

# Higgs combination results

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On behalf of the ATLAS collaboration

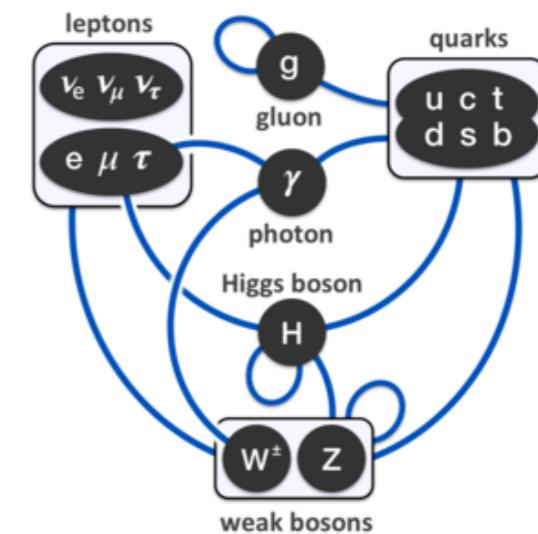
Higgs Hunting, July 30th, 2019



# Higgs coupling measurements

## Standard Model predicts the couplings

- Higgs couplings to fermions  $\sim m_F$
- Higgs couplings to bosons  $\sim m_V^2$



## Measuring the couplings gives crucial insight into the nature of the Higgs boson and the Higgs mechanism

- deviations predicted by many new physics models (can be small!)
- best precision can be reached by **combining** measurements in all available production and decay channels

## ATLAS coupling combination

- 24-80 fb<sup>-1</sup>, documented in ATLAS-CONF-2019-005
- multiple categories used in every analysis/decay channel
- combination performed by constructing combined likelihood model
- Very powerful: Many choices of parameters and interpretations possible



# Combination of measurements in all major production and decay channels

ATLAS-CONF-2019-005

	ggF	VBF	VH	ttH
bosons				
$\gamma\gamma$	✓	✓	✓	✓
$ZZ$	✓	✓	✓	✓
$WW$	✓	✓	✓	✓
$\tau\tau$	✓	✓	-	✓
$bb$	✓	✓/✓	✓	✓

✓: channel available, but not included in the combination

✓/✓: used in a subset of results

Also in a subset of results:

- + H->inv searches
- + on-shell/off-shell width measurement

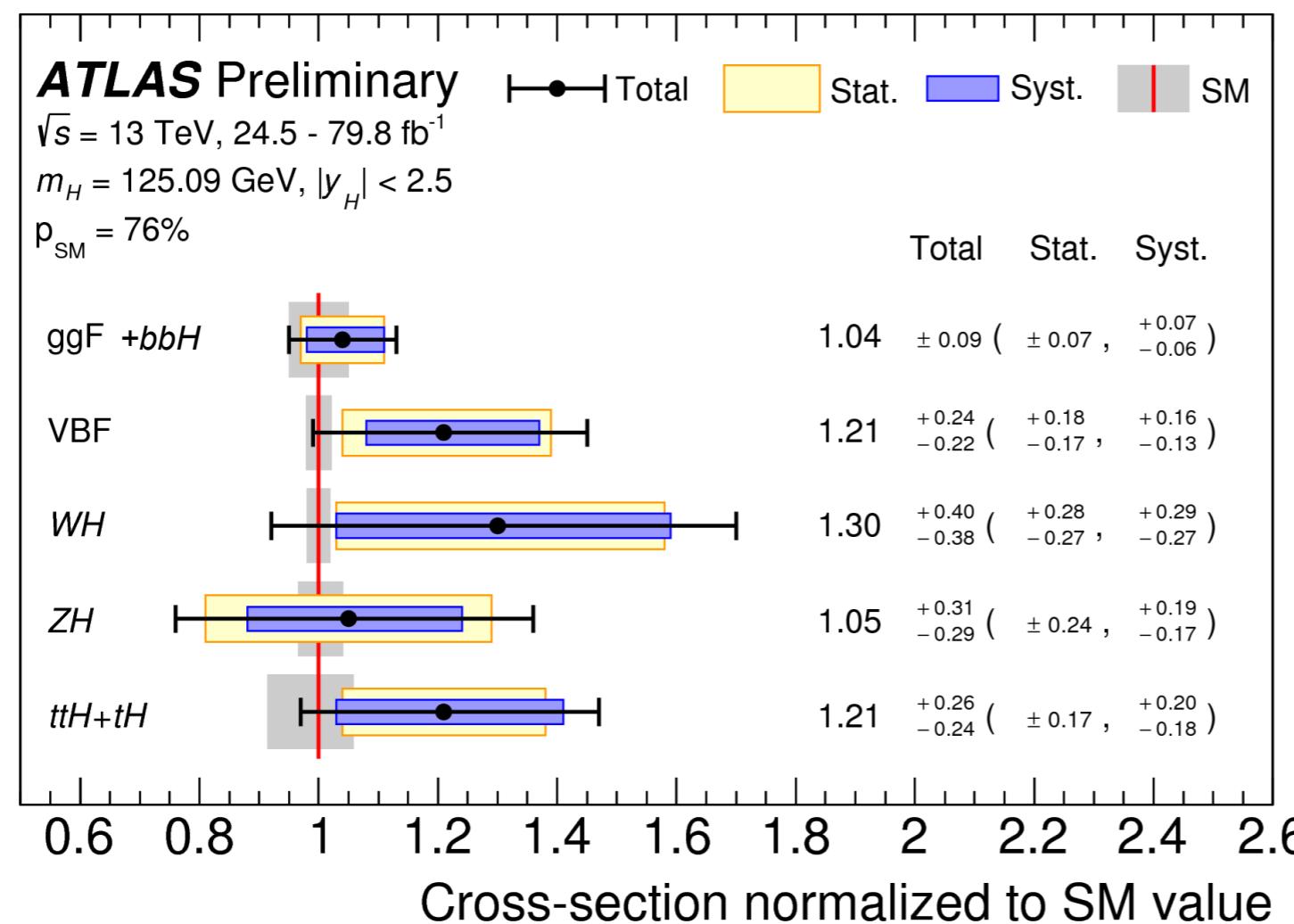


# Incl. Signal strength and production modes

$$\mu = \frac{(\sigma \times B)_{\text{obs}}}{(\sigma \times B)_{\text{SM}}}$$

$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(\text{stat.})^{+0.05}_{-0.04}(\text{exp.})^{+0.05}_{-0.04}(\text{sig.th.}) \pm 0.03(\text{bkg.th.})$$

## Production cross sections, assuming SM branching ratios

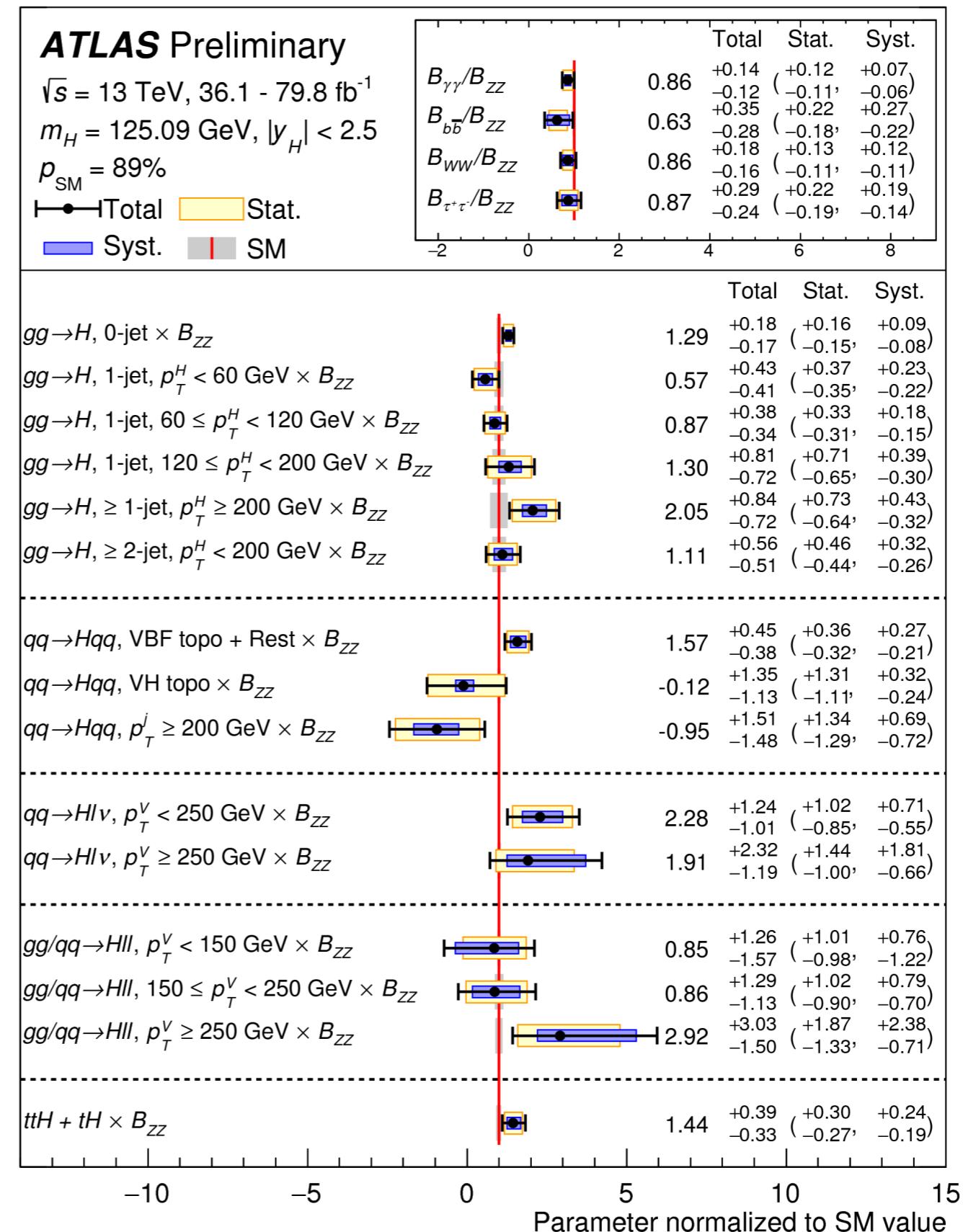


- all major production modes observed!  
(also all major decay modes)
- single experiment observation of VBF
- smaller correlations than in previous analyses,  
-15% for ggF vs VBF



