Combination of Higgs measurements:

Couplings and κ-framework

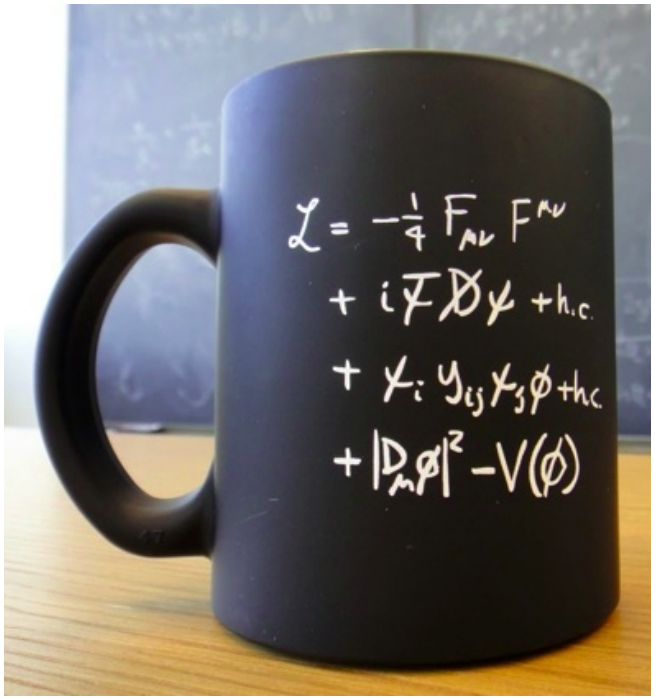
Jonathon Langford

On behalf of the ATLAS and CMS Collaborations

LHCP 2020

The Higgs sector

- Higgs boson is the only fundamental scalar particle (spin 0) in the SM



- Run 2: focus shifted towards **precision measurements** of H couplings
  - unique tool to scrutinize predictions of SM

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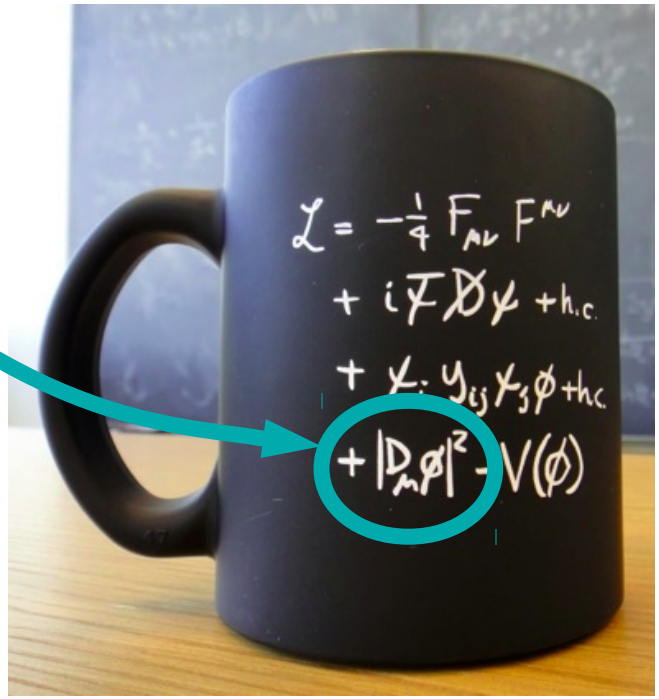
  - Gauge boson interactions: H-V couplings



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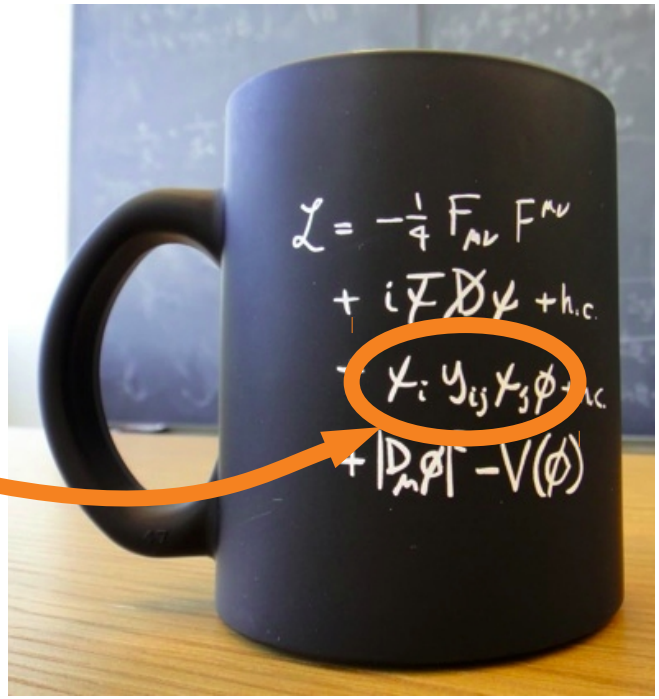
  - Gauge boson interactions: H-V couplings
  - Yukawa interactions: H-f couplings



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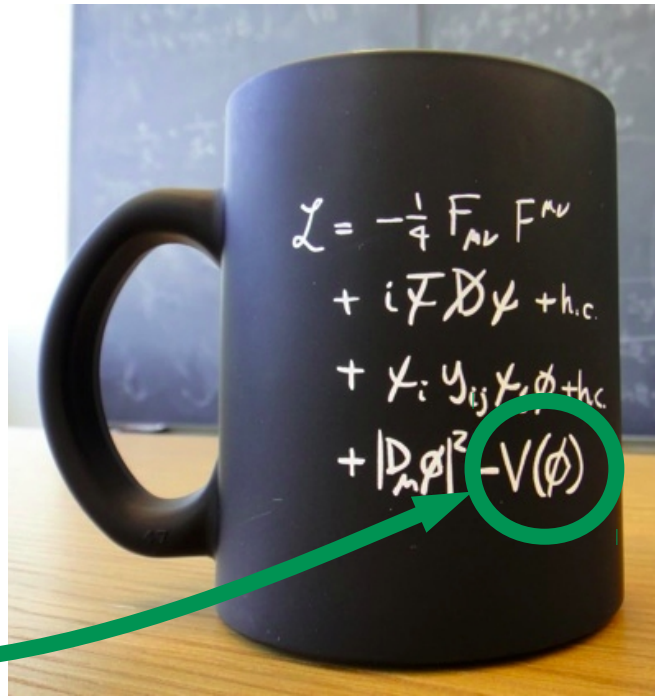
The Higgs sector

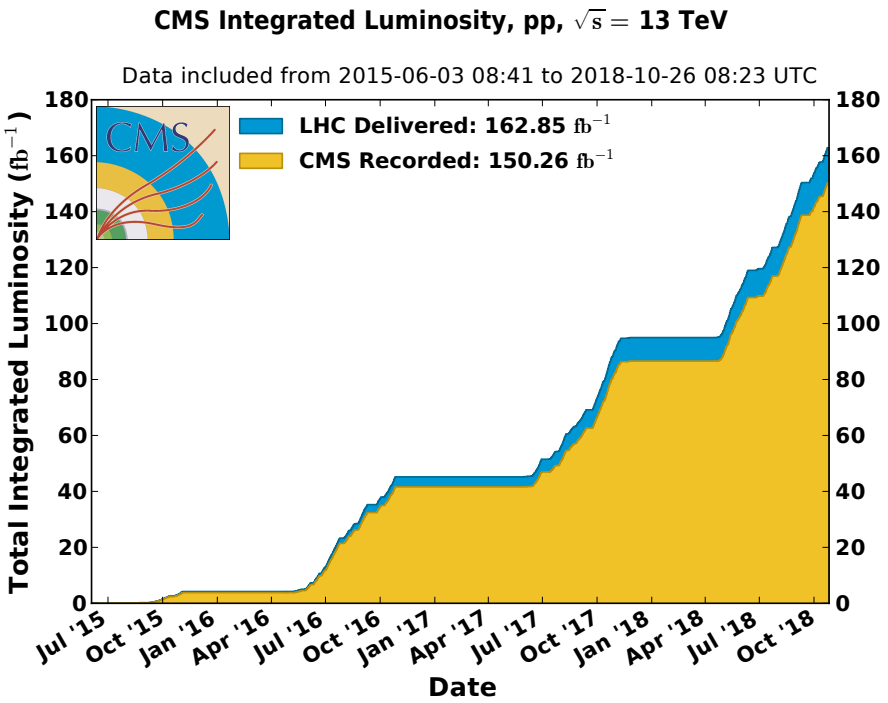
- Higgs boson is the only fundamental scalar particle (spin 0) in the SM

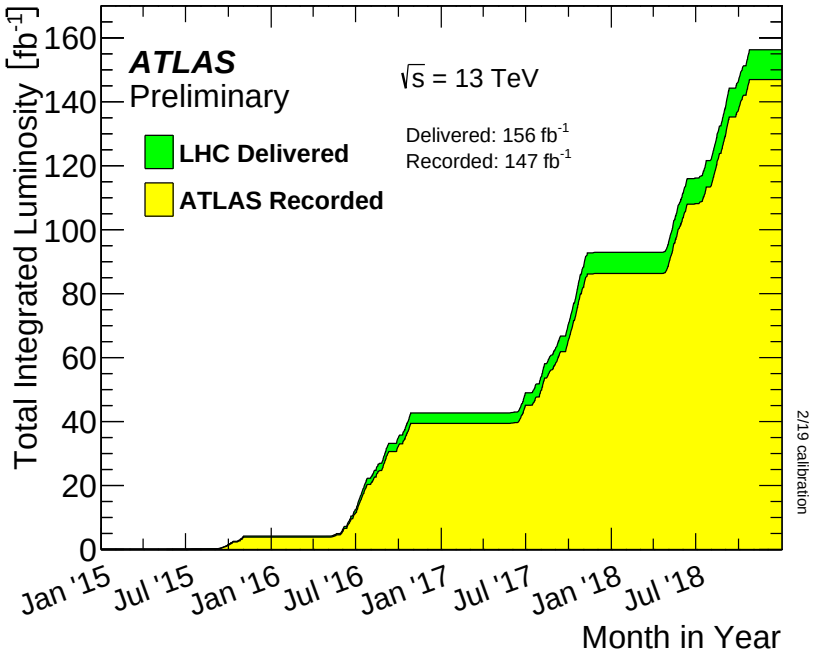
  - Gauge boson interactions: H-V couplings
  - Yukawa interactions: H-f couplings
  - Higgs potential: self couplings



- Run 2: focus shifted towards **precision measurements** of H couplings
  - unique tool to scrutinize predictions of SM

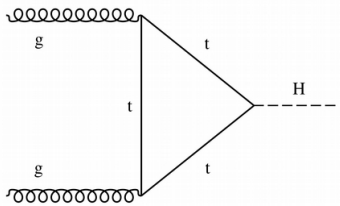
Run 2 combinations

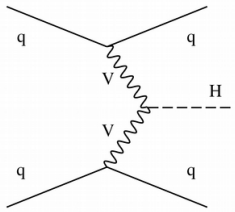


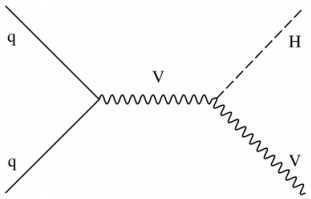


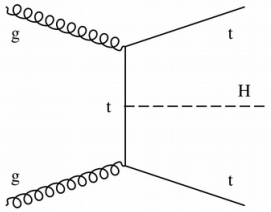
- Wealth of data allows for unprecedented levels of precision!
  - tighter constraints on BSM models which distort H couplings
- Combinations across decay channels provides ultimate sensitivity
  - both collaborations completing full Run II analyses in individual channels
- This talk: focus on latest **intermediate combinations** from CMS & ATLAS:
  - CMS 35.9–137 fb^{-1} (Jan 2020): CMS-PAS-HIG-19-005
  - ATLAS 24.5–79.8 fb^{-1} (Sept 2019): Phys. Rev. D 101, 012002

Input analyses









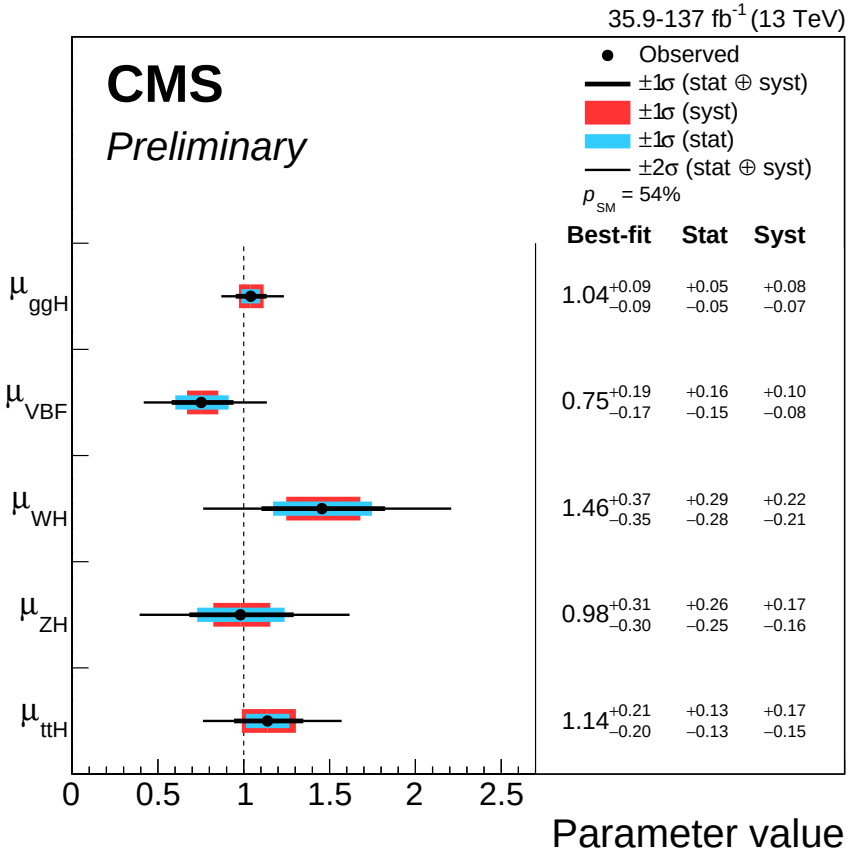
	CMS Lumi (fbinv)	ggH	VBF	VH	ttH	Refs	ATLAS Lumi (fbinv)	ggH	VBF	VH	ttH	Refs
H→ $\gamma\gamma$	77	✓	✓			[CMS-PAS-HIG-18-029]	80	✓	✓	✓	✓	[ATLAS-CONF-2018-028]
					✓	[CMS-PAS-HIG-18-018]						
H→ZZ* → 4ℓ	137	✓	✓	✓	✓	[CMS-PAS-HIG-19-001]	80	✓	✓	✓	✓	[ATLAS-CONF-2018-018]
H→WW	36	✓	✓	✓		[Phys. Lett. B 791 (2019) 96]	36	✓	✓			[Phys. Lett. B 789 (2019) 508]
H→bb	77			✓		[Phys. Rev. Lett. 121, 121801 (2018)]	80			✓		[JHEP 05 (2019) 141]
	77				✓	[CMS-PAS-HIG-18-030]	36				✓	[Phys. Rev. D 97, 072016 (2018)]
	36	✓ boost				[Phys. Rev. Lett. 120, 071802 (2018)]	31		✓			[Phys. Rev. D 98, 052003 (2018)]
H→ $\tau\tau$	77	✓	✓	✓		[CMS-PAS-HIG-18-032]	77	✓	✓			[Phys. Rev. D 99, 072001 (2019)]
	36			✓		[JHEP 06 (2019) 093]						
ttH→multilepton ($\tau\tau$, WW, ZZ)	77				✓	[CMS-PAS-HIG-18-019]	77				✓	[Phys. Rev. D 97, 072003 (2018)]
H→ $\mu\mu$	36	✓	✓			[Phys. Rev. Lett. 122, 021801 (2019)]	80	✓	✓			[ATLAS-CONF-2018-026]
						H→invisible	24-30		✓	✓		[Phys. Rev. Lett. 122, 231801 (2019)]
						Offshell H→ZZ*	36	For constraint on Γ_H				[Phys. Lett. B 786 (2018) 223]

