

# Rare decays of Higgs in Standard Model

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*On behalf of*  
ATLAS & CMS collaborations, LHC, CERN.



LHCP (virtual) conference, 2021

7 June, 2021.

# Motivation

- After a decade since the start of the LHC, the mandate to search extensively for indirect hints of *New Physics* (NP) beyond Standard Model (SM) has never been so strong.  
⇒ Higgs physics has grandly opened the door for it.
- The decay modes of Higgs, already observed, cover almost 90% of the total width.  
Measurements so far are consistent with SM.
- The dominant (2-body) decays proceed mostly via tree level processes:  $H \rightarrow WW$ ,  $ZZ$ ,  $ff$ ,  $f \equiv$  fermion.
- However, not all the decay channels of Higgs have been established as yet experimentally ⇒ incomplete characterization of the Higgs sector.
- Specially, the rare ones often proceed via loops; eg.,  $H \rightarrow \gamma\gamma$   
⇒ potentially get affected by physics beyond SM.

# Searching for rare decays of Higgs in SM

- $NP$  in loops  $\implies$  possible enhancement of branching fraction  $\implies$  observation with moderate luminosity ( $\mathcal{L}$ ).
- Hence it is crucial to look for as yet unseen **difficult and rare** decay modes for a better understanding of Higgs physics as well as to look for hints of  $NP$ .
- Run2 data provided 2-fold gain for probing such decay modes:
  - increase in Higgs production rate
  - increase in  $\mathcal{L}$
- However, expect small  $S/B$ .  
 $\implies$  Advanced analysis techniques have won the day in several cases!

H decay mode	Approx. $\mathcal{B}_{SM}$
$H \rightarrow bb$	0.58
$H \rightarrow W^+W^-$	0.22
$H \rightarrow gg$	0.086
$H \rightarrow \tau^+\tau^-$	0.063
$H \rightarrow c\bar{c}$	0.029
$H \rightarrow ZZ$	0.027
$H \rightarrow \gamma\gamma$	$2.3 \times 10^{-3}$
$H \rightarrow Z\gamma$	$1.5 \times 10^{-3}$
$H \rightarrow \mu^+\mu^-$	$2.2 \times 10^{-4}$
$H \rightarrow e^+e^-\gamma$	$7.2 \times 10^{-5}$
$H \rightarrow \mu^+\mu^-\gamma$ $m_{\ell\ell} < 30 \text{ GeV}$	$3.4 \times 10^{-5}$
$H \rightarrow ZJ/\psi$	$1.1 \times 10^{-6}$
..	..
$H \rightarrow e^+e^-$	$5 \times 10^{-9}$

- Measure signal strength:  
 $\mu = \sigma \cdot \mathcal{B}/(\sigma \cdot \mathcal{B})_{SM}$
- Estimate Higgs coupling modifier.  
For  $Hff$  coupling :  $\kappa_f = y_f/(y_f)_{SM}$

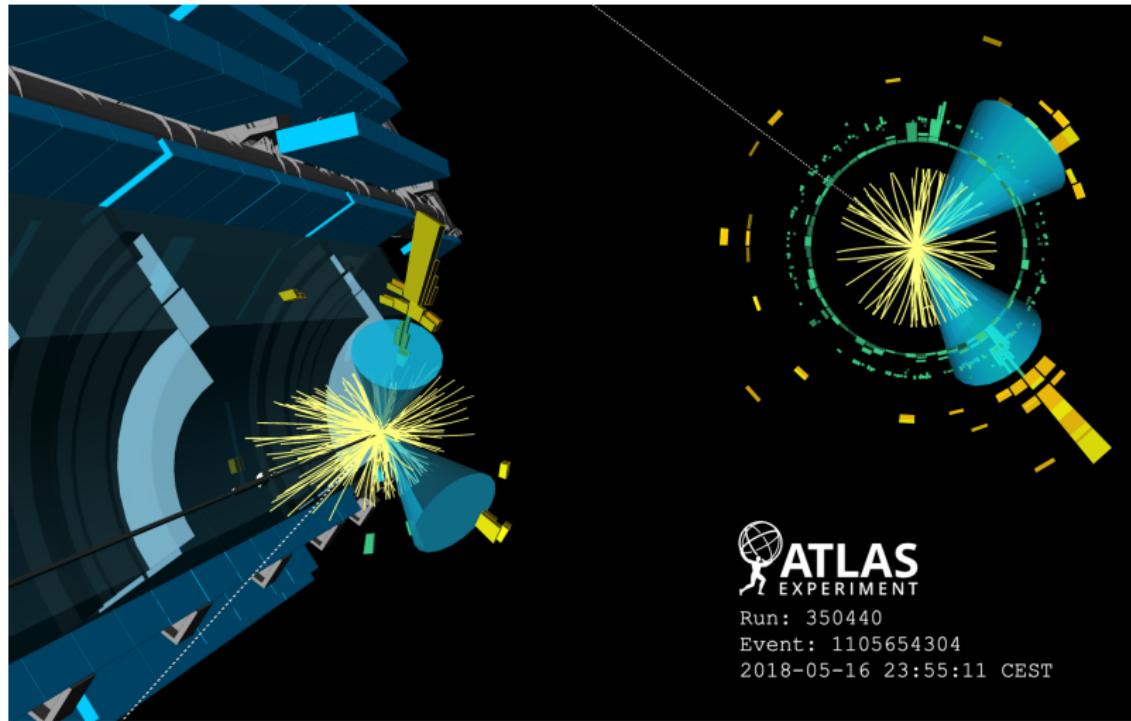
This talk will cover only recent results from exploration of the rare decays allowed in SM.

- Not really *rare*, but interesting; *extremely challenging* as well.
- **HOT, new result from ATLAS collaboration in this conference!**  
With complete Run2 data ( $\mathcal{L} = 139 \text{ fb}^{-1}$ ) **improved results** compared to the earlier ones from ATLAS and CMS based on limited Run2 data.
- VH,  $V = W/Z$  production with reasonably high  $p_T^V$  and  $W/Z \rightarrow \text{lepton(s)}$ .  
3 channels based on charged lepton multiplicity ( $n_\ell = 0, 1, 2$ ) and multiple further classifications  $\rightarrow 44$  regions (16 for signal)!
- Charm-tagging crucial: use multi-variate techniques. **Resolved c-jets**.  
c-jet ident. eff.: 27%, while  $b-$  and light-jet mis-ids: 8%, 1.6% resp.ly.
- Veto b-jets: i) **orthogonality with  $W/ZH, H \rightarrow b\bar{b}$  analysis**, ii) suppress other backgrounds
- Reconstruct  $m_{cc}$  from 2 highest  $p_T$  jets, atleast 1 *c-tagged*.
- Binned maximum likelihood fit of  $m_{cc}$  distribution, simultaneously in all categories, *along with WW, WZ & ZZ, where one  $W/Z \rightarrow \geq 1$  c-jet*.