# Simplified template cross sections (STXS)

- STXS: cross sections binned by production mode and kinematic regions (reduces acceptance uncertainty)
- Parametrization based on cross sections in the H->ZZ channel and ratio of branching ratios
- good compatibility with SM ( $p = 89\%$ )
- results with higher granularity (full Stage 1) also available



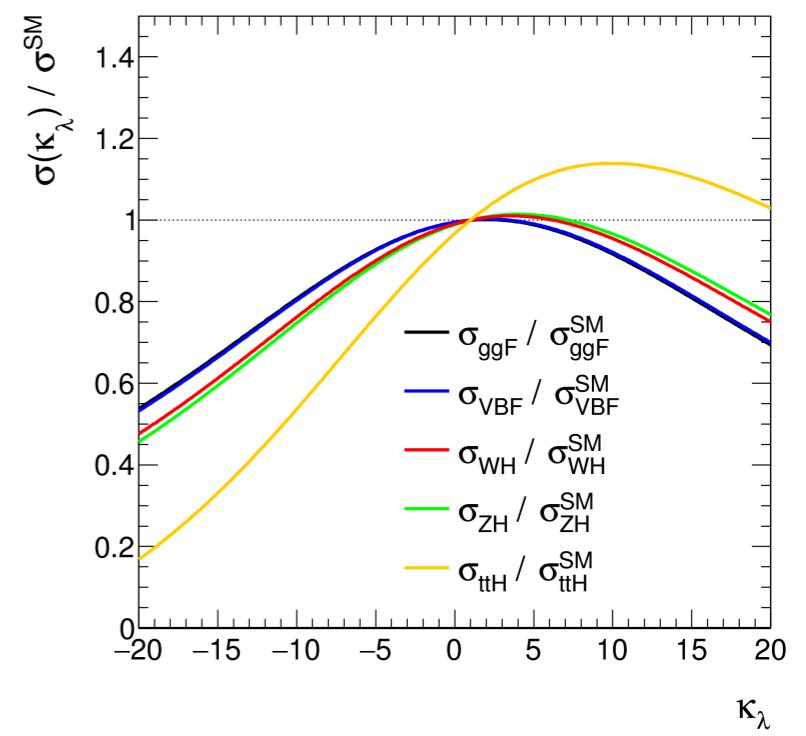
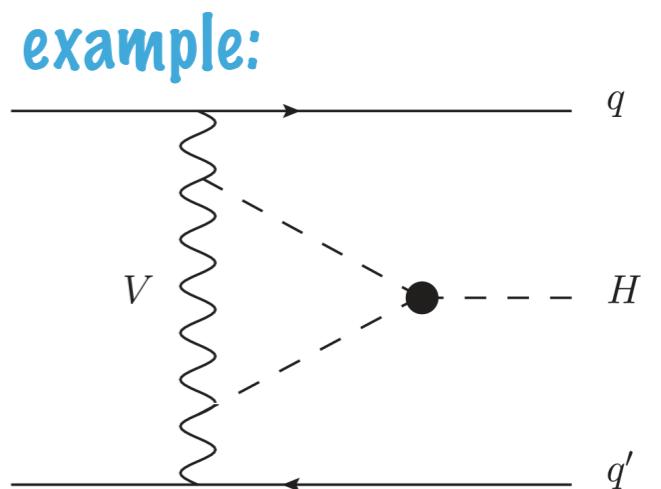


# Self couplings probed using STXS

ATLAS-PUB-2019-009

$$V(H) = \frac{1}{2}m_H^2 H^2 + \boxed{\lambda_3 \nu H^3} + \frac{1}{4}\lambda_4 H^4 + \mathcal{O}(H^5)$$

- usually studied in di-Higgs searches
- it is possible to extract the self-coupling in single-Higgs events through NLO EW corrections
- use inclusive XS for ggF, ttH
- use STXS bins for VBF and VH
- assume all single-Higgs couplings to be SM
- fit for  $\kappa_\lambda = \frac{\lambda_3}{\lambda_3(\text{SM})}$
- $\kappa_\lambda = [-3.2, 11.9] @ 95\% \text{CL}$  (di-Higgs: [-5, 12])
- results similar to di-Higgs fit





# Kappa framework

- assign coupling modifiers to each interaction vertex (LO motivated)

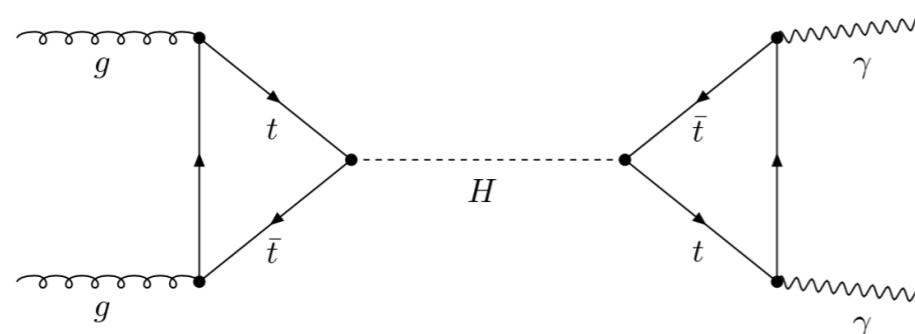
$$\sigma(i \rightarrow H \rightarrow f) = \kappa_i^2 \sigma_i^{\text{SM}} \frac{\kappa_f^2 \Gamma_f^{\text{SM}}}{\kappa_H^2 \Gamma_H^{\text{SM}}}$$

- can also adjust the width

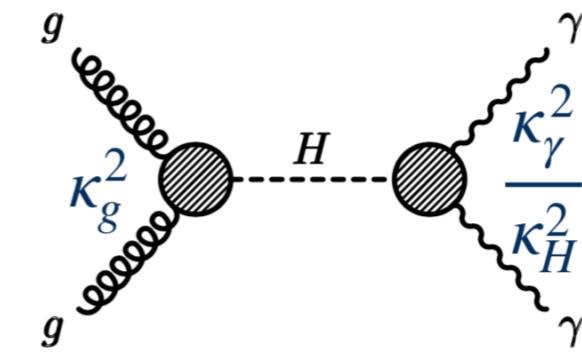
Can add results of H->inv  
searches and off-shell width  
constraints to the combination

$$\Gamma_H(\kappa_i, B_{\text{inv}}, B_{\text{undet}}) = \frac{\kappa_H^2(\kappa_i)}{1 - B_{\text{inv}} - B_{\text{undet}}} \Gamma_H^{\text{SM}}$$