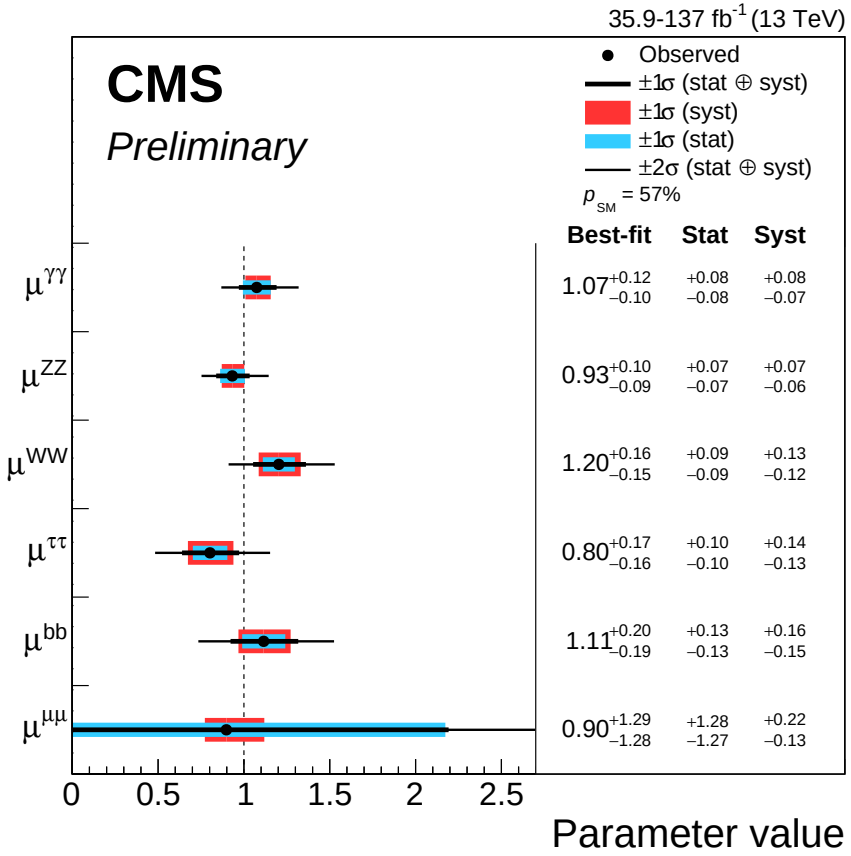
(*) Not included in all results

(*) Some inputs have now been superseded with full Run 2 analyses

Signal strengths: μ = rate of H boson production / SM prediction

- Inclusive: all signal rates scale according to single μ
  - CMS $\mu = 1.02 \pm 0.04(\text{th.}) \pm 0.04(\text{exp.}) \pm 0.04(\text{stat.})$
  - ATLAS EXPERIMENT $\mu = 1.11^{+0.05}_{-0.04}(\text{sig th.}) \pm 0.03(\text{bkg th.})^{+0.05}_{-0.04}(\text{exp.}) \pm 0.05(\text{stat.})$

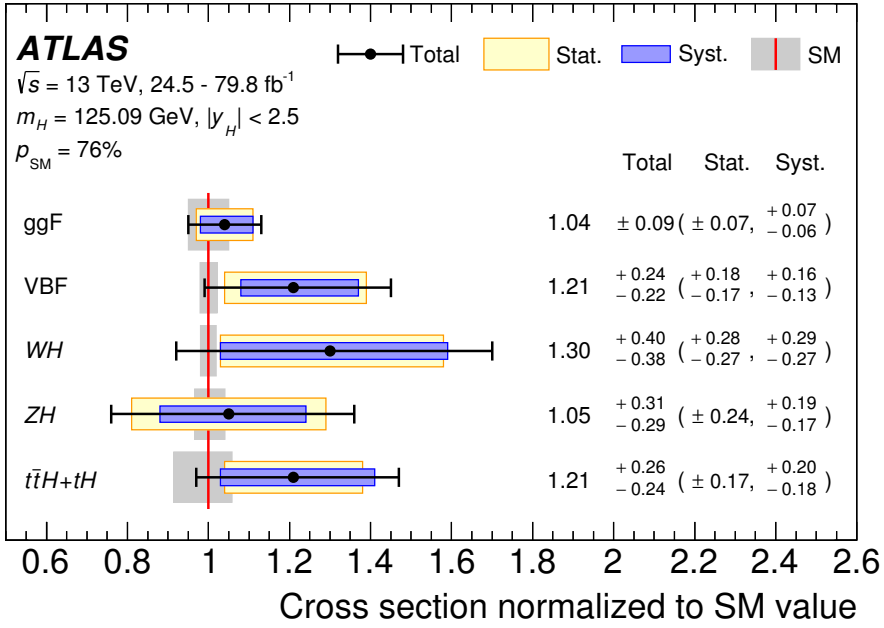


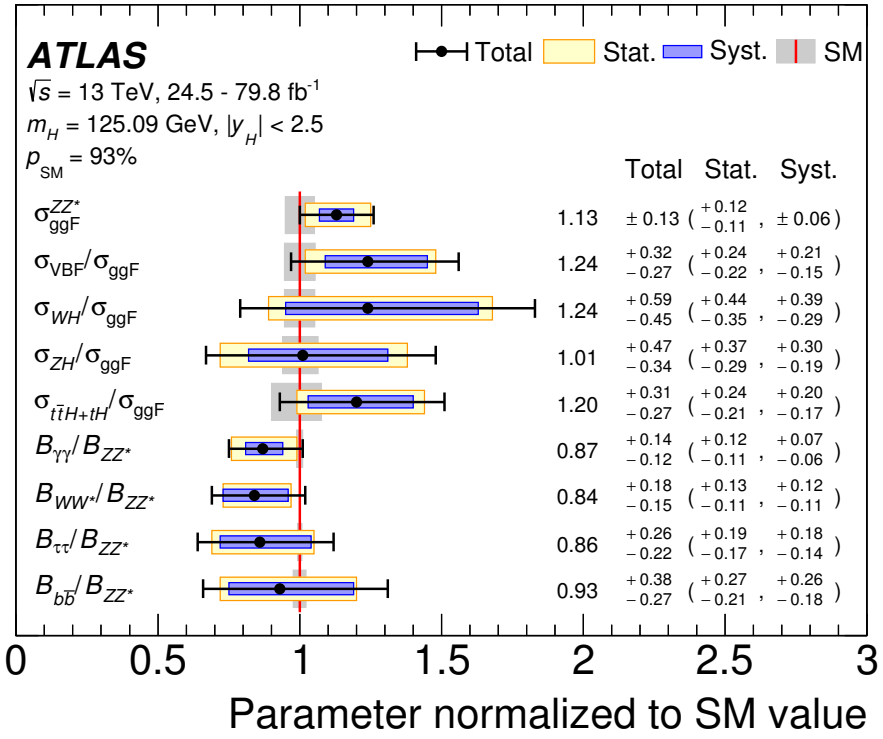


- Systematic uncertainties are becoming increasingly important!
  - adapt measurement framework to reduce theory dependencies...

Cross sections

- Measure cross sections (and their ratios) as opposed to signal strengths
  - dominant theory uncertainties cancel in ratios



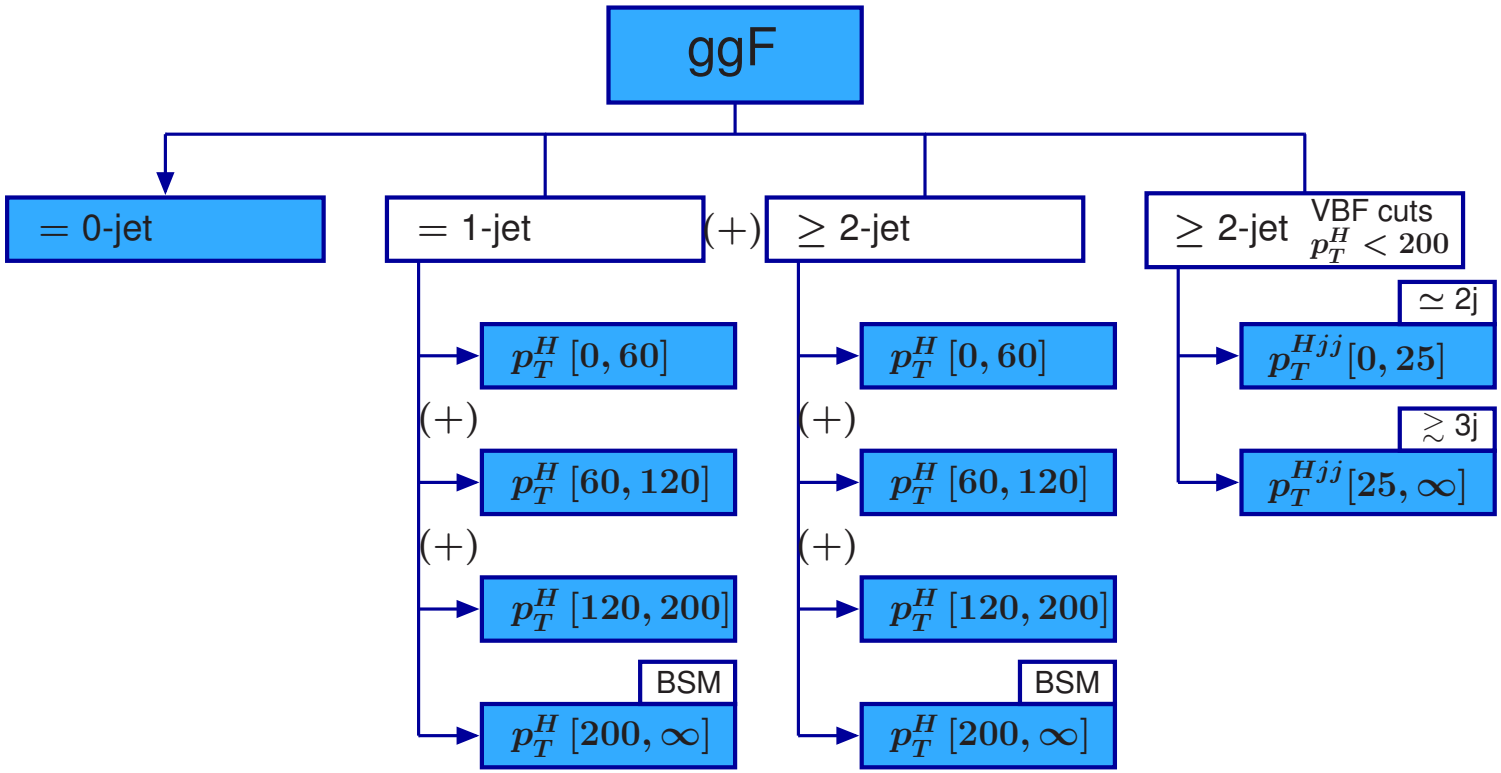


- Both CMS & ATLAS report significances $\geq 5\sigma$ for major production modes

- All results consistent with SM predictions
  - more granular fits (μ_i^f) in Back-up

Simplified template cross sections: more detail in Back-up

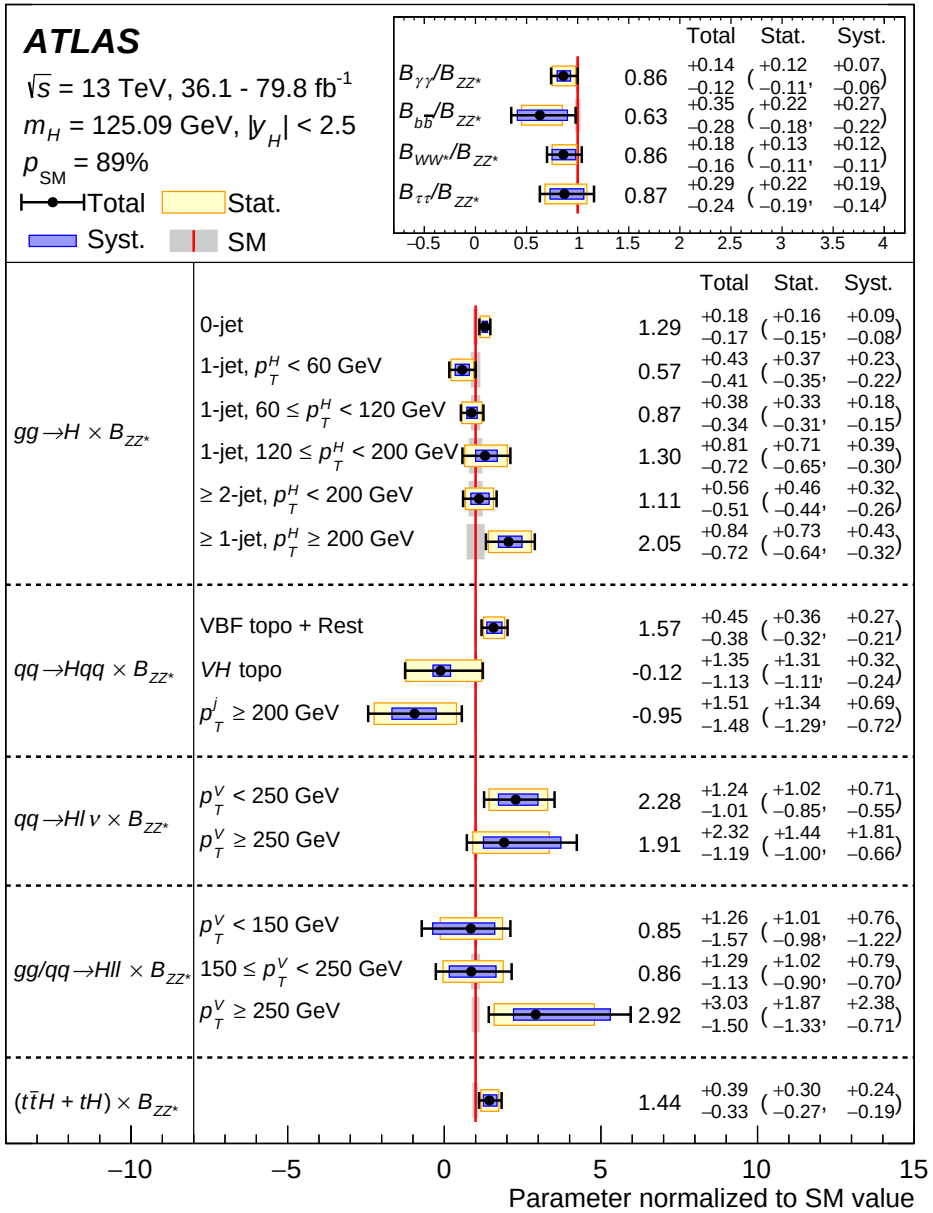
- Measure cross sections in increasingly granular "bins"
  - split by production mode + kinematics ($|y_H| < 2.5$)



- Leave no stone/region of space space unturned!
  - full Run 2 measurements will adhere to stage 1.2 binning Back-up

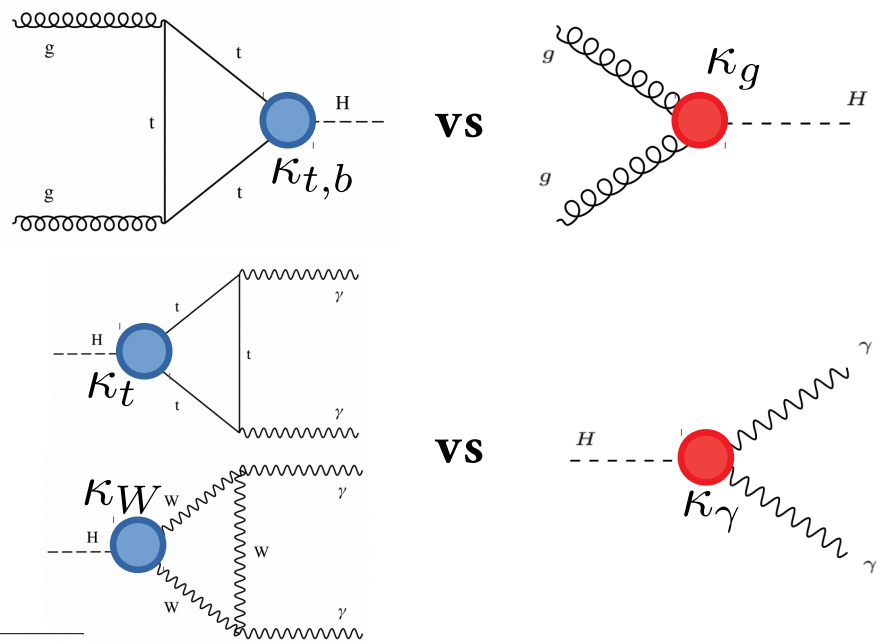
Simplified template cross sections

- Insufficient scope to measure all bins of STXS given current datasets
  - merge bins with low sensitivity ($\gtrsim$100%) or high (anti)-correlations
  - increases model dependence
  - e.g. ATLAS EXPERIMENT: 19 parameter fit
    $\Rightarrow$ also finer granularity fit: Back-up
- At this level of splitting
  $\Rightarrow$ stat unc. dominate
- Differential information
  - motivates (re)-interpretation
  - + provide full correlation matrix between fitted params: Back-up
- Very much in agreement with SM!

