Preliminary

Precision Measurements in the Higgs Sector at ATLAS and CMS

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on behalf of the ATLAS and CMS Collaborations

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Tihany, Hungary
9-14 June 2019

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Recent_Results
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG/index.html

Outline

- Higgs boson mass and width
- Higgs boson couplings to bosons
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ$
  - $H \rightarrow WW$
- Higgs boson couplings to fermions
  - $H \rightarrow \tau\tau$
  - $H \rightarrow bb$
  - $H \rightarrow tt$
  - $H \rightarrow \mu\mu$
- Differential Higgs boson decay cross-sections
- Rare Higgs boson decays
- Higgs boson decays to invisible particles
- Higgs boson production modes (ggF, VBF, VH, ttH)
- Single top-Higgs production tH, Higgs boson pair-production HH
- Relation of coupling and fermion mass
- Outlook

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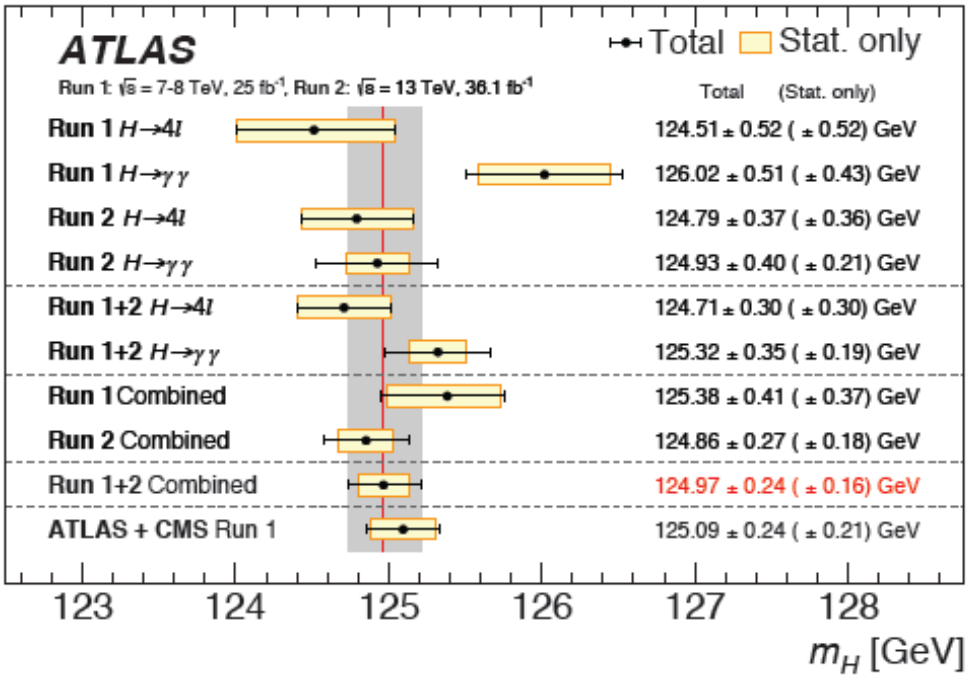
Higgs boson mass

ATLAS, PLB 784 (2018) 345

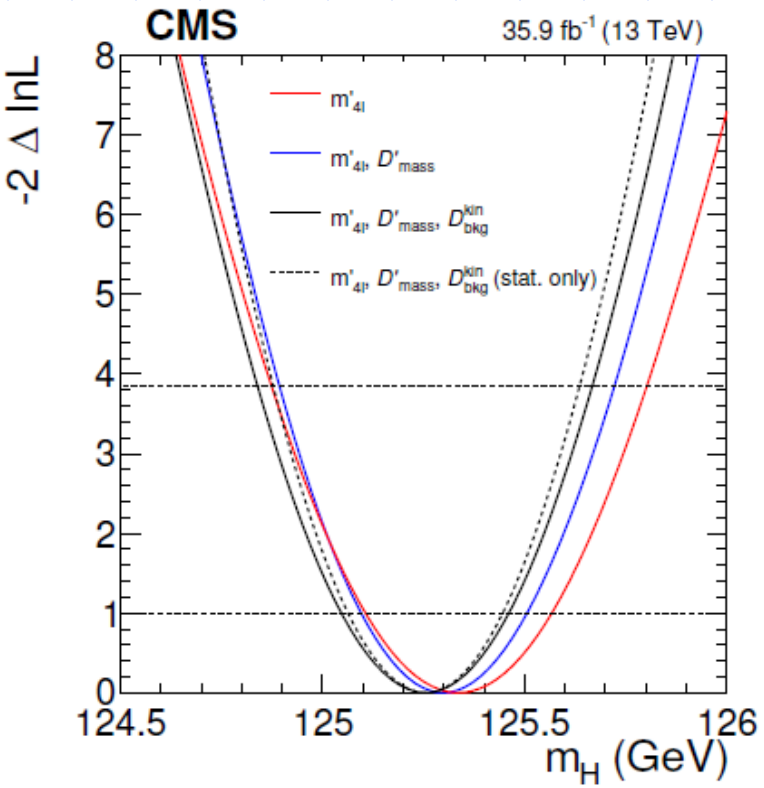
- **m_H = 124.97 ± 0.24 GeV**
- Combination H → γγ and H→ZZ→4l decay channels
- H → γγ: syst. uncertainties dominant
- H→ZZ→4l: stat. and sys. uncertainties comparable at 140 fb^{-1}



CMS, JHEP 11 (2017) 047

m_H = 125.26
± 0.20 (stat)
± 0.08 (syst)

- 4-lepton mass with kinematic discriminant to reduce ZZ bgd

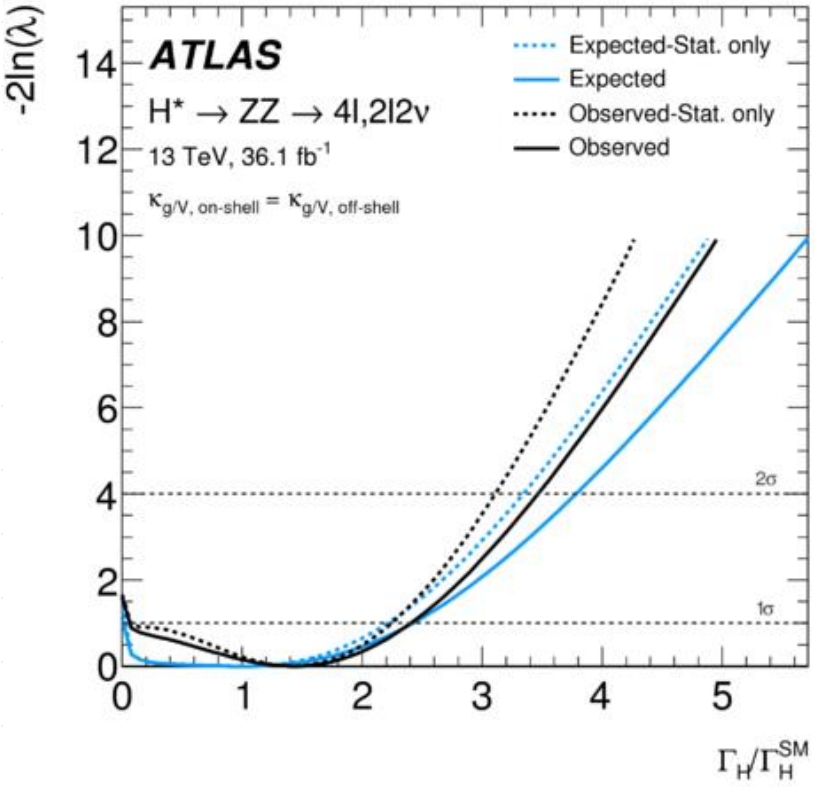


Higgs boson width

Detector resolution much larger than expected SM width (4.07 MeV, PDG)

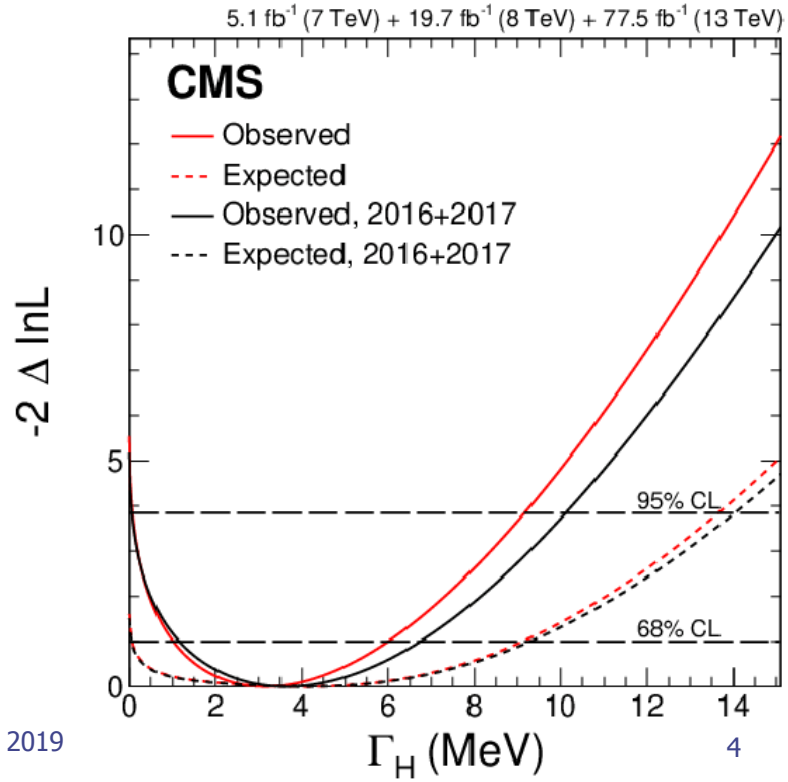
ATLAS

- Indirect limit, PLB786 (2018) 223
  Γ_H <14.4 MeV at 95% CL
  on- and off-shell signal strengths



CMS

- Indirect limit, arXiv:1901.00174
  Γ_H < 9.16 MeV at 95% CL
  on- and off-shell signal strengths
- Direct peak reconstruction in H→4l:
  < 1.10 GeV at 95% CL, JHEP 11 (2017) 047



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Produced numbers of Higgs bosons in four production modes

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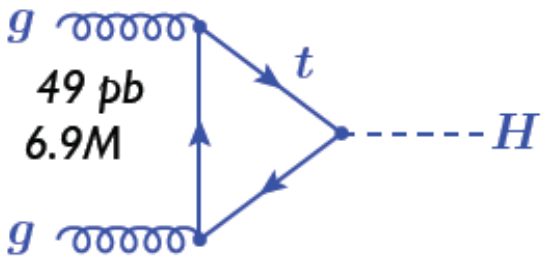
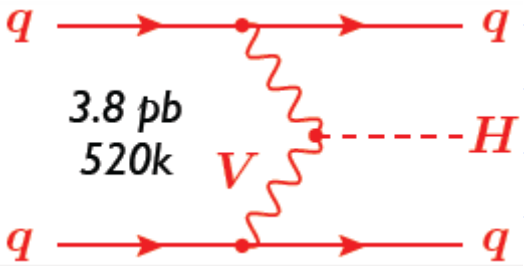
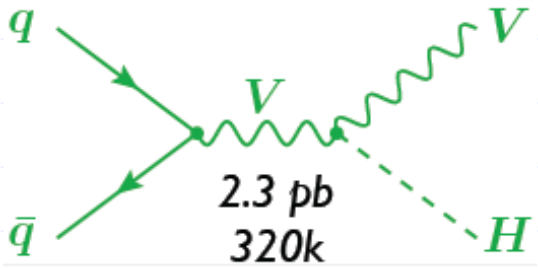
Gluon-gluon fusion (ggF)

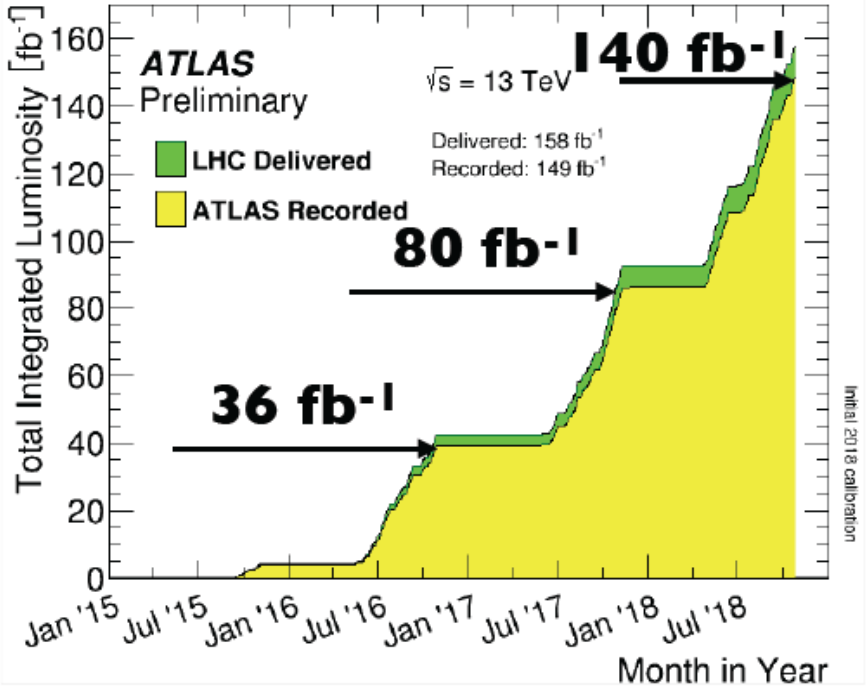


Vector boson fusion (VBF)

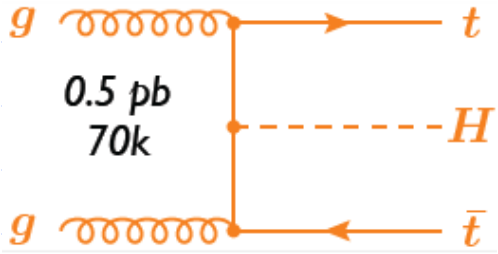


Associated production (VH)





Top-top Higgs (ttH)



Cross-sections for 13 TeV
and
number of events for 140 fb^{-1}

Higgs boson decay branching fraction and expected final states

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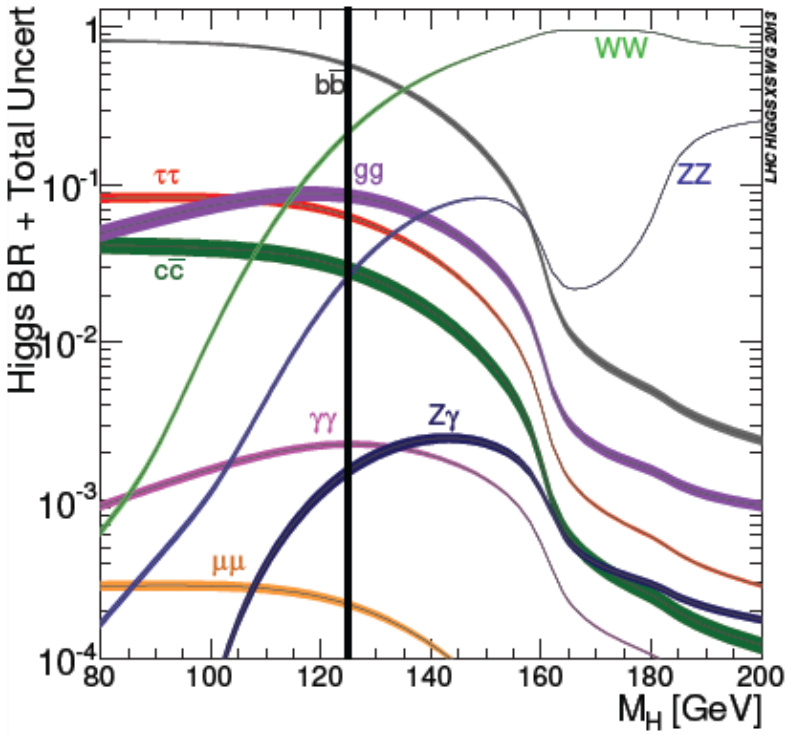
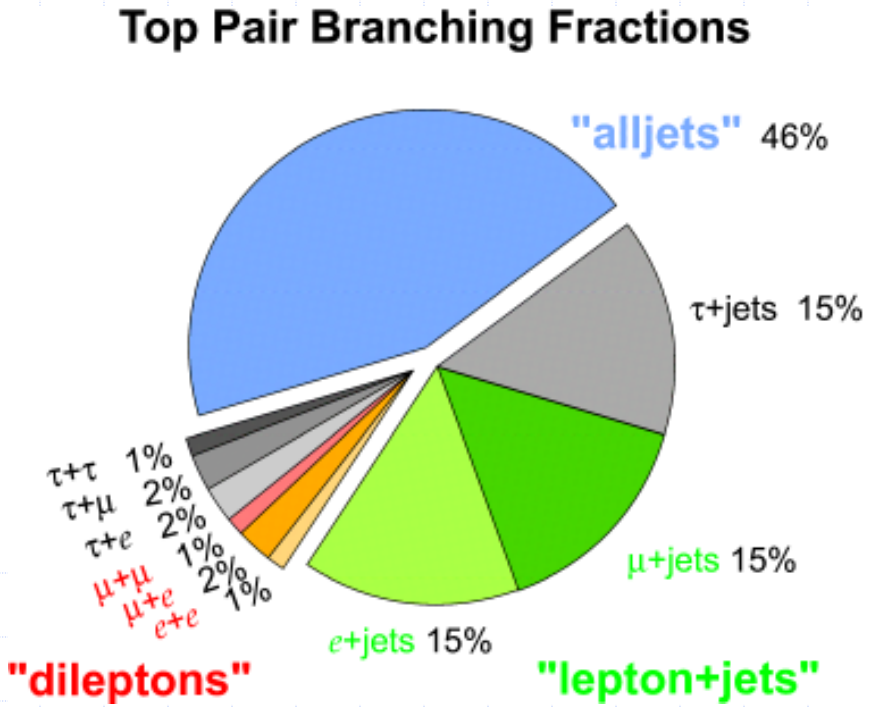


- H → bb: 58%
- H → WW*: 21%
- H → ττ: 6.3%
- H → ZZ*: 2.6%
- H → γγ: 0.23%

ttH production and decay



Higgs boson couplings to bosons
$H \rightarrow \gamma\gamma$

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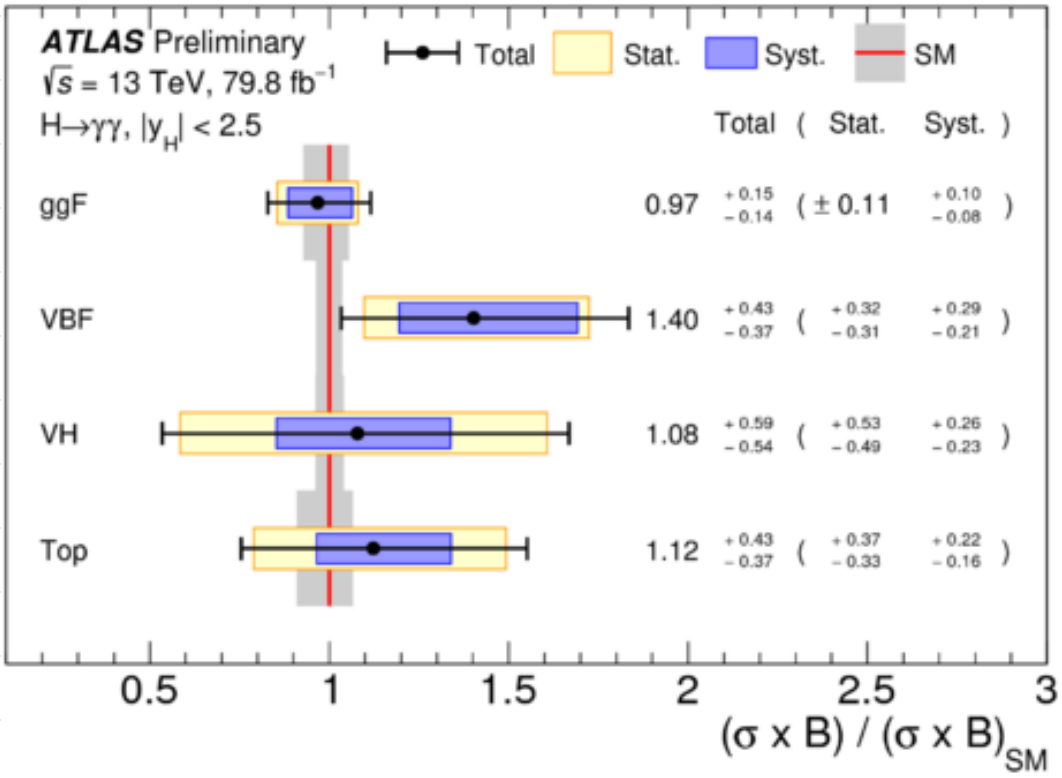
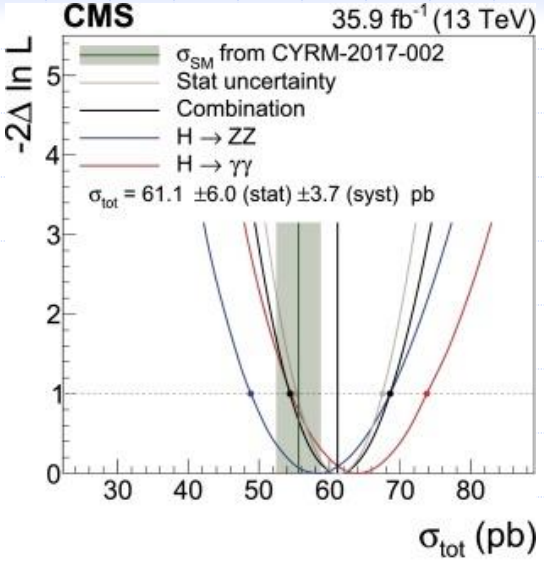
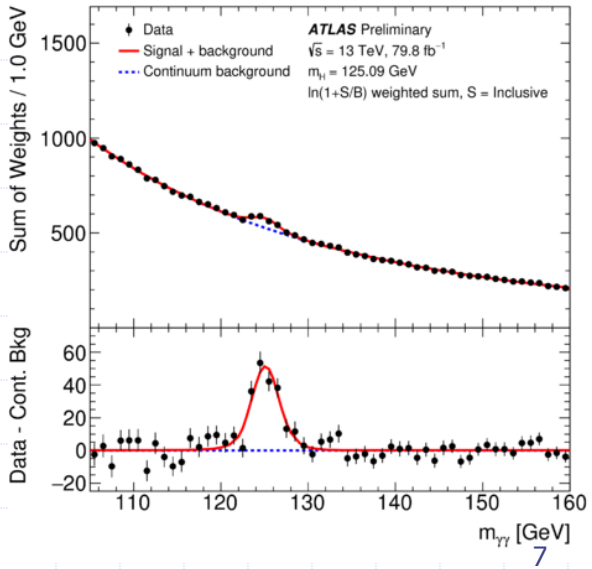
- ATLAS 79.8 fb^{-1}: ggF, VBF, VH and ttH:
  σ x B consistent with SM expectations
- CMS 36.9 fb^{-1}: σ_{tot} = 61.1 ± 6.0 (stat) ± 3.7 (sys) pb
  SM: σ_{tot} = 55.6 ± 2.5 pb





