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Combined Higgs-boson measurements at the ATLAS experiment: BSM interpretation

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ATLAS

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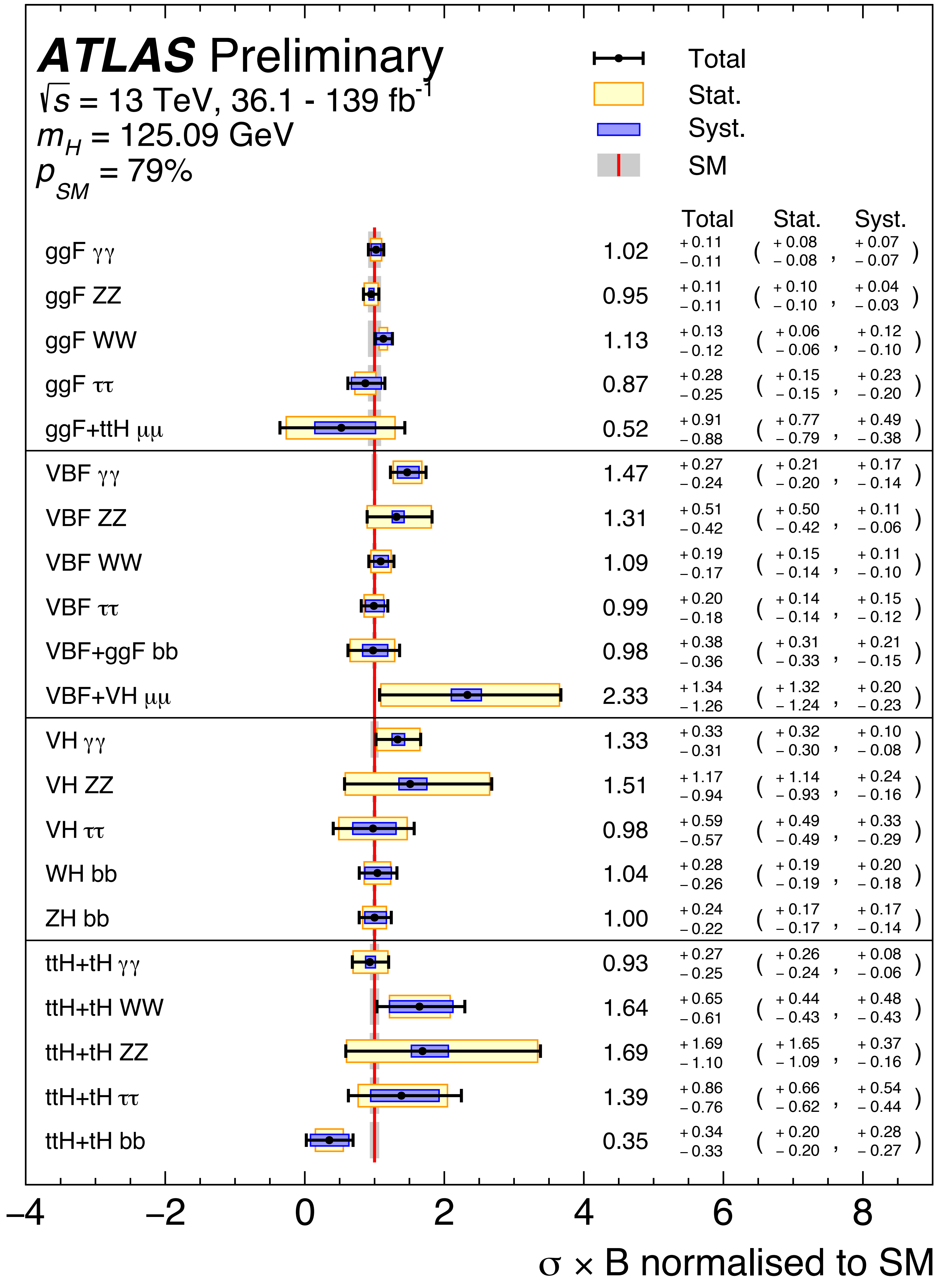
Higgs combination cont'd

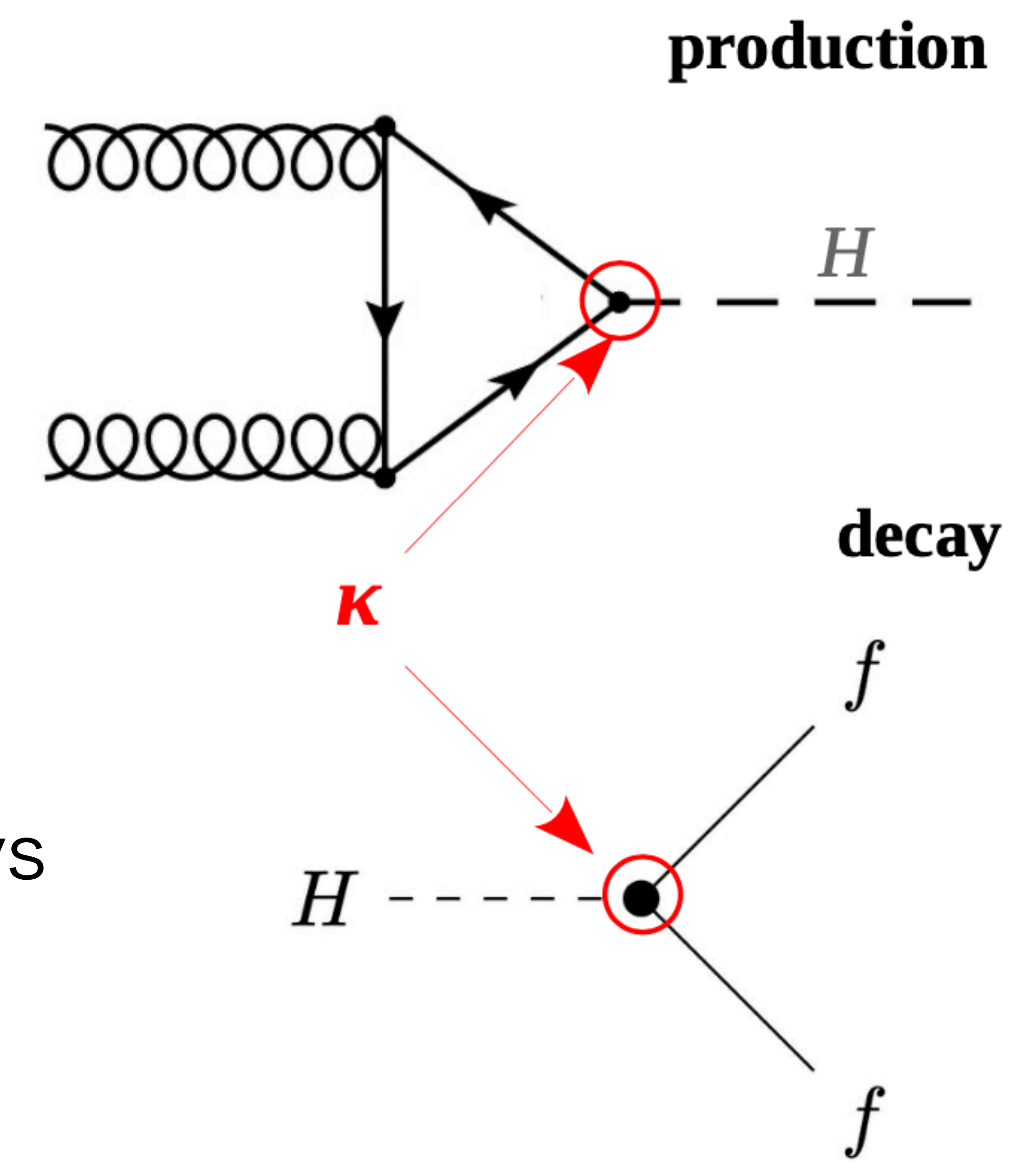
- ATLAS published a wealth of measurements and searches to pin down the Higgs boson production and its decays
- Combining them allows
  - For the most precise measurements of the SM expectation
  - Identifying and interpreting potential features that are not statistically significant in individual channels
  - These have been discussed in Kunlin's talk (Thur, 15:15)
    Combined Higgs-boson measurements of the ATLAS experiment: SM measurement
- Also, combination allows for the constraints of potential beyond-the-Standard Model (BSM) modifications:
  - Interpretation in the κ framework
  - EFT interpretation
  - Model-dependent interpretation: 2HDM
  - These will be discussed in **this talk**