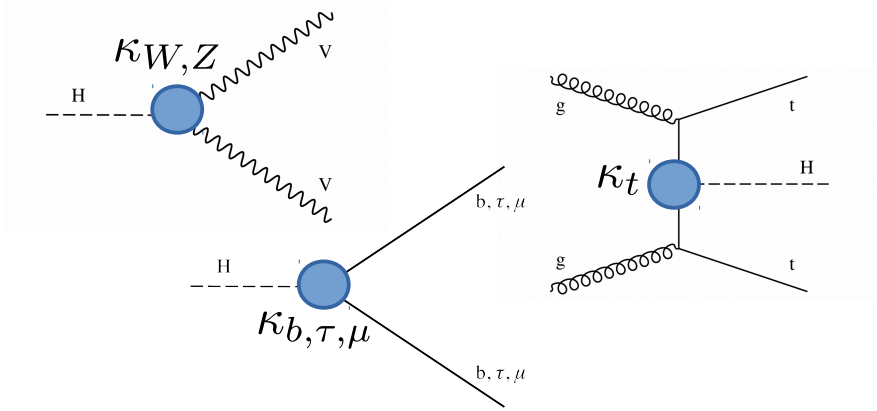


κ-framework: $\mu \rightarrow \mu(\vec{\kappa})$

- Multiplicative coupling modifiers
  $\Rightarrow$ SM: positive + equal to unity
- Two possible treatments for loop diagrams:
  - resolved into SM components
  - effective vertices



	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(ggH)$	✓	g-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
$\sigma(VBF)$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(WH)$	—	—		κ_W^2
$\sigma(qq/qg \rightarrow ZH)$	—	—		κ_Z^2
$\sigma(gg \rightarrow ZH)$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
$\sigma(ttH)$	—	—		κ_t^2
$\sigma(gb \rightarrow WtH)$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(qb \rightarrow tHq)$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(bbH)$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width for $\mathcal{B}_{BSM} = 0$				
Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 + 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 + 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$



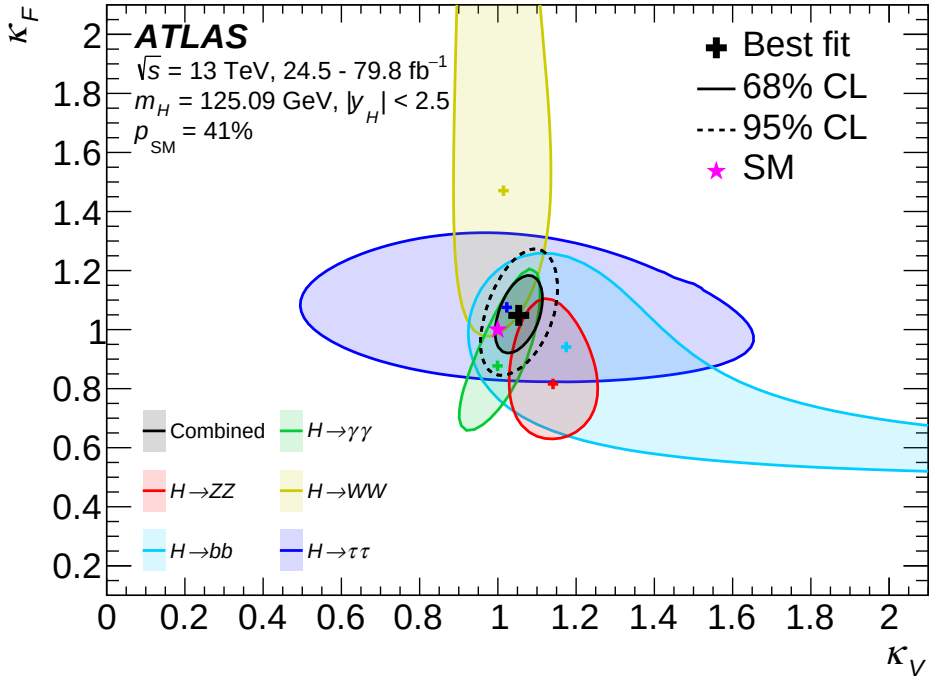
Limitations

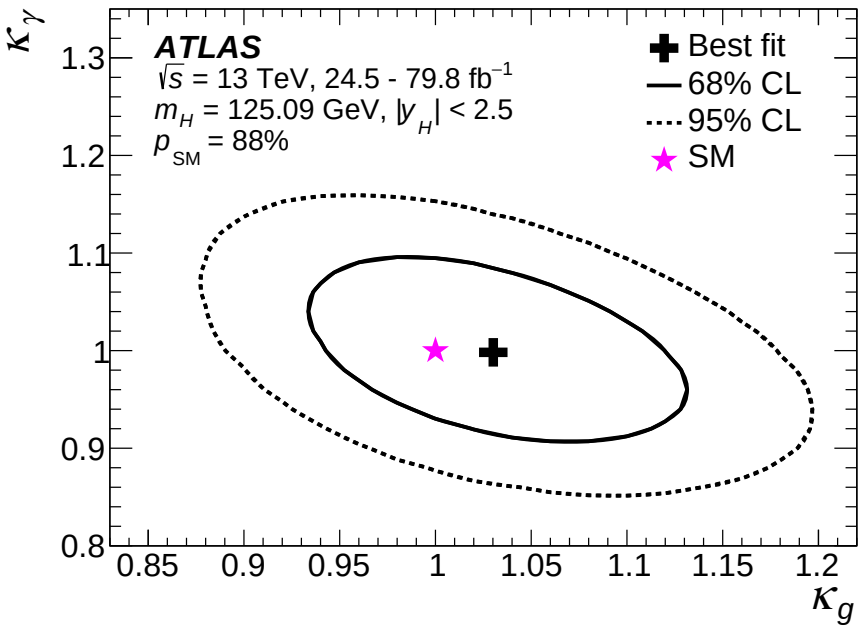
1. LO framework
2. Ignores shape effects
3. Specific to H physics

κ-framework

- Under assumption of no additional H boson decays beyond SM particles

- Universal modifiers for H couplings to V bosons (κ_V) and fermions (κ_F)
  - resolve loops into SM components
  - $\kappa_V = \kappa_Z = \kappa_W$
  - $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$

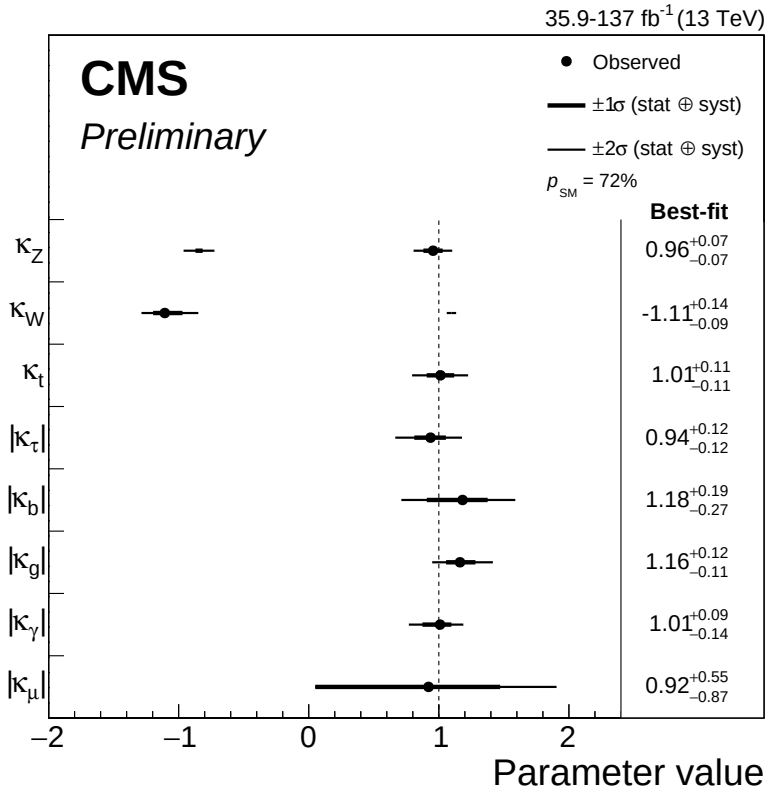


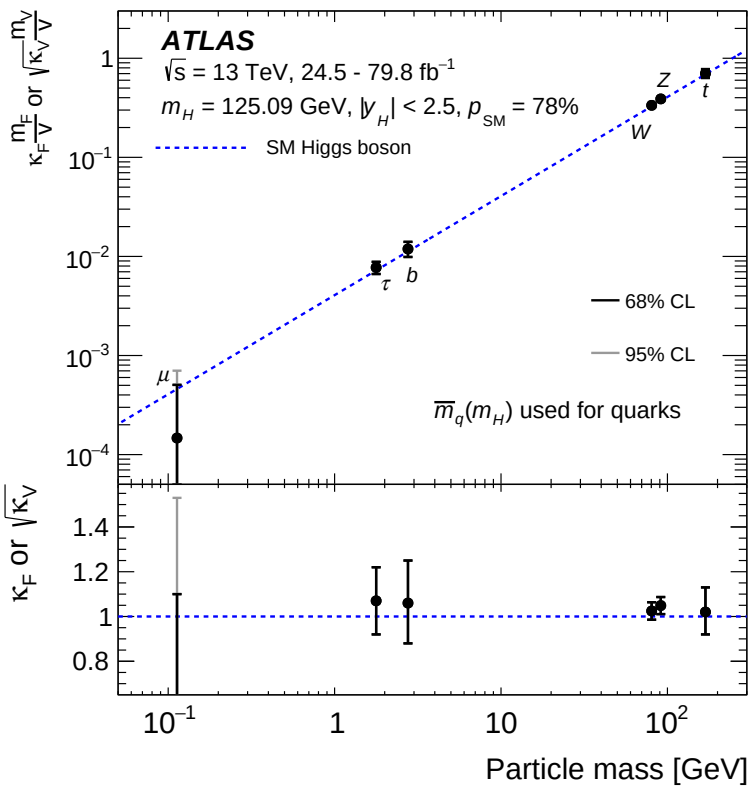


- Probe new particles in loops: $\Rightarrow$ ggH, H$\rightarrow \gamma\gamma$:
  - effective coupling strengths: κ_g, κ_γ
  - assume all other $\kappa_j = 1$

κ-framework Extend to include Higgs boson self coupling (κ_λ), see talk by Stefano

- Under assumption of no additional H boson decays beyond SM particles





- ~5–20% precision on H couplings to gauge bosons & 3rd gen fermions. Agrees with SM!
  - correlation matrix in Back-up
- Sensitive to relative sign of $\kappa_{W,Z}$-κ_t
  - effective model: via interference in tH + ggZH processes

Parameter	Result
κ_Z	1.10 ± 0.08
κ_W	1.05 ± 0.08
κ_b	$1.06\ ^{+\ 0.19}_{-\ 0.18}$
κ_t	$1.02\ ^{+\ 0.11}_{-\ 0.10}$
κ_τ	1.07 ± 0.15
κ_μ	< 1.53 at 95% CL

κ-framework: beyond SM

- ATLAS additional benchmarks to account for BSM effects in H decay
  - on-shell production...

$$\sigma_i \cdot \mathcal{B}^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa}, \mathcal{B}_{\rm inv}, \mathcal{B}_{\rm undet})}$$

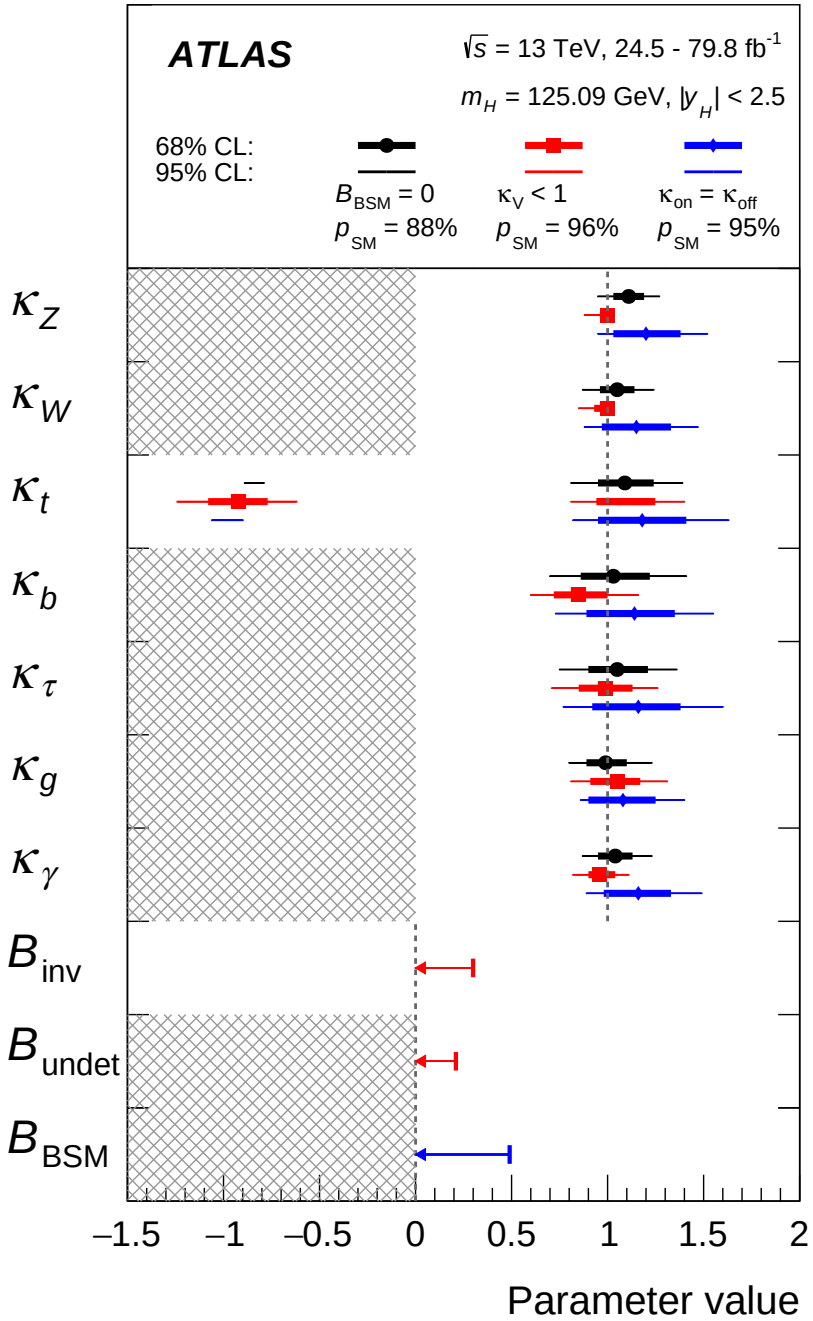
  - $\mathcal{B}_{\rm inv}$: H→invisible decays (MET)
  - $\mathcal{B}_{\rm undet}$: final states not measured

1. $\mathcal{B}_{\rm undet} > 0$, $\kappa_V < 1$:
   - includes results from H→inv. searches
   - $\mathcal{B}_{\rm undet} < 21\%$ & $\mathcal{B}_{\rm inv} < 30\%$ @ 95% C.L.
2. $\mathcal{B}_{\rm BSM} = \mathcal{B}_{\rm undet} + \mathcal{B}_{\rm inv}$
   - includes off-shell H→ZZ* meas.
   - assumes $\kappa_{\rm on} = \kappa_{\rm off}$

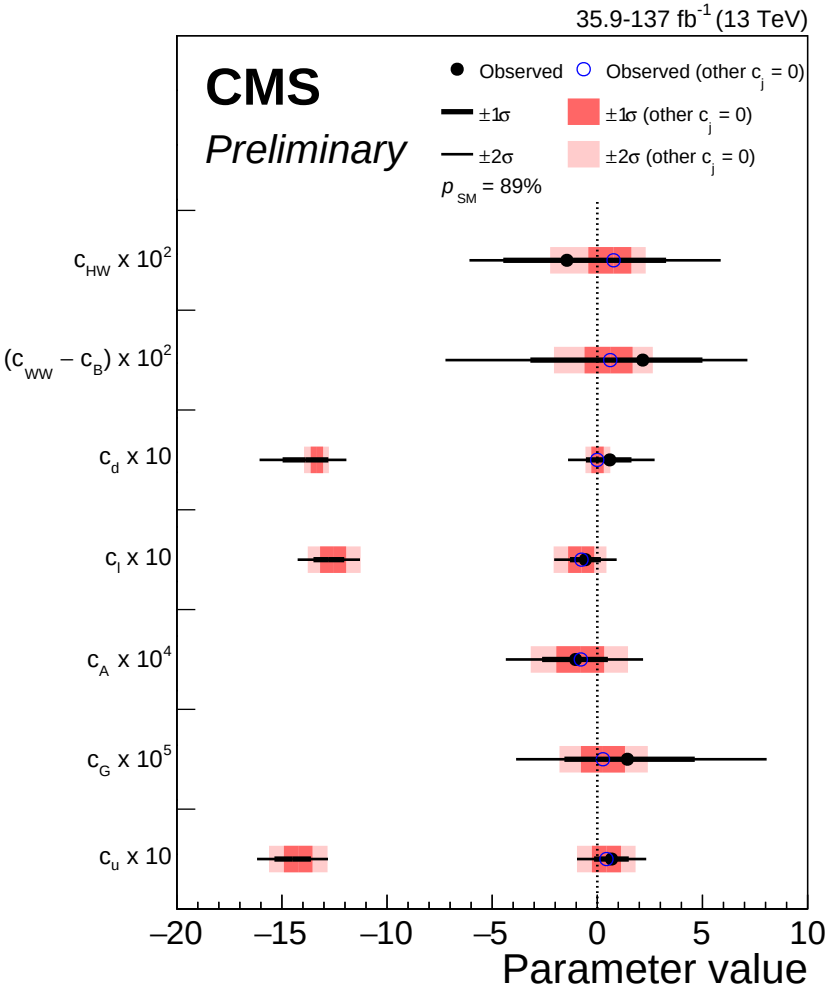
$$(\sigma_i \cdot \mathcal{B}^f)_{\rm off-shell} \sim \sigma_i(\vec{\kappa_{\rm off}})\Gamma^f(\vec{\kappa_{\rm off}})$$

   - $\mathcal{B}_{\rm BSM} < 49\%$ @ 95% C.L.

