Higgs boson *coupling measurements*

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on behalf of the ATLAS collaboration

Higgs Hunting
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Introduction

- LHC's third run recently started, most analyses with Run 2 data closing
- Full Run-2 dataset contains about 30 times more Higgs Bosons than its Run-1 counterpart
  - Precise measurement of Higgs production cross-sections and decay rates
    - Observation of all main LHC production processes: ggF, VBF, WH, ZH, $t\bar{t}H + tH$
    - Increased precision on $H \to \gamma\gamma$, ZZ, $W^{\pm}W^{\mp}$, $\tau^{+}\tau^{-}$, observation of $H \to b\bar{b}$, $\geq 2\sigma$ on $H \to \mu\mu$, $> 3\sigma$ on $H \to Z\gamma$
  - Interpretation of results in terms of couplings to SM particles (κ framework) including self-coupling
  - Study of kinematic properties of Higgs production processes (STXS framework) — differential cross-sections not included today
- In most cases results improved by much more than expected from increase in luminosity between Run 1 and Run 2!
  - Improvements in all areas: objects, analysis design, machine learning, theory predictions, …
- Most results can be found in Nature 607, 52-59 (2022), unless specified
  - Note: auxiliary plots and more details (NLL scans, correlation matrices, exact values, etc.) made available on HEPData

Input analyses/method

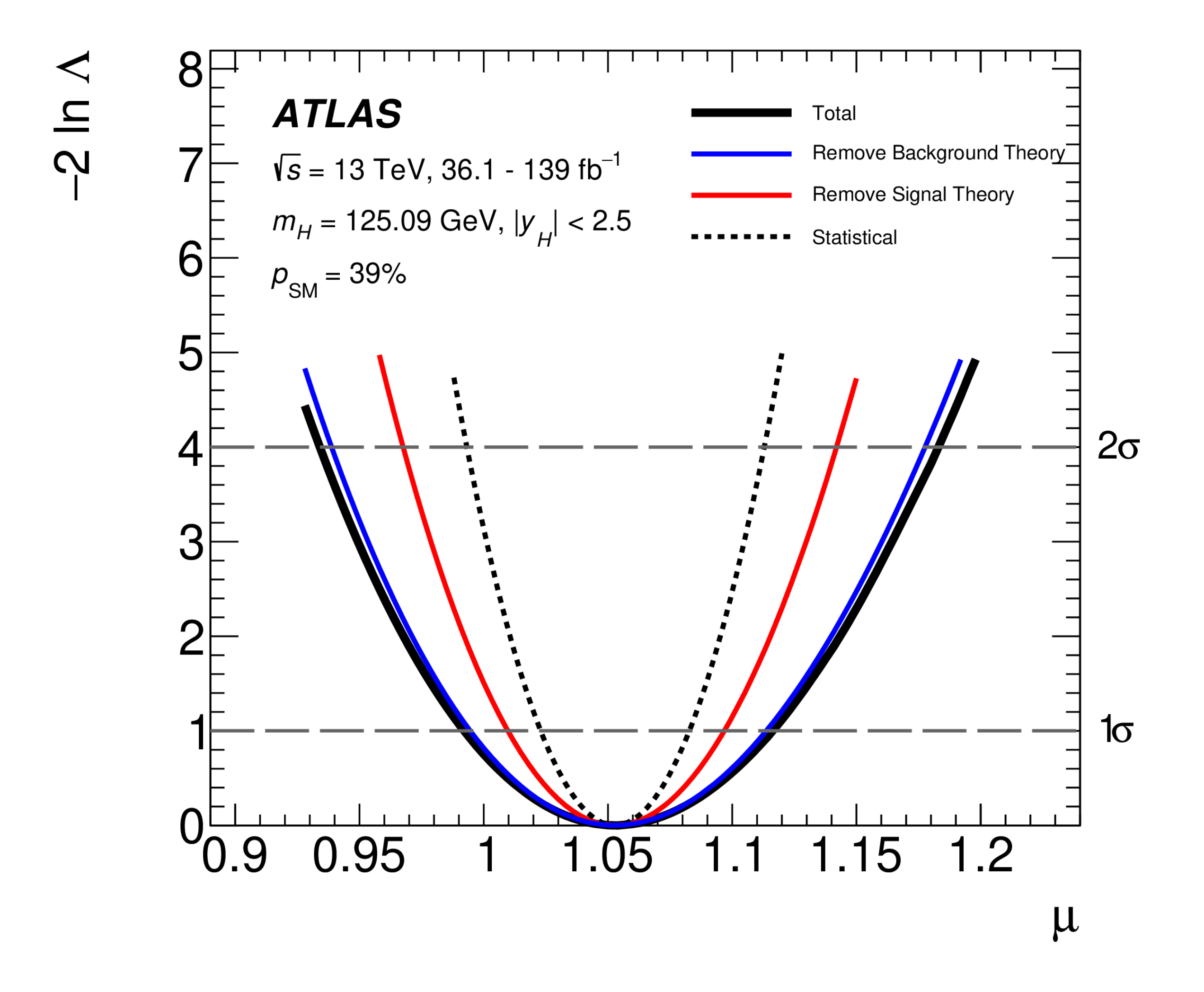
- Almost all measurements updated with full Run-2 dataset
- A few measurements excluded from some results due to their limited sensitivity
  - $H \to b\bar{b}$ boosted only in STXS
  - $V(H \to W^{\pm}W^{\mp}), t\bar{t}(H \to \text{multilepton}),$ $H \to \mu\mu, Z\gamma$ in all but STXS
  - $H \to \text{inv}$ only in κ with $B_{\text{inv.}}, B_{\text{u.}}$
  - $H \to c\bar{c}$ only in κ_c measurement

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to WW$	ggF, VBF	139
	WH, ZH	36.1
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to Z\gamma$	inclusive	139
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H + tH$	139
	inclusive	139
$H \to \tau\tau$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$	139
$H \to c\bar{c}$	$WH + ZH$	139
$H \to$ invisible	VBF	139
	ZH	139

- Combination of results at likelihood level
  - Systematic uncertainties correlated where possible
  - Overlap between analysis regions is either negligible or has been shown to have a very limited impact on the results

