Combined measurements of Higgs boson production and decay at ATLAS

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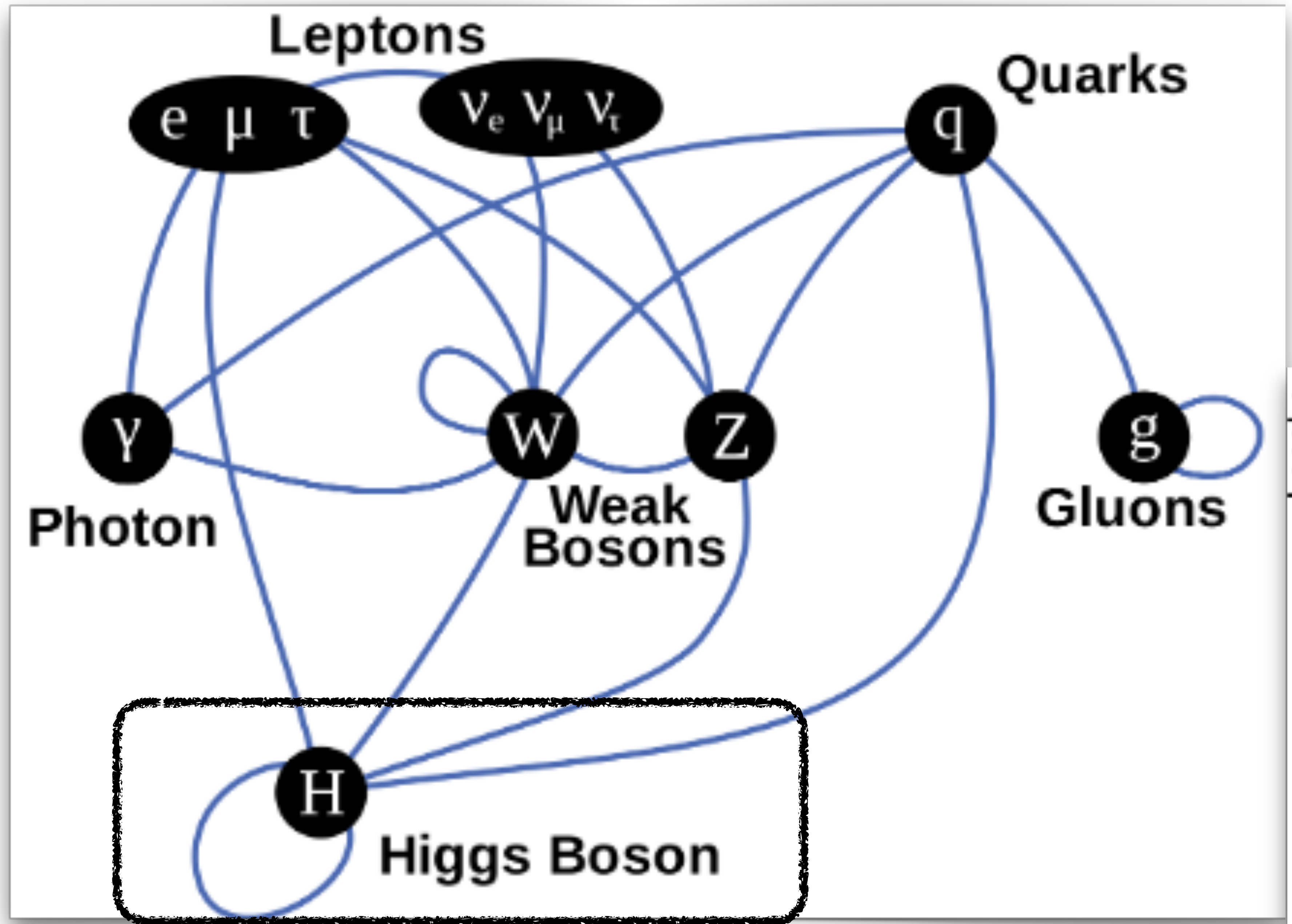
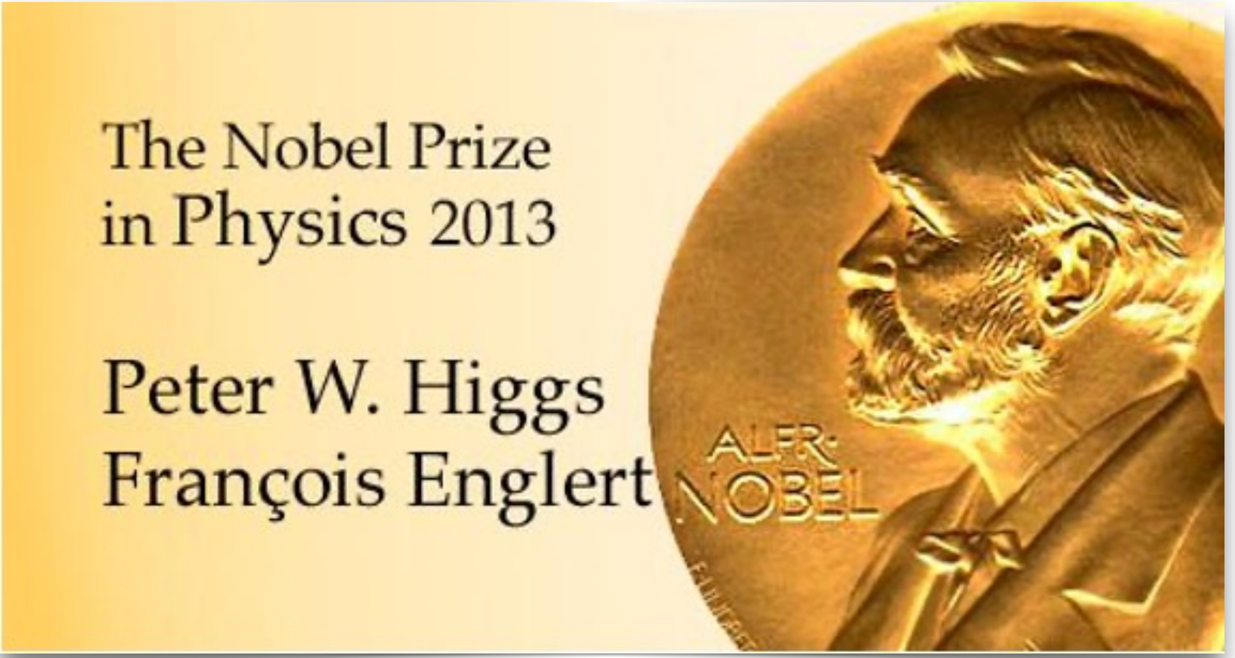
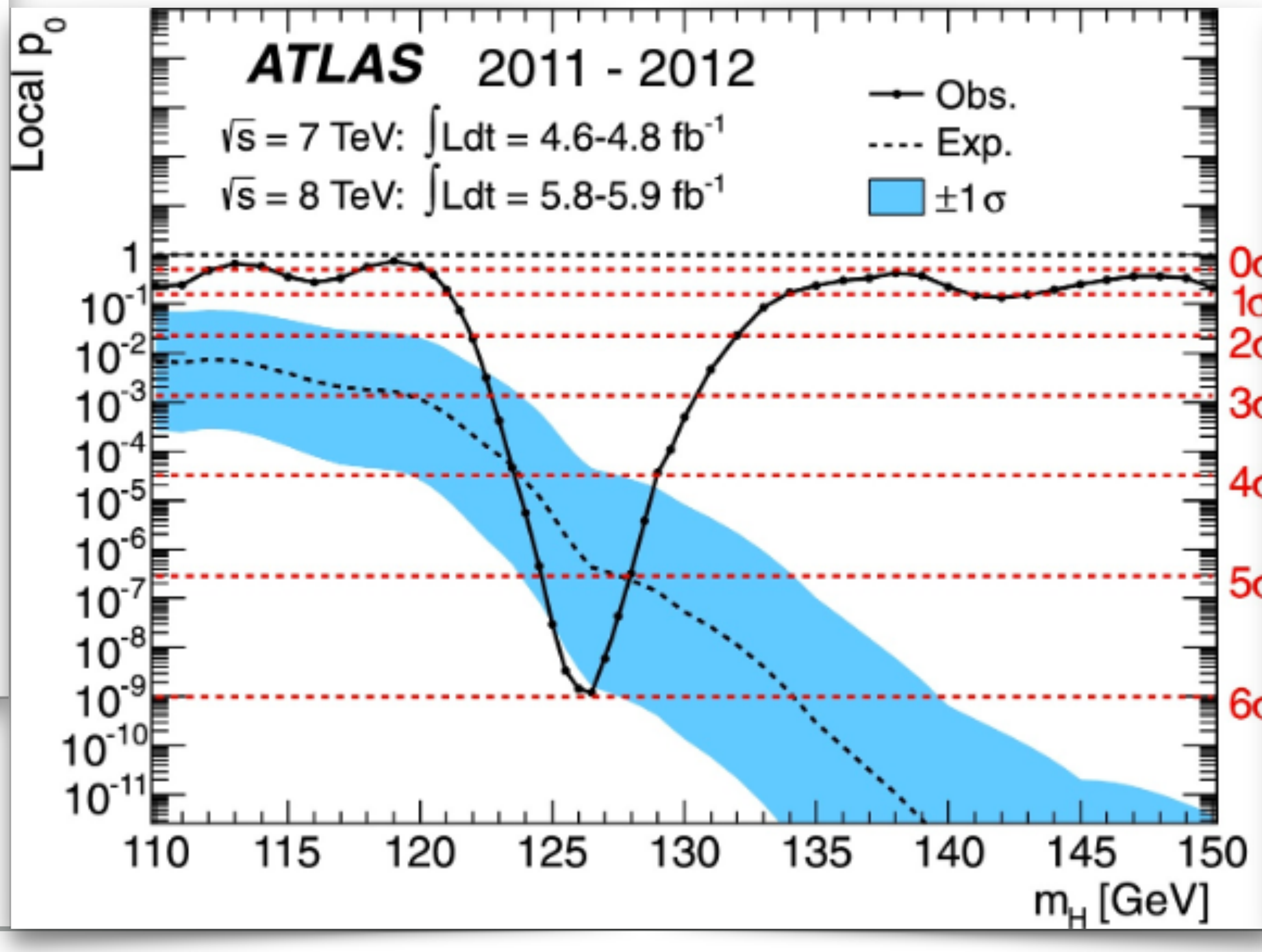
Introduction

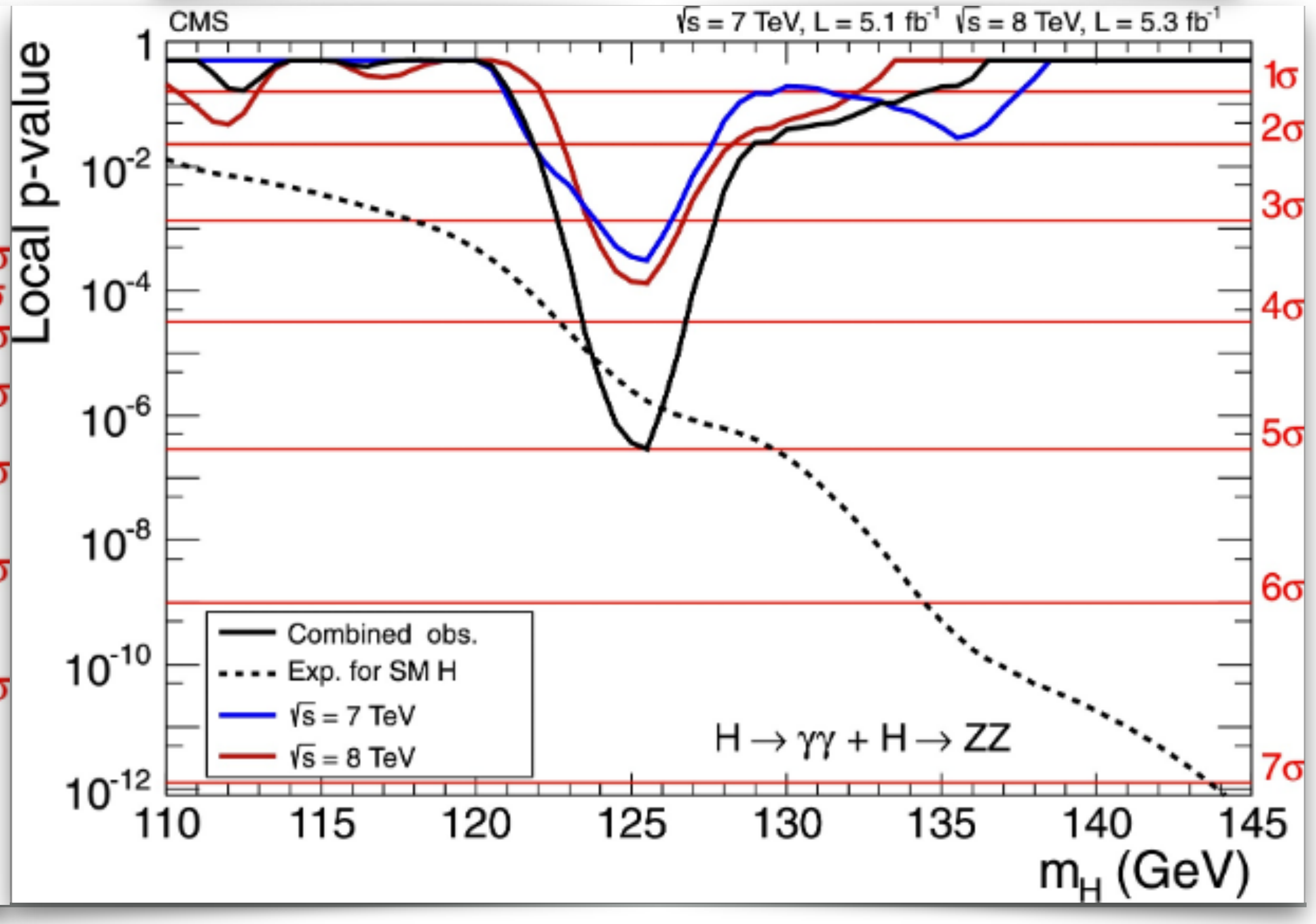
- The SM is one of the most successful theories in particle physics
- It introduces the electroweak spontaneous symmetry breaking trough the Higgs mechanism, predicts the Higgs boson, gives masses of element particles