- also fit ratios of coupling modifiers ▸ Back-up
- + 2HDM/hMSSM interpretations ▸ Back-up



EFT interpretation of STXS measurements



- More info in talk by Nikita

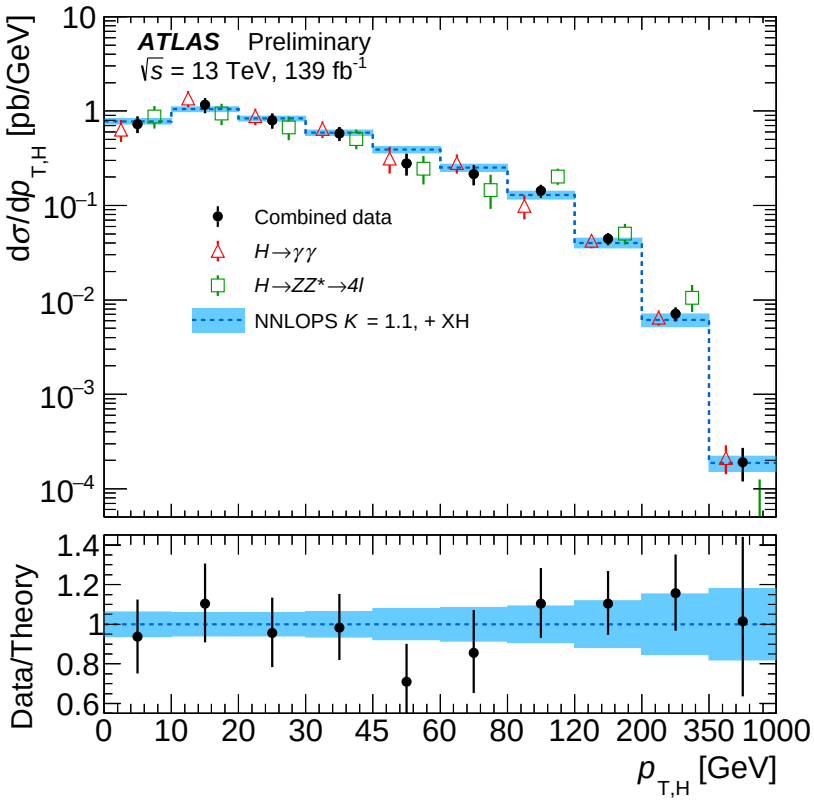
- Extend $\mathcal{L}_{\mathrm{SM}}$ with higher-dim operators:

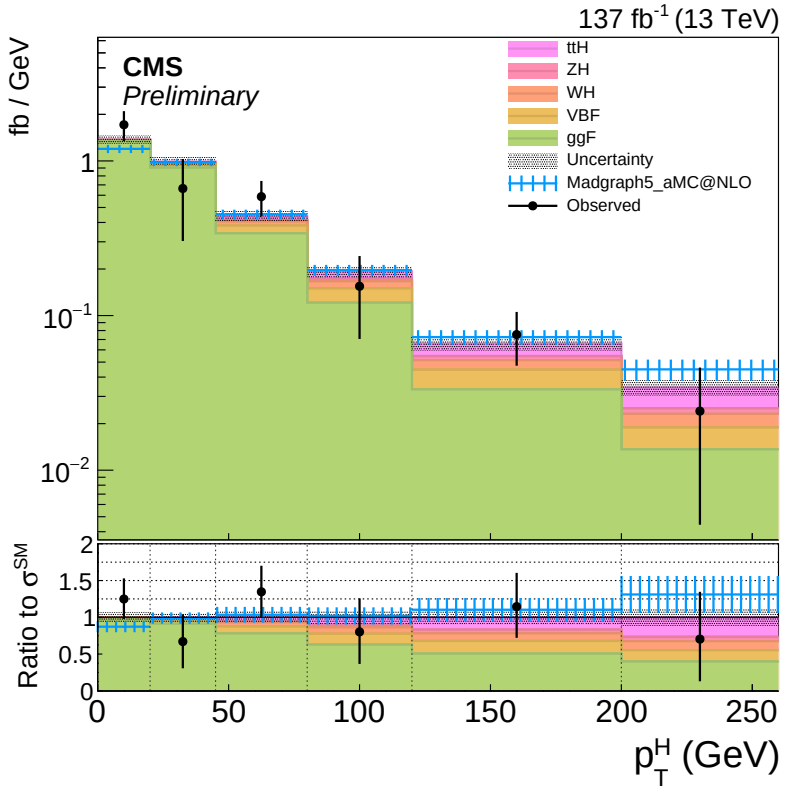
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_j f_j \mathcal{O}_j / \Lambda^2$$

- Parametrize σ + BR as function of EFT parameters: $c_j \propto f_j/\Lambda^2$
  - for each bin of STXS
  - beyond κ's: shape effects
- CMS using Higgs Effective Lagrangian
  - SILH basis
  - combination of STXS stage 0, 1 and 1.1
- Neglected **acceptance corrections**
  - sizeable in some channels: e.g. ATLAS EXPERIMENT $H \to 4\ell$: submitted to EPJC
  - future EFT interpretations will account for such effects!
- $\Rightarrow$ SMEFT (Warsaw)

Differential combinations: more detail in talk by Andrea

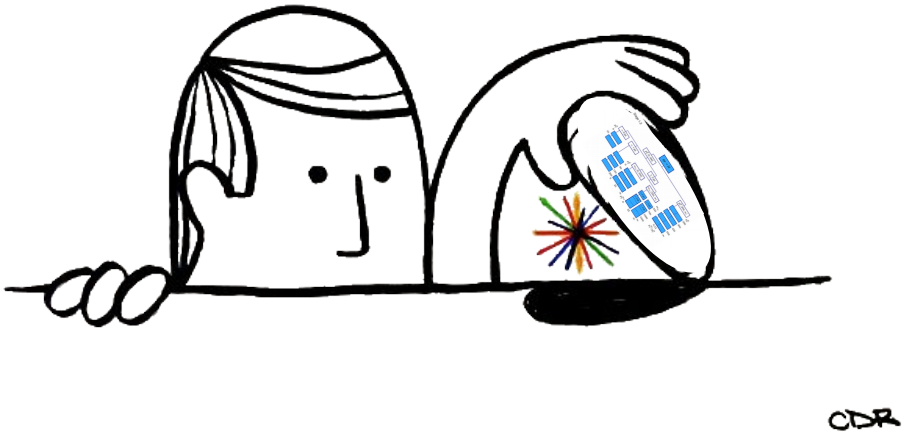
- Also combination of $d\sigma/dX$ measurements across major channels
- Fiducial $\Leftrightarrow$ model independence
- Shape is sensitive to Yukawa couplings + new physics in loop diagrams!
  - ATLAS EXPERIMENT $4\ell + \gamma\gamma$ using full Run 2 data (140 fb^{-1}): ATLAS-CONF-2019-032
  - CMS Several full Run 2 inputs ready e.g. H→WW...





Looking to the future

- Presented results of Higgs combinations using partial Run 2 data
  - signal strengths, cross sections, STXS, κ-framework, EFT
  - all in agreement with SM predictions
- Full Run 2 combinations will provide never-before-reached levels of precision
  - both collaborations completing full Run 2 analyses in individual channels
- STXS + differential measurements offer finer granularity
- Interpretation: emphasis shifting κ-framework $\Rightarrow$ EFT
- Ultimate precision: inter-collaboration combination (as in Run 1)



Back-Up Slides

Statistical procedure for combination

- Methodology used by ATLAS and CMS collaborations
- Profile likelihood ratio: $q(\vec{\alpha})$
  - estimate POIs ($\vec{\alpha}$) and corresponding confidence intervals e.g. μ, κ etc.
  - $\vec{\theta}$: nuisance param (NP) describing experimental + theoretical unc.

$$q(\vec{\alpha}) = -2 \ln \left(\frac{L(\vec{\alpha}, \hat{\vec{\theta}}_{\vec{\alpha}})}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})} \right)$$

- Confidence intervals: regions where $q(\vec{\alpha})$ below threshold in $F^{-1}_{\chi^2_n}(1-p)$
  - $F^{-1}_{\chi^2_n}$: quantile function of χ^2 dist. with n d.o.f
  - compatibility with SM measured with p-value: $p_{\mathrm{SM}} = 1 - F_{\chi^2_n}(q(\vec{\alpha}_{\mathrm{SM}}))$
- e.g. 1D measurements: 1σ (2σ) intervals $\rightarrow q(\vec{\alpha}) < 1$ ($q(\vec{\alpha}) < 4$)
  - models with more than one POI: treat other POIs as NP (profiling)
- For expected results: construct likelihood functions w.r.t. Asimov data set
  - using expected (SM) values of the POIs

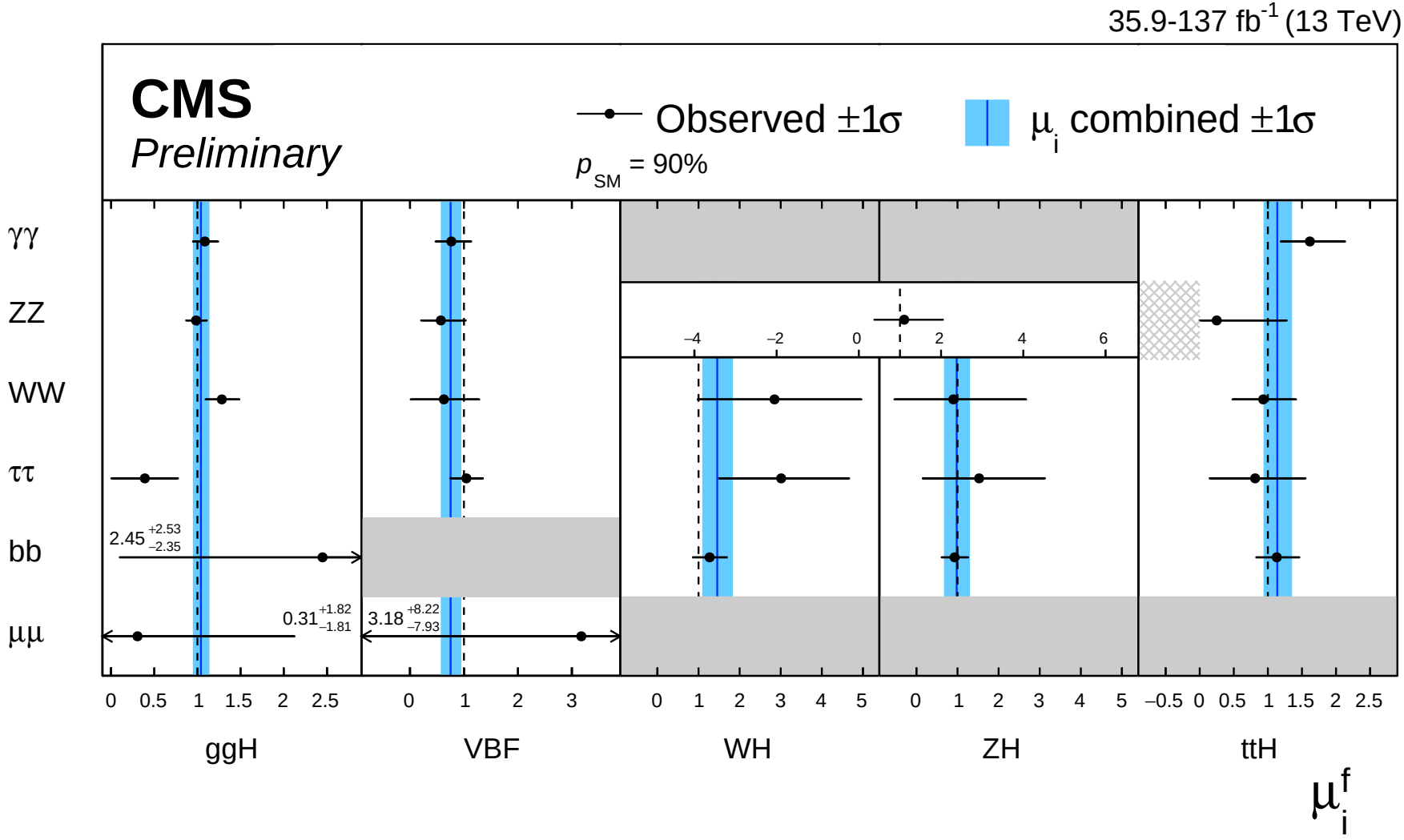
Global signal strength: uncertainty breakdown

- ATLAS EXPERIMENT:

Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.4
Flavor tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

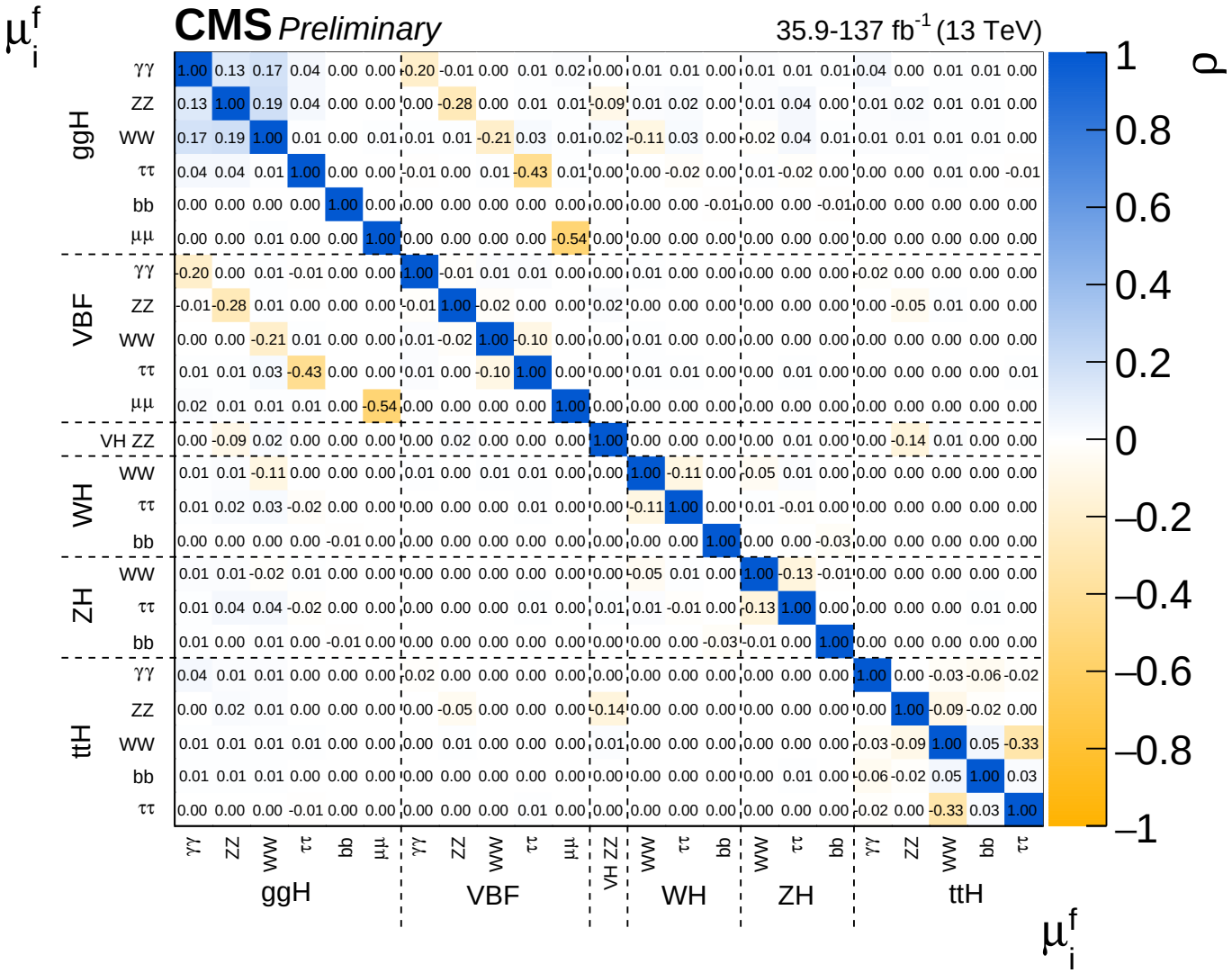
CMS: μ_i^f

- Separate signal strengths for all possible production mode ($i \rightarrow$H) $\times$ decay channel (H$\rightarrow f$) combinations