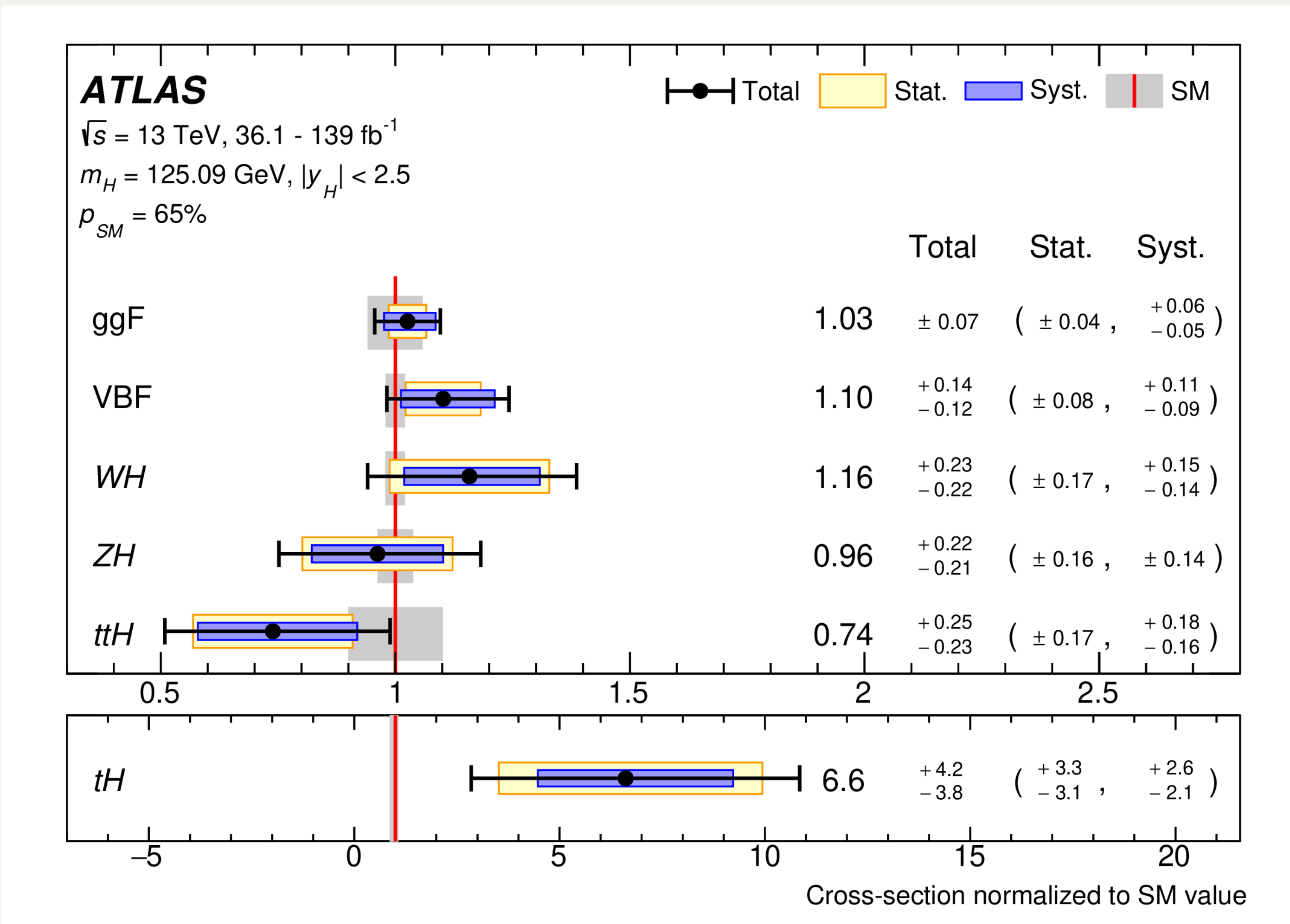
Higgs signal strength

- **Considering all production and decay modes together:**
  - $\mu = \frac{\sigma_{H,\text{ obs}}}{\sigma_{H,\text{ SM}}} = 1.05 \pm 0.06 = 1.05 \pm 0.03\ (\text{stat.})\ \pm 0.03\ (\text{exp.})\ \pm 0.04\ (\text{sig . th.})\ \pm 0.02\ (\text{bkg . th.})$
    - Experimental and theory uncertainties reduced by a factor of ≈2 wrt Run 1 result
  - Precision: 6%



Production cross sections

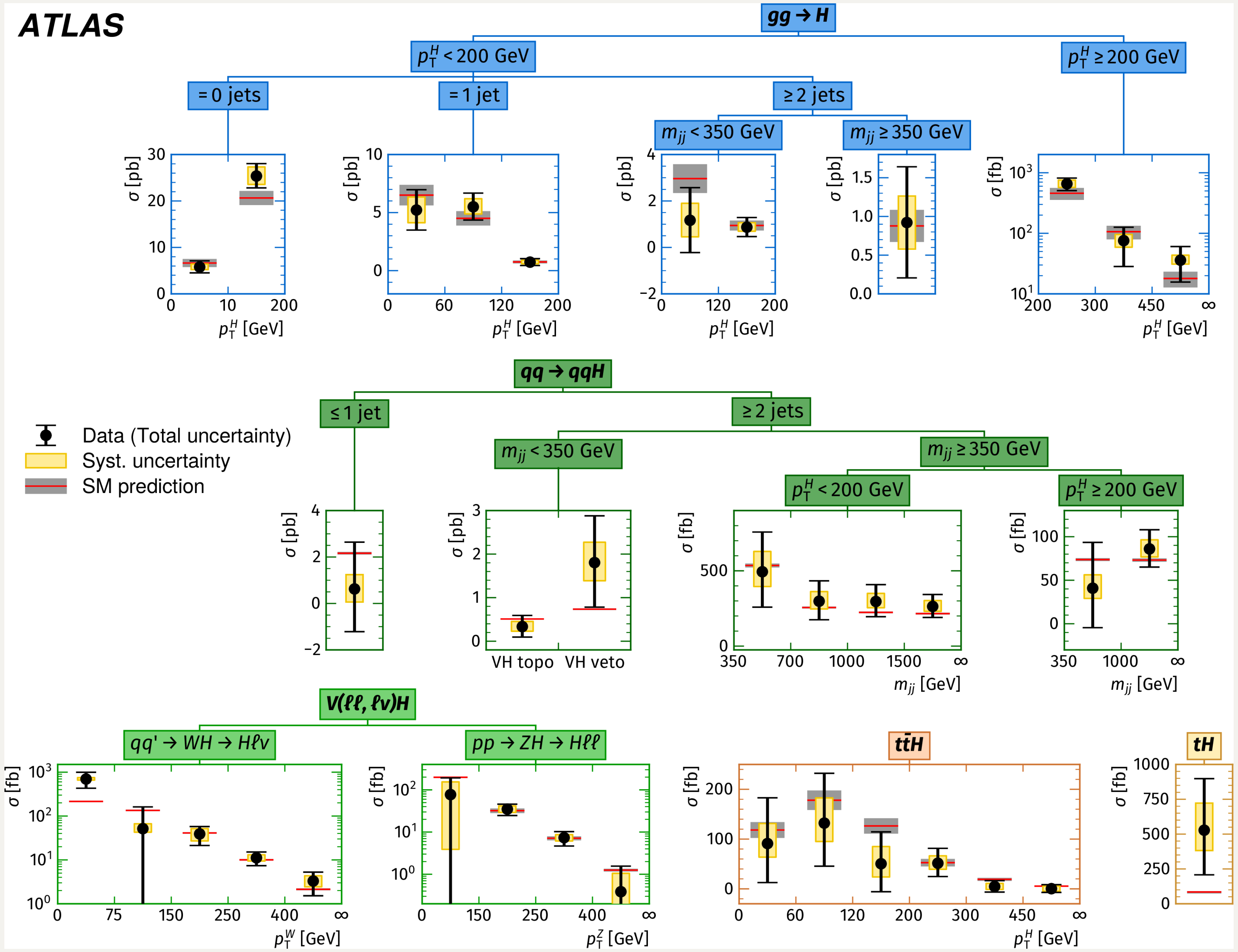
- **Production cross sections:**
  - Branching ratios are assumed to be SM-like when combining processes/measurements



