Multiboson final states with Higgs bosons in CMS and ATLAS

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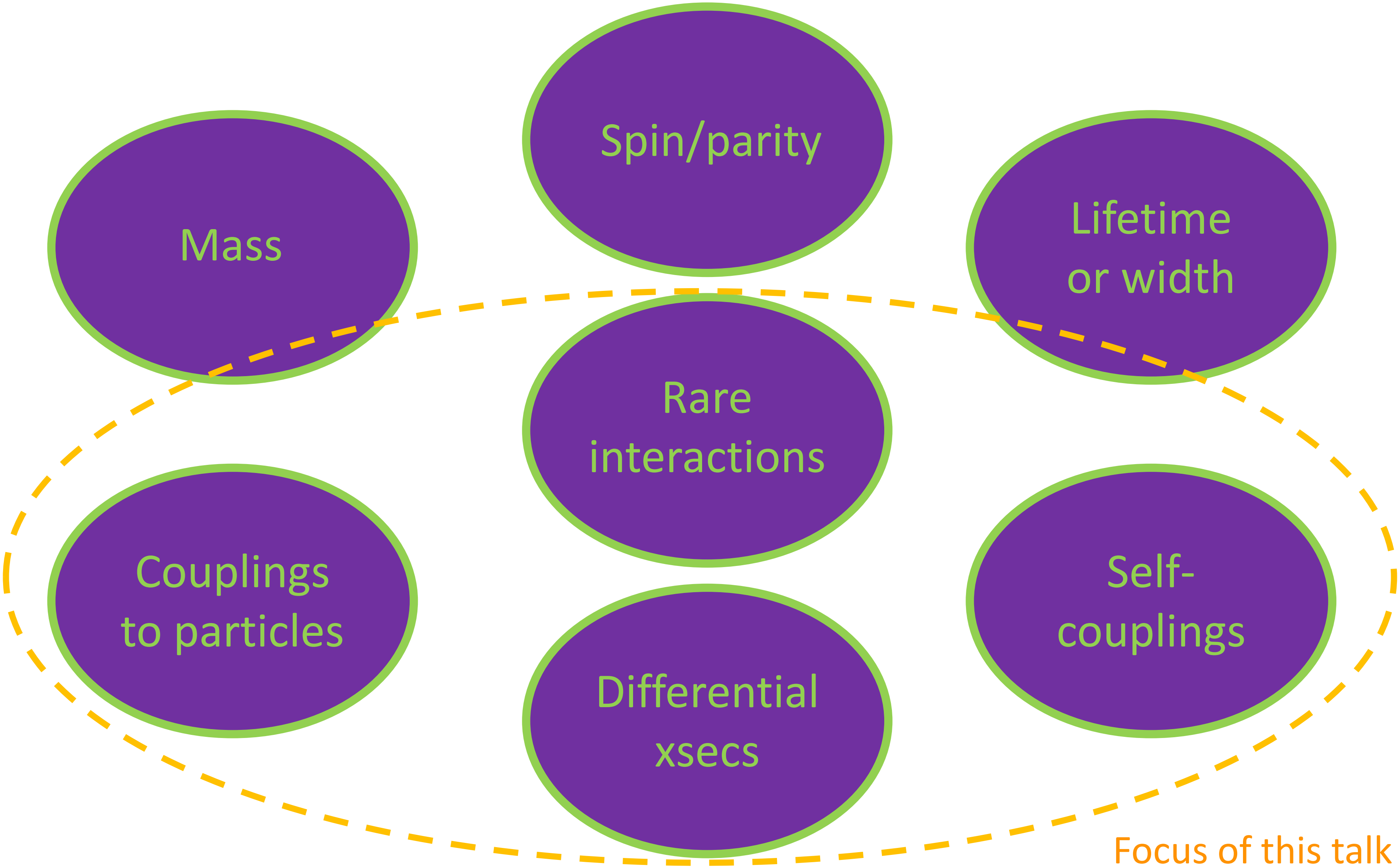
Progress over a decade in measuring...

- Mass
- Spin/parity
- Lifetime or width
- Rare interactions
- Couplings to particles
- Self-couplings
- Differential xsecs

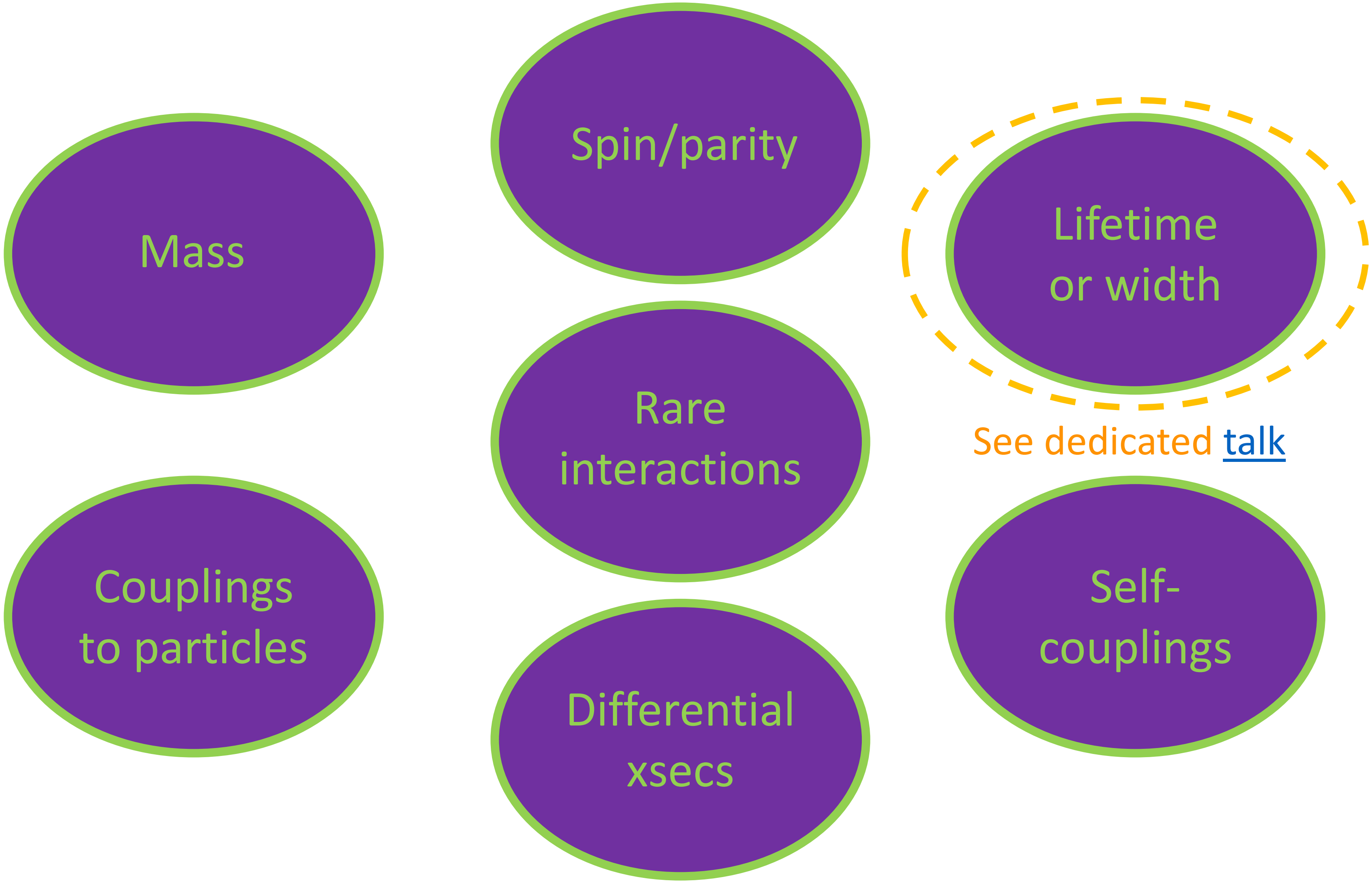
...of the Higgs boson

Progress over a decade in measuring...



...of the Higgs boson

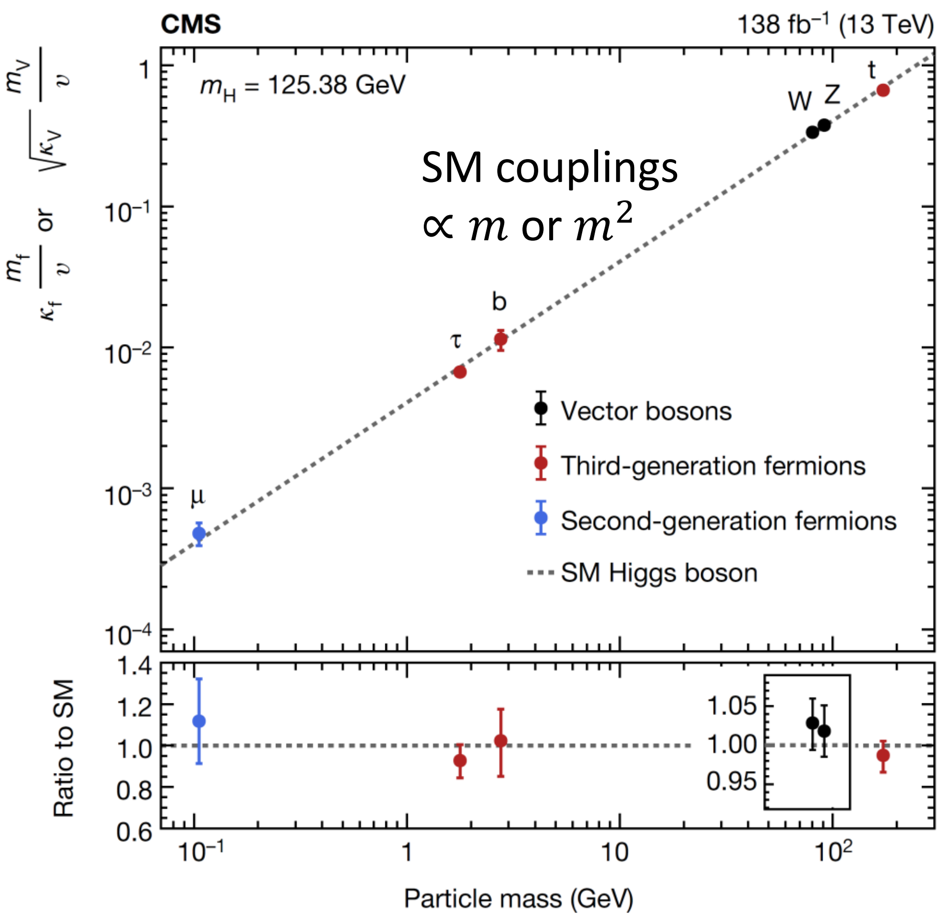
Progress over a decade in measuring...



...of the Higgs boson

Higgs couplings to other particles

Measurements performed using a combination of multiple Higgs decays



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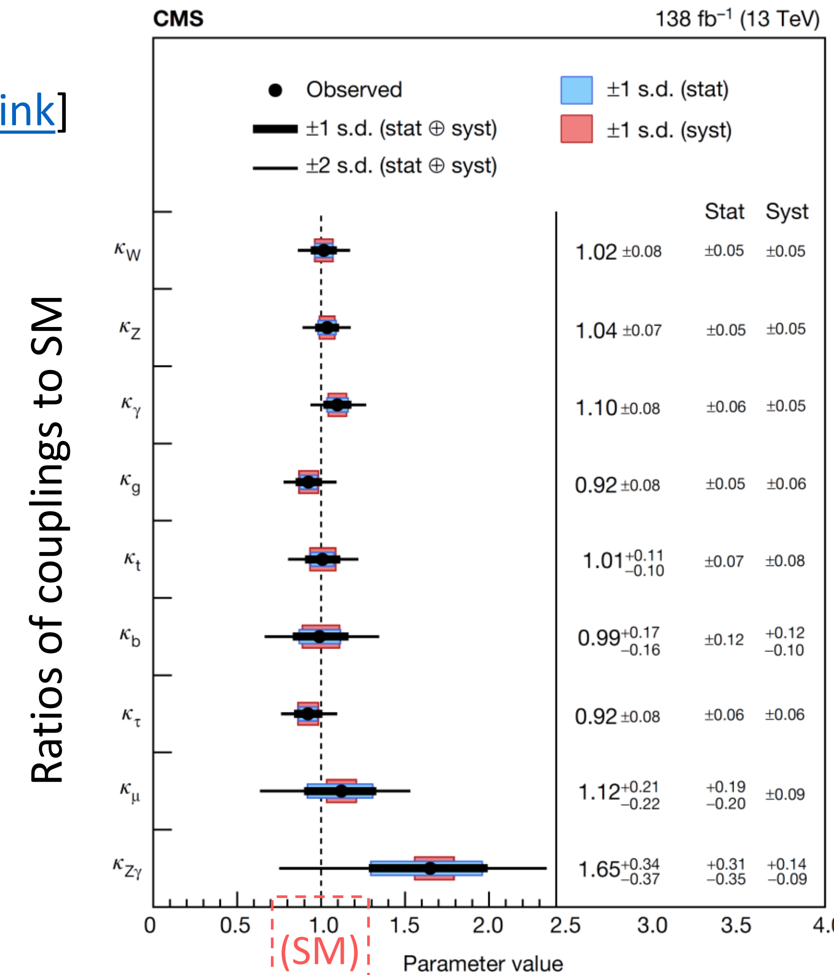

Couplings can be represented in different ways

→ O(**10%**) precision in most

→ Also notable from $\boldsymbol{VH, H \to c\bar{c}}$ analysis (link):

$$1.1 < |\kappa_c| < 5.5 \text{ @ 95\% CL}$$

Limitations still statistical

→ Uncertainties $\sim 1/\sqrt{N}$.

Higgs couplings to other particles

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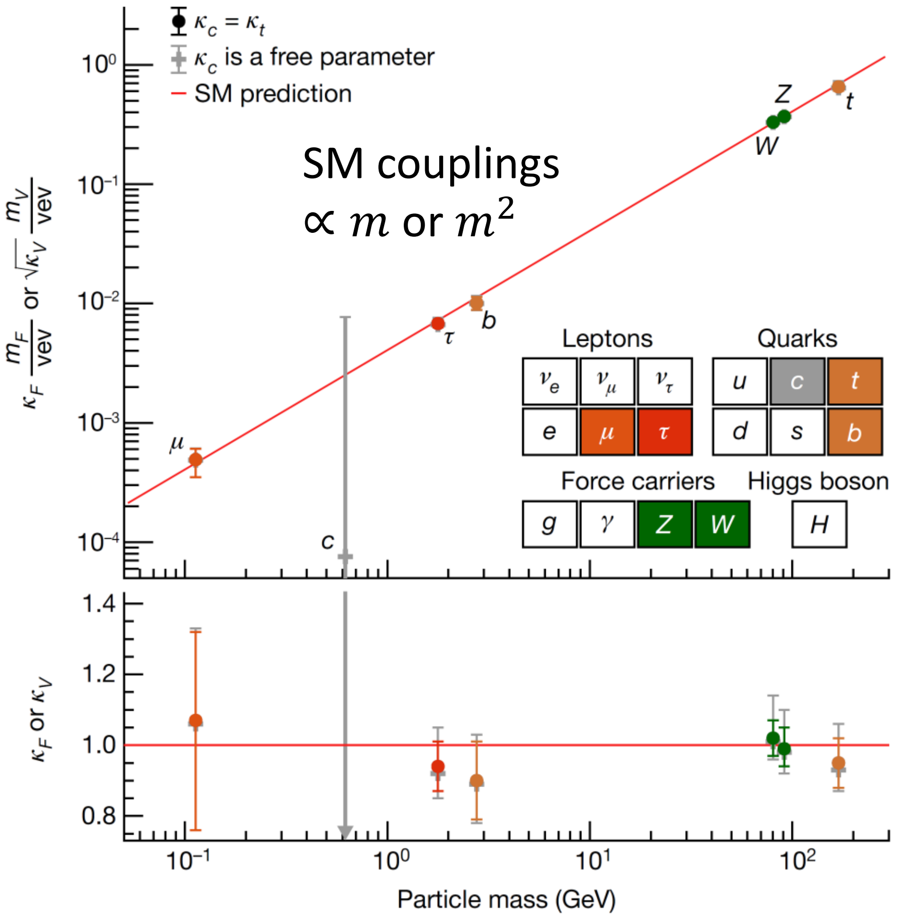
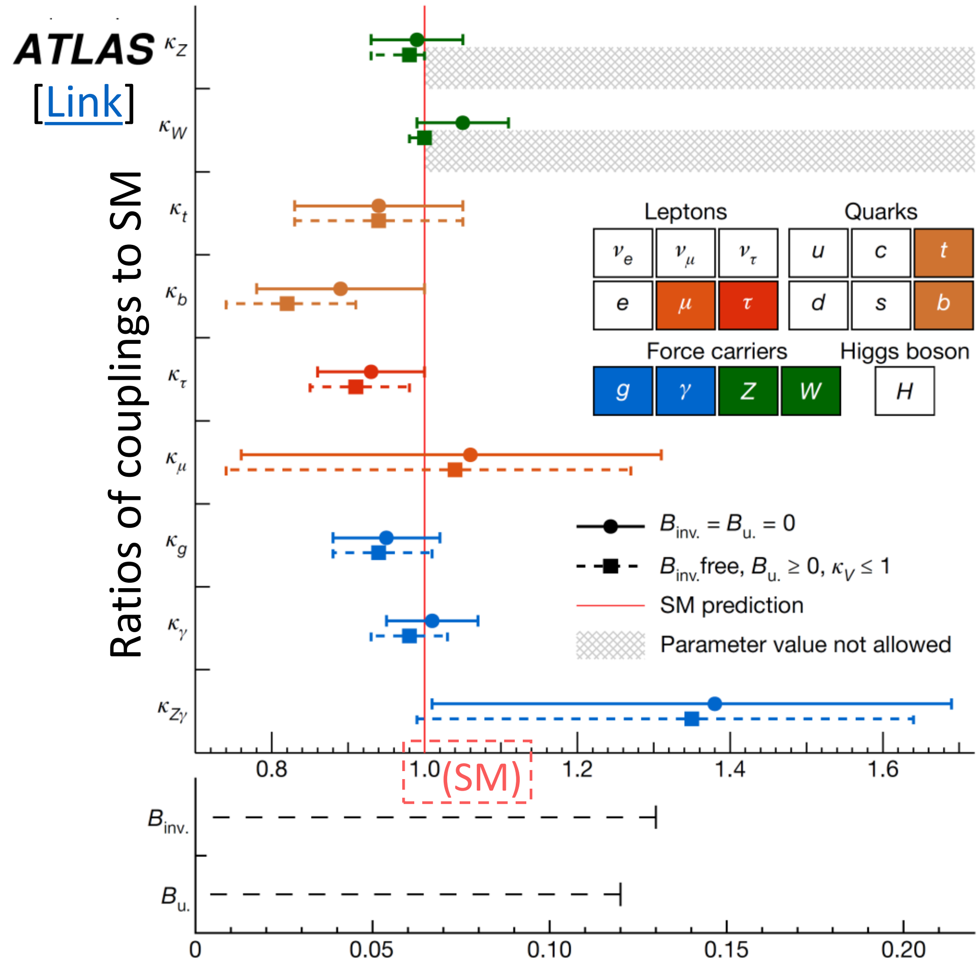
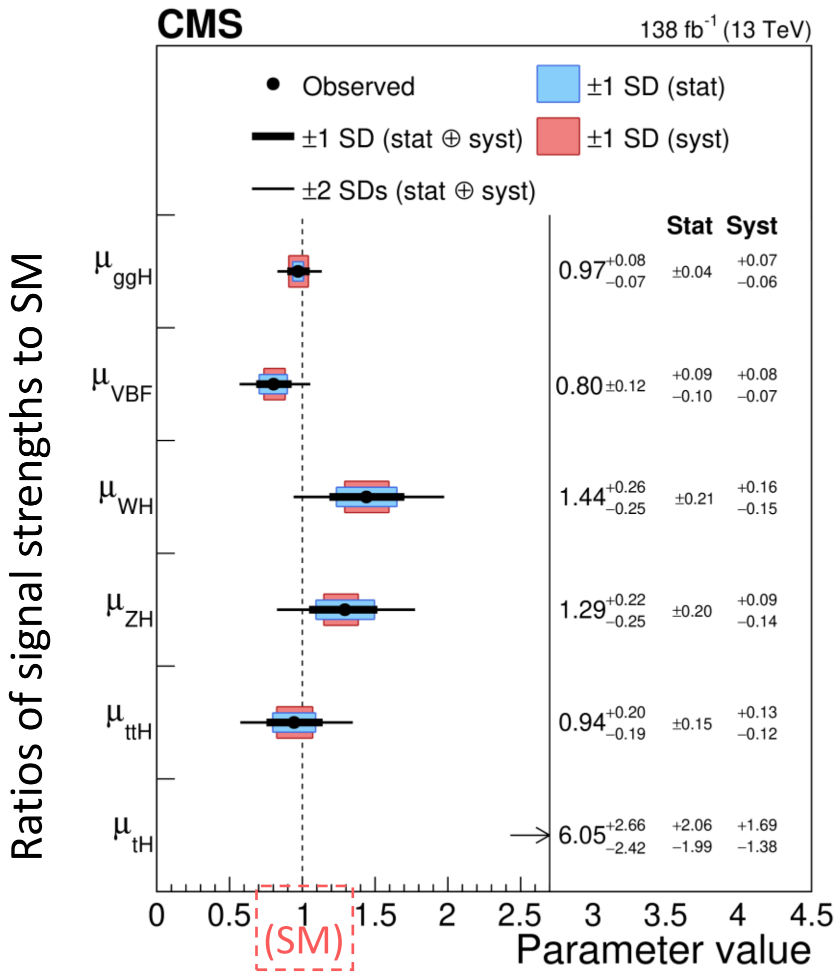




Similar to CMS, O(**10%**) precision in most couplings

Limitations still statistical
→ Uncertainties $\sim 1/\sqrt{N}$.