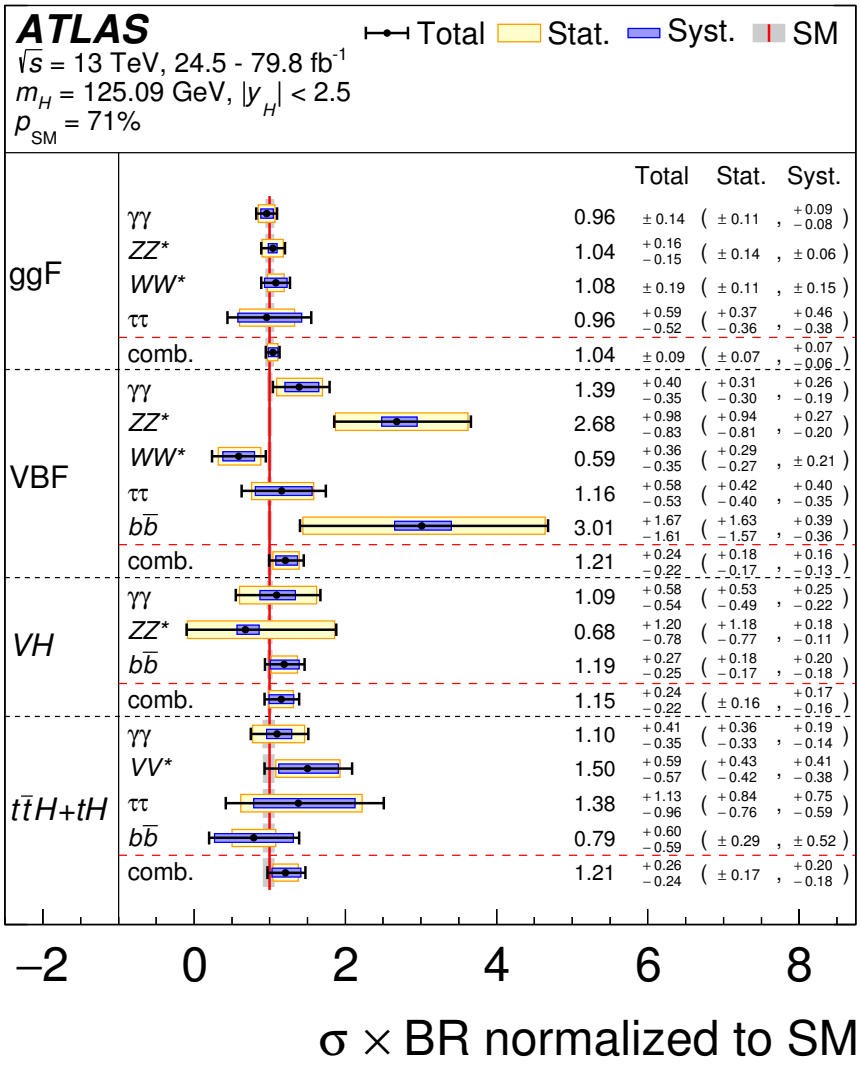
CMS: μ_i^f correlations

- Separate signal strengths for all possible production mode ($i \rightarrow$H) $\times$ decay channel (H$\rightarrow f$) combinations



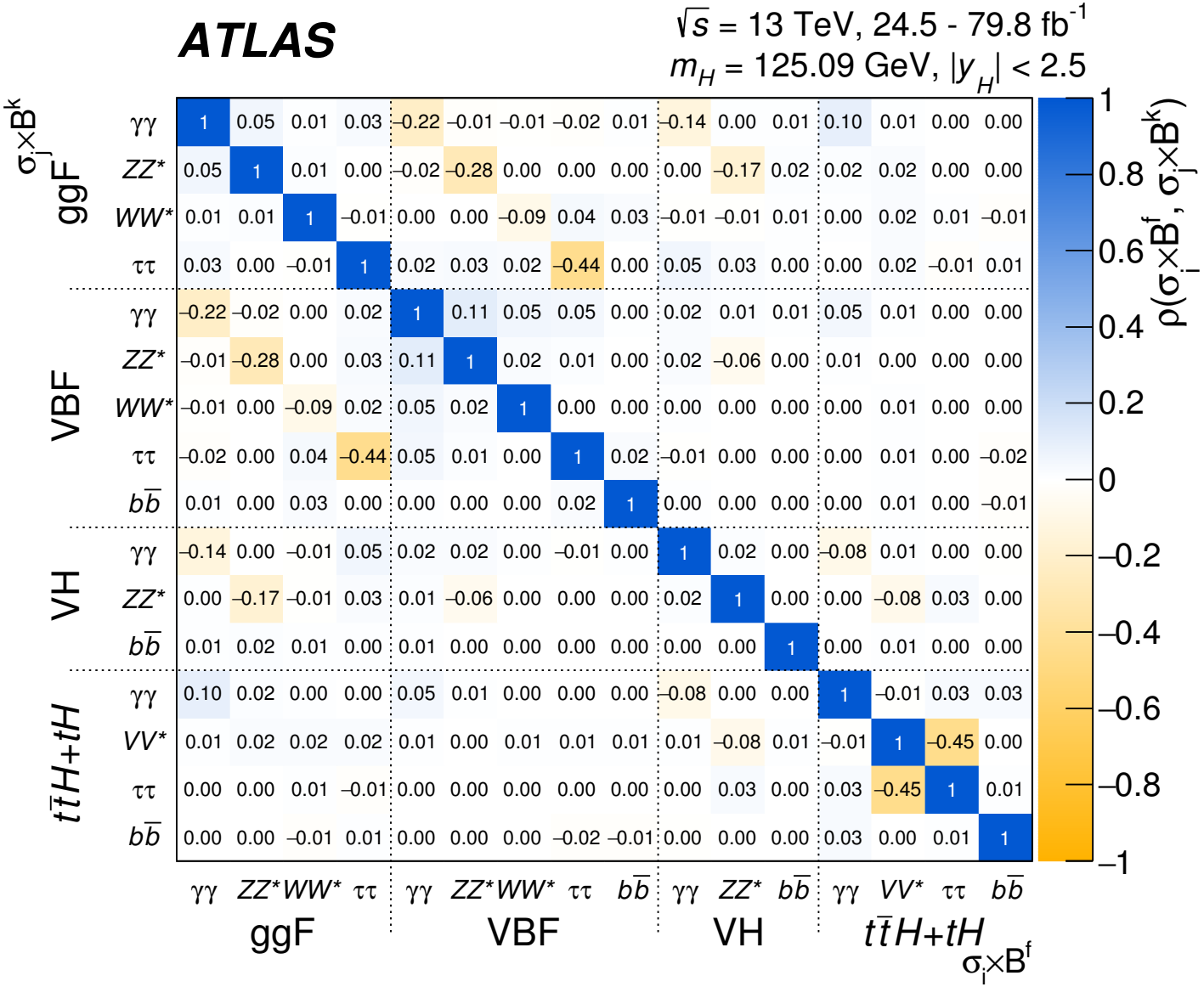
ATLAS: $\sigma_i \times \mathrm{BR}(\mathrm{H} \to f)$

- Separate parameters for all possible production mode ($i \to$H) $\times$ decay channel (H$\to f$) combinations



ATLAS: $\sigma_i \times \mathrm{BR}(\mathrm{H} \to f)$ correlations

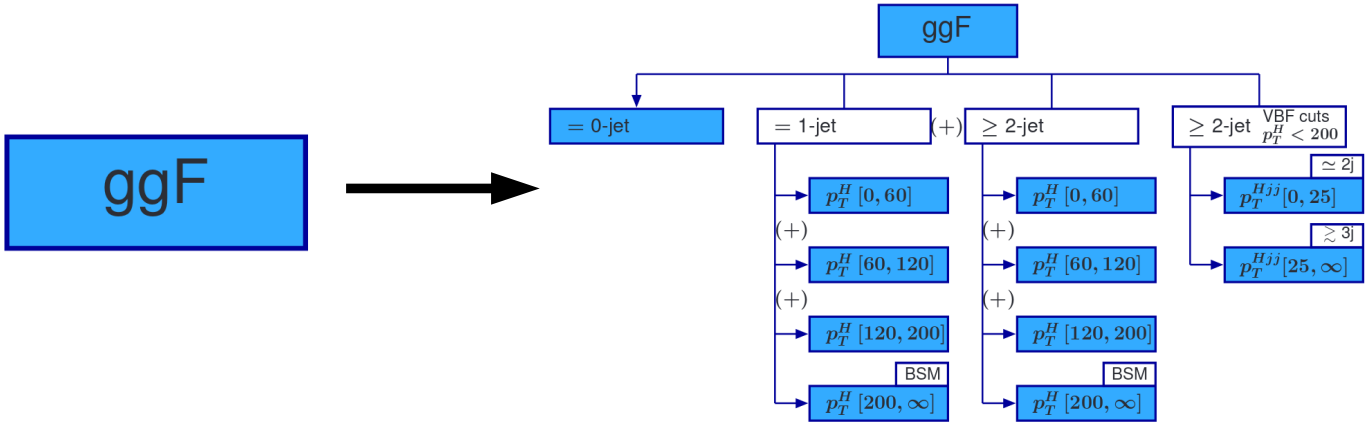
- Separate parameters for all possible production mode ($i \to$H) $\times$ decay channel (H$\to f$) combinations



	γγ	ZZ*	WW*	ττ	γγ	ZZ*	WW*	ττ	bb̄	γγ	ZZ*	bb̄	γγ	VV*	ττ	bb̄
ggF γγ	1	0.05	0.01	0.03	–0.22	–0.01	–0.01	–0.02	0.01	–0.14	0.00	0.01	0.10	0.01	0.00	0.00
ggF ZZ*	0.05	1	0.01	0.00	–0.02	–0.28	0.00	0.00	0.00	0.00	–0.17	0.02	0.02	0.02	0.00	0.00
ggF WW*	0.01	0.01	1	–0.01	0.00	0.00	–0.09	0.04	0.03	–0.01	–0.01	0.01	0.00	0.02	0.01	–0.01
ggF ττ	0.03	0.00	–0.01	1	0.02	0.03	0.02	–0.44	0.00	0.05	0.03	0.00	0.00	0.02	–0.01	0.01
VBF γγ	–0.22	–0.02	0.00	0.02	1	0.11	0.05	0.05	0.00	0.02	0.01	0.01	0.05	0.01	0.00	0.00
VBF ZZ*	–0.01	–0.28	0.00	0.03	0.11	1	0.02	0.01	0.00	0.02	–0.06	0.00	0.01	0.00	0.00	0.00
VBF WW*	–0.01	0.00	–0.09	0.02	0.05	0.02	1	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
VBF ττ	–0.02	0.00	0.04	–0.44	0.05	0.01	0.00	1	0.02	–0.01	0.00	0.00	0.00	0.01	0.00	–0.02
VBF bb̄	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.02	1	0.00	0.00	0.00	0.00	0.01	0.00	–0.01
VH γγ	–0.14	0.00	–0.01	0.05	0.02	0.02	0.00	–0.01	0.00	1	0.02	0.00	–0.08	0.01	0.00	0.00
VH ZZ*	0.00	–0.17	–0.01	0.03	0.01	–0.06	0.00	0.00	0.00	0.02	1	0.00	0.00	–0.08	0.03	0.00
VH bb̄	0.01	0.02	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.01	0.00	0.00
tt̄H+tH γγ	0.10	0.02	0.00	0.00	0.05	0.01	0.00	0.00	0.00	–0.08	0.00	0.00	1	–0.01	0.03	0.03
tt̄H+tH VV*	0.01	0.02	0.02	0.02	0.01	0.00	0.01	0.01	0.01	0.01	–0.08	0.01	–0.01	1	–0.45	0.00
tt̄H+tH ττ	0.00	0.00	0.01	–0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.03	–0.45	1	0.01
tt̄H+tH bb̄	0.00	0.00	–0.01	0.01	0.00	0.00	0.00	–0.02	–0.01	0.00	0.00	0.00	0.03	0.00	0.01	1

Simplified template cross sections

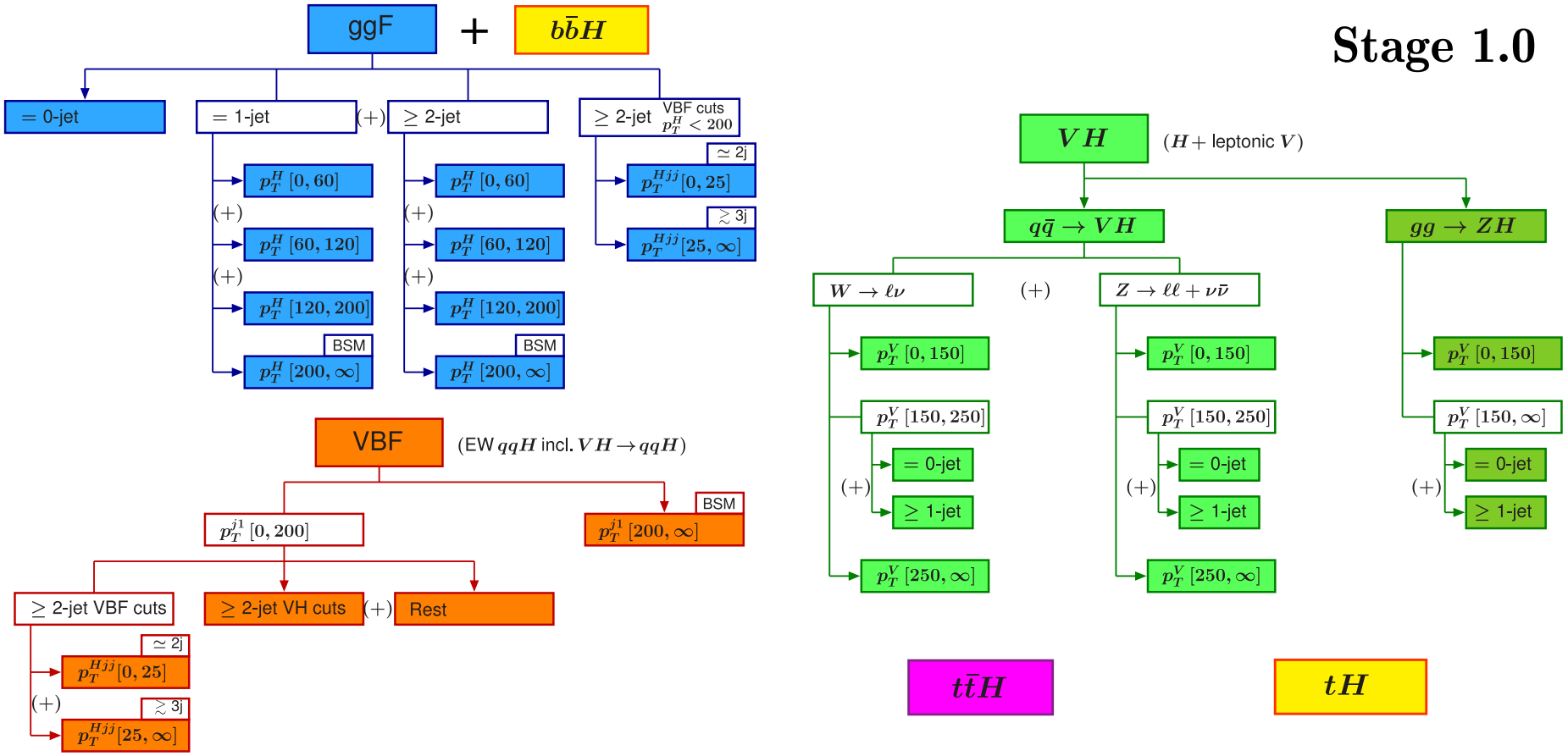
- Coherent framework for increasingly granular Higgs measurements
  - isolate mutually exclusive regions of Higgs phase space (bins)
  - split by production mode + kinematics ($|y_H| < 2.5$)