- <u>Updated measurements:</u>
  - ggF now at precision of 7%
  - VBF now at precision of 12%
- <u>New milestones in Run 2:</u>
  - WH, ZH, $t\bar{t}H + tH$ now observed with 5.8σ (5.1σ), 5.0σ (5.5σ), 6.4σ (6.6σ)
- <u>Rare production mode:</u>
  - Upper limit on tH of $15(7) \times$ SM at 95% CL
    - Strong correlation with $t\bar{t}H$ measurement

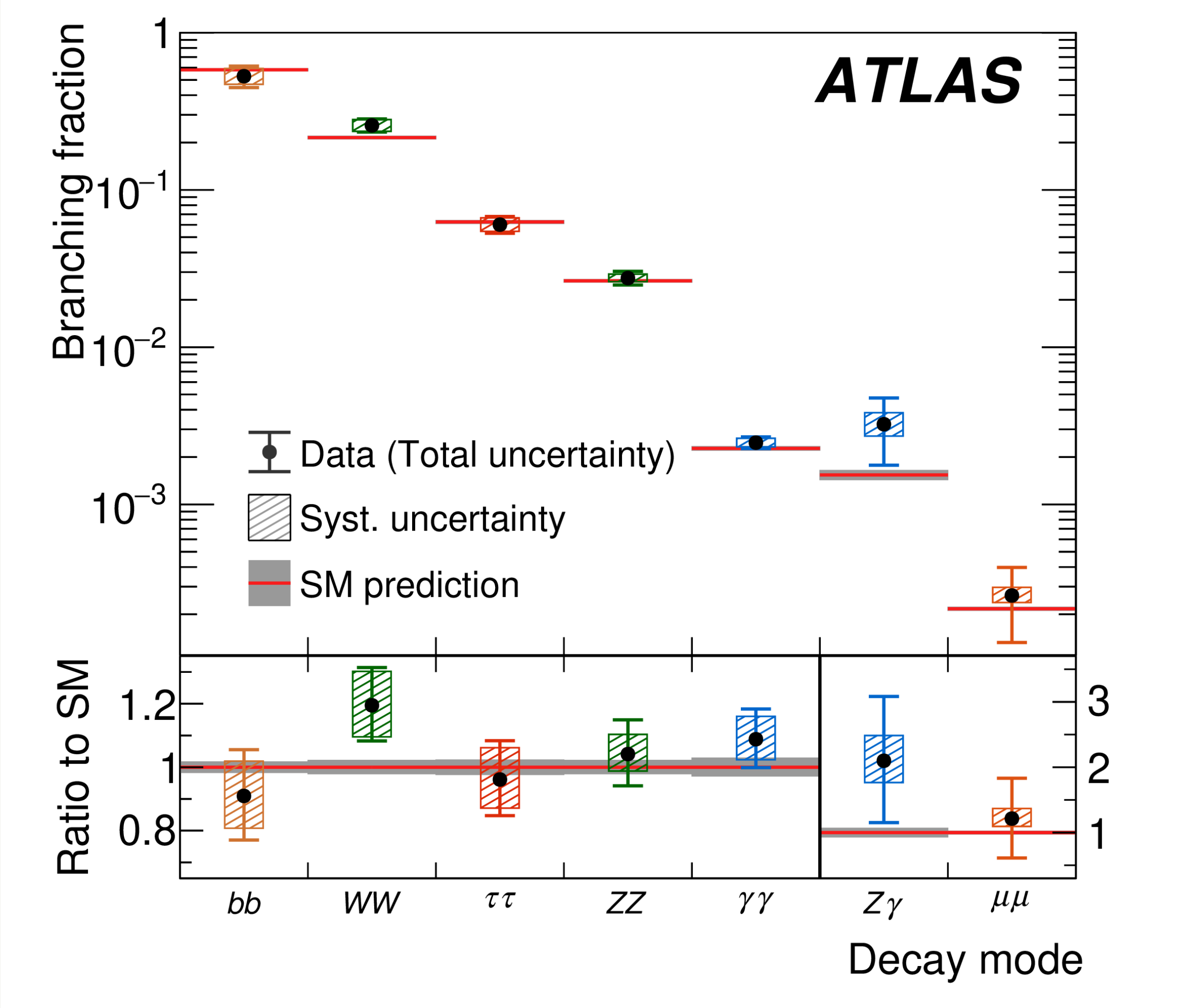
STXS framework

- Split phase space of Higgs production processes into 36 kinematic regions
  - Defined by kinematics of Higgs Boson and of associated jets, W, Z bosons where relevant
  - Branching ratios and kinematics of Higgs Boson decays are assumed to be SM-like
  - All values available on HEPData



Decay branching ratios

- **Branching ratios:**
  - Production cross sections are assumed to be SM-like when combining processes/measurements
  - Updated measurements:
    - $H \to \gamma\gamma, ZZ, W^{\pm}W^{\mp}, \tau^+\tau^-$ now all at precisions between 10% and 12%
  - New milestones in Run 2:
    - $H \to b\bar{b}$ now observed with 7.0σ (7.7σ)
  - Rare decay modes:
    - $H \to \mu\mu$, $Z\gamma$ with significances of 2.0σ (1.7σ), 2.3σ (1.1σ)