# 0 lepton: $Z(\rightarrow \nu\nu)H(\rightarrow c\bar{c})$

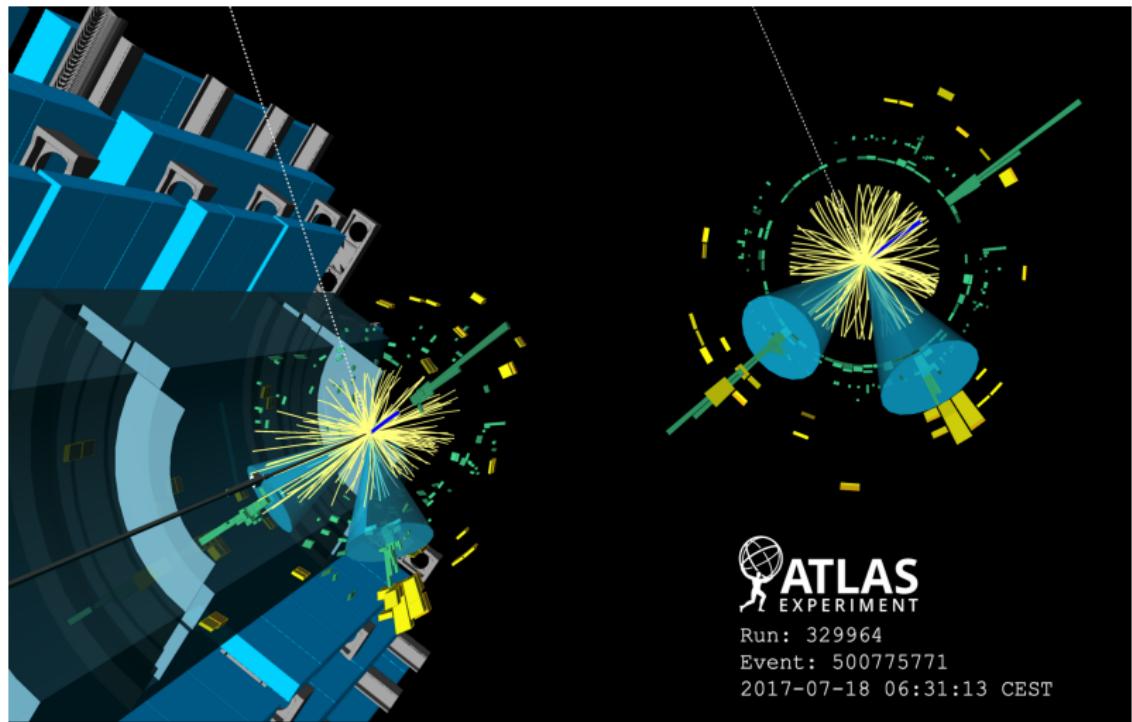
ATLAS: CONF-2021-21



$$p_T^{\text{miss}} = 155 \text{ GeV}, p_T^{c1} = 176 \text{ GeV}, p_T^{c2} = 22 \text{ GeV}, m_{cc} = 125 \text{ GeV}$$

1 lepton:  $W(\rightarrow e\nu)H(\rightarrow c\bar{c})$

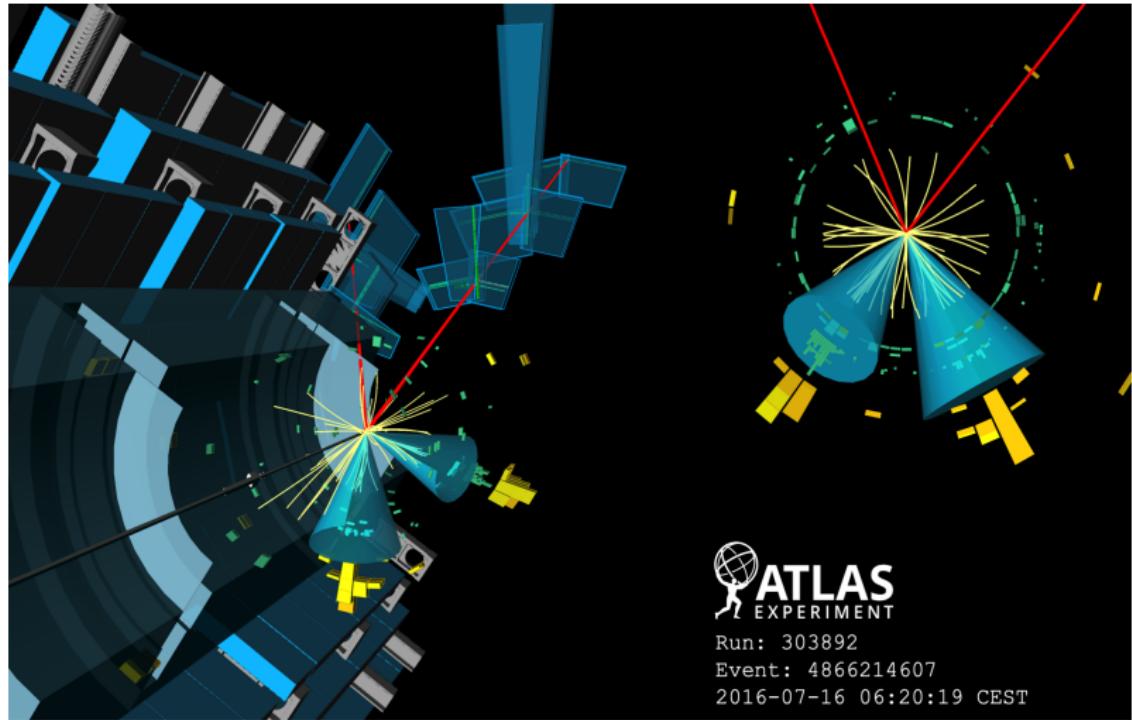
ATLAS: CONF-2021-21



$$p_T^{\text{miss}} = 116 \text{ GeV}, p_T^e = 151 \text{ GeV}, m_T^W = 72 \text{ GeV}, p_T^{c1} = 111 \text{ GeV}, p_T^{c2} = 81 \text{ GeV}, \\ m_{cc} = 123 \text{ GeV}$$

# 2 leptons: $Z(\rightarrow \ell\ell)H(\rightarrow c\bar{c})$

ATLAS: CONF-2021-21



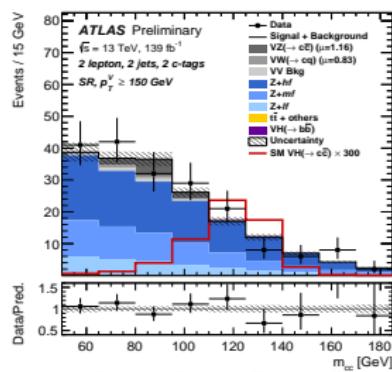
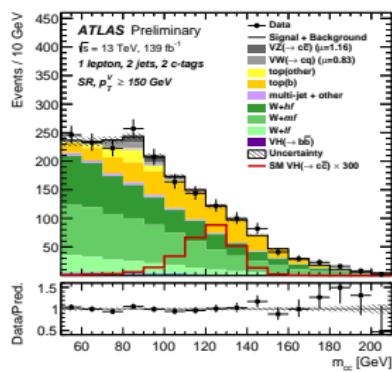
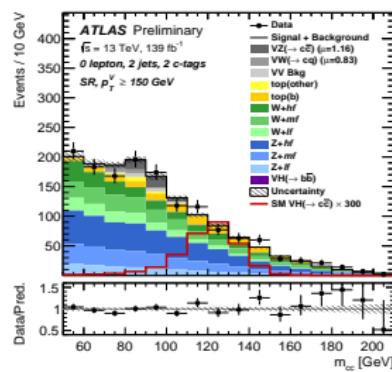
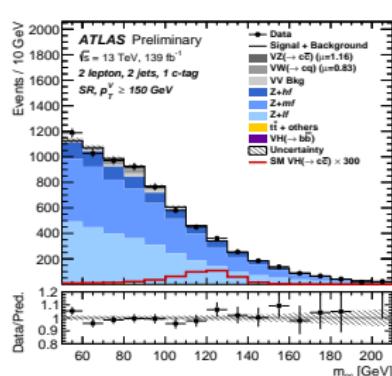
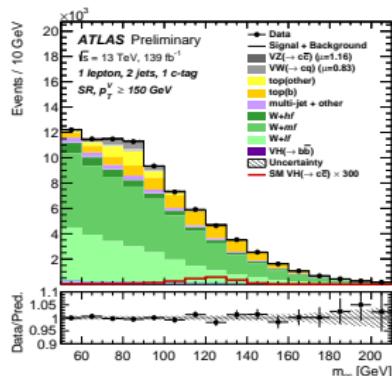
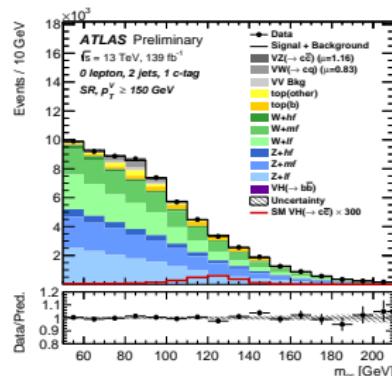
$$m_{\ell\ell} = 92 \text{ GeV}, p_T^Z = 150 \text{ GeV}, p_T^{c1} = 123 \text{ GeV}, p_T^{c2} = 71 \text{ GeV}, m_{cc} = 123 \text{ GeV}$$

