Recent Higgs boson measurements at the LHC



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Outline

- Introduction
- Higgs mass measurements
- Higgs cross section measurements
- Combined measurements of Higgs coupling parameters
- Measurements of CP structure of Higgs boson couplings
- Recent searches of Higgs to invisible decay
- Search for di-Higgs production
- Search for $H \rightarrow cc$ decay
- Evidence for Higgs to muon pair decay
- Search for Higgs to two leptons + photon decay
- Future prospects

*not covering all topics, only selected recent updates are presented



The ATLAS and CMS detectors at the LHC

• Two general-purpose particle physics experiments

 \bullet



Designed to exploit the full discovery potential and vast range of physics opportunities that LHC provides

ATLAS and CMS Run 2 period (2015-2018)

- luminosity at pp 13 TeV centre-of-mass energy in full Run 2 period
 - Big thanks to the CERN accelerator team for the excellent LHC performance!

CMS Integrated Luminosity, pp, $\sqrt{s} = 13$ TeV



ATLAS and CMS experiments have each successfully collected ~140 fb⁻¹



ATLAS and CMS detectors performance

- Good understanding of the detector is critical
- careful data-driven calibrations
- Several improvements during the last years using machine learning techniques (e.g. b-tagging, τ -identification,...)



• Reconstruction of physics objects (e, γ , μ , τ , jets, ...) precisely known from



CMS-DP-2019-033

The Higgs boson

It is the only fundamental scalar with spin 0 we have seen so far



Discovery allows to access a new sector in the Lagrangian:

- <u>Scalar-Gauge boson</u> interactions
- Yukawa couplings (new type of interaction)
- <u>Higgs potential:</u> cornerstone of BEH mechanism, not yet probed experimentally



Higgs boson production and decay at the LHC







Higgs boson observation timeline at the LHC Large Hadron Collider (LHC) HL-LHC





Higgs boson mass measurements

- Run 1 (ATLAS+CMS): m_H = 125.09 ±0.21(stat) ±0.11(syst) GeV (0.2% precision) Phys.Rev.Lett. 114 (2015) 191803
- ATLAS Run 2 measurement $H \rightarrow ZZ \rightarrow 4I$ (139 fb⁻¹)
 - $m_H = 124.92 \pm 0.21 \text{ GeV}$ ATLAS-CONF-2020-005
- CMS Run 2 measurement in $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ \rightarrow 4I$ (36 fb⁻¹), in combination with CMS Run 1 measurements:
 - $m_{\rm H} = 125.38 \pm 0.14 \, {\rm GeV}$ Phys. Lett. B 805 (2020) 135425
 - Most precise measurement at present (0.11%)
- Measurements still dominated by statistical uncertainty



Higgs signal strength measurements



 $\sigma \times B$ normalized to SM

+ 0.08)

+ 0.47 - 0.39

 ± 0.05

+ 0.18

-0.15

+ 0.12

- 0.08

± 0.21

+0.40

- 0.35

+0.38

-0.24

+0.12

+0.11

-0.09

+ 0.28

-0.21

+0.14 -0.12

+0.12

+0.09

-0.06

+ 0.38

-0.34

+ 0.70

-0.57 + 0.52

-0.51

+ 0.14

-0.13



Higgs cross section measurements

- - Total Higgs boson production cross section at 13 TeV is 55.4 ±3.1(stat) ±2.9(syst) pb
 - In agreement with the Standard Model prediction \bullet



Inclusive cross-section measurement in γγ and ZZ channels at 7, 8 and 13 TeV

ATLAS-CONF-2019-032



Higgs cross section measurements

• Differential cross-section measurements in Higgs p_T , Higgs rapidity and N_{jets}

• Combination of $H \rightarrow \gamma \gamma$, ZZ (and bb) channels





Higgs cross section measurements

- Differential cross-section measurements in Higgs p_T , Higgs rapidity and N_{jets}



Phys. Lett. B 792 (2019) 369



Simplified Template Cross-Sections (STXS)

- template with the goal of:

 - different decay channels



arXiv:1605.04692, arXiv:1906.02754, arXiv:2003.01700

Higgs STXS measurements

 Good agreement between data and SM so far, in particular in high-p **BSM-sensitive bins**

