Combined Higgs boson measurements at the ATLAS experiment

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ATLAS EXPERIMENT

Physics
UNIVERSITY OF TORONTO

Overview

- ATLAS analyses target different Higgs boson production modes and decay channels
  - Many of measured quantities are **independent** of the Higgs boson production/decay
- Statistical combination of the most current measurements to get best precision and limits on important parameters in the Standard Model (SM)
  - Updated to full Run 2 dataset for some of the input analysis
  - Previous publication for 2015-2017 dataset [arXiv:1909.02845]

Focus Today

Couplings - (ATLAS-CONF-2020-027)

- Global signal strength
- Production mode cross sections (XS) and branching ratios (BR)
- Simplified template cross section (STXS) results
- Interpretations
  - κ-framework
  - EFT(ATLAS-CONF-2020-053)

Differential - (ATLAS-CONF-2019-032)

- $p_{T,H}$ combination for $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$

Input to combined measurements

- So far $H \to ZZ^* \to 4\ell$, $H \to \gamma\gamma$, VH→bb analyses used for STXS combination
- H→μμ and H→inv used in a subset of the κ-framework results

Analysis Decay Channel	Target Prod. Modes	$\mathcal{L}$ [fb^{-1}]	Link	Signal Strength	Prod. Modes Branching Ratios	STXS	κ-interp	EFT
$H \to \gamma\gamma$	ggF,VBF,$WH, ZH, t\bar{t}H, tH$	139	ATLAS-CONF-2020-026	✓	✓	✓	✓	✓
$H \to ZZ^*$	ggF,VBF,$WH, ZH, t\bar{t}H(4\ell)$	139	arXiv:2004.03447	✓	✓	✓	✓	✓
	$t\bar{t}H$ excl. $H \to ZZ^* \to 4\ell$	36.1	arXiv:1712.08891, arXiv:1806.00425	✓	✓		✓	
$H \to WW^*$	ggF,VBF	36.1	arXiv:1808.09054	✓	✓		✓	
	$t\bar{t}H$		arXiv:1712.08891, arXiv:1806.00425					
$H \to \tau\tau$	ggF,VBF	36.1	arXiv:1811.08856	✓	✓		✓	
	$t\bar{t}H$		arXiv:1712.08891, arXiv:1806.00425					
$H \to b\bar{b}$	VBF	24.5 – 30.6	arXiv:1807.08639	✓	✓		✓	
	WH, ZH	139	arXiv:2007.02873	✓	✓	✓	✓	✓
	$t\bar{t}H$	36.1	arXiv:1712.08895, arXiv:1806.00425	✓	✓		✓	
$H \to \mu\mu$	ggF,VBF,$VH, t\bar{t}H, tH$	139	arXiv:2007.07830				✓	
$H \to inv$	VBF	139	ATLAS-CONF-2020-008				✓	

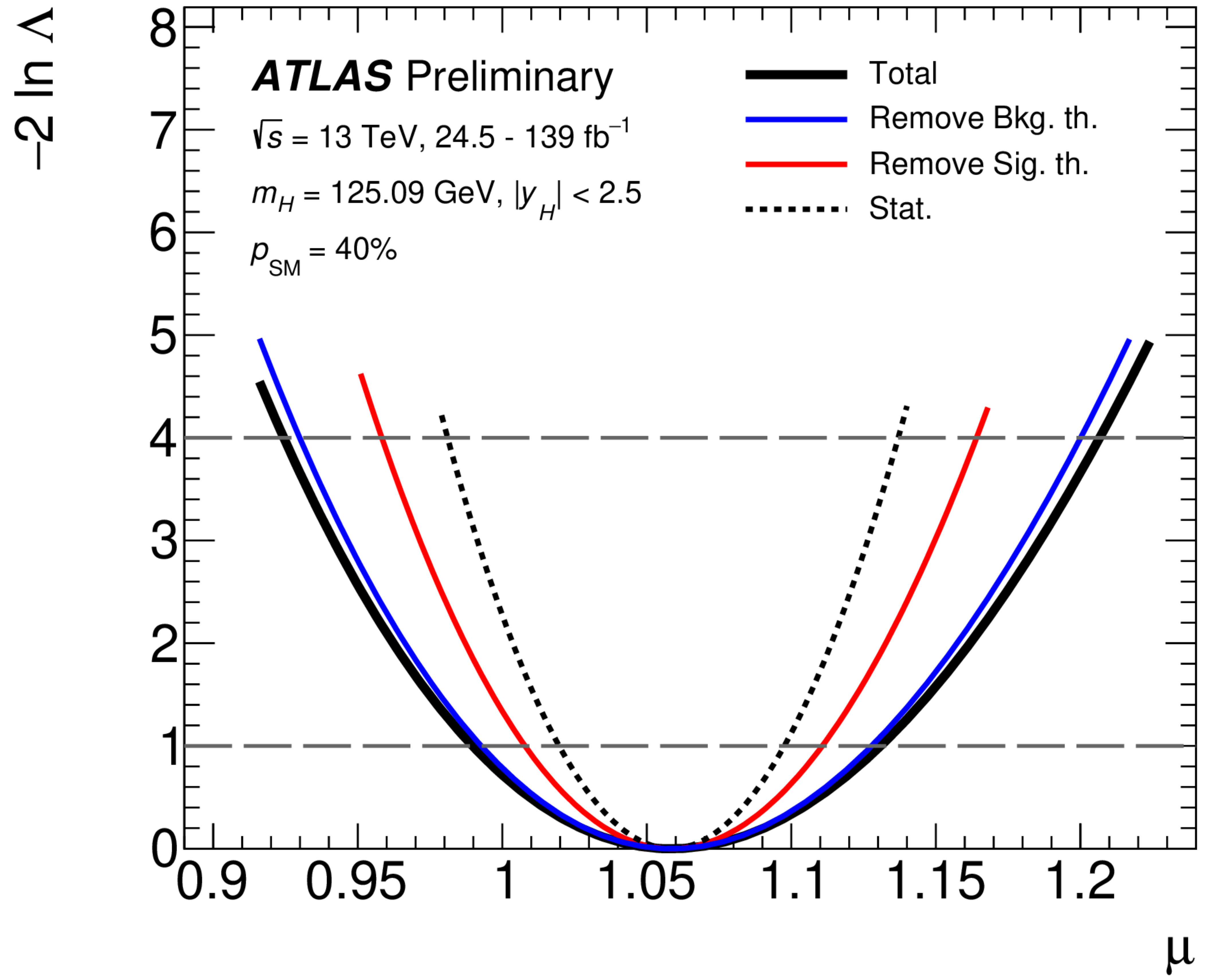
- Results of combination obtained from product of likelihood functions
- Systematics from same sources are correlated

Global Signal Strength

- Simultaneous measurement of parameter μ (where $\mu_{if} = (\sigma_i \times BR_f)/(\sigma_i \times BR_f)_{SM}$)

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

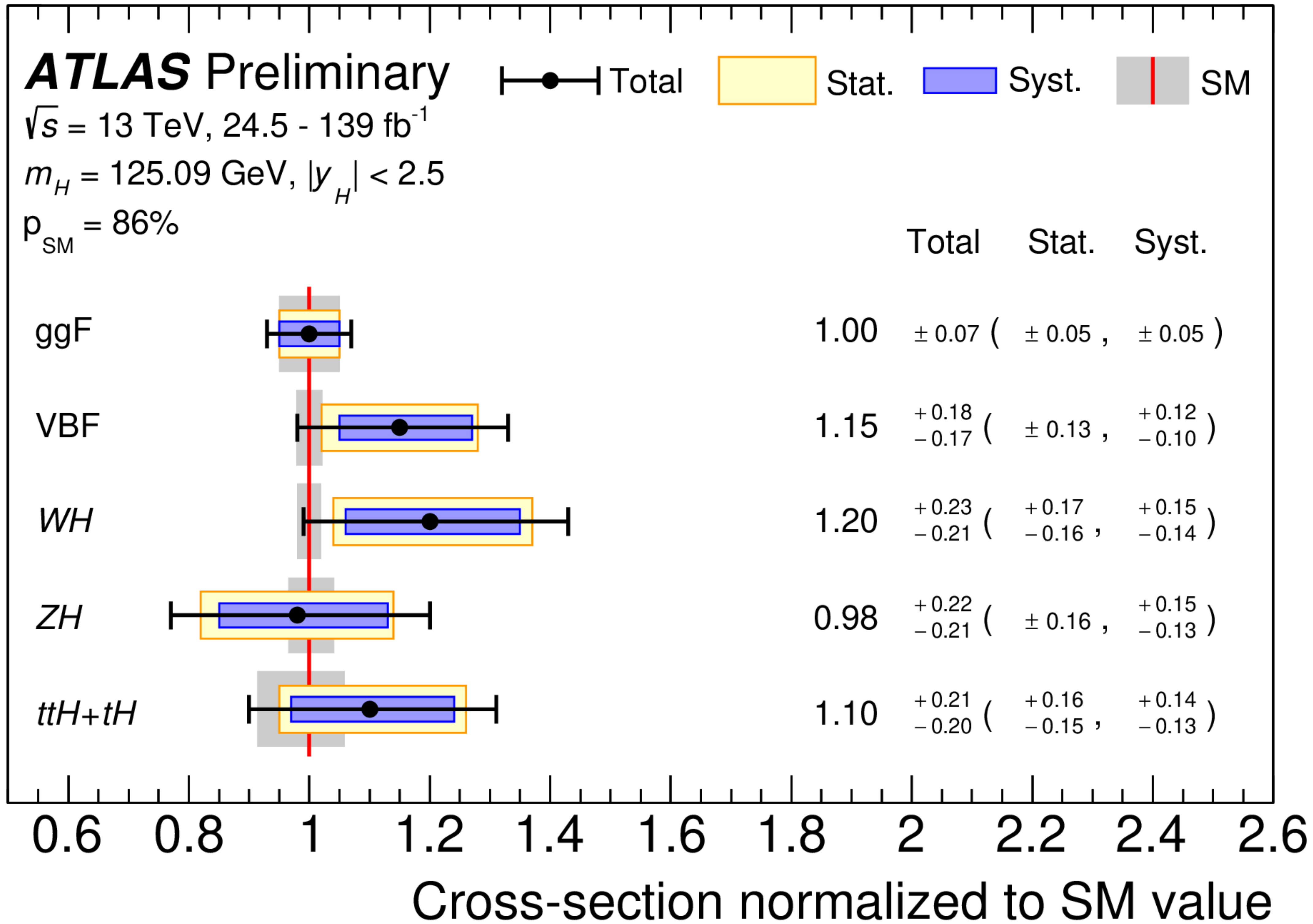
- Systematic uncertainties **dominate** due to smaller statistical uncertainty from full Run-2 dataset
- Largest theory uncertainties are included
    - QCD scale (~4% on ggF)
    - PDF and α_s uncertainty (~3% on ggF)
    - Note that ggF is ~90% of signal and is predicted at N3LO
- Consistent with SM (μ =1) with a p-value of 40%

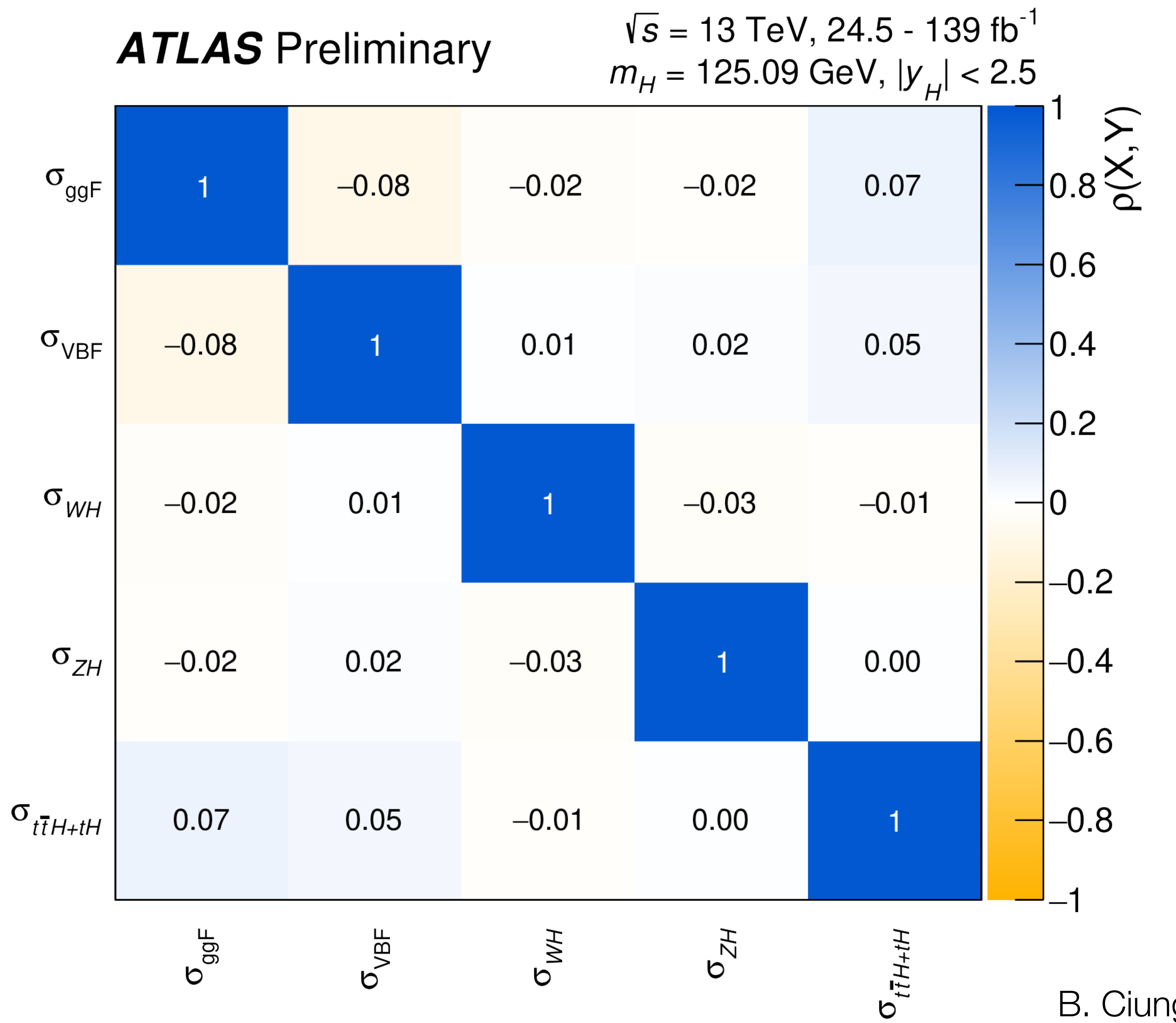


Production Modes

- Branching fractions fixed to SM expectations, cross sections are simultaneously determined in the fit to data
- Decrease in ggF and VBF correlation compared to previous publication (~15% → 8%)
    - Mainly from updated $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ results
- Above 5σ observed for all production modes
    - First observation of *WH* with observed (expected) significances of 6.3σ (5.2σ)

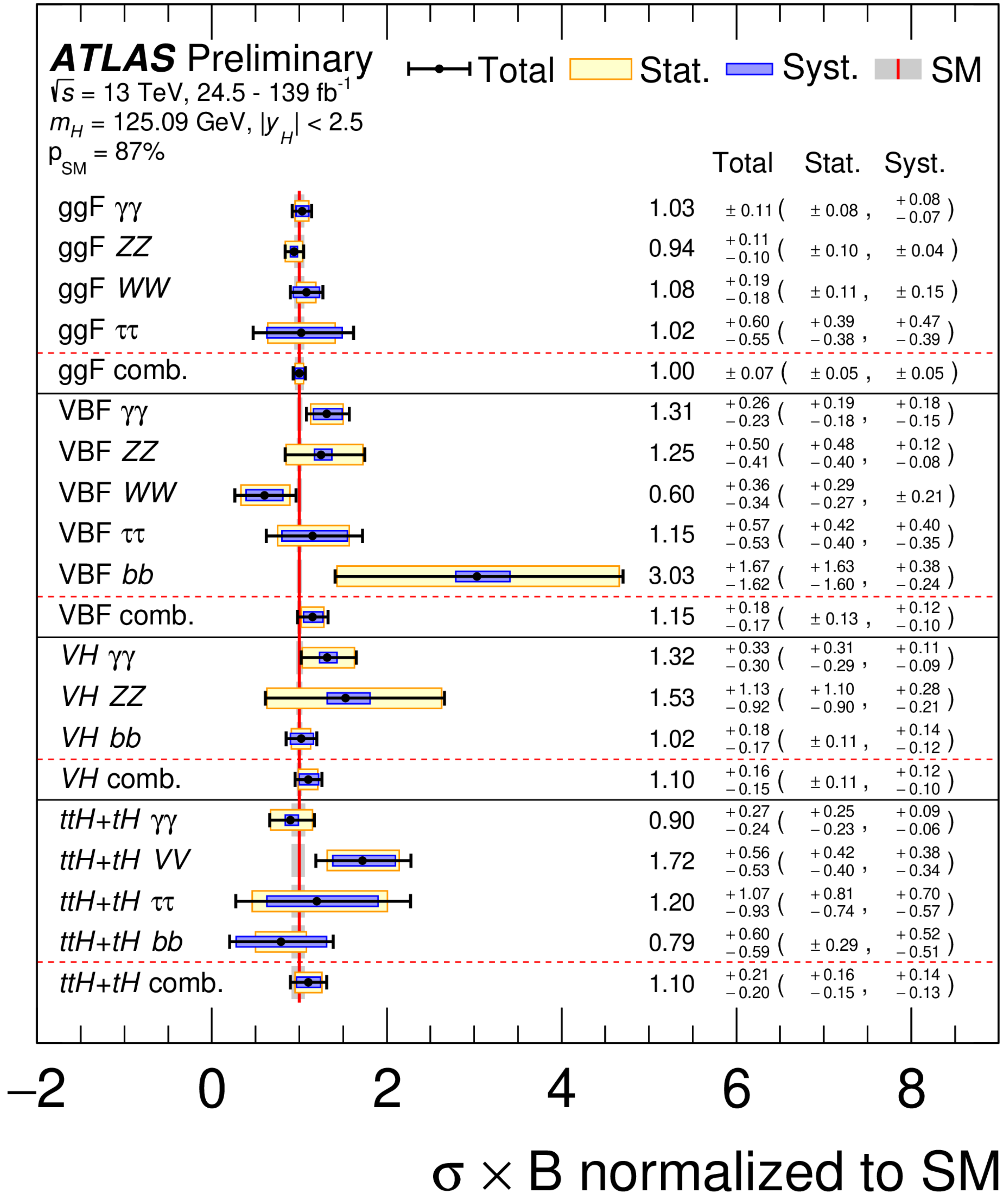
Systematic uncertainty same/approaching statistical uncertainty





Production and Decay

- Can also test the SM by measuring $(\sigma \times B)_{if}$
  - ggF driven by $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$
  - VBF driven by H→WW, $H \to \gamma\gamma$, and H→ττ
  - VH driven by H→bb
- Statistically limited channels are fixed to the SM
  - ggF→H→bb
  - VH, H →WW/ττ
- Relative fraction of ZH and WH fixed to the SM
- Good agreement with the SM (p-value of 87%)



STXS Scheme

- STXS scheme has bins of *exclusive phase space*

STXS Motivation

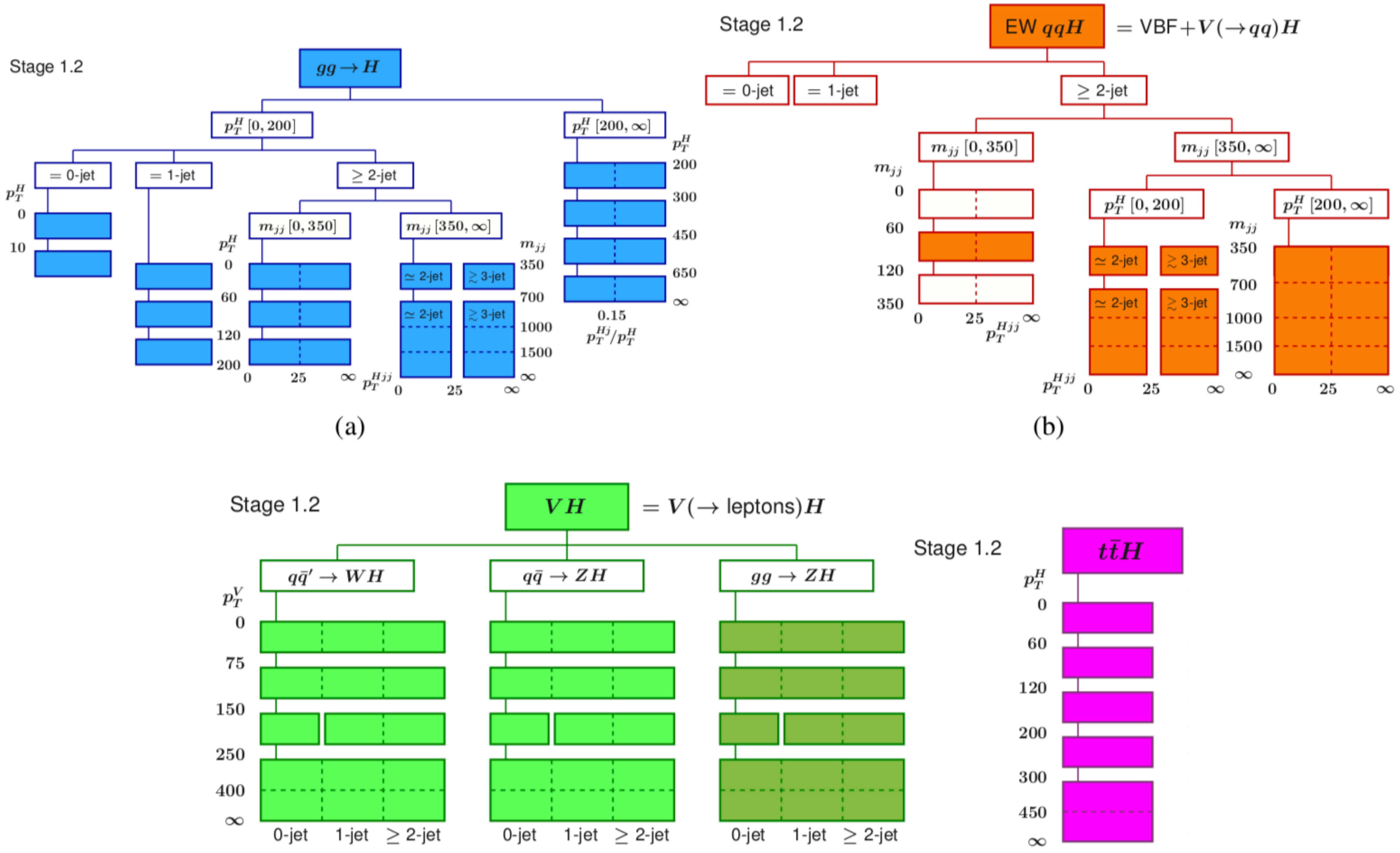
- Reduce large theory uncertainties
- Bins are sensitive to BSM contributions
- Easier combination of different final states