Constraints on production and visible decays



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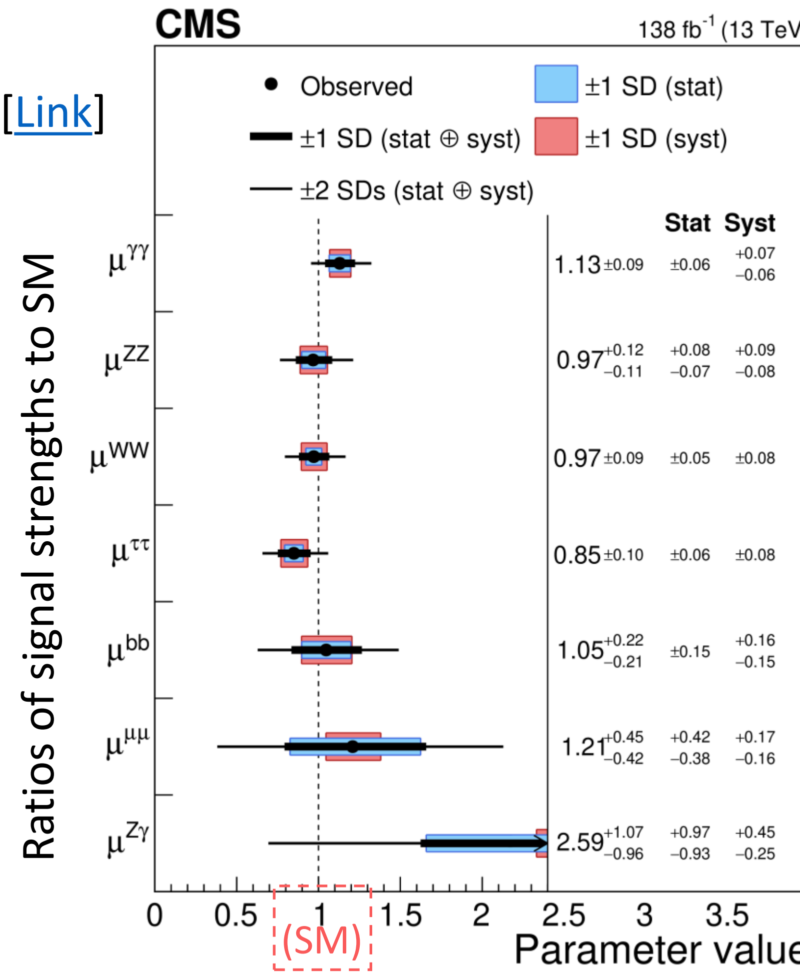


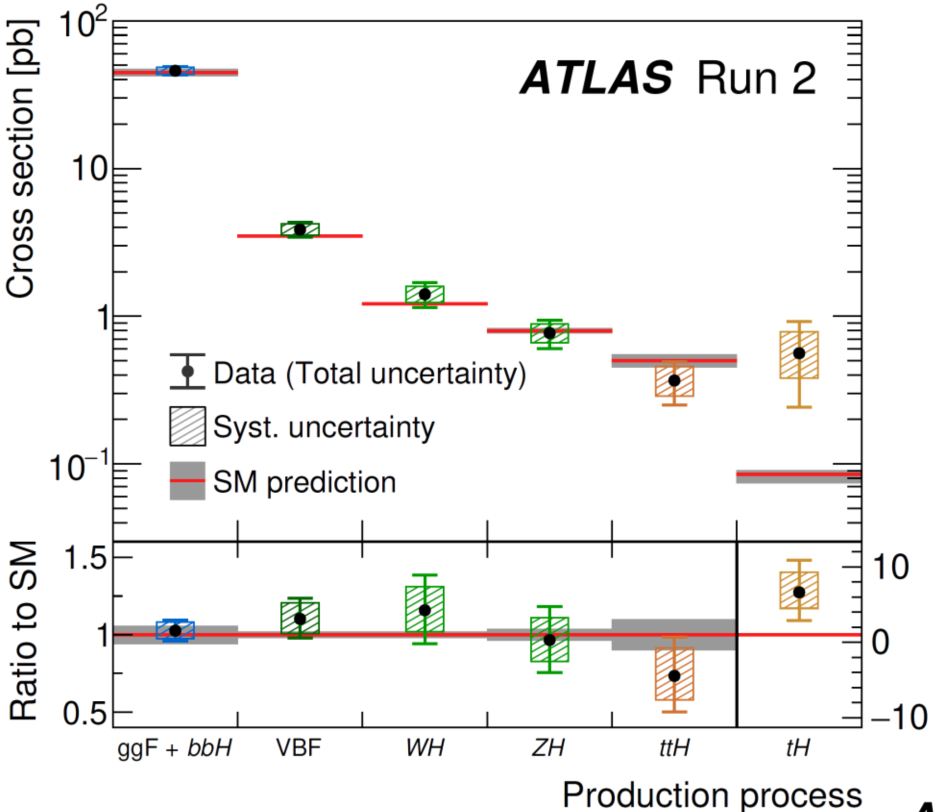
→ Measurements so far consistent with the SM

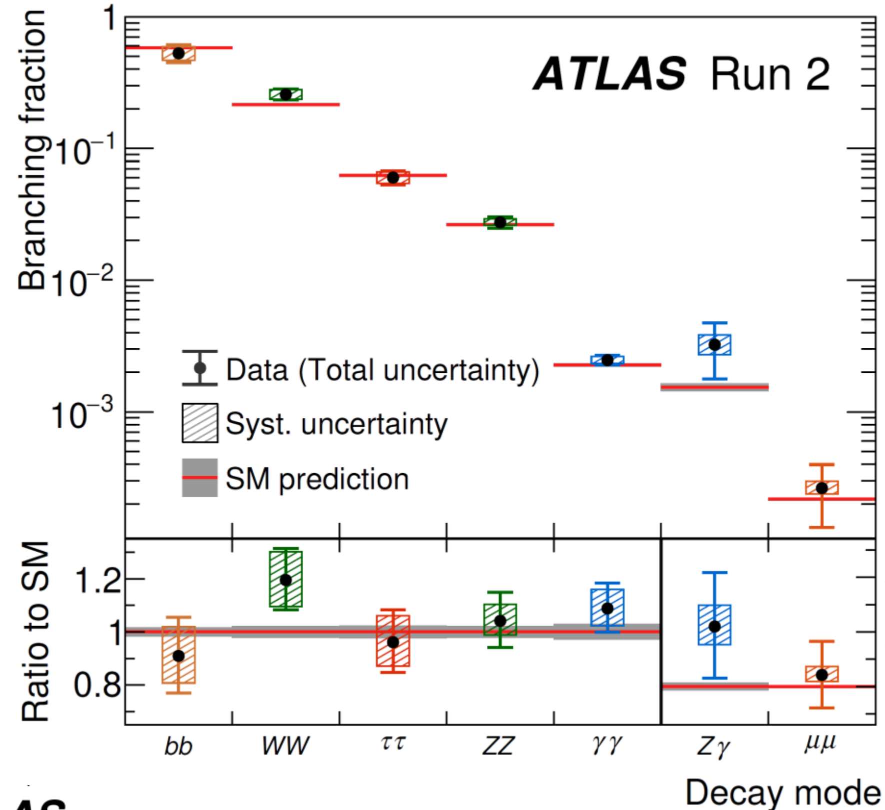
→ **Gluon fusion** within ~**5%**, **VBF** within ~**10%**

→ Consistent excess in tH, but large uncertainty due to small xsec and $t\bar{t}H$ contamination

→ Precision in $\boldsymbol{ZZ}, \boldsymbol{WW}, \boldsymbol{\gamma\gamma}$, and $\boldsymbol{\tau\tau}$ decays ~**10%**, consistent excess in $Z\gamma$

Constraints on production and visible decays





ATLAS

[Link]

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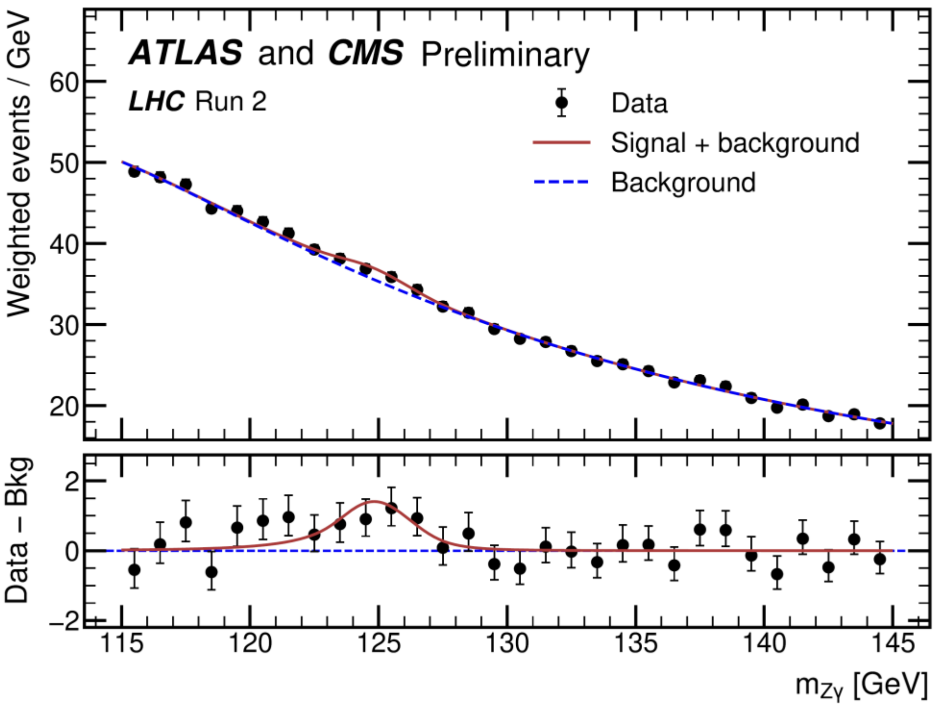
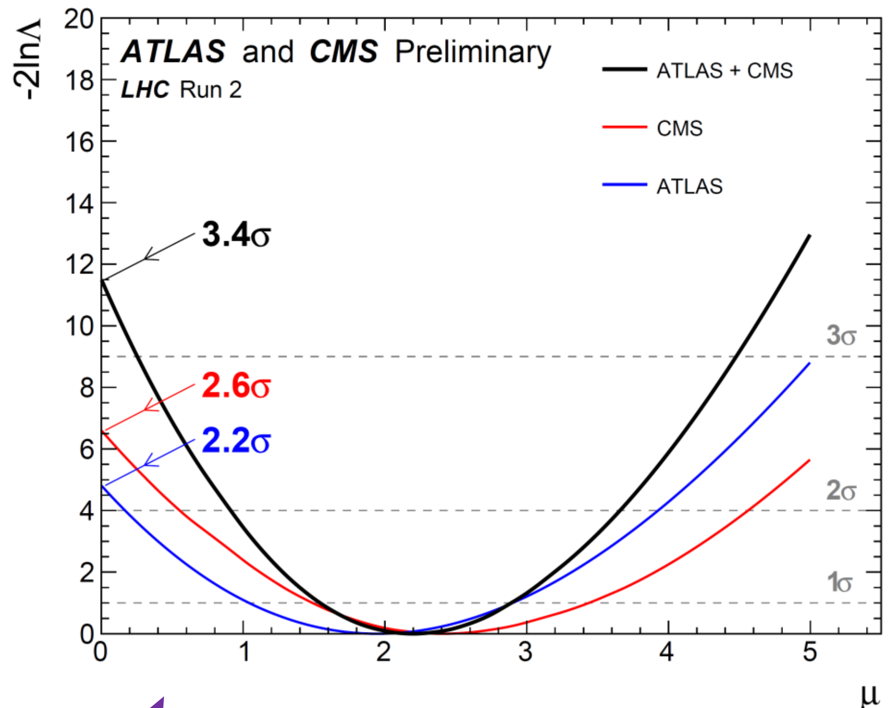
- → Precision in $\boldsymbol{ZZ}$, $\boldsymbol{WW}$, $\boldsymbol{\gamma\gamma}$, and $\boldsymbol{\tau\tau}$ decays ~**10%**, consistent excess in $Z\gamma$

Evidence for rare $Z\gamma$ decays





[Link]

Recent

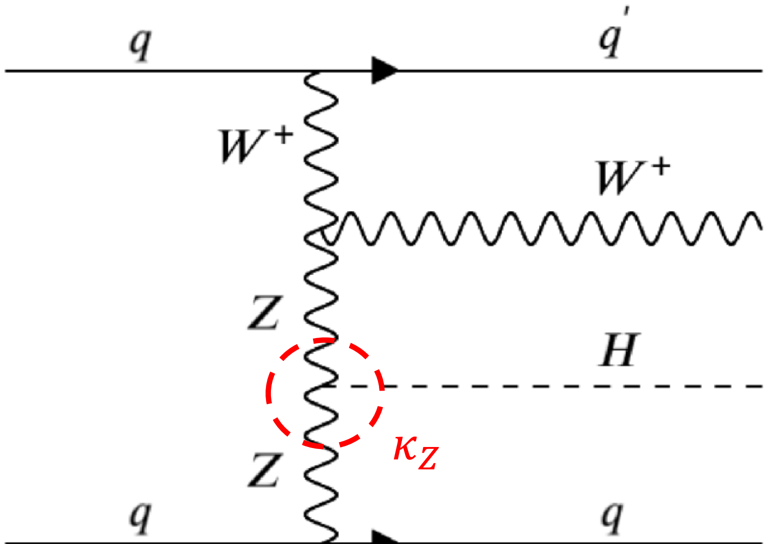
Recent analyses of CMS and ATLAS combined:

→ $\mathrm{H} \to Z\gamma$ evidence @ 3.4 std. dev.

→ $\mu_{Z\gamma} = 2.2 \pm 0.7$ $(1.0 \pm 0.6$ exp.)

→ Agrees with the SM within 1.9 std. dev.

VBF WH



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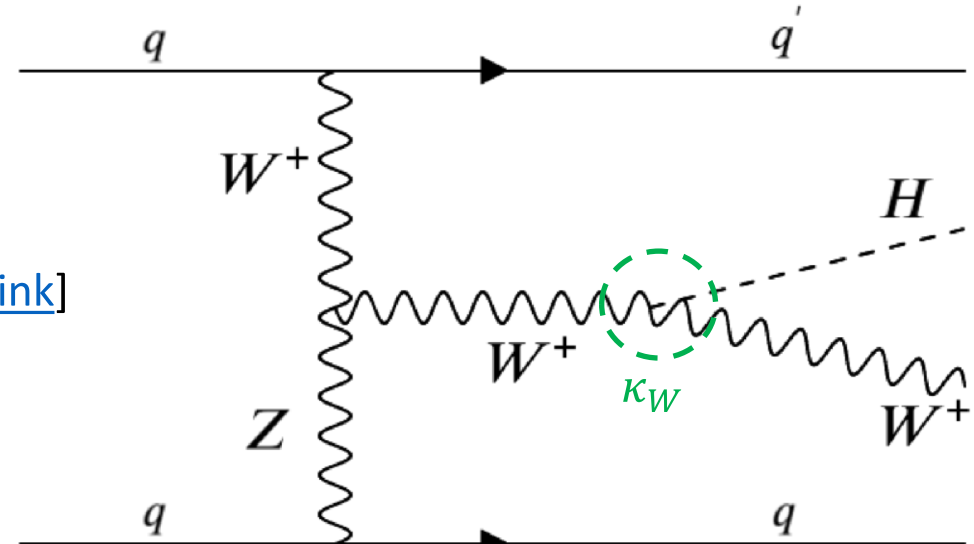


Recent

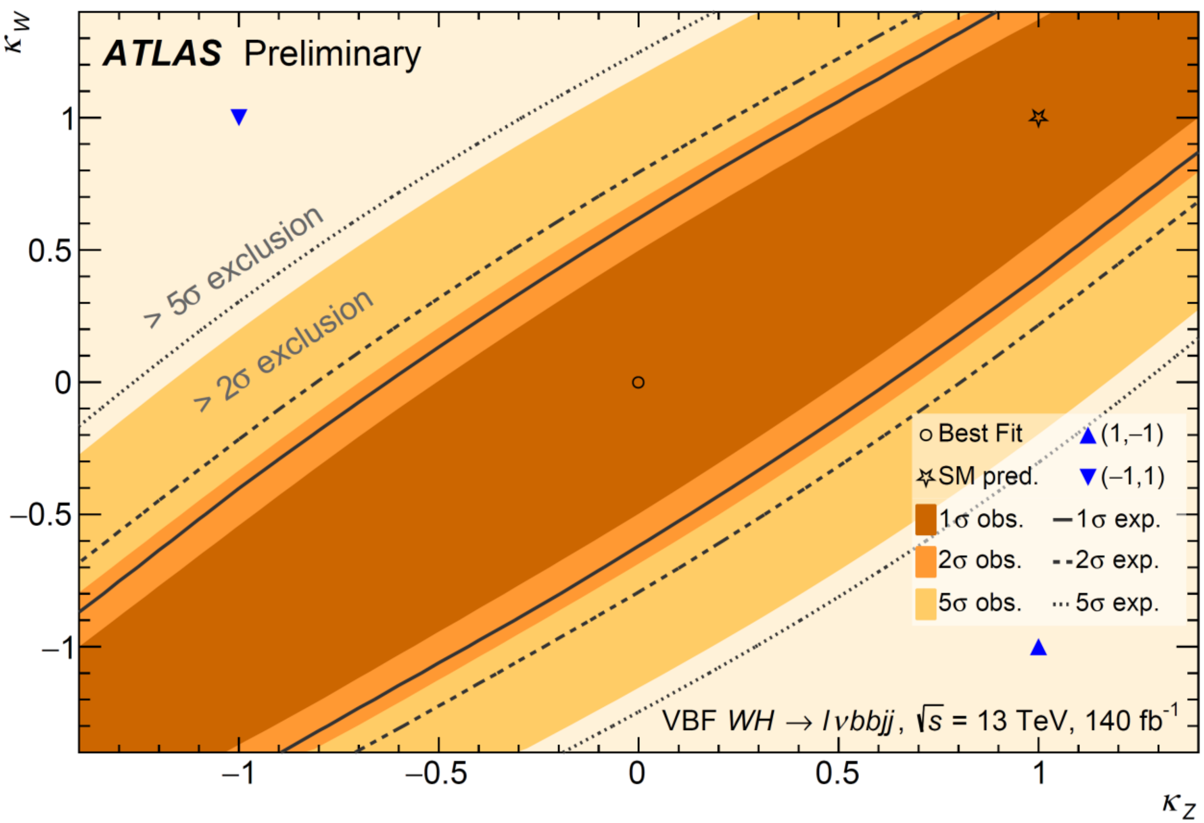
Essentially no sensitivity to sign of κ_Z vs. κ_W from processes that drive their measurements

→ Destructive interference when $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} > 0$, especially observable at high p_{T}^{H}/W

→ ATLAS analysis with $H \to b\bar{b}$ and $W \to \ell\nu$

→ SR^{-}, $\mathrm{SR}^{+}_{\mathrm{loose}}$, and $\mathrm{SR}^{+}_{\mathrm{tight}}$ for different sensitivities to sign of λ_{WZ} (see backup for the SR definitions)

VBF WH



[Link]

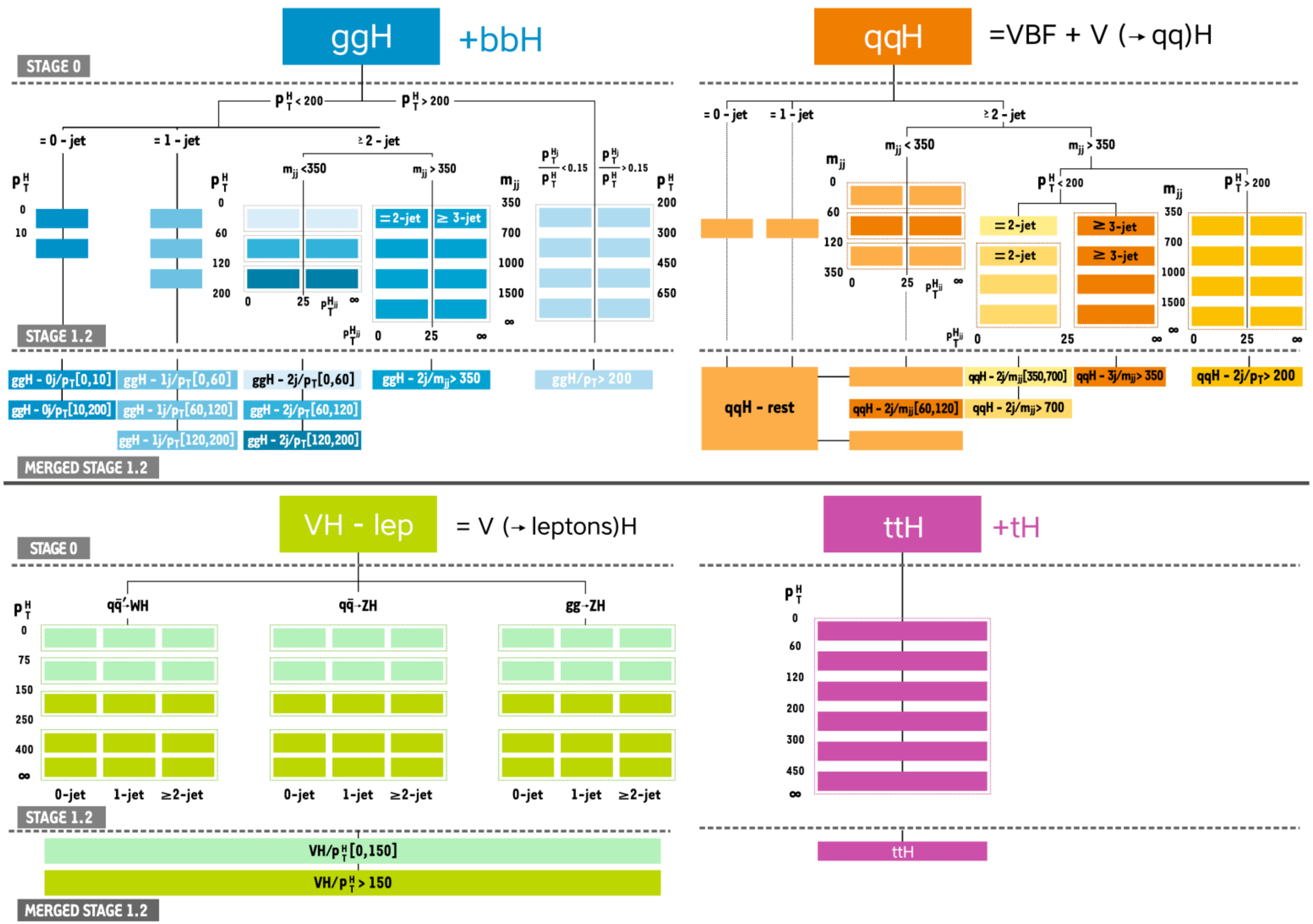
All values of $\lambda_{WZ} < 0$ consistent with Nature Higgs couplings results excluded beyond 8 std. dev.

