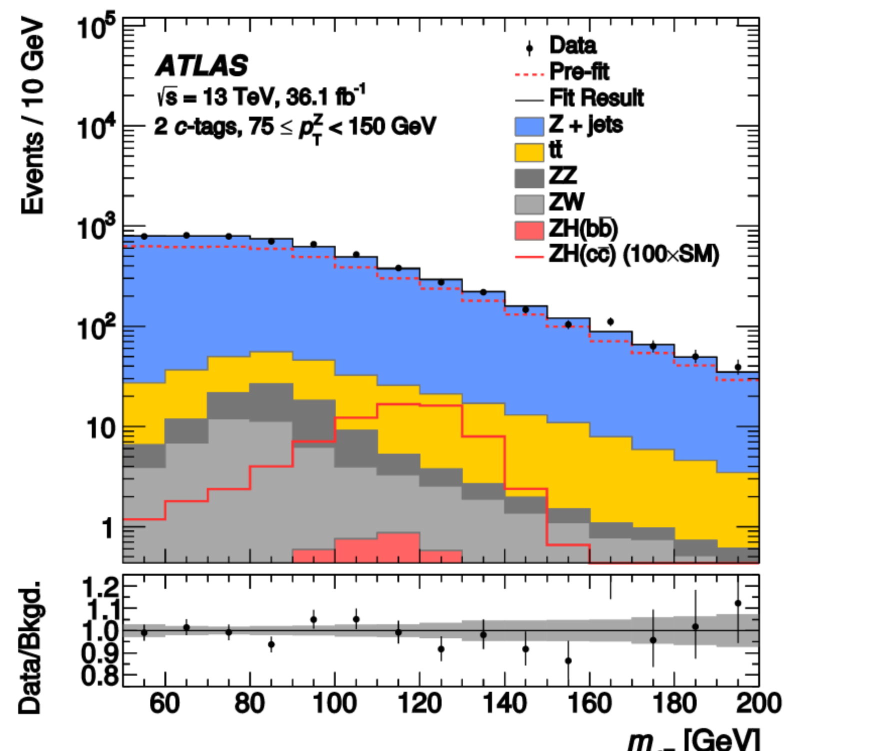
- The production mode ZH is studied. Z is tagged by decays into e^+e^- or $\mu^+\mu^-$
- BDT is trained to separate c-jets from light jets and b-jets. 41% efficiency WP selected with rejection power 4 and 20 for b- and l-jets respectively
- 4 Categories: 2 by Z pt (75 — 150 GeV, > 150 GeV) and 2 by the number of c-tags (1 or 2)
- Signal has harder Z pt distribution than Z+jets
- Joint binned maximum-profile-likelihood fit in categories to m_{cc} is performed to determine signal strength
- The observed (expected) upper limit on σ(pp→ZH)B(H→cc): 2.7 ($3.9^{+2.1}_{-1.1}$) pb, while SM value is 26 fb.

Very similar analysis H→bb will be presented today by Louis

Source	σ/σ_{tot}
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%



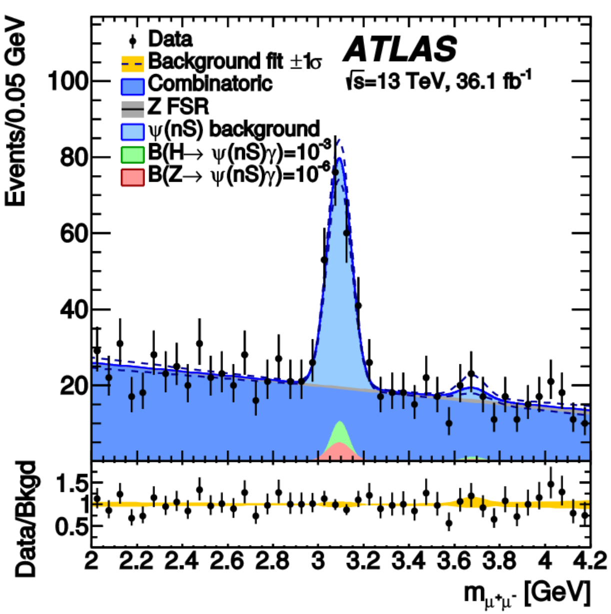
No significat excess observed so far in 36.1 fb^{-1} Run-2 dataset



