ICNFP *2020*

SEPTEMBER 4TH, 2020

The Higgs boson at the *LHC*

Sebastián Olivares (Universidad de Tarapacá)

on behalf of the ATLAS and CMS Collaborations

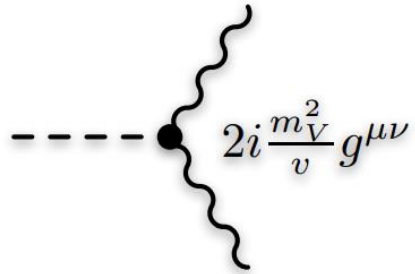
The standard model Higgs boson

The Higgs boson is part of the **23 free parameters** of the standard model (SM)

$$\mathcal{L}_{SM,H} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H) - \left(y_{ij} H \bar{\psi}_i \psi_j + h.c.\right)$$

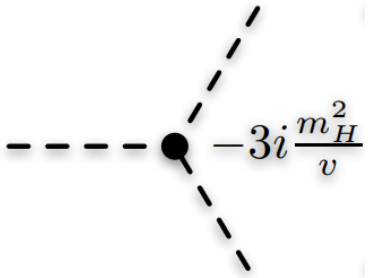
Couplings to vector bosons

$$\left[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_{\mu 0}\right] \cdot \left(1 + \frac{h}{v}\right)^2$$



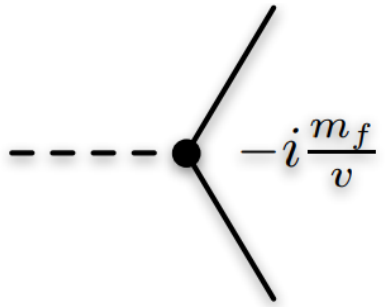
Higgs self-couplings (triple Higgs)

$$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$$



Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



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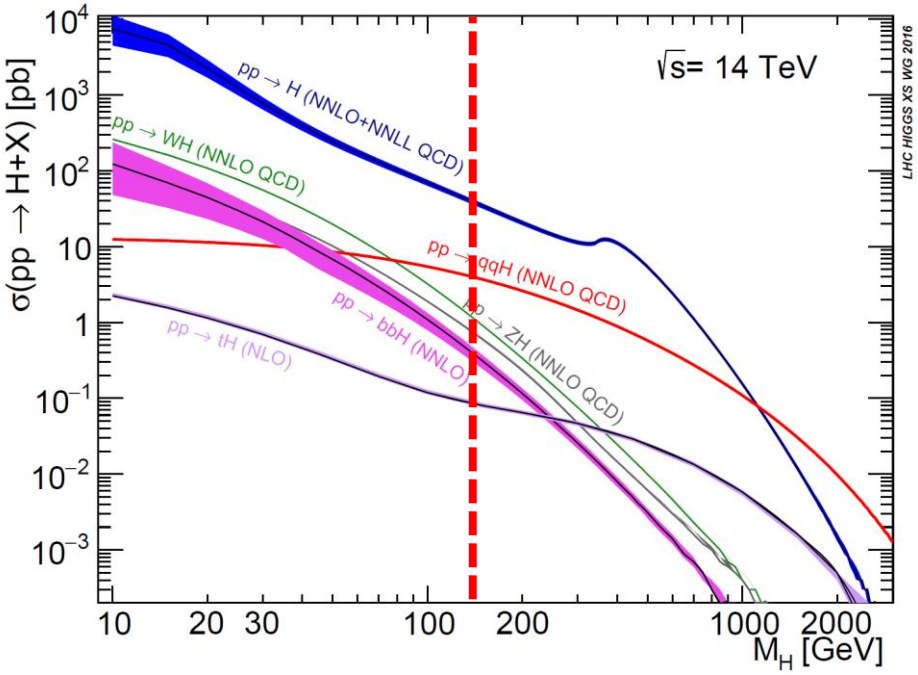


Fixing Higgs parameters

Higgs sector → 3 free parameters

» 1983: W/Z bosons discovery (**2 free parameters**)

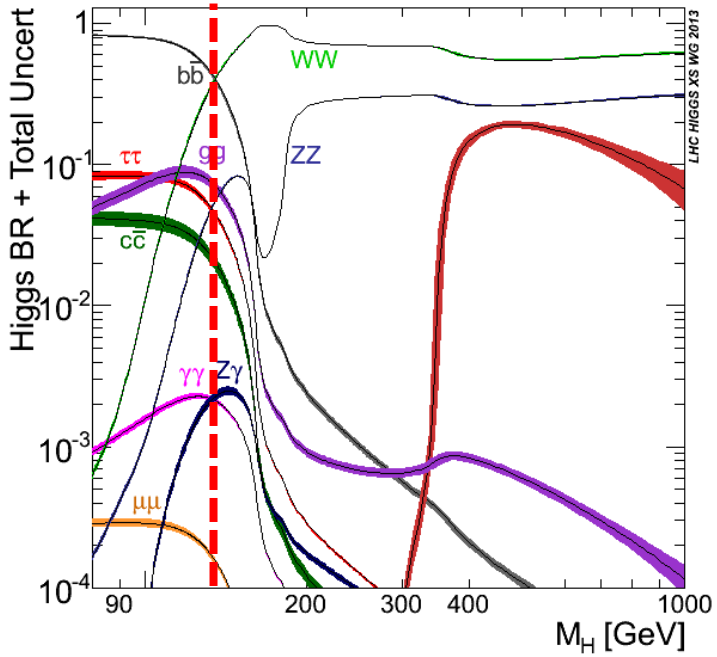
$$\lambda = \frac{\kappa}{v^2} = \frac{m_h^2}{2v^2} \qquad v = \frac{g}{2m_W} = 246\ GeV$$

precision: 0.02 %

» 2012: Higgs boson discovery (**all parameters fixed**)

$$m_h = 125.09\ GeV \qquad \lambda = 0.129$$

precision: 0.2 %



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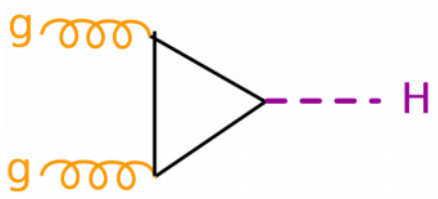
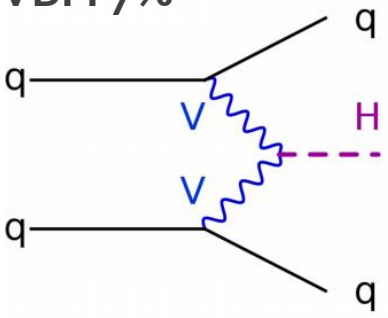
Production (13 TeV)

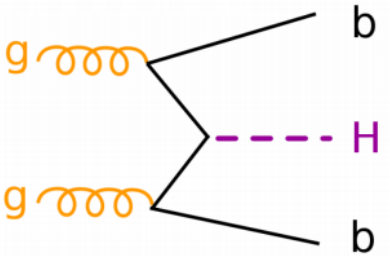
ggF: 87%



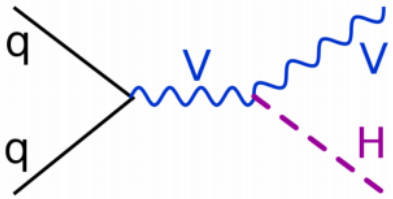
VBF: 7%



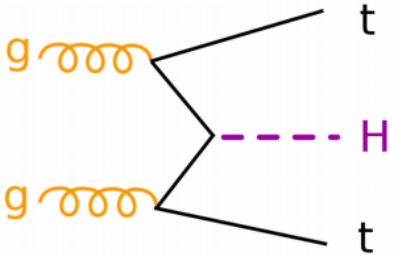
bbH: 1%



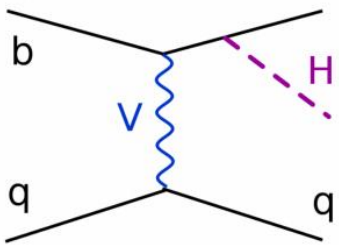
VH: 4%



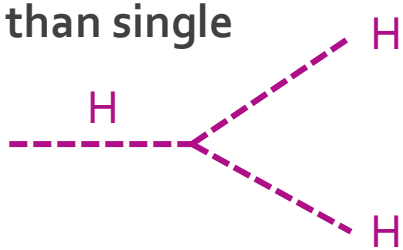
ttH: 1%



tH: 0.1%



HH: ~10^3 smaller than single



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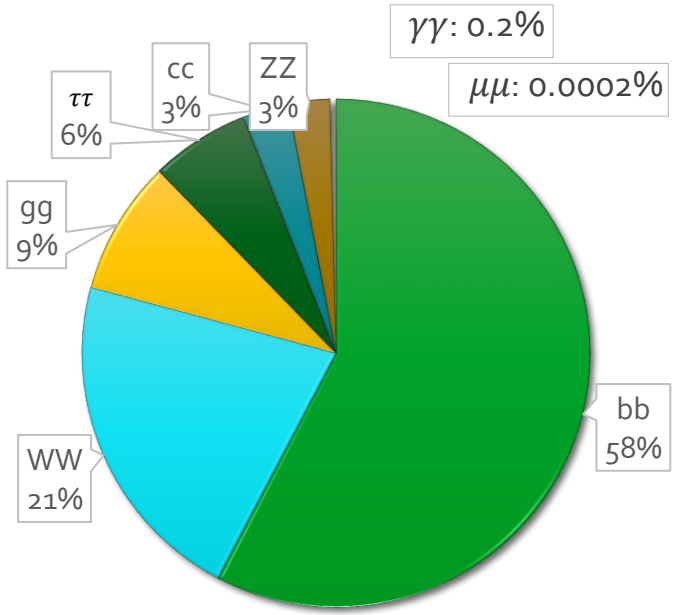
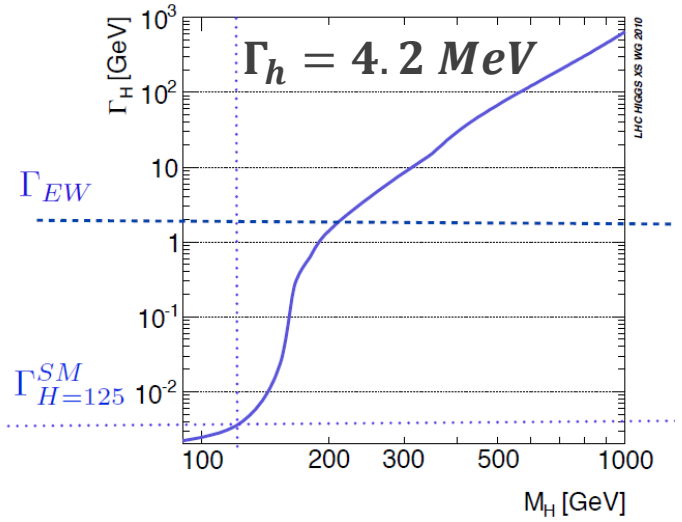
Decay

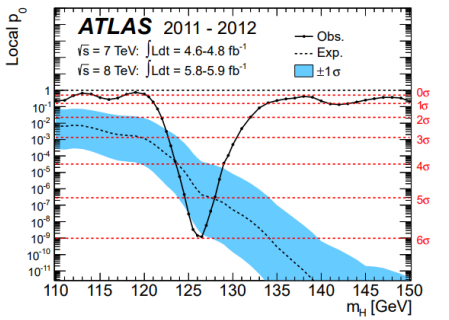


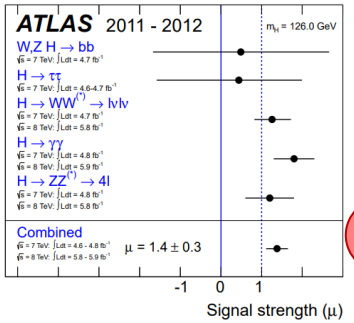


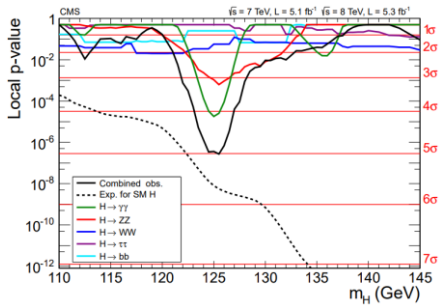
The Higgs boson at the LHC

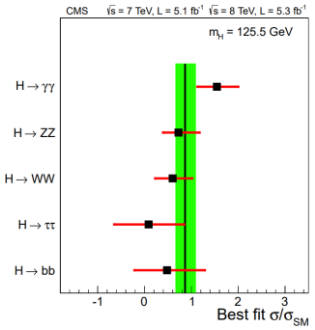
July 2012: Discovery

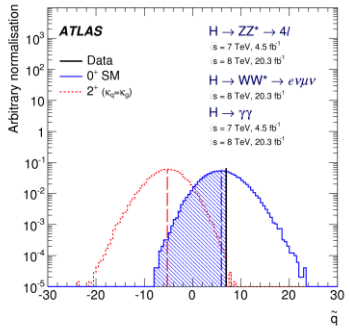
Run-2

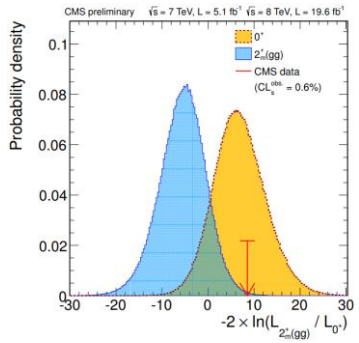




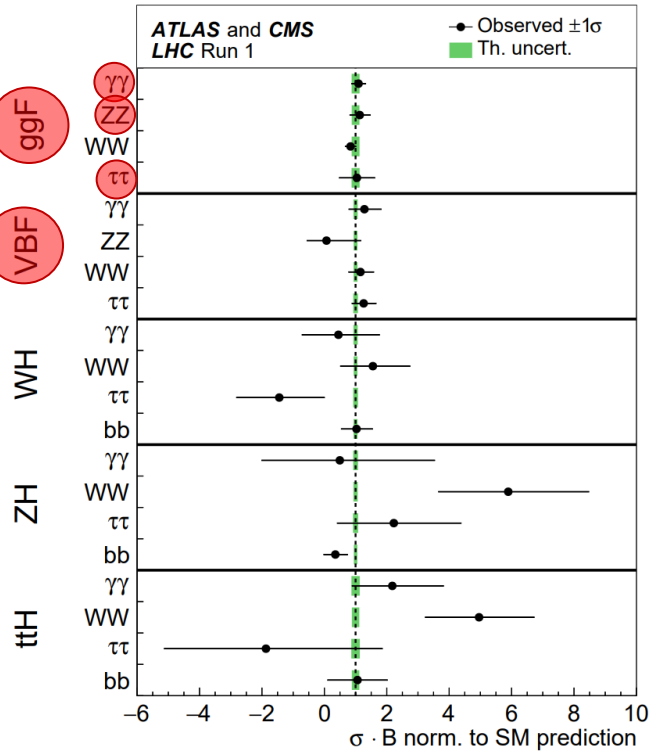




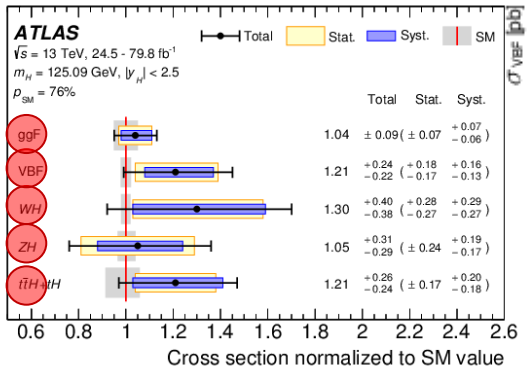


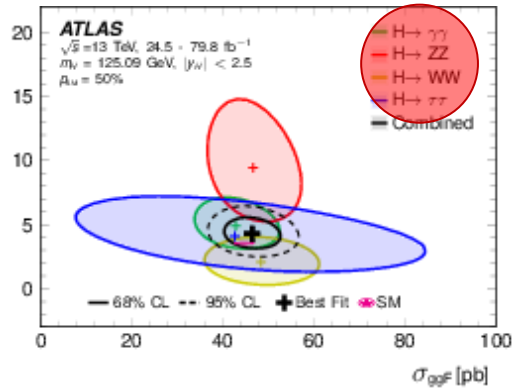


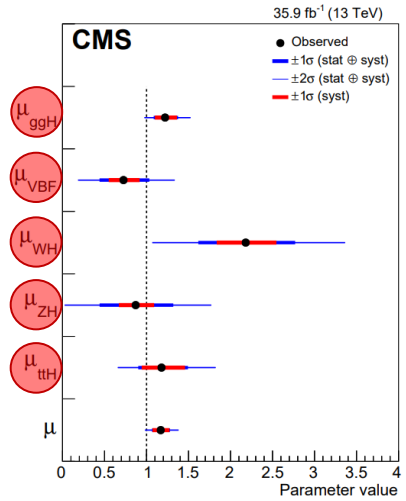
End of Run-1

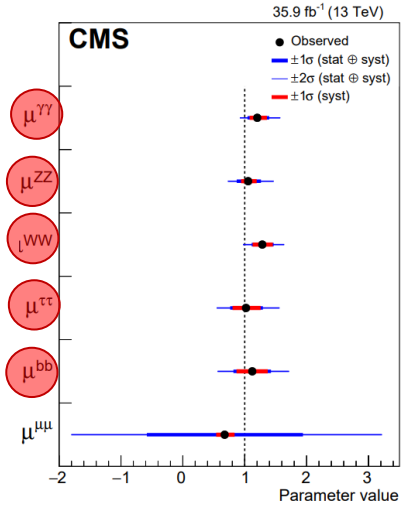


observed









ICNFP 2020

The Higgs boson at the LHC

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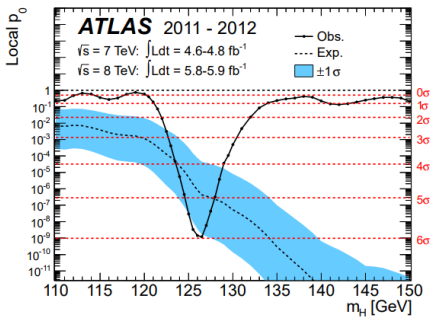
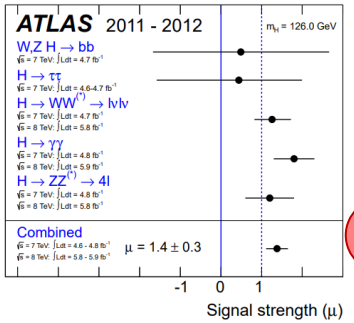
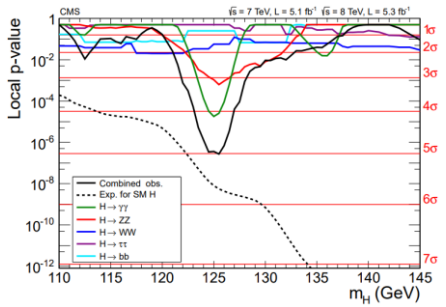
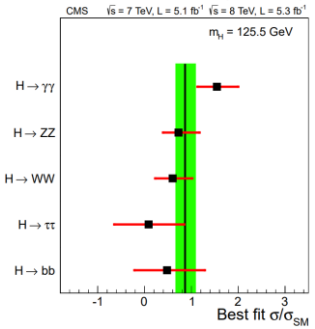
July 2012: Discovery