CMS yy



CMS-PAS-HIG-19-015



• ATLAS (combination)

Higgs STXS measurements

Do not forget about (quite spectacular!) correlation matrix \bullet

	ATLAS Prelim	ninary _m ,	√ <i>s</i> = 13 TeV, 139 _/ = 125.09 GeV, <i>y</i> _µ <	fb ^{₋1} 2.5
0-iet, $p^H < 10$ GeV		0 00 0 04 0 03 0 02 0 11 0 09 0		
0-jet, $p_T < 10 \text{ GeV}$		0.050 02 0.02 0.02 0.11 0.09 0.		· >
1-iet, $p_T^H < 60 \text{ GeV}$	0.02-0.28 1 0 13 0 12-0.040 020 03 0 05 0 02 0 024	0.310 04 0 03 0 04 0 11 0 06 0		
1-jet, $60 \le p_{-}^{H} < 120 \text{ GeV}$	0.07 0.26 0.13 1 0.29-0.210.10 0.02 0.24 0.08 0.08	0.460.02 0.02 0.08 0.18 0.11 0	.07 0.06 0.07 0.08 0.01 0.08 0.07 0.03 0.05 0.05 0.05 0.01 0.28 0.08	$-0.8 \times$
1-jet, 120 ≤ <i>p</i> ^{<i>H</i>} < 200 GeV	0.03 0.14 0.12 0.29 1 -0.030.070.01 0.14 0.05 0.05	0.440.00 0.02 0.04 0.09 0.05 0	03 0 02 0 02 0 03 0 00 0 03 0 02 0 01 0 02 0 02	
et, $m_{ii} < 350 \text{ GeV}, p_{-}^{H} < 120 \text{ GeV}$	0.03-0.06-0.04-0.21-0.03 1 0.17 0.01 0.13 0.11 0.06	0.01-0.46-0.18 0.01 0.00-0.010	.01 0.01 0.01 0.01 0.00 0.01 0.01 0.01	
< 350 GeV, 120 $\leq p_{\tau}^{H}$ < 200 GeV	0.02 0.13-0.020.10-0.07 0.17 1 0.00 0.23 0.15 0.11	0.01-0.48-0.28 0.04 0.02 0.01 0.	.03 0.03 0.04 0.04+0.01 0.03 0.04 0.02 0.03 0.03 0.04+0.01+0.15+0.04	-0.6
et, $m_{ii} \ge 350 \text{ GeV}, p_{\tau}^{H} < 200 \text{ GeV}$	0.07 0.03 0.03 0.02 0.01 0.01 0.00 1 0.08 0.05 0.06	0.03-0.05 0.04-0.46 0.20 0.04 0.	.05 0.04 0.04 0.04 0.01 0.05 0.04 0.03 0.05 0.06 0.08 0.06 0.17 0.05	
$200 \le p_{\tau}^{H} < 300 \text{ GeV}$	0.07 0.22 0.05 0.24 0.14 0.13 0.23 0.08 1 0.10 0.12	0.15-0.26-0.17 0.06 0.13-0.05 0.	.08 0.08 0.06 0.07 0.01 0.07 0.06 0.04 0.06 0.07 0.07 0.03 0.32 0.07	
$300 \le p_{\tau}^{H} < 450 \text{ GeV}$	0.01 0.06 0.02 0.08 0.05 0.11 0.15 0.05 0.10 1 0.05	0.07-0.20-0.10 0.01 0.01-0.09.0	.01 0.02 0.01 0.01 0.00 0.01 0.01 0.02 0.02	-0.4
<i>p_T^H</i> ≥ 450 GeV	0.03 0.08 0.02 0.08 0.05 0.06 0.11 0.06 0.12 0.05 1	0.04-0.11-0.010.02 0.06-0.010	.03 0.03 0.03 0.04 0.00 0.04 0.04 0.02 0.03 0.05 0.03 0.01 0.14 0.04	••••
≤ 1-jet	0.00-0.05 <mark>-0.310.46-0.44</mark> 0.01 0.01-0.03 <mark>-0.15-</mark> 0.07-0.04	1 -0.01-0.01-0.04 <mark>0.12</mark> -0.02 0.	.01 0.01 0.01 0.01 0.00 0.01 0.01 0.01	
