Higgs Property Measurement @ ATLAS

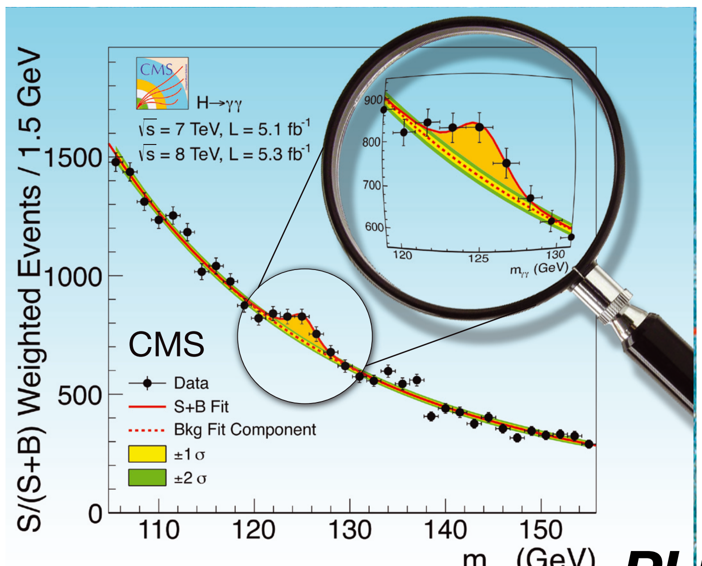
Yanping Huang

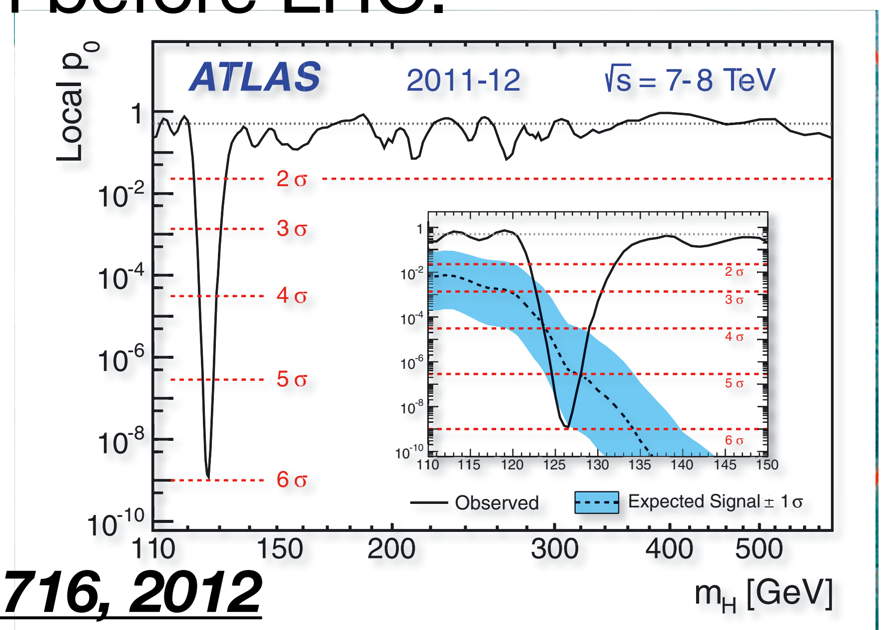
(IHEP, CHINA)

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

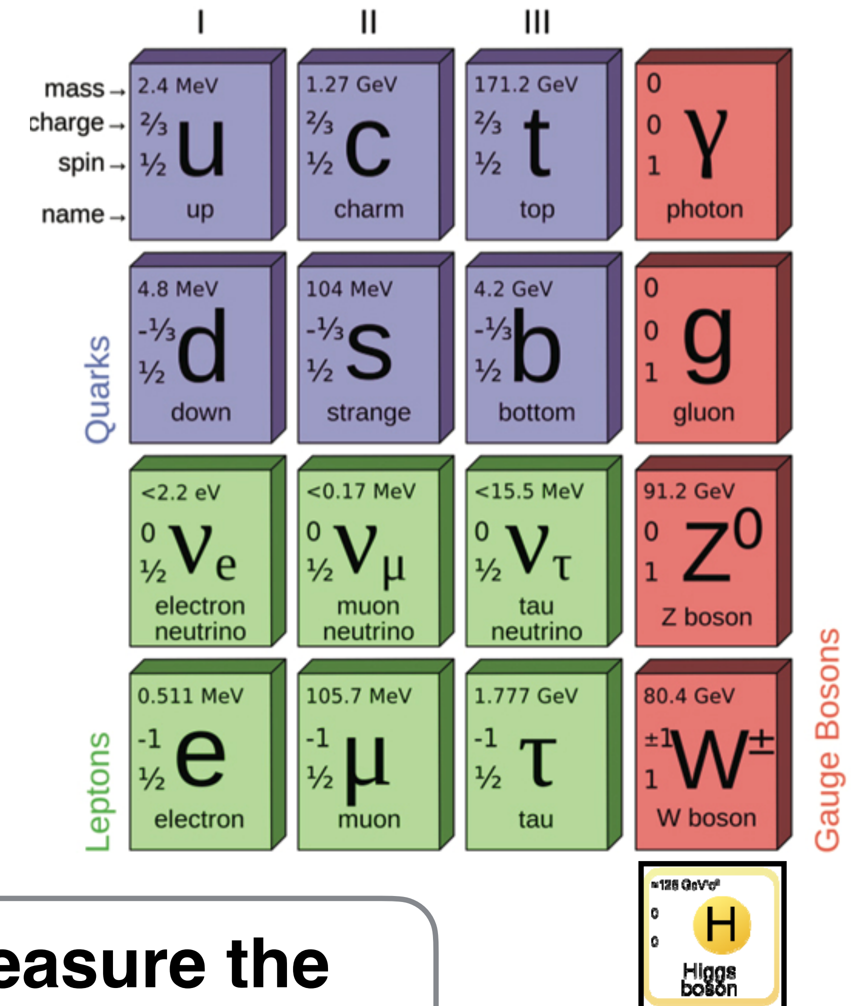
Higgs particle

- The Higgs particle is **responsible for the masses of elementary particles**, while was the **missing corner stone** of the SM before LHC.





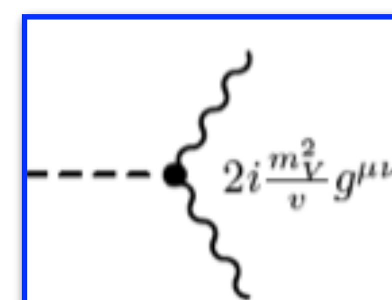
PLB, 716, 2012



Higgs discovery: A new era of particle physics — measure the properties of the new particle

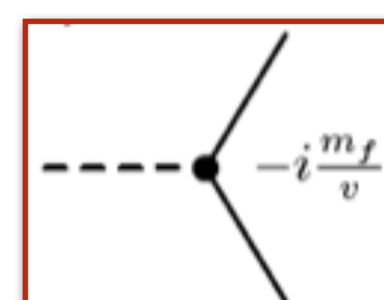
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

Gauge coupling



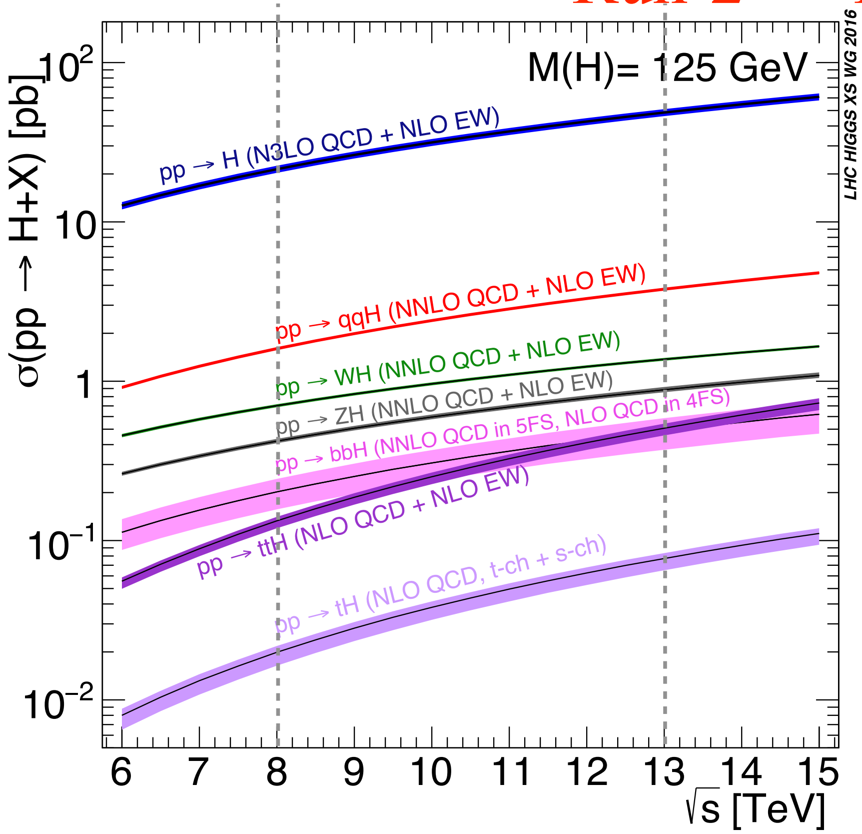
Self-coupling

Yukawa coupling



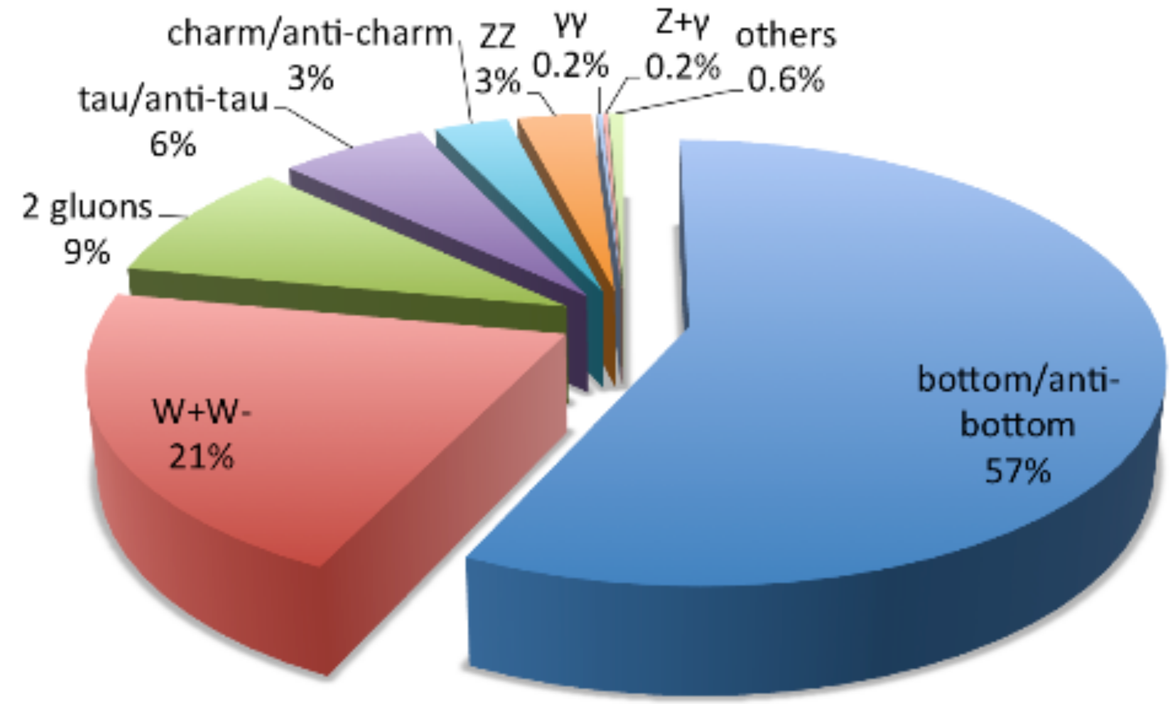
Higgs boson production and decays @ LHC

Run-1 Run-2 Run-2/1

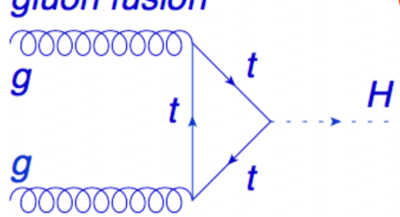


2.3
2.4
2.0
2.1
3.9
~4 (missing WtH)

Many decay modes accessible with different properties

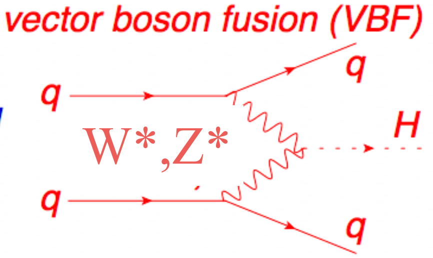


gluon fusion



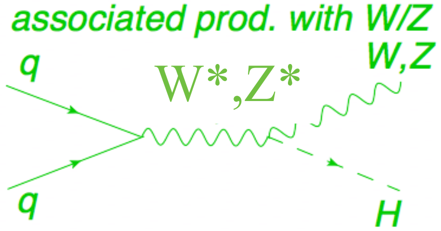
~48.6 pb (88%)

vector boson fusion (VBF)



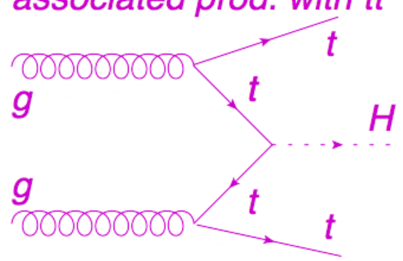
~3.8 pb (7%)

associated prod. with W/Z



~2.3 pb (4%)

associated prod. with tt



~0.5 pb (1%)

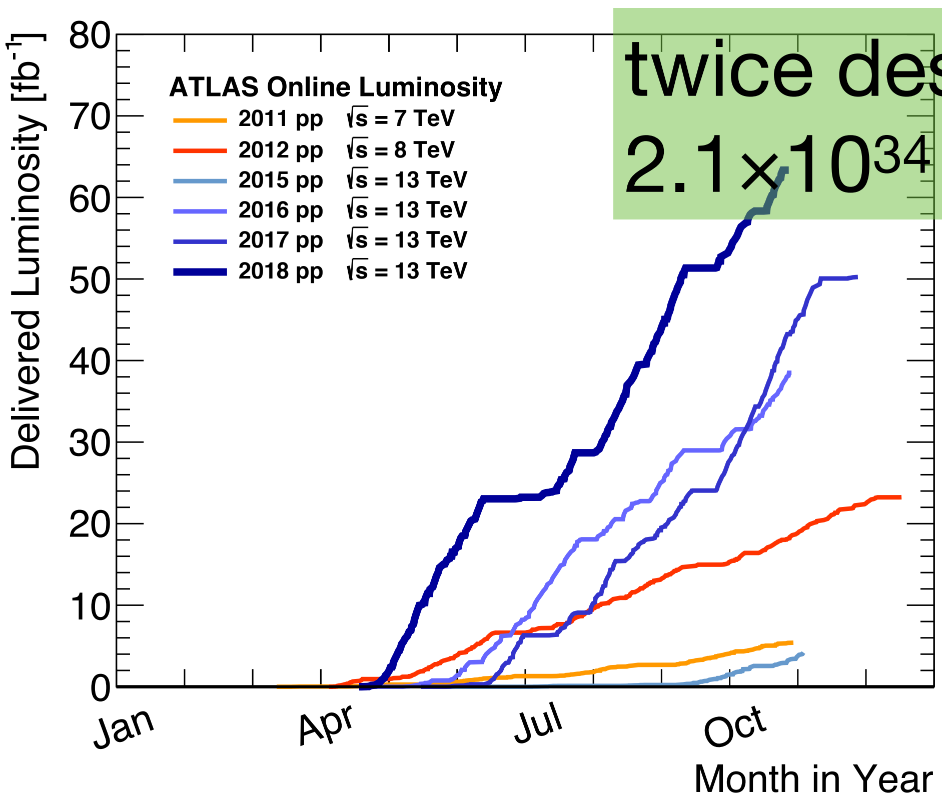
ZZ* and γγ: high resolution and precise differential measurements

WW*: high BR but low mass resolution

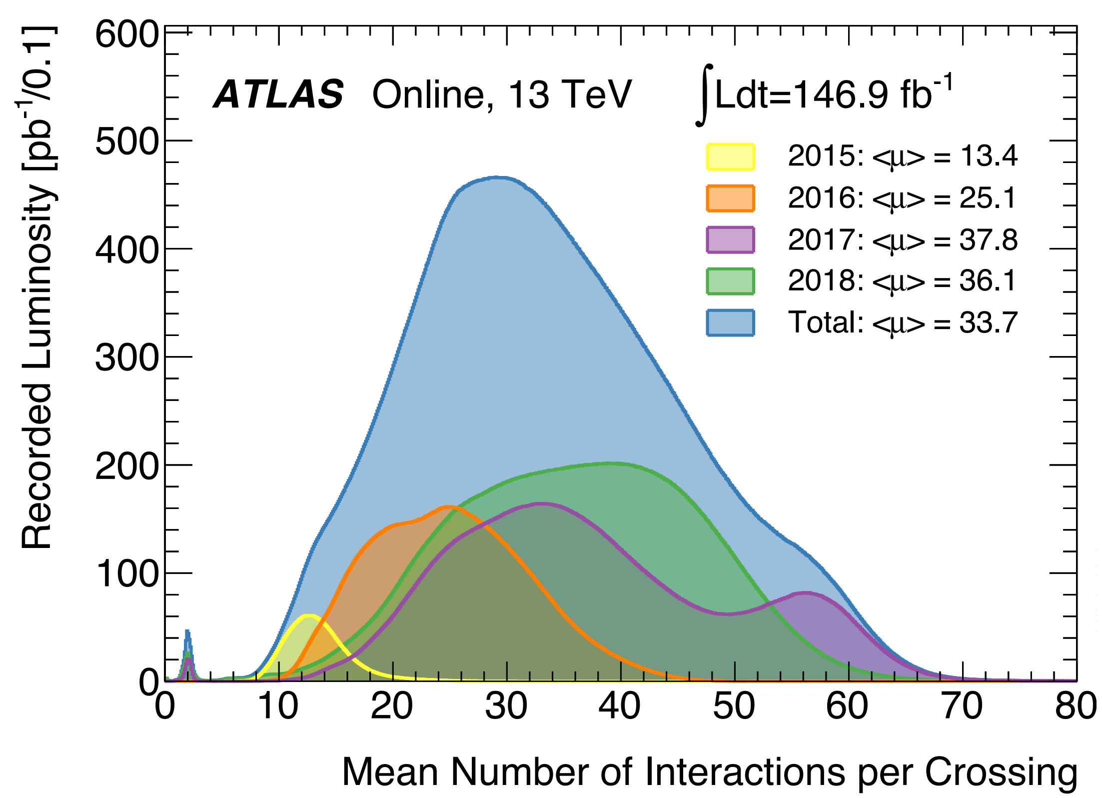
ττ and bb: high BR but low S/B, important to directly probe Yukawa coupling with 3rd generation

μμ: very small BR but access to Yukawa coupling with 2nd generation fermions

LHC/ATLAS



twice design:
$2.1{\times}10^{34}$ cm^{-2}s^{-1}

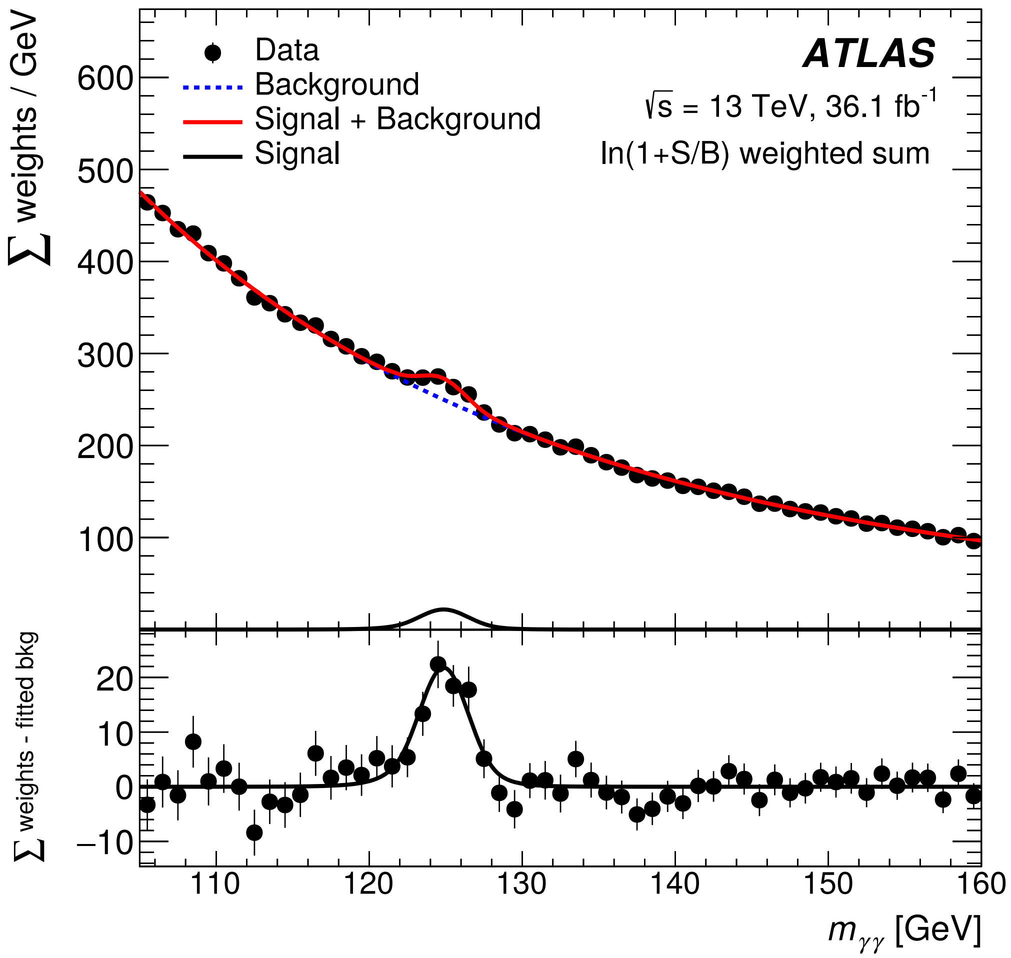


Full Run2 data-taking finished (~ 140 fb^{-1}): 13 TeV, 25 ns bunch spacing

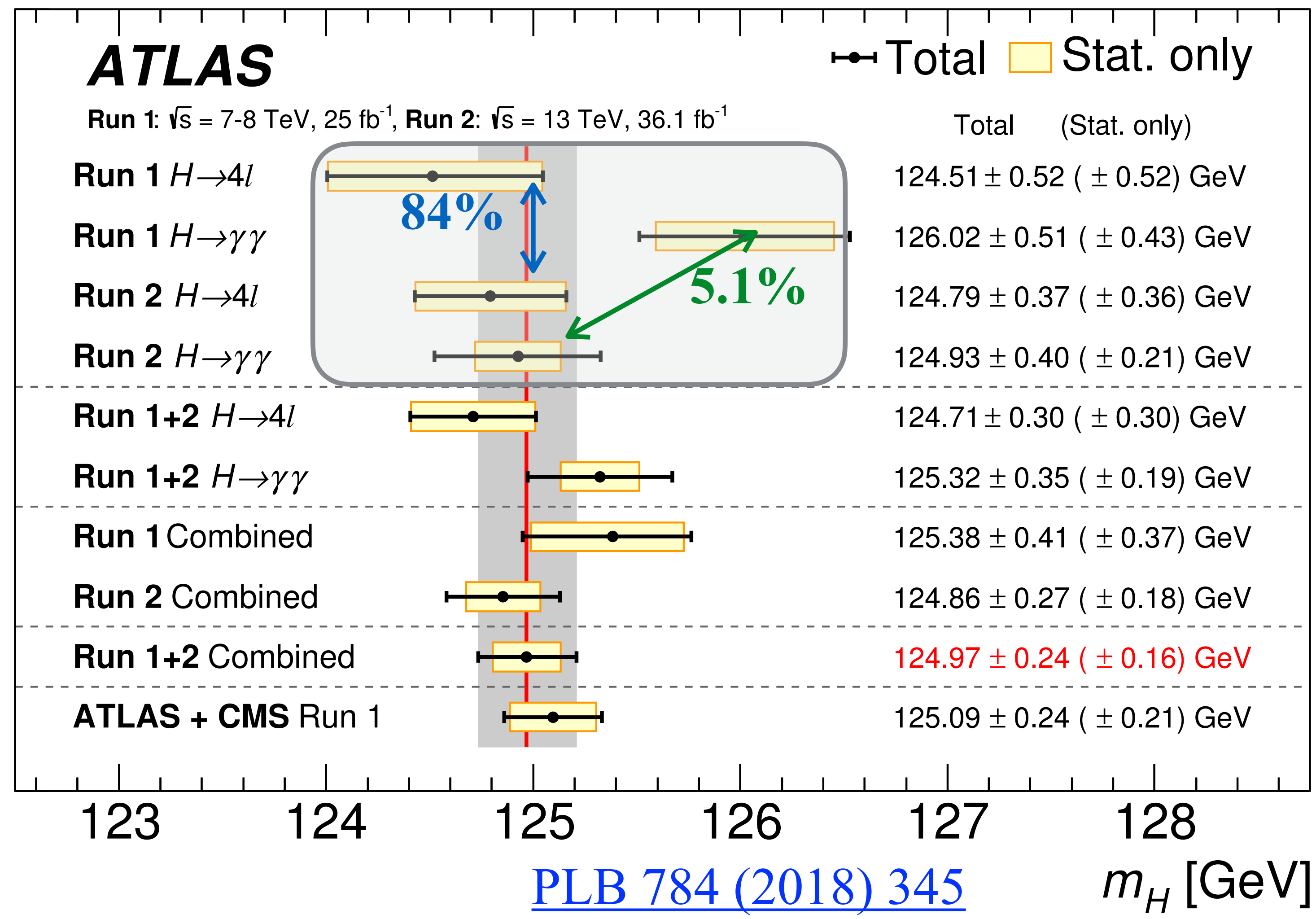
Outline

- **Higgs mass and width**
- **Higgs combination measurement and interpretation:**
  - Coupling/STXS/Diff. XS
- **Di-Higgs search**
- **Higgs rare decays**
  - $H \rightarrow inv$
  - $H \rightarrow \mu\mu$
  - $H \rightarrow Z\gamma$

Higgs Mass



Compatible with 12.3%



PLB 784 (2018) 345

CMS :125.26±0.21(±0.20±0.08)GeV (0.17%) JHEP 11(2017)047

- Precise measurements with excellent detector performance : **$\sigma(m_H)/m_H$ ~ 0.17% (CMS) and 0.21% (ATLAS),** are better/comparable w.r.t. **ATLAS+CMS Run-1 combination 0.19%**
- Still dominated by statistical uncertainties, uncertainty on coupling ~ 0.5%

Higgs Width

It is impossible to extract the coupling and Higgs width separately from on-shell cross section measurement → Importance of Γ_H measurement.

$$\sigma^{on-shell}_{i\to H\to f}(SM) \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