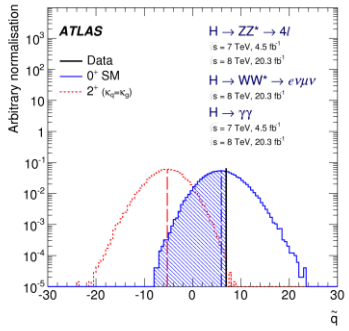
Run-2

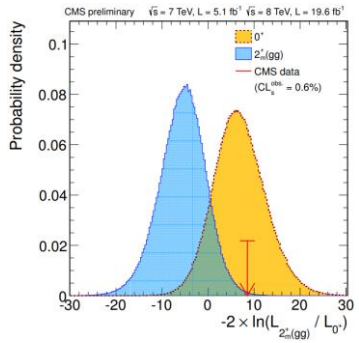












ggF

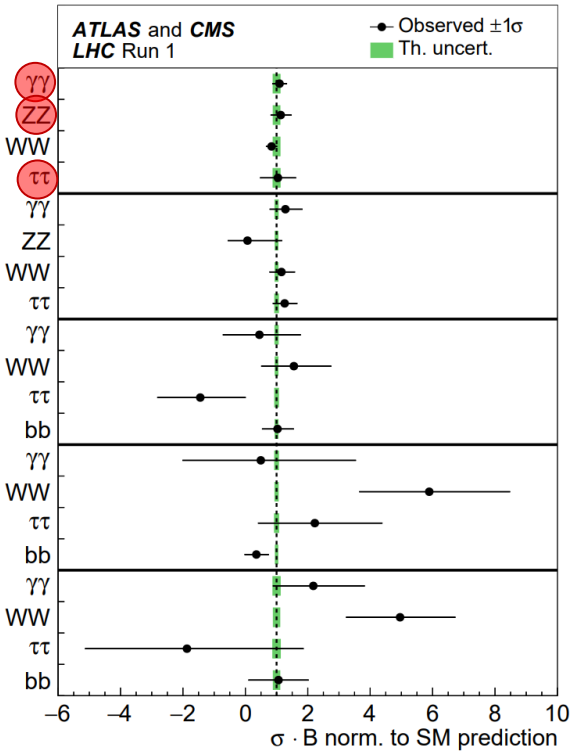
VBF

WH

ZH

ttH

End of Run-1



- All main production modes observed
- All accessible 3rd generation Yukawa couplings discovered
- Most couplings measured with precision at 10-30% level
- Higher-order MC corrections available
- Access to differential distributions in various phase spaces with common theory/experiment template
- Efforts to observe low cross-section processes, as 2nd generation Yukawa couplings and Higgs-self coupling

ICNFP 2020

The Higgs boson at the LHC

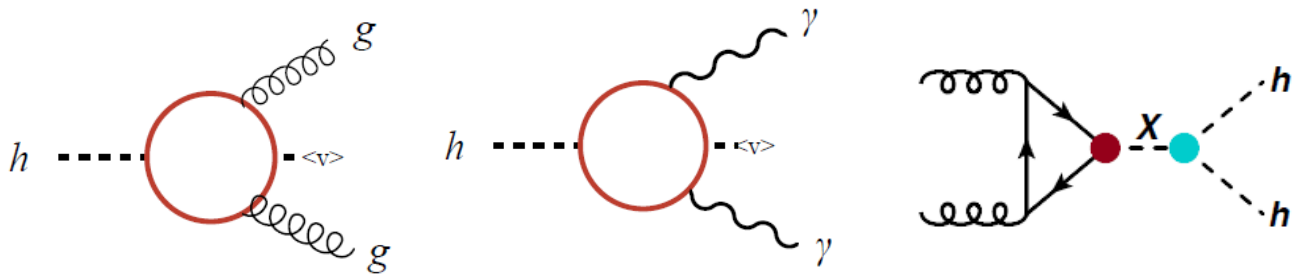
observed

Couplings

Signal strength

» Rates of production and decays are parametrised by the signal strength (μ)

$$\boldsymbol{\mu} = \frac{\sigma_i \times B_f}{(\sigma_i \times B_f)_{SM}}$$



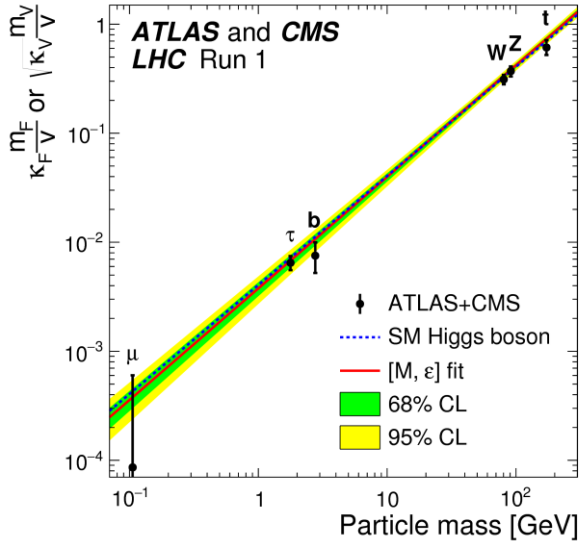
Direct or indirect new physics might modify production and/or decay couplings (or both!)

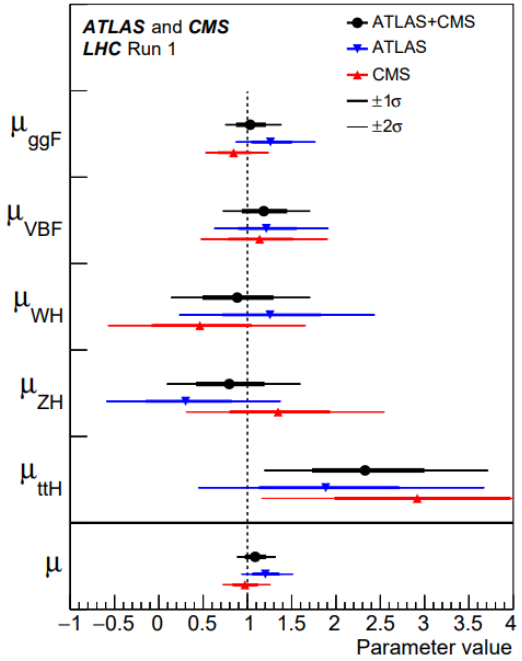
κ-framework

» Direct or indirect deviations from the SM rates through coupling strength can be sized with a leading-order κ framework

$$\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}$$

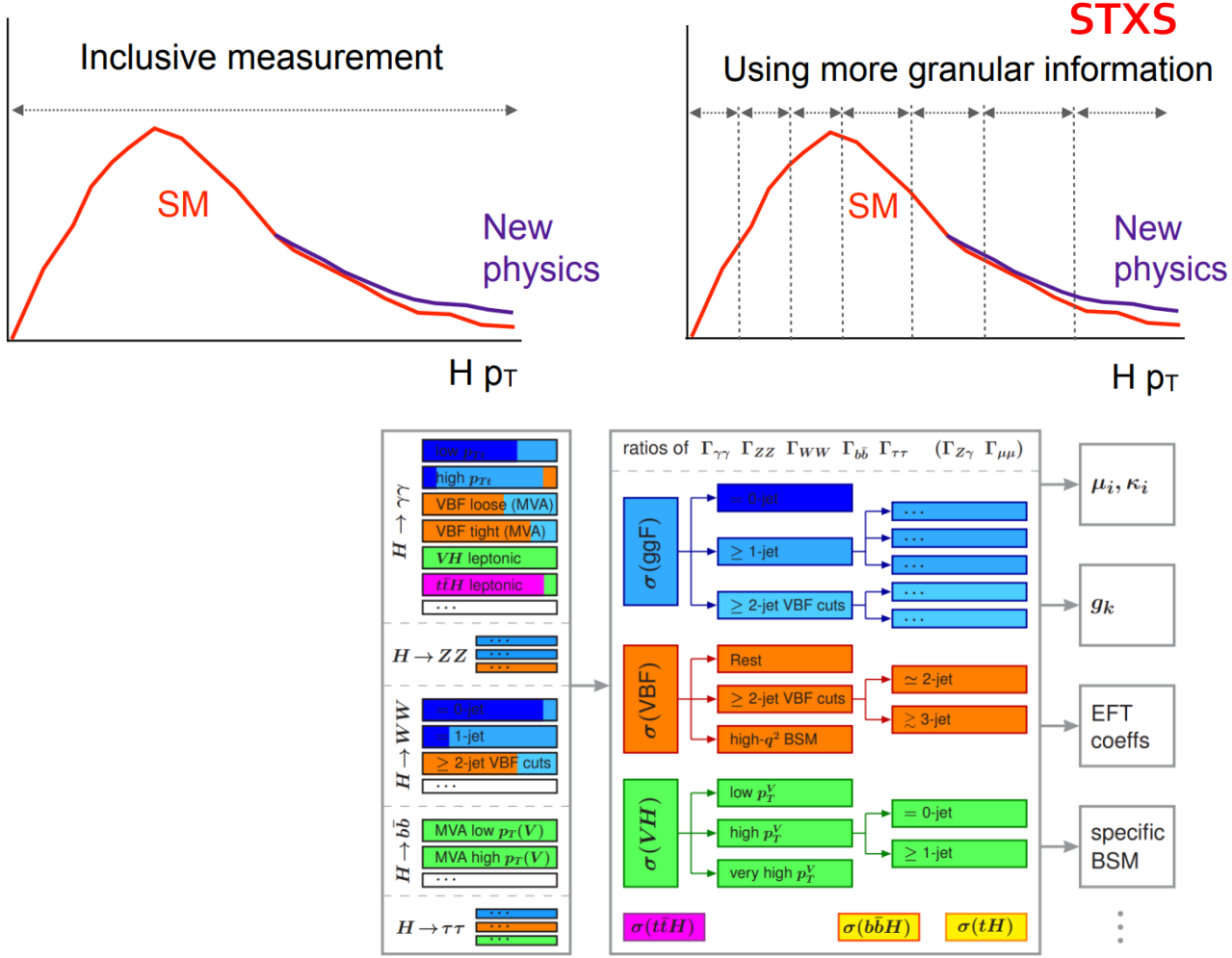
$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \qquad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$





Simplified template cross sections STXS

- Evolution of signal strength measurement
- Fine-grained measurement for individual Higgs production modes in different kinematic categories
- Reduce theoretical uncertainties and minimise theory dependence
- Provide a common framework for combination of different channels and experiments
- Provides sensitivity to measure signal strength μ and coupling modifiers κ
- Easy interpretation: isolate BSM regions
- Measurements can be used as inputs for EFT Lagrangians coefficients



Outline

- Mass measurements
- Spin/CP properties
- Invisible decays
- Hadronic decays
- Di-muon decay
- Production with top quarks
- Decay to bosons
- Coupling combination
- Higgs self-coupling
- Rare decays
- Dark portal

Outline

Roberto (CMS)

Alyssa (ATLAS)

- Mass measurements
- Spin/CP properties

Antonio (ATLAS)

- Invisible decays
- Hadronic decays
- Di-muon decay
- Production with top quarks
- Decay to bosons
- Coupling combination
- Higgs self-coupling

Jana (ATLAS)

- Rare decays

Tomomi (ATLAS)

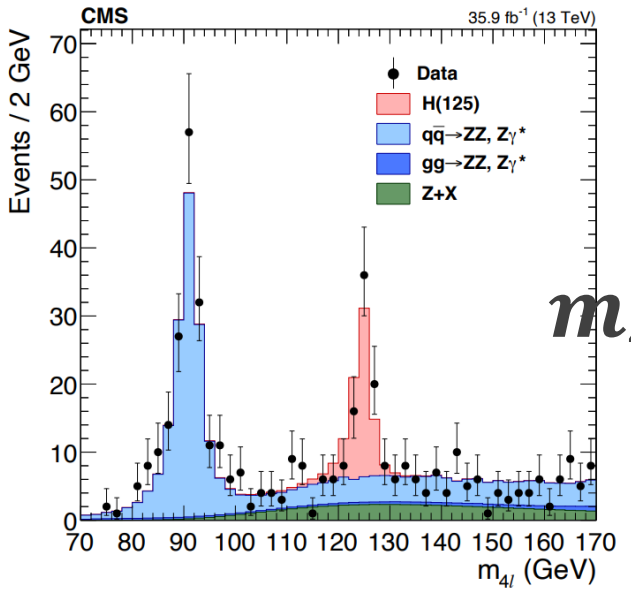
- Dark portal

Theodota

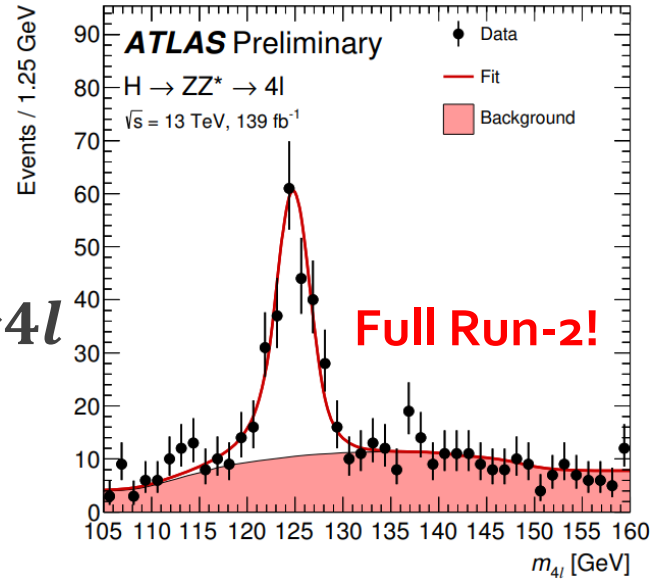
Mass measurement

$$H \rightarrow ZZ^* \rightarrow 4\ell$$

- Fully reconstructed final state
- 4 low p_T isolated leptons
- Main bkg: $qq \rightarrow ZZ$ continuum
- BR~0.12%, S/B~2



m_{4l}

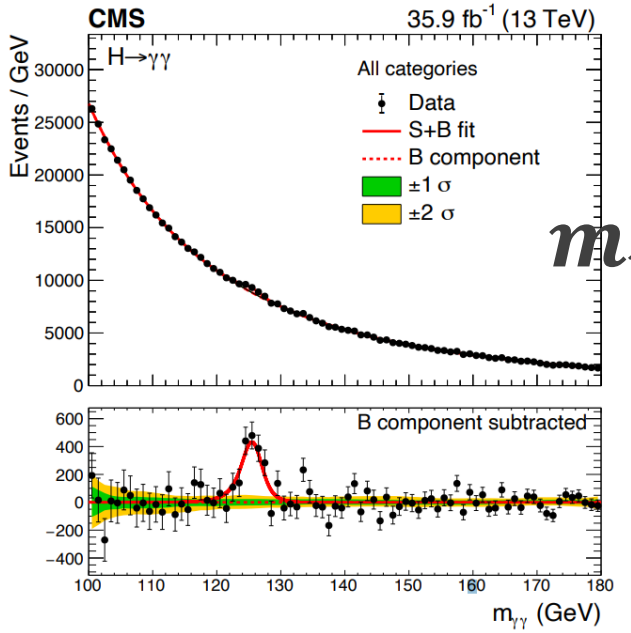


❖ JHEP 11 (2017) 047

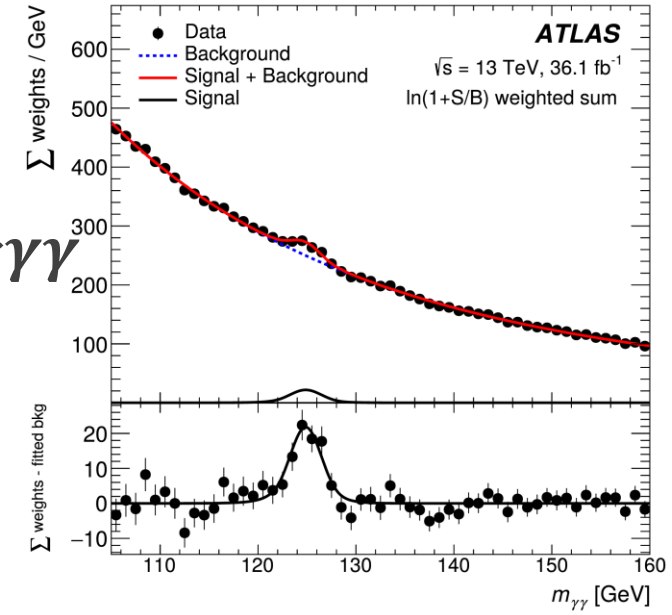
❖ ATLAS-CONF-2020-005

$$H \rightarrow \gamma\gamma$$

- Fully reconstructed final state
- 2 isolated photons
- Main bkg: $\gamma\gamma$ continuum
- BR~0.2%, S/B~0.1

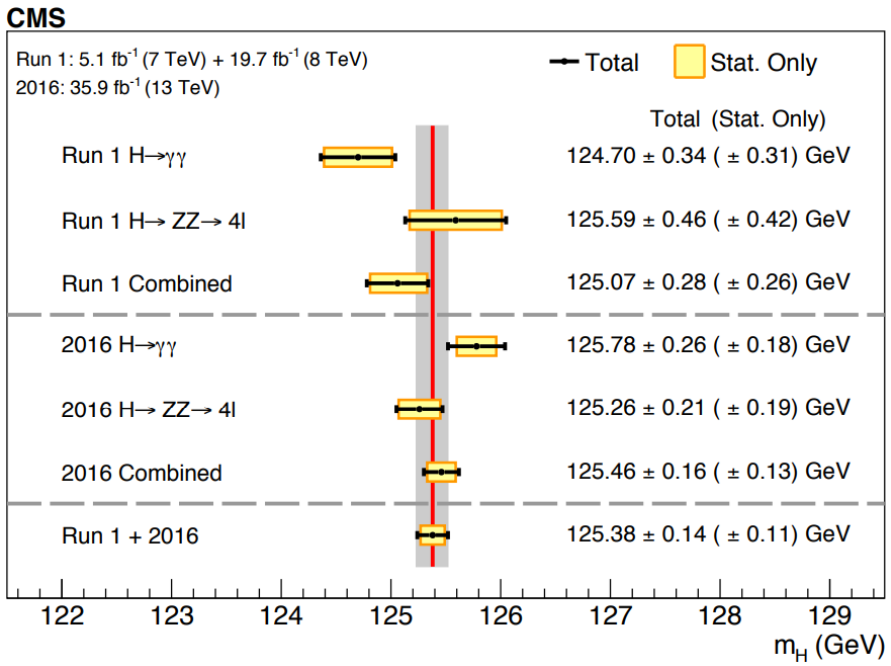


$m_{\gamma\gamma}$



❖ Phys.Lett. B805 (2020) 135425

❖ Phys.Lett. B784 (2018) 345-366



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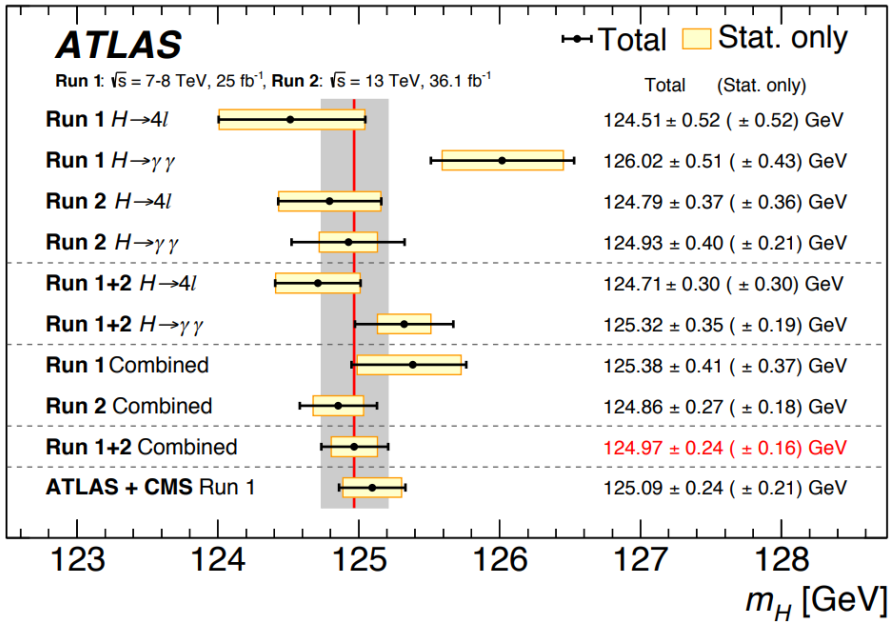


❖ JHEP 11 (2017) 047

Mass measurement

$$H \to ZZ^* \to 4\ell$$

» ATLAS (Run-2 @140 fb^{-1}): $m_h = 124.92 \pm 0.21$ GeV

❖ ATLAS-CONF-2020-005

» CMS (Run-2 @36 fb^{-1}): $m_h = 125.26 \pm 0.21$ GeV

4 times more data — same precision

❖ Phys.Lett. B784 (2018) 345-366

Combination

» ATLAS (Run-1 + Run-2@36 fb^{-1}):
$m_h = 124.97 \pm 0.24$ GeV

» CMS (Run-1 + Run-2@36 fb^{-1}):
$m_h = 125.38 \pm 0.14$ GeV

All results compatible!