PLB 792 (2019) 369



ATLAS-CONF-2018-018

Higgs boson couplings to bosons
H → ZZ

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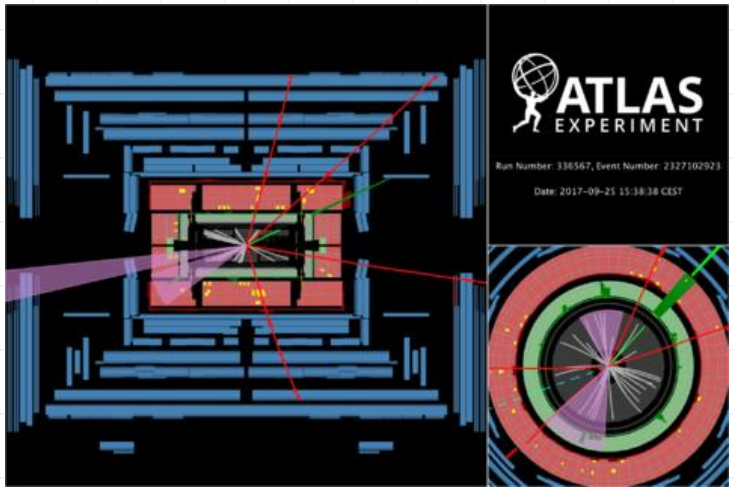
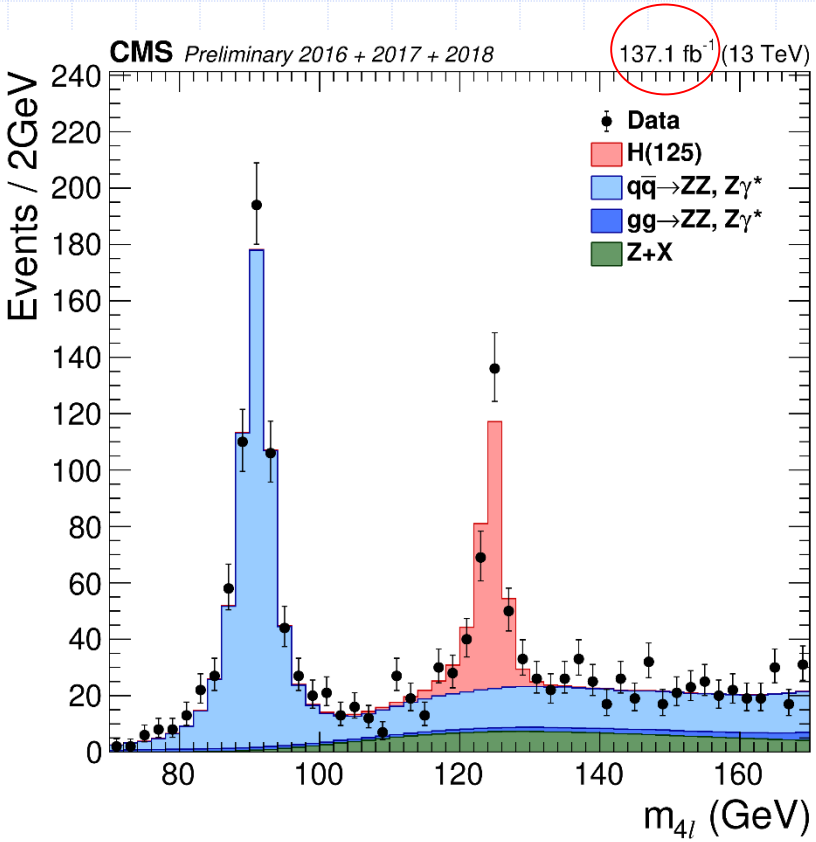
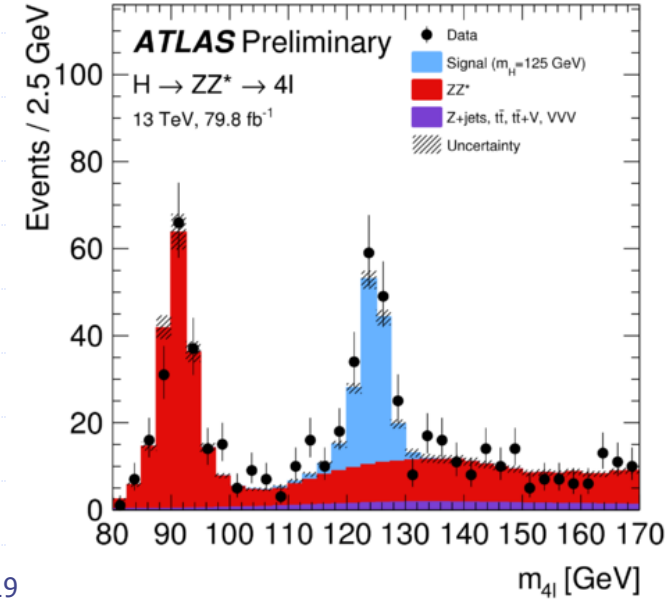
- H→ZZ→4l
  ATLAS-CONF-2018-018 (79.8 fb^{-1})
  CMS-PAS-HIG-19-001 (137.1 fb^{-1})
- Clear signal over background







Higgs boson couplings to bosons
H → ZZ

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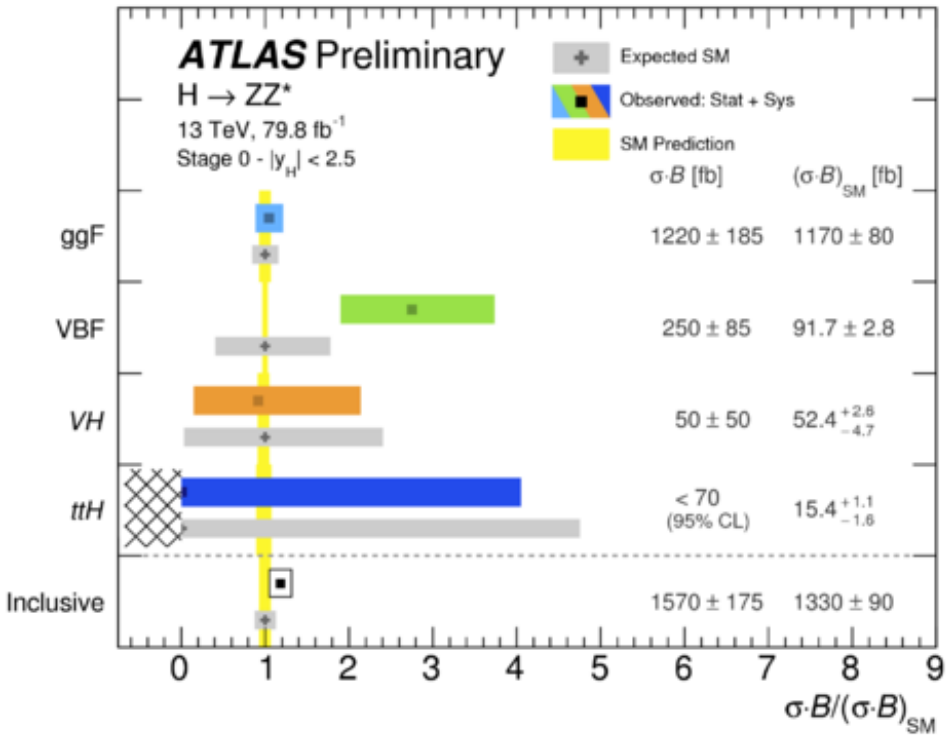
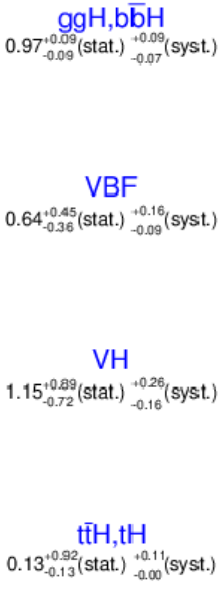
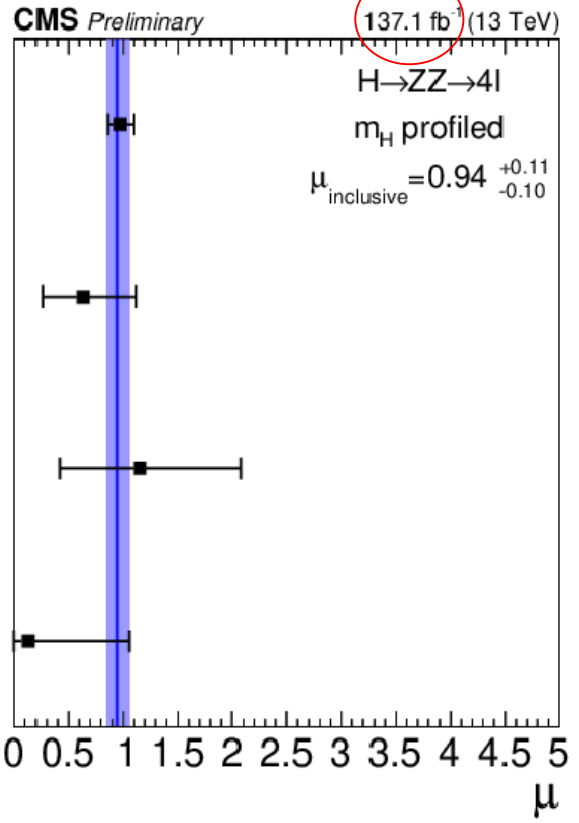
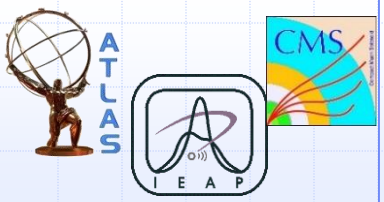
- H→ZZ→4l, ATLAS-CONF-2018-018, CMS-PAS-HIG-19-001
- ggF: σ x B uncertainty 15%,
  other production modes probing
- rate consistent with SM expectation with 11% uncertainty
-







Higgs boson couplings to bosons
H → WW



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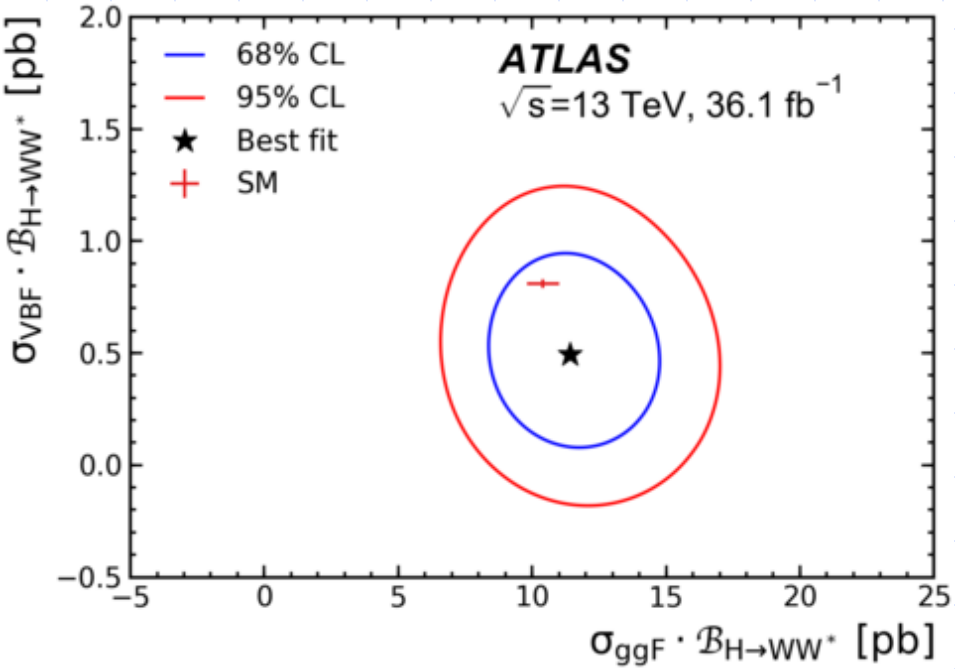
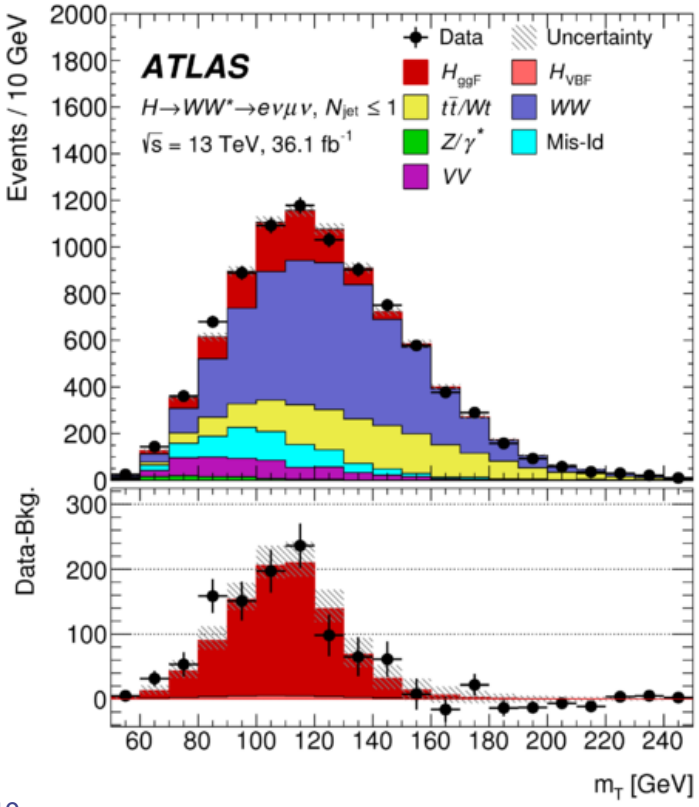
- ggF σ x B
  - Measurement: $11.4^{+1.2}_{-1.1}$ (stat) $^{+1.2}_{-1.1}$ (theo syst) $^{+1.4}_{-1.3}$ (exp syst) pb
  - SM: 10.4 ± 0.6 pb
- VBF σ x B
  - Measurement: $0.5^{+0.24}_{-0.22}$ (stat) ± 0.10 (theo syst) $^{+0.12}_{-0.13}$ (exp syst) pb
  - SM: 0.81 ± 0.02 pb





Higgs boson couplings to fermions
$H \rightarrow \tau\tau$

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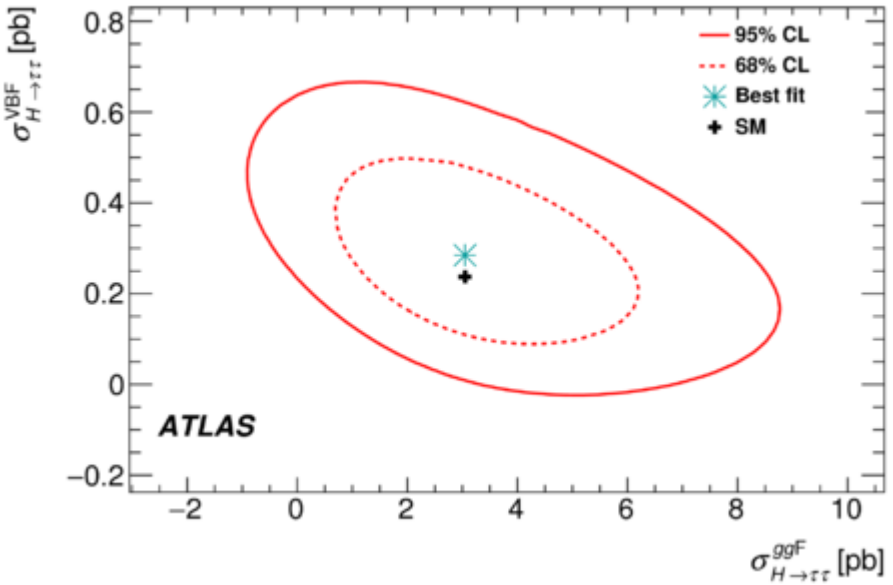
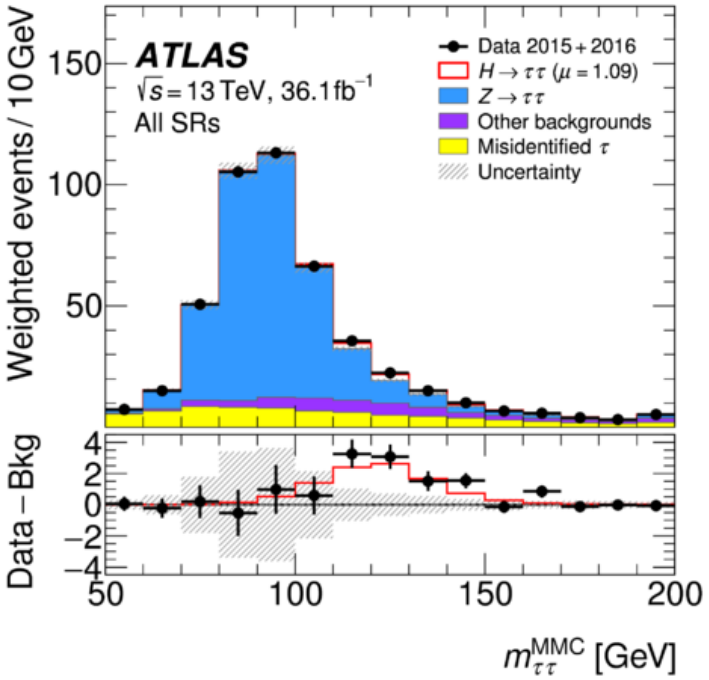
- ATLAS+CMS data combined (LHC Run-1):
  observation with 5.5 (5.0) st.dev., JHEP 08 (2016) 045
- ATLAS Run-1 and 36 fb^{-1} Run-2 data:
  6.4 (5.4) standard deviations, PRD 99 (2019) 072001
  - ggF:
    Measurement: 3.1 ± 0.1 (stat) $^{+0.16}_{-0.13}$ (syst) pb
    SM: 3.05 ± 0.13 pb
  - VBF:
    Measurement: 0.28 ± 0.09 (stat) $^{+0.11}_{-0.09}$ (syst) pb
    SM: 0.237 ± 0.006 pb