## H → c $\bar{c}$ post-fit distributions in categories

ATLAS: CONF-2021-21

0, 1, 2 leptons →

1 c-tag, 2 c-tags ↓



# VW, VZ, VH signal strengths

ATLAS: CONF-2021-21

## Signal strengths:

$$\mu_{VH}(c\bar{c}) = -9 \pm 10.0 \text{ (stat)} \pm 12 \text{ (syst)}$$

$$\mu_{VW}(cq) = 0.83 \pm 0.11 \text{ (stat)} \pm 0.21 \text{ (syst)}$$

$$\mu_{VZ}(c\bar{c}) = 1.16 \pm 0.32 \text{ (stat)} \pm 0.36 \text{ (syst)}$$

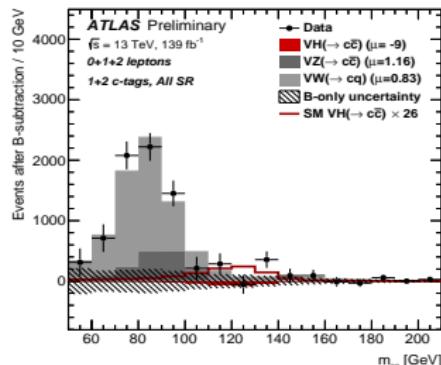
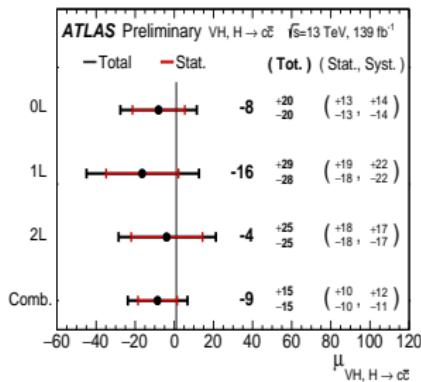
No excess in data.

Diboson significance obs.(exp.)

$$VW(cq) : 3.8(4.6)\sigma$$

$$VZ(cc) : 2.6(2.2)\sigma$$

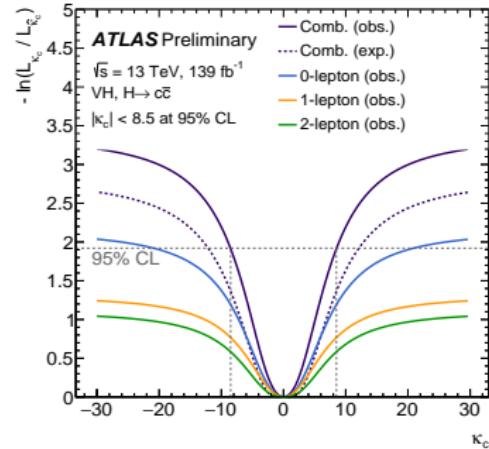
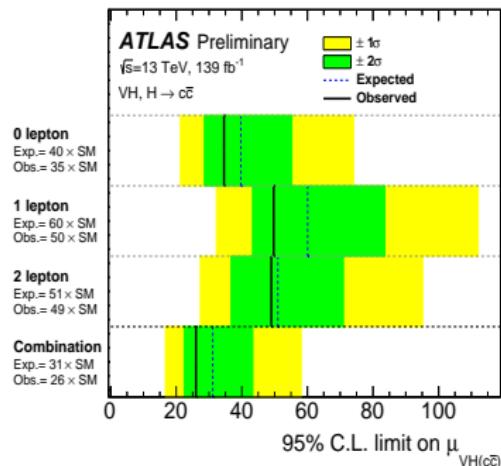
Compatibility with SM (all 3 POI equal to unity): @ 84%



Post-fit distributions, summed over all signal regions (1 c-tag & 2 c-tags), after bkg. subtraction except VW, VZ

$VH \rightarrow c\bar{c}$ ,  $VW(cq)$  &  $VZ(c\bar{c})$  with extracted  $\mu$  values and  $26 \times$  SM signal.

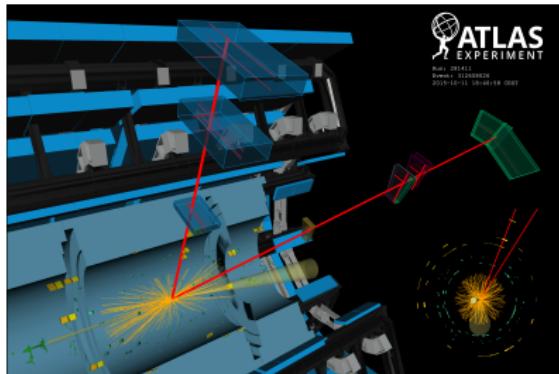
$VH, H \rightarrow b\bar{b}$  background 8 (2) times larger in the signal regions of 1 c-tag (2-c tags).



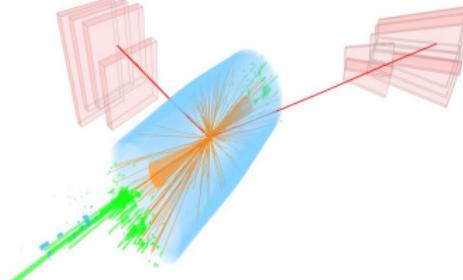
- At 95% CL, upper limit on signal strength observed (exp.)  
 $\mu_{VH}(c\bar{c}) = 26 (31^{+12}_{-8})$
- At 95% CL, constraint on coupling modifier: obs. (exp.)  
 $|\kappa_c| < 8.5 (12.4)$
- First direct limit on  $Hc\bar{c}$  interaction with minimal assumptions!

assume all other couplings are SM-like.

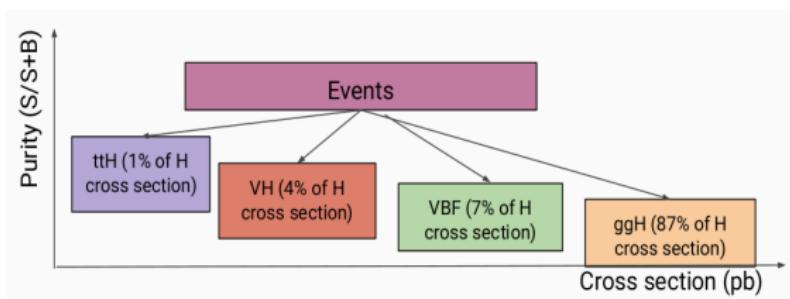
- Most probably the only 2nd generation interaction accessible at the LHC being a clean signature.
- Search for narrow resonance in invariant mass spectrum of dimuon above background of Drell-Yan,  $t\bar{t}$ , single top, dibosons, etc.
- $\sigma(pp \rightarrow H + X) \cdot \mathcal{B}(H \rightarrow \mu\mu)_{\text{SM}} \sim 10 \text{ fb}$
- $S/B \sim 1/500$  for  $m_{\mu\mu} : [120 - 130] \text{ GeV}$ .
- VBF process has the best sensitivity for combating the irreducible bkg of DY production of dimuons.