→ $\mu_{\mathrm{VBF}\,WH} < 11.2$ @ 95% CL for $\lambda_{WZ} > 0$

Recent

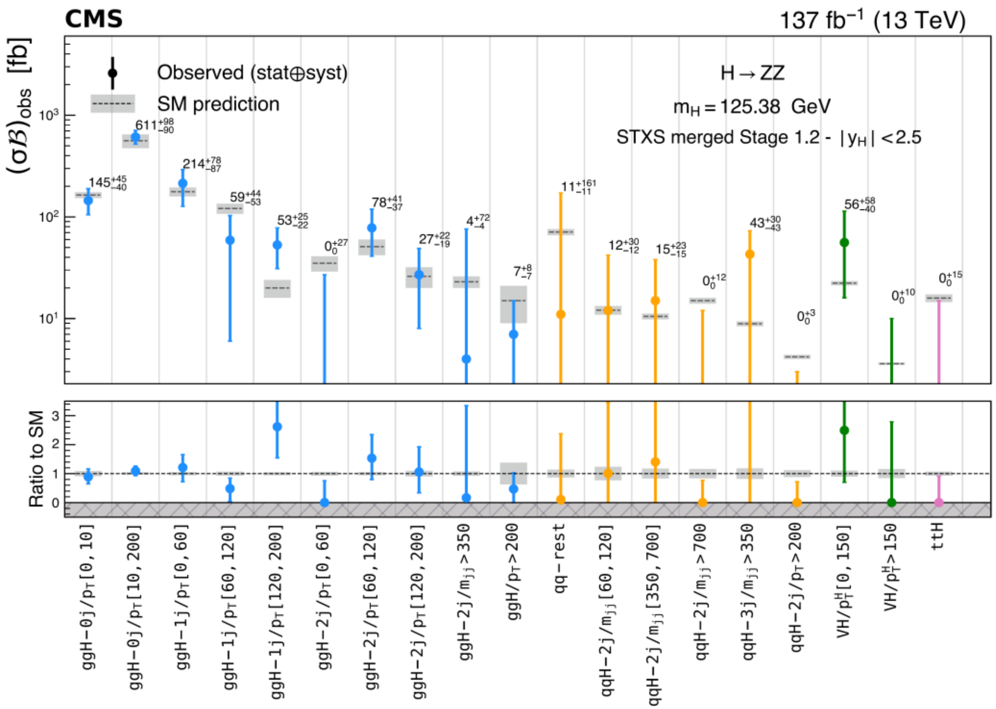
Beyond couplings: STXS

Split production modes finer in specific final states, p_{T}^{H}, or m_{jj}
Measure the cross section for each 'production bin'



Results from individual (multiboson) channels:
ZZ [link]
WW [link]
$\gamma\gamma$ [link]

Beyond couplings: STXS (ZZ)

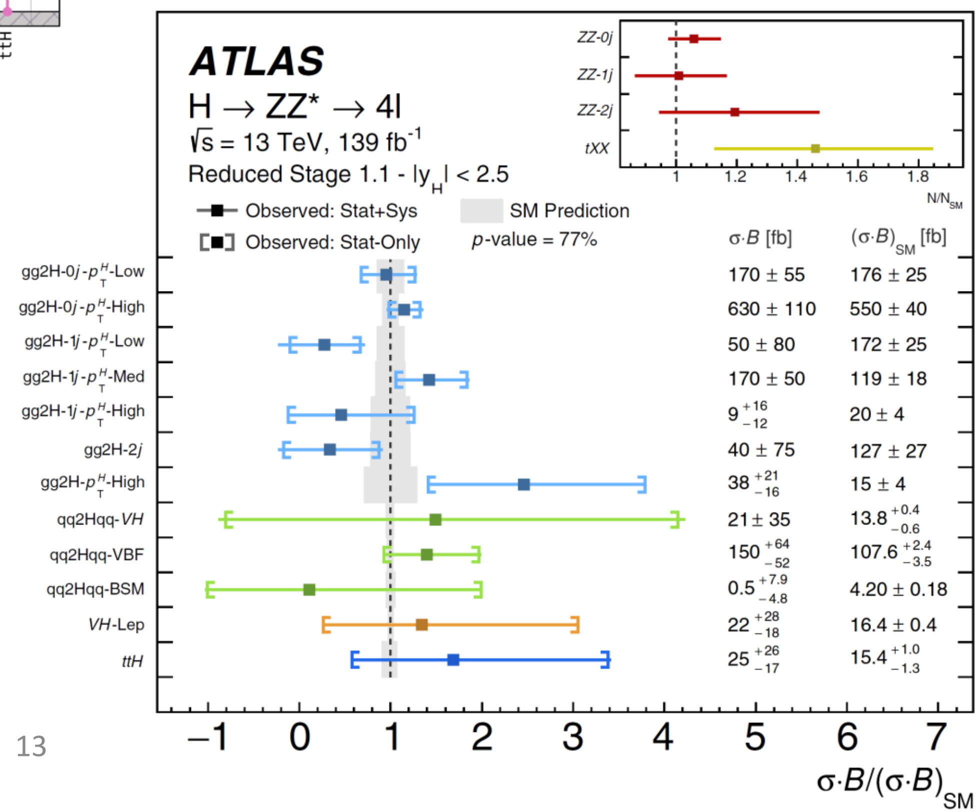


CMS results [link]

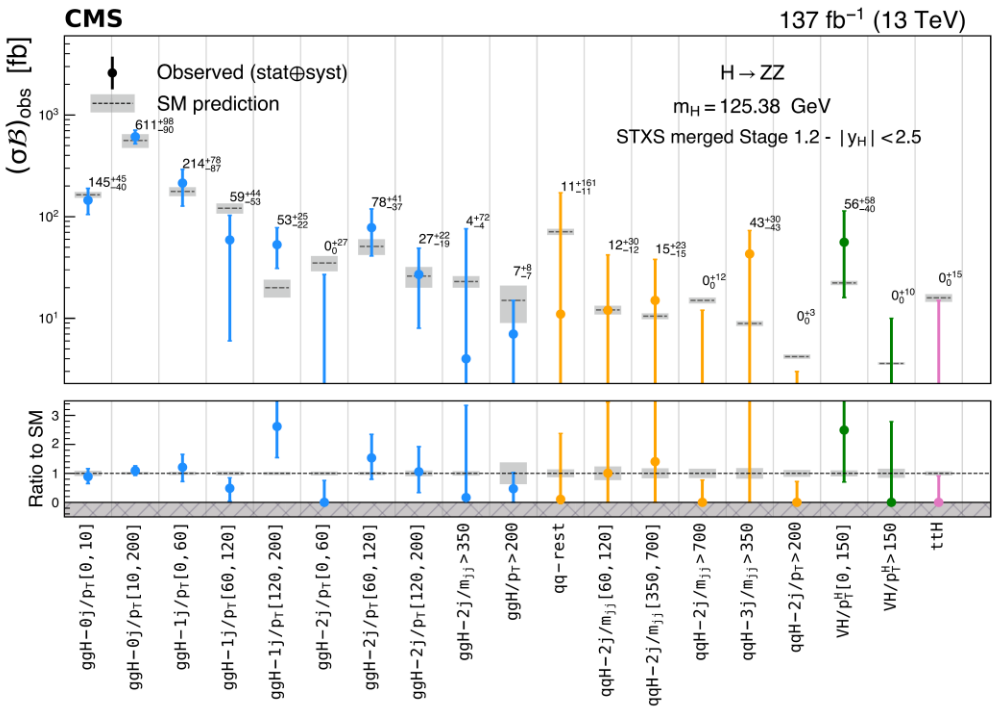
→ CMS results in 4ℓ feature a merged STXS 1.2 scheme down to ttH categories
→ Analysis relies heavily on matrix element discriminants for event categorization or background discrimination

→ 12 STXS categories (reduced Stage 1.1)
→ NN discriminants in many reco. event categories
(see backup for categories)

ATLAS results [link]



Beyond couplings: STXS (ZZ)



CMS results [link]

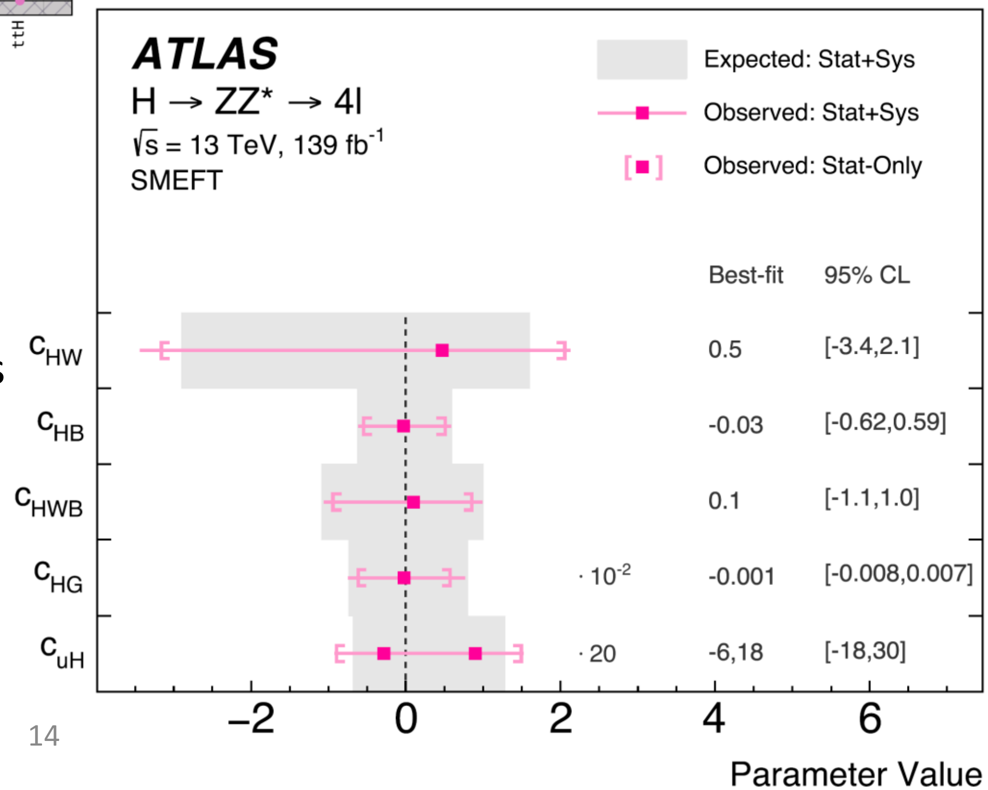
→ CMS results in 4ℓ feature a merged STXS 1.2 scheme down to ttH categories

→ Analysis relies heavily on matrix element discriminants for event categorization or background discrimination

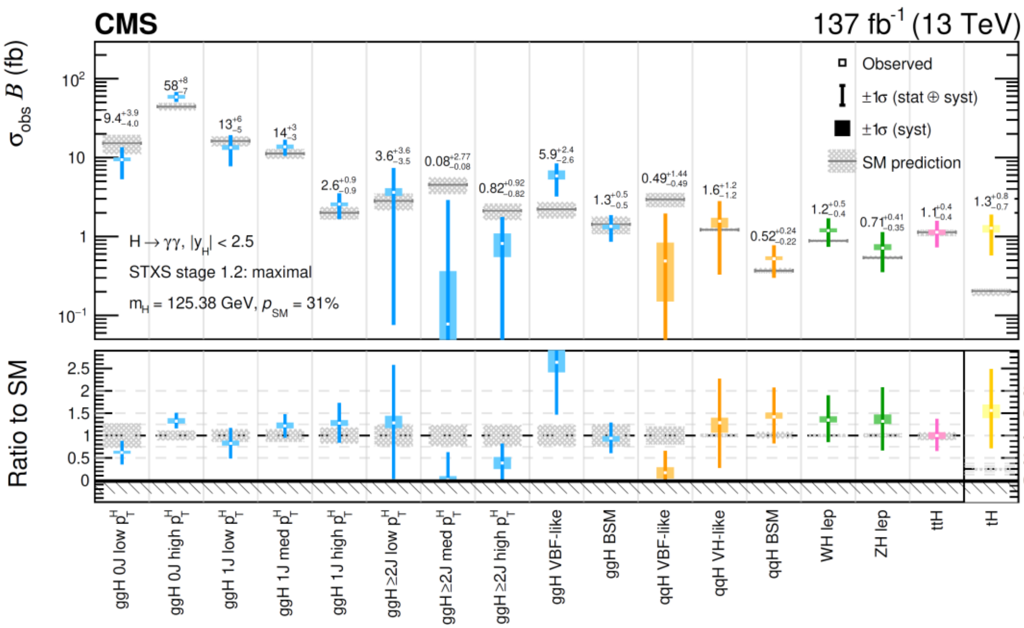
→ Also feature SMEFT interpretation in the Warsaw basis

→ Consistent with the SM so far

ATLAS results [link]



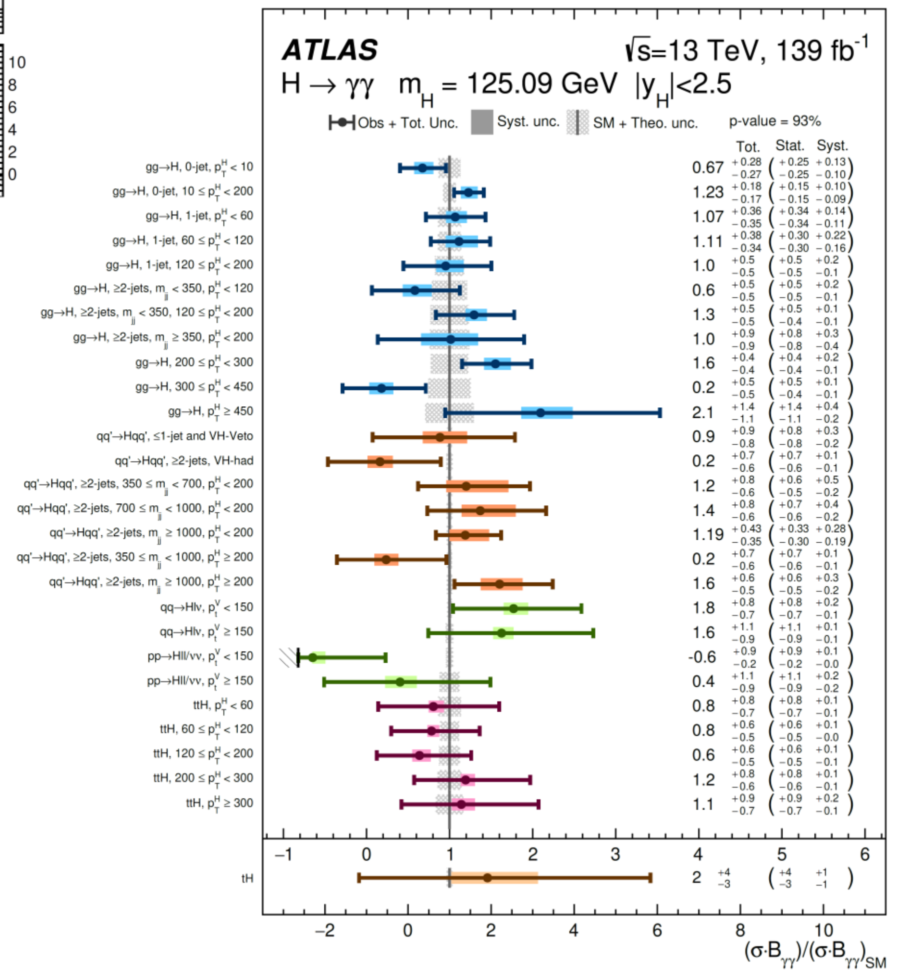
Beyond couplings: STXS ($\gamma\gamma$)



CMS results [link]

→ Merged STXS 1.2 scheme down to ttH categories

→ Slightly different merging than 4ℓ



→ 28 STXS bins optimized to avoid large correlations

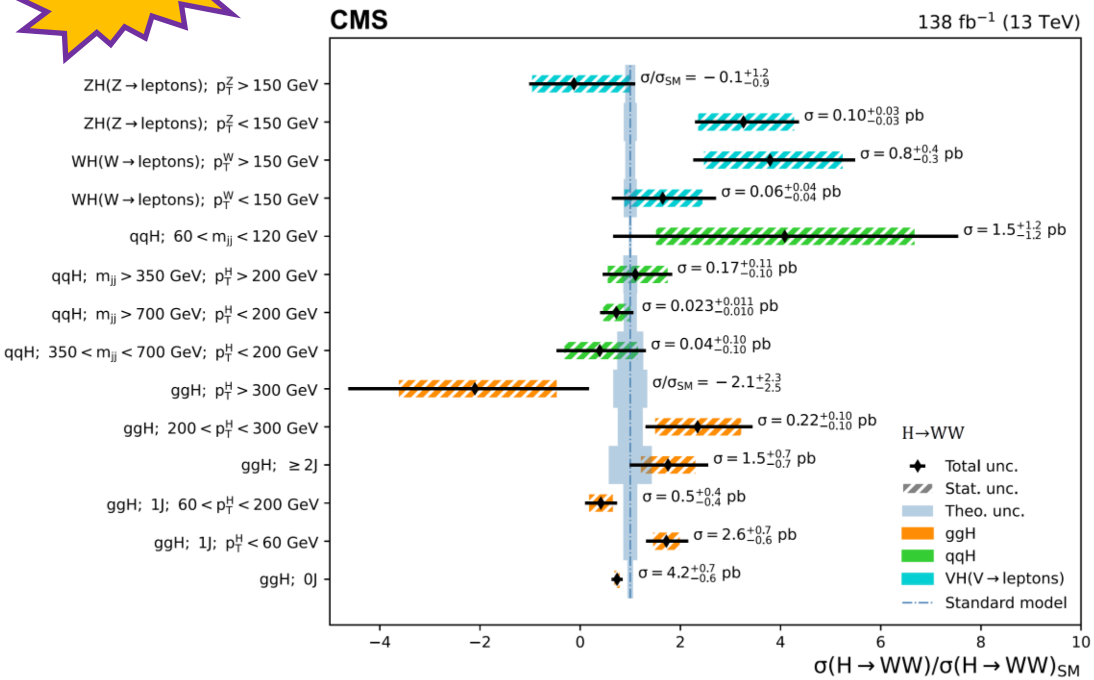
→ Event categorization with multiclass BDTs for each STXS bin

→ Further binary classifiers for analysis

ATLAS results [link]

Recent

Beyond couplings: STXS (WW)



CMS results [link]

→ Analysis targets ggH, VBF, WH, and ZH productions

→ Competitive VH results from semileptonic WW

→ 14 STXS bins

→ $m_T^{\ell\ell}$, $m_{\ell\ell}$, and MVA discriminants (see backup for reco. event cats.)

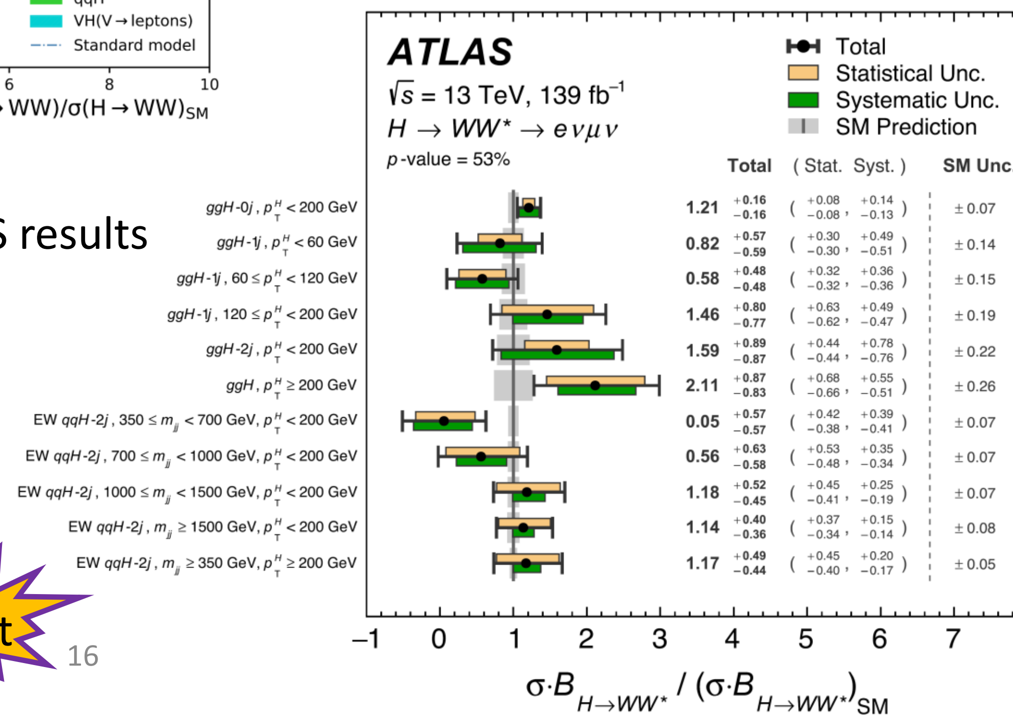
→ Analysis targets ggH and VBF

→ 11 STXS bins

→ Reco. events split in N_j

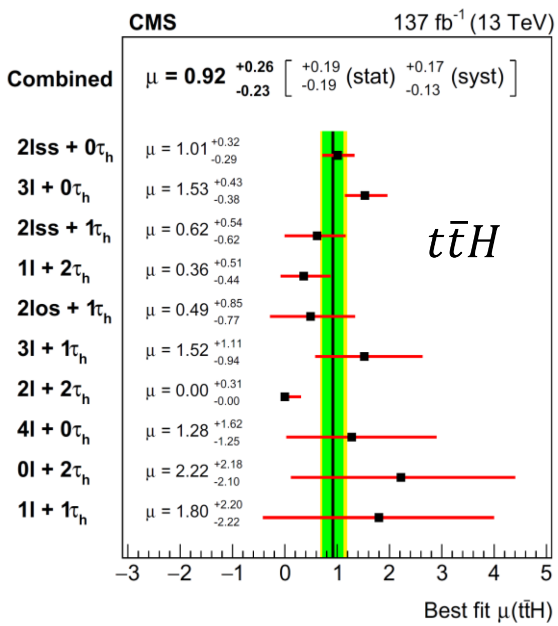
→ $m_T^{\ell\ell}$ (ggH) and NN (VBF) discriminants (see backup for event categories)

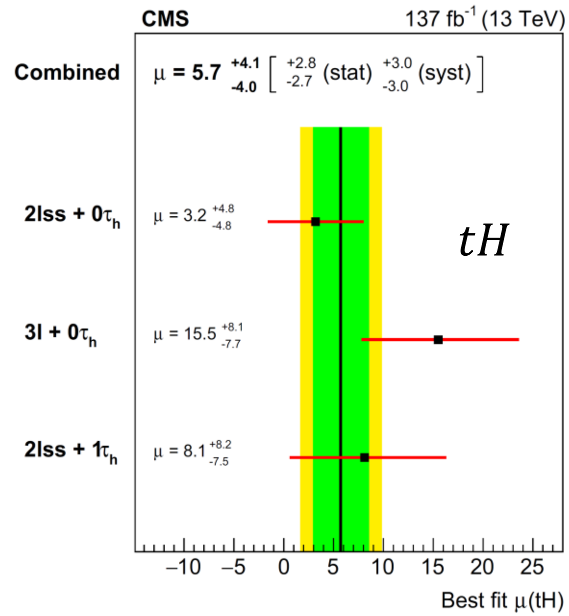
ATLAS results [link]