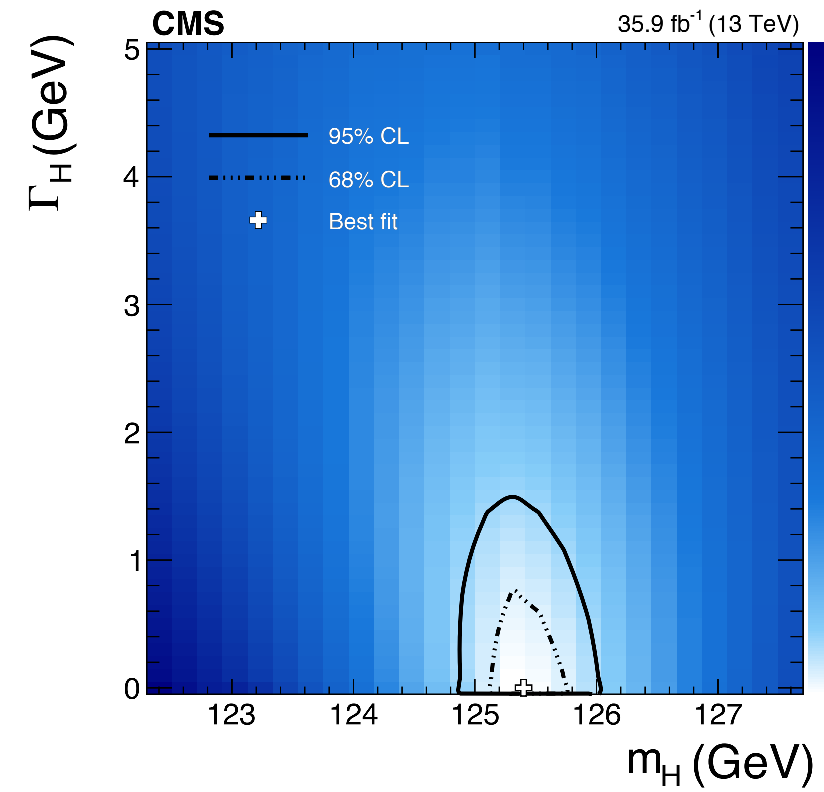
SM: $m_H = 125\text{GeV} \rightarrow \Gamma_H = 4.07\text{MeV}$
Γ_H cannot be accessed directly due to the experiment resolution

Run-1 direct Higgs width measurement:

Γ: obs.(exp.) @ 95% CL	H→γγ	H→ZZ
ATLAS	5.0 (6.2) GeV	2.6 (6.2) GeV
CMS	2.4 (3.1) GeV	3.4 (2.8) GeV

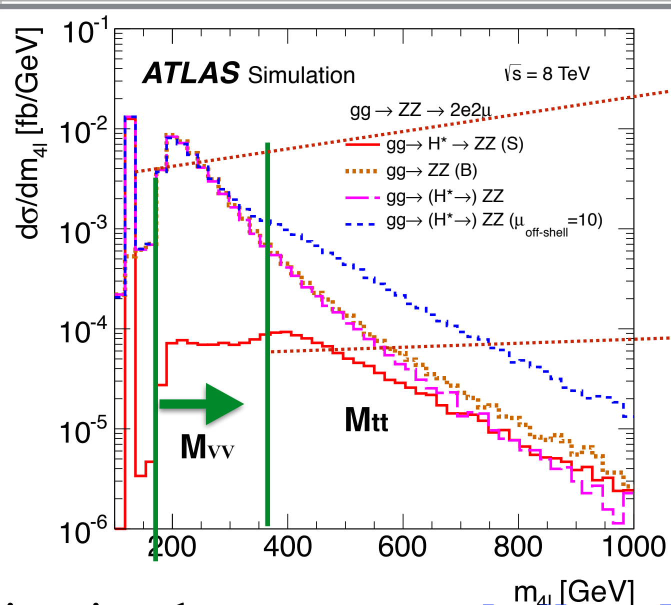
Latest CMS: 1.1 (1.6) GeV

3 orders of magnitude larger than SM width



JHEP 11(2017) 047

Indirect Higgs Width Measurement



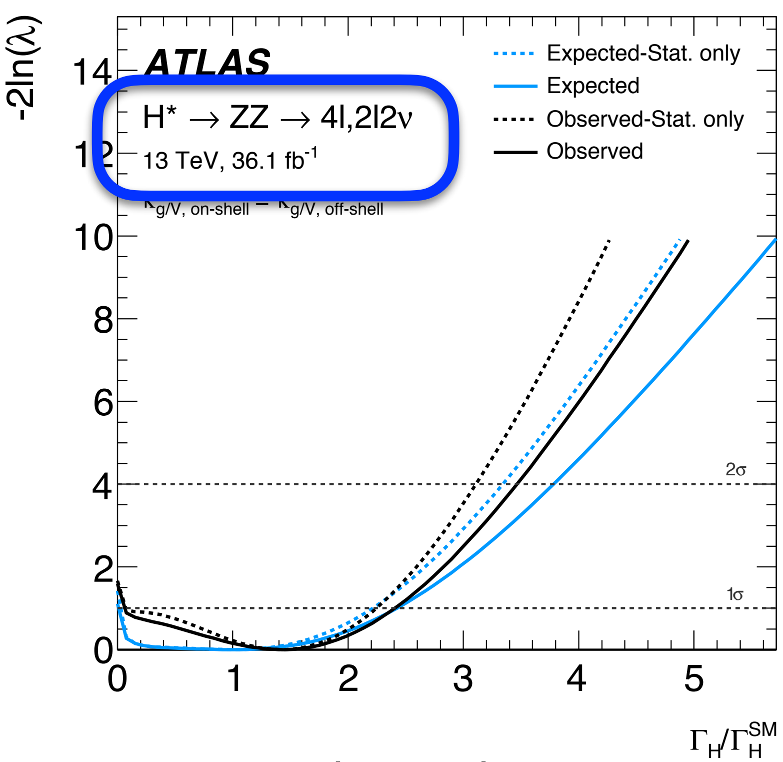
$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{offshell} = \mu_{onshell} \times \Gamma_H / \Gamma_H(SM)$$

With the combination between **on-shell and off-shell analyses**

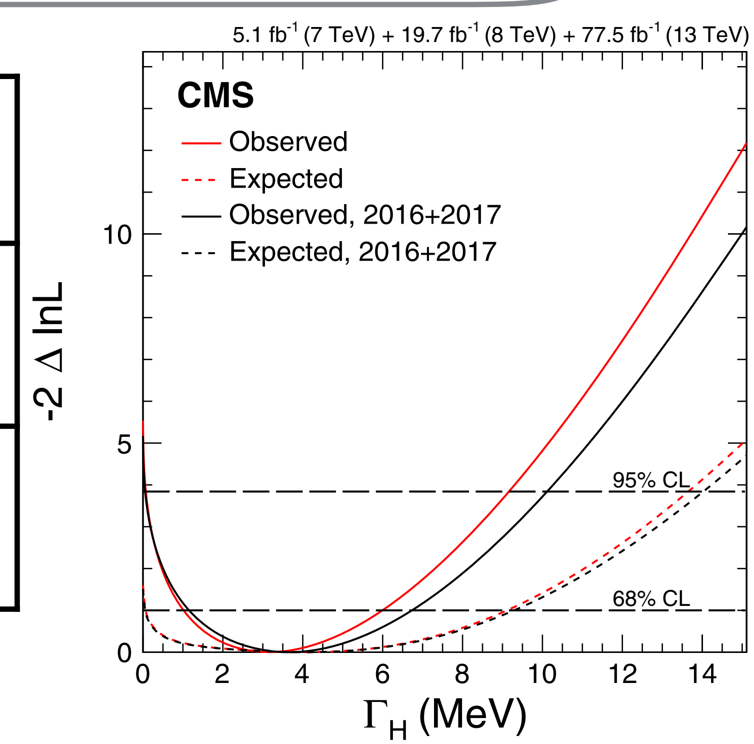
- ✦ **Assuming the on-shell coupling modifiers are the same as the off-shell coupling modifiers**
- ✦ Assuming NP modifying off-shell coupling **without the modification of other background and signal expectation.**



PLB 786 (2018) 223

Γ_H	Obs. (Exp.) @95 CL.
ATLAS @95 CL.	<14.4 (15.2) MeV <3.8 (3.4) $\times\Gamma_{SM}$
CMS	9.16 (13.7) MeV 2.2 (3.3) $\times\Gamma_{SM}$

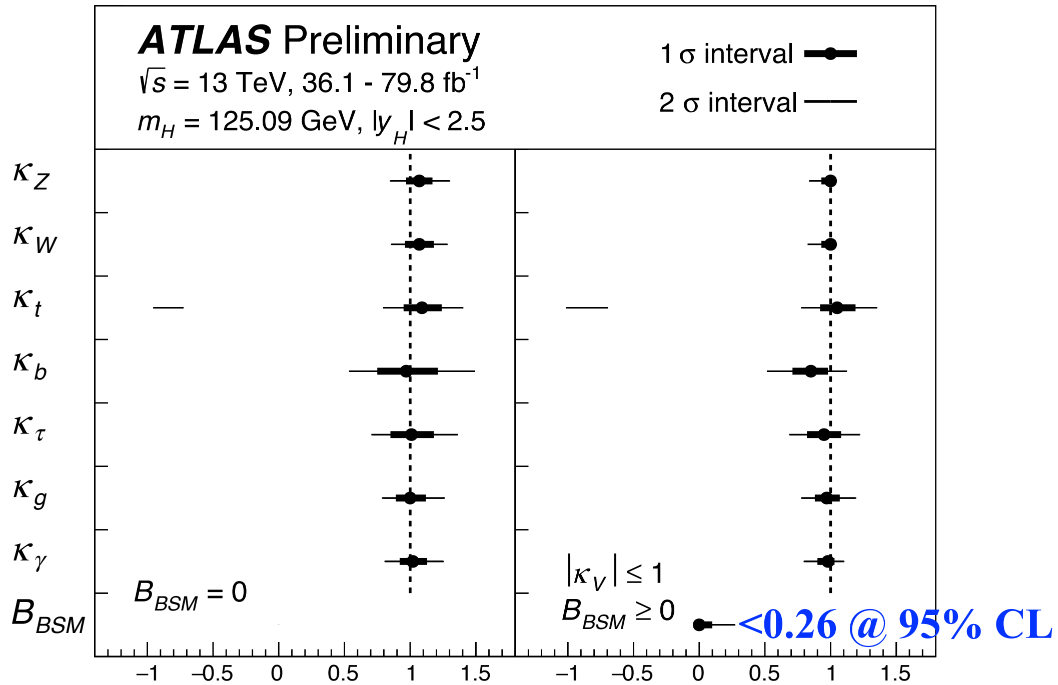
Latest CMS: $3.2^{+2.8}_{-2.2}(4.1^{+5.0}_{-4.0})$ MeV

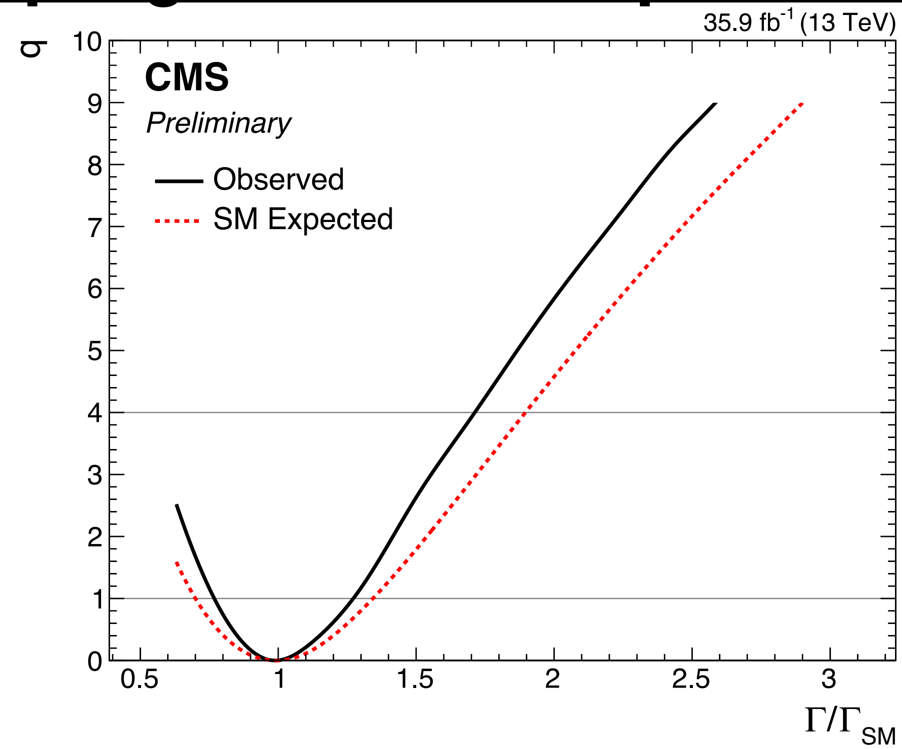


PRD 99 (2019) 112003

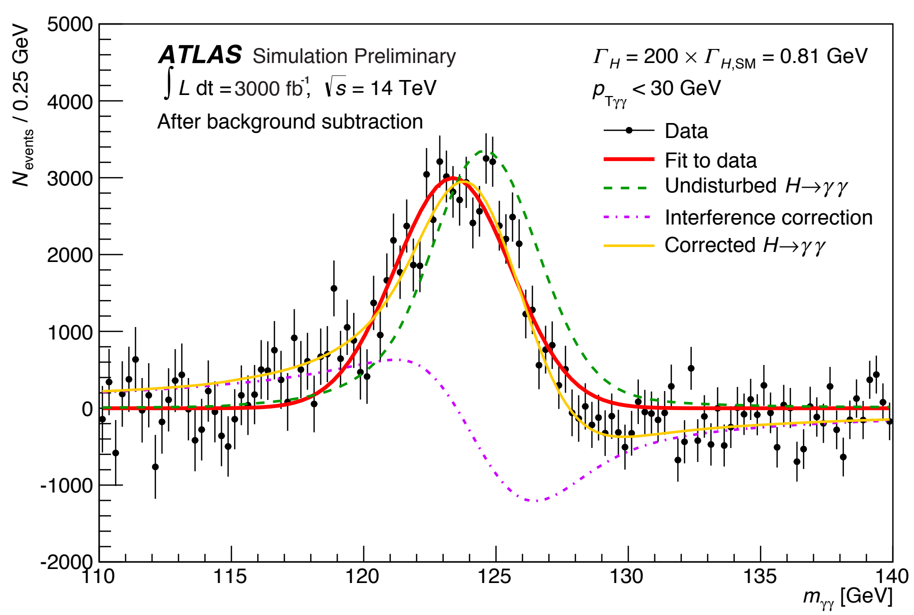
Indirect Higgs Width Measurement

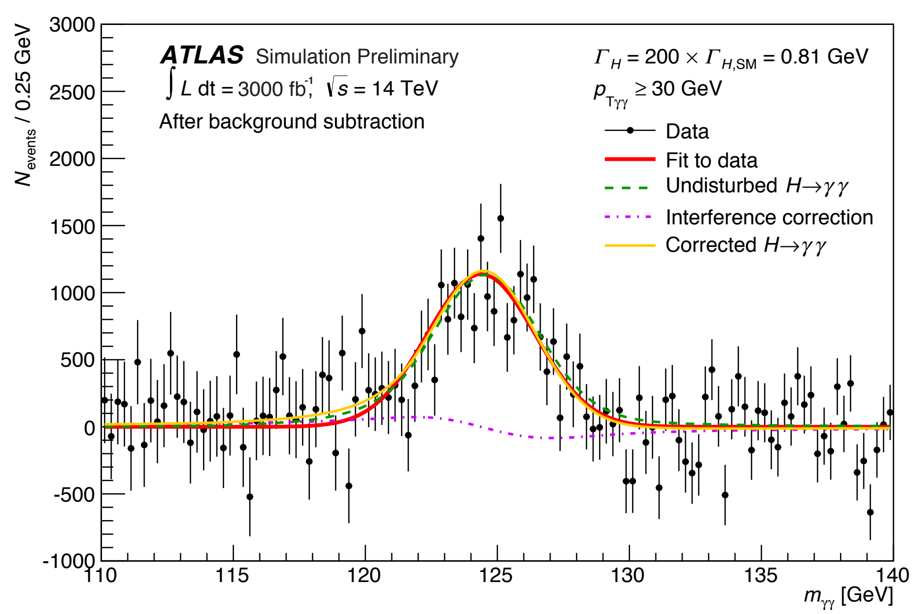
Introduce the BSM contribution in the Coupling combination parametrization





Extract the Higgs width with **the mass shift from the interference** of the H→γγ w.r.t the continuum background (gg→γγ box diagrams)





ATLAS @ 3000 fb^{-1}: <160MeV @95%

Coupling/XS Measurement Methodology

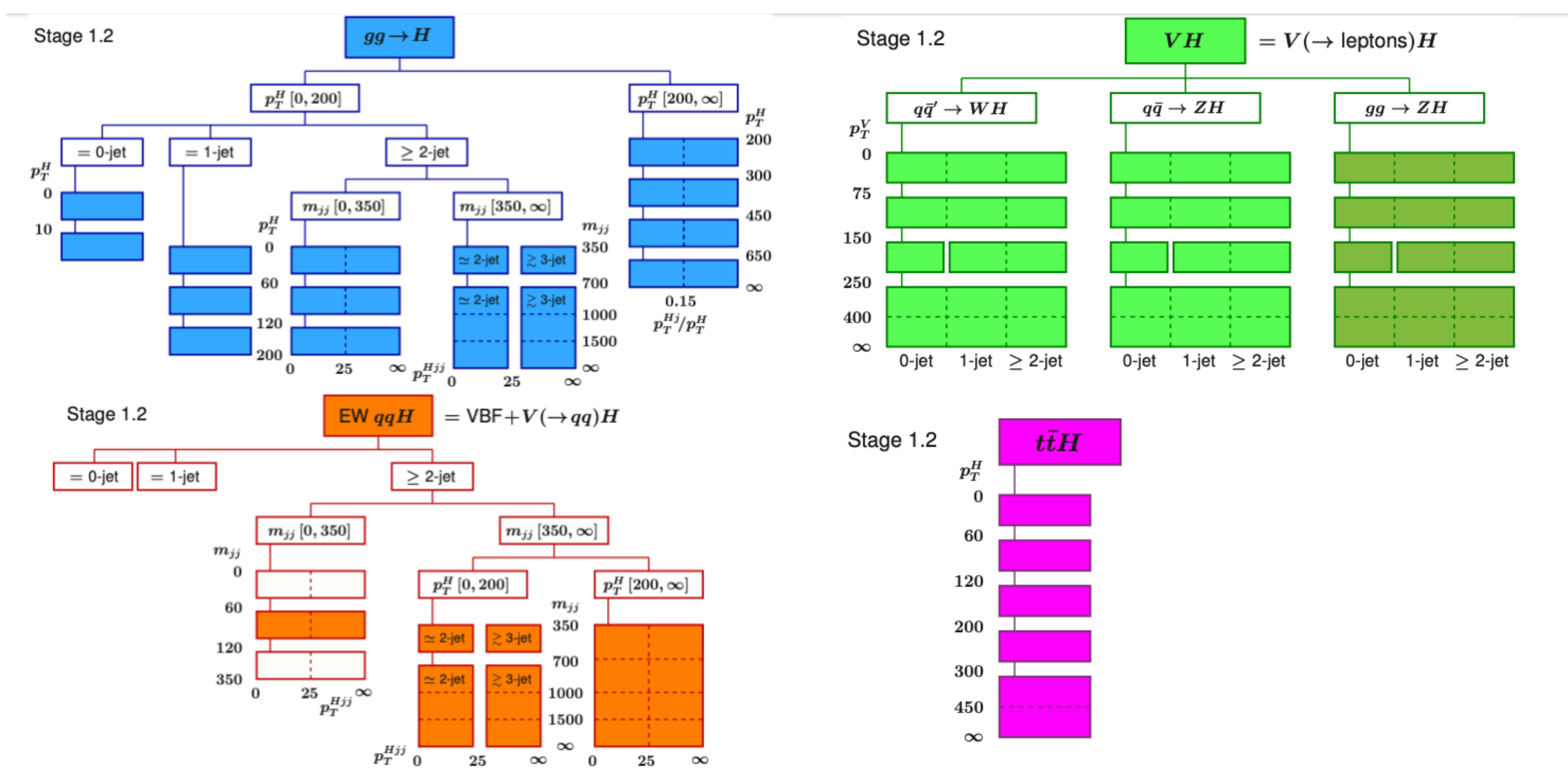
Run 1-style coupling measurements: μ, kappa

Simplified template cross sections

Fiducial/differential cross sections

Model independence →

← Analysis power



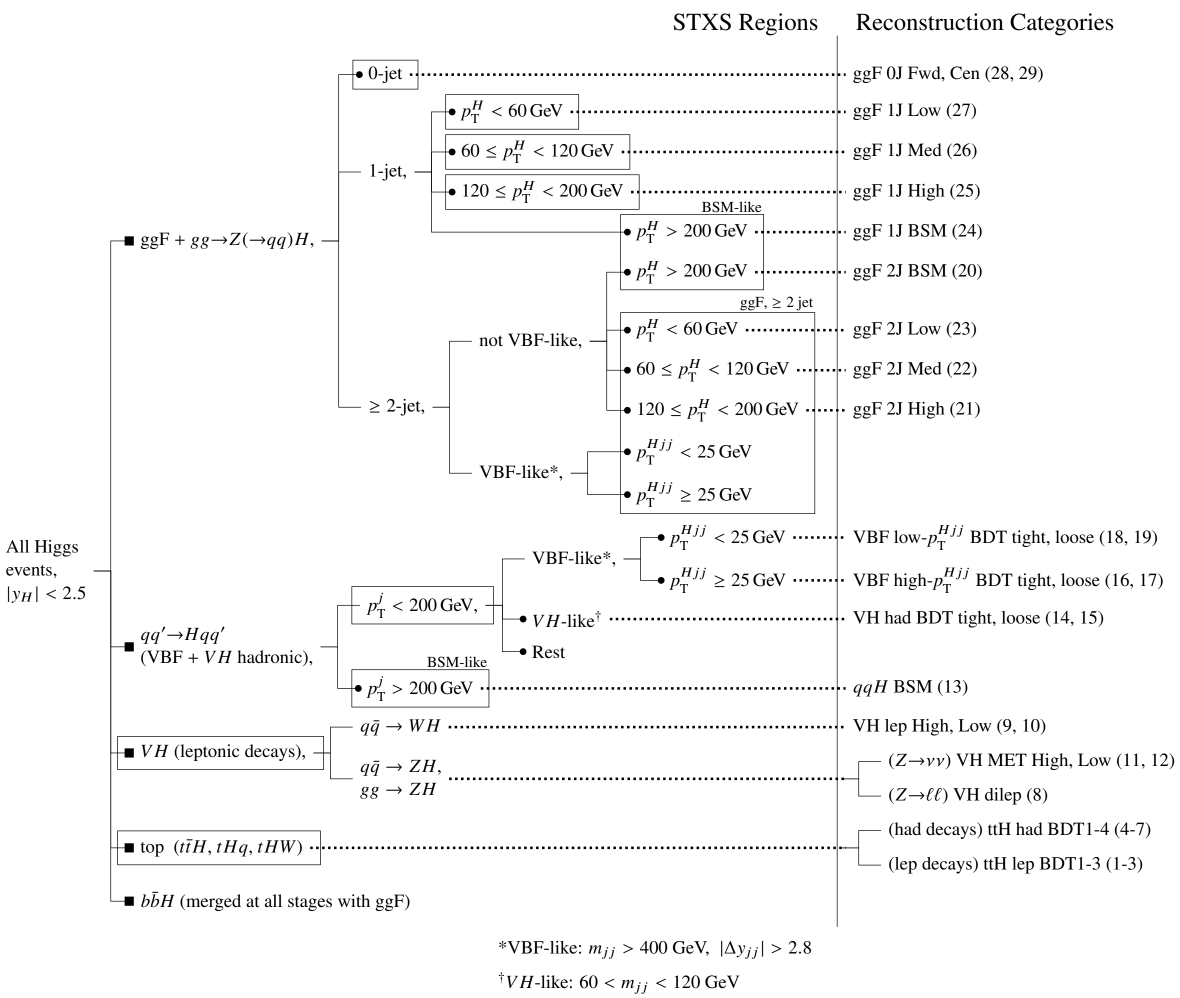
◈ Less model dependence

◈ Make use of Rec. optimization for sensitive improvement

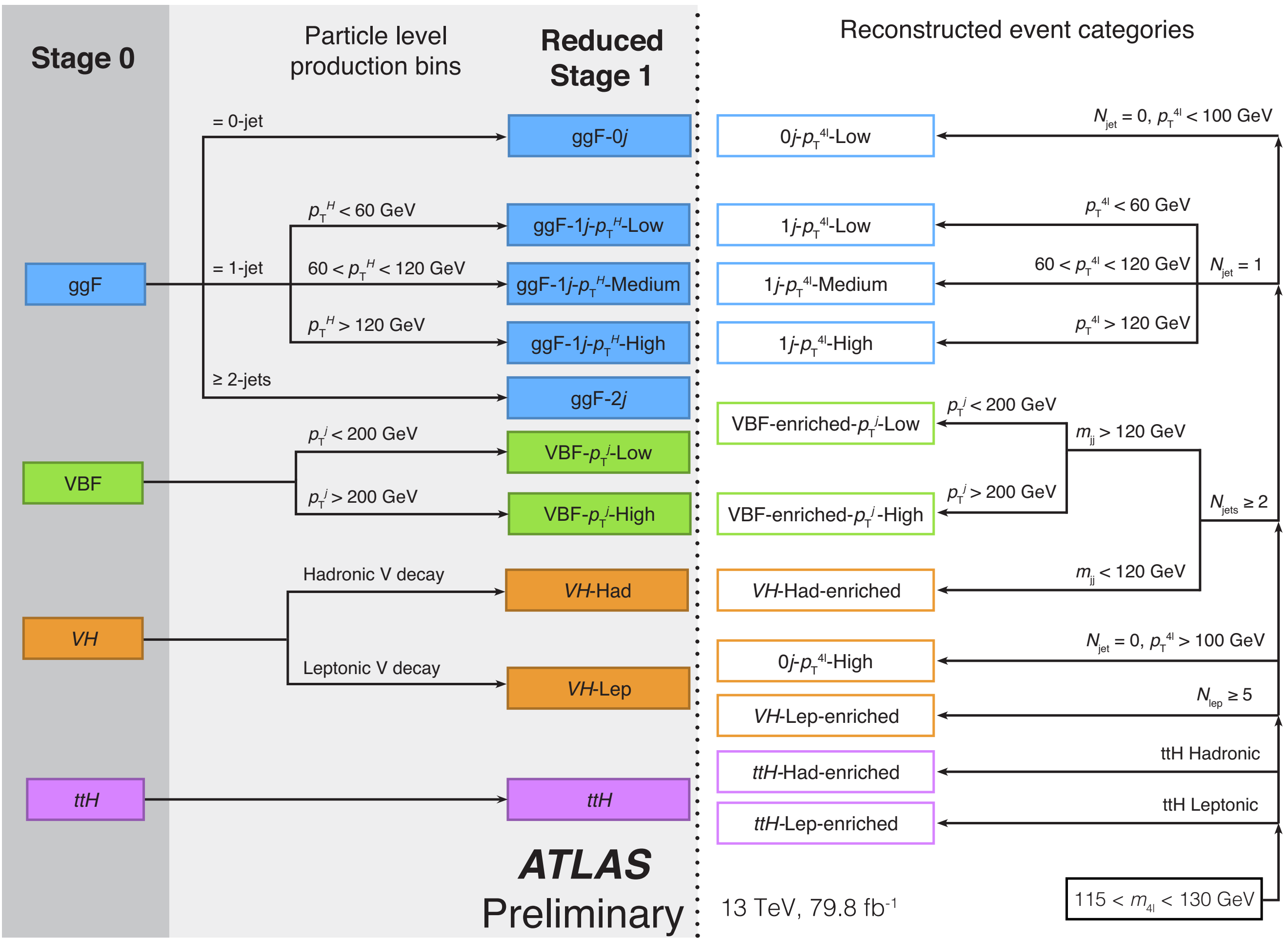
◈ Further combination and interpretation (signal strength, EFT, BSM)

