Combined Higgs boson measurements and interpretations at ATLAS

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on behalf of the ATLAS Collaboration

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Introduction

- ~ 9 million Higgs bosons in ATLAS Run 2 dataset
  - ATLAS has launched extensive measurement programs to study the Higgs boson

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

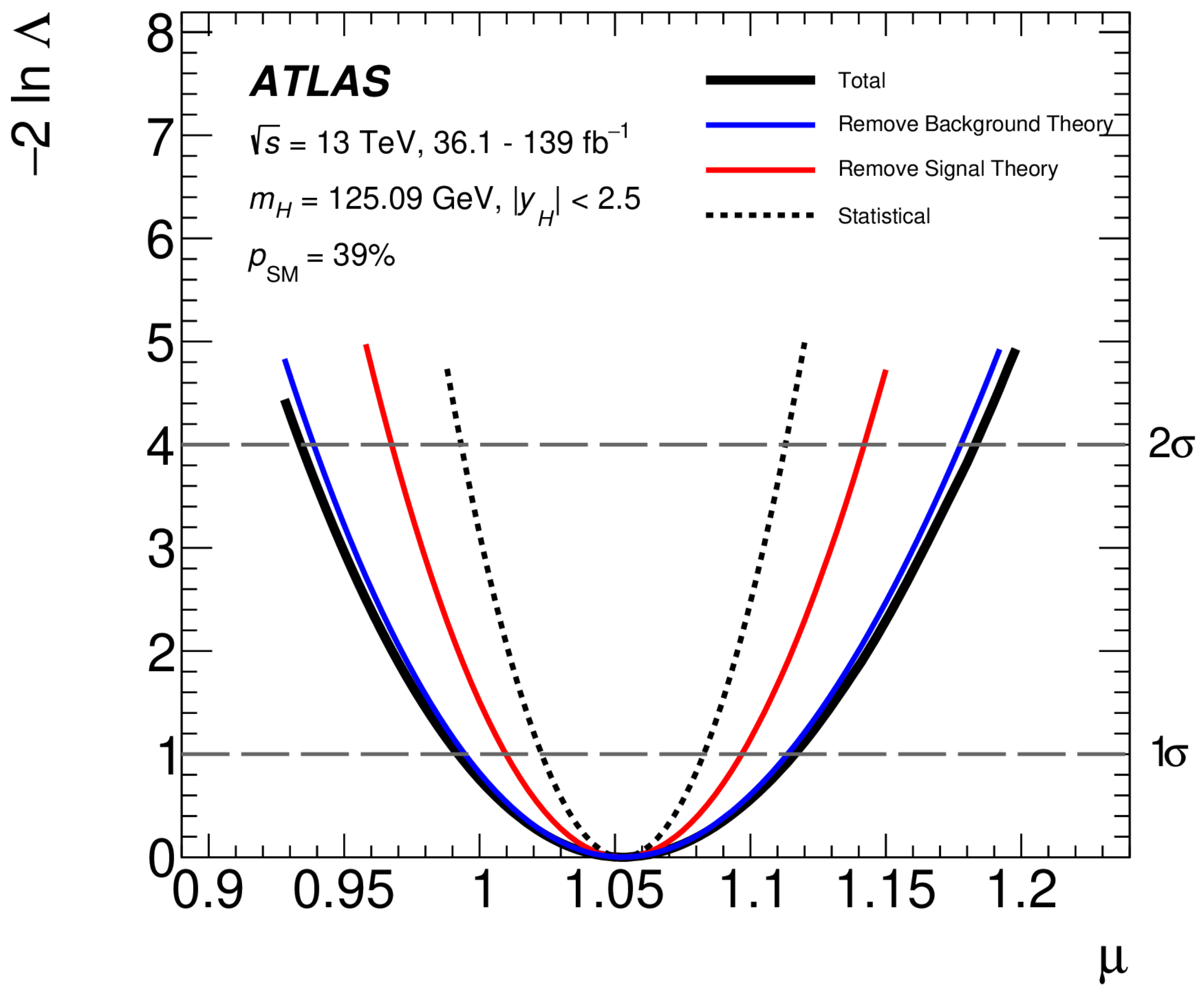
- Best sensitivity can be achieved by combining individual measurements
  - Latest ATLAS Higgs combination: Nature 607, 52 (2022)
  - Measurement using H→γγ+4ℓ: JHEP 05 (2023) 028
- Any deviations from the predicted properties by the SM are a smoking gun for New Physics!

New

  - Interpretation of ATLAS Higgs combination under effective field theory and BSM models: arXiv:2402.05742
- HH combination on Thursday

The global Higgs signal strength

- Global signal strength measured with respect to the SM prediction $\mu = (\sigma/\sigma^{SM}) \times (B/B^{SM})$
  - Production process (σ) and decay mode (B) not distinguished
  - Assume all channels scale the same
- p-value for the SM Higgs is 39%,
- Systematic uncertainty reduced by 2x from Run 1 ATLAS+CMS result