\geq 2-jet, m_{jj} < 350 GeV, VH veto	0.04 0.02 0.04 0.02 0.00 <mark>-0.460.48</mark> -0.05 <mark>-0.26 0.20 -0.11</mark>	0.01 1 0.11 0.00 0.14 0.10 0	.03 0.02 0.02 0.02 0.01 0.03 0.02 0.01 0.01 0.03 0.02 0.00 0.09 0.02	-0.2
\geq 2-jet, m_{jj} < 350 GeV, VH topo	0.03 0.02 0.03 0.02 0.02 <mark>-0.180.28</mark> 0.04 <mark>-0.17-0.10</mark> -0.01	0.010.11 1 0.00 0.04 0.06 0	.02 0.02 0.01 0.02 0.01 0.02 0.02 0.01 0.02 0.01 0.02 0.00 -0.09 0.02	0
$\leq m_{jj} < 700 \text{ GeV}, p_T^H < 200 \text{ GeV}$	0.02 0.09 0.04 0.08 0.04 0.01 0.04 0.46 0.06 0.01 0.02	0.040.00 0.00 1 0.21 0.09 0	.03 0.03 0.03 0.02 0.01 0.03 0.03 0.01 0.02 0.02 0.02 0.02 0 .02	
et, $m_{jj} \ge 700 \text{ GeV}, p_T^H < 200 \text{ GeV}$	0.11 0.18 0.11 0.18 0.09 0.00 0.02- <mark>0.20</mark> 0.13 0.01 0.06	0.120.14 0.04 0.21 1 0.22 0.	.10 0.08 0.08 0.08 0.02 0.09 0.08 0.05 0.07 0.08 0.09 0.02 <mark>-0.38</mark> 0.09	
et, $m_{jj} \ge 350 \text{ GeV}, p_T^H \ge 200 \text{ GeV}$	0.09 0.13 0.06 0.11 0.05-0.010.01 0.04-0.05-0.09-0.01	0.020.10 0.06 0.09 0.22 1 0.	.08 0.07 0.07 0.08 0.01 0.08 0.07 0.04 0.06 0.06 0.08 0.01 <mark>-0.32</mark> -0.08	
ρ ^V _τ < 75 GeV	0.07 0.10 0.01 0.07 0.03 0.01 0.03 0.05 0.08 0.01 0.03	0.01 0.03 0.02 0.03 0.10 0.08	1 -0.16 0.10 0.08-0.04 0.08 0.08 0.03 0.04 0.05 0.07-0.03-0.23-0.09	
$75 \le p_{T}^{V} < 150 \text{ GeV}$	0.06 0.10 0.02 0.06 0.02 0.01 0.03 0.04 0.08 0.02 0.03	0.01 0.02 0.02 0.03 <mark>0.08 0.07 0</mark>	0.16 1 -0.12-0.03 0.12-0.03 0.04 0.03 0.04 0.04 0.06 0.05 0.20 0.05	-0.2
$150 \le p_{ au}^V < 250 ext{ GeV}$	0.06 0.10 0.02 0.07 0.02 0.01 0.04 0.04 0.06 0.01 0.03	0.01 0.02 0.01 0.03 0.08 0.07 0	.10-0.12 1 0.62 0.27 0.60 0.65 0.03 0.04 0.02 0.04 0.04 0.21 0.76	0.2
<i>p</i> ^V _τ ≥ 250 GeV	0.06 0.11 0.01 0.08 0.03 0.01 0.04 0.04 0.07 0.01 0.04	0.01 0.02 0.02 0.02 <mark>0.08 0.08 0</mark> .	.08–0.03 <mark>0.62 1 20.24</mark> 0.67 0.68 0.03 0.04 0.03 0.04 20.03 0.22 0.83	
p_{T}^{V} < 150 GeV	0.01-0.010.02-0.010.00 0.00-0.010.01 0.01 0.00 0.00	0.00 0.01 0.01 0.01 0.02 0.01 0	0.04 <mark>-0.12-0.27-0.24</mark> 1 0.26-0.250.00 0.00 0.01 0.01 0.01 +0.02 0.30	0_4
$150 \le p_{T}^{V} < 250 \text{ GeV}$	0.07 0.10 0.02 0.08 0.03 0.01 0.03 0.05 0.07 0.01 0.04	0.01 0.03 0.02 0.03 0.09 0.08 0	.08-0.03 0.60 0.67 <mark>-0.26 1 0.69</mark> 0.03 0.04 0.04 0.04 -0.03-0.22 <mark>-0.79</mark>	0.1
