

Higgs Physics End Game



Saturday May 20, 2023 — Patrick Bryant — Mel Fest





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Higgs Physics End Game



Starting in September

Saturday May 20, 2023 — Patrick Bryant — Mel Fest









- Observed 'Higgs like' boson in phenomenological sweet spot
 - A little lighter \rightarrow bosonic decays suppressed
 - A little heavier \rightarrow fermionic decays suppressed





- So many fun things to measure!
 - Observed four primary g_{lelle} production modes and five g see decay modes

 $q_1 - - -$

 $q_2 - - -$

	ATLAS Preliminary		Total
	$\sqrt{s} = 13 \text{ TeV}, 36.1 - 139 \text{ fb}^{-1}$		Stat. Svot
	$m_H = 125.09 \text{ GeV}$		Syst. SM
	$p_{SM} = 79\%$		OW
\frown	ggF γγ	1.02	TotalStat.Syst.+0.11(+0.08+0.07-0.11(-0.08, -0.07
	ggF ZZ	0.95	$ \begin{array}{c} +0.11 \\ -0.11 \end{array} \left(\begin{array}{c} +0.10 \\ -0.10 \end{array} \right. \begin{array}{c} +0.04 \\ -0.03 \end{array} \right) $
	ggF WW	1.13	+0.13 ($+0.06$, $+0.12$) -0.12 (-0.06 , -0.10)
	ggF ττ ι	0.87	+0.28 + 0.15 + 0.23 + 0.23 - 0.25 - 0.15 + 0.23
	ggF+ttH μμ μ	0.52	+0.91 ($+0.77$ $+0.49$) -0.88 (-0.79 , -0.38)
q_3	VBF γγ	1.47	+0.27 ($+0.21$ + 0.17) -0.24 (-0.20 , -0.14)
$\overline{} W^+, Z$	VBF ZZ	1.31	$^{+0.51}_{-0.42}$ ($^{+0.50}_{-0.42}$, $^{+0.11}_{-0.06}$)
	VBF WW	1.09	+0.19 + 0.17 + 0.15 + 0.11 - 0.17 + 0.14 + 0.10 + 0.10
H	VBF ττ	0.99	$\begin{array}{c} +0.20 \\ -0.18 \end{array} \left(\begin{array}{c} +0.14 \\ -0.14 \end{array} \right. +0.15 \\ -0.12 \end{array}\right)$
$\swarrow W^-, Z$	VBF+ggF bb	0.98	$\begin{array}{c} + 0.38 \\ - 0.36 \end{array} \left(\begin{array}{c} + 0.31 \\ - 0.33 \end{array} \right. \begin{array}{c} + 0.21 \\ - 0.15 \end{array}\right)$
	VBF+VH μμ	2.33	$\begin{array}{c} +1.34 \\ -1.26 \end{array} \left(\begin{array}{c} +1.32 \\ -1.24 \end{array}\right. + 0.20 \\ -0.23 \end{array}\right)$
W, Z	VH γγ	1.33	$ \begin{array}{c} +0.33 \\ -0.31 \end{array} \left(\begin{array}{c} +0.32 \\ -0.30 \end{array} \right. + 0.10 \\ \left0.08 \end{array} \right) $
سمر	VH ZZ	1.51	+1.17 ($+1.14$ $+0.24$) -0.94 (-0.93 , -0.16)
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	VH ττ <b>μ</b>	0.98	$^{+0.59}_{-0.57}$ ( $^{+0.49}_{-0.49}$ , $^{+0.33}_{-0.29}$ )
	WH bb	1.04	$ \begin{array}{c} + 0.28 \\ - 0.26 \end{array} \left( \begin{array}{c} + 0.19 \\ - 0.19 \end{array} \right. \begin{array}{c} + 0.20 \\ - 0.19 \end{array} \right) $
H	ZH bb	1.00	$ \begin{array}{c} +0.24 \\ -0.22 \end{array} \left( \begin{array}{c} +0.17 \\ -0.17 \end{array} \right. \begin{array}{c} +0.17 \\ -0.14 \end{array} \right) $
$ \overline{t} $	ttH+tH γγ	0.93	$\begin{array}{c} +0.27 \\ -0.25 \end{array} \left(\begin{array}{c} +0.26 \\ -0.24 \end{array}, \begin{array}{c} +0.08 \\ -0.06 \end{array}\right)$
	ttH+tH WW	1.64	+0.65 $(+0.44$ $+0.48$ $)$ $-0.61$ $(-0.43$ $,-0.43$ $)$
	ttH+tH ZZ	1.69	$\begin{array}{c} +1.69 \\ -1.10 \end{array} \left(\begin{array}{c} +1.65 \\ -1.09 \end{array}\right) + 0.37 \\ -0.16 \end{array}\right)$
> H	ttH+tH ττ	1.39	+0.86 + 0.66 + 0.54 - 0.76 - 0.62 + 0.62 + 0.54
	ttH+tH bb	0.35	$^{+0.34}_{-0.33}$ ( $^{+0.20}_{-0.20}$ , $^{+0.28}_{-0.27}$ )
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- So many fun things to measure!
  - Observed four primary











- So many fun things to measure!
  - Observed four primary  $g_{\text{lles}}$ production modes and five* g Jeels decay modes
  - Very 'Higgs like'

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### Higgs Physics

			<u> </u>
	ATLAS Preliminary		Total
	<i>\s</i> = 13 TeV, 36.1 - 139 fb ⁻ '		Stat.
	$m_{\rm H} = 125.09 {\rm GeV}$		SM
	$P_{SM} = 7976$	_	
leelee	ggF γγ	1.02	Total Stat. Syst. +0.11 ( $^{+0.08}_{-0.08}$ , $^{+0.07}_{-0.07}$ )
$\checkmark t$ $\rightarrow \cdots \rightarrow H$	ggF ZZ 🙀	0.95	$ \begin{array}{c} + \ 0.11 \\ - \ 0.11 \end{array} \left( \begin{array}{c} + \ 0.10 \\ - \ 0.10 \end{array} \right. \begin{array}{c} + \ 0.04 \\ - \ 0.03 \end{array} \right) $
	ggF WW	1.13	$ \begin{array}{c} + \ 0.13 \\ - \ 0.12 \end{array} \left( \begin{array}{c} + \ 0.06 \\ - \ 0.06 \end{array} \right. \begin{array}{c} + \ 0.12 \\ - \ 0.10 \end{array} \right) $
000000	ggF ττ	0.87	$ \begin{array}{c} + \ 0.28 \\ - \ 0.25 \end{array} \left( \begin{array}{c} + \ 0.15 \\ - \ 0.15 \end{array} \right. \begin{array}{c} + \ 0.23 \\ - \ 0.20 \end{array} \right) $
	ggF+ttH μμ μ	0.52	$^{+0.91}_{-0.88}$ ( $^{+0.77}_{-0.79}$ , $^{+0.49}_{-0.38}$ )
$q_3$	VBF γγ	1.47	$\begin{array}{c} +0.27 \\ -0.24 \end{array} \left(\begin{array}{c} +0.21 \\ -0.20 \end{array} \right. + 0.17 \\ \left0.14 \end{array}\right)$
$\longrightarrow$ $W^+, Z$	VBF ZZ	1.31	$^{+0.51}_{-0.42}$ ( $^{+0.50}_{-0.42}$ , $^{+0.11}_{-0.06}$ )
	VBFWW	1.09	+0.19 + 0.17 + 0.15 + 0.11 - 0.17 + 0.17 + 0.14 + 0.10 + 0.10
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$\swarrow$ $W^-, Z$	VBF+ggF bb	0.98	$ \begin{array}{c} +0.38 \\ -0.36 \end{array} \left( \begin{array}{c} +0.31 \\ -0.33 \end{array} \right) + 0.21 \\ -0.15 \end{array} \right) $
	VBF+VH μμ	2.33	+1.34 + 1.32 + 0.20 - 1.26 + 1.32 + 0.23
$\bar{q}_2$ $W, Z$	VH γγ	1.33	$\begin{array}{c} +0.33 \\ -0.31 \end{array} \left( \begin{array}{c} +0.32 \\ -0.30 \end{array} \right) + 0.10 \\ -0.08 \end{array} \right)$
	VH ZZ	1.51	$ \begin{array}{c} +1.17 \\ -0.94 \end{array} \left( \begin{array}{c} +1.14 \\ -0.93 \end{array} \right. + \begin{array}{c} +0.24 \\ -0.16 \end{array} \right) $
	VΗ ττ <b>μ</b>	0.98	$ \begin{array}{c} +0.59 \\ -0.57 \\ -0.49 \\ \end{array} , \begin{array}{c} +0.49 \\ -0.29 \\ -0.29 \end{array} , \begin{array}{c} +0.33 \\ -0.29 \\ -0.29 \end{array} , $
	WH bb	1.04	$^{+0.28}_{-0.26}$ ( $^{+0.19}_{-0.19}$ , $^{+0.20}_{-0.18}$ )
$q_1$ H	ZH bb	1.00	$ \begin{array}{c} +0.24 \\ -0.22 \end{array} \left( \begin{array}{c} +0.17 \\ -0.17 \end{array} \right) + 0.17 \\ -0.14 \end{array} \right) $
$$	ttH+tH γγ	0.93	+0.27 ( $+0.26$ + $0.08$ ) -0.25 ( $-0.24$ , $-0.06$ )
000000	ttH+tH WW	1.64	$\begin{array}{c} +0.65 \\ -0.61 \end{array} \left( \begin{array}{c} +0.44 \\ -0.43 \end{array} \right) + 0.48 \\ -0.43 \end{array} \right)$
	ttH+tH ZZ	<b>1</b> .69	$\begin{array}{c} +1.69 \\ -1.10 \end{array} \left( \begin{array}{c} +1.65 \\ -1.09 \end{array} \right) + 0.37 \\ -0.16 \end{array} \right)$
	ttH+tH ττ	1.39	$\begin{array}{c} +0.86 \\ -0.76 \end{array} \left( \begin{array}{c} +0.66 \\ -0.62 \end{array} \right) + 0.54 \\ -0.62 \end{array} \right)$
	ttH+tH bb	0.35	$\begin{array}{c} +0.34 \\ -0.33 \end{array} \left( \begin{array}{c} +0.20 \\ -0.20 \end{array} \right) + 0.28 \\ -0.27 \end{array} \right)$
222222222	•		
	-4 -2 0 2	4	6 8
-t	<u>ATLAS-CONF-2021-053</u>	$\sigma \times B n$	ormalised to SM







- Four parts of the Higgs mechanism to check:
  - Higgs self-coupling
  - Higgs total width
  - Higgs to invisible
  - Yukawa CP violation





#### • Standard HH measurements combined with all single H measurements













#### • $b\bar{b}\gamma\gamma$ , $b\bar{b}\tau\tau$ , $b\bar{b}b\bar{b}$ remarkably competitive!



<u>HDBS-2022-03</u> 10





- $b\bar{b}\gamma\gamma$ ,  $b\bar{b}\tau\tau$ ,  $b\bar{b}b\bar{b}$  remarkably competitive!
  - Standard candles for  $b\bar{b}\tau\tau$ ,  $b\bar{b}b\bar{b}$ , critical for anyone to believe results

$$\frac{\sigma(pp \to ZZ \to b\bar{b}b\bar{b})}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 31$$
$$\frac{\sigma(pp \to ZH \to b\bar{b}b\bar{b})}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 7$$

$$\frac{\sigma(pp \to ZZ \to b\bar{b}\tau\tau)}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 63$$
$$\frac{\sigma(pp \to ZH \to b\bar{b}\tau\tau)}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 13^{*}$$

 $*(3.5[b\bar{b}\tau\tau] + 9.7[\tau\tau b\bar{b}])$ 





#### • Combination with single H measurements mostly serves to constrain $\kappa_{t}$









# Higgs Width

- Any new couplings can change width, particularly BSM decay modes which may be hard to observe directly
  - Direct measurement is hopeless
  - Rely on ratio of off/on-shell cross section, some model dependence

$$\frac{\sigma_{gg \to H \to ZZ}^{\text{off-shell}}}{\sigma_{gg \to H \to ZZ}^{\text{on-shell}}} \propto \frac{\Gamma_H m_H}{m_{ZZ}^2} \times f(\text{scale dep})$$

pendence of HZZ and ggH couplings)





# Higgs Width

10

 $10^{-2}$ 

Exp.

Data /

Event 10 • Precision calculations of non-10⁵ 10 10 resonant ZZ cross section 10² 10 - NLO QCD k-factors as 10-10⁻² function of  $m_{ZZ}$  1.5-2 Data / Exp. - N3LO QCD norm k-factor 1.32 Events - Impressive to find  $3\sigma$  evidence 10[°]  $10^{5}$ 10 of an effect which is smaller  $10^{\circ}$  $10^{2}$ than these k-factors 10



#### HIGG-2018-32







# Higgs Width

- Precision calculations of nonresonant ZZ cross section
  - NLO QCD k-factors as function of  $m_{ZZ}$  1.5-2
  - N3LO QCD norm k-factor 1.32
  - Impressive to find  $3\sigma$  evidence of an effect which is smaller than these k-factors

HIGG-2018-32









- on BSM Higgs to invisible BR.
  - Direct search in VBF production gives strongest constraint



#### Higgs $\rightarrow$ Invisible

#### • Combination of visible Higgs decays gives indirect and model dependent constraint











• Another impressive measurement relying on large theory k-factors - In this case double ratio

of EW Z/W+jets vs  $m_{ii}$ 





#### Higgs $\rightarrow$ Invisible

#### EXOT-2020-11









#### Yukawa CPV

- Tree level CP Violation is possible in Yukawa couplings
  - CPV in gauge couplings is suppressed by  $\Lambda^{-2}$
  - $H \rightarrow \tau \tau$  is the only option at the LHC









#### Yukawa CPV

#### • Pure CP-odd hypothesis disfavored at $3.4\sigma$

- 10 different combinations of  $\tau$  decay modes, 16 signal regions







### Conclusions

- Incredibly rich Higgs phenomenology made possible by  $m_{\rm H} = 125 \, {\rm GeV}$
- Huge combination of measurements consistent with SM Higgs
  - LHC beginning to constrain:
    - Self-coupling
    - Width
    - BR(H $\rightarrow$ Inv.)
    - Yukawa CP violation
- My money is on SM Higgs
  - If you have to retire and do something else, now is the time