- Full scheme measurement is statistically limited → merge bins

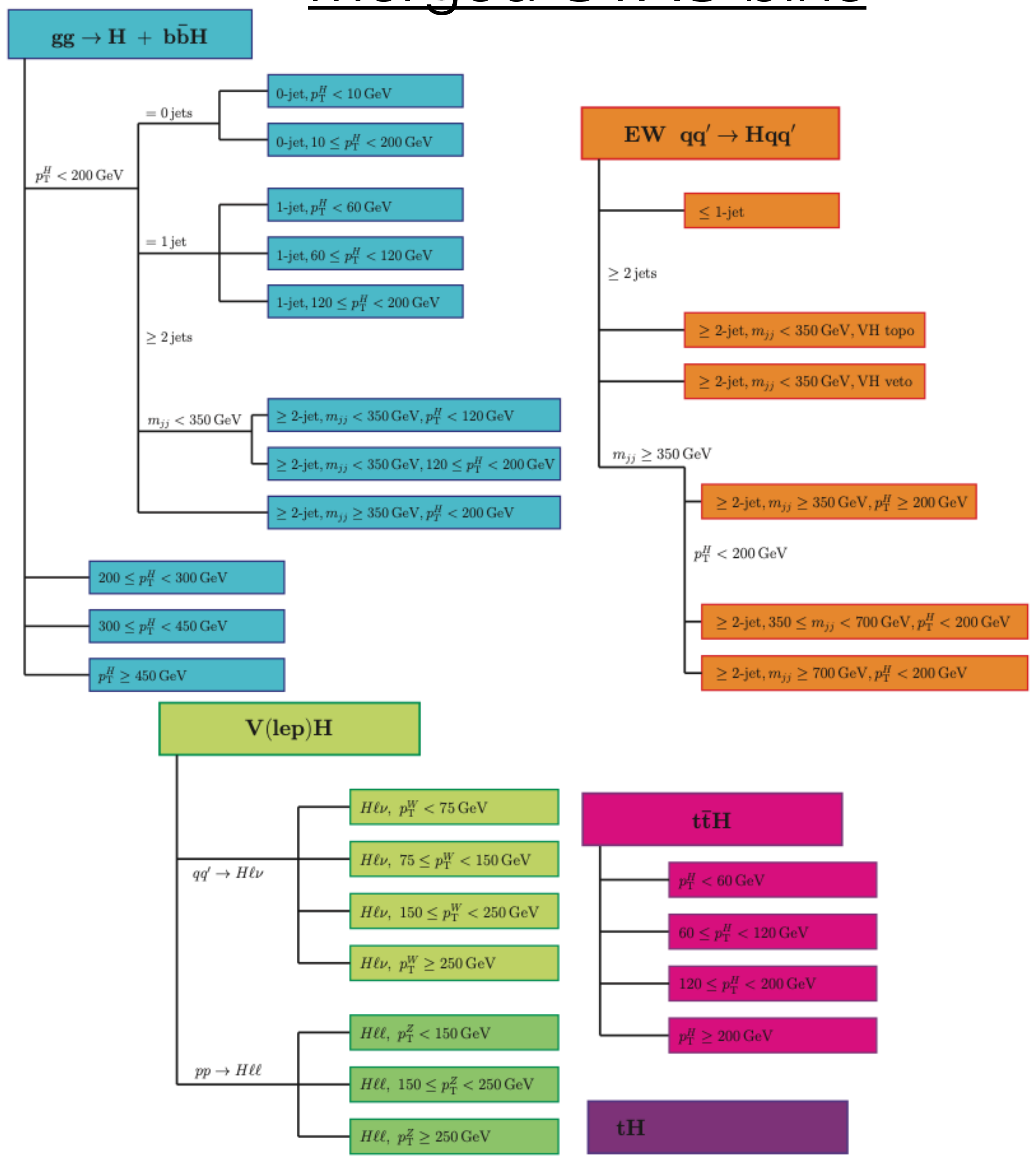
Considerations for bin merging

- Merge highly correlated STXS bins
- Keep uncertainties < 100% with the exception of bins sensitive to BSM physics

All STXS bins

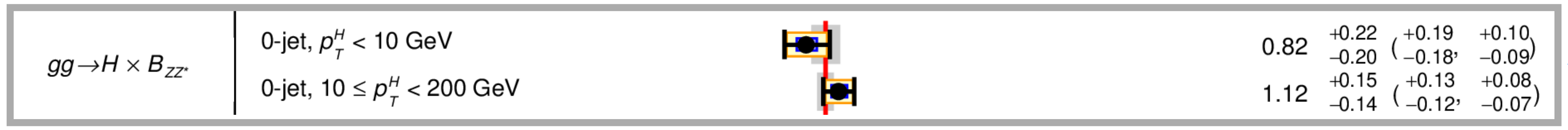


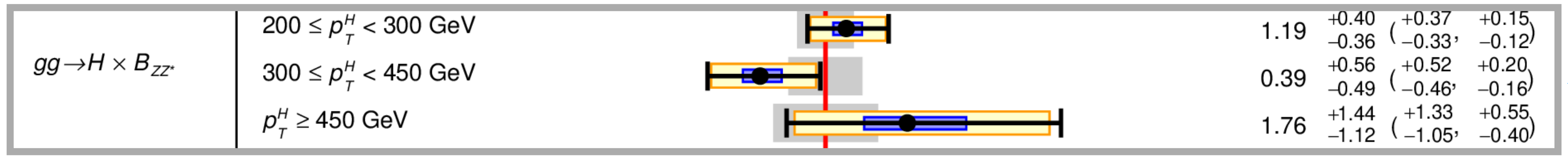
Merged STXS bins

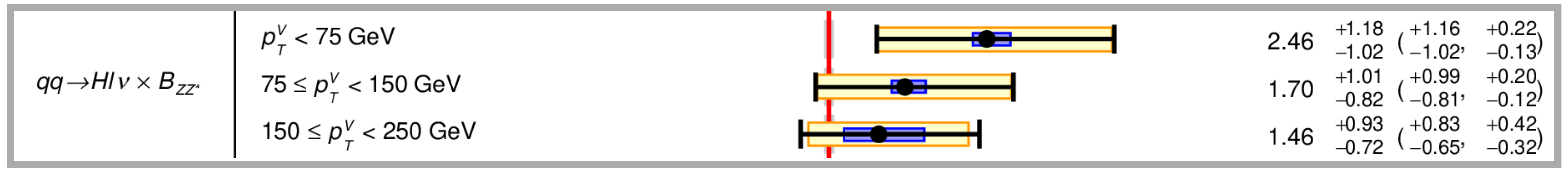


STXS Results

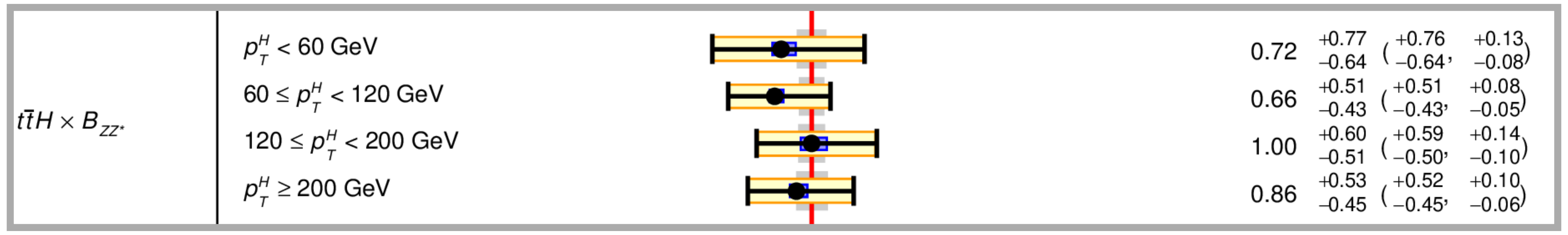
- Measure finer granularity of p_T bins



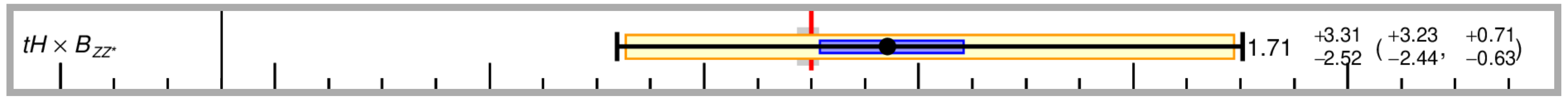




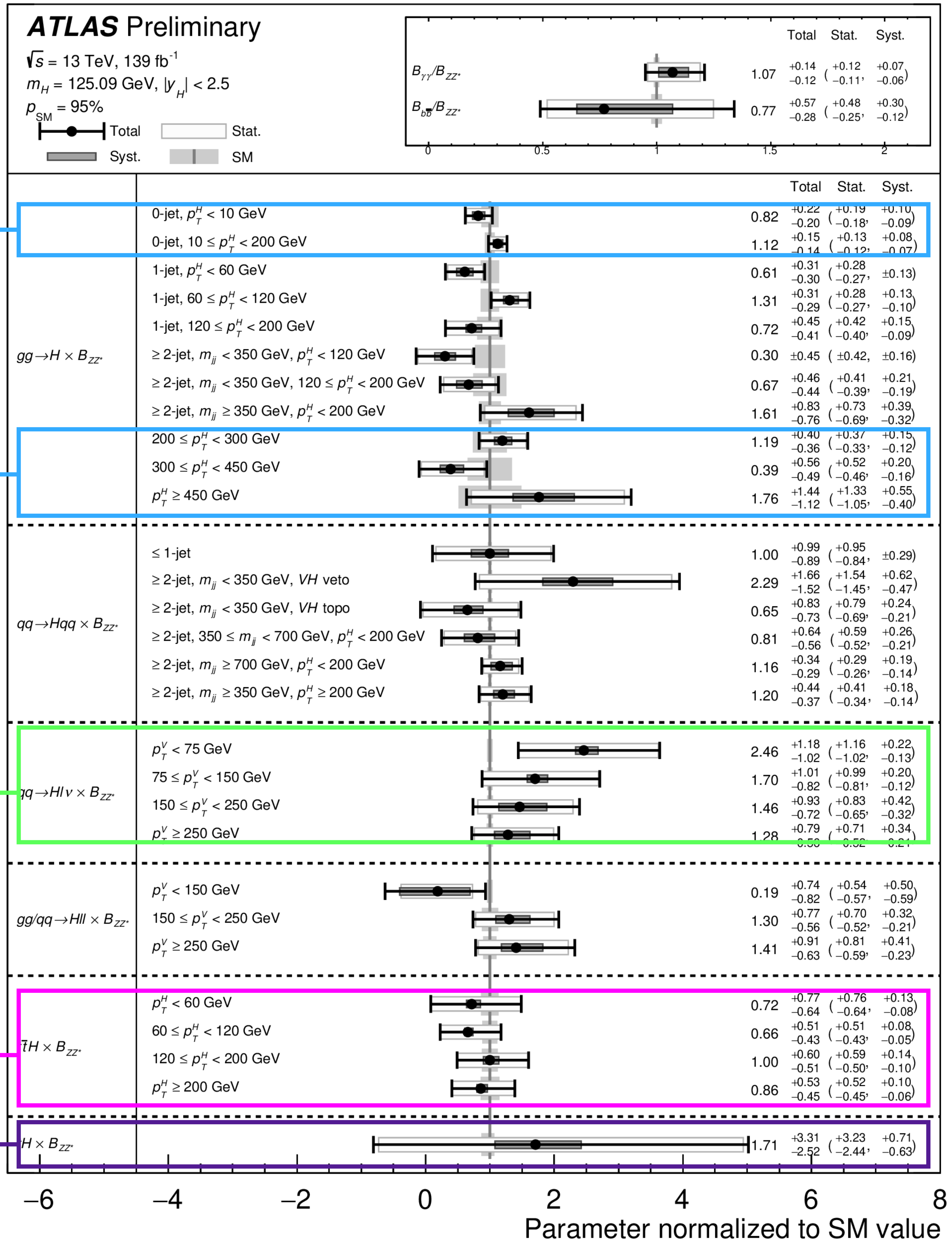
- Differential measurements for ttH production



- First combined measurement of tH



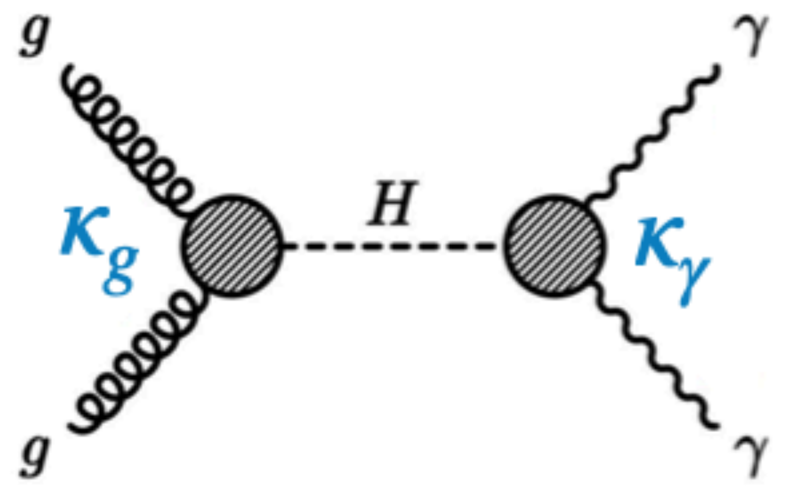
- Large correlation between VH and BR_{bb} (up to 83% in highest p_{TV} bin)
  - Sensitivity for these come from VH→bb and correlations will reduce when sensitivity from other production/decay channels improves
- Good agreement with the SM (p-value of 95%)



Interpretations: K-Framework

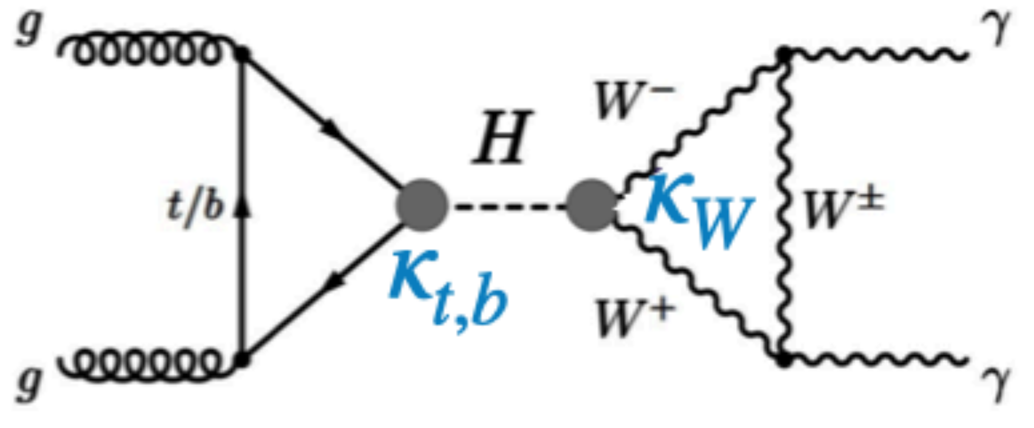
- Multiplicative factors (κ_i) factors applied to the SM XSs and BRs and can be used to constrain the couplings of the Higgs boson to particles
- Two ways to do this, for example in H→$\gamma\gamma$:

Use effective H→$\gamma\gamma$ coupling



or

Use SM (e.g. κ_t) in model

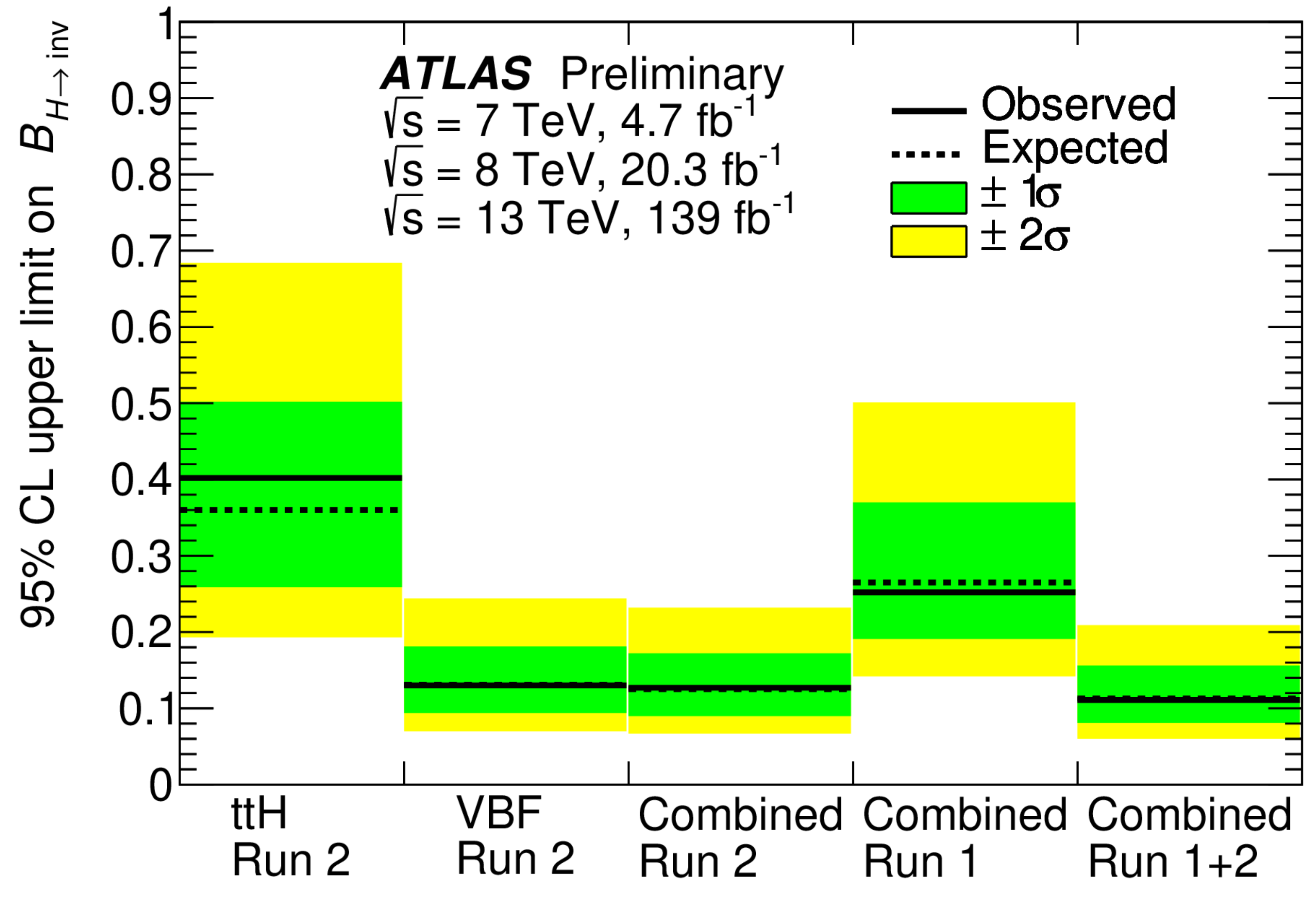


+...