Spin/CP properties

The SM Higgs boson is scalar with $J^P = 0^+$

» ATLAS and CMS excluded several alternative hypotheses, using a combination of bosonic channels ($ZZ^* \to 4\ell$, $WW^* \to 2\ell 2\nu$, $\gamma\gamma$), in favour of the SM Higgs boson at more than 99.9% confidence level (CL)

❖ Eur.Phys.J. C75 (2015) no.10, 476

$t\bar{t}H(\gamma\gamma)$

Direct probe of the CP-structure of the Higgs-top Yukawa coupling (k_t)

» Reconstructed final state with a Higgs candidate, 2 energetic photons, 2 top candidates

» Several BDT categorisations for both CP hypotheses

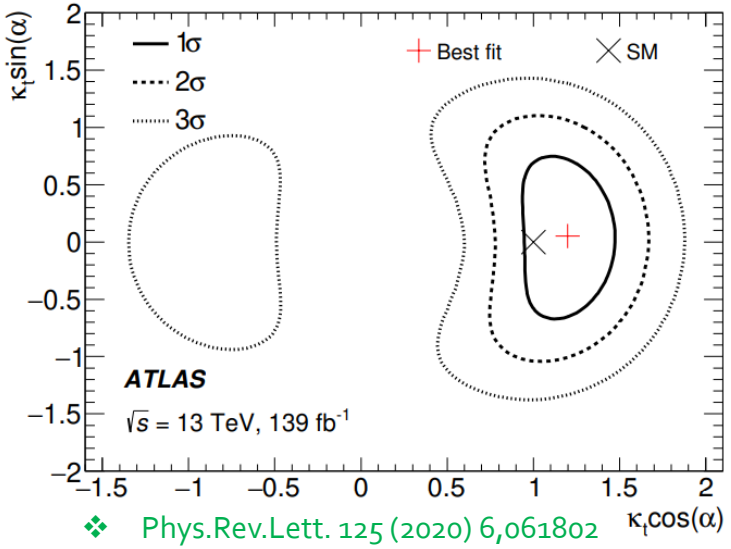
» $|\alpha| > 43^o$ and $\left|f_{CP}^{Htt}\right| < 0.67$ excluded @ 95 CL

» Pure CP-odd coupling excluded in ATLAS @ 3.9σ (2.5σ) and CMS @ 3.2σ (2.6σ)

$$\mathcal{L}_{H,t} = -\frac{m_t}{v}\left(\overline{\psi}_t \kappa_t [\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\right)H$$

CP-even: $\kappa_t = 1,\ \alpha = 0$

CP-odd: $\alpha = 90^o$

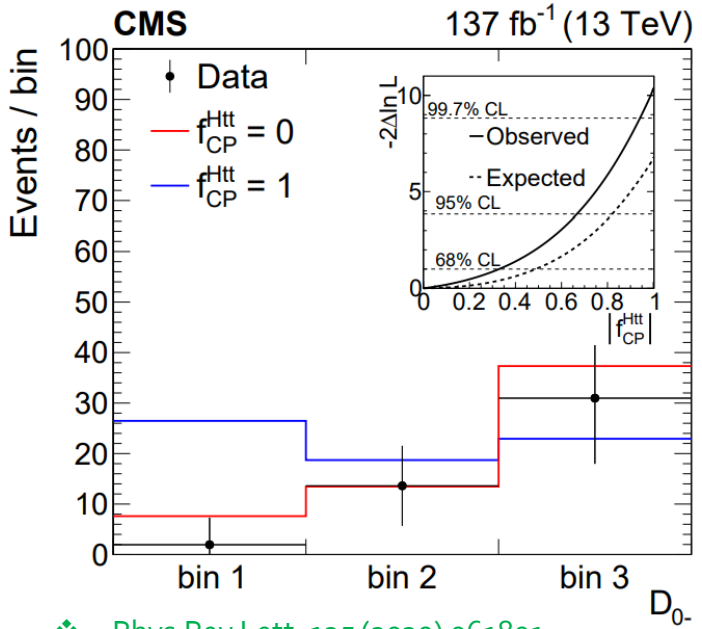


❖ Phys.Rev.Lett. 125 (2020) 6,061802

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}$$

CP-even: $f_{CP}^{Htt} = 0$

CP-odd: $f_{CP}^{Htt} = 1$



❖ Phys.Rev.Lett. 125 (2020) 061801

Spin/CP properties

$H \to \tau\tau$

$$\mathcal{L}_{H,\tau} = -\frac{m_\tau}{v}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \tilde{g}_{HAA} H\tilde{A}_{\mu\nu}A^{\mu\nu} + \tilde{g}_{HZA}\, H\tilde{A}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HWW}\, H\tilde{W}_{\mu\nu}W^{\mu\nu}$$

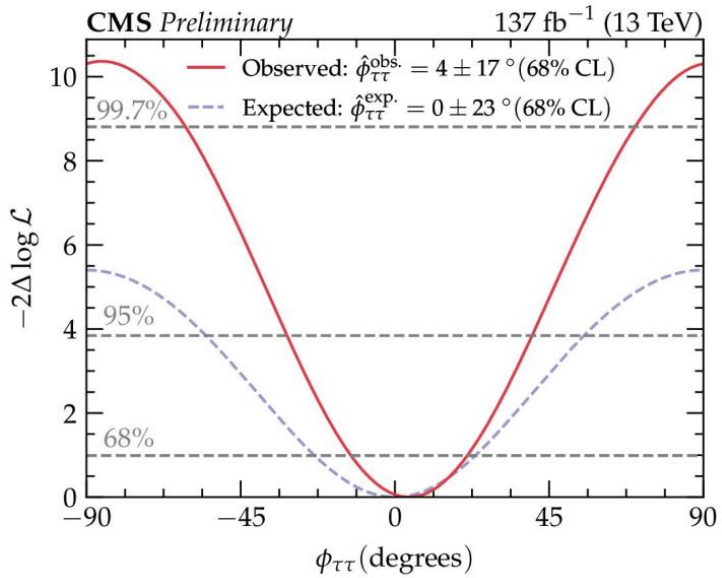
$$\tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}$$

CMS

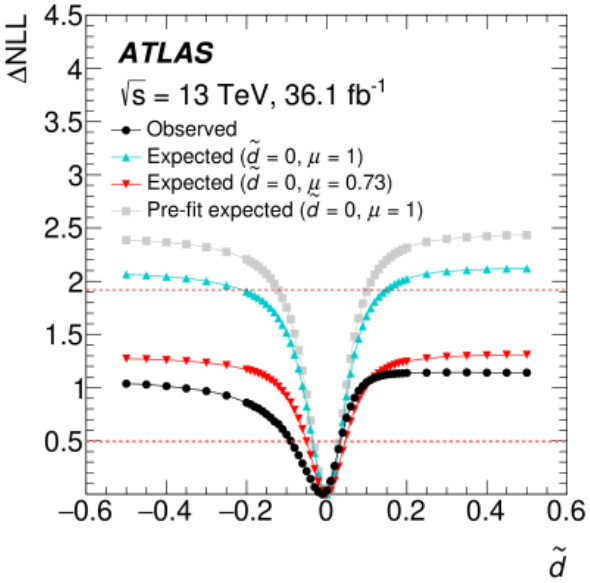
- CP structure of the VH coupling
- CP mixing angle $\phi_{\tau\tau}$ ($\tan(\theta_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$)
  - $\phi_{\tau\tau} = 0^o$: CP-even
  - $\phi_{\tau\tau} = 90^o$: CP-odd
  - $\phi_{\tau\tau} = 45^o$: maximum-mixing CP
- **Compatible with the SM prediction,** pure CP-odd scenario is excluded at 3.2σ

ATLAS

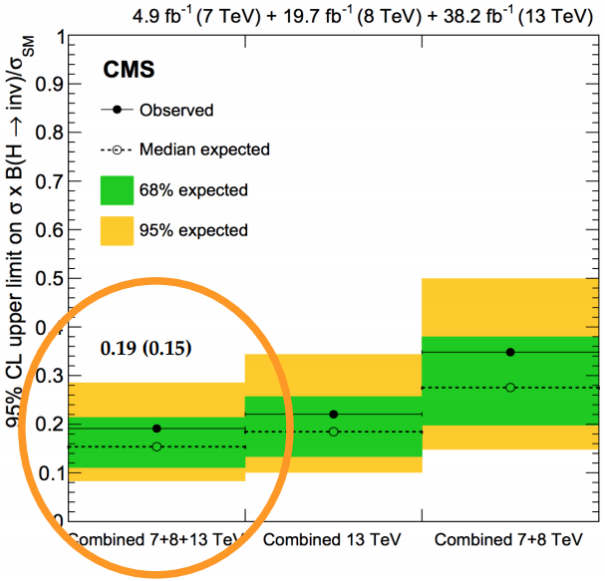
- CP invariance in VBF using a dim-6o CP-Odd effective Lagrangian
- Operators can be expressed in terms of $\tilde{d}$ and $\tilde{d}_B$
- Limits on $\tilde{d}$ are **consistent ($\tilde{d}$=0) with the SM**



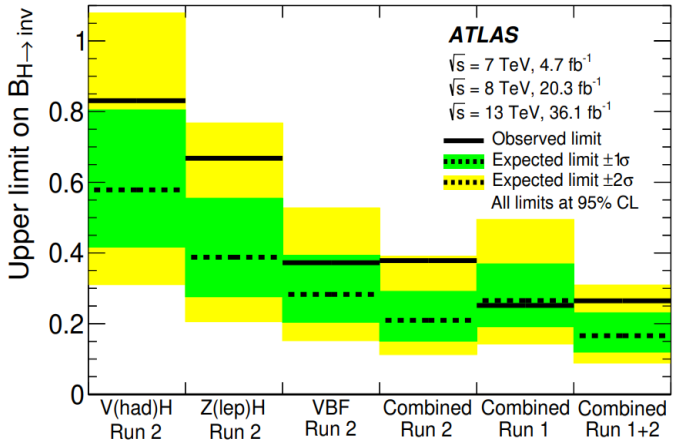
❖ CMS-PAS-HIG-20-006



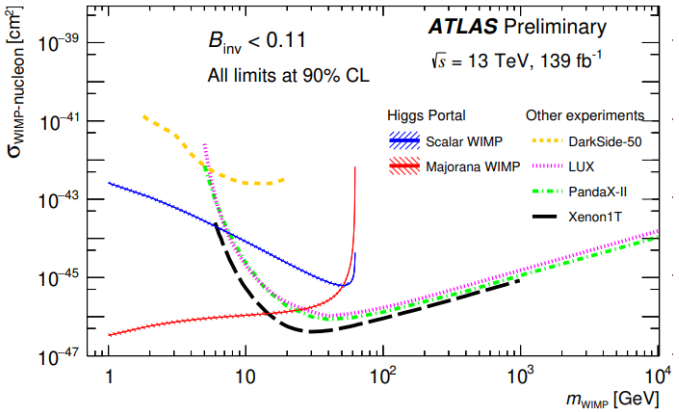
❖ Phys.Rev.Lett. B 805 (2020) 135426



❖ Phys.Lett. B. 793 (2019)



❖ Phys.Lett. B784 (2018) 345-366



❖ ATLAS-CONF-2020-005

Invisible decays

- Signature with Higgs production plus large E_T^{miss}
- Unlikely SM process ($BF \approx 0.01$), so it can represent a good way of testing for new physics
- Higgs boson can be a mediator between SM and DM particles, enhancing the BF
- **VBF** analysis strategy: search for boosted jet pair plus large E_T^{miss}
- **Monojet** analysis strategy: search for at least one jet (ISR) plus large E_T^{miss}
- **VH** analysis: search for energetic jets plus large E_T^{miss} V(qq), or lepton pair plus large E_T^{miss} Z(ll)
- Main bkg (shared analyses): Z($\nu\nu$)+jets, W($\ell\nu$)+jets

CMS

- B($H \rightarrow inv$)=0.19 (0.15) **Run-1+Run-2**
- B($H \rightarrow inv$)=0.29 (0.25) **Full Run-2 Z(ll)H(inv)**

❖ CMS-PAS-EXO-19-003

ATLAS

- B($H \rightarrow inv$)=0.26 (0.17) **Run-1+Run-2**
- B($H \rightarrow inv$)=0.13 (0.13) **Full Run-2 VBF** best limit!
- B($H \rightarrow inv$)=0.63 (0.57) **Full Run-2 monojet**

Hadronic decays

$H \to b\bar{b}$, $H \to c\bar{c}$

- Dominant decays of the SM Higgs boson
- Large multi-jet background, making the analysis extremely challenging at hadron colliders
- $H \to c\bar{c}$ limited by the flavour tagging capabilities and S/B yields
- Couplings and differential cross sections are becoming accessible in the bb final state
- ggF and VBF difficult to distinguish from non-resonant b-quark production (VBF+γ improves triggering)
- VH production most sensitive mode
- Resolved vs Boosted topologies

➢ ttH production (not in the slides) its hard to observe due to large multi-jet background and large theory uncertainty of irreducible $t\bar{t} + b\bar{b}$ background. Both ATLAS obtained with Run-2 @36fb^{-1}: 1.4σ (1.6σ), while CMS with Run-2@80fb^{-1}: 3.7σ (3.5σ).

- Phys. Rev. Lett. D. 97, (2018) 072016
- CMS-PAS-HIG-18-030

Hadronic decays

VH production $H \to b\bar{b}$

CMS

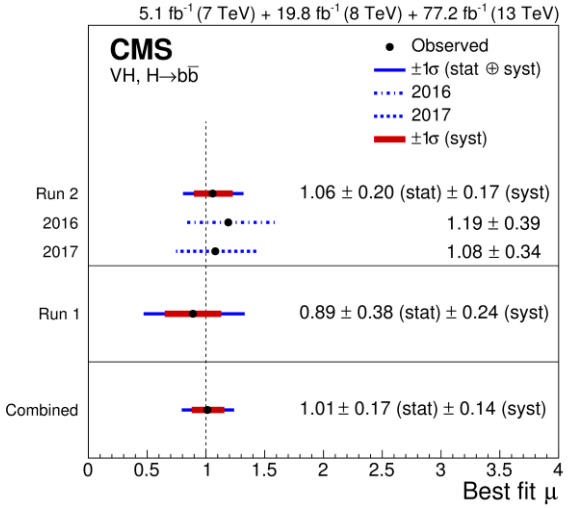
- Run-2 @ 77.2 fb^{-1}
- DNN categorisation
- Significance: 5.6σ (5.5σ)

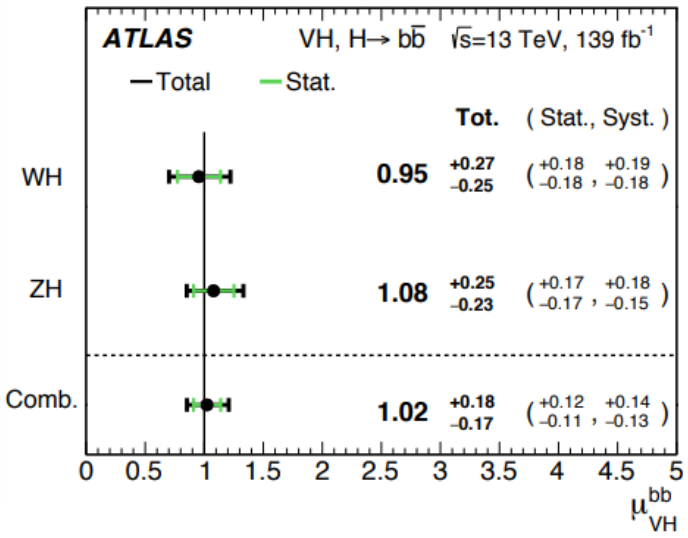
$$\mu_{VH}^{bb} = 1.01^{+0.17}_{-0.14}$$

ATLAS

- Full Run-2
- p_T^V split at 250 GeV (boosted) to better align STXS bins
- Improved BDT for CR/SR separation and multi-dimensional bkg parametrization
- Significance: 6.7σ (6.7σ)