- Aims: maximise experimental sensitivity whilst systematically reducing theory dependence folded into measurements
  - design bins to have constant theory unc.
  - + isolate possible BSM physics
  - decouple interpretation from measurement: long-term useful
  - coherence permits **combinations across decay channels**
- Build up more granular picture of the Higgs Boson

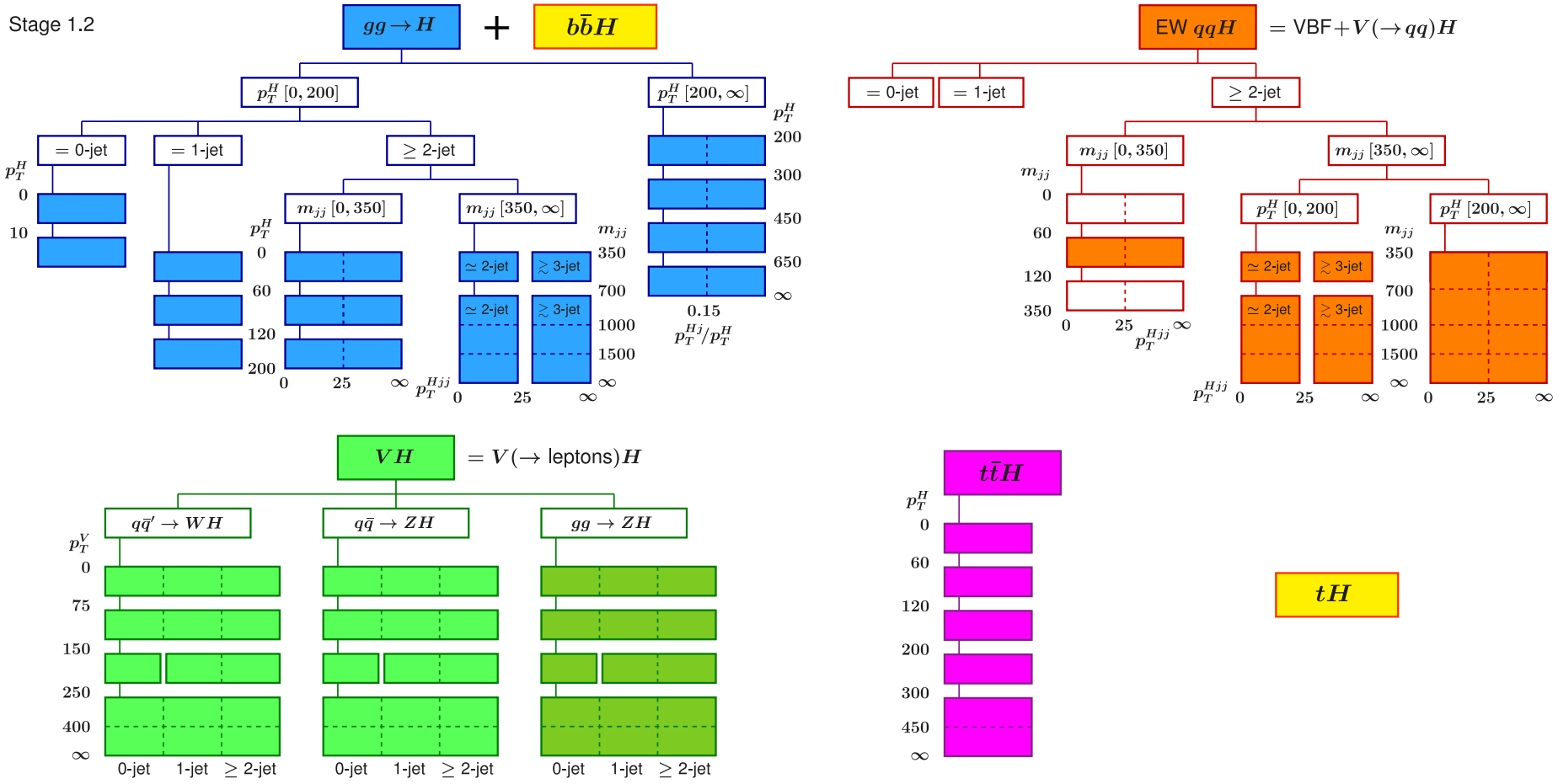
STXS stage 1.0

- Measure cross sections in increasingly granular "bins"
  - split by production mode + kinematics ($|y_H| < 2.5$)

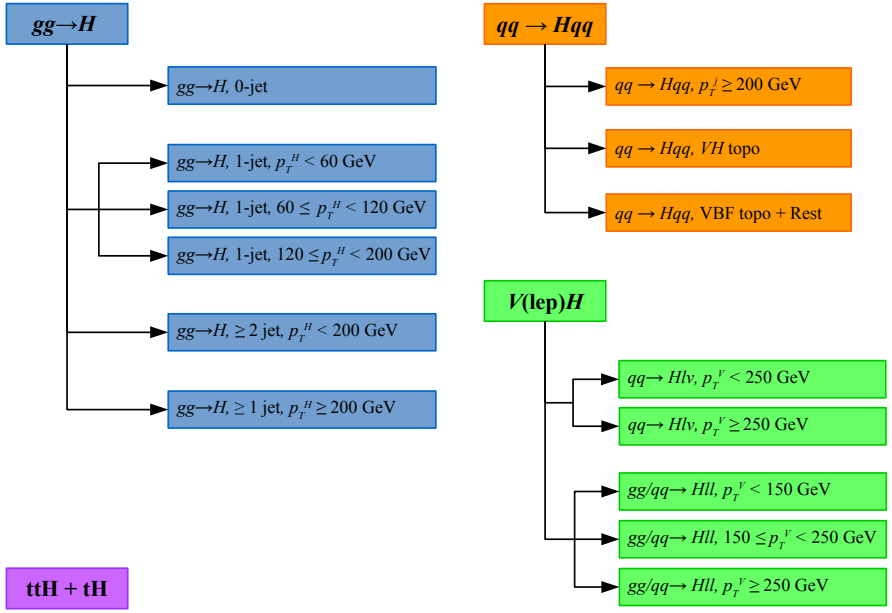


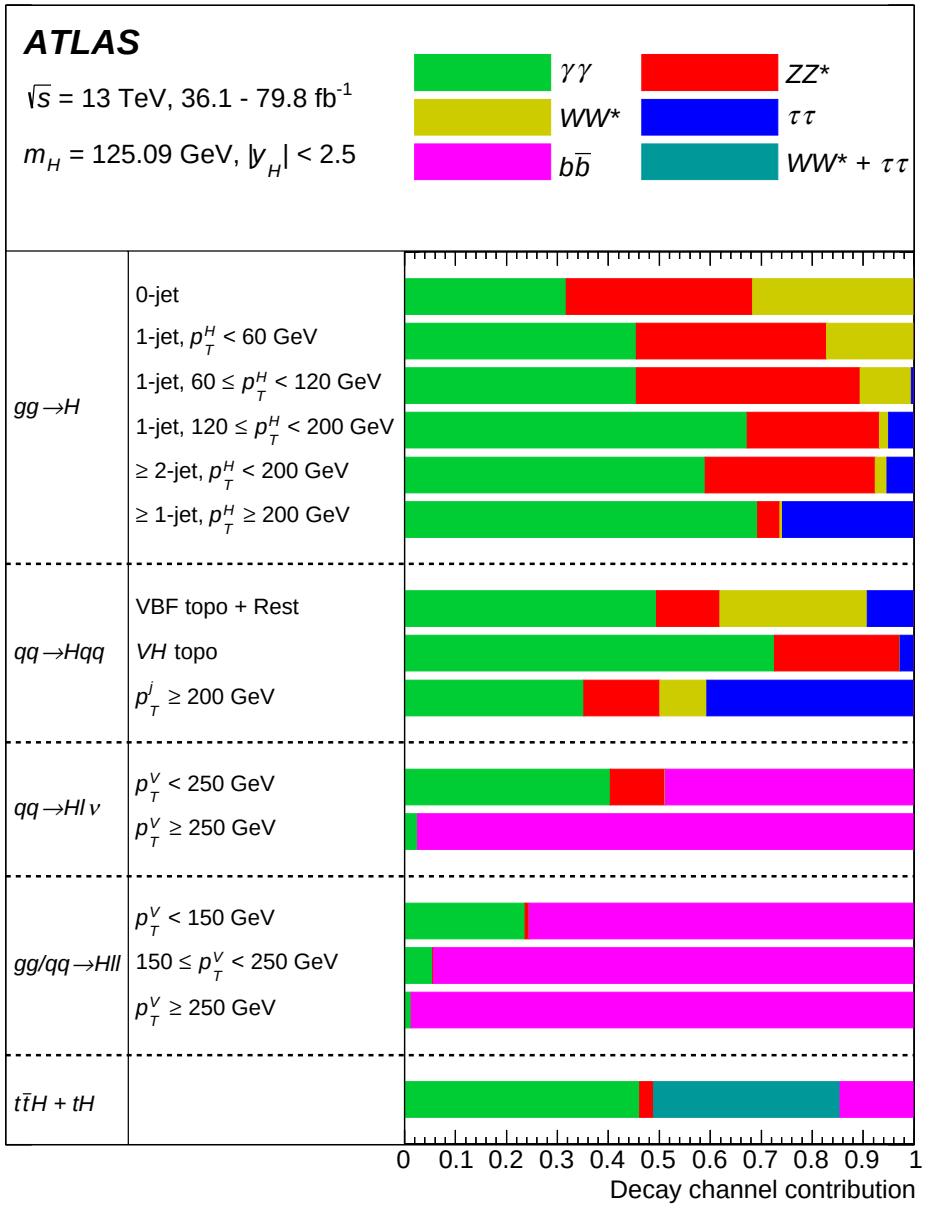
STXS stage 1.2

- Evolves in stages: increased granularity to match increase in statistics
- Updates w.r.t stage 1.1: split ttH and ggH $p_T^H > 200$ GeV...



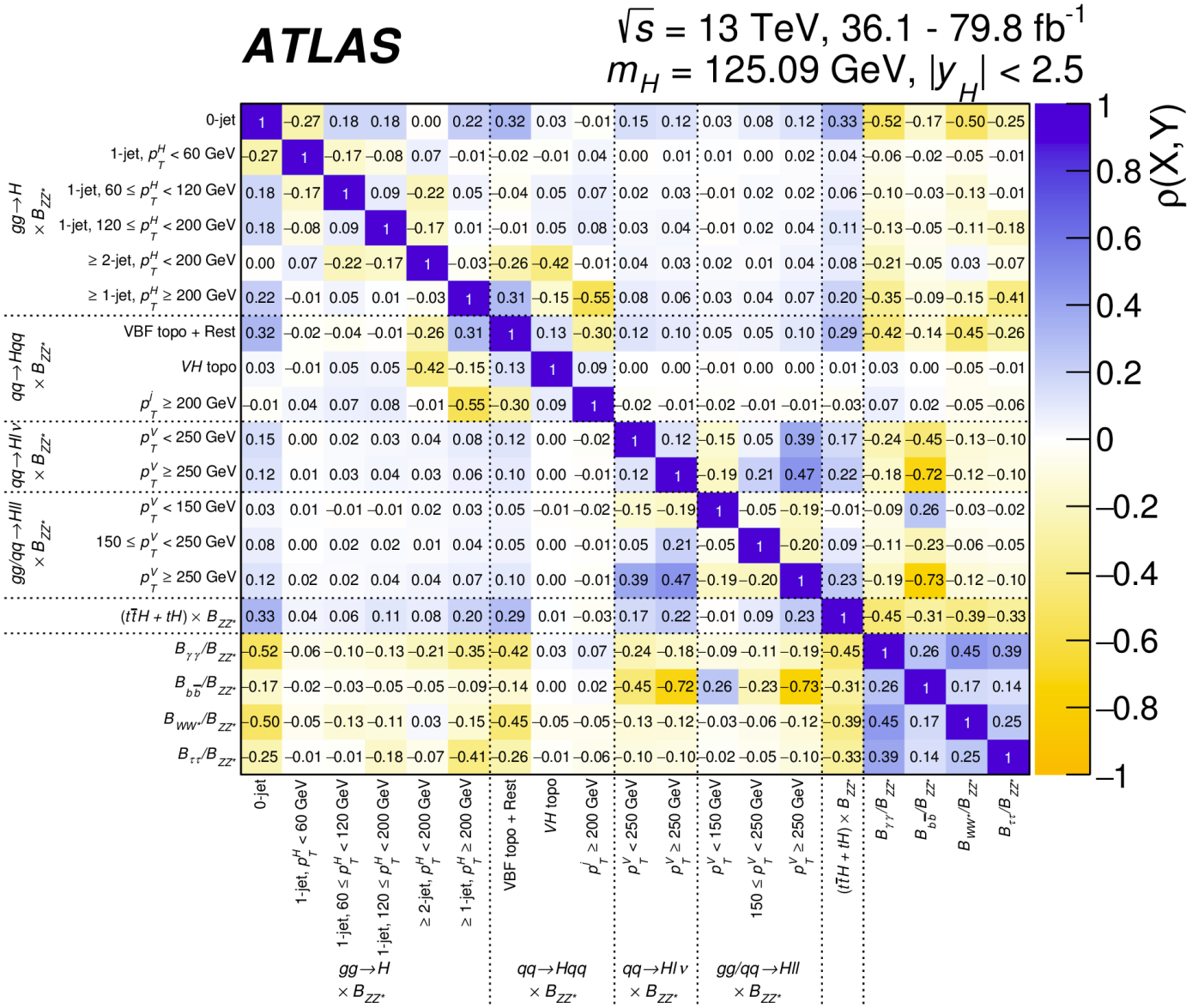
STXS: ATLAS merging scheme + sensitivity breakdown