Interpretation in the κ framework

- Assumption: BSM physics modifies only the strength of the Higgs-boson coupling
- Introduce **coupling-strength modifiers** $\boldsymbol{\kappa}$ to the leading-order contributions to each production and decay

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}$$



- Modifiers on Cross-section and partial decay width for SM process j:

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\rm SM}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\rm SM}}$$

- Higgs total decay width: $B_{\rm i./u.}$: branching ratio of invisible/undetected BSM decays

$$\Gamma_H(\boldsymbol{\kappa}, B_{\rm i.}, B_{\rm u.}) = \kappa_H^2(\boldsymbol{\kappa}, B_{\rm i.}, B_{\rm u.})\,\Gamma_H^{\rm SM}$$

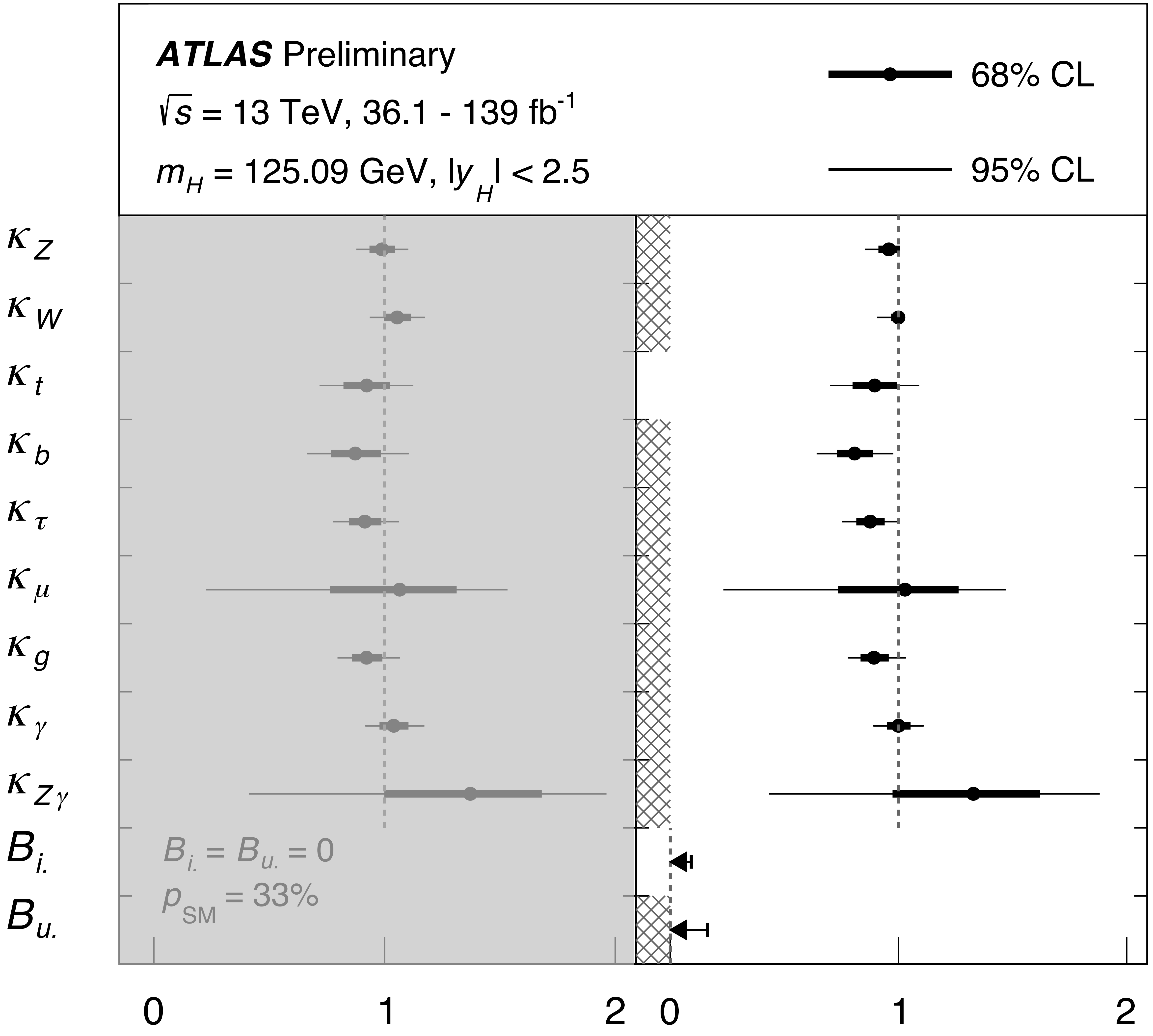
where $$\kappa_H^2(\boldsymbol{\kappa}, B_{\rm i.}, B_{\rm u.}) = \frac{\sum_j B_j^{\rm SM}\kappa_j^2}{(1 - B_{\rm i.} - B_{\rm u.})}$$

- BSM contributions may manifest themselves as $\kappa_j \neq 1$ or $B_{\rm i./u.} \neq 0$.

Interpretation in the κ framework

- $\kappa_{c/s}$ scales as $\kappa_{t/b}$; $\kappa_{u/d/e}$ = 1
- Higgs boson coupling modifiers per particle type with $B_{i./u.}$ = 0 (left)
- Bi. and Bu. included as free parameters (right)
  - VBF, H→ inv. included to constrain Bi.
  - By definition, Bu. is not directly constrained by any measurement additional assumption $\kappa_{W,Z} \leqslant 1$

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



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SMEFT

- Introduce new effective operators with free coefficients to capture new physics appearing beyond scale Λ (typically chosen as 1 TeV)
- New heavy internal particles are integrated out and are represented as vertices in the new effective theory
- Most common: Warsaw-basis (JHEP 10 (2010) 085) forming a complete set of all dim-6 operators allowed by the SM gauge symmetries
- Interpretation performed in SMEFT framework

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} \mathcal{O}_i^{(8)} + \ldots$$

- SMEFT in a nutshell:
  - $\mathscr{L}_{\mathrm{SM}}$ is dim-4, high orders only valid in the low-energy regime E ≪ Λ
  - terms with odd dimensionality violate lepton and/or baryon symmetry and are usually not considered for LHC physics
  - Wilson coefficients c ≡ 0 for SM, deviations might indicate new physics