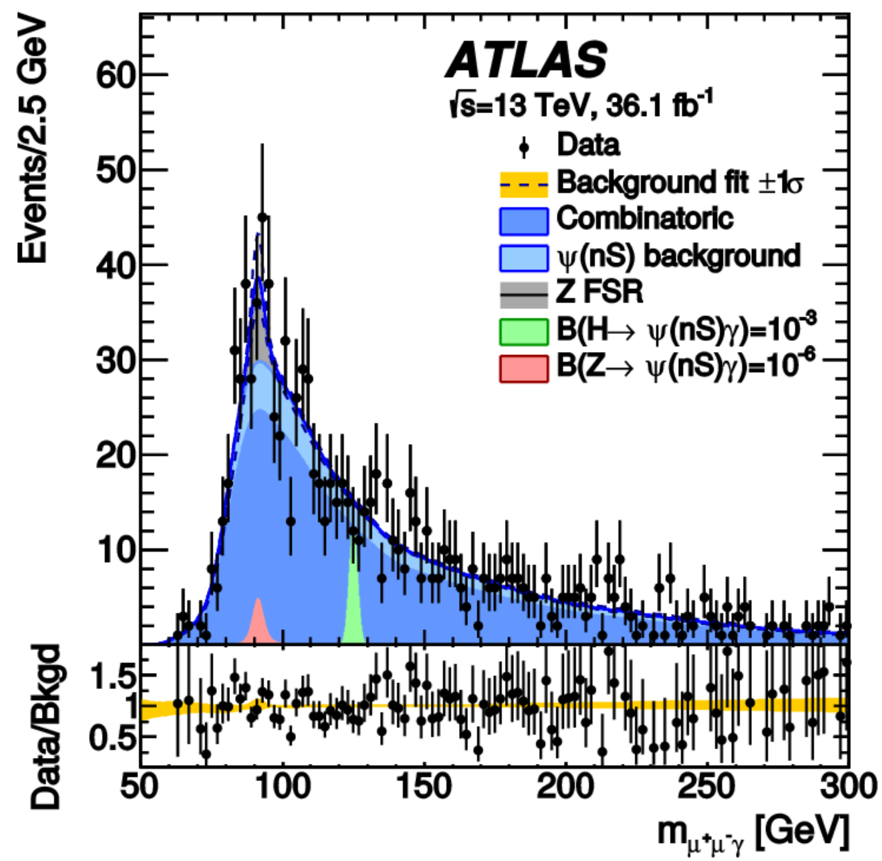
$H \rightarrow J/\psi\gamma$

- Also sensitive Yukawa coupling of H to c, but has very small branching ratio
- Only clean final state with $J/\psi \rightarrow \mu^+\mu^-$ decay is considered
- Two main sources of background:
  - non-resonant production of $\psi\gamma$. Estimated by extracting template from data and normalization from fit
  - resonant $Z \rightarrow \mu^+\mu^-\gamma$. Shape is from MC, normalization from fit to data
- Unbinned maximum likelihood fit to $m_{\mu+\mu-\gamma}$
- Upper limit on $H \rightarrow J/\psi\gamma$ branching: 3.5 * 10^{-4}, factor of 4 improvement w.r.t. Run-1 result

Source of systematic uncertainty	Yield uncertainty $H(Z) \rightarrow Q\gamma$
Total $H(Z)$ cross section	7.0% (2.9%)
Integrated luminosity	2.1%
$H(Z)$ QCD modelling	1.8% (6%)
Trigger efficiency	2.0%
Photon identification	1.4%
Muon reconstruction	2.8%
Photon energy scale	0.3%
Muon momentum scale	0.2%



No significat excess observed so far in 36.1 fb^{-1} Run-2 dataset



Conclusions

- ATLAS has an extensive program of Higgs boson properties measurements
- Higgs interactions with fermions present an important sector to test the nature of Higgs boson
- **ttH** production: provides direct sensitivity to y_t Yukawa coupling. ATLAS reached observation sensitivity with 79.8 fb^{-1}. Significance in combination with Run-1: 6.3σ (5.1σ) observed (expected).
  Measured: σ(pp→ttH) = 670 ± 90 (stat) +110/-100 (syst) fb
  Standard Model: 507 +35/-50 fb
- **H→ττ**: provides Higgs coupling measurement to 3rd generation leptons. Observation in combination of 36.1 fb-1 Run-2 data with Run-1: 6.4σ (5.4σ) observed (expected) significance.
  Measured: σ(pp→H→ττ) = 3.71 ± 0.59 (stat) +0.87/-0.74 (syst) pb
  Standard Model: 3.43 ± 0.13 pb
- **H→μμ**: allows to study Higgs couplings to 2nd generation leptons, but we are still far from reaching enough sensitivity. Signal strength limits with 36.1 fb-1 data: μ < 2.1 (2.0) observed (expected)
- **H→$c\bar{c}$ and H→J/ψγ**: both allow to study Higgs couplings to 2nd generation quarks, but current experimental sensitivity is still very far from observation.
- All results are in agreement with the Standard Model