# Higgs Production at the LHĆ

Matt Klein, Southern Methodist University 2024 May 20

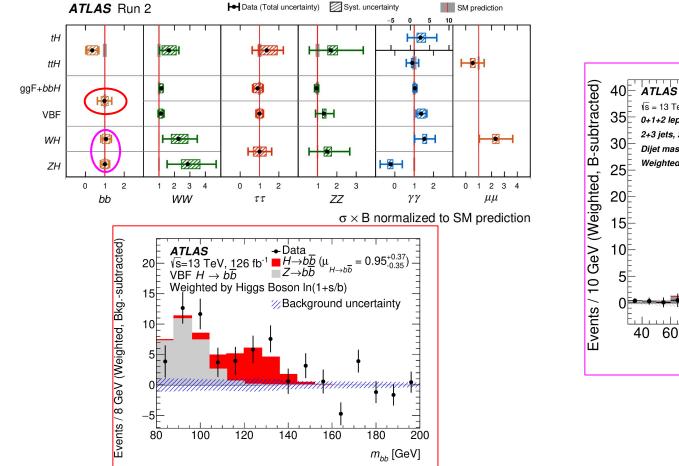


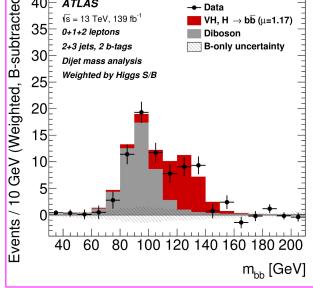


# Overview

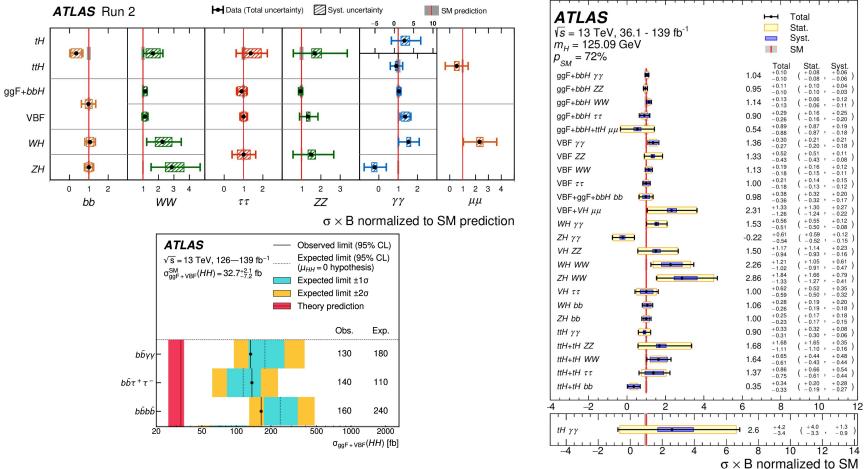
- Individual Measurements
  - Production Mode x Decay
  - Semi-differential: STXS
  - Fully differential
- Interpretations
  - Combined x-sections
  - $\circ \quad \text{Combined STXS} \quad$
  - Kappa-framework
- Properties
  - $\circ \quad \text{Mass}$
  - $\circ$  Width