$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$$

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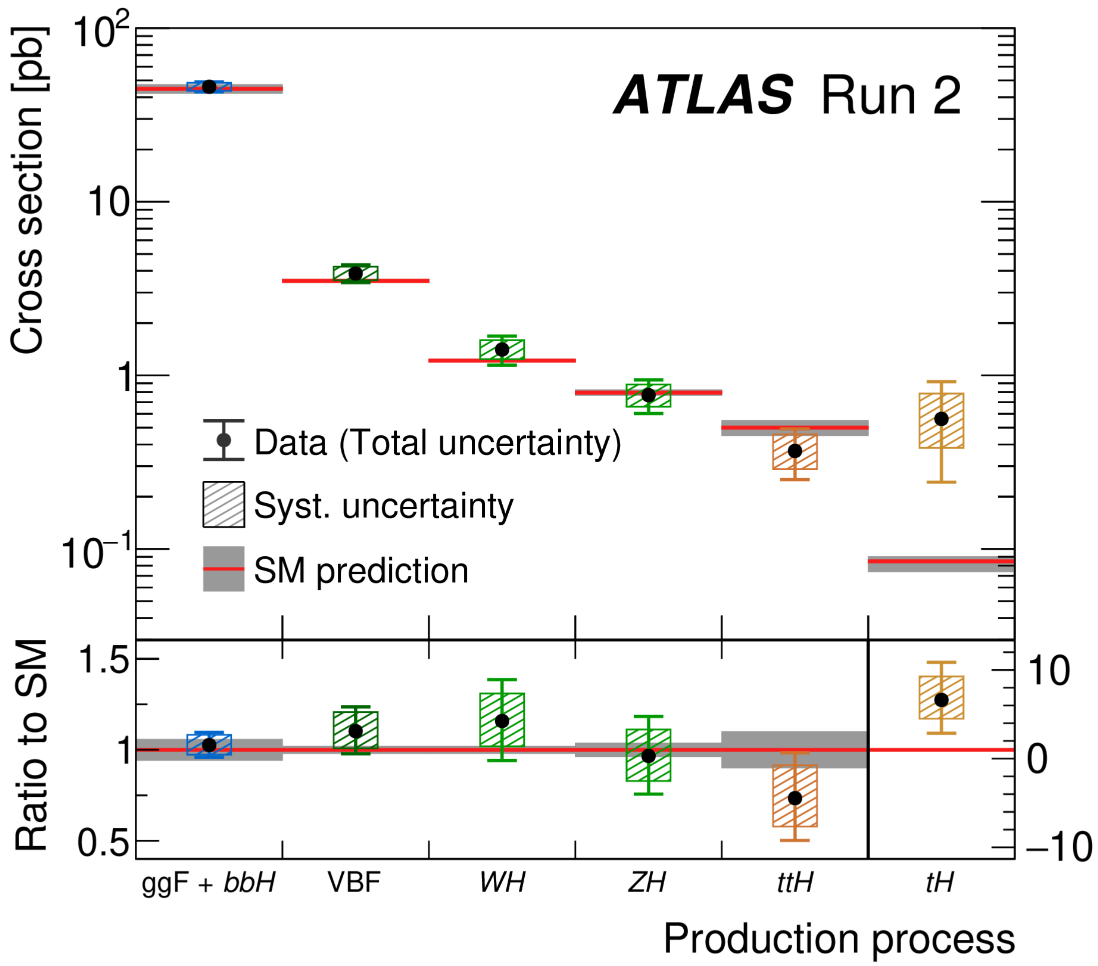
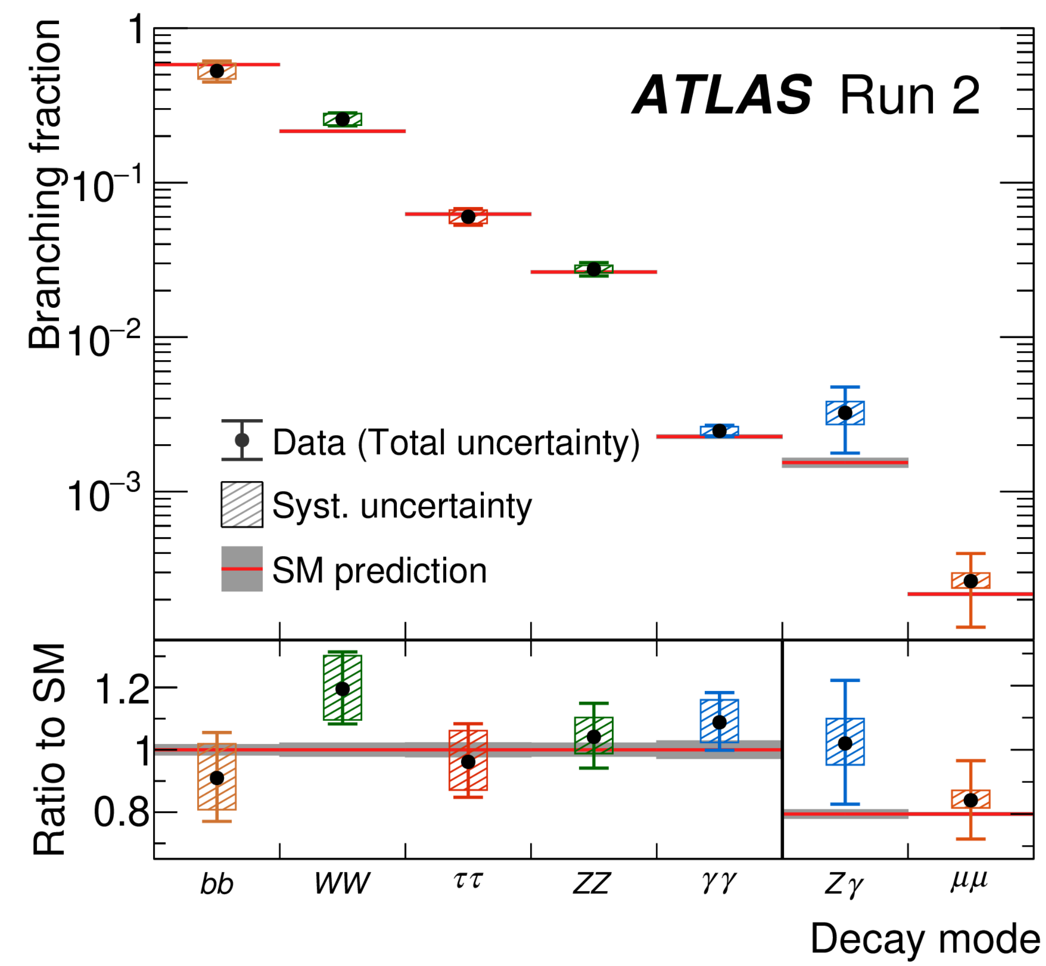
Per production and decay mode measurement

- All major Higgs productions observed:
  - ggF (VBF) precision is 7% (12%)
  - WH (ZH) significance is 5.8σ (5.0σ)
  - ttH + tH significance is 6.4σ
- Gauge and 3rd gen. Yukawa observed:
  - *B*(*bb*) precision better than 15% (7σ significance)
  - *WW* / *ττ* / *ZZ* / *γγ* precision 10—12%
  - *B*(*μμ*) and *B*(*Zγ*) 2.0σ and 2.3σ significance





When measuring production processes assume that decays are SM-like and vice-versa

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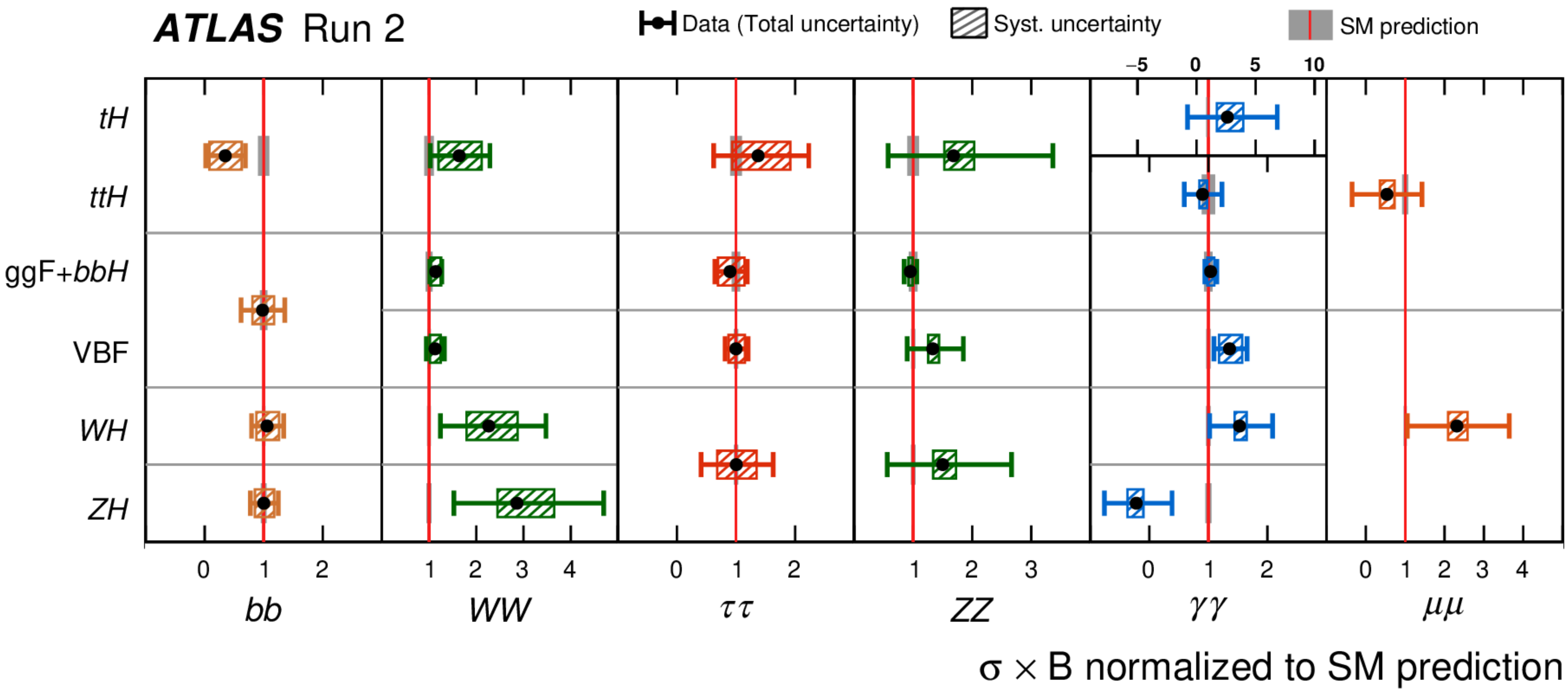
Production and decay simultaneously measurement