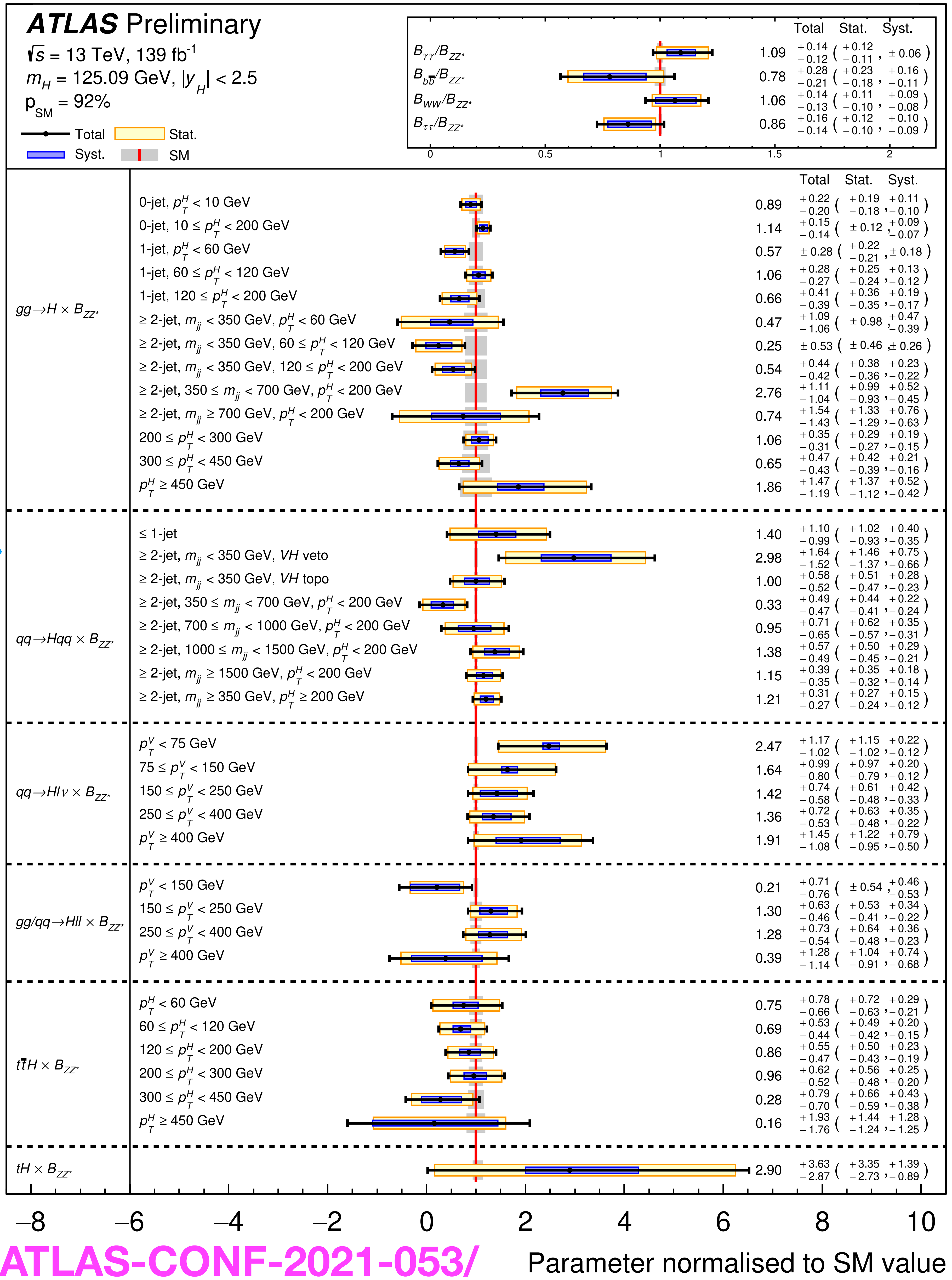
SMEFT Interpretation: operators

- $\Lambda = 1$TeV and Warsaw-basis

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	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

- Considering only EFT contributions from the interference between the SM and the dim-6 SMEFT operators
  - pure dim-6 BSM not considered: as being suppressed by a factor $1/\Lambda^4$, expected to be small

impact



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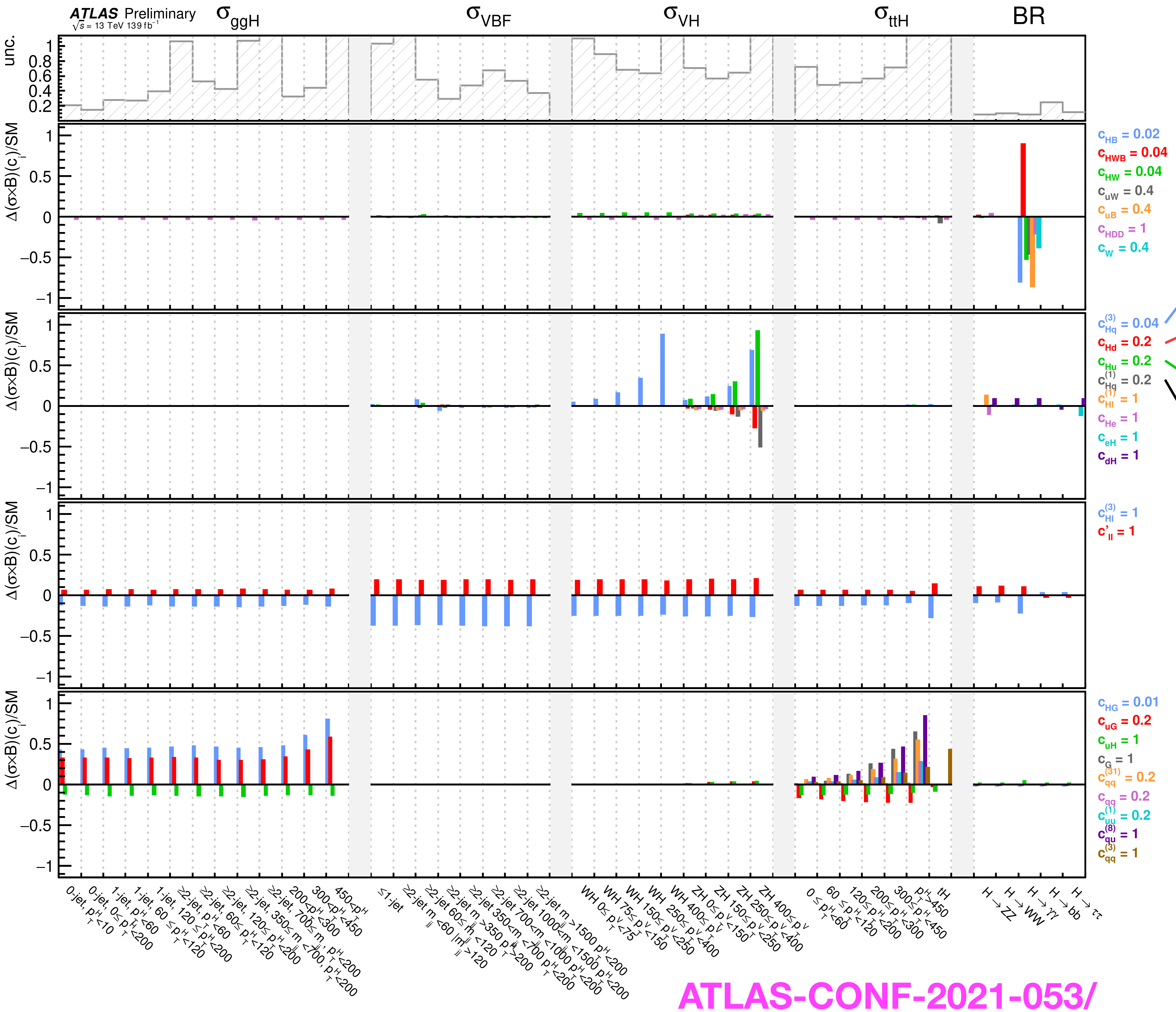
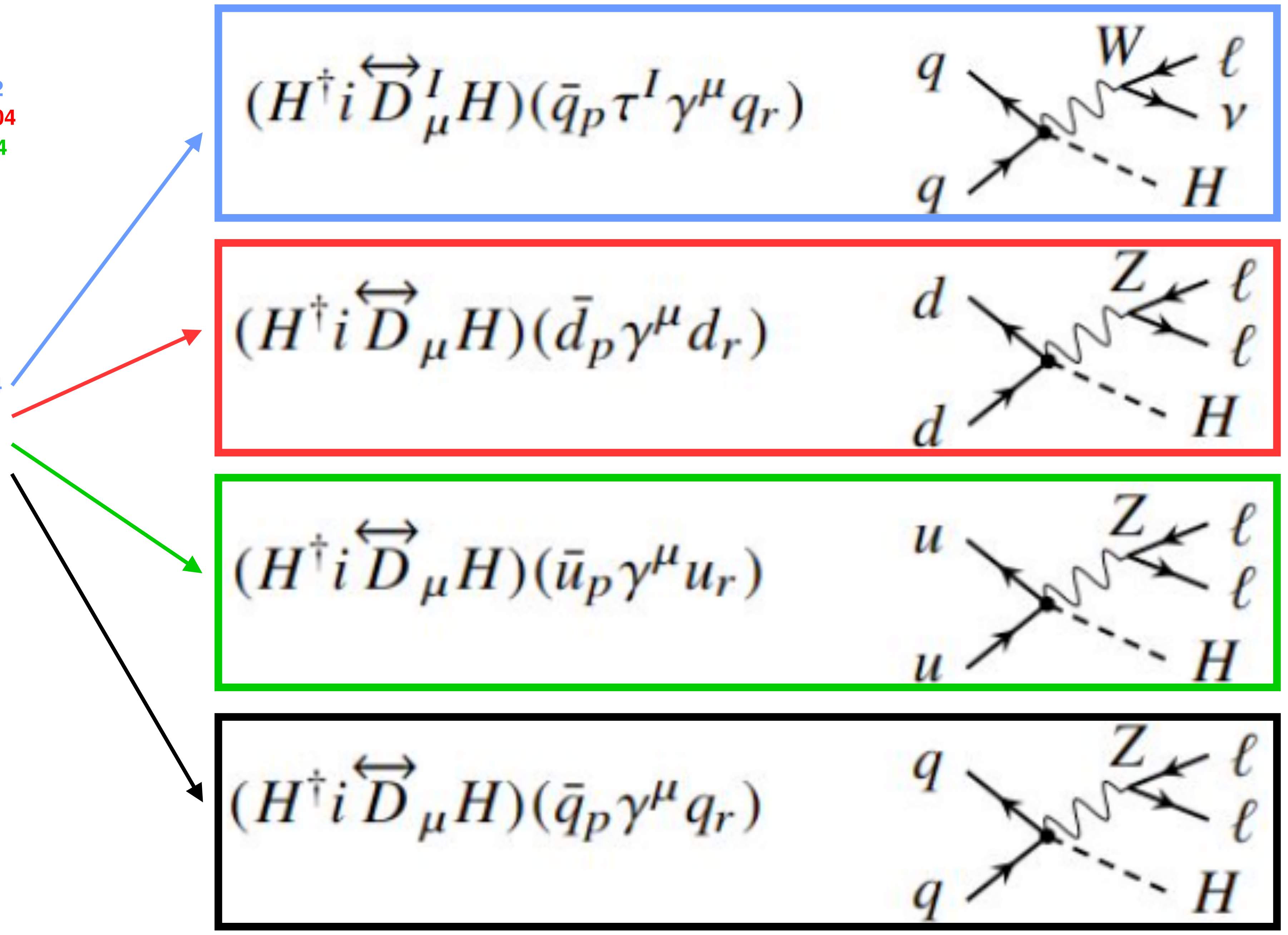
SMEFT Interpretation: impact on STXS bin