- Higgs width can also be affected by
  - Invisible decays ($B_{i.}$): Identified through E_T^{miss} (SM H→ZZ*→4ν)
  - Undetected decays ($B_{u.}$): final states that analyses are not sensitive to (such as, light quarks, BSM particles without sizeable E_T^{miss})

$$\Gamma_H(\kappa, B_{i.}, B_{u.}) = \frac{\Sigma_j B_j^{SM} \kappa_j^2}{1 - B_{i.} - B_{u.}} \Gamma_H^{SM}$$

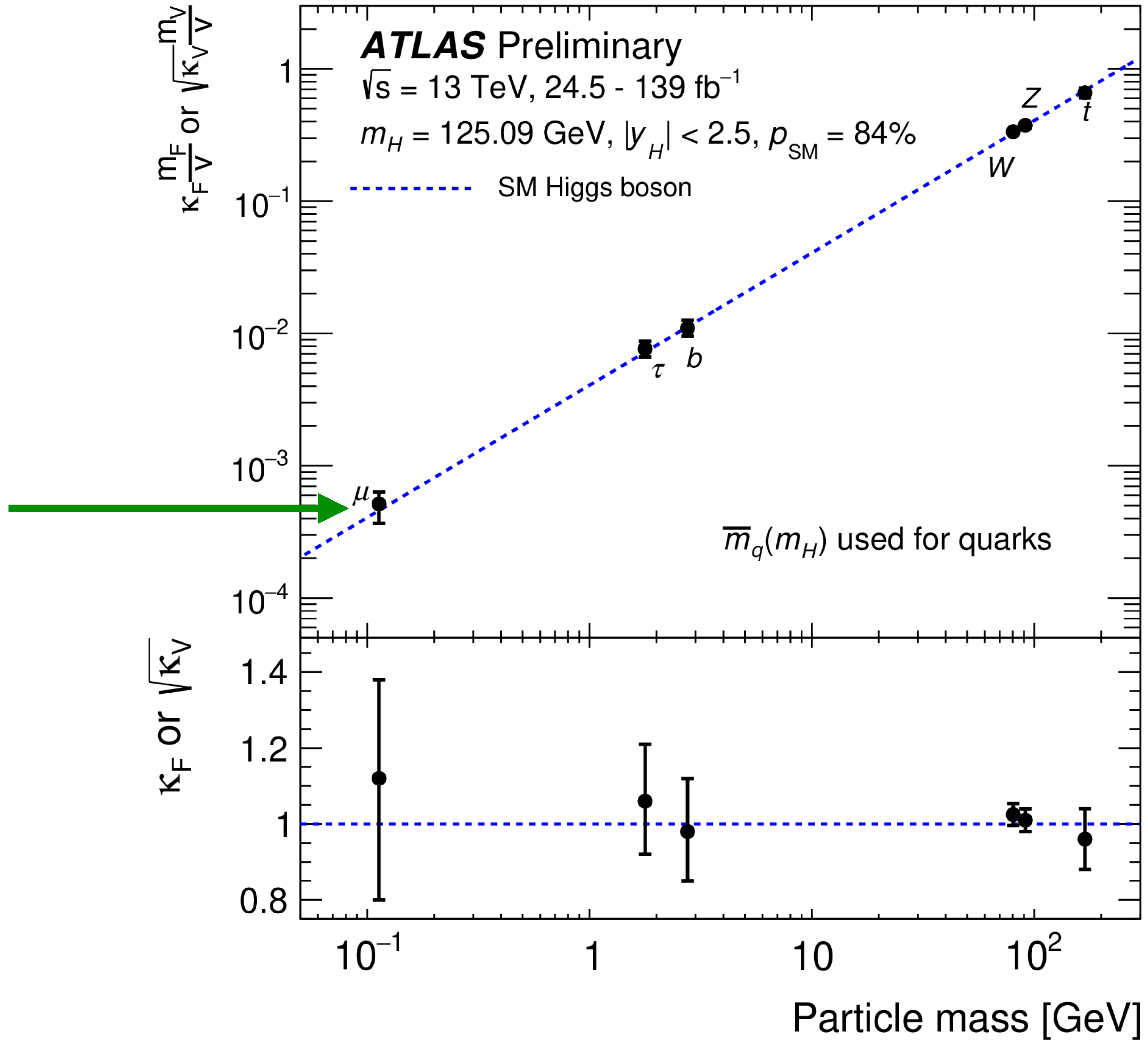
Not covered here: new results (with interpretations) of H→inv combination available — ATLAS-CONF-2020-052



+15% improvement on Run-2 VBF only result

Measurement of Yukawa couplings

- Assuming no new physics affects loop-induced processes or Higgs boson total width
    - Fit κ for W, Z, t, b, τ and μ
- κ_μ is no longer a limit but a measurement with full Run-2 dataset using latest H→μμ result
- Good agreement with SM expectation through three orders of magnitude of particle mass

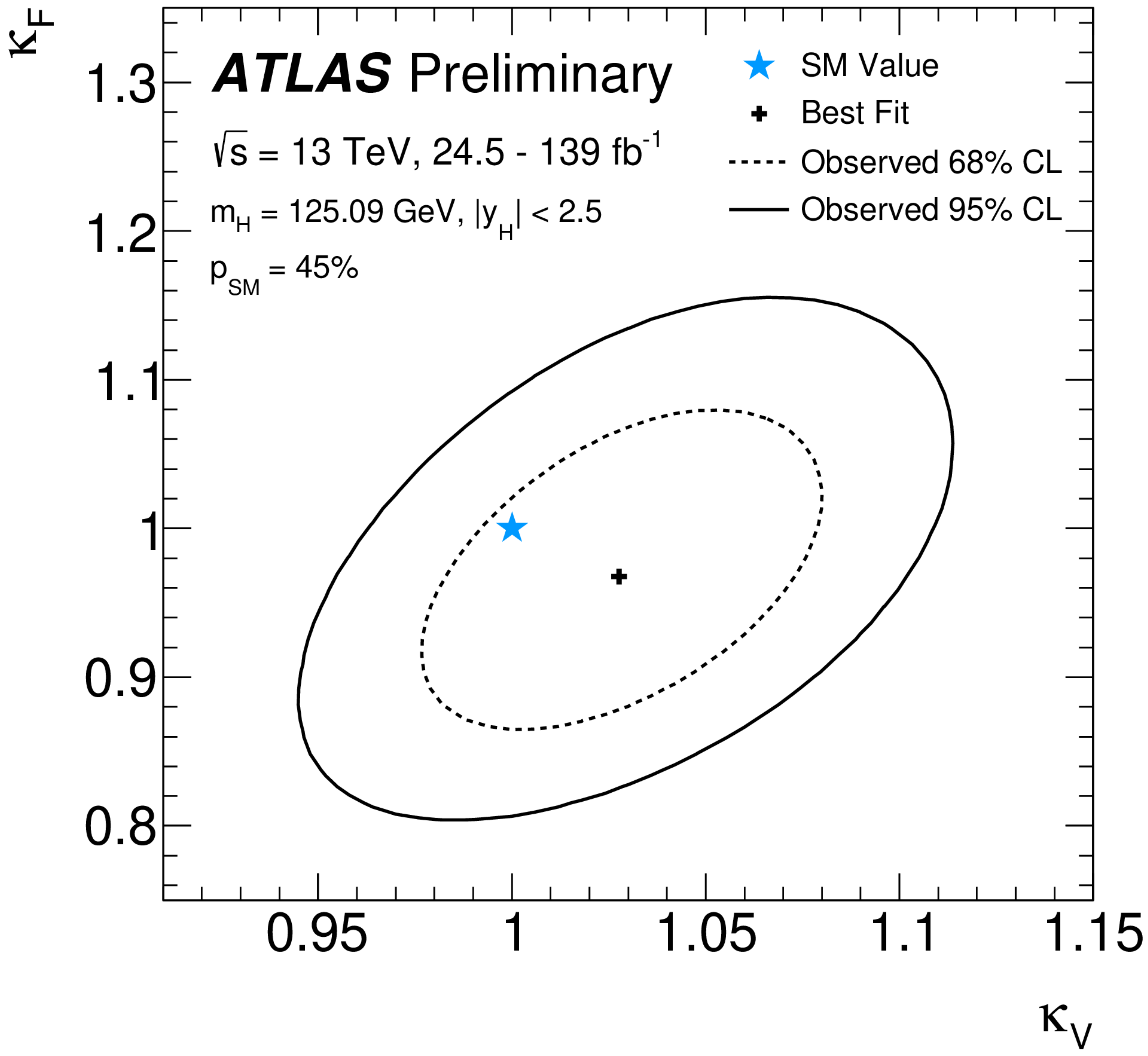


Fermion and gauge boson couplings: κ_V and κ_F

- Study the universal coupling-strength of:
  - Gauge bosons $\kappa_V = \kappa_W = \kappa_Z$
  - Fermions $\kappa_F = \kappa_t = \kappa_b = \kappa_\mu = \kappa_\tau$
- Assume no invisible or undetected decays and that $\kappa_V, \kappa_F > 0$

- Best-fit values:

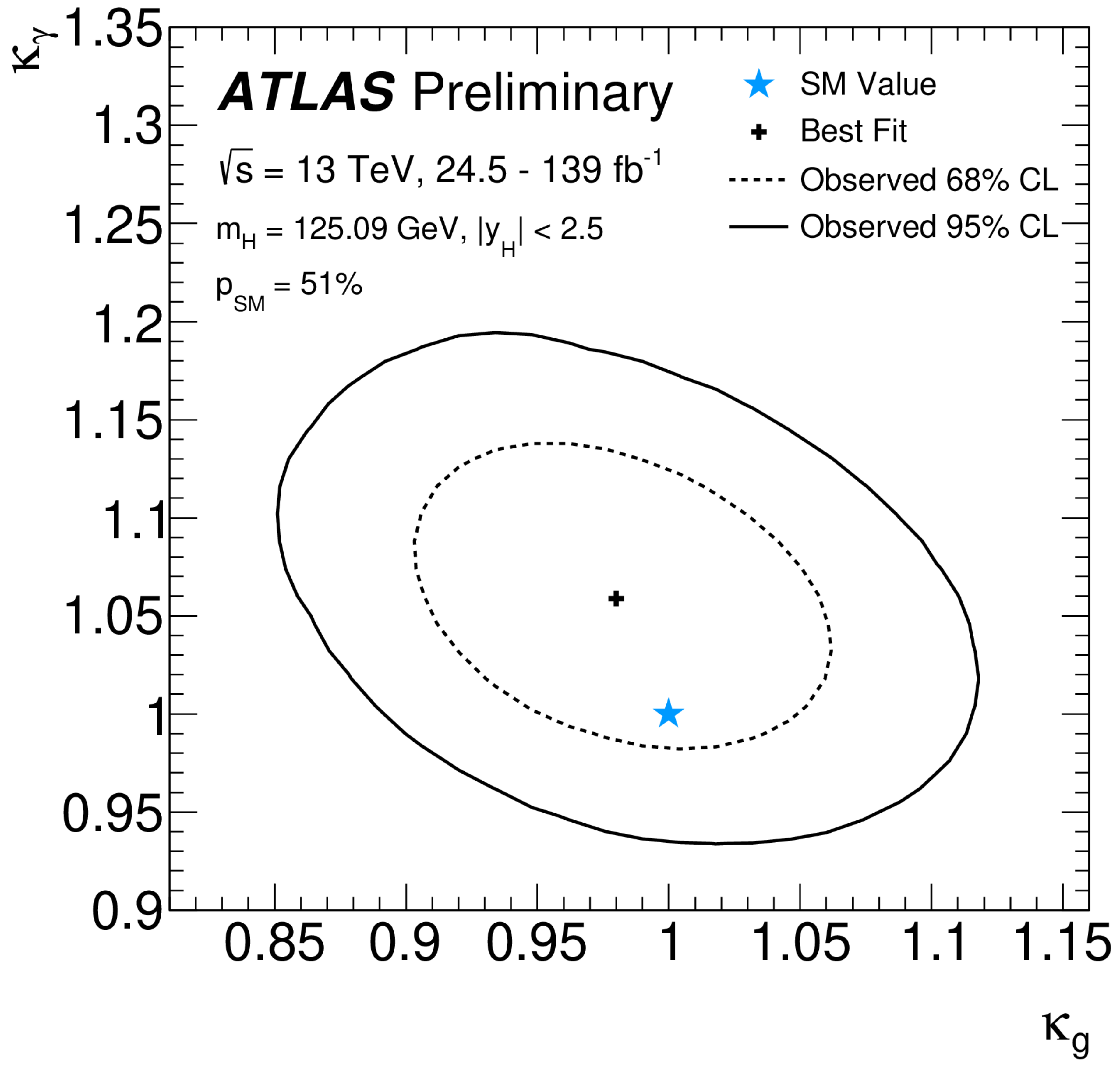
$$\kappa_V = 1.03 \pm 0.03$$
$$\kappa_F = 0.97 \pm 0.07$$



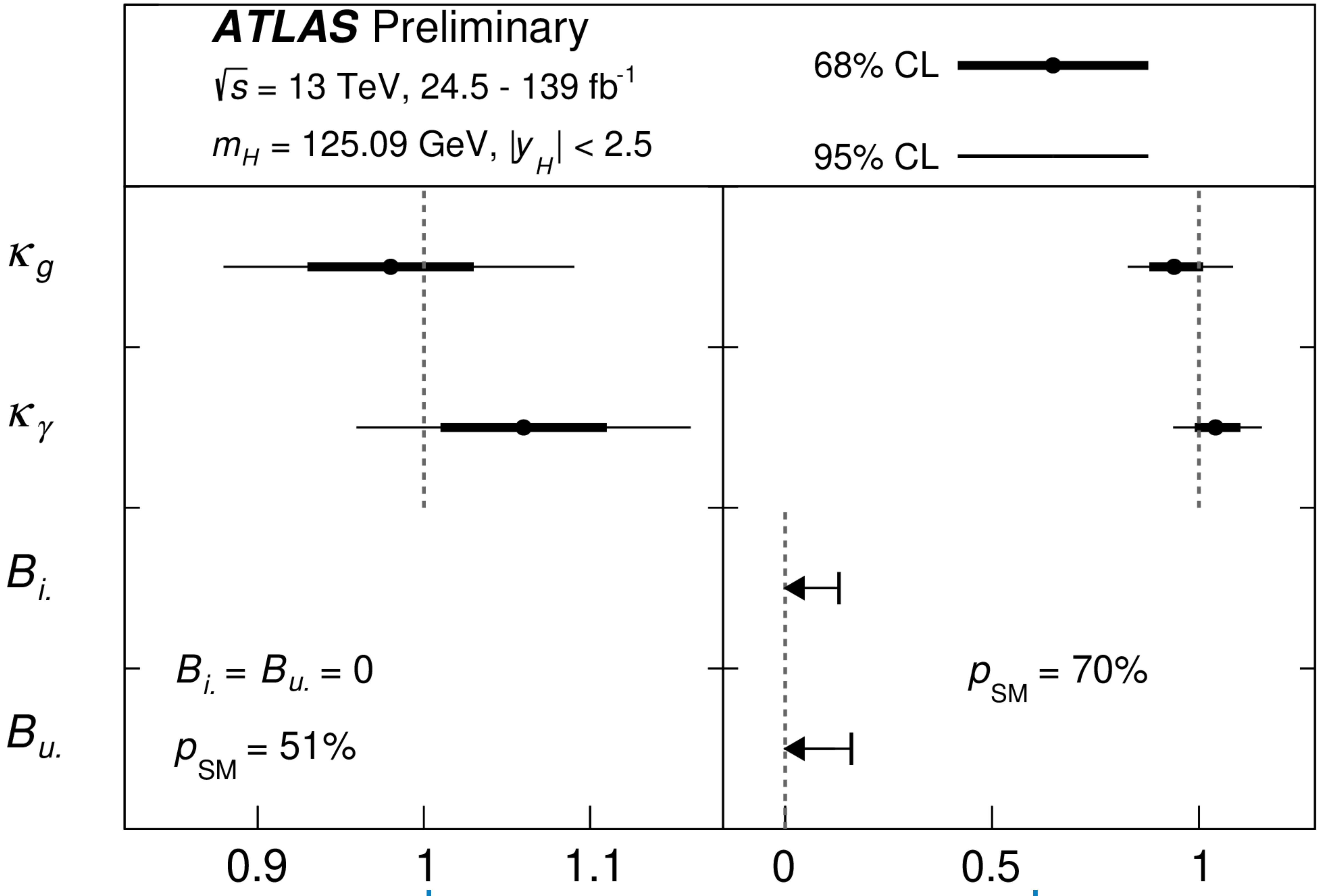
Probe BSM contributions in loops and decays: κ_g and κ_γ

- Effective couplings κ_g and κ_γ are sensitive to new physics in loops
- Investigate two assumptions ($B_{i.}$, $B_{u.}$ are fixed or floated)

Assuming no BSM ($B_{u.}$, $B_{i.}$ = 0)



$B_{u.}$, $B_{i.}$ Fixed and Floated



$\kappa_\gamma = 1.06 \pm 0.05$

$\kappa_g = 0.98 \pm 0.05.$

$\kappa_\gamma = 1.04^{+0.06}_{-0.05}$

$\kappa_g = 0.94^{+0.07}_{-0.06}$

$B_{\text{inv}} < 0.13$ at 95% CL (< 0.13 expected)

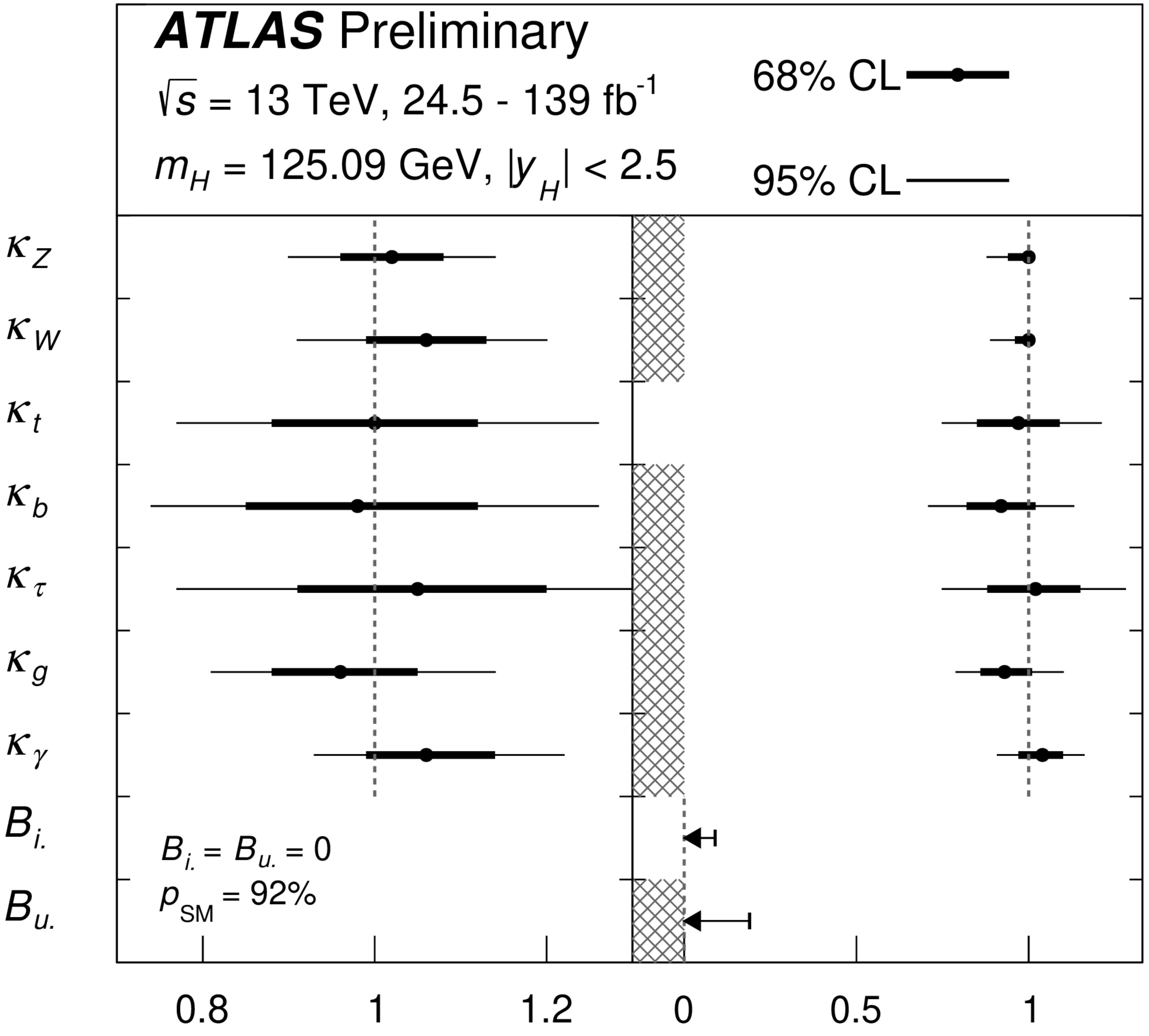
$B_{\text{undet}} < 0.16$ at 95% CL (< 0.23 expected)

Generic parametrization

- Effective coupling-strength modifiers, κ_g and κ_γ, for loop processes

- Two scenarios considered — $B_{i.}$, $B_{u.}$ fixed and floated
  - Assume $|\kappa_V| < 1$ to constrain undetected BR

- Negative κ_t excluded at a p-value of 0.0037 (or 2.7σ) assuming no BSM contributions to total width



κ-framework Limitations

- Inherently leading order
- Missing sensitivity to differential information

Motivates use of frameworks such as EFT or models such as 2HDM, MSSM (backup slides) among others

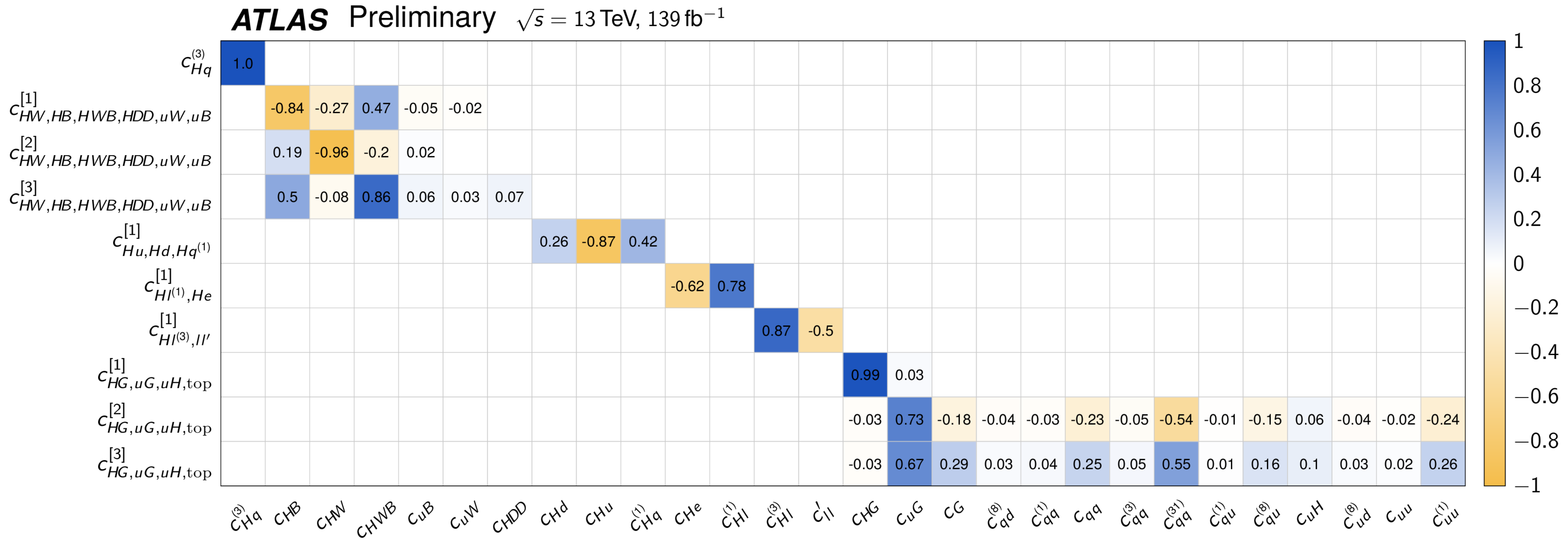
Interpretations: SM Effective Field Theory