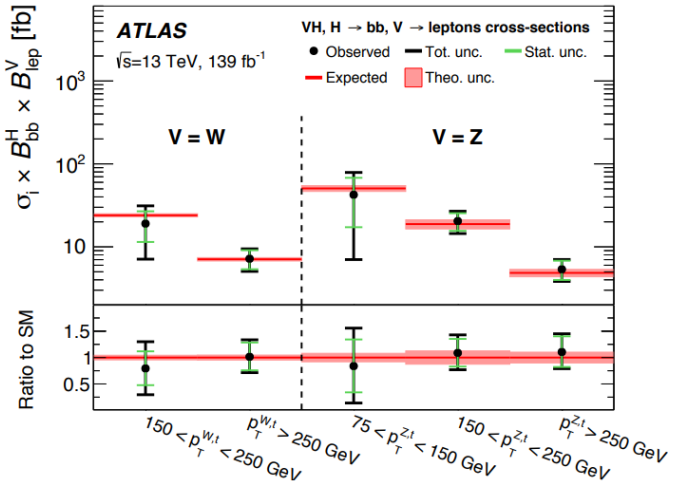
$$\mu_{VH}^{bb} = 1.02^{+0.18}_{-0.17}$$

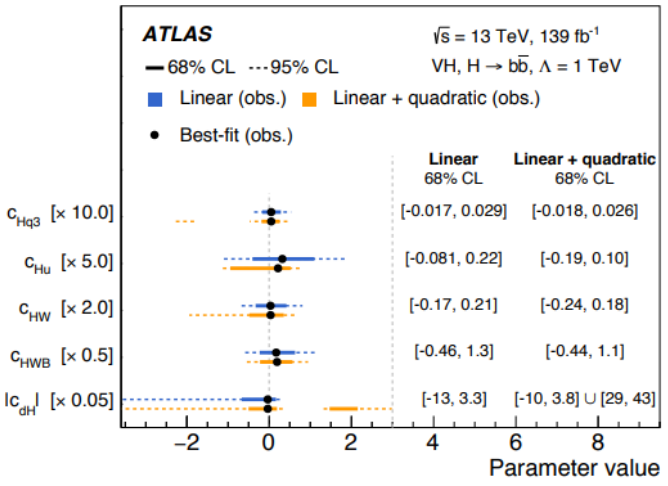




❖ Phys. Rev. Lett. 121 (2018) 121801

Dim-6 Warsaw Lagrangian





❖ CERN-EP-2020-087

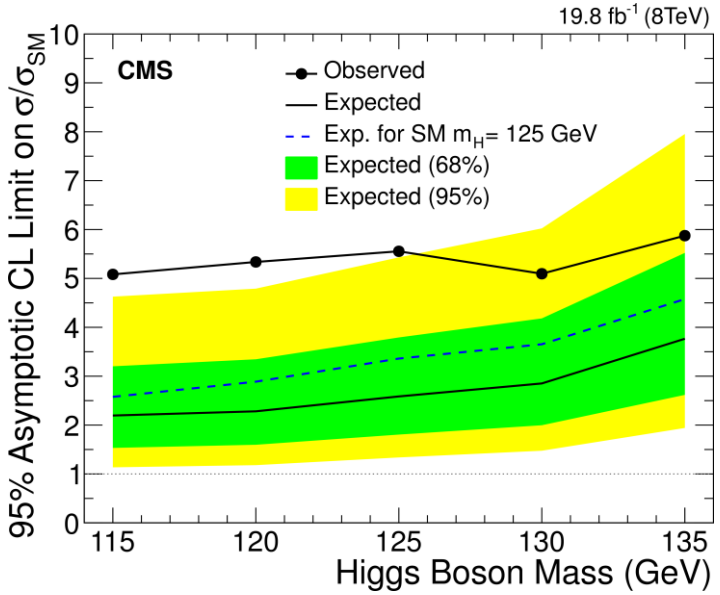
Hadronic decays

VBF production $H \rightarrow b\bar{b}$

CMS

- Run-1
- PF event reconstruction + CSV b-tagger
- Significance: 2.2σ (0.8σ)

$$\mu_{VBF}^{bb} = 2.8^{+1.6}_{-1.4}$$

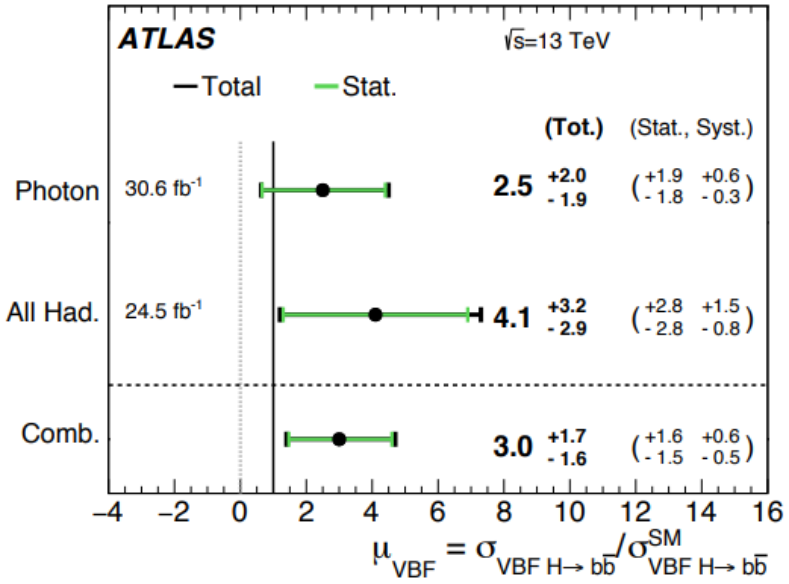


❖ Phys. Rev. D 92 (2015) 032008

ATLAS

- Run-2 @ 36.1 fb^{-1}
- Signal events characterized by 2 central b-jets + 2 light-quark jets with large rapidity gap (VBF jets)
  - qqH(→bb) with central and forward jet
  - qqH(→bb)γ production in association with energetic photon
- BDT for CR/SR separation
- Significance: bb: 1.9σ (0.7σ), $bb\gamma$: 1.4σ (0.6σ)

$$\mu_{VBF}^{bb} = 3.0^{+1.7}_{-1.6} \qquad \mu_{VBF}^{bb\gamma} = 2.5^{+2.0}_{-1.9}$$

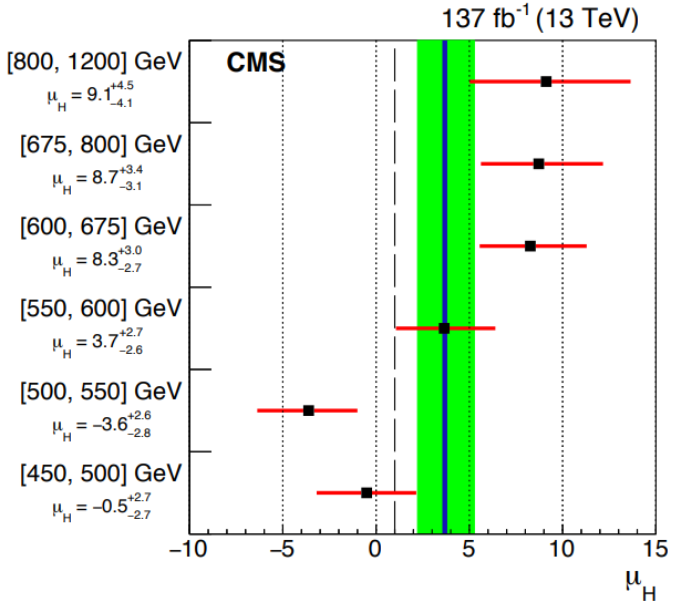


❖ Phys. Rev. Lett. D 98 (2018) 052003

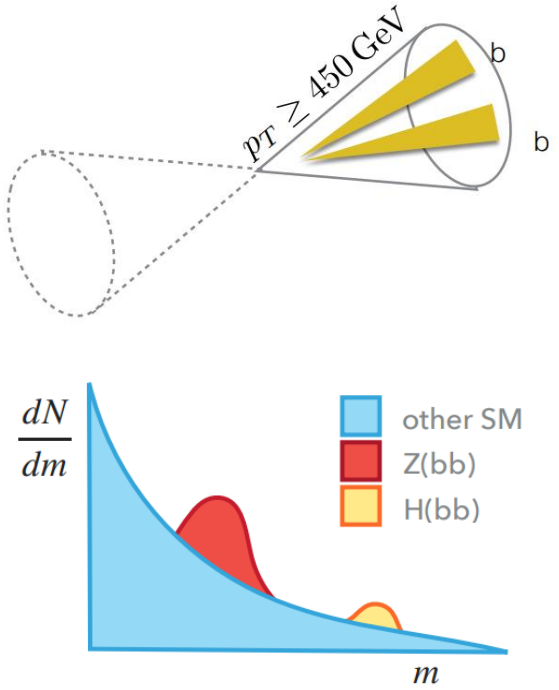
Hadronic decays

Inclusive boosted searches

- Full Run-2 analyses (CMS) , Run-2@80fb^{-1} (ATLAS)
- Tested with $Z \rightarrow bb$ decays with more than 5σ
- Search for peak in jet mass distribution



❖ CERN-EP-2020-107



CMS

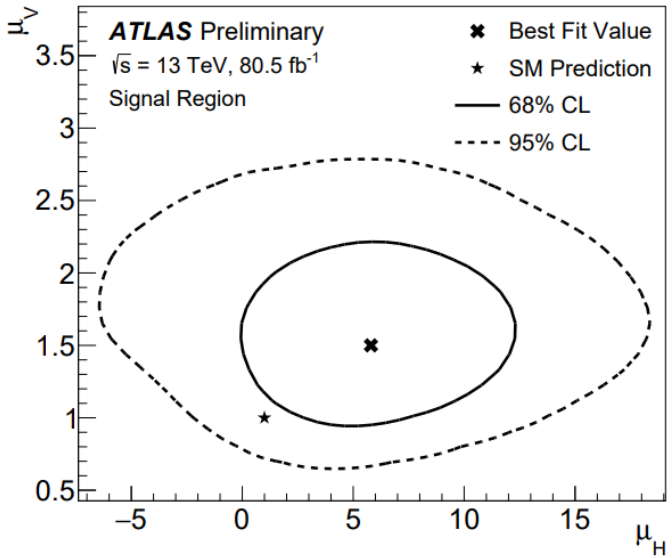
- Preselect boosted large-radius jet with two-prong
- DeepDoubleB tagger to select bb
- H(bb) observed significance of 3.7σ

$$\mu_H = 3.7 \pm 1.2(stat.)^{+0.6}_{-0.5}(syst.)$$

ATLAS

- Candidate reconstructed as leading p_T large-R jet, at least two leading b-tagged VR track jets associated
- ggF and VH production modes
- H(bb) observed significance of 1.6σ

$$\mu_V = 5.8 \pm 3.1(stat.)^{+1.9}_{-1.9}(syst.)$$



❖ ATLAS-CONF-2018-052

Hadronic decays

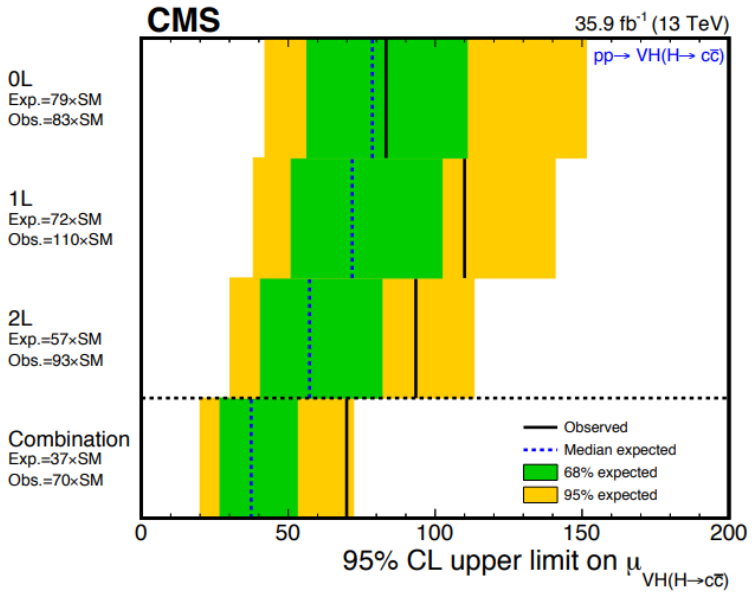
$H \to c\bar{c}$

- Second generation Yukawa coupling
- VH production, tagging the Z/W the boson
- Run-2 @ 36.1 fb^{-1}

CMS

- Resolved and boosted strategies
- 3 final states
- DNN categorization (DeepCSV, DeepAK8)

$$\mu_{H\to cc} < 70 \ @95\% \ CL$$

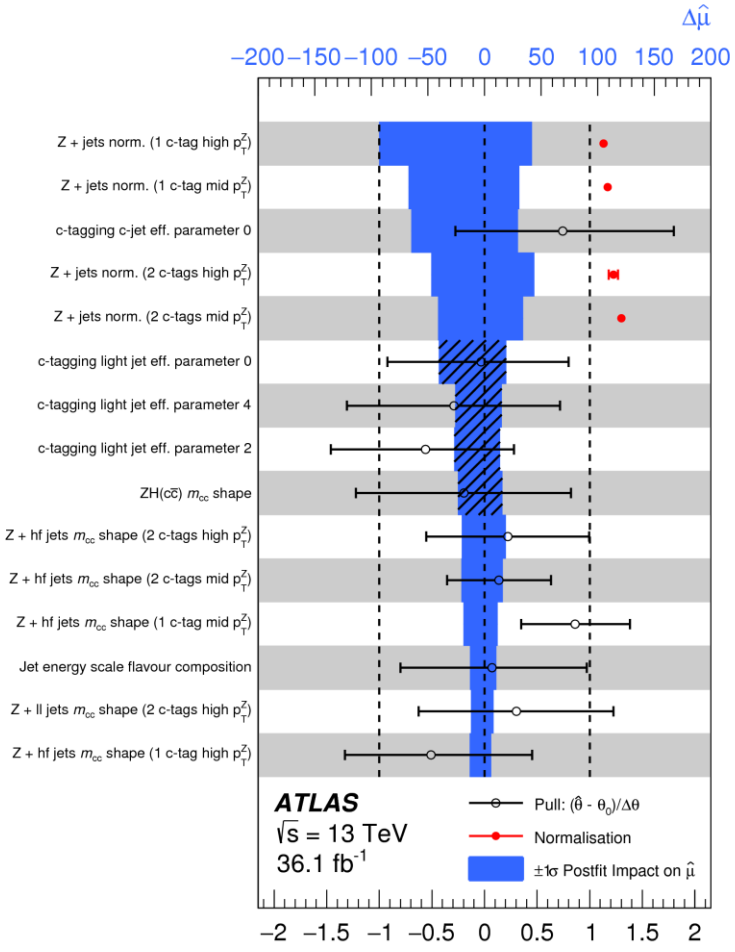


❖ JHEP 02 (2020) 131

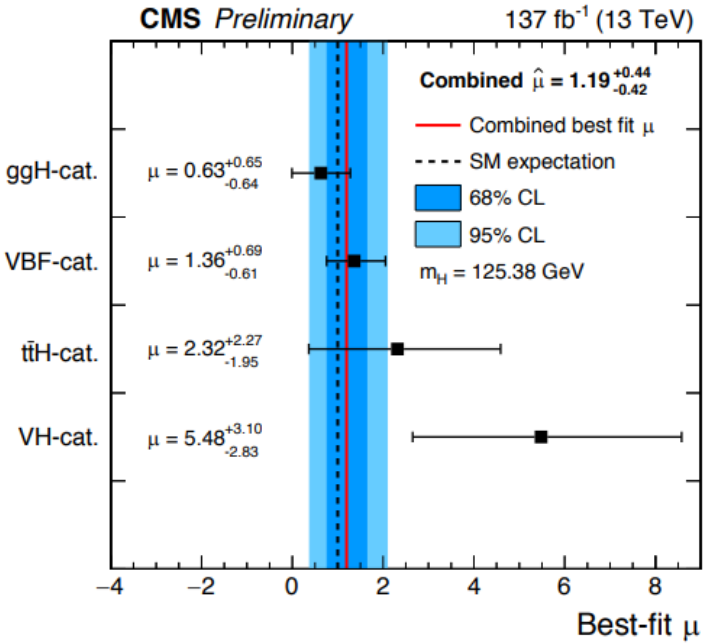
ATLAS

- Resolved strategy
- Only 2 lepton final state
- m_{bb} fit after categorizing on selection cuts

$$\mu_{H\to cc} < 110 \ @95\% \ CL$$



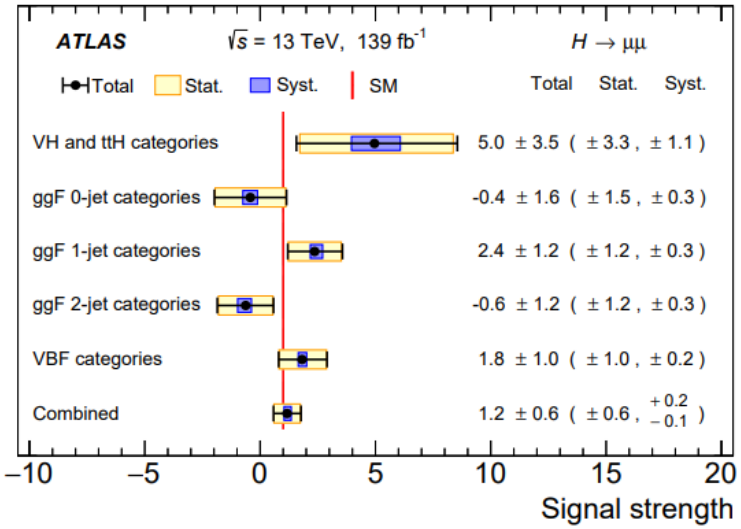
❖ Phys. Rev. Lett. 120 (2018) 211802



CMS

$\mu_{\mu\mu} = 1.19^{+0.44}_{-0,42}$

❖ CMS-PAS-HIG-19-006



ATLAS

$\mu_{\mu\mu} = 1.2 \pm 0.6$

❖ CERN-EP-2020-117

di-muon decay

- Second generation Yukawa coupling
- Simple analysis that selects two opposite-charged muons
- ttH, VH, VBF and ggF production modes
- Small signal and large irreducible DY bkg (S/B = 0.2%)