Higgs boson couplings to fermions
$H \rightarrow \tau\tau$

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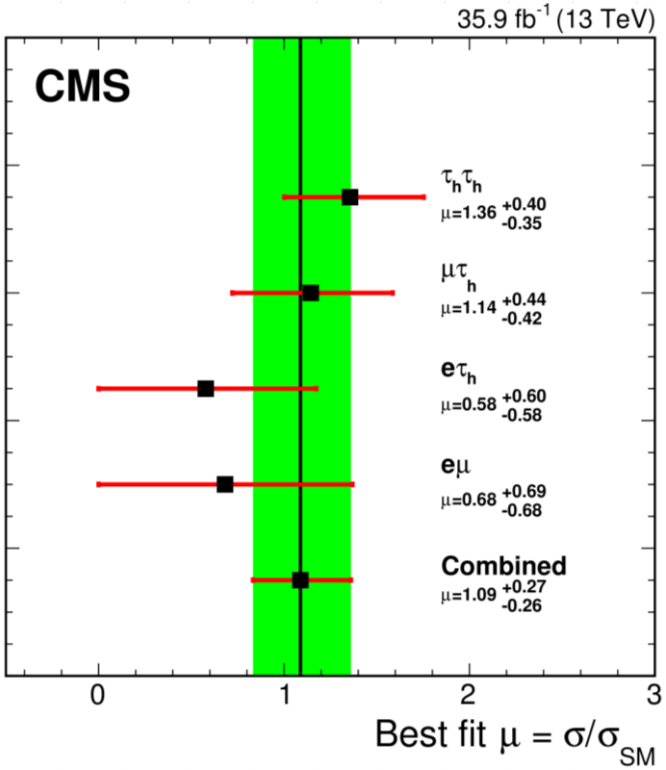
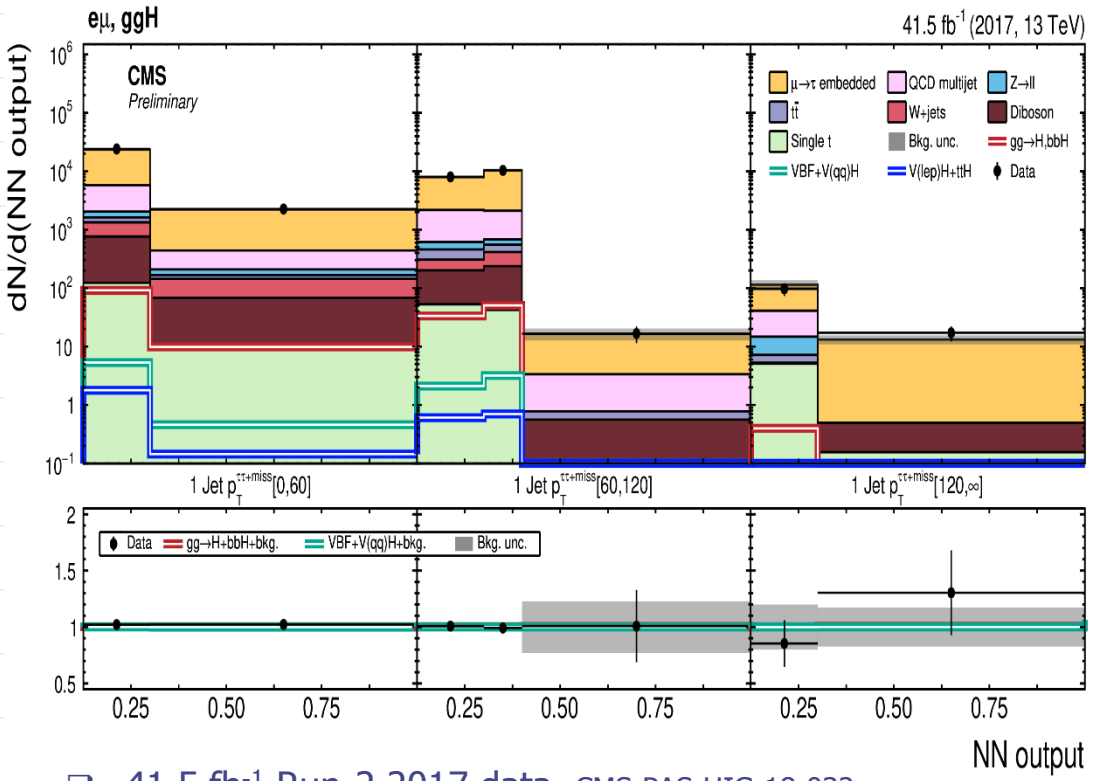
- 35.9 fb^{-1} Run-2 2016 data, PLB 779 (2018) 283
- 4.9 (4.7) st.dev.
- 5.9 (5.9) st.dev. combined with Run-1





- 41.5 fb^{-1} Run-2 2017 data, CMS-PAS-HIG-18-032
- Stage-1 simplified template cross-sections 35.9+41.5 fb^{-1}
- σxB($H\rightarrow\tau\tau$) = 2.56 ± 0.48 (stat) ± 0.34 (syst) pb
- $\sigma(gg\rightarrow H,bbH)$xB($H\rightarrow\tau\tau$)=1.11±0.81 (stat)±0.78 (syst) pb
  σ(VBF)xB($H\rightarrow\tau\tau$) = 0.34 ± 0.08 (stat) ± 0.09 (syst) pb

Higgs boson couplings to fermions
H → bb

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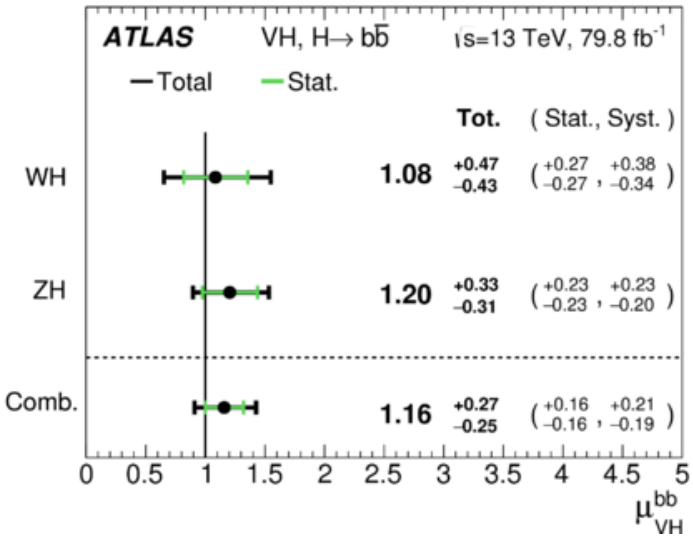
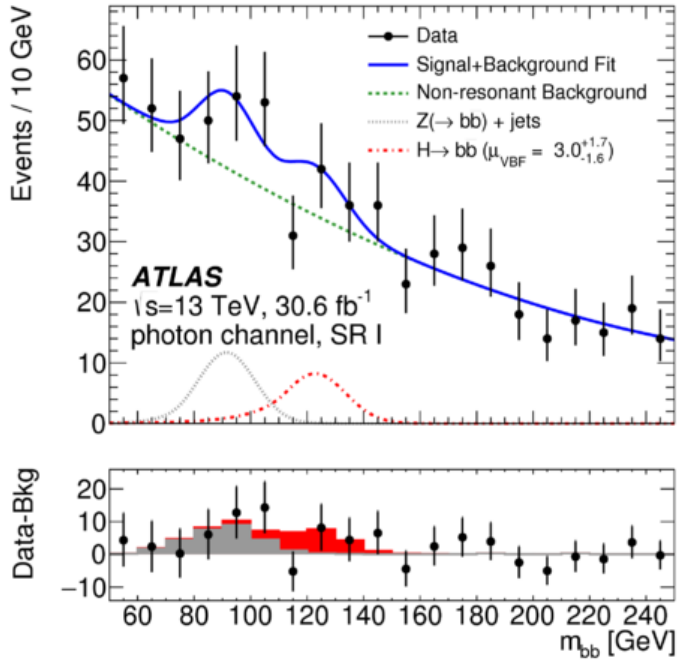
- Difficult channel despite the large branching ratio (58%) due to large backgrounds
- Most sensitive production mode: VH
- Further searches using ggF, VBF, and ttH
- 5.4 (5.5) st.dev., PRD 98 (2018) 052003
- stage-1 simplified template cross-sections times H → bb branching, arXiv:1903.04618

VH

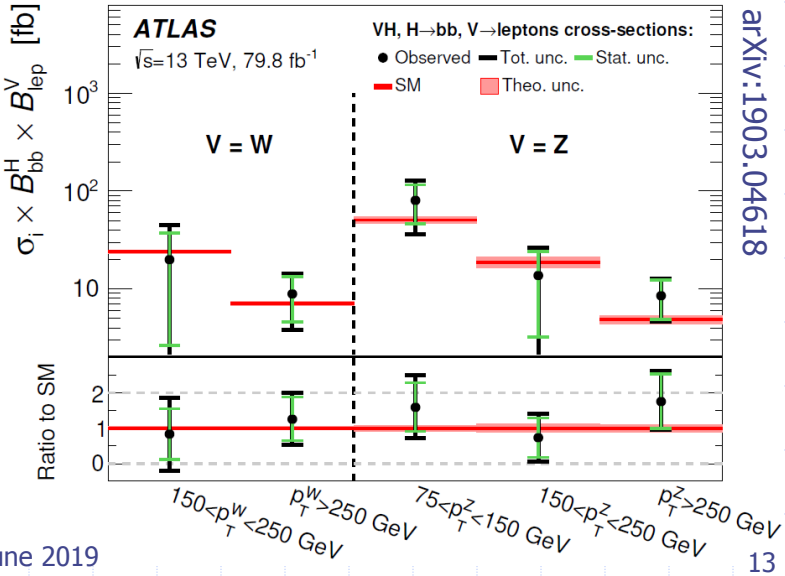


PLB 786 (2018) 59

VBF



PLB 786 (2018) 59



arXiv:1903.04618

Higgs boson couplings to fermions
H → bb

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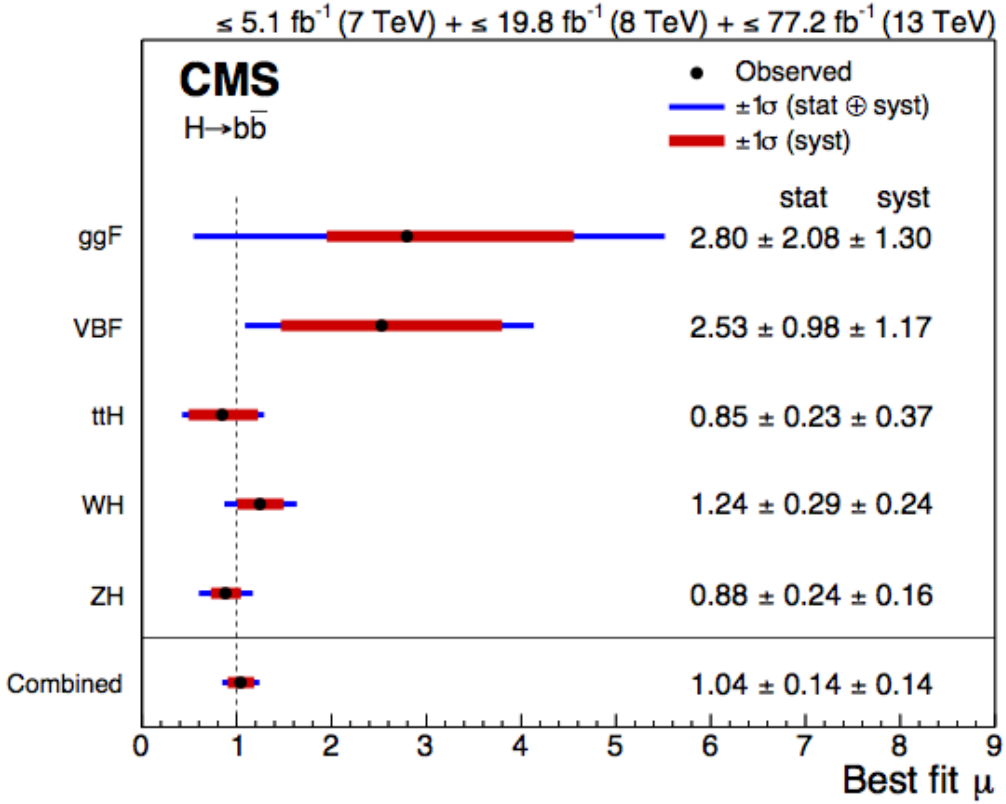
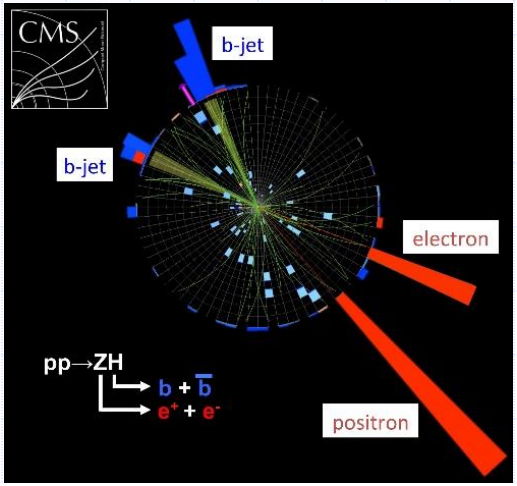
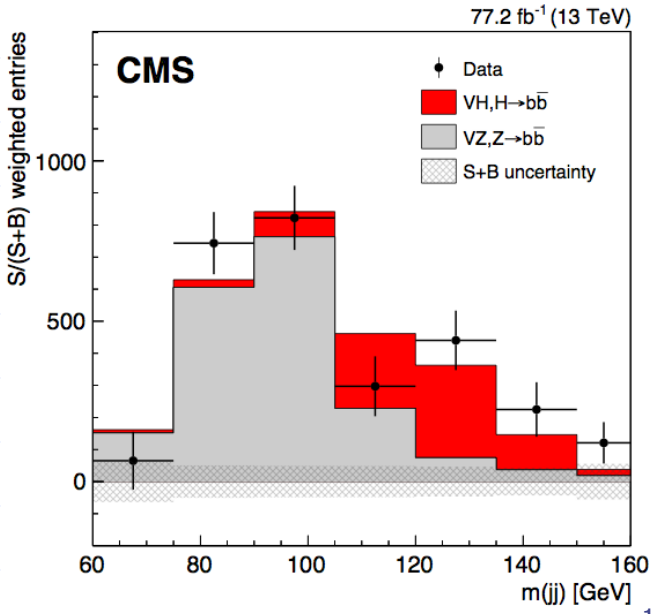
PRL 121 (2018) 121801

- Dedicated searches in ttH, VBF, ggH, and VH production modes
- 5.6 (5.5) st.dev.
- μ = 1.04 ± 0.20







Higgs boson couplings to fermions
H → tt via ttH direct probe, photons

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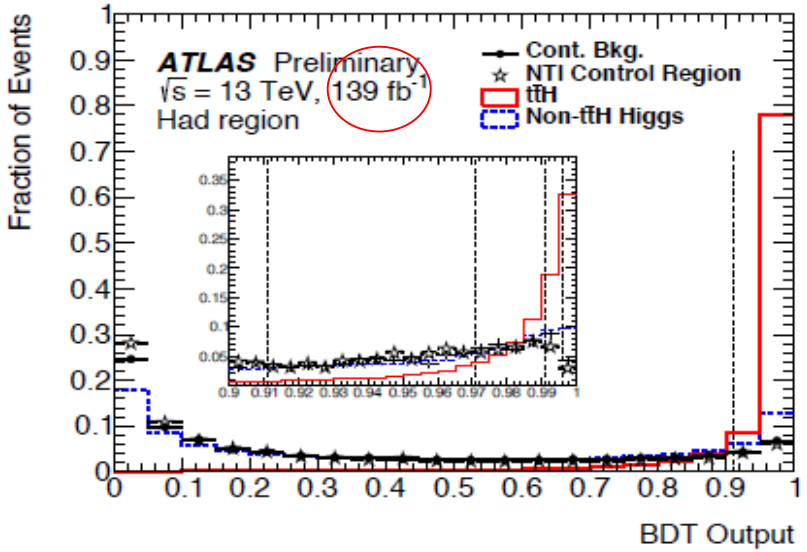
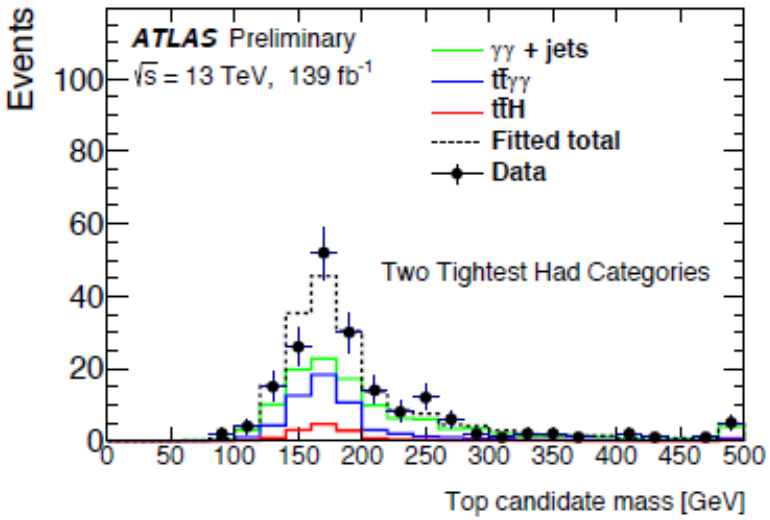
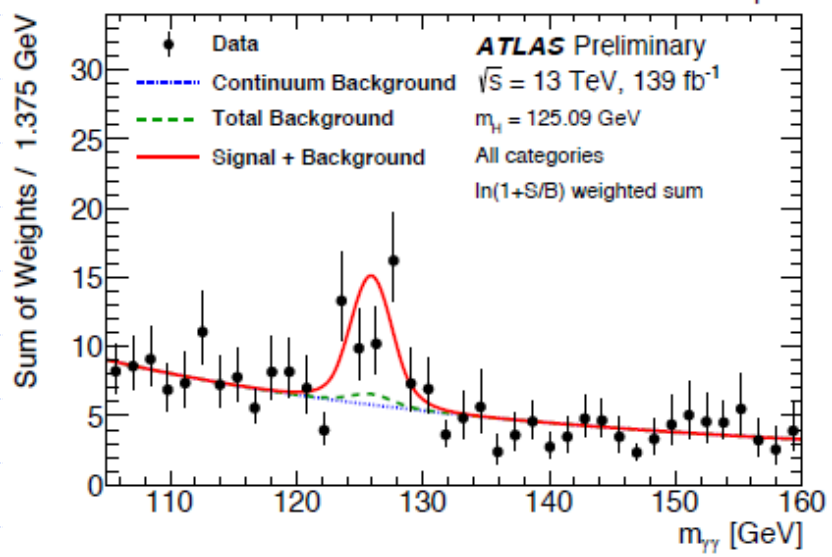
- **ttH observation**
  ATLAS: 5.8 (4.9) st.dev., PLB 784 (2018) 173
  CMS: 5.2 (4.2) st.dev., PRL 120 (2018) 231801
- **Full Run-2 data set**
  ttH(H→γγ), 139 fb^{-1}, ATLAS-CONF-2019-004
- Separate events by decay of top quarks
  - hadronic region / leptonic region
- Construct templates from top mass distributions in ttγγ, γγ+jets, and ttH MC
- Decompose the continuum background by a template fit to the data







Higgs boson couplings to fermions
H → tt via ttH direct probe, photons

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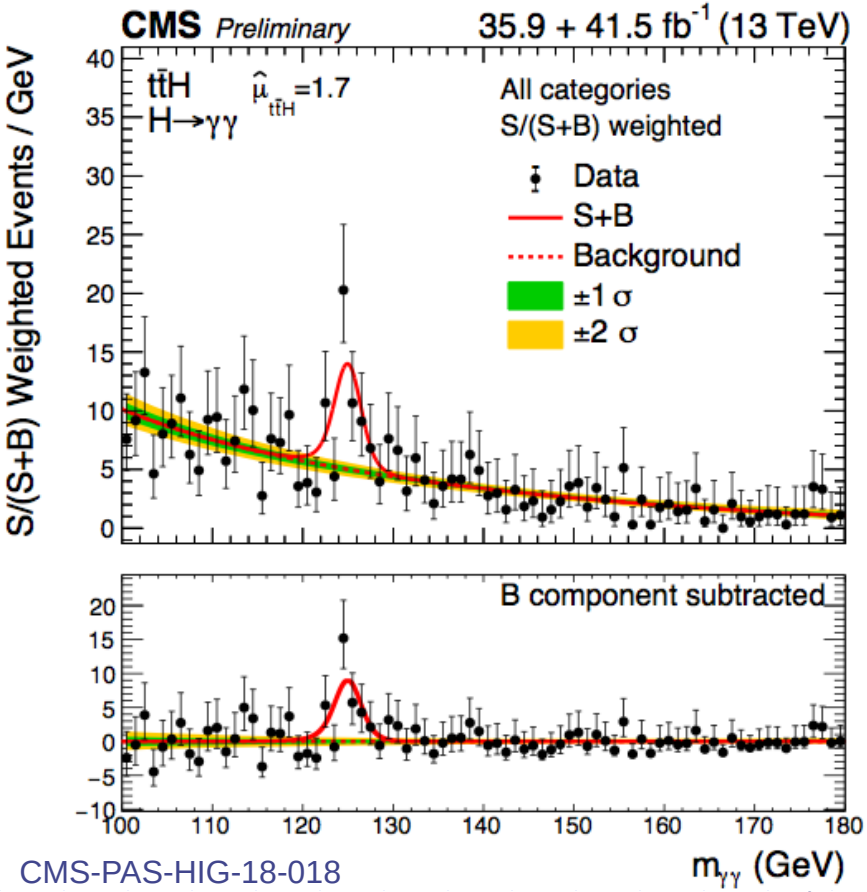
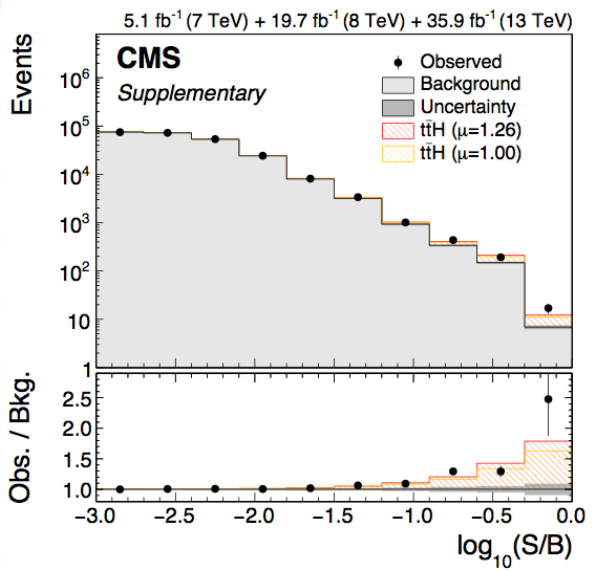
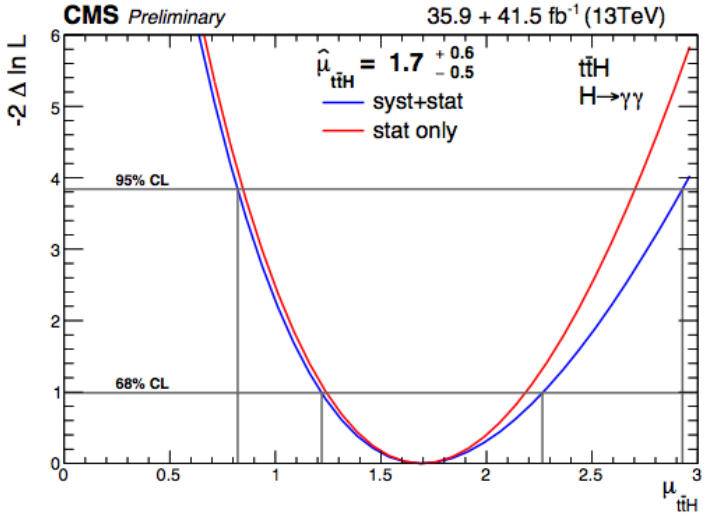
- Observation with 2016 data: 5.2 (4.2) st.dev. (combination of bb, multilepton, γγ, ZZ channels)
- Including 2017 data ttH(H→γγ): $\mu = 1.7^{+0.6}_{-0.5}$