$p_{\tau}^{V} \ge 250 \text{ GeV}$	0.06 0.10 0.02 0.07 0.02 0.01 0.04 0.04 0.06 0.01 0.04	0.01 0.02 0.02 0.03 <mark>0.08 0.07 0</mark> .	.08-0.04 0.65 0.68 0.25 0.69 1 0.03 0.04 0.03 0.03+0.03+0.21 <mark>0.84</mark>	
$p_T^H < 60 \text{ GeV}$	0.03 0.04 0.01 0.03 0.01 0.01 0.02 0.03 0.04 0.02 0.02	0.01 0.01 0.01 0.01 0.05 0.04 0	.03 0.03 0.03 0.03 0.00 0.03 0.03 1 0.01 0.0	0.6
60 ≤ p ^H _L < 120 GeV	0.05 0.06 0.02 0.05 0.02 0.01 0.03 0.05 0.06 0.02 0.03	0.01 0.01 0.02 0.02 0.07 0.06 0	.04 0.04 0.04 0.04 0.00 0.04 0.04 0.01 1 0.03 0.11 0.20 0.15 0.04	0.0
120 ≤ <i>p</i> ^{<i>H</i>} _{<i>L</i>} < 200 GeV	0.05 0.08 0.02 0.05 0.02 0.02 0.03 0.06 0.07 0.06 0.05	0.02 0.03 0.01 0.02 0.08 0.06 0	.05 0.04 0.02 0.03 0.01 0.04 0.03 0.04 0.03 1 0.11+0.210.17-0.03	
<i>p</i> ^{<i>r</i>} _{<i>T</i>} ≥ 200 GeV	0.06 0.08 0.02 0.05 0.02 0.03 0.04 0.08 0.07 0.01 0.03	0.02 0.02 0.02 0.02 0.02 0.09 0.08 0	.07 0.06 0.04 0.04 0.01 0.04 0.03 0.06 0.11 0.11 1 <mark>-0.4+0.20</mark> -0.04	<u> </u>
$tH \times B_{ZZ^*}$	0.02 0.02 0.01 0.01 0.00-0.02-0.01-0.06-0.03-0.03-0.01	0.02 0.00 0.00 0.02 0.02 0.01 -0).03-0.05-0.04-0.030.01-0.03-0.03-0.11-0.20-0.21-0.41 1 0.050.03	0.0
$B_{\gamma\gamma}/B_{ZZ^*}$	<mark>0.27-0.38</mark> -0.09 <mark>-0.28</mark> -0.12-0.05-0.15-0.17-0.32-0.04-0.14-	0.06-0.09-0.09-0.12 <mark>0.38-0.32-0</mark>	0.23-0.20-0.21-0.22-0.02-0.22-0.210.10-0.15-0.17-0.20-0.05 1 0.24	
B _b ⁻ B _{ZZ}	0.06-0.10-0.010.08-0.03-0.010.04-0.05-0.07-0.01-0.04-	0.010.02-0.02-0.020.09-0.08-0	0.090.05- <mark>0.76-0.83</mark> 0.30- <mark>0.79-0.84</mark> 0.03-0.04-0.03-0.040.03 0.24 1	/
	GeV GeV GeV GeV GeV GeV GeV	1-je vetc topc Ge/ Ge/ Ge/	Gev	•
	10 200 200 200 200 200 200 200 200	× H V VH ×	75 150 150 150 150 150 150 150 150 150 15	
		00000		
	0-j- 1- 1- 1- 1- 1- 1- 1- 1- 1- 1- 1- 1- 1- 1	 < 35 <li< td=""><td>75 150 120 120</td><td></td></li<>	75 150 120 120	
	-jet,, jet,, 1 350 350	n _{ji} - 700 700		
		jet, ⊳ <		
	350 	2 -2 -2 - ,		
	$\eta_{jj}^{2} < 2$ -jet	50 ≤ 50 ≤ .		
	st,	i∧ ∧ 3		
	- <u>J</u>	2-je		
	$aa \rightarrow H$	aa→Haa	aa→Hlv aa/aa→Hll tŦH	
	× B _{zz*}	× B _{zz} .	$\times B_{ZZ^*} \times B_{ZZ^*} \times B_{ZZ^*}$	