Event categorization @ Rec. level

H→γγ



H→ZZ



Event categories are defined based on kinematic properties of the γγ/4l system + extra particles in the event

- **Sensitivity optimization is constrained in the STXS bins:** new physics beyond that, lost some global sensitivity, complicated bins and no sensitivity for some bins given current statistics (anti-correlation)

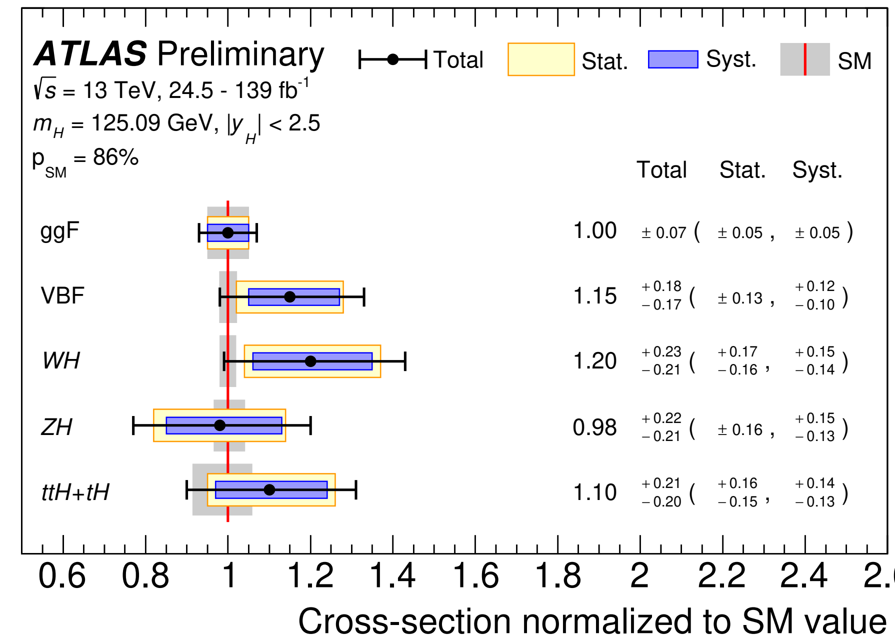
Signal strength

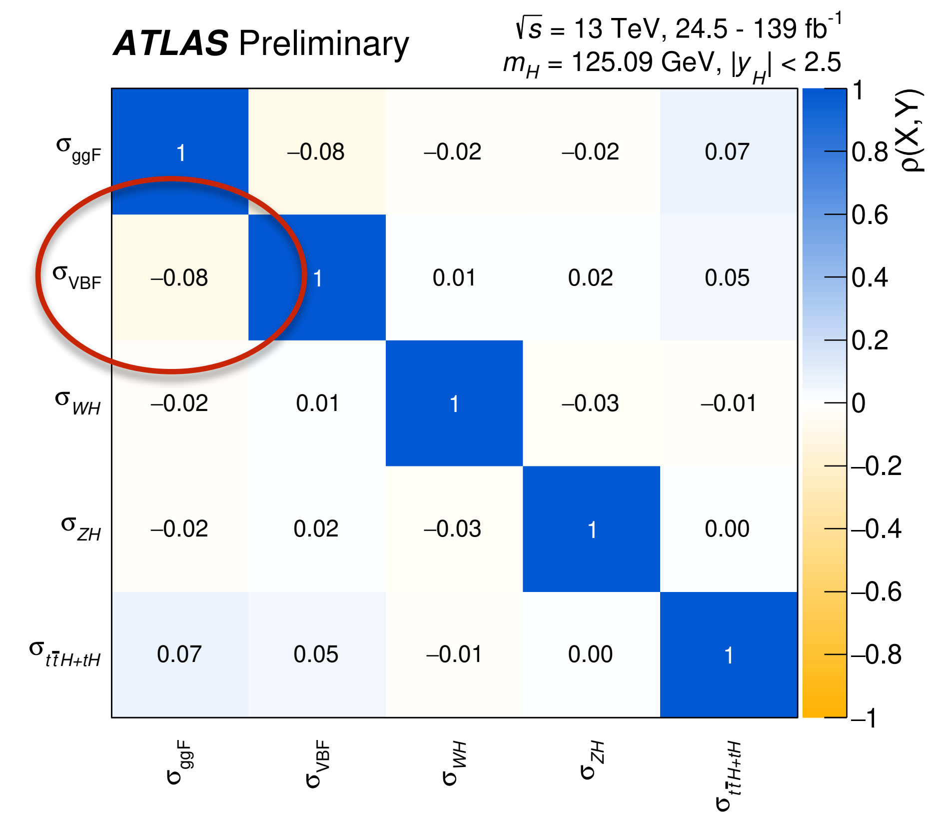
$$\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04\,(\text{stat.}) \pm 0.03\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$$

7%

Analysis decay channel	Target Prod. 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
	$t\bar{t}H$ excl. $H \to ZZ^* \to 4\ell$	36.1
$H \to WW^*$	ggF, VBF	36.1
	$t\bar{t}H$	
$H \to \tau\tau$	ggF, VBF	36.1
	$t\bar{t}H$	
$H \to b\bar{b}$	VBF	24.5 – 30.6
	WH, ZH	139
	$t\bar{t}H$	36.1
$H \to \mu\mu$	ggF, VBF, $VH, t\bar{t}H$	139
$H \to inv$	VBF	139

Process ($\lvert y_H\rvert < 2.5$)	Value [pb]	Total	SM pred. [pb]
ggF	44.7	± 3.1	44.7 ± 2.2
VBF	4.0	± 0.6	$3.51\,^{+0.08}_{-0.07}$
WH	1.45	$^{+0.28}_{-0.25}$	1.204 ± 0.024
ZH	0.78	$^{+0.18}_{-0.17}$	$0.797\,^{+0.033}_{-0.026}$
$t\bar{t}H + tH$	0.64	± 0.12	$0.59\,^{+0.03}_{-0.05}$

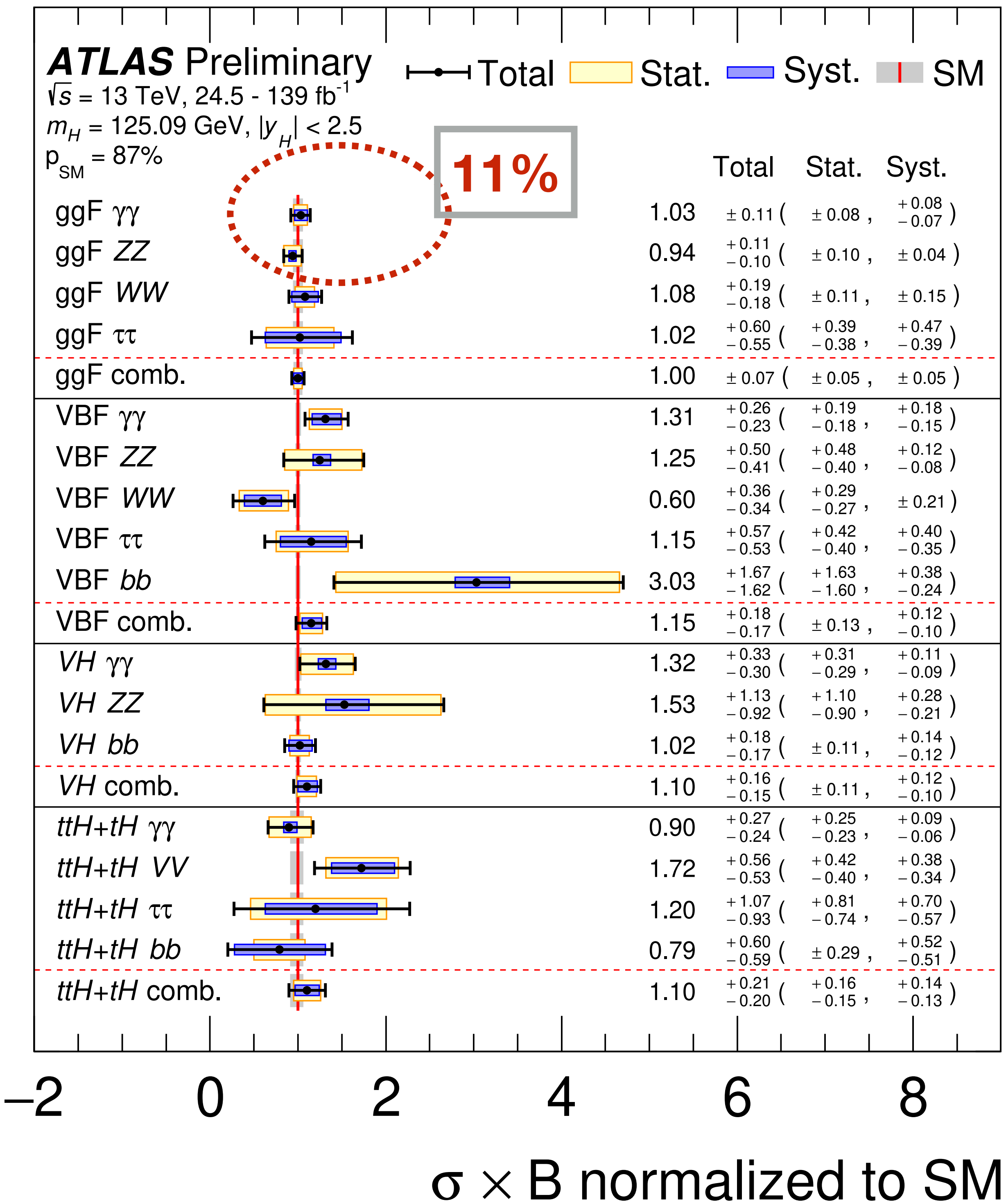


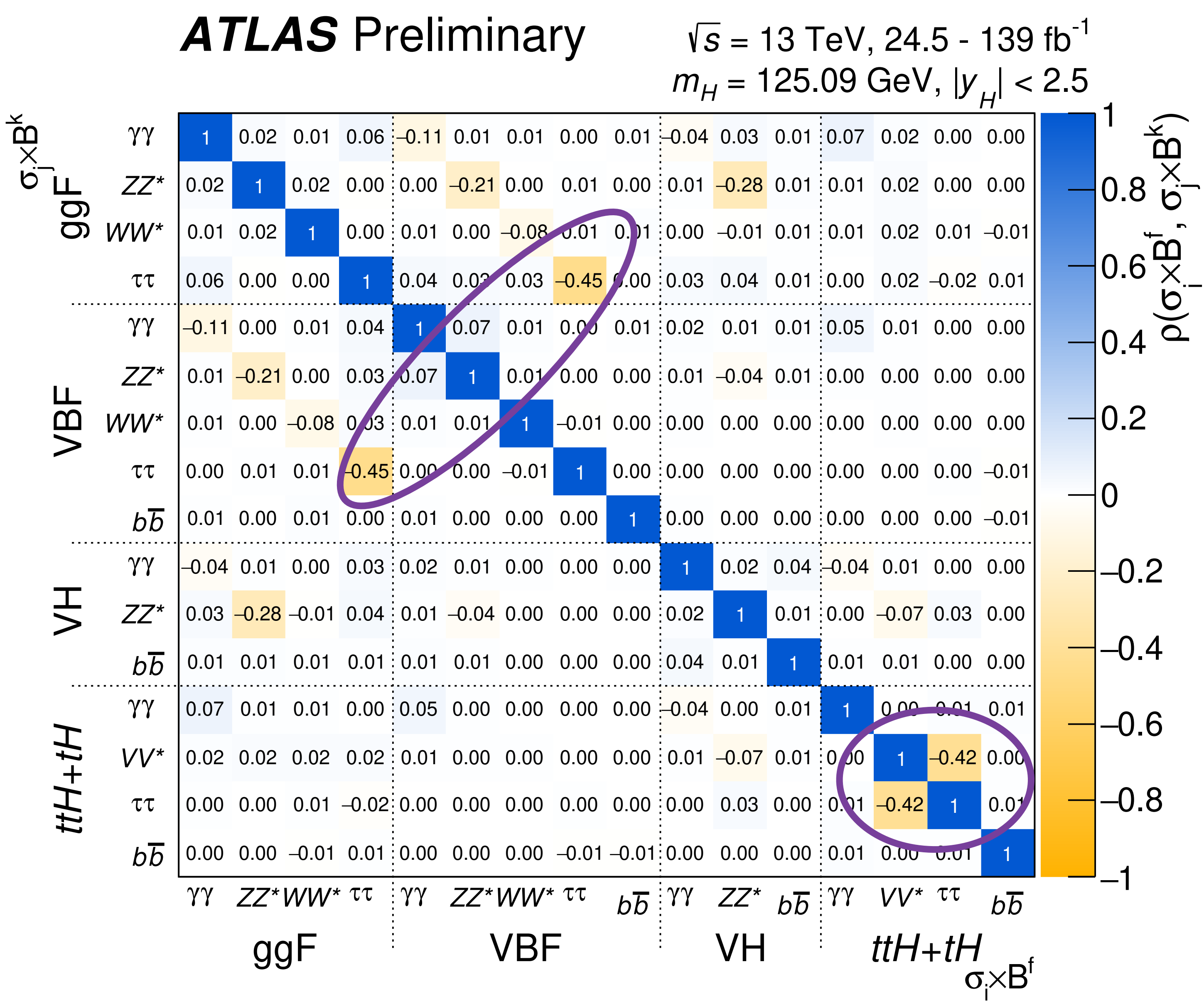


ATL-CONF-2020-027

- Significances of all major production modes (ggF, VBF, WH, ZH, tty) > 5σ
- **First observation for WH:** obs(exp) significances are 6.3 (5.2) σ for WH and 5.0 (5.4) σ for ZH

Product of production XS and BR



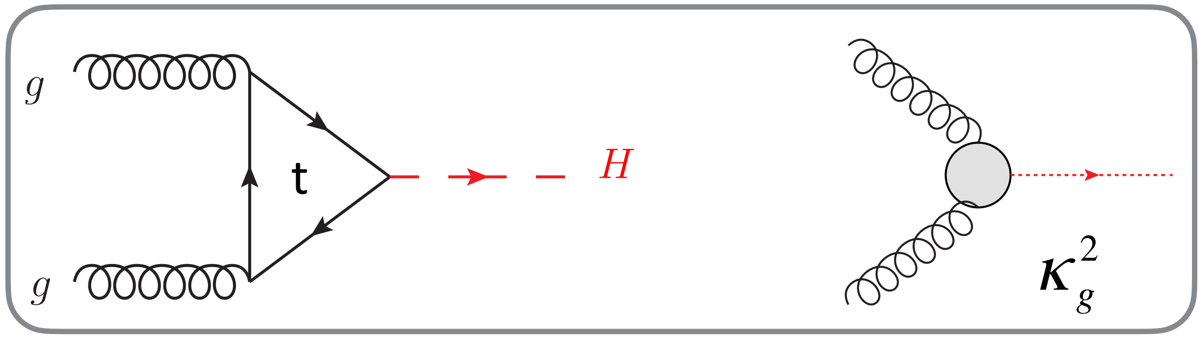


κ-framework

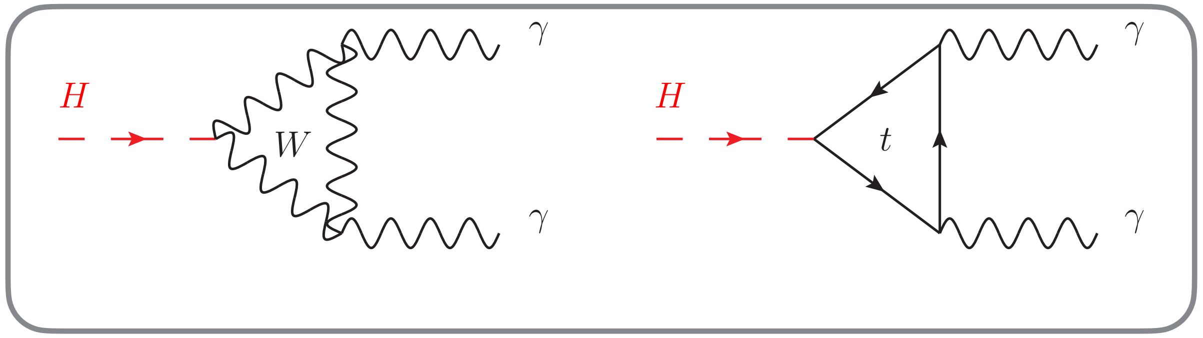
- **Assumptions:**
  - Single state, spin 0 and CP-even.
  - Narrow-width approximation: $(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \dfrac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$
- **Methodology:** parametrize deviations with coupling scale factors $\{\kappa_x\}$

Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(\mathrm{ggF})$	✓	$t-b$	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	-	-	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	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 ($B_{inv} = B_{undet} = 0$)				
Γ_H	✓	-	κ_H^2	$0.58\,\kappa_b^2 + 0.22\,\kappa_W^2$ $+0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2$ $+0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

- Assume that κ_c varies as κ_t and κ_S varies as κ_b
- SM assumption for κ_u, κ_d and κ_e

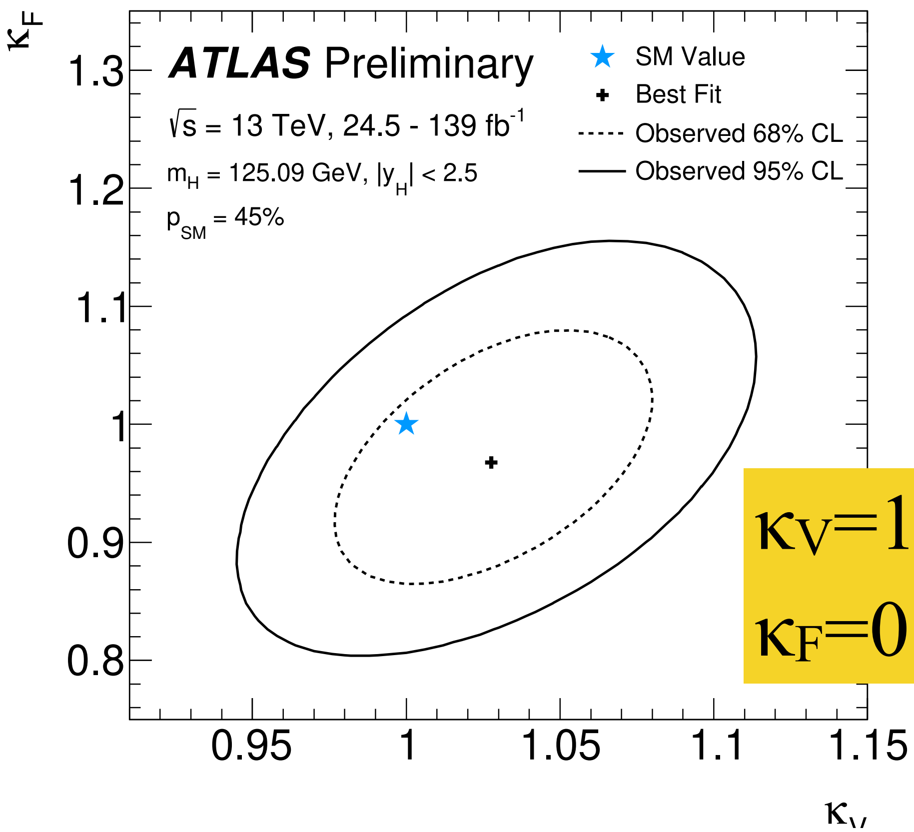


$$\kappa_g^2 = 1.042\kappa_t^2 + 0.002\kappa_b^2 - 0.040\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0005\kappa_b\kappa_c + 0.00002\kappa_c^2$$



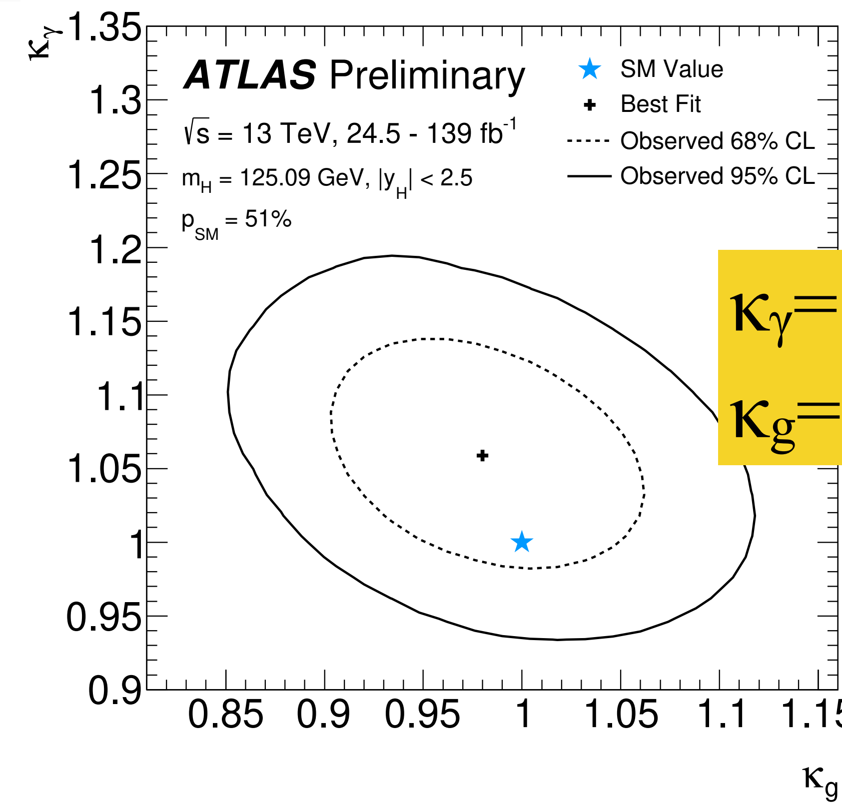
$$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