- Higgs discovery
  - [Phys.Lett. B716 (2012) 1-29]
  - [Phys. Lett. B 716 (2012) 30]

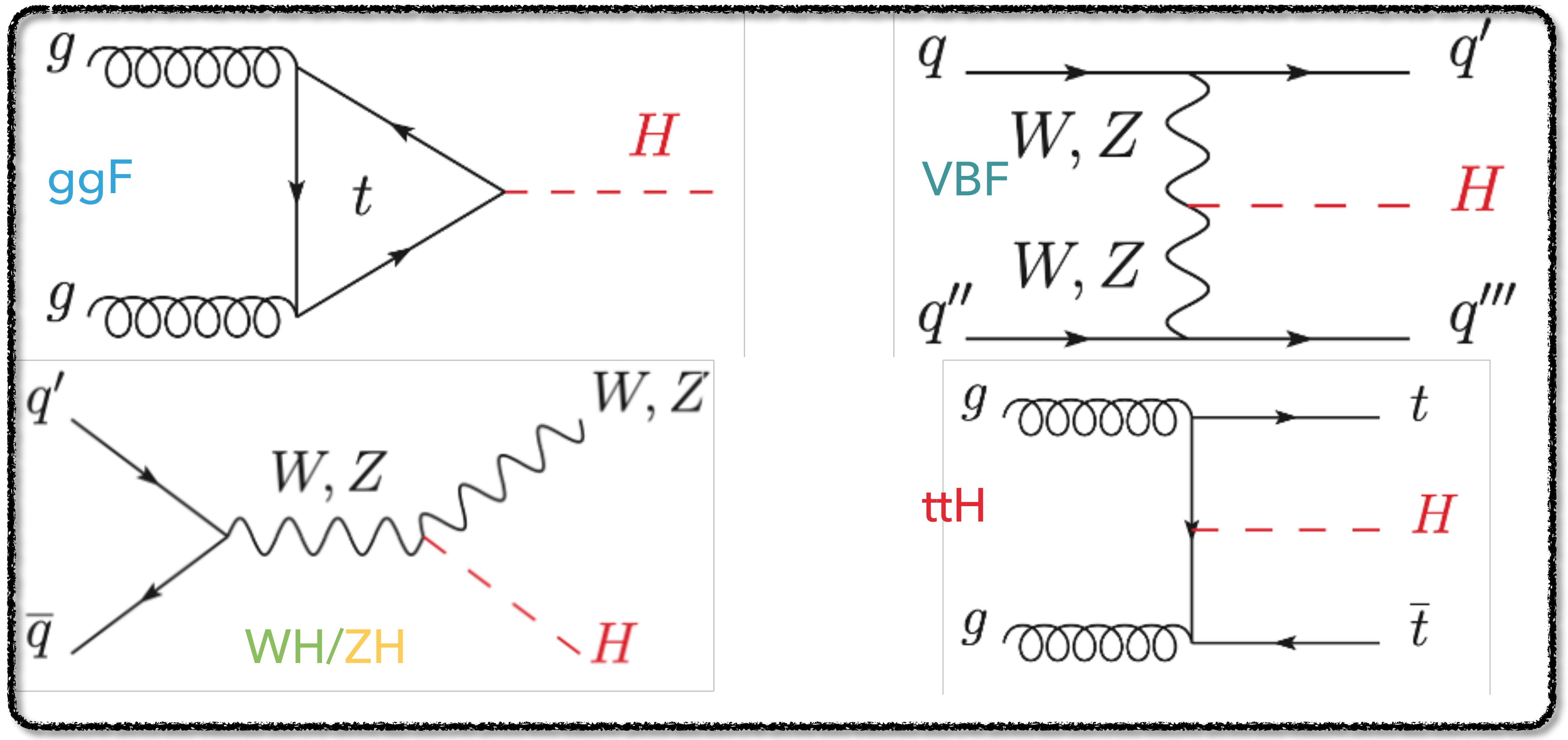


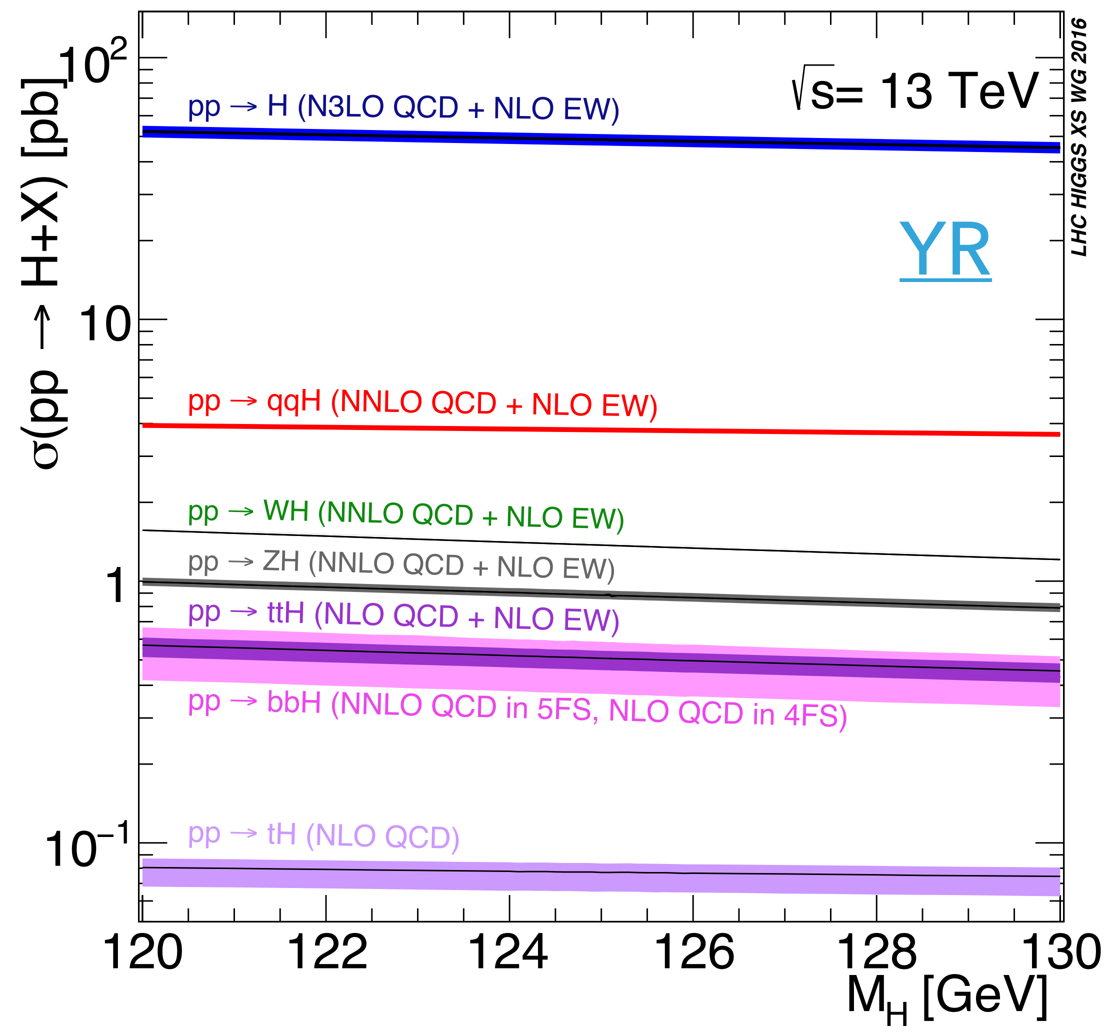




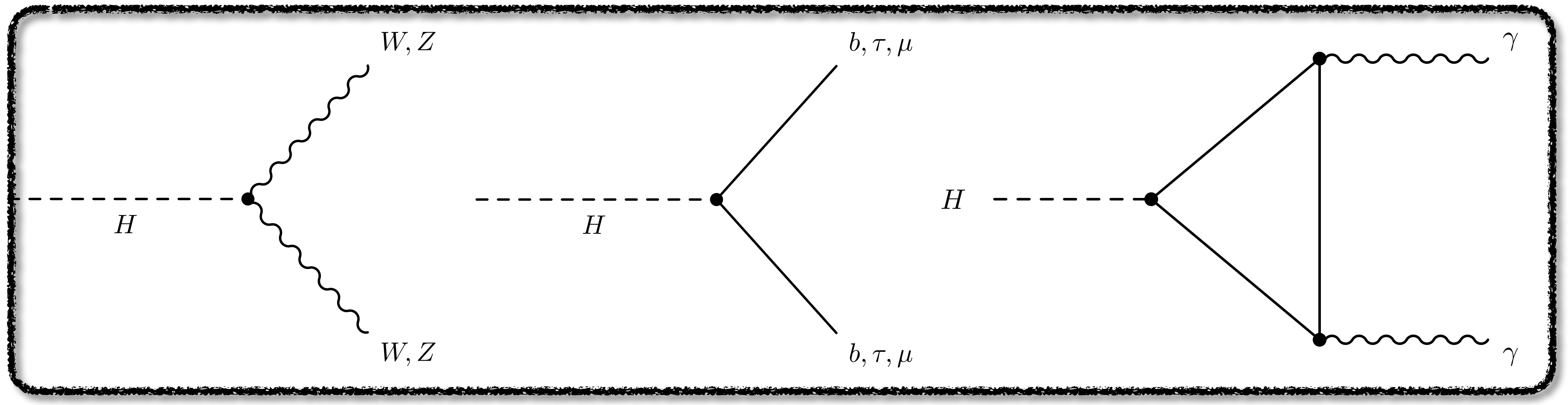
Higgs production/decay

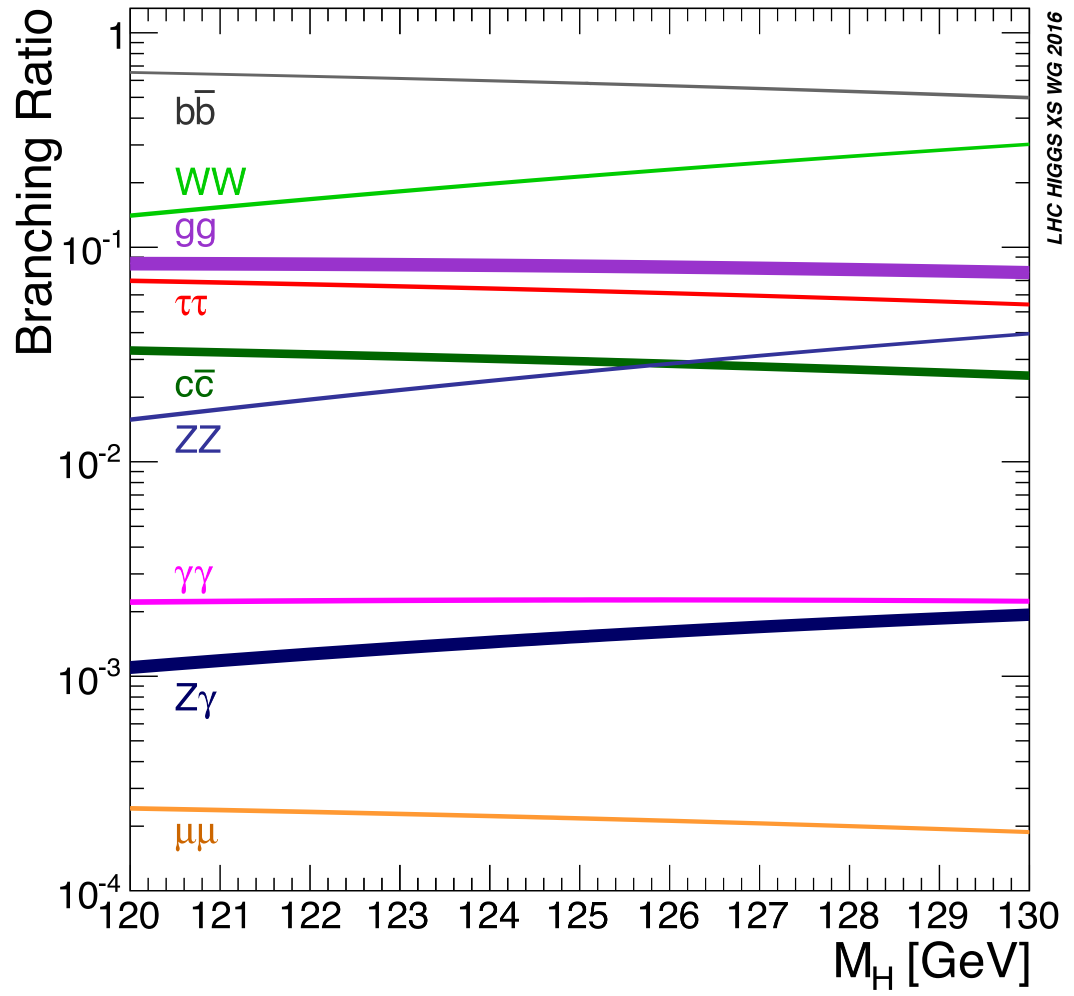
- Higgs production modes in *pp* collisions