Recent

Beyond couplings: WW cont., $t\bar{t}H/tH$



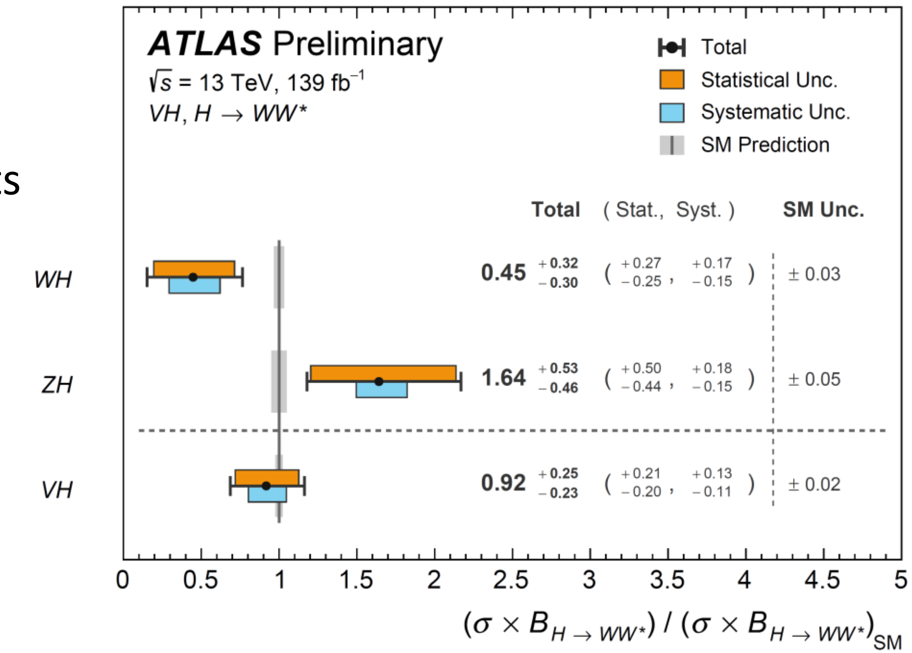


CMS results [link]

→ Dedicated analysis of multilepton events for $t\bar{t}H/tH$ productions

→ Combination of final states in 10 categories

→ NN discriminants to distinguish backgrounds and ttH/tH



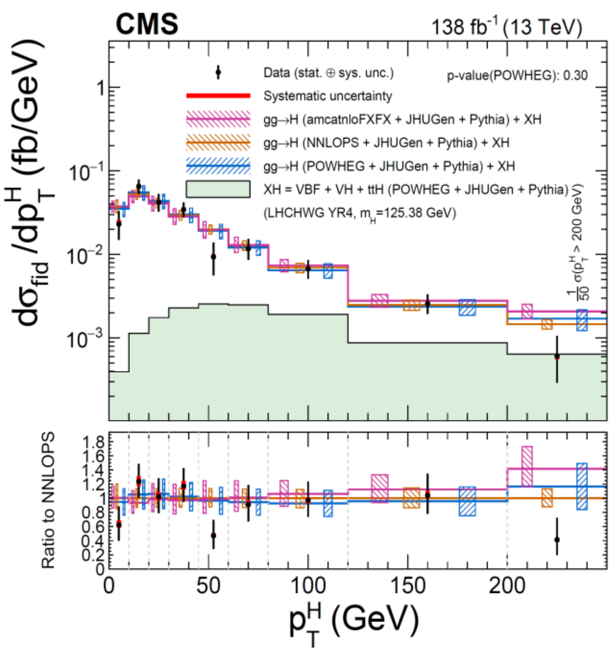
→ Dedicated analysis from ATLAS for VH, $H \to WW$

→ Includes semileptonic WW decays as in CMS analysis

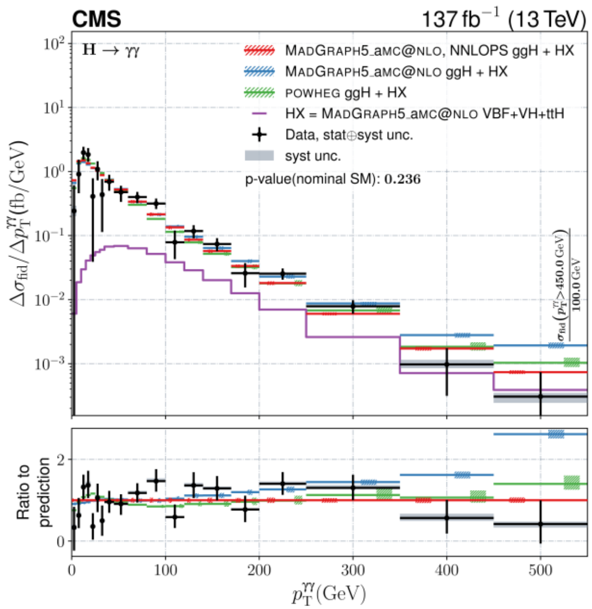
→ NN discriminants in different lepton cats.

ATLAS results [link]

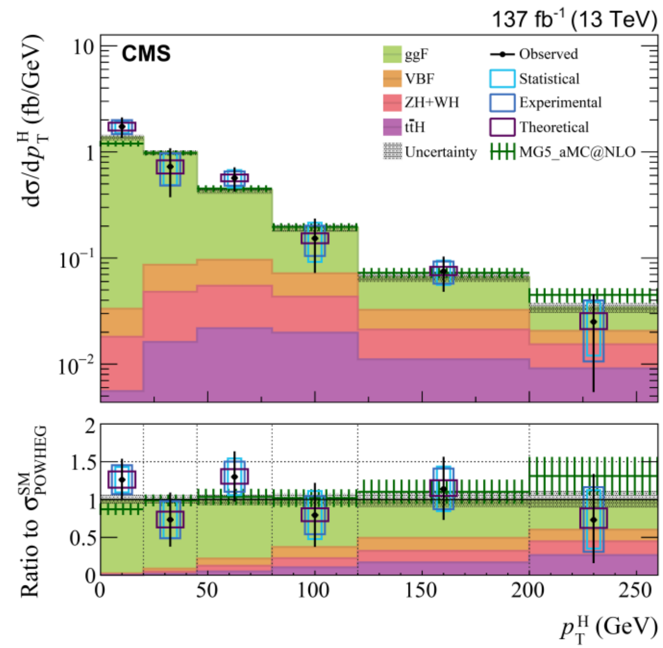
Beyond couplings: Fiducial differential xsecs



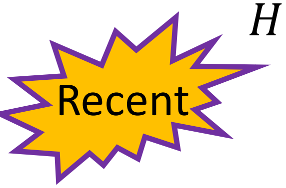
$H \rightarrow 4\ell$ [link]



$H \rightarrow \gamma\gamma$ [link]



$H \rightarrow WW$ [link]



CMS results

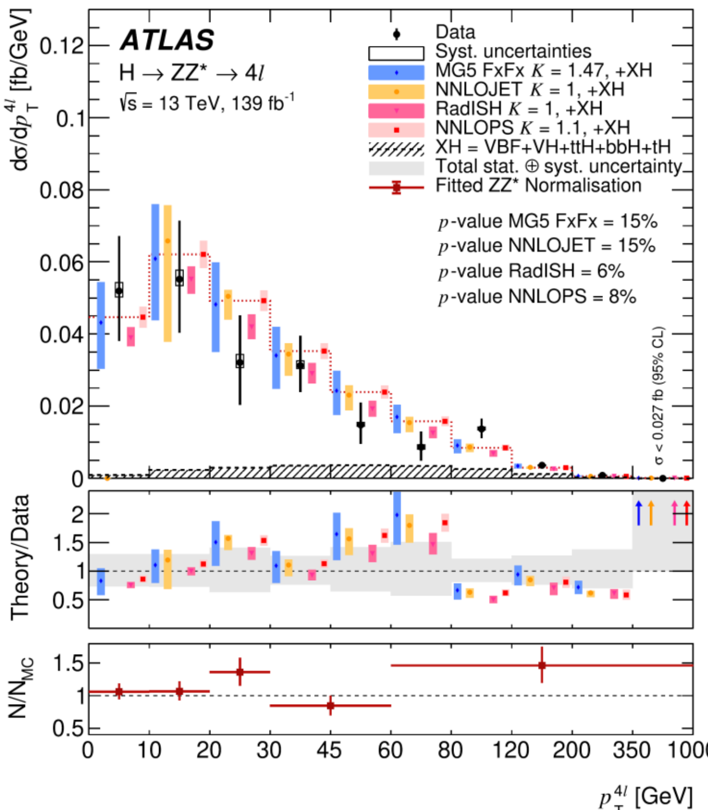
Measure total Higgs xsec in bins of p_T^H, y_H or other variables within a fiducial selection volume

→ Examples for p_T^H

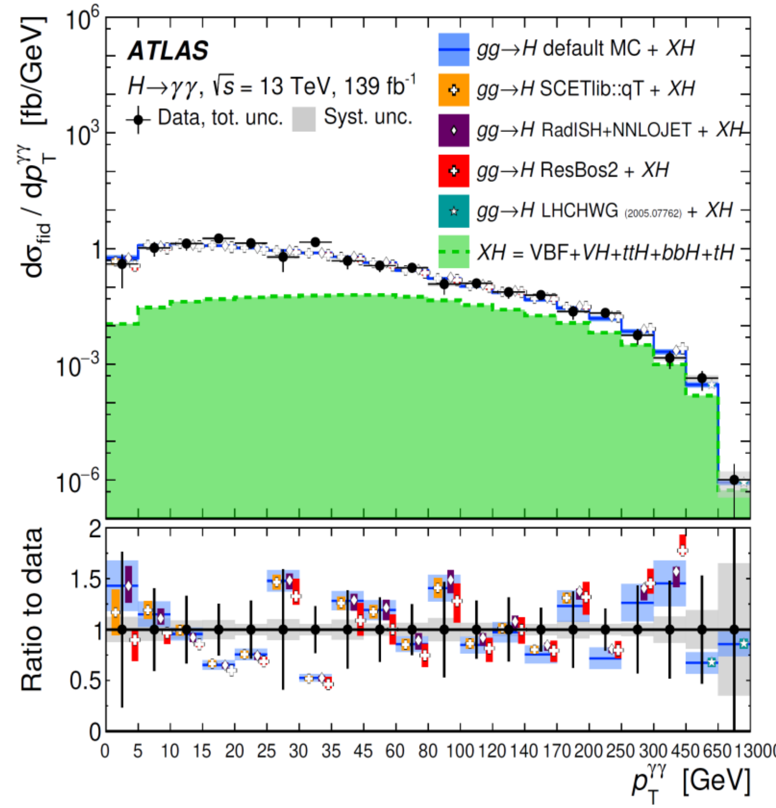
→ More observables in the linked references

→ Data consistent with SM so far

Beyond couplings: Fiducial differential xsecs



$H \to 4\ell$ [link]



$H \to \gamma\gamma$ [link]

ATLAS results

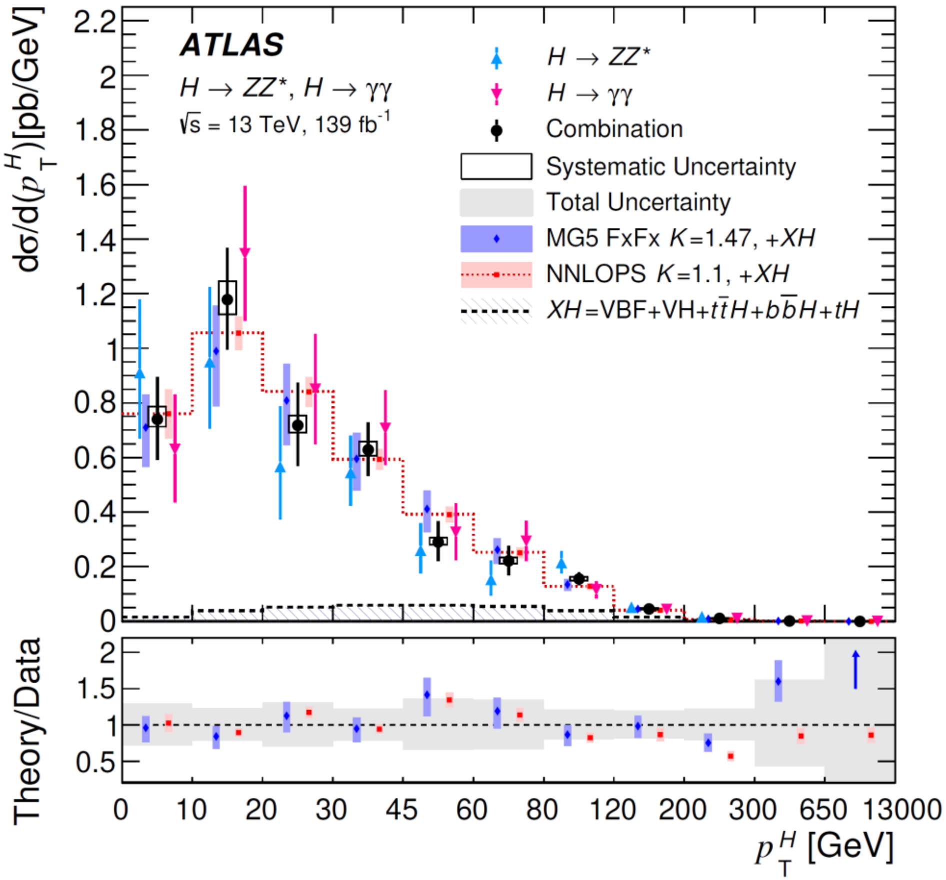
Examples for p_{T}^{H} in ATLAS 4ℓ and $\gamma\gamma$ measurements

→ More observables in the linked references

→ Data consistent with SM so far

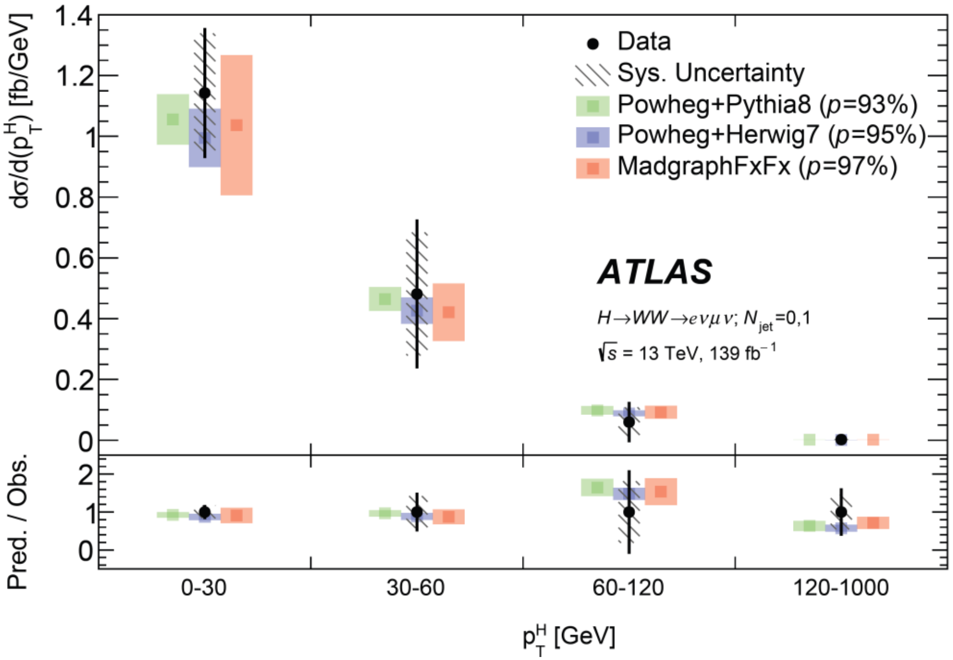
Beyond couplings: Fiducial differential xsecs

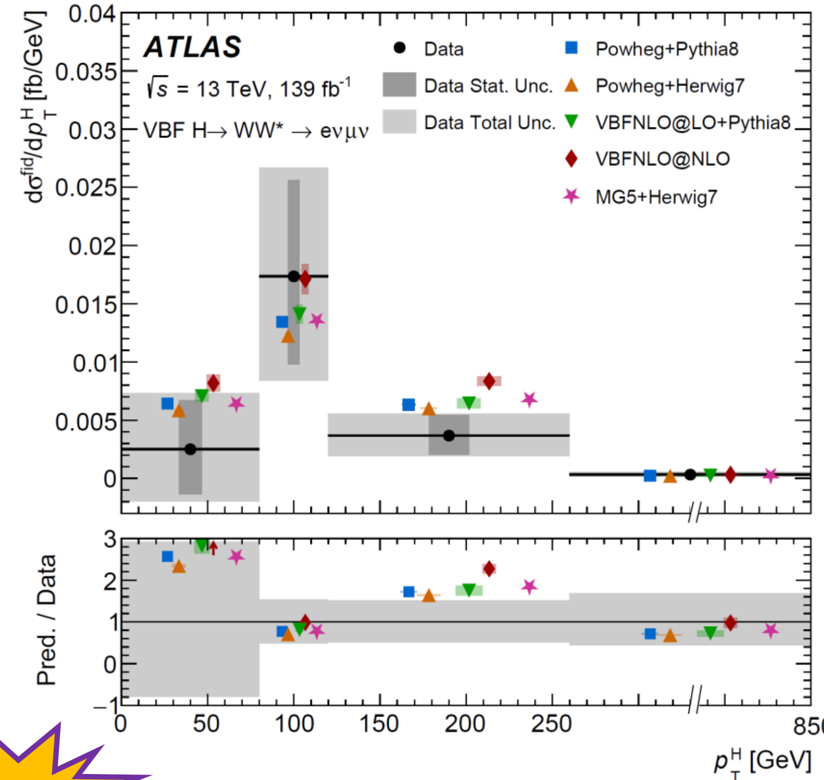
ATLAS
$H \rightarrow 4\ell + \gamma\gamma$
[link]



Combination of 4ℓ and $\gamma\gamma$ also available from ATLAS
→ Better compatibility with NNLOPS predictions
→ Both NNLOPS and aMC@NLO FxFx apply K-factors for N3LO xsec

Beyond couplings: Fiducial differential xsecs





ATLAS $gg \to H \to WW$ [link]

Recent

ATLAS VBF $H \to WW$ [link]

Separate analyses for gluon fusion and VBF production for $H \to WW$

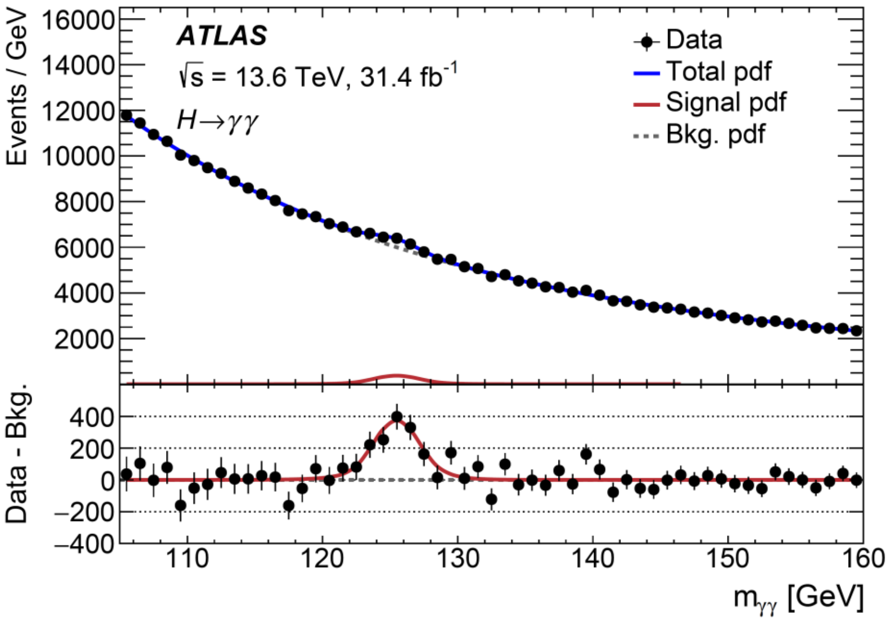
→ Competitive sensitivity to other channels in gluon fusion at $p_{\mathrm{T}}^{H} > 120$ GeV

→ BDT discriminants in $N_J \geq 2$ for VBF measurement

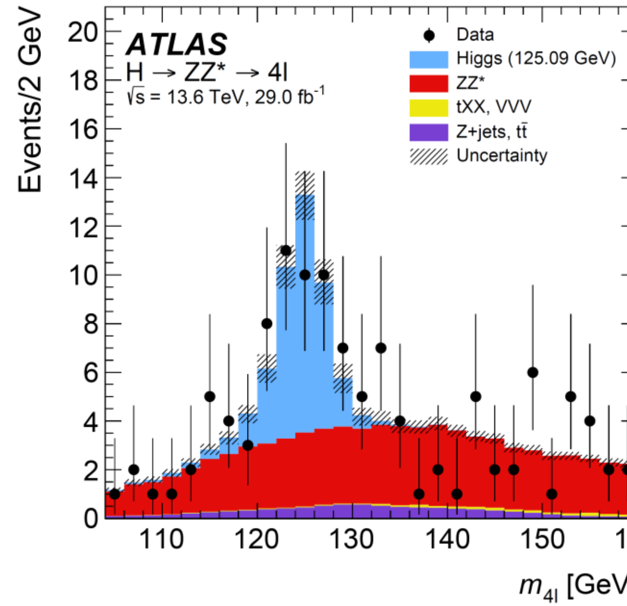
→ Total $\sigma_{\mathrm{fid}}^{\mathrm{VBF}} = 1.68 \pm 0.40$ fb, overest. in simulation but within ~1 std. dev.