κ-framework



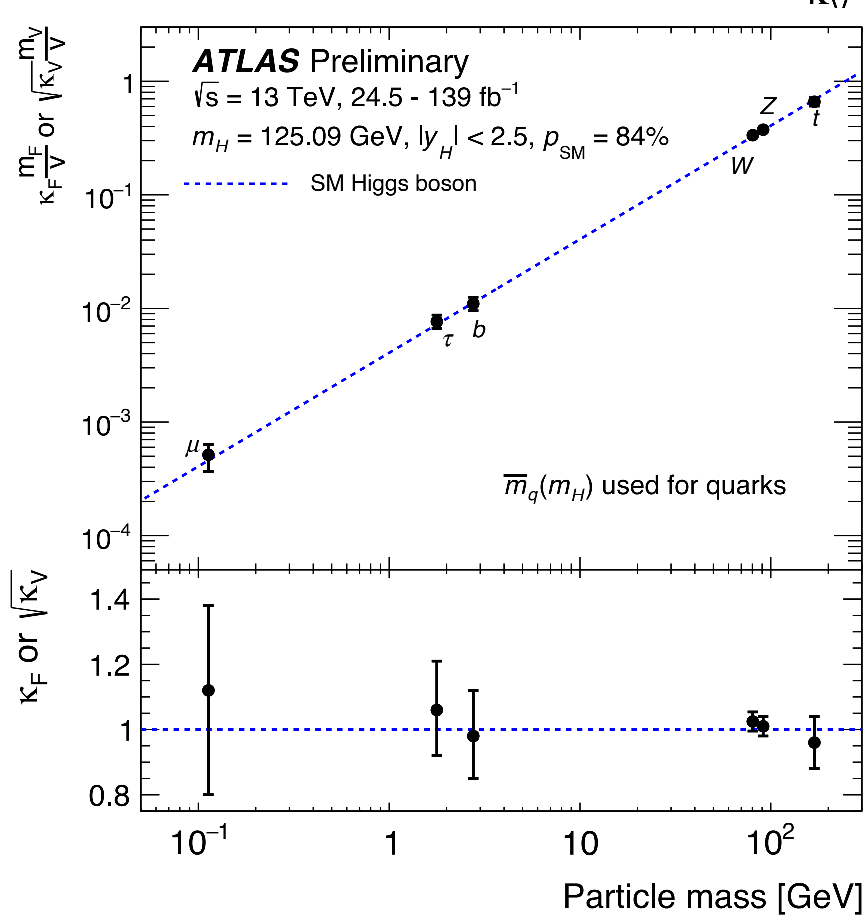
κ_V=1.03±0.03

κ_F=0.97±0.07



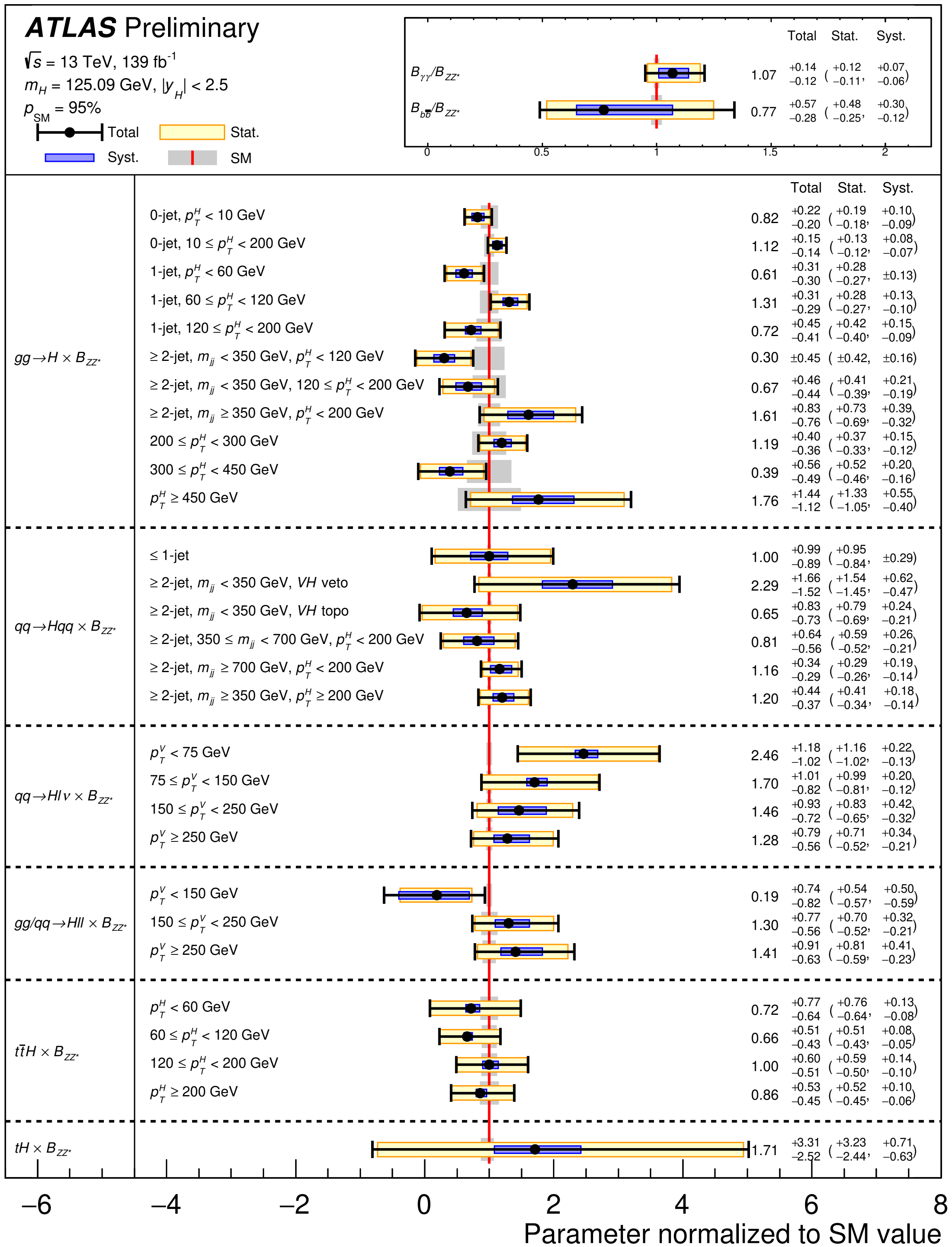
κ_γ=1.06±0.05

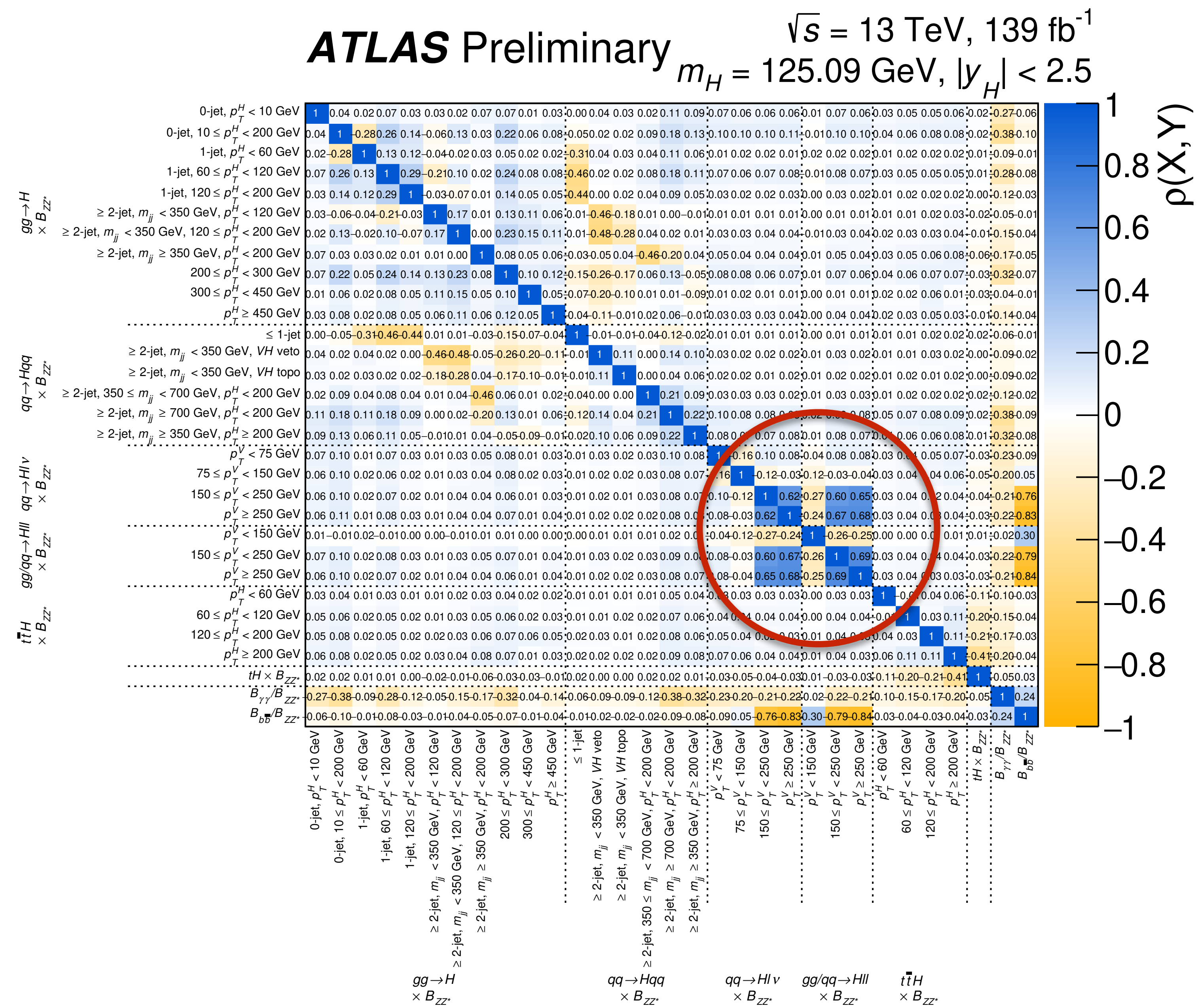
κ_g=0.98±0.05



Parameter	Result
κ_Z	1.02 ± 0.06
κ_W	1.05 ± 0.06
κ_b	$0.98^{+0.14}_{-0.13}$
κ_t	0.96 ± 0.08
κ_τ	$1.06^{+0.15}_{-0.14}$
κ_μ	$1.12^{+0.26}_{-0.32}$

STXS measurement





Interpretation of the combined STXS measurements

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

$$(\sigma\times B)^{i,H\to X} = (\sigma\times B)^{i,H\to X}_{\rm SM,(N(N))NLO}\left(1 + \frac{\sigma^i_{\rm int,(N)LO}}{\sigma^i_{\rm SM,(N)LO}} + \frac{\sigma^i_{\rm BSM,(N)LO}}{\sigma^i_{\rm SM,(N)LO}}\right)\left(\frac{1 + \frac{\Gamma^{H\to X}_{\rm int}}{\Gamma^{H\to X}_{\rm SM}} + \frac{\Gamma^{H\to X}_{\rm BSM}}{\Gamma^{H\to X}_{\rm SM}}}{1 + \frac{\Gamma^{H}_{\rm int}}{\Gamma^{H}_{\rm SM}} + \frac{\Gamma^{H}_{\rm BSM}}{\Gamma^{H}_{\rm SM}}}\right)$$

$$s_k(c_i,\boldsymbol{\theta}) = \sum_{i,X}\left(\mu^{i,X} \equiv \frac{(\sigma\times B)^{i,H\to X}_{\rm SMEFT}(c_i)}{(\sigma\times B)_{\rm SM,MC}}\right) \times \mathcal{L} \times (\sigma\times B)^{i,X}_{\rm SM,MC}(\boldsymbol{\theta}) \times \epsilon^{i,X}_k(\boldsymbol{\theta})$$

Wilson coefficients

Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$	c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p\gamma_\mu l_t)(\bar{l}_r\gamma^\mu l_s)$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r\widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r\widetilde{H})$	c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

Eigenvectors

Parameter		Definition	Eigenvalue	Fit Para-meter
$c^{(3)}_{Hq}$		$c^{(3)}_{Hq}$	1900	✓
$c^{[i]}_{HW,HB,HWB,HDD,uW,uB}$	1	$-0.27c_{HW} - 0.84c_{HB} + 0.47c_{HWB} - 0.02c_{uW} - 0.05c_{uB}$	245000	✓
	2	$-0.96c_{HW} + 0.19c_{HB} - 0.20c_{HWB} + 0.02c_{uB}$	33	✓
	3	$-0.08c_{HW} + 0.50c_{HB} + 0.86c_{HWB} + 0.07c_{HDD} + 0.03c_{uW} + 0.06c_{uB}$	4	✓
	4	$0.03c_{HWB} - 0.85c_{HDD} + 0.32c_{uW} + 0.43c_{uB}$	0.017	
	5	$-0.01c_{HW} + 0.07c_{HB} + 0.05c_{HWB} - 0.44c_{HDD} - 0.86c_{uW} - 0.23c_{uB}$	0.0077	
	6	$-0.01c_{HW} + 0.06c_{HB} + 0.04c_{HWB} - 0.29c_{HDD} + 0.39c_{uW} - 0.87c_{uB}$	0.0025	
$c^{[i]}_{HG,uG,uH,\rm top}$	1	$+0.999c_{HG} + 0.038c_{uG}$	176000	✓
	2	$-0.03c_{HG} + 0.73c_{uG} - 0.03c^{(1)}_{qq} - 0.23c_{qq} - 0.05c^{(3)}_{qq} - 0.54c^{(31)}_{qq} - 0.02c_{uu} - 0.24c^{(1)}_{uu} - 0.04c^{(8)}_{ud} - 0.01c^{(1)}_{qu} - 0.15c^{(8)}_{qu} - 0.04c^{(8)}_{qd} - 0.18c_G + 0.06c_{uH}$	20	✓
	3	$-0.03c_{HG} + 0.67c_{uG} + 0.04c^{(1)}_{qq} + 0.25c_{qq} + 0.05c^{(3)}_{qq} + 0.55c^{(31)}_{qq} + 0.02c_{uu} + 0.26c^{(1)}_{uu} + 0.03c^{(8)}_{ud} + 0.01c^{(1)}_{qu} + 0.16c^{(8)}_{qu} + 0.03c^{(8)}_{qd} + 0.29c_G + 0.1c_{uH}$	1.3	✓
	4	$+0.11c_{uG} + 0.01c_{qq} - 0.018c^{(3)}_{qq} + 0.029c^{(31)}_{qq} + 0.012c^{(1)}_{uu} - 0.993c_{uH}$	0.14	
	5	$+0.02c_{qq} - 1.0c^{(3)}_{qq} + 0.06c^{(31)}_{qq} + 0.03c^{(1)}_{uu} + 0.02c^{(8)}_{qu} + 0.02c_{uH}$	0.02	
	6	$+0.07c_{uG} - 0.02c^{(1)}_{qq} + 0.07c_{qq} + 0.03c^{(3)}_{qq} + 0.32c^{(31)}_{qq} + 0.06c^{(1)}_{uu} + 0.04c^{(8)}_{ud} + 0.08c^{(8)}_{qu} + 0.04c^{(8)}_{qd} - 0.94c_G + 0.02c_{uH}$	0.0092	
$c^{[1]}_{Hl^{(1)},He}$		$+0.78c^{(1)}_{Hl} - 0.62c_{He}$	2.6	✓
$c^{[2]}_{Hl^{(1)},He}$		$+0.62c^{(1)}_{Hl} + 0.78c_{He}$	0.056	
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$		$-0.87c_{Hu} + 0.26c_{Hd} + 0.42c^{(1)}_{Hq}$	59	✓
$c^{[2]}_{Hu,Hd,Hq^{(1)}}$		$+0.41c_{Hu} - 0.09c_{Hd} + 0.91c^{(1)}_{Hq}$	0.10	
$c^{[3]}_{Hu,Hd,Hq^{(1)}}$		$-0.28c_{Hu} - 0.96c_{Hd} + 0.03c^{(1)}_{Hq}$	0.0018	
$c^{[1]}_{Hl^{(3)},ll'}$		$0.87c^{(3)}_{Hl} - 0.50c'_{ll}$	27	✓
$c^{[2]}_{Hl^{(3)},ll'}$		$0.50c^{(3)}_{Hl} + 0.87c'_{ll}$	0.33	

- Parametrize the signal strength directly with wilson coefficients of SMEFT operators
- Sensitive elgenvectors are chosen as the measured parameters (more orthogonal).

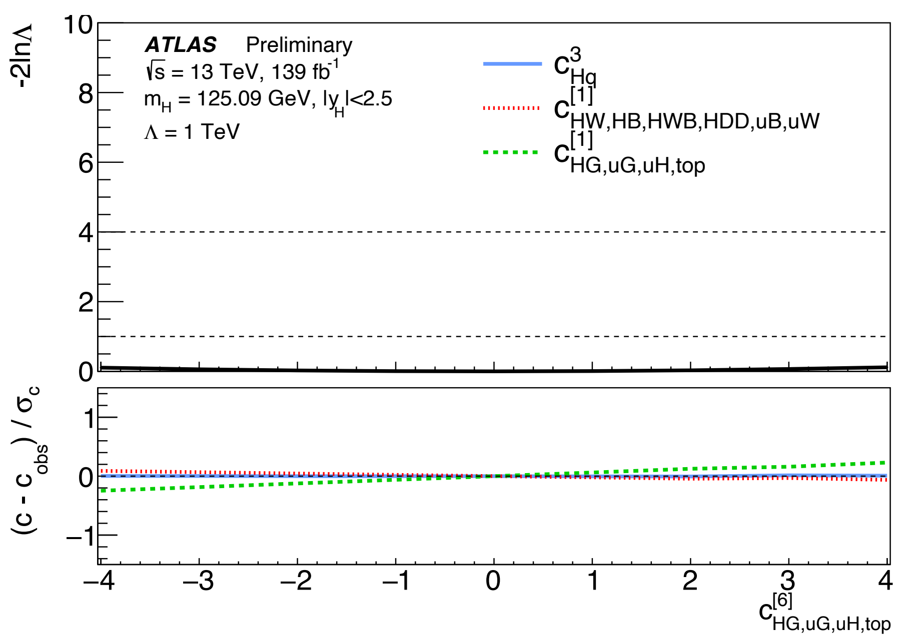
Interpretation of the combined STXS measurements

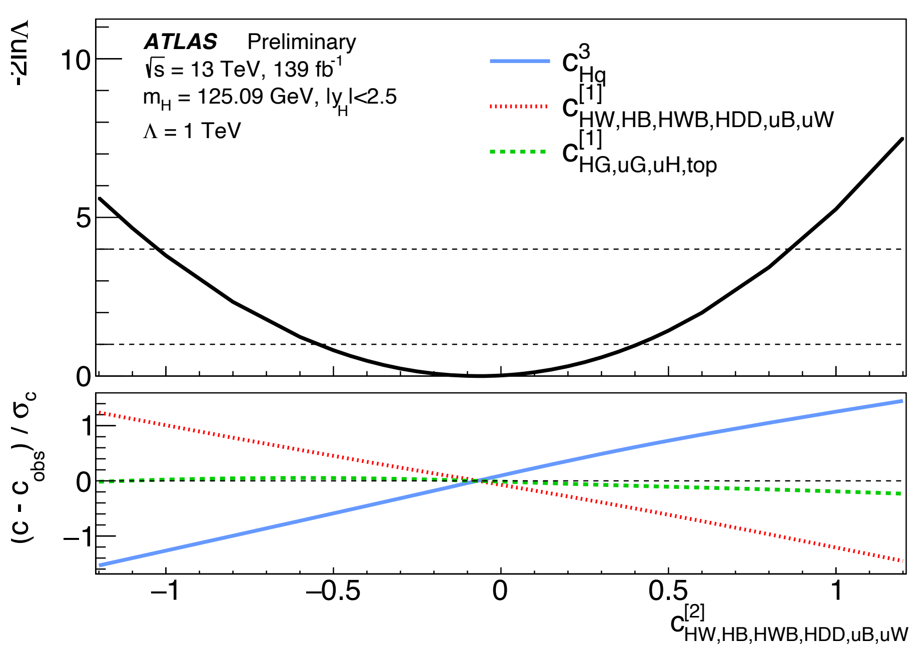
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots$$

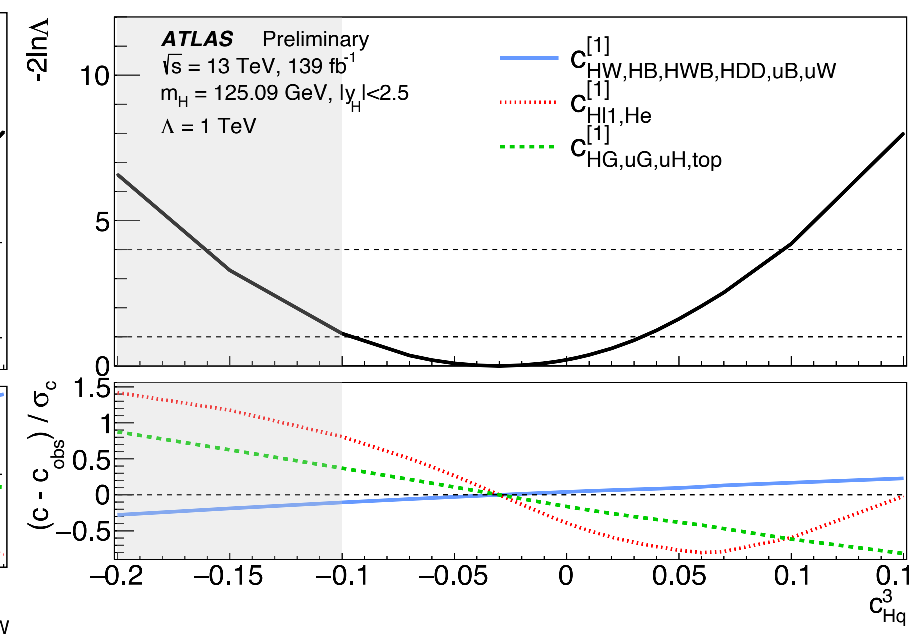
$$(\sigma\times B)^{i,H\to X} = (\sigma\times B)^{i,H\to X}_{\text{SM,(N(N))NLO}} \left(1 + \frac{\sigma^i_{\text{int,(N)LO}}}{\sigma^i_{\text{SM,(N)LO}}} + \frac{\sigma^i_{\text{BSM,(N)LO}}}{\sigma^i_{\text{SM,(N)LO}}}\right) \left(\frac{1 + \frac{\Gamma^{H\to X}_{\text{int}}}{\Gamma^{H\to X}_{\text{SM}}} + \frac{\Gamma^{H\to X}_{\text{BSM}}}{\Gamma^{H\to X}_{\text{SM}}}}{1 + \frac{\Gamma^{H}_{\text{int}}}{\Gamma^{H}_{\text{SM}}} + \frac{\Gamma^{H}_{\text{BSM}}}{\Gamma^{H}_{\text{SM}}}}\right)$$

$$s_k(c_i,\boldsymbol{\theta}) = \sum_{i,X}\left(\mu^{i,X} \equiv \frac{(\sigma\times B)^{i,H\to X}_{\text{SMEFT}}(c_i)}{(\sigma\times B)_{\text{SM,MC}}}\right) \times \mathcal{L} \times (\sigma\times B)^{i,X}_{\text{SM,MC}}(\boldsymbol{\theta}) \times \epsilon^{i,X}_k(\boldsymbol{\theta})$$

1-dimensional profile likelihood scan





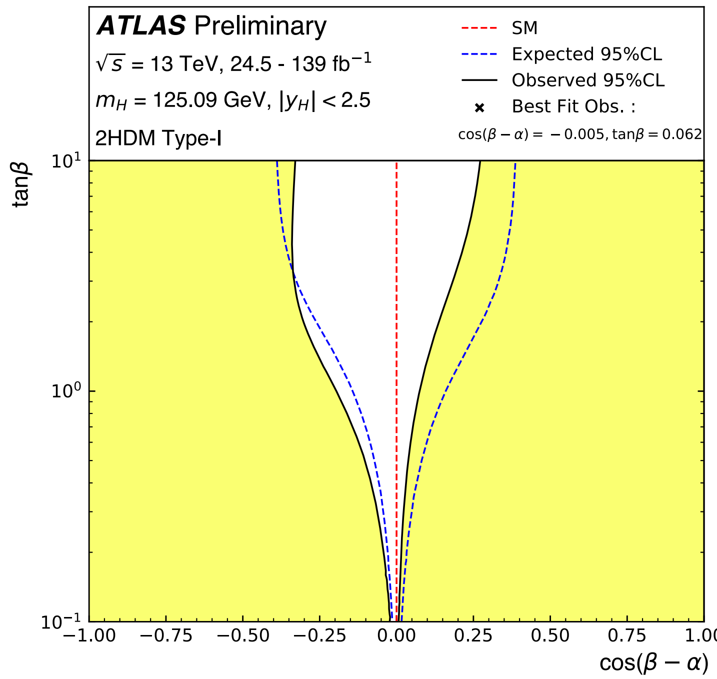


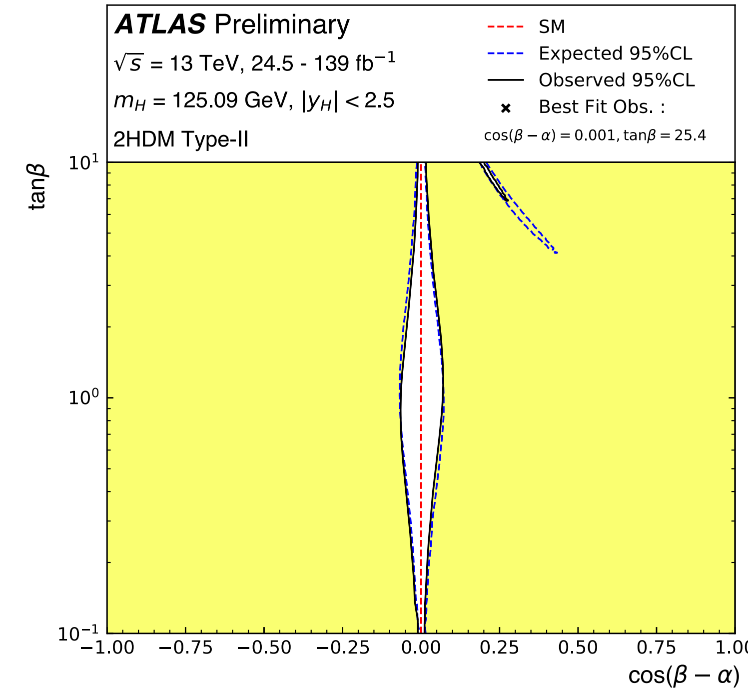
Absence of constraints with weak eigenvalues

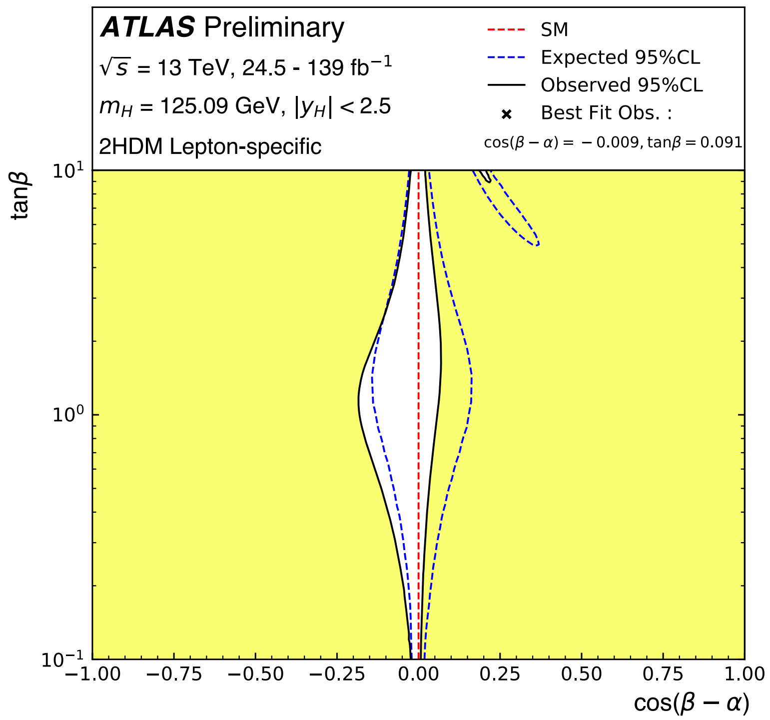
Linear behavior

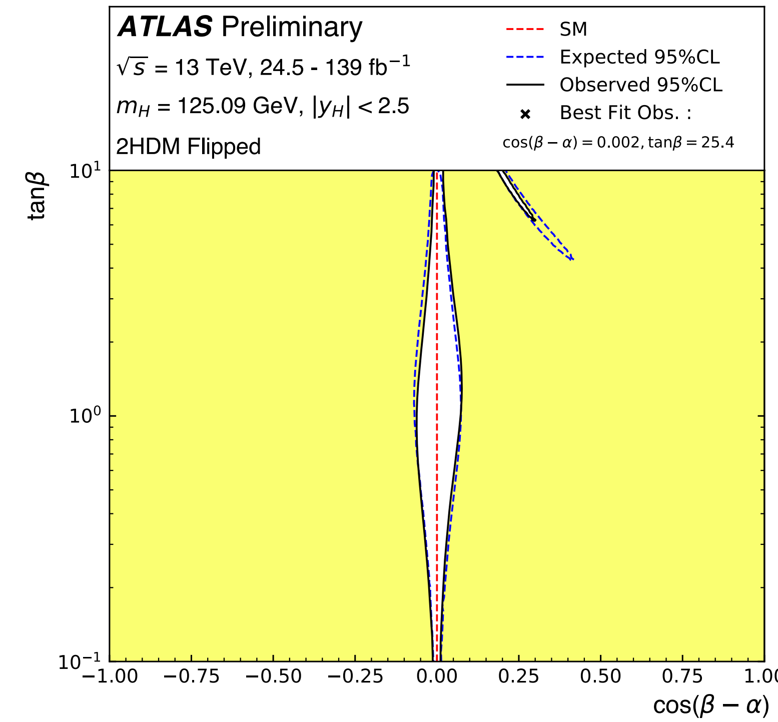
Now-linear effect introduced from acceptance correction

Interpretation on BSM model (2HDM)







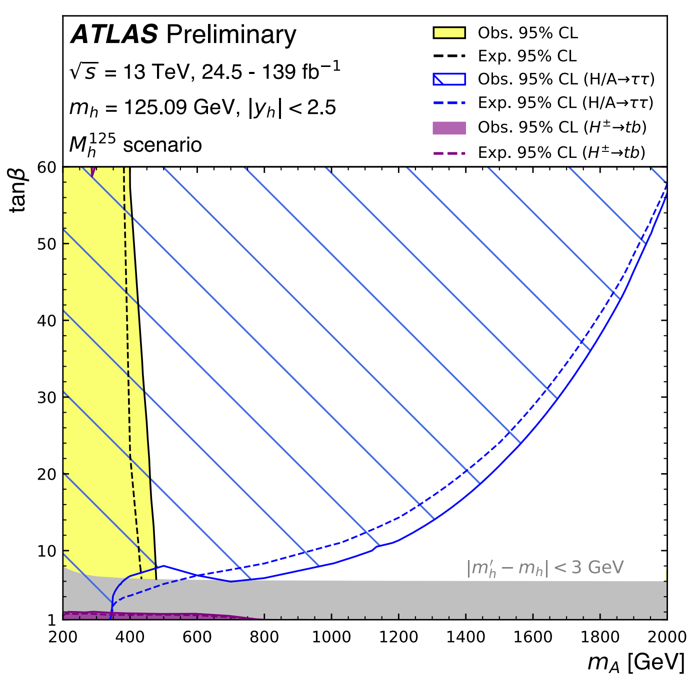


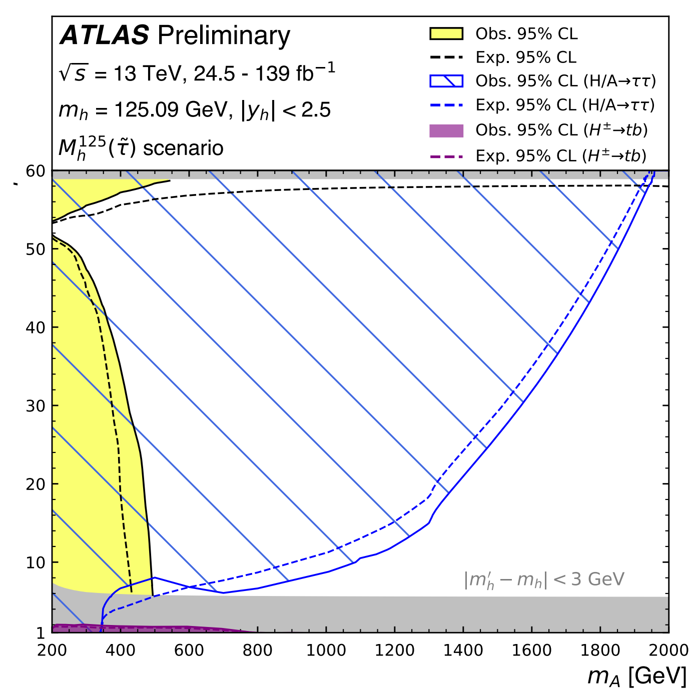
Based on the coupling strength modifiers (κ-framework), 2HDM constraints indicate no significant deviations from SM prediction.