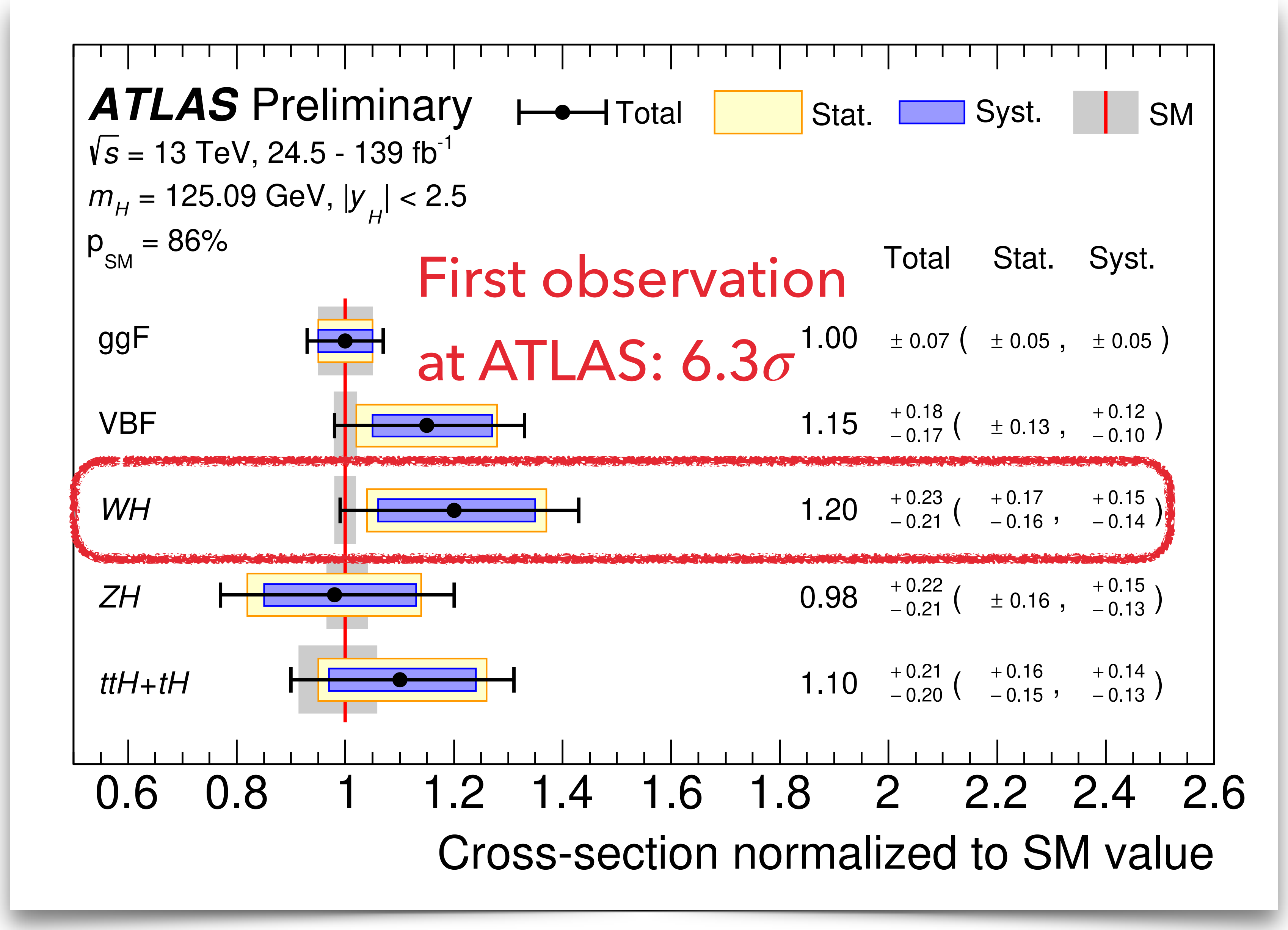
- Higgs decay

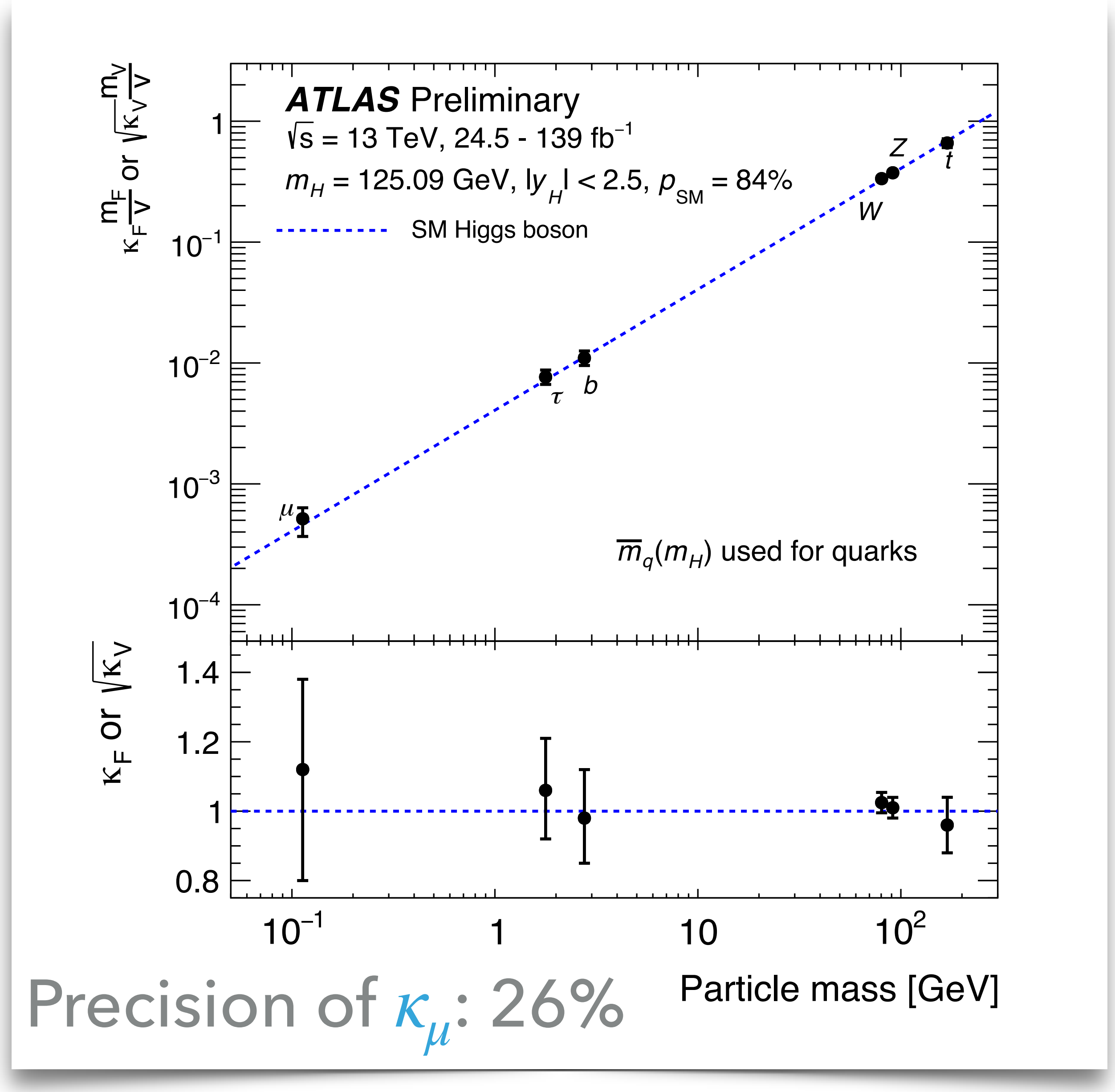




Previous coupling combination

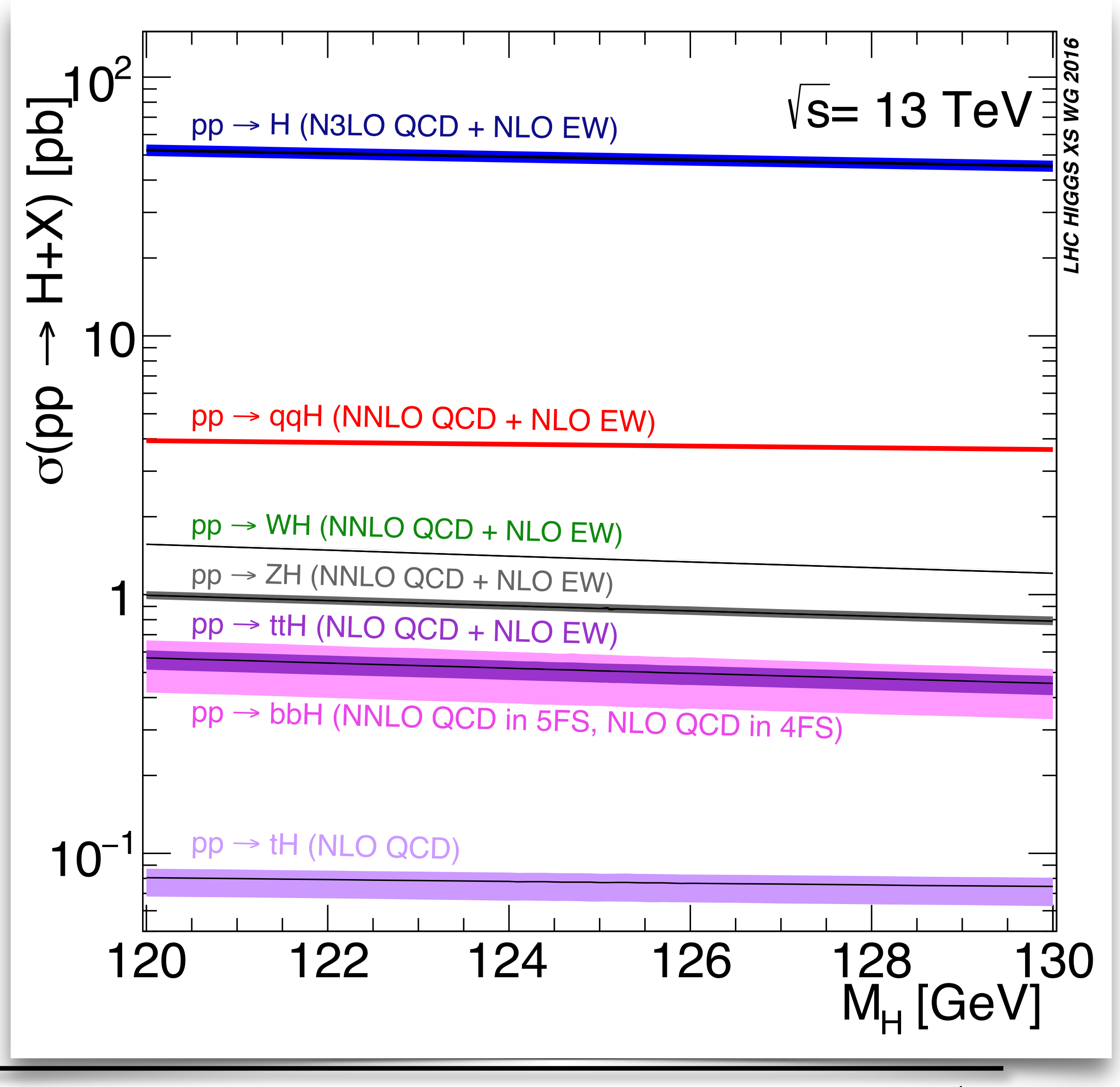
- Following the discovery of the Higgs by the ATLAS and CMS, its coupling properties to other SM particles can be precisely probed, providing stringent tests of the SM validity
- Run2 coupling combination at ATLAS with dataset up to 139 fb^{-1}, ATLAS-CONF-2020-027
  - Global $\mu = 1.06 \pm 0.07$