CMS Experiment at the LHC, CERN  
Data recorded: 2018-04-03 00:19:17.320393 GMT  
Run / Event / LS: 323840 / 44897008 / 05



- Multivariate analysis techniques used in several exclusive paths targeting kinematic features of the main production modes to enhance the sensitivity and maximise the reach.
- Categorization in CMS analysis:
  - VBF: VBF selection, no b-jets, no additional lepton (reject ttH, VH)
  - ggH: veto on VBF selection, no b-jets, no additional lepton
  - WH (ZH): no b jets (reject ttH), 1 (2) additional lepton from V decay.
  - ttH: leptonic (hadronic, only for CMS)  $\geq 1$  b-jet, 2 (1) additional  $\mu/e$



# Enhancing $H \rightarrow \mu\mu$ signal

ATLAS: PLB 812 (2021) 135980, CMS: JHEP 01 (2021) 148

- Mass resolution crucial

CMS  $\rightarrow \Delta m_{\mu\mu} \sim 1.5 - 2.5$  GeV,  
depending on  $p_T$ ,  $\eta$  of the muons.

- Recovery of final state radiation:

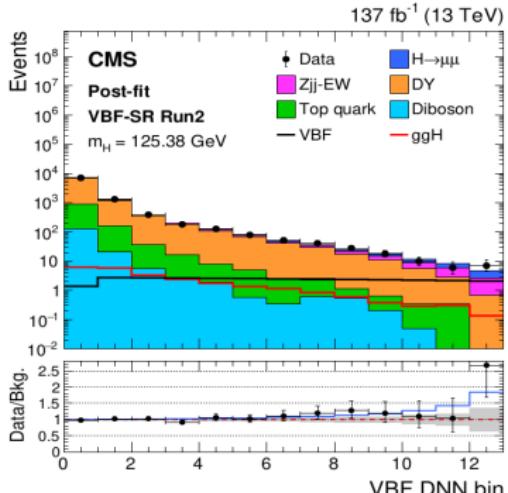
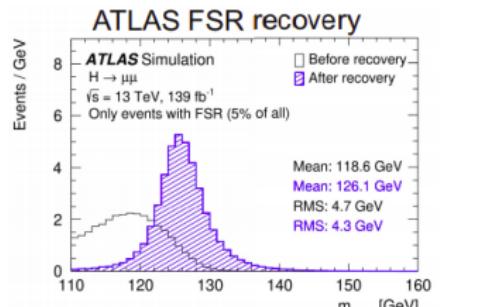
ATLAS  $\rightarrow p_T$  resolution (3%)  
 $\rightarrow$  signal efficiency (2%)

- Primary vertex in muon track fit

ATLAS  $\rightarrow p_T$  resolution (3 - 10%)

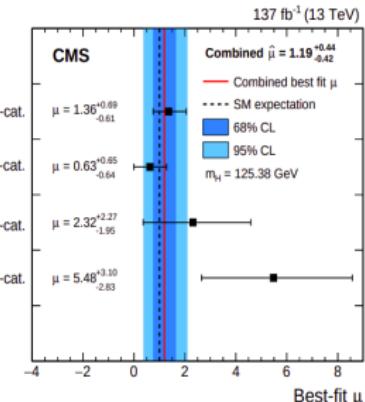
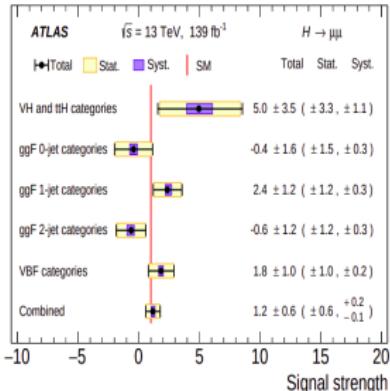
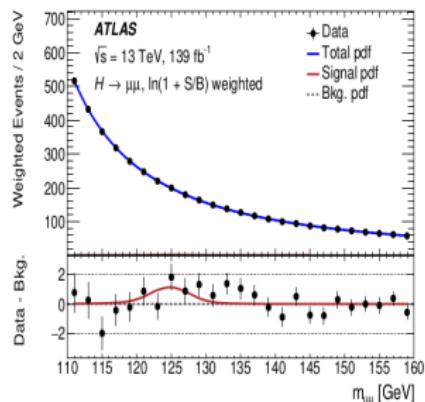
- Fit  $m_{\mu\mu}$  in range [110, 150/160] GeV

- Background determined from data using parametric modeling;  
except for VBF category in CMS, where background is estimated from Monte Carlo and signal extracted by fitting DNN discriminator score.



# $H \rightarrow \mu\mu$ results

ATLAS: PLB 812 (2021) 135980, CMS: JHEP 01(2021)148



- **ATLAS: Signal significance:  $2\sigma$  (exp.  $1.7\sigma$ )**  
**Signal strength**  $\mu = 1.2 \pm 0.6(\text{stat})^{+0.2}_{-0.1}(\text{syst})$   
Assuming SM production rate,  $\mathcal{B}(H \rightarrow \mu\mu) < 4.7 \times 10^{-4}$  at 95% CL.
- **CMS: Signal significance:  $3\sigma$ , (exp.  $2.5\sigma$ )**  
**Signal strength:**  $\mu = 1.19^{+0.44}_{-0.39}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$   
 $0.8 \times 10^{-4} < \mathcal{B}(H \rightarrow \mu\mu) < 4.5 \times 10^{-4}$
- **First evidence of Higgs interaction with 2nd generation fermions!**

# Higgs coupling to muons

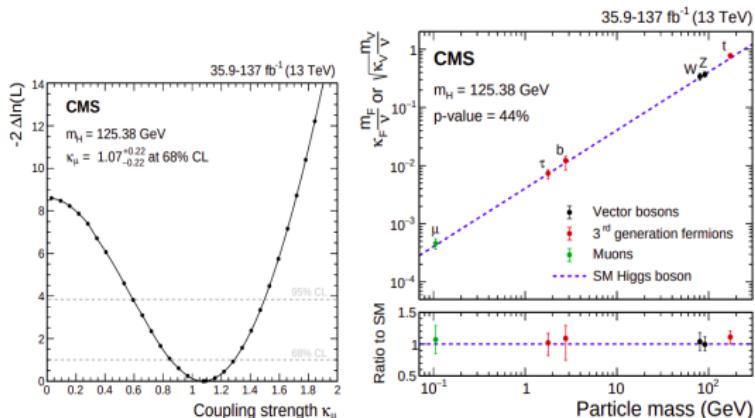
CMS: JHEP 01(2021)148

- at 68% CL

$$0.85 < \kappa_\mu < 1.29$$

- Best fit:

$$\kappa_\mu = 1.07$$



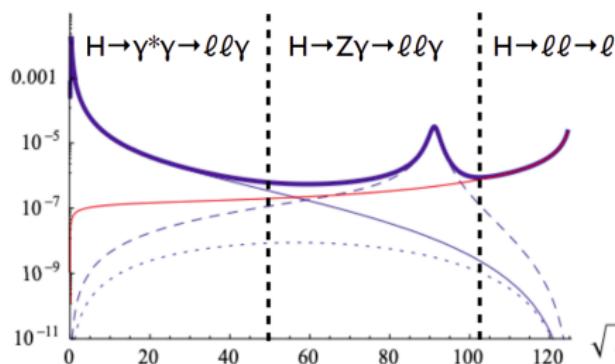
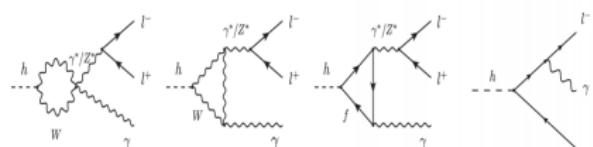
- $H\mu\mu$  coupling strength using resolved kappa framework → combine measurements of other Higgs channels to extract  $\kappa_\mu$ .
- Coupling vs. mass relation agrees with SM expectations over 3 orders of magnitude!  $\implies$  underlines remarkable success of SM.
- Assuming no improvements or losses, expect  $\sim 4\sigma$  significance per experiment using Run2+Run3 datasets.

# $H \rightarrow \gamma^*(\rightarrow \ell^+\ell^-)\gamma$ decay

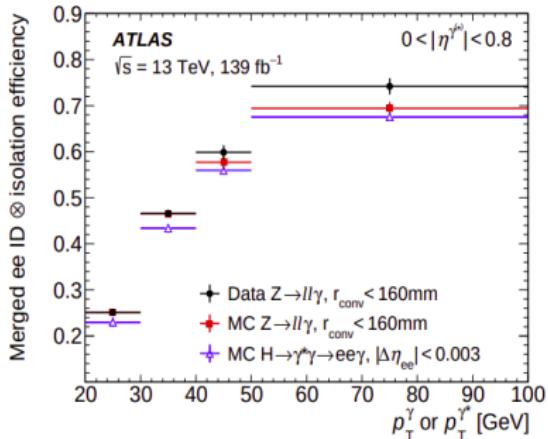
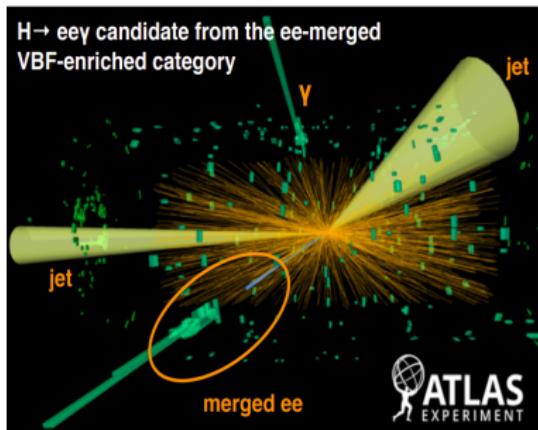
ATLAS: 10.1016/j.physletb.2021.136412

- Numerous loop-induced processes!
- 3 particles in the final state  $\rightarrow$  suitable for probing CP nature of Higgs.
- Diverse kinematics  $\rightarrow$  dedicated analyses for different regions of phase space.
- For high  $m_{\ell\ell} = M_Z \pm 10$  GeV, extracted signal strength  $\mu = 2.0 \pm 0.9$  (stat)  $\pm 0.4/0.3$  (syst)  
**obs.(exp.) significance**  $2.2(1.2)\sigma$

full Run2 data, ATLAS: PLB 809(2020) 135754



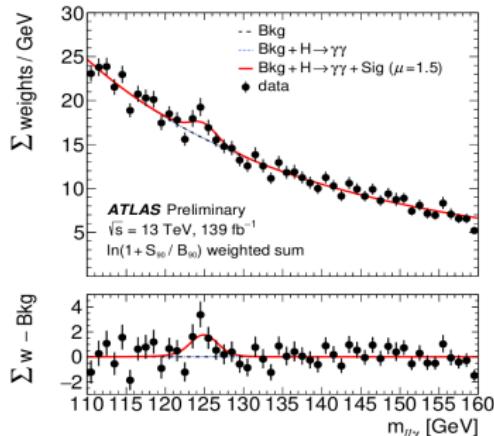
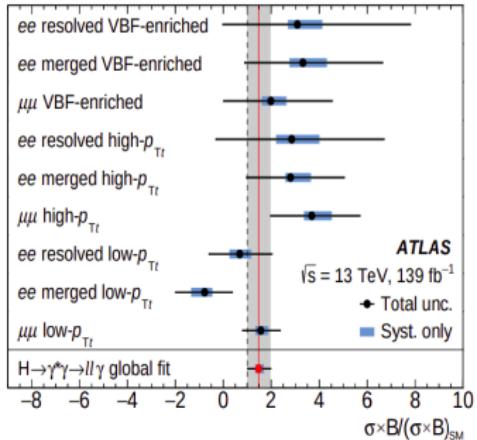
- First evidence of the Higgs boson decaying to low mass dilepton system  $m_{\ell\ell} < 30$  GeV  $\mathcal{B}_{SM} \sim \mathcal{O}(10^{-5})$ .  
⇒ First evidence for any  $\ell\ell\gamma$  decay of Higgs!
- One of the rarest Higgs boson decays seen at the LHC till now.



- Boosted and hence **merged**  $e^+e^-$  **pair** ( $p_T^e > 20$  GeV) produce overlapping shower in electromagnetic calorimeter  
→ **recovery crucial**.  
Dedicated reconstruction using info from various subsystems.
- Kinematics:  $p_T^\gamma/m_{ll\gamma} > 0.3$ ,  $p_T^{\ell\ell}/m_{ll} > 0.3$

## Results on $H \rightarrow \gamma^*(\rightarrow \ell^+\ell^-)\gamma$

ATLAS: 10.1016/j.physletb.2021.136412



- Fitted range  $105 < m_{\ell\ell\gamma} < 160$  GeV,  $\Delta m_{\ell\ell\gamma} = 1 - 3\%$
  - **Signal strength**  $\mu = 1.5 \pm 0.5$  (stat) $^{+0.2}_{-0.1}$  (syst) =  $1.5 \pm 0.5$   
**Signal significance**  $3.2\sigma$
  - **Fiducial cross section**  $\times \mathcal{B}(H \rightarrow \ell\ell\gamma) = 8.7^{+2.8}_{-2.7}$  fb  
 $= 8.7 \pm 2.7$  (stat.) $^{+0.7}_{-0.6}$  (syst.) fb.

# Conclusion

- Studying rare decays of Higgs is essential for a critical probe of Higgs sector as well as to search for indirect hints of beyond Standard Model physics.
- Several interesting decay modes of Higgs have already started showing up in the LHC experiments.

**Already prized efforts: Higgs decays to 2nd generation fermions:**

$H \rightarrow c\bar{c}$ ,  $H \rightarrow \mu\mu$

Though miles to go before we sleep!