- Parametrized their impact on the signal yields in each STXS bin x 5 BR





Many parameters: for illustration, focus on a set that largely affects VH

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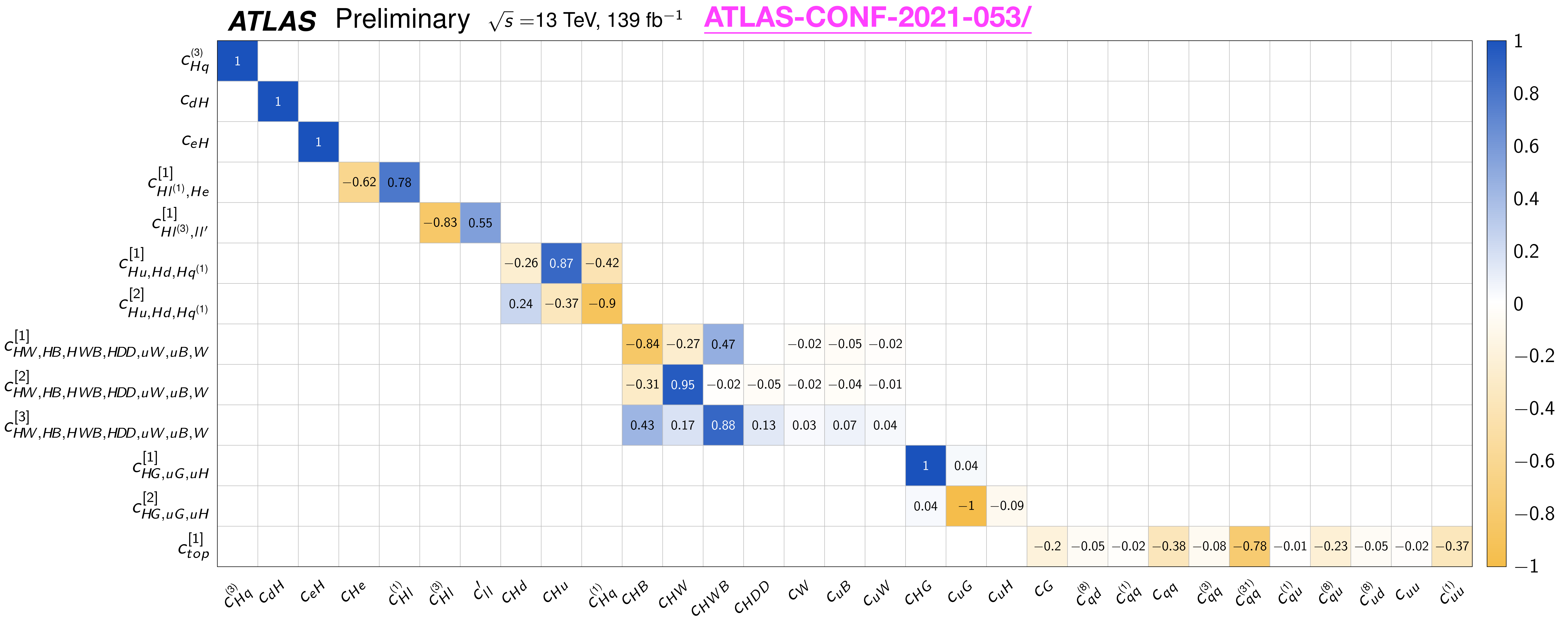
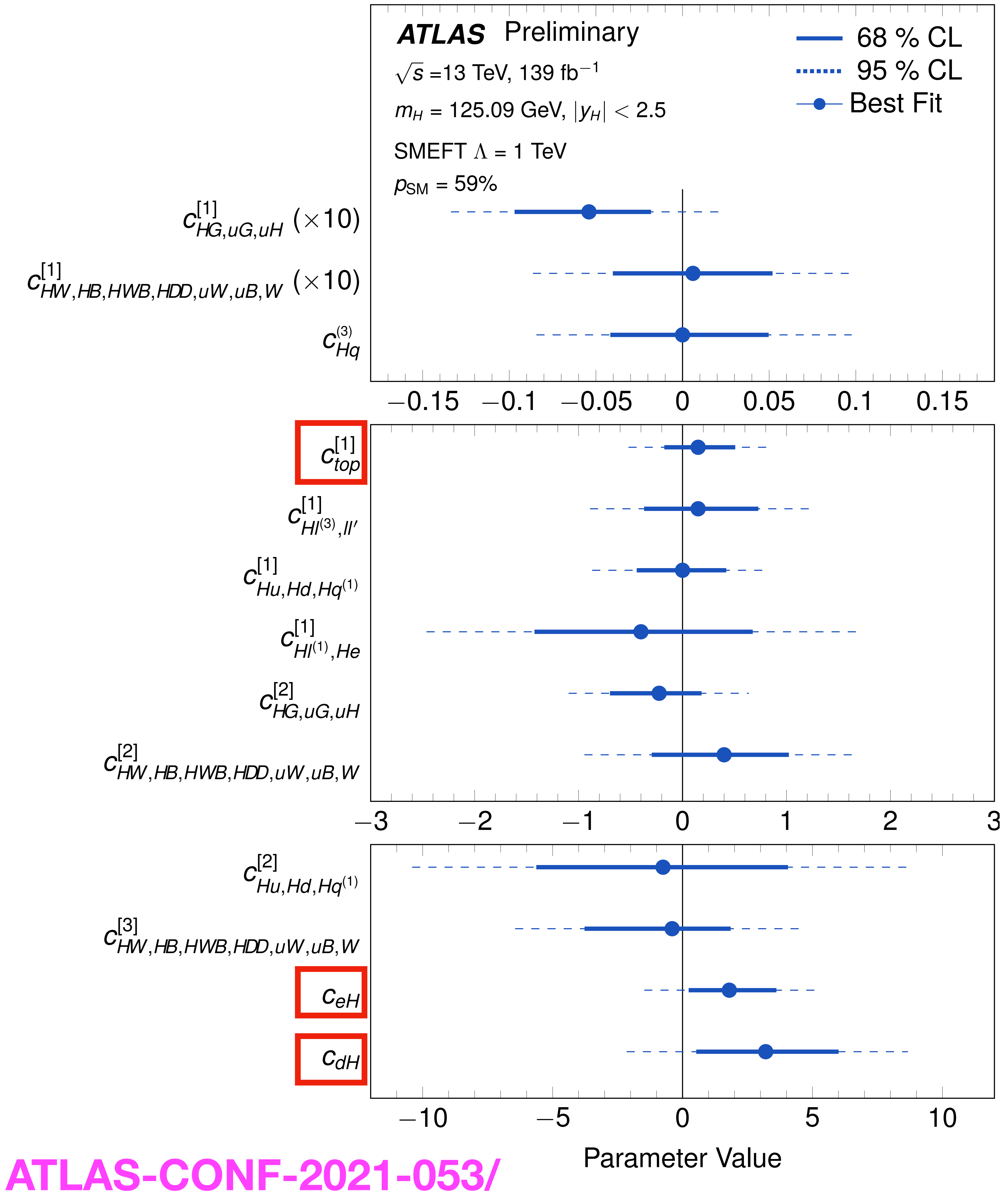
SMEFT Interpretation