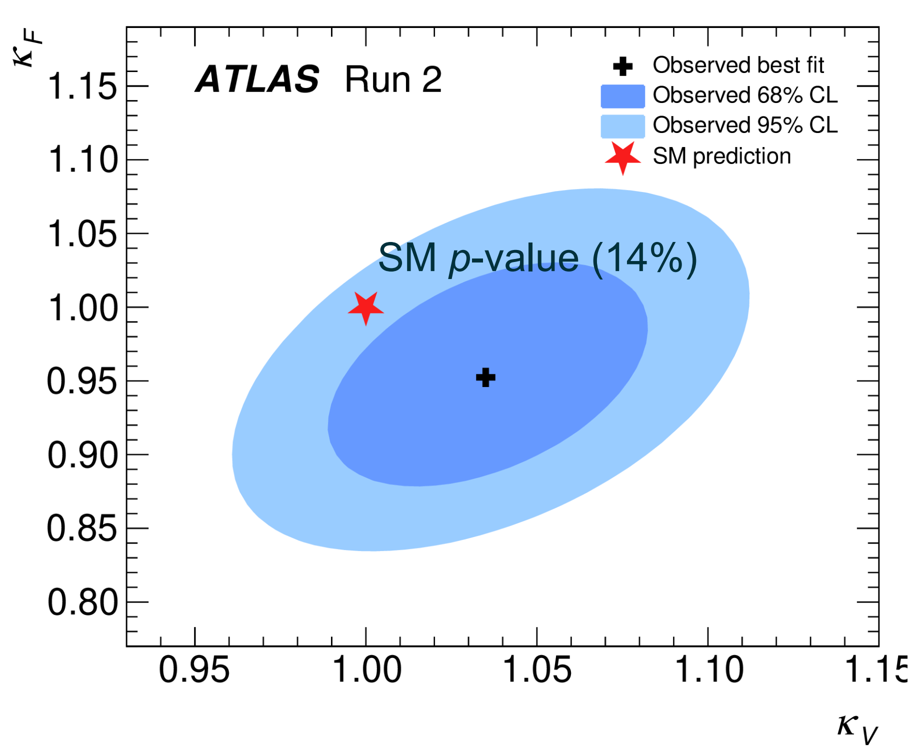
- Production modes and branching ratios measured also simultaneously
- Already down to 10% precision in a few individual ggF channels
- Many channels still dominated by the statistical uncertainty— room for big improvements in Run 3!

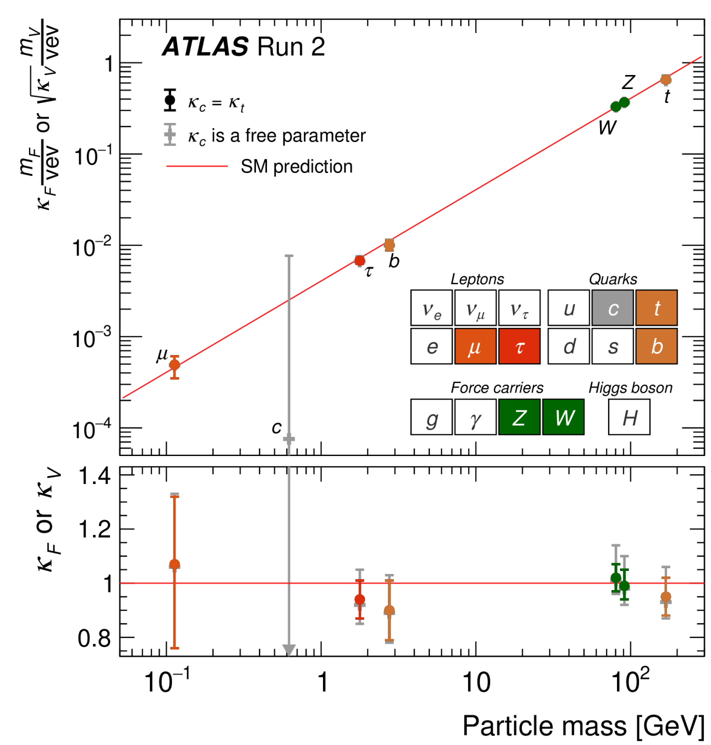


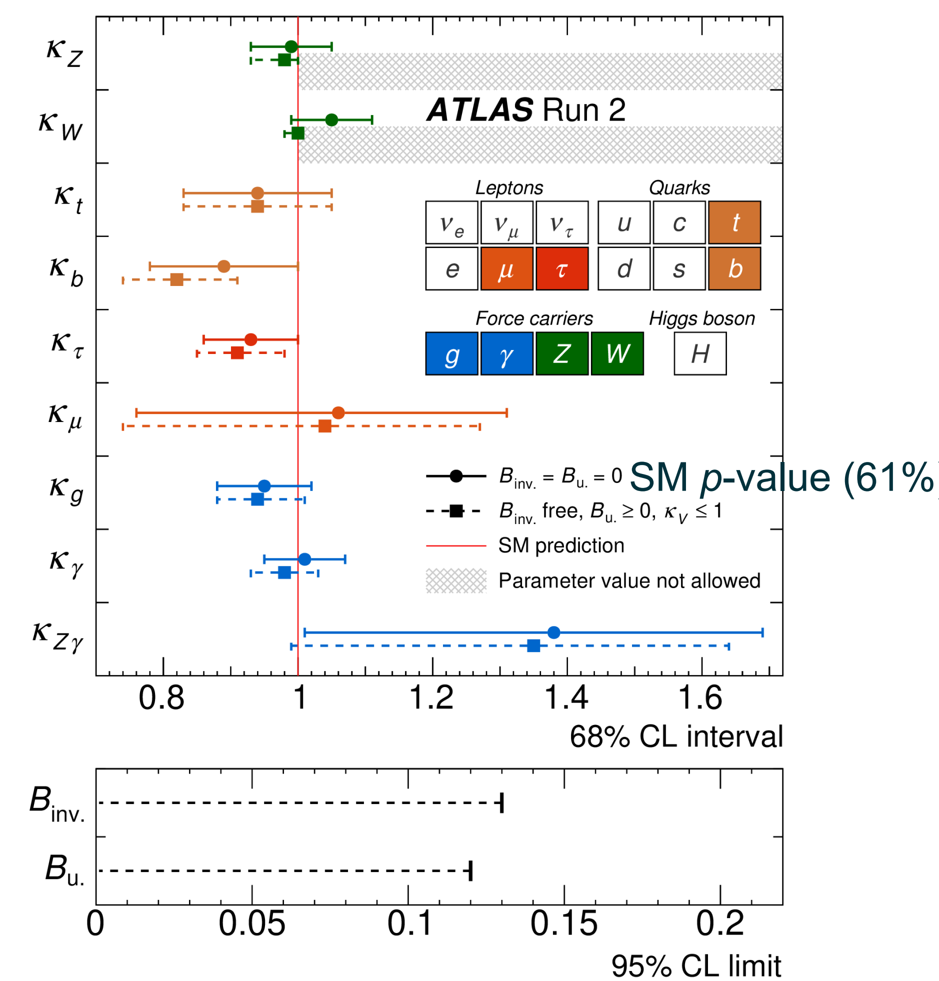
κ framework

$$\kappa_p^2 = \sigma_p/\sigma_p^{SM}$$
$$\kappa_p^2 = \Gamma_p/\Gamma_p^{SM}$$

- Used to determine the Higgs coupling to individual particle *p* (affecting both production *σ* and decay *Γ*)
  - Modified for the total Higgs width: $\kappa_H = \kappa_H(\kappa_b, \kappa_W, \kappa_\tau, \kappa_Z, \kappa_c, \kappa_s, \kappa_\mu, B_{invis.}, B_{und.})$
- Three models with progressively fewer assumptions studied:
  1) Single modifier for vector bosons and single modifier for fermion couplings
  2) Coupling modifiers for *W*, *Z*, *t*, *b*, *c*, *τ*, *μ* treated independently, loop processes resolved
  3) Same as 2) with coupling modifiers for non-SM particles in loop processes