- can choose to resolve or not resolve the ggF and  $\gamma\gamma$  decay loops

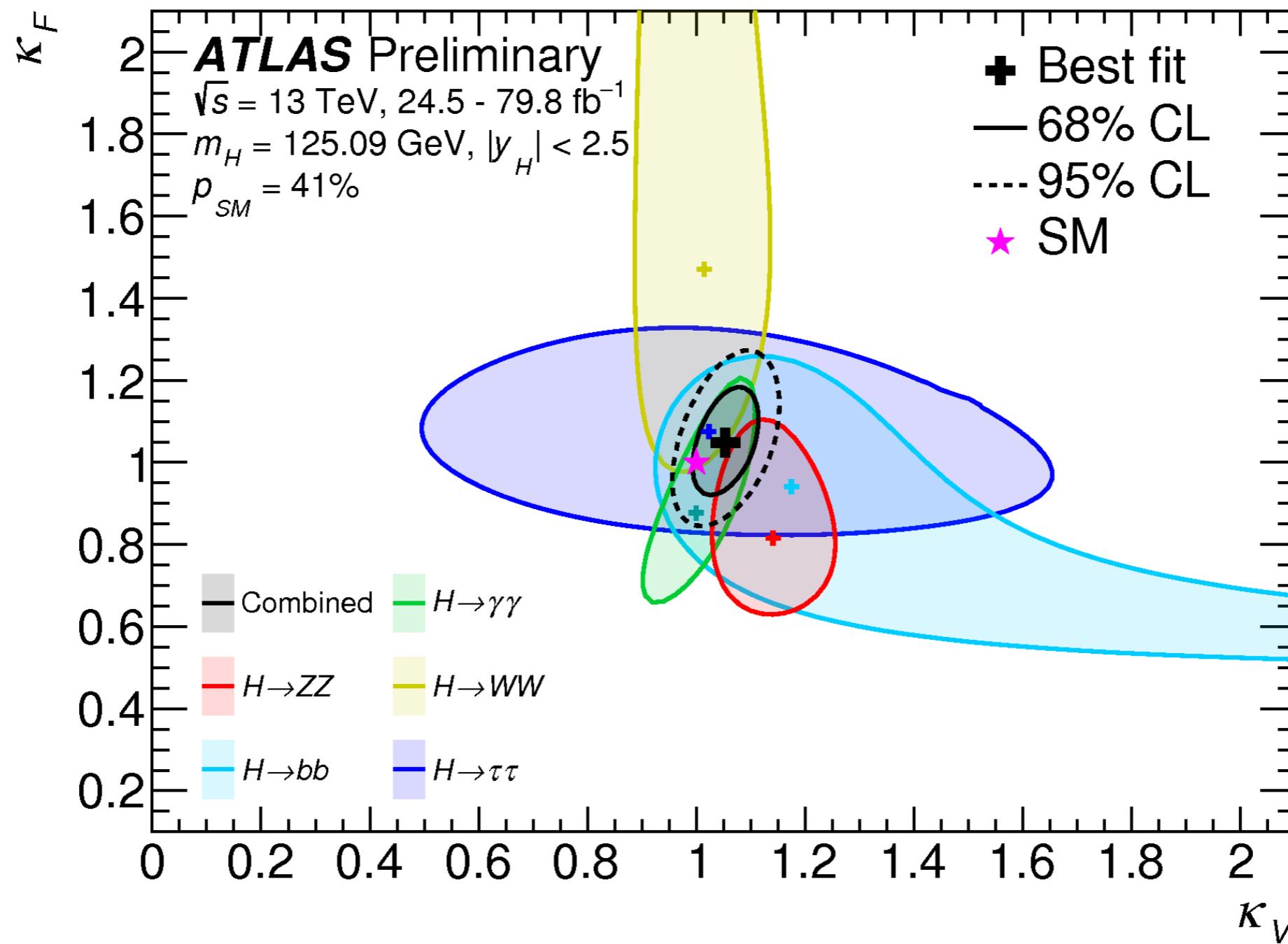


vs.





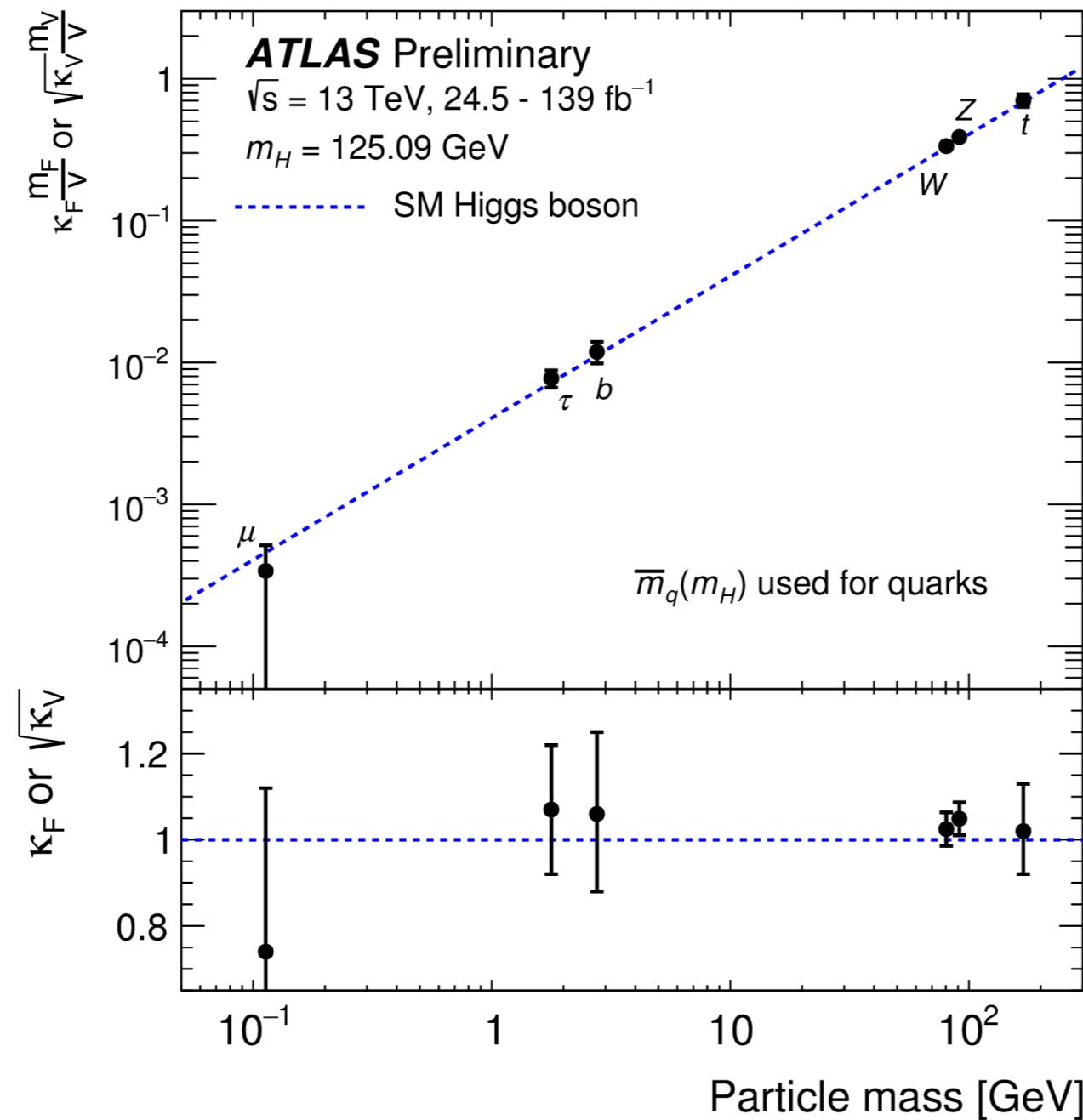
## $\kappa_F$ VS $\kappa_V$



- $\kappa_V = \kappa_W = \kappa_Z$  and  $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$
- Resolve loops, assume no BSM contribution in the loops or total width

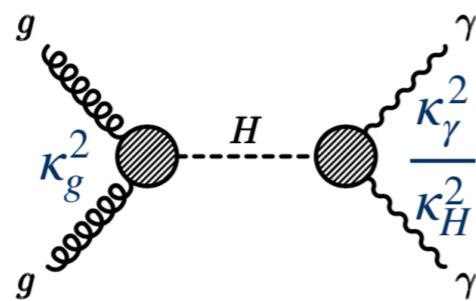
# Diagonal plot

New for EPS!



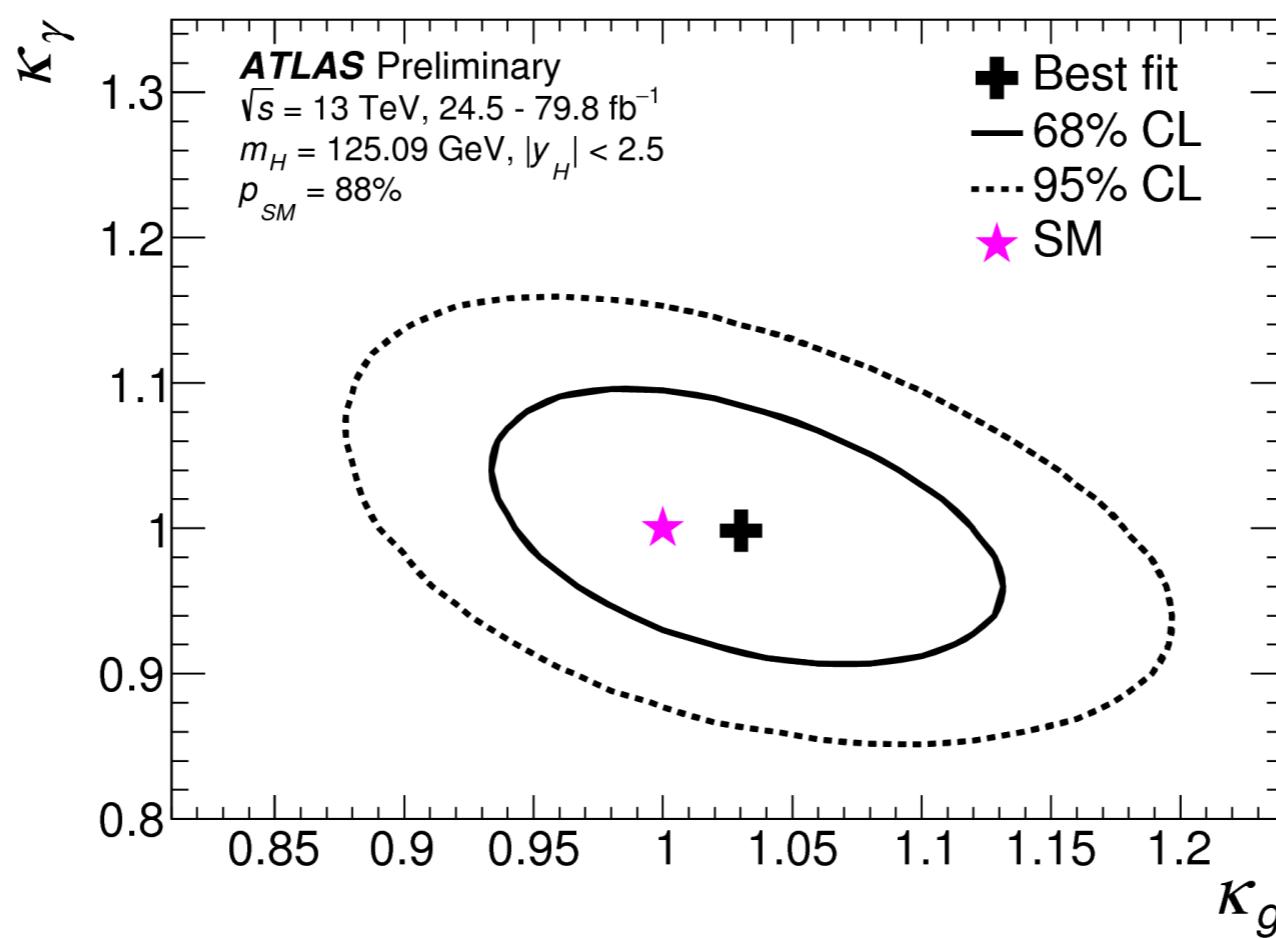
- Resolve loops, assume no BSM contribution in the loops or total width
- This plot was updated to include the  $H \rightarrow \mu\mu$  search with  $139 \text{ fb}^{-1}$