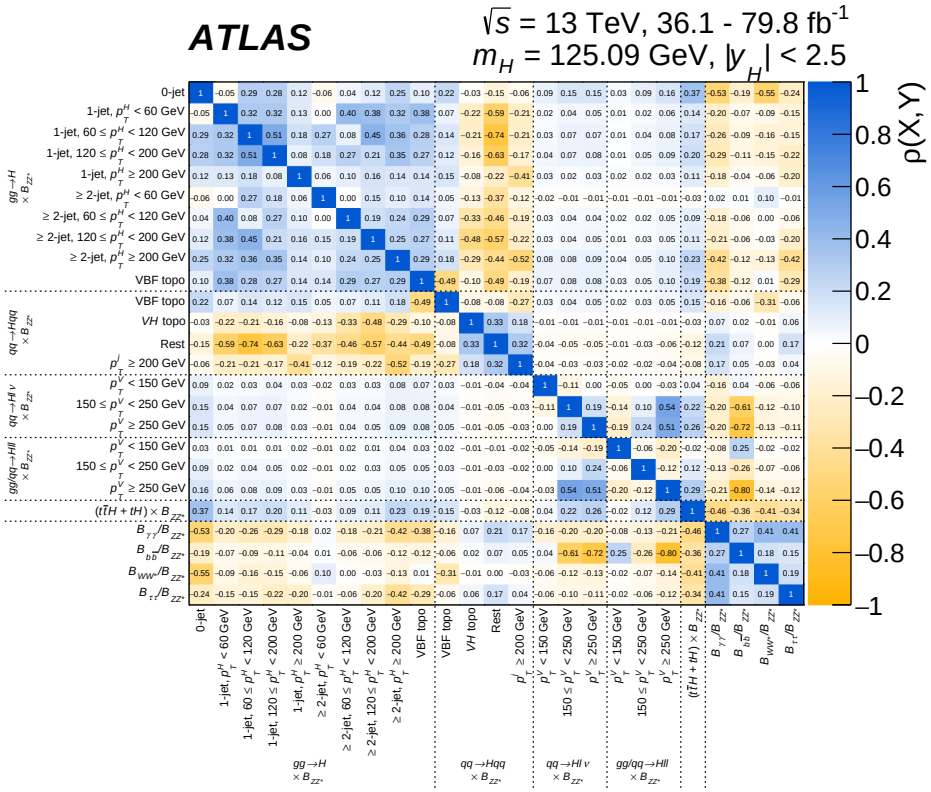
STXS: correlations

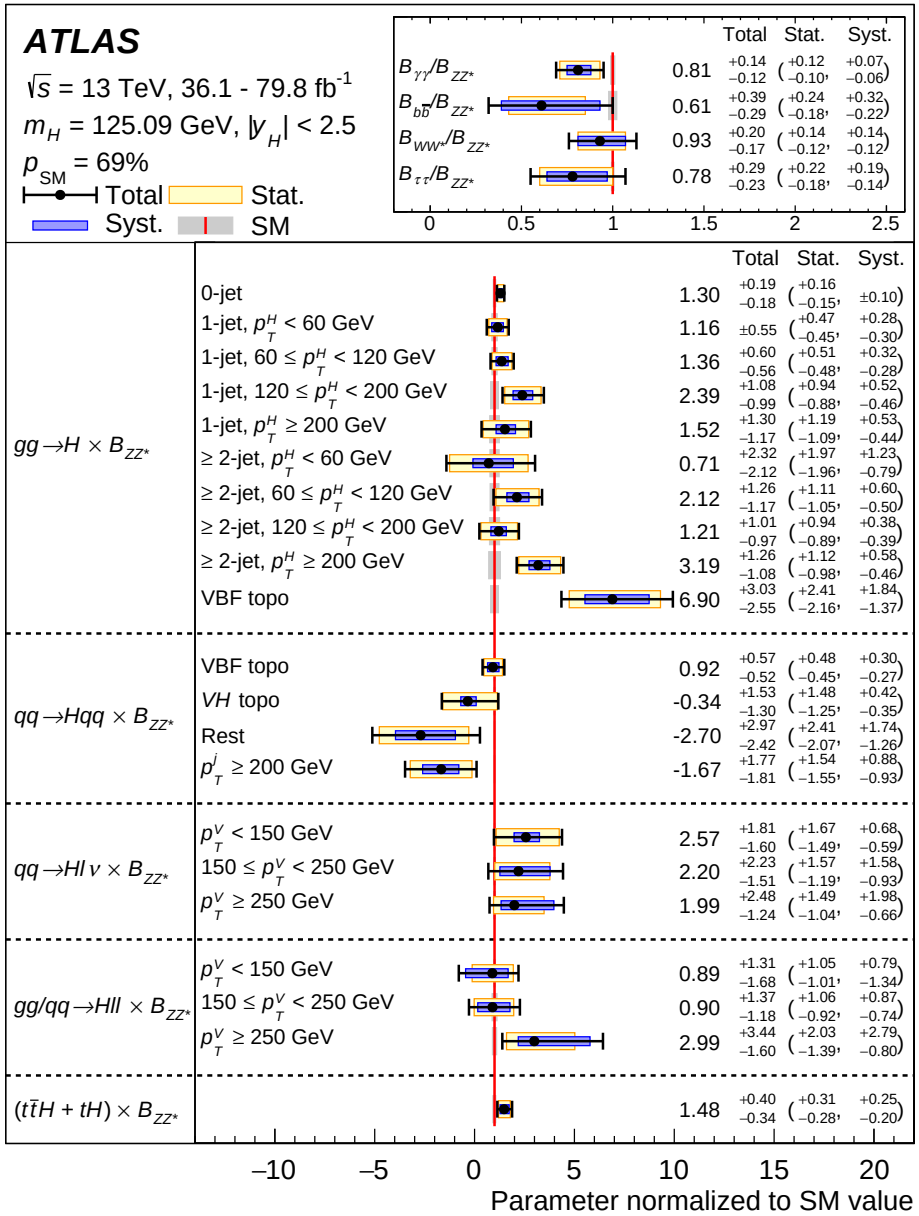
- Correlation matrix between fitted parameters: **crucial for re-interpretation**



STXS: finer granularity

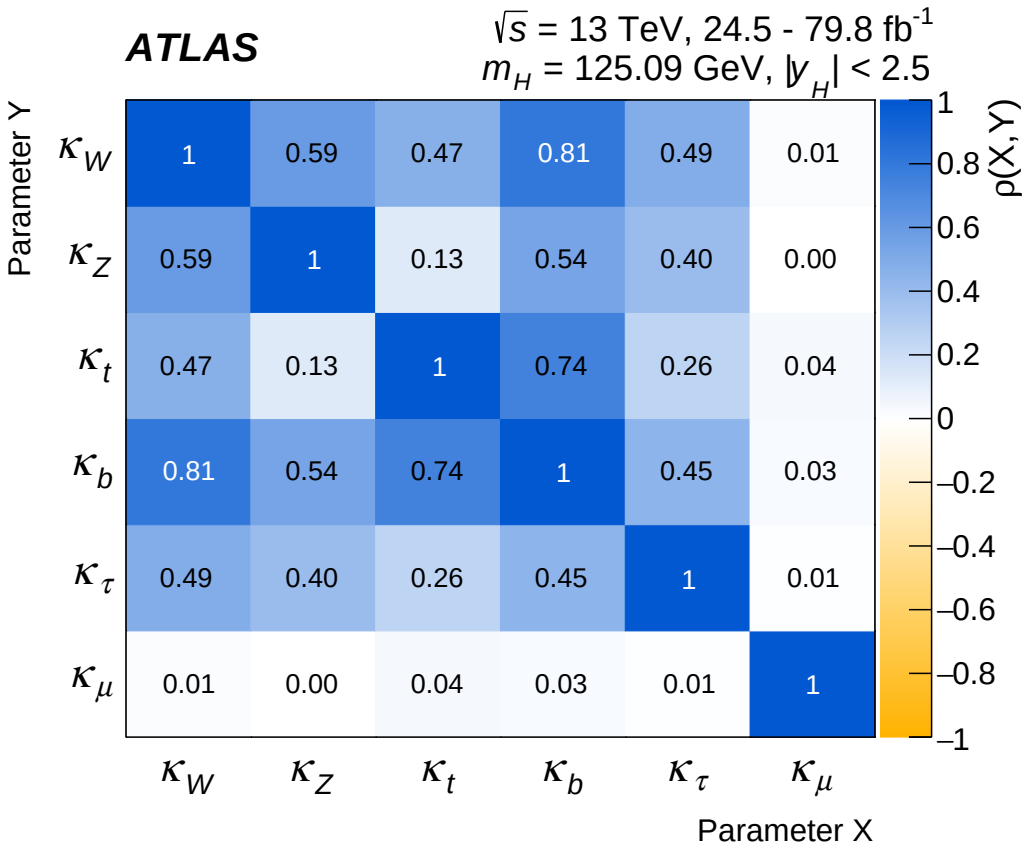
- ATLAS EXPERIMENT finer granularity fit
- Closer to nominal STXS stage 1.0 definition
- Reduced model dependence!





κ framework

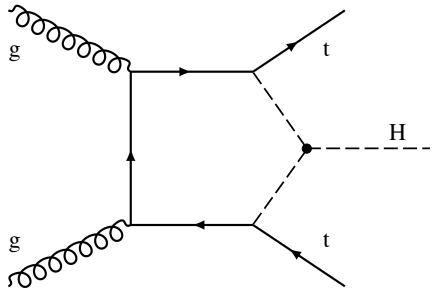
- Correlations matrices indicate how parameters influence eachother
- Positive correlations due to total width: Γ_H

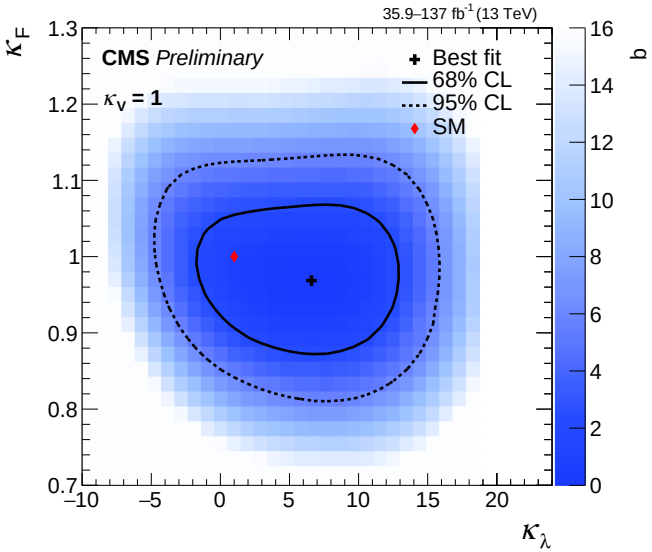


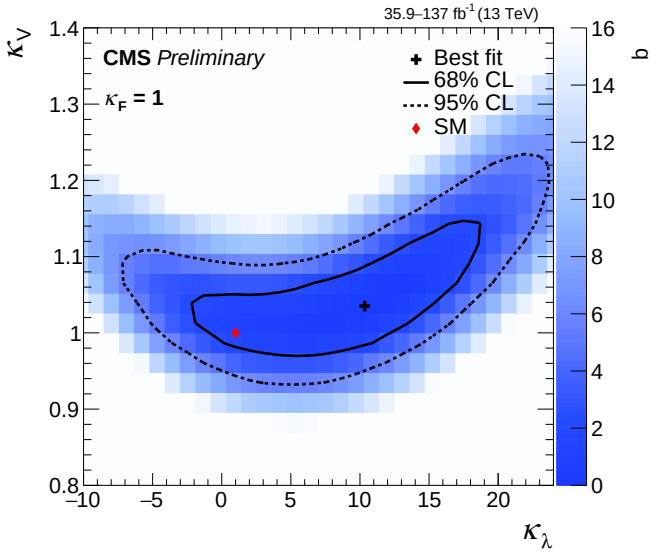
Higgs boson self coupling

- Indirect probe of H self coupling (λ_3) using single H measurements
  - via NLO EWK corrections to σ & BR

- Anomolous coupling parametrization: $\kappa_\lambda = \lambda_3/\lambda_3^{\mathrm{SM}}$
  - described in [JHEP 1612, 080 (2016)] and [Eur. Phys. J. C (2017) 77: 887]
  - Three parameter model: κ_V, κ_F, κ_λ





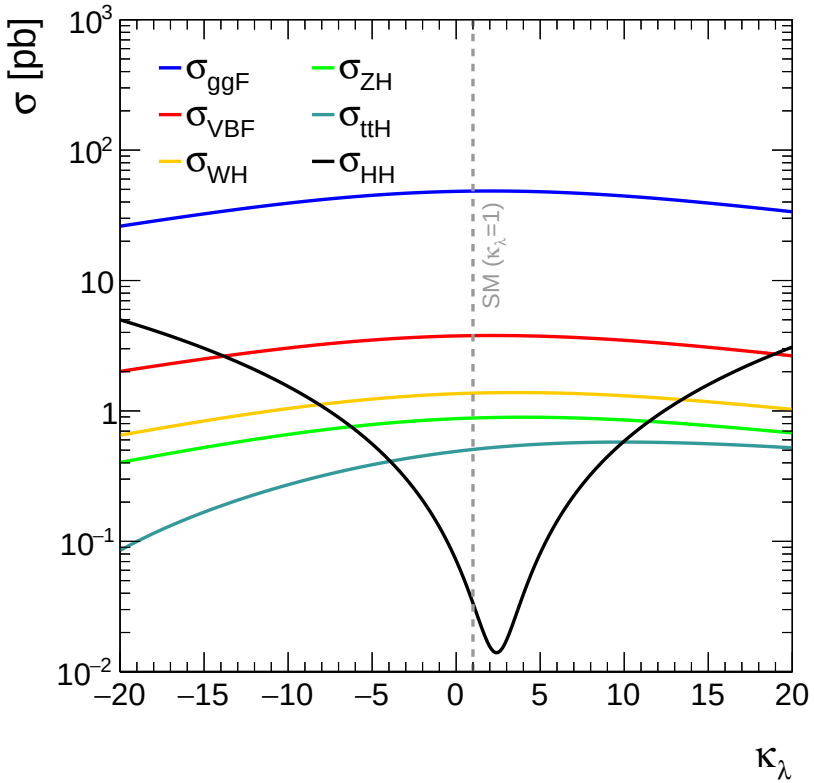


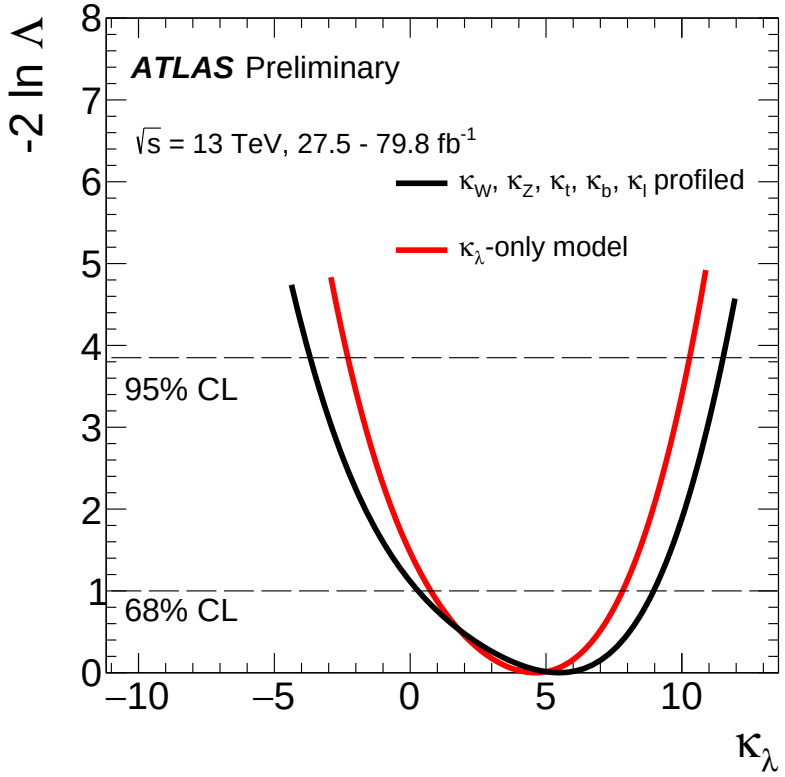
Assumption	Best fit κ_λ	95% CL interval
$\kappa_F = \kappa_V = 1$	$6.7^{+4.6}_{-6.6}$ $\left(^{+8.3}_{-3.8}\right)$	$[-3.5, 14.5]$ $\left([-5.1, 13.7]\right)$
$\kappa_F = 1$	$10.3^{+6.1}_{-10.0}$ $\left(^{+8.8}_{-5.0}\right)$	$[-5.5, 21.7]$ $\left([-7.4, 17.2]\right)$
$\kappa_V = 1$	$6.6^{+4.5}_{-6.1}$ $\left(^{+8.2}_{-4.0}\right)$	$[-3.3, 14.4]$ $\left([-5.5, 13.8]\right)$

- Lose sensitivity to κ_λ if float both κ_V and κ_F in fit
- Kinematic effects are neglected
  - only inclusive shifts in production mode and decay channel rates

H + HH combination

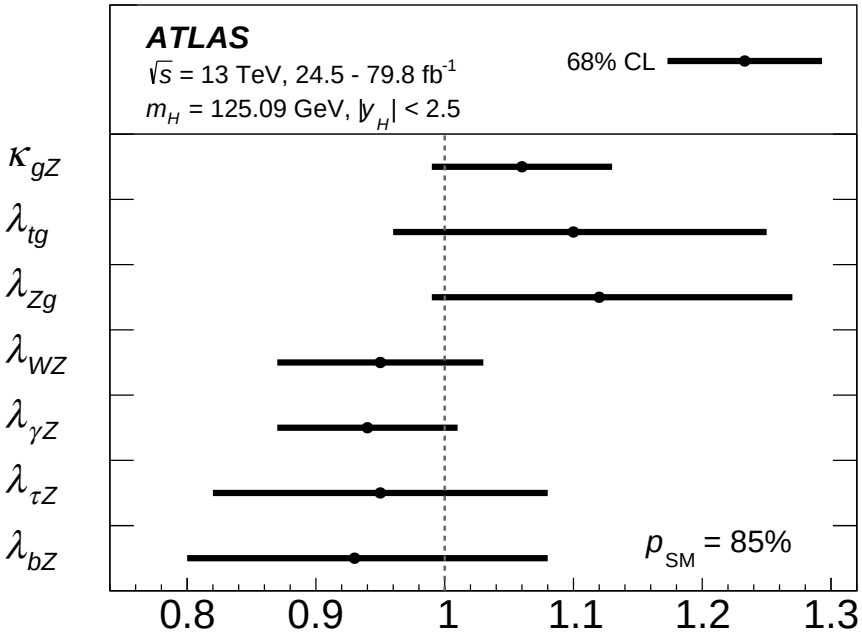
- True scope realised in combining with HH measurements
- ATLAS EXPERIMENT H (79.8 fb^{-1}) + HH combination (36.1 fb^{-1}): ATLAS-CONF-2019-049
  - H inputs: $\gamma\gamma$, ZZ*, WW, $\tau\tau$ and bb
  - HH inputs: bbbb, bb$\tau\tau$, bb$\gamma\gamma$
  - extra caution to remove overlap between input analyses
- Remain sensitive to κ_λ including other coupling modifiers to SM particles