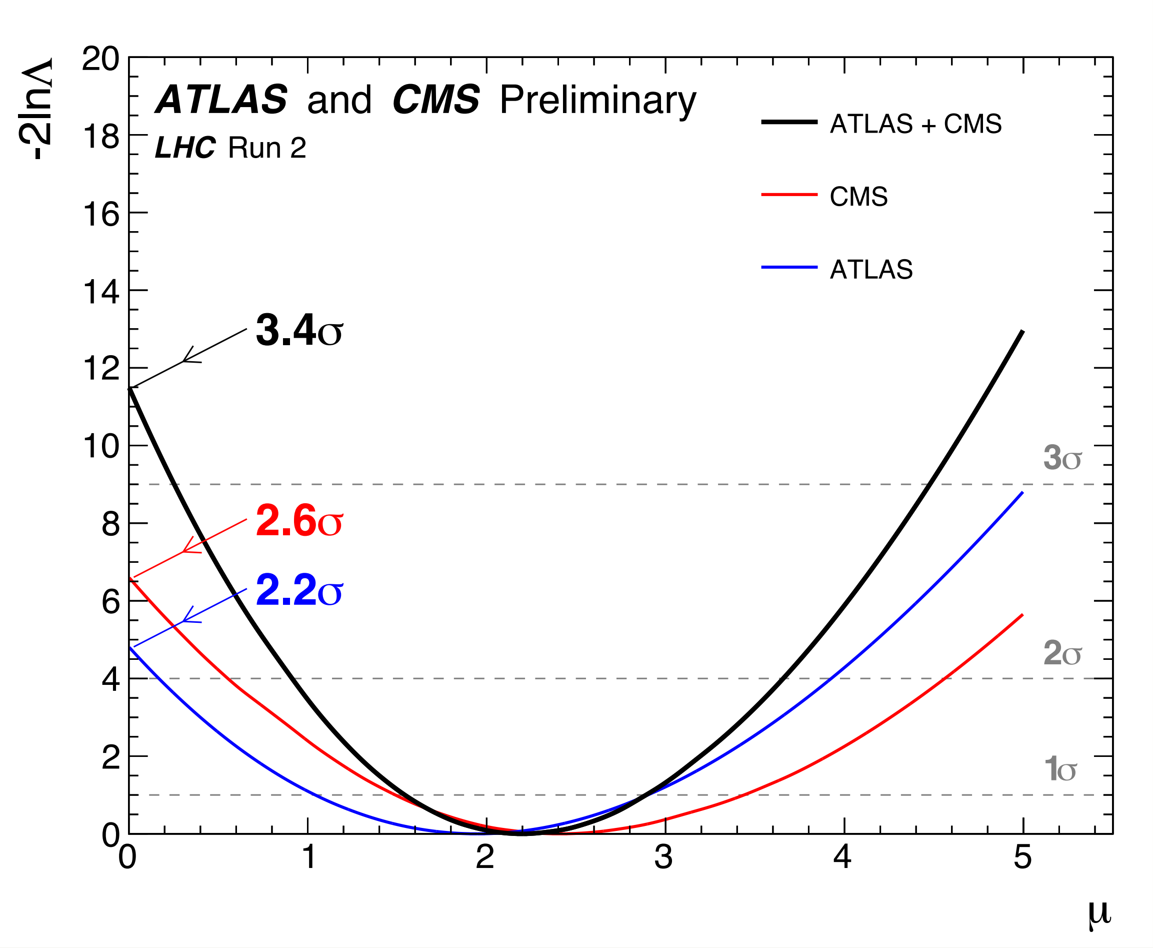


$H \to Z\gamma$

★ New!

ATLAS-CONF-2023-025; CMS-PAS-HIG-23-002

- New (preliminary) results from a combination of ATLAS and CMS
  - Signal strength $\mu_{H\to Z\gamma} = \frac{\sigma_{\text{obs}}}{\sigma_{\text{SM}}}(H \to Z\gamma) = 2.2 \pm 0.7$, or branching ratio of $(3.4 \pm 1.1) \times 10^{-3}$
    - Observed significance of 3.4σ
    - SM compatibility (p-value) 6%



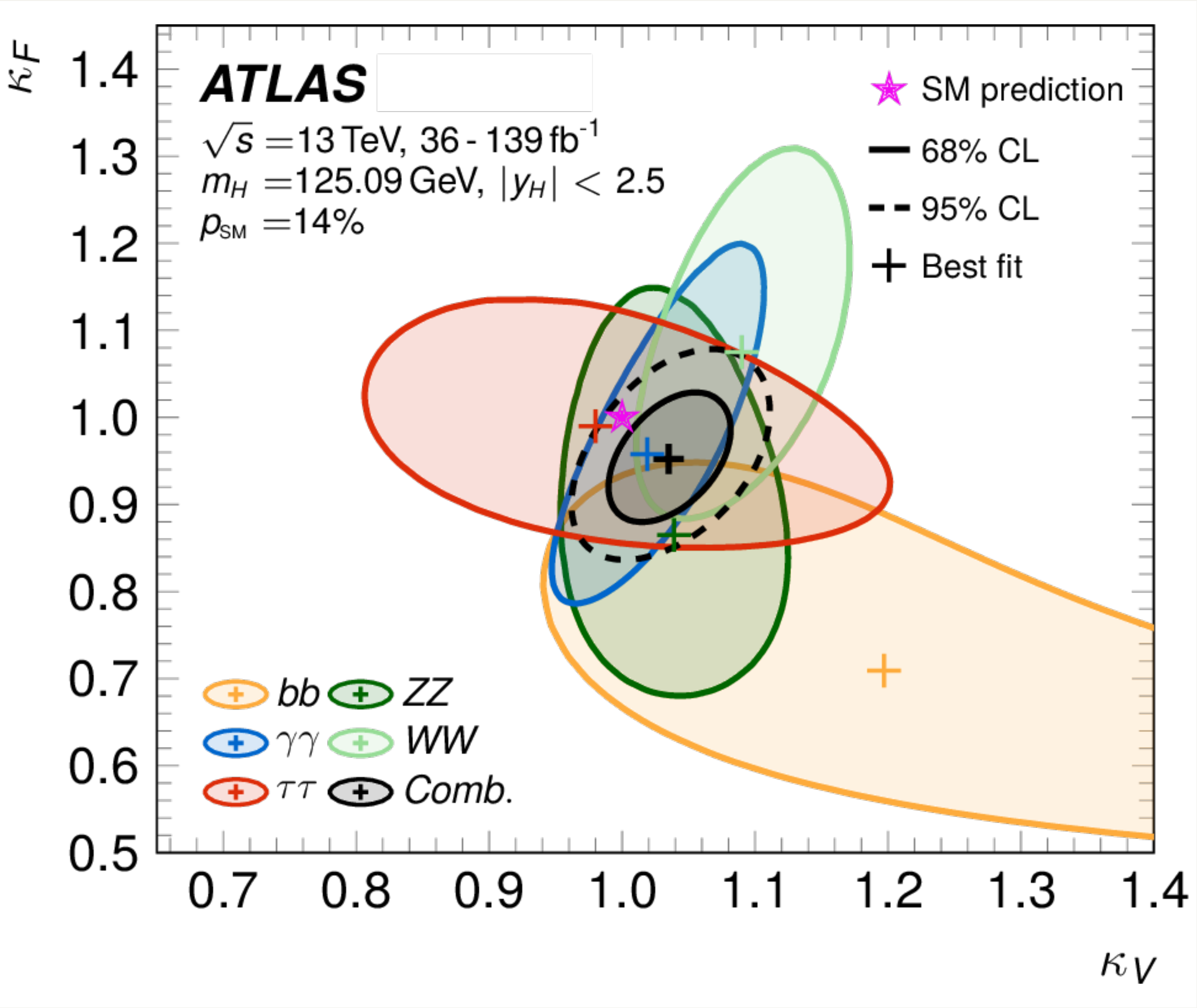
Couplings: κ framework

- Simultaneous fit of many individual measurements
  - Cross section and branching ratio measurements re-parametrised
    - κ modifiers: affect strength Higgs Boson couplings (not structure), also included in Higgs width calculation
    - Set $\kappa_s = \kappa_b$, SM values assumed for first-generation fermions
  - Different setups with varying levels of model assumptions:
    - κ_V vs κ_F
    - $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_c, \kappa_\tau, \kappa_\mu$
    - $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_c, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$ (+ with $B_{\text{inv.}}, B_{\text{u.}}$)

Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
$\sigma(\text{VBF})$	-	-	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.46\,\kappa_Z^2 + 0.46\,\kappa_t^2 - 1.90\,\kappa_Z\kappa_t$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.91\,\kappa_t^2 + 2.31\,\kappa_W^2 - 4.22\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.63\,\kappa_t^2 + 3.58\,\kappa_W^2 - 5.21\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.11\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.12\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.12\,\kappa_W^2 - 0.12\,\kappa_W\kappa_t$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{inv}} = B_{\text{undet}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.58\,\kappa_b^2 + 0.22\,\kappa_W^2$ $+0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2$ $+0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