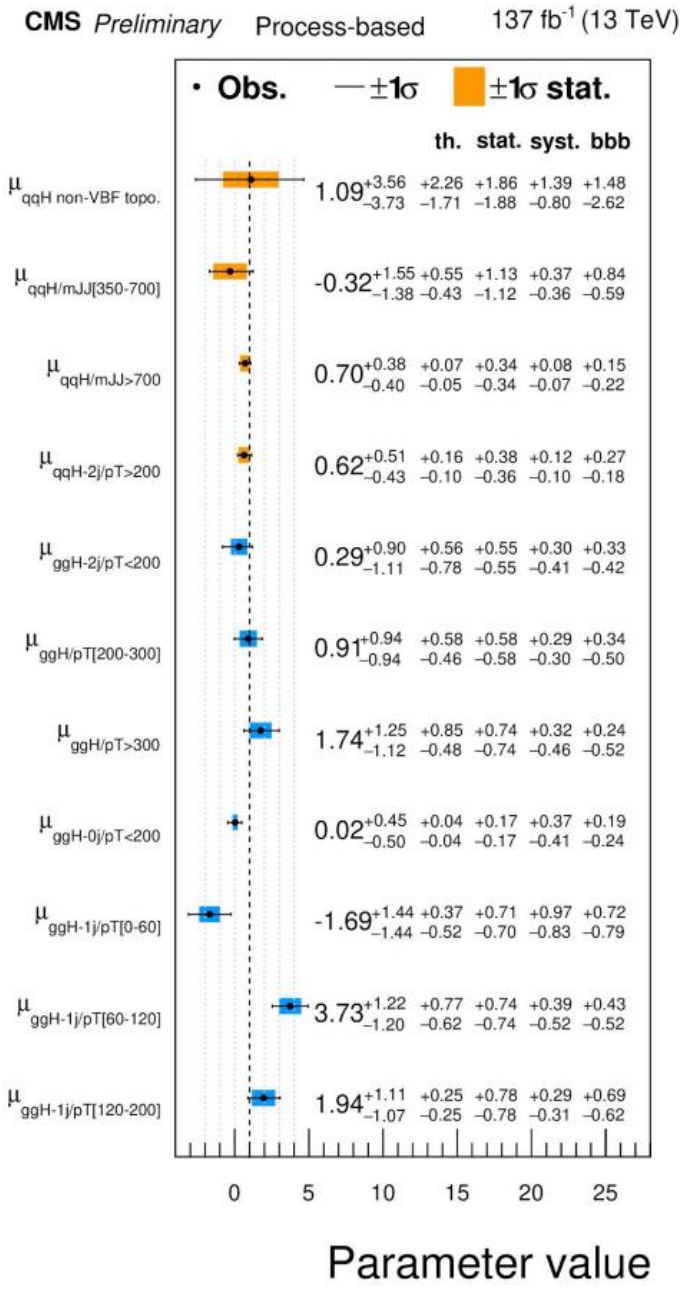
CMS

- BDT, DNN categorisation depending on the production mechanism
- Signal extraction from di-muon mass fit or DNN
- **Significance: 3.0σ (2.5σ)**

Magnetic field difference

ATLAS :

- BDT categorisation for production modes
- Signal extraction from di-muon mass fit
- Significance: 2.0σ (1.7σ)



❖ CMS-PAS-HIG-19-010

di-tau decay

- Has a relatively high BF, so it can be used to probe regions of phase space with small cross section (VBF-like phase space, boosted Higgs)
- But taus are unstable and decay to hadrons and leptons (both associated with neutrinos)

CMS

- Leptonically and hadronically decays
- Multiclass DNN categorization (DeepTau)
- Events are splits in 3 categories (no jet, VBF and boosted) which then are slip into STXS sub-categories
- Inclusive cross-section:

$$\mu_{\tau\tau} = 0.85^{+0.12}_{-0,11}$$

Production with top quarks

- Direct measurement of the largest Yukawa coupling y_t and sensitive to presence of new physics
- Low cross section: $\sigma_{t\bar{t}H} \approx 0.5$ pb, $\sigma_{tH} \approx 0.074$ pb
- ttH measurement categorise by Higgs boson decay:
  - $t\bar{t}H(bb)$
  - $t\bar{t}H$ multi-leptons $(WW^*, \tau\tau, ZZ^*)$
  - $t\bar{t}H(\gamma\gamma)$
- Full Run-2
- BDT classifier + STXS

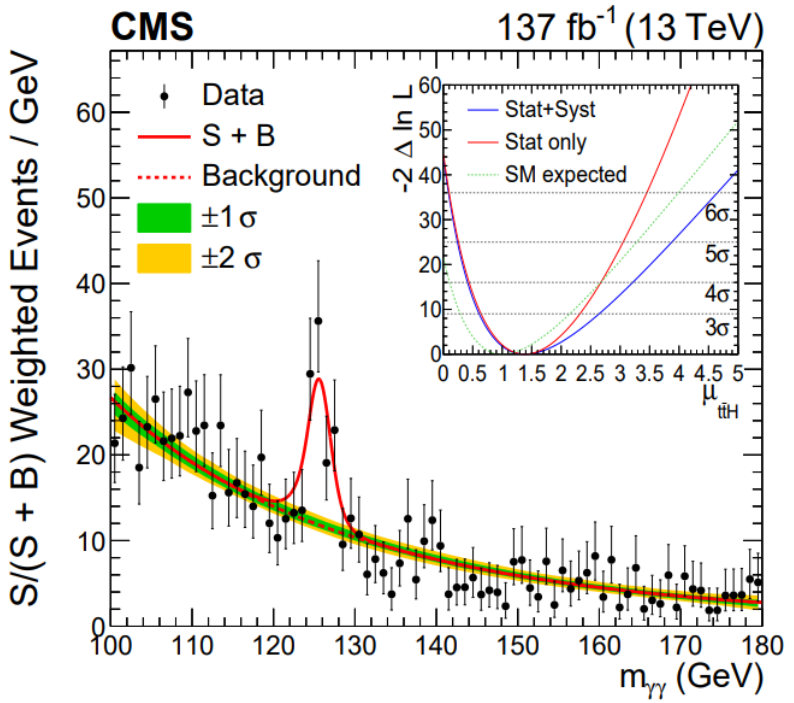
CMS

- Significance: 6.6σ (4.7σ) $\quad \mu_{t\bar{t}H(\gamma\gamma)} = 1.38^{+0.36}_{-0.29}$

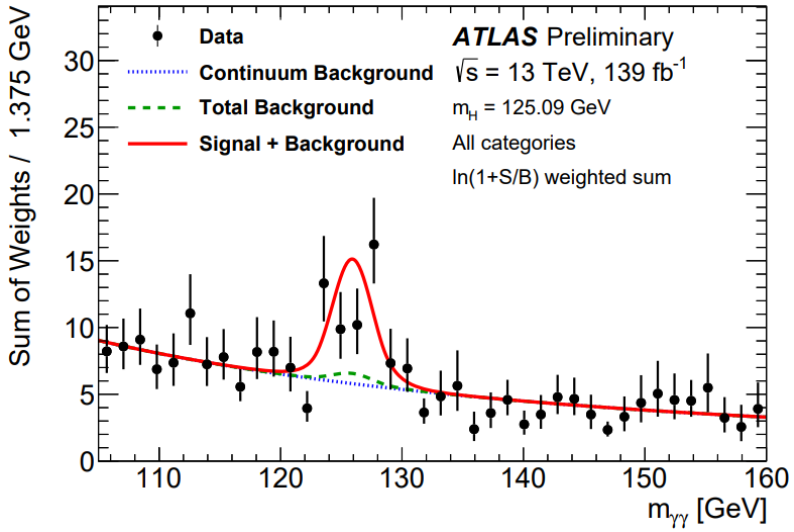
ATLAS

- Significance: 4.9σ (4.2σ) $\quad \mu_{t\bar{t}H(\gamma\gamma)} = 1.38^{+0.41}_{-0.36}$
- Significance: 4.7σ (5.0σ) - $t\bar{t}H + tH$

❖ ATLAS-CONF-2020-026



❖ CERN-EP-2020-028



❖ ATLAS-CONF-2019-004

Production with top quarks

- Direct measurement of the largest Yukawa coupling y_t and sensitive to presence of new physics
- Low cross section: $\sigma_{t\bar{t}H} \approx 0.5$ pb, $\sigma_{tH} \approx 0.074$ pb
- ttH measurement categorise by Higgs boson decay:
  - $t\bar{t}H(bb)$
  - $t\bar{t}H$ multi-leptons $(WW^*, \tau\tau, ZZ^*)$
  - $t\bar{t}H(\gamma\gamma)$

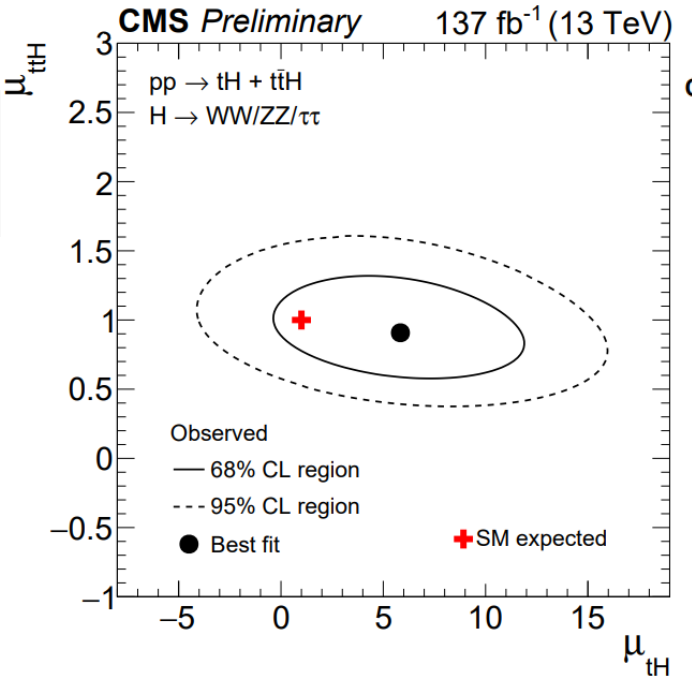
- Run-2 @ 80 fb^{-1} (ATLAS) Full Run-2 (CMS)
- BDT + DNN classifier

CMS

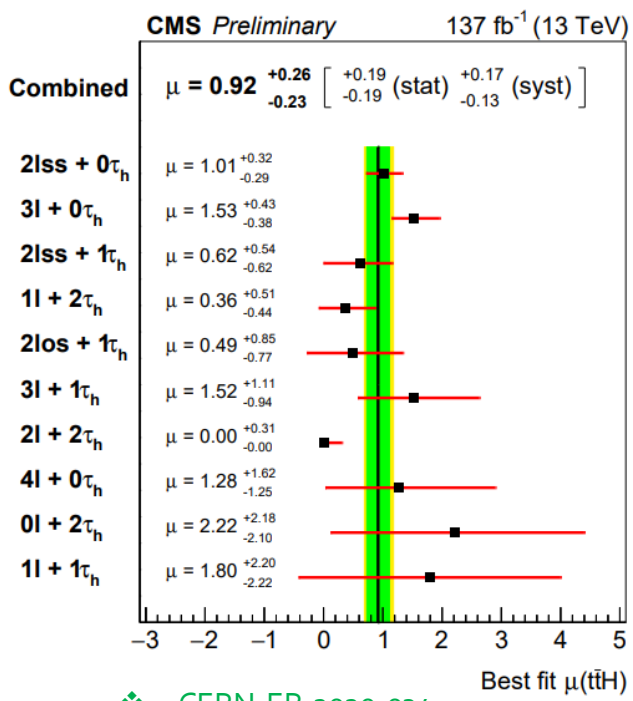
- Significance: 4.7σ (5.2σ) $\mu_{t\bar{t}H(lep)} = 0.92^{+0.26}_{-0.23}$
- Significance: 1.4σ (0.3σ) $\mu_{tH(lep)} = 5.7^{+4.1}_{-4.0}$

ATLAS

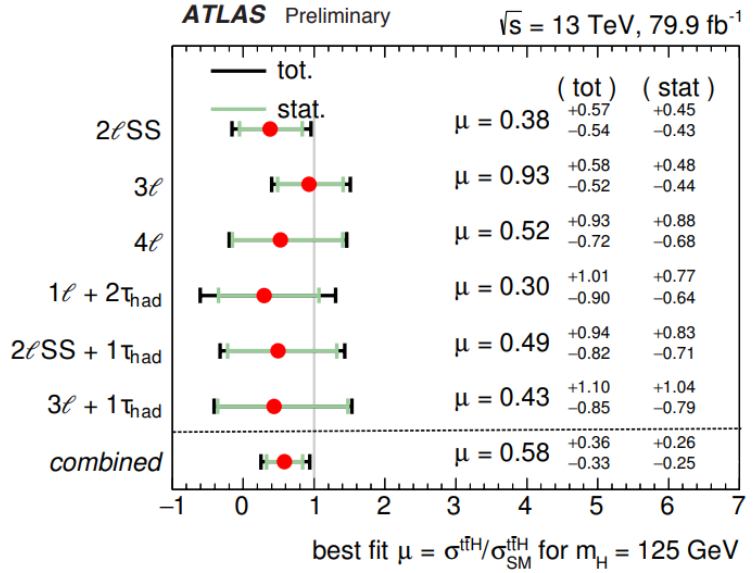
- Significance: 1.8σ (3.1σ) $\mu_{t\bar{t}H(lep)} = 0.58^{+0.36}_{-0.33}$



❖ CMS-PAS-HIG-19-008

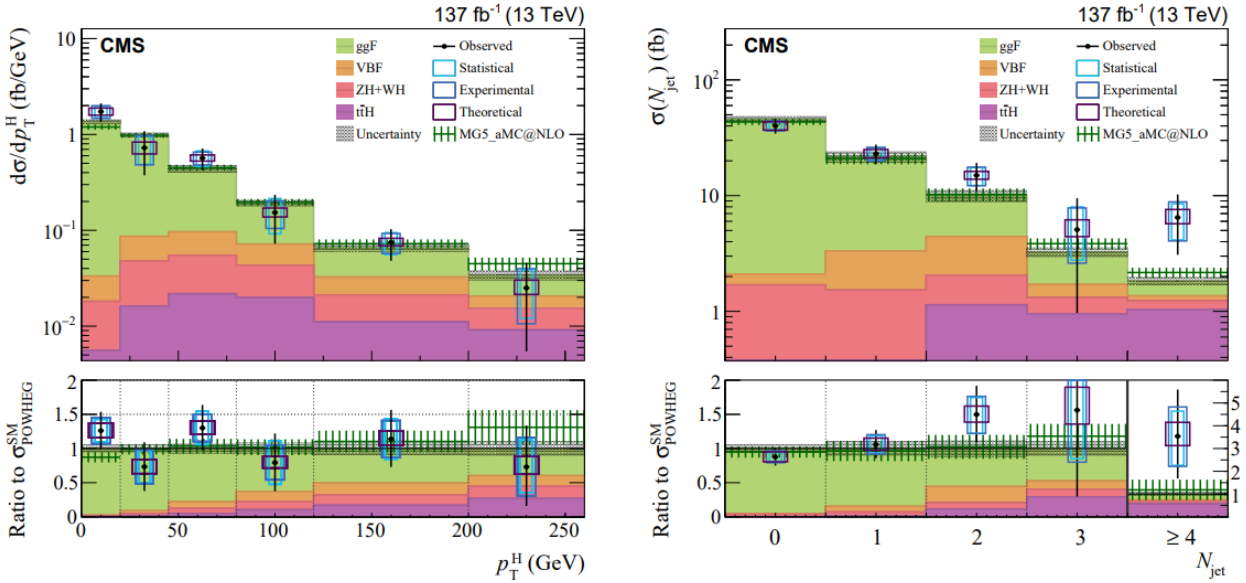


❖ CERN-EP-2020-034



❖ ATLAS-CONF-2019-045

❖ CMS-PAS-HIG-19-002



» Uncertainties around 15-20% at low N_{jet} and p_T^H values

» Good agreement with theoretical predictions in all bins

- Largest discrepancy for $N_{jet} \geq 4$ (1.4σ)

$$\mu^{fid} = 1.05 \pm 0.12$$

$$\sigma^{fid} = 86.5 \pm 9.5 \text{ fb} \qquad \sigma_{SM} = 82.5 \pm 4.2 \text{ fb}$$

Decay to bosons

Fiducial and differential cross section

» Inclusive Higgs boson measurement limited by systematic uncertainties

» More information can be extracted from fiducial differential cross section

» The higher model-independency of fiducial measurements are ideal to look for BSM effect in specific phase spaces

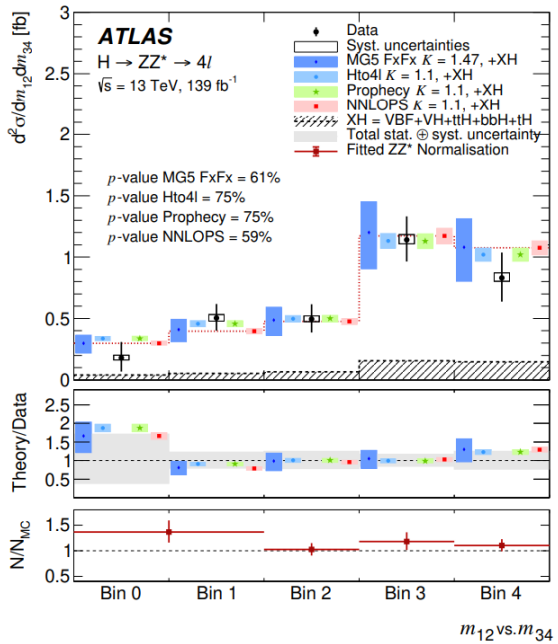
❑ Differential: measure cross section in bins of some observable (p_T^H, jet multiplicity, …)

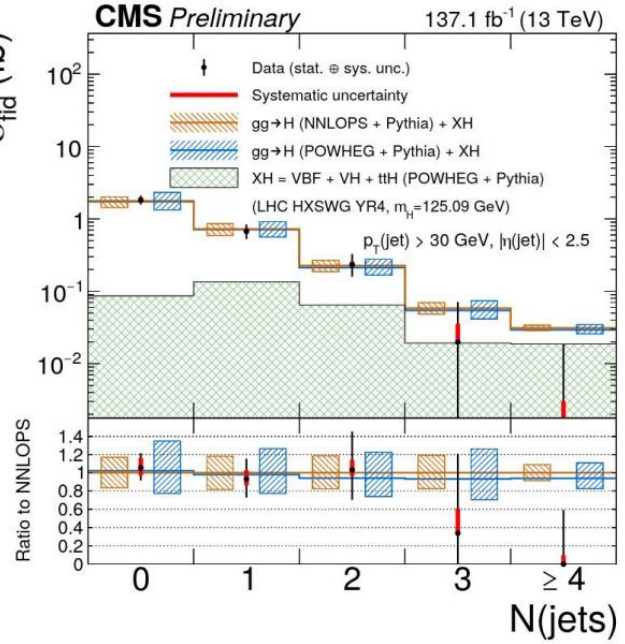
❑ Fiducial: extrapolate the measurement to a phase space that closely matches the experimental selection

» $H \rightarrow WW$: Full Run-2 (CMS)

» $H \rightarrow ZZ$: Full Run-2 (ATLAS, CMS)

» $H \rightarrow \gamma\gamma$: Full Run-2 (ATLAS), Run-2@ 36 fb^{-1} (CMS)





CMS ❖ CERN-EP-2020-035 ❖ CMS-PAS-HIG-19-001

» ~20-30% precision for $N_{jets} < 3$ and $p_T(jet) < 200$ GeV

» Good agreements with POWHEG and NNLOPS

$$\sigma^{fid} = 2.73^{\pm 0.23}_{\pm 0.22}\,(stat)^{\pm 0.24}_{\pm 0.19}(syst)\ \text{fb}$$
$$\sigma_{SM} = 2.76 \pm 0.14\ \text{fb}$$

ATLAS

» ~10% precision (stat. dominated)