- Due to large number of parameters with complicated correlation, cannot separately constrain all parameters
- Decompose into subspaces, motivated by correlations and physics concerns
- Set parameters with weak eigenvalues to 0 and fit resulting parameter set: fit 13 parameters



SMEFT Interpretation: results

- Parameter measurements



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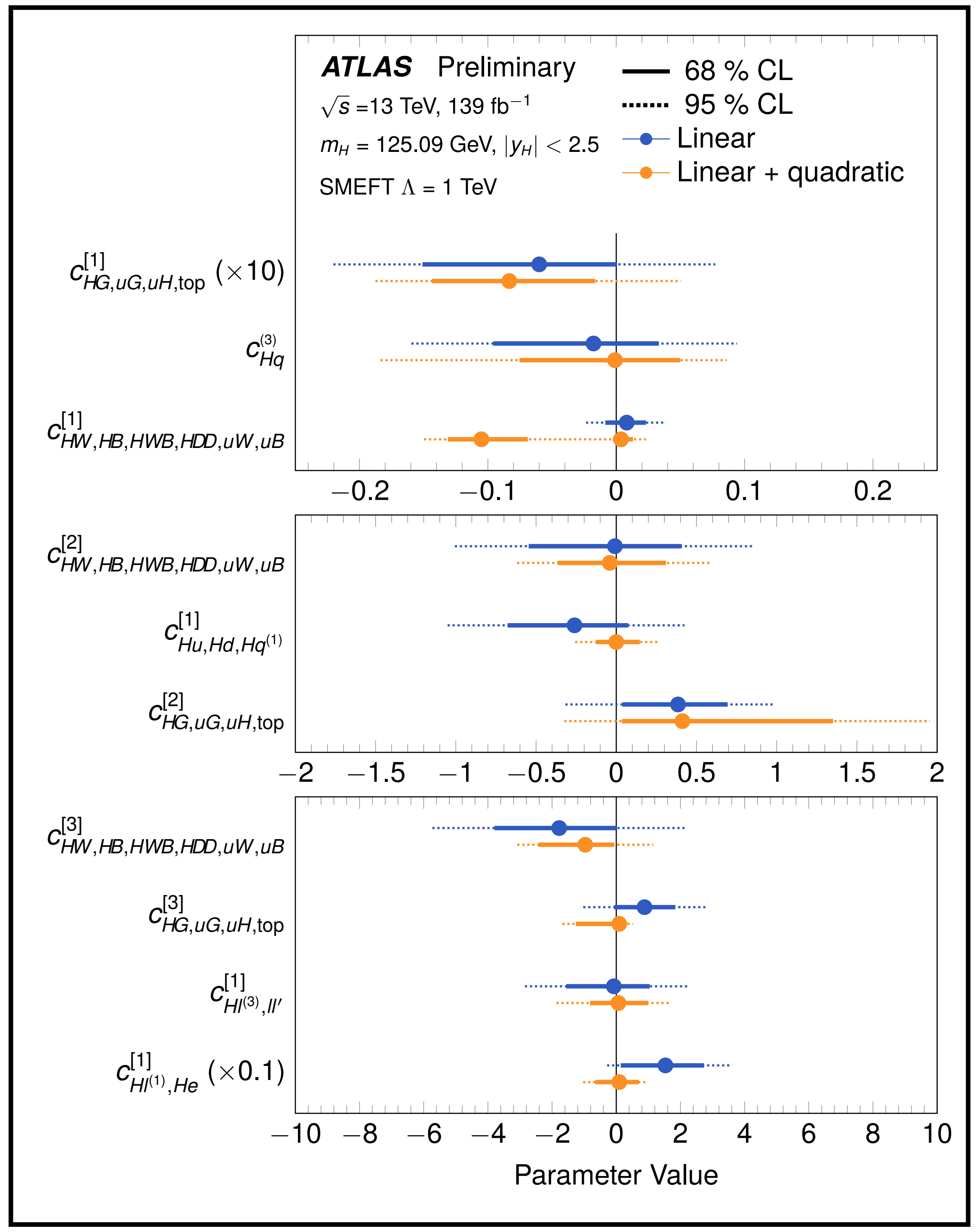


Compared with the previous results:

Updated H→$\tau\tau$ result, c_{eH} can now be constrained

VBF and ttH with H→bb: c_{dH} and c_{top}

Consistent with SM expectations, pSM = 59%

Model-dependent interpretation: 2HDM

Benchmark model for UV-complete BSM theory

- Extended Higgs sector (2nd SU(2) doublet)→ 5 Higgs boson:
  - Two neutral CP-even: h,H
  - One neutral CP-odd: A
  - Two charged Higgs boson $H^{\pm}$
- Light CP-even Higgs boson h identified with observed Higgs boson
  - SM production and decay modes
  - Deviations from SM prediction expressed in terms of α and $\tan\beta$
    - α: mixing angle between two CP-even Higgs bosons (h, H)
    - $\tan\beta$: ratio of the vacuum expectation values of the two SU(2) doublets
  - $H_{SM} = h \cdot \sin(\beta - \alpha) + H \cdot \cos(\beta - \alpha)$
  - $\cos(\beta - \alpha) = 0$ (**alignment limit**) ⇒ h indistinguishable from H_{SM}