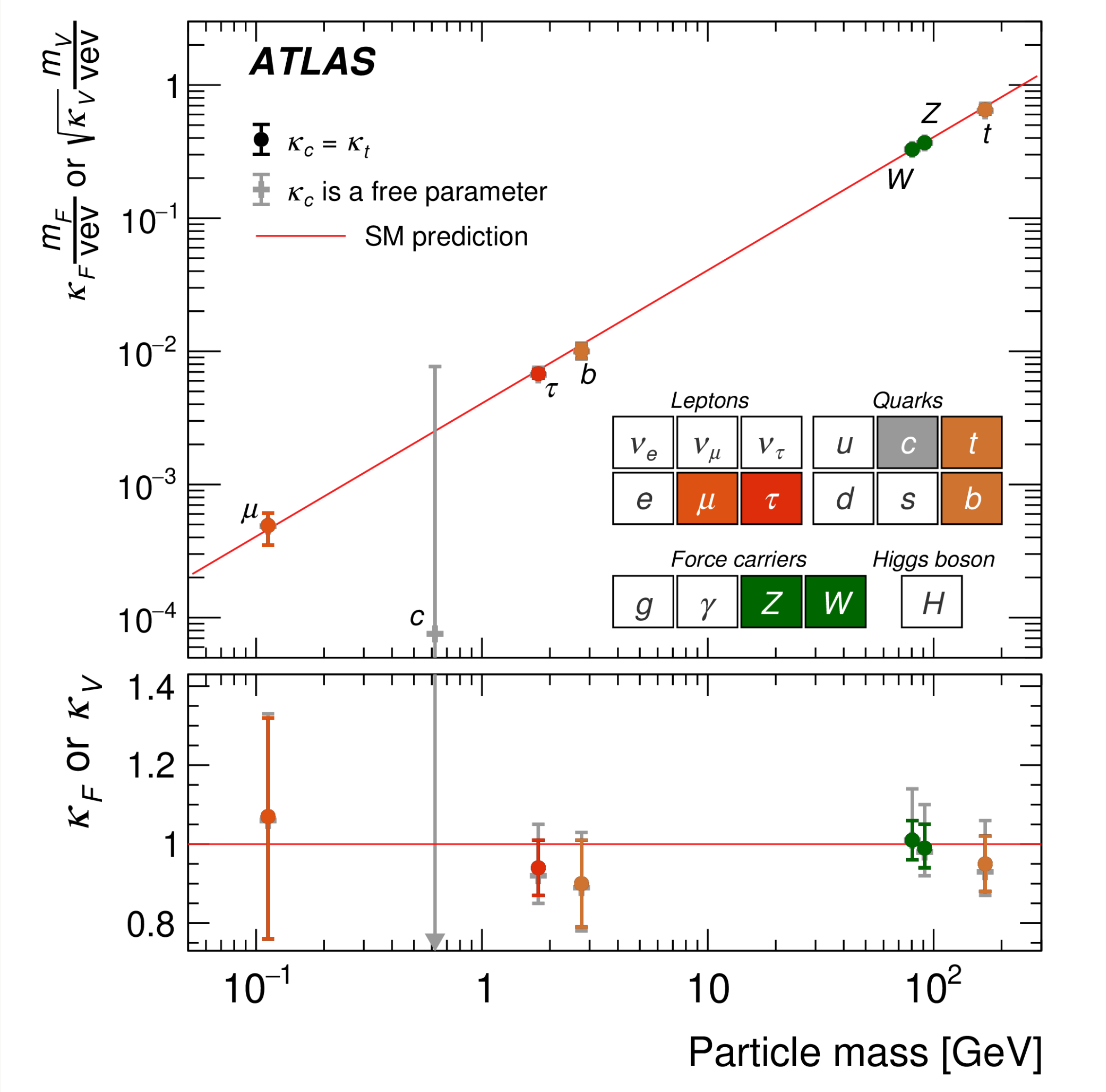
Couplings: κ framework

- κ_V vs κ_F: one scale factor for vector bosons and one for fermions
  - Loop processes resolved according to the SM particles that contribute to them
  - SM compatibility (p-value): 14%



Couplings: κ framework

- $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_c, \kappa_\tau, \kappa_\mu$:
  - All κ modifiers assumed to be positive
  - Only SM particles in loop processes
  - No invisible or undetected non-SM Higgs decays
  - Two setups: with and without κ_c to cope with low sensitivity
    - Upper limit on κ_c of $5.7(7.6) \times \mathrm{SM}$ at 95% CL
  - Coupling measurements:
    - Fermions (t, b, τ): precision between 7% and 12%
      - Muon: precision of 37%
    - Vector bosons (W, Z): precision of 5-6%

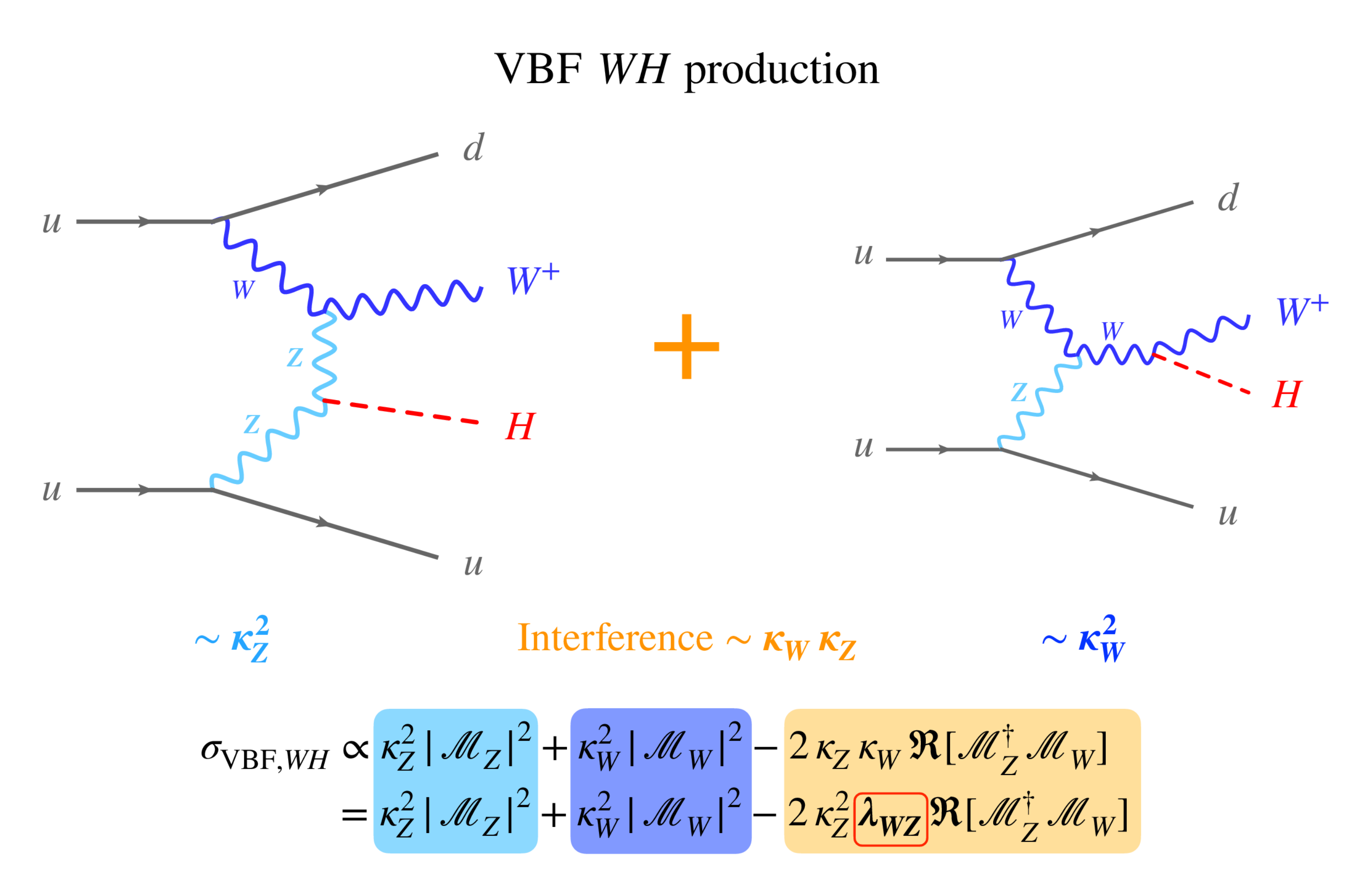


Couplings: κ framework

★ New!