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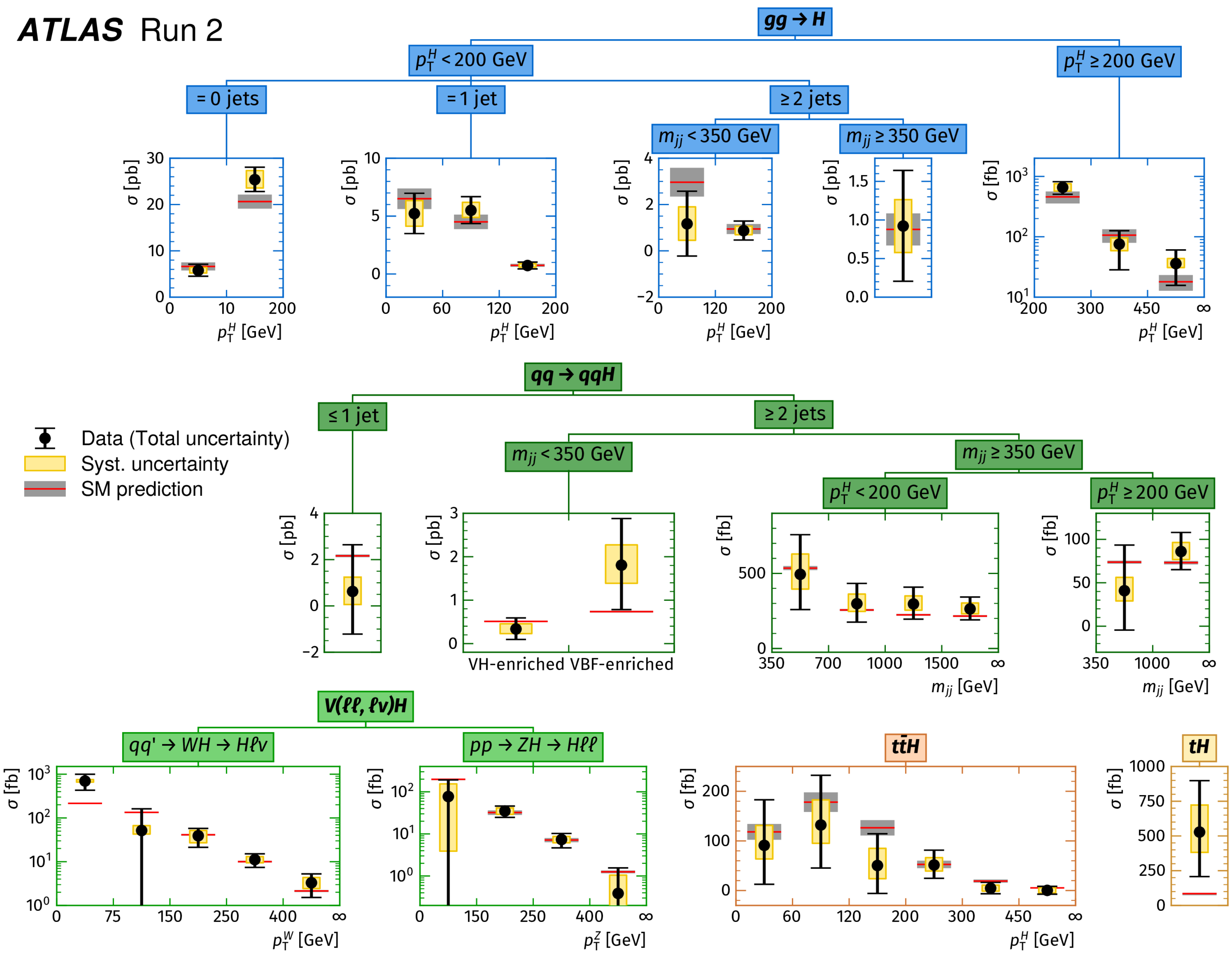
Simplified template cross sections (STXS) framework

- Signal cross sections measured in specific kinematic phase spaces.



11 **ggF** regions

9 **VBF** regions

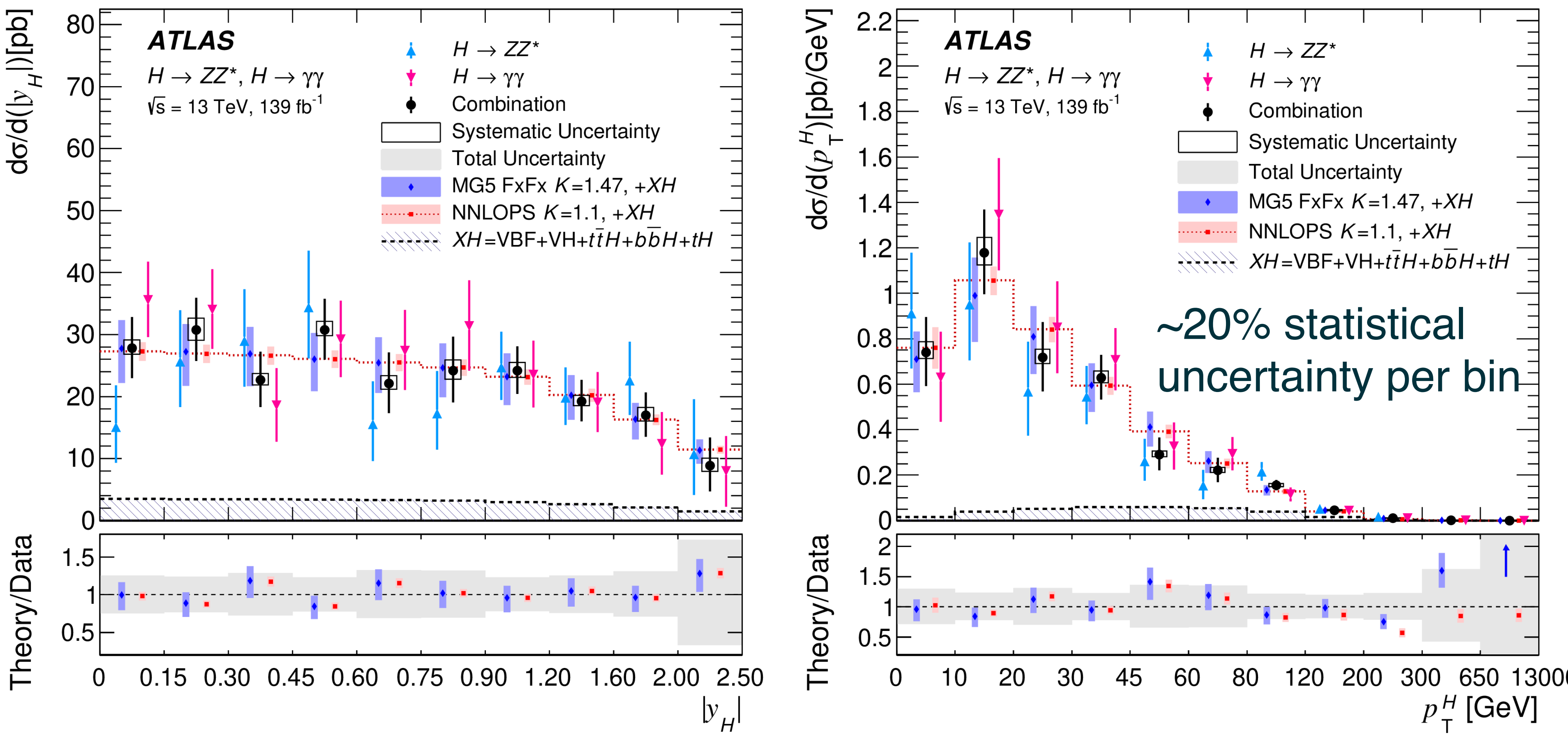
9 **VH** regions

7 **ttH+tH** regions

36 **total** regions

Differential cross section in H to γγ+4ℓ

- Higgs production cross sections measured also in finer bins and variables beyond STXS
  - Combined $H \to \gamma\gamma$ and $H \to 4\ell$ production cross section measurement