# Not resolving ggF and $\gamma\gamma$ loops



$$\sigma \times B(gg \rightarrow H \rightarrow \gamma\gamma) \propto \kappa_g^2 \frac{\kappa_\gamma^2}{\kappa_H^2}(\kappa_g, \kappa_\gamma)$$

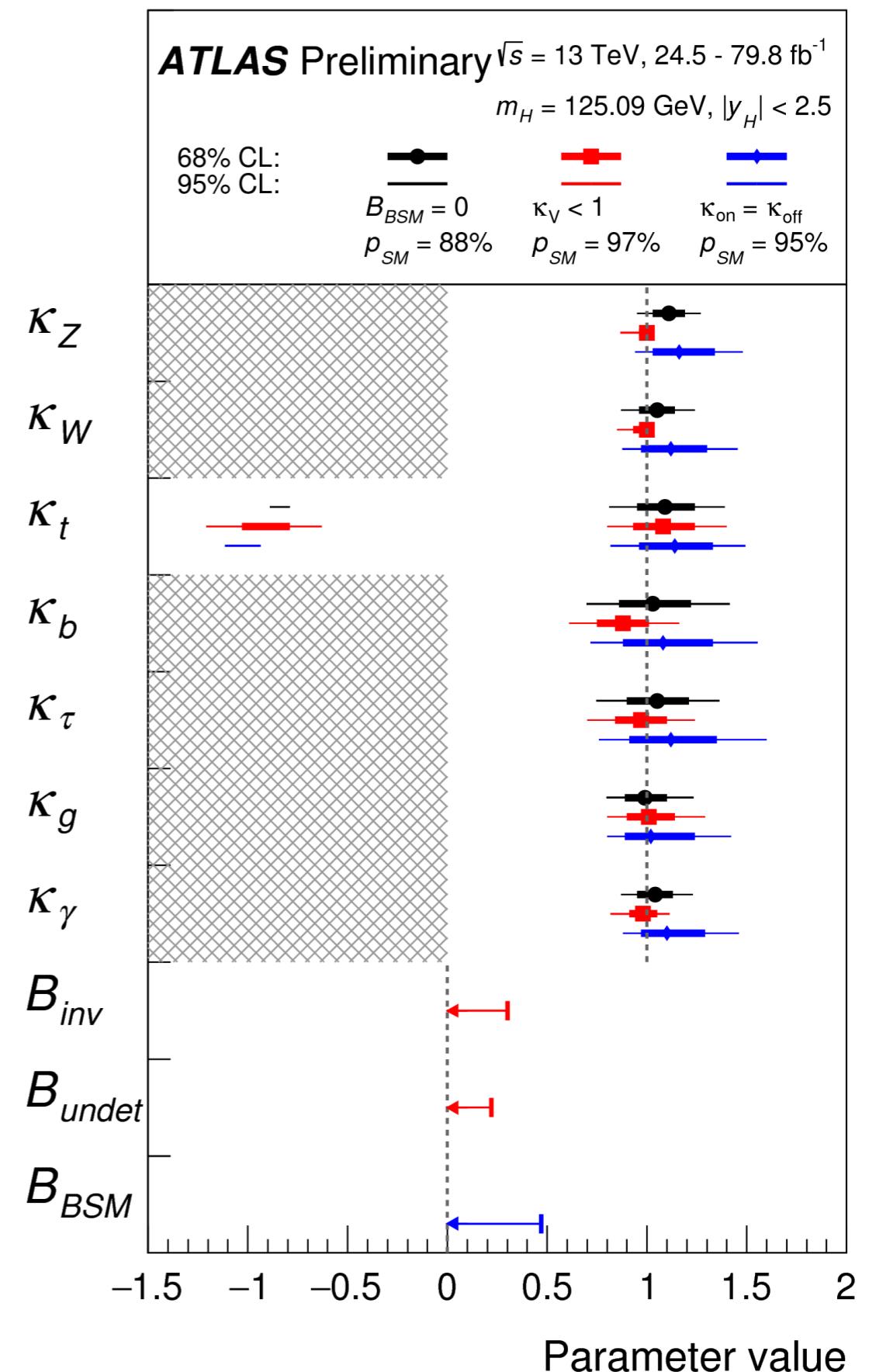
Assume all other couplings to be as predicted by the SM



Assume SM width

# Generic kappa parametrization

- **Black:** assume  $B_{inv} = B_{undet} = 0$
- **Red:** constrain  $B_{inv}$  and  $B_{undet}$  using  $H \rightarrow inv$  analyses and  $\kappa_V < 1$
- **Blue:** constrain  $B_{BSM} = B_{inv} + B_{undet}$  using off-shell analysis and  $\kappa_{on} = \kappa_{off}$
- good agreement with SM
- Uncertainties ( $B_{inv} = B_{undet} = 0$ ): 7-18%