→ Also features results in the SMEFT framework

First Run 3 results: Inclusive fiducial xsecs



Recent



ATLAS $4\ell + \gamma\gamma$ [link]

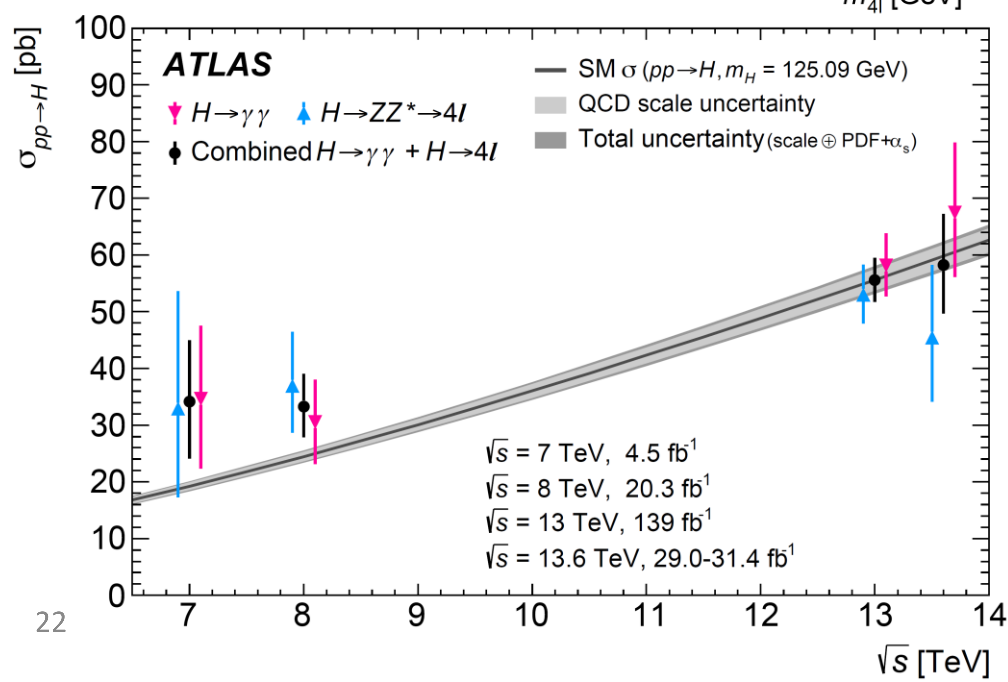
First Run 3 measurements from ATLAS:

→ Full PS $\sigma_{\text{fid}} = 58.2 \pm 8.7$ fb

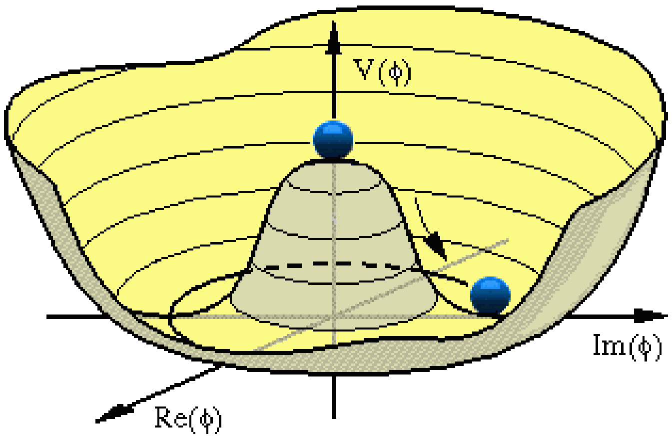
→ 4ℓ: $\sigma_{\text{fid}} = 46 \pm 12$ fb

→ $\gamma\gamma$: $\sigma_{\text{fid}} = 67^{+12}_{-11}$ fb

→ SM: $\sigma_{\text{fid}} = 59.9 \pm 2.6$ fb



Higgs self-couplings: Di-Higgs final states



SM Higgs potential:

$$V(\phi) = 1/2\,\mu^2\phi^\dagger\phi + 1/4\,\lambda\left(\phi^\dagger\phi\right)^2$$

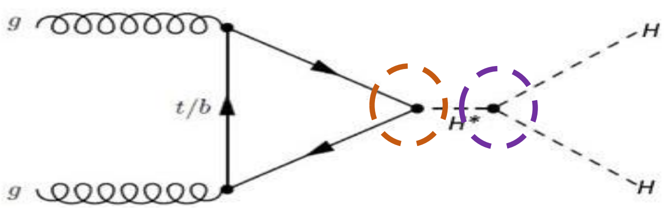
→ After gauge rotations and using the vacuum expectation v:

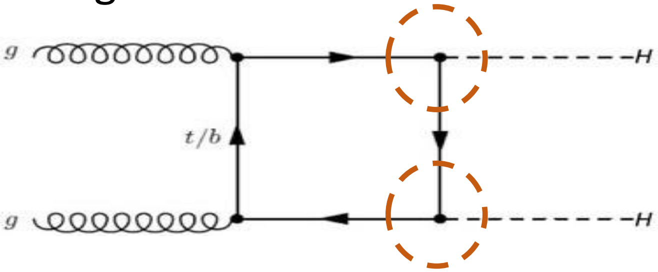
$$V(H) = V_0 + \lambda v^2 H^2 + \lambda v H^3 + 1/4 H^4$$

→ Allows triple and quartic Higgs couplings

→ Di-Higgs final state @ LHC

SM features interference of two diagrams:





Left diagram sensitive to the triple-Higgs coupling through λ

→ Both sensitive to different powers of Htt & Hbb couplings

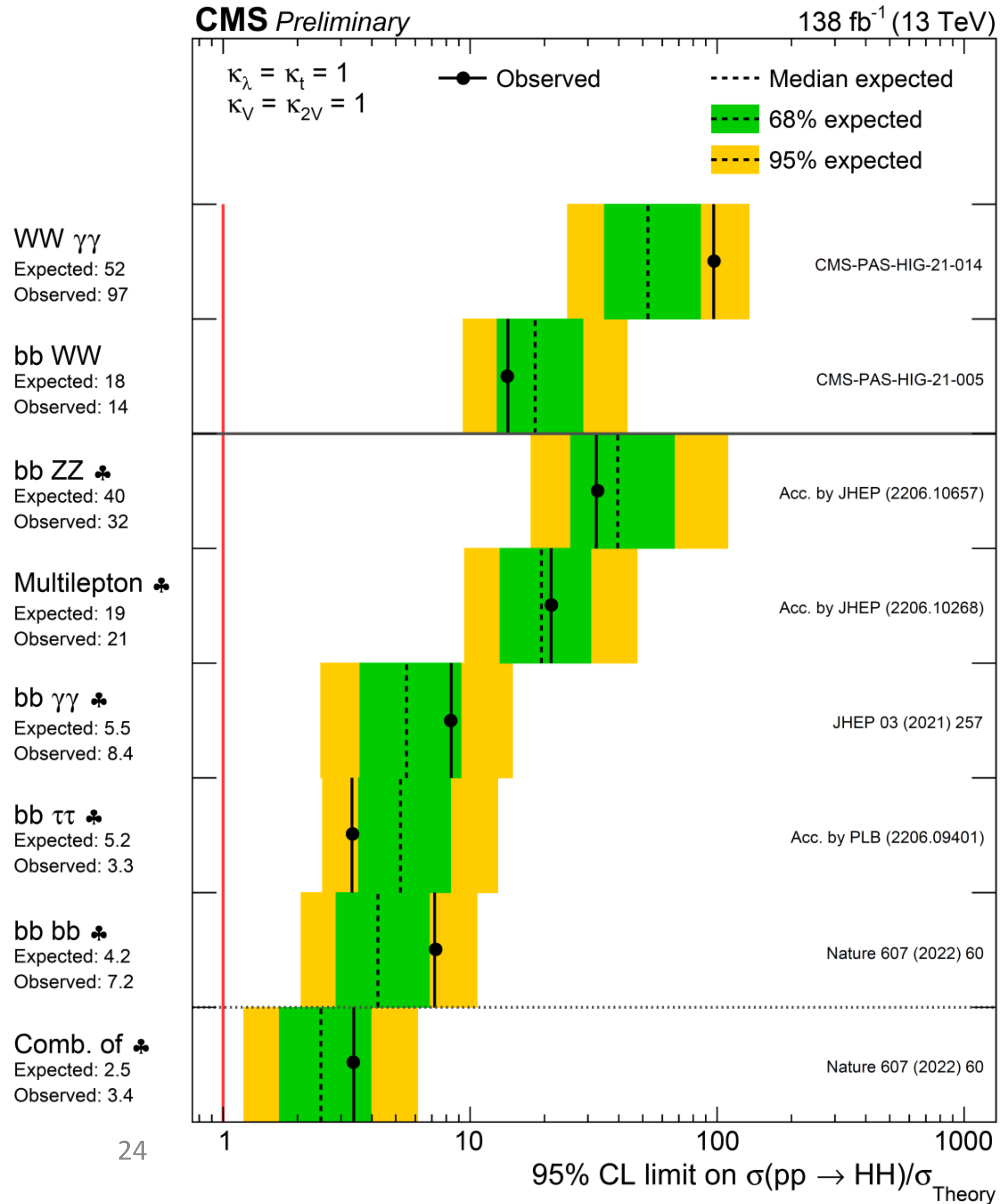
→ Different ways new physics could change this interaction

Higgs self-couplings: Di-Higgs final states

Di-Higgs measurements done using events with a larger multiplicity of particles and/or jets

Different final states either dirtier but with larger Higgs decay probability (e.g., $HH \to 4b$), or cleaner in bkgs. with smaller decay rates ($HH \to b\bar{b}\gamma\gamma$).

Uncertainties statistically dominated, but some channels will only barely reach an observation threshold by the end of HL-LHC.



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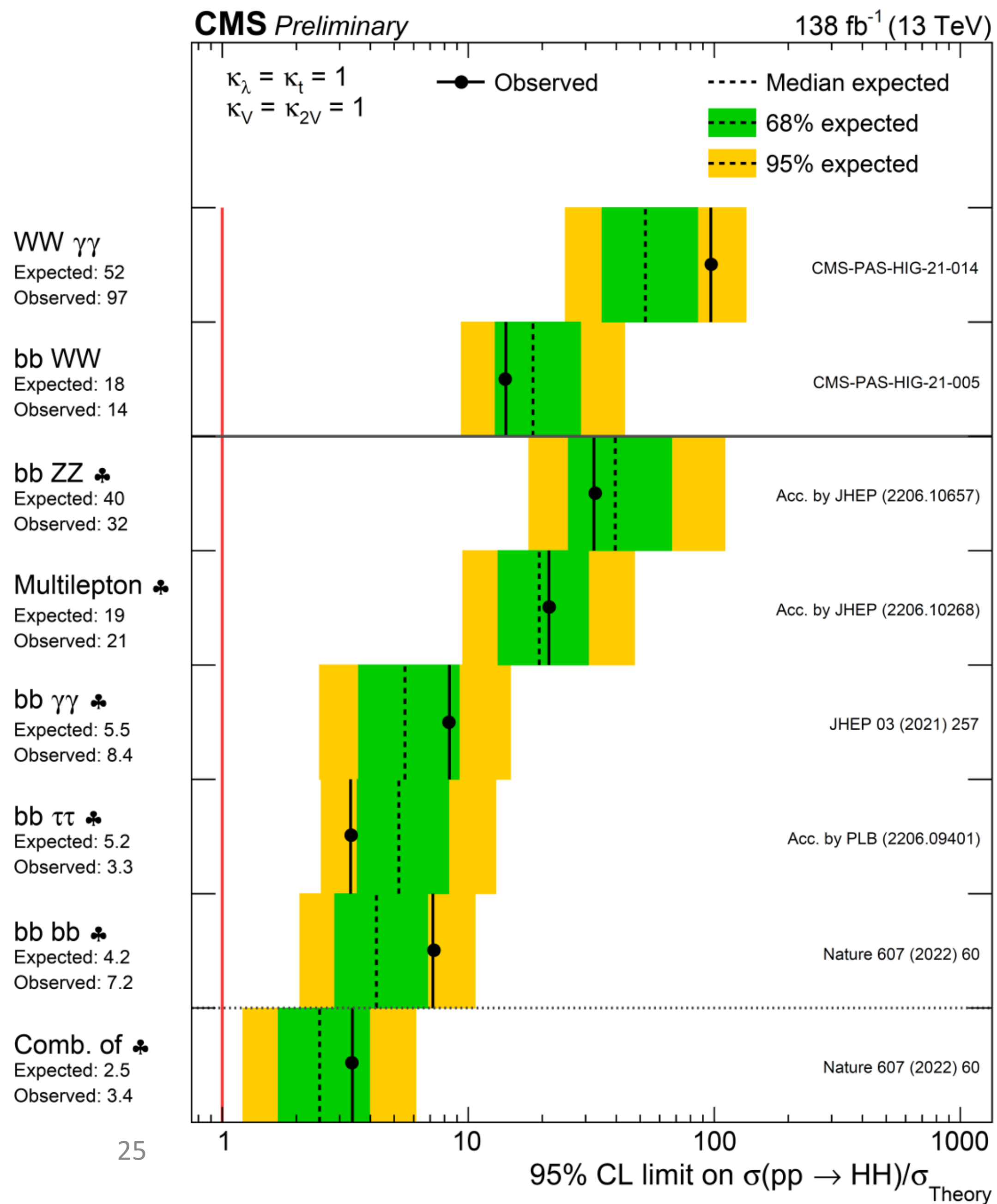
Interaction rate is tiny, so we can only place limits.
→ Take $HH \to 4b$:
Max. ~ 1450 events / 10^{16} pp interactions
→ Rates enhances in BSM cases



Higgs self-couplings: Di-Higgs final states

Di-Higgs measurements done using events with a larger multiplicity of particles and/or jets

Recent

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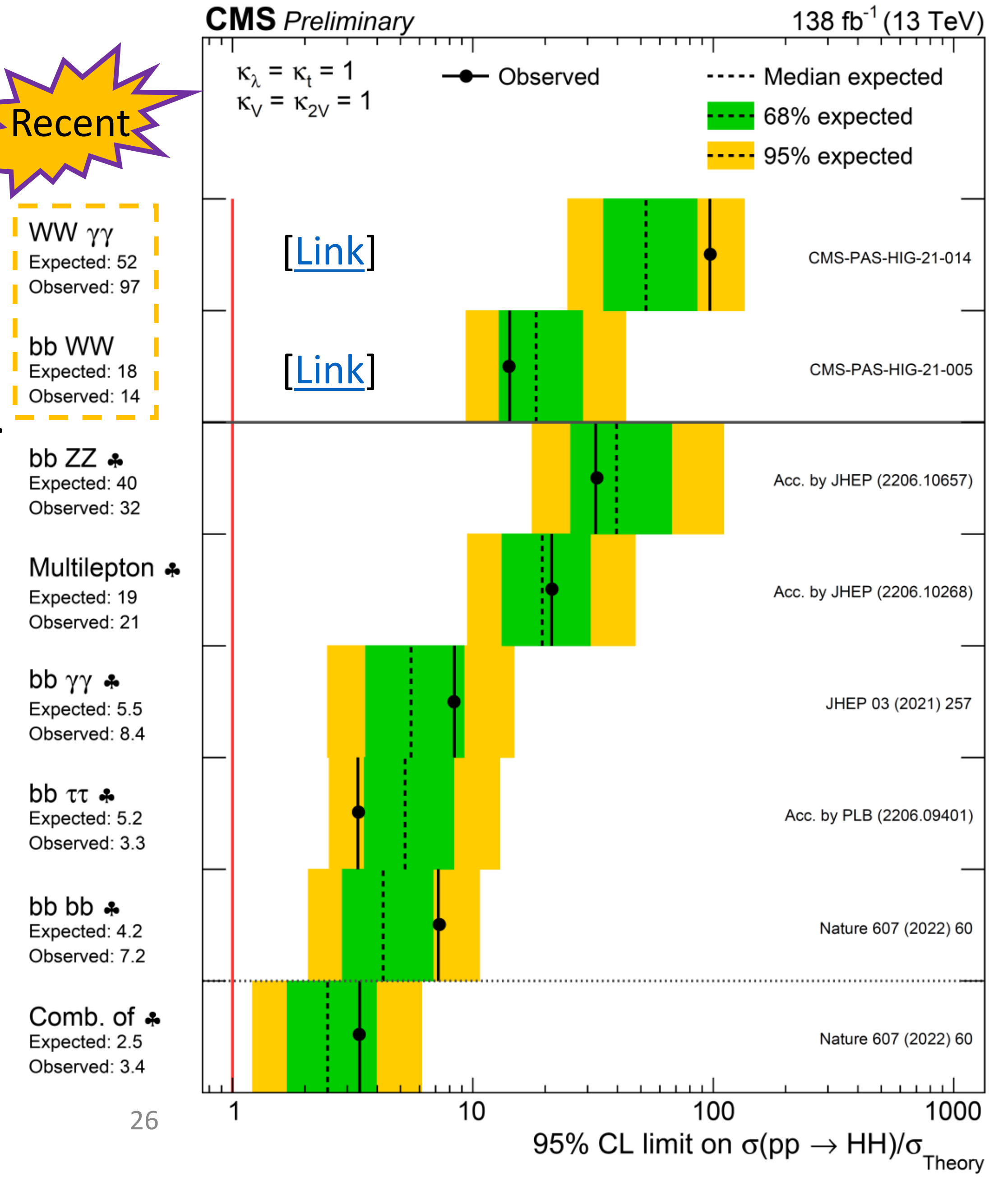

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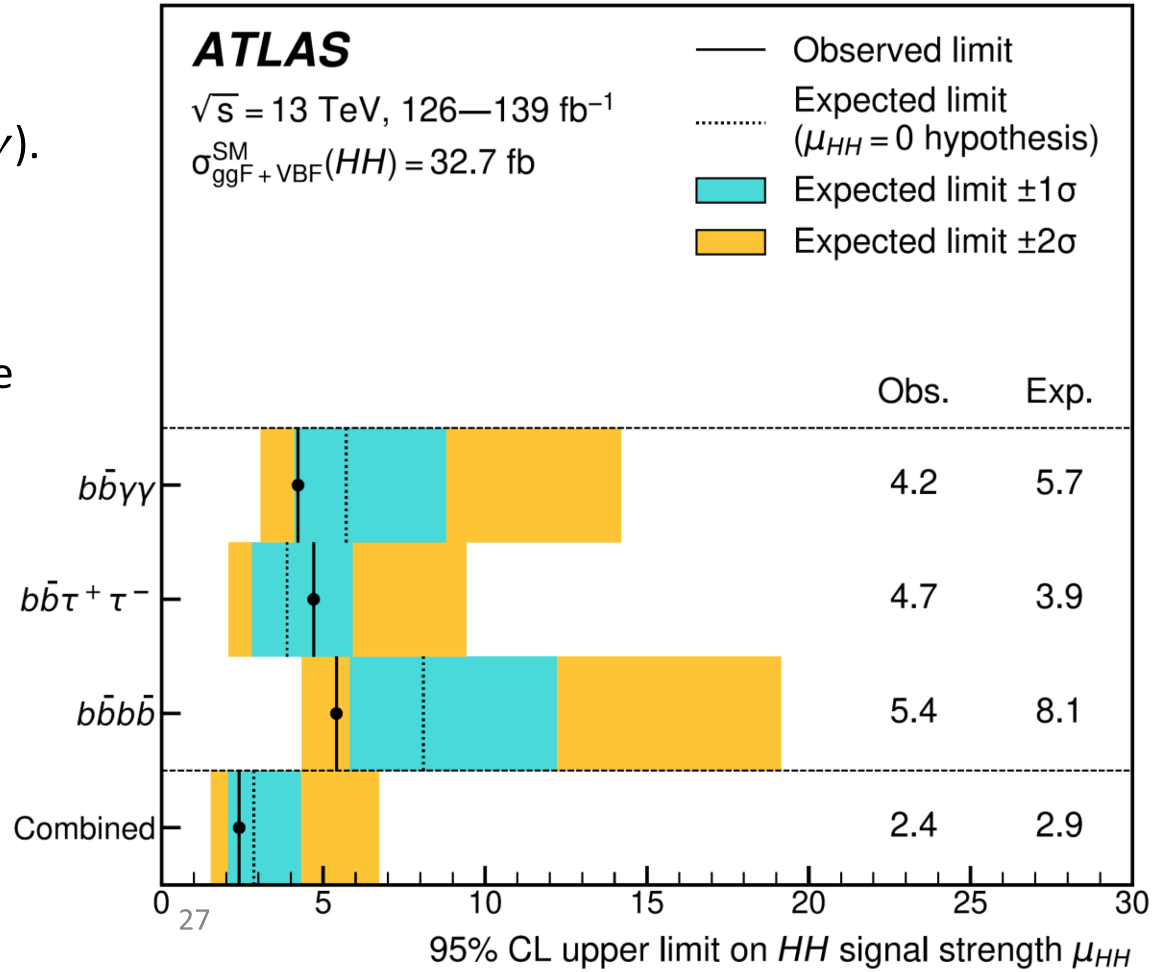
[Link]

Summary of ATLAS results



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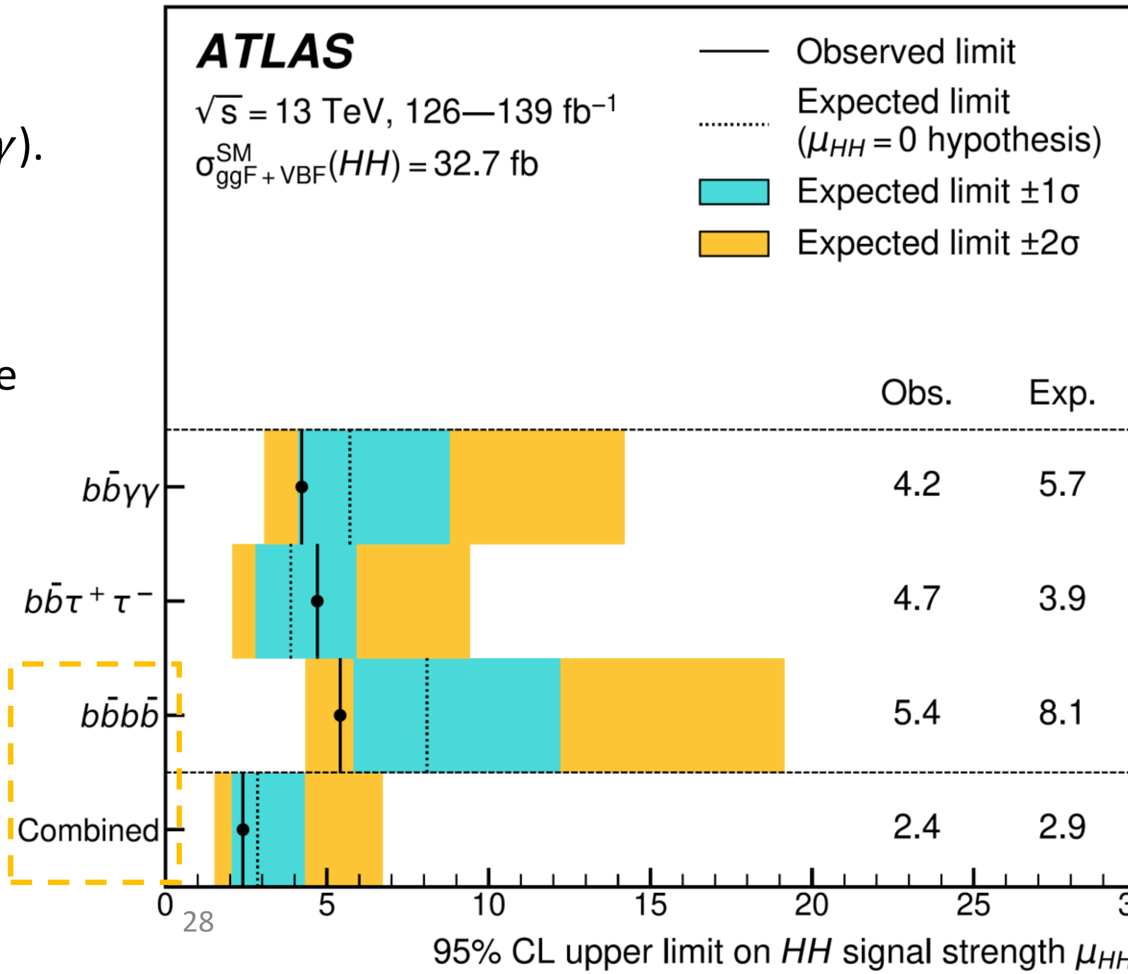