	0-jet, p_{τ}^{H} < 10 Ge
	0-jet, $10 \le p_{\tau}^{H'} < 200$ Ge
	1-jet, $p_{\tau}^{'H}$ < 60 Ge
	1-jet, $60 \le p_{T}^{H'} < 120$ Ge
I in	1-jet, 120 $\leq p_{T}^{H}$ < 200 Ge
βa	≥ 2-jet, m_{jj} < 350 GeV, p_{τ}^{H} < 120 Ge
З X	\geq 2-jet, m_{jj} < 350 GeV, 120 $\leq p_{T}^{H}$ < 200 Ge
	\geq 2-jet, $m_{jj} \geq$ 350 GeV, p_T^H < 200 Ge
	$200 \le p_{T_{c}}^{H} < 300 \text{ Ge}$
	$300 \le p_T^H < 450 \text{ Ge}$
	$p_{\tau}^{H} \ge 450 \text{ Ge}$
	≤ 1-
bb :z	\geq 2-jet, m_{jj} < 350 GeV, VH ve
EΩ	\geq 2-jet, $m_{jj} < 350 \text{ GeV}, VH$ to
-bb	\geq 2-jet, 350 $\leq m_{jj} <$ 700 GeV, $p_T^{+} <$ 200 Ge
	≥ 2 -jet, $m_{jj} \geq 700$ GeV, $p_T^H \geq 200$ Ge
	≥ 2 -jet, $m_{jj} \geq 350$ GeV, $p_{T} \geq 200$ GeV
-z-	$p_{T} < 73 \text{ Ge}$
ŤΞ	$150 \le p_T^V \le 250$ Ge
bb ×	$p^V \ge 250 \text{ Ge}$
토	$p_{-}^{V} < 150 \text{Ge}$
βΩ	$150 \le p_{\pi}^{V} < 250 \text{ Ge}$
¢∕bi ×	$p_T^V \ge 250 \text{ Ge}$
6	p_{_{T}}^{H} < 60 Ge
Ľ.	$60 \le p_{T}^{H} < 120 \text{ Ge}$
±t⊢ × ⊟	$120 \le p_T^H < 200 \text{ Ge}$
	$p_{T}^{H} \ge 200 \text{ Ge}$
	$tH \times B_Z$
	$B_{\gamma\gamma}/B_{z}$