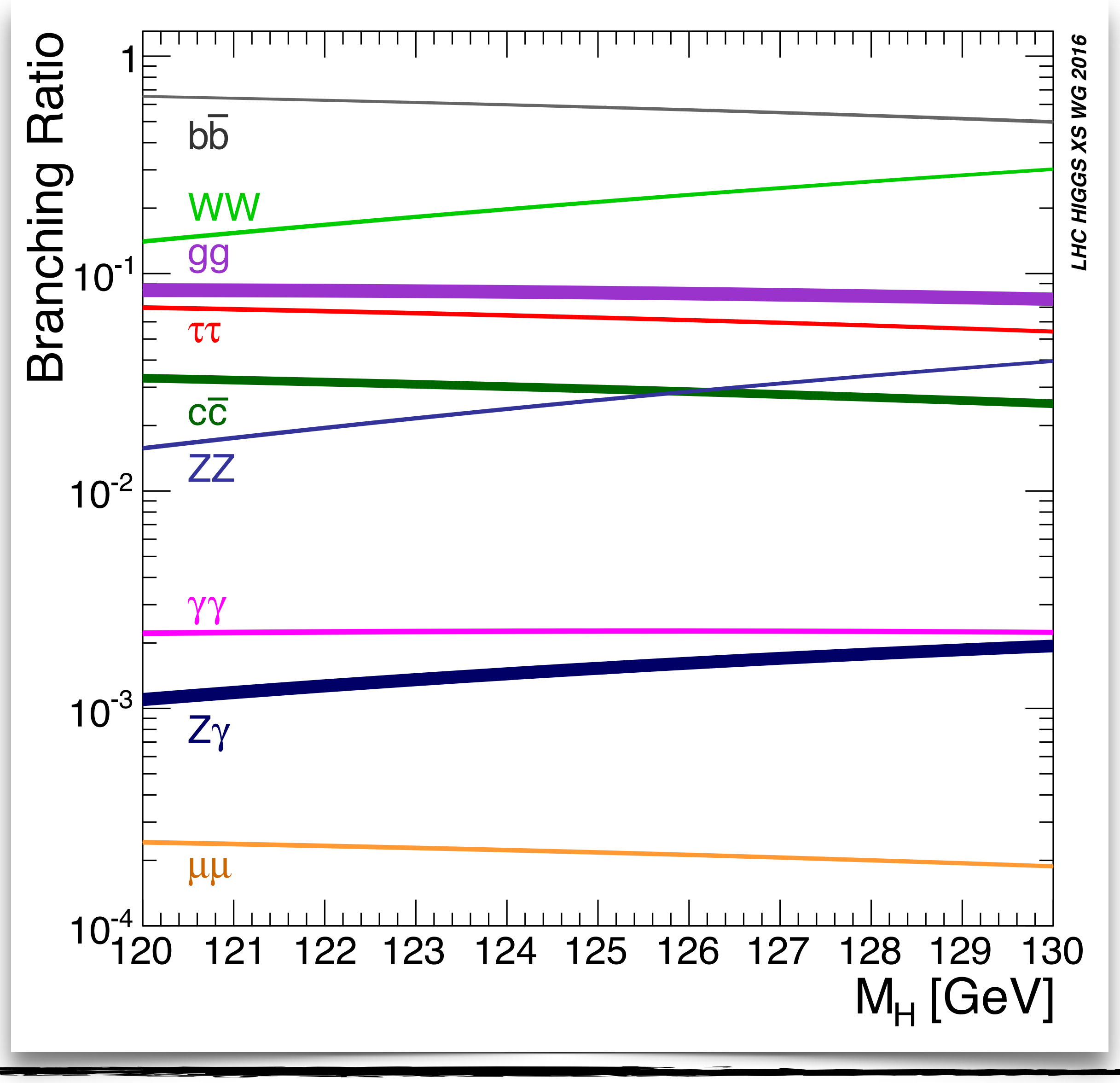




- Consistent with the SM prediction
- The measurements are extended with more channels updated to the full Run2 data, to probe Higgs properties more precisely [ATLAS-CONF-2021-053]

Combined production modes/decays





Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139
$H \to ZZ^*$	ggF, VBF, WH, ZH, $t\bar{t}H(4\ell)$	139
	$t\bar{t}H$	36.1
$H \to WW^*$	ggF, VBF	139
	$t\bar{t}H$	36.1
$H \to \tau\tau$	ggF, VBF, WH, ZH, $t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139
	$t\bar{t}H$	36.1
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139
$H \to \mu\mu$	ggF, VBF, VH, $t\bar{t}H$	139
$H \to Z\gamma$	ggF, VBF, VH, $t\bar{t}H$	139
$H \to inv$	VBF	139

Update

New with boosted (high p_T^V) bb

New

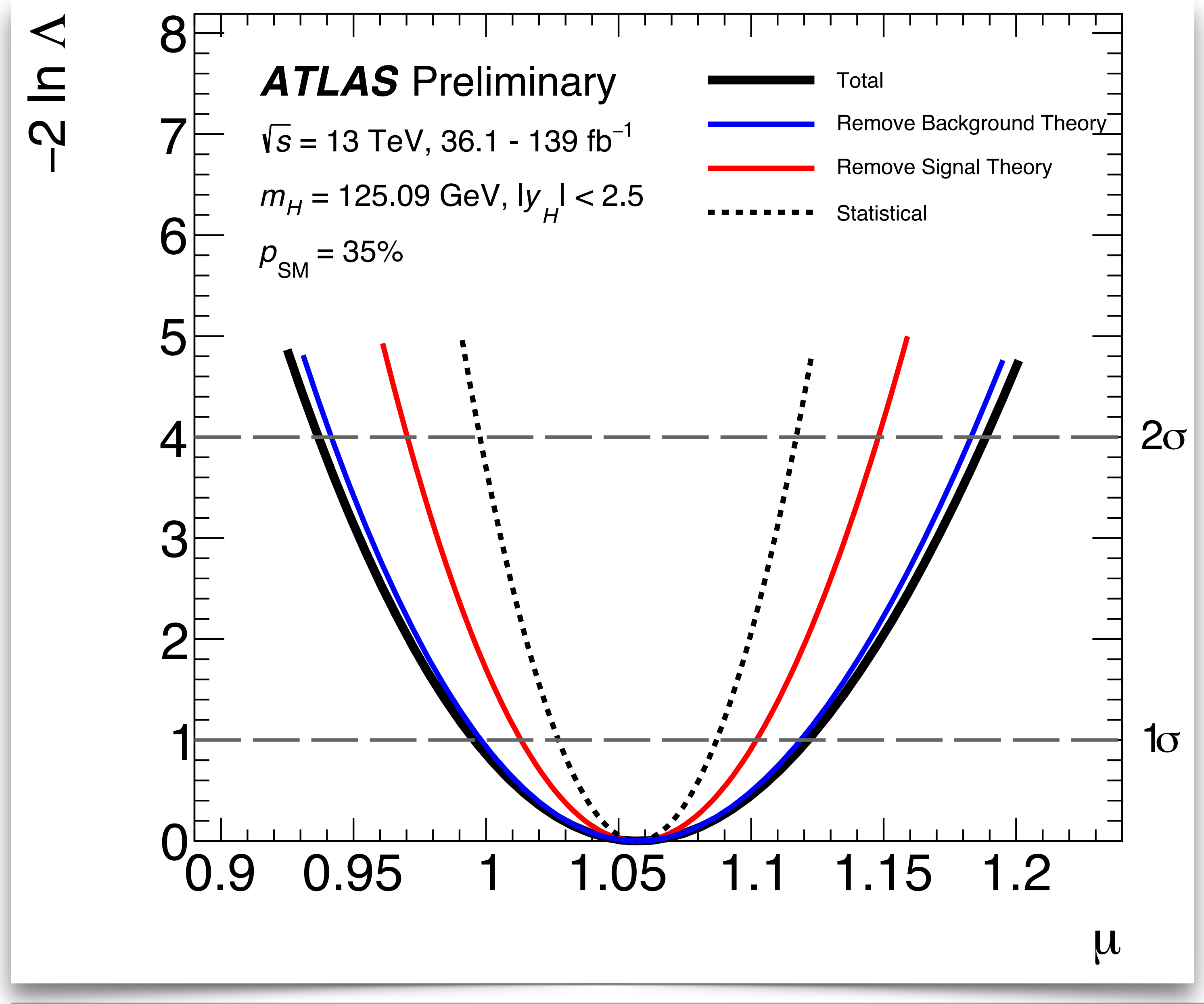
- $H \to b\bar{b}$, $H \to WW$, $H \to \tau\tau$
  - Large BR; Lower resolution
- $H \to ZZ^* \to 4l$, $H \to \gamma\gamma$
  - Low BR; Excellent resolution; High precision channels
- Rare decay
  - $H \to \mu\mu$: Higgs Yukawa coupling to the second generation fermions
  - $H \to Z\gamma$: Prob Higgs properties in loop processes
  - $H \to inv$: investigate BSM

Global signal strength

- Global signal strength μ: common scaling of the expected Higgs boson yield, showing the overall sensitivity

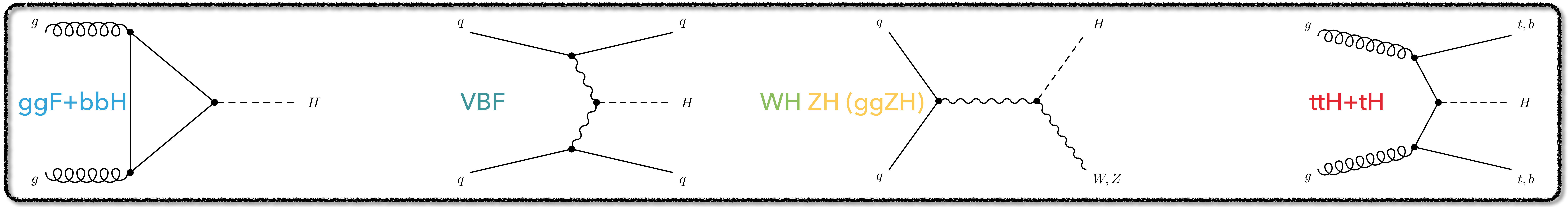
$$\mu = \frac{(\sigma \times B)_H}{(\sigma \times B)_H^{SM}}$$

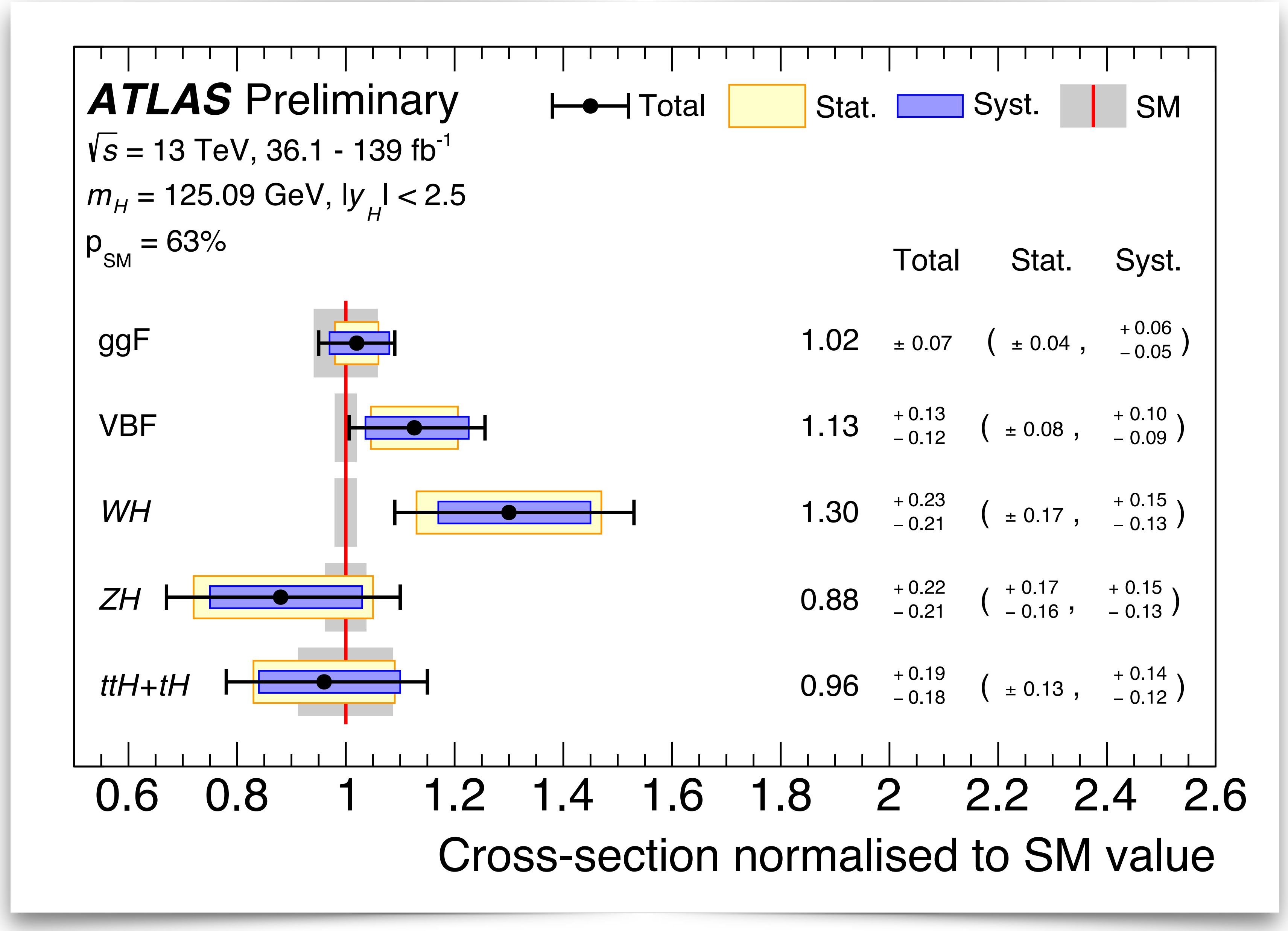
- $\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03(stat.) \pm 0.03(exp.) \pm 0.04(sig.th.) \pm 0.02(bkg.th.)$