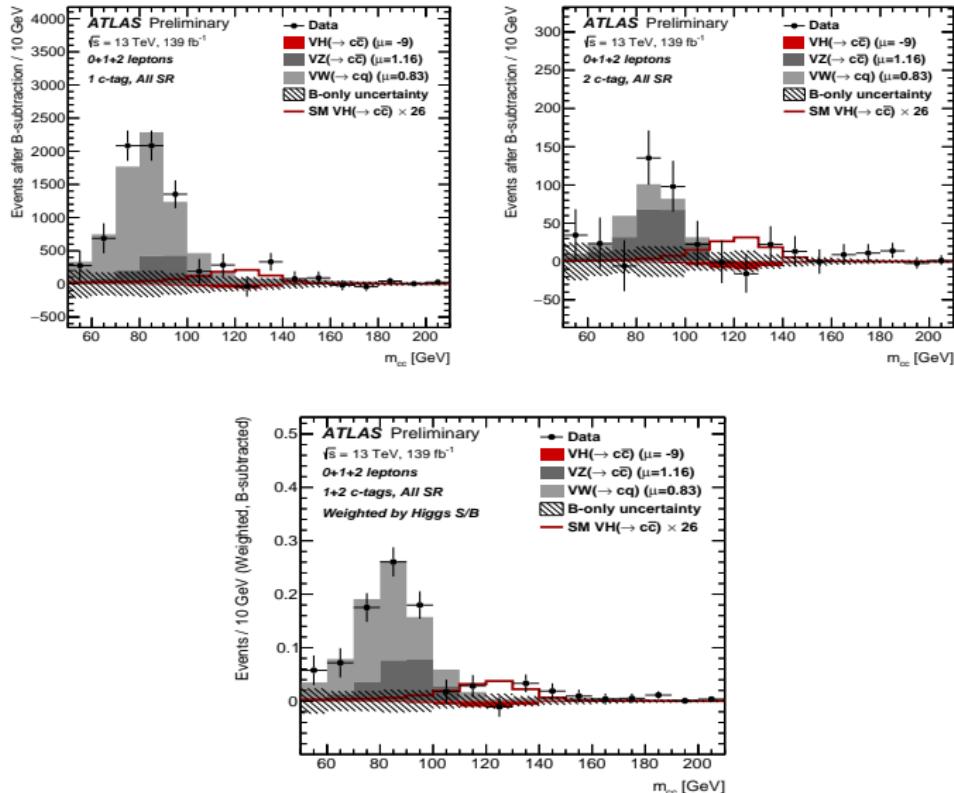
- Complete analysis of legacy LHC Run2 yet to be completed  $\Rightarrow$  stay tuned.
- With Run3 data (expected  $\mathcal{L} \sim 200 \text{ fb}^{-1}$ ), existence of some more of the rare decays may be established.
- With vast amount of data expected from the High-Luminosity LHC programme, such studies will be the new norm.

**Thank you!**

# Backup

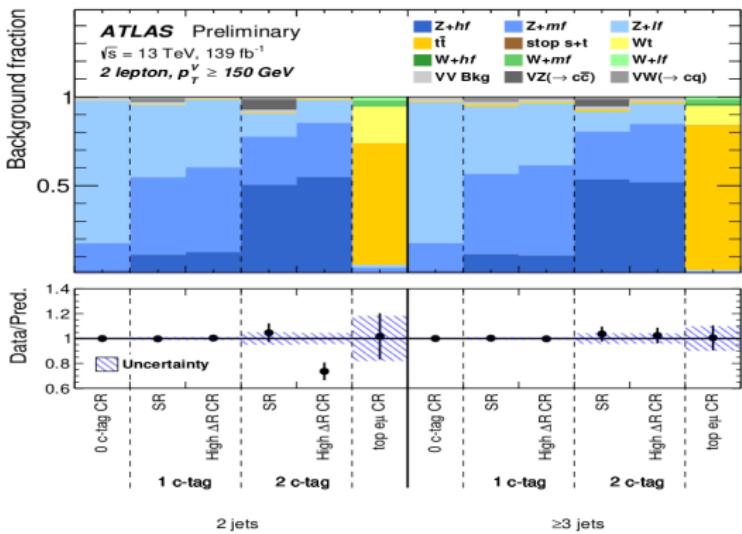
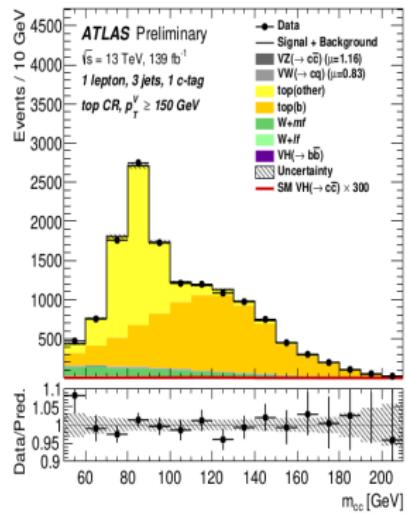
# $H \rightarrow c\bar{c}$ event distribution: 1 c-tag, 2 c-tags

ATLAS: CONF-2021-21



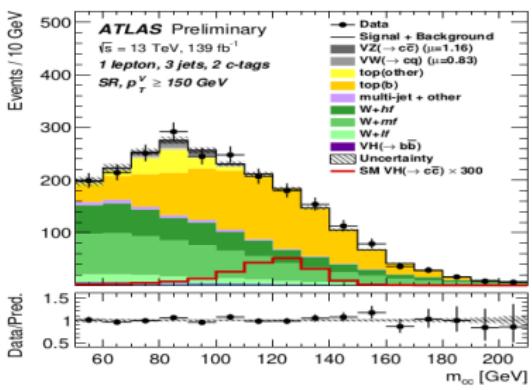
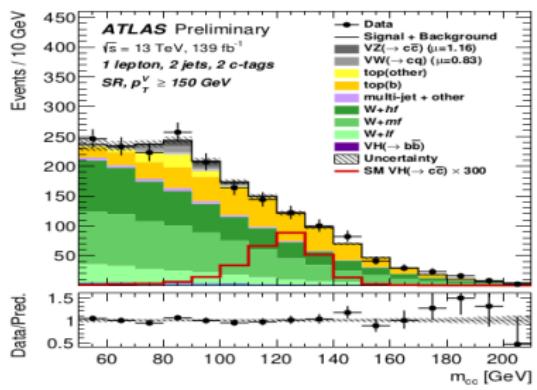
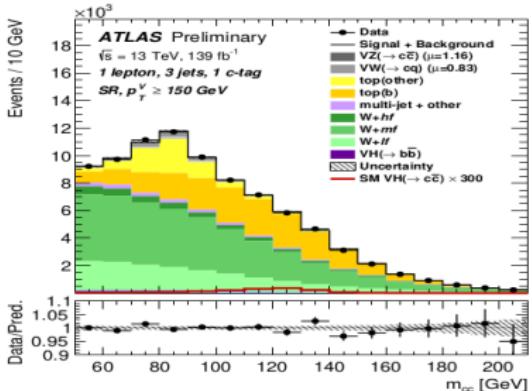
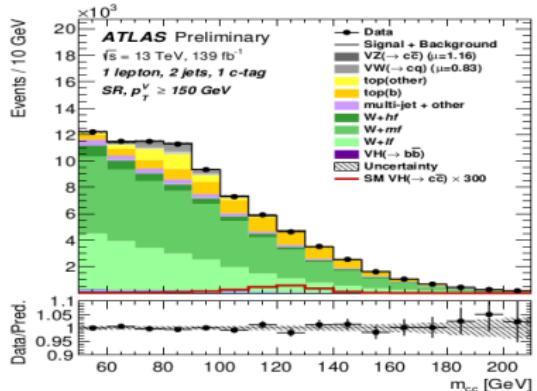
# $H \rightarrow c\bar{c}$ background composition (2 $\ell$ SR, CR)