Higgs coupling measurements - the kappa framework

- Parameterisations of Higgs boson production cross-sections and decay widths as a function of coupling strength modifiers using kappa framework
- Considering leading order contributions only
 - Other assumptions are typically made

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\text{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\text{SM}}}$$

Production	Loops	Main	Effective	Pasalvad modifiar		
Fioduction		interference	modifier	Resolved modifier		
$\sigma(ggF)$	\checkmark	t-b	κ_g^2	$1.040 \kappa_t^2 + 0.002 \kappa_b^2 - 0.038 \kappa_t \kappa_b - 0.000 \kappa_t^2 \kappa_b - 0.000 \kappa_b - 0.$		
$\sigma(\text{VBF})$	-	-	-	$0.733 \kappa_W^2 + 0.267 \kappa_Z^2$		
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2		
$\sigma(aa \rightarrow 7H)$./	t_7	K	$2.456 \kappa_Z^2 + 0.456 \kappa_t^2 - 1.903 \kappa_Z \kappa_t$		
$O(gg \rightarrow ZH)$	$g \rightarrow ZH$) \checkmark $t-Z$ $\kappa_{(ggZH)}$ -0.01		$-0.011\kappa_Z\kappa_b+0.003\kappa_t\kappa_b$			
$\sigma(WH)$	-	-	-	κ_W^2		
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2		
$\sigma(tHW)$	-	t-W	-	$2.909 \kappa_t^2 + 2.310 \kappa_W^2 - 4.220 \kappa_t \kappa_W$		
$\sigma(tHq)$	-	t-W	-	$2.633 \kappa_t^2 + 3.578 \kappa_W^2 - 5.211 \kappa_t \kappa_W$		
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2		
Partial decay width						
Γ^{bb}	-	-	-	κ_{h}^{2}		
Γ^{WW}	-	-	-	κ_W^2		
Γ^{gg}	\checkmark	t-b	κ_{g}^{2}	$1.111 \kappa_t^2 + 0.012 \kappa_b^2 - 0.123 \kappa_t \kappa_b$		
$\Gamma^{\tau \tau}$	-	-	-	κ_{τ}^2		
Γ^{ZZ}	-	-	-	κ_Z^2		
Γ^{cc}	-	-	-	$\kappa_c^2 \ (= \kappa_t^2)$		
				$1.589 \kappa_W^2 + 0.072 \kappa_t^2 - 0.674 \kappa_W \kappa_t$		
$\Gamma^{\gamma\gamma}$	\checkmark	t-W	κ_{γ}^2	$+0.009 \kappa_W \kappa_\tau + 0.008 \kappa_W \kappa_b$		
				$-0.002 \kappa_t \kappa_b - 0.002 \kappa_t \kappa_\tau$		
$\Gamma^{Z\gamma}$	\checkmark	t-W	$\kappa^2_{(Z,\gamma)}$	$1.118 \kappa_W^2 - 0.125 \kappa_W \kappa_t + 0.004 \kappa_t^2 +$		
Γ^{ss}	-	-	-	$\kappa_s^2 \ (= \kappa_h^2)$		
$\Gamma^{\mu\mu}$	-	-	-	κ_{μ}^2		
Total width $(B_{i.} = B_{u.} = 0)$						
				$0.581 \kappa_{h}^{2} + 0.215 \kappa_{W}^{2} + 0.082 \kappa_{g}^{2}$		
				$+0.063 \kappa_{\tau}^2 + 0.026 \kappa_Z^2 + 0.029 \kappa_c^2$		
Γ_H	\checkmark	-	κ_H^2	$+0.0023 \kappa_{\gamma}^{2} + 0.0015 \kappa_{(7\alpha)}^{2}$		
				$+0.0004 \kappa_s^2 + 0.00022 \kappa_\mu^2$		
				<i>•</i> •		







Higgs coupling measurements

- ATLAS and CMS have performed global fit of coupling modifiers (using kappa framework)
 - ~6% uncertainty on Higgs to vector boson couplings
 - ~10-15% uncertainty on Higgs to the 3rd generation fermion couplings

Footprint of SM Higgs boson: mass versus coupling correlation





Measurements of CP structure of Higgs boson couplings

- With full Run 2 dataset, both ATLAS & CMS have observed ttH in $H \rightarrow \gamma \gamma$ channel
 - This reaction is used to probe **CP mixing in top-Yukawa coupling**
 - The data disfavour **pure CP-odd** model of **Htt** coupling at 3.9σ and 3.2σ from ATLAS and CMS

• $(H \rightarrow WW)$ +jj production is used by ATLAS to:

- Constrain CP properties of the **effective Hgg vertex** (in ggF): ratio of CP-odd to CP-even coupling strength scale factors is measured to be 0.0 ± 0.4 (stat) ± 0.3 (syst)
- Access Higgs couplings to **longitudinally** and **transversely** polarised **W** and **Z** bosons in VBF process:

$$a_{\rm L} = 0.91^{+0.10}_{-0.18} (\text{stat.})^{+0.09}_{-0.18} (\text{syst.}) \qquad a_{\rm L} = \frac{g_{HV_{\rm L}V_{\rm L}}}{g_{HVV}},$$

$$a_{\rm T} = 1.16 \pm 0.4 (\text{stat.})^{+0.4}_{-0.3} (\text{syst.})$$

(results consistent with the SM predictions)

CMS Data ശ Events Background PRL125 (2020) 061802 (ATLAS) PRL125 (2020) 061801 (CMS) Weighted â S/(S 110

 $g_{HV_{T}V_{T}}$ $a_{\rm T} =$ g_{HVV}





Stat+Syst

SM expected

Stat only

Higgs to invisible searches

- and CMS
 - Observed upper limit $B(H \rightarrow inv.) = 0.11$ (95% CL) from recent ATLAS combination



Searches have been performed in VBF, ttH and VH channels in both ATLAS





Higgs to invisible searches

- Matter (DM) limits under certain assumptions (Higgs portal scenarios)
 - LHC provides the best limit for low-mass DM in model-specific scenarios



Higgs to invisible is sensitive to BSM phenomena that can be recast in Dark



Di-Higgs production

production





VBF channel offers access to the **HHVV quartic coupling** (not present in ggF production). Here also cancellations lead to decreasing cross section.