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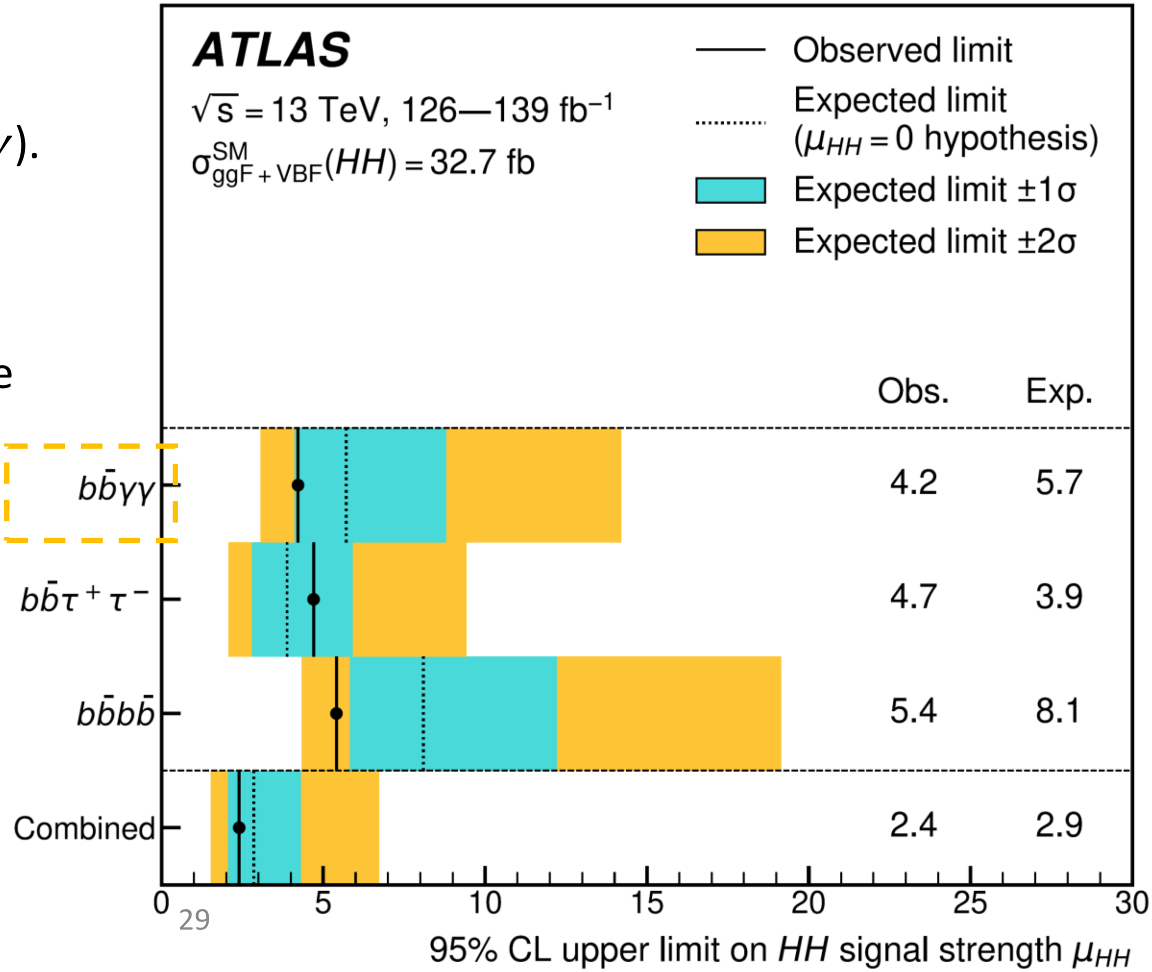
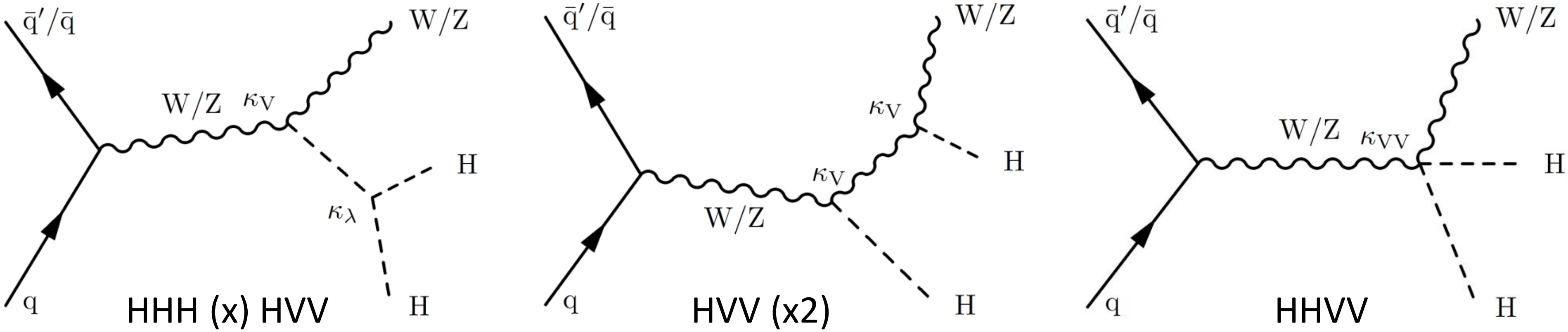
See talk by Abe on more details for more recent $bb\gamma\gamma$ results

[Link]

Summary of ATLAS results



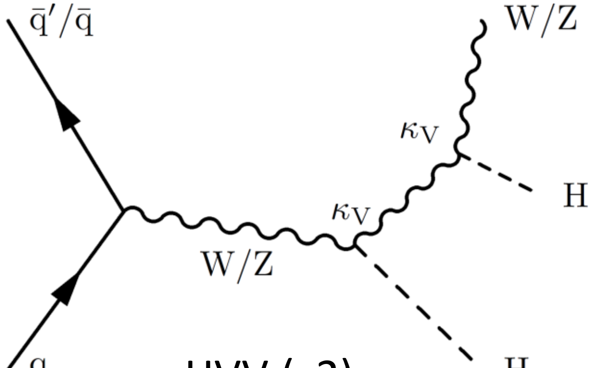
Higgs self-couplings: Di-Higgs in VHH



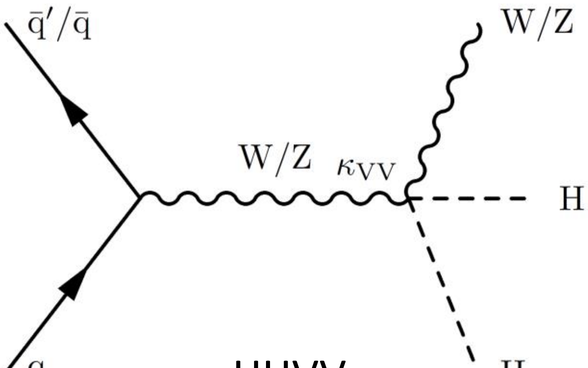
Can have proportions of
HHH (x) HVV, HVV (x2), and HHVV diagrams different from the SM
→ $HH \to 4b$ in both CMS & ATLAS

Higgs self-couplings: Di-Higgs in VHH

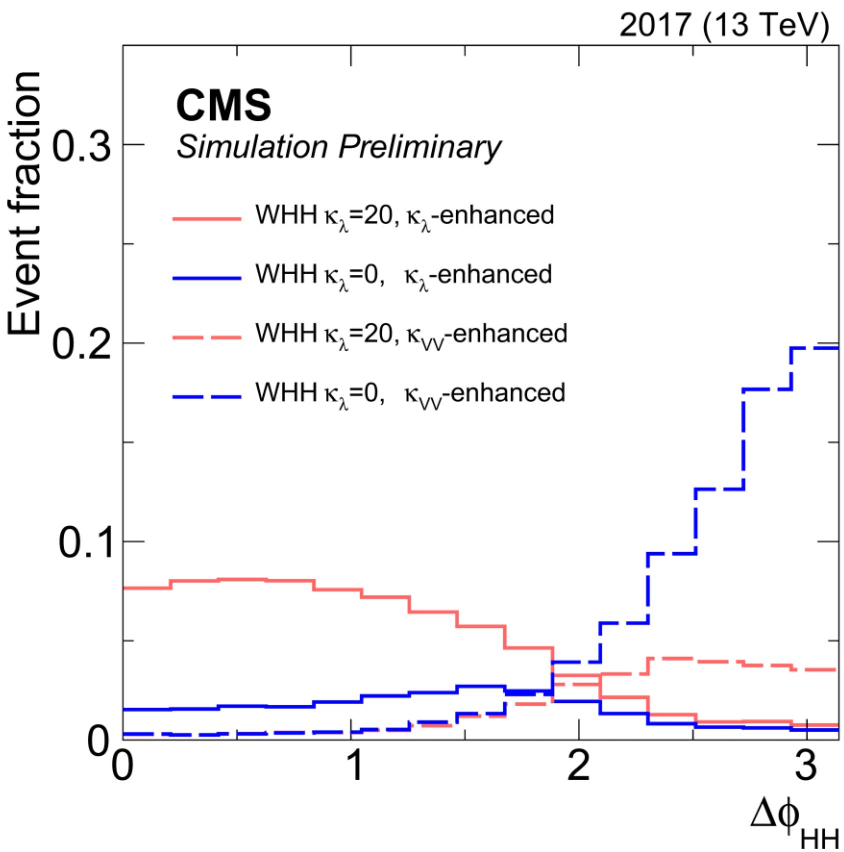
HHH (x) HVV



HVV (x2)



HHVV

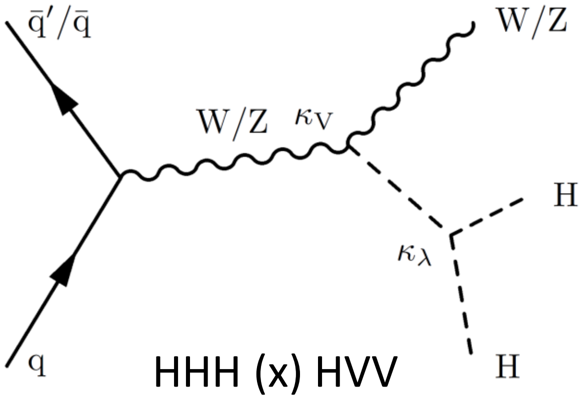


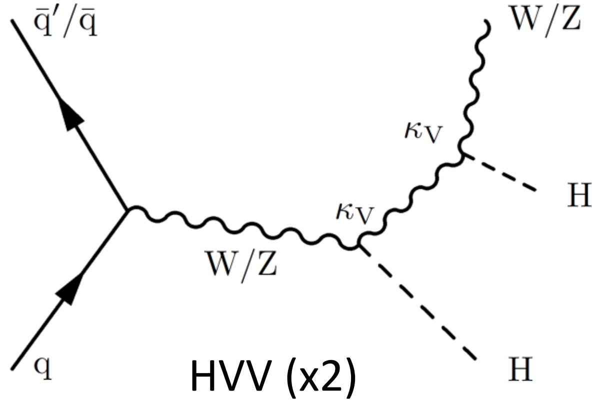
[Link]

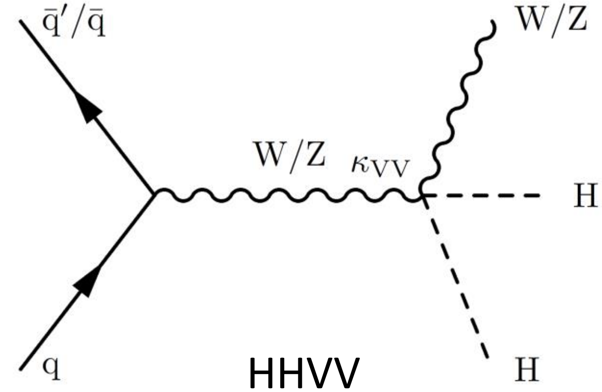
Can have proportions of
HHH (x) HVV, HVV (x2), and HHVV diagrams different from the SM
→ $HH \rightarrow 4b$ in both CMS & ATLAS
→ Different couplings reflect on kinematics
→ Use BDTs to separate couplings

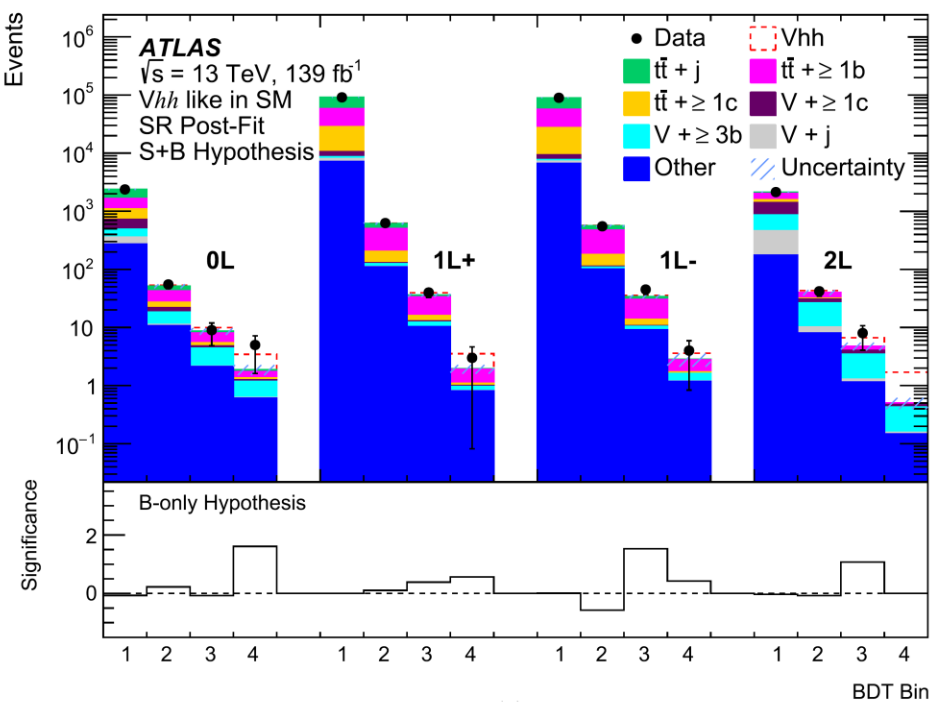
Recent

Higgs self-couplings: Di-Higgs in VHH









[Link]

Can have proportions of
HHH (x) HVV, HVV (x2), and HHVV diagrams different from the SM

→ $HH \rightarrow 4b$ in both CMS & ATLAS

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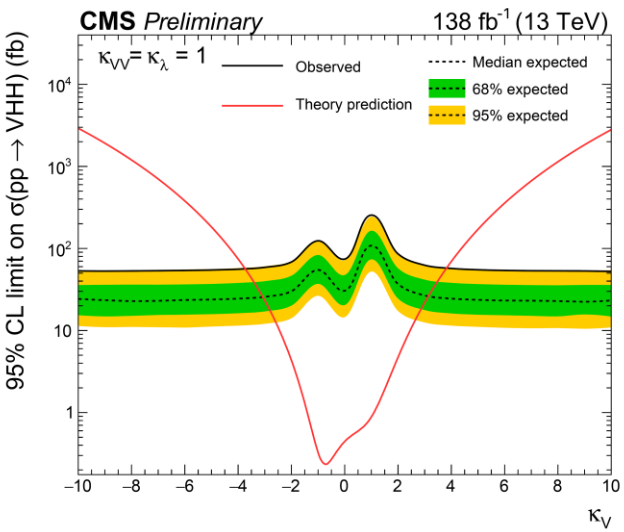
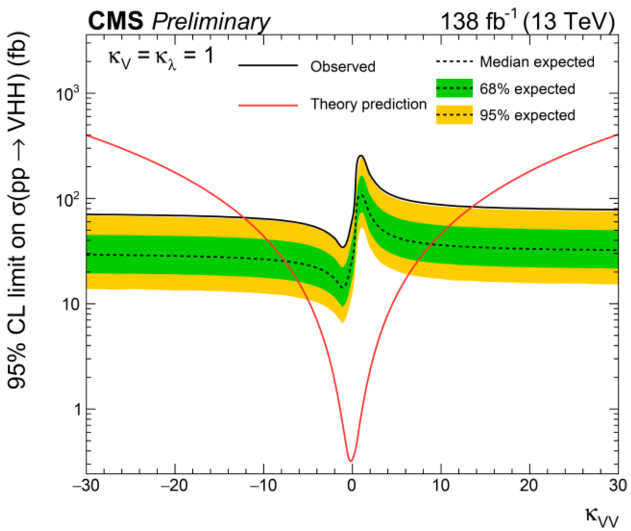
→ Use BDTs to separate couplings

Recent

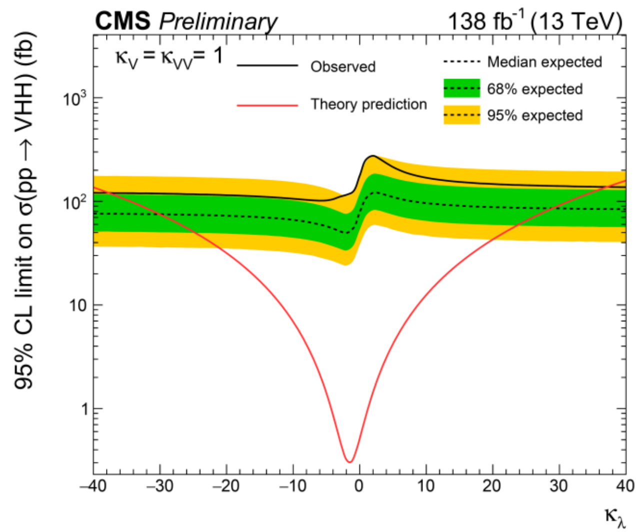
Higgs self-couplings: Di-Higgs in VHH (CMS)



κ_V



κ_{VV}



κ_λ

Recent

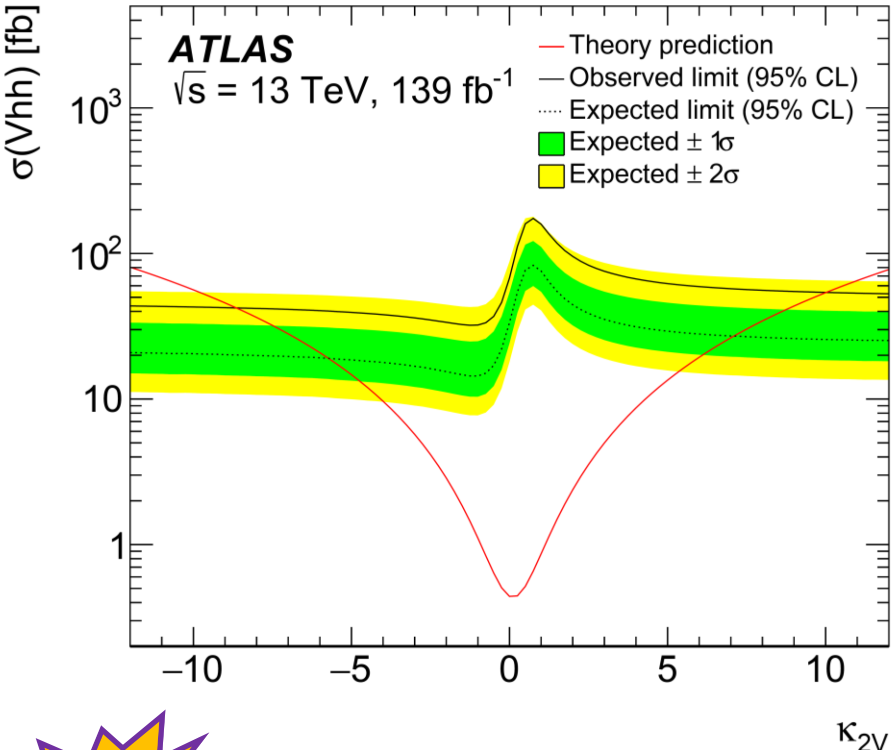
CMS results [link]

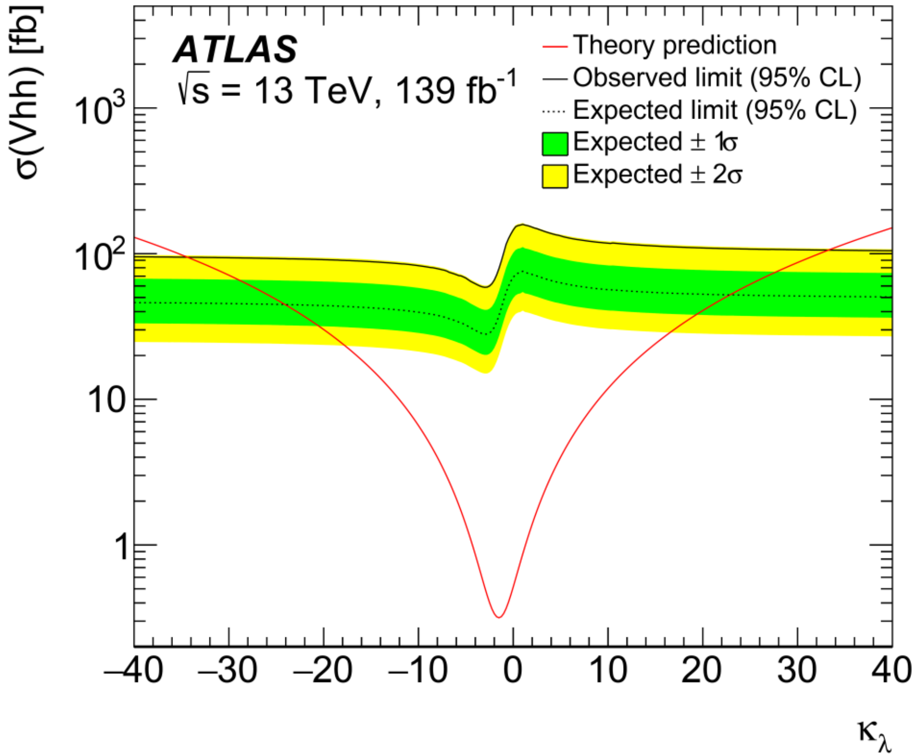
Results obtained by keeping the parameters not shown fixed to SM

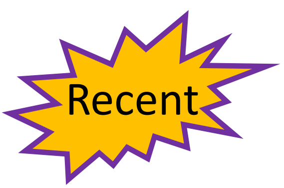
→ Complementary to HH final state results

→ Independent of κ_t and modelling of loops

Higgs self-couplings: Di-Higgs in VHH (ATLAS)