CMS-PAS-HIG-18-018



PRL 120 (2018) 231801



ttH: two same-sign leptons and one hadronic tau final state

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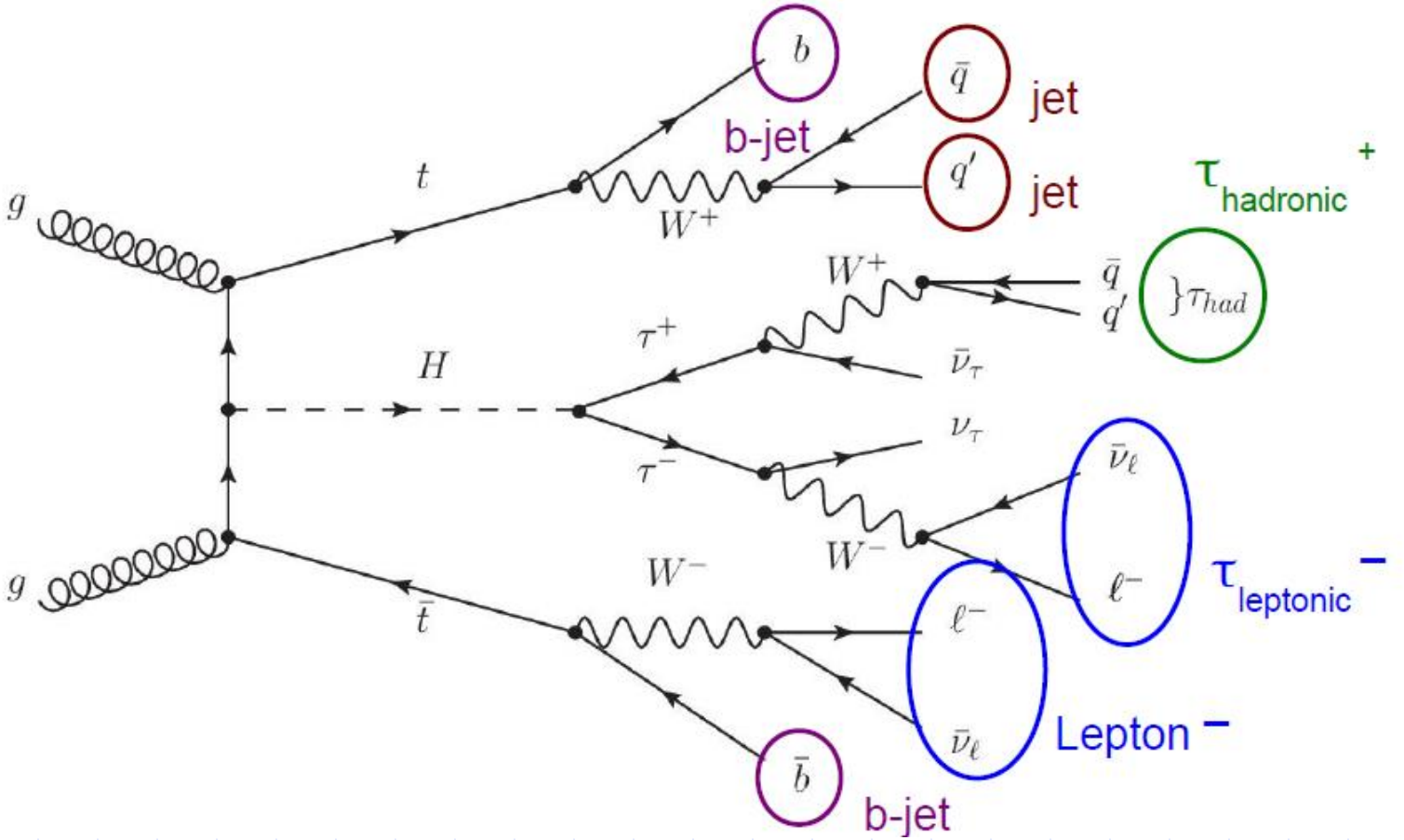
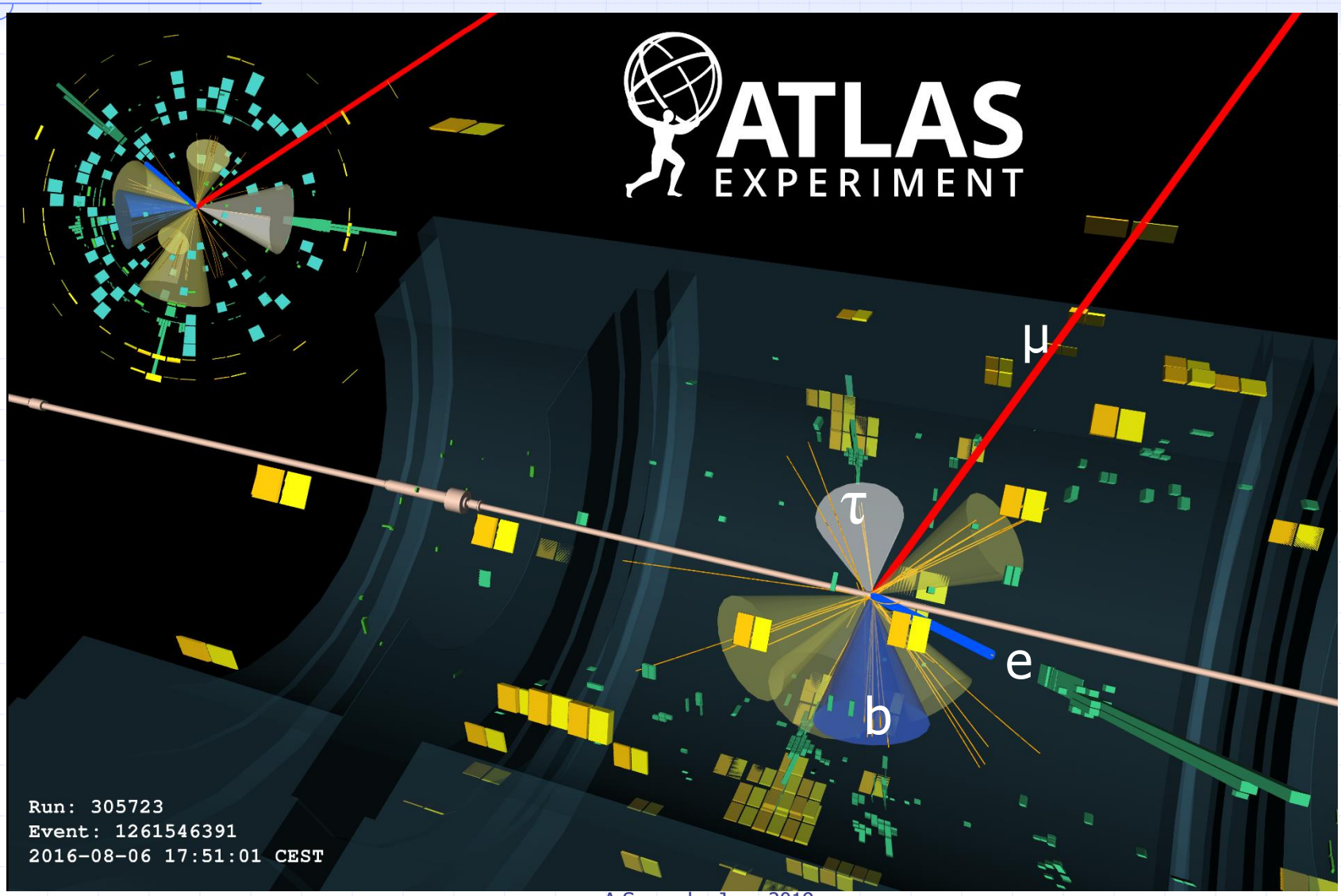


- Main backgrounds: tt and ttV
- Fake background estimate determined from data

ttH candidate (multi-leptons) same-sign e and μ and tau-jet



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PRD 97 (2018) 072003

Higgs boson couplings to fermions
H → tt via ttH direct probe, leptons

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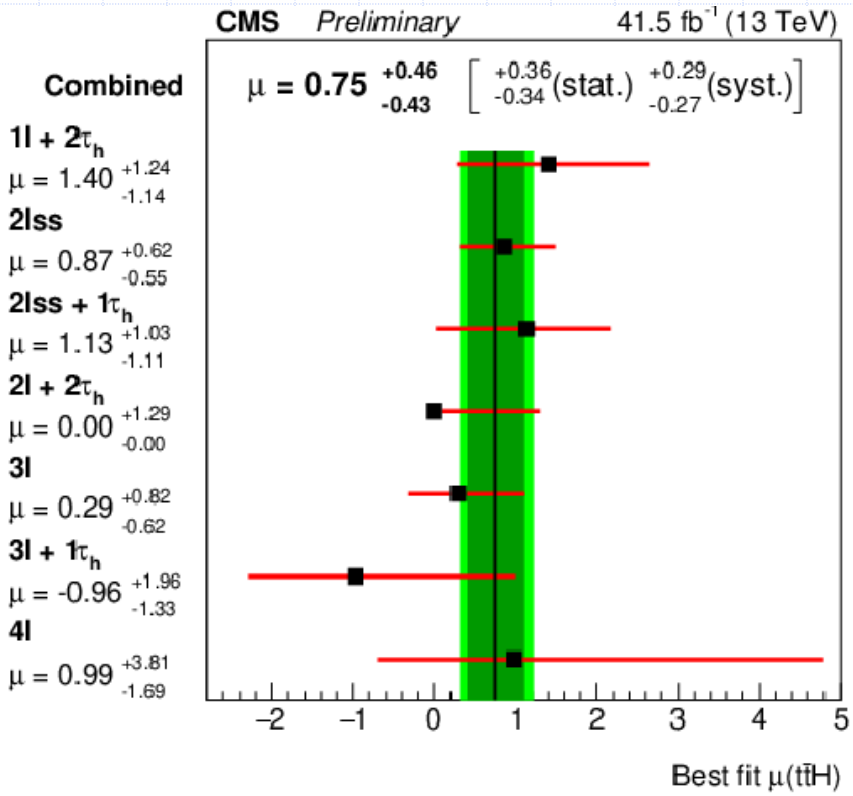
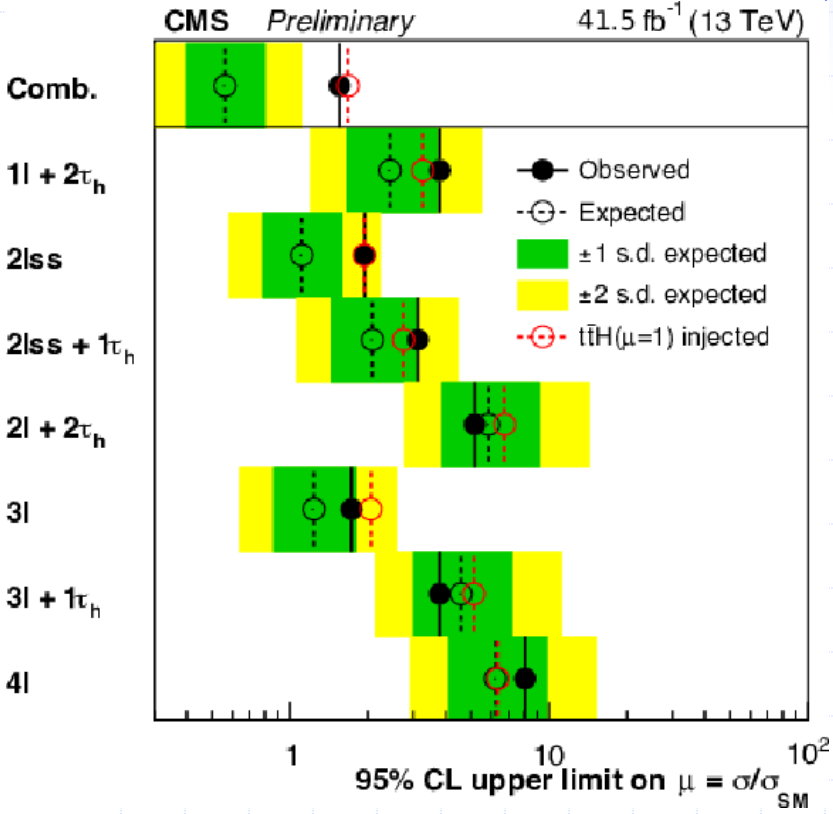
- ttH: multilepton channels with l = e or μ, τ(hadronic decay), CMS-PAS-HIG-18-018
- $\mu = 0.96^{+0.34}_{-0.31}$ $(1.00^{+0.30}_{-0.27})$ for 35.9 fb^{-1} (2016) and 41.5 fb^{-1} (2017) data
- 3.2 (4.0) st.dev.





- ATLAS, PRD 97 (2018) 072003 (36.1 fb^{-1})
- 4.1 (2.8) st.dev. (multileptons)

Higgs boson couplings to fermions
H → tt via ttH direct probe

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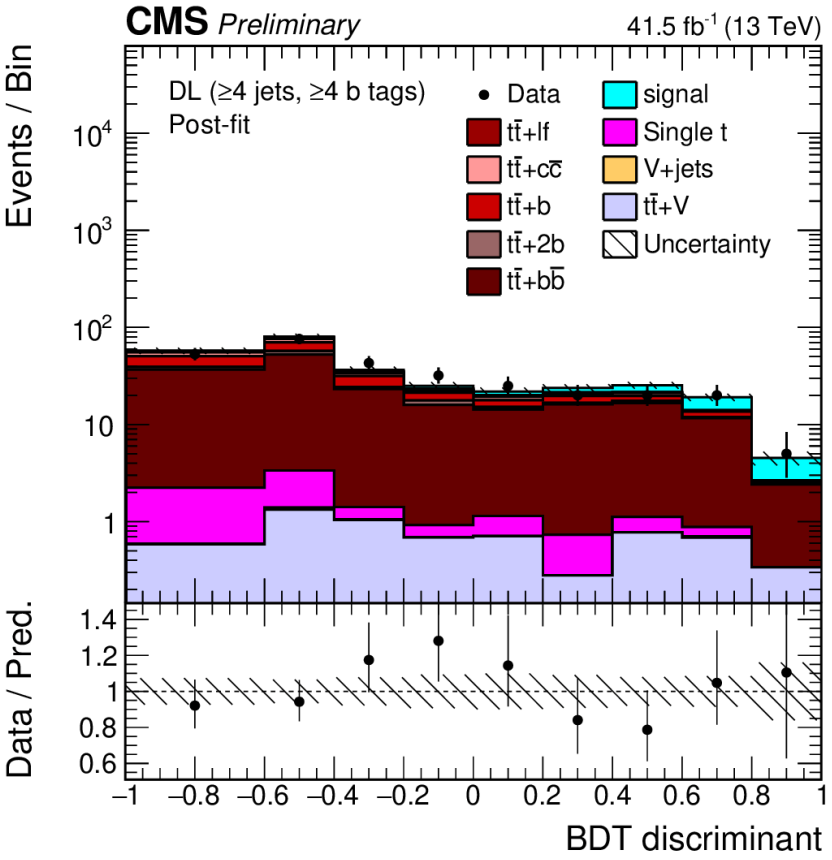
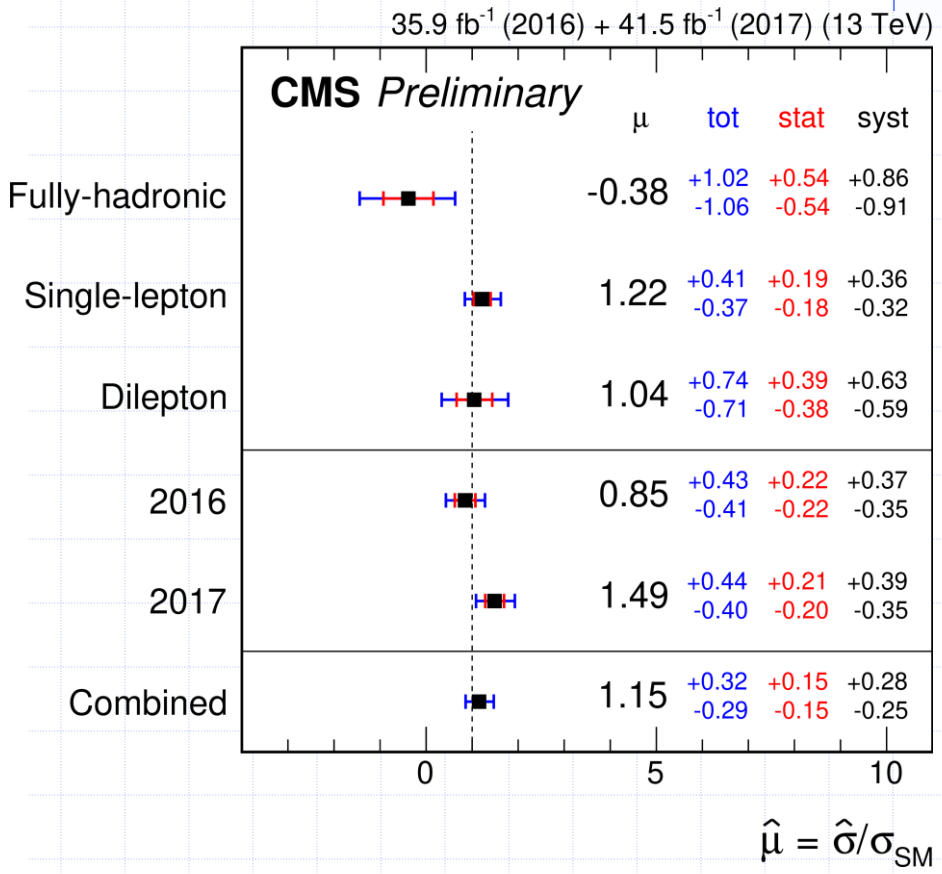
- ttH(H→bb)
- fully hadronic, single-lepton, double-lepton final states
- 3.7 (2.6) st.dev.