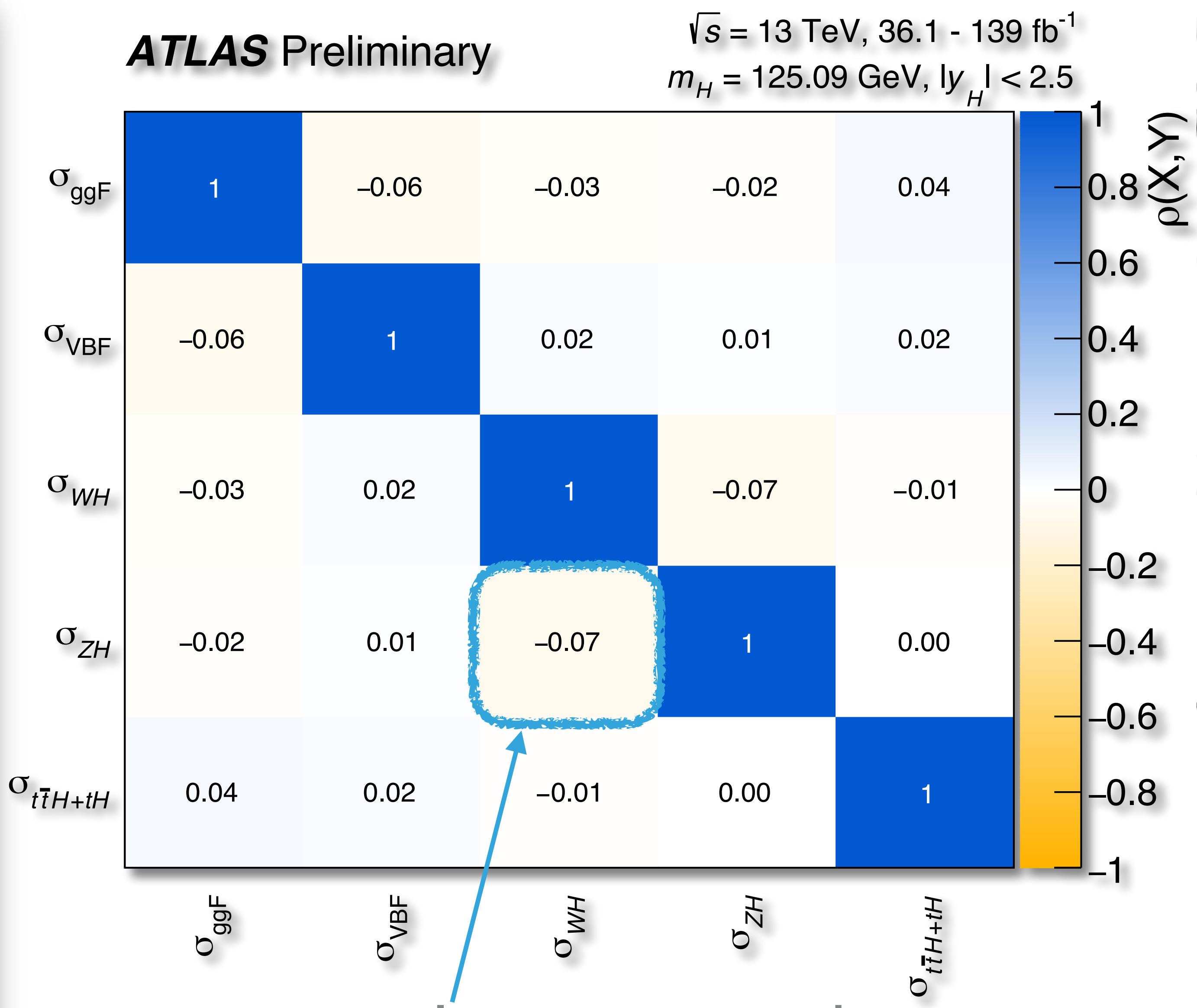


- 10% improvement in accuracy comparing to ATLAS-CONF-2020-027, 44% improvement comparing to Run1
- Consistent with the SM: $p_{SM} = 35\,\%$
- The precision is dominantly constrained by the systematical uncertainties

Production cross sections





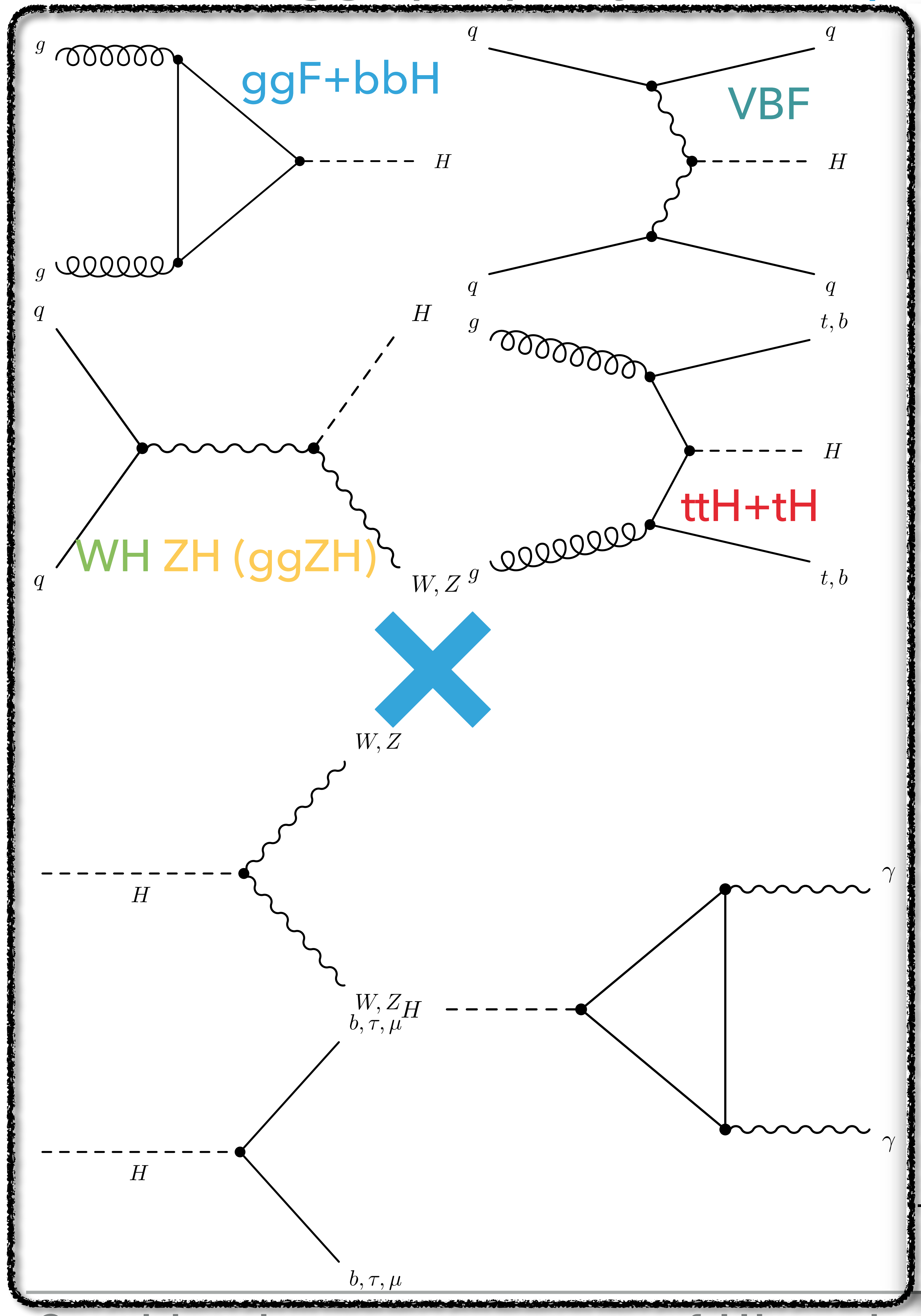


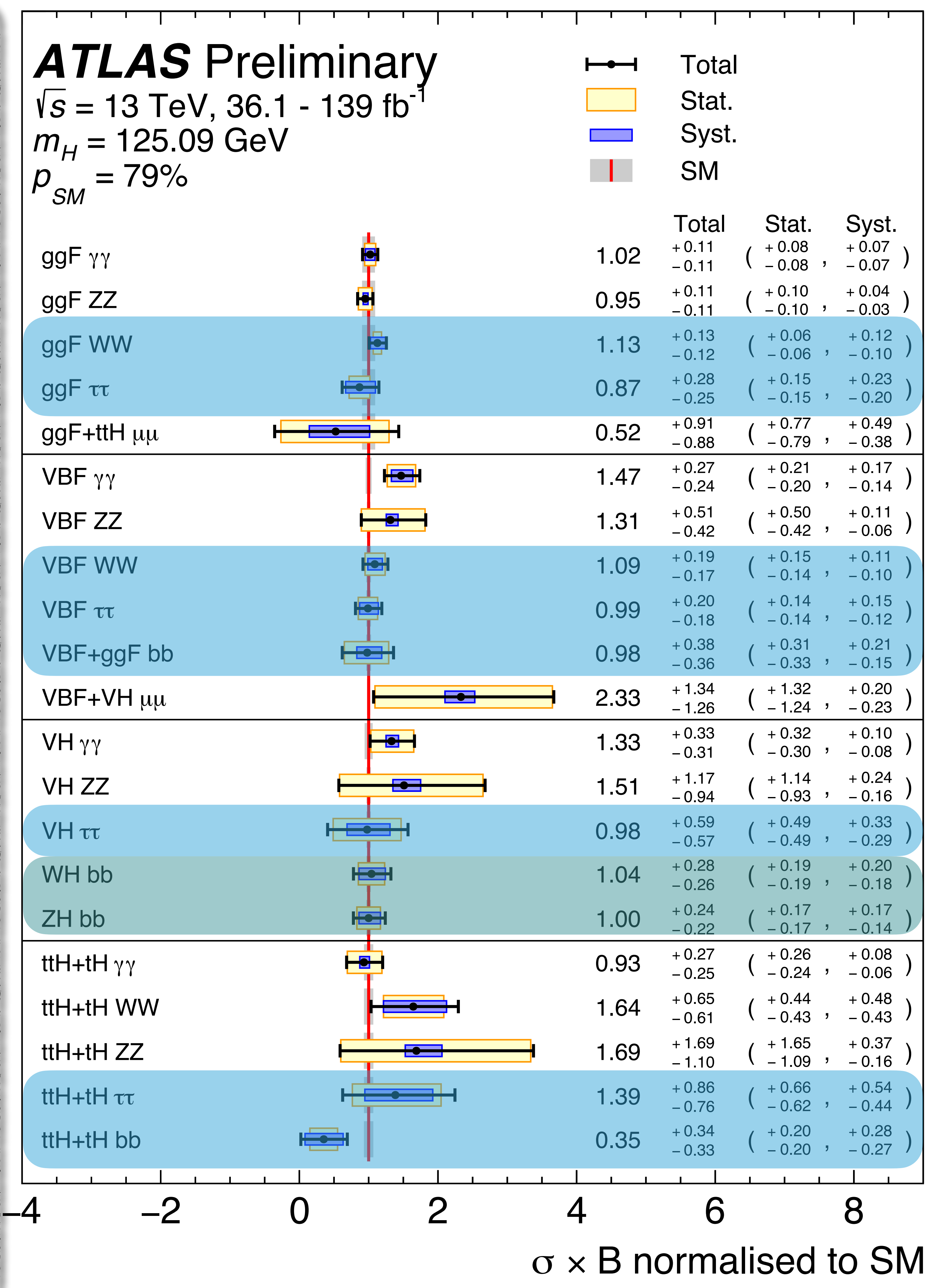
Mainly constrained by $H \to \tau\tau$

- Due to various powerful analyses contributing to different production modes and optimized analysis strategies:
  - Precision improve by 2% - 27%
  - Correlations decrease by ~3%