» Interpretation with pseudo-observables (compatible with the SM expectation)

$$\sigma^{fid} = 3.28 \pm 0.30(stat) \pm 0.11(syst)\ \text{fb}$$
$$\sigma_{SM} = 3.41 \pm 0.18\ \text{fb}$$

Decay to bosons

Fiducial and differential cross section

» Inclusive Higgs boson measurement limited by systematic uncertainties

» More information can be extracted from fiducial differential cross section

» The higher model-independency of fiducial measurements are ideal to look for BSM effect in specific phase spaces

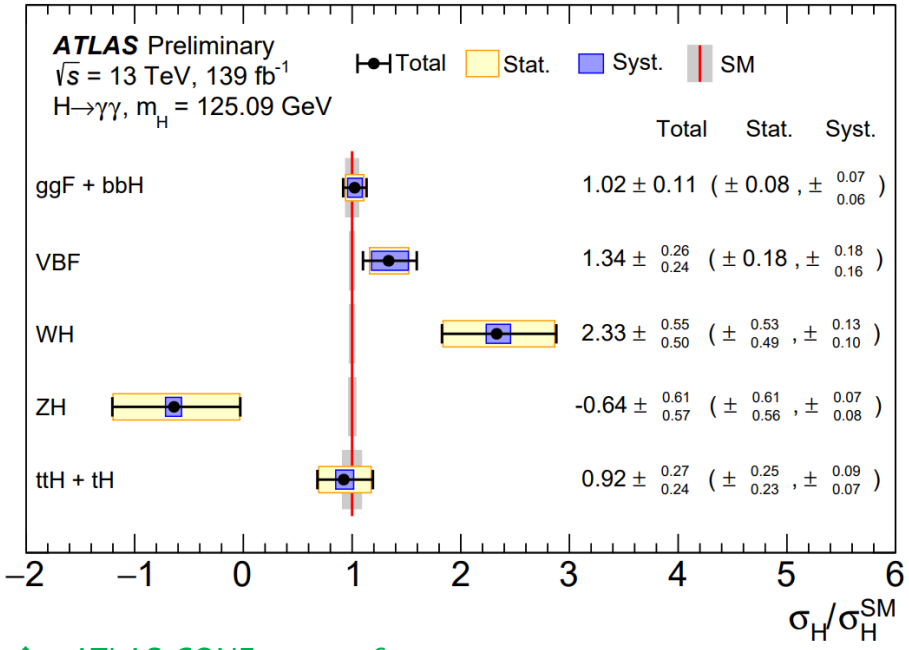
❑ Differential: measure cross section in bins of some observable (p_T^H, jet multiplicity, …)

❑ Fiducial: extrapolate the measurement to a phase space that closely matches the experimental selection

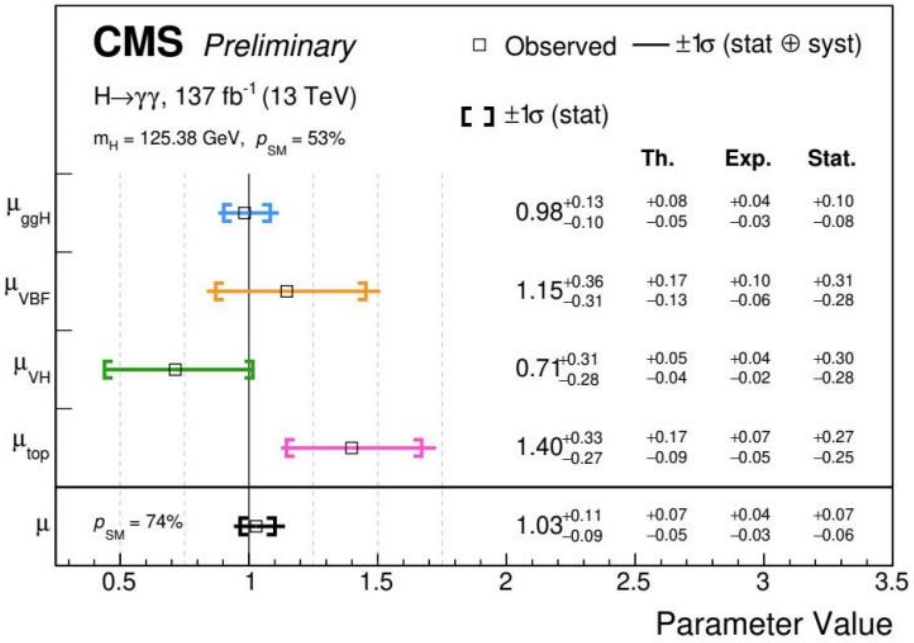
» $H \to WW$: Full Run-2 (CMS)

» $H \to ZZ$: Full Run-2 (ATLAS, CMS)

» $H \to \gamma\gamma$: Full Run-2 (ATLAS), Run-2@ 36 fb^{-1} (CMS)



❖ ATLAS-CONF-2020-026



❖ CMS-PAS-HIG-19-015

Decay to bosons

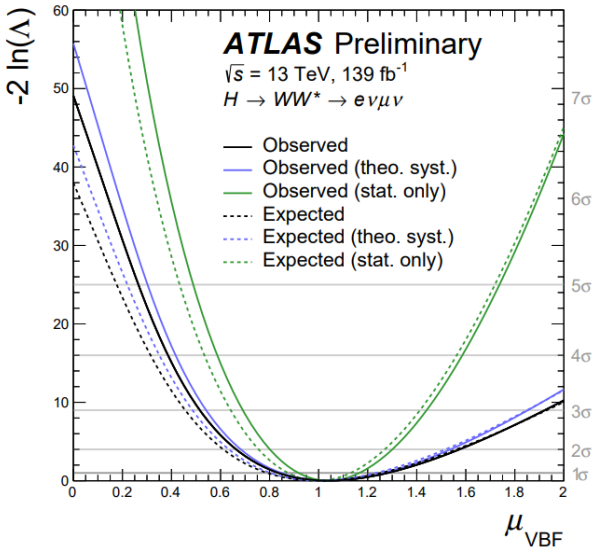
STXS - $H \to \gamma\gamma$

ATLAS

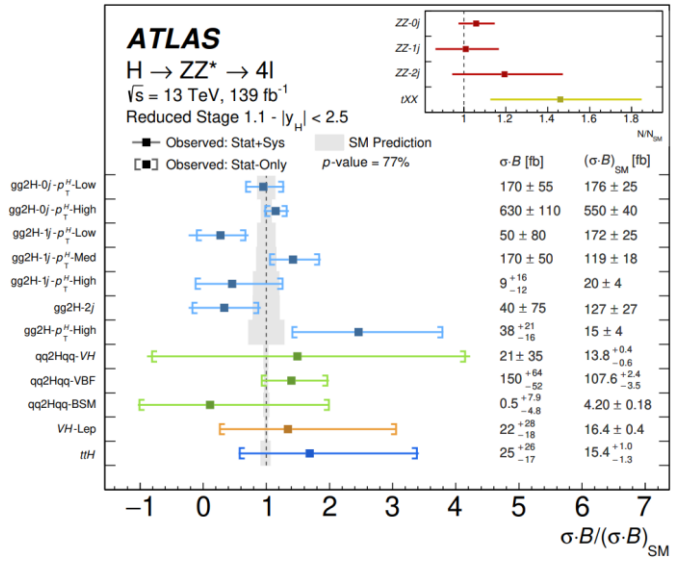
- Increased granularity; 27 STXS 1.2 categories from 88 reconstruction categories
- Simultaneous multi-class BDT for each STXS bin
- ggF and VBF stat.uncert. ≈ syst. uncert.
- Compatible with the SM (p-value: 3% - because of WH and ZH fluctuations)

CMS

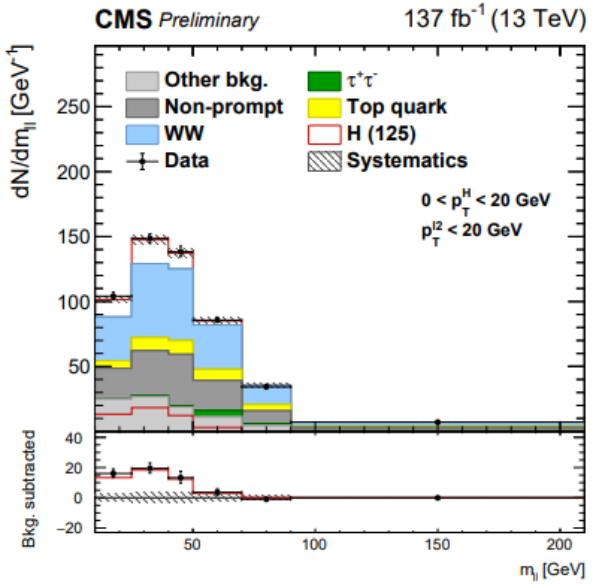
- Phase spaces for all five production modes using 81 categories at STXS stage 1.2
- Each region under dedicated BDT or DNN
- Compatible with the SM (p-value: 74%)



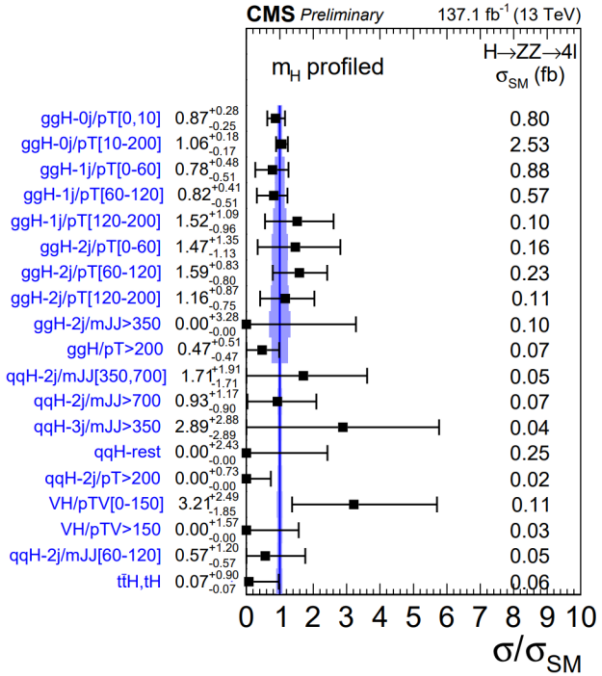
❖ ATLAS-CONF-2020-045



❖ CERN-EP-2020-034



❖ CERN-EP-2020-106



❖ CMS-PAS-HIG-19-001

Decay to bosons

STXS - $H \to VV$

ATLAS

- WW (VBF): optimisation of central jet veto and DNN discriminator in 7 regions
- WW (VBF): Significance: 7.0σ (6.2σ)
- ZZ: good modeling of all kinematic observables

CMS

- ZZ: 22 STXS 1.1 categories based on jet and lepton multiplicity and MEM-based discriminants
- ZZ: consistent with the SM with stat.≈ syst. uncert.
- WW: 30 STXS 1.1 categories using jet and lepton multiplicity and kinematic variables

Coupling combination

Global signal strength

CMS

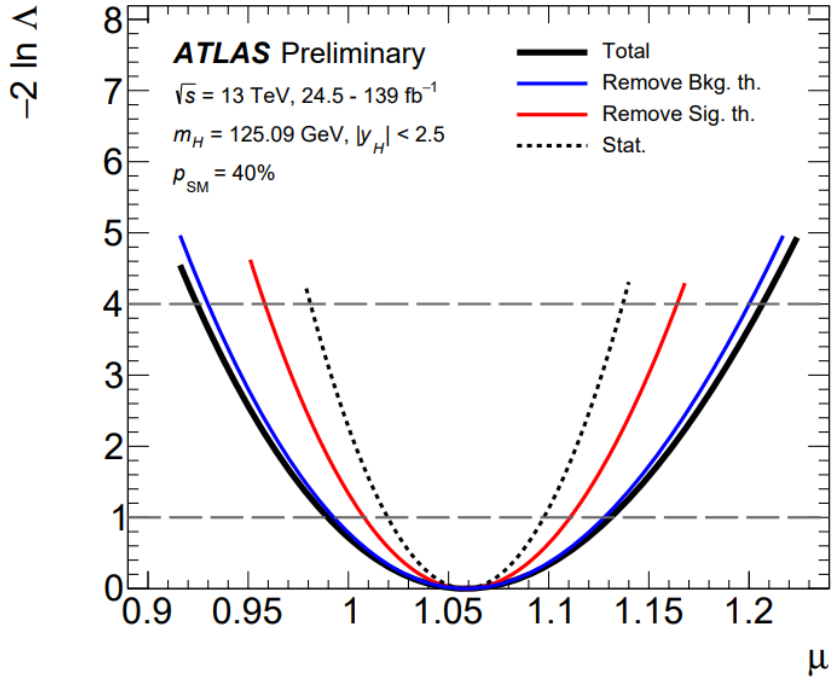
- 25% improvement in precision w.r.t. last combination
- Good agreement with SM expectation

$$\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(stat.) \pm 0.04(exp.) \pm 0.04(th.)$$

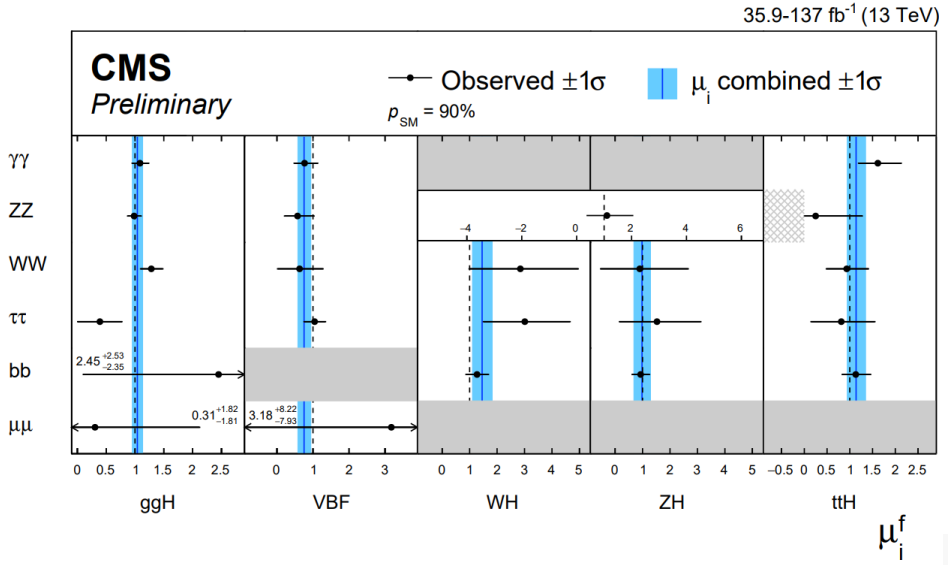
ATLAS

- Over 5σ in all five production modes
- ggF stat. error comparable with SM theory error
- Good agreement with SM expectation

$$\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(stat.) \pm 0.03(exp.) \; {}^{+0.05}_{-0.04}(th.)$$



❖ ATLAS-CONF-2020-027

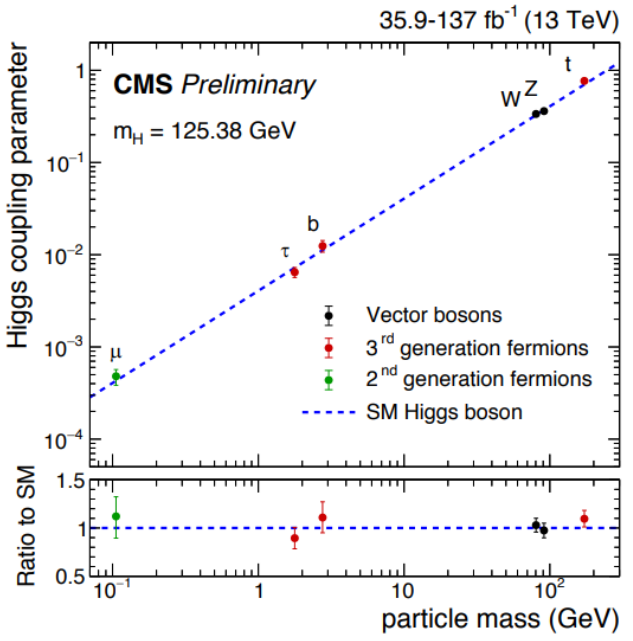


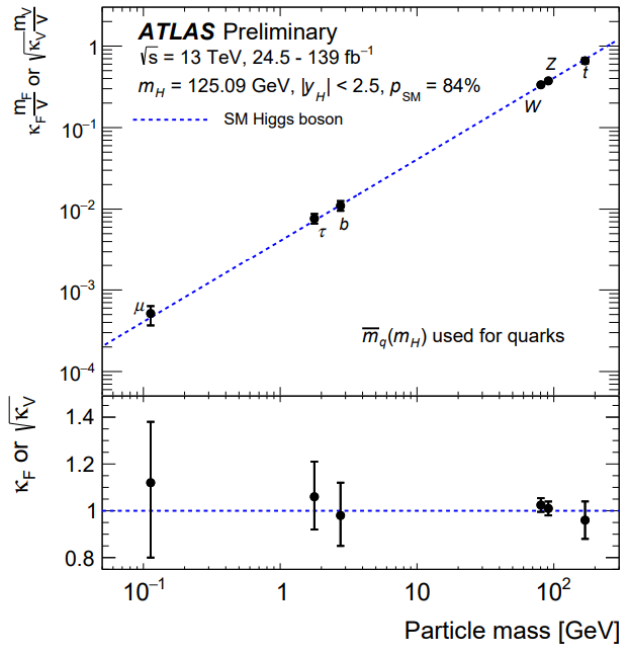
❖ CMS-PAS-HIG-19-005

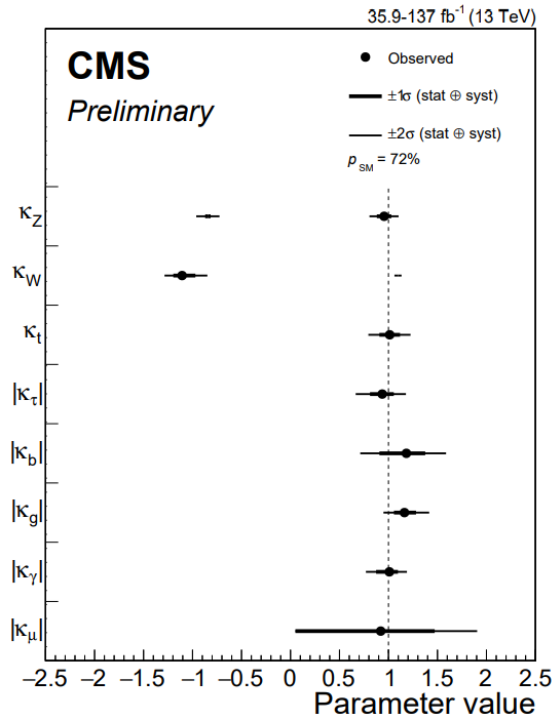
Coupling combination

Coupling modifiers (κ)