ATLAS: CONF-2021-21



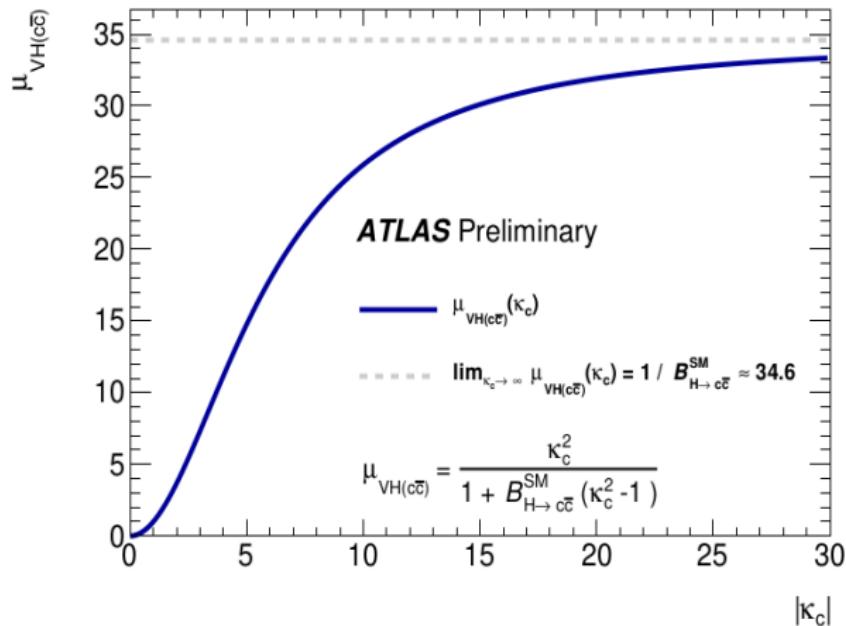
# $H \rightarrow c\bar{c}$ top background (1 $\ell$ category)

ATLAS: CONF-2021-21



Background	$p_T^V$	Jets	Value
top(b)			$0.91 \pm 0.06$
top(other)			$0.94 \pm 0.08$
$t\bar{t}$ (2 lep)	$p_T^V > 150$ GeV	2	$0.76 \pm 0.22$
		3	$0.96 \pm 0.13$
$W+hf$	$75 < p_T^V < 150$ GeV	2	$1.08 \pm 0.08$
		3	$1.06 \pm 0.07$
$W+mf$			$1.16 \pm 0.35$
$W+lf$		2	$1.02 \pm 0.04$
		3	$0.97 \pm 0.05$
$Z+hf$	$p_T^V > 150$ GeV		$1.19 \pm 0.22$
	$75 < p_T^V < 150$ GeV		$1.25 \pm 0.25$
$Z+mf$	$p_T^V > 150$ GeV		$1.10 \pm 0.15$
	$75 < p_T^V < 150$ GeV		$1.11 \pm 0.15$
$Z+lf$	$p_T^V > 150$ GeV	2	$1.07 \pm 0.03$
		3	$1.08 \pm 0.05$
	$75 < p_T^V < 150$ GeV	2	$1.12 \pm 0.04$
		3	$1.07 \pm 0.06$

Source of uncertainty	$\mu_{VH(c\bar{c})}$	$\mu_{VW(cq)}$	$\mu_{VZ(c\bar{c})}$
Total	15.3	0.24	0.48
Statistical	10.0	0.11	0.32
Systematics	11.5	0.21	0.36
<b>Statistical uncertainties</b>			
Data statistics only	7.8	0.05	0.23
Floating normalisations	5.1	0.09	0.22
<b>Theoretical and modelling uncertainties</b>			
$VH(\rightarrow c\bar{c})$	2.1	< 0.01	0.01
$Z + \text{jets}$	7.0	0.05	0.17
Top-quark	3.9	0.13	0.09
$W + \text{jets}$	3.0	0.05	0.11
Diboson	1.0	0.09	0.12
$VH(\rightarrow b\bar{b})$	0.8	< 0.01	0.01
Multi-Jet	1.0	0.03	0.02
<b>Simulation statistics</b>	<b>4.2</b>	<b>0.09</b>	<b>0.13</b>
<b>Experimental uncertainties</b>			
Jets	2.8	0.06	0.13
Leptons	0.5	0.01	0.01
$E_T^{\text{miss}}$	0.2	0.01	0.01
Pile-up and luminosity	0.3	0.01	0.01
Flavour tagging	$c$ -jets	1.6	0.05
	$b$ -jets	1.1	0.01
	light-jets	0.4	0.01
	$\tau$ -jets	0.3	0.01
Truth-flavour tagging	$\Delta R$ correction	3.3	0.10
	Residual non-closure	1.7	0.03



# $H \rightarrow c\bar{c}$ signal selection

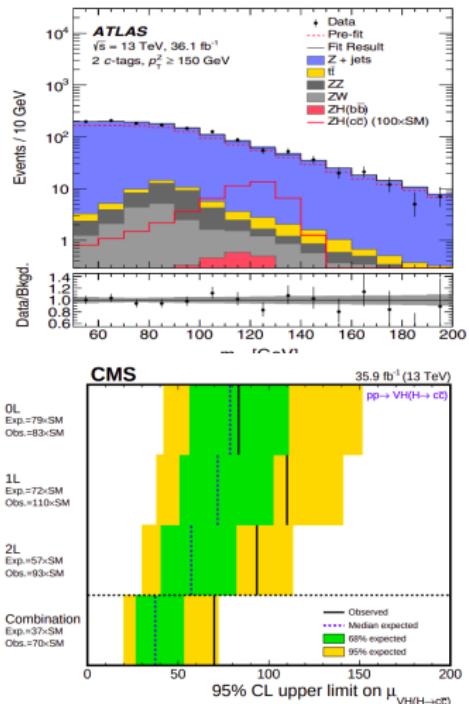
ATLAS: CONF-HIGG-2021-21

Common Selections	
Central jets	$\geq 2$
Signal jet $p_T$	$\geq 1$ signal jet with $p_T > 45$ GeV
$c$ -jets	1 or 2 $c$ -tagged signal jets
$b$ -jets	No $b$ -tagged non-signal jets
Jets	2, 3 (0- and 1-lepton), 2, $\geq 3$ (2-lepton)
$p_T^V$ regions	75–150 GeV (2-lepton) $> 150$ GeV 75–150 GeV: $\Delta R \leq 2.3$
$\Delta R$ (jet 1, jet 2)	150–250 GeV: $\Delta R \leq 1.6$ $> 250$ GeV: $\Delta R \leq 1.2$
.	.
1 Lepton	
Trigger	$e$ sub-channel: single electron $\mu$ sub-channel: $E_T^{\text{miss}}$
Leptons	1 <i>tight</i> lepton and no additional <i>loose</i> leptons
$E_T^{\text{miss}}$	$> 30$ GeV ( $e$ sub-channel)
$m_T^W$	$< 120$ GeV
0 Lepton	
Trigger	$E_T^{\text{miss}}$
Leptons	0 <i>loose</i> leptons
$E_T^{\text{miss}}$	$> 150$ GeV
$p_T^{\text{miss}}$	$> 30$ GeV
$H_T$	$> 120$ GeV (2 jets), $> 150$ GeV (3 jets)
$\min  \Delta\phi(E_T^{\text{miss}}, \text{jet}) $	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)
$ \Delta\phi(E_T^{\text{miss}}, H) $	$> 120^\circ$
$ \Delta\phi(\text{jet}1, \text{jet}2) $	$< 140^\circ$
$ \Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) $	$< 90^\circ$
2 Lepton	
Trigger	single lepton
Leptons	2 <i>loose</i> leptons
$m_{ll}$	Same flavour, opposite-charge for $\mu\mu$ $81 < m_{ll} < 101$ GeV