HH production at the LHC is dominated by the ggF process, followed by VBF

PLB 732 (2014) 142-149

Search for di-Higgs production

- Early Run 2 results (36 fb⁻¹) focused on ggF production
- Limits on cross section and self-coupling were obtained
 - $\sigma_{HH}/\sigma_{HH}(SM)$: < 6.9 (ATLAS), < 22 (CMS)
 - κ_{λ} = $\lambda/\lambda_{\text{SM}}$ \in [-5, 12] (ATLAS), [-12, 19] (CMS)



1 on ggF production upling were obtained





Search for di-Higgs production

- Recent HH searches with full Run 2 data
 - Constraints on κ_{2v} : -0.76 < κ_{2v} < 2.90 (ATLAS bbbb), -1.3 < κ_{2v} < 3.5 (CMS $\gamma\gamma$ bb)
 - New CMS bbyy result with full Run 2 luminosity: $\sigma_{HH} \times B(HH \rightarrow \gamma\gamma bb) < 7.7$ (5.2) obs. (exp.) times SM prediction







Search for $H \rightarrow cc$ decay

- Latest CMS search with 35.9 fb⁻¹: $\sigma/\sigma(SM) < 70$ (37) obs. (exp.)





• Very challenging channel, large background from $H \rightarrow bb$, c-tagging is critical



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Evidence for $H \rightarrow \mu\mu$ decay channel

- Very rare decay channel: $B(H \rightarrow \mu\mu) = 2.2 \times 10^{-4}$
- Huge Drell-Yan background to "beat"
 - Signal extraction by topology of production mode ullet
 - Use machine learning techniques to increase sensitivity lacksquare







Evidence for $H \rightarrow \mu \mu$ decay channel

- CMS result: 3.0σ (2.5 σ) obs. (exp.), $\mu = 1.19 \pm 0.40$ (stat) ± 0.15 (syst)



• ATLAS result: 2.0σ (1.7 σ) obs. (exp.) significance, measured $\mu = 1.2 \pm 0.6$

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Search for $H \rightarrow IIV$ decays

- Very rare process
- Several processes contribute to the final state
 - BSM sensitivity through loops
- Diverse final state kinematics
 - Dedicated analyses are typically performed for each region of phase-space











Search for $H \rightarrow Zy$ decays

- Updated $H \rightarrow Z\gamma$ search with 139 fb⁻¹ by ATLAS
 - Events categorised according to production modes
 - Additional BDT VBF categorisation to enhance sensitivity lacksquare
- Observed (expected) significance is 2.2σ (1.2 σ)
 - Upper limit on $\sigma_H \times B(H \rightarrow Z\gamma)$: 3.6 times the SM prediction





Category	Events	<i>S</i> ₆₈	B_{68}	N ₆₈	w ₆₈ [GeV]	S_{68}/B_{68}
VBF-enriched	194	2.7	16.7	17	3.7	16.2
High relative $p_{\rm T}$	2276	7.6	108.5	118	3.7	7.0
High $p_{\mathrm{T}t} \ ee$	5567	9.9	474.7	498	3.8	2.1
Low $p_{\mathrm{T}t} \ ee$	76679	34.5	6418.6	6505	4.1	0.5
High $p_{Tt} \mu \mu$	6979	12.0	634.4	632	3.9	1.9
Low $p_{\mathrm{T}t} \ \mu\mu$	100876	43.5	8506.9	8491	4.0	0.5
Inclusive	192571	110.2	16159.8	16261	4.0	0.7

Phys. Lett. B 809 (2020) 135754



Evidence for $H \rightarrow IIV$ decays at low-m_{II}

- New ATLAS analysis exploring m_{II} < 30 GeV
 - Region dominated by $H \rightarrow \gamma^* \gamma \rightarrow II\gamma$ decay mechanism
 - B(H→eeγ) = **7.2** ×10⁻⁵, B(H→μμγ) = **3.4** ×10⁻⁵ lacksquare
- Due to the low-mass of the dilepton system leptons are often very collimated
 - Dedicated identification algorithms for merged-ee objects
 - Merged-ee ID efficiency is measured in data using radiative Z decays with early photon conversion