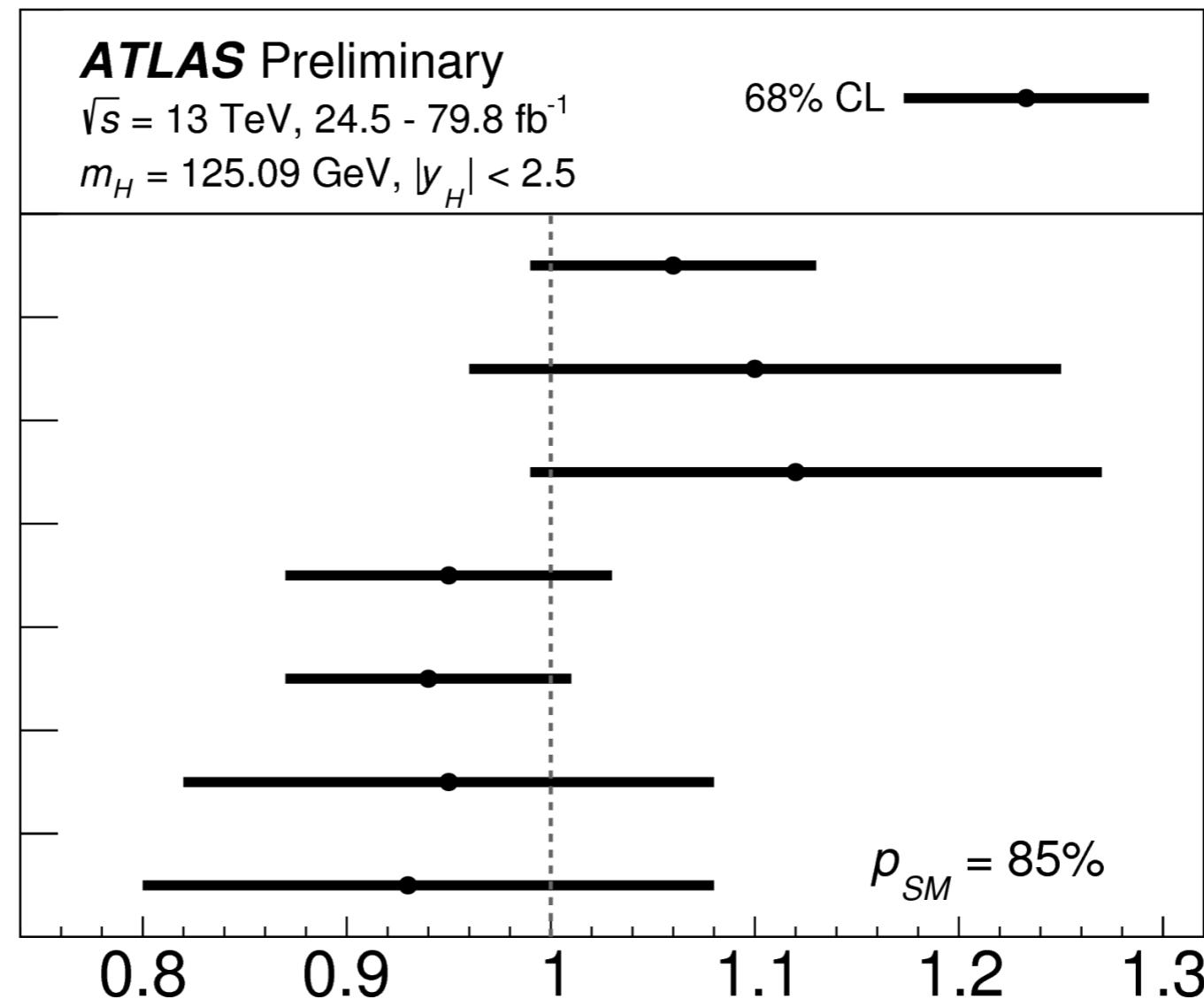


# Alternative: Lambda parametrization

- ratios of kappas
- removes assumption on total width
- good agreement with the SM

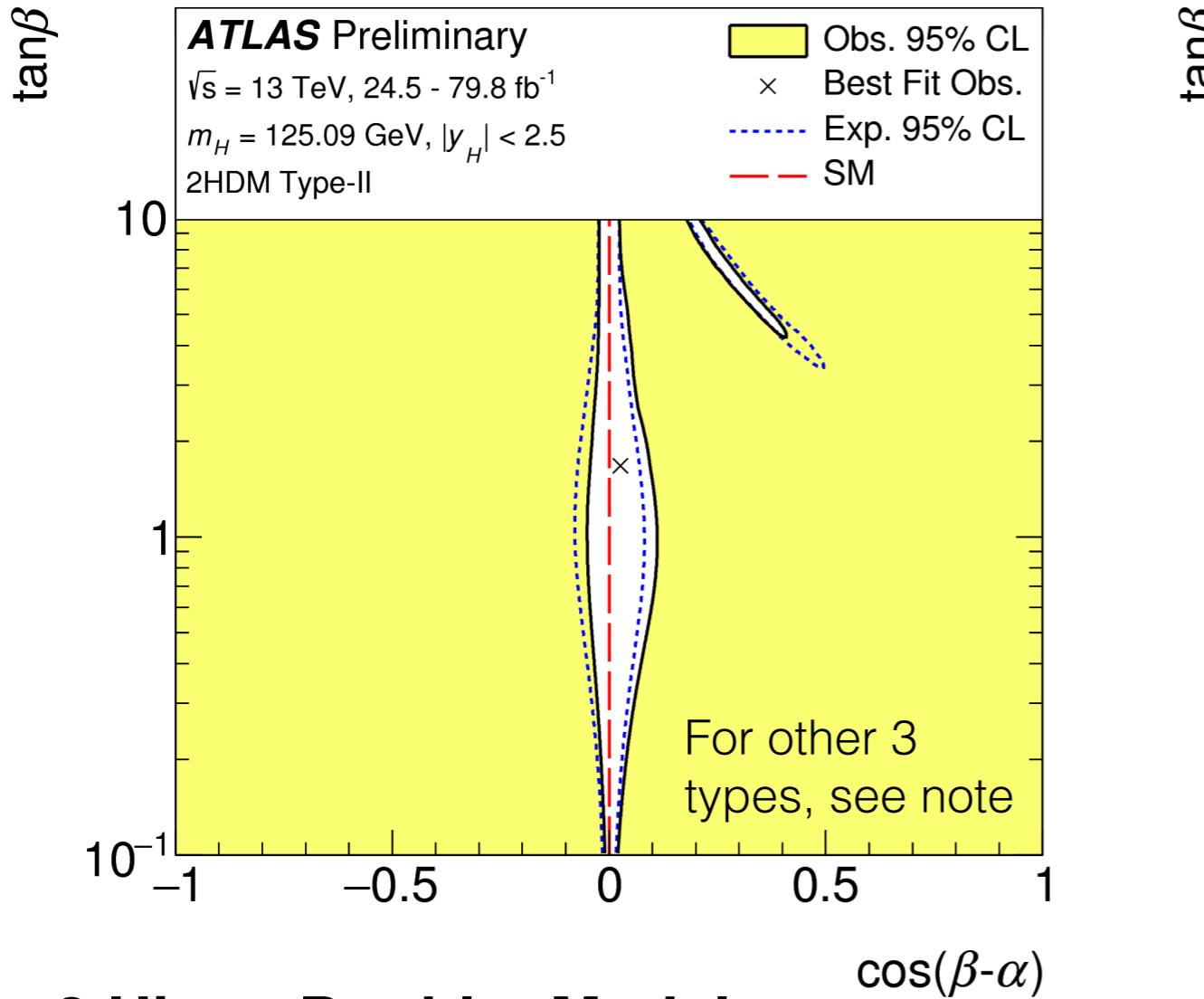
$\kappa_g \kappa_Z / \kappa_H$   
 $\kappa_t / \kappa_g$   
 $\kappa_Z / \kappa_g$   
 $\kappa_W / \kappa_Z$   
 $\kappa_\gamma / \kappa_Z$   
 $\kappa_\tau / \kappa_Z$   
 $\kappa_b / \kappa_Z$

$\kappa_{gZ}$   
 $\lambda_{tg}$   
 $\lambda_{Zg}$   
 $\lambda_{WZ}$   
 $\lambda_{\gamma Z}$   
 $\lambda_{\tau Z}$   
 $\lambda_{bZ}$



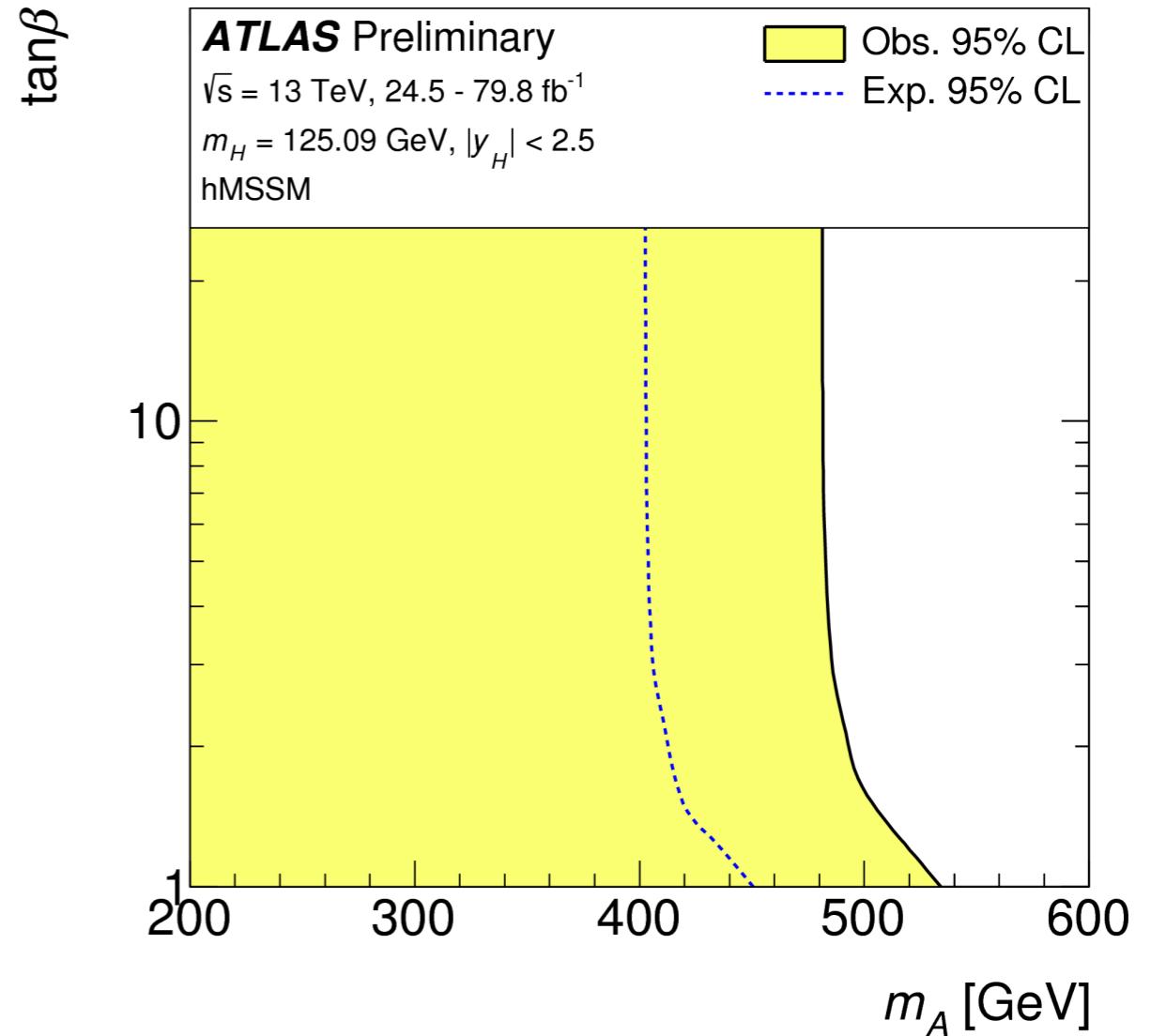


# Interpretation for BSM



## 2 Higgs Doublet Model

- assume Higgs is the light scalar h
- Exclusions in a plane of
- mixing angle between h and H
  - ratio of vacuum expectation values