- Model independent way to parametrize effects of BSM theories
- Parametrized as higher dimensional operators that respect SM symmetry → cross-sections measurements used to constrain Wilson coefficient (c_i) at fixed scale (Λ = 1 TeV)

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

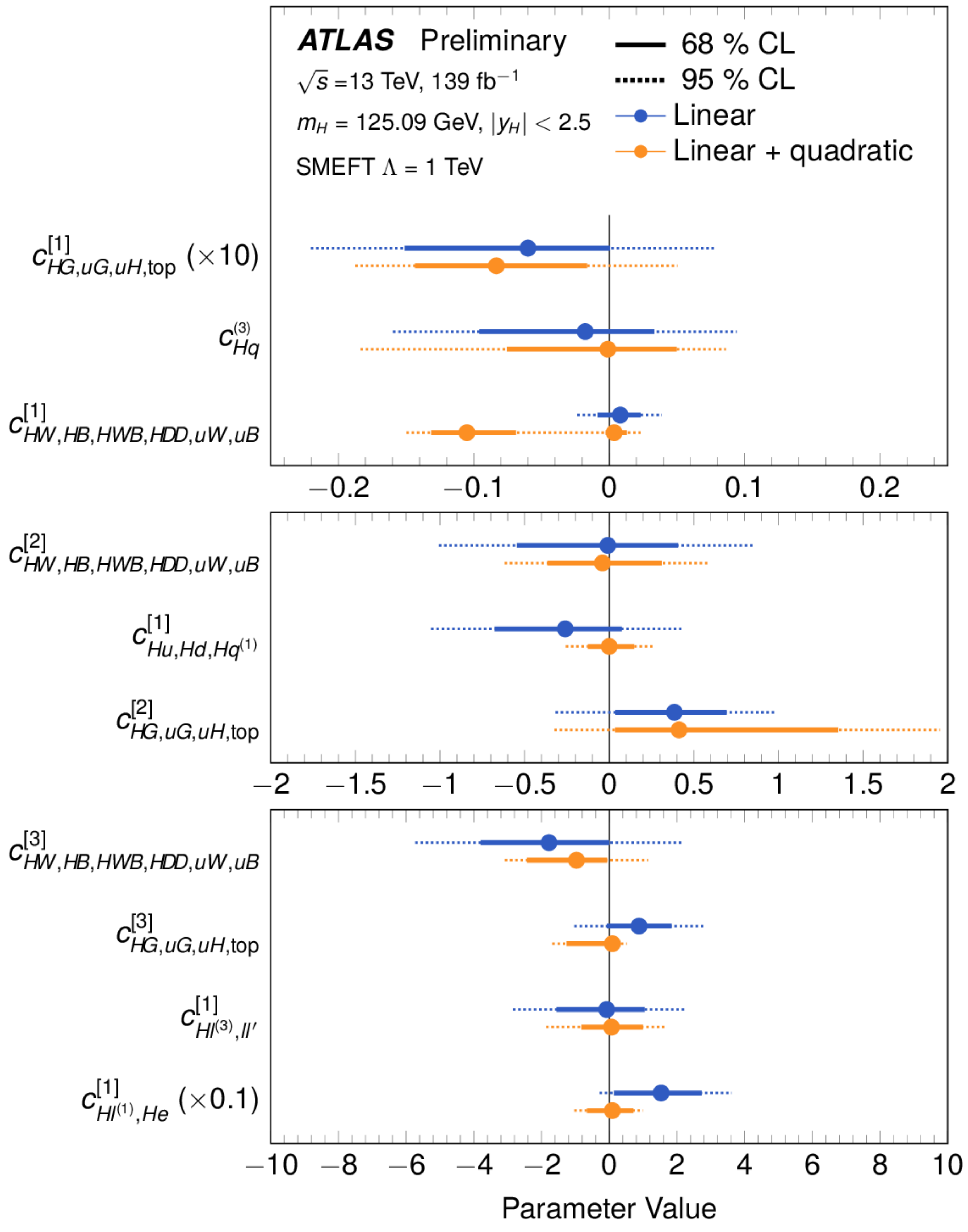
- Consider d = 6 operators using the Warsaw basis

- Interpretations using full STXS scheme
- Probe as many c_i as possible
- Eigenvector decomposition to determine combinations of SMEFT operators analysis is sensitive to



SM Effective Field Theory

- Matrix element squared from d=6 operators have linear (c_j/Λ^{-2}) and quadratic ($c_j c_k/\Lambda^{-4}$) terms
- Parametrize (σ x B) using linear or linear+quadratic terms
  - For quadratic terms, interference with d = 8 operators not considered
- Including quadratic terms shows non-negligible influence
- All results compatible with the SM
- For more details on combination: ATLAS-CONF-2020-053

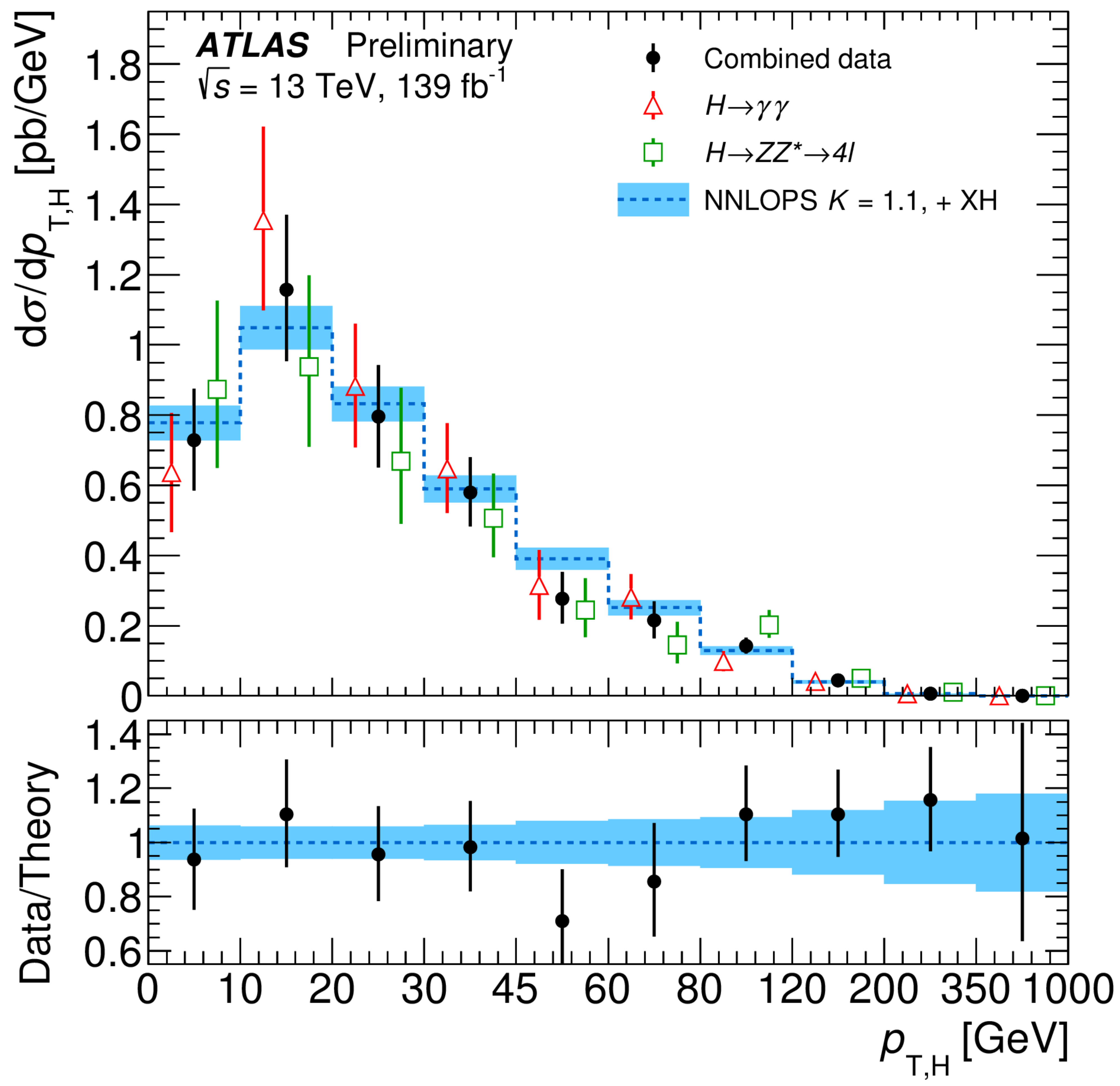


Differential combination: $p_{T,H}$

- Measuring differential XS probes the SM and is largely model independent
  - Deviations in $p_{T,H}$ distribution can indicate BSM physics such as:
    - Modified light quark coupling at low $p_{T,H}$
    - New BSM particles in ggF loop at high $p_{T,H}$
- Input results:

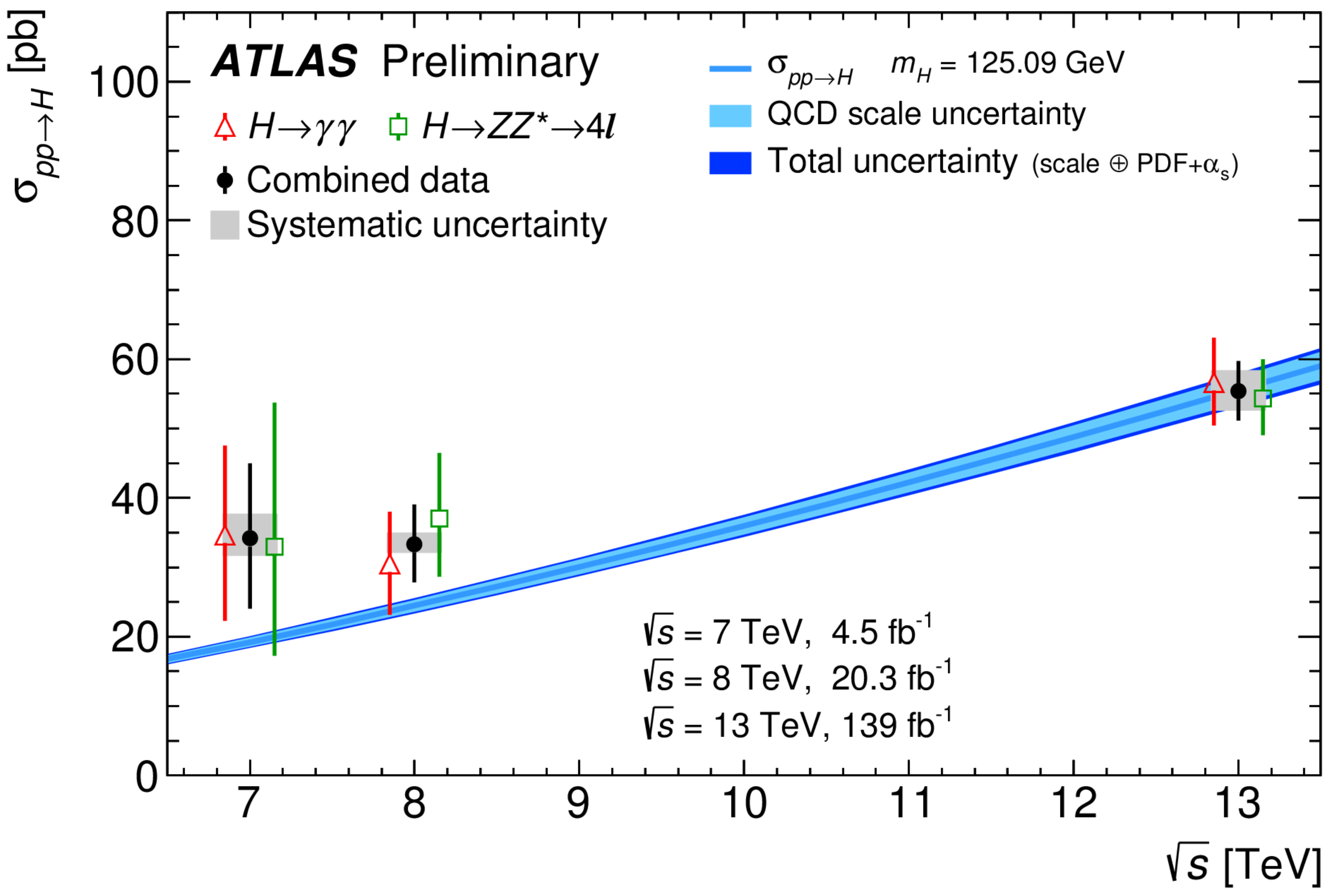
Analysis Decay Channel	Prod. Modes	$\mathcal{L}$ [fb^{-1}]	Link
$H \to \gamma\gamma$	All	139	ATLAS-CONF-2019-029
$H \to ZZ^*$	All	139	arXiv:1504.05833

- P-value of 78%, compatible with SM
- More results to be added, detailed interpretations on combined to be performed
  - Other observables to be included in combination



Summary

From ATLAS-CONF-2019-032



Couplings

- Extended to include full Run-2 results for several channels!
- Signal strength, production modes and branching ratios combined measurements made with latest available results from analyses
- Extended phase space measured in STXS!
- Interpretations of XS and BRs show consistency with SM

Differential

- $p_{T,H}$ combination for $H\to ZZ^*\to 4\ell$ and $H\to\gamma\gamma$ show good agreement with SM

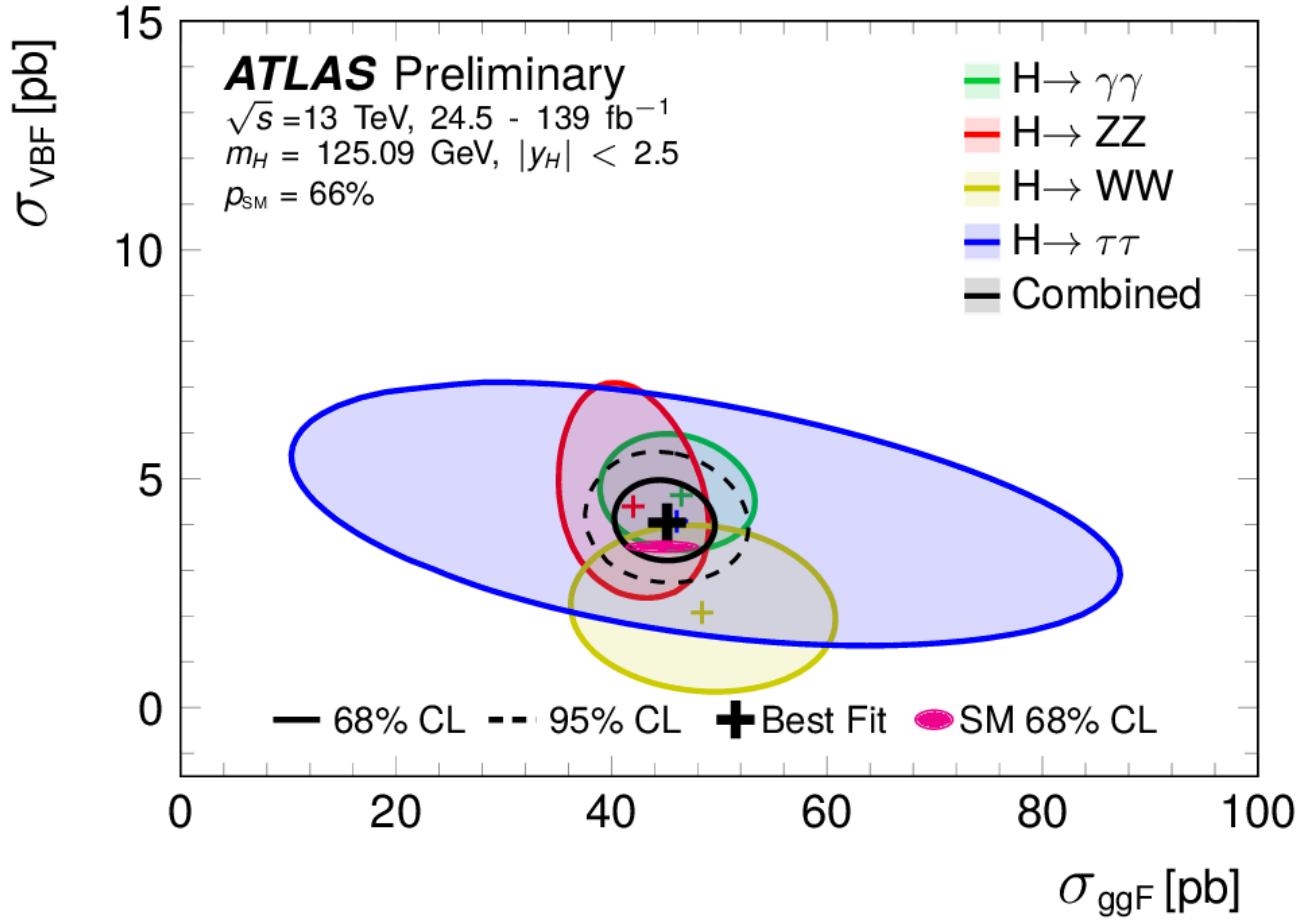
Outlook

- More full Run-2 results to be added to combinations soon!
    - Most recent H→WW (ATLAS-CONF-2021-014)
    - Increased precision in several regions of phase space with addition of analyses
- Combination work on other observables to come soon too!

Backup

Production mode measurements: Additional information

- Observed likelihood contours for VBF and ggF XS

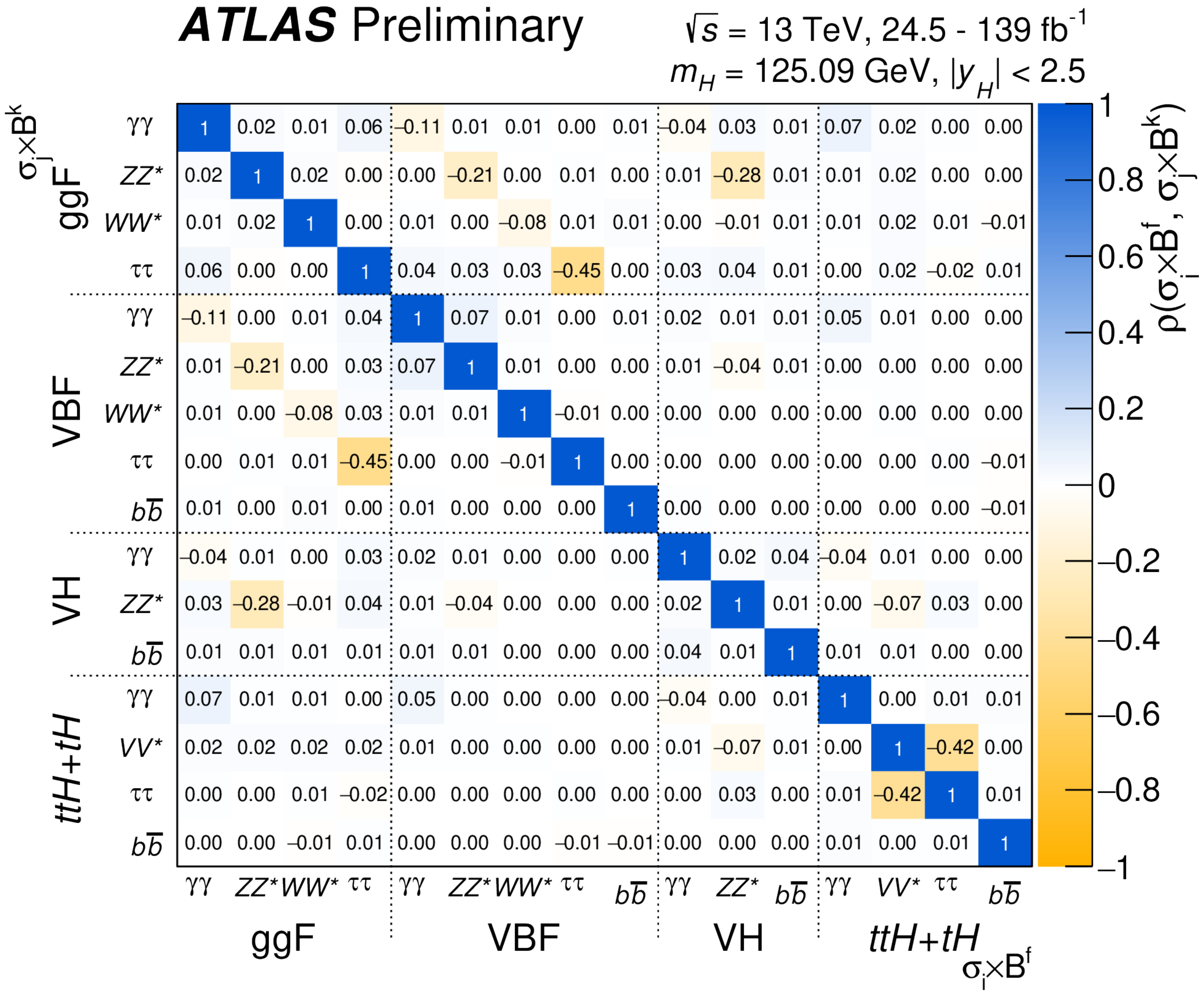


- Decomposition of uncertainty into components
- Systematic uncertainty approaching/same as statistical uncertainty

Process	Value	Uncertainty [pb]						SM pred.
($\|y_H\|$ < 2.5)	[pb]	Total	Stat.	Syst.	Exp.	Sig. Th.	Bkg. Th.	[pb]
ggF	44.7	± 3.1	± 2.2	± 2.2	$^{+1.8}_{-1.7}$	$^{+1.0}_{-0.9}$	$^{+0.9}_{-0.7}$	44.7 ± 2.2
VBF	4.0	± 0.6	± 0.5	± 0.4	$^{+0.3}_{-0.2}$	± 0.3	± 0.1	$3.51\ ^{+0.08}_{-0.07}$
WH	1.45	$^{+0.28}_{-0.25}$	$^{+0.20}_{-0.19}$	$^{+0.18}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.08}_{-0.06}$	$^{+0.10}_{-0.09}$	1.204 ± 0.024
ZH	0.78	$^{+0.18}_{-0.17}$	± 0.13	$^{+0.12}_{-0.10}$	$^{+0.08}_{-0.07}$	$^{+0.07}_{-0.05}$	± 0.06	$0.797\ ^{+0.033}_{-0.026}$
$t\bar{t}H + tH$	0.64	± 0.12	± 0.09	± 0.08	$^{+0.06}_{-0.05}$	$^{+0.03}_{-0.02}$	± 0.05	$0.59\ ^{+0.03}_{-0.05}$

Production mode and branching ratios correlation matrix

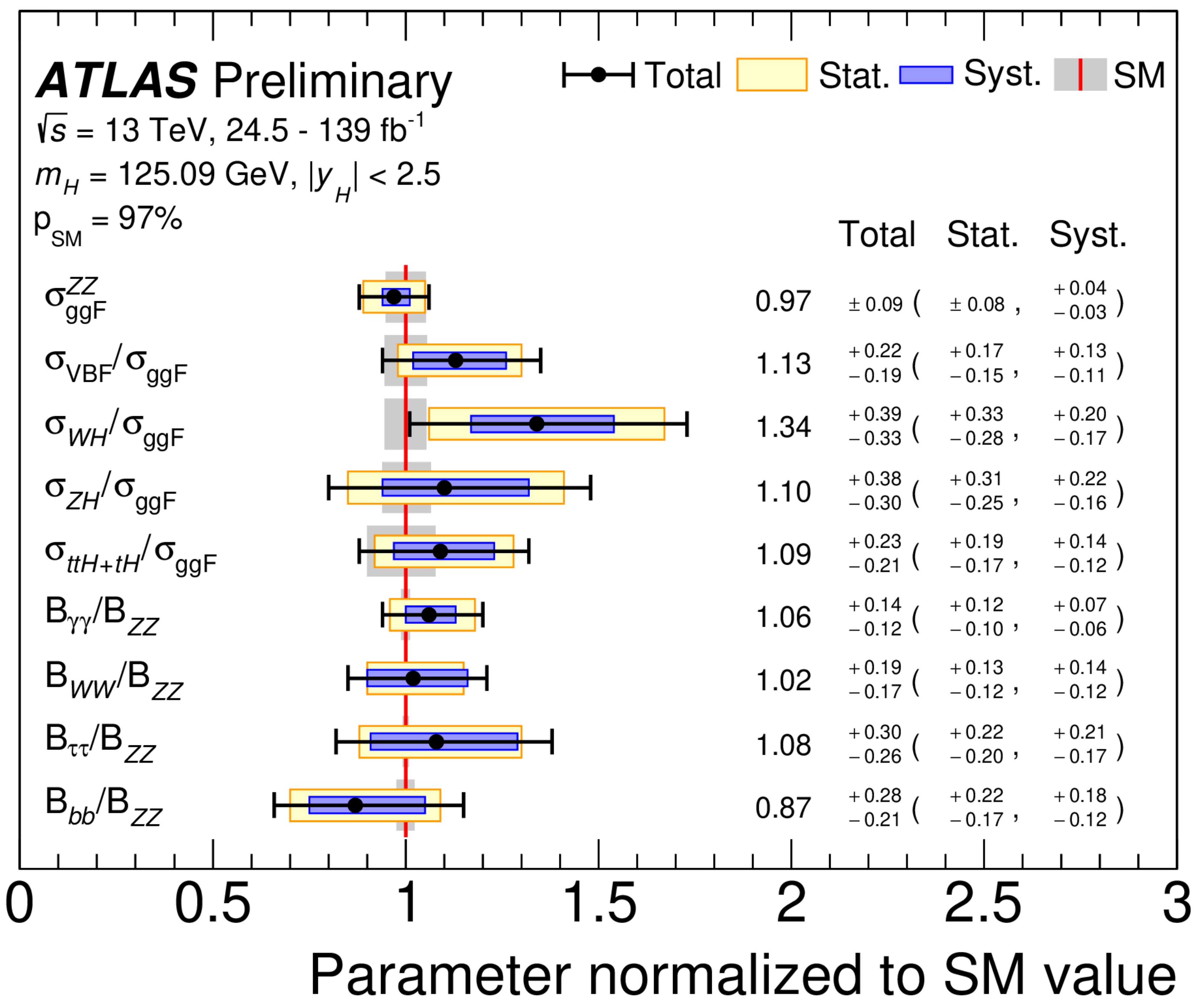
- Can also test the SM by measuring $(\sigma \times B)_{if}$
- Statistically limited channels are fixed to the SM
  - ggF→H→bb
  - VH, H →WW/ττ
- Relative fraction of ZH and WH fixed to the SM
- Good agreement with the SM (p-value of 87%)

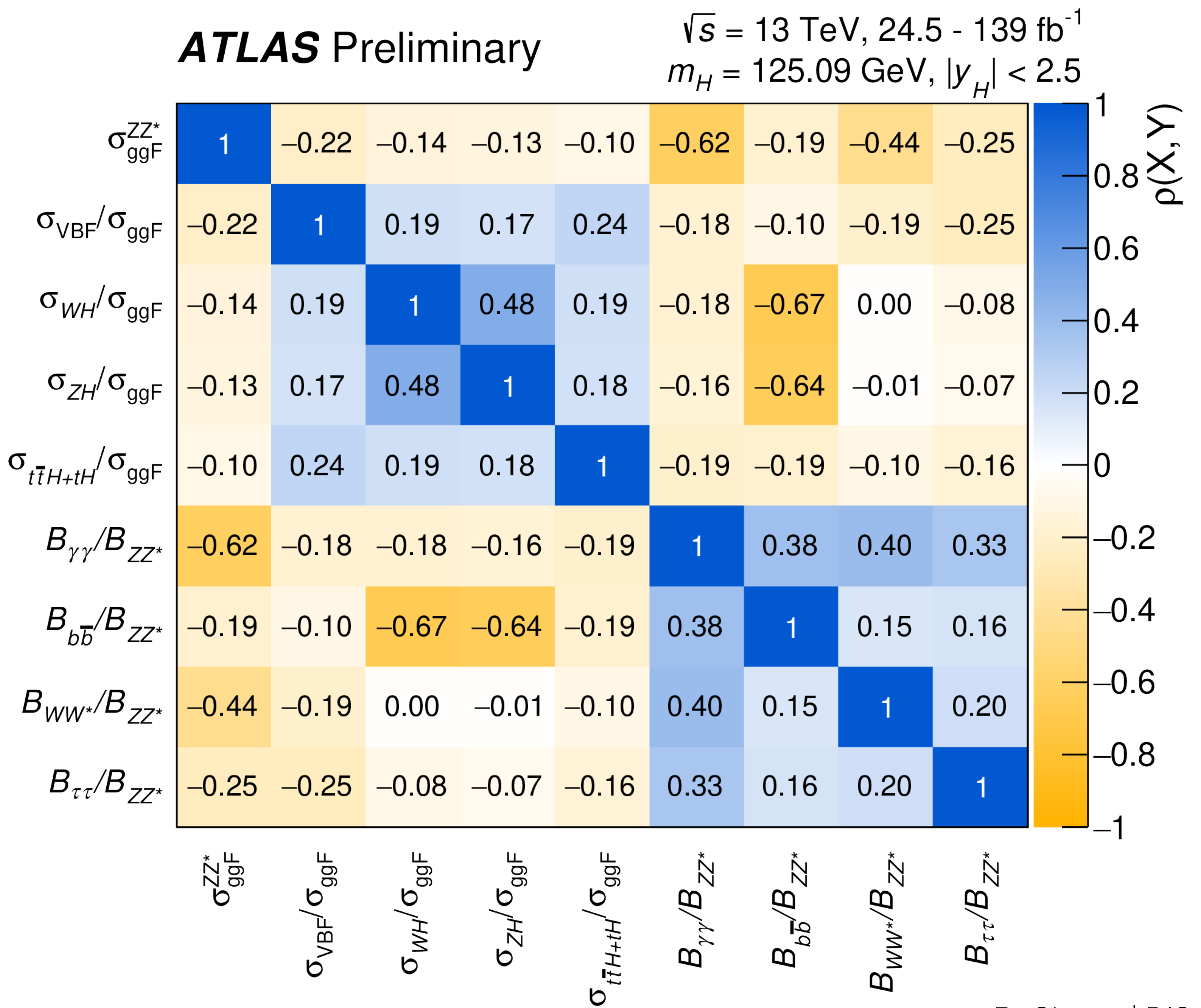


Production mode and branching ratios: ratio model

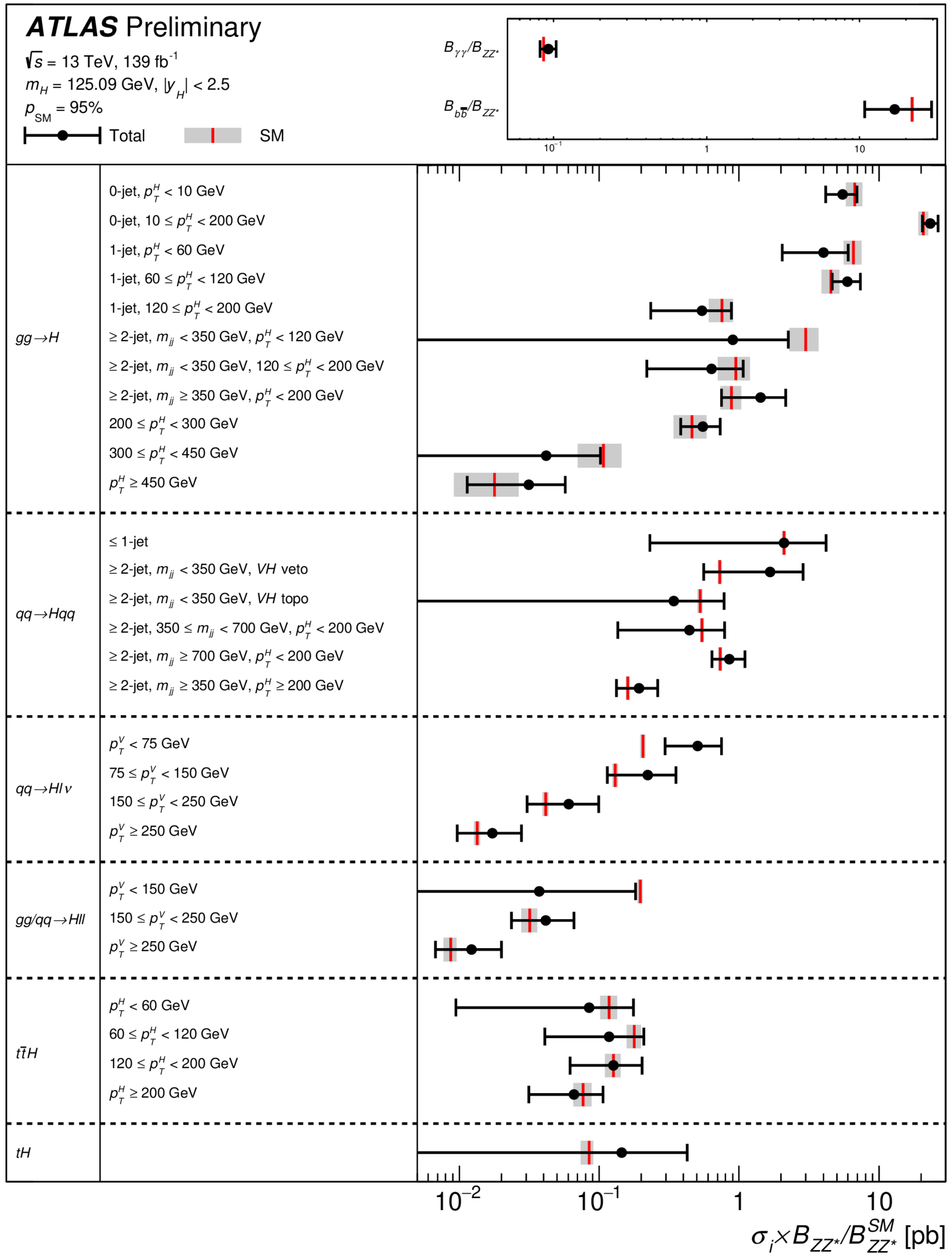
- Can also measure $(\sigma \times B)_{if}$ with respect to a reference process
- $gg \rightarrow H \rightarrow 4\ell$ chosen due to its small experimental uncertainties
  - Systematics cancel in the ratio!

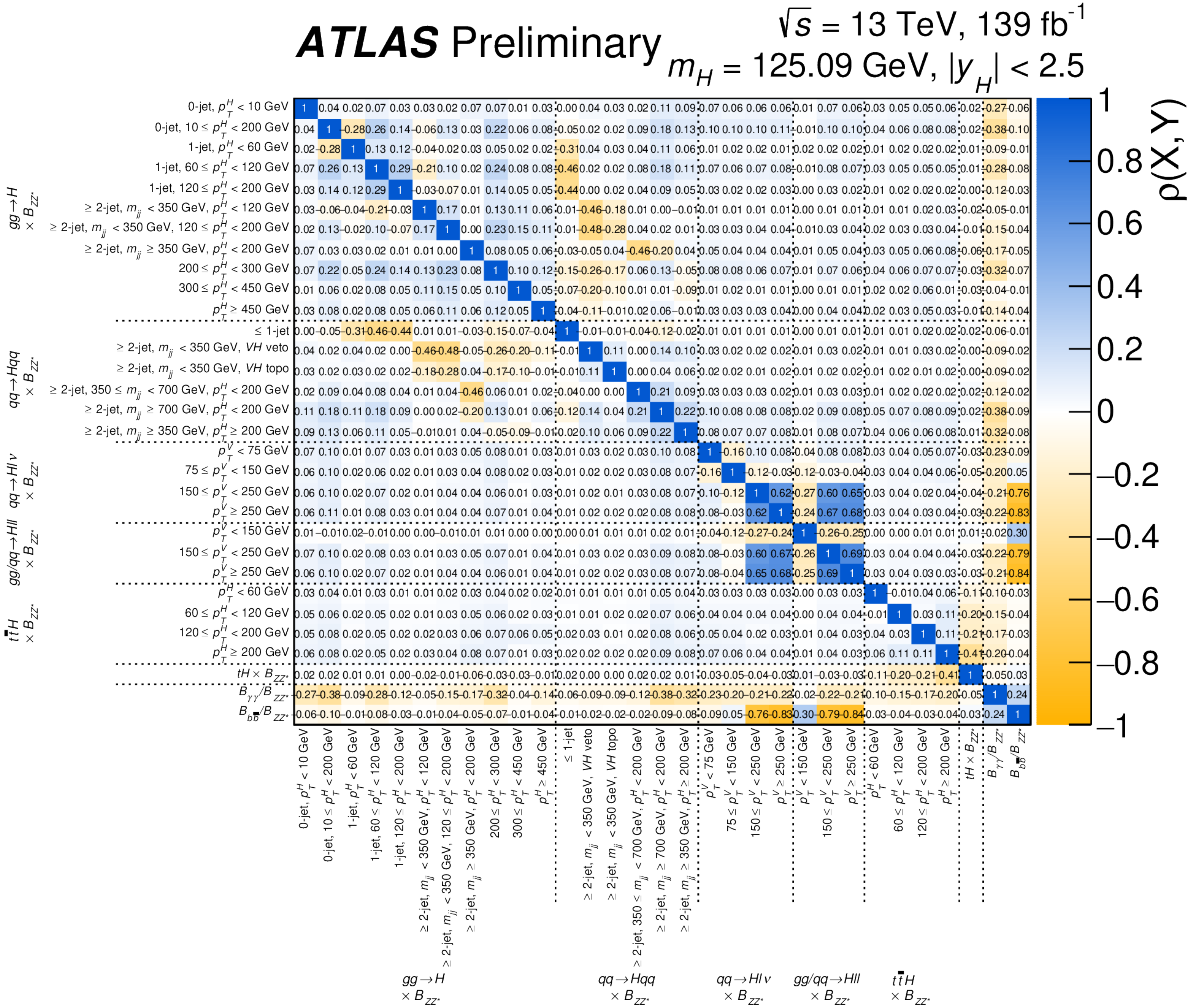
$$(\sigma \times B)_{if} = \sigma^{ZZ}_{\mathrm{ggF}} \cdot \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \cdot \left(\frac{B_f}{B_{ZZ}}\right)$$





Additional results: STXS

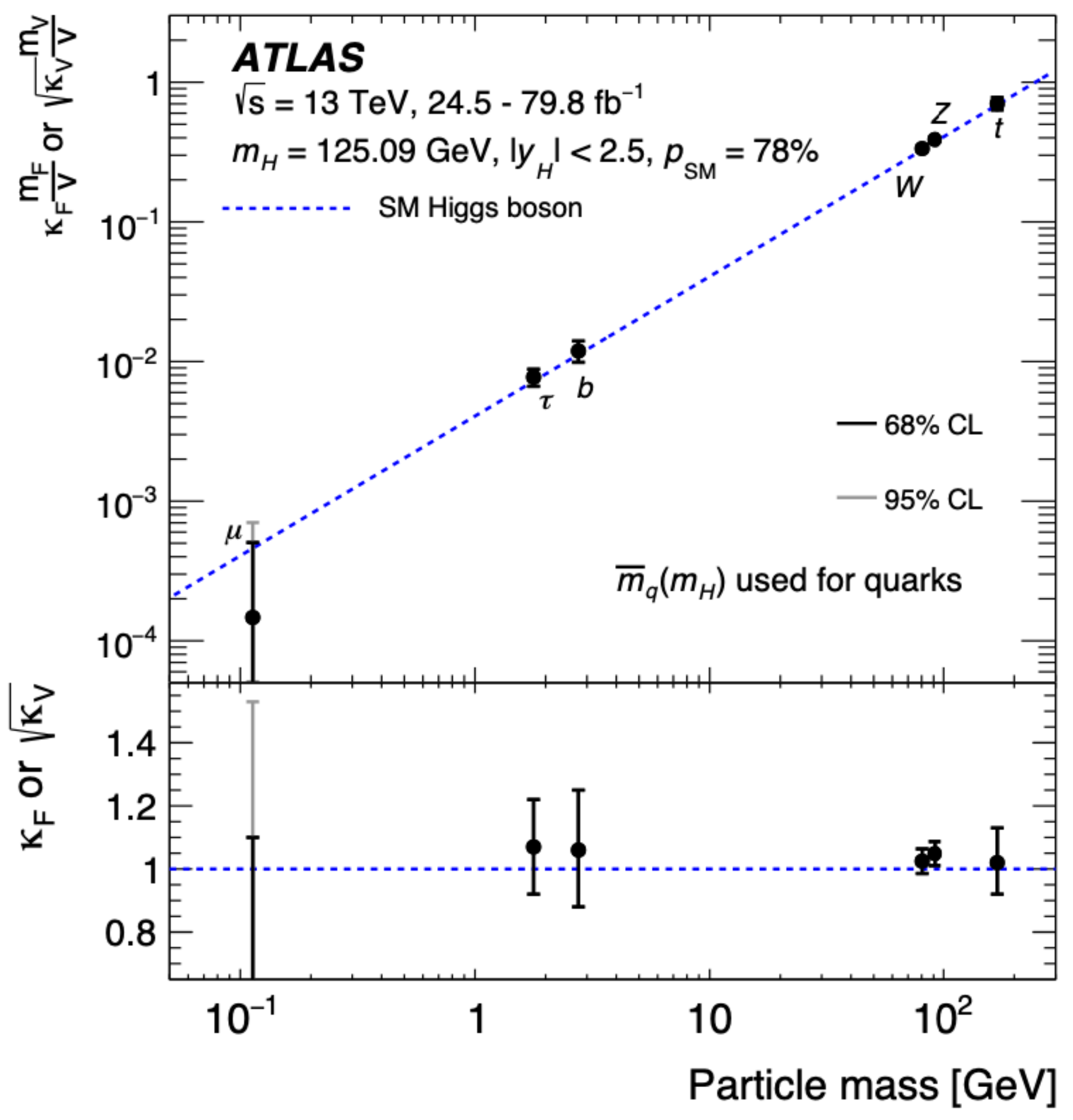




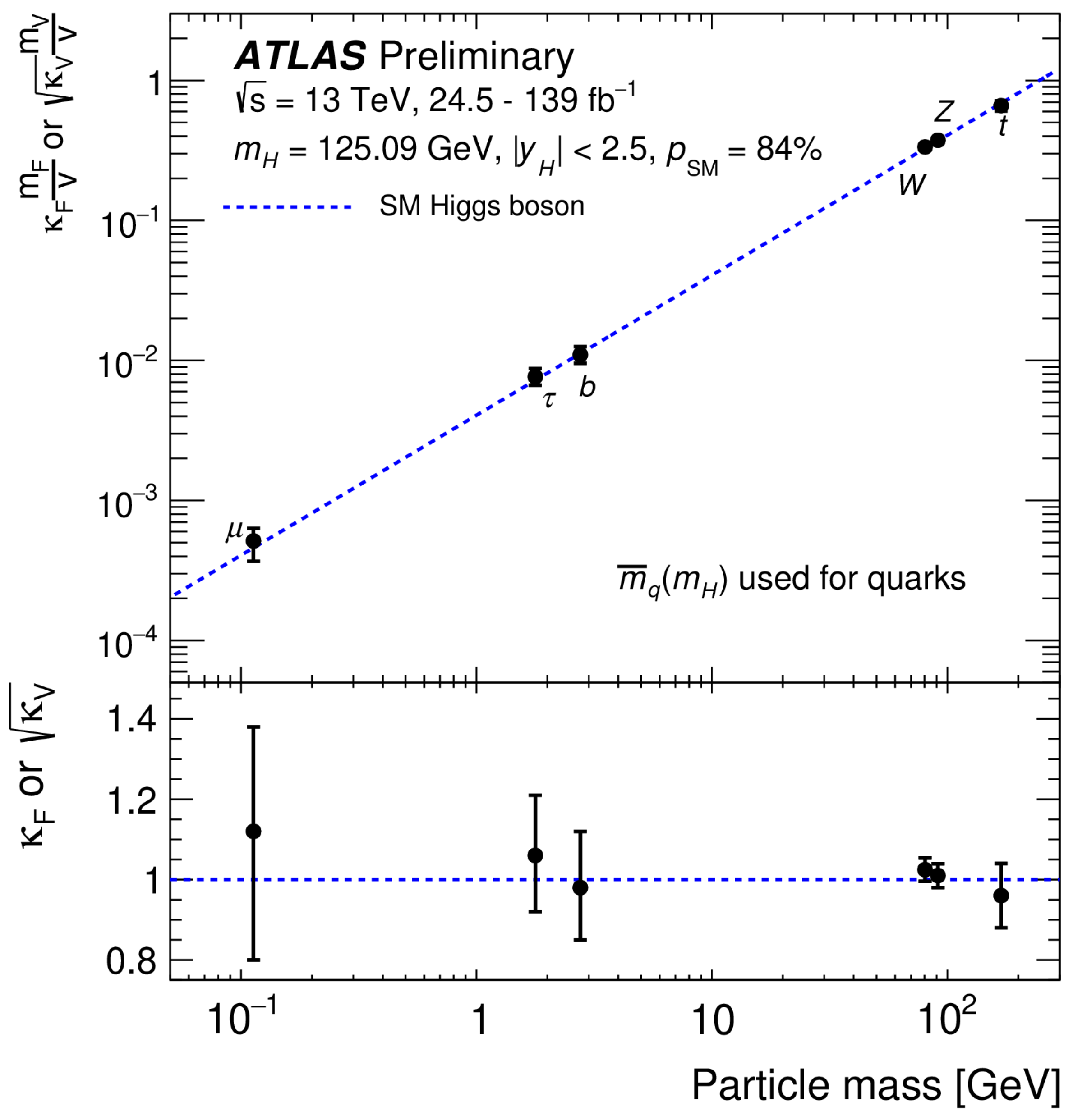
Generic parametrization

- Excluding BSM couplings, fit for κ for W, Z, t, b, τ and μ

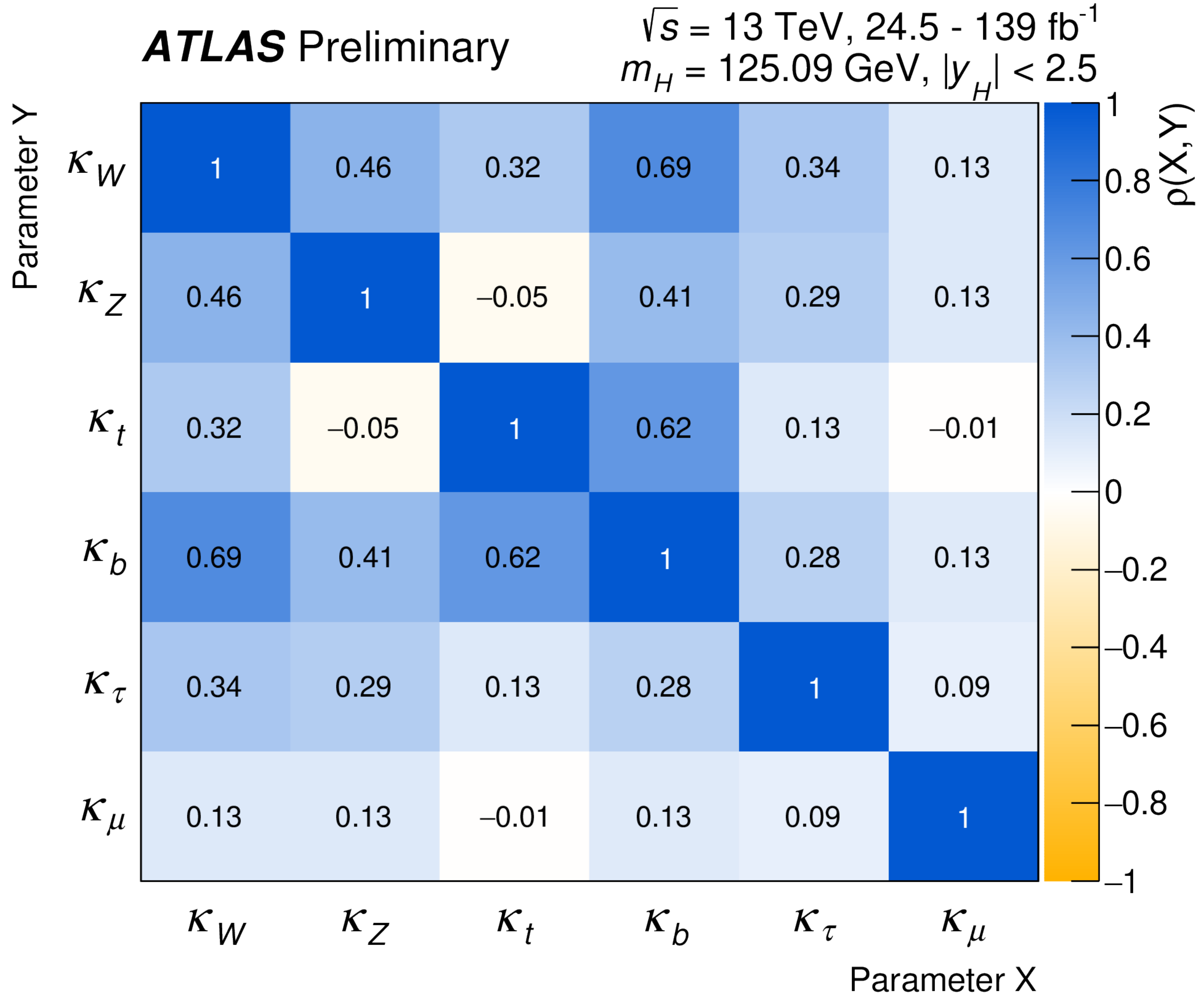
Publication for 2015-2017 data
arXiv:1909.02845



Current
ATLAS-CONF-2020-027

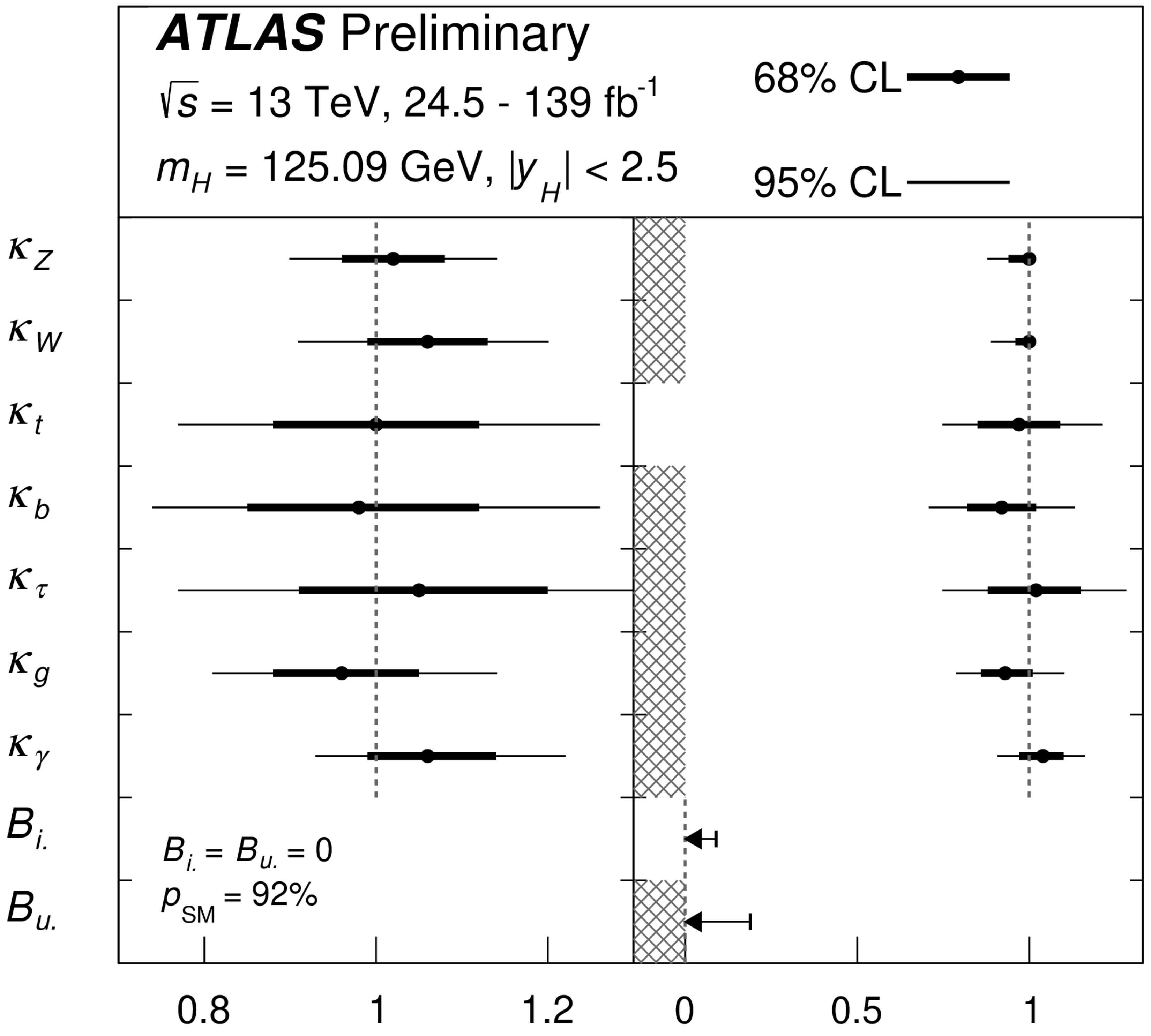


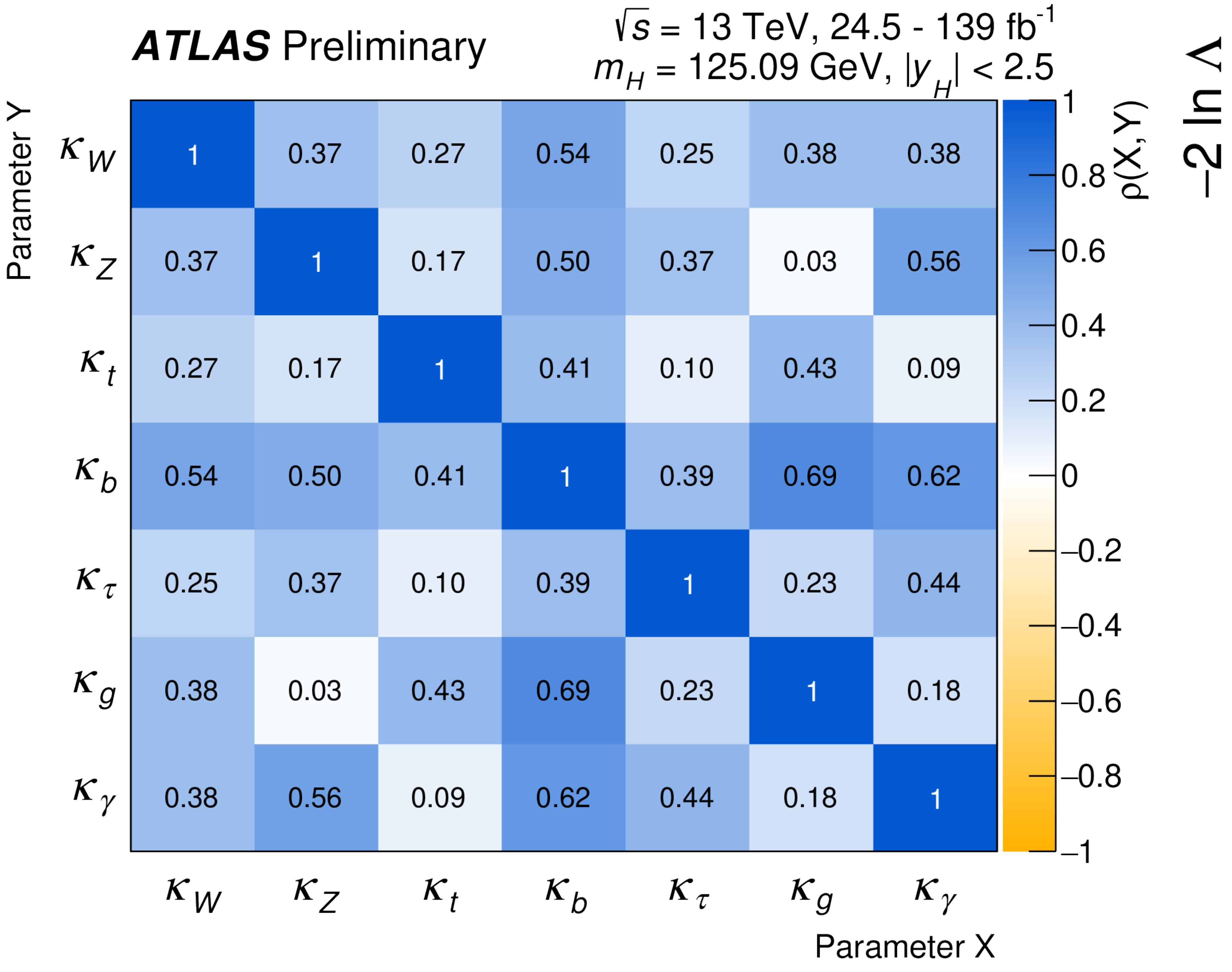
Parameter	Result
κ_Z	1.02 ± 0.06
κ_W	1.05 ± 0.06
κ_b	$0.98^{+0.14}_{-0.13}$
κ_t	0.96 ± 0.08
κ_τ	$1.06^{+0.15}_{-0.14}$
κ_μ	$1.12^{+0.26}_{-0.32}$

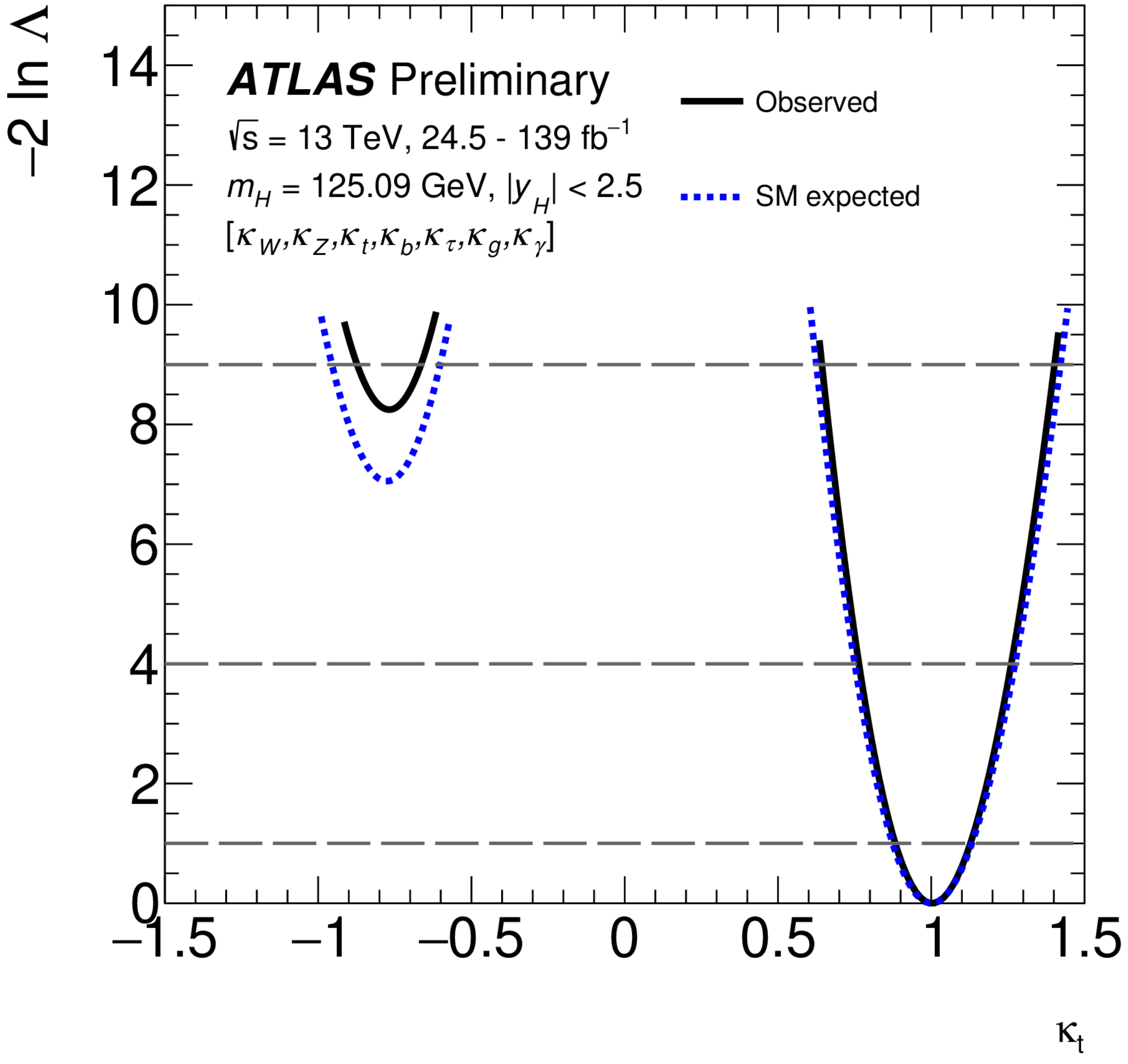


Generic parametrization: float effective couplings

- Effective coupling-strength modifiers, κ_g and κ_γ, for loop processes
- Negative κ_t excluded at 2.9σ (2.7σ expected) assuming no BSM contributions to total width





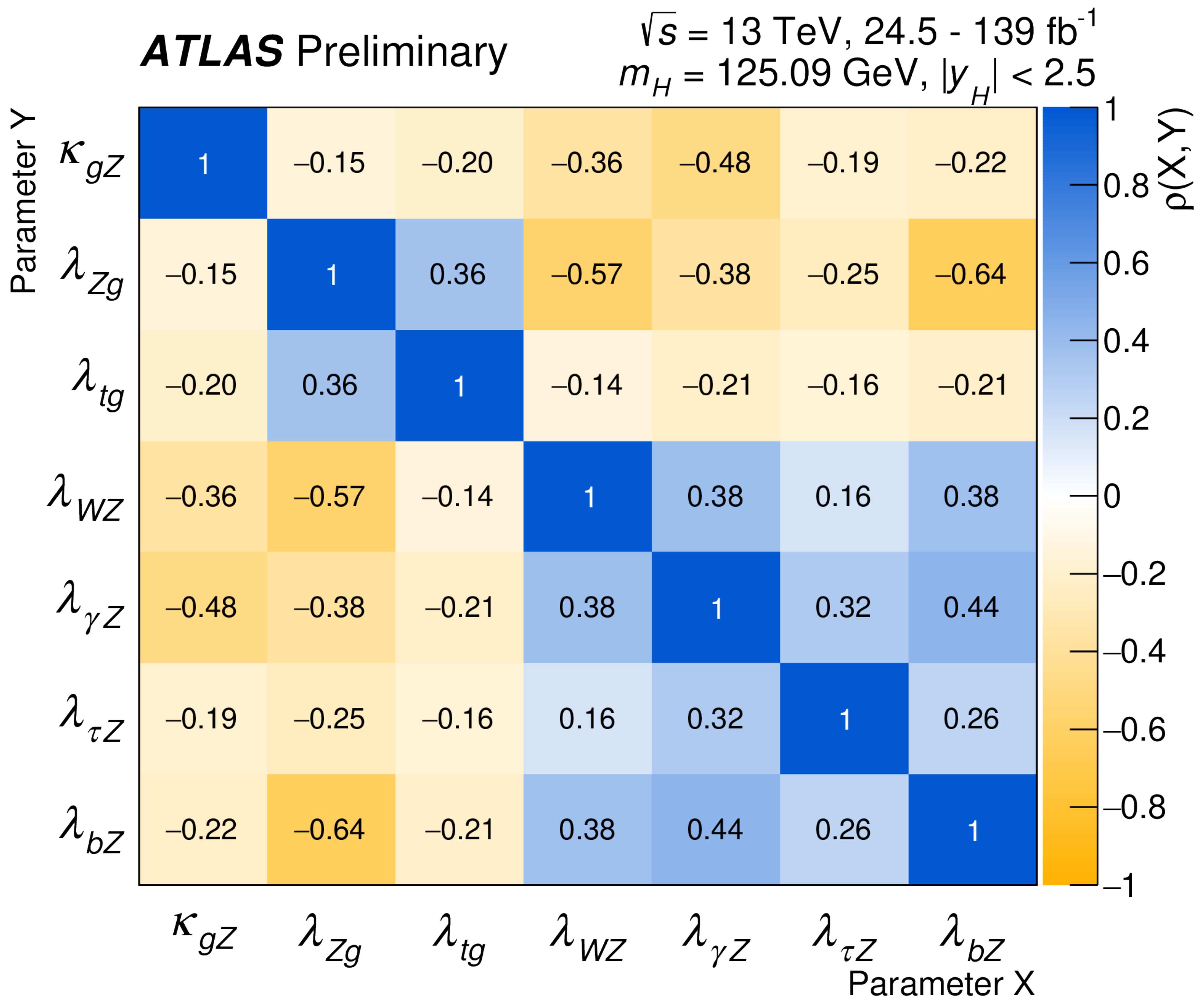


Generic parametrization using ratios

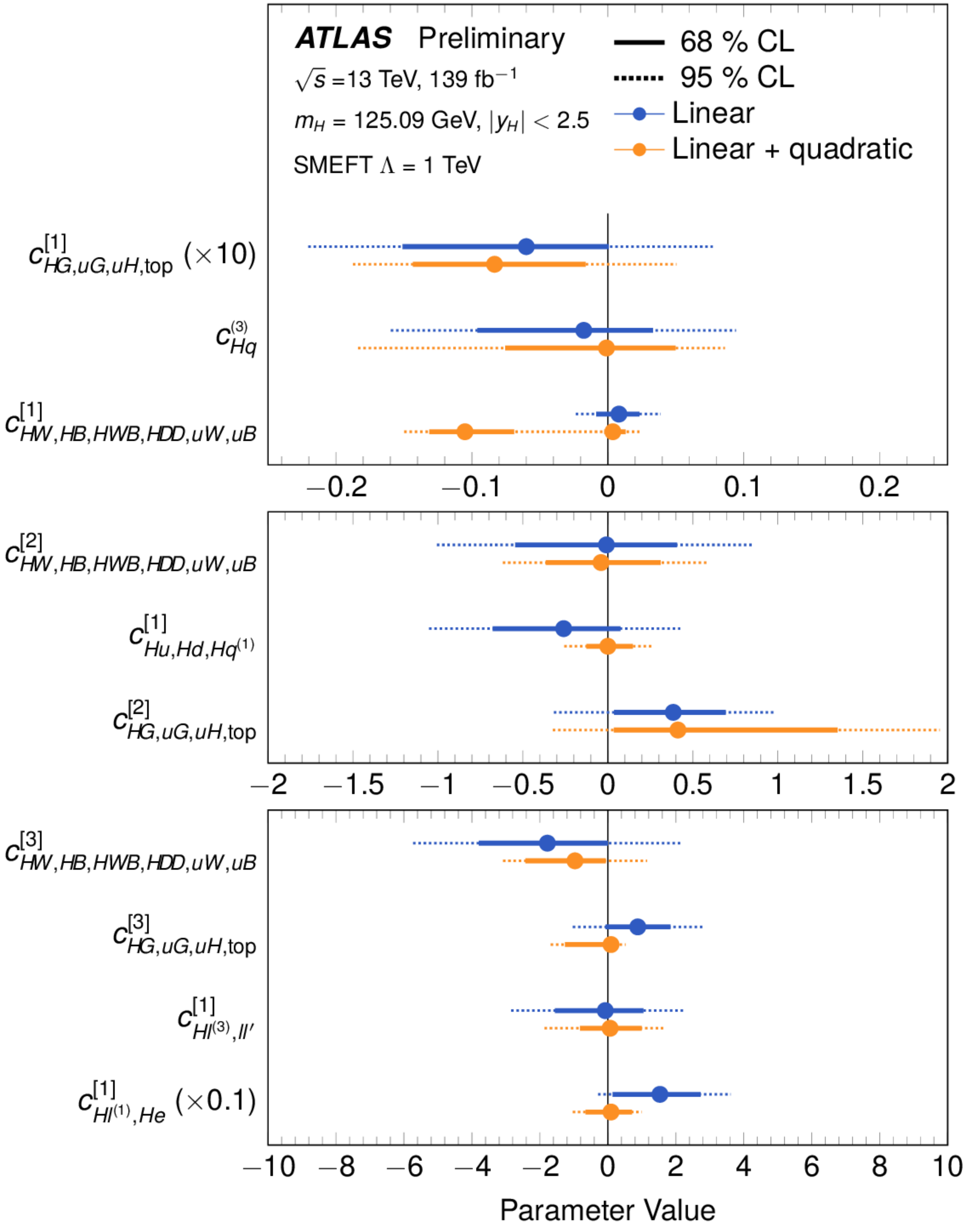
- Express coupling-strength ($\kappa_t,\kappa_b,\kappa_\tau,\kappa_W,\kappa_Z$) and effective loop ($\kappa_g,\kappa_\gamma$) scale factors as ratios to $gg \rightarrow H \rightarrow ZZ^*$
  - Ratios are independent of assumptions on total width

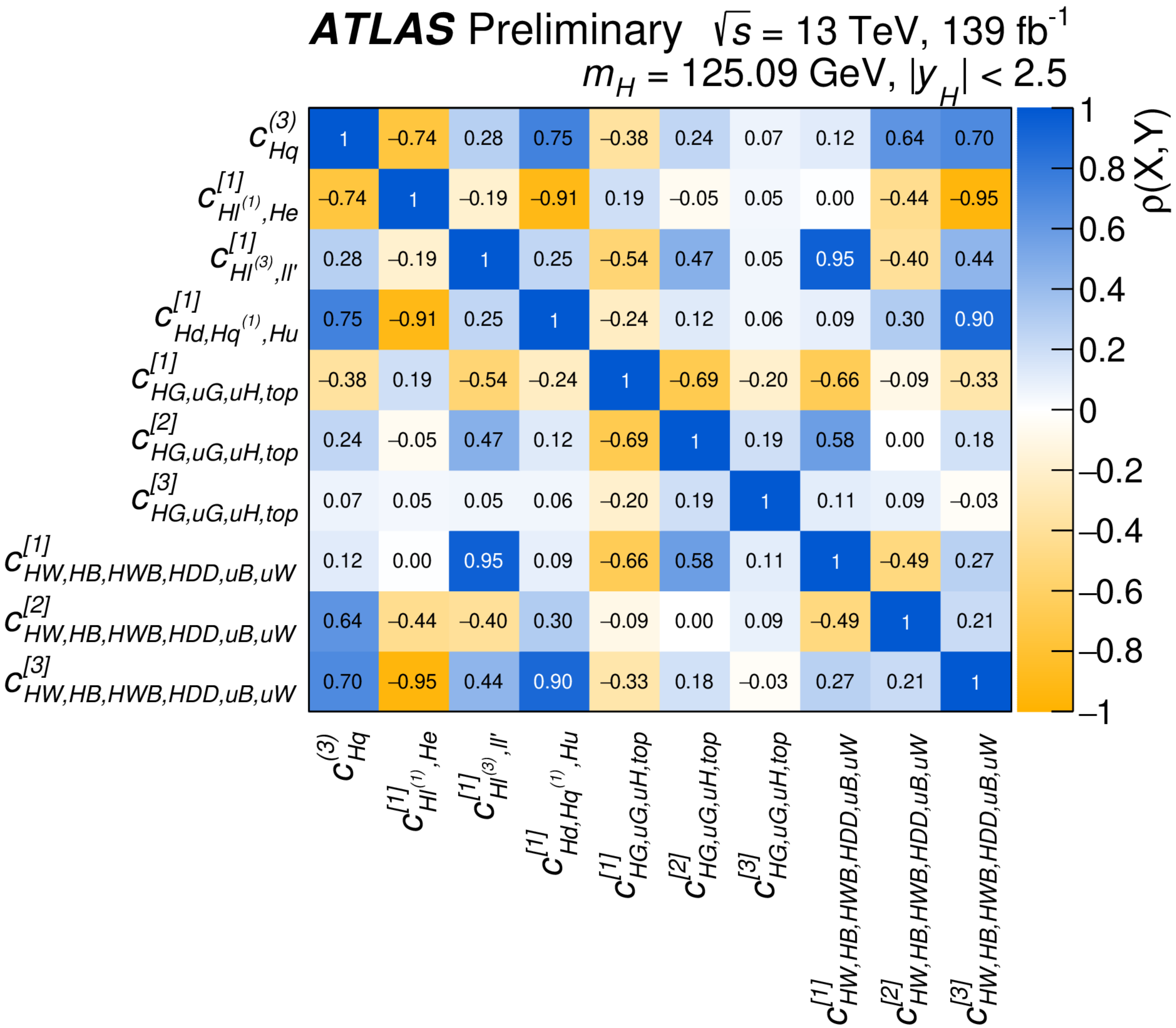
- λ_{WZ} should be 1
  - required by SU(2) custodial symmetry and
  - ρ measurements at LEP and Tevatron
- $\lambda_{\gamma Z}$ sensitive to charge particle contribution in loops
- λ_{tg} sensitive to new coloured particles in ggF loop

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	1.04 ± 0.12
λ_{Zg}	κ_Z/κ_g	$1.06\ ^{+\,0.12}_{-\,0.11}$
λ_{WZ}	κ_W/κ_Z	$1.04\ ^{+\,0.08}_{-\,0.07}$
$\lambda_{\gamma Z}$	κ_γ/κ_Z	$1.04\ ^{+\,0.07}_{-\,0.06}$
$\lambda_{\tau Z}$	κ_τ/κ_Z	1.04 ± 0.13
λ_{bZ}	κ_b/κ_Z	$0.96\ ^{+\,0.12}_{-\,0.11}$



SMEFT Correlation matrix



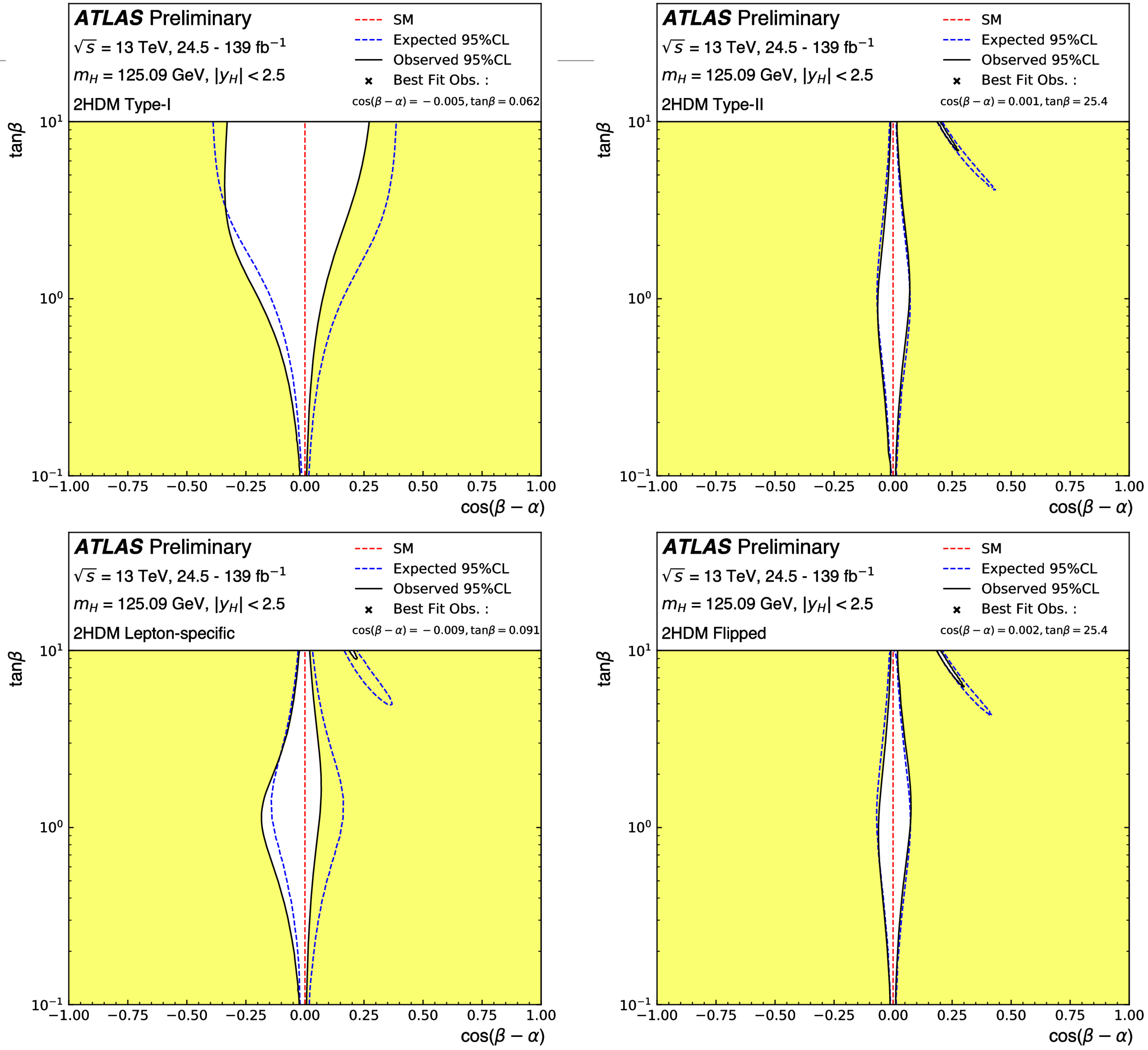


	$c^{(3)}_{Hq}$	$c^{[1]}_{Hl^{(1)},He}$	$c^{[1]}_{Hl^{(3)},ll'}$	$c^{[1]}_{Hd,Hq^{(1)},Hu}$	$c^{[1]}_{HG,uG,uH,top}$	$c^{[2]}_{HG,uG,uH,top}$	$c^{[3]}_{HG,uG,uH,top}$	$c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$	$c^{[2]}_{HW,HB,HWB,HDD,uB,uW}$	$c^{[3]}_{HW,HB,HWB,HDD,uB,uW}$
$c^{(3)}_{Hq}$	1	−0.74	0.28	0.75	−0.38	0.24	0.07	0.12	0.64	0.70
$c^{[1]}_{Hl^{(1)},He}$	−0.74	1	−0.19	−0.91	0.19	−0.05	0.05	0.00	−0.44	−0.95
$c^{[1]}_{Hl^{(3)},ll'}$	0.28	−0.19	1	0.25	−0.54	0.47	0.05	0.95	−0.40	0.44
$c^{[1]}_{Hd,Hq^{(1)},Hu}$	0.75	−0.91	0.25	1	−0.24	0.12	0.06	0.09	0.30	0.90
$c^{[1]}_{HG,uG,uH,top}$	−0.38	0.19	−0.54	−0.24	1	−0.69	−0.20	−0.66	−0.09	−0.33
$c^{[2]}_{HG,uG,uH,top}$	0.24	−0.05	0.47	0.12	−0.69	1	0.19	0.58	0.00	0.18
$c^{[3]}_{HG,uG,uH,top}$	0.07	0.05	0.05	0.06	−0.20	0.19	1	0.11	0.09	−0.03
$c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$	0.12	0.00	0.95	0.09	−0.66	0.58	0.11	1	−0.49	0.27
$c^{[2]}_{HW,HB,HWB,HDD,uB,uW}$	0.64	−0.44	−0.40	0.30	−0.09	0.00	0.09	−0.49	1	0.21
$c^{[3]}_{HW,HB,HWB,HDD,uB,uW}$	0.70	−0.95	0.44	0.90	−0.33	0.18	−0.03	0.27	0.21	1

2HDM

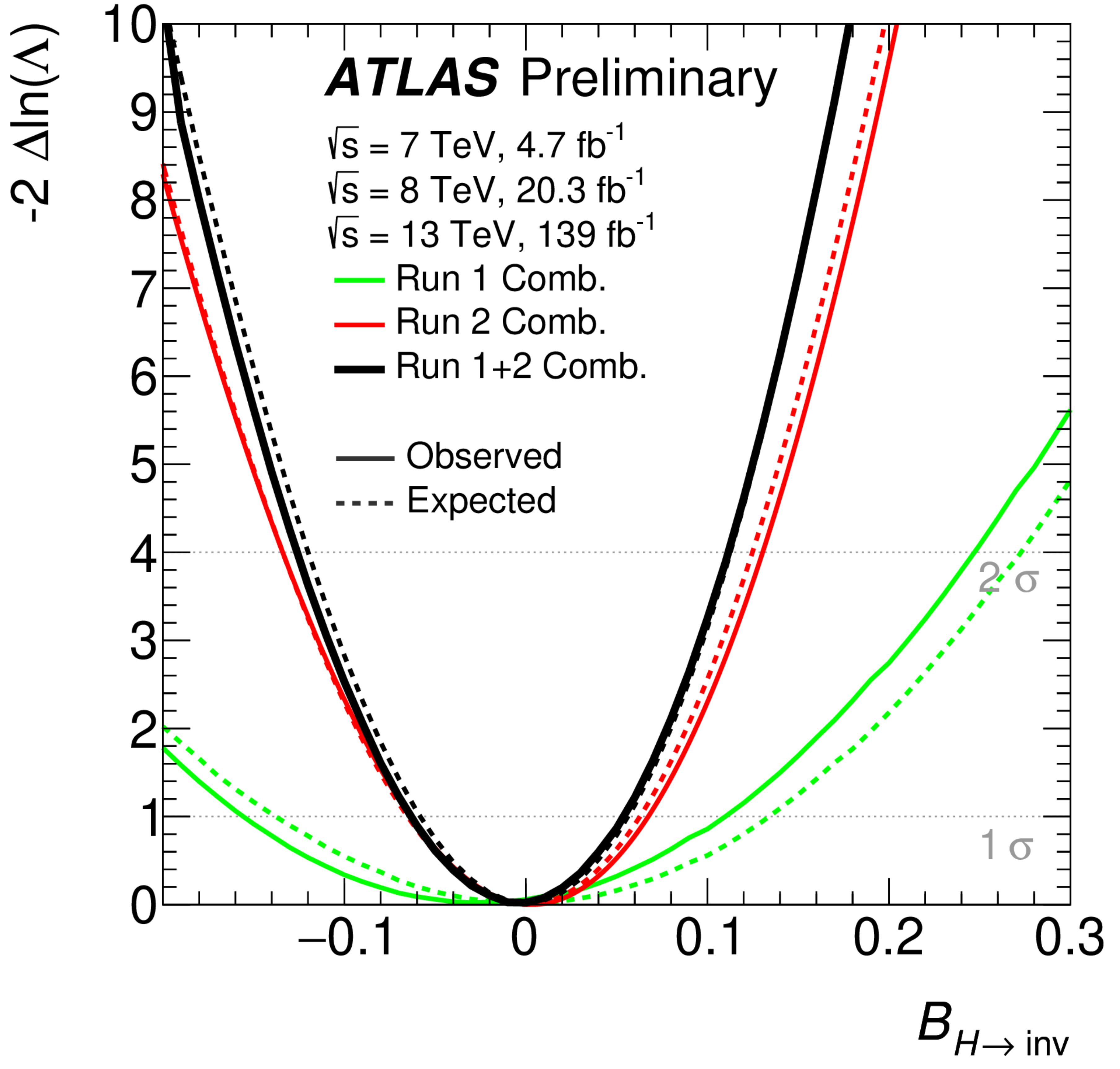
- Can interpret results in 2HDM
  - Reparametrization of κ_Z, κ_b, κ_W, κ_t, κ_τ, and κ_μ
- Use coupling to each SM particle, assume no BSM contribution to total width

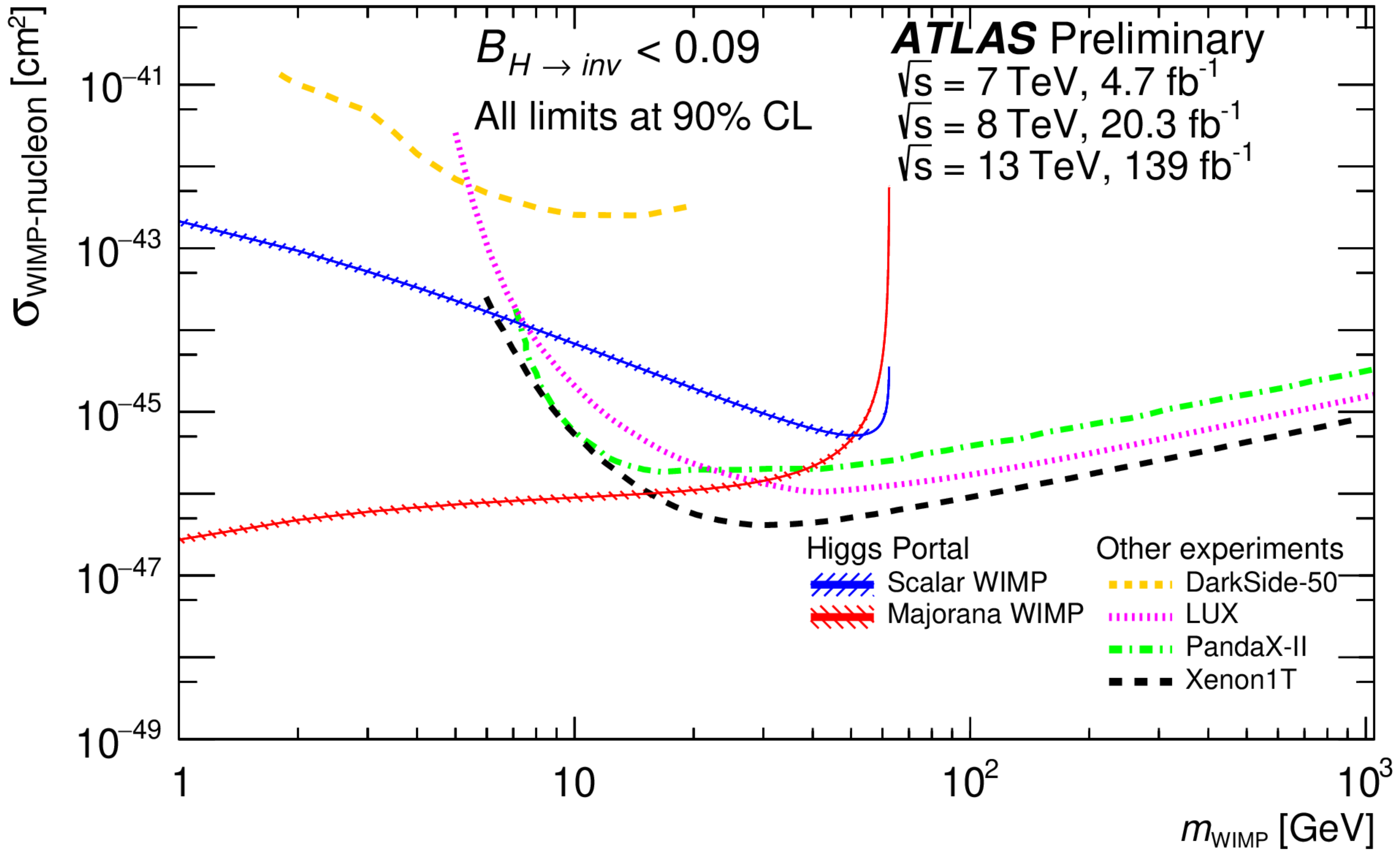
A. Type I: One Higgs doublet couples to vector bosons, other couples to fermions
B. Type II: One Higgs doublet couples to up-type quarks and other to down-type quarks and charged leptons
C. Lepton-specific: The Higgs bosons have the same coupling to quarks as in Type I and to charged leptons as in Type II
D. Flipped: The Higgs bosons have the same couplings to quarks as in Type II model and to charged leptons as in Type I



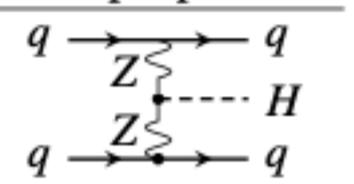
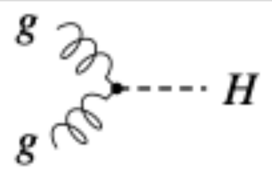
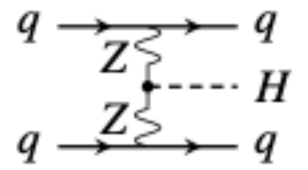
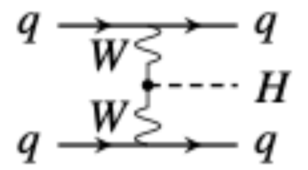
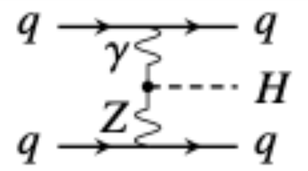
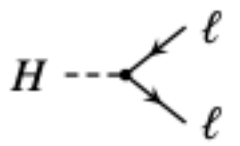
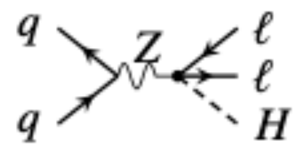
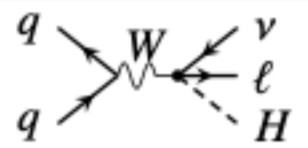
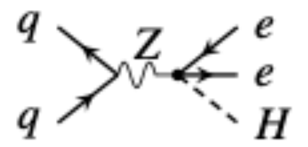
B-Inv

- Provides a complementary search space to direct-search experiments

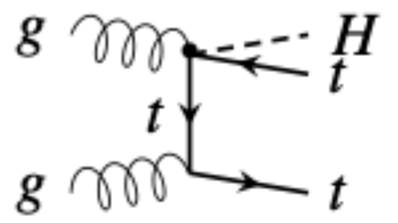
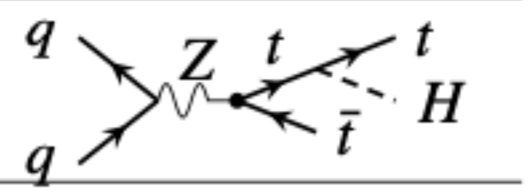
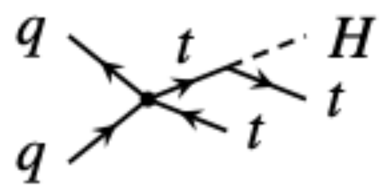
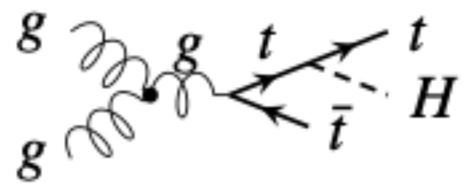




SM EFT diagrams

Coefficient	Operator	Example process
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

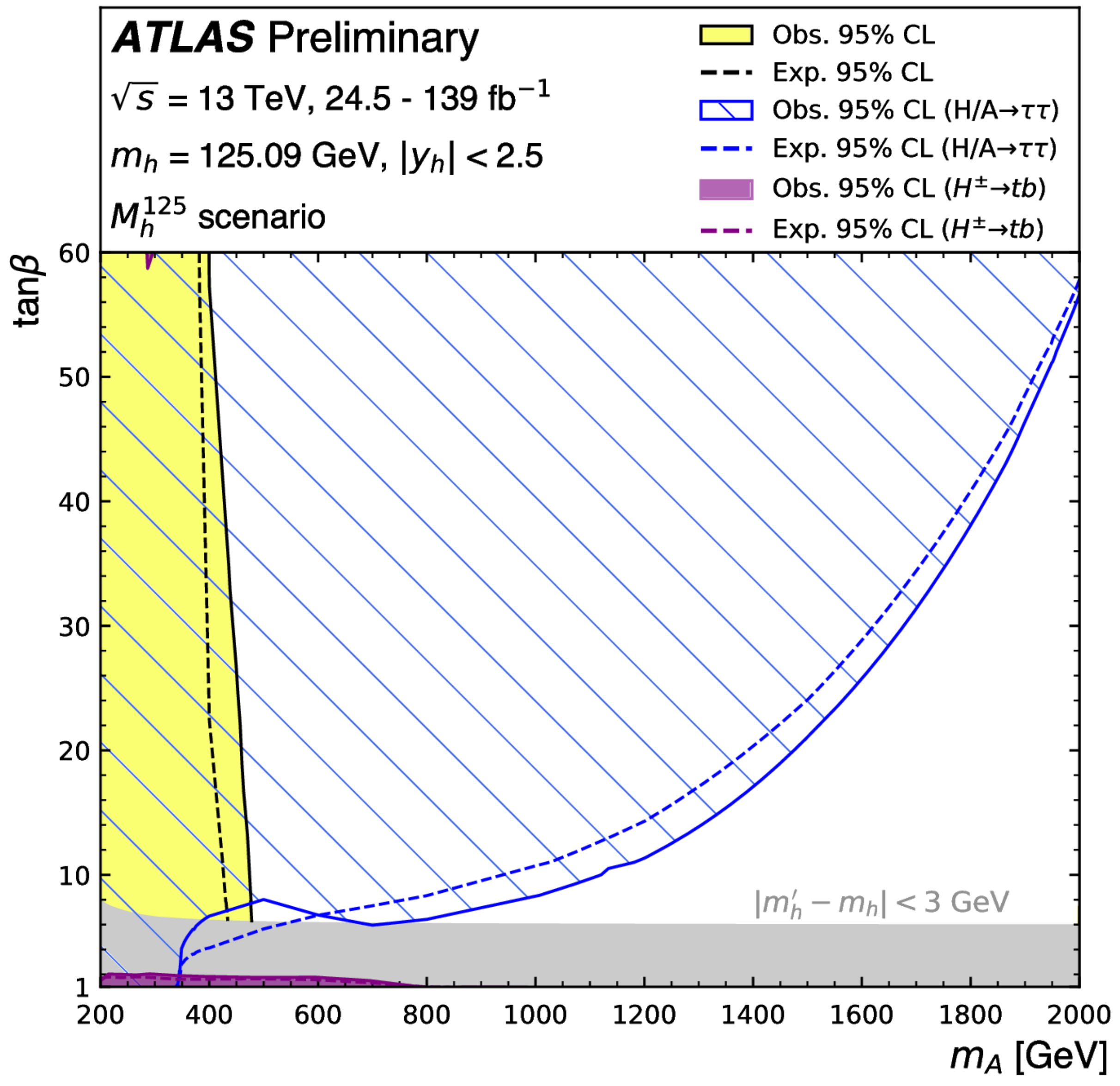
- Most relevant EFT operators affecting Higgs boson production and decay in the considered phase space with examples

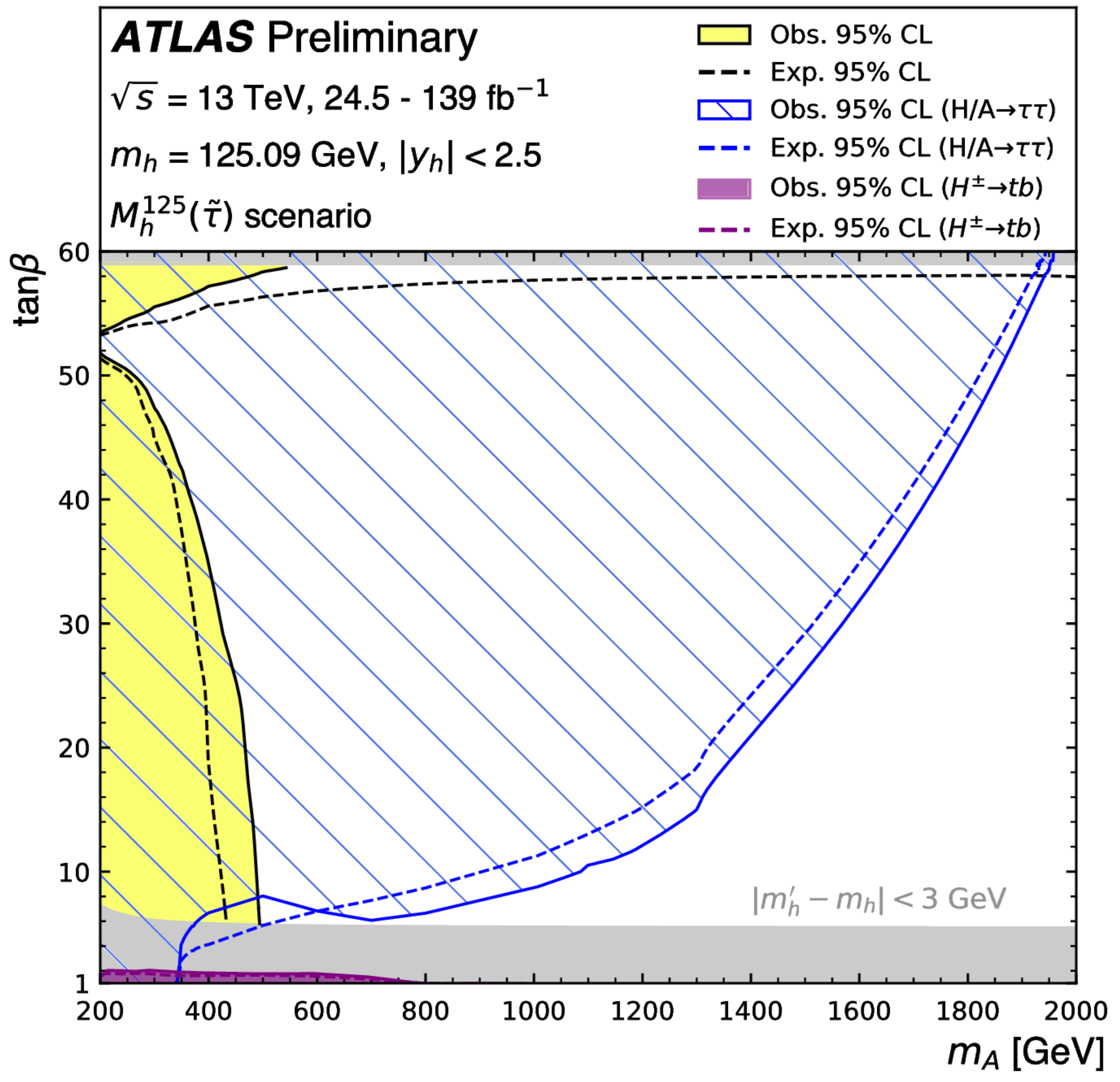
Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$	
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	
$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	
c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(31)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$	
c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	
$c^{(1)}_{uu}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$	
$c^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$	
$c^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
$c^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$	
$c^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
c_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	

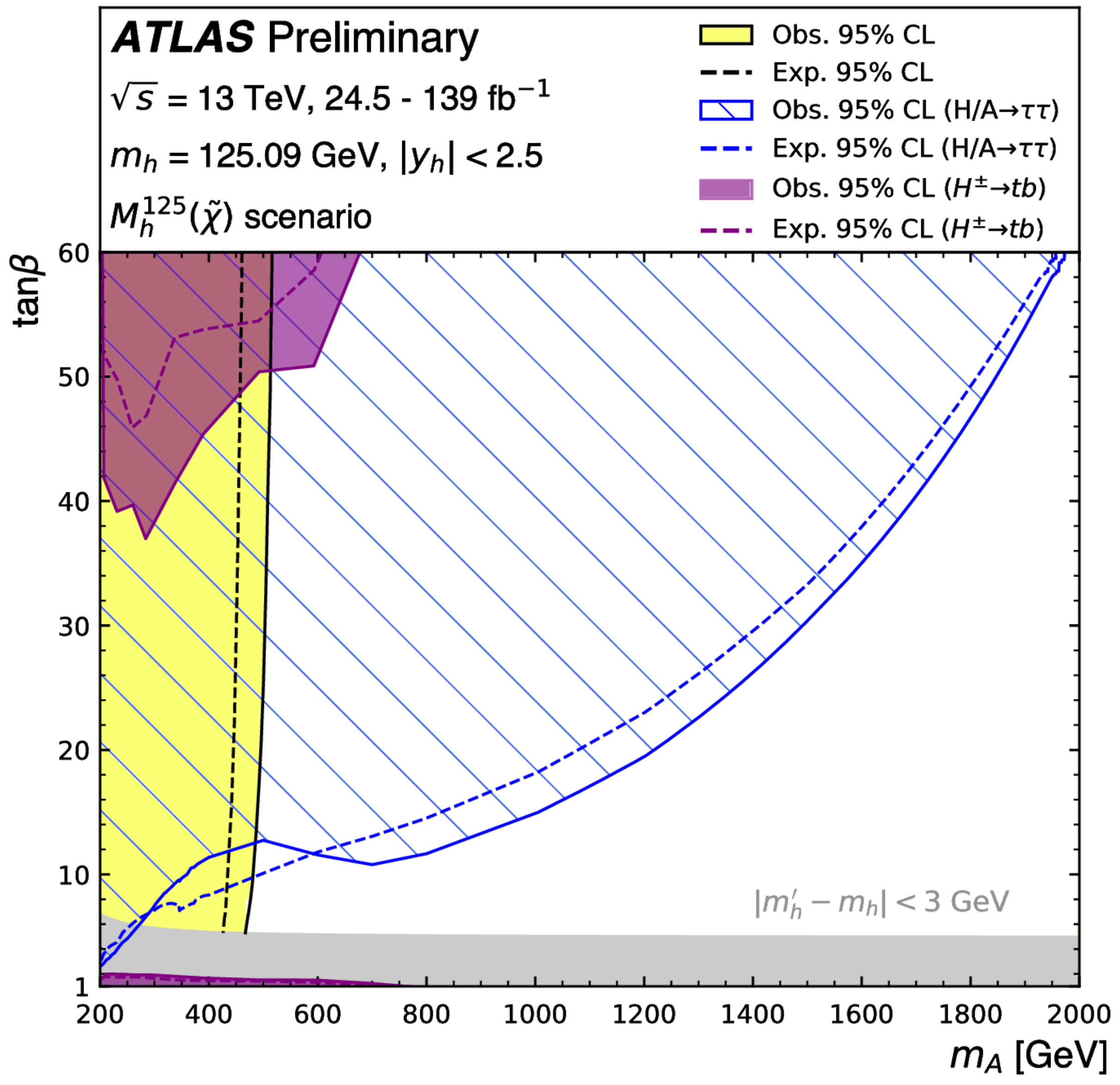
Minimal supersymmetric extension of SM (MSSM)

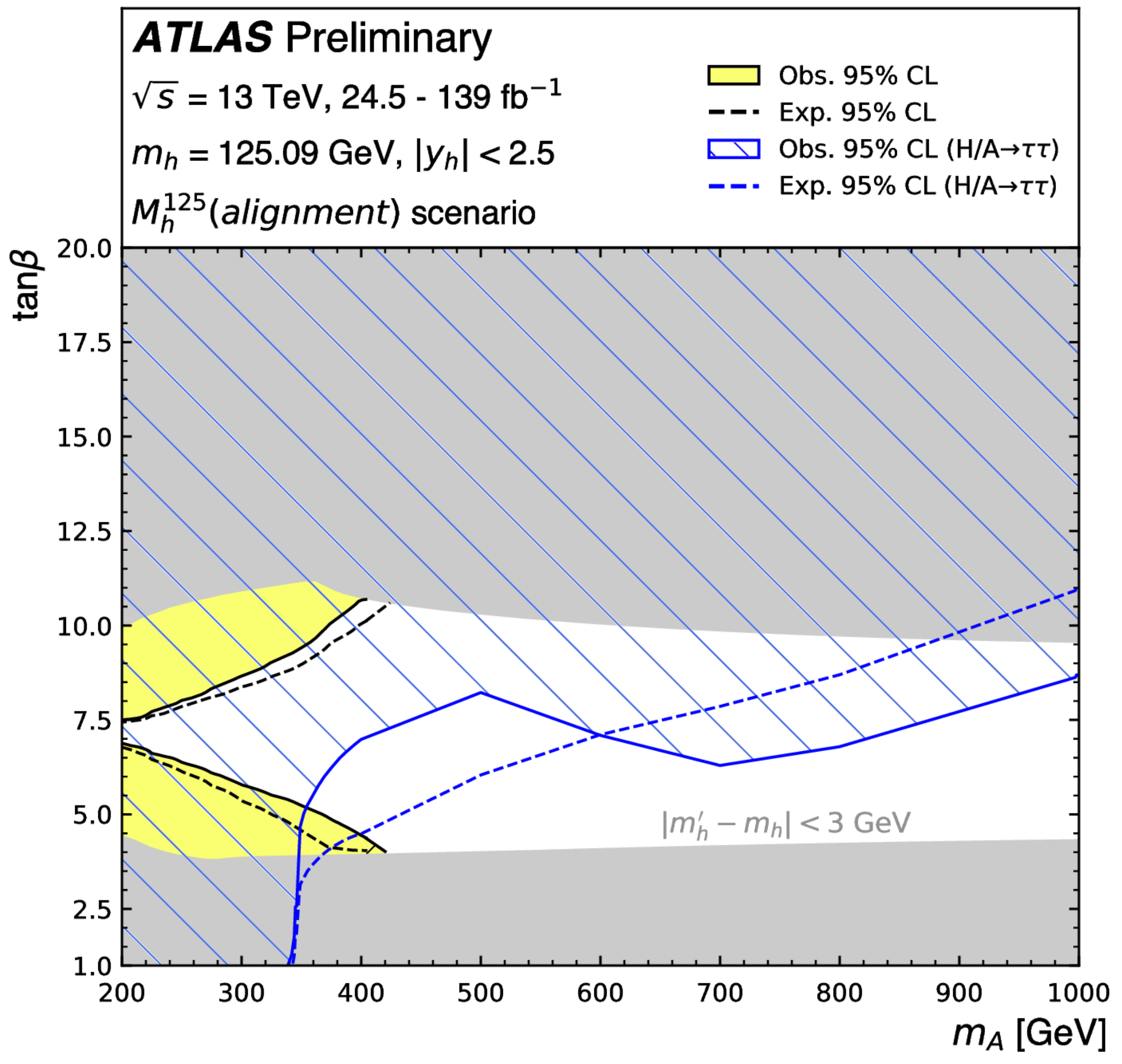
- Supersymmetry is theoretically motivated to address unanswered questions in the SM
- Minimal SUSY (MSSM) predicts partners for SM states and two SU(2) doubles which both acquire a VEV, v1 and v2 with ratio $\beta = \nu_2/\nu_1$
- Over 100 parameters in MSSM but under certain assumptions can reduce the parameter space
- Observed Higgs boson in light CP-even Higgs boson h of MSSM

1. M_h^{125}: Superparticles are so heavy that production/decay of MSSM Higgs bosons are only mildly affected
2. $M_h^{125}(\tilde{\tau})$: Light staus and gaugino-like charginos and neutrinos
3. $M_h^{125}(\tilde{\chi})$: Chargino & neutralinos relatively light with significant higgsino-gaugino mixing
4. M_h^{125}(alignment): For a given $\tan(\beta)$, one of the two neutral CP-even scalars has SM-like couplings independently of the mass spectrum of the remaining Higgs bosons









Minimal supersymmetric extension of SM (MSSM)

5. $M_{h,EFT}^{125}$ scenario: characterized by a flexible mass scale of the superpartners. In 1-4 sfermions are tried to TeV scale. To reopen $\tan(\beta)$<5 the sfermion mass scale is adjusted dynamically to achieve a 125 GeV Higgs boson. All super particles chosen to be heavy.
6. $M_{h,EFT}^{125}(\tilde{\chi})$ scenario: Similar to $M_{h,EFT}^{125}$ but features light neutralinos and charginos that significantly alter phenomenology of Higgs boson. SUSY scale adjusted at every parameter point to achieve 125 GeV Higgs