ATLAS-CONF-2023-057

- Another new (preliminary) result
- VBF WH production process provides sensitivity to the sign between κ_W and κ_Z
  - Two main processes interfere constructively (destructively) if κ_W and κ_Z have opposite (same) signs
  - Cross section increases by ~6x for opposite sign contributions

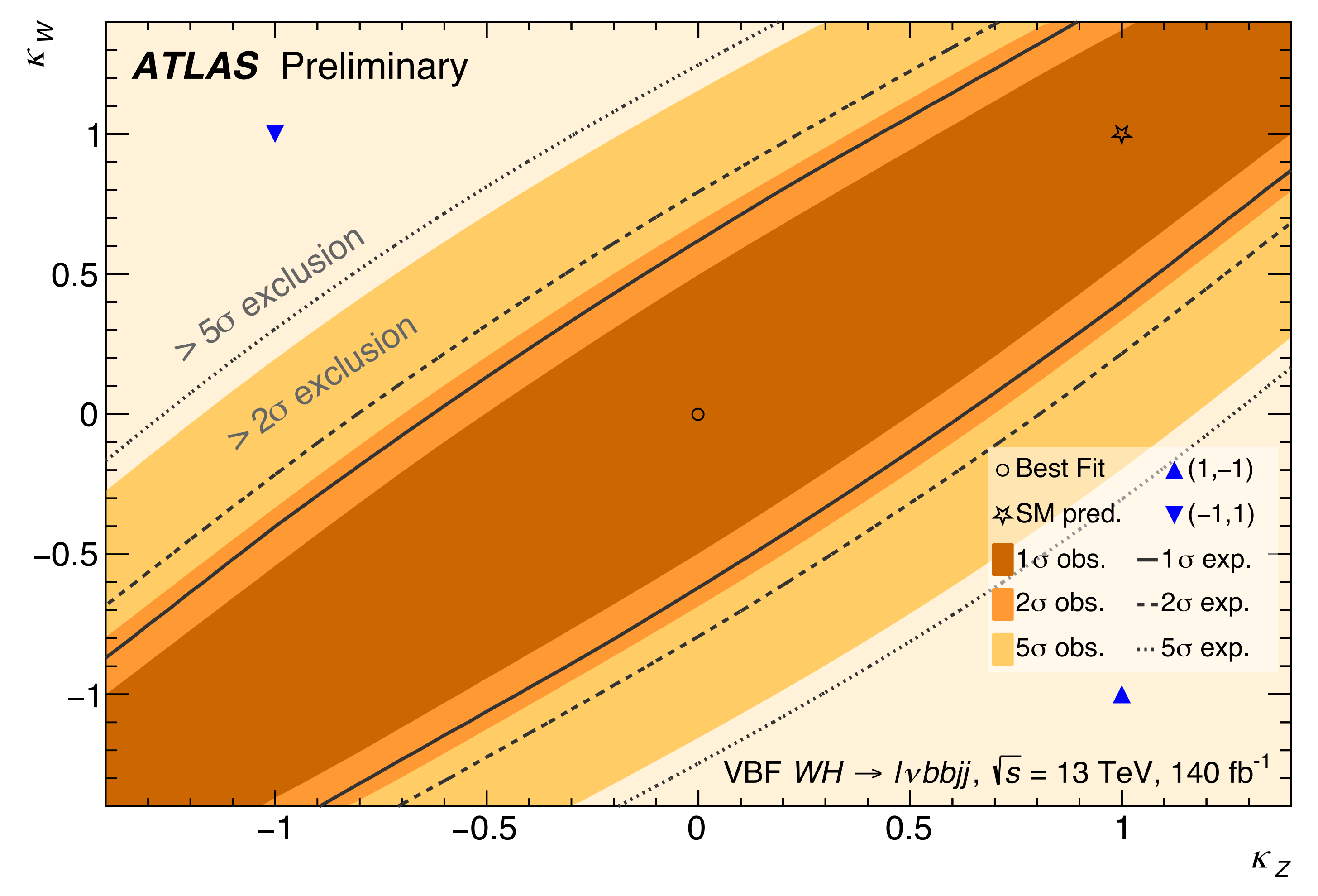


Couplings: κ framework

★ New!