Production cross sections X BR

- Prob Higgs property in each production and decay: $(\sigma \times B)_{if}$



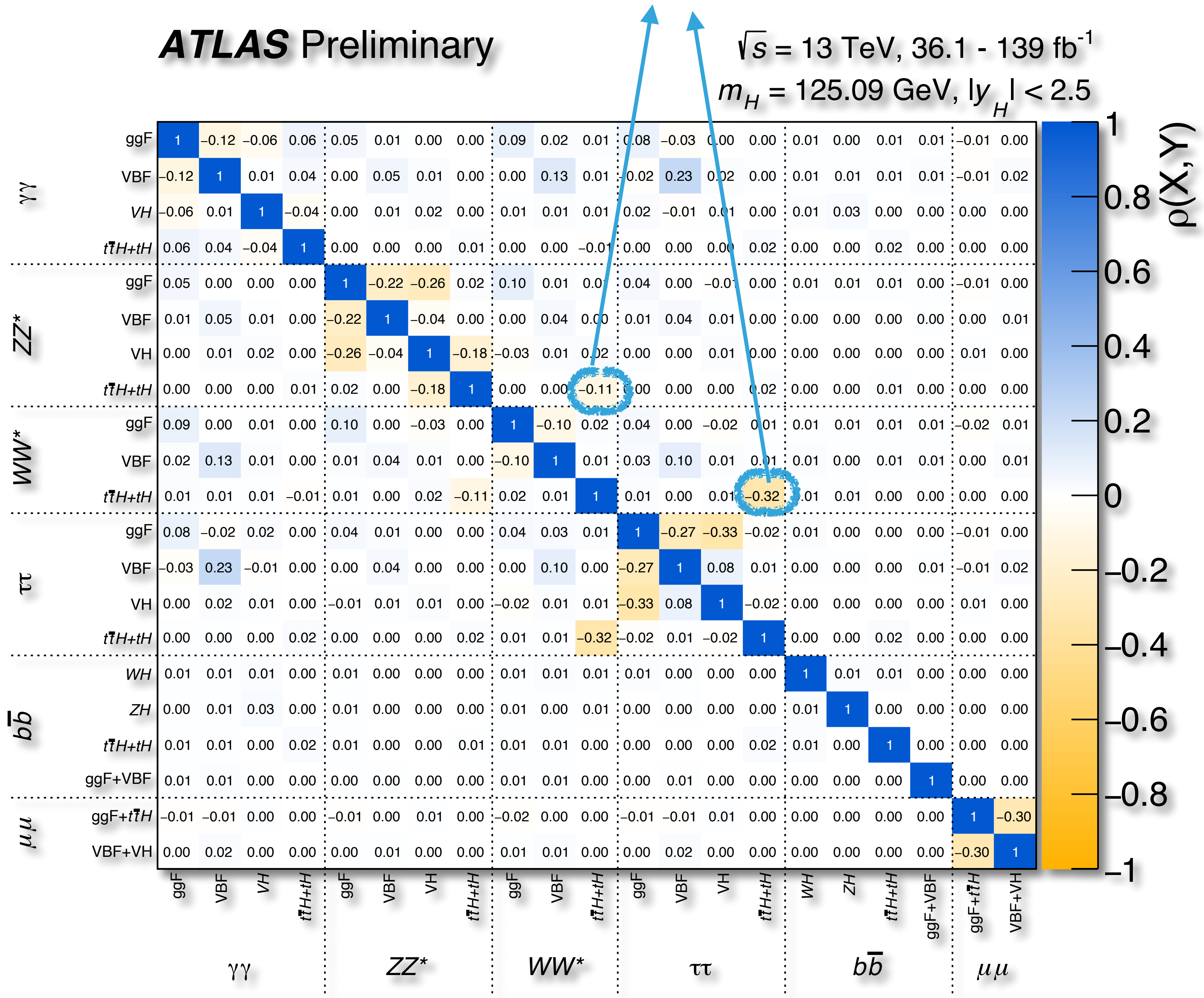


Update

New

- **First** full Run2 results containing **all major Higgs decays**

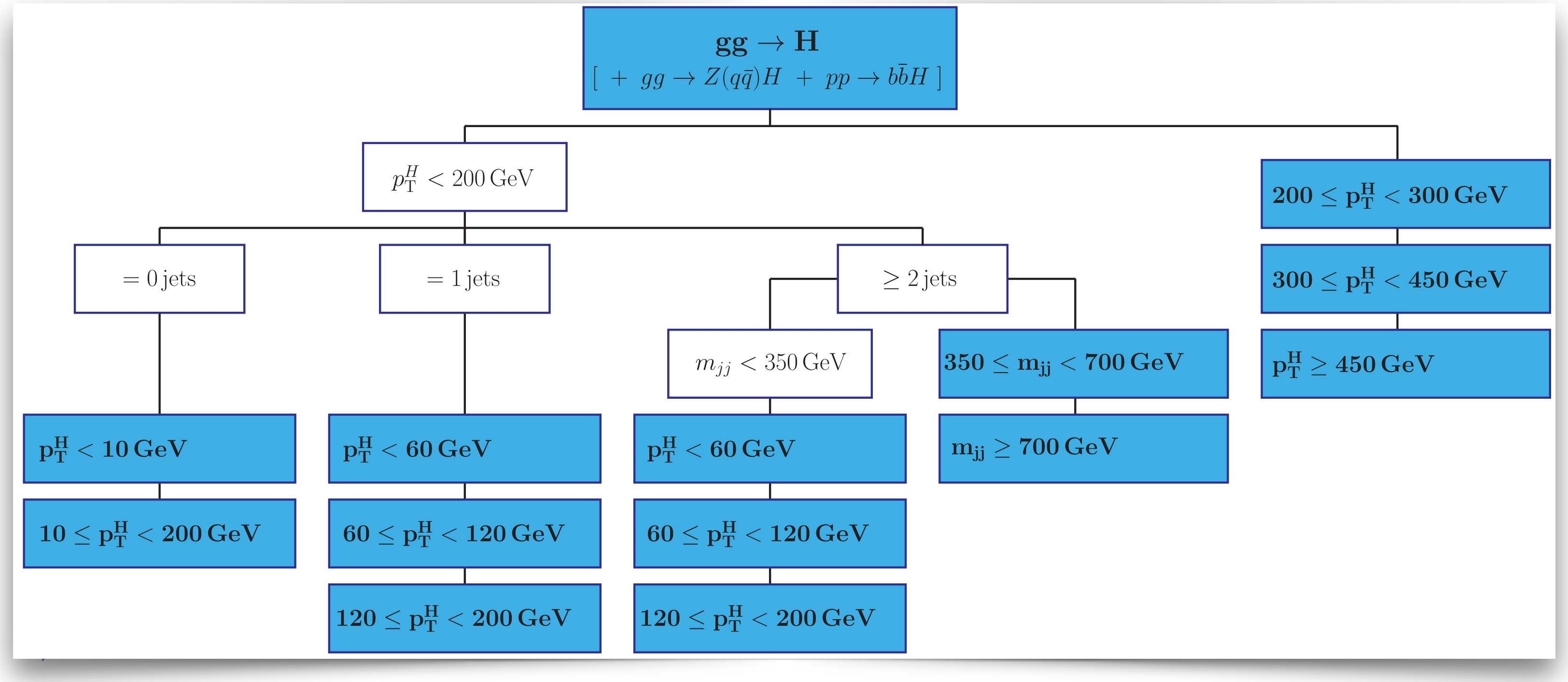
Cross contamination in the ttH (ML)

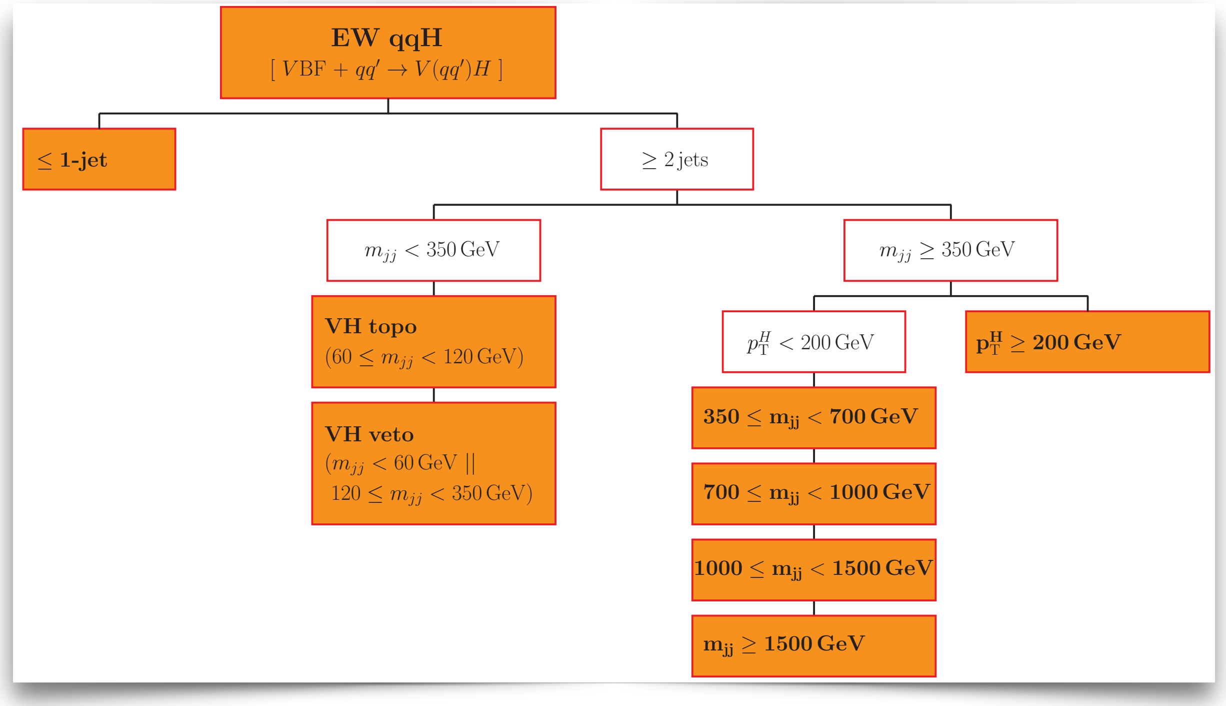


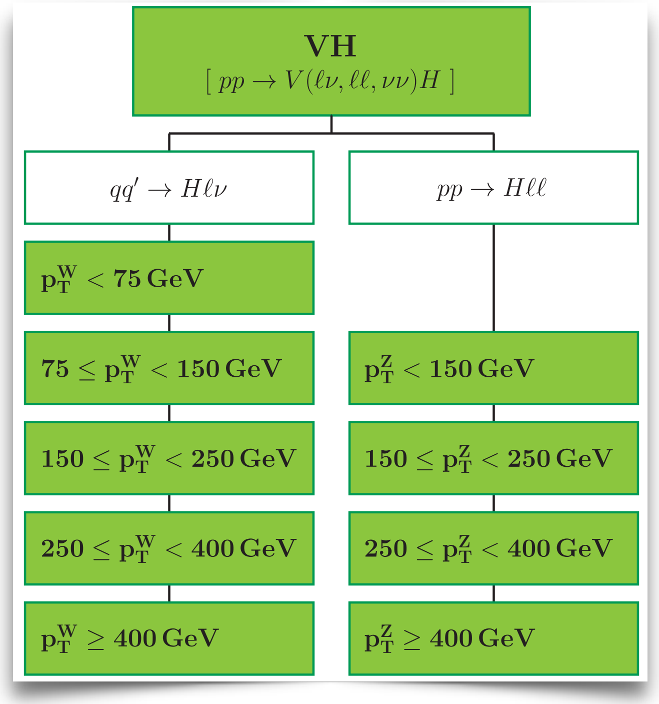
Simplified template cross section

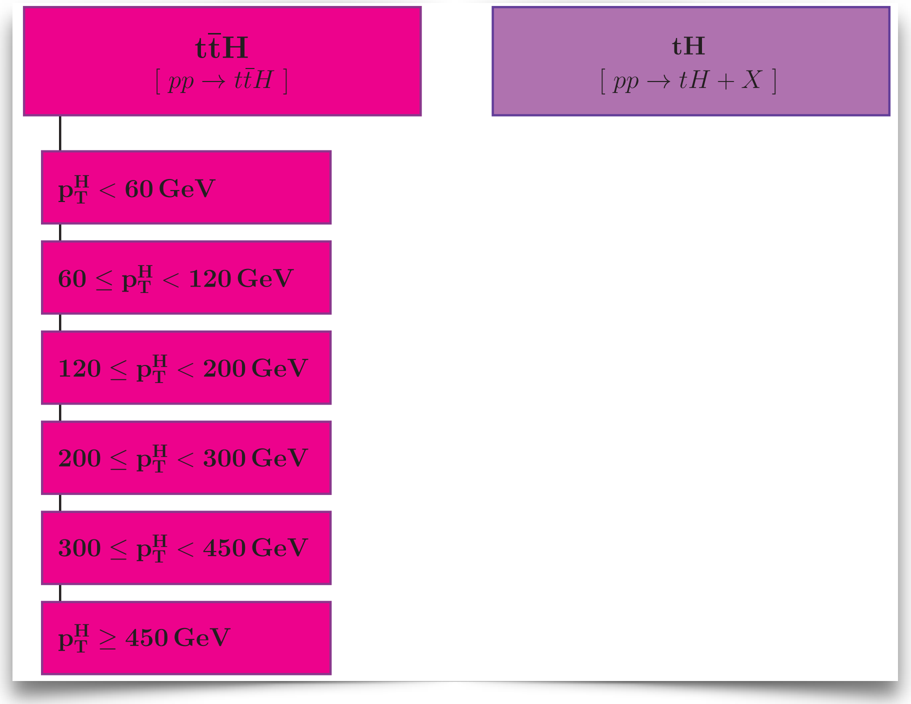
- STXS is defined trough a partition of the phase space of the Higgs production process, independently of the Higgs decay process, aim to
  - Have good sensitivity
  - Avoid large theory uncertainties
  - Approximately match experimental selections, to minimize model-dependent extrapolations

- Merged Stage 1.2
  - Show the finest granularity that provides adequate sensitivity with the current combination