Observable	Total	p_T^H	$\lvert y_H \rvert$	p_T^H vs $\lvert y_H \rvert$	N_{jets}	$p_T^{\text{lead. jet}}$
Compatibility p-value	49%	20%	23%	69%	80%	37%

arXiv:2402.05742

Interpretation within SMEFT with STXS

- SMEFT: extension of SM by adding higher-dimensional operators built upon SM fields

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

- Warsaw basis used: complete set of d=6 operators, assuming Λ = 1 TeV
- "Top" flavour scheme:
  - First two generation quarks treated similarly
  - All lepton generations separately
  - 204 CP-even operators, 50 related to Higgs measurement considered in this analysis

Wilson coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$
c_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$c_{Hl,11}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_1 \gamma^\mu l_1)$
$c_{Hl,22}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_2 \gamma^\mu l_2)$
$c_{Hl,33}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_3 \gamma^\mu l_3)$
$c_{Hl,11}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_1 \tau^I \gamma^\mu l_1)$
$c_{Hl,22}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_2 \tau^I \gamma^\mu l_2)$
$c_{Hl,33}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_3 \tau^I \gamma^\mu l_3)$
$c_{He,11}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_1 \gamma^\mu e_1)$
$c_{He,22}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_2 \gamma^\mu e_2)$
$c_{He,33}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_3 \gamma^\mu e_3)$
$c_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q} \gamma^\mu q)$
$c_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q} \tau^I \gamma^\mu q)$
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$c_{HQ}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q} \gamma^\mu Q)$
$c_{HQ}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{Q} \tau^I \gamma^\mu Q)$
c_{Ht}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t} \gamma^\mu t)$
c_{Hb}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{b} \gamma^\mu b)$

Wilson coefficient	Operator
$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$
$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
$c_{tu}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
$c_{td}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$
$c_{td}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$
$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$
$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$
$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$
$c_{eH,22}$	$(H^\dagger H)(\bar{l}_2 e_2 H)$
$c_{eH,33}$	$(H^\dagger H)(\bar{l}_3 e_3 H)$
c_{uH}	$(H^\dagger H)(\bar{q} Y_u^\dagger u \widetilde{H})$
c_{tH}	$(H^\dagger H)(\bar{Q} \widetilde{H} t)$
c_{bH}	$(H^\dagger H)(\bar{Q} H b)$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\, G_{\mu\nu}^A$
c_{tW}	$(\bar{Q}\sigma^{\mu\nu} t)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
c_{tB}	$(\bar{Q}\sigma^{\mu\nu} t)\widetilde{H}\, B_{\mu\nu}$
$c_{ll,1221}$	$(\bar{l}_1\gamma_\mu l_2)(\bar{l}_2\gamma^\mu l_1)$

Parameterisation

$$(\sigma\times\mathcal{B})^{i,k',H\to X}_{\mathrm{SMEFT}} = \sigma^{i,k'}_{\mathrm{SMEFT}} \times \mathcal{B}^{H\to X}_{\mathrm{SMEFT}} = \left(\sigma^{i,k'}_{\mathrm{SM}} + \boxed{\sigma^{i,k'}_{\mathrm{int}}} + \sigma^{i,k'}_{\mathrm{BSM}}\right) \times \left(\frac{\Gamma^{H\to X}_{\mathrm{SM}} + \boxed{\Gamma^{H\to X}_{\mathrm{int}}} + \Gamma^{H\to X}_{\mathrm{BSM}}}{\Gamma^{H}_{\mathrm{SM}} + \boxed{\Gamma^{H}_{\mathrm{int}}} + \Gamma^{H}_{\mathrm{BSM}}}\right)$$

- Linear term: interference between dim-6 operators and SM
- Quadric term: pure BSM term, product of two dim-6 operators

$$\frac{\sigma^{i,k'}_{\mathrm{int}}}{\sigma^{i,k'}_{\mathrm{SM}}} = \sum_j A^{\sigma_{i,k'}}_j c_j \qquad \frac{\sigma^{i,k'}_{\mathrm{BSM}}}{\sigma^{i,k'}_{\mathrm{SM}}} = \sum_{j,l\geq j} B^{\sigma_{i,k'}}_{jl} c_j c_l$$

$$\frac{\Gamma^{H\to X}_{\mathrm{int}}}{\Gamma^{H\to X}_{\mathrm{SM}}} = \sum_j A^{\Gamma^{H\to X}}_j c_j \qquad \frac{\Gamma^{H\to X}_{\mathrm{BSM}}}{\Gamma^{H\to X}_{\mathrm{SM}}} = \sum_{j,l\geq j} B^{\Gamma^{H\to X}}_{jl} c_j c_l$$

$$\frac{\Gamma^{H}_{\mathrm{int}}}{\Gamma^{H}_{\mathrm{SM}}} = \sum_j A^{\Gamma^H}_j c_j \qquad \frac{\Gamma^{H}_{\mathrm{BSM}}}{\Gamma^{H}_{\mathrm{SM}}} = \sum_{j,l\geq j} B^{\Gamma^H}_{jl} c_j c_l,$$