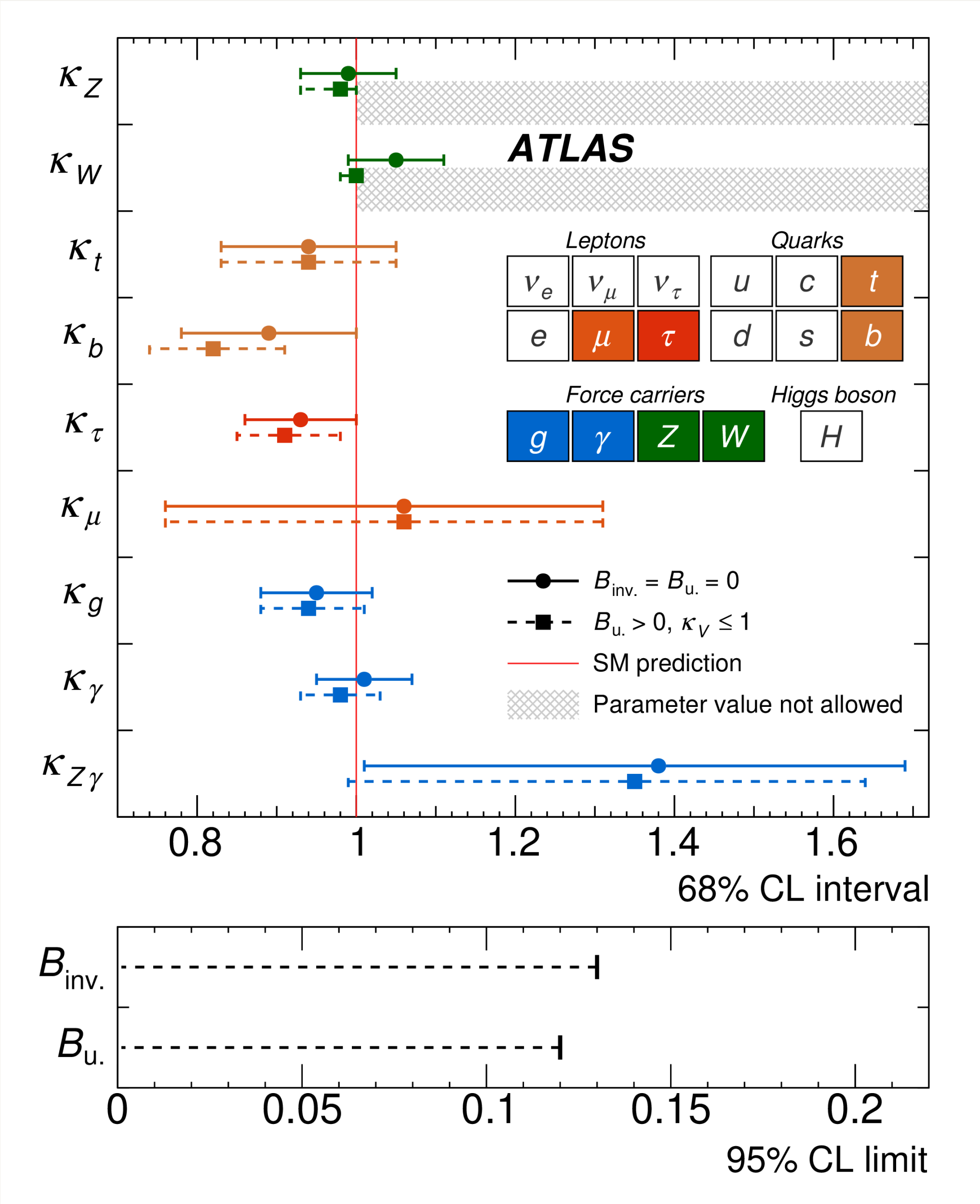
ATLAS-CONF-2023-057

- Another new (preliminary) result
- VBF WH production process provides sensitivity to the sign between κ_W and κ_Z
  - Recall that in previous result, all coupling modifiers are *assumed* to be positive!
  - Opposite sign coupling excluded with significance $> 8.0\sigma$



Couplings: κ framework

- $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_c, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$ **(+ with $B_{\text{inv.}}, B_{\text{u.}}$):**
  - Similar to previous setup with this time allowing for non-SM particles in loop processes
    - Effective coupling strengths for κ_g, κ_γ, $\kappa_{Z\gamma}$
    - Does not include combined $H \to Z\gamma$ result or the κ_W/κ_Z relative sign result
  - κ_t allowed to be negative
  - Two setups: with and without invisible and undetected non-SM Higgs decays
    - Impacts the width
  - Upper limits on $B_{\text{inv.}}$ and $B_{\text{u.}}$ of 0.13 (0.08) and 0.12 (0.21) at 95% CL
    - Limit of 0.107 (0.077) on $B_{\text{inv.}}$ from updated results in combination of dedicated searches [arXiv:2301.10731]



Couplings: self-coupling

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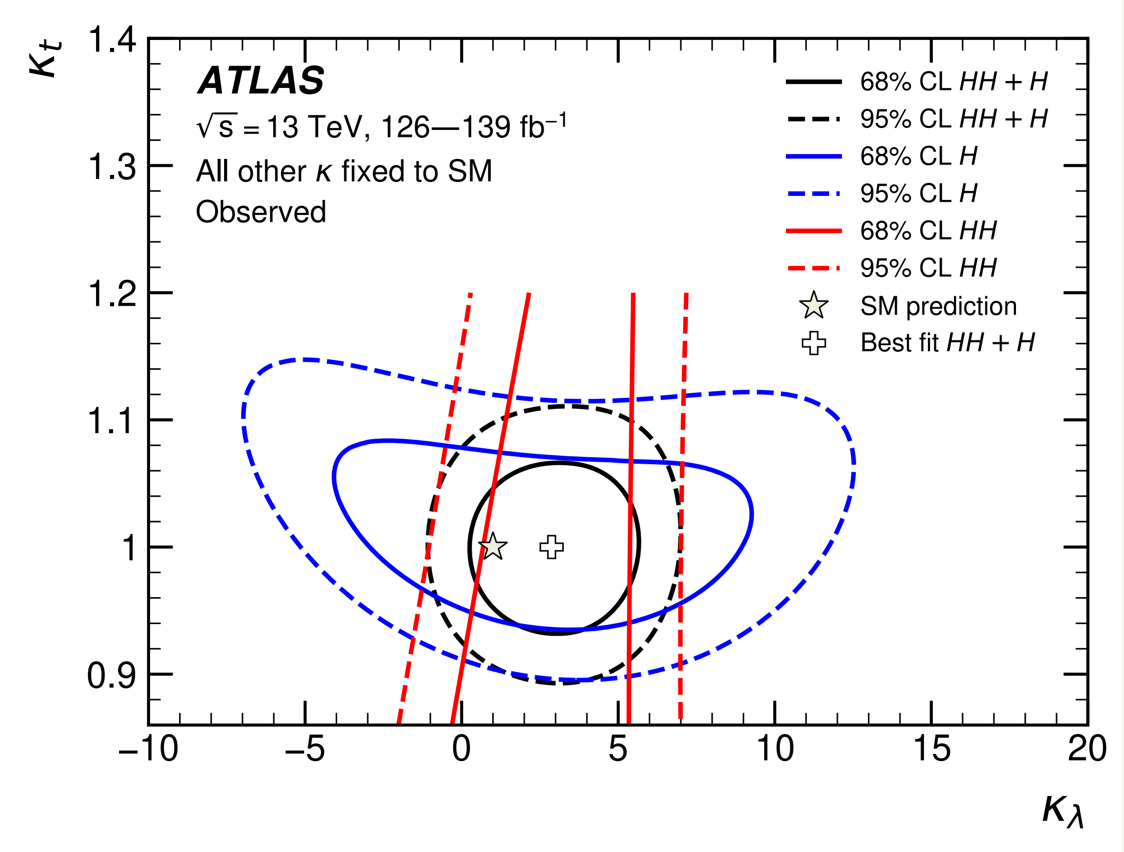
- More information about HH in a dedicated talk
  - Combination of H and HH results allows to relax assumptions in the constraints on κ_λ (e.g. about the strength of κ_t)



Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

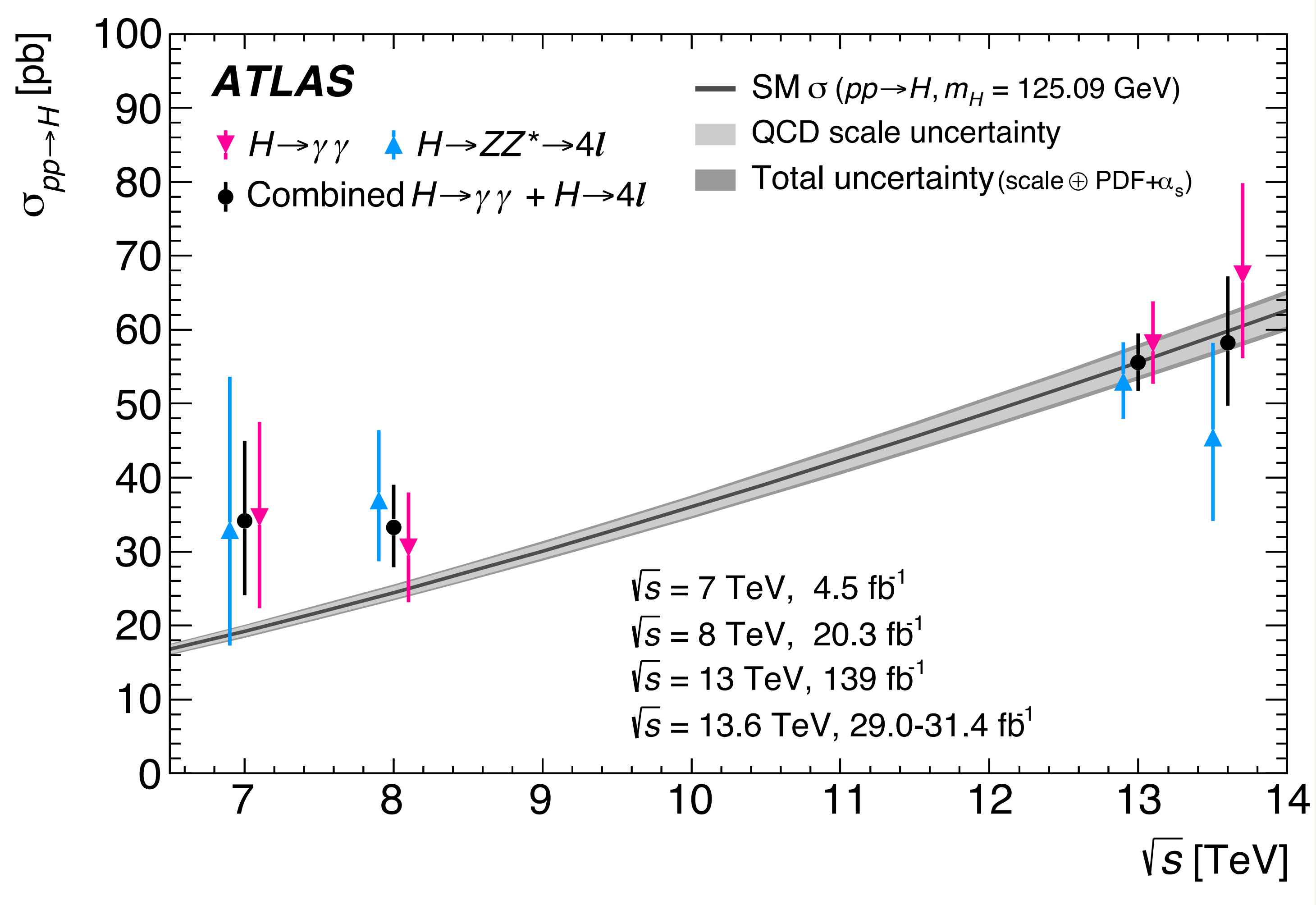
Conclusion (Run 2)

- A lot of measurements have been performed by the ATLAS collaboration, with confirmation that the (coupling) properties of the Higgs Boson show excellent agreement with the SM predictions
  - All main production modes have been observed
  - Hints of rare Higgs decays have been seen
    - New results in combination from CMS shows evidence for the $H \to Z\gamma$ decay
  - Couplings to vector bosons and heavy fermions have been measured with precisions of 5% and 7-12% respectively
    - Opposite sign of coupling to W and Z bosons excluded with $> 8.0\sigma$
  - Higgs self-coupling constraints from combined $H + HH$ results, with less assumptions
  - Kinematic dependence of production cross sections has been studied across a wide range of phase space and across several orders of magnitude (STXS)
    - Differential measurements also available in a combination of $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ [arXiv:2207.08615] and in $H \to WW^*$ [arXiv:2304.03053, arXiv:2301.06822] — not shown here

Conclusion (Run 3)

★ New!
arXiv:2306.11379

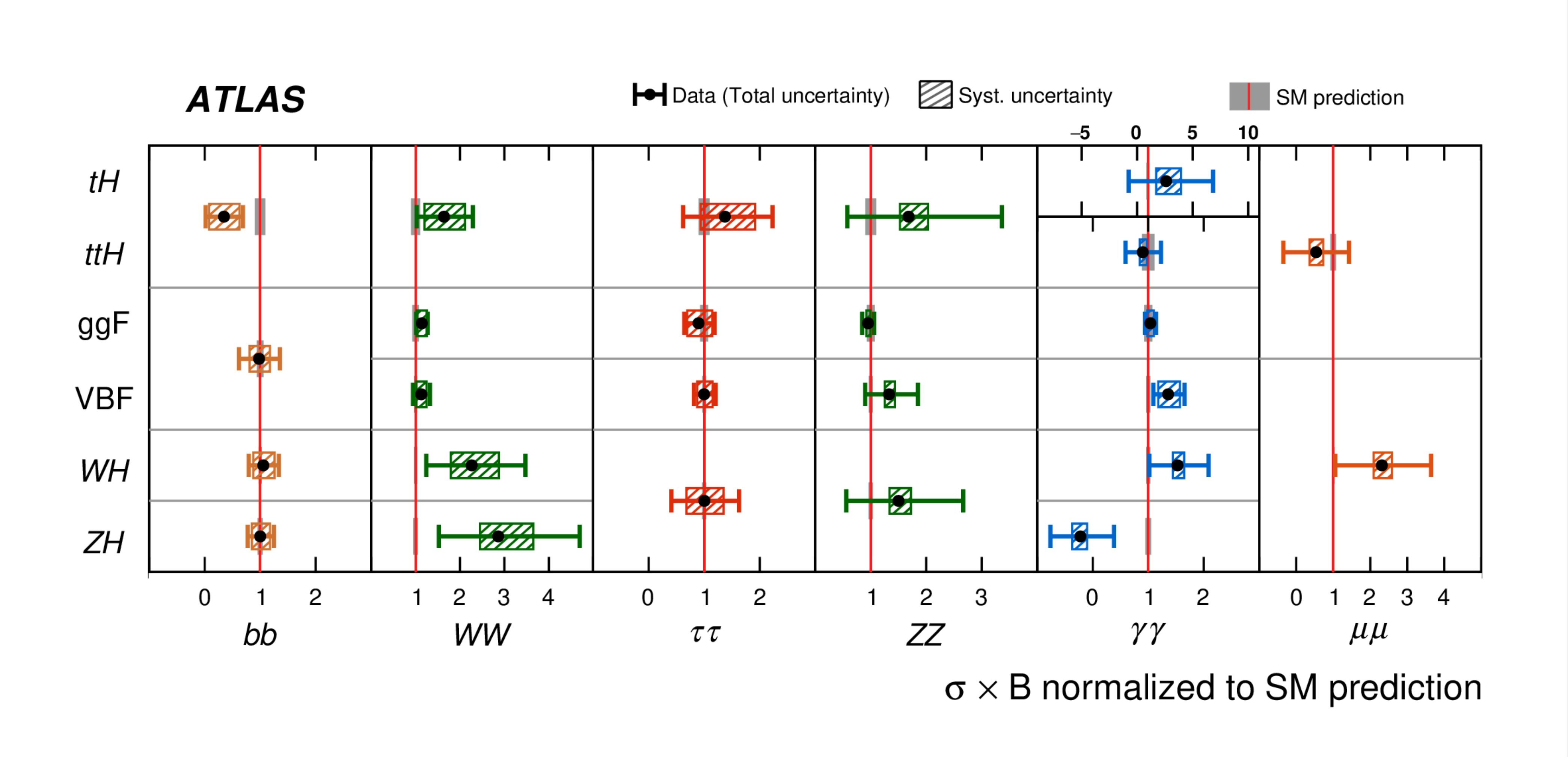
- First measurement(s) in Run 3 already available, more to come!
    - Dedicated talk later today



Backup

Production & decay

- **Cross sections x branching ratios:**
  - Measurements for all available cross sections and branching ratios
  - Assumptions from previous measurements relaxed



Kappa ratios