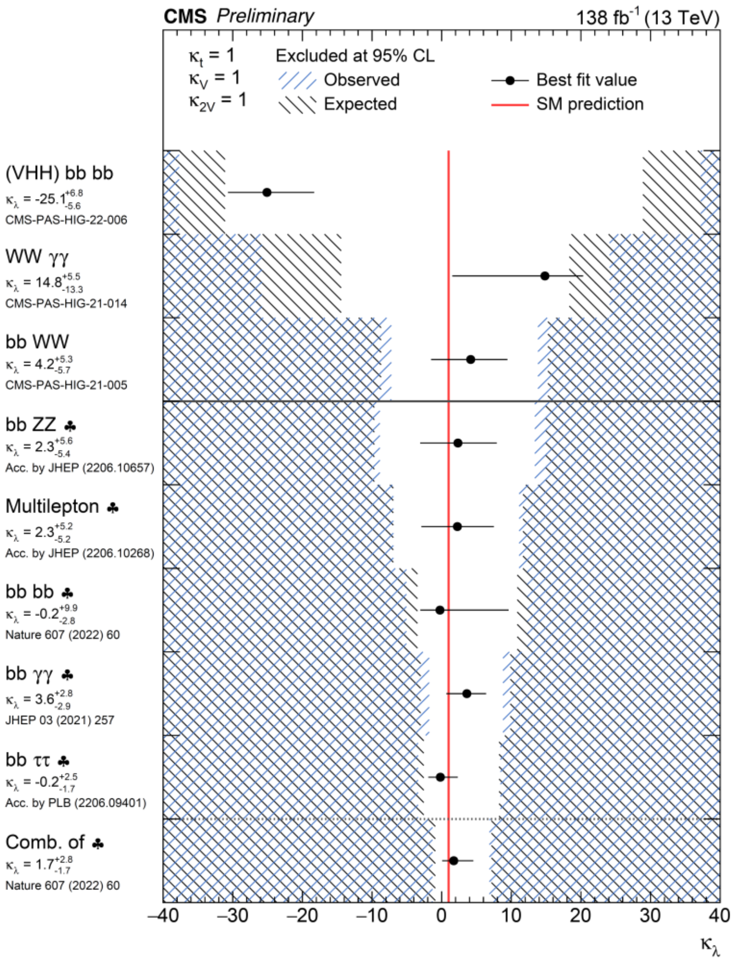


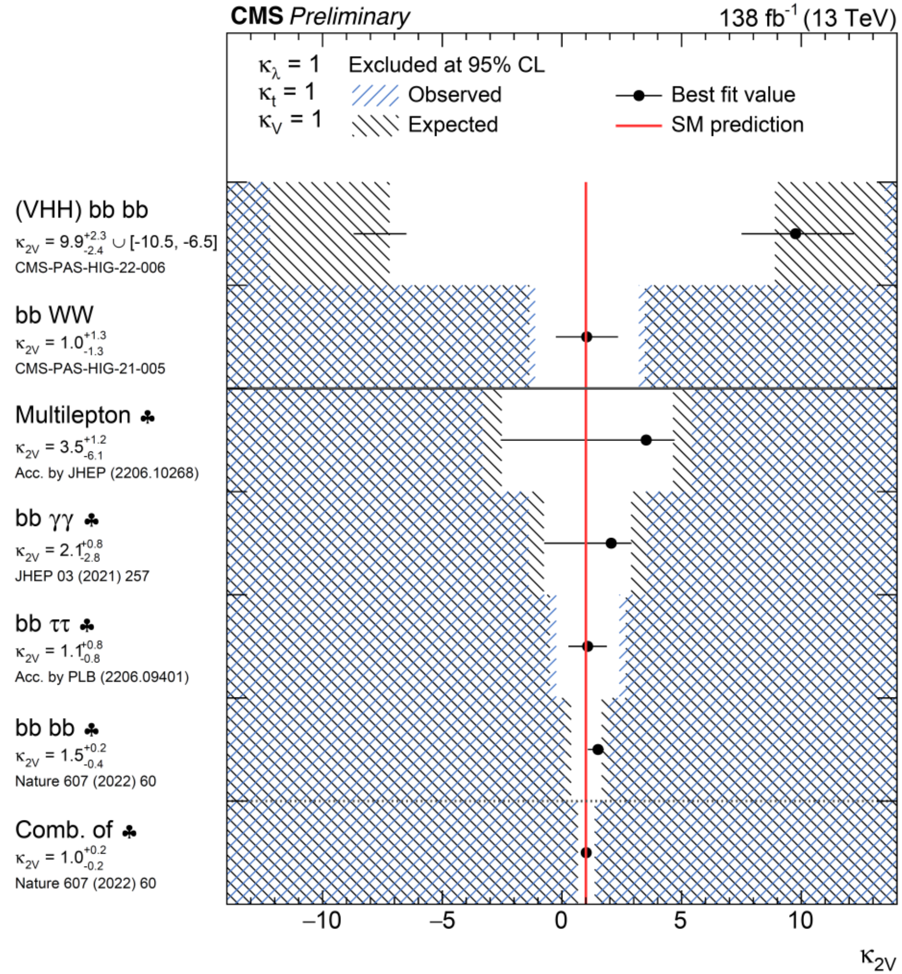


ATLAS results [link]

Results in κ_{2V} and κ_{λ}
→ Constraints similar to CMS
→ Additional results in terms of κ_{2Z} and κ_{2W}, or high-mass spin-0 bosons also featured

Higgs self-couplings: Di-Higgs final states





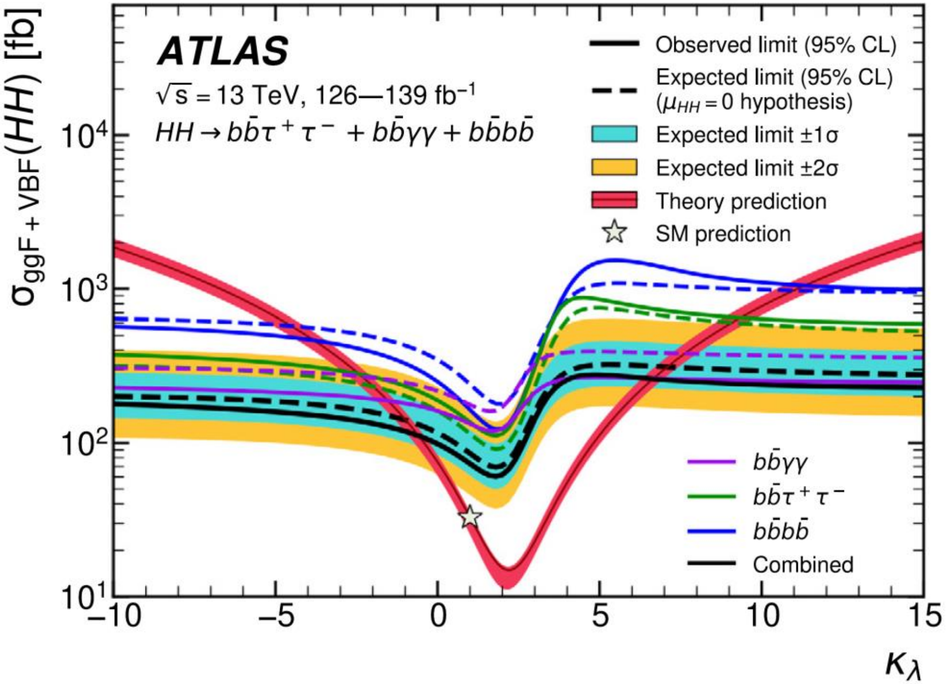
Summary of κ_λ and κ_{2V} limits from CMS analyses

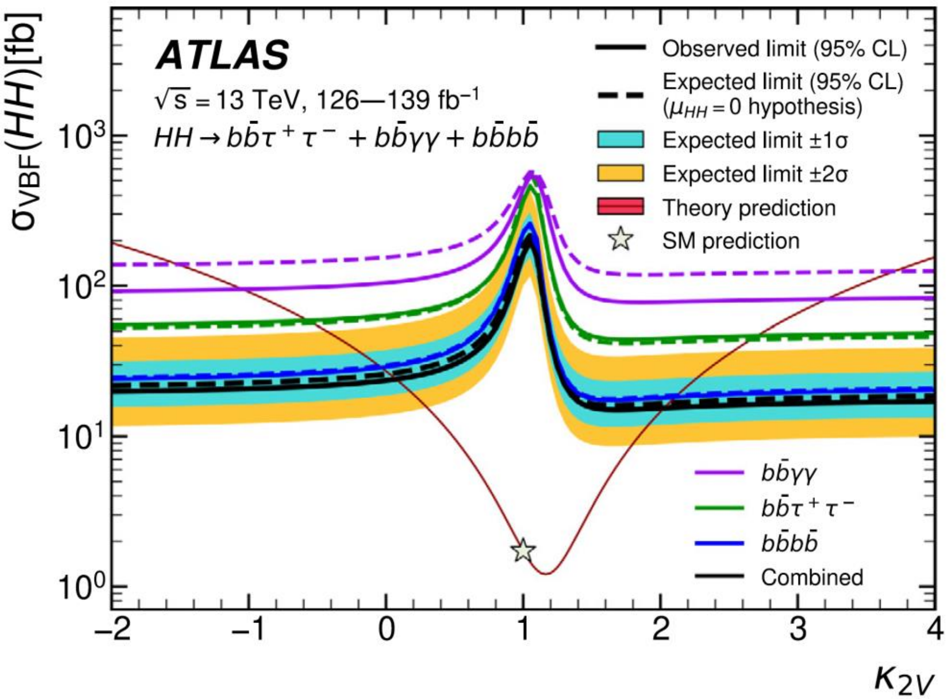
→ Limits @ 95% CL from Nature publication:

$$-1.24 < \kappa_\lambda < 6.49$$

$$0.67 < \kappa_{2V} < 1.38$$

Higgs self-couplings: Di-Higgs final states





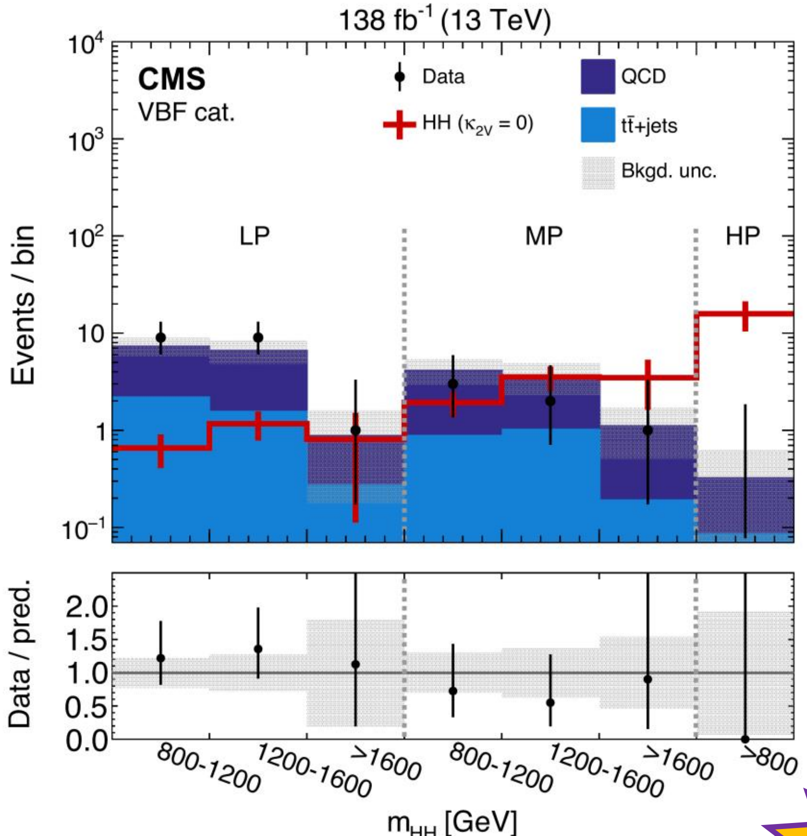
Summary of κ_λ and κ_{2V} limits from ATLAS analyses

Limits @ 95% CL:

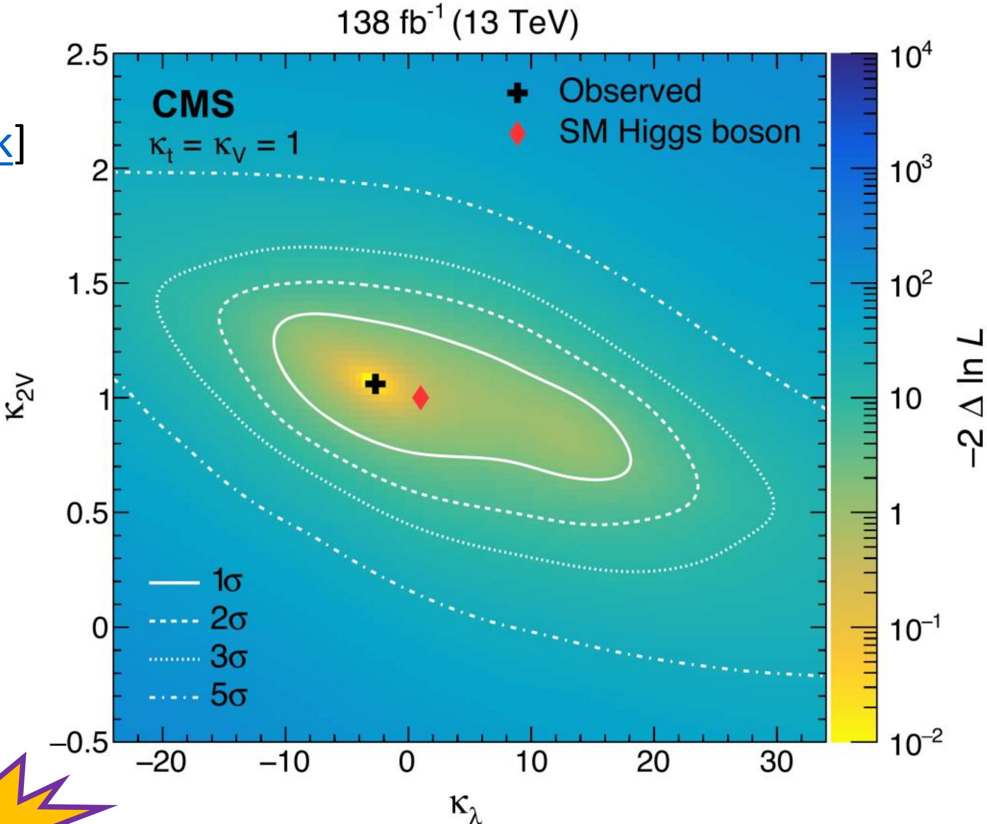
$-1.4 < \kappa_\lambda < 6.1$ ($H + HH$ comb.)

$0.1 < \kappa_{2V} < 2.0$

Higgs self-couplings: Di-Higgs final states



[Link]



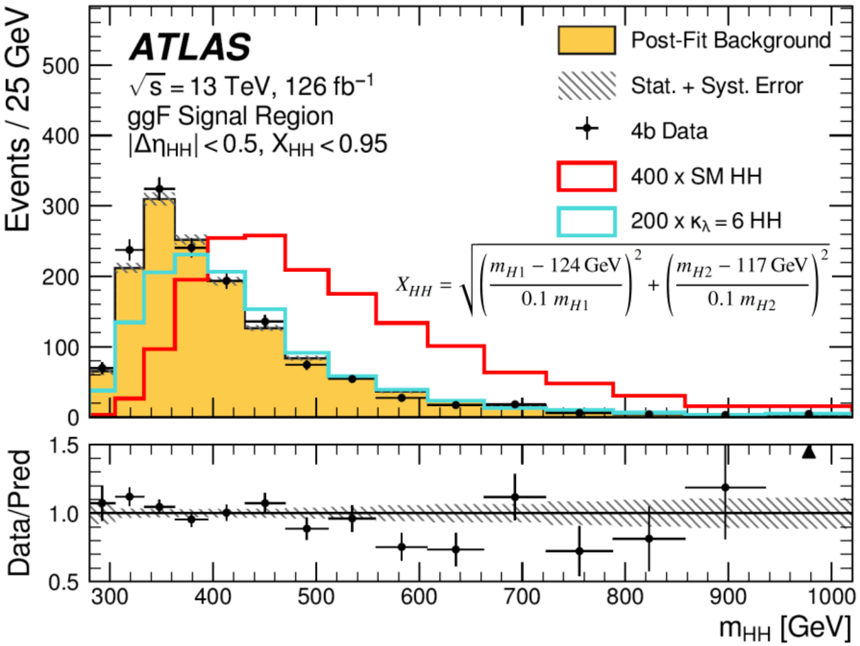
Recent

CMS nonresonant $HH \rightarrow 4b$

Event categories for ggF and different levels of VBF purity
→ VBF categories shown above

Limits @ 95% CL:
$-9.9 < \kappa_\lambda < 16.9$
$0.62 < \kappa_{2V} < 1.41$

Higgs self-couplings: Di-Higgs final states



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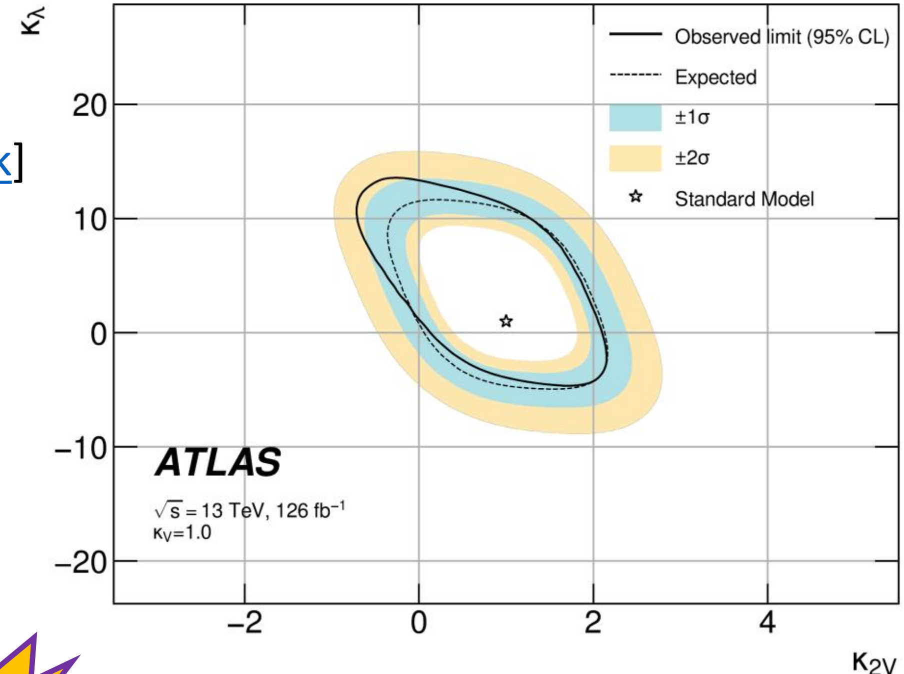
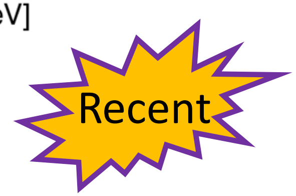




ATLAS nonresonant $HH \rightarrow 4b$

Event categories for ggF and VBF with SR and CR divisions along $m_{H1} - m_{H2}$ plane

Limits @ 95% CL:
$-3.9 < \kappa_\lambda < 11.1$
$-0.03 < \kappa_{2V} < 2.11$
$\mu_{HH} < 5.4$

Many exciting results from CMS and ATLAS to understand Higgs boson properties.

Excellent progress in exploiting kinematic information, more progress in the horizon.

No new physics yet ☹, but we have just started looking for it ☺.

Stay tuned for
→ dedicated talks on some of the measurements, and
→ more exciting results in the future!

CMS references

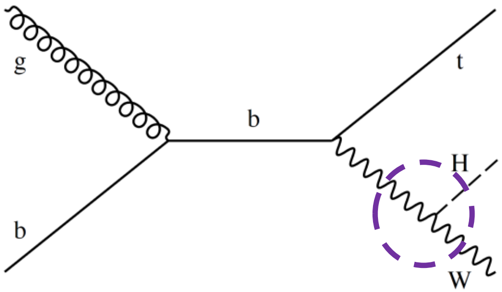
Run 2 couplings combination: https://doi.org/10.1038/s41586-022-04892-x
Run 2 $VH, H \to c\bar{c}$: http://arxiv.org/abs/2205.05550
Run 2 $Z\gamma$ measurement: https://doi.org/10.1007/JHEP05(2023)233
Run 2 $\gamma\gamma$ cross sections: https://doi.org/10.1007/JHEP07(2021)027
Run 2 4ℓ cross sections: https://doi.org/10.1140/epjc/s10052-021-09200-x
Run 2 $\gamma\gamma$ fiducial cross sections: https://arxiv.org/abs/2208.12279
Run 2 WW fiducial cross sections: https://doi.org/10.1007/JHEP03(2021)003
Run 2 WW cross sections: https://doi.org/10.1140/epjc/s10052-023-11632-6
Run 2 ttH multilepton cross sections: https://doi.org/10.1140/epjc/s10052-021-09014-x
Run 2 4ℓ fiducial cross sections: https://doi.org/10.1007/JHEP08(2023)040
Run 2 di-Higgs $bbWW$: https://cds.cern.ch/record/2853597
Run 2 di-Higgs $WW\gamma\gamma$: https://cds.cern.ch/record/2840773
Run 2 di-Higgs, nonresonant $HH \to 4b$: https://doi.org/10.1103/PhysRevLett.131.041803
Run 2 VHH: https://cds.cern.ch/record/2853338

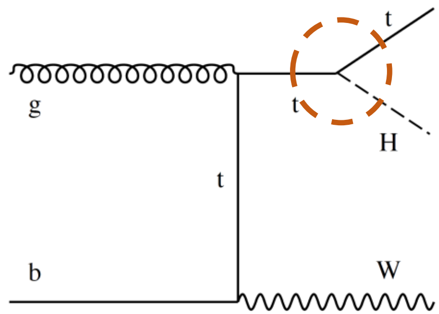
ATLAS references

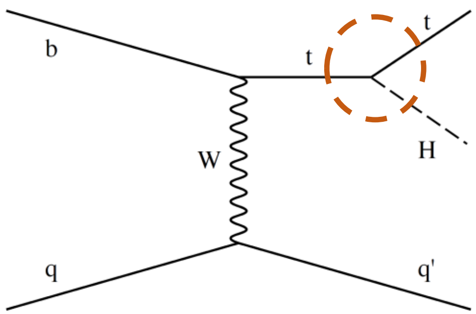
Run 2 couplings combination: https://www.nature.com/articles/s41586-022-04893-w
Run 2 $Z\gamma$ measurement: https://doi.org/10.1016/j.physletb.2020.135754
Run 2 $Z\gamma$ combination w/ CMS: http://cds.cern.ch/record/2860129
Run 2 VBF WH: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-057
Run 2 4ℓ cross sections: https://doi.org/10.1140/epjc/s10052-020-8227-9
Run 2 WW cross sections: https://doi.org/10.1103/PhysRevD.108.032005
Run 2 $VH, H \to WW$ cross sections: https://cds.cern.ch/record/2842519
Run 2 $\gamma\gamma$ cross sections: https://doi.org/10.1007/JHEP07(2023)088
Run 2 4ℓ fiducial cross sections: https://doi.org/10.1140/epjc/s10052-020-8223-0
Run 2 $\gamma\gamma$ fiducial cross sections: https://doi.org/10.1007/JHEP08(2022)027
Run 2 $4\ell + \gamma\gamma$ fiducial cross sections combination: https://doi.org/10.1007/JHEP05(2023)028
Run 2 $\mathrm{gg} \to \mathrm{H} \to WW$ fiducial cross sections: https://cds.cern.ch/record/2846335
Run 2 VBF $\mathrm{H} \to WW$ fiducial cross sections: https://cds.cern.ch/record/2855725
First Run 3 results on $4\ell + \gamma\gamma$ fiducial cross sections: https://cds.cern.ch/record/2862412
Run 2 VHH: https://doi.org/10.1140/epjc/s10052-023-11559-y
Run 2 Di-Higgs combination: https://doi.org/10.1016/j.physletb.2023.137745
Run 2 Di-Higgs $HH \to bb\gamma\gamma$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-050
Run 2 Di-Higgs nonresonant $HH \to 4b$: https://cds.cern.ch/record/2845544