## Simplified Minimal Supersymmetric Standard Model

(example for 2HDM)

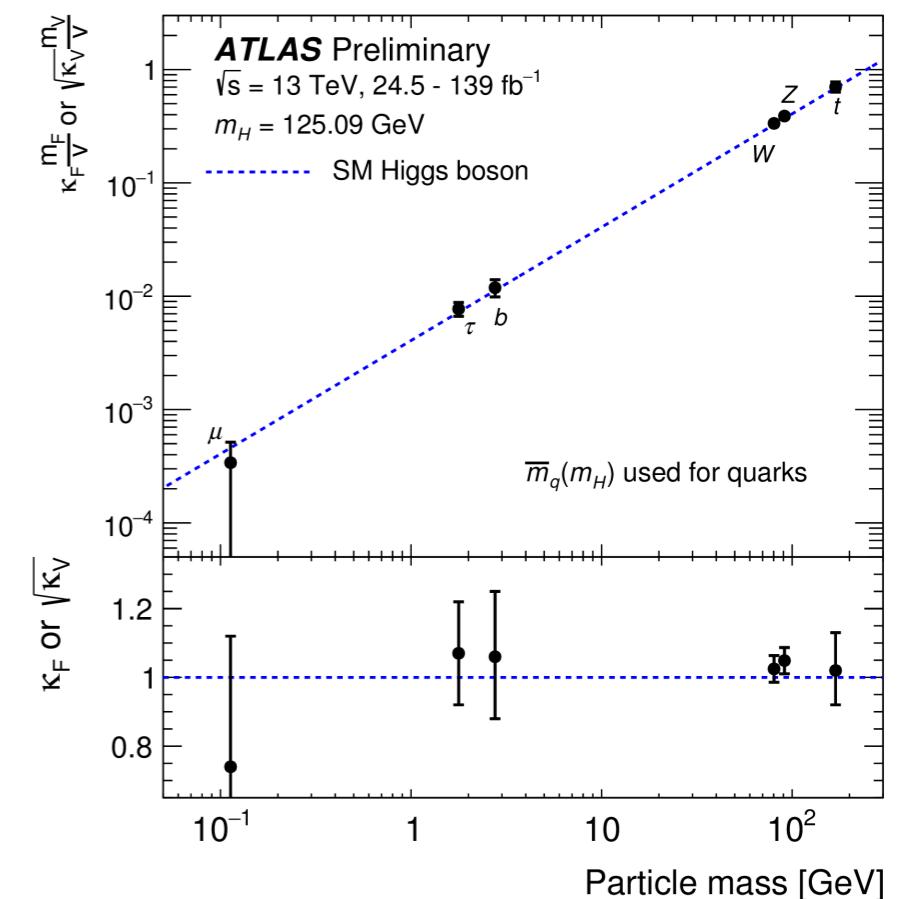
Exclusions in a plane of

- ratio of vacuum expectation values
- mass of CP odd scalar A



# Conclusion

- Higgs combinations are important to achieve precision for stringent tests of the Standard Model
- This talk: Measurement of Higgs couplings using 24-80  $\text{fb}^{-1}$
- For ATLAS differential cross section combinations, and combination of Di-Higgs measurements, see talks by L. Xu and S. Shresta
- So far all measurements agree with the SM predictions
- Looking forward to results with more data
  - using full data set and ATLAS - CMS combination, we should be able to improve the precision by a factor of  $\sim 2$