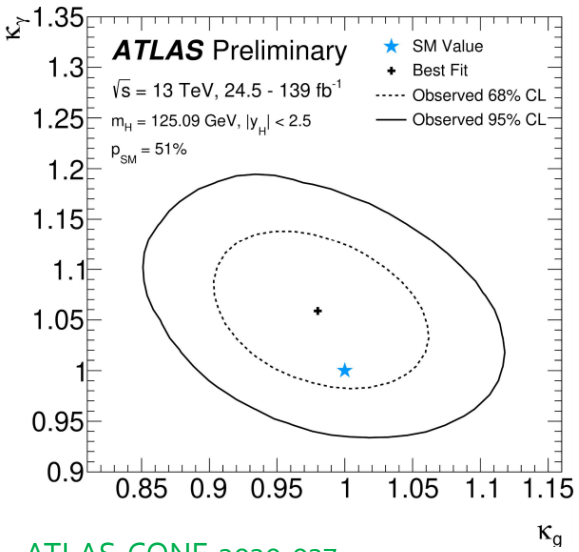
- Most couplings measured with 10-20% precision
- Effective couplings κ_g and κ_γ sensitive to new physics within their loops
- Constrain on invisible and undetected BF
- Excellent agreement of coupling through three orders of magnitude of particle mass







❖ CMS-PAS-HIG-19-005



❖ ATLAS-CONF-2020-027

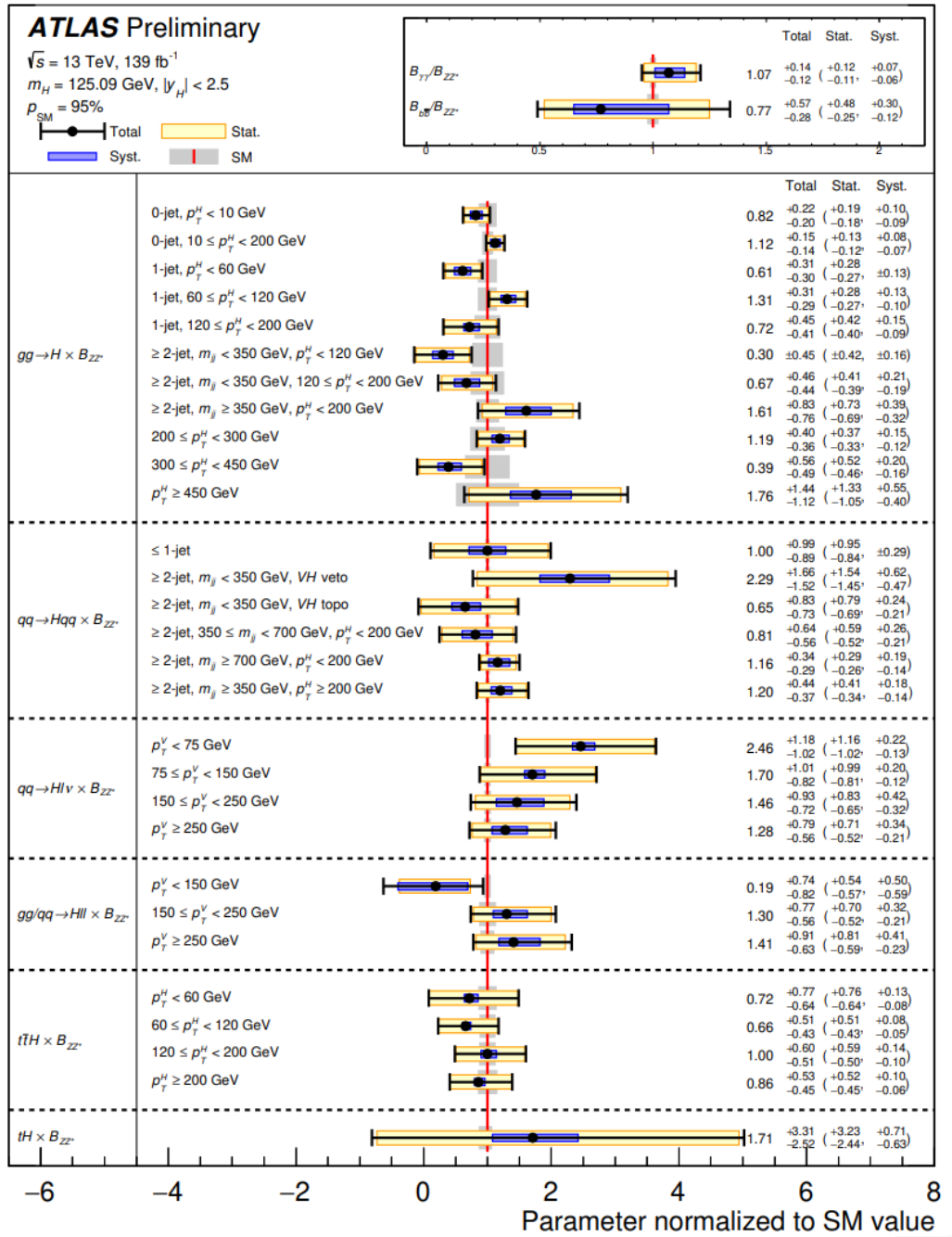
Coupling combination

STXS

- Fit parameters for ATLAS combination are the Higgs boson cross section in STXS region i times BF of $H \to ZZ^*$ decay, $(\sigma \times B)_{i,ZZ}$, and the ratios of BF, B_f / B_{ZZ}, for other final states f

$$(\sigma \times B)_{if} = (\sigma \times B)_{i,ZZ} \cdot \left(\frac{B_f}{B_{ZZ}} \right)$$

- Results are in agreement with the SM prediction with a p-value of $p_{SM} = 95\%$
- Differential measurements are **feasible with good precision in many categories**, in all production modes



❖ ATLAS-CONF-2020-027

Coupling combination

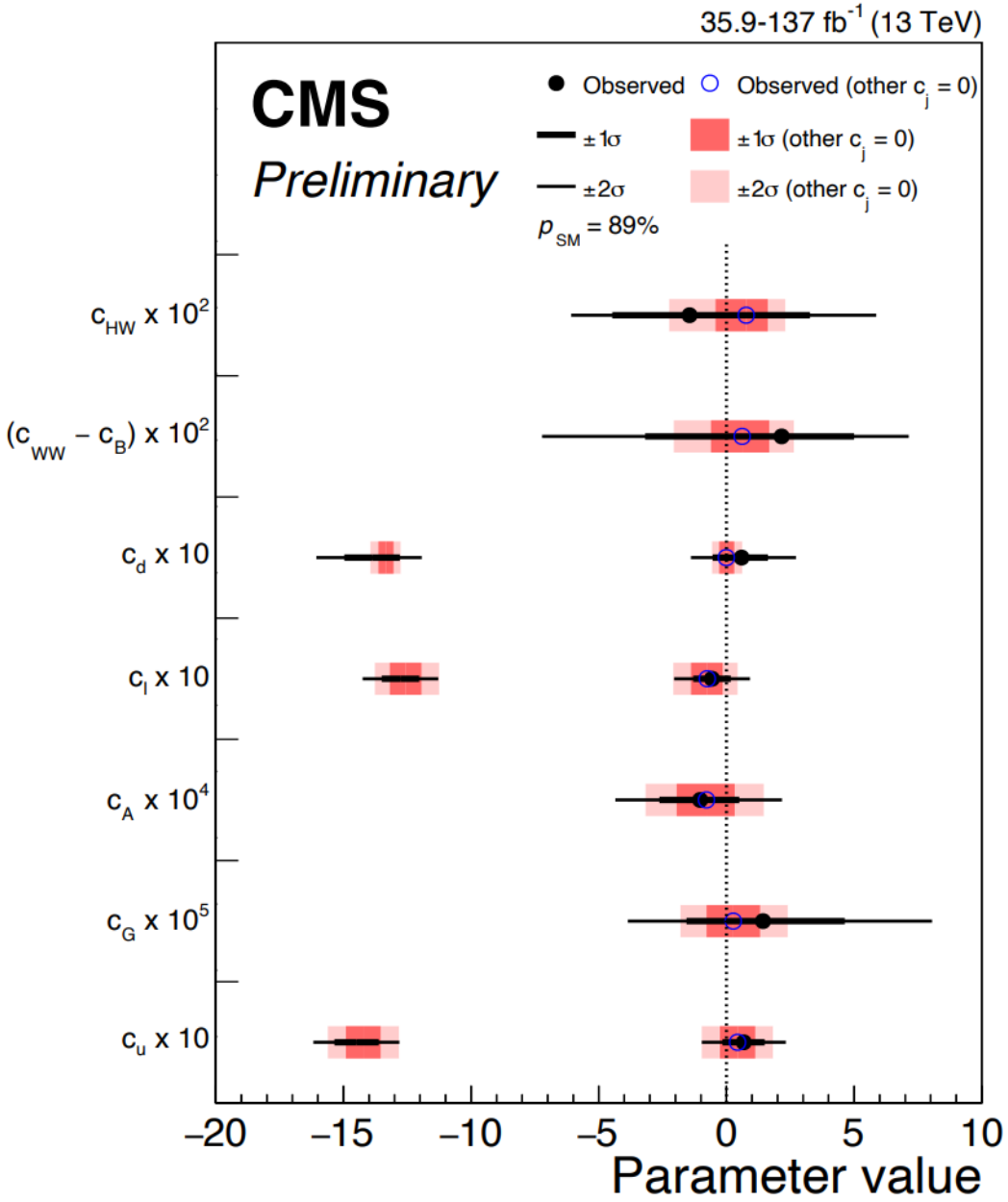
EFT coefficients

$$\mathcal{L}_{HEL} = \mathcal{L}_{SM} + \sum_j \frac{O_j f_j}{\Lambda^2}$$

$$\sigma_i = \sigma_i^{SM} + \sigma_i^{int} + \sigma_i^{BSM}$$

$$scaling_i(c_j) = \frac{\sigma_i^{EFT}}{\sigma_i^{SM}} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- STXS categorisation
- 7 HEL coefficients affecting the Higgs sector (CP-violating operators ignored)
- Coefficients compatible with SM expectation (~0)



❖ CMS-PAS-HIG-19-005

Coupling combination

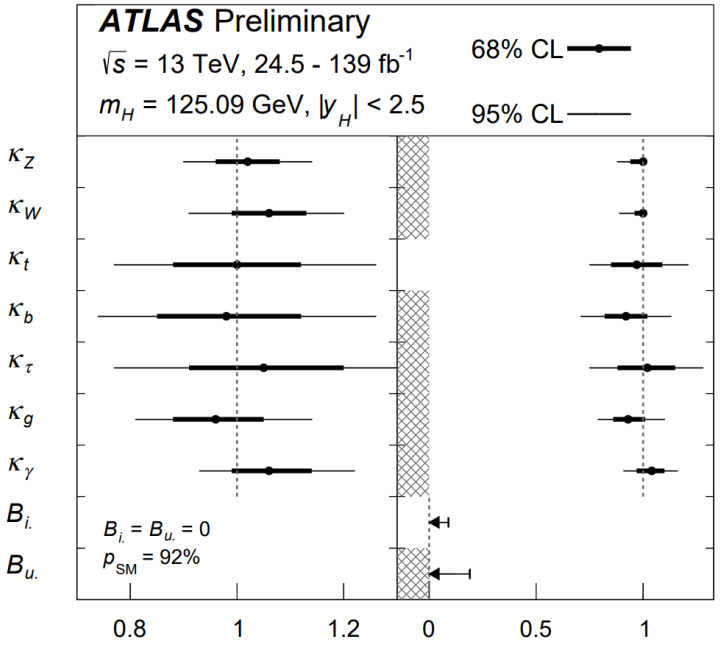
BSM interpretations

- $H \to gg$ and $H \to \gamma\gamma$ loop processes are parametrised using EFT coupling-strength modifiers κ_g and κ_γ
- BSM contributions to the total width ($B_{i.} < 0.09, B_{u.} < 0.19$ @ 95 CL) compatible with SM expectation
- Ratio of scale factors that represents the most model-independent determination of coupling-strength
- Compatibility with the SM hypothesis with p-value of: $p_{SM} = 92\ \%$

$$\Gamma_H(\kappa, B_{i.}, B_{u.}) = \kappa_H^2(\kappa, B_{i.}, B_{u.})\Gamma_H^{SM}$$

$$\kappa_H^2(\kappa, B_{i.}, B_{u.}) = \frac{\sum_j B_j^{SM}\kappa_j^2}{(1 - B_{i.} - B_{u.})}$$

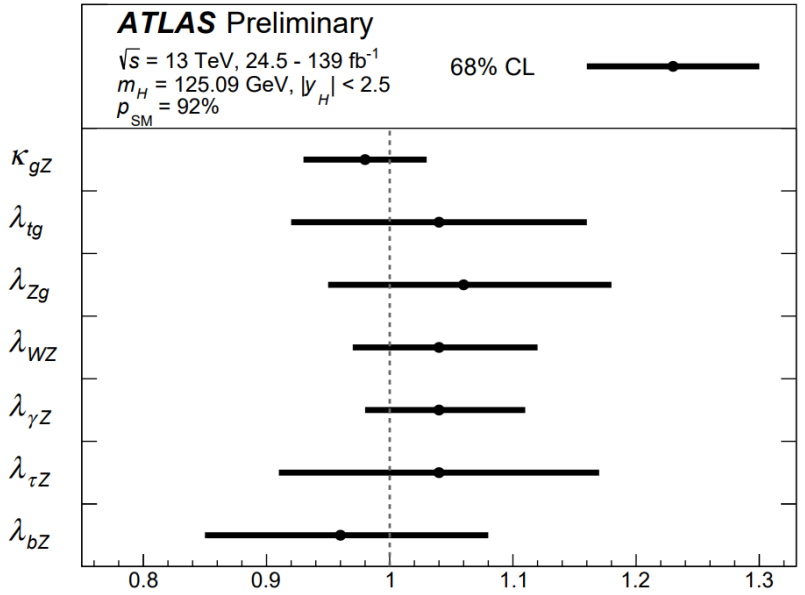
Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g\kappa_Z/\kappa_H$	0.98 ± 0.05
λ_{tg}	κ_t/κ_g	1.04 ± 0.12
λ_{Zg}	κ_Z/κ_g	$1.06\ ^{+0.12}_{-0.11}$
λ_{WZ}	κ_W/κ_Z	$1.04\ ^{+0.08}_{-0.07}$
$\lambda_{\gamma Z}$	κ_γ/κ_Z	$1.04\ ^{+0.07}_{-0.06}$
$\lambda_{\tau Z}$	κ_τ/κ_Z	1.04 ± 0.13
λ_{bZ}	κ_b/κ_Z	$0.96\ ^{+0.12}_{-0.11}$



Sensitive to new coloured particles in ggF loop

Required to be close to 1 by symmetry and LEP

Sensitive to new charged particles



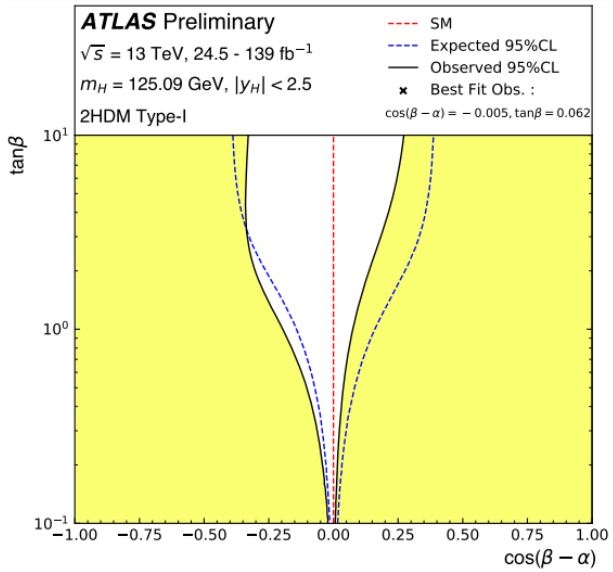
❖ ATLAS-CONF-2020-027

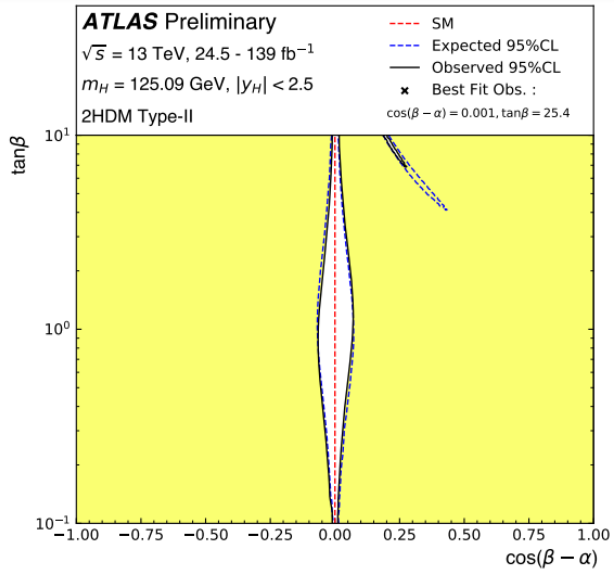
Coupling combination

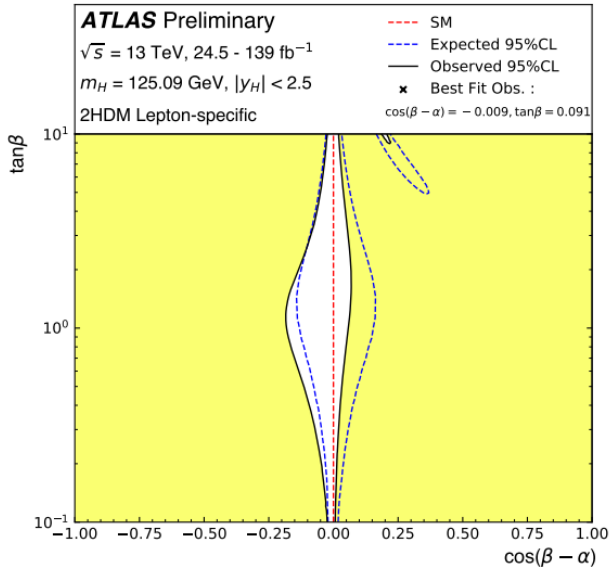
2HDM

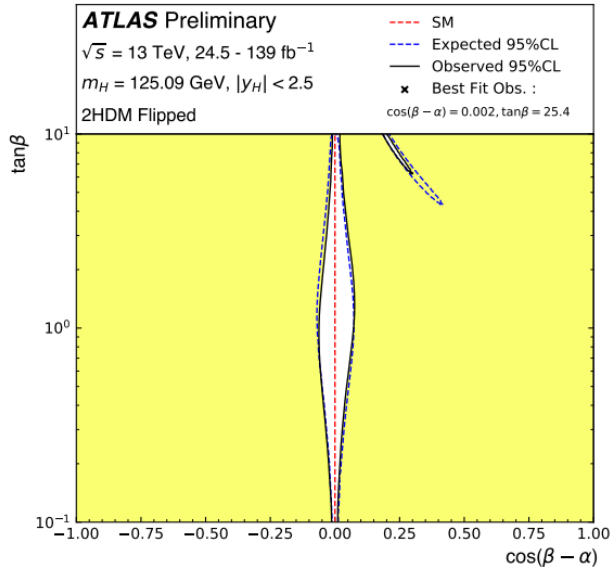
» Constraints on 4 2HDM benchmarks

- Type I: one doublet couples to bosons (fermiophobic) while the other to fermions
- Type II: one doublet couples to up-type quarks while the other to down-type quarks and charged leptons
- Lepton-specific: couplings to quarks as in type I and to charged leptons as in type II
- Flipped: coupling to quarks as in type II and to charged leptons as in type I









