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Link to CMS Slides

General Higgs Combinations

—

ATLAS-CMS Comparisons

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Inputs and Global μ

Decay channel	ggF		VBF		VH		ttH+tH	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	**139**	**77**	**139**	**77**	**139**		**139**	**77**
$H \to ZZ^* \to 4\ell$	**139**	**137**	**139**	**137**	**139**	**137**	**139**	**137**
$H \to WW^*$	36[1]	36	36[1]	36		36		
$H \to bb$		36	<31[1]		**139**	**77**	36[1]	**77**
$H \to \tau\tau$	36[1]	**77**	36[1]	**77**		**77**		
ttH multilepton							36[1]	**77**
$H \to \mu\mu$	**139**[1]	36	**139**[1]	36	**139**[1]		**139**[1]	
$H \to$ invisible			**139**[1]					

Full Run 2

[1] Not used in STXS fit

Global signal strength:

- ATLAS: $\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(\text{stat.}) \pm 0.03(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$
- CMS: $\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\text{stat}) \pm 0.04(\text{exp}) \pm 0.04(\text{theo})$

Inputs and Global μ

Decay channel	ggF		VBF		VH		ttH+tH	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	**139**	**77** ↻	**139**	**77** ↻	**139**	↻	**139**	**77** ↻
$H \to ZZ^* \to 4\ell$	**139**	**137** ↻	**139**	**137** ↻	**139**	**137** ↻	**139**	**137** ↻
$H \to WW^*$	36[1] ↻	36	36[1] ↻	36		36 ↻		
$H \to bb$	↻	36 ↻	<31[1] ↻		**139**	**77**	36[1] ↻	**77**
$H \to \tau\tau$	36[1] ↻	**77** ↻	36[1] ↻	**77** ↻	↻	**77**	↻	
ttH multilepton							36[1] ↻	**77** ↻
$H \to \mu\mu$	**139**[1]	36 ↻	**139**[1]	36 ↻	**139**[1]	↻	**139**[1]	↻
$H \to$ invisible		↻	**139**[1]		↻	↻	↻	

Full Run 2

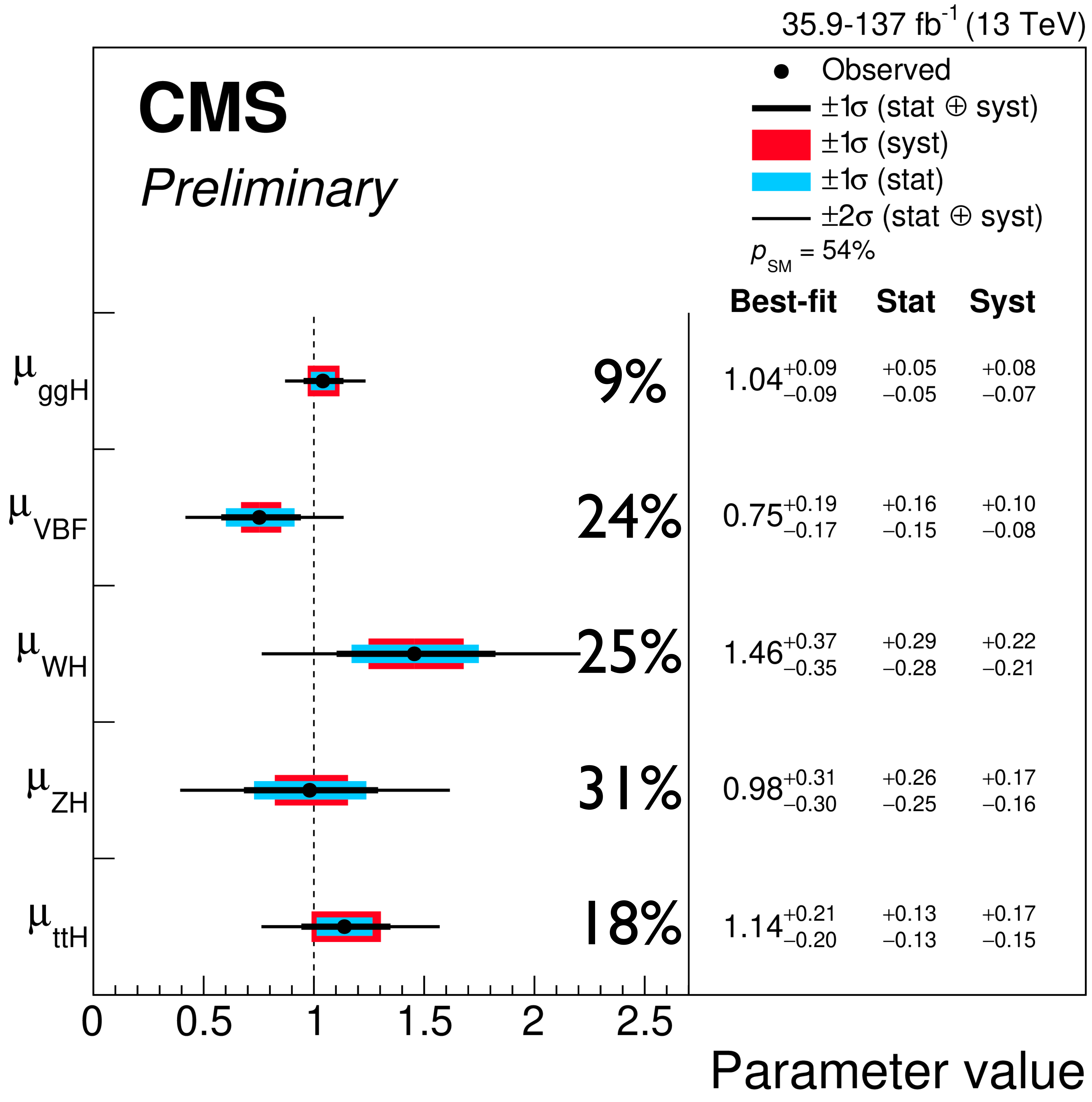
↻ Updated result available; not yet in main public combination

1) Not used in STXS fit

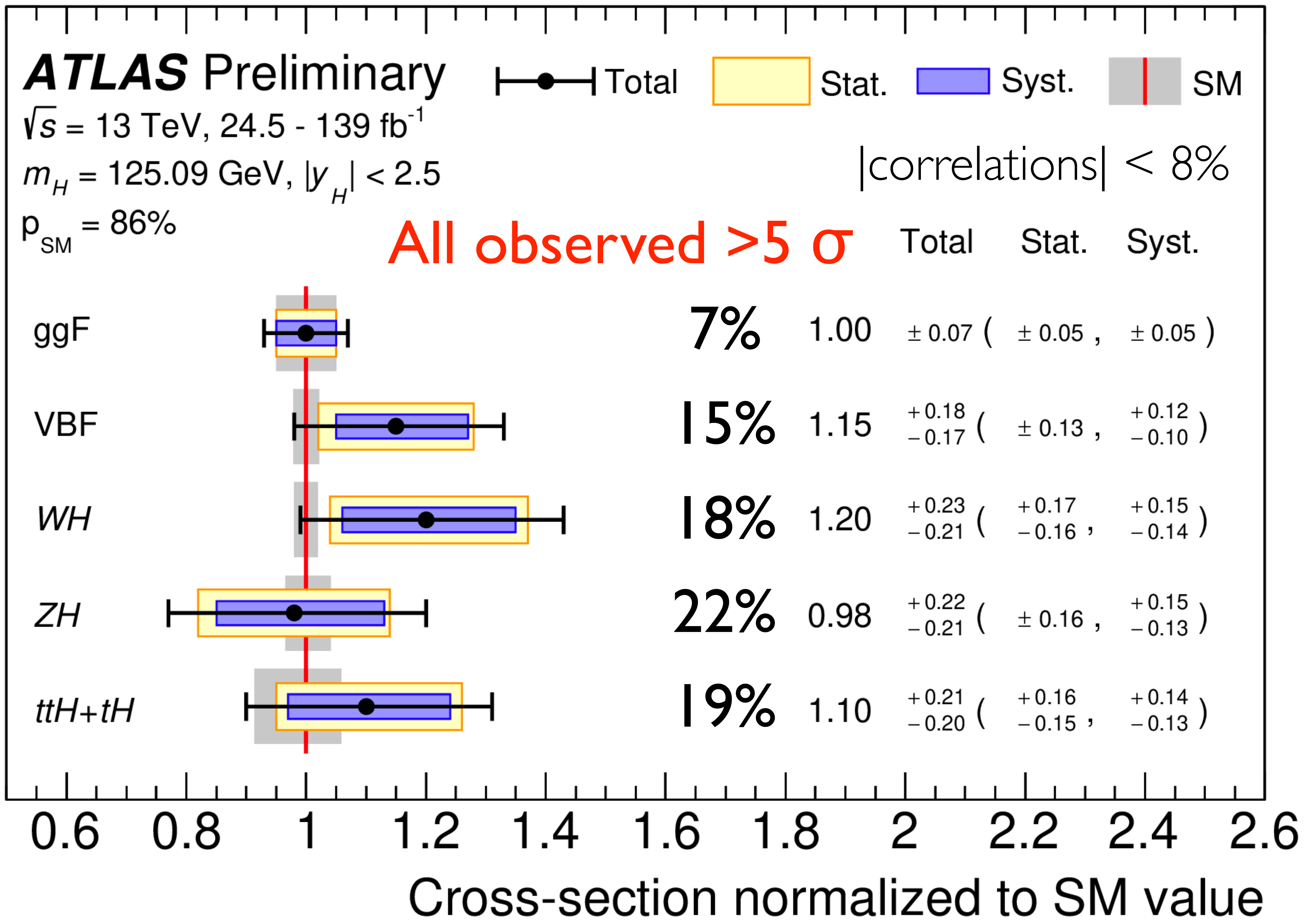
Global signal strength:

- ATLAS: $\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(\text{stat.}) \pm 0.03(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$
- CMS: $\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\text{stat}) \pm 0.04(\text{exp}) \pm 0.04(\text{theo})$

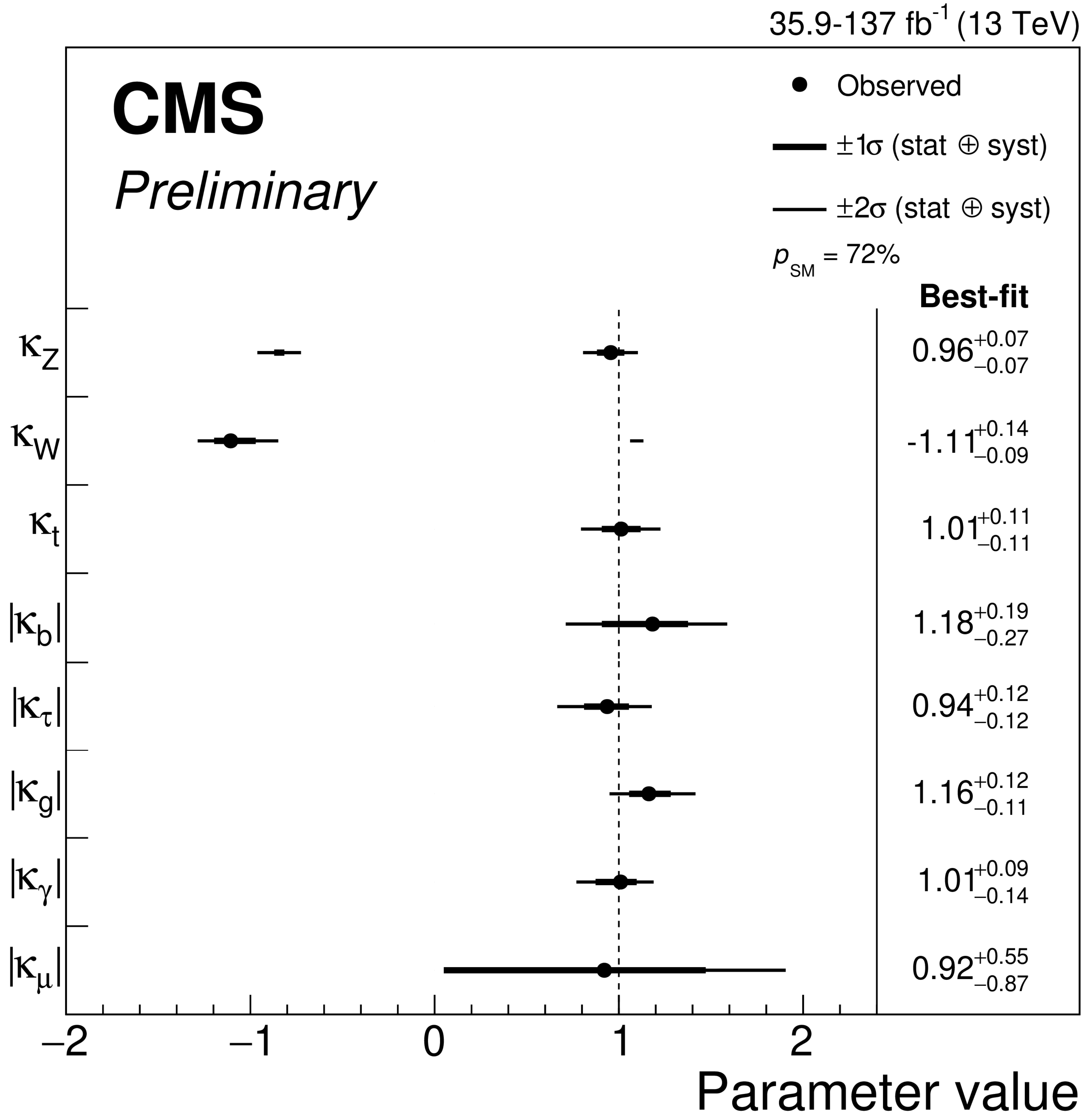
Production modes



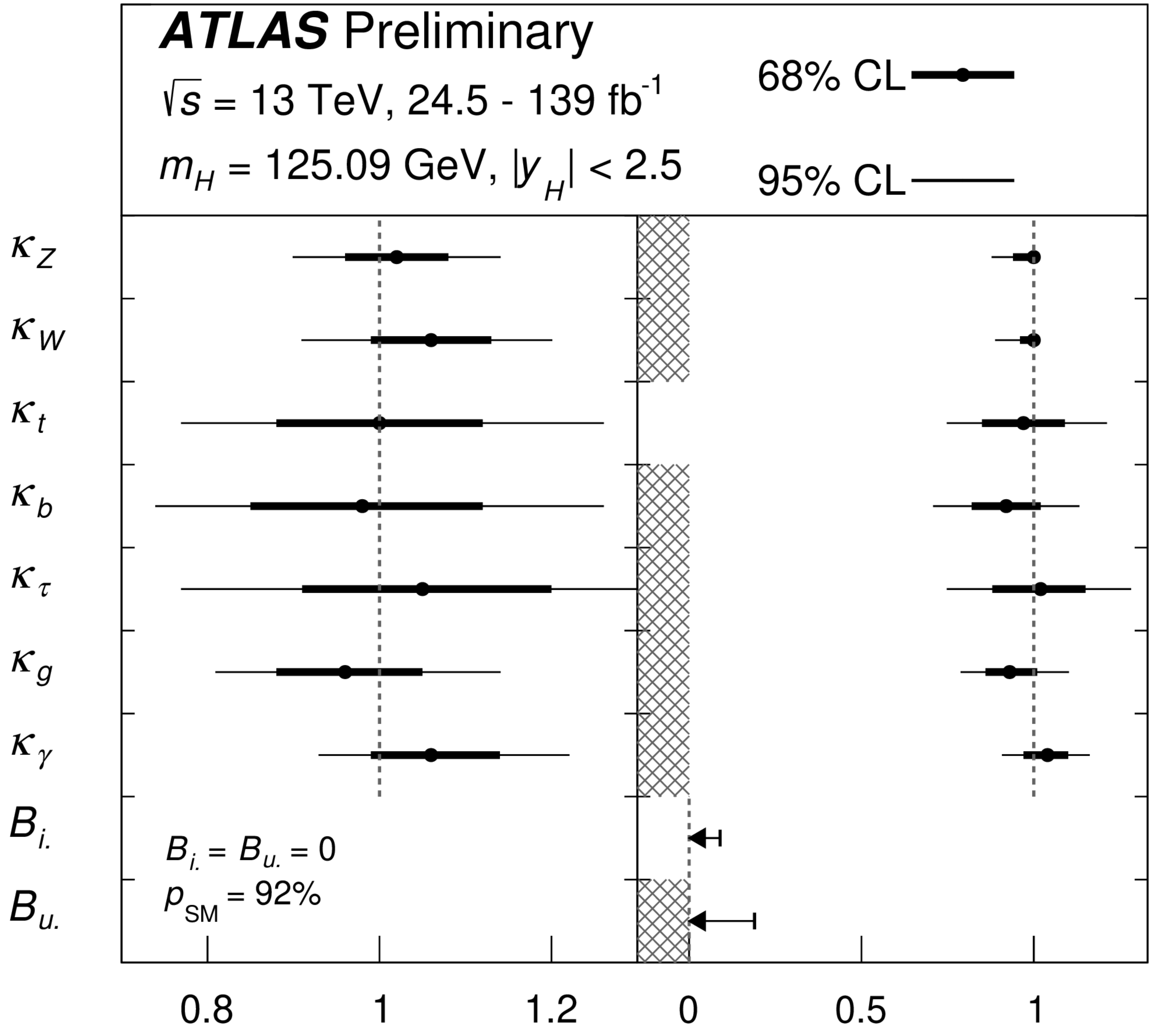
- Signal strength vs. cross-section



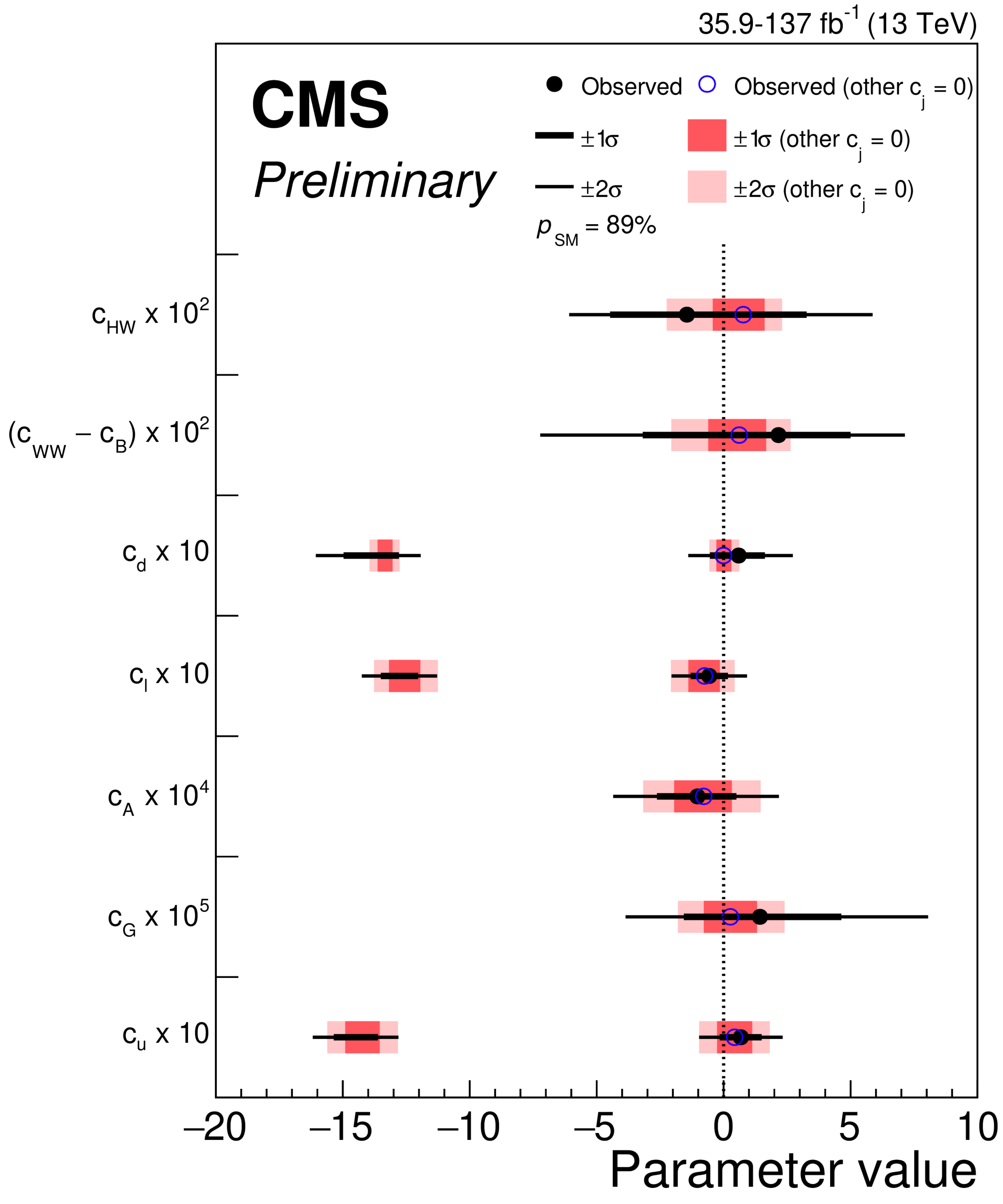
κ Framework



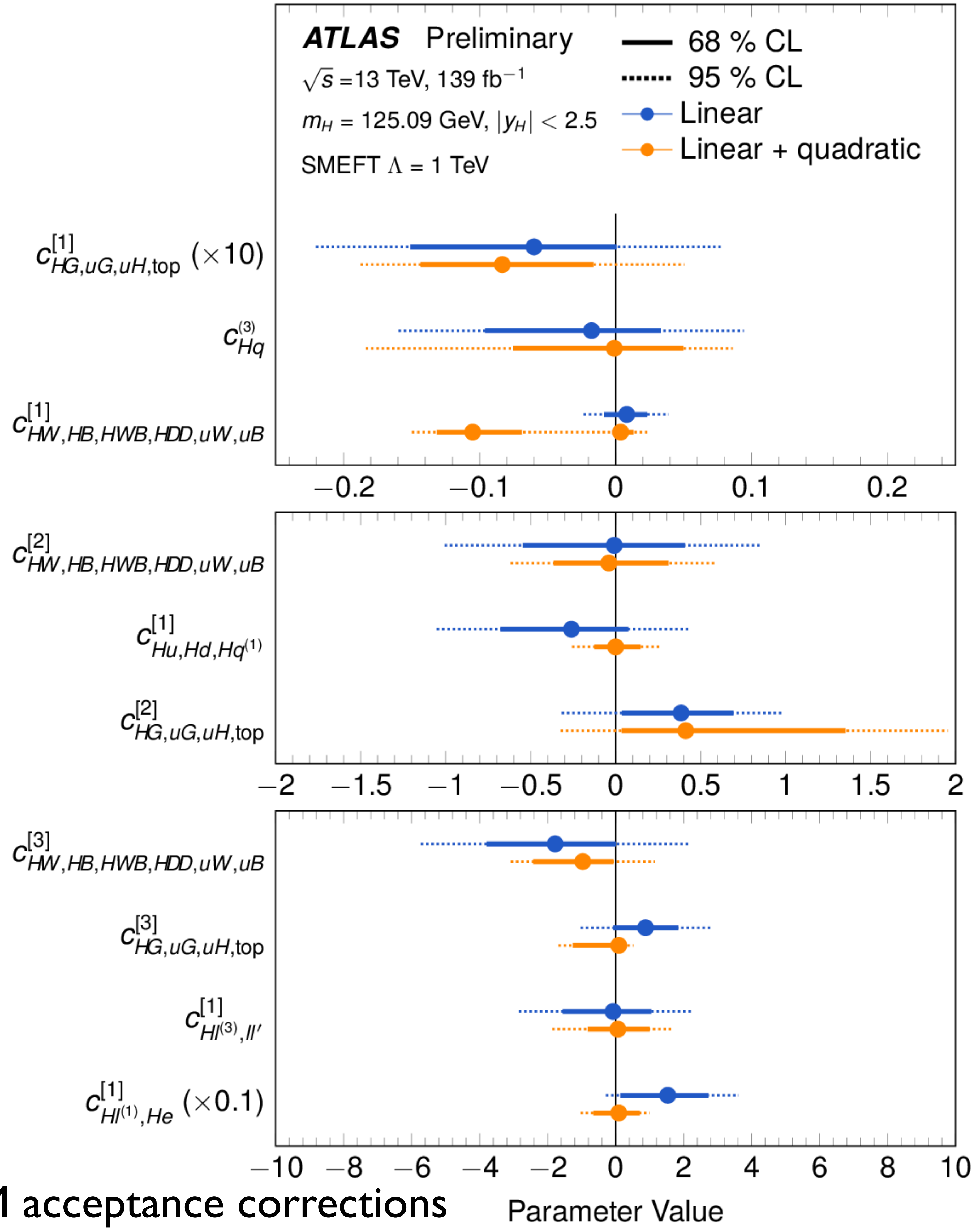
CMS	ATLAS	
7%	6%	κ_Z
8%	7%	κ_W
11%	13%	κ_t
16%	12%	κ_b
13%	13%	κ_τ
9%	7%	κ_g
9%	8%	κ_γ



Effective Field Theories: HEL vs SMEFT



- Leading D=6 CP-even EFT operators
- Different EFT bases:
  - HEL vs SMEFT
- Different procedures
  - Finding (non-) sensitive directions
  - Acceptance corrections



No BSM acceptance corrections

BSM acceptance corrections for $H \to ZZ^* \to 4\ell$

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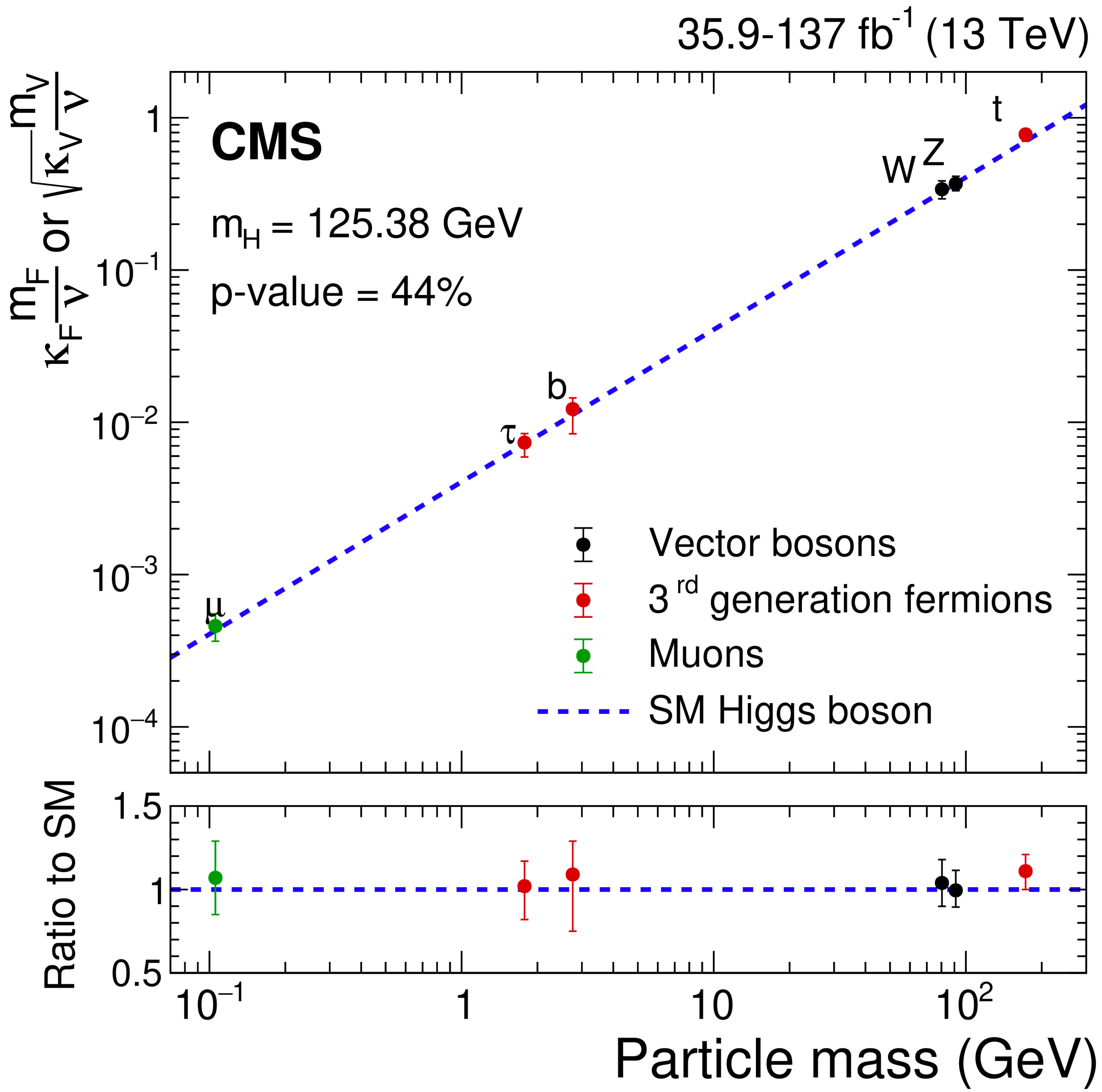
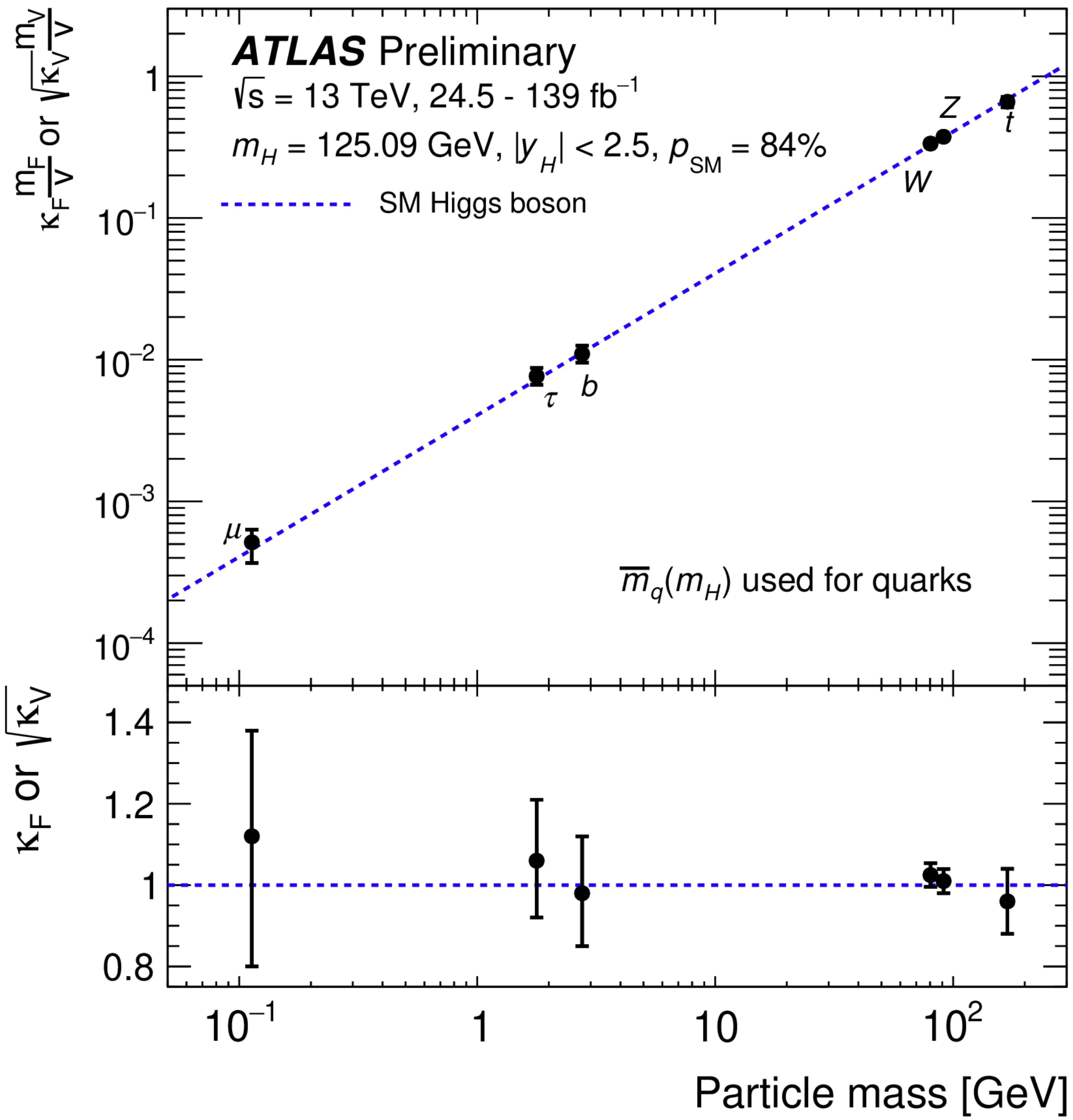
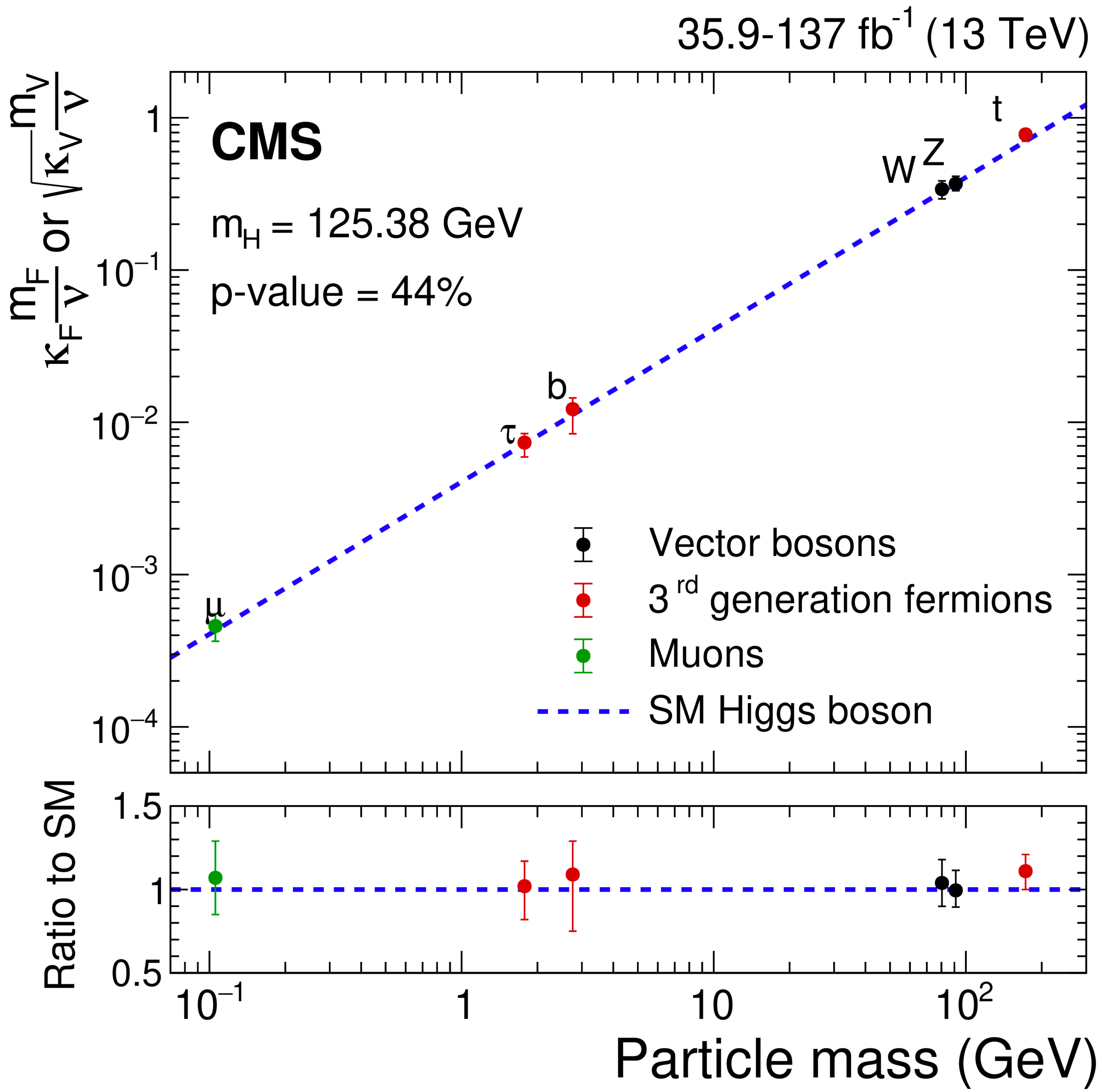
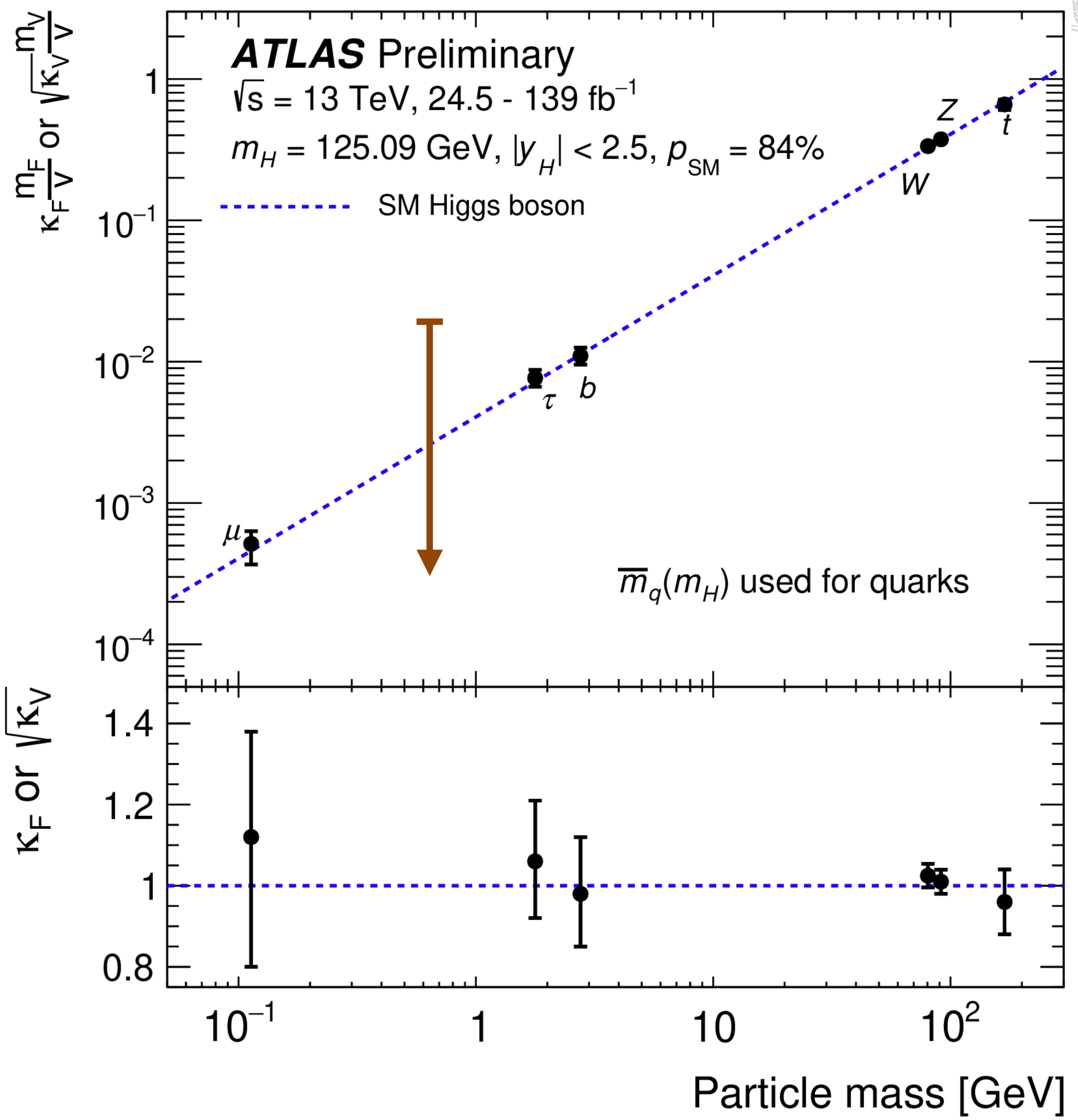
κ Framework


35.9-137 fb-1 (13 TeV)
CMS
mH = 125.38 GeV
p-value = 44%
Vector bosons
3rd generation fermions
Muons
SM Higgs boson
Ratio to SM
Particle mass (GeV)


ATLAS Preliminary
√s = 13 TeV, 24.5 - 139 fb-1
mH = 125.09 GeV, |yH| < 2.5, pSM = 84%
SM Higgs boson
m̄q(mH) used for quarks
Particle mass [GeV]

κ Framework


35.9-137 fb^{-1} (13 TeV)
CMS
m_H = 125.38 GeV
p-value = 44%
Vector bosons
3rd generation fermions
Muons
SM Higgs boson
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
Ratio to SM
Particle mass (GeV)
μ
τ
b
W
Z
t


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 24.5 - 139 fb^{-1}
m_H = 125.09 GeV, $|y_H|$ < 2.5, p_{SM} = 84%
SM Higgs boson
$\overline{m}_q(m_H)$ used for quarks
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
κ_F or $\sqrt{\kappa_V}$
Particle mass [GeV]
μ
τ
b
W
Z
t

κ Framework

Ratio to SM
1.5
1
0.5
10^{-1}
1
10
10^2
Particle mass (GeV)
κ_F or $\sqrt{\kappa_V}$

ATLAS Slides

ATLAS

EXPERIMENT

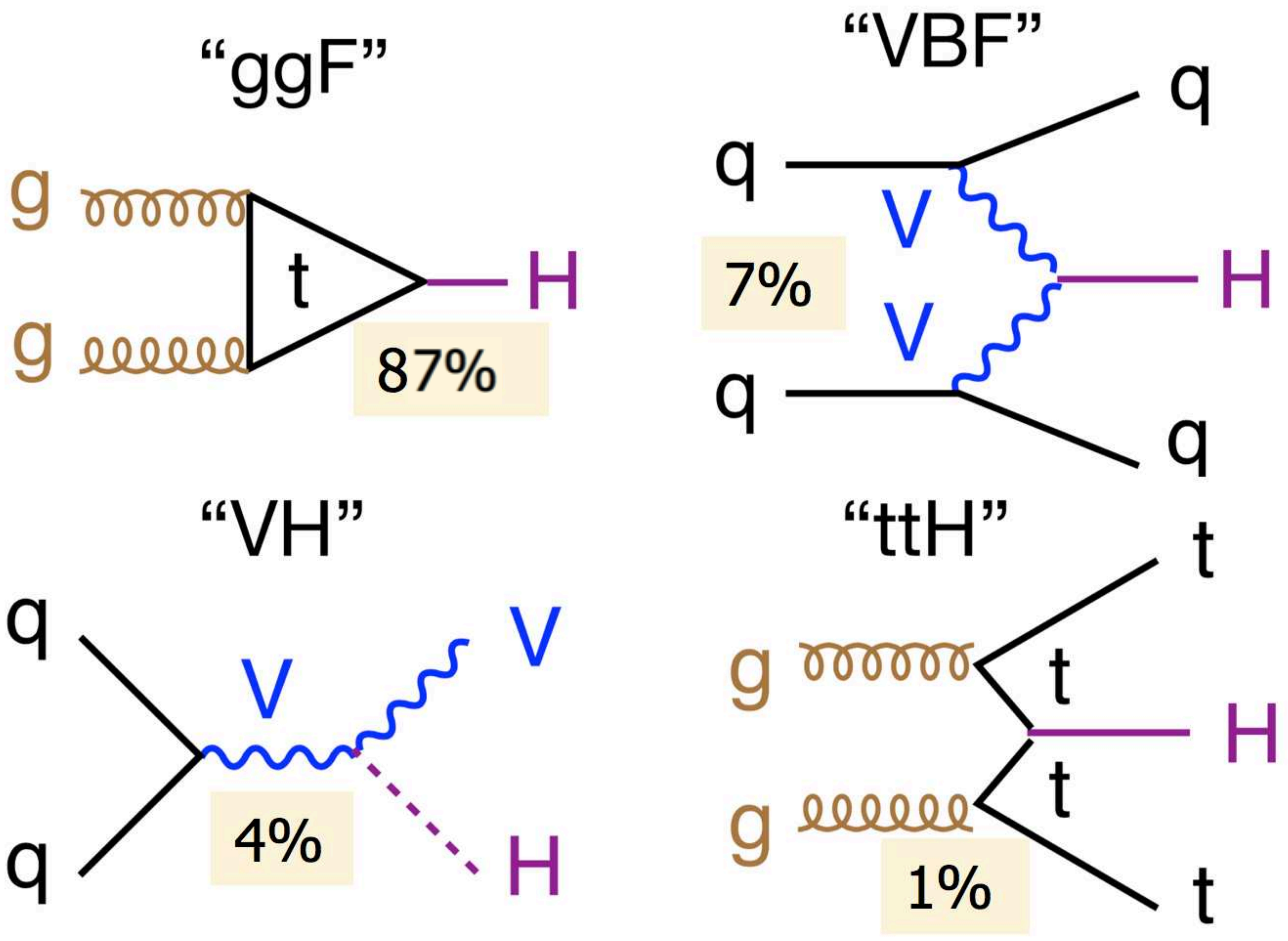
ATLAS Higgs Combination

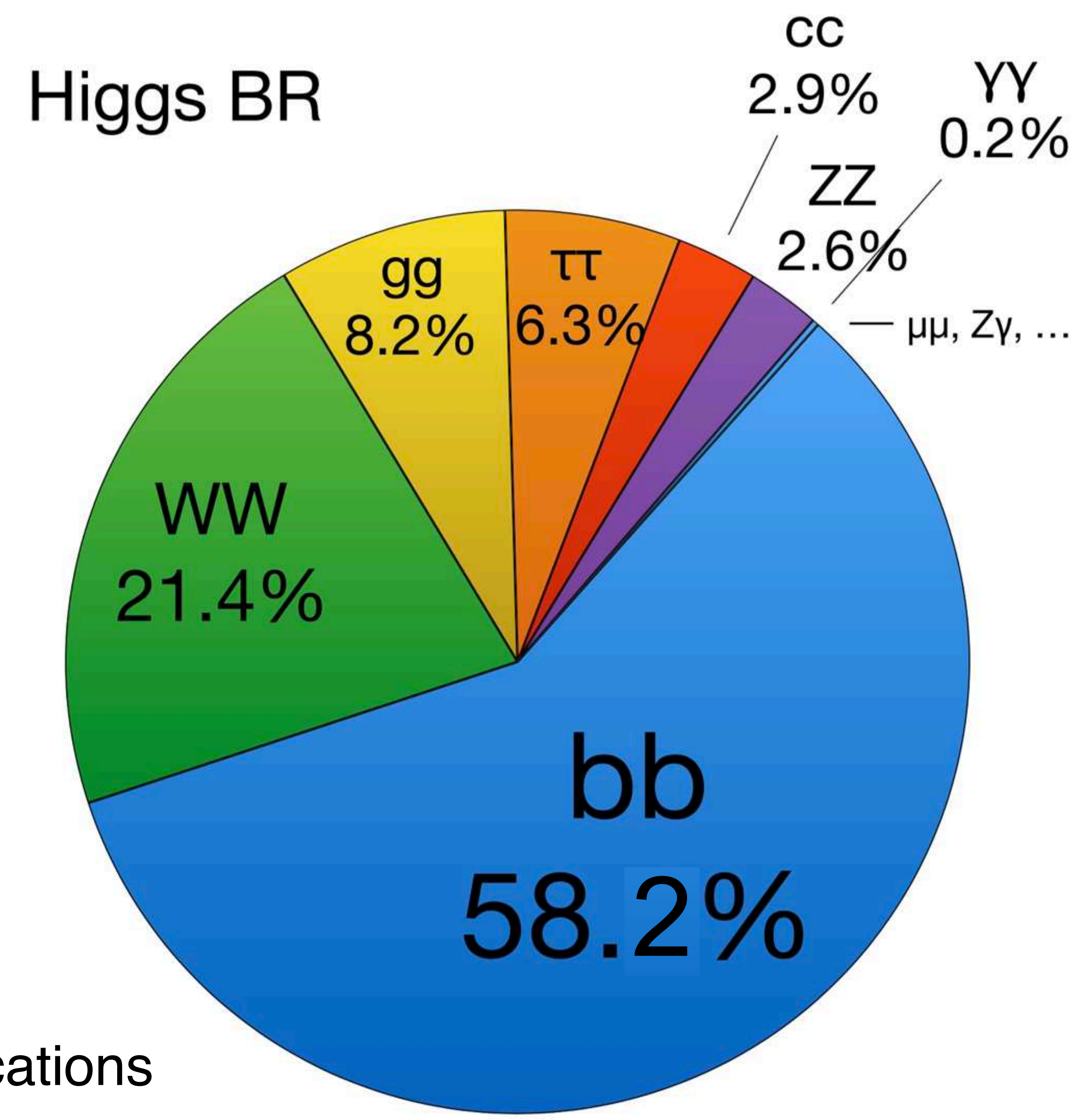
Chen Zhou (University of Wisconsin)
on behalf of the ATLAS Collaboration

September 20-22, 2021 - Orsay-Paris
Higgs Hunting Workshop

Introduction

- Since the Higgs discovery by ATLAS and CMS in 2012, many **Higgs property studies** (mass, spin, parity, couplings, cross sections, etc.) have been performed
- Today: combined measurements of Higgs boson using **13 TeV data** collected with the ATLAS detector (ATLAS-CONF-2020-027, ATLAS-CONF-2020-053, ATLAS-CONF-2019-032)





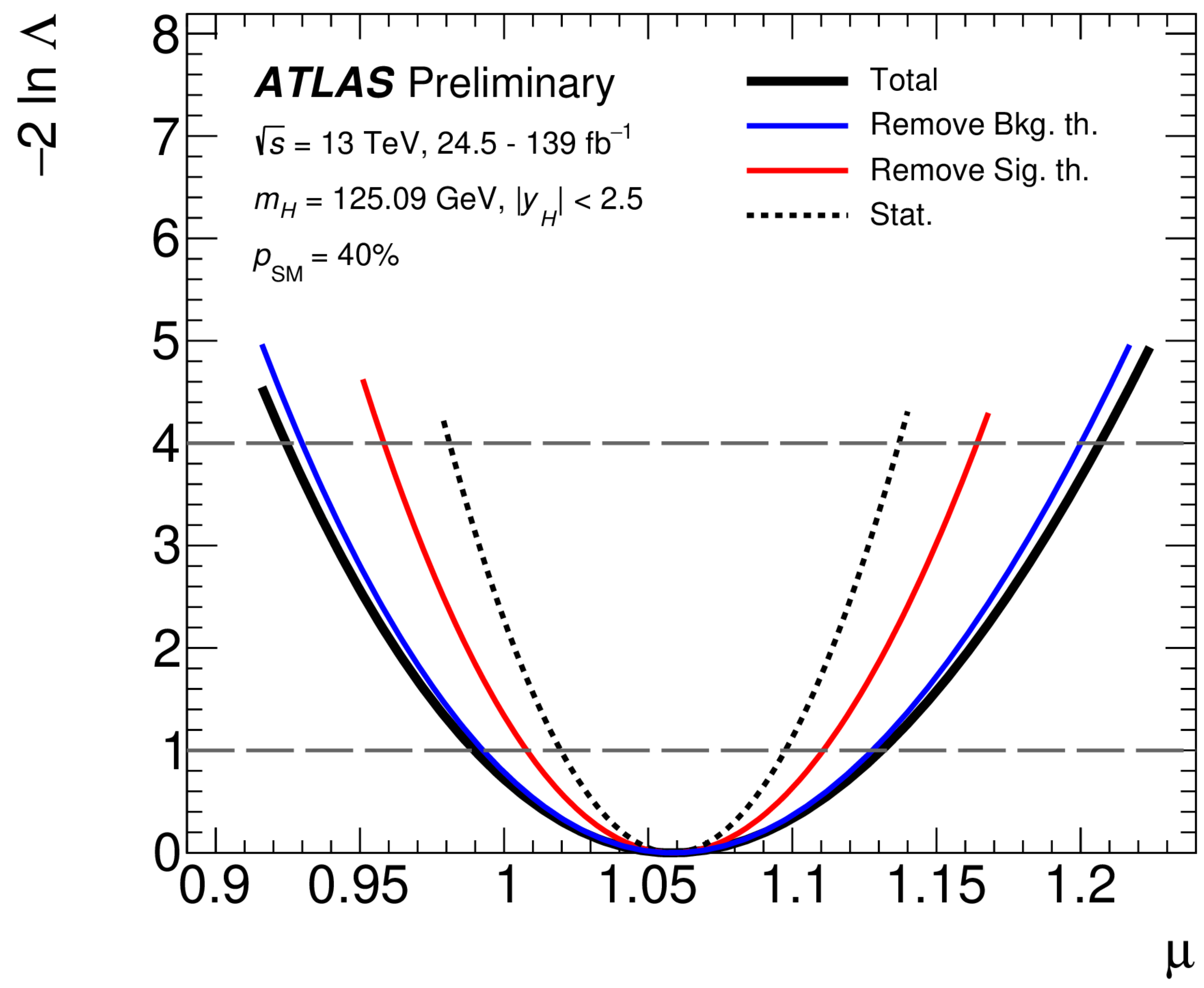
Figures from https://msneubauer.github.io with modifications for Higgs Mass = 125 GeV

Signal strength & production cross-section measurements

	ggF	VBF	VH	ttH+tH
H→γγ	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
H→ZZ	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (36-139 fb^{-1})
H→WW	✔ (36 fb^{-1})	✔ (36 fb^{-1})		
H→ττ	✔ (36 fb^{-1})	✔ (36 fb^{-1})		
H→bb		✔ (25-31 fb^{-1})	✔ (139 fb^{-1})	✔ (36 fb^{-1})

✔: channel included in the combination

Inclusive signal strength



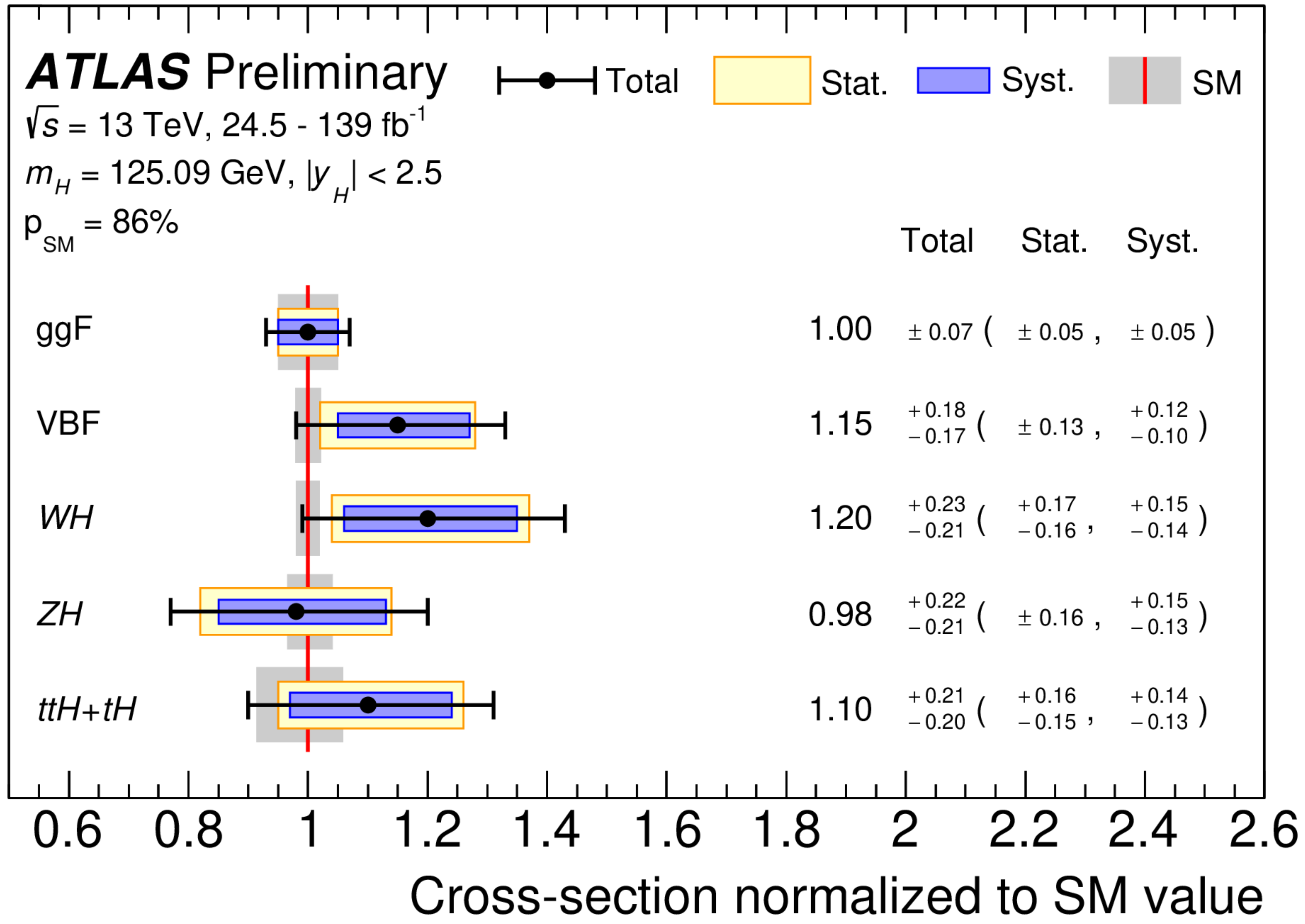
ATLAS-CONF-2020-027

- Inclusive signal strength, defined as the measured Higgs boson signal yield normalized to its SM prediction, is determined to be

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

- This measurement is systematically limited

Production mode cross sections (assuming the SM decays)



ATLAS-CONF-2020-027

- ggF cross section is now measured with 7% precision
  - Precision of N3LO cross section prediction: 5%
- All major production modes (ggF, VBF, WH, ZH, ttH) are observed!
  - WH: 6.3σ, ZH: 5.0σ

Simplified template cross section (STXS) measurements

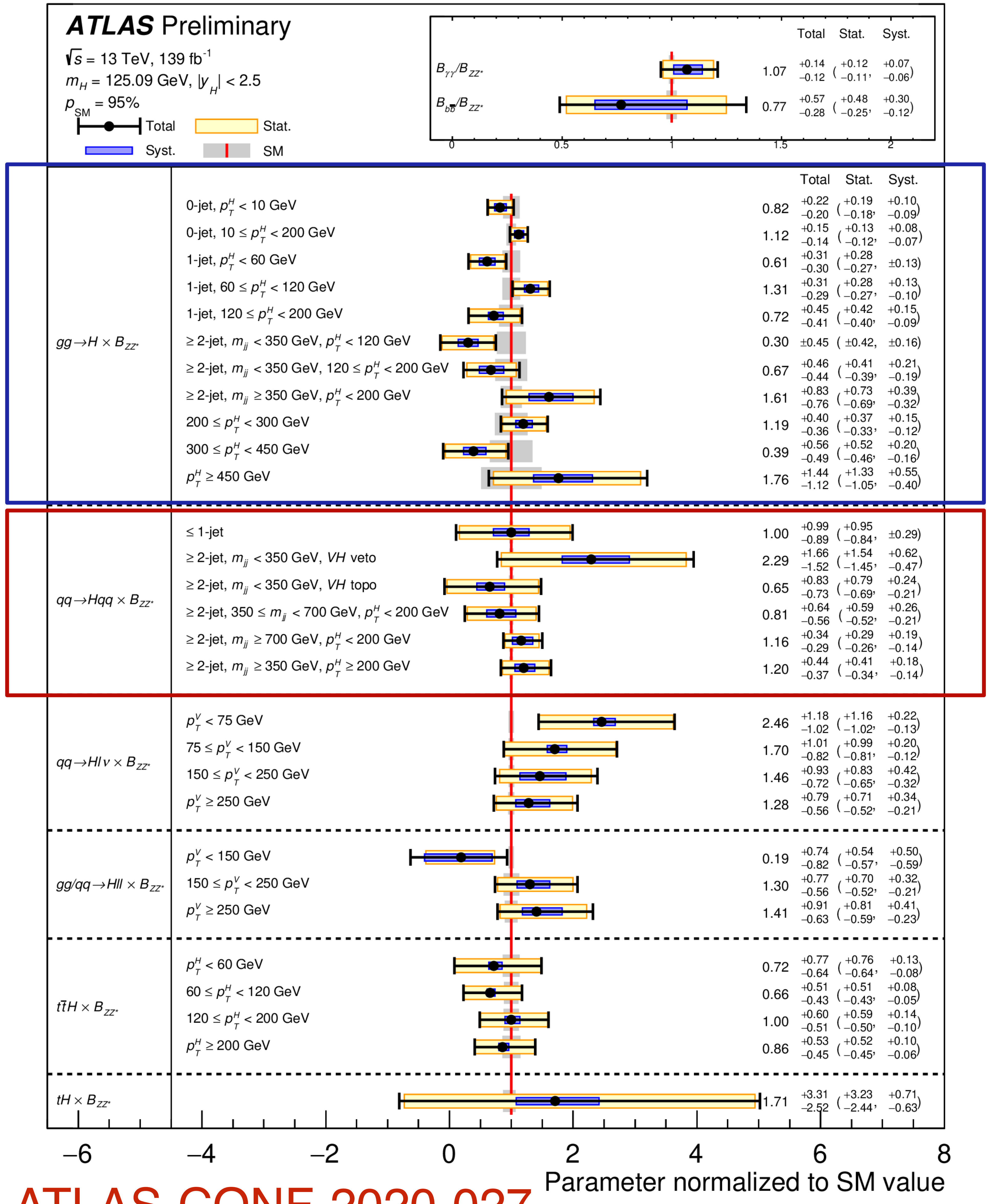
	ggF	VBF	VH	ttH+tH
$H\to\gamma\gamma$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\to ZZ$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\to bb$			✔ (139 fb^{-1})	

✔: channel included in the combination

Simplified template cross sections

- Measure production mode cross-sections in various phase-space regions, which are chosen according to
  - sensitivity to BSM effects
  - avoidance of large theory uncertainties
  - matching to experimental selections
- Within each region, use the SM predicted signal templates to fit data
  - Can still exploit powerful analysis techniques (e.g. MVA)
- STXS are measured granularly in this combination
  - without assuming the SM decays of Higgs boson

STXS results



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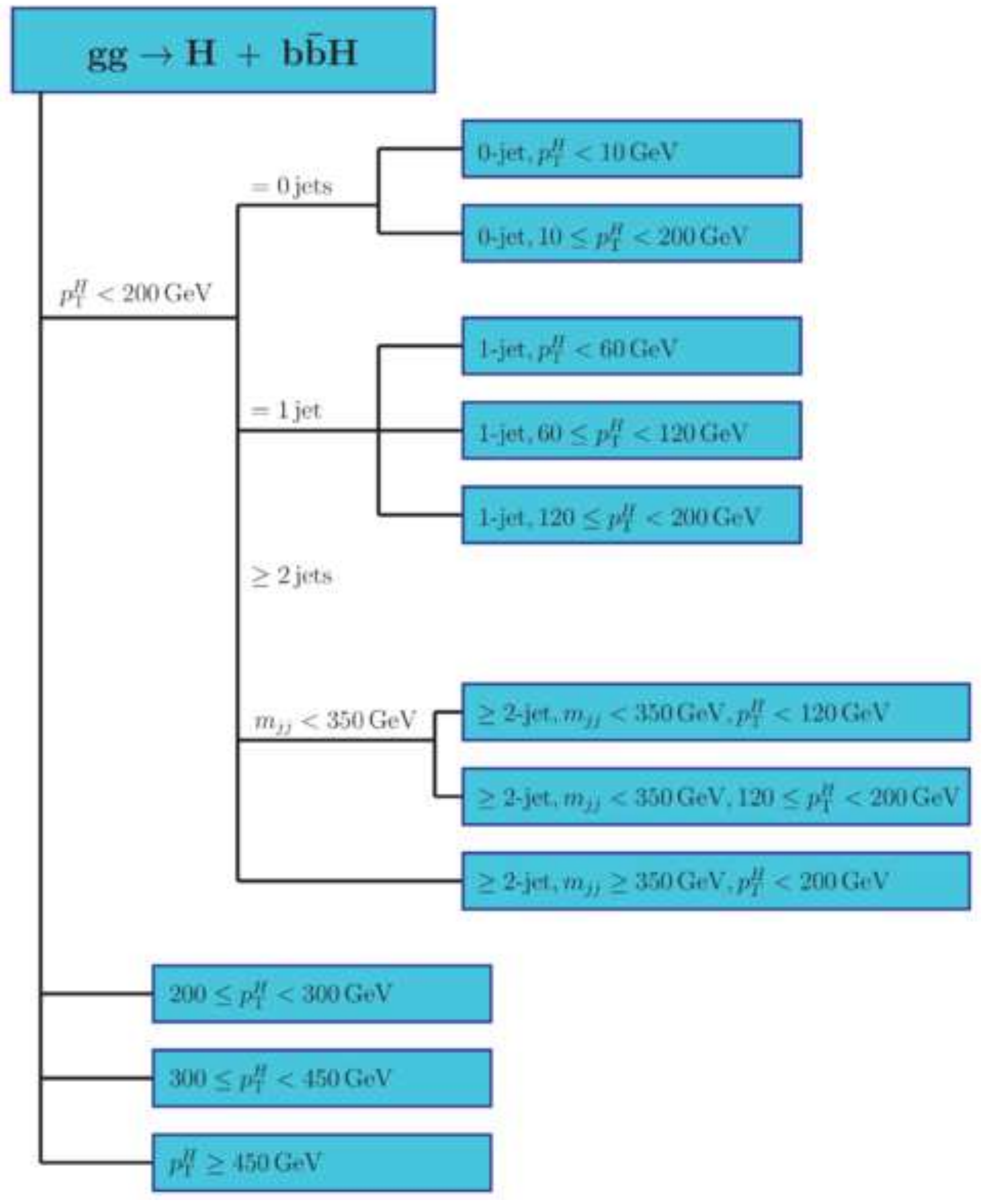
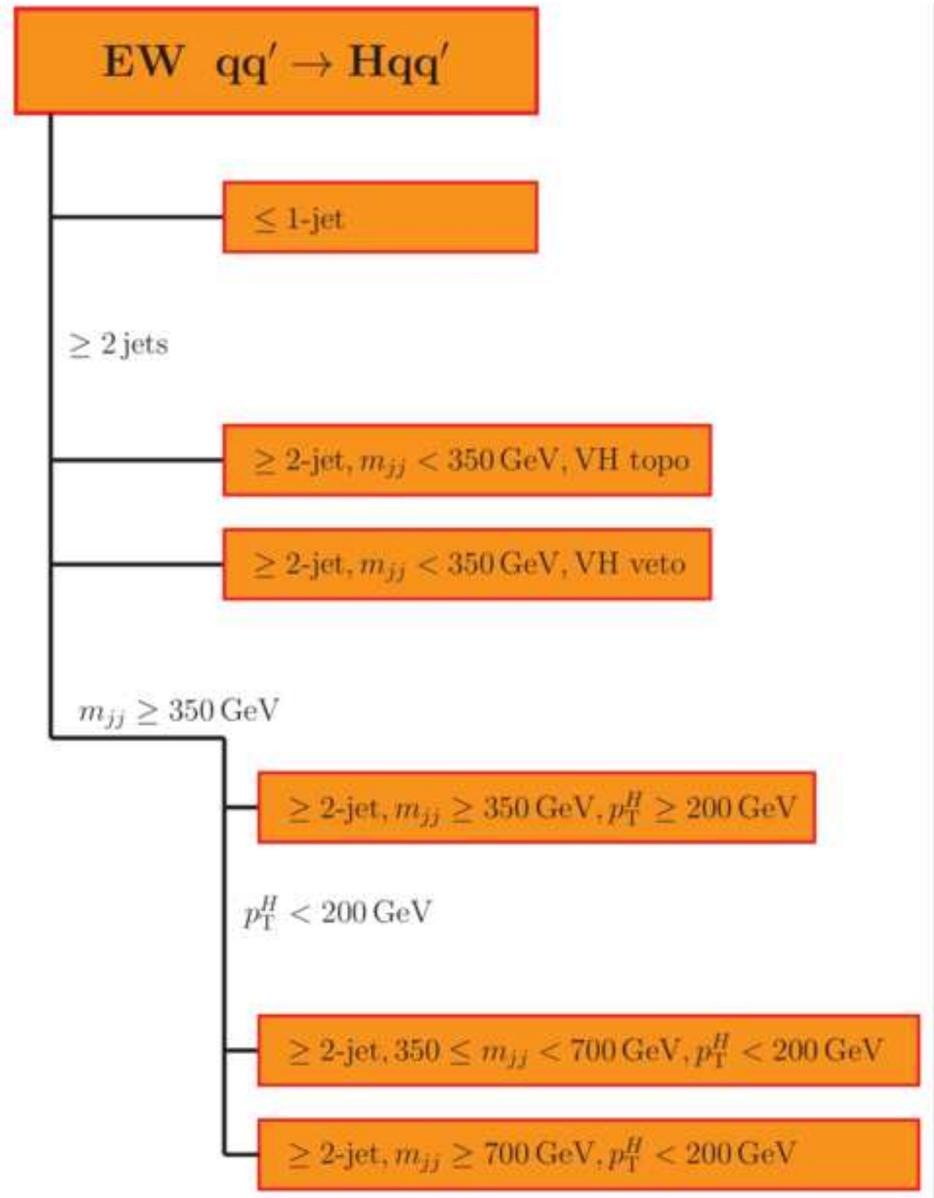
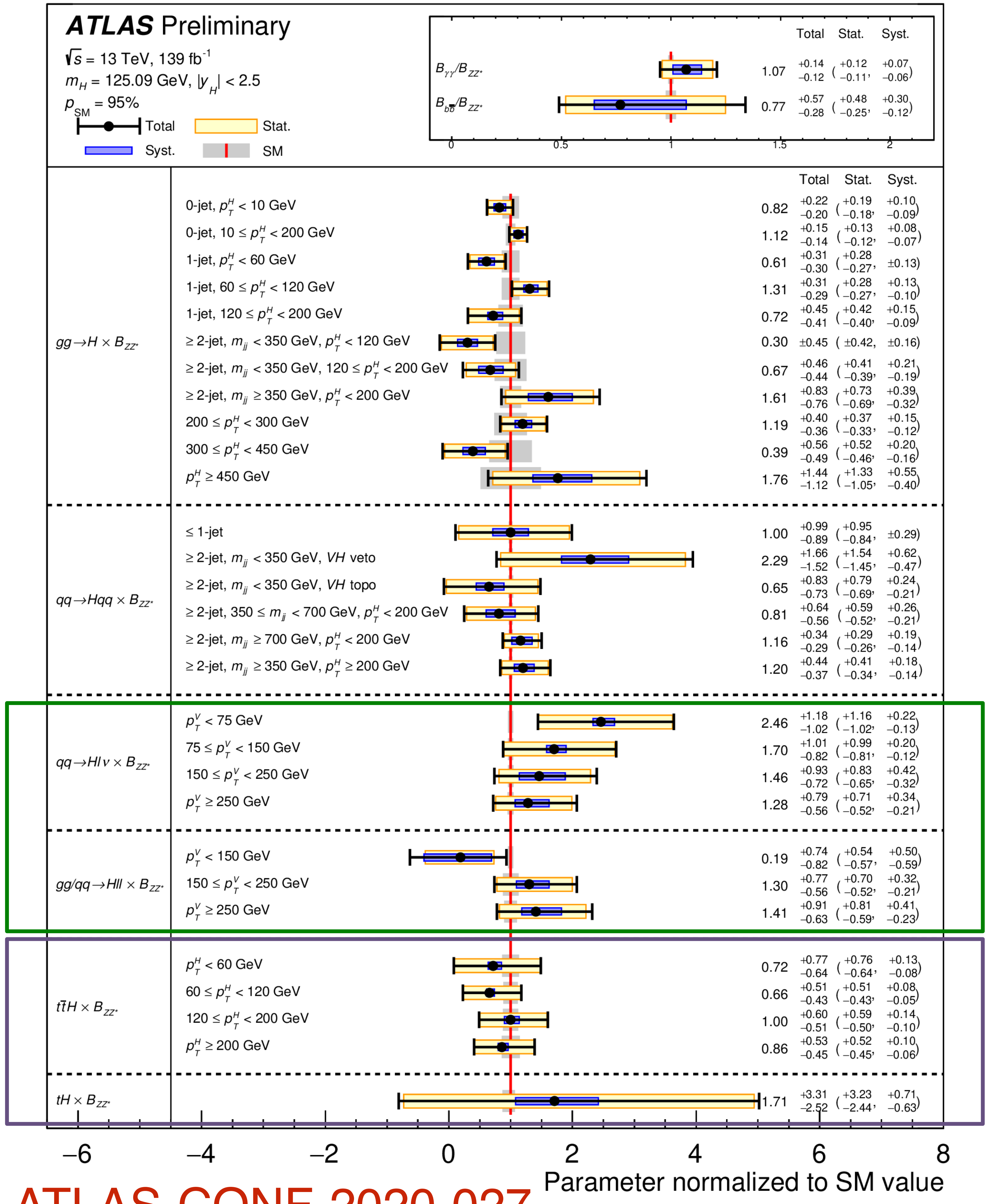




STXS results



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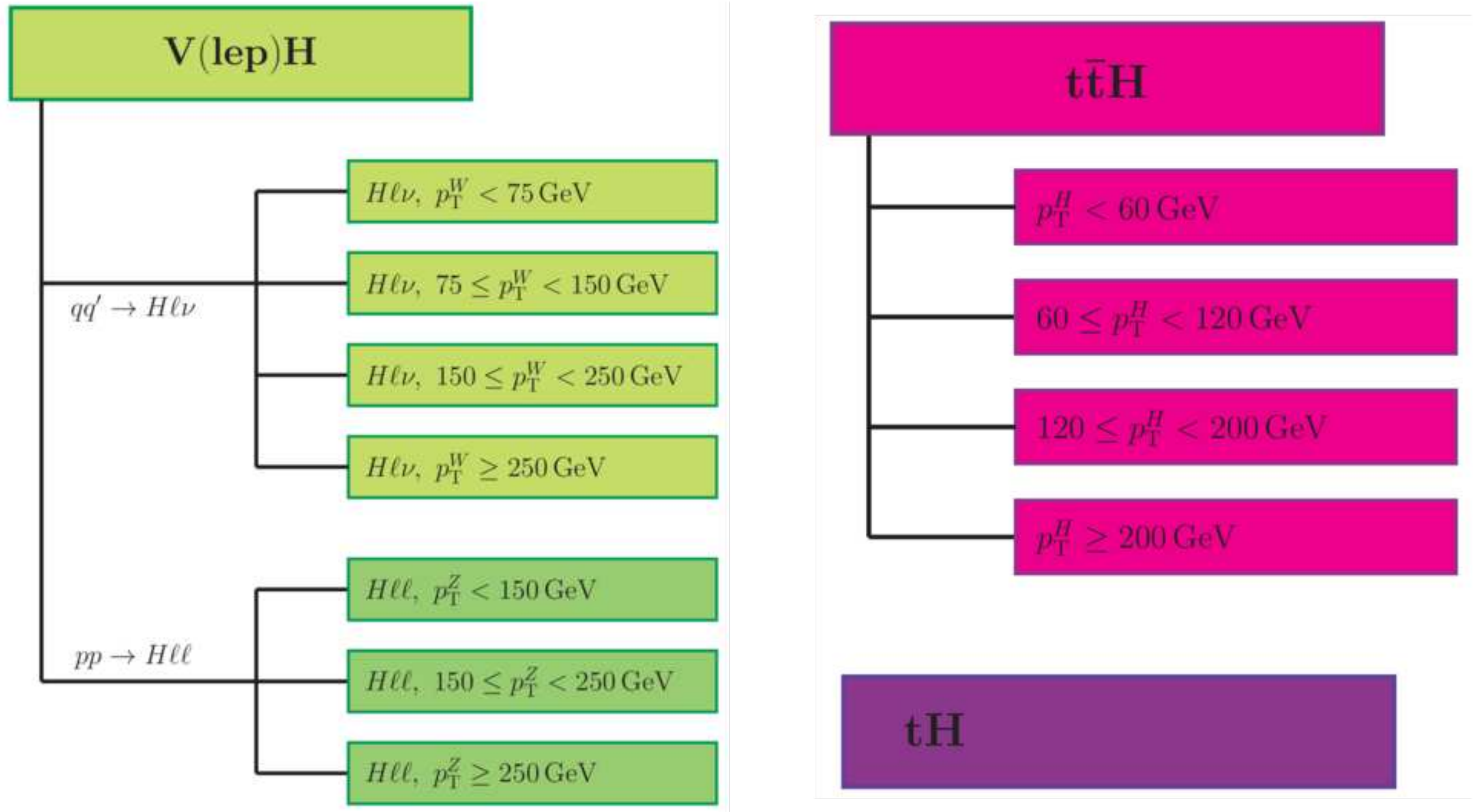


- 29 regions are probed, good compatibility with the SM prediction
- All regions are statistically limited; in some regions (e.g. ggF 0-jet) systematics are not negligible
- The upper limit on the tH cross section is 8.4 times the SM prediction

Coupling modifier ("kappa") interpretation

	ggF	VBF	VH	ttH+tH
$H\to\gamma\gamma$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\to ZZ$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (36-139 fb^{-1})
$H\to WW$	✔ (36 fb^{-1})	✔ (36 fb^{-1})		
$H\to\tau\tau$	✔ (36 fb^{-1})	✔ (36 fb^{-1})		
$H\to bb$		✔ (25-31 fb^{-1})	✔ (139 fb^{-1})	✔ (36 fb^{-1})

✔: channel included in the combination

Analyses of $H\to\mu\mu$ (139 fb^{-1}) and $H\to$invisible (139 fb^{-1}) are also included in relevant studies

Coupling modifier ("kappa")

- Leading order motivated framework: assign coupling modifier to each (effective) interaction vertex (e.g. κ_W, κ_t…)
- In this framework, production cross section times decay branch fraction of i→H→f can be parameterized as

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

  - (this allows for a consistent treatment of production and decay)
- Total width of Higgs boson can be expressed as

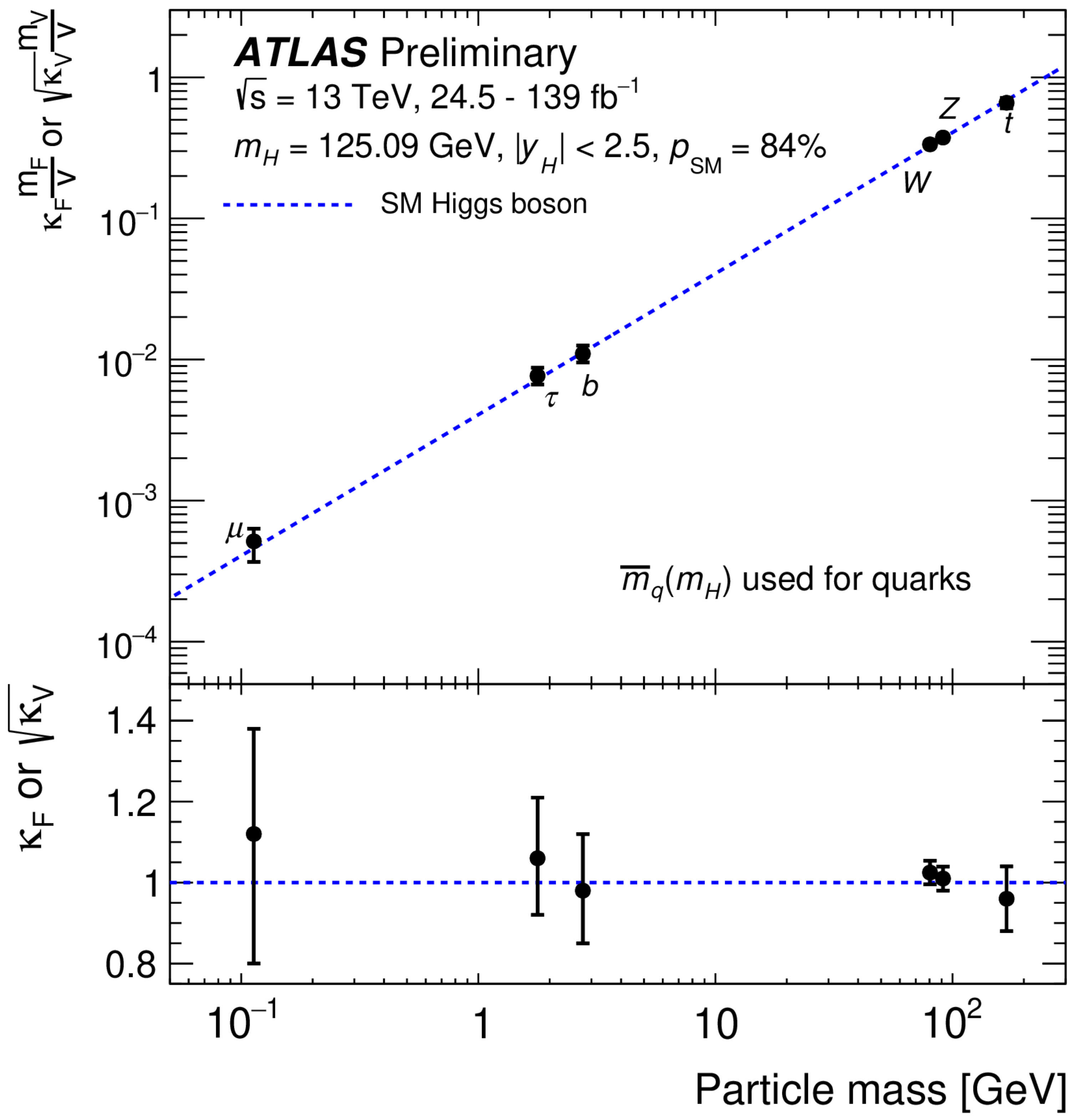
$$\Gamma_H(\boldsymbol{\kappa}, B_{\text{i.}}, B_{\text{u.}}) = \kappa_H^2(\boldsymbol{\kappa}, B_{\text{i.}}, B_{\text{u.}})\, \Gamma_H^{\text{SM}}$$

$B_{i.}$= BSM contribution to BR of invisible decays which are identified through a missing transverse momentum signature

$B_{u.}$= BSM contribution to BR of undetected decays to which none of the analyses in the combination are sensitive

Coupling modifier vs. particle mass

- Assume no BSM contribution in loop-induced processes (ggF, H→γγ etc.) or total width. Resolve ggF and Hγγ effective vertices
- Good agreement with the SM across 3 orders of magnitude of particle mass!



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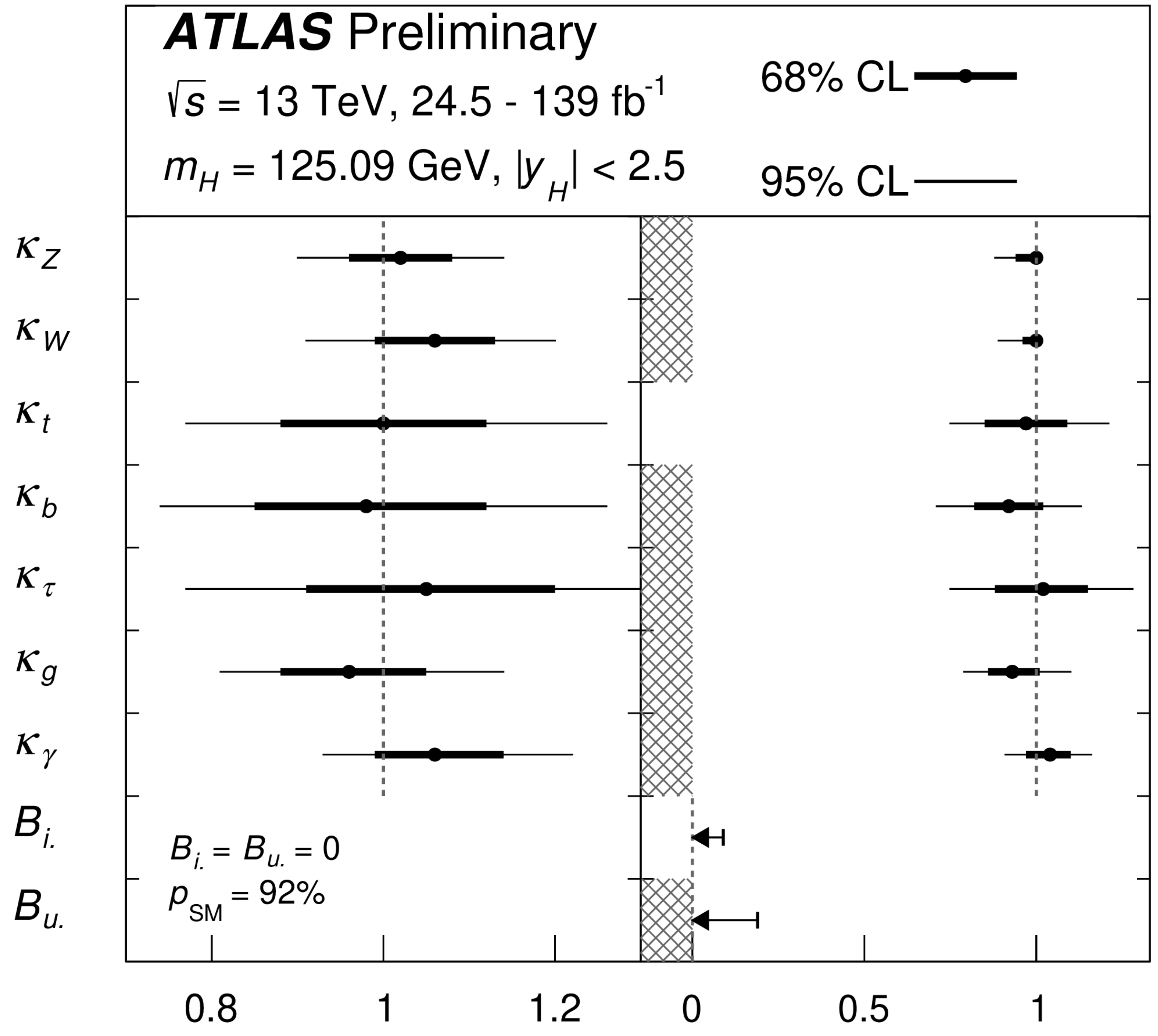
Coupling modifier: different scenarios

- Not resolving ggF and Hγγ effective vertices (and introducing corresponding coupling modifiers κ_g, κ_γ), explore two different scenarios for total width:
  - **Left**: assume $B_{i.}=B_{u.}=0$
  - **Right**: constrain $B_{i.}$ and $B_{u.}$ using H→invisible analysis and $\kappa_V < 1$
- All coupling modifiers are measured to be compatible with the SM



$B_{i.}<0.09$ at 95% CL
$B_{u.}<0.19$ at 95% CL

ATLAS-CONF-2020-027

Interpretation of STXS measurements with Effective Field Theory (EFT)

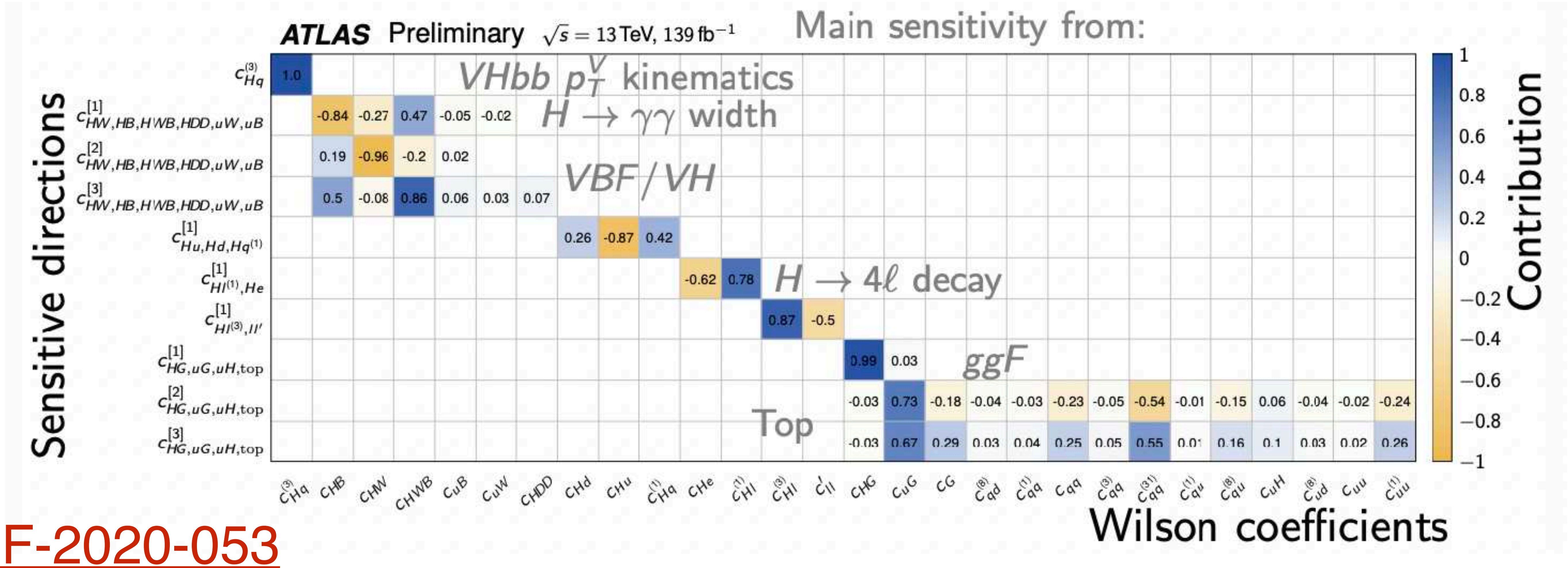
	ggF	VBF	VH	ttH+tH
$H\to\gamma\gamma$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\to ZZ$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\to bb$			✔ (139 fb^{-1})	

✔: channel included in the combination

Interpretation of STXS with EFT

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

- Parameterize the signal strengths, $(XS*BR)_{meas}/(XS*BR)_{SM}$, directly with Wilson coefficients of d=6 SMEFT operators
- Rotate the SMEFT basis cj to eigenvector cj' and fit 10 sensitive eigenvectors simultaneously
  - these eigenvectors are obtained from identifying groups of operators with similar impact and performing eigenvector decomposition for the covariance matrix of the measurement



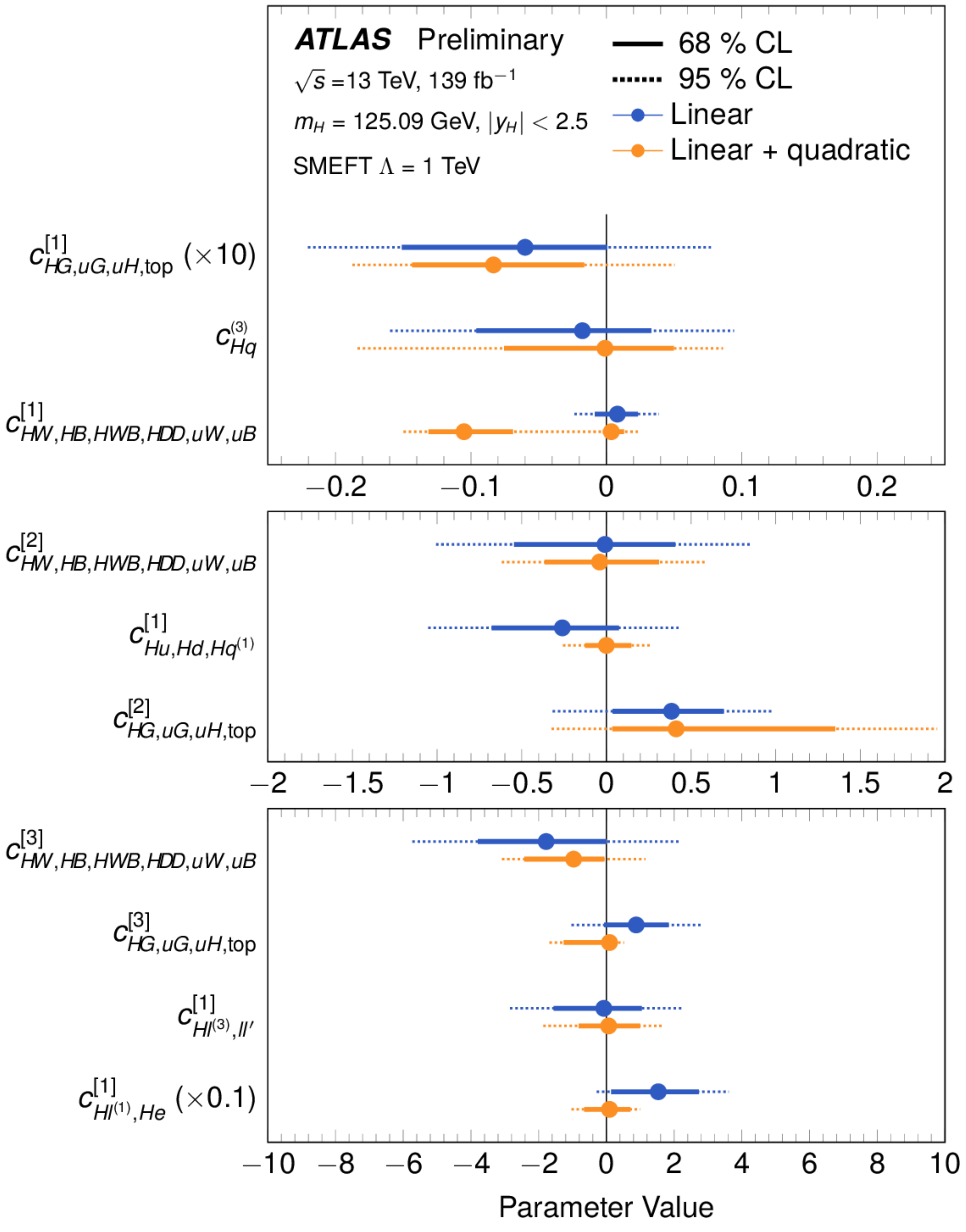
ATLAS-CONF-2020-053

Interpretation of STXS with EFT

From a simultaneous fit

- All measured parameters are consistent with the SM expectation within their uncertainties

- Comparison of the linear model and the linear+quadratic model shows sizeable sensitivity to operators suppressed by Λ^4



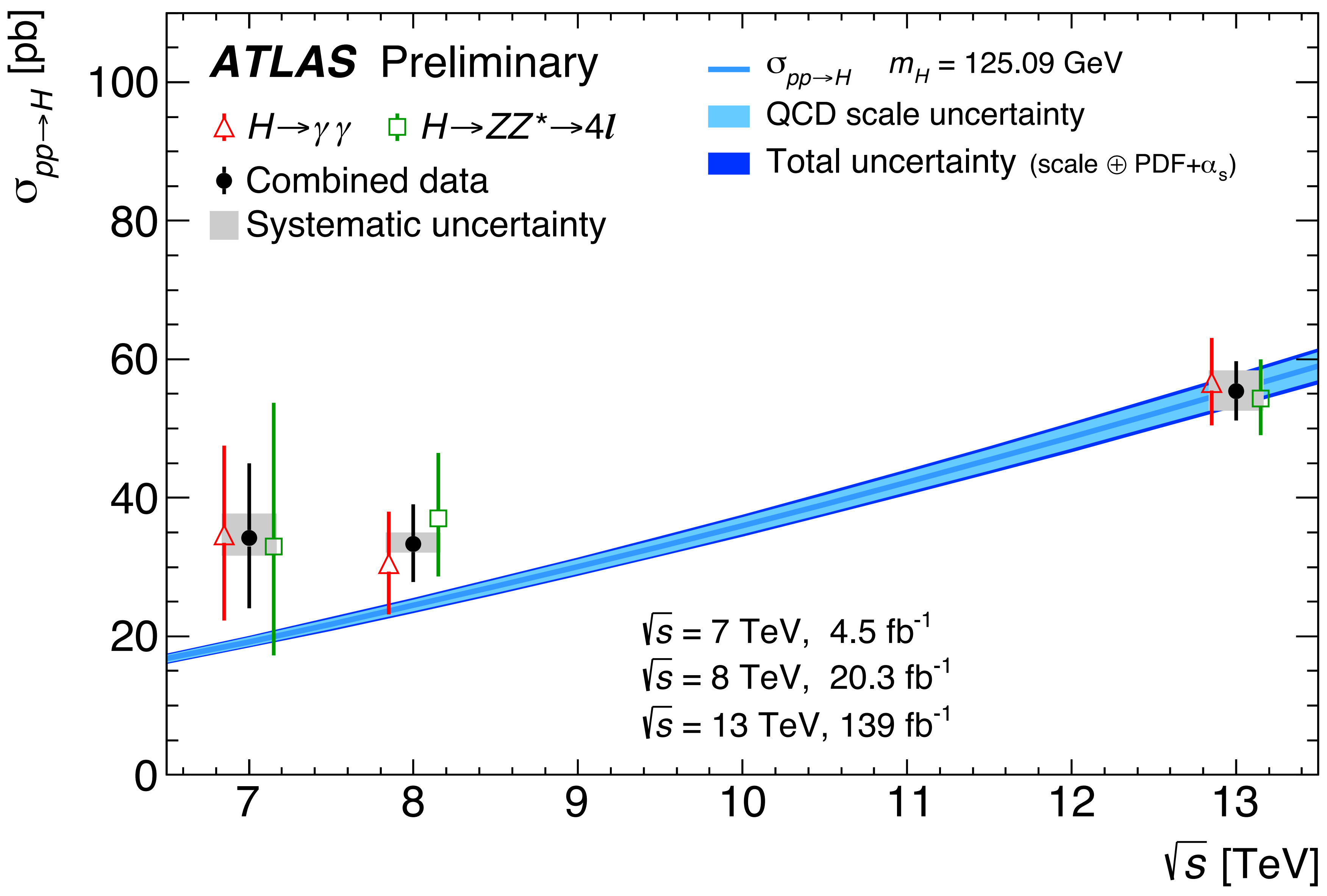
ATLAS-CONF-2020-053

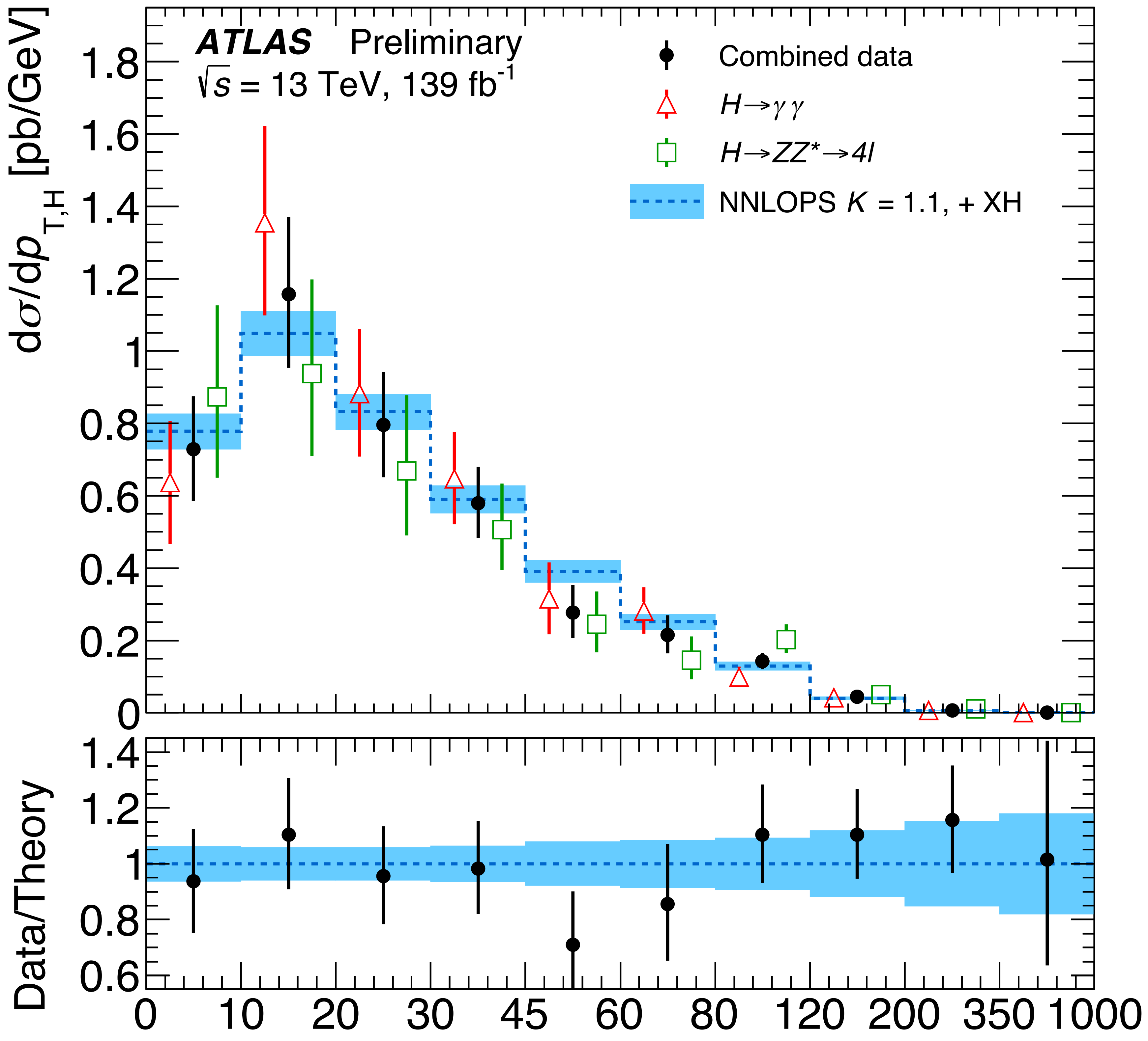
Combined measurements of the total and differential cross sections of Higgs boson production

Including the $H \to \gamma\gamma$ and $H \to ZZ^* \to$ 4-lepton decay channels

Using the full Run-2 dataset recorded by ATLAS, corresponding to 139 fb^{-1}

Total and differential cross sections





For total cross section at 13 TeV,

$$combined\ measurement : 55.4^{+4.3}_{-4.2} pb$$

(~8% precision)

$$SM\ prediction : 55.6 \pm 2.5 pb$$

Higgs transverse momentum

(~20% precision in 9 bins)

ATLAS-CONF-2019-032

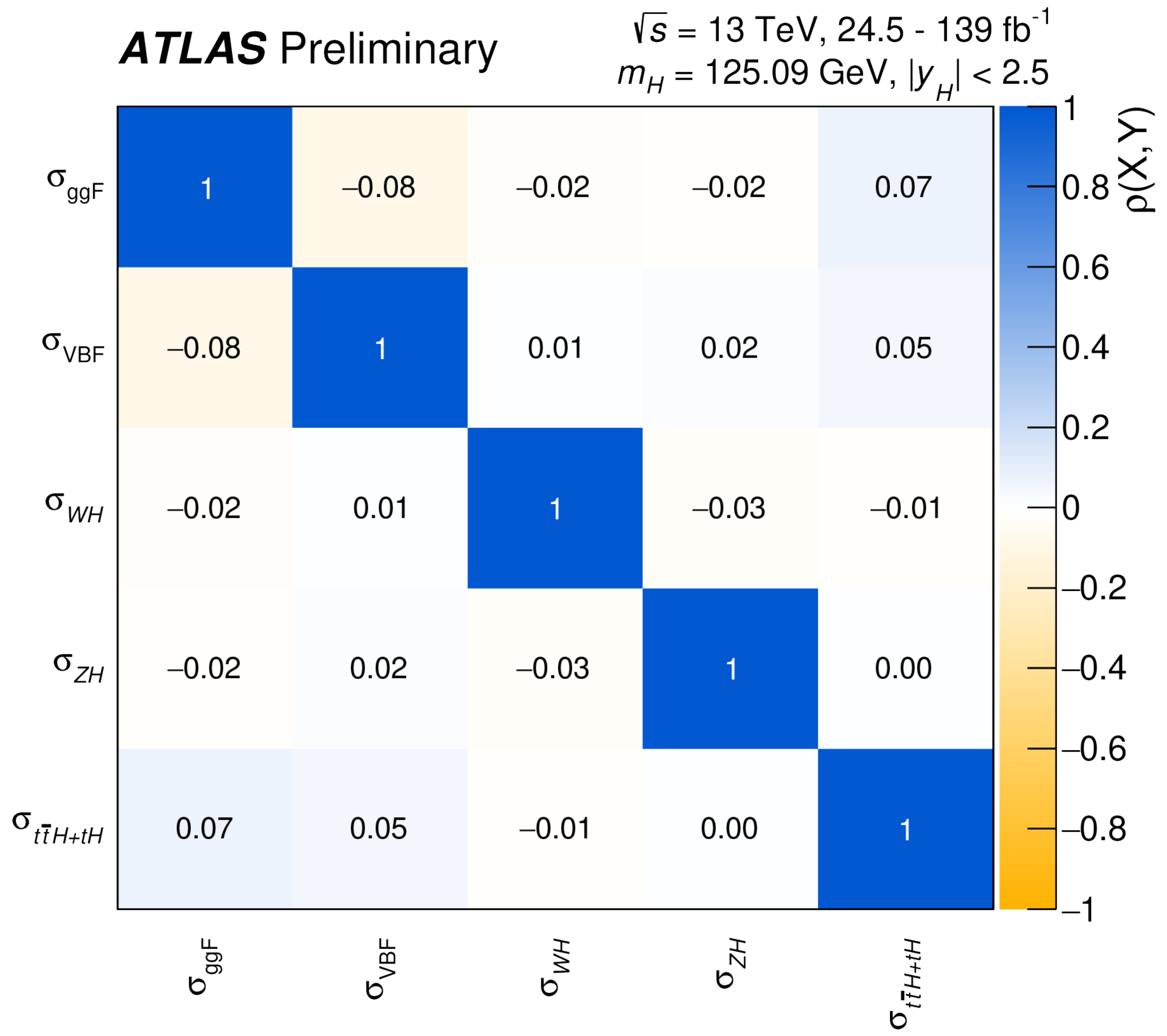
- The results from the two decay channels are found to be compatible with each other, and their combination agrees with the Standard Model prediction

Summary

- Based on up to **139 fb^{-1}** of Run 2 data, ATLAS performed combined measurements of Higgs boson production and decays:
  - inclusive signal strength
  - production cross sections
  - simplified template cross sections
- Based on **139 fb^{-1}** of full Run 2 data, ATLAS performed combined measurements of total and differential Higgs boson cross sections
- All major production modes (ggF, VBF, WH, ZH, ttH) are observed
- All measurements are in agreement with the SM within the improved uncertainties
- Results can be interpreted using “kappa”, EFT and BSM models

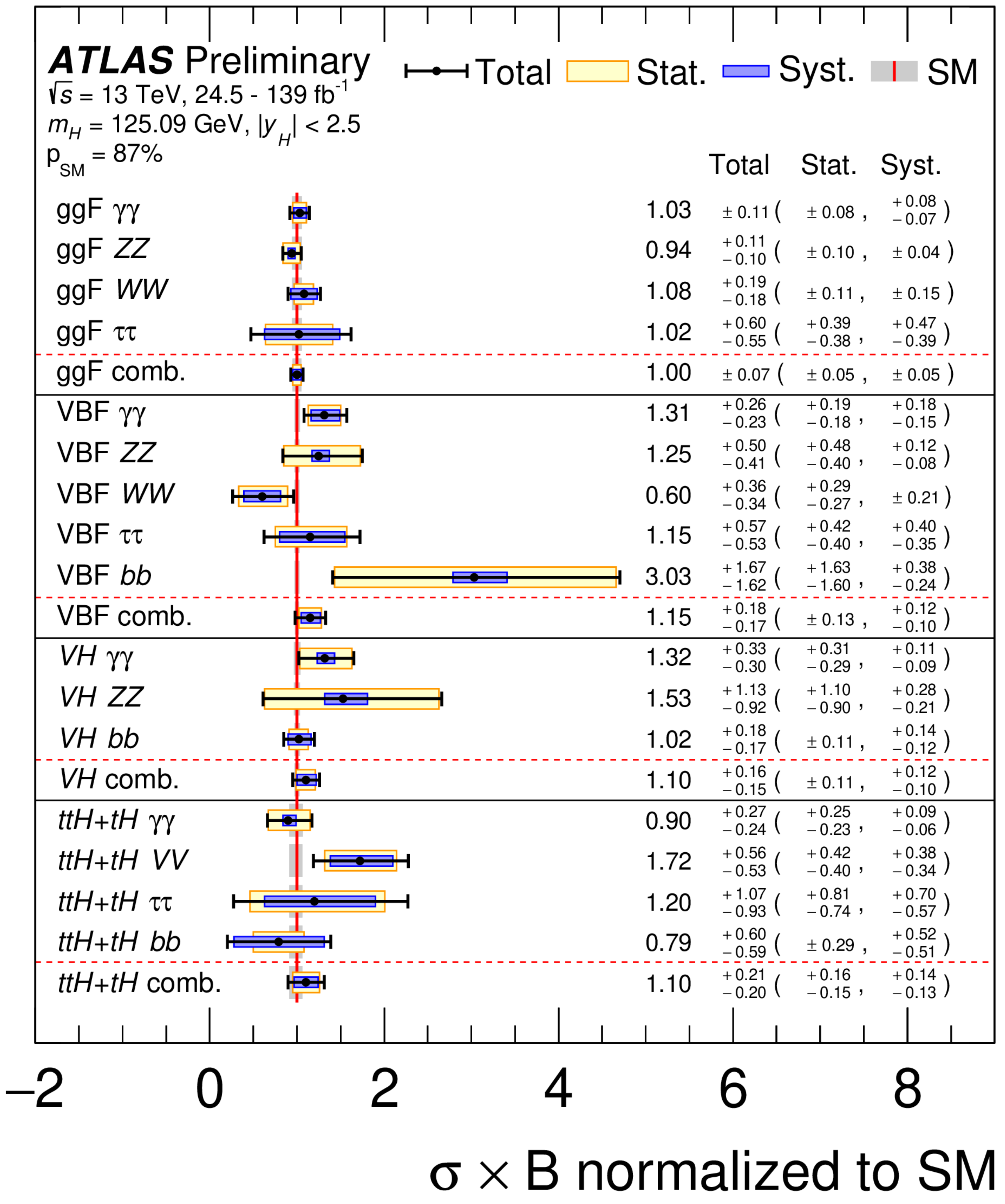
Backup slides

Production mode cross sections (assuming the SM decays)



ATLAS-CONF-2020-027

Production mode cross sections in each decay channel



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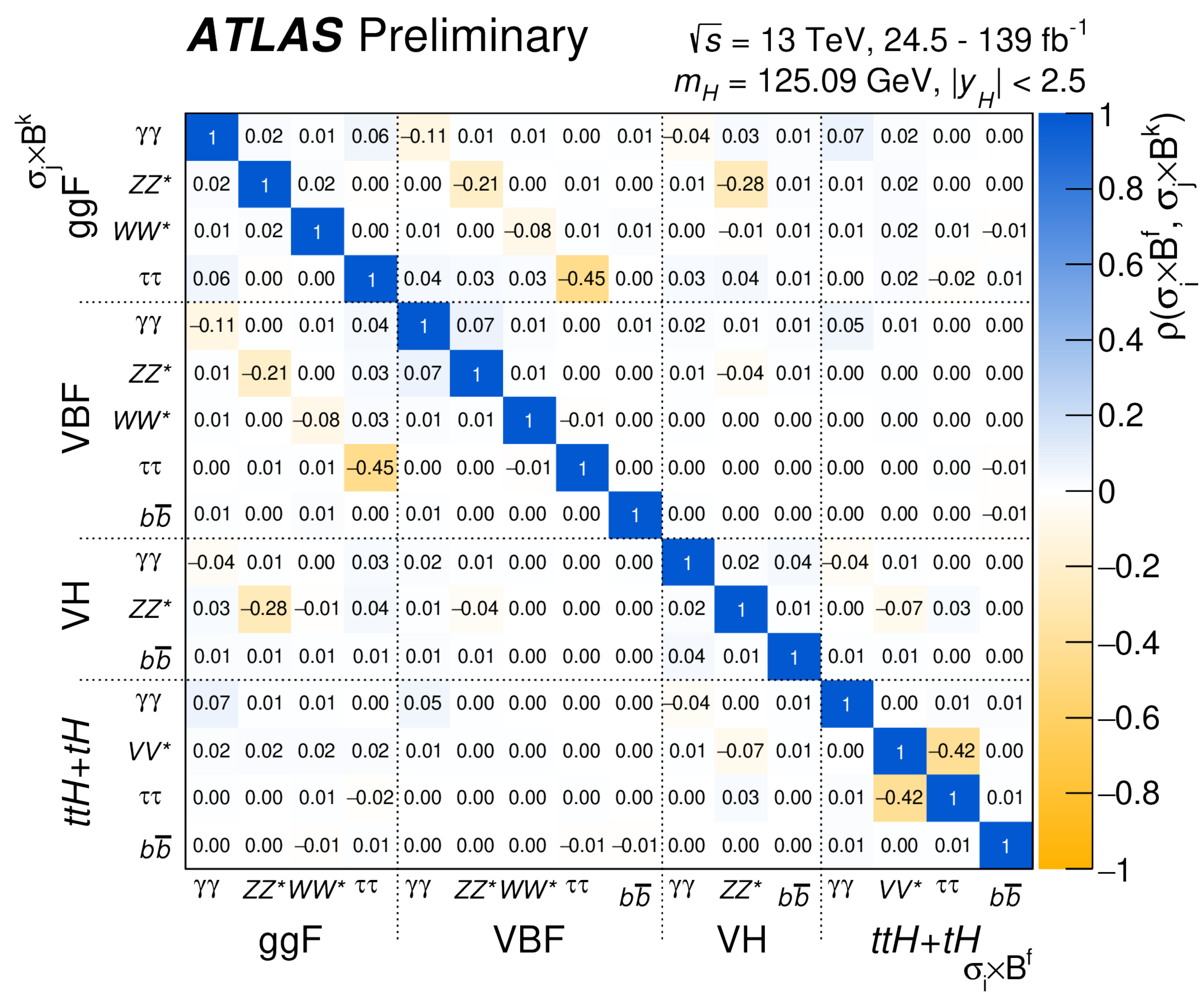
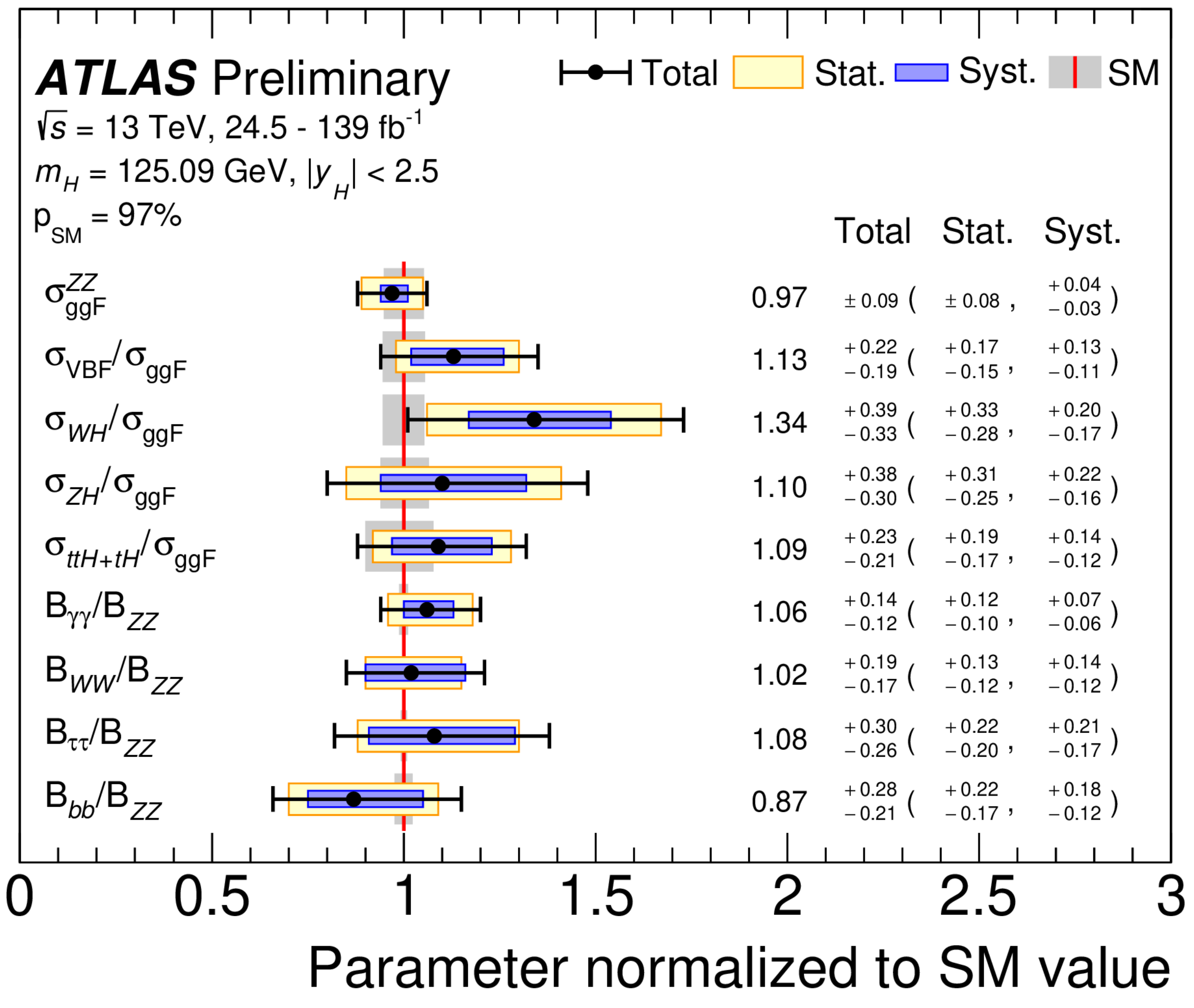
Production mode cross sections in each decay channel



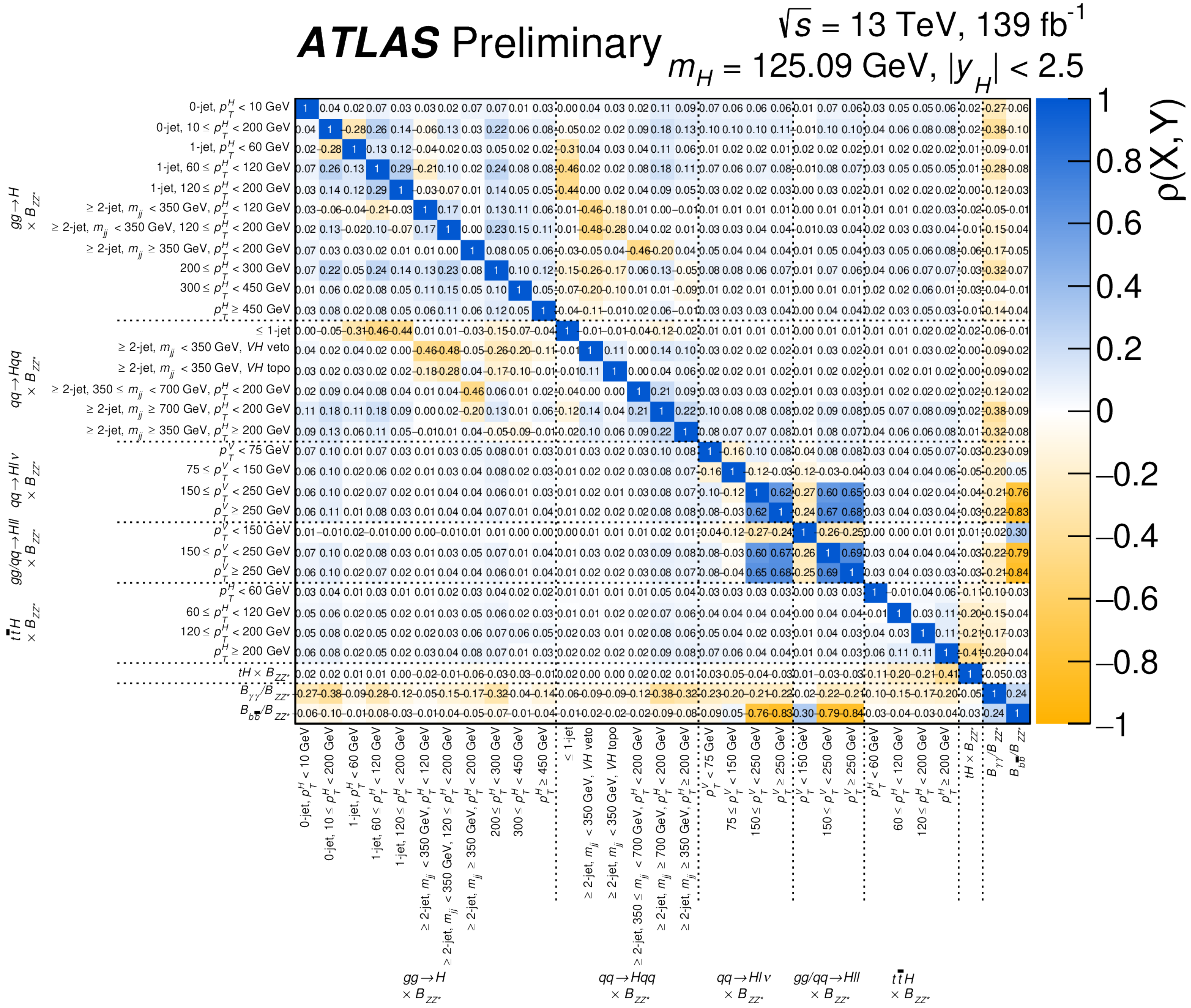
ATLAS-CONF-2020-027

Production mode cross sections and decay branch ratios



ATLAS-CONF-2020-027

STXS results



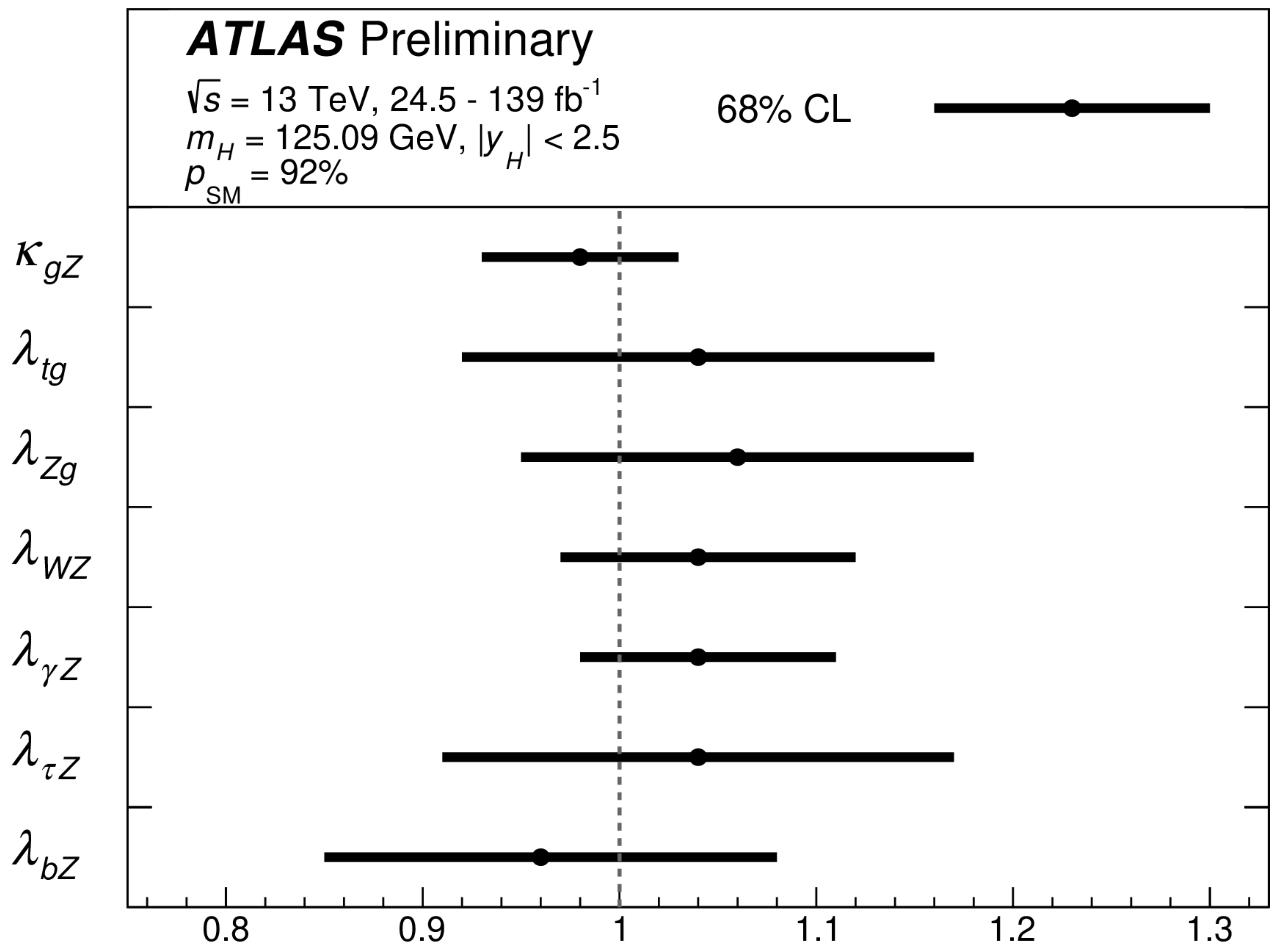
ATLAS-CONF-2020-027

Parametrizations using coupling modifier ("kappa")

Production	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
$\sigma(t\bar{t}H)$	-	-	-	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	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	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	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

ATLAS-CONF-2020-027

Coupling modifier interpretation: no assumption on total width



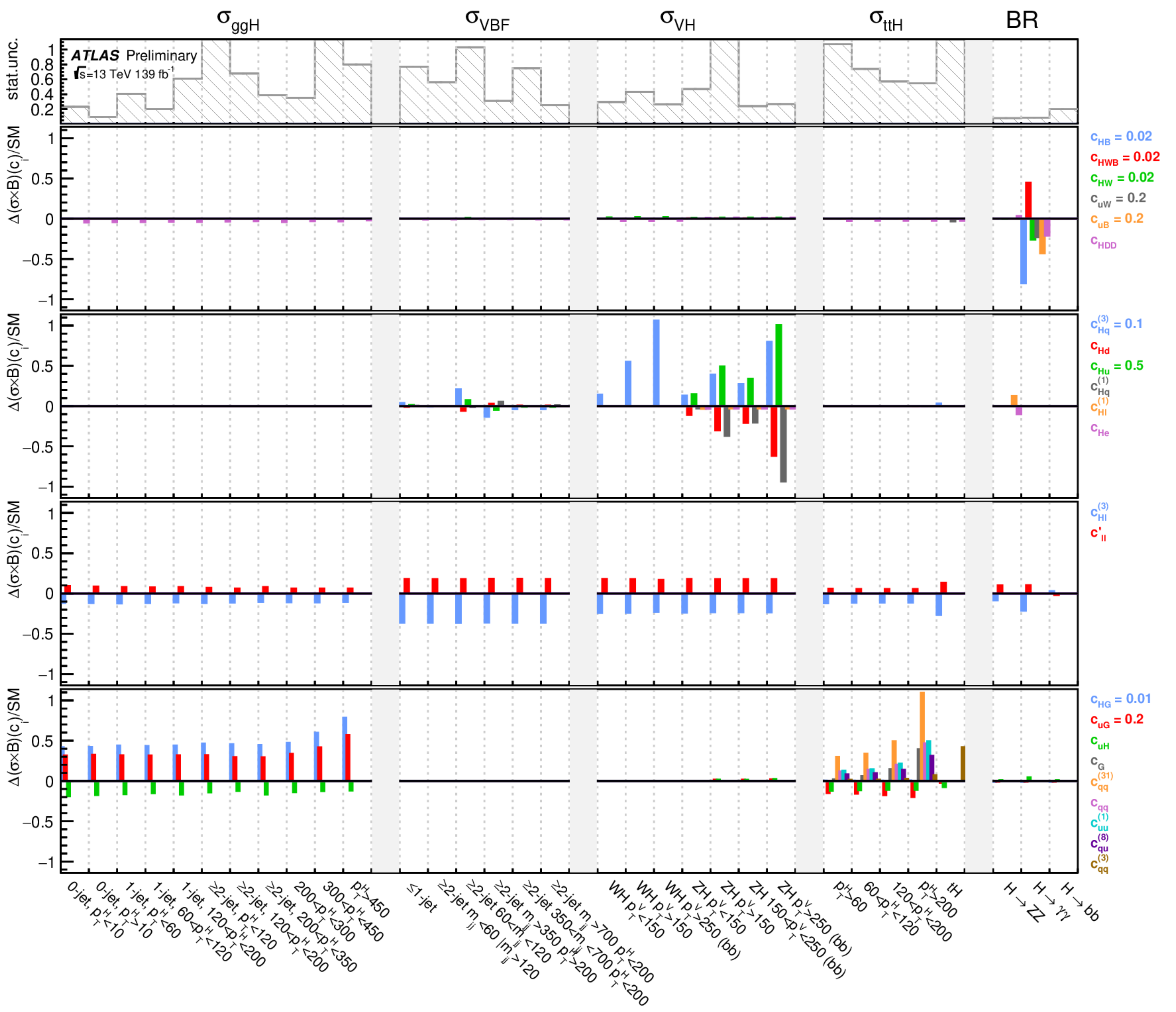
ATLAS-CONF-2020-027

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

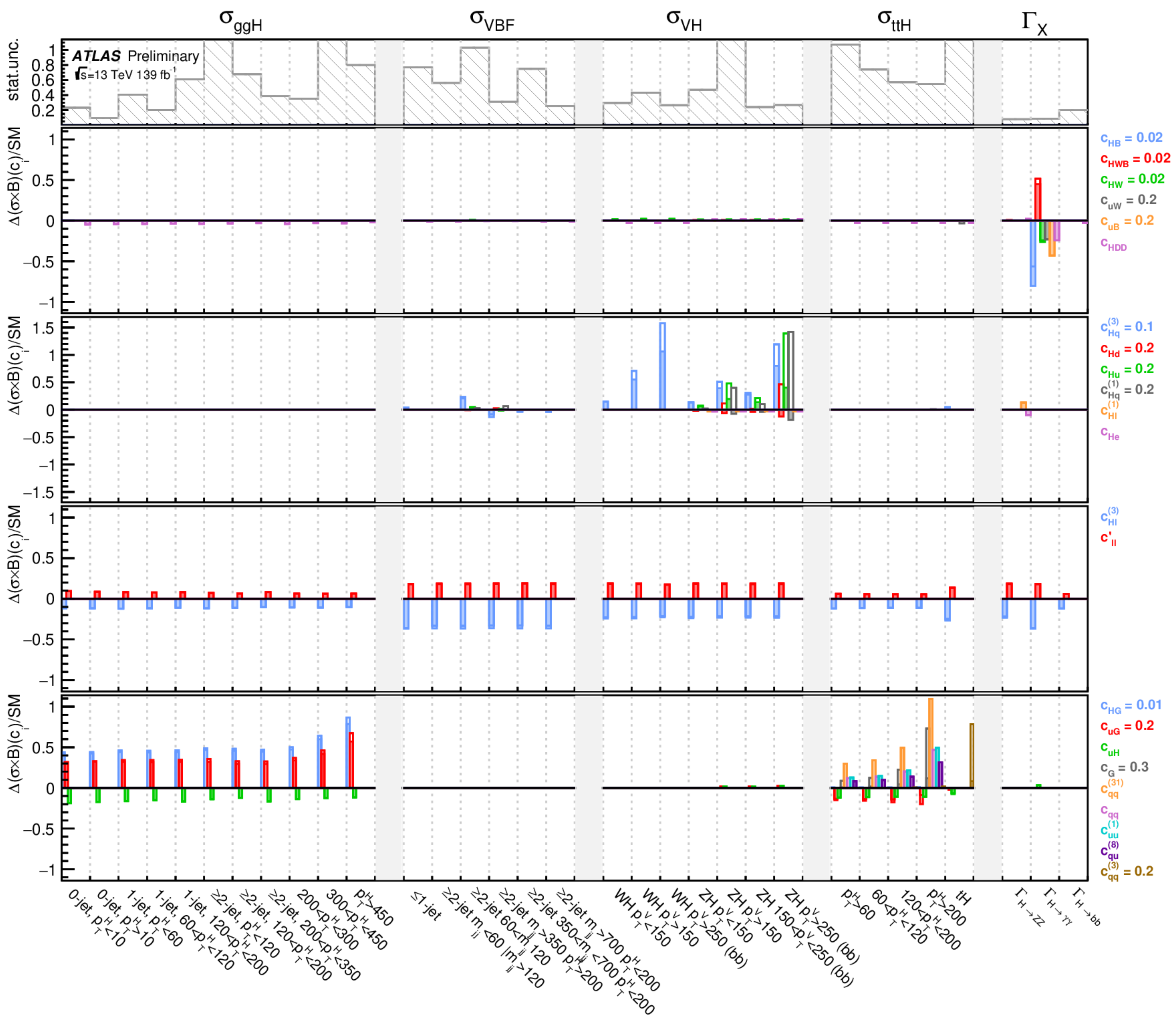
ATL-PHYS-CONF-2020-053

Interpretation of STXS with EFT



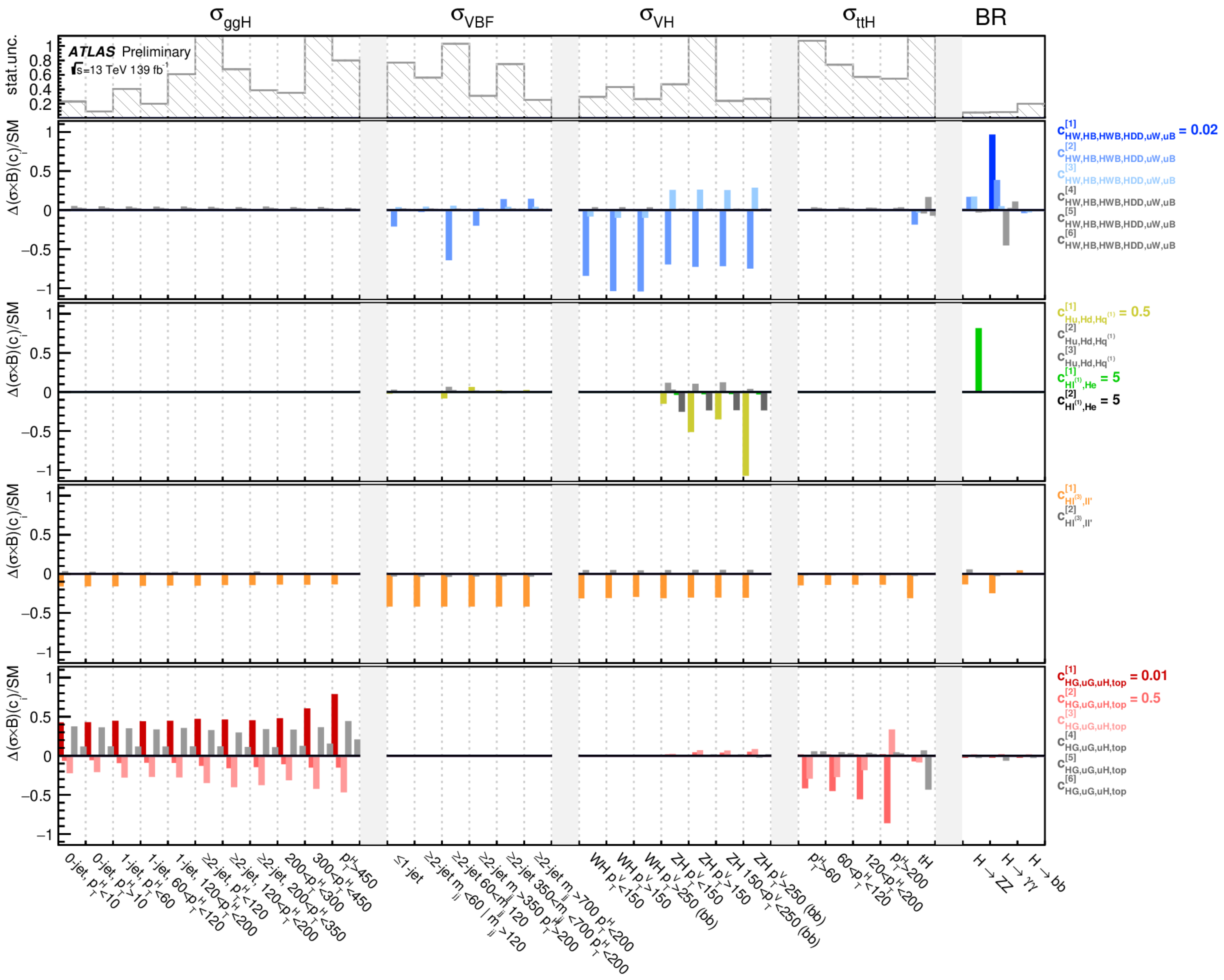
ATL-PHYS-CONF-2020-053

Interpretation of STXS with EFT



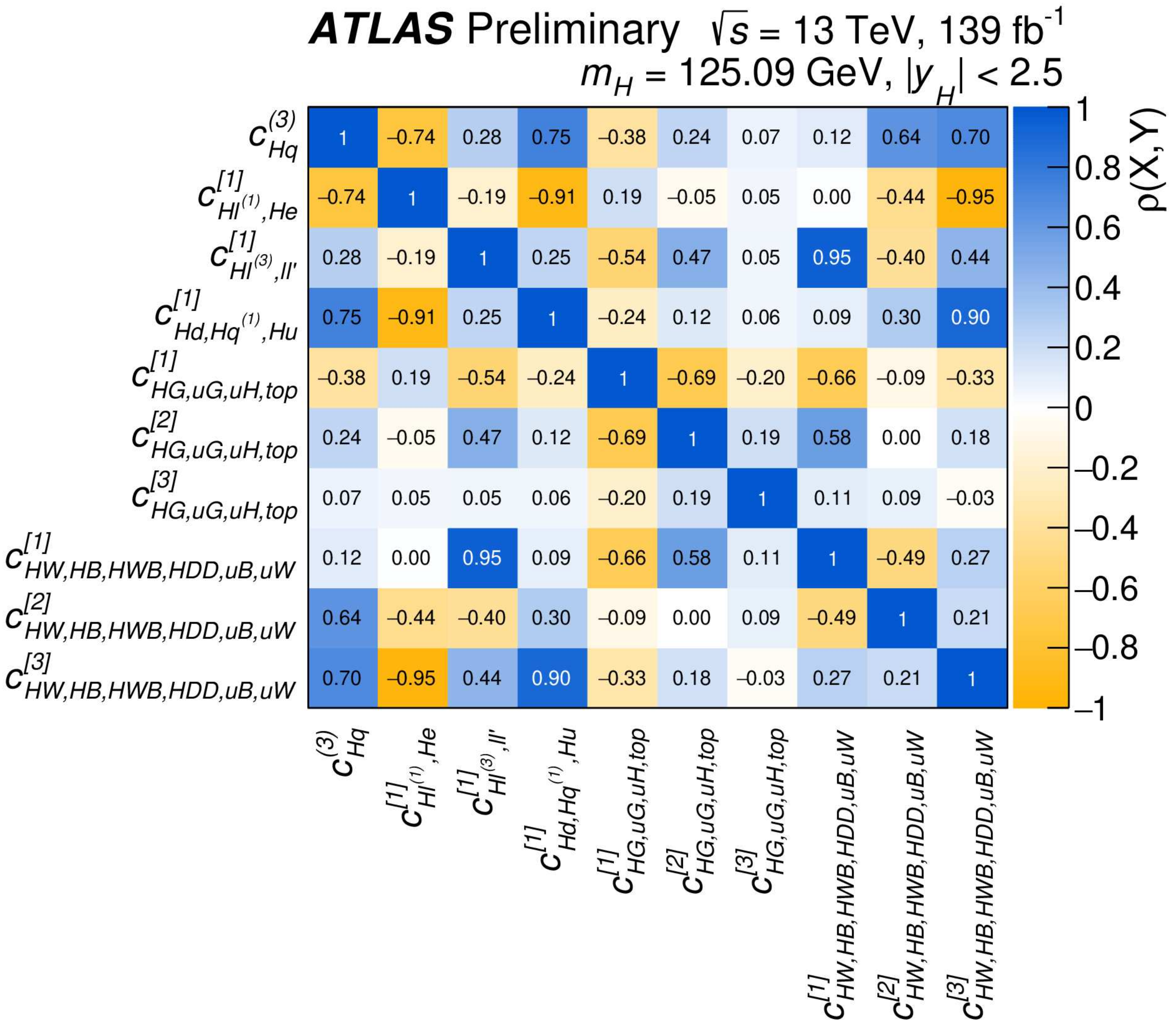
ATL-PHYS-CONF-2020-053

Interpretation of STXS with EFT



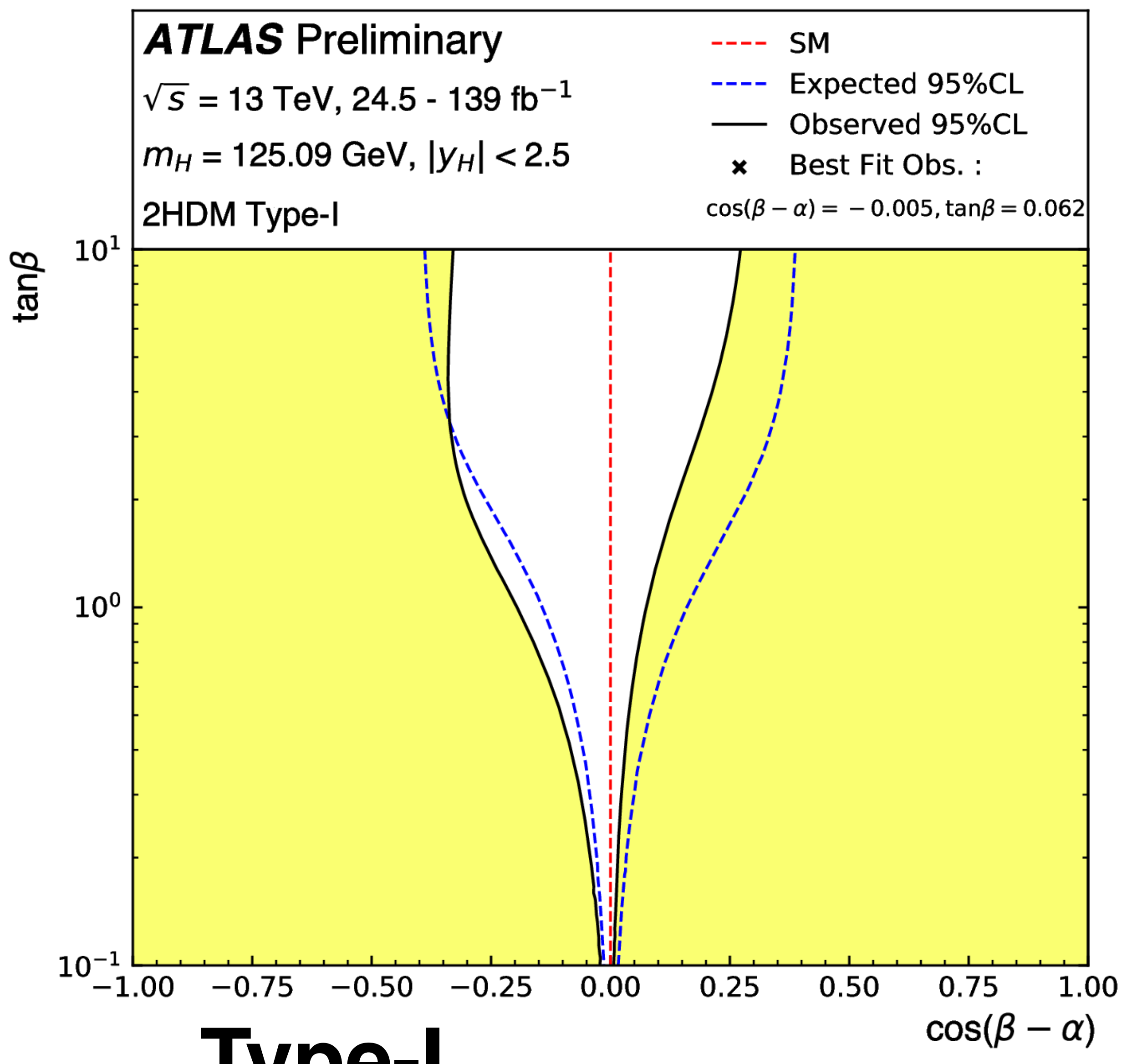
ATL-PHYS-CONF-2020-053

Interpretation of STXS with EFT

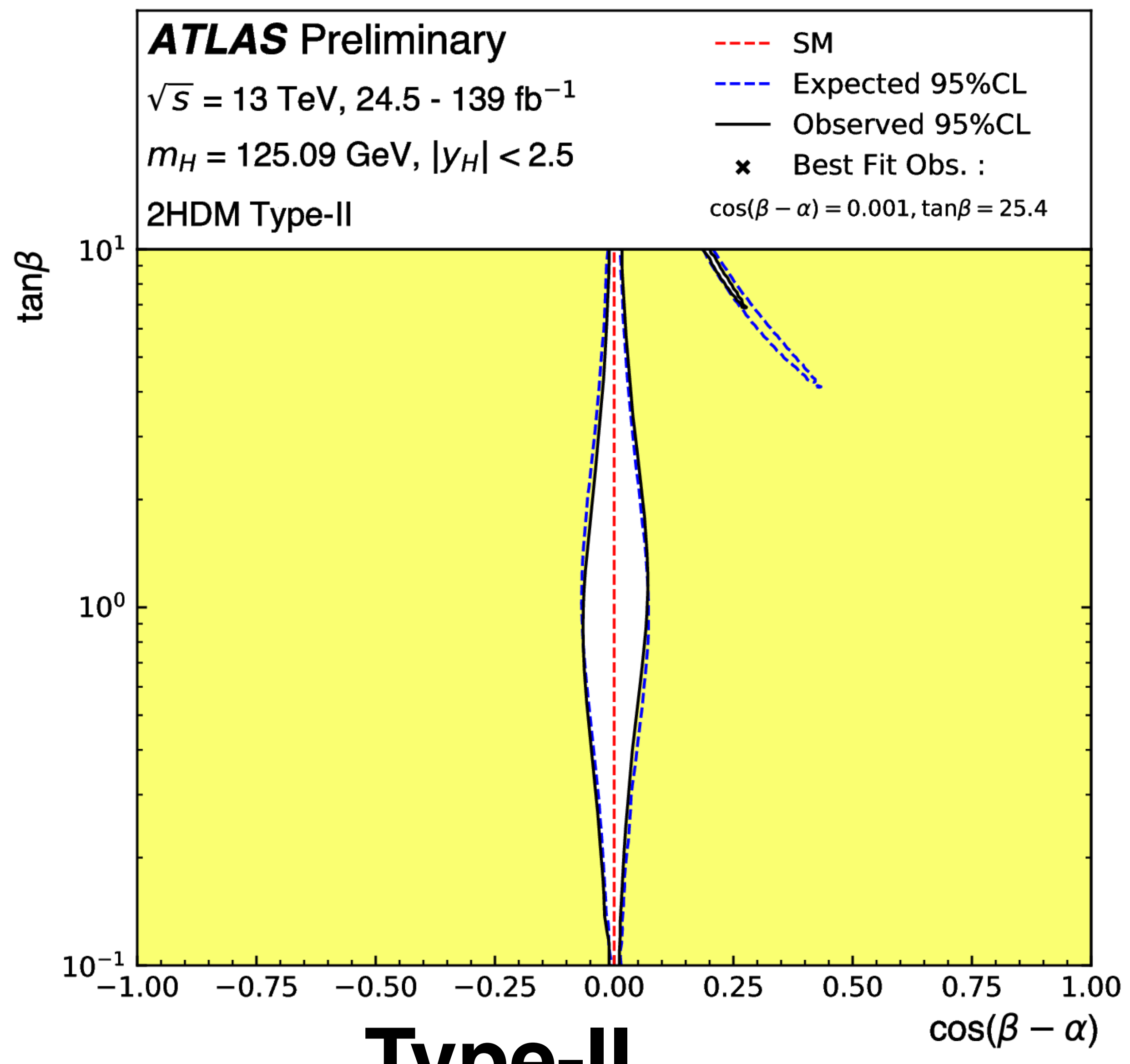


ATL-PHYS-CONF-2020-053