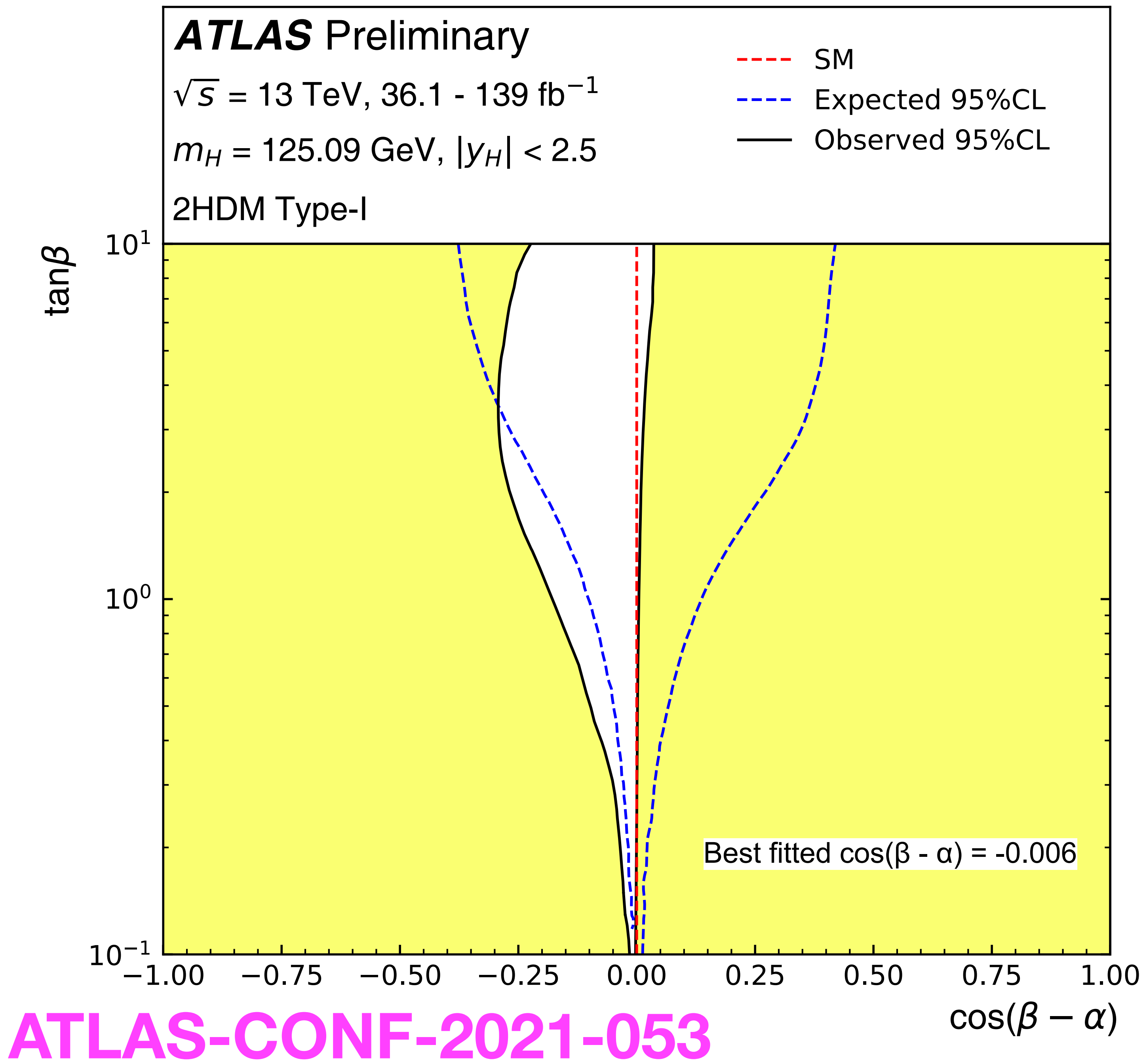
Model-dependent interpretation: 2HDM

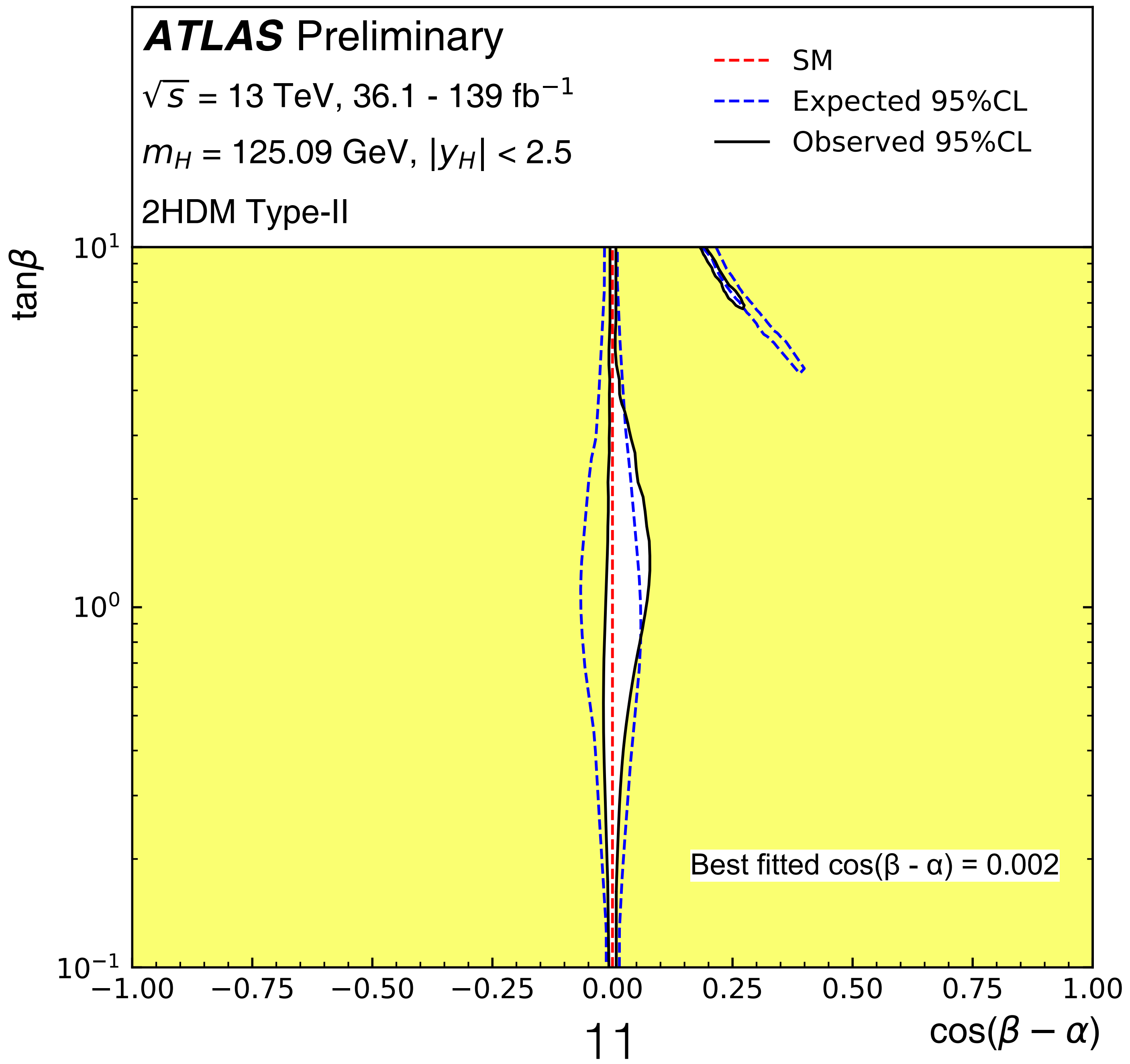
Four 2HDM types can be defined w/o tree-level flavour-changing neutral currents

- Variation over allowed couplings to SM particles

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Limits on $\cos(\beta-\alpha)$ vs $\tan\beta$ (2/4 shown)





The data is consistent with the alignment limit within 1std. or even better

"petal" allowed regions: correspond to regions with $\cos(\beta+\alpha) \approx 0$, some fermion couplings have the same magnitude as in the SM, but the opposite sign

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Conclusion

- Combination of each individual Higgs measurement allows for the constraints of potential beyond-the-Standard Model (BSM) modifications
- In latest combination measurement (ATLAS-CONF-2021-053), a few interpretation performed:
  - Interpretation in the κ framework:
    - The limit set on the decay invisible and undetected decay B: $B_i < 0.09$ and $B_{u.} < 0.16$ @ 95 CL
  - Interpretation to the SMEFT:
    - Thanks to the newly added channel, c_{eH} ,c_{dH} and c_{top} allowed to be measured
    - The coefficients of the operators measured and their values compatible with the SM
  - Model-dependent interpretation: 2HDM
    - Limits set on $\cos(\beta-\alpha)$ vs $\tan\beta$ for four type of 2HDM
    - The data is consistent with the alignment within 1std. or even better
- Plan for a journal paper:
  - Update for the individual channels and add the Higgs self-coupling measurements etc.