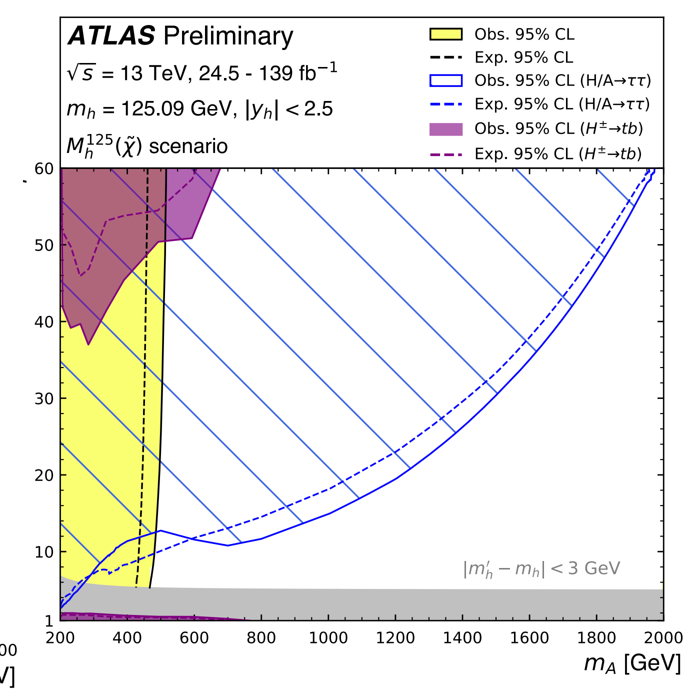
Interpretation on BSM model (MSSM)

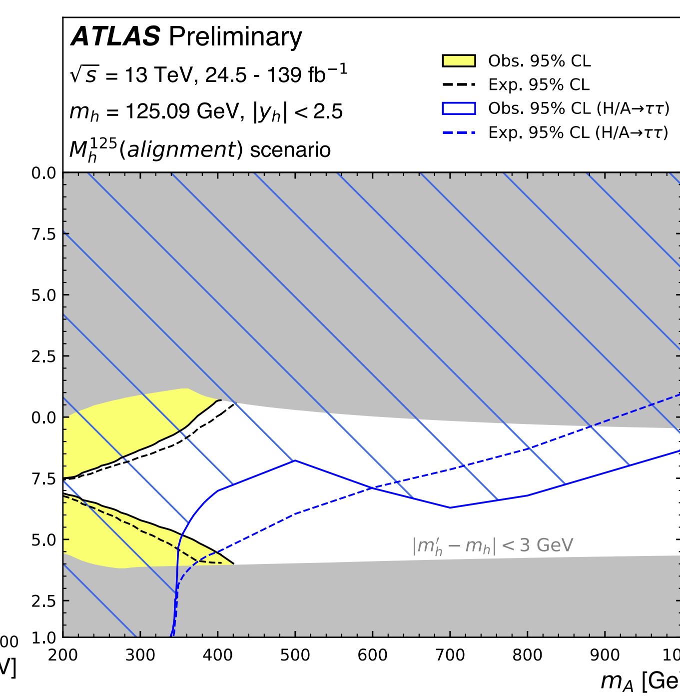
Assuming the observe boson is the **light CP-even h of the MSSM theory**, six MSSM benchmark scenarios:

- **M^{125}_h scenario**: All superparticles are heavy that production and decays of MSSM Higgs boson are only mildly affected
- **$M^{125}_h(\chi)$ scenario**: All chargions and neutrinos are relatively light, with significant higgsino-gaugino mixing
- **$M^{125}_h(\tau)$ scenario**: Light staus and light gauging-like charginos and neutralinos
- **M^{125}_h(alignment) scenario**: alignment without decoupling scenario







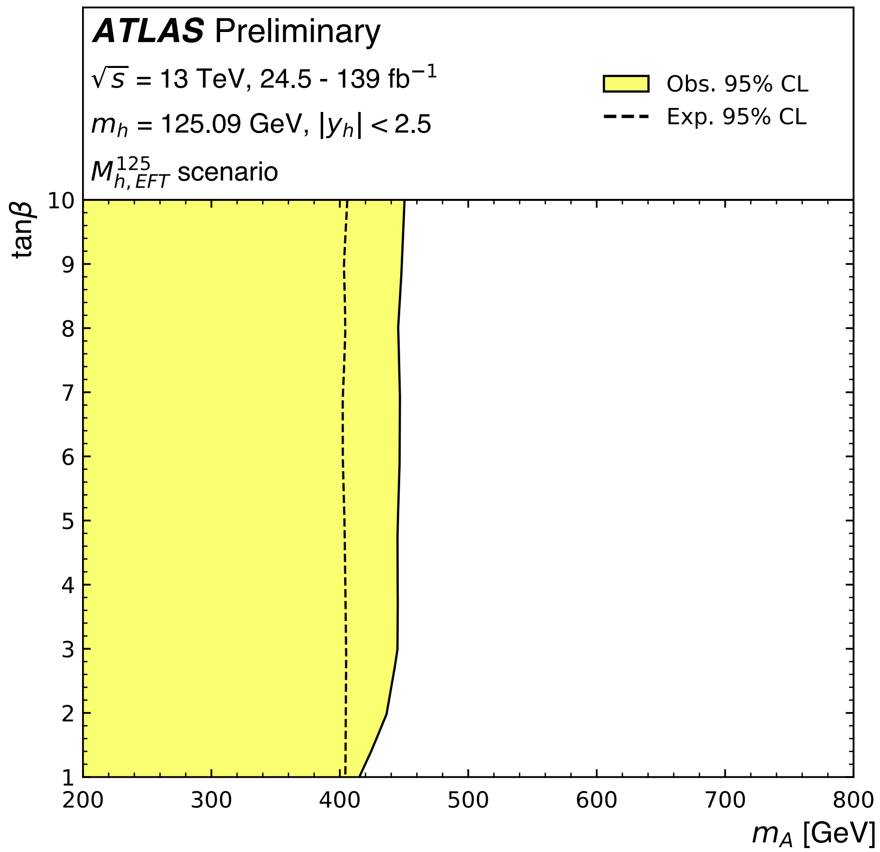


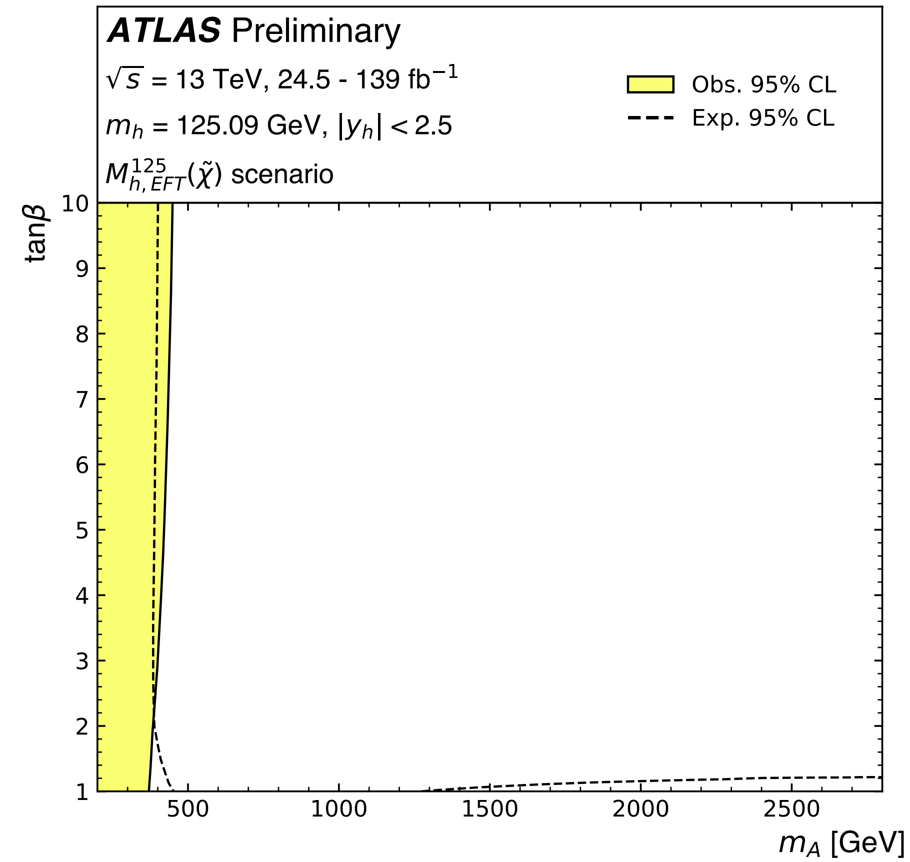
Generally exclude the low mA regime and low tanβ range

Interpretation on BSM model (MSSM)

Assuming the observe boson is the **light CP-even h of the MSSM theory**, six MSSM benchmark scenarios:

- **$M^{125}_{h,EFT}$ scenario**: a flexible mass scale MSUSY of super partners (6TeV - 10^{16}TeV)
- **$M^{125}_{h}(\chi)$ scenario**: light neutralinos and charginos



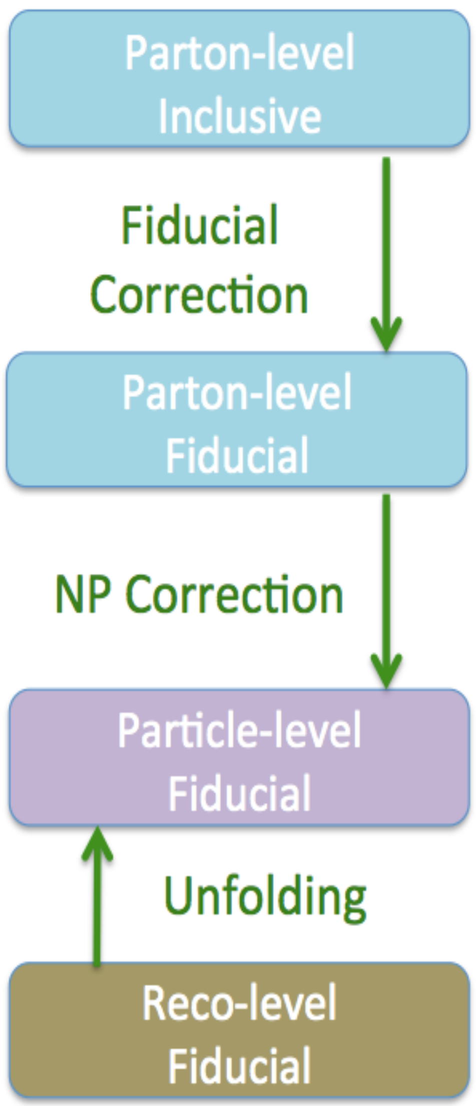


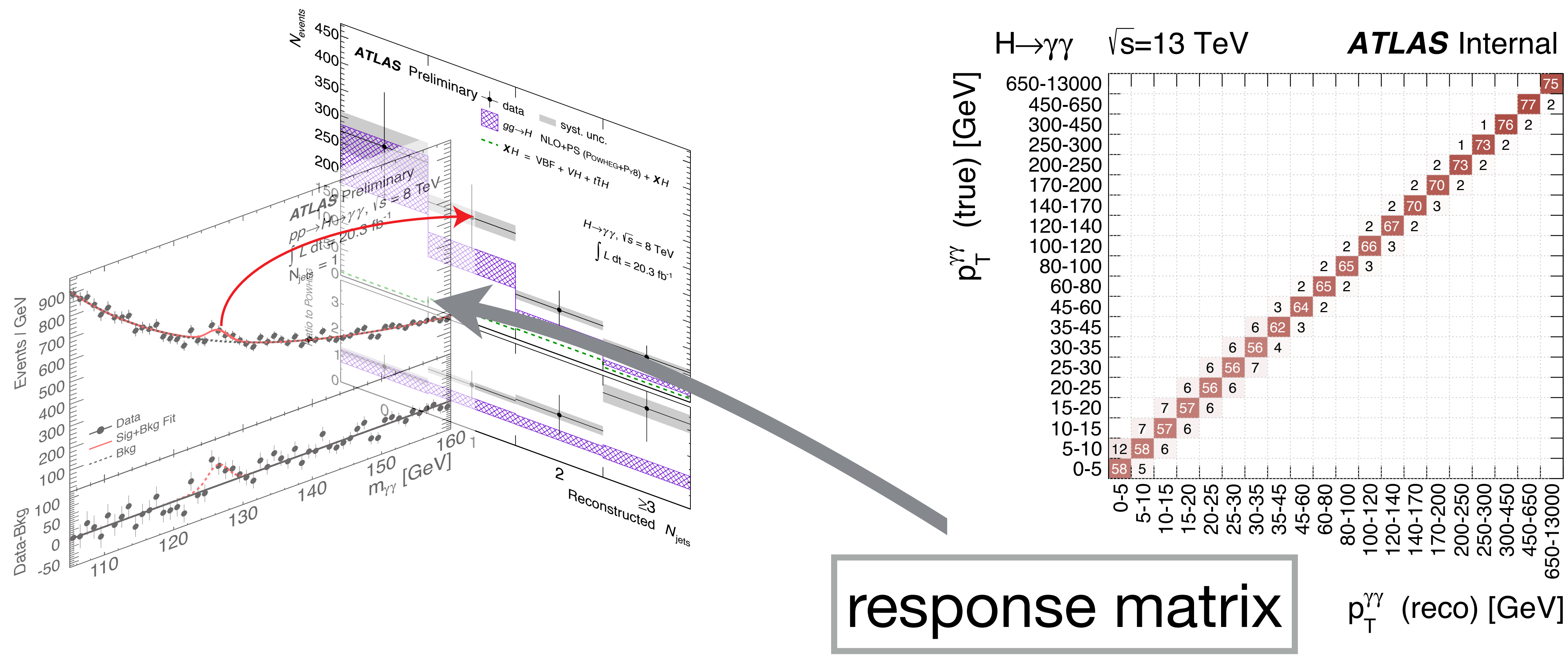
No results of direct search are available for the two benchmarks

All the results are complementary to limits from direct searches for additional Higgs bosons

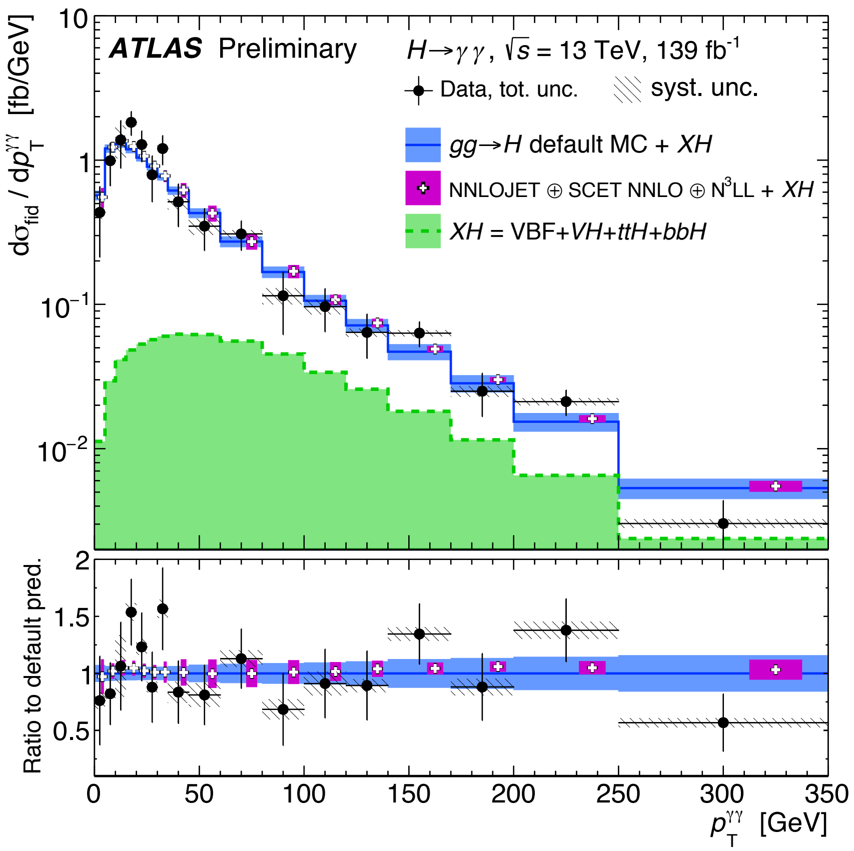
Fiducial and differential cross section

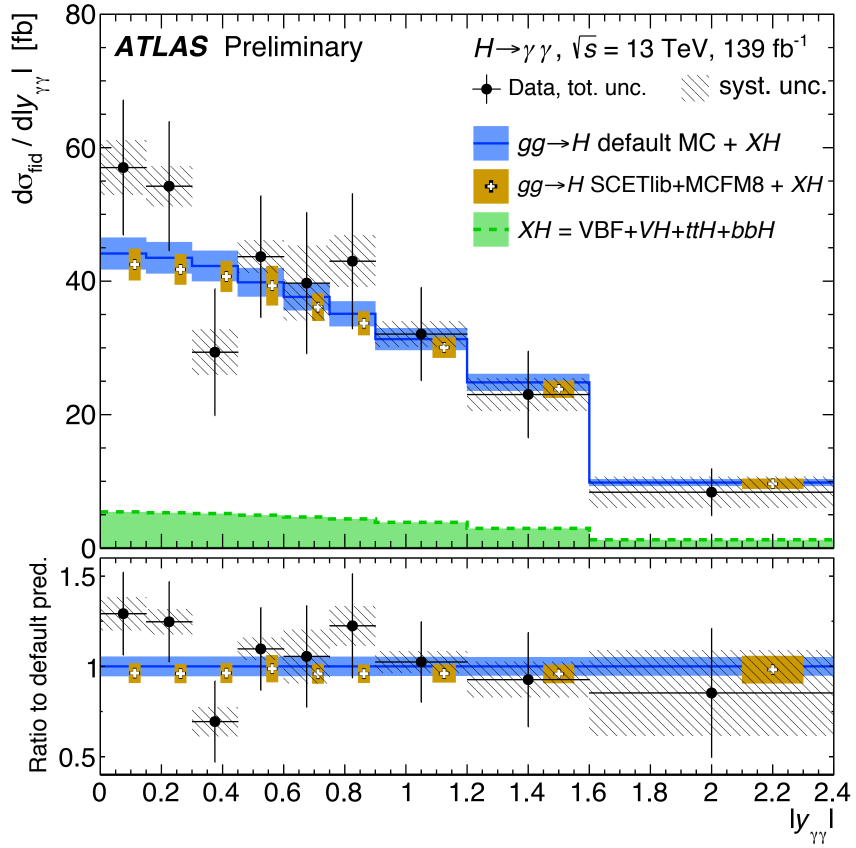
- Measurement designed as **model independent** as possible.
- Direct **comparison with theoretical predictions** at particle level.
- A wide and diverse range of physical phenomena to be probed:
  - Higgs boson kinematics, Jet activity, VBF-sensitive variables, Spin-CP sensitive variables