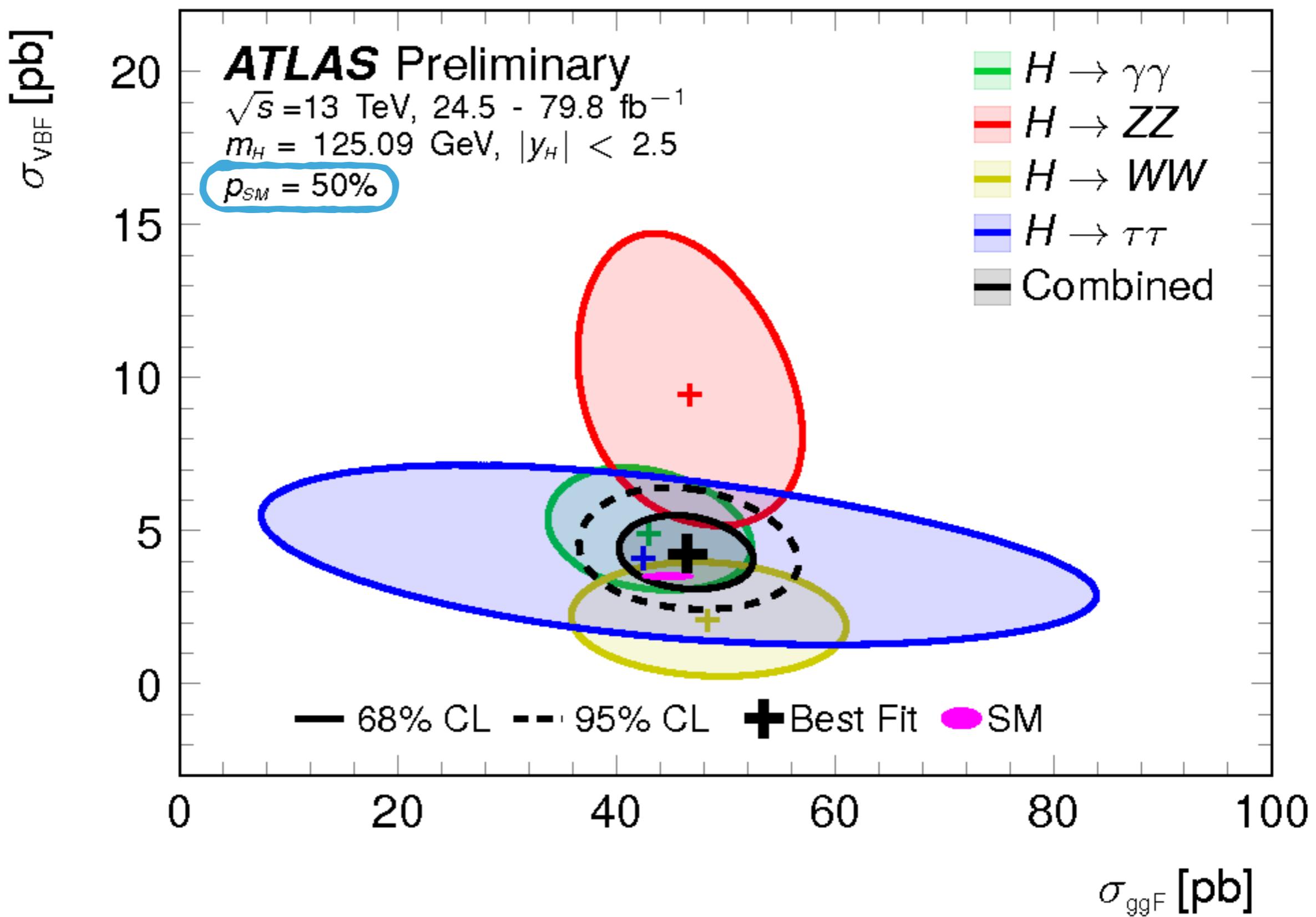
# BACKUP

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# ggF vs VBF contour

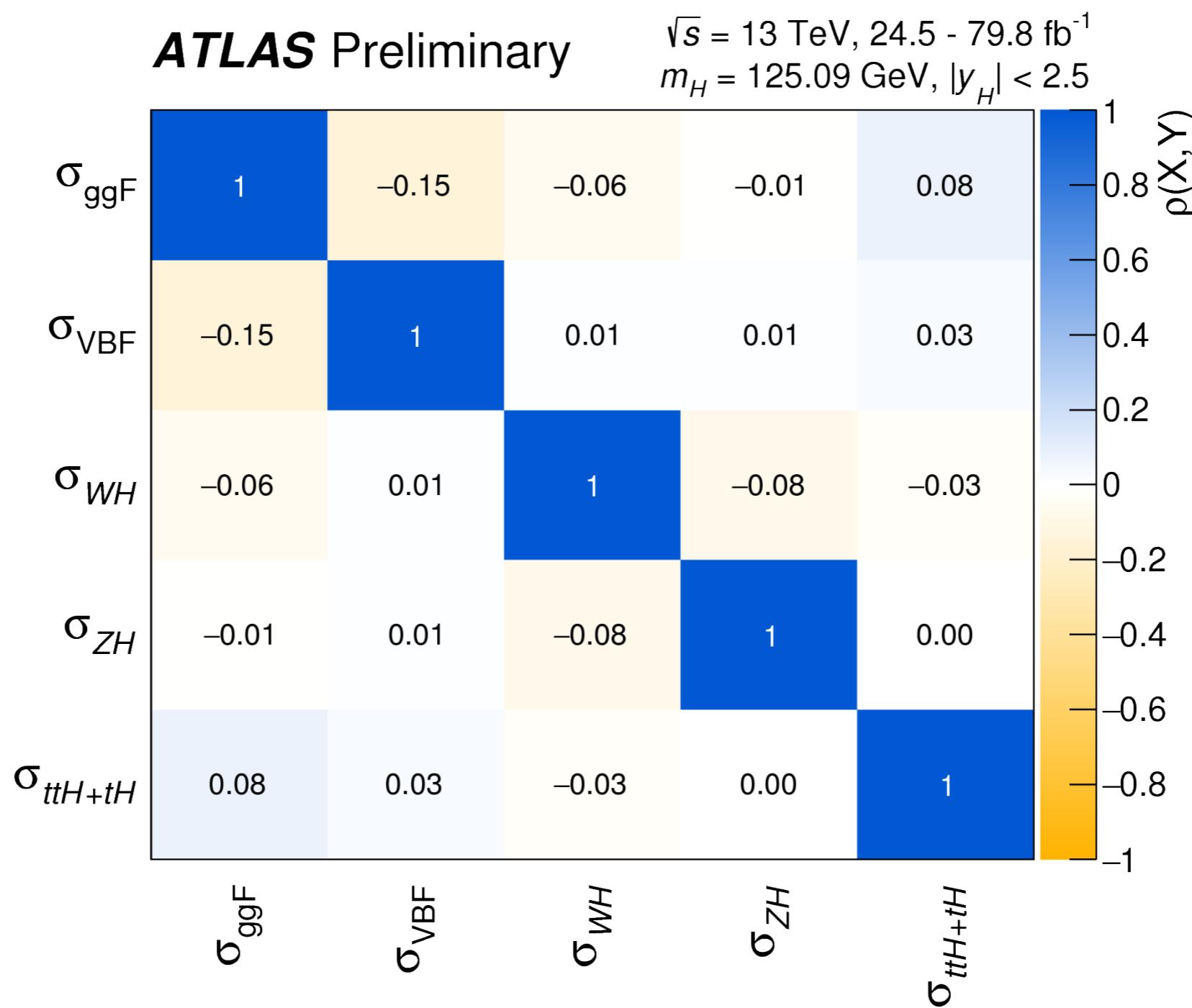
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# BACKUP: Correlation matrices

Production mode cross sections



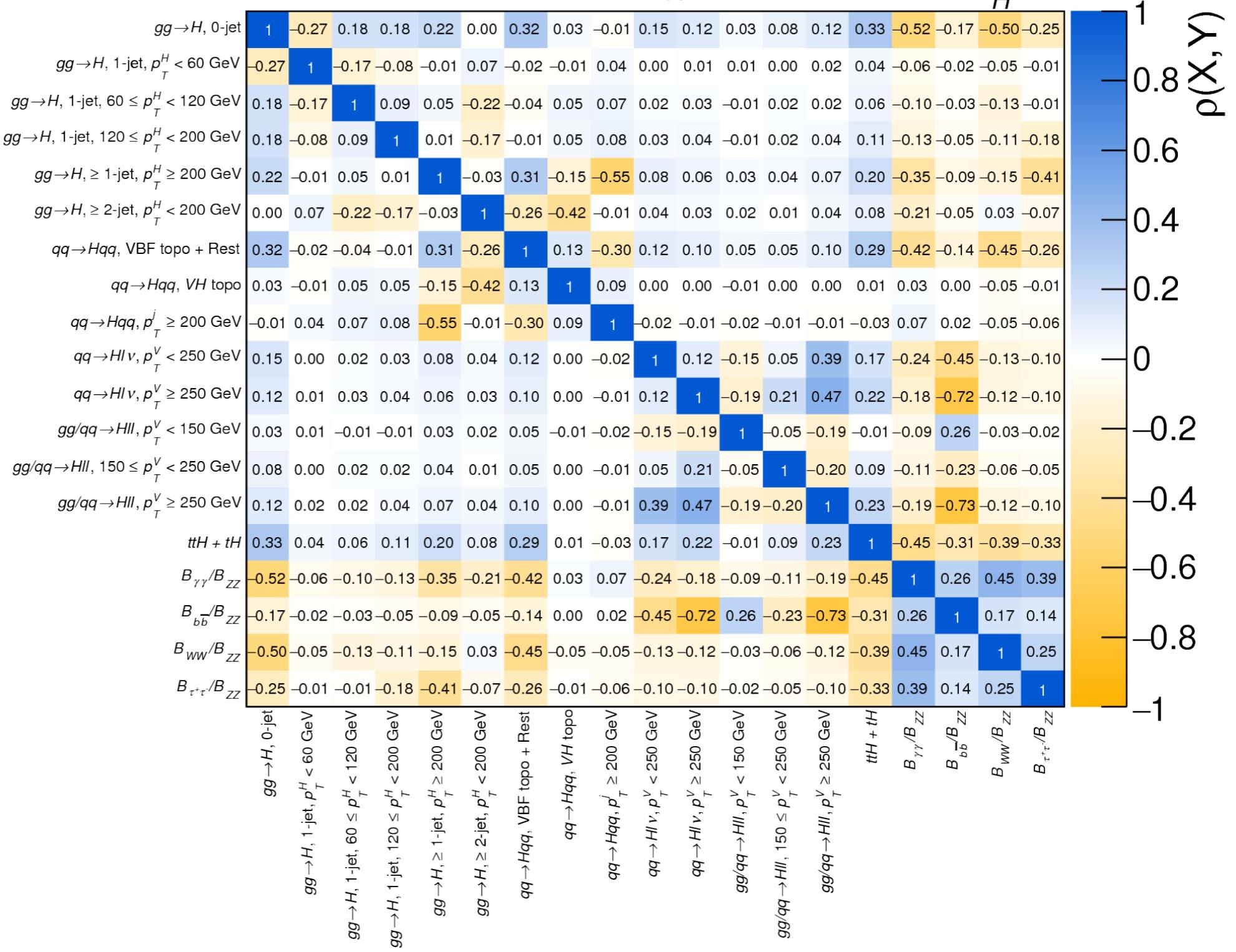


# BACKUP: Correlation matrices

**ATLAS Preliminary**

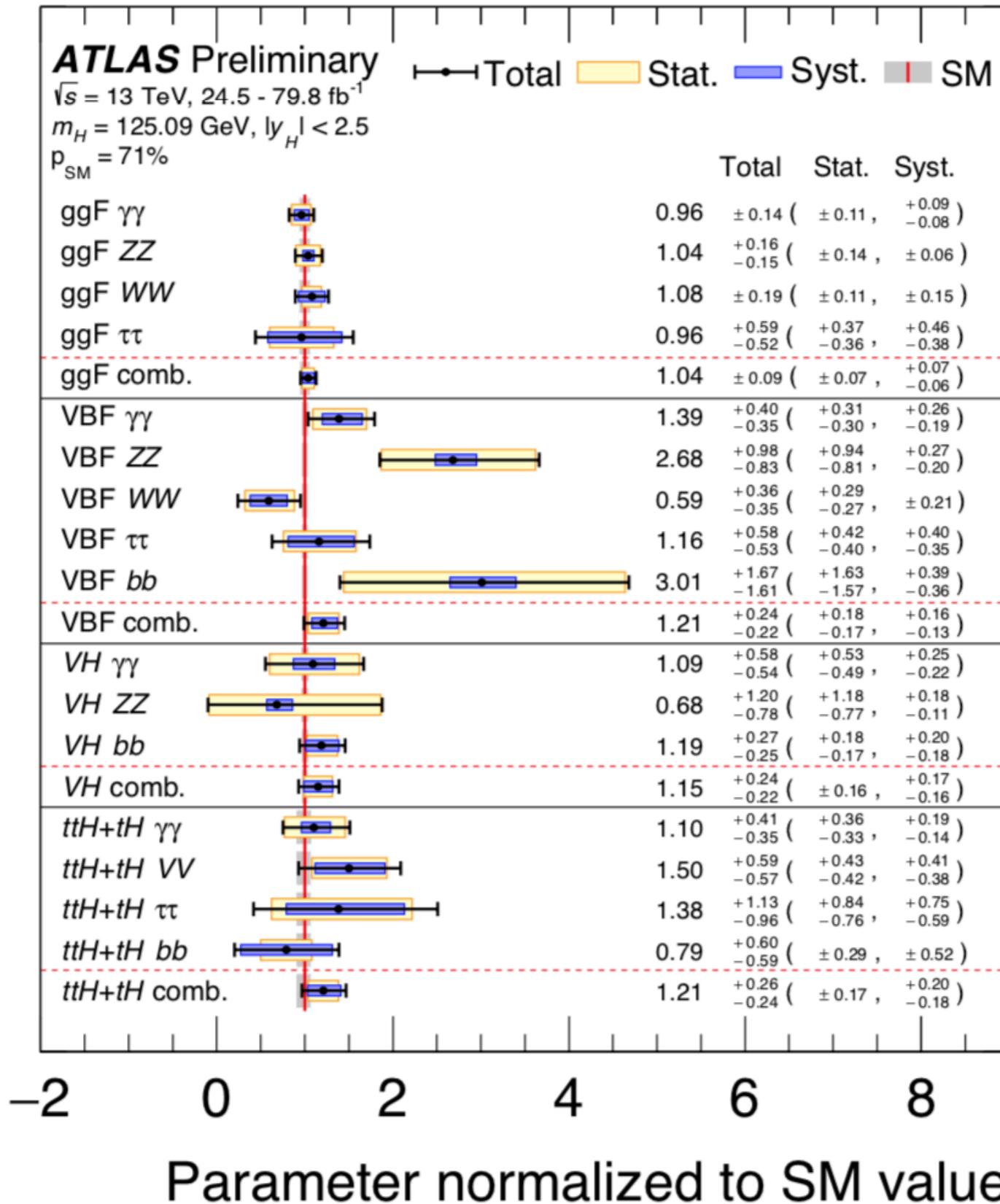
$\sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1}$   
 $m_H = 125.09 \text{ GeV}, |y_H| < 2.5$