# Measurements: Cross-section (1)





# Measurements: Cross-section (2)

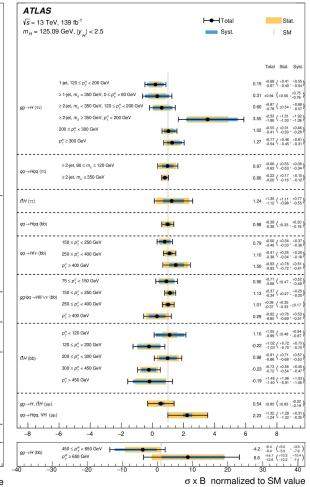


## Measurements: STXS

m <sub>H</sub> = 125.0	99 GeV,  y <sub>H</sub>   < 2.5	Syst.	SM
			Total Stat. Sys
<i>gg→H</i> (WW*)	0-jet, $p_T^H$ < 200 GeV	1.27	$^{+0.18}_{-0.17}$ ( $_{\pm 0.08}$ , $^{+0.1}_{-0.1}$
	1-jet, $p_T^H < 60 \text{ GeV}$	0.66	$^{+0.59}_{-0.58}$ ( $^{+0.30}_{-0.29}$ , $^{+0.5}_{-0.58}$
	1-jet, $60 \le p_T^H < 120 \text{ GeV}$	H 0.68	$^{+0.49}_{-0.46}$ (±0.32 $^{+0.3}_{-0.3}$
	1-jet, $120 \le p_T^{\prime\prime} < 200 \text{ GeV}$	1.43	+0.89 (+0.63 +0.6 -0.62 +0.6
	$\geq$ 2-jet, $p_{\tau}^{\prime\prime}$ < 200 GeV	1.54	$^{+0.95}_{-0.84}$ ( $^{+0.43}_{-0.42}$ , $^{+0.8}_{-0.7}$
	$p_{\tau}^{\prime\prime} \ge 200 \text{ GeV}$	<b>••</b> 1.37	+0.91 (+0.63 +0.6 -0.76 (-0.62 ,-0.4
qq→Hqq (WW*)	≥ 2-jet, 350 ≤ $m_{ii}$ < 700 GeV, $p_{i}^{ii}$ < 200 GeV	0.12	+0.60 (+0.45 -0.58 (-0.41 ,±0.4
	≥ 2-jet, 700 ≤ $m_{ii}$ < 1000 GeV, $p_{ii}^{H}$ < 200 GeV	0.57	+0.68 (+0.57 ,+0.3 -0.61 (-0.51 ,-0.3
	≥ 2-jet, 1000 ≤ m <sub>y</sub> < 1500 GeV, p <sub>T</sub> <sup>H</sup> < 200 GeV	1.32	+0.64 (+0.50 +0.4 -0.51 (-0.45 -0.4
	≥ 2-jet, $m_j \ge 1500 \text{ GeV}, p_\tau^H < 200 \text{ GeV}$	1.19	+0.48 (+0.42 +0.2 -0.42 (-0.38 +-0.1
	$\geq$ 2-jet, $m_{j} \geq$ 350 GeV, $p_{_{T}}^{^{H}} \geq$ 200 GeV	1.54	+0.61 (+0.51 +0.3 -0.51 (-0.46 -0.2
	0-jet, p <sup>H</sup> <sub>T</sub> < 10 GeV	0.93	+0.36 (+0.30 ,+0. -0.30 (-0.27 ,-0.
	0-jet, 10 ≤ $p_T^H$ < 200 GeV	1.15	+0.23 (+0.18 +0.1 -0.20 (-0.17 -0.1
gg →H (ZZ*)	1-jet, $p_T^H < 60 \text{ GeV}$	0.31	+0.43 (+0.40 +0.1 -0.38 (-0.36 -0.1
	1-jet, 60 ≤ $\rho_T^{\mu}$ < 120 GeV	1.42	+0.52 (+0.42 +0.3
	1-jet, $120 \le p_T^H < 200 \text{ GeV}$	0.41	+0.84 (+0.80 +0.2 -0.59 (-0.58 -0.0
	$\geq$ 2-jet, $p_{\tau}^{\prime\prime}$ < 200 GeV	0.35	+0.60 (+0.55 +0.2
	$p_{\tau}^{H} \ge 200 \text{ GeV}$	2.41	+1.52 (+1.32 +0.7 -1.09 (-1.04 ,-0.3
qq→Hqq (ZZ*)	VBF	1.49	+0.63 (+0.61 +0.1 -0.50 (-0.50 ,-0.0
	≥ 2-jet, 60 < m <sub>j</sub> < 120 GeV	1.51	+2.83 (+2.79 +0.4 -2.24 (-2.22 '-0.2
	≥ 2-jet, $m_j$ ≥ 350 GeV, $p_{\gamma}^H$ ≥ 200 GeV	0.18	+2.09 (+2.08 ,+0.1
VH-lep (ZZ*)	 =	• 1.29	+1.67 (+1.67 +0. -1.05 (-1.05 -0.1
tīH (ZZ*)		1.73	+1.77 (+1.72 +0.3