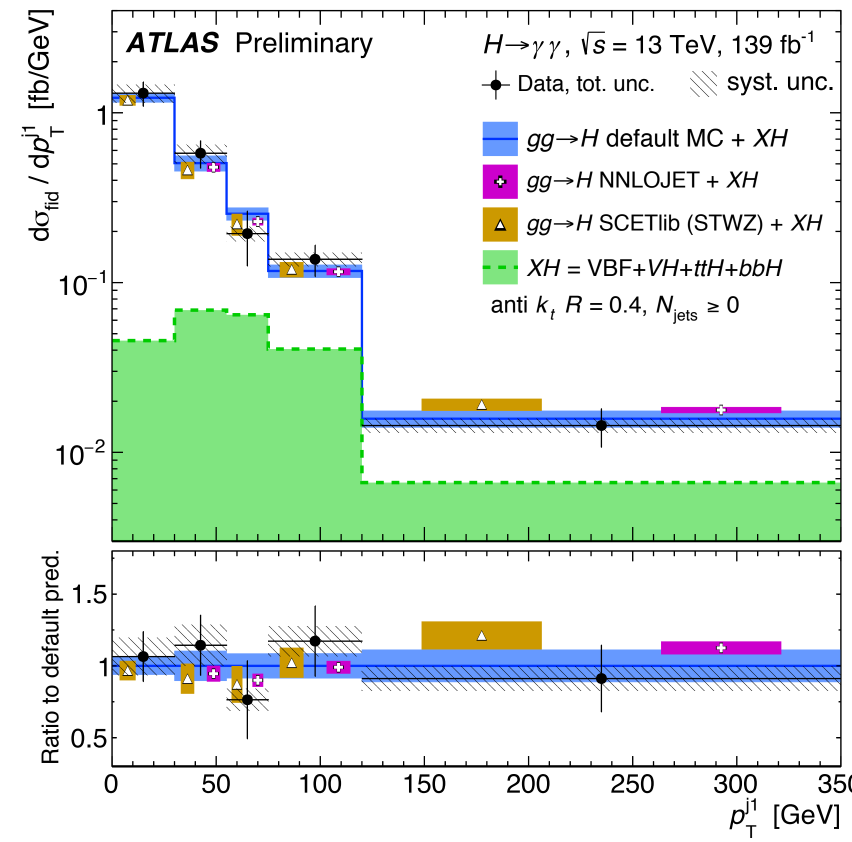


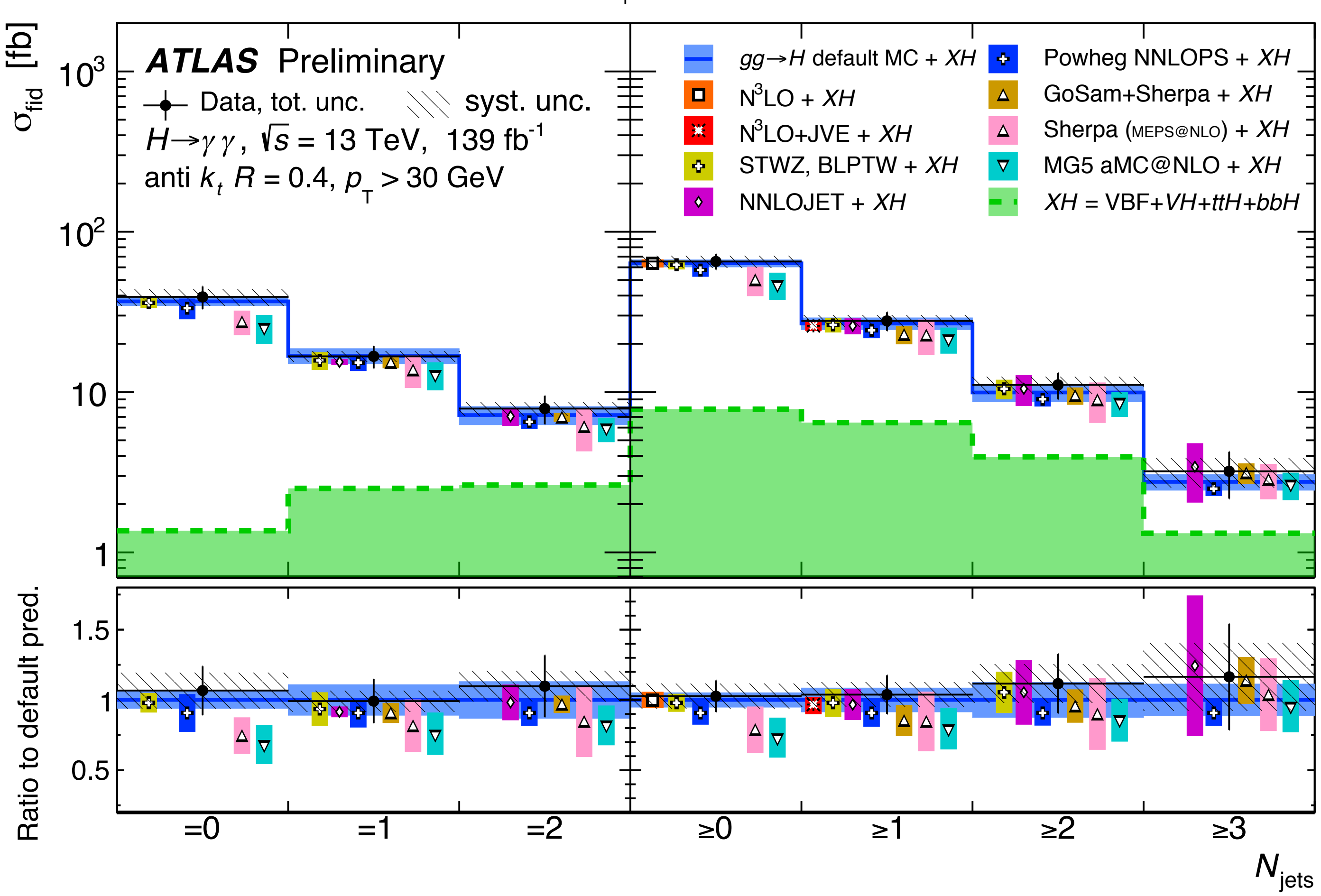


Differential Cross Section







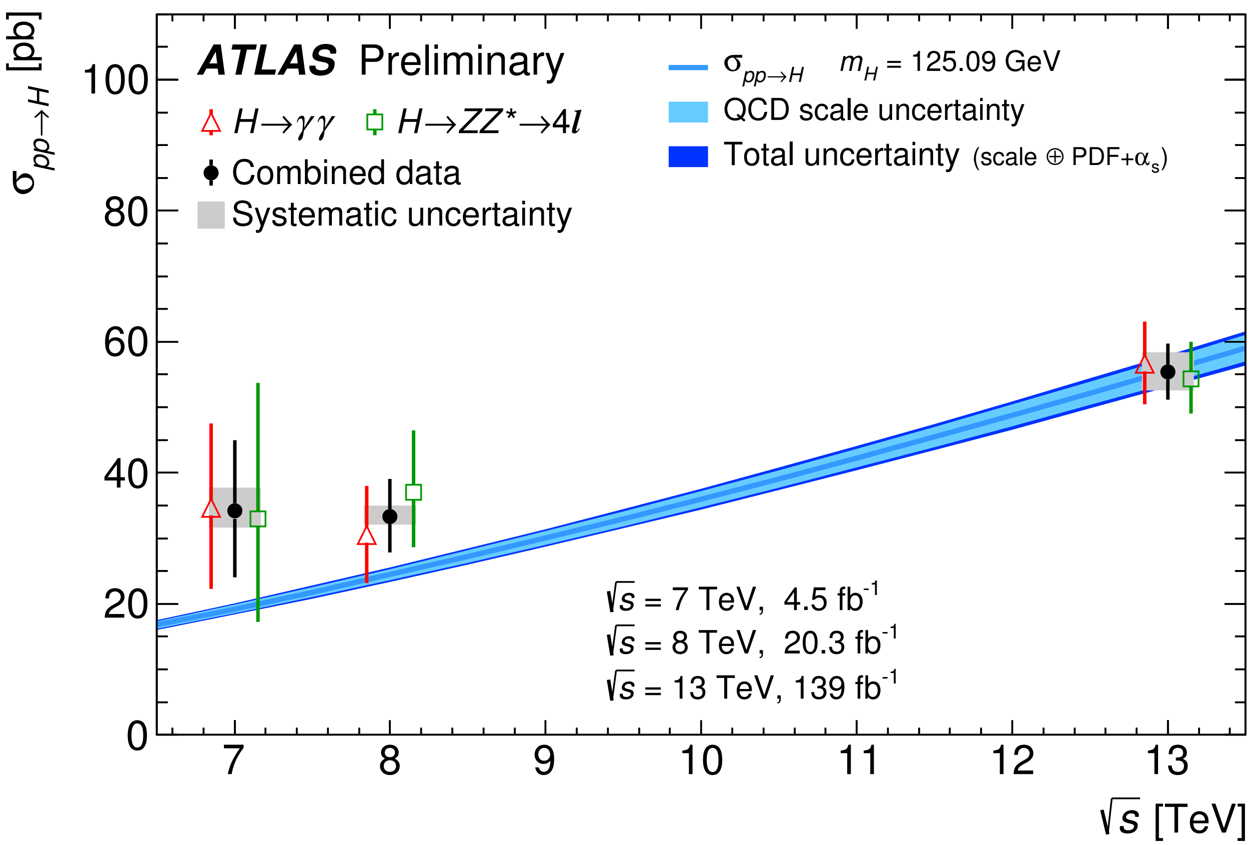


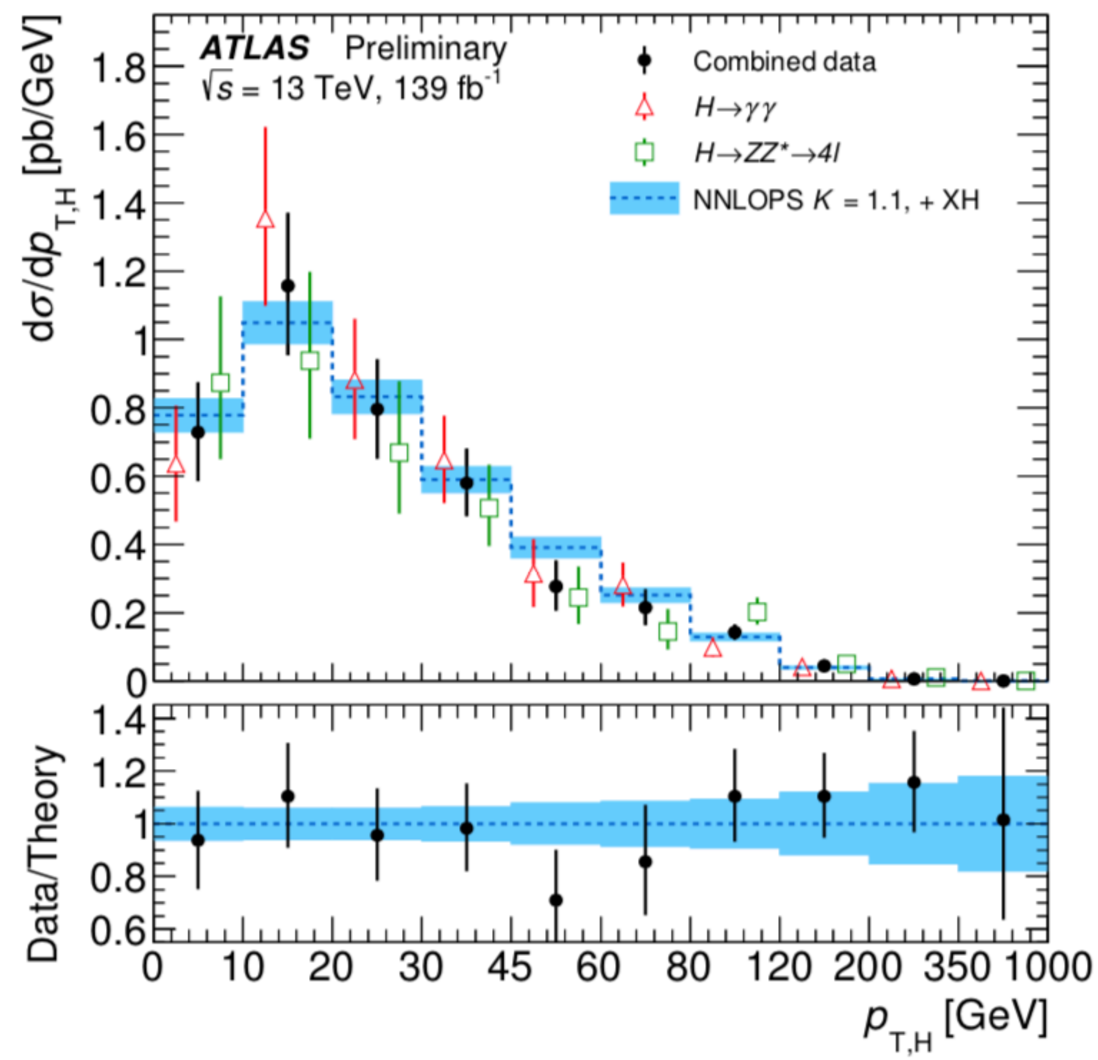
Distribution	$p(\chi^2)$ with Default MC Prediction
$p_T^{\gamma\gamma}$	44%
$\lvert y_{\gamma\gamma} \rvert$	68%
$p_T^{j_1}$	77%
N_{jets}	96%
$\Delta\phi_{jj}$	82%
m_{jj}	75%

Combined measurement

Total Higgs boson production cross section measurement (8%):

$55.4^{+4.3}_{-4.2}$pb ($\pm$3.1(stat.)$^{+3.0}_{-2.8}$(sys.)) (SM prediction of 55.6±2.5pb)

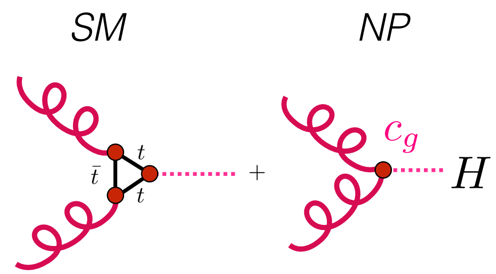




4l, $p_{T,H}$	0–10		10–20		20–30		30–45		45–60
$\gamma\gamma$, $p_{T,H}$	0–5	5–10	10–15	15–20	20–25	25–30	30–35	35–45	45–60
Combination	0–10		10–20		20–30		30–45		45–60
4l, $p_{T,H}$	60–80	80–120			120–200		200–350		350–1000
$\gamma\gamma$, $p_{T,H}$	60–80	80–100	100–120	120–140	140–170	170–200	200–250	250–350	350–1000
Combination	60–80	80–120			120–200		200–350		350–1000

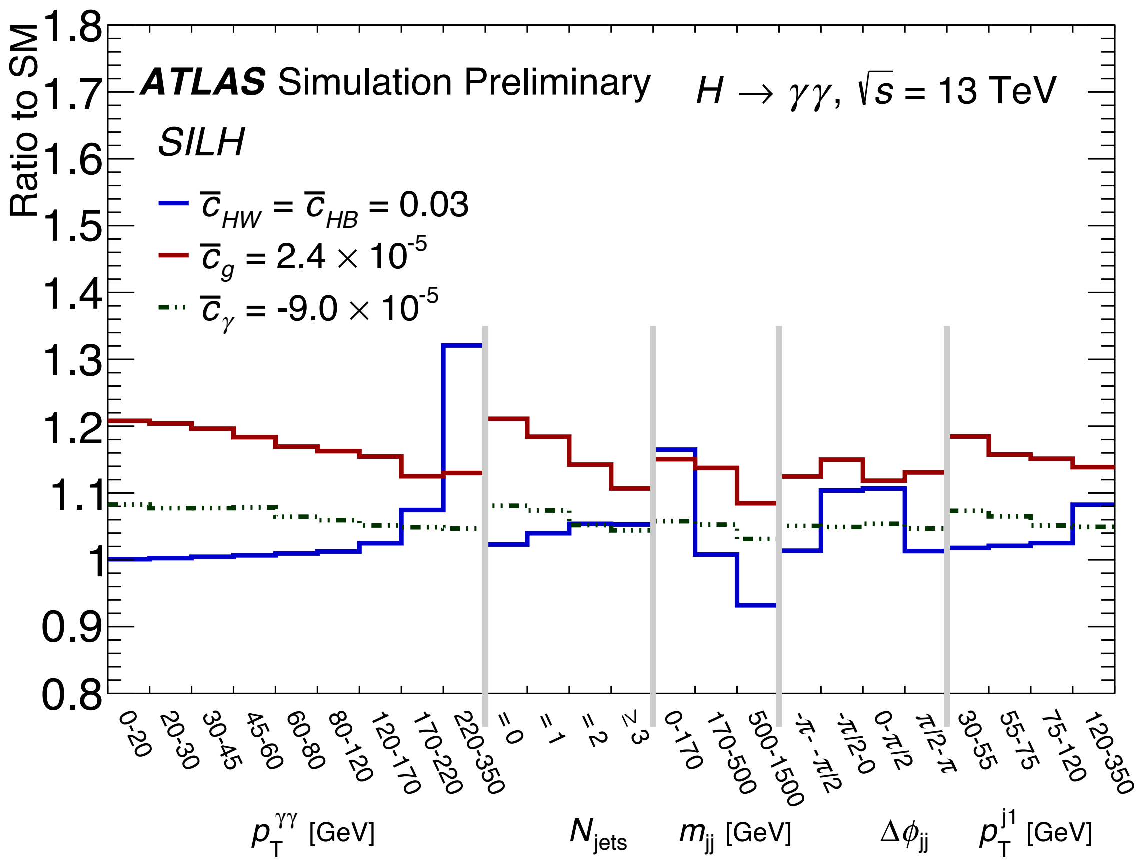
EFT interpretation on Diff. cross section

EFT approach with differential cross sections



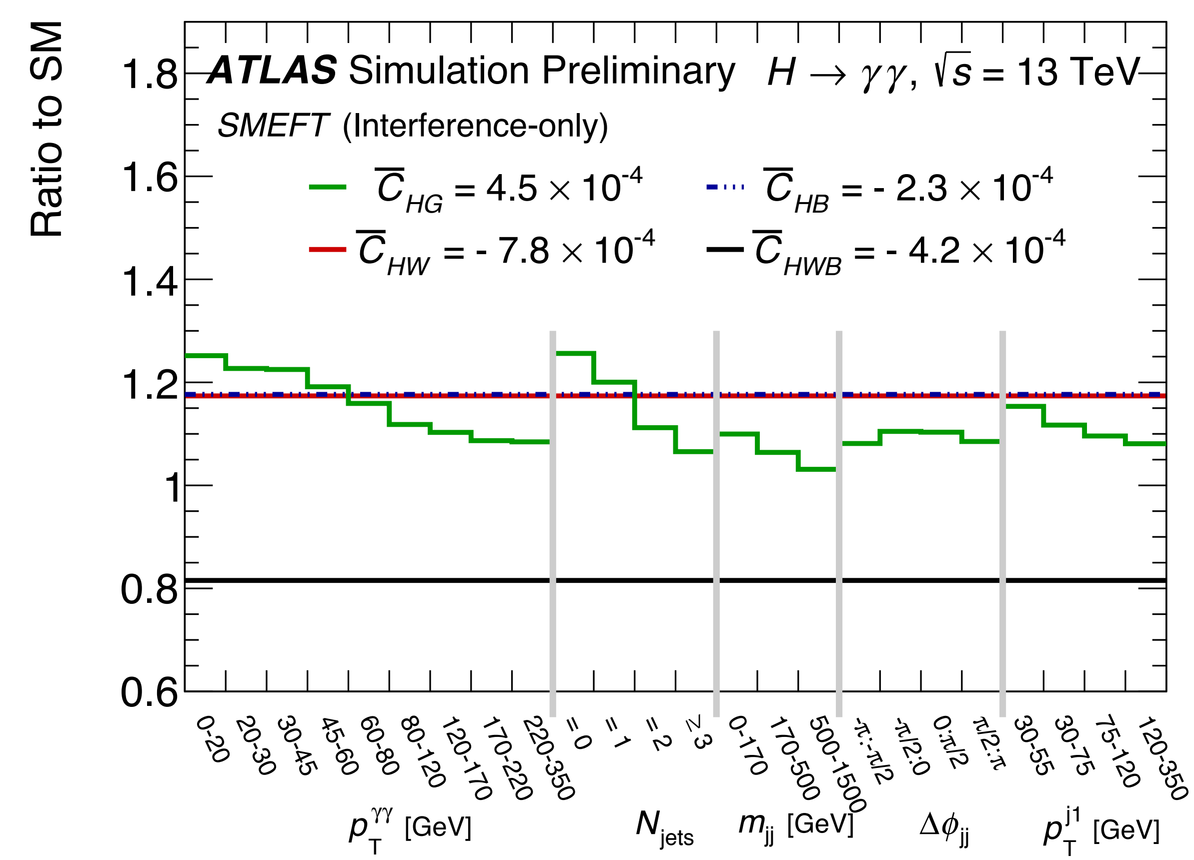
Strongly Interaction Light Higgs (SILH) basis

$$\mathcal{L}_{\rm eff}^{\rm SILH} \supset \bar{c}_g O_g + \bar{c}_\gamma O_\gamma + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_g \tilde{O}_g + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$



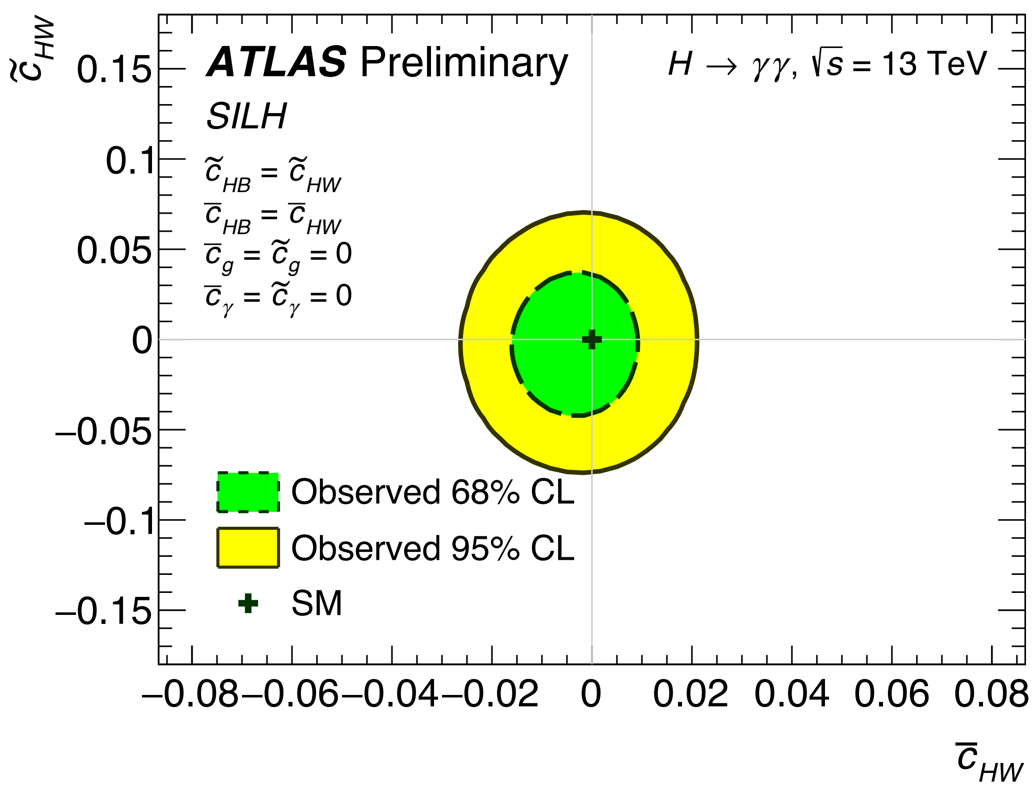
SMEFT (Warsaw) basis

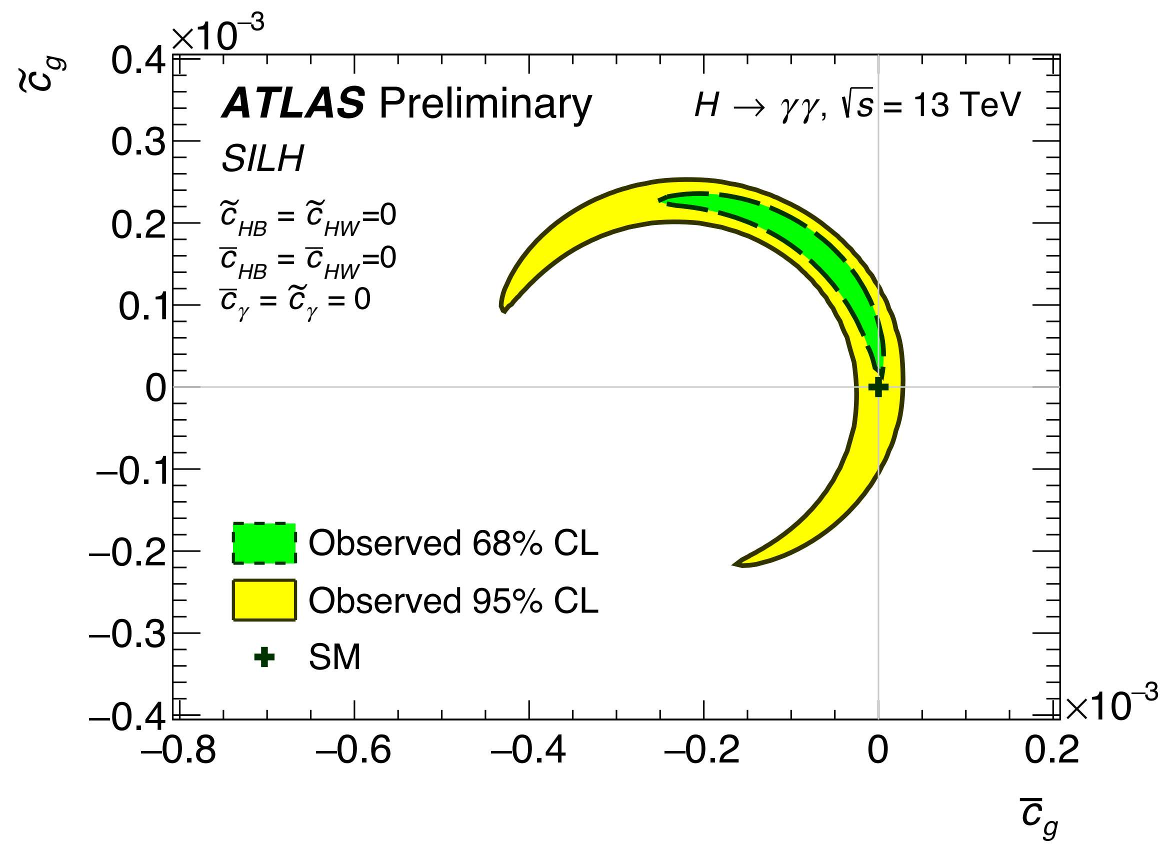
$$\mathcal{L}_{\rm eff}^{\rm SMEFT} \supset \overline{C}_{HG} O'_g + \overline{C}_{HW} O'_{HW} + \overline{C}_{HB} O'_{HB} + \overline{C}_{HWB} O'_{HWB} + \tilde{C}_{HG} \tilde{O}'_g + \tilde{C}_{HW} \tilde{O}'_{HW} + \tilde{C}_{HB} \tilde{O}'_{HB} + \tilde{C}_{HWB} \tilde{O}'_{HWB}$$



EFT interpretation on Diff. cross section

Coefficient	Observed 95% CL limit	Expected 95% CL limit
$\bar{c}_g$	$[-0.26, 0.26] \times 10^{-4}$	$[-0.25, 0.25] \cup [-4.7, -4.3] \times 10^{-4}$
$\tilde{c}_g$	$[-1.3, 1.1] \times 10^{-4}$	$[-1.1, 1.1] \times 10^{-4}$
$\bar{c}_{HW}$	$[-2.5, 2.2] \times 10^{-2}$	$[-3.0, 3.0] \times 10^{-2}$
$\tilde{c}_{HW}$	$[-6.5, 6.3] \times 10^{-2}$	$[-7.0, 7.0] \times 10^{-2}$
$\bar{c}_\gamma$	$[-1.1, 1.1] \times 10^{-4}$	$[-1.0, 1.2] \times 10^{-4}$
$\tilde{c}_\gamma$	$[-2.8, 4.3] \times 10^{-4}$	$[-2.9, 3.8] \times 10^{-4}$



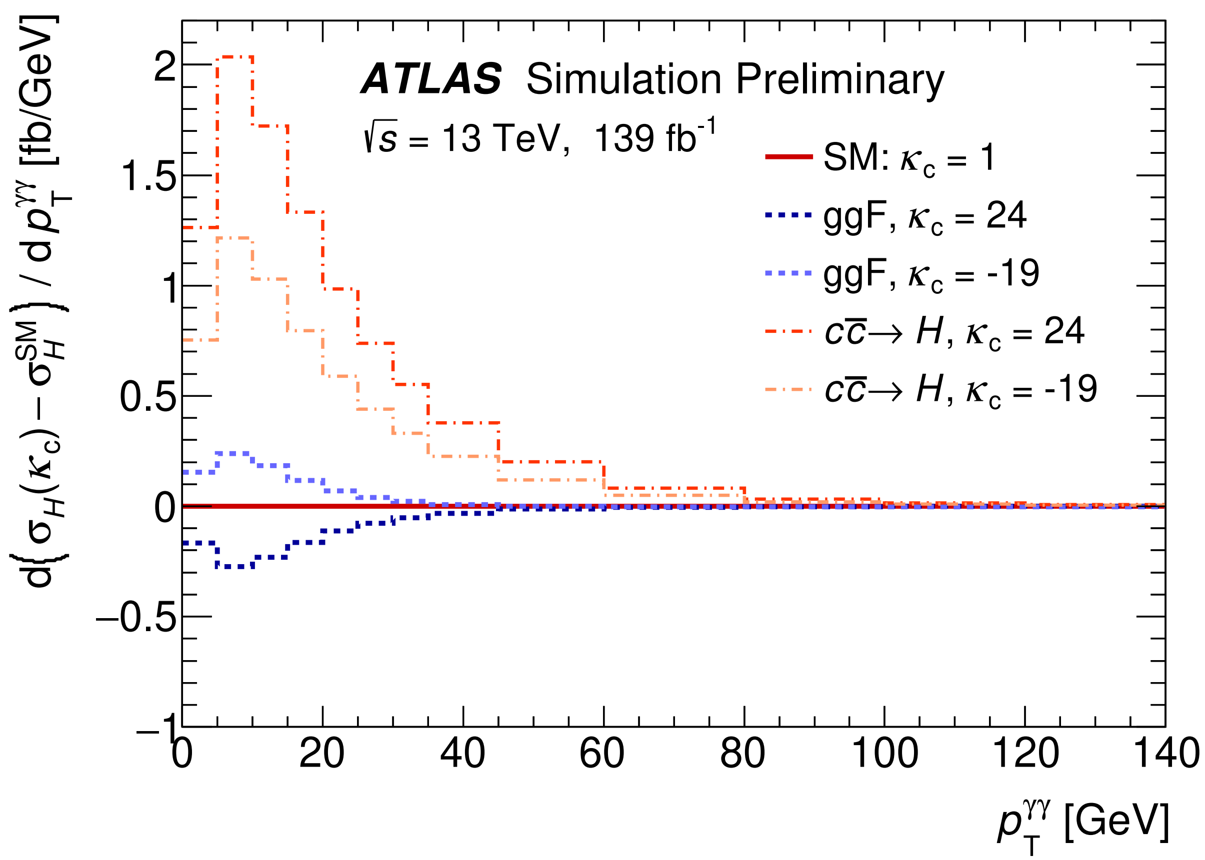


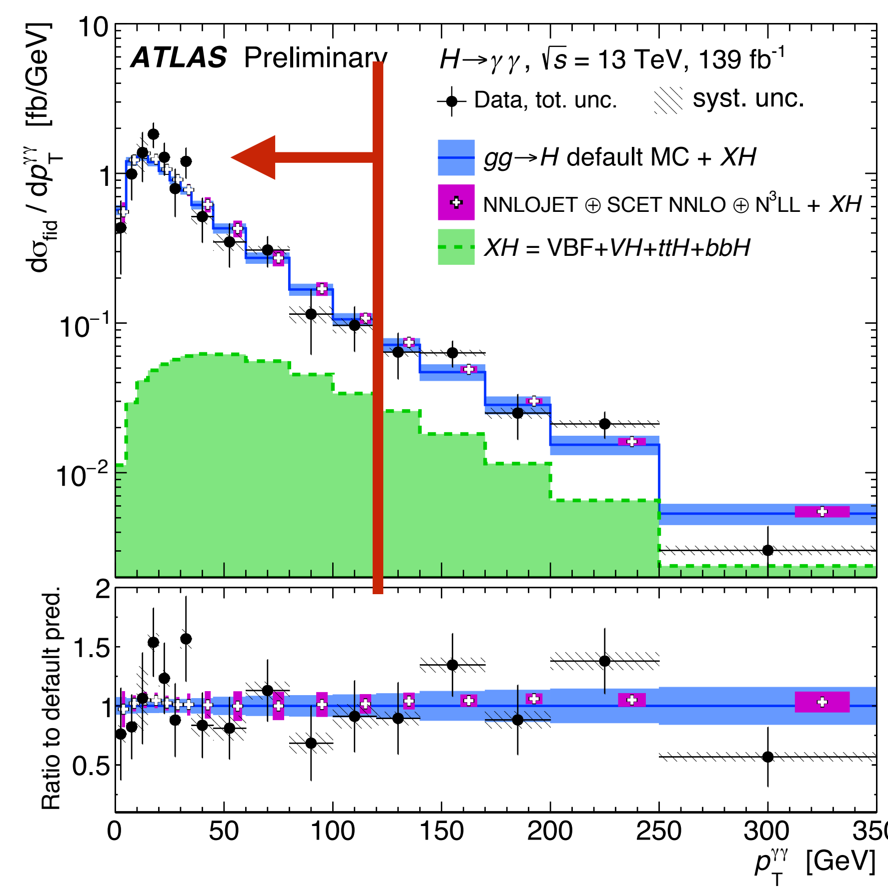
No significant deviation from SM

Limit on the c-quark Yukawa coupling

A modification in the coupling strength:

- impact the **ggF and quark-initiate production**
- affect both the **normalization and the shape** of the **Higgs pT** distribution