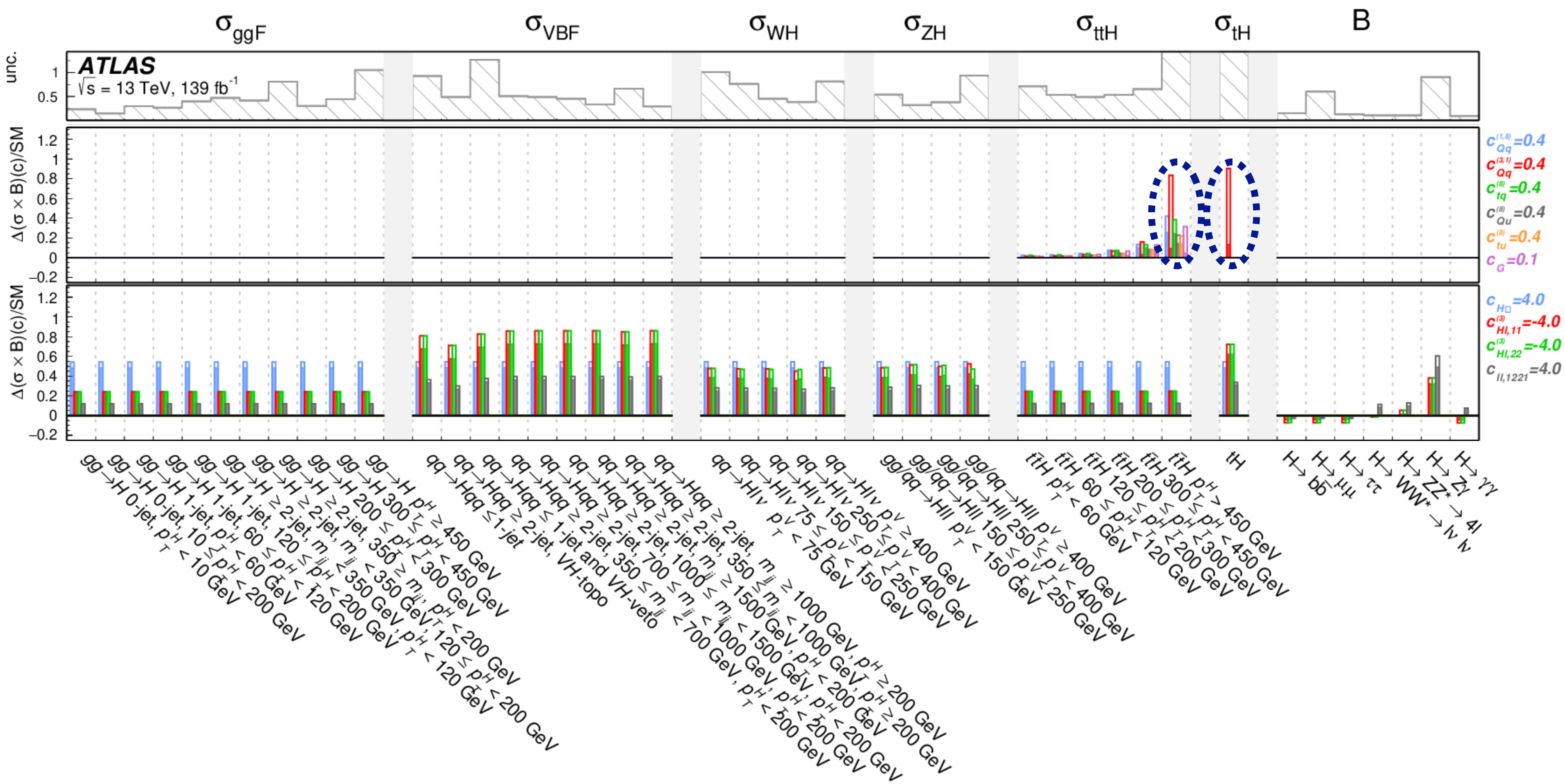
$$A^{\Gamma^H}_j = \frac{\sum_X \Gamma^{H\to X}_{\mathrm{SM}} A^{\Gamma^{H\to X}}_j}{\sum_X \Gamma^{H\to X}_{\mathrm{SM}}} \qquad B^{\Gamma^H}_{jl} = \frac{\sum_X \Gamma^{H\to X}_{\mathrm{SM}} B^{\Gamma^{H\to X}}_{jl}}{\sum_X \Gamma^{H\to X}_{\mathrm{SM}}}$$

- Measurements are re-parameterised in terms of Wilson coefficients

linear model: $$(\sigma\times\mathcal{B})^{i,k',H\to X}_{\mathrm{SM,((N)N)NLO}} \times \left(\frac{1+\sum_j \left(A^{\sigma_{i,k'}}_j + A^{\Gamma^{H\to X}}_j\right) c_j + O\left(\Lambda^{-4}\right)}{1+\sum_j A^{\Gamma^H}_j c_j + O\left(\Lambda^{-4}\right)}\right)$$

Quadric model: $$(\sigma\times\mathcal{B})^{i,k',H\to X}_{\mathrm{SM,((N)N)NLO}} \cdot \left(\frac{1+\sum_j\left(A^{\sigma_{i,k'}}_j + A^{\Gamma^{H\to X}}_j\right)c_j + \sum_{j,l}\left(A^{\sigma_{i,k'}}_j A^{\Gamma^{H\to X}}_l\right)c_j c_l + \sum_{j,l\geq j}\left(B^{\sigma_{i,k'}}_{jl} + B^{\Gamma^{H\to X}}_{jl}\right)c_j c_l + O\left(\Lambda^{-6}\right)}{1+\sum_j\left(A^{\Gamma^H}_j\right)c_j + \sum_{j,l\geq j}\left(B^{\Gamma^H}_{jl}\right)c_j c_l + O\left(\Lambda^{-6}\right)}\right)$$

Impact from the modified basis

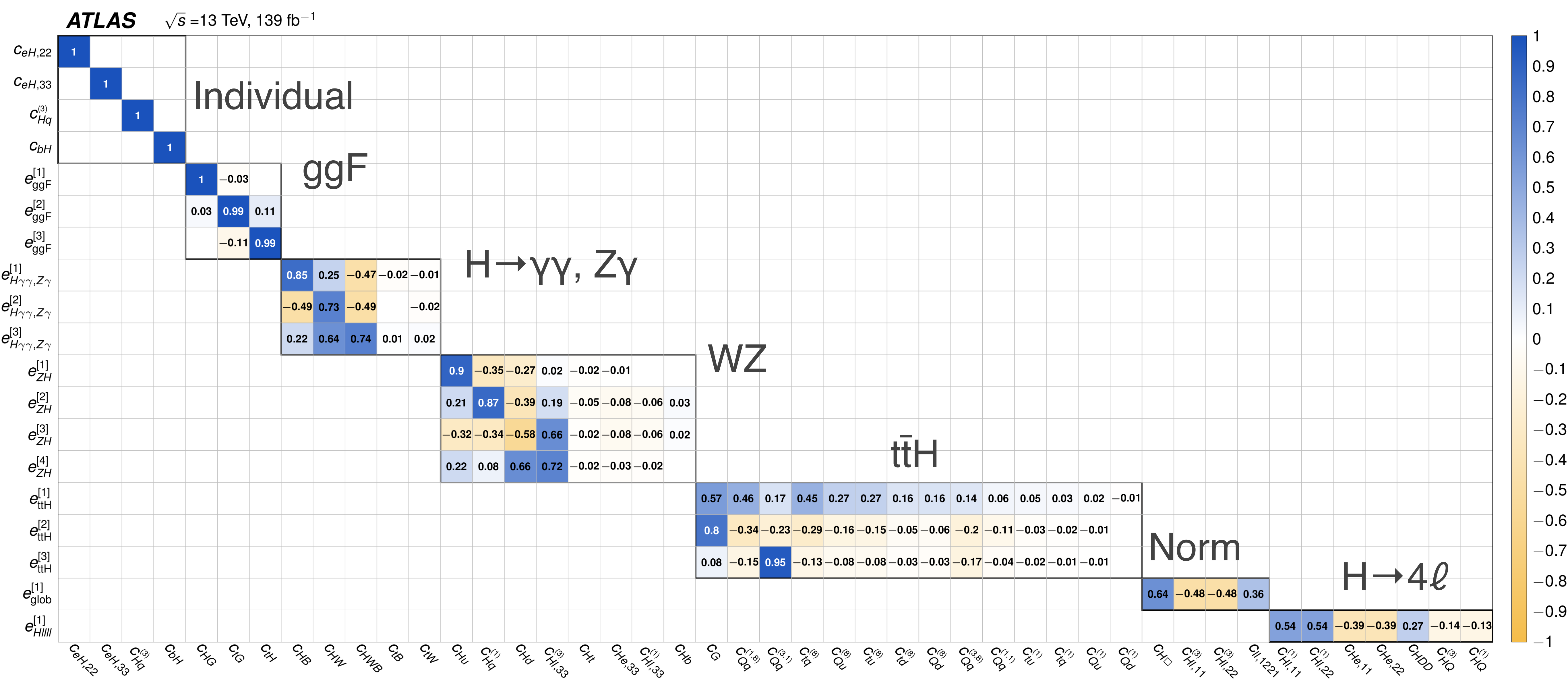


- Impact of coefficients of the basis on the STXS regions
  - Linear model (filled histograms); Linear+quadric model (open histogram)
- Uncertainties on corresponding regions is shown in the top panel

arXiv:2402.05742

Reorganise coefficients

- Converting Warsaw basis coefficients to fit basis coefficients
  - 19 directions based on the principal component analysis and physics motivations
  - The rest directions are fixed to 0 in fitting