Backup

κ parametrization

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	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

Invisible decays: decays which are identified through an Emiss signature in the analyses

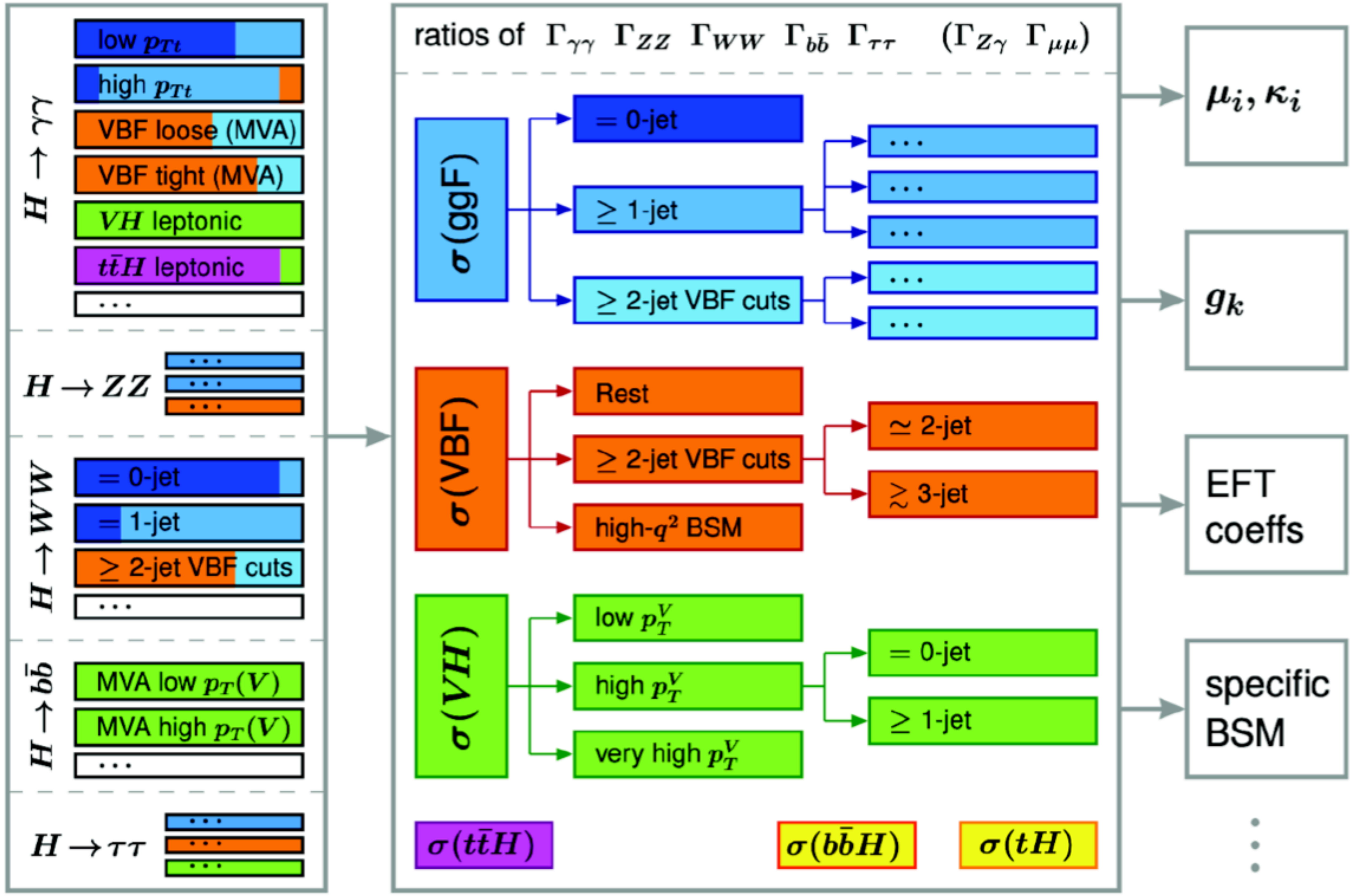
Undetected decays: decays to which none of the analyses included in this combination are sensitive, such as decays to light quarks which have not yet been resolved (11%), or undetected BSM particles without a sizable E^{miss} in the final state ($B_{u.}$).

Handbook of LHC Higgs cross sections: 3. Higgs Properties CERN-2013-004 (2013)

- $\kappa_{W,Z} \leqslant 1$. This assumption is theoretically well motivated in the sense that it holds in a wide class of models.

The STXS framework

Simplified Template Cross-Sections: common framework for **Higgs cross-section measurements per production mode** in exclusive kinematic regions

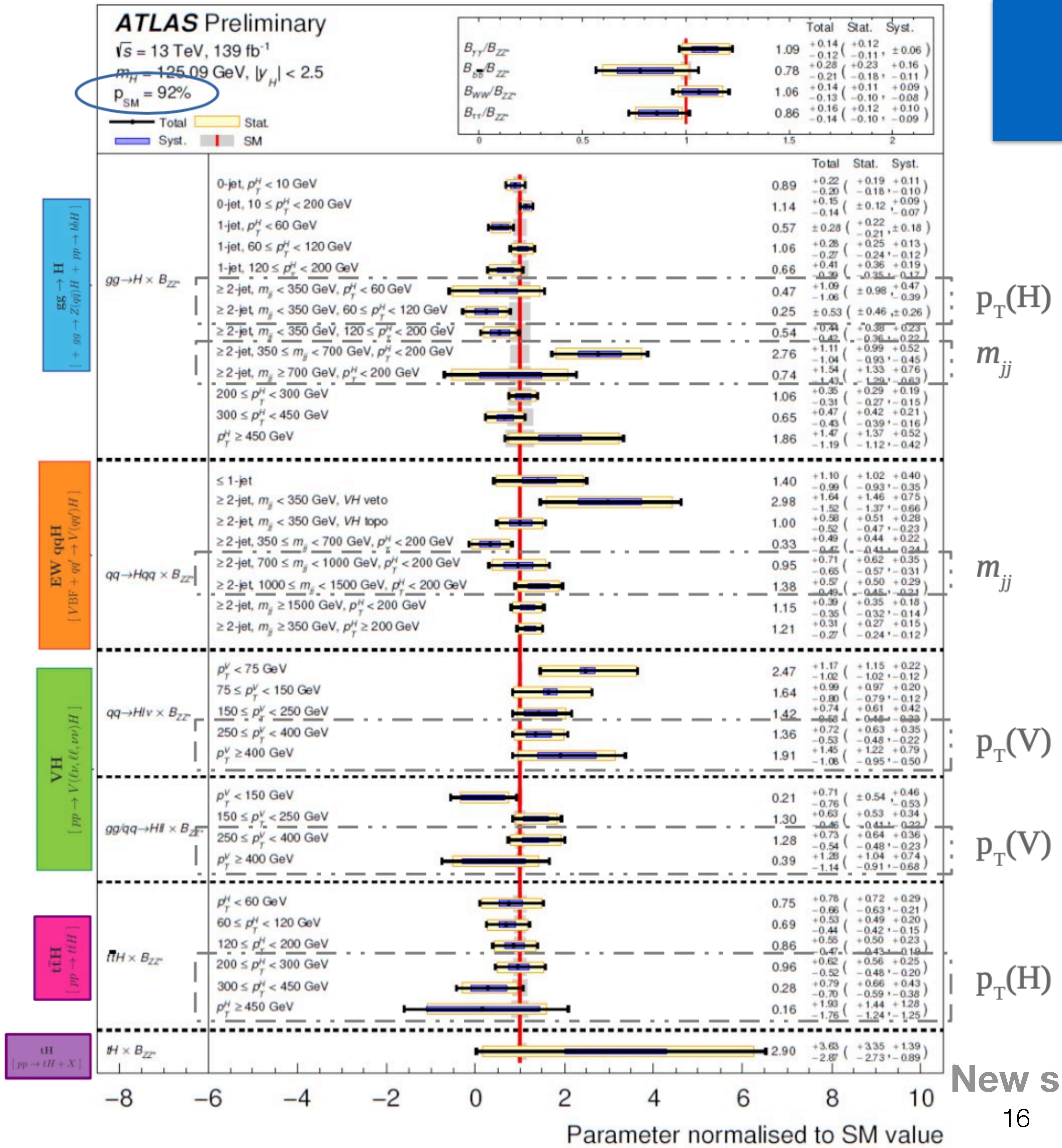


Schematic

- Minimize theory dependence
  – theory uncertainties can evolve with time for different phase-space regions
- Isolate regions where BSM effects are predicted to appear enhanced
- Maximise the experimental sensitivity
  - by allowing use of e.g. MVAs
- Simplify combination of measurements in different decay channels

How: Signal predictions per STXS 'bins' provide **templates** that are simultaneously fit to the data

- evolves in 'stages' with increasing granularity and precision: 1.0, 1.1, 1.2,..