CMS-PAS-HIG-18-030





Higgs boson couplings to fermions
H → μμ

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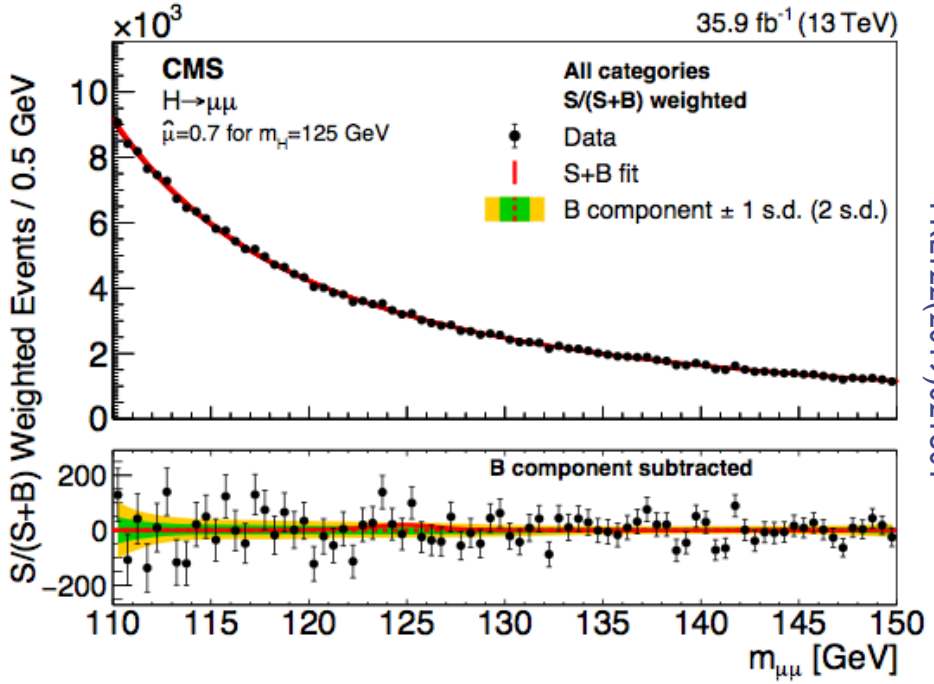
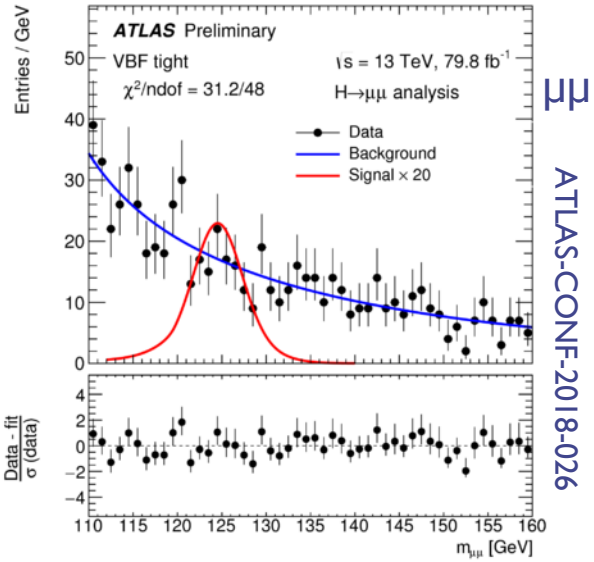
- Standard Model BR(H→μμ): ~0.022%
- Current limits at 95% CL
  on μ = σBR(H→μμ) / σBR(H→μμ)$_{SM}$
  - < 2.1 (2.0) x SM (ATLAS)
  - < 2.9 (2.2) x SM (CMS)

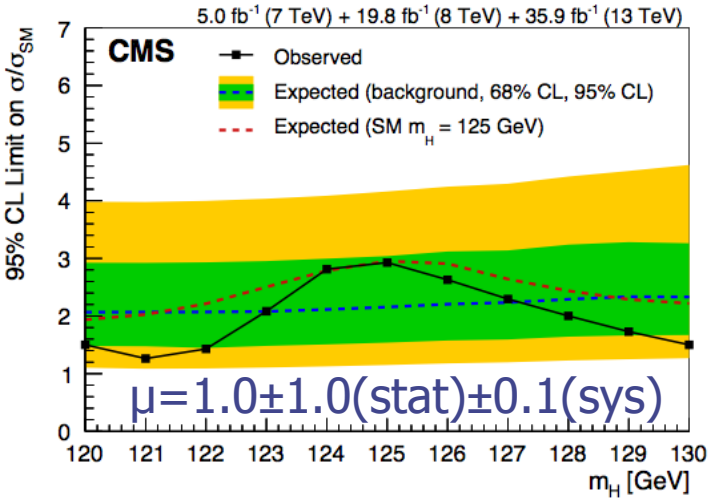


PRL122(2019)021801



μμ

ATLAS-CONF-2018-026



Simplified template cross-sections STXS

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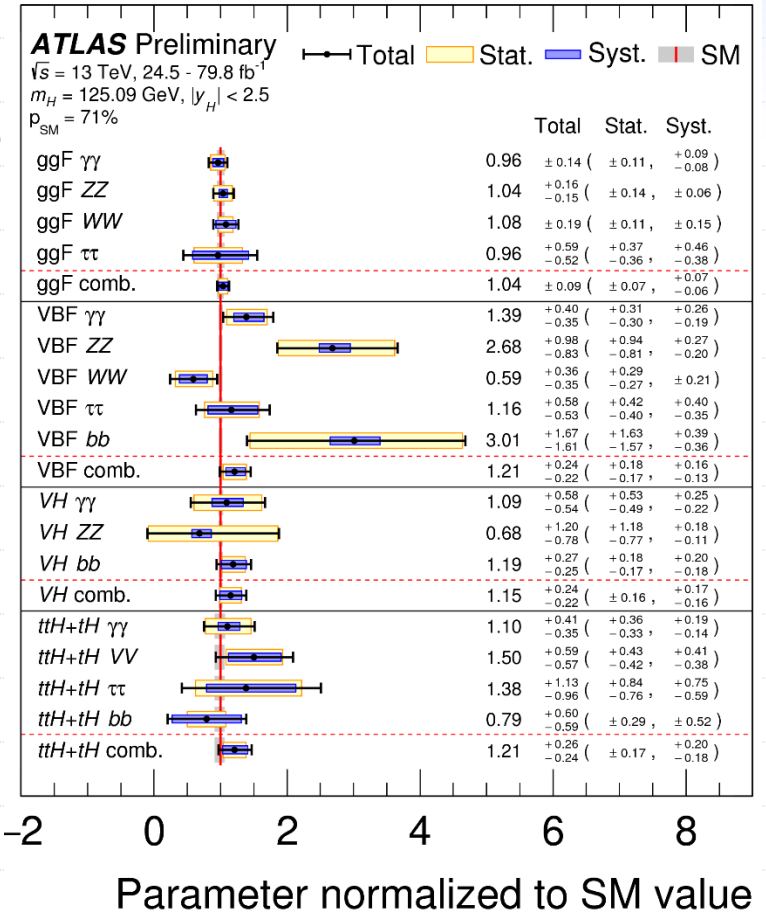
- Proposed at Les Houches'15 (Proceedings) & LHC Higgs cross-section working group
- Common to ATLAS, CMS, and theory. Goals:
  - Measure cross-sections per production modes (ggF, VBF, VH, ttH) in different phase space, signal templates: Pt(H), Pt(V)... reducing model dependency and maximizing sensitivity to BSM effects
  - Combine different decay channels to increase sensitivity
- **Combination of main channels:** STXS stage-1, ATLAS-CONF-2019-005
- STXS: several channels contribute to different kinematic regions of same production mode, e.g., VH dominated by H→bb in high Pt(V), while gg and ZZ* relevant at low Pt(V)
- No significant deviations from SM prediction in any kinematic region: **p-value wrt SM hypothesis 80%**



Simplified template cross-sections STXS

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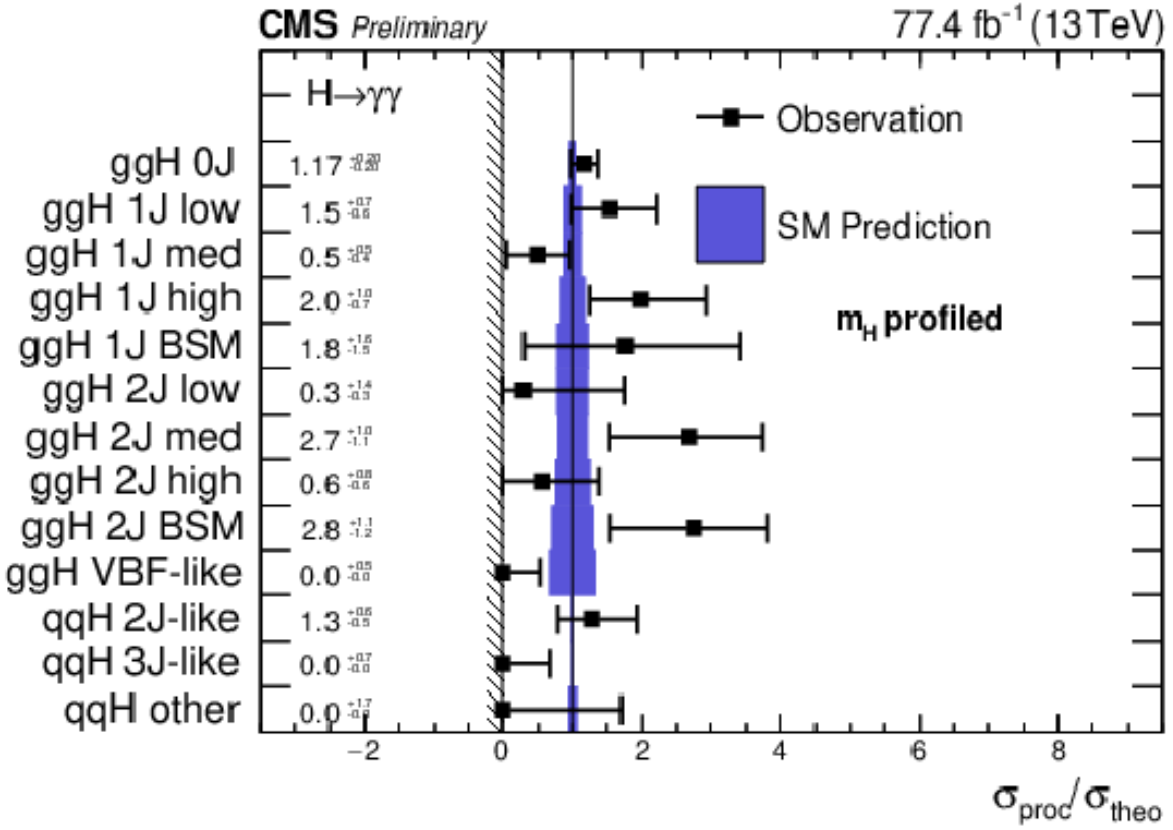
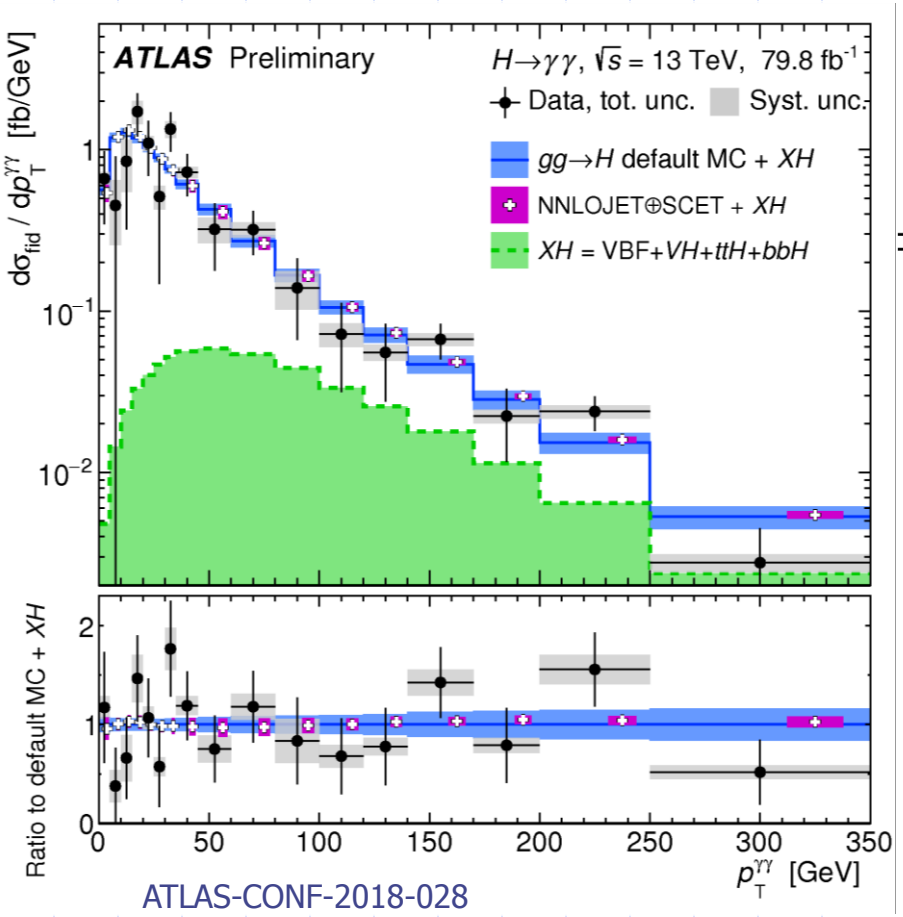
- Experimental selection can be different and use advanced techniques (MVAs)
- Aims to balance experimental precision and theory uncertainties
- Combination of various decay channels with 35.9 fb^{-1}, arXiv:1809.10733
- STXS stage 1: ggH and VBF bins using $H \rightarrow \gamma\gamma$ based on 77.4 fb^{-1}, CMS-PAS-HIG-18-029

- 10 ggH and 3 VBF parameters
- Very good agreement with SM prediction

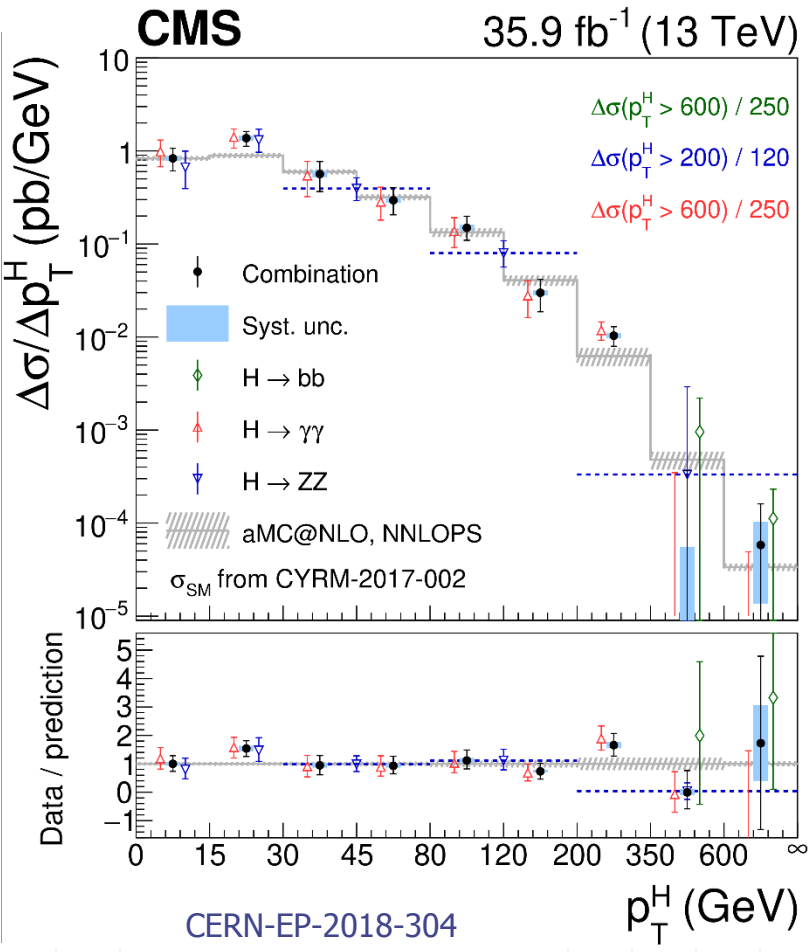


Differential Higgs boson decay cross-sections, Pt(H)

- ATLAS: H→γγ
- CMS: Combined H→γγ, H→ZZ→4l, H→bb



ATLAS-CONF-2018-028



CERN-EP-2018-304

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Rare Higgs boson decays

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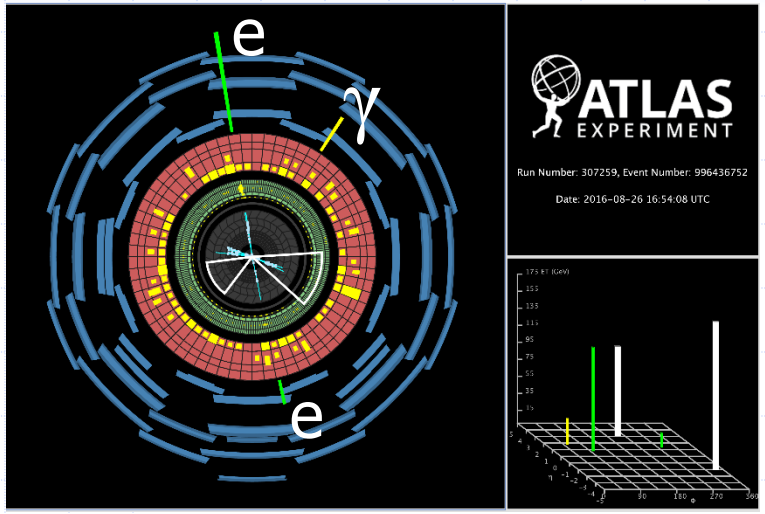
Further SM Higgs boson decay modes can be in reach with growing LHC data sets.
Current limits at 95% CL:

- H→Zγ: < 6.6 (4.4) x SM
- H→cc:
  - < ZH(cc): 110 x SM
  - <J/ψγ: 120 x SM

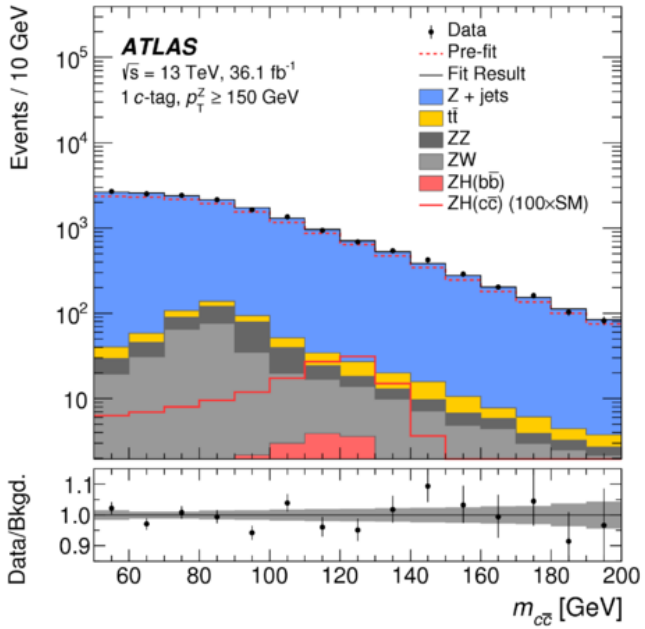


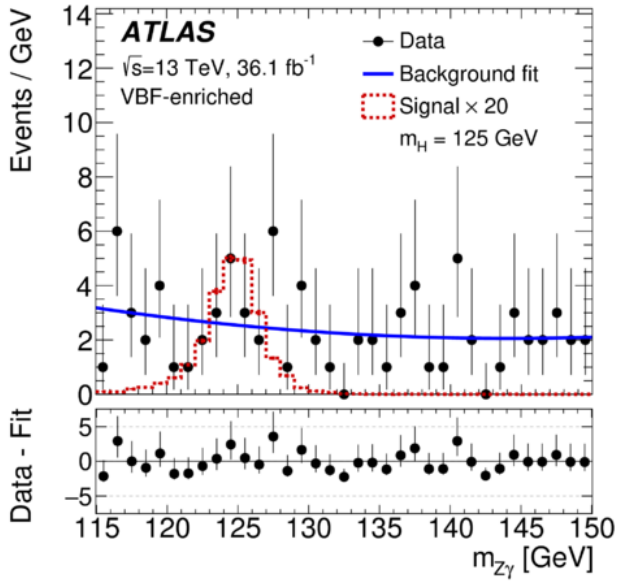
Zγ

JHEP 10 (2017) 112

cc

PRL 120 (2018) 211802





Rare Higgs boson decays

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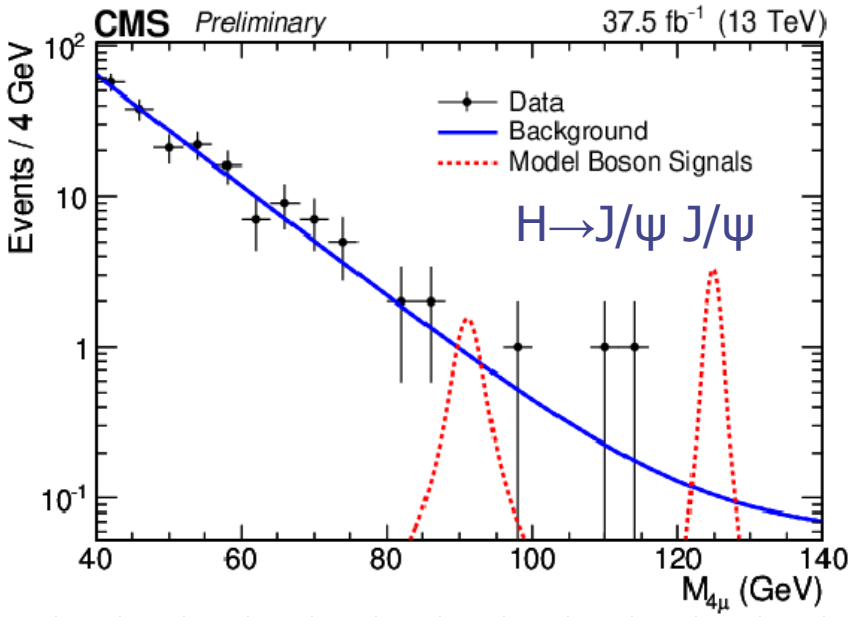
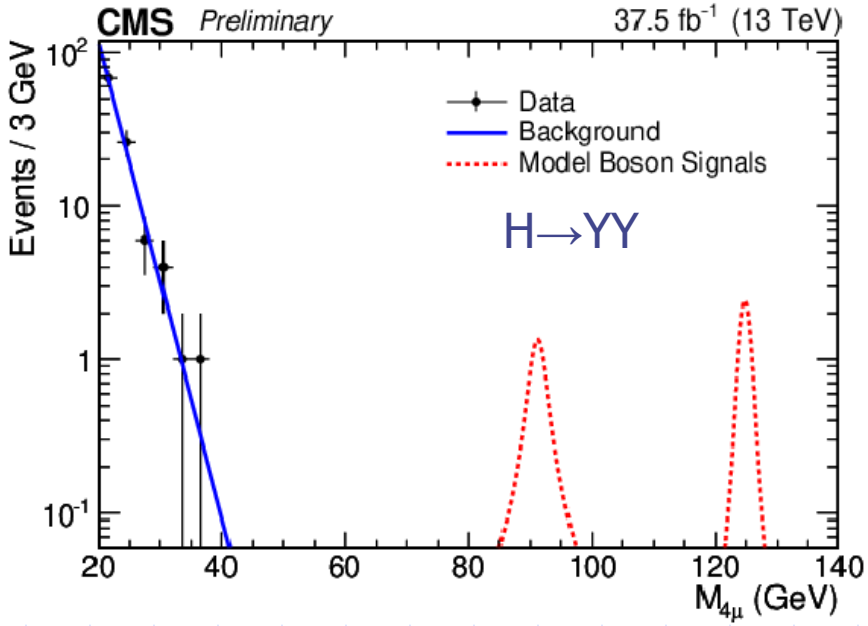
- Four-muon final state experimentally clean with very small SM backgrounds
- Some expected SM branching fractions several orders of magnitude below sensitivity
- Limits at 95% CL:

CMS-PAS-HIG-18-025

	observed	expected
$\mathcal{B}(H \to J/\psi J/\psi) \times 10^3$	1.8	$1.8^{+0.2}_{-0.1}$
$\mathcal{B}(H \to YY) \times 10^3$	1.4	1.4 ± 0.1





Anomalous couplings

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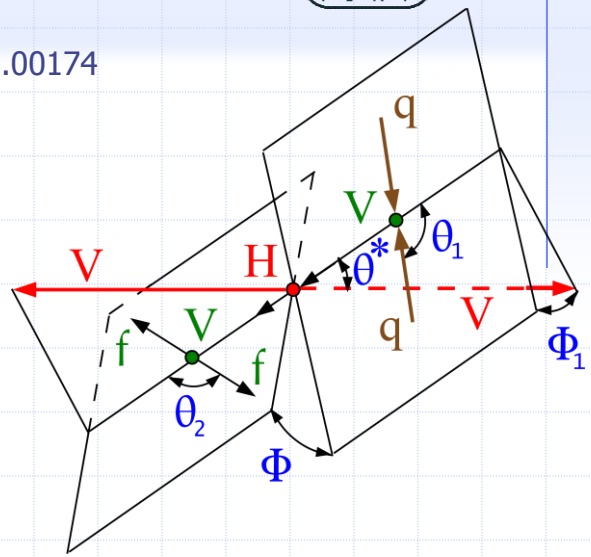
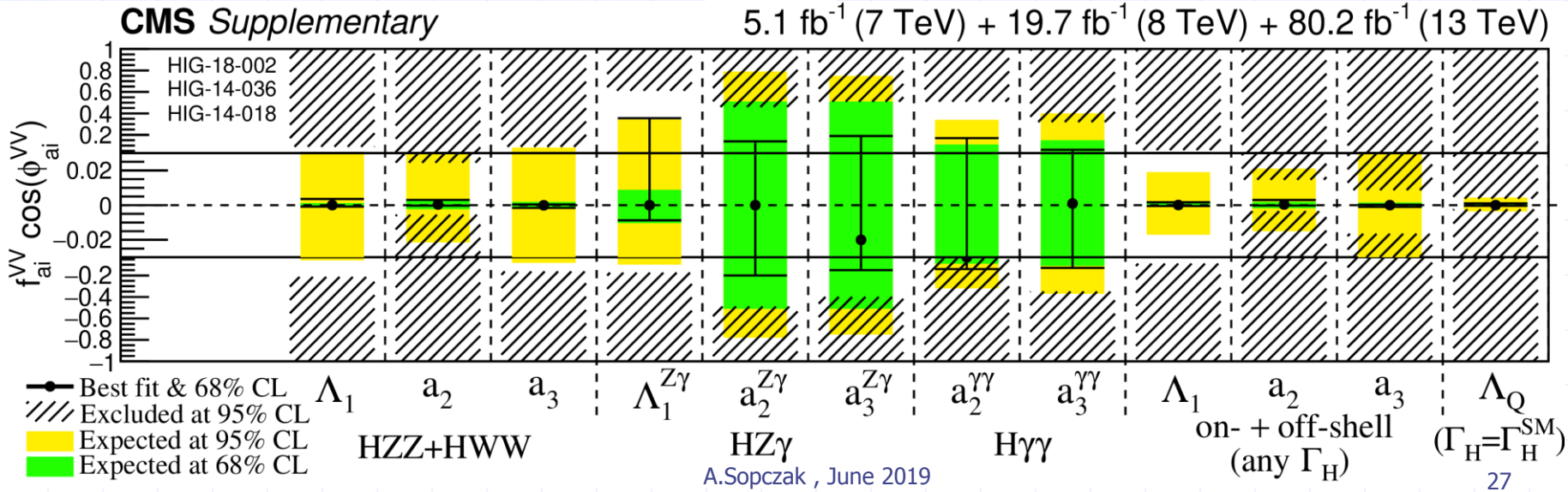
$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{HVV}} + \frac{\kappa_1^{\mathrm{HVV}} q_{V_1}^2 + \kappa_2^{\mathrm{HVV}} q_{V_2}^2}{\left(\Lambda_1^{\mathrm{HVV}}\right)^2} \right] m_{V_1}^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + a_2^{\mathrm{HVV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{HVV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

- a2 : CP-even interaction
- a3 : CP-odd interaction (pure pseudo-scalar)
- Λ_1 : leading momentum expansion

arXiv:1901.00174



Exclusion at 95% CL: sub-percent anomalous couplings in VBF production



Higgs boson decays to invisible particles

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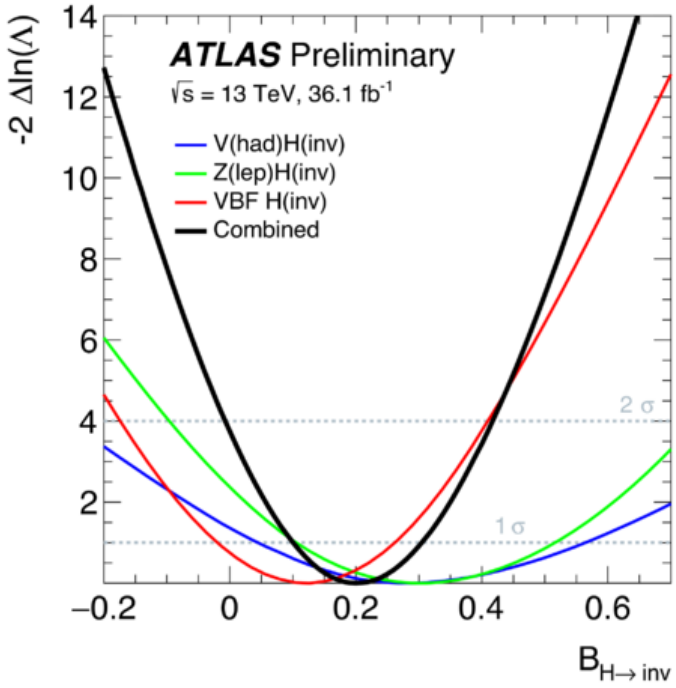
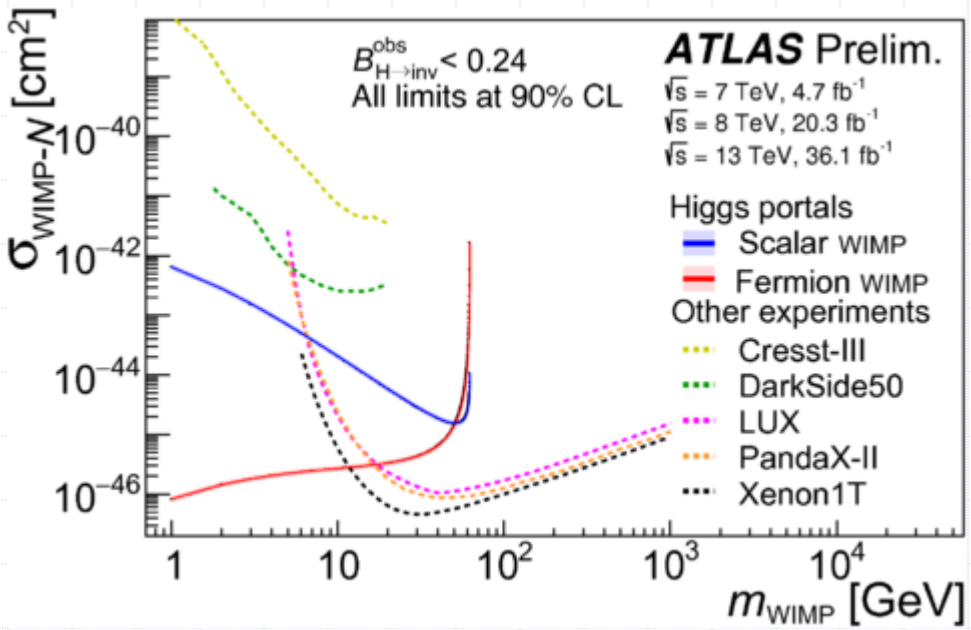
Motivation: Patt, Wilczek, "Higgs-field Portal into Hidden Sectors", arXiv:0605188

- Indirect: constraints from coupling fits
- Direct: searches for Higgs to decays to invisible particles
- Three separate ATLAS searches: V(had)H(inv), Z(lep)H(inv), VBF H(inv)
- B(H→inv) < 0.26 (0.17) at 95% CL, assuming SM production cross-section





ATLAS-CONF-2018-054

Higgs boson decays to invisible particles

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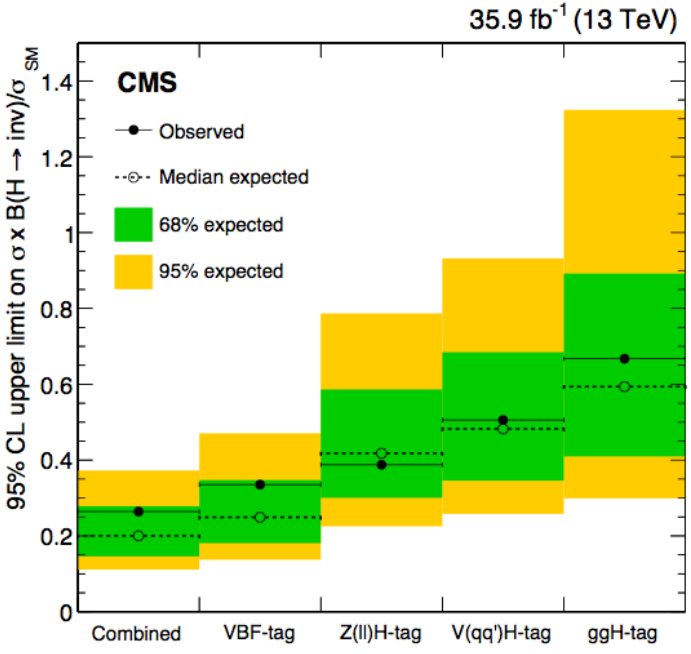
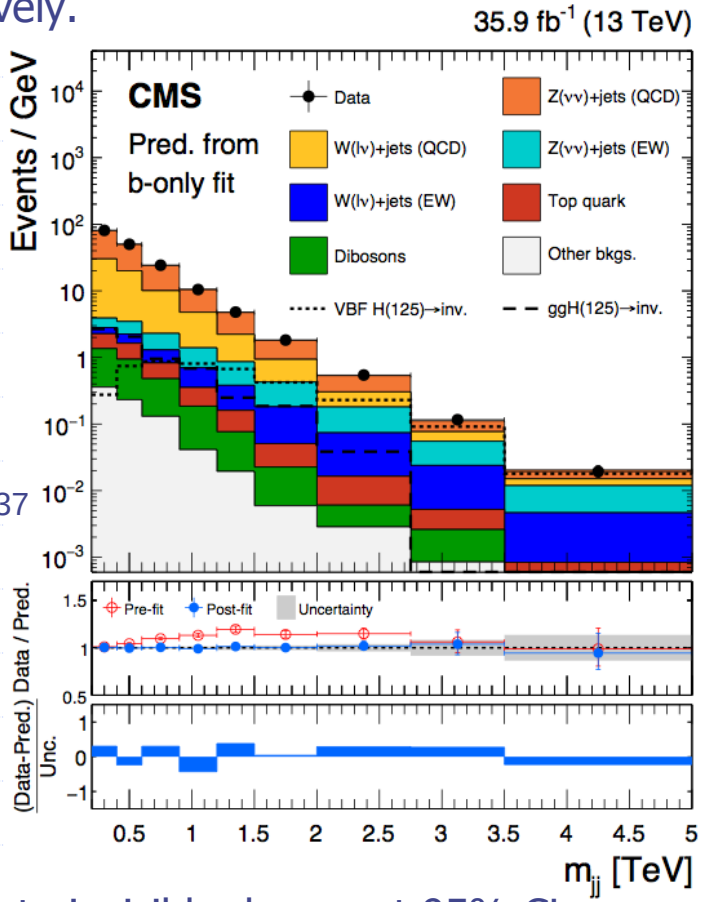
- Dominant backgrounds: Z(νν)+jets and W(ℓν)+jets, extrapolated from 2-lepton sideband, and from 1-lepton sideband, respectively.
- VBF production channel most sensitive
  - 2016 VBF-only: B(H→inv) < 0.33 (0.25)
  - O(25%) improvement in sensitivity by adding VH and ggH channels
  - B(H→inv) < 0.26 (0.20) at 95% CL (13 TeV data)
- B(H→inv) < 0.19 (0.15) using 7,8,13 TeV data



arXiv:1809.05937



- ttH limit to invisible decays at 95% CL
- B(H→inv) < 0.46 (0.48), CMS-PAS-HIG-18-008

ATLAS combination (24.5 to 79.8 fb^{-1})

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	$H\to\gamma\gamma$	$H\to ZZ^*$	$H\to WW^*$	$H\to\tau\tau$	$H\to b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 ℓ + 2 $\tau_{\rm had}$ $t\bar{t}H$ multilepton 2 opposite-sign ℓ + 1 $\tau_{\rm had}$ $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 $\tau_{\rm had}$) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 $\tau_{\rm had}$) $t\bar{t}H$ multilepton 4 ℓ (except $H\to ZZ^*\to 4\ell$) $t\bar{t}H$ leptonic, $H\to ZZ^*\to 4\ell$ $t\bar{t}H$ hadronic, $H\to ZZ^*\to 4\ell$			$t\bar{t}H$ 1 ℓ, boosted $t\bar{t}H$ 1 ℓ, resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH	VH 2 ℓ VH 1 ℓ, $p_{\rm T}^{\ell+E_{\rm T}^{\rm miss}}\geq 150$ GeV VH 1 ℓ, $p_{\rm T}^{\ell+E_{\rm T}^{\rm miss}}<150$ GeV VH $E_{\rm T}^{\rm miss}$, $E_{\rm T}^{\rm miss}\geq 150$ GeV VH $E_{\rm T}^{\rm miss}$, $E_{\rm T}^{\rm miss}<150$ GeV VH+VBF $p_{\rm T}^{j1}\geq 200$ GeV VH hadronic (2 categories)	VH leptonic 0-jet, $p_{\rm T}^{4\ell}\geq 100$ GeV 2-jet, $m_{jj}<120$ GeV			2 ℓ, $75\leq p_{\rm T}^{V}<150$ GeV, $N_{\rm jets}=2$ 2 ℓ, $75\leq p_{\rm T}^{V}<150$ GeV, $N_{\rm jets}\geq 3$ 2 ℓ, $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=2$ 2 ℓ, $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}\geq 3$ 1 ℓ $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=2$ 1 ℓ $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=3$ 0 ℓ, $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=2$ 0 ℓ, $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=3$
VBF	VBF, $p_{\rm T}^{\gamma\gamma jj}\geq 25$ GeV (2 categories) VBF, $p_{\rm T}^{\gamma\gamma jj}<25$ GeV (2 categories)	2-jet VBF, $p_{\rm T}^{j1}\geq 200$ GeV 2-jet VBF, $p_{\rm T}^{j1}<200$ GeV	2-jet VBF	VBF $p_{\rm T}^{\tau\tau}>140$ GeV ($\tau_{\rm had}\tau_{\rm had}$ only) VBF high-m_{jj} VBF low-m_{jj}	VBF, two central jets VBF, four central jets VBF +γ
ggF	2-jet, $p_{\rm T}^{\gamma\gamma}\geq 200$ GeV 2-jet, 120 GeV $\leq p_{\rm T}^{\gamma\gamma}$¡200 GeV 2-jet, 60 GeV $\leq p_{\rm T}^{\gamma\gamma}$¡120 GeV 2-jet, $p_{\rm T}^{\gamma\gamma}<60$ GeV 1-jet, $p_{\rm T}^{\gamma\gamma}\geq 200$ GeV 1-jet, 120 GeV $\leq p_{\rm T}^{\gamma\gamma}$¡200 GeV 1-jet, 60 GeV $\leq p_{\rm T}^{\gamma\gamma}$¡120 GeV 1-jet, $p_{\rm T}^{\gamma\gamma}<60$ GeV 0-jet (2 categories)	1-jet, $p_{\rm T}^{4\ell}\geq 120$ GeV 1-jet, 60 GeV$\leq p_{\rm T}^{4\ell}$¡120 GeV 1-jet, $p_{\rm T}^{4\ell}<60$ GeV 0-jet, $p_{\rm T}^{4\ell}<100$ GeV	1-jet, $m_{\ell\ell}<30$ GeV, $p_{\rm T}^{\ell_2}<20$ GeV 1-jet, $m_{\ell\ell}<30$ GeV, $p_{\rm T}^{\ell_2}\geq 20$ GeV 1-jet, $m_{\ell\ell}\geq 30$ GeV, $p_{\rm T}^{\ell_2}<20$ GeV 1-jet, $m_{\ell\ell}\geq 30$ GeV, $p_{\rm T}^{\ell_2}\geq 20$ GeV 0-jet, $m_{\ell\ell}<30$ GeV, $p_{\rm T}^{\ell_2}<20$ GeV 0-jet, $m_{\ell\ell}<30$ GeV, $p_{\rm T}^{\ell_2}\geq 20$ GeV 0-jet, $m_{\ell\ell}\geq 30$ GeV, $p_{\rm T}^{\ell_2}<20$ GeV 0-jet, $m_{\ell\ell}\geq 30$ GeV, $p_{\rm T}^{\ell_2}\geq 20$ GeV	Boosted, $p_{\rm T}^{\tau\tau}>140$ GeV Boosted, $p_{\rm T}^{\tau\tau}\leq 140$ GeV	

$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.})\,^{+0.03}_{-0.03}\,(\text{bkg. th.})$$

ATLAS-CONF-2019-005

Higgs boson production modes ggF, VBF, VH and ttH established

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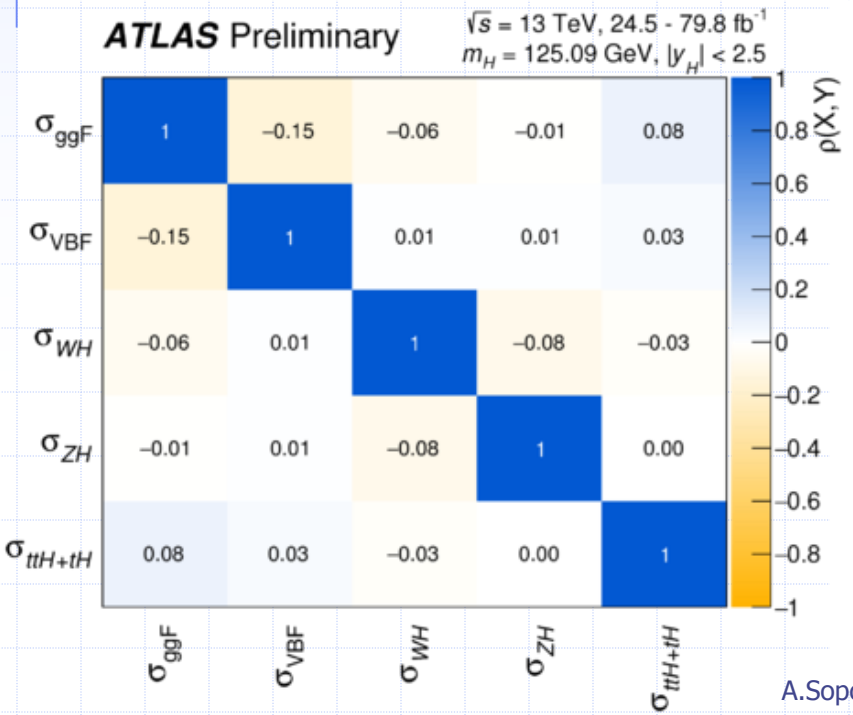
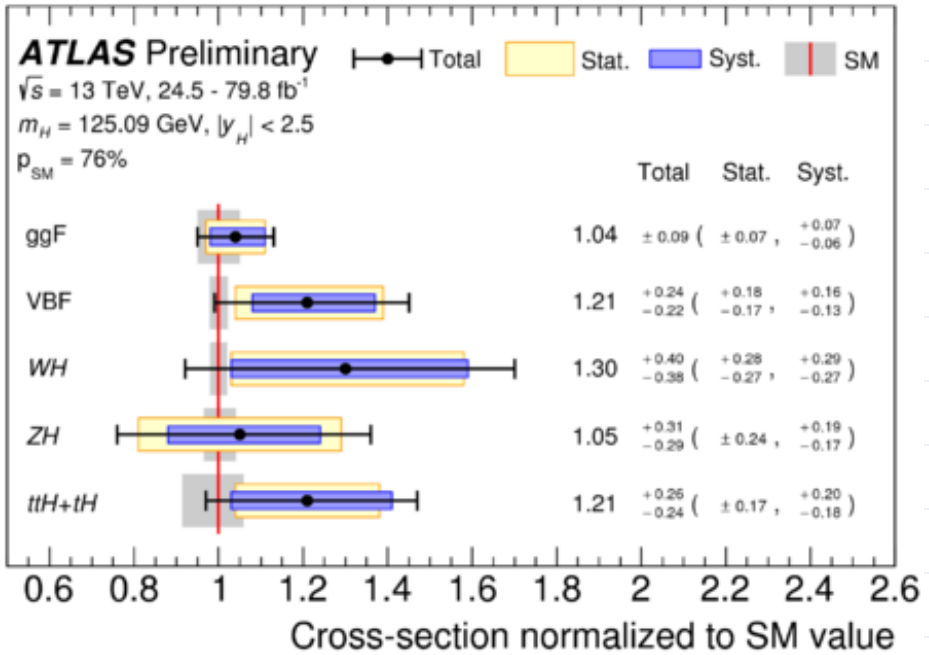
- Observations (>5 st.dev., σ), ATLAS-CONF-2019-005 (79.8 fb^{-1})
  ggF,
  VBF (6.5σ),
  VH (5.3σ), and
  ttH (5.8σ)
  Higgs boson production modes, assuming SM branching ratios
- Low correlations between production modes
- Results consistent with Standard Model expectations