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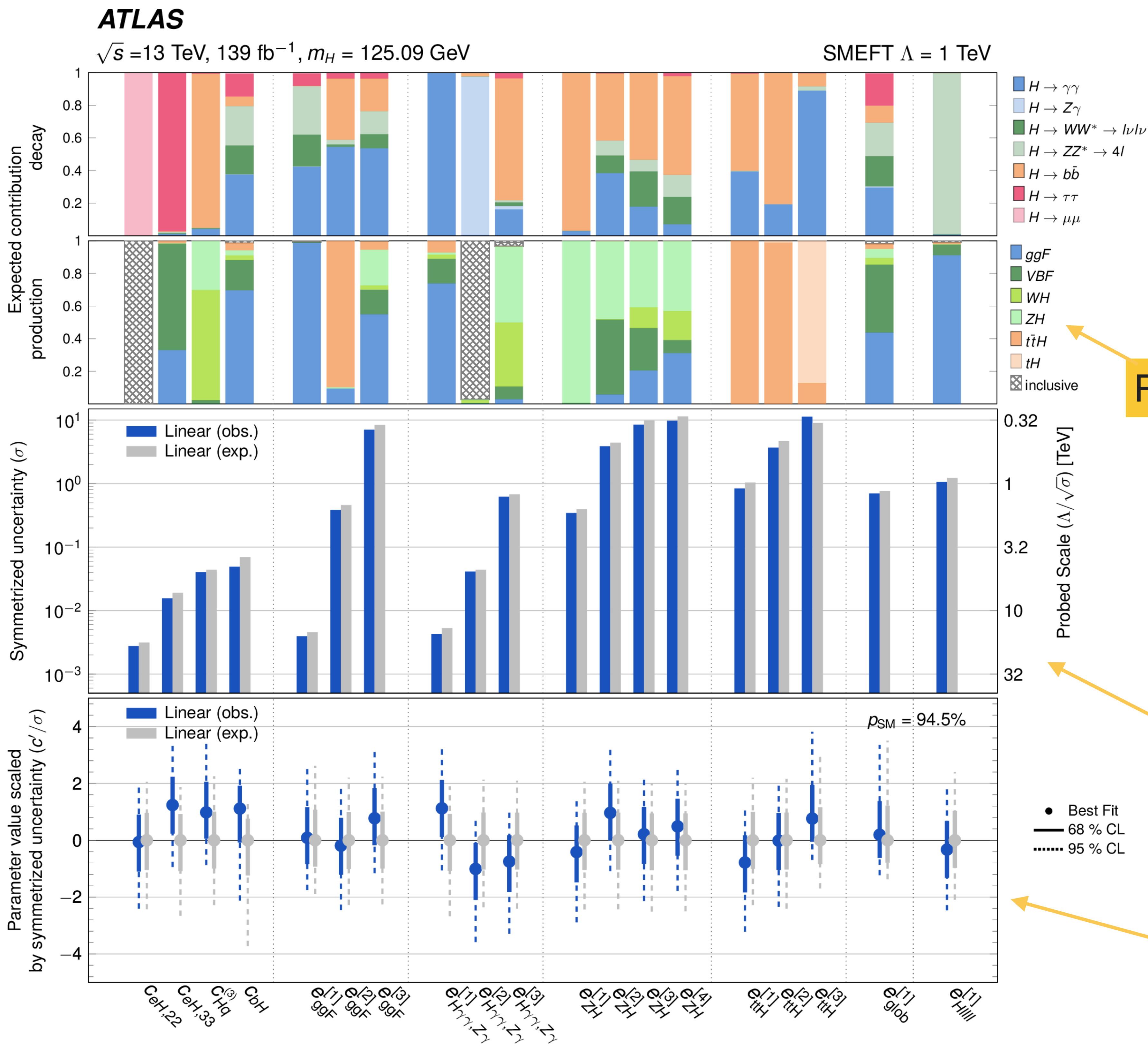
Constraints on SMEFT - linear model



- Tight constraint observed for process that is suppressed in SM, but not in SMEFT
- No significant deviation from SM