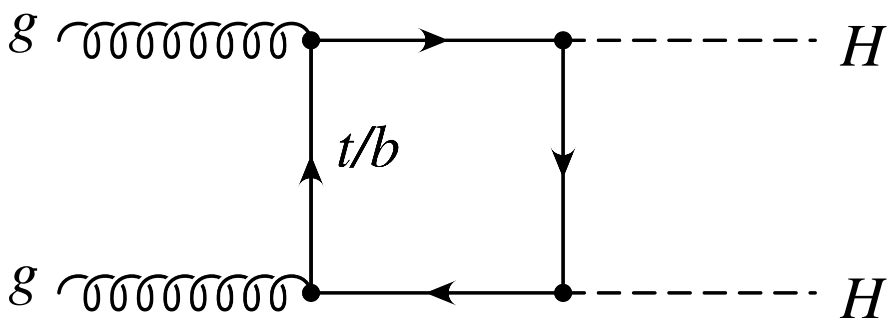


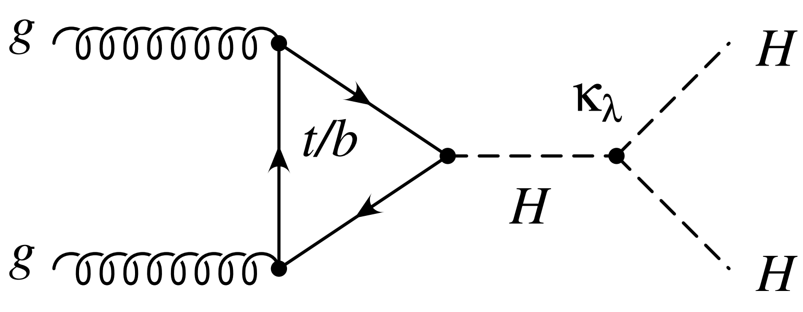


Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	$[-19, 24]$	$[-15, 19]$

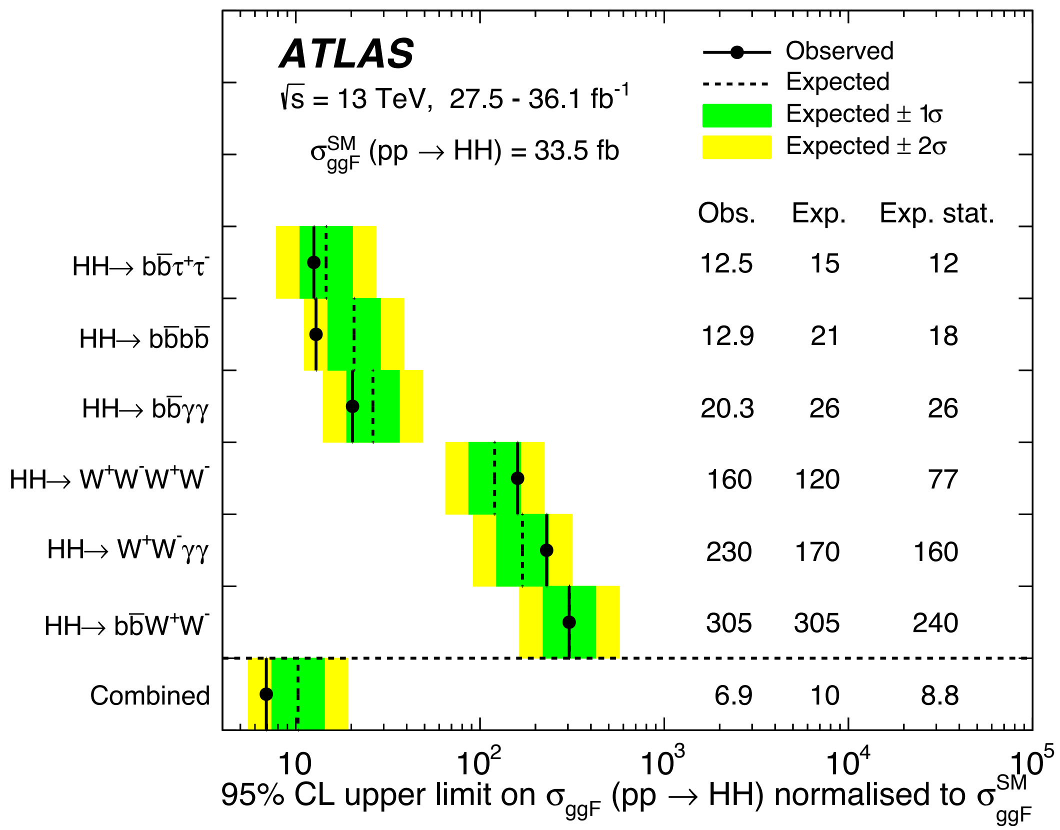
The fit only uses shape information, while the normalization is profiled

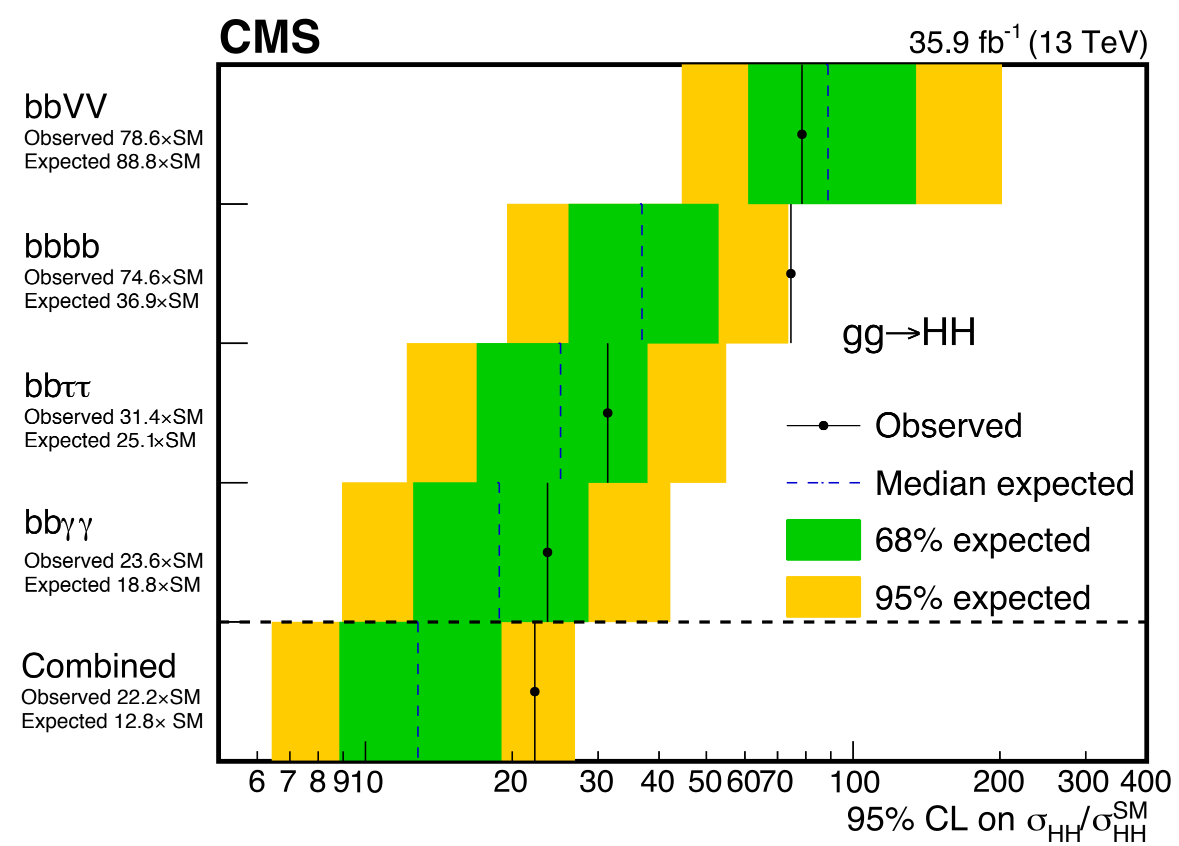
Search for di-Higgs





Assume all kinematic properties of HH pair are same as SM prediction, and only ggF XS can deviate from SM



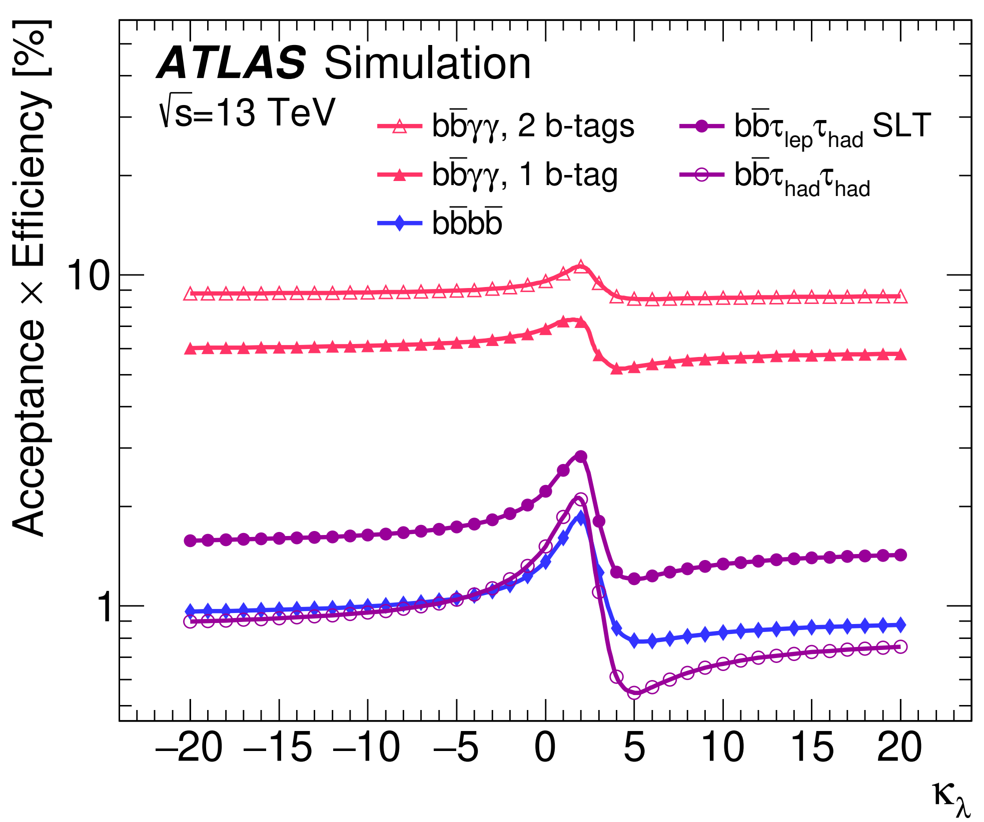


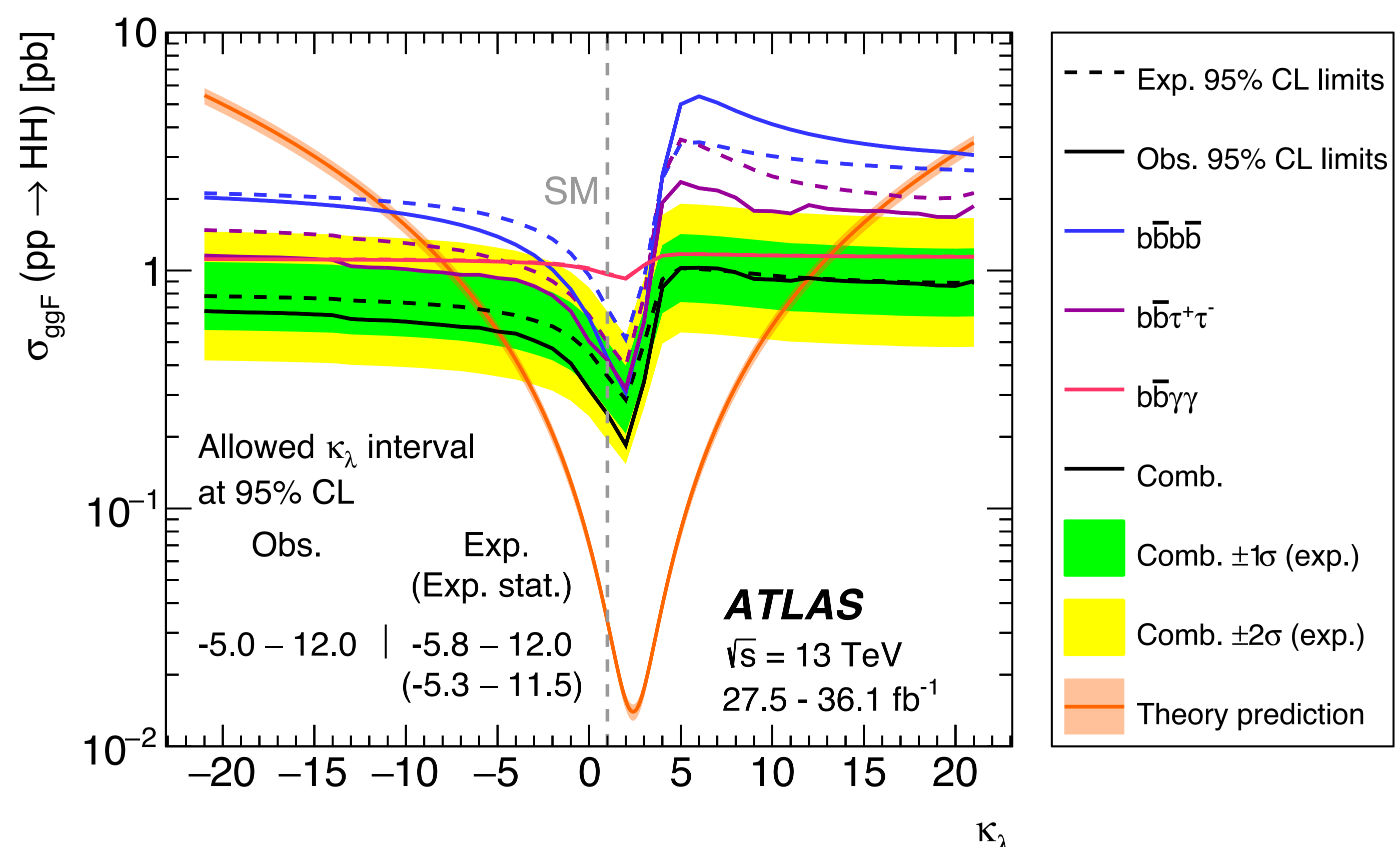
Getting close to **10*SM rate** for Di-Higgs production

Constraint on the Higgs self-coupling

- Kinematic dependence on κ_λ is estimated with LO prediction, and K-factor is only estimated with $\kappa_\lambda=1$
- Amplitude dependence on κ_λ can be expressed with 3 reference samples

$$|A(k_t,k_\lambda)|^2 = k_t^2\left[\frac{90k_t^2+9k_\lambda^2-99k_tk_\lambda}{90}|A(1,0)|^2+\frac{100k_tk_\lambda-10k_\lambda^2}{90}|A(1,1)|^2+\frac{k_\lambda^2-k_tk_\lambda}{90}|A(1,10)|^2\right]$$



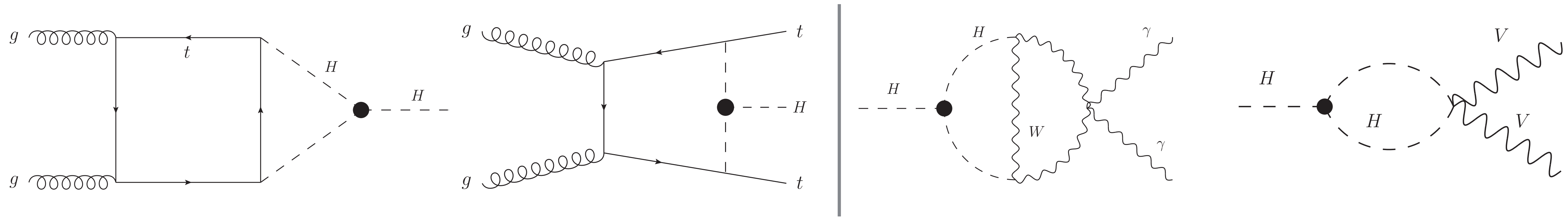


Constraint on **self-coupling (obs/exp) @ 95% CL:**

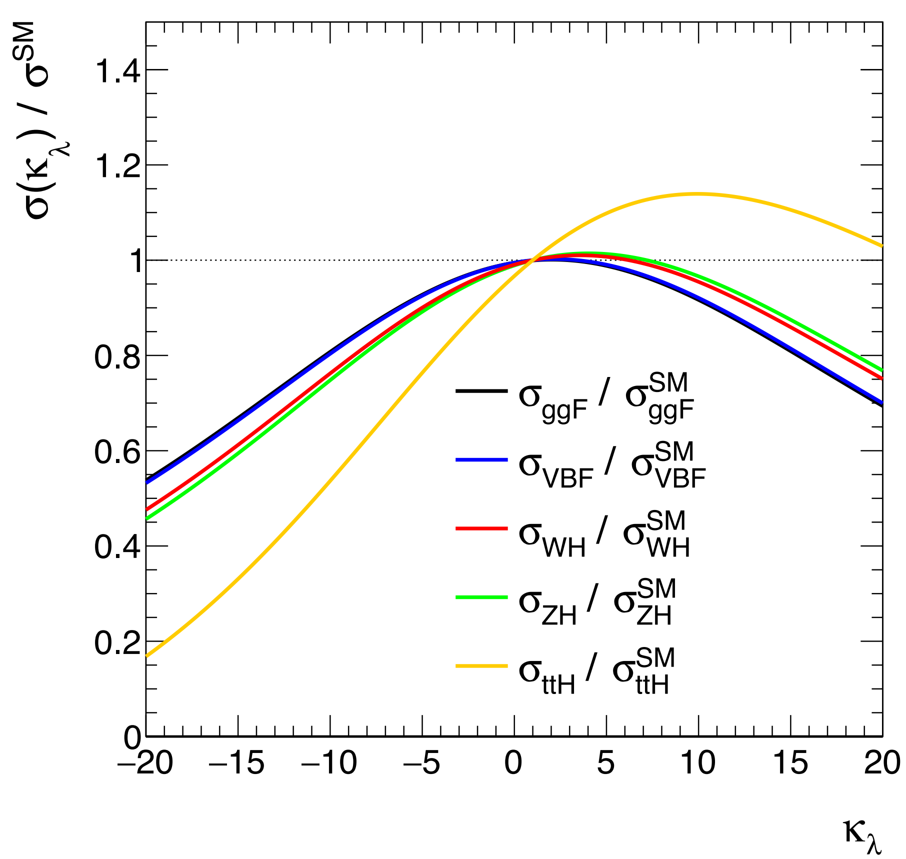
- $-5.0<\kappa_\lambda<12.0$ / $-5.8<\kappa_\lambda<12.0$

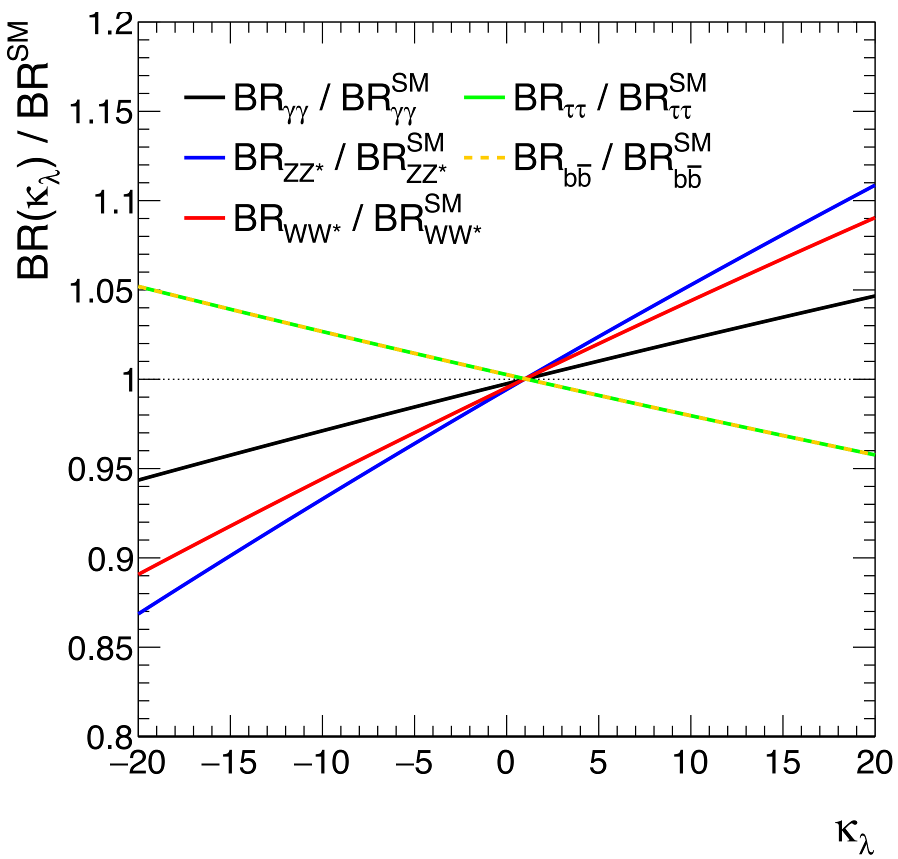
Self-coupling from single Higgs

All the single Higgs production and decay processes are affected by an anomalous trilinear (**<u>not quartic</u>**) Higgs self coupling, parametrized by κ_λ.

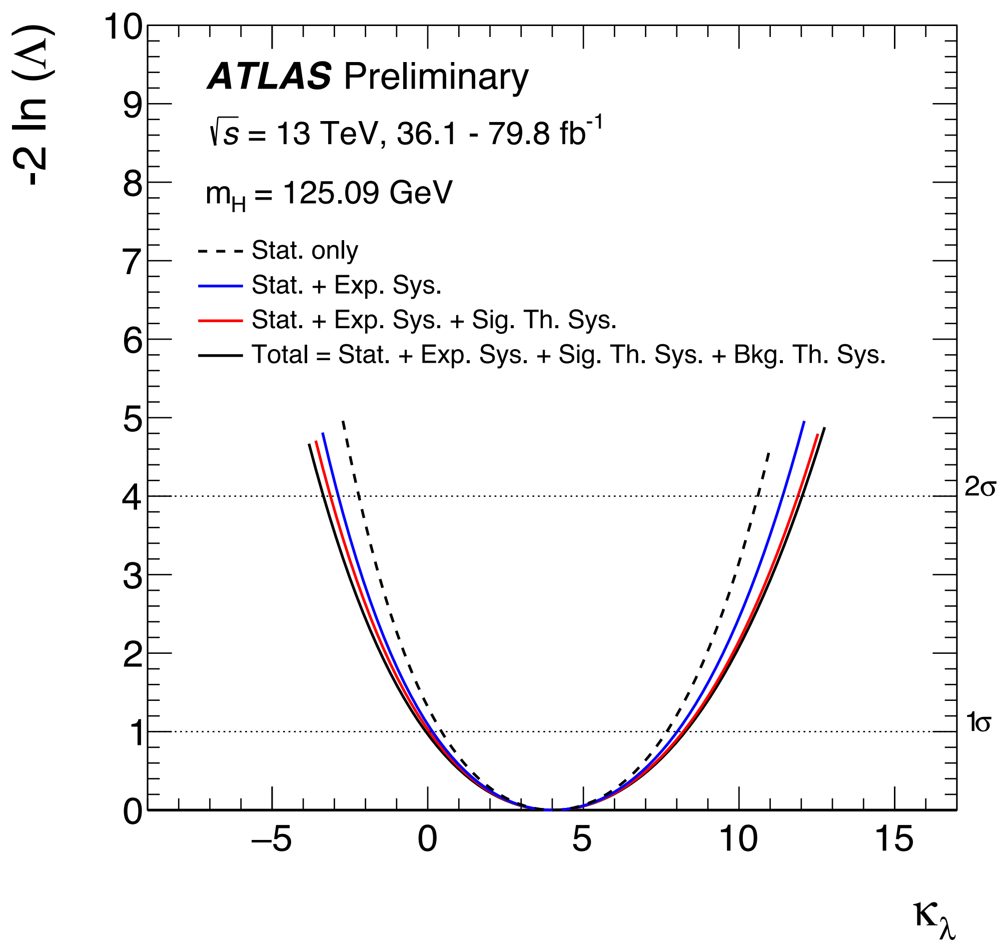


All the different signal strengths μ_i^f have a different dependence on a single parameter κ_λ, which can thus be constrained via a global fit.