STXS



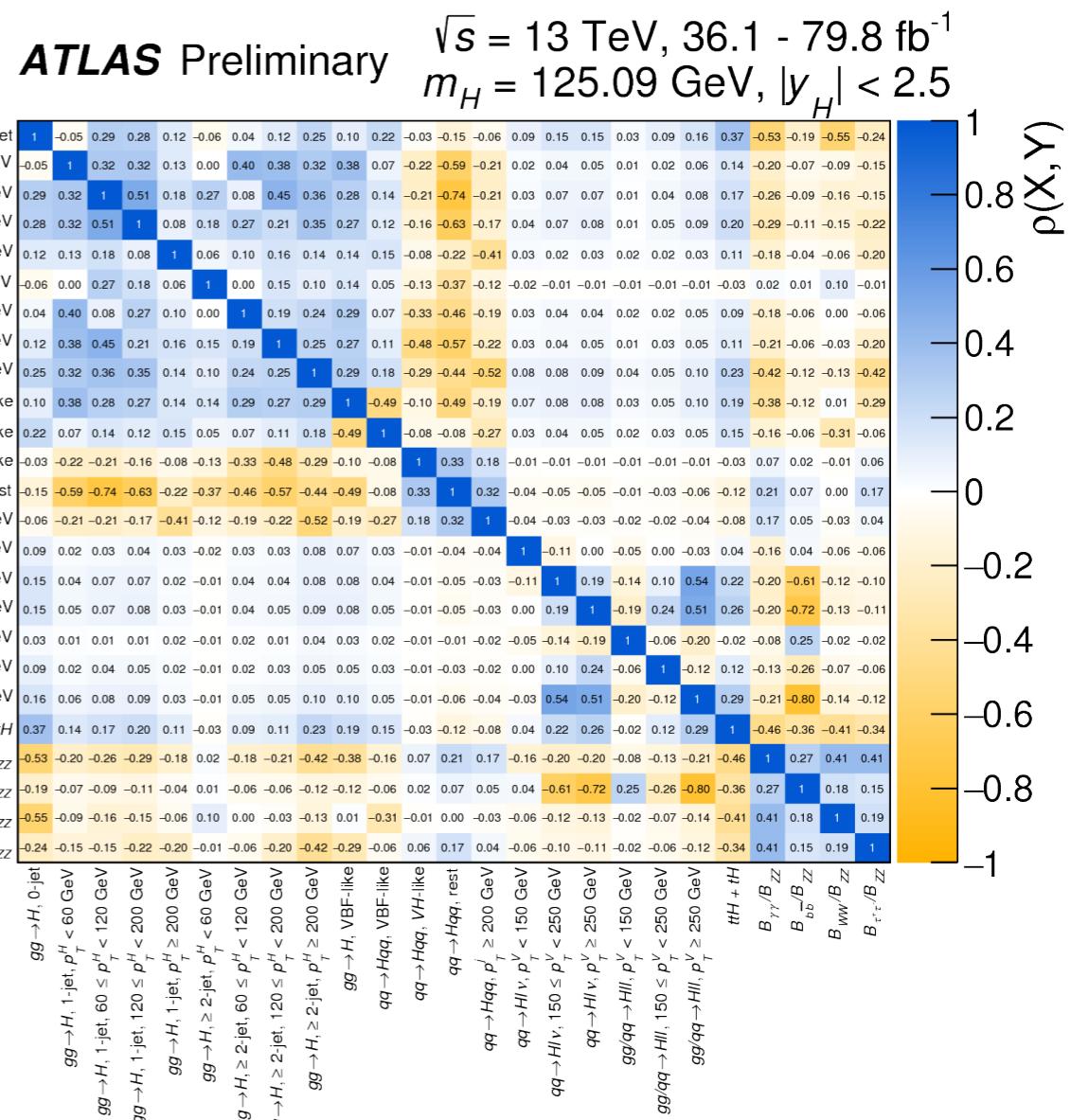
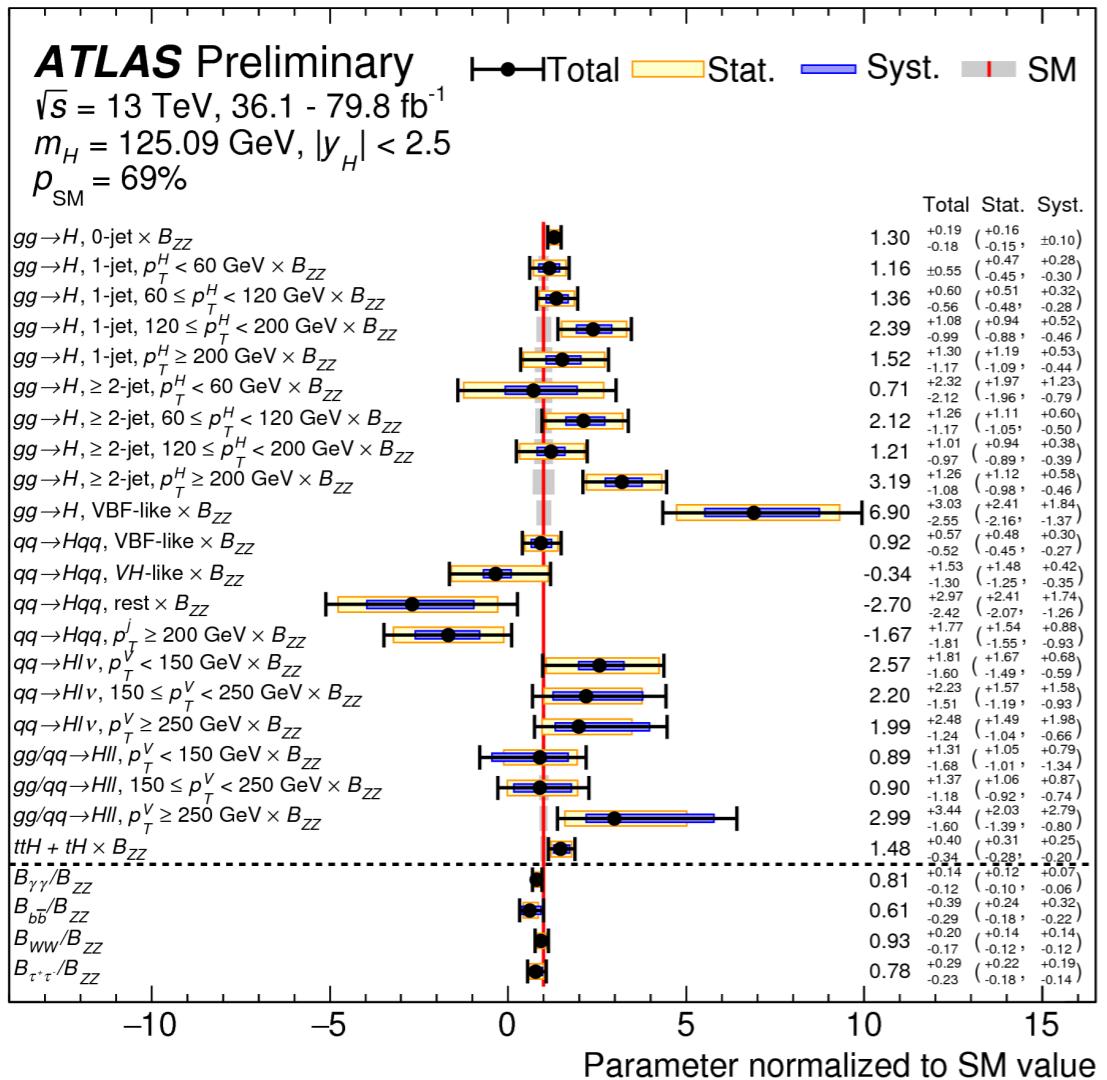


# BACKUP: Production \* decay





# BACKUP: STXS with finer granularity





# BACKUP: kappa parametrization

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