CMS combination
CERN-EP-2018-263 (35.9 fb^{-1})



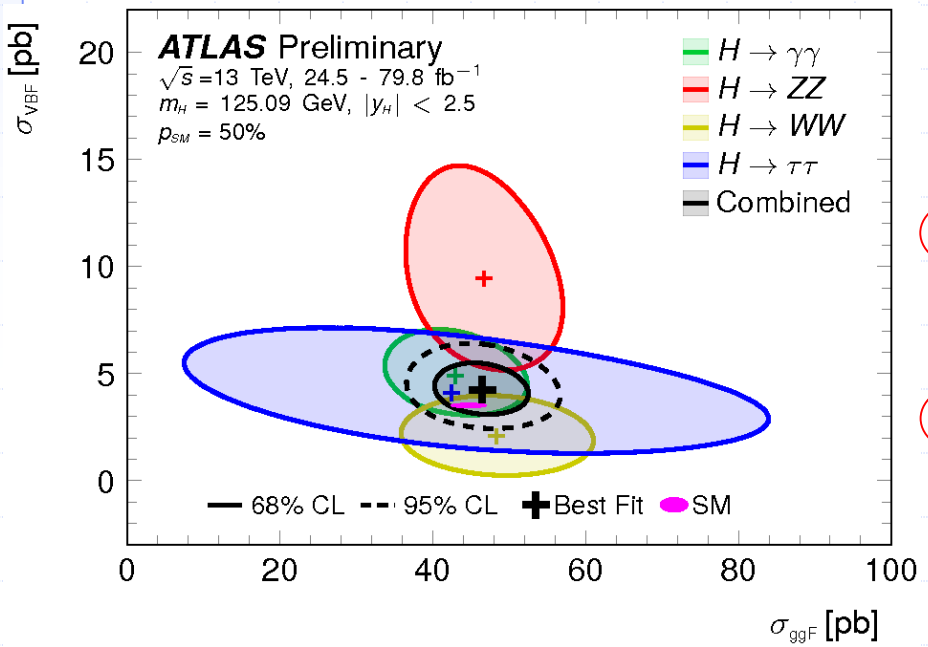


Higgs boson production modes

ATLAS-CONF-2019-005

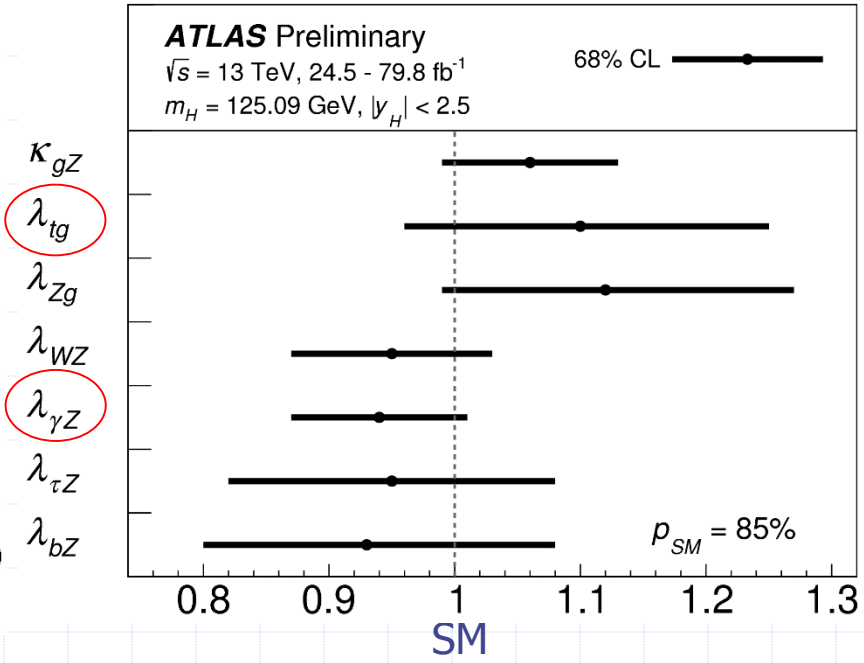
Cross-section:

- VBF versus ggF
- Individual and combined decays
- Agreement with SM expectation



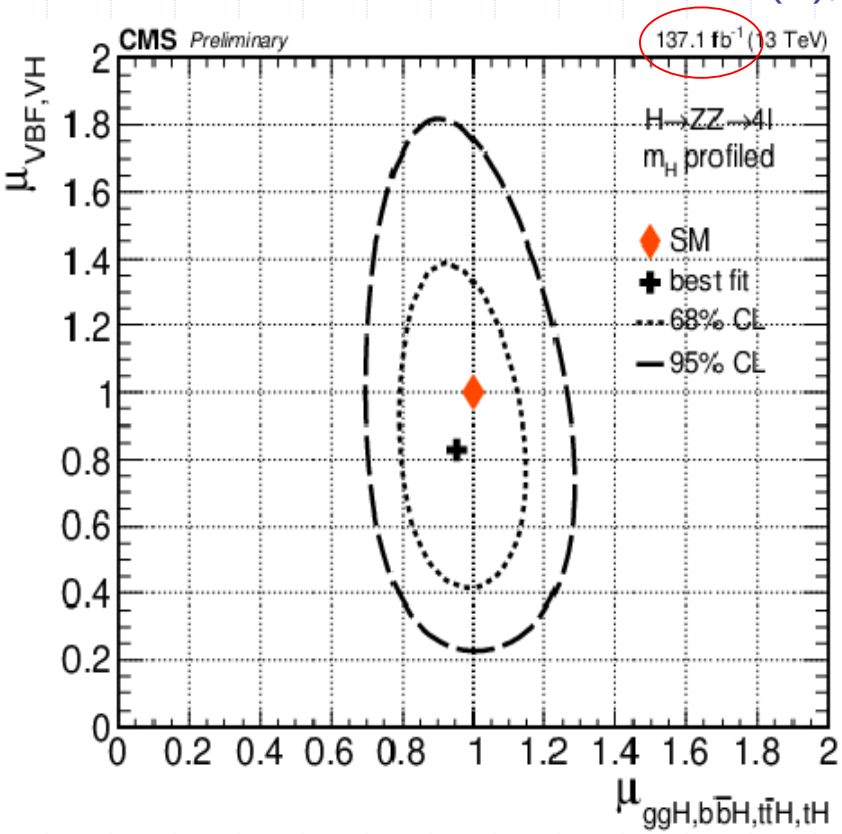
Generic parameterization:

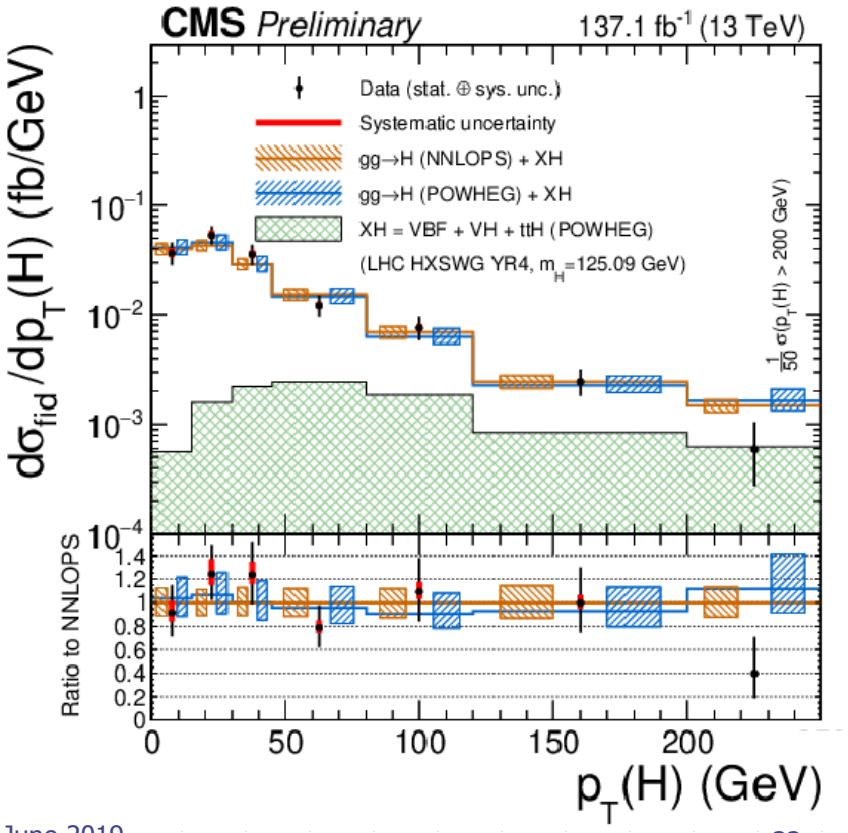
- Measured couplings wrt SM
- λ_{tg} contributing through ggF loop as compared to ttH
- $\lambda_{\gamma Z}$ contributing H → γγ loop as compared to H → ZZ decays
- Agreement with SM expectation



Higgs boson production

- 137 fb^{-1}, CMS-PAS-HIG-19-001
- H→ZZ→4ℓ channel (ℓ = e or μ)
- Measurement: $\sigma = 2.73^{+0.23}_{-0.22}$ (stat) $^{+0.24}_{-0.19}$ (syst) fb
- SM: 2.76 ± 0.14 fb
- Differential cross-sections versus Pt(H), H rapidity and number of jets





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Single top and Higgs boson production tH

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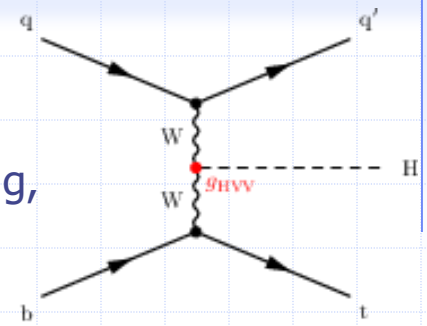
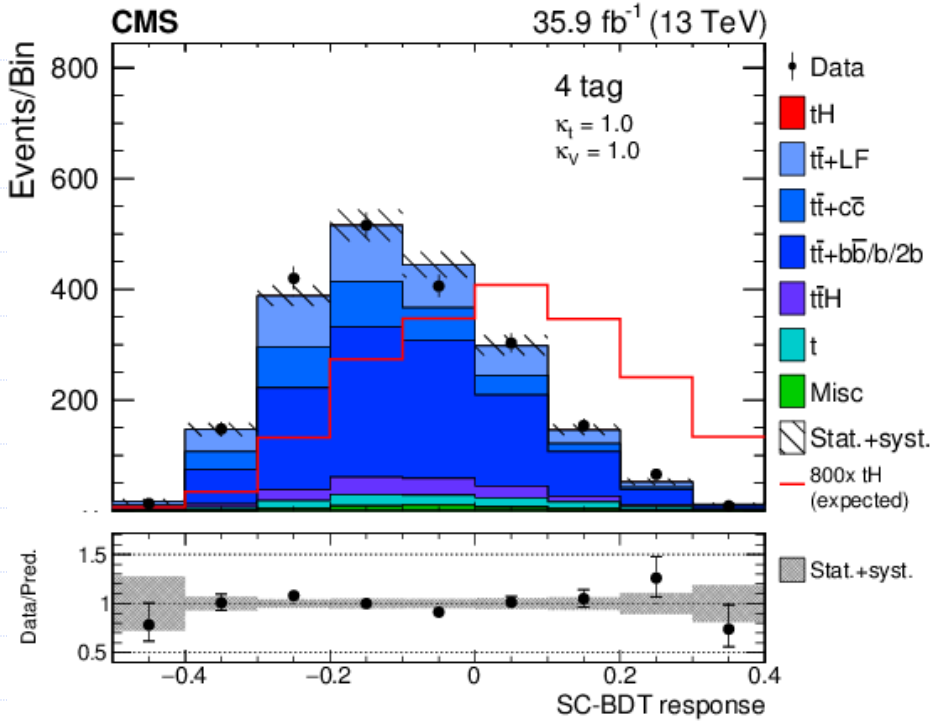
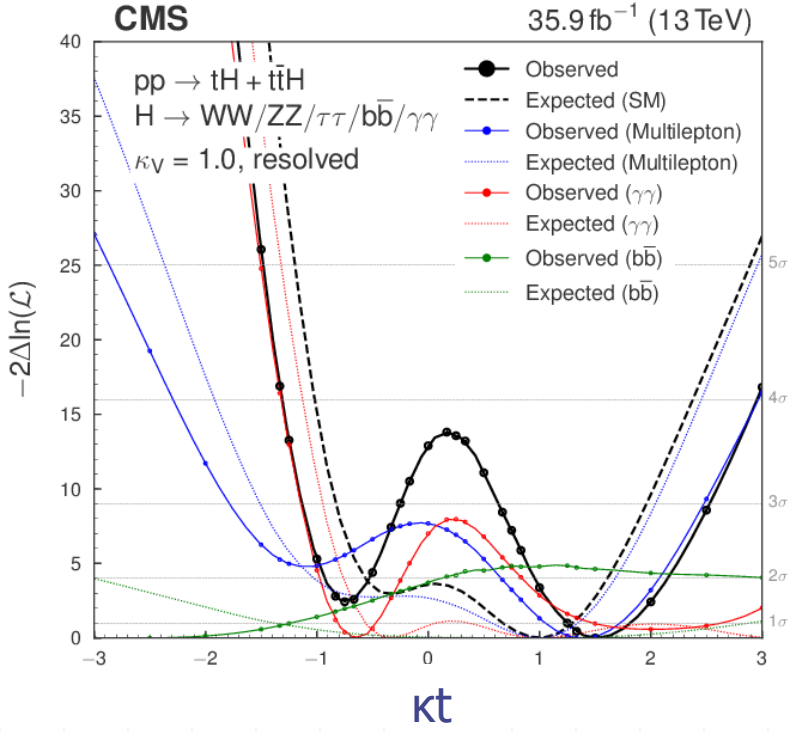
- tH, H → WW/ZZ/ττ and H → bb
- Combination with ttH, H → γγ
- Sensitive to the absolute values if the top quark Yukawa coupling, the Higgs boson coupling to vector bosons, gHVV, and, uniquely, to their relative sign
- SM-like signal favours a κt = 1.0 over κt = −1.0 by > 1.5 st.dev.

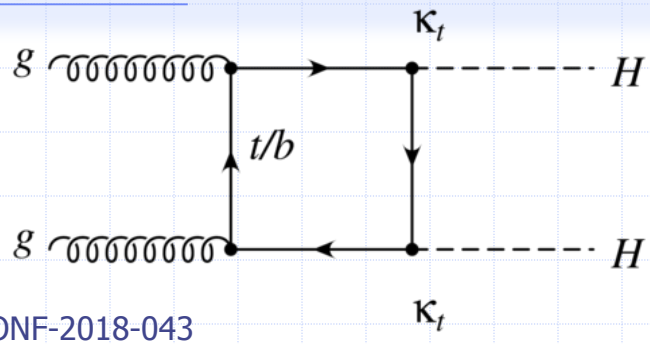
arXiv:1811.09696



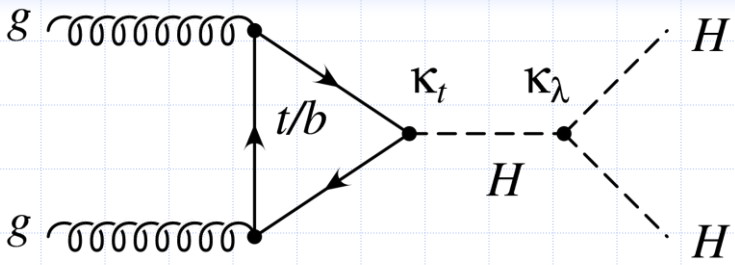




Higgs boson pair-production HH

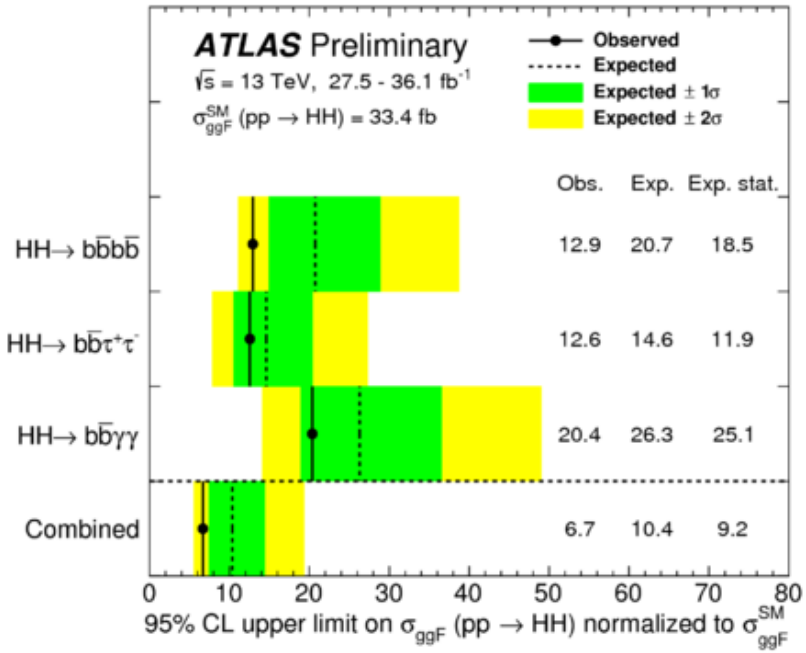


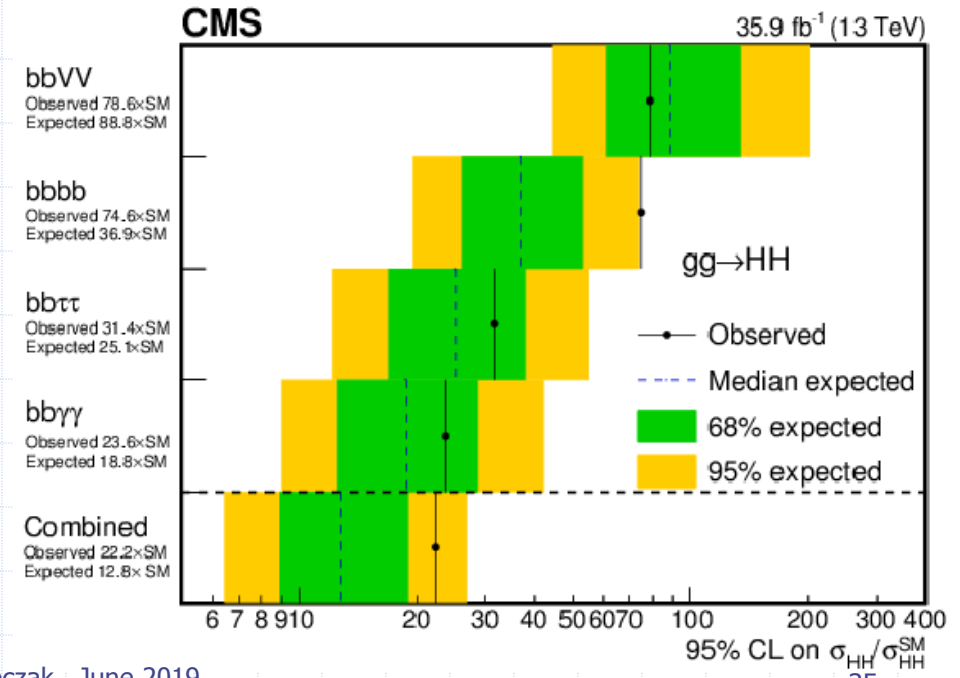
ATLAS-CONF-2018-043



CMS-HIG-17-030

- ATLAS: HH → bbbb, bbττ, bbγγ
  < 6.7 (10.4) x SM at 95% CL
- CMS: HH → bbVV, bbbb, bbττ, bbγγ
  < 22.2 (12.8) x SM at 95% CL





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Relation of coupling and fermion mass

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Interpretation of results in the κ framework as a function of the particle mass, assuming no BSM contributions to the total width