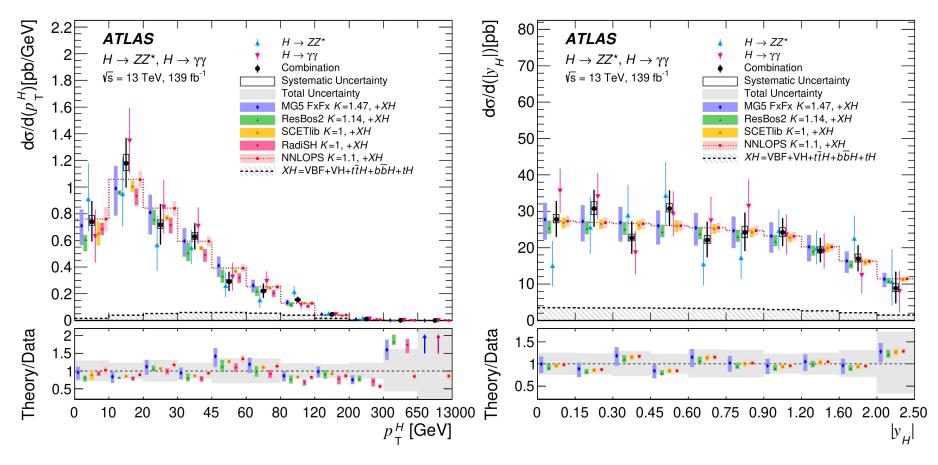
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ATLAS			0
	eV, 139 fb <sup>-1</sup>	⊢●⊣Total	Stat.
$m_{H} = 125$	.09 GeV,  y <sub>H</sub>   < 2.5	Syst.	SM
			Total Stat. Syst
	0-jet, p <sup>#</sup> < 10 GeV	0.66	+0.27 -0.26 (±0.24 , +0.12
<i>9</i> 3 → <i>H</i> (γγ)	$0 - jet, 10 \le p_{\gamma}^{\mu} < 200 \text{ GeV}$	1.24	
	1-jet, p <sup>µ</sup> <sub>r</sub> < 60 GeV	1.24	-0.17 (±0.15 , -0.06 +0.39 (±0.36 , -0.11
	$1 - jet, \beta_r < 0.0 \text{ GeV}$		
	1-jet, 120 ≤ $p_{\tau}^{H}$ < 200 GeV	1.14	
		0.93	-0.330.36 -0.1
	≥2-jet, $m_{ij}$ < 350 GeV, $p_{T}^{\prime\prime}$ < 120 GeV	0.58	-0.54 -0.52 ' -0.1
	$\geq$ 2-jet, $m_g$ < 350 GeV, 120 $\leq \rho_{\tau}^{H}$ < 200 GeV	1.31	-0.48 -0.47 '-0.0
	$\geq$ 2-jet, $m_{ij} \geq$ 350 GeV, $p_{T}^{H} <$ 200 GeV	1.09	10.00 (-0.89 -0.3
	$200 \le p_{\gamma}^{\prime\prime} < 300 \text{ GeV}$	1.56	-0.41 (-0.39 '-0.1
	$300 \le p_{\gamma}^{H} < 450 \text{ GeV}$	0.17	+0.56 -0.49 (+0.54 -0.47 , +0.1
	<i>p</i> <sup><i>H</i></sup> <sub><i>T</i></sub> ≥ 450 GeV	2.11	+1.47 -1.18 (+1.42 +0.4 -1.15 -0.2
			40.96 (40.90 40.3
	≤ 1-jet and VH-veto	1.05	-0.000.04 -0.1
	≥2-jet, VH-had	0.21	-0.03 +-0.020.1
qq→Hqiq (yy)	≥ 2-jet, 350 ≤ $m_j$ < 700 GeV, $p_{\gamma}^{H}$ < 200 GeV	1.28	-0.60 -0.56 -0.2
	$\geq$ 2-jet, 700 $\leq$ $m_{i}$ < 1000 GeV, $p_{\gamma}^{H}$ < 200 GeV	1.47	-0.68 -0.64 -0.2
	≥ 2-jet, $m_{\theta}$ ≥ 1000 GeV, $p_{\tau}^{H}$ < 200 GeV	1.31	+0.46 -0.38 (+0.36 ,+0.2 -0.33 ,-0.2
	$\geq$ 2-jet, 350 $\leq$ $m_g$ $<$ 1000 GeV, $p_T^{\prime\prime} \geq$ 200 GeV	0.31	-0.01 -0.00 -0.1
	$\geq$ 2-jet, $m_{ij} \geq$ 1000 GeV, $p_{\tau}^{H} \geq$ 200 GeV	1.69	+0.67 -0.57 (+0.61 +0.2 -0.52 + -0.2
	p <sup>v</sup> <sub>2</sub> < 150 GeV	1.75	+0.82 (+0.80 +0.1
$q \rightarrow H v (\gamma \gamma)$	p <sup>v</sup> <sub>r</sub> ≥ 150 GeV	1.65	
			-0.90 \-0.89 \-0.1
g/qq→Hll/vv (	γγ) ρ <sup>v</sup> <sub>τ</sub> < 150 GeV	-0.64	+0.88 (+0.87 , +0.1
	$\rho_T^{\vee} \ge 150 \text{ GeV}$	0.39	+1.10 (+1.08 +0.2 -0.92 (-0.91 +-0.1
đн (үү)	<i>p</i> <sup><i>µ</i></sup> / <sub><i>r</i></sub> < 60 GeV →	0.83	+0.82 (+0.81 +0.1
	60 ≤ <i>p</i> <sup>#</sup> < 120 GeV	0.81	+0.60 (+0.59 +0.0
	120 ≤ p <sup>µ</sup> <sub>1</sub> < 200 GeV	0.65	-0.51 C0.50 '-0.0 +0.64 (+0.63 +0.1 -0.54 (-0.53 -0.0
	200 ≤ p <sup>4</sup> <sub>7</sub> < 300 GeV	1.23	
	p <sup>µ</sup> <sub>7</sub> ≥ 300 GeV		-0.65 (-0.65 '-0.0 +0.96 (+0.95 +0.1 -0.75 (-0.74 '-0.1
	p <sub>7</sub> 2 300 dev	1.17	-0.75 (-0.74 '-0.1
 + (γγ)	<b>—</b>	2.06	+4.13 (+3.94 , +1.2 -3.27 (-3.14 , -0.9
/(Z γ)		2.05	+0.97 (+0.88 , +0.4
∽ <i>n</i> Cilii			-0.00 -0.07 -0.0
-8	-6 -4 -2 0 2	4 6	8 10