Relative contributions

Best fit uncertainties

Best fit values

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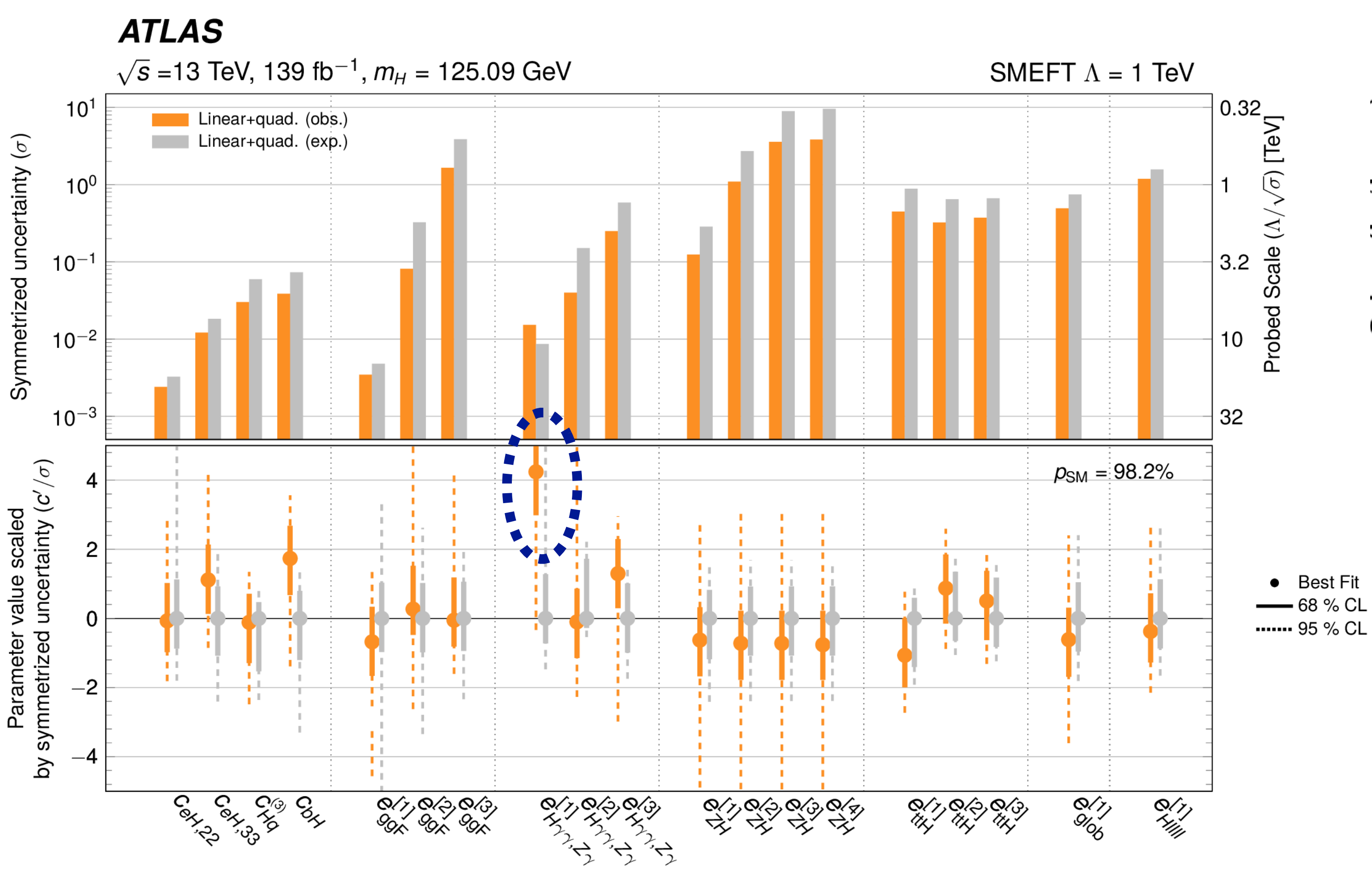
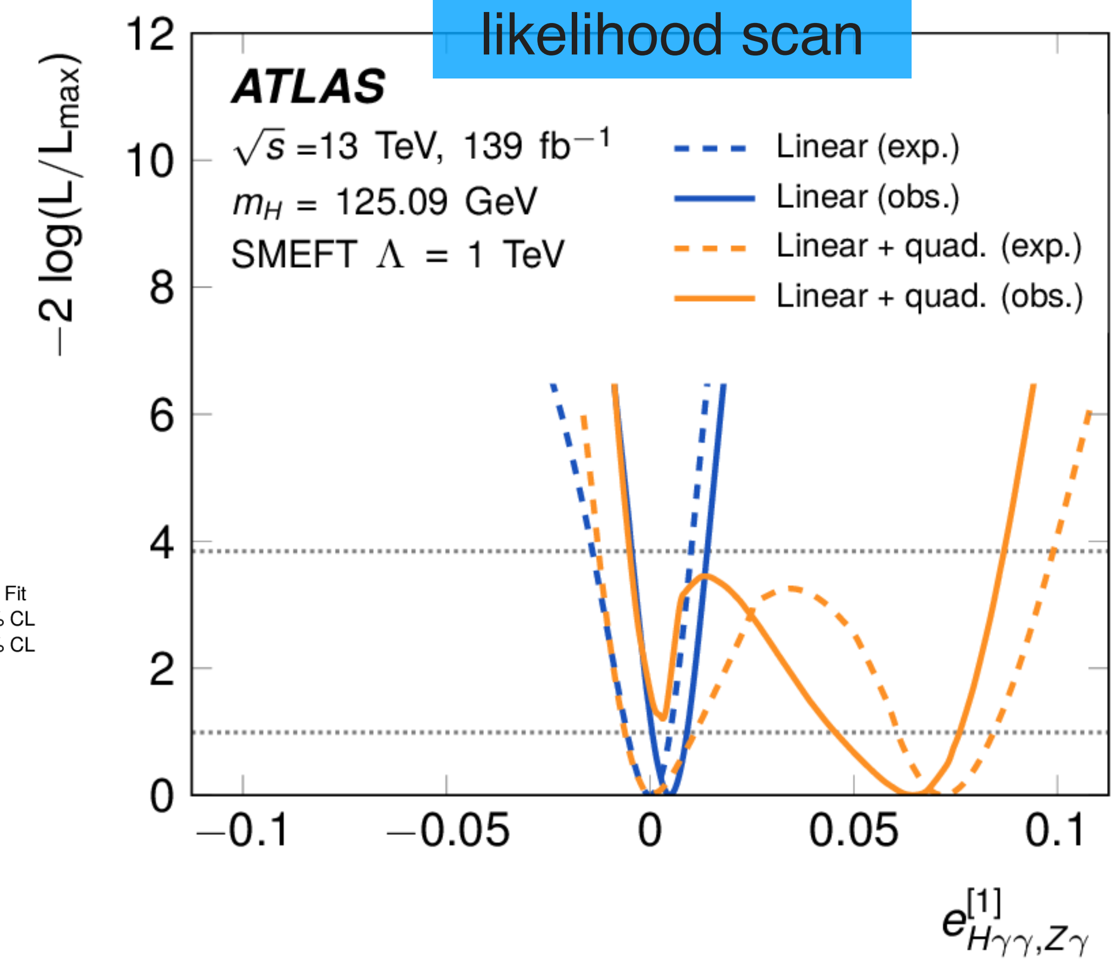
Constraints on SMEFT - quadric model

- Most operators have more stringent constraints than linear models as the linear+quadric impact is larger than linear one
- Impact from quad term can be big in some operators due to double minima

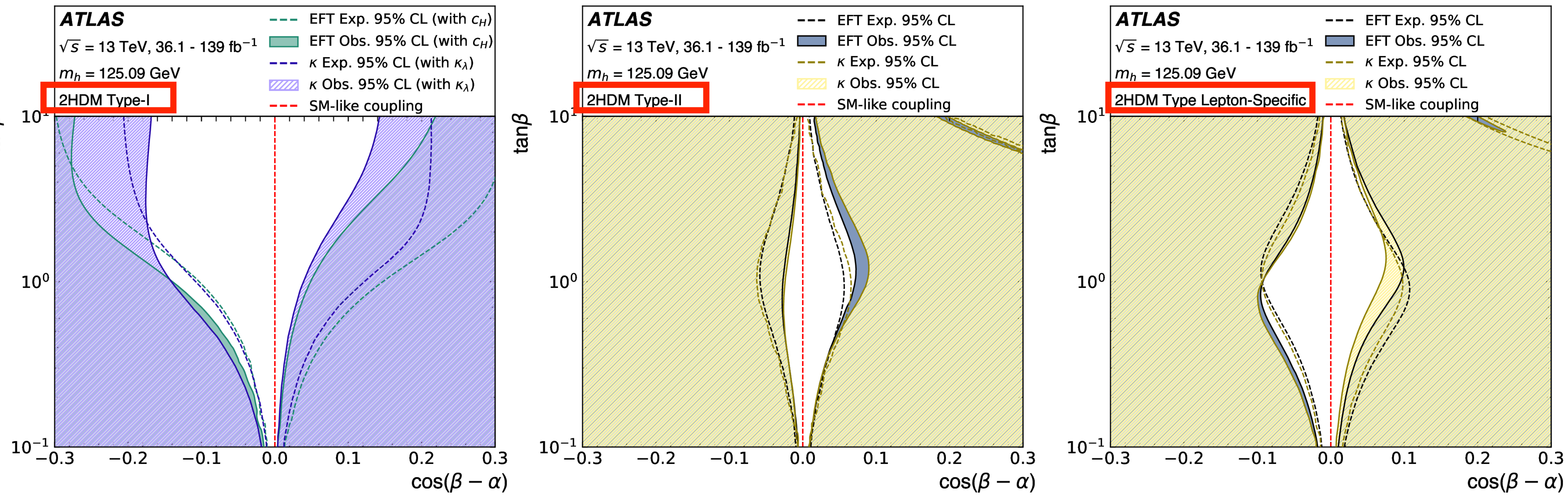


An example of likelihood scan



BSM interpretation

- Interpreted under 4 benchmarks of 2HDM and 7 of MSSM + hMSSM
- Can also be done through the results of EFT which is a low-energy approximation of high energy scale UV-complete model
- A direct interpretation and EFT-based approach are compared and show reasonable agreement
  - The EFT-based approach has weaker constraint than direct interpretation in Type-I, due to the missing of dim-8 operators



Summary

- A detailed check of the SM prediction from the combination of the measurements in the κ and the STXS framework
  - All results are in excellent agreement with the SM prediction
- Results are interpreted under EFT & BSM
- The linear and linear+quadric model are used for the interpretation on STXS measurements
  - No significant deviation from SM is observed

Exciting future ahead with the upcoming Run 3 dataset!

Backup

Impact of rotated SMEFT operators on H→γγ and H→ZZ