New splits

STXS results

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New

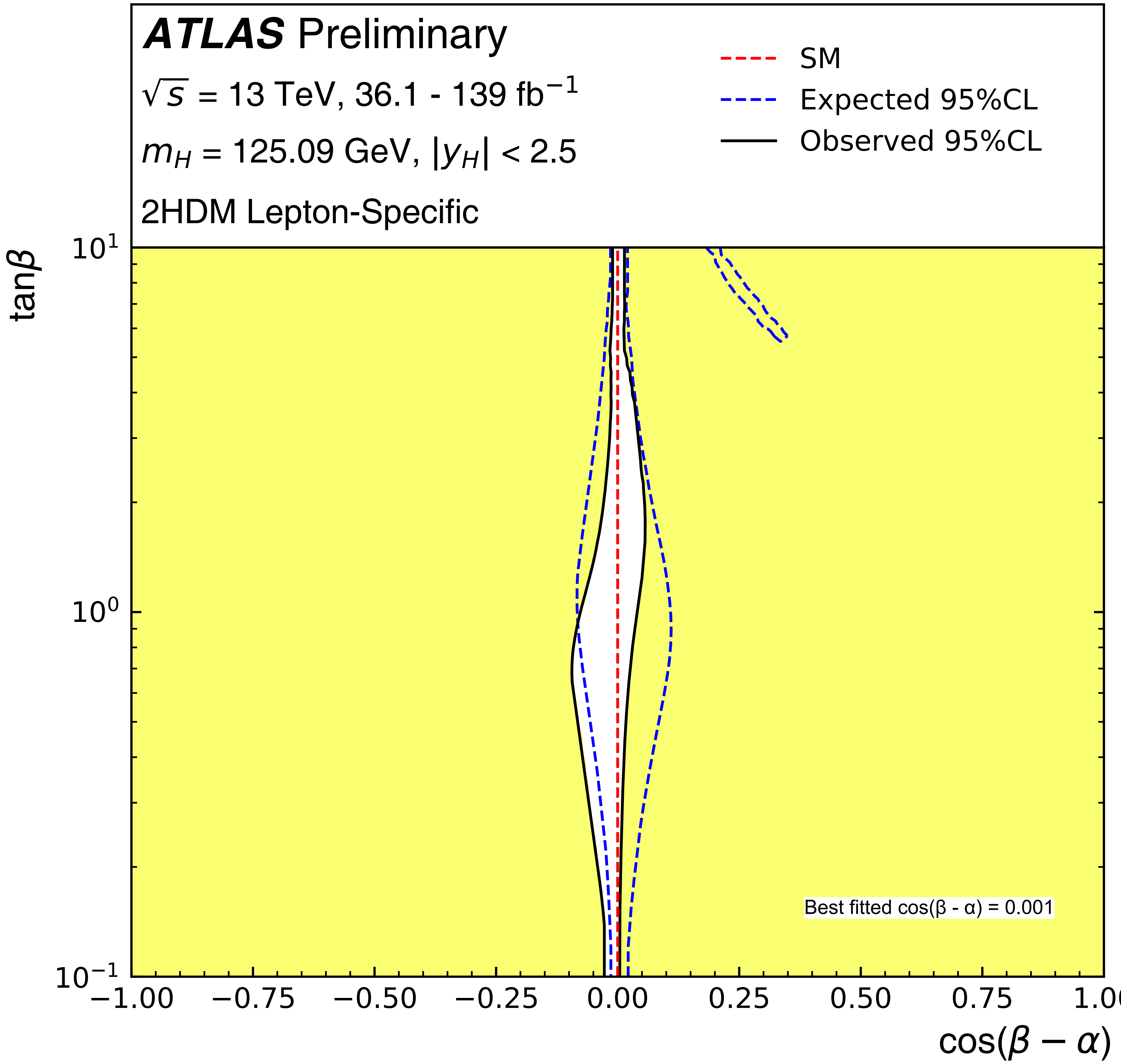
$$(\sigma \times B)_{if} = (\sigma \times B)_{i,ZZ} \cdot \left(\frac{B_f}{B_{ZZ}}\right)$$

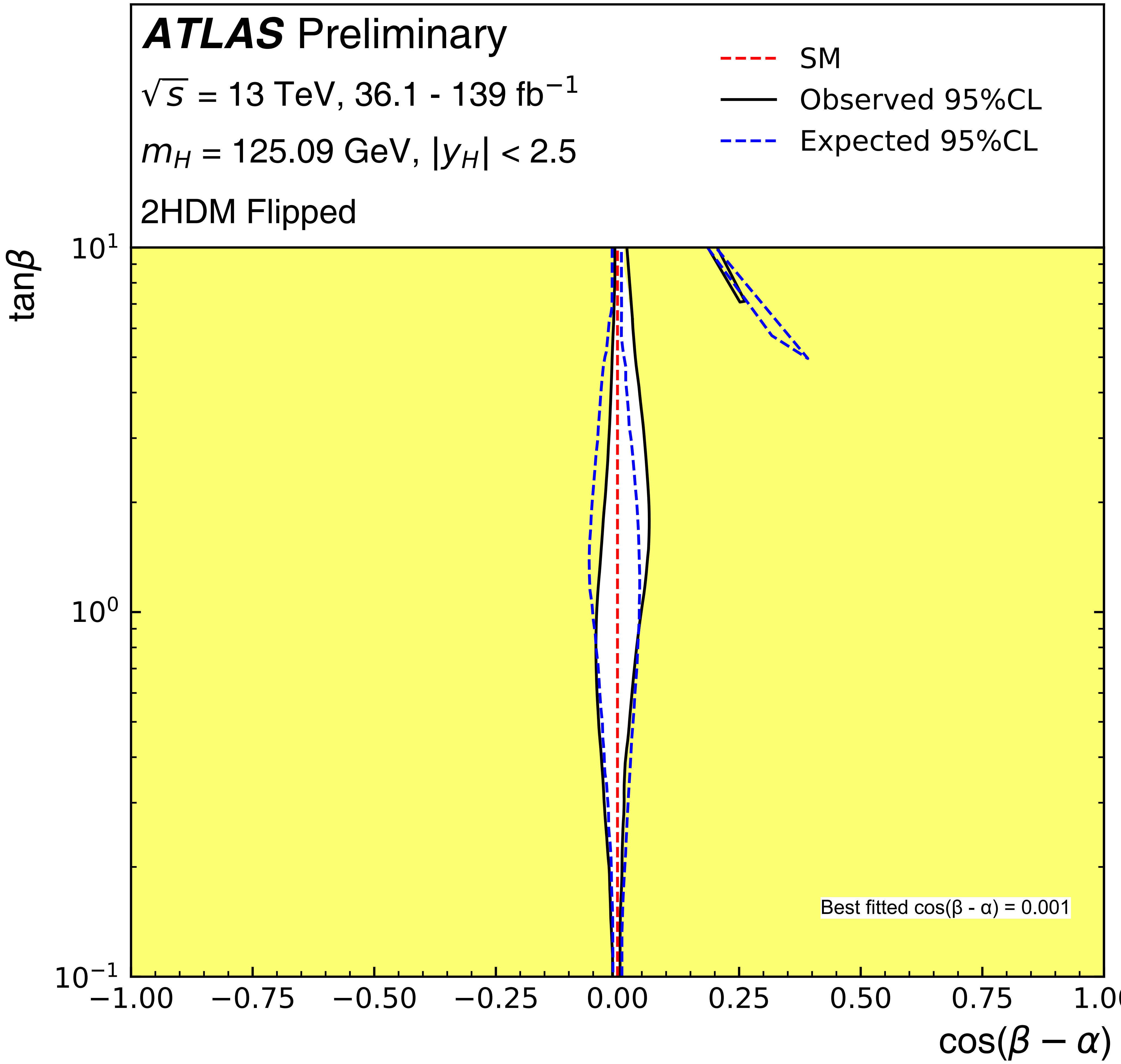
$f \neq ZZ^*$

- **Most granular, simultaneous measurement** to date (41 POI-fit!) – thanks to inclusion of new data and improved analyses
- For all bins **stat. unc. dominating**; only in few bins syst. unc. start to matter (e.g. ggF 0 jet)
- tH production:
  - Obs. (exp.) significance: 1.0 (0.4)σ
  - Obs. (exp.) limit @95% CL: 9.3 (6.7) × SM prediction
- **Very good agreement with SM prediction**

w/o $H \to \mu\mu$, $H \to inv.$, $H \to Z\gamma$, ttH($\to$ multi. leptons)

Model-dependent interpretation: 2HDM





SMEFT Interpretation

- Parameter correlations