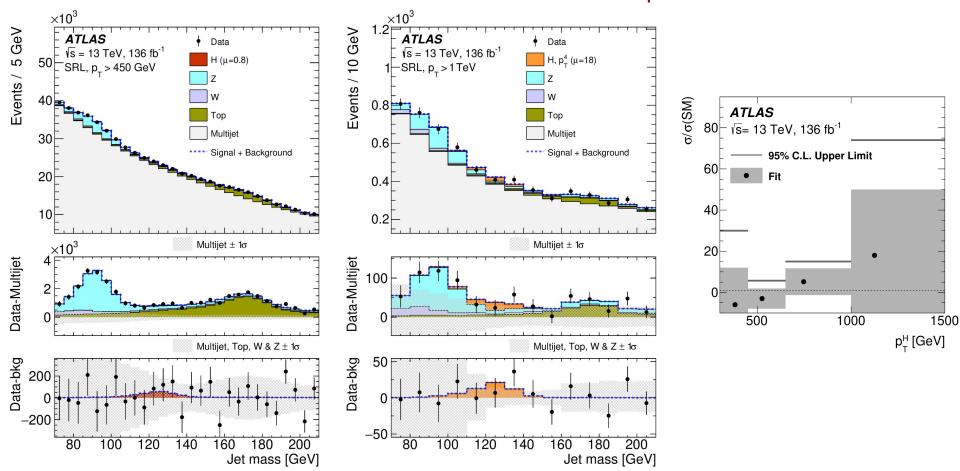


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# Measurements: Differential