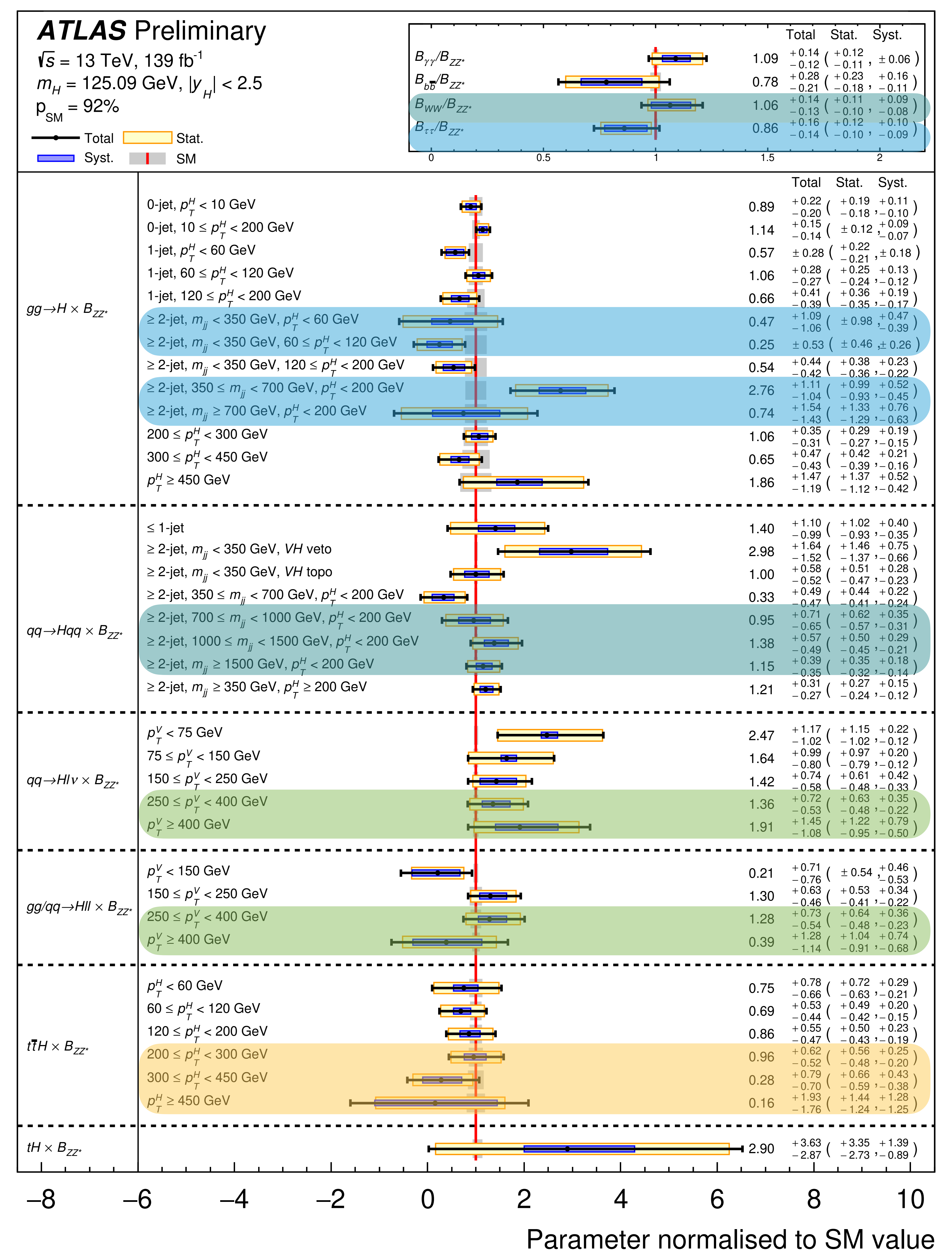








STXS measurements



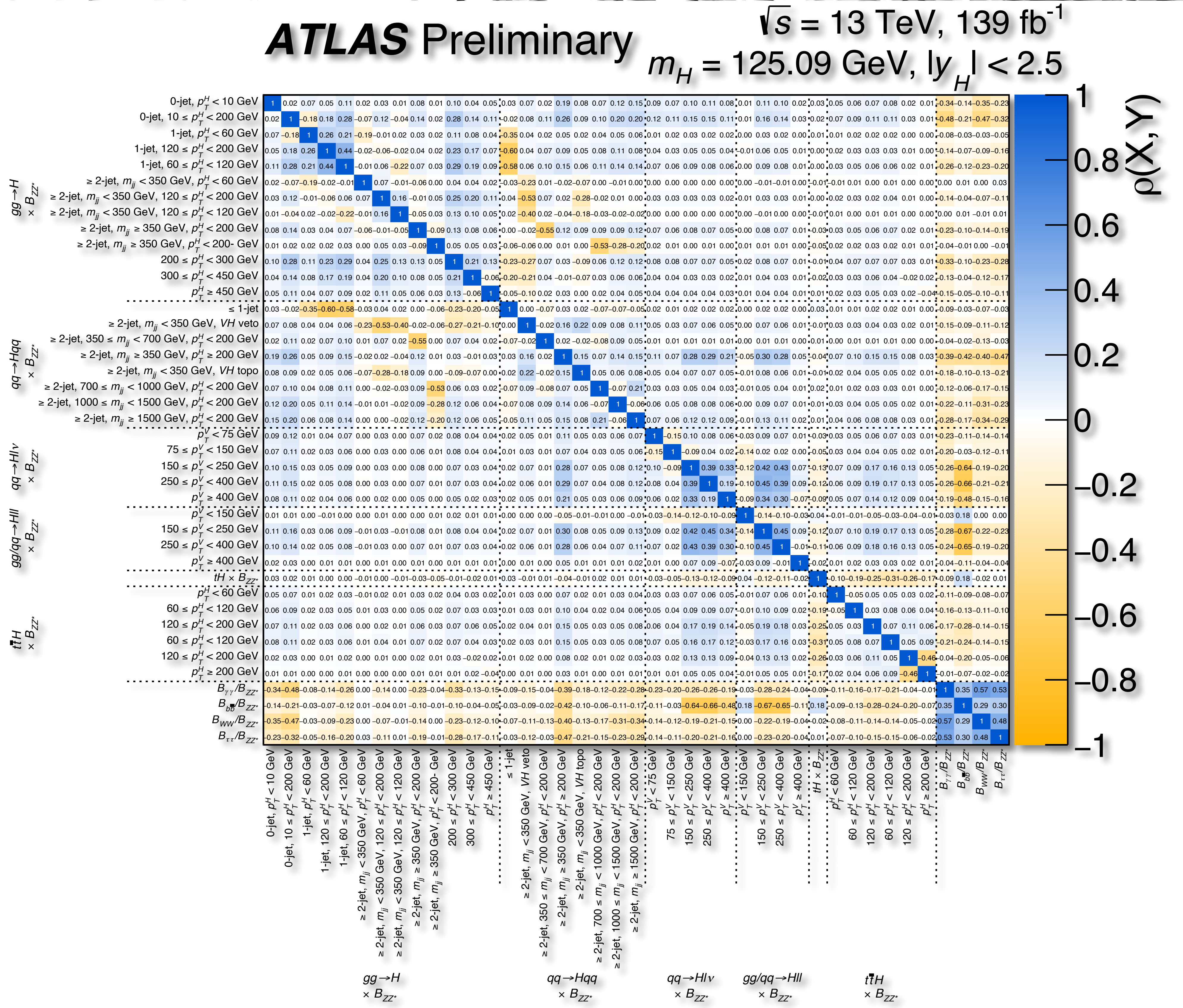
H → ττ

H → WW

Boosted VHbb

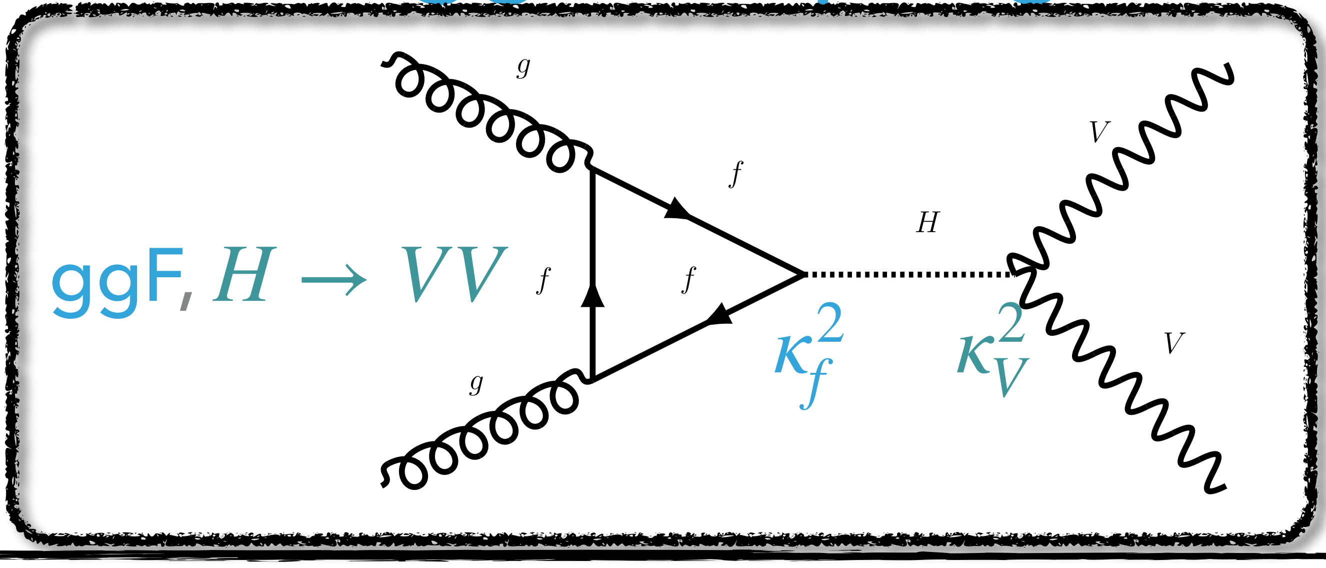
ttHbb

- Increased datasets and optimized analysis strategies result in estimating the STXS in the finest kinematic regions so far
- Newly updated analyses contribute sensitivities in finer splittings comparing to ATLAS-CONF-2020-027



κ framework

- To measure Higgs coupling strengths directly, and to test deviations from SM



- κ framework
  - Coupling modifiers to productions and decays

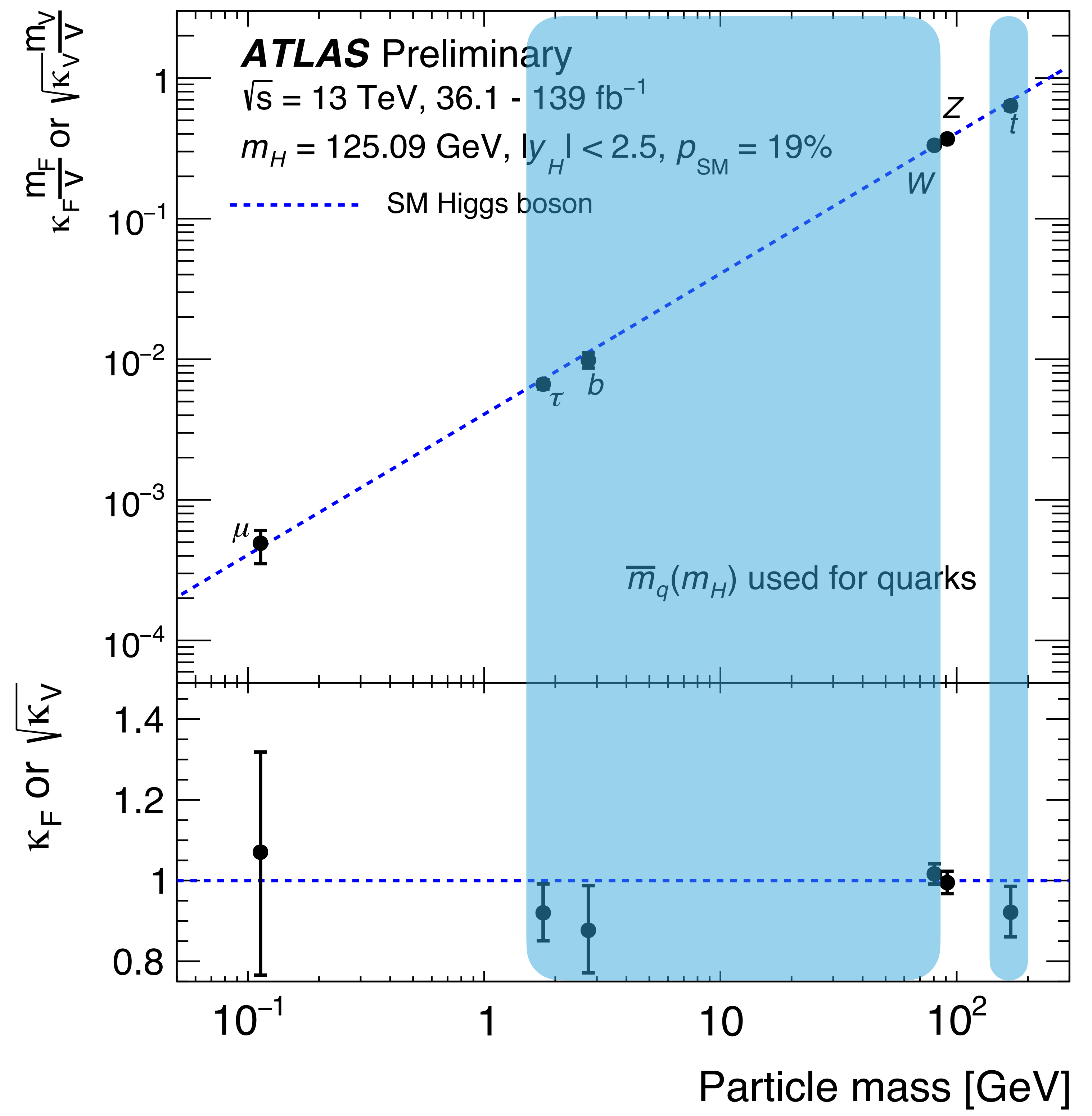
- $$\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}, \kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}, \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$$

- $$\frac{\Gamma_H}{\Gamma_H^{SM}} = \kappa_H^2(\kappa, B_i, B_u) = \frac{\sum_j B_f^{SM} \kappa_j^2}{1 - B_i - B_u}$$
  - B_i: Invisible decays
  - B_u: Non-sensitive decay signatures for the ATLAS

Production cross section	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{i.}} = B_{\text{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