Ratios of coupling modifiers

- Most model-independent coupling strength measurement in κ framework
  - independent of assumptions on total width, Γ_H
- Of particular interest...
  - λ_{WZ}: identical coupling strength for W/Z required by tight bounds on SU(2) custodial symmetry + ρ parameter measured @ LEP & Tevatron
  - $\lambda_{\gamma Z}$: sensitive to NP in H$\rightarrow \gamma\gamma$ loop, unlike H$\rightarrow ZZ^*$
  - λ_{tg}: new coloured particle in ggH loop, unlike ttH

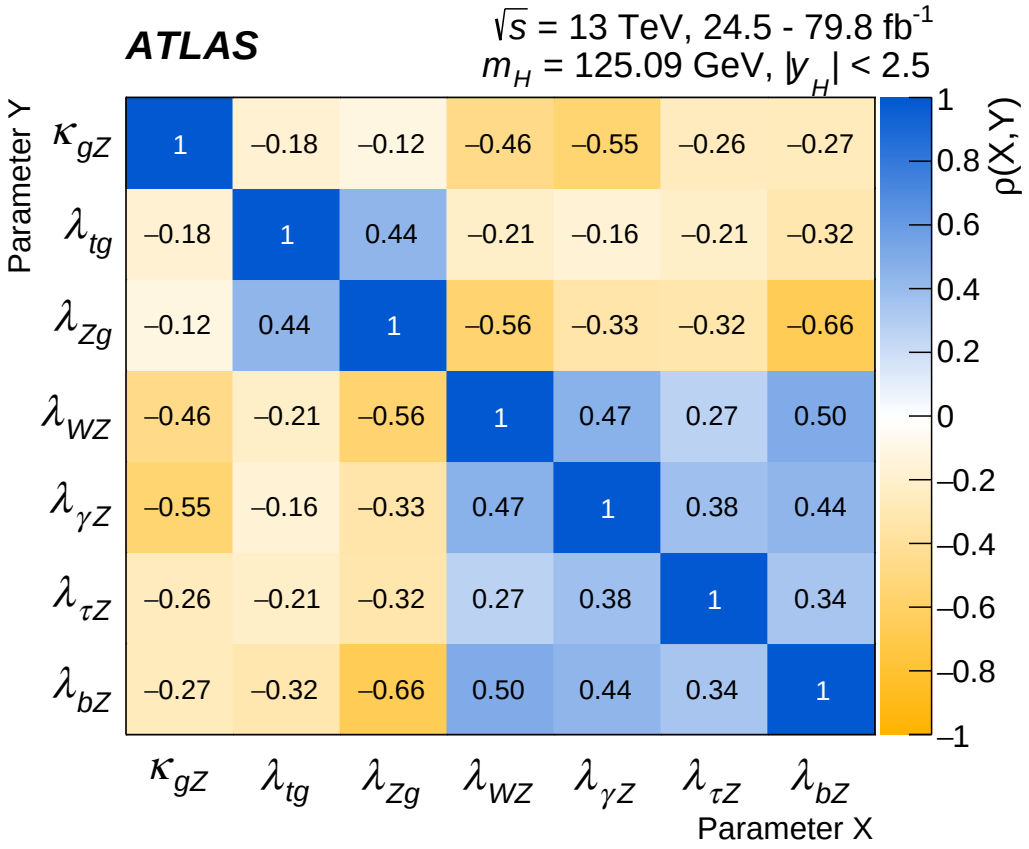


Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g\kappa_Z/\kappa_H$	1.06 ± 0.07
λ_{tg}	κ_t/κ_g	$1.10\ ^{+0.15}_{-0.14}$
λ_{Zg}	κ_Z/κ_g	$1.12\ ^{+0.15}_{-0.13}$
λ_{WZ}	κ_W/κ_Z	0.95 ± 0.08
$\lambda_{\gamma Z}$	κ_γ/κ_Z	0.94 ± 0.07
$\lambda_{\tau Z}$	κ_τ/κ_Z	0.95 ± 0.13
λ_{bZ}	κ_b/κ_Z	$0.93\ ^{+0.15}_{-0.13}$

- All in agreement with SM!

Ratios of coupling modifiers: correlations

- Correlations matrices indicate how parameters influence eachother
- Independent of total width: observe negative correlations



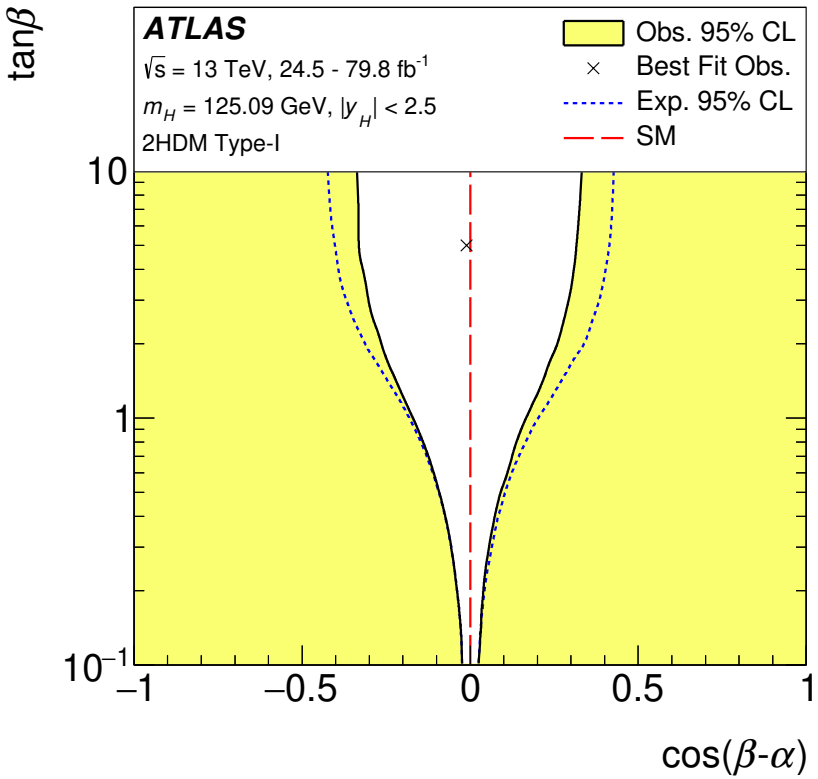
2HDM/hMSSM interpretations

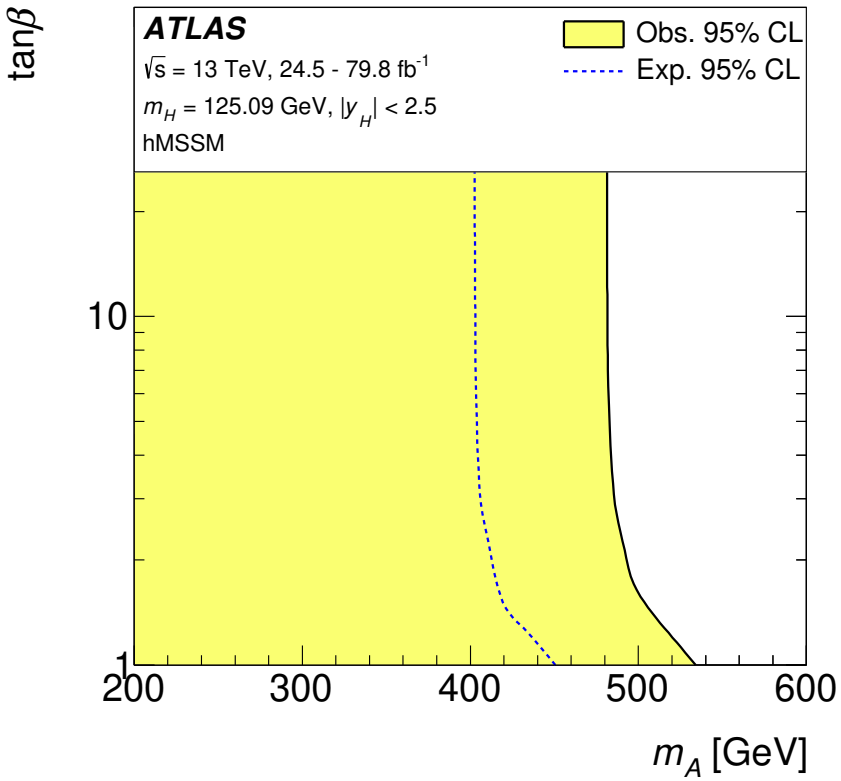
- Cast coupling modifiers into parameters of benchmark SUSY models

	2HDM				hMSSM
	Type I	Type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$

$$s_u = \frac{1}{\sqrt{1+\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{(m_Z^2+m_A^2\tan^2\beta-m_h^2(1+\tan^2\beta))^2}}}$$

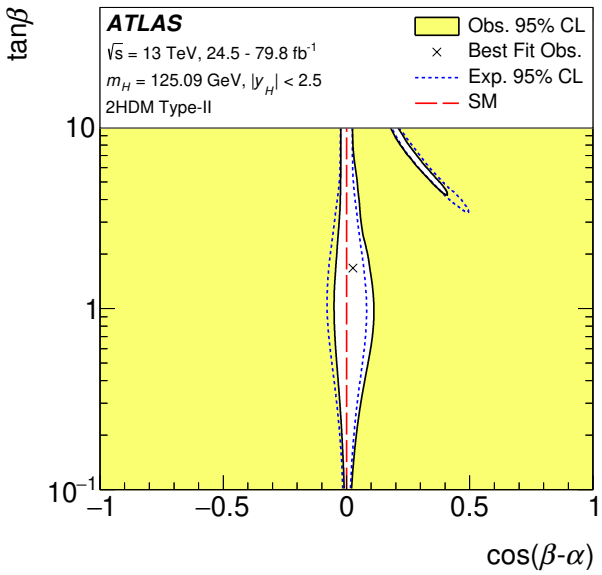
$$s_d = \frac{(m_A^2+m_Z^2)\tan\beta}{m_Z^2+m_A^2\tan^2\beta-m_h^2(1+\tan^2\beta)}\,s_u$$

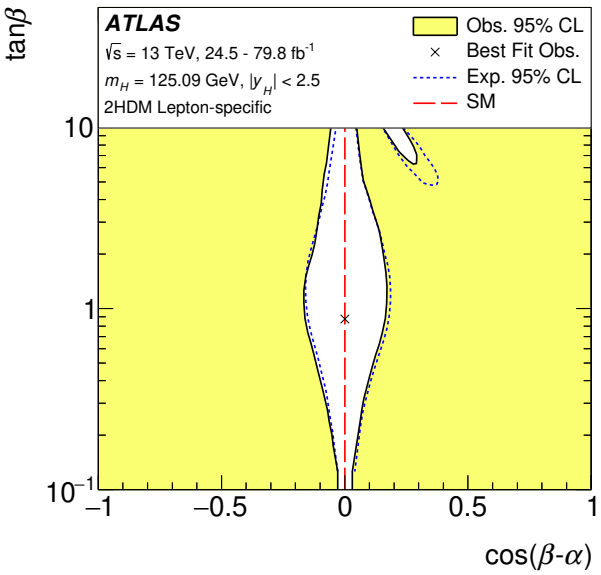


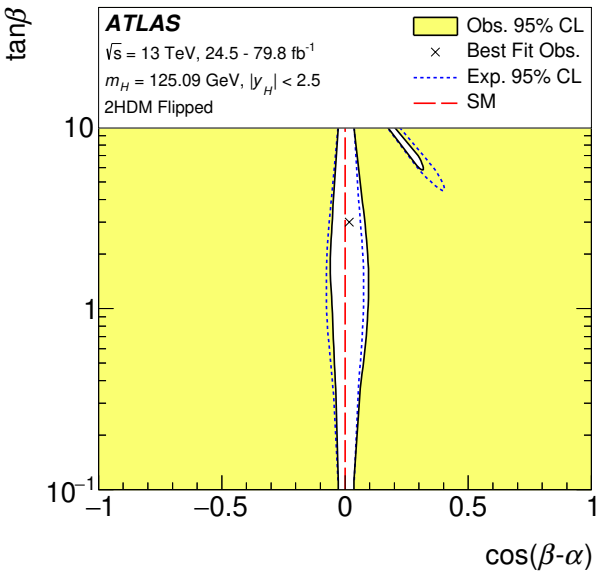


Additional 2HDM interpretations

- Type I: One Higgs doublet couples to vector bosons, while the other one couples to fermions. The first doublet is *fermiophobic* in the limit where the two Higgs doublets do not mix.
- Type II: One Higgs doublet couples to up-type quarks and the other one to down-type quarks and charged leptons.
- Lepton-specific: The Higgs bosons have the same couplings to quarks as in the Type I model and to charged leptons as in Type II.
- Flipped: The Higgs bosons have the same couplings to quarks as in the Type II model and to charged leptons as in Type I.







Effective field theory couplings: STXS re-interpretation

- EFT: in light of no new physics @ TeV scale, assume exists at $\Lambda >> q^2$
  - couplings in Lagrangian modified by higher dimensional operators

- Parametrize STXS bin in terms of EFT params: Higgs Effective Lagrangian (HEL)

$$\mathcal{L}_{\mathrm{HEL}} = \mathcal{L}_{\mathrm{SM}} + \sum_j \mathcal{O}_j^{(6)} f_j/\Lambda^2$$

  - introduces 39 flavor independent dim-6 operators
  - new physics: deviations from 0 in f_j
  - CMS consider eight of these

- **Scaling functions**: $\mu_i(c_j) = \sigma_i^{\mathrm{EFT}}/\sigma_i^{\mathrm{SM}}$
  - for each STXS bin, i, where $c_j \propto f_j$

$$\sigma_i^{\mathrm{EFT}} = \sigma_i^{\mathrm{SM}} + \sigma_i^{\mathrm{int}} + \sigma_i^{\mathrm{BSM}}$$

$$\Rightarrow \mu_i(c_j) = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- Derive A_j and B_{jk} coefficients for each STXS bin

$\mathcal{O}_g = |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

$\tilde{\mathcal{O}}_g = |H|^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$

$\mathcal{O}_\gamma = |H|^2 B_{\mu\nu} B^{\mu\nu}$

$\tilde{\mathcal{O}}_\gamma = |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$

$\mathcal{O}_u = y_u |H|^2 \bar{Q}_L H^\dagger u_R + \mathrm{h.c.}$

$\mathcal{O}_d = y_d |H|^2 \bar{Q}_L H d_R + \mathrm{h.c.}$

$\mathcal{O}_\ell = y_\ell |H|^2 \bar{L}_L H \ell_R + \mathrm{h.c.}$

$\mathcal{O}_H = \left(\partial^\mu |H|^2\right)^2$

$\mathcal{O}_6 = \left(H^\dagger H\right)^3$

$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger\, \sigma^a (D^\nu H) W^a_{\mu\nu}$

$\tilde{\mathcal{O}}_{HW} = i\,(D^\mu H)^\dagger\, \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$

$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger\, (D^\nu H) B_{\mu\nu}$

$\tilde{\mathcal{O}}_{HB} = i\,(D^\mu H)^\dagger\, (D^\nu H) \tilde{B}_{\mu\nu}$

$\mathcal{O}_W = i\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$

$\mathcal{O}_B = i\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$

EFT parametrization: derivation

$$\mu_i(c_j) = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- Using EFT2Obs tool: not specific to Higgs

1. Generate events per Higgs prod. mode (LO): MADGRAPH w/ PYTHIA showering
2. Import HEL (UFO): reweight events for different points in HEL param space
   ⇒ SM: all $c_j = 0$
   ⇒ vary c_j individually: (c_j = w,0,...,0), (0,w,0,...,0), ...
   ⇒ pairwise to calc. B_{jk} cross terms ($j \neq k$): (w,w,0,...0), (w,0,w,0,...,0), ...
3. Propagate events through RIVET tool: STXS classification (0, 1 and 1.1)
4. Extract dependence of STXS bin, i, on c_j (or $c_j c_k$): A_j & B_{jk}
   ⇒ comparing reweighted cross section to SM

WH Leptonic

$$\boxed{p_T^V\,[0, 150]} = 1 + 33\, c_{WW} + 12\, c_{HW} + 320\, c_{WW}^2 + ...$$

- Complete HEL parametrization of STXS stage 0, 1 and 1.1 bins provided

EFT interpretation: correlations

- Correlations matrices indicate how parameters influence eachother