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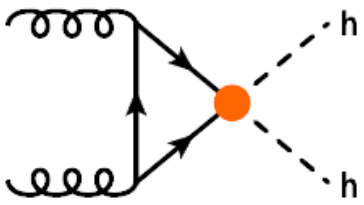
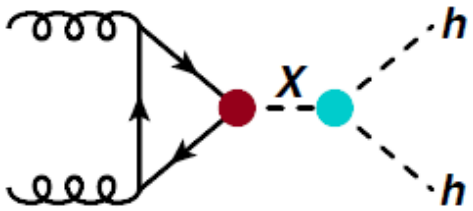
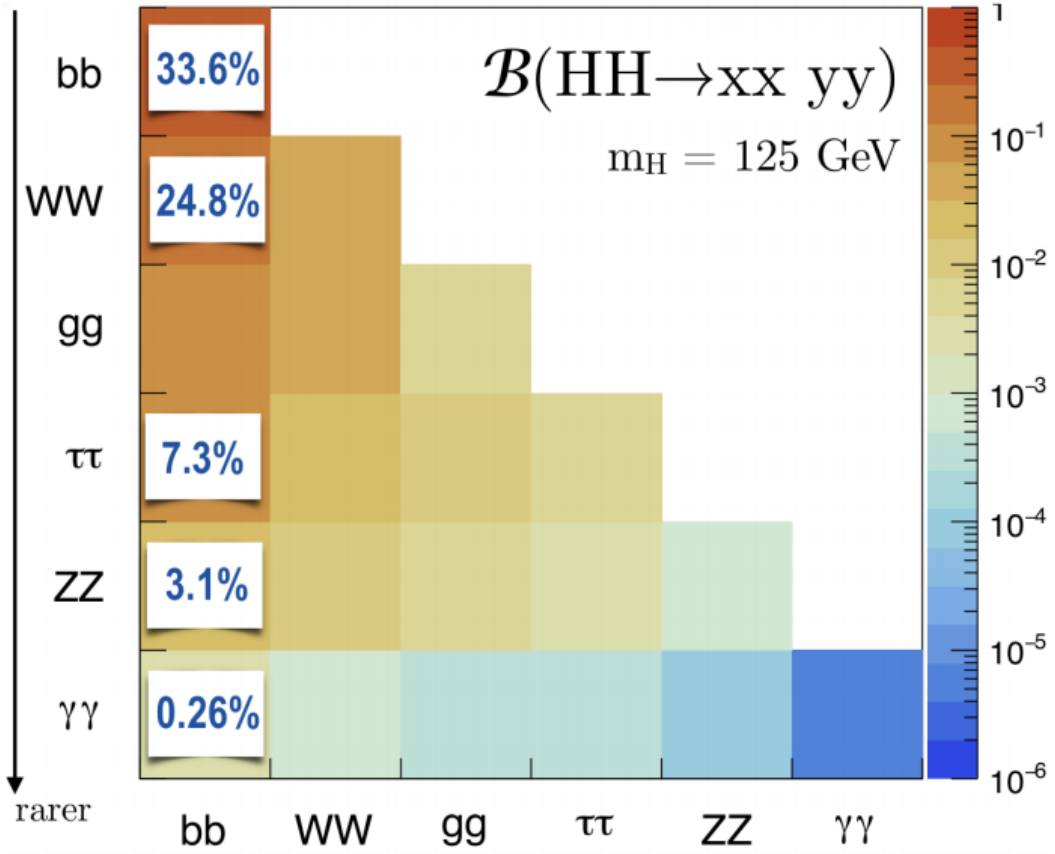


non-resonant



resonant

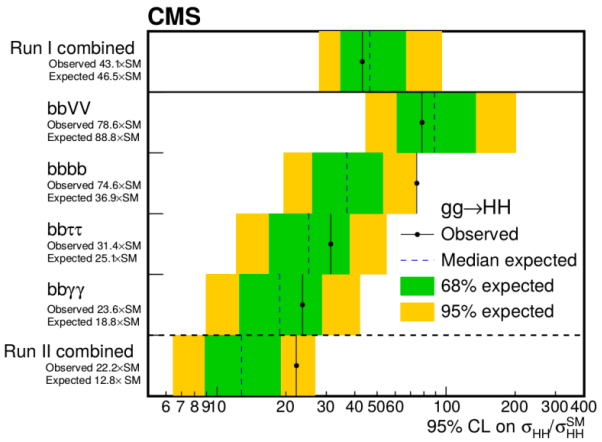


Higgs self-coupling

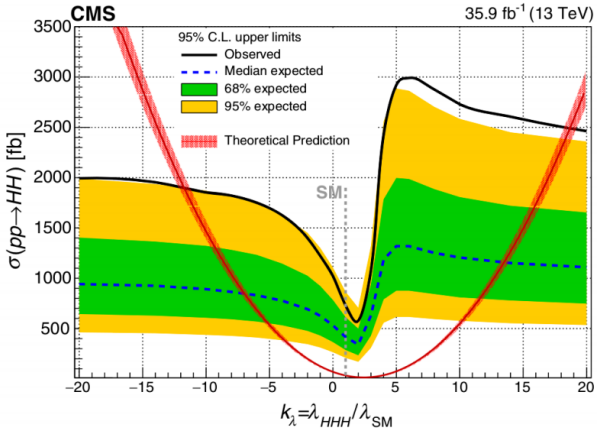
- Crucial to verify the EWK symmetry breaking mechanism of the SM
- Higgs self-coupling ⟶ di-Higgs final state (?)
- $\sigma(gg \to H) \sim 1600 \times \sigma(gg \to HH)$
- BSM can appear via resonant or non-resonant processes
- Various final states:
  - $b\bar{b}b\bar{b}$: highest BF, but high QCD contamination
  - $b\bar{b}WW$: high BF, but large irreducible $t\bar{t}$
  - $b\bar{b}\tau\tau$: relatively low background
  - $b\bar{b}ZZ$ and $b\bar{b}\gamma\gamma$: small BF, but low background
- Novel idea includes single-Higgs final state sensitive to Higgs self-coupling by NLO EW corrections

Higgs self-coupling

- Combination with Run-2 @36 fb^{-1} (non-resonant results)
- New results from CMS: $b\bar{b}ZZ$
- New results from ATLAS: $b\bar{b}b\bar{b}$(VBF), $b\bar{b}(WW, ZZ, \tau\tau)$, $b\bar{b}\tau\tau$(boosted)

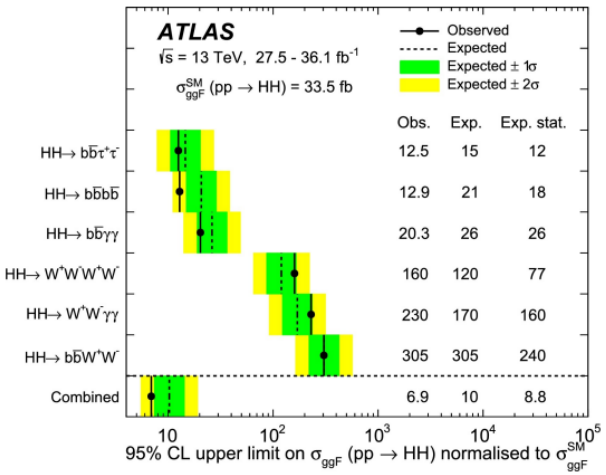


❖ Phys. Rev. Lett. 122, 121803



CMS

$$\sigma_{HH} < 22.2\ (12.8)$$
$$-11.8 < \kappa_\lambda < 18.8$$

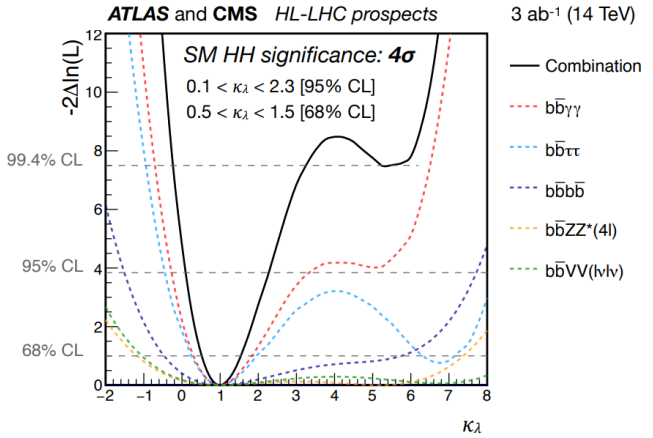


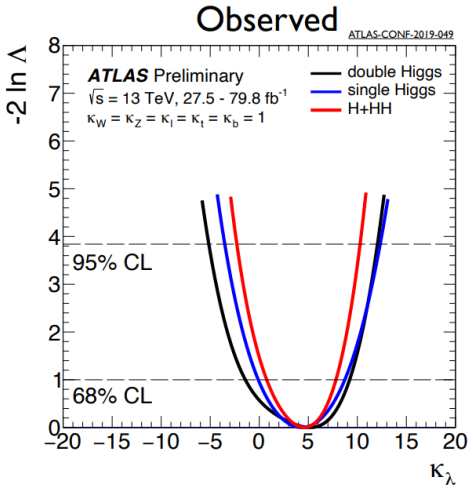
❖ Phys. Rev. Lett. B 800 (2020) 135103

ATLAS

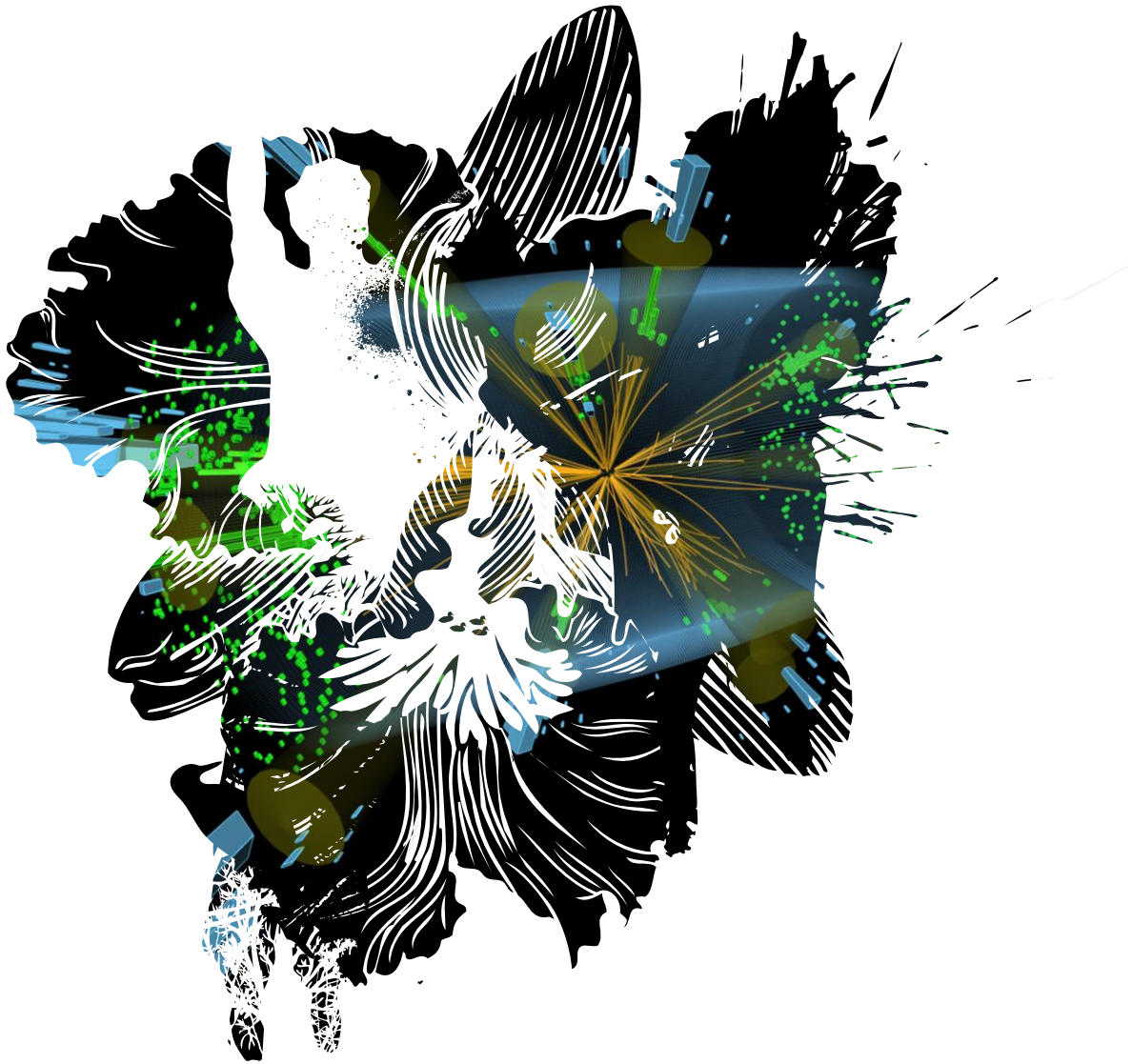
$$\sigma_{HH} < 6.9\ (10)$$
$$-5.0 < \kappa_\lambda < 12.0$$

❖ ATLAS-CONF-2019-049





❖ CERN Yellow Rep. 7 (2019) 221-584



Conclusions

- So far, the Higgs boson is compatible with the SM expectation, but there is still room for new physics
- Run-2 has started "the Higgs precision era"; where differential measurements became standard, and the statistical and systematic uncertainties are getting closer
- Run-3 and the HL-LHC are the stages to measure anomalous Higgs couplings and possibly observe new physics

ICNFP *2020*

The Higgs boson at the LHC

Thank You

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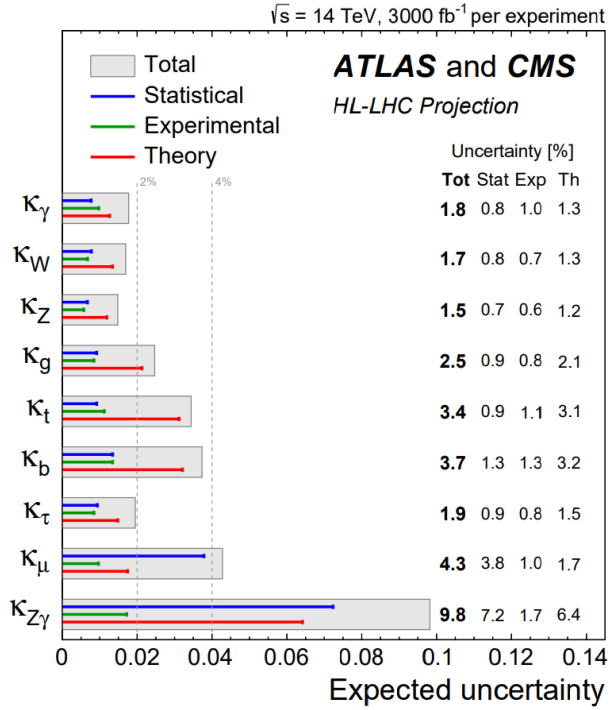
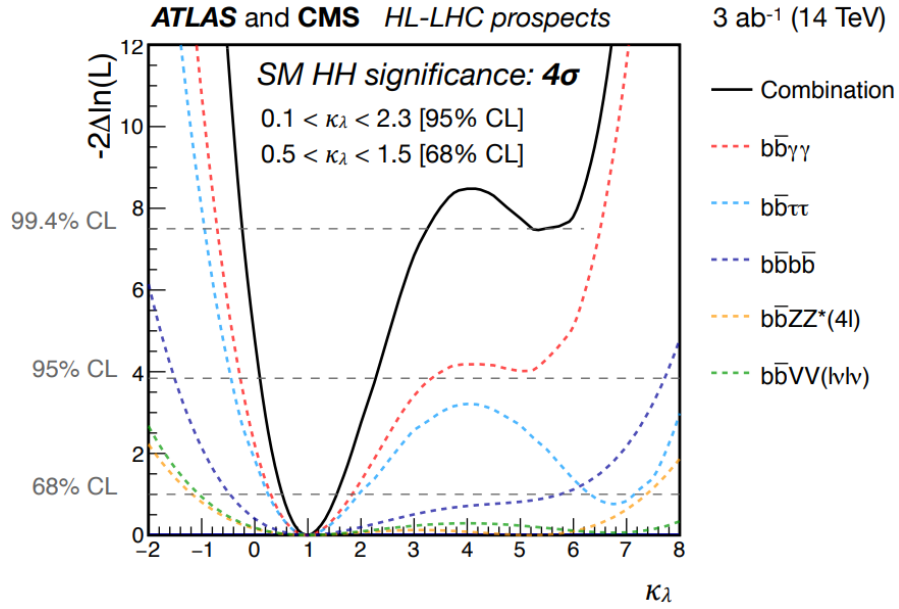
Prospects for High-luminosity LHC

HL-LHC





❖ CERN Yellow Rep.Monogr. 7 (2019) 221-584

Coupling combination

CMS	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb	$\mu\mu$
ggF	$77.4\ fb^{-1}$	$137\ fb^{-1}$	$35.9\ fb^{-1}$	$77.4\ fb^{-1}$	$35.9\ fb^{-1}$	$35.9\ fb^{-1}$
VBF	$77.4\ fb^{-1}$	$137\ fb^{-1}$	$35.9\ fb^{-1}$	$77.4\ fb^{-1}$	-	$35.9\ fb^{-1}$
VH	-	$137\ fb^{-1}$	$35.9\ fb^{-1}$	$77.4\ fb^{-1}$	$77.4\ fb^{-1}$	-
ttH	$77.4\ fb^{-1}$	$77.4\ fb^{-1}$	$77.4\ fb^{-1}$	$77.4\ fb^{-1}$	$77.4\ fb^{-1}$	-

ATLAS	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb	$\mu\mu$
ggF	$139\ fb^{-1}$	$139\ fb^{-1}$	$36.1\ fb^{-1}$	$36.1\ fb^{-1}$	-	$139\ fb^{-1}$
VBF	$139\ fb^{-1}$	$139\ fb^{-1}$	$36.1\ fb^{-1}$	$36.1\ fb^{-1}$	$36.1\ fb^{-1}$	$139\ fb^{-1}$
VH	$139\ fb^{-1}$	$139\ fb^{-1}$	-	-	$139\ fb^{-1}$	$139\ fb^{-1}$
ttH	$139\ fb^{-1}$	$139\ fb^{-1}$	-	-	$36.1\ fb^{-1}$	$139\ fb^{-1}$
tH	$139\ fb^{-1}$	-	-	-	-	-

- JHEP 02 (2020) 131
- Phys. Rev. Lett. 120 (2018) 211802