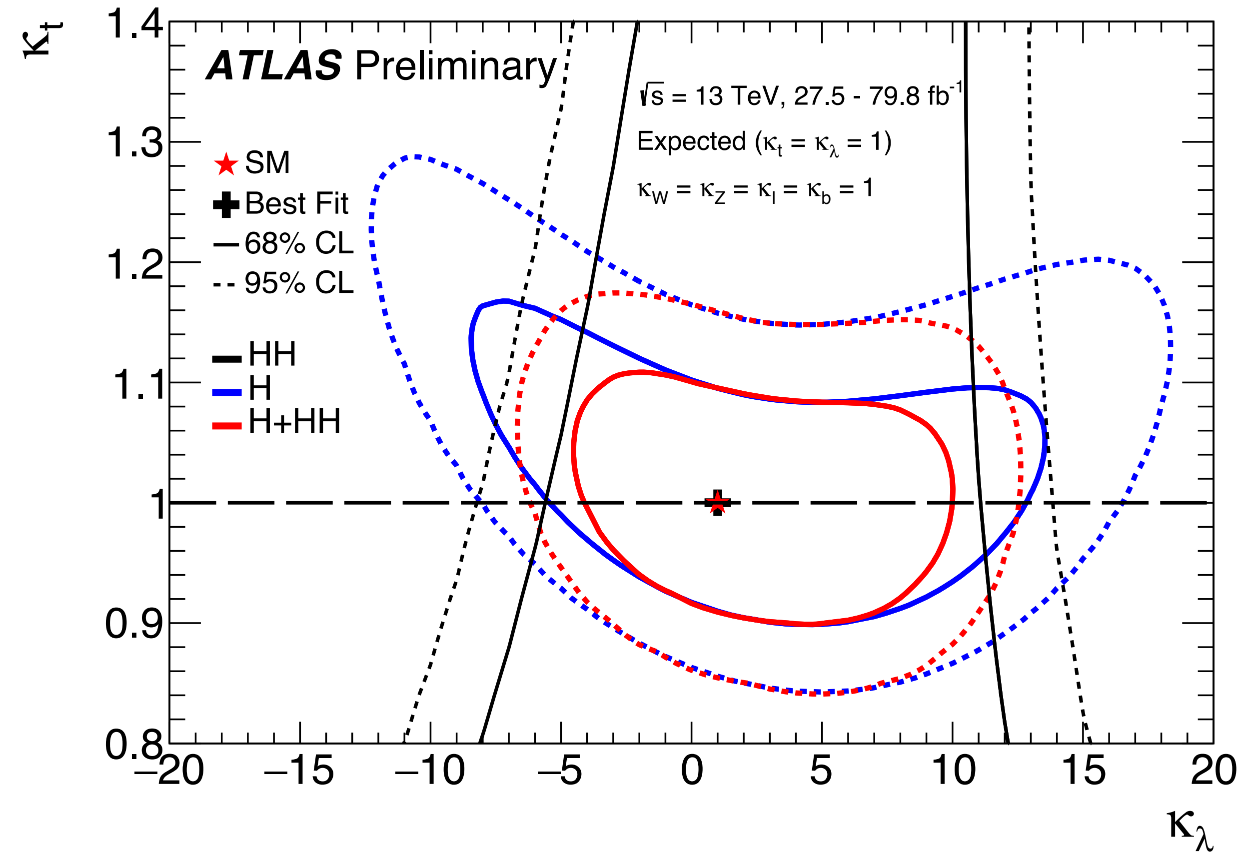




Self-coupling from single Higgs



ATL-PHYS-PUB-2019-009



ATL-CONF-2019-012

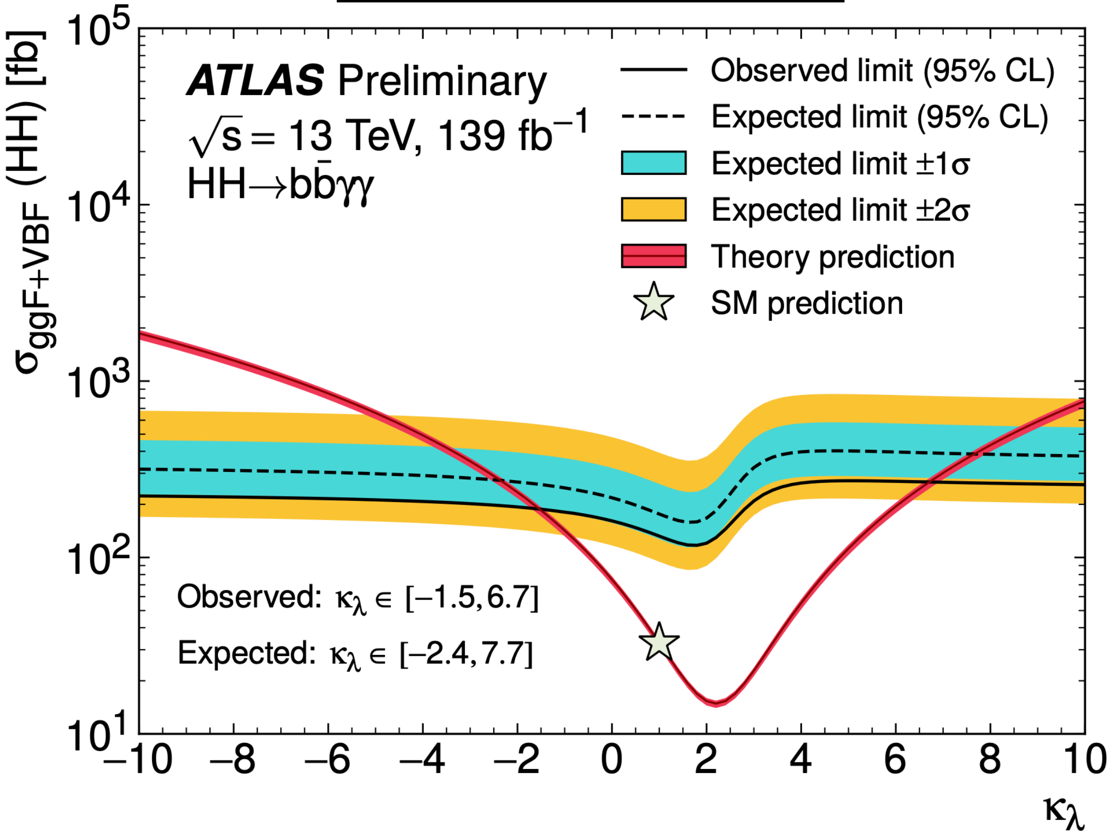
Constraint on **self-coupling (obs/exp) @ 95% CL:**

- **ATLAS (H): -3.2<κλ<11.9 / -6.2<κλ<14.4**
- **ATLAS (HH):** -5.0<κλ<12.0 / -5.8<κλ<12.0
- **ATLAS (H+HH): -2.3<κλ<10.3 / -5.1<κλ<11.2**
- **CMS(HH):** -5.8<κλ<12.0 / -5<κλ<12.1

Update on the individual decay modes

HH→bbγγ

ATL-CONF-2021-016

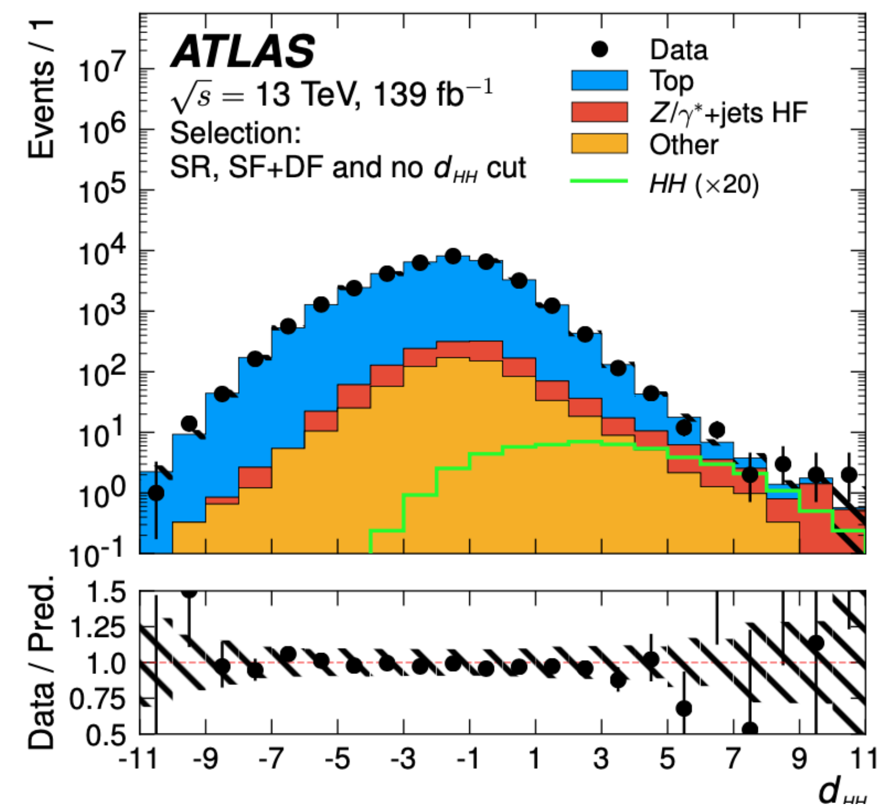


$\sigma(pp \to HH) = 4.1\ (5.5)$*SM @95% CL

Best Constraint

HH→bbWW

PLB 801 (2020) 135145

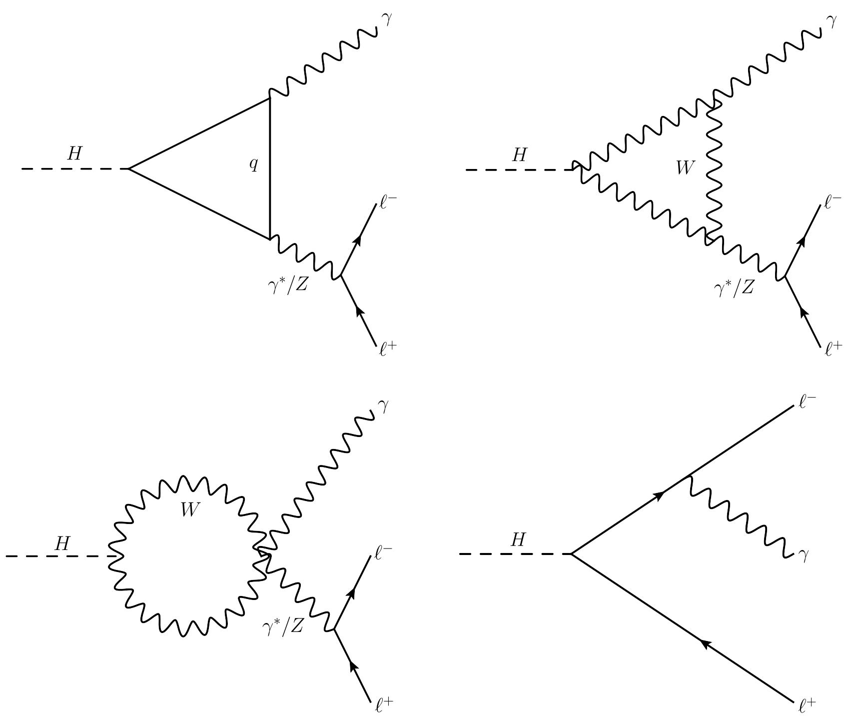


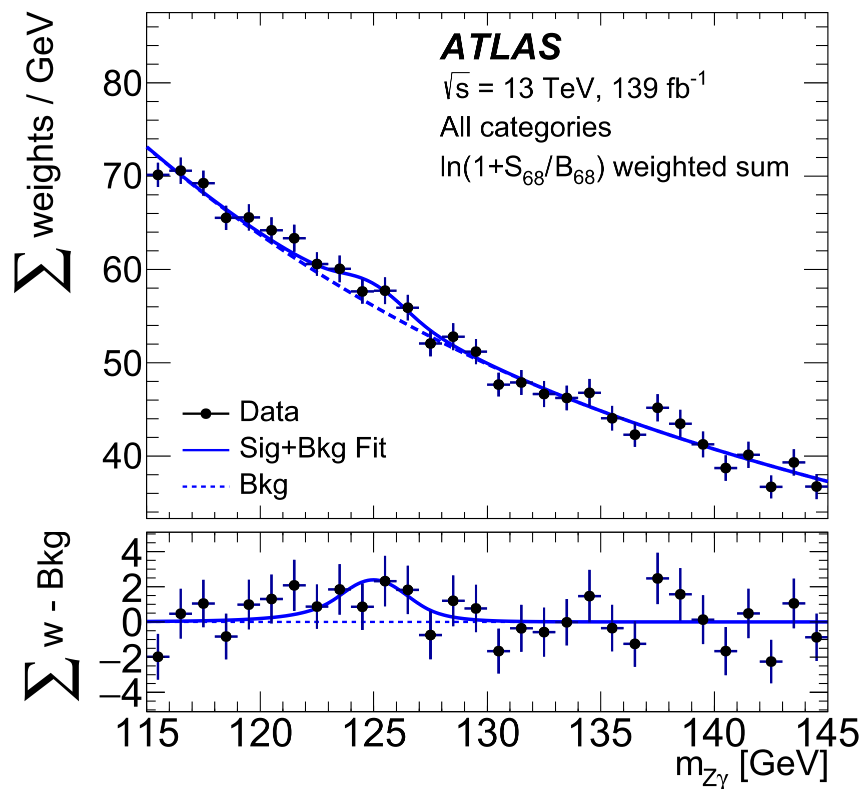
	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \to HH)/\sigma^{SM}(gg \to HH)$	14	20	29	43	62	40

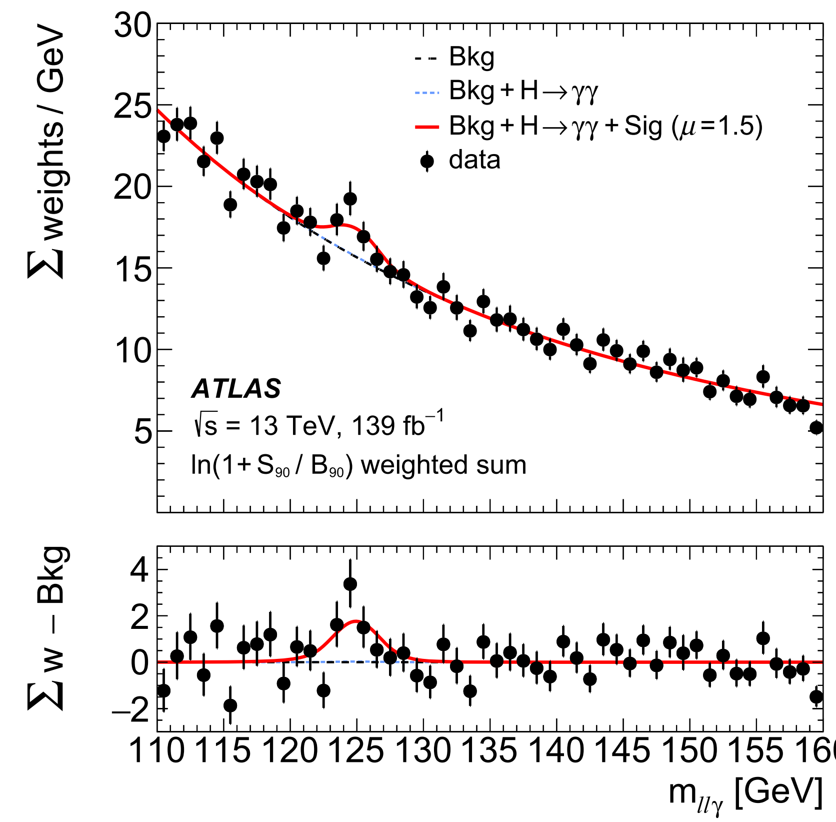
More precise measurements are coming soon

H→Zγ/γγ* search

- H→Zγ search is important to probe the Higgs loop interaction
- Multiple processes contribute to H→llγ, including H→γγ*



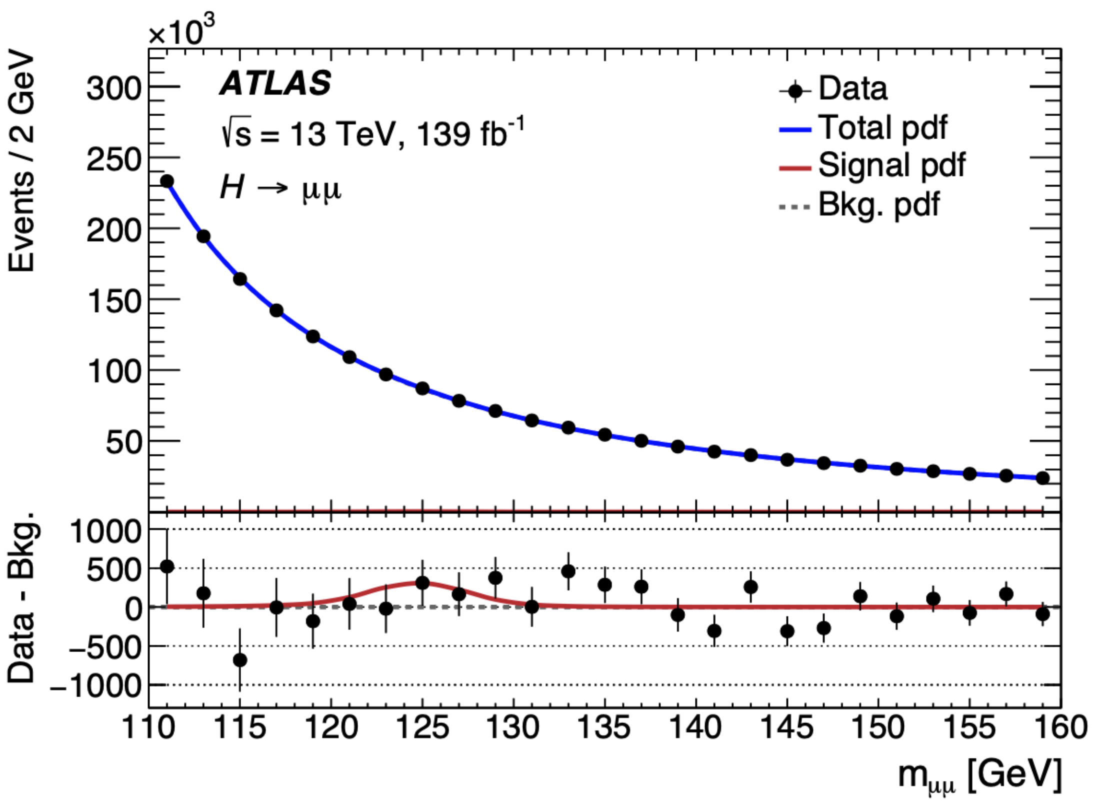


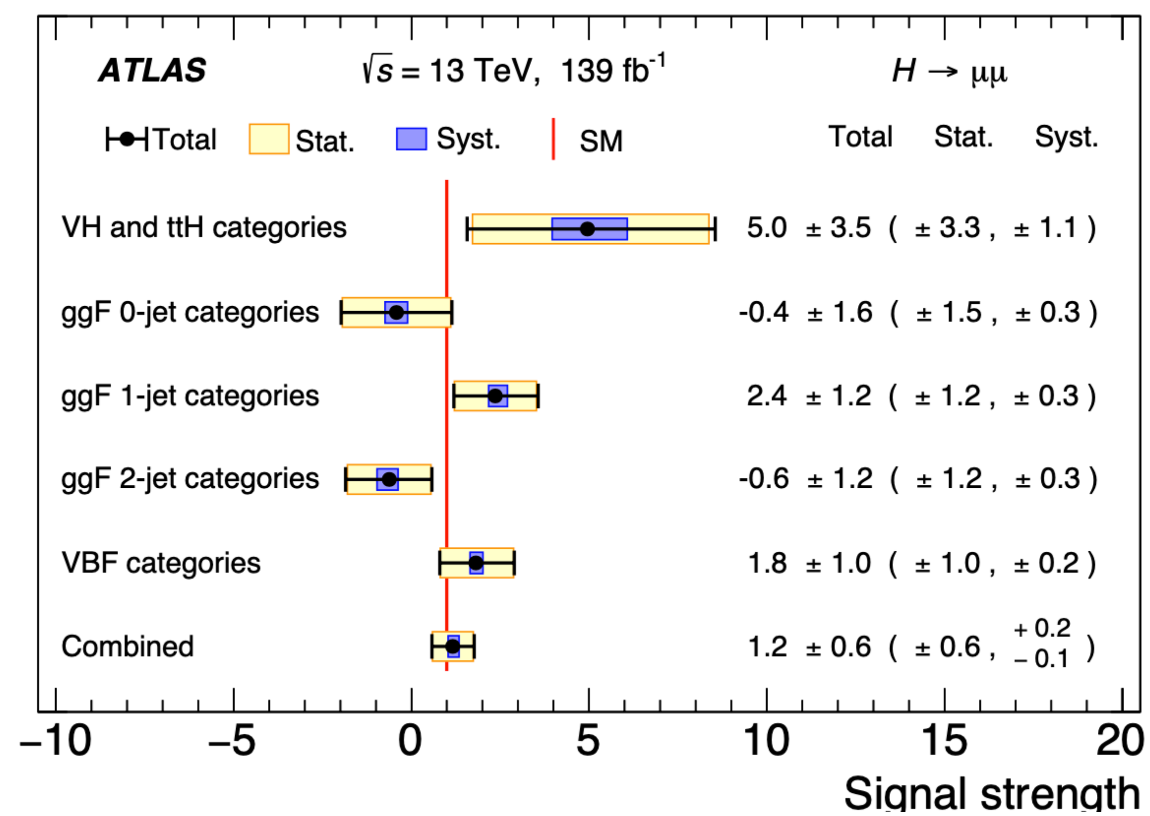


	Obs.	Exp.	**σ×B(H→llγ)**
H→Zγ	2.0 σ	1.2 σ	$2.0^{+1.0}_{-0.9}$
H→γ*γ	3.2 σ	2.1 σ	1.5 ± 0.5

H→μμ

- **H→μμ can probe the coupling between Higgs and 2nd-generation Fermion**
  - Benefit from the precise measurement of muon





Obs. (Exp.) significance: 2.0 (1.7)σ

Search for Higgs invisible decay

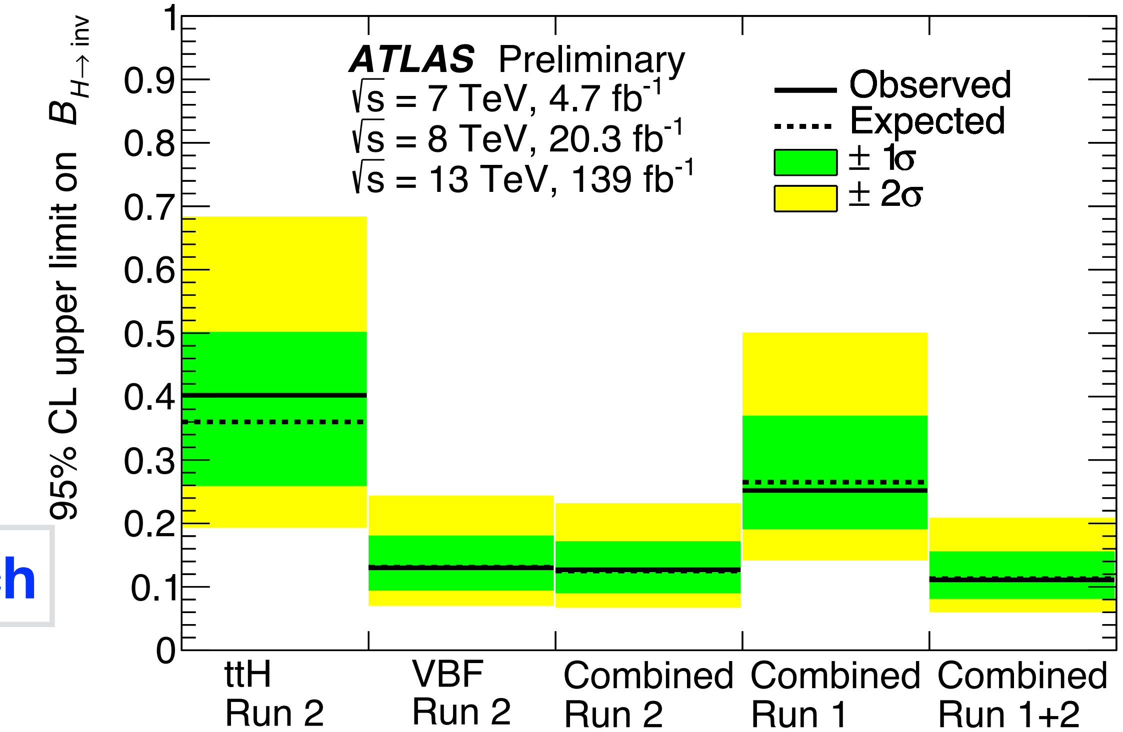
- In SM, B(H→inv) =0.1% from H→ZZ*→4ν decays
- BSMs predict DM productions @ LHC, including Higgs portal models:
  - **Higgs acts as a portal between a dark sector and the SM sector**
  - **DM particles can only be indirectly inferred through MET, termed as “invisible”**

Input channels: ttH-0l @ Run2, ttH-2l @ Run2, VBF @ Run2 and Run1

Analysis	$\sqrt{s}$ [TeV]	Int. luminosity [fb^{-1}]	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
Run 2 VBF	13	139	$0.00^{+0.07}_{-0.07}$	0.13	$0.13^{+0.05}_{-0.04}$
Run 2 $t\bar{t}H$	13	139	$0.04^{+0.20}_{-0.20}$	0.40	$0.36^{+0.15}_{-0.10}$
Run 2 Comb.	13	139	$0.00^{+0.06}_{-0.07}$	0.13	$0.12^{+0.05}_{-0.04}$
Run 1 Comb.	7, 8	4.7, 20.3	$-0.02^{+0.14}_{-0.13}$	0.25	$0.27^{+0.10}_{-0.08}$
Run 1+2 Comb.	7, 8, 13	4.7, 20.3, 139	$0.00^{+0.06}_{-0.06}$	0.11	$0.11^{+0.04}_{-0.03}$

VBF mode provides most sensitivity for inv. search

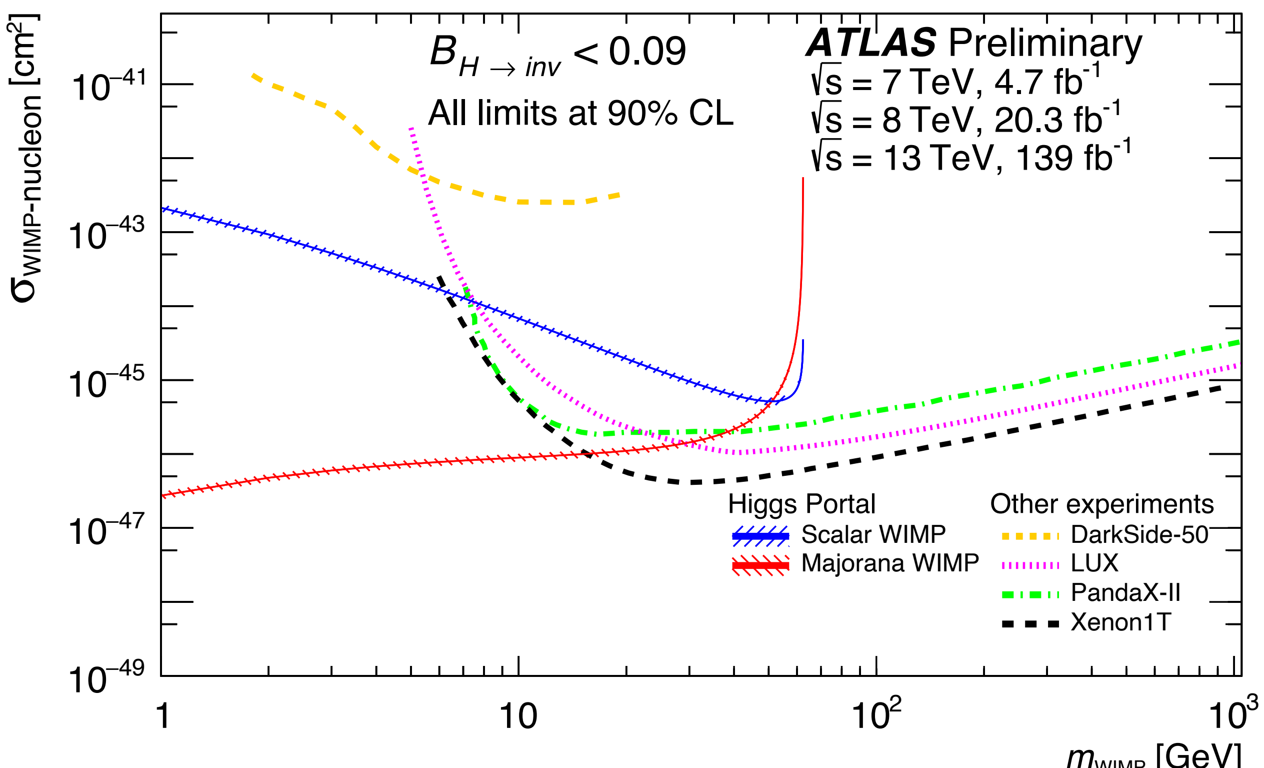
ATL-CONF-2020-052



- **Dominated by systematic uncertainties** (statistics of simulation MC, Rec and ID of Jet/lepton, background modelling)
- More stringent constraint is coming with the combination of **VH and Higgs visible decay modes** (κ-framework)

DM search

- In "Higgs portal" models, H→inv can be translated to constraint on the WIMP-nucleon scattering cross section σ_{WINP-N} on an EFT approach
  - ✦ **Scale WIMP scenario: $\sigma_{WIMP-N} < 10^{-45}$ cm²**
  - ✦ **Majorana fermion WIMP scenario: $\sigma_{WIMP-N} < 2*10^{-47}$ cm²**



ATL-CONF-2020-052

Highlighting the complementarity of DM searches at the LHC and direct detection experiments

Summary

- **Comprehensive Higgs property measurements:** mass, width, fiducial/differential cross section, simplified template cross section: everything is in good agreement with SM

- More precise measurements are coming soon.