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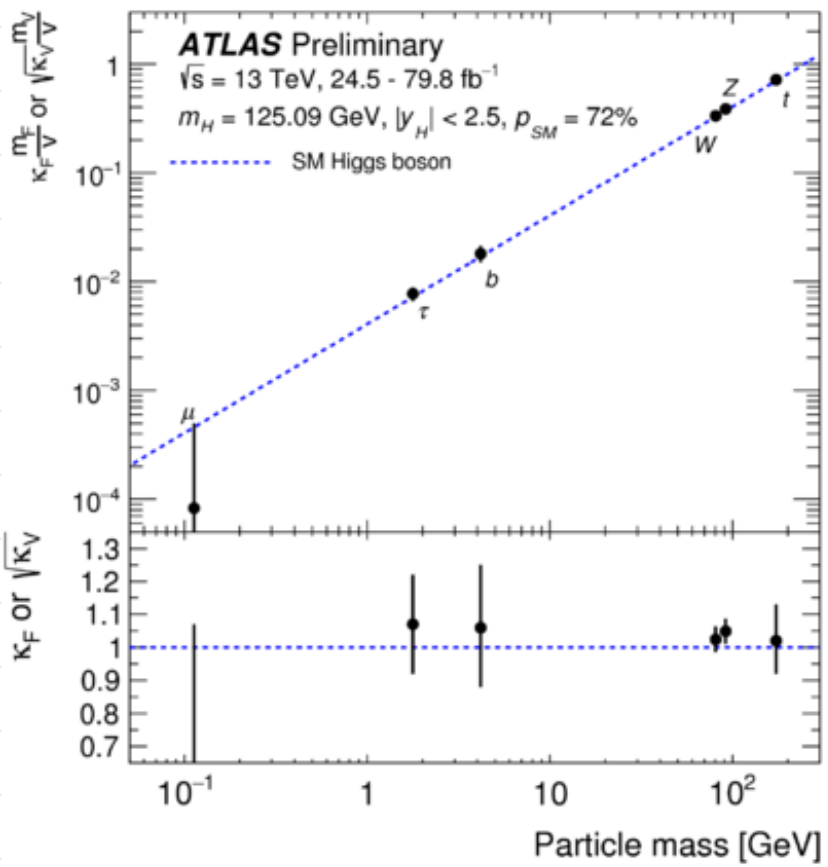

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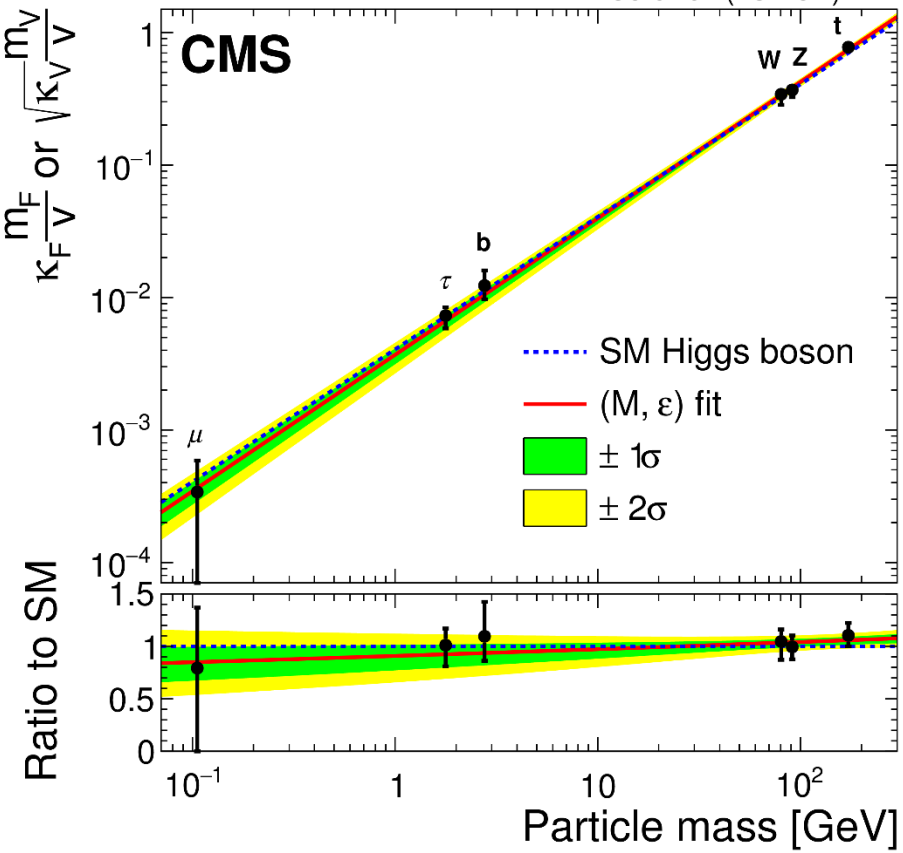
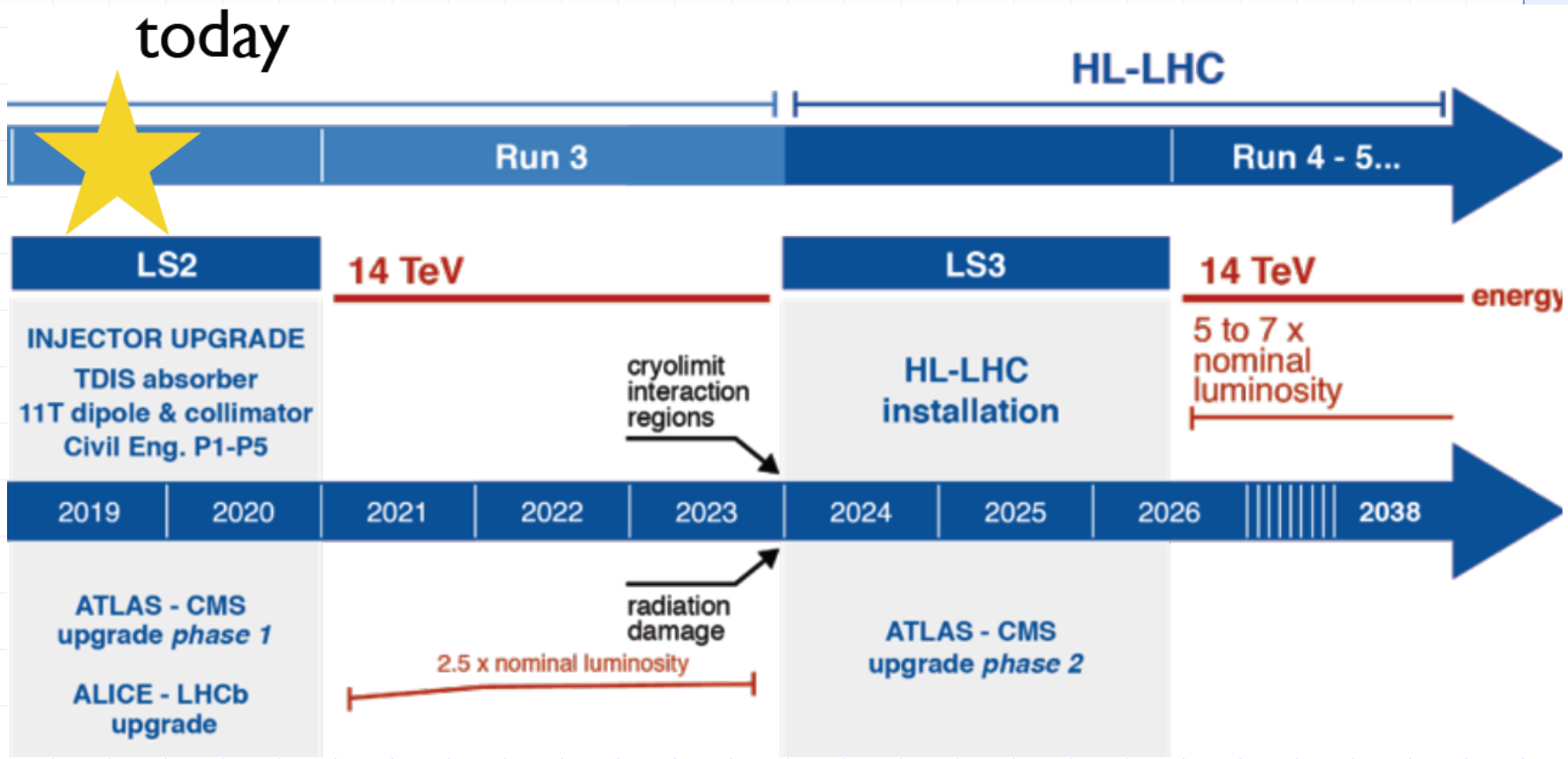


Outlook



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Conclusions – Highlights of Higgs physics

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- Very successful **LHC Run-2 operation**
- Observation of the coupling **Higgs to tau leptons**
- Observation of the coupling **Higgs to bottom quarks**
- Observation of the coupling **Higgs to top quarks**
- Approaching sensitivity to the coupling **Higgs to muon leptons**
- Most inclusive measurements established, **focus on differential measurements**
- Combination with observations of **all main LHC Higgs production modes**
- So far, all Higgs boson properties in **excellent agreement with SM expectations**

Outlook

- Some analyses already with complete **LHC Run-2 data set (~140 fb^{-1})**
- Potential to **understand data more in detail** and increase measurement precisions
- **Combination of ATLAS and CMS results**: increase of sensitivities
- LHC Run-3 anticipated to add 300 fb^{-1} (2021 to 2023),
  HL-LHC approved for 3000 fb^{-1} (2026 -): **new eras of measurement precision**
- **Strong and approved LHC programme for new discoveries**

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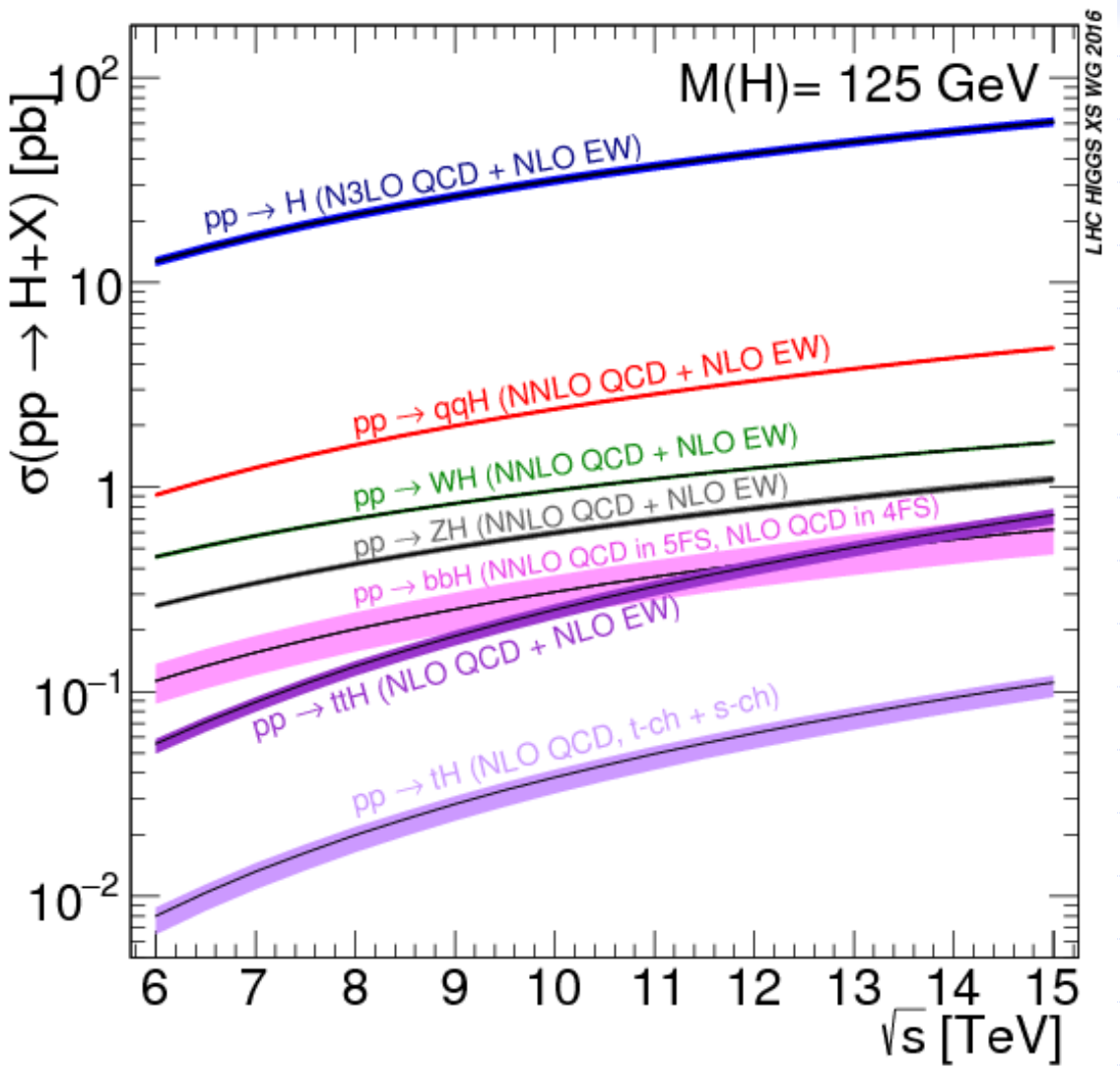
Supplements

Higgs boson production modes at LHC



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Analyses and their luminosities used in ATLAS combination

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Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	79.8
VBF, $H \to b\bar{b}$	24.5 – 30.6
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$H \to$ invisible	36.1
Off-shell $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$	36.1

ATLAS Combination Systematics

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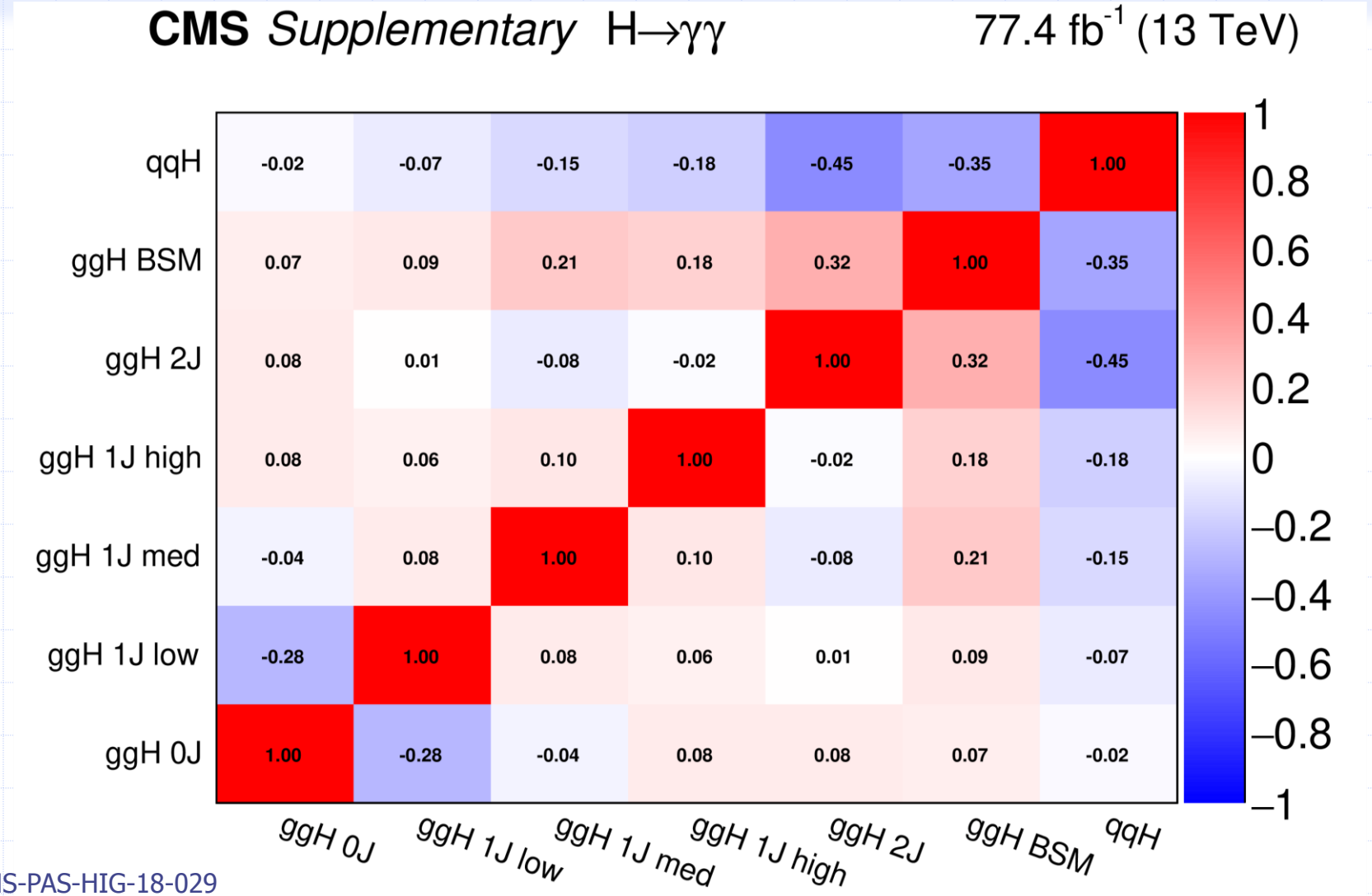
Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

CMS
Correlations STXS framework



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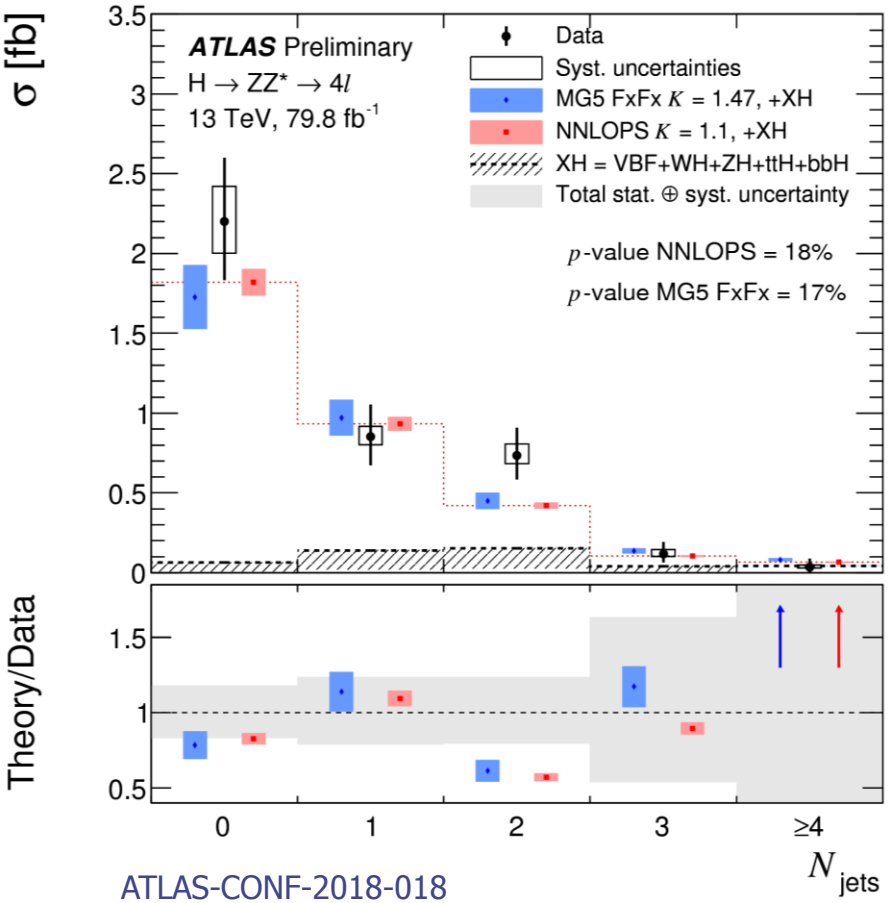
Differential Higgs boson decay cross-sections, N_{jets}

- ATLAS: H→ZZ→4l
- CMS: Combined H→γγ, H→ZZ→4l, H→bb



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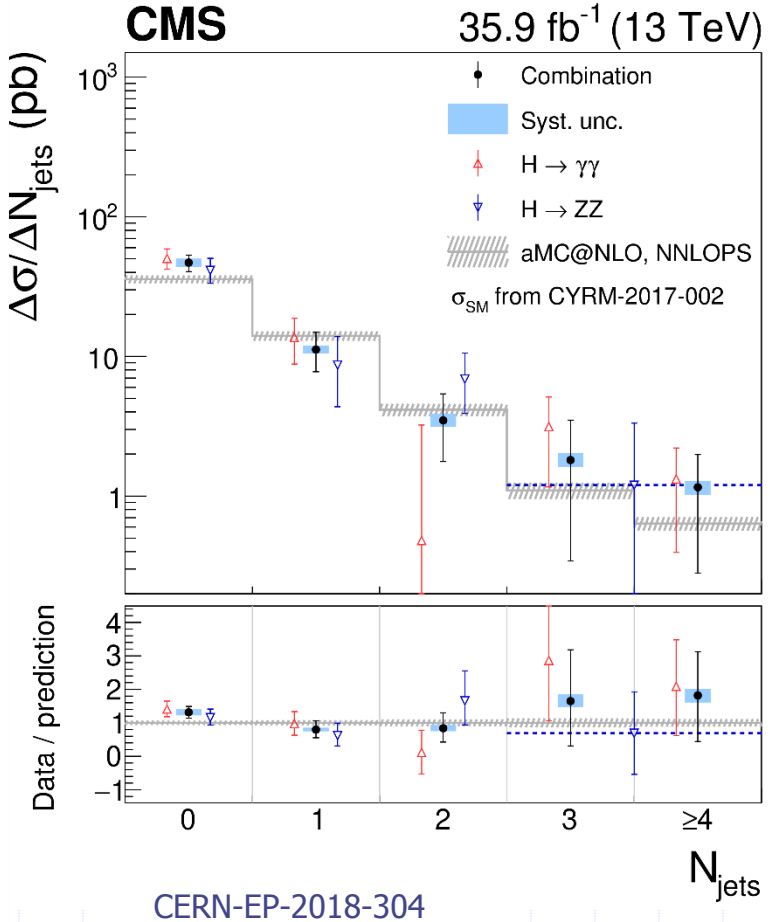

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