ATLAS-CONF-2021-002





Evidence for $H \rightarrow II\gamma$ decays at low- m_{II}

- Measured fiducial $\sigma_H \times B(H \rightarrow II\gamma)$ (m_{II} < 30 GeV): 8.7 ± 2.8 fb
 - Corresponds to the signal strength $\mu = 1.5 \pm 0.5$
- Significance above background-only hypothesis: 3.2σ (2.1 σ expected)
 - First evidence for $H \rightarrow IIy$ decay



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Evidence for $H \rightarrow IIy$ decays at low-m



ATLAS-CONF-2021-002

Event display of a candidate $H \rightarrow ee\gamma$ event from the ee-merged VBF-enriched category

The High-Luminosity LHC

- 20 times more integrated luminosity than LHC Run 2 Up to 200 pp interactions per bunch crossing! ullet
- Better detectors, larger acceptance, better triggers
- Improved theory and analysis methods

	2020 2021	2022 2023 2024	4 2025 2026	2027 2028 2029 20	030 2031 20	32 2033 2034
		LHC	High-Luminosity LHC			
	LS2	Run 3	LS3	Run 4	LS4	Run 5
ATLAS and CMS		2 x 10 ³⁴ 300 fb ⁻¹	Detector Upgrade	5-7 x 10 ³⁴ ~1000 fb ⁻¹		5-7 x 10 ³⁴ 3000 fb ⁻¹





Prospects at High-Luminosity LHC (3000 fb⁻¹)

- 3-8% precision of Higgs Br to W/Z, 3rd gen. fermions and muons
- Discovery of $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$ decays
- $H \rightarrow cc$: $\sigma/\sigma(SM) < 6$ from ATLAS Run 2 result extrapolation





arXiv:1902.00134



Prospects at High-Luminosity LHC (3000 fb⁻¹)

factor of 10 at HL-LHC w.r.t. current measurements



Uncertainties in the Higgs p_T measurement at high-p_T can be reduced by a



arXiv:1902.00134



Prospects at High-Luminosity LHC (3000 fb⁻¹)

with full HL-LHC dataset





arXiv:1902.00134

At 95% CL, ATLAS+CMS is anticipated to exclude no Higgs trilinear coupling









Summary

- ATLAS and CMS collaborations continue to probe the nature of the Higgs boson using full LHC Run 2 data at 13 TeV (~140 fb⁻¹)
- Higgs physics at the LHC moves towards precision measurement era
- LHC starts to have sensitivity to Higgs couplings with 2nd generation fermion
- Other rare Higgs boson decays start to be accessible (e.g. $H \rightarrow II\gamma$)
- ~5% of the LHC integrated luminosity has been achieved so far
 - HL-LHC will be able to precisely probe Higgs couplings with the 2nd generation fermion and be able to set strong constraints on Higgs self-coupling parameter
- Stay tuned for new measurements!

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Backup



H self-coupling from single H production

- Single H production sensitive to λ through NLO EW corrections
- ATLAS and CMS extracted limits on κ_{λ} as part of recent Higgs combinations
- This method achieves similar sensitivity to direct HH searches, but uses some assumption assumptions









Constraints on Higgs boson width

- Indirect measurement from off-shell production in $H \rightarrow ZZ$ channel
- Obs. limit on Higgs width:
 - ATLAS Run 2 (36.1fb⁻¹): < **14.4 MeV**
 - CMS Run 1+2 (77 fb⁻¹): • [0.08, 9.16] MeV
 - SM prediction: **4.1 MeV**

HL-LHC projections: CMS: $4.1^{+1.0}_{-1.1}$ MeV ATLAS: $4.2^{+1.5}_{-2.1}$ MeV arXiv:1902.00134



 $\sigma_{vv \to H \to 4\ell}^{\text{on-shell}} \propto \mu_{vvH}$ and $\sigma_{vv \to H \to 4\ell}^{\text{off-shell}} \propto \mu_{vvH} \Gamma_{H}$

PRD 99 (2019) 112003

PLB 786 (2018) 223