κ model with direct couplings

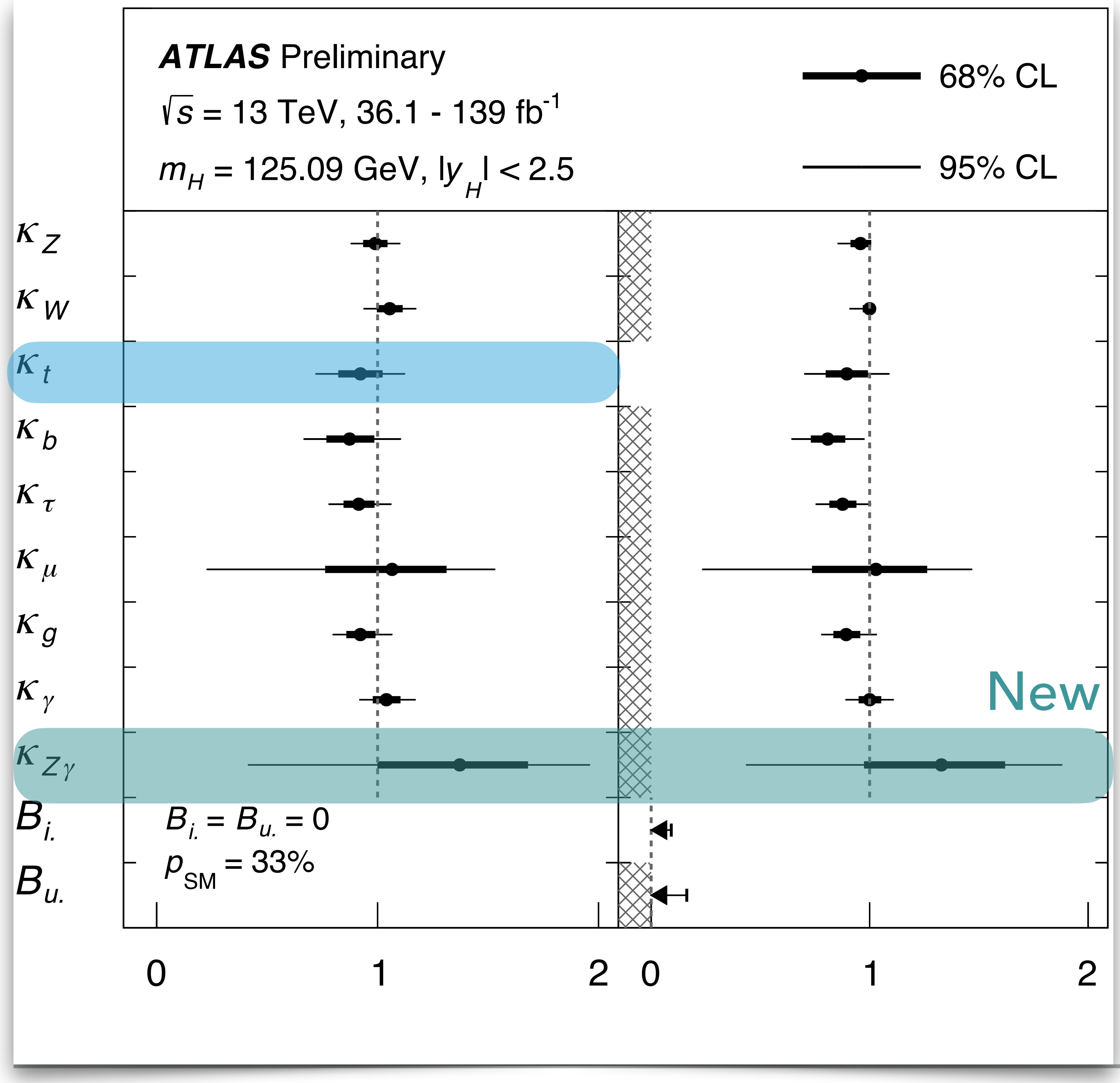
- Direct couplings: κ_W, κ_Z, κ_t (κ_c), κ_b (κ_s), κ_τ, κ_μ
- Assumption
  - All $\kappa \geq 0$
  - Only SM particle contribute to Higgs vertices
  - $B_i = B_u = 0$
- Newly updated $H \rightarrow WW$, (VBF, VH, ttH) bb, $H \rightarrow \tau\tau$ largely improve the precisions of κ_W, κ_t, κ_b, κ_τ by 9%~44% comparing to [ATLAS-CONF-2020-027]



Parameter	Result
κ_Z	0.99 ± 0.06
κ_W	1.03 ± 0.05
κ_b	0.88 ± 0.11
κ_t	0.92 ± 0.06
κ_τ	0.92 ± 0.07
κ_μ	$1.07\ ^{+\,0.25}_{-\,0.31}$

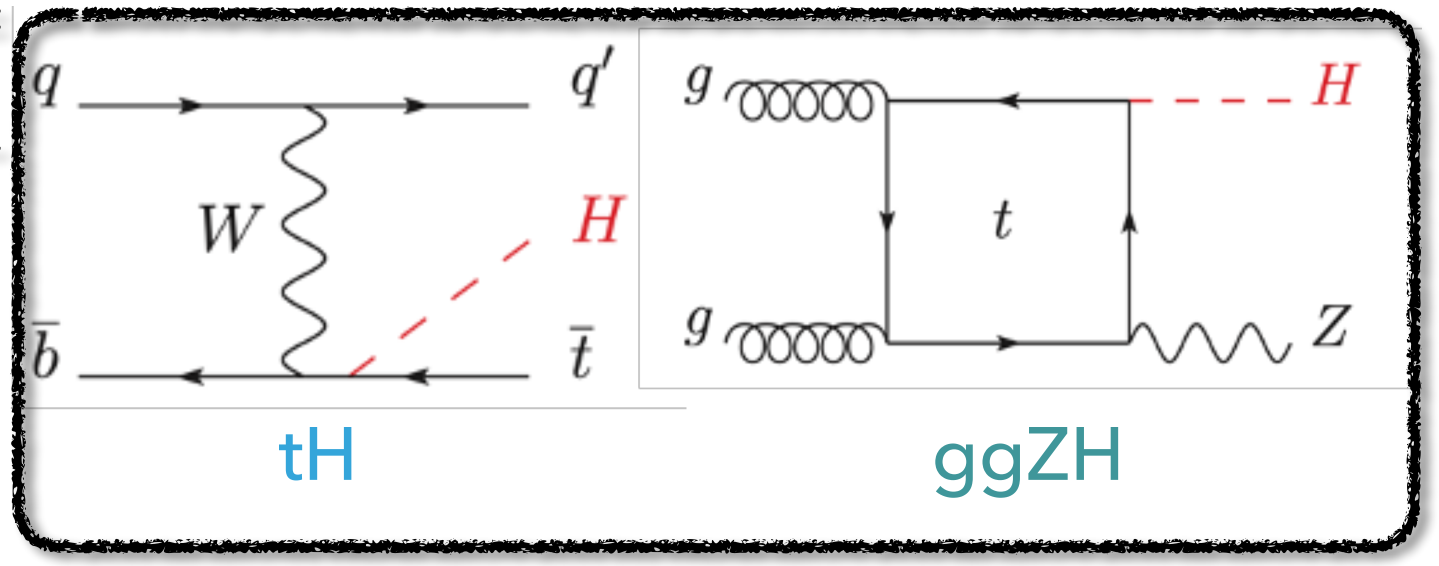
Generic model with/without BSM contributions

- $\kappa_W, \kappa_Z, \kappa_t\ (\kappa_c), \kappa_b\ (\kappa_s), \kappa_\tau, \kappa_\mu, \kappa_\gamma, \kappa_g, \kappa_{Z\gamma}\ (B_i, B_u)$
  - Effective κ_γ: $H \to \gamma\gamma$; κ_g: ggF, $H \to gg$; $\kappa_{Z\gamma}$: $H \to Z\gamma$ (new)
- All $\kappa \geq 0$ except κ_t



Parameter	(a) $B_{i.} = B_{u.} = 0$	(b) $B_{i.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	0.99 ± 0.06	$0.96\ ^{+0.04}_{-0.05}$
κ_W	1.06 ± 0.06	$1.00\ ^{+0.00}_{-0.03}$
κ_b	0.87 ± 0.11	0.81 ± 0.08
κ_t	0.92 ± 0.10	0.90 ± 0.10
κ_μ	$1.07\ ^{+0.25}_{-0.30}$	$1.03\ ^{+0.23}_{-0.29}$
κ_τ	0.92 ± 0.07	0.88 ± 0.06
κ_γ	1.04 ± 0.06	1.00 ± 0.05
$\kappa_{Z\gamma}$	$1.37\ ^{+0.31}_{-0.37}$	$1.33\ ^{+0.29}_{-0.35}$
κ_g	$0.92\ ^{+0.07}_{-0.06}$	$0.89\ ^{+0.07}_{-0.06}$
$B_{i.}$	-	< 0.09 at 95% CL
$B_{u.}$	-	< 0.16 at 95% CL

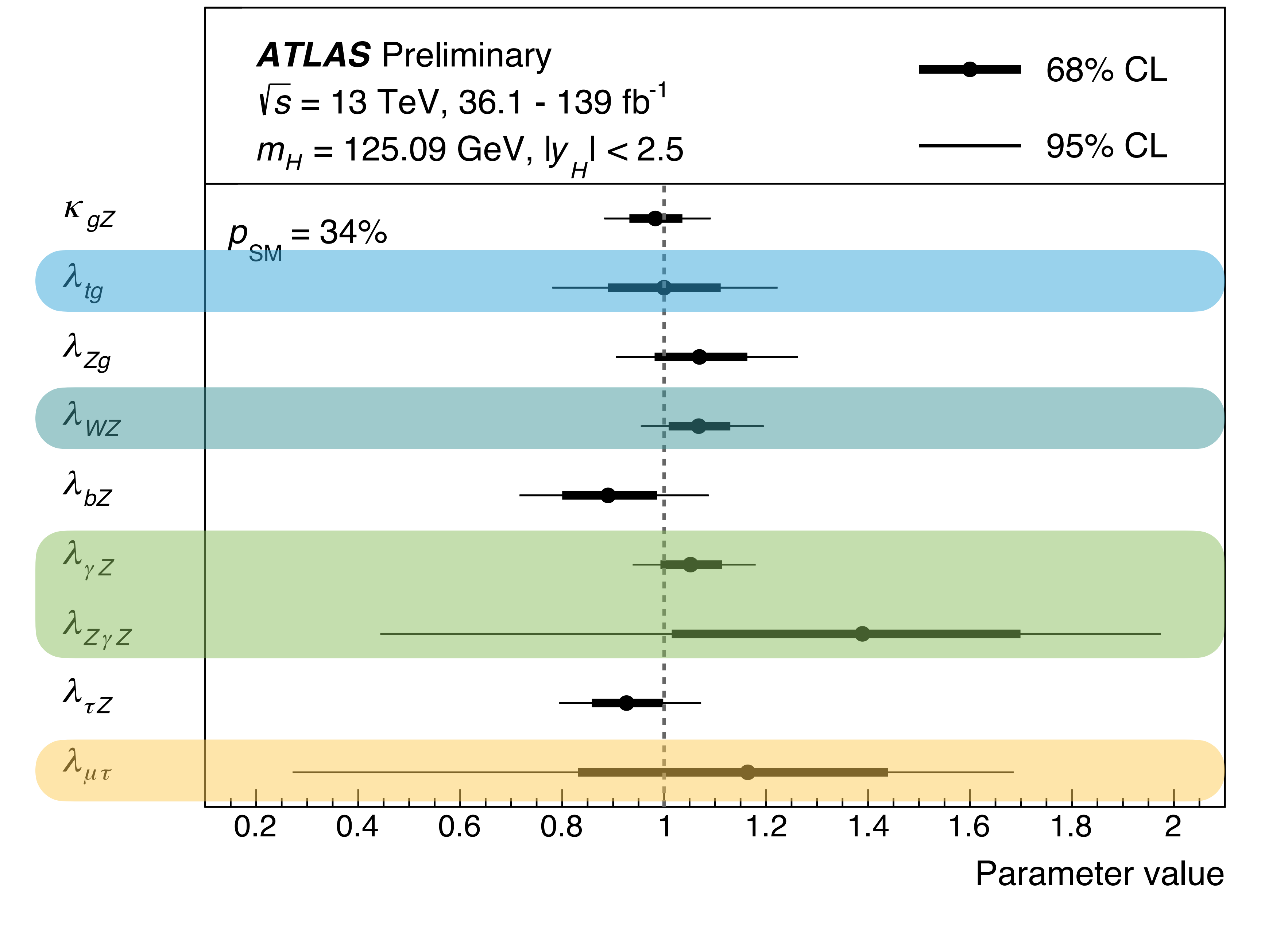
New



- Significance for excluding the negative κ_t: 4.3σ, mostly due to the tH (κ_t, κ_W) and ggZH (κ_t, κ_Z) contributions

Generic ratio model

- Most model-independent
  - Without assumptions about κ_H; Common systematics canceled out



Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g\kappa_Z/\kappa_H$	0.98 ± 0.05
λ_{tg}	κ_t/κ_g	1.00 ± 0.11
λ_{Zg}	κ_Z/κ_g	1.07 ± 0.09
λ_{WZ}	κ_W/κ_Z	1.07 ± 0.06
$\lambda_{\gamma Z}$	κ_γ/κ_Z	1.05 ± 0.06
$\lambda_{Z\gamma Z}$	$\kappa_{Z\gamma}/\kappa_Z$	$1.39^{+0.31}_{-0.37}$
$\lambda_{\tau Z}$	κ_τ/κ_Z	0.93 ± 0.07
λ_{bZ}	κ_b/κ_Z	$0.89^{+0.10}_{-0.09}$
$\lambda_{\mu\tau}$	κ_μ/κ_τ	$1.16^{+0.28}_{-0.33}$

- λ_{tg}: sensitive to new colored particles through ggF loop unlike in ttH/tH events
- λ_{WZ}: deviation of $\kappa_W = \kappa_Z$, which is required within tight bounds by SU(2) custodial symmetry
- $\lambda_{\gamma Z}$, $\lambda_{Z\gamma Z}$: sensitive to new charged particles contributing to $H \to \gamma\gamma$, $H \to Z\gamma$ loops unlike in $H \to ZZ$
- $\lambda_{\mu\tau}$: deviation of Higgs Yukawa couplings to the second/third generation fermions

Summary

- Higgs coupling properties are measured by combining Run2 data up to 139 fb^{-1} to reach the highest precision [ATLAS-CONF-2021-053]
  - First full Run2 results containing all major Higgs decays
- Global signal strength $\mu = 1.06 \pm 0.06$
  - 10% improvement in accuracy comparing to ATLAS-CONF-2020-027, 44% improvement comparing to Run1
- Higgs production cross sections and decay BR are measured
  - Precision largely improved due to various powerful analyses contributing to different modes and optimized analysis strategies
- Finest STXS stage 1.2 measurements so far
- Higgs couplings are directly measured within κ frameworks
- No derivations from the SM predictions are observed
- BSM interpretation: Changqiao
- Precise measurements of Higgs boson properties at HL-LHC are helpful to address open questions about the universe
  - Possible to observe Higgs rare decays (expected precision of $BR(H \to \mu\mu)$: 14%, $BR(H \to Z\gamma)$: 24% ATL-PHYS-PUB-2018-054)