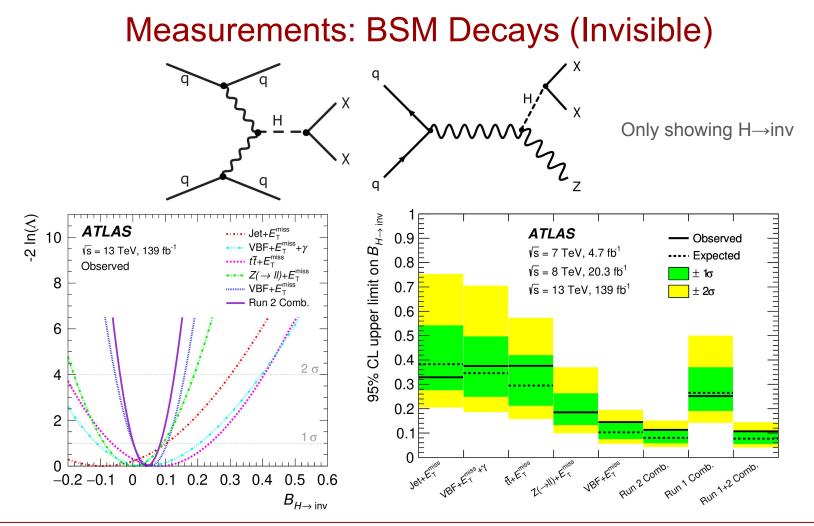


# Measurements: High $p_{\tau}$

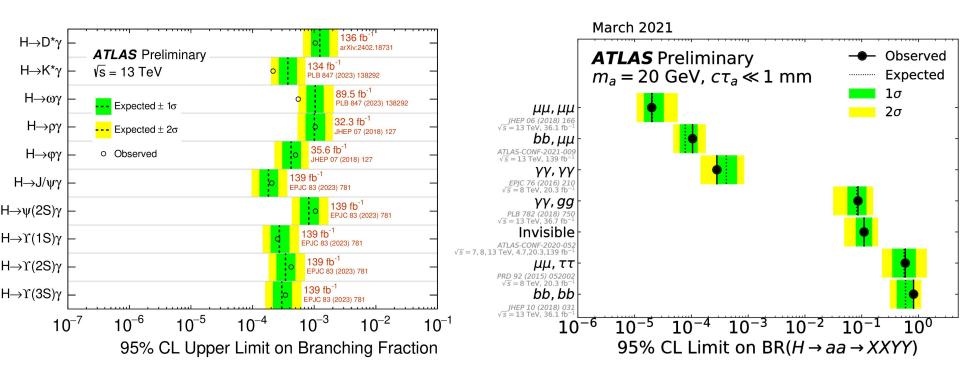


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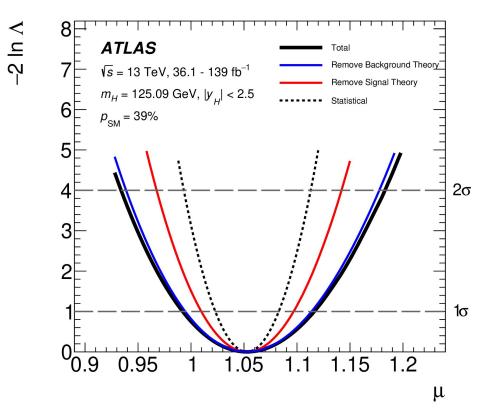