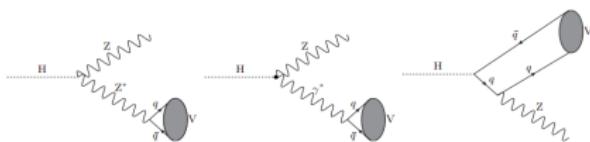
# Previous $H \rightarrow cc$ results

ATLAS: PRL 120 (2018) 211802, CMS: JHEP 03 (2020) 131

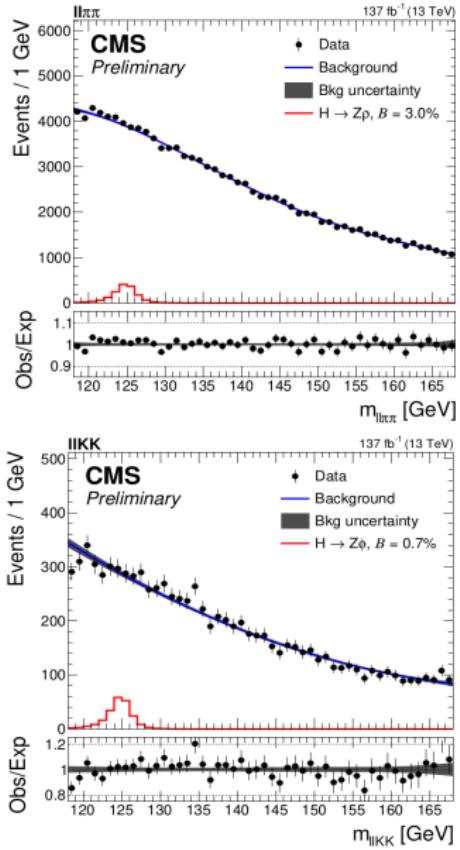
- Use VH,  $V = W, Z \rightarrow \text{lepton(s)}$   
ATLAS:  $ZH, Z \rightarrow \ell\ell$   
CMS:  $WH, W \rightarrow \mu/e + \nu$   
 $ZH, Z \rightarrow \ell\ell$
- 2 kinematic regions defined by  $p_T^H$ 
  - i) resolved charm jets
  - ii) boosted fat jet.
- Obs. (exp.) upper limit @95% CL:  
 $\sigma(pp \rightarrow ZH) \cdot \mathcal{B}(H \rightarrow cc) \cdot \mathcal{B}(W/Z \rightarrow \ell)$   
**ATLAS (36.1  $\text{fb}^{-1}$ ):**  $110(150) \times \text{SM}$   
**CMS (35.9  $\text{fb}^{-1}$ ):**  $70(37) \times \text{SM}$
- CMS:  
$$\sigma(pp \rightarrow VZ) \times \mathcal{B}(Z \rightarrow cc) = 0.55^{+0.86}_{-0.84}$$
- For ATLAS uncertainties in bkg. modeling larger.



Additional access via indirect methods: i) measure  $\mathcal{B}(H \rightarrow ZJ/\Psi, Z\eta_c)$ ,  
ii) differential distribution of  $p_T^H \rightarrow$  has similar sensitivity.

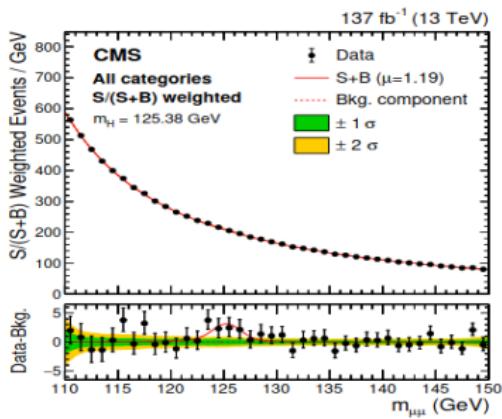
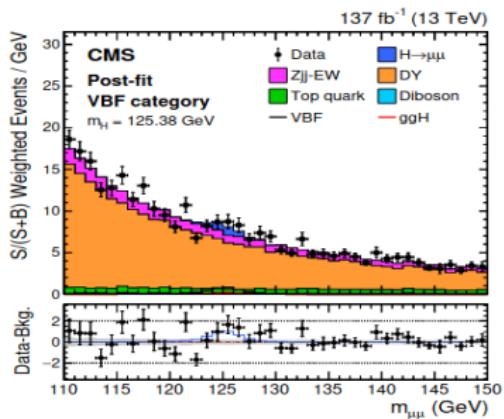
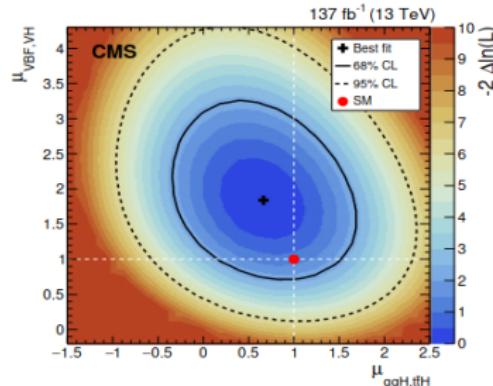
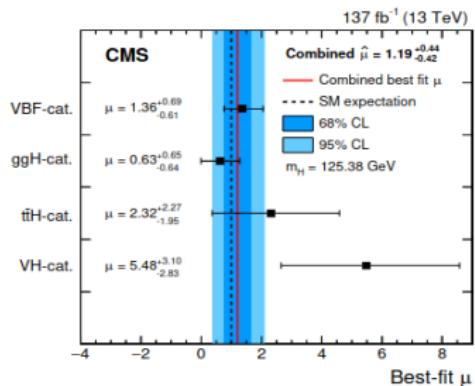


- Search in  $H \rightarrow Z(\rightarrow \ell\ell) \rho(\rightarrow \pi\pi)$  and  $H \rightarrow Z(\rightarrow \ell\ell) \phi(\rightarrow KK)$ 
  - i) Assume value of  $\mathcal{B}(H \rightarrow Z\rho)$
  - ii) Do not allow other  $H \rightarrow ZV$  process where  $V$  is another resonance.
- First experimental limits on  $\mathcal{B}$  at 95% CL
  - $\mathcal{B}(H \rightarrow Z\rho) \leq 1.21 - 1.89\%$   
 $= (860 - 1350) \times \text{SM}$
  - $\mathcal{B}(H \rightarrow Z\phi) \leq (0.36 - 0.58)\%$   
 $= (860 - 1380) \times \text{SM}.$
- $\mathcal{B}$  depends on the polarization of the decay product.



# $H \rightarrow \mu\mu$ : more results from CMS

CMS: JHEP 01(2021)148



- Branching fraction  $\mathcal{B}(H \rightarrow f\bar{f}) \propto \frac{m_f^2}{v^2}$ .  
This flavour dependence of Yukawa coupling for each and every fermion must be established for checking the consistency of SM.
- $\mathcal{B}(H \rightarrow ee)_{SM} \propto m_e^2 = \mathcal{O}(10^{-9}) = \frac{1}{40000} \times \mathcal{B}(H \rightarrow \mu\mu) !!$
- Analysis similar to  $H \rightarrow \mu\mu$  search.  
→ essentially a bump hunt above HUGE background.
- Dominant background estimated using high statistics ( $10^9$ ), fast simulation sample.
- First result from ATLAS**  
Upper limit @95% CL: obs. (exp.):  
 $\mathcal{B}(H \rightarrow ee) \leq 3.6(3.5) \times 10^{-4}$
- Long way to see the SM process!*