Back-up

(Less) common ways to produce a SM Higgs in *pp* collisions

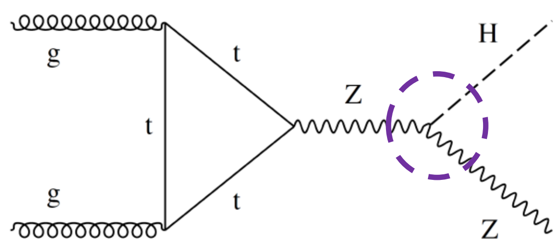


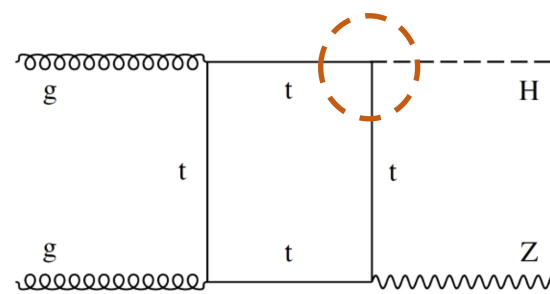




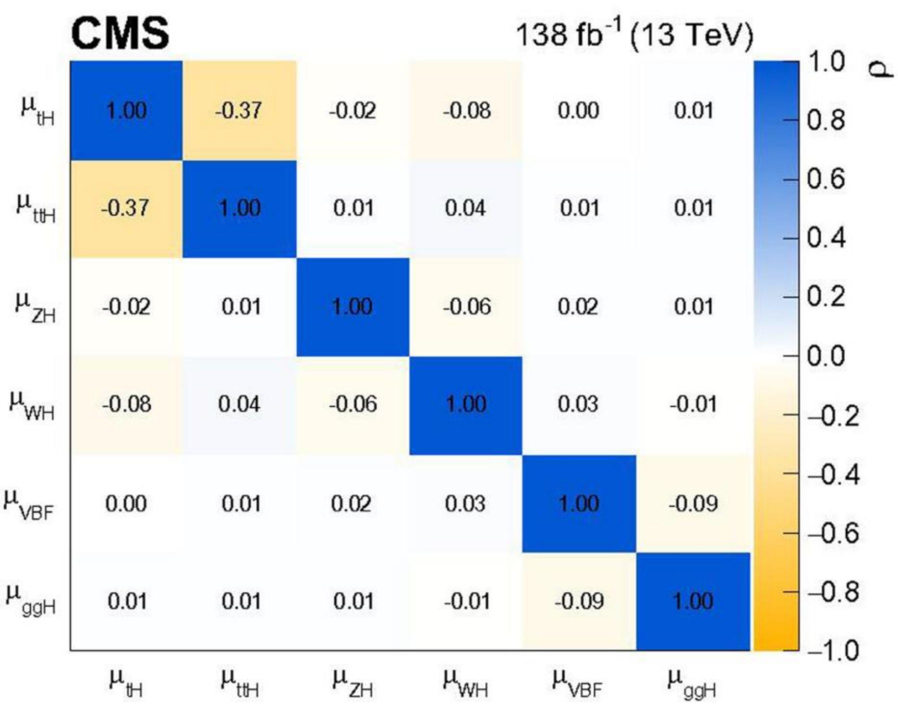
tH and tHW: Allows to resolve relative phase of Htt and HWW couplings

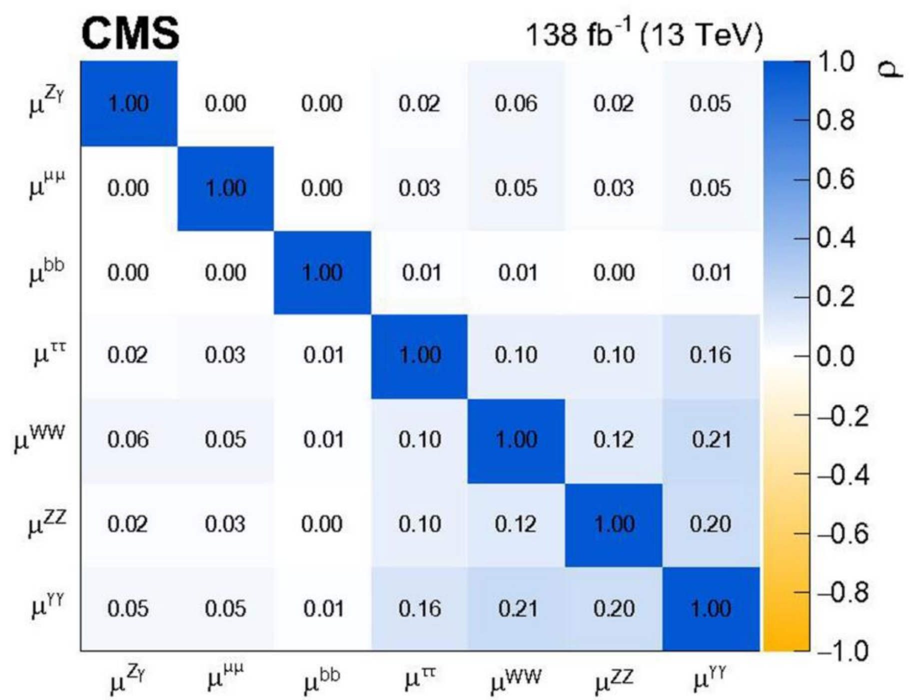
$gg \rightarrow ZH$: Allows to resolve relative phase of Htt and HZZ couplings





Correlations of signal strengths (CMS)





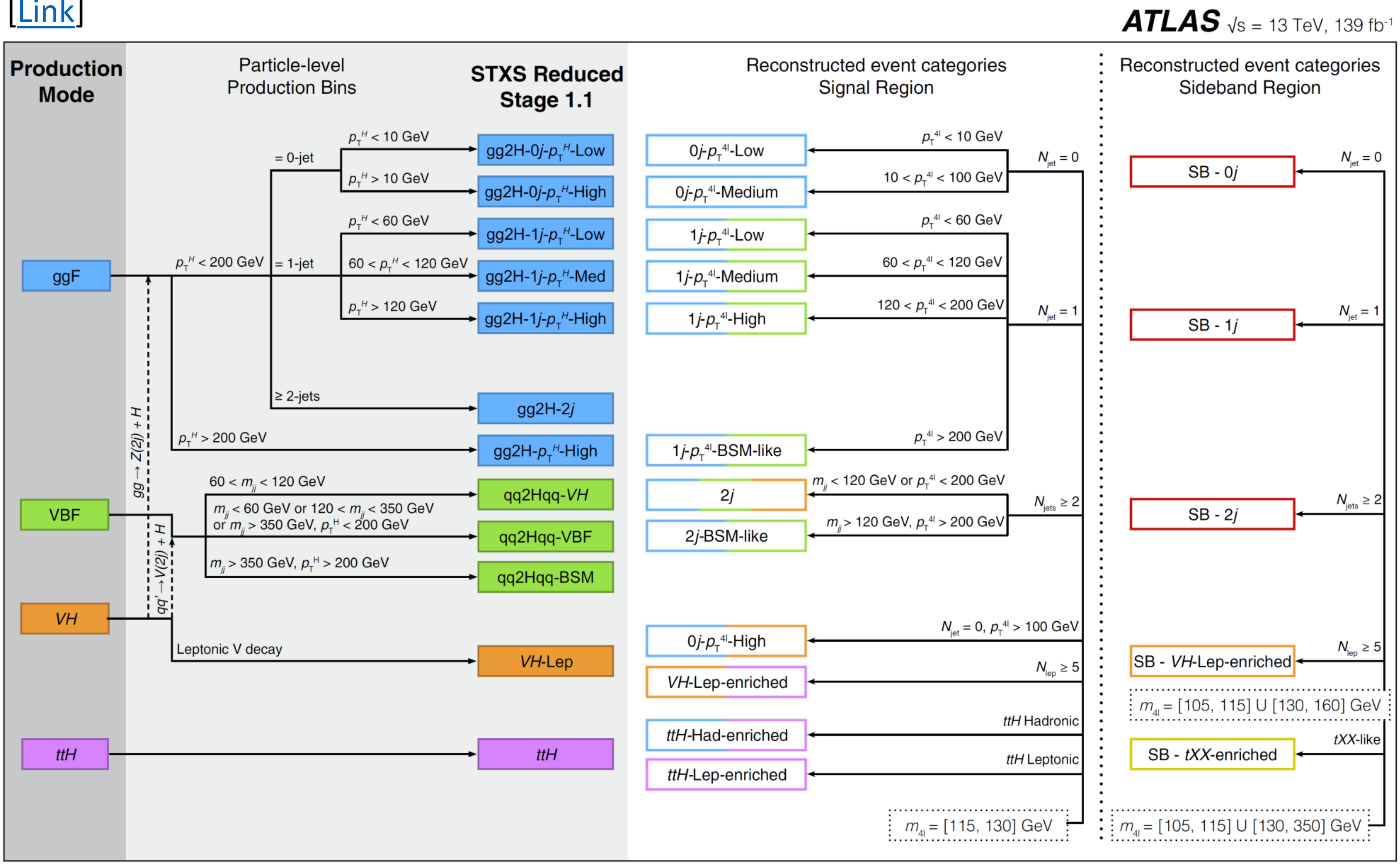
ATLAS VBF WH analysis categories

Variable	Description	SR^-	SR^+_{loose}	SR^+_{tight}
$m_{b\bar{b}}$	Invariant mass of the two b-jets ($b\bar{b}$ system).	$\in (105, 145)$ GeV	$\in (105, 145)$ GeV	$\in (105, 145)$ GeV
$\Delta R_{b\bar{b}}$	ΔR between the two b-jets.	< 1.2	< 1.6	< 1.2
$p_T^{b\bar{b}}$	p_T of the $b\bar{b}$ system.	> 250 GeV	> 100 GeV	> 180 GeV
m_{jj}	Invariant mass of the VBF jets.	–	> 600 GeV	> 1000 GeV
$\lvert\Delta y_{jj}\rvert$	Rapidity separation of the VBF jets.	> 4.4	> 3.0	> 3.0
m_{top}^{lep}	Invariant mass of the W and either b-jet which is closest to 172.7 GeV.	> 260 GeV	> 260 GeV	> 260 GeV
$\xi_{Wb\bar{b}}$	$\frac{\lvert y_{Wb\bar{b}} - y_{jj}\rvert}{\lvert\Delta y_{jj}\rvert}$, where $y_{Wb\bar{b}}$ and y_{jj} are the rapidity of the $Wb\bar{b}$ system and the VBF-jet system.	< 0.3	< 0.3	< 0.3
$\Delta\phi(Wb\bar{b}, jj)$	Azimuthal separation between the $Wb\bar{b}$ system and the VBF-jet system.	–	–	> 2.7
N_{jets}^{veto}	Number of non-tagged, non-VBF jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$.	–	≤ 1	$= 0$

[Link]

ATLAS STXS ZZ categories

[Link]



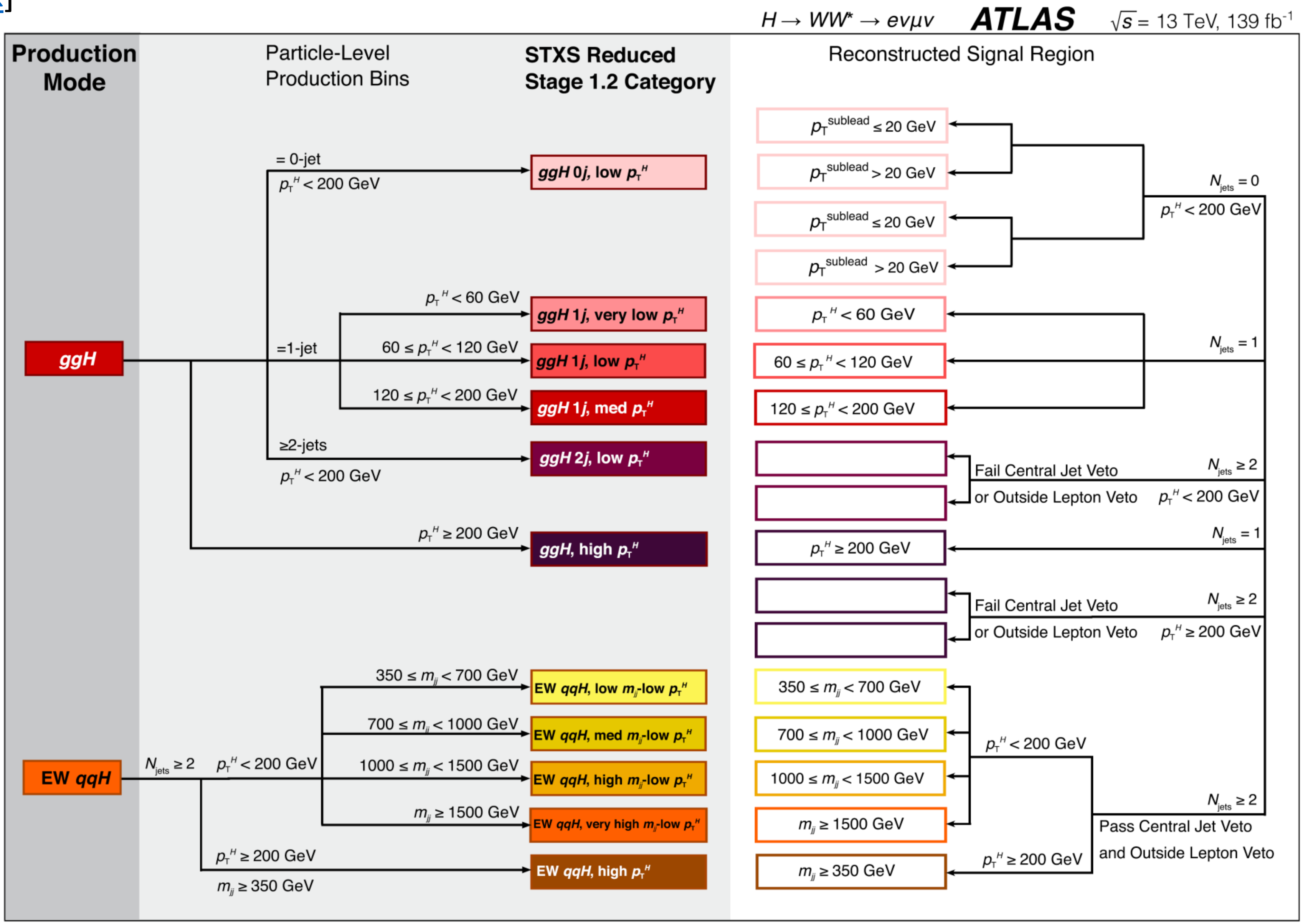
CMS STXS WW categories

[Link]

Category	SR subcategorization	SR fit variable	Contributing CRs	$N_{\text{subcategories}}$
ggH DF	(0j, 1j) $\times$ ($p_{T2} \lessgtr 20$ GeV) $\times$ ($\ell^{\pm}\ell^{\mp}$), ($\geq$2j)	$(m_{\ell\ell}, m_T^H)$	Top quark, $\tau\tau$	15
ggH SF	(0j, 1j, $\geq$2j) $\times$ (ee, $\mu\mu$)	N_{events}	Top quark, WW	12
VBF DF	$\max_j C_j$	DNN output	Top quark, $\tau\tau$	6
VBF SF	(ee, $\mu\mu$)	N_{events}	Top quark, WW	4
WHSS	(DF, SF) $\times$ (1j, 2j)	$\widetilde{m}_H$	WZ	4
WH3ℓ	SF lepton pair with opposite or same sign	BDT output	WZ, Zγ	4
ZH3ℓ	(1j, 2j)	m_T^H	WZ	4
ZH4ℓ	(DF, SF)	BDT output	ZZ	3
VH2j DF	—	$m_{\ell\ell}$	Top quark, $\tau\tau$	3
VH2j SF	(ee, $\mu\mu$)	N_{events}	Top quark, WW	4

ATLAS STXS WW categories

[Link]



Beyond couplings: Fiducial differential xsecs

→ Another way to go beyond simple coupling constants is to measure the aggregate Higgs boson production xsec in bins of p_T^H, y_H or other kinematic variables within a fiducial selection volume.

→ Example fiducial volume from CMS 4ℓ analysis (also in next slide):

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,\text{GeV}$
Next-to-leading lepton p_T	$p_T > 10\,\text{GeV}$
Additional electrons (muons) p_T	$p_T > 7(5)\,\text{GeV}$
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5\ (2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,\text{GeV}$

→ Higgs boson production outside of the fiducial volume is ‘background’.
→ Measure true cross section after unfolding, and efficiency and acceptance corrections.

Fiducial volume in CMS 4ℓ

Requirements for the $\mathrm{H} \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_{T}	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$
Next-to-leading lepton p_{T}	$p_{\mathrm{T}} > 10\,\mathrm{GeV}$
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Fiducial volume and obs. in CMS $\gamma\gamma$

Phase Space Region	Observable	Bin boundaries							
	$p_T^{\gamma\gamma}$	0	5	10	15	20	25	30	35
		45	60	80	100	120	140	170	200
		250	350	450	∞				
	n_{jets}	0	1	2	3	≥ 4			
	$\lvert y^{\gamma\gamma}\rvert$	0.0	0.1	0.2	0.3	0.45	0.6	0.75	0.90
Baseline		2.5							
$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$	$\lvert\cos(\theta^*)\rvert$	0.0	0.07	0.15	0.22	0.35	0.45	0.55	0.75
		1.0							
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$	$\lvert\phi_\eta^*\rvert$	0.0	0.05	0.1	0.2	0.3	0.4	0.5	0.7
$\lvert\eta^\gamma\rvert < 2.5$		1.0	1.5						
$\mathcal{I}_{gen}^\gamma < 10\,\mathrm{GeV}$		2.5	4.0	∞					
	$p_T^{\gamma\gamma}, n_{jets} = 0$	0	5	10	15	20	25	30	35
		45	60	∞					
	$p_T^{\gamma\gamma}, n_{jets} = 1$	0	30	60	100	170	∞		
	$p_T^{\gamma\gamma}, n_{jets} > 1$	0	100	170	250	350	∞		
	n_{jets}^b	0	1	≥ 2					
	$n_{leptons}$	0	1	≥ 2					
	p_T^{miss}	0	30	50	100	200	∞		
	$p_T^{j_1}$	30	40	55	75	95	120	150	200
		∞							
	$\lvert y^{j_1}\rvert$	0.0	0.3	0.6	0.9	1.2	1.6	2.0	2.5
1-jet	$\lvert\Delta\phi_{\gamma\gamma,j_1}\rvert$	0.0	2.0	2.6	2.85	3.0	3.07	π	
Baseline + $\geq$ 1 jet	$\lvert\Delta y_{\gamma\gamma,j_1}\rvert$	0.0	0.3	0.6	1.0	1.4	1.9	2.5	∞
$p_T^j > 30$ GeV	τ_C^j	< 15	15	20	30	50	80	∞	
$\lvert\eta^j\rvert < 2.5$	$p_T^{\gamma\gamma}, \tau_{Cj} < 15$ GeV	0	45	120	∞				
	$p_T^{\gamma\gamma}$, 15 GeV $\leq \tau_C^j <$ 25 GeV	0	45	120	∞				
	$p_T^{\gamma\gamma}$, 25 GeV $\leq \tau_C^j <$ 40 GeV	0	120	∞					
	$p_T^{\gamma\gamma}$, 40 GeV $\leq \tau_C^j$	0	200	350	∞				
	$p_T^{j_2}$	30	40	65	90	150	∞		
2-jets	$\lvert y^{j_2}\rvert$	0.0	0.6	1.2	1.8	2.5	3.5	5.0	
Baseline + $\geq$ 2 jets	$\lvert\Delta\phi_{j_1,j_2}\rvert$	0.0	0.5	0.9	1.3	1.7	2.5	π	
$p_T^j > 30$ GeV	$\lvert\Delta\phi_{\gamma\gamma,j_1j_2}\rvert$	0.0	2.0	2.7	2.95	3.07	π		
$\lvert\eta^j\rvert < 4.7$	$\lvert\bar{\eta}_{j_1j_2} - \eta_{\gamma\gamma}\rvert$	0.0	0.2	0.5	0.85	1.2	1.7	∞	
	m^{jj}	0	75	120	180	300	500	1000	∞
	$\lvert\Delta\eta_{j_1,j_2}\rvert$	0.0	0.7	1.6	3.0	5.0	∞		
VBF-enriched	$p_T^{\gamma\gamma}$	0	30	60	120	200	∞		
2-jets + $n_{jets} \geq 2$	$p_T^{j_2}$	30	40	65	90	150	∞		
$\Delta\eta^{jj} > 3.5$	$\lvert\Delta\phi_{j_1,j_2}\rvert$	0.0	0.5	0.9	1.3	1.7	2.5	π	
$m^{jj} > 200\,\mathrm{GeV}$	$\lvert\Delta\phi_{\gamma\gamma,j_1j_2}\rvert$	0.0	2.0	2.7	2.95	3.07	π		

Fiducial volume and obs. in CMS WW

Observable	Condition
Lepton origin	Direct decay of $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$
Lepton flavors; lepton charge	eμ(not from τdecay); opposite
Leading lepton p_T	$p_\mathrm{T}^{l_1} > 25\,\mathrm{GeV}$
Trailing lepton p_T	$p_\mathrm{T}^{l_2} > 13\,\mathrm{GeV}$
$\lvert\eta\rvert$ of leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m^{ll} > 12\,\mathrm{GeV}$
p_T of the dilepton system	$p_\mathrm{T}^{ll} > 30\,\mathrm{GeV}$
Transverse mass using trailing lepton	$m_\mathrm{T}^{l_2} > 30\,\mathrm{GeV}$
Higgs boson transverse mass	$m_\mathrm{T}^\mathrm{H} > 60\,\mathrm{GeV}$

Jet counting: All jets clustered with the anti-k_T algo. with $p_\mathrm{T} > 30$ GeV