# Measurements: BSM Decays (Other)

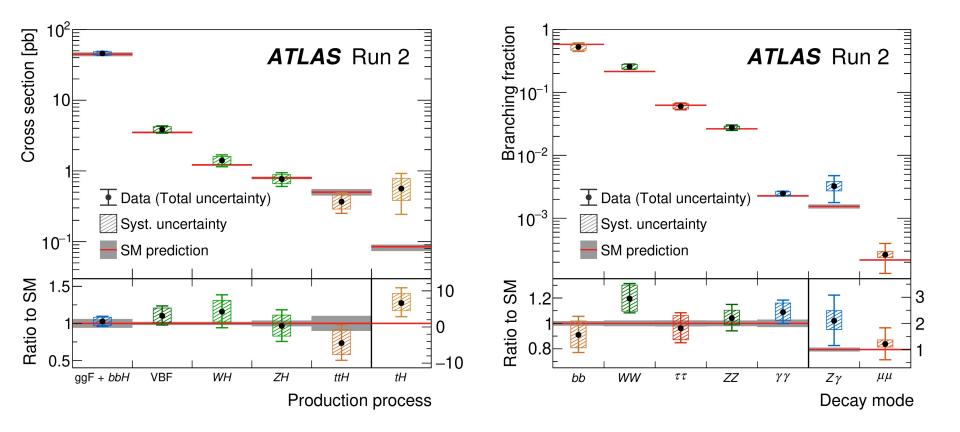


#### Interpretations: Inclusive Cross-section

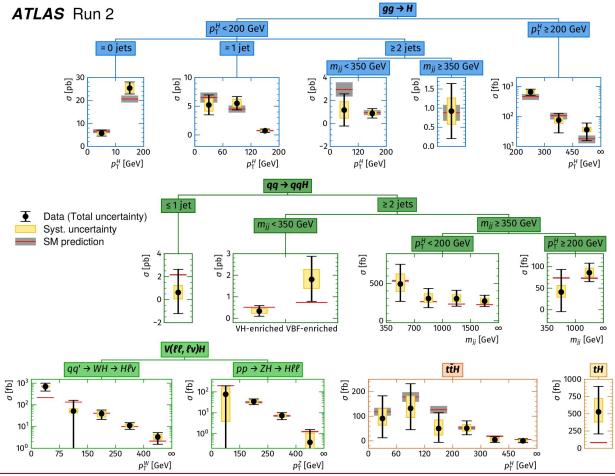
 $\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03$  (stat.)  $\pm 0.03$  (exp.)  $\pm 0.04$  (sig. th.)  $\pm 0.02$  (bkg. th.)



#### Interpretations: Production and Decays



#### **Interpretations: STXS**

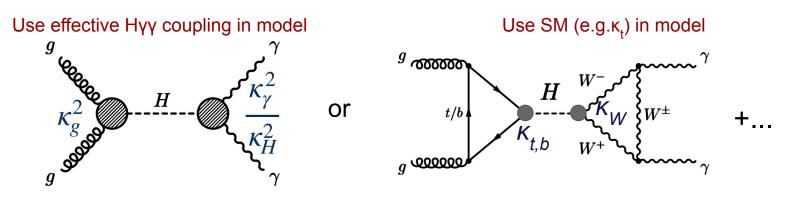


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# Interpretations: Kappa-Framework (1)

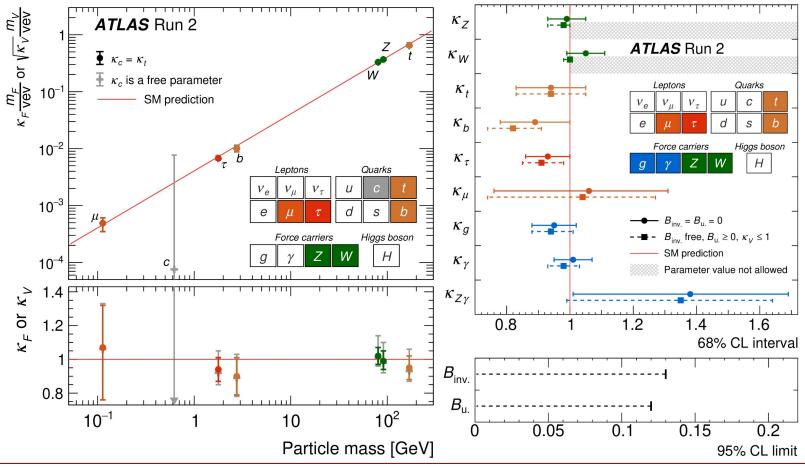
- Assign modifiers  $(\kappa_i)$  to couplings to SM particles
- Two choices for effective couplings (e.g. Hγγ)



• Higgs width also affected by addition of invisible and undetected decays

$$\kappa_H^2(\kappa, B_{\rm inv}, B_{\rm undet}) = \frac{\sum_j B_j^{\rm SM} \kappa_j^2}{(1 - B_{\rm inv} - B_{\rm undet})}$$

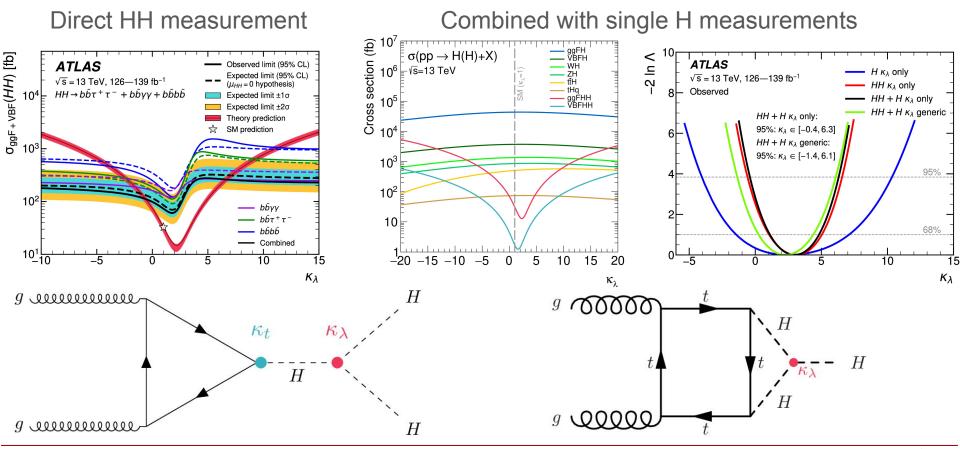
# Interpretations: Kappa-Framework (2)



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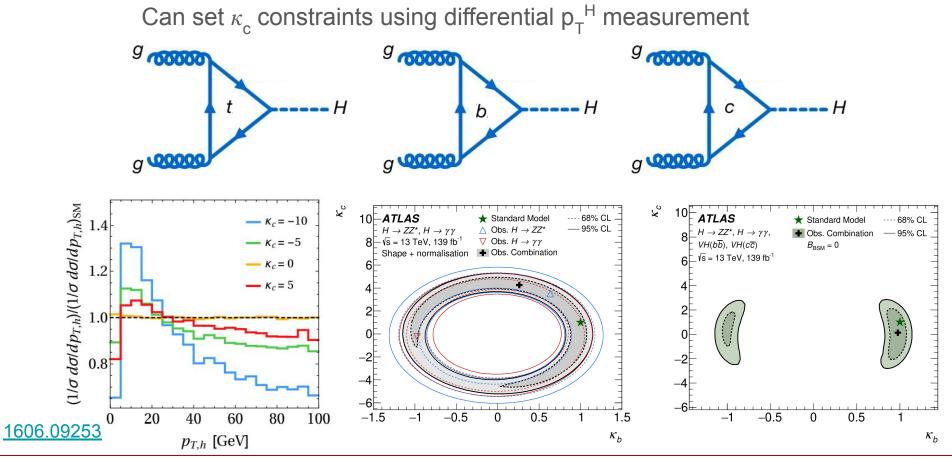
# Interpretations: Higgs Self-Coupling



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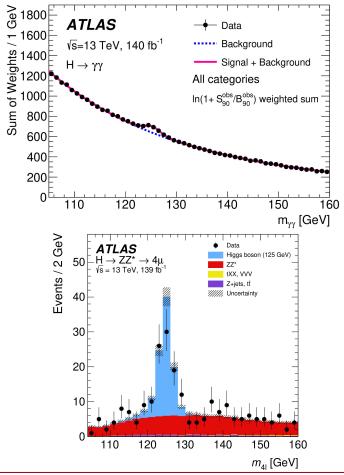
## Interpretations: Differential

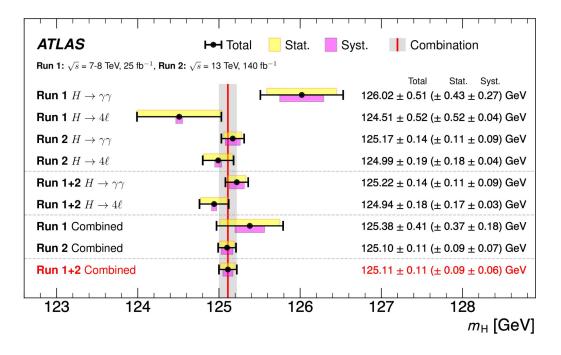


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# **Properties: Higgs Boson Mass**



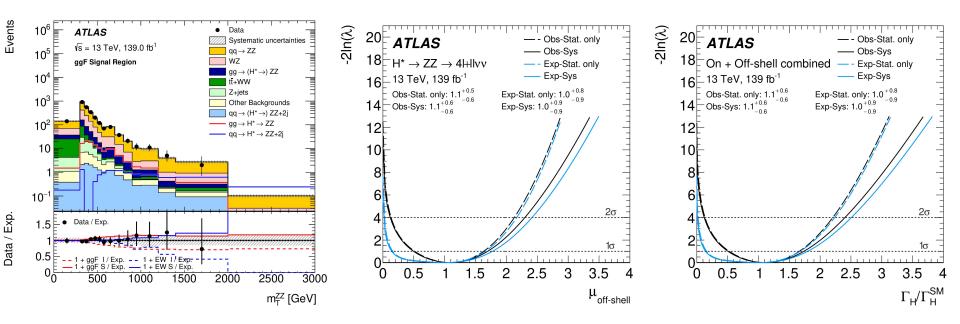


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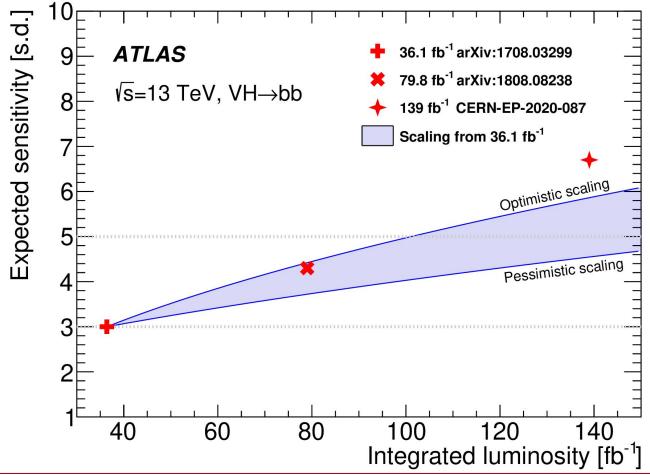
# Properties: Higgs Boson Width

Indirect, based on measurement of off-shell production

SM width too narrow to measure directly



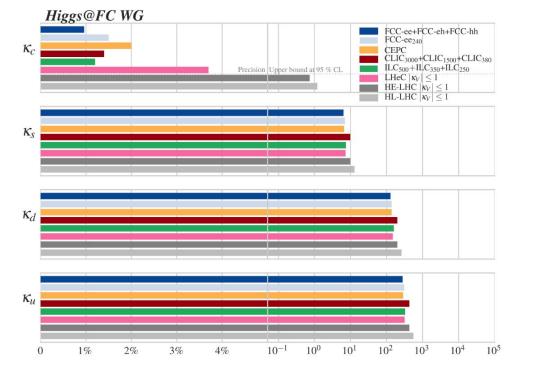
#### The Future?



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# Conclusions

- ATLAS and CMS have many Higgs boson measurements
- Technically what I showed is still just a subset
- Can expect large improvements in the long and very long term



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1905.03764

#### Backup

#### References

- <u>Coupling combination</u>
- HH combination
- Differential combination
- Boosted Hbb
- Offshell production
- <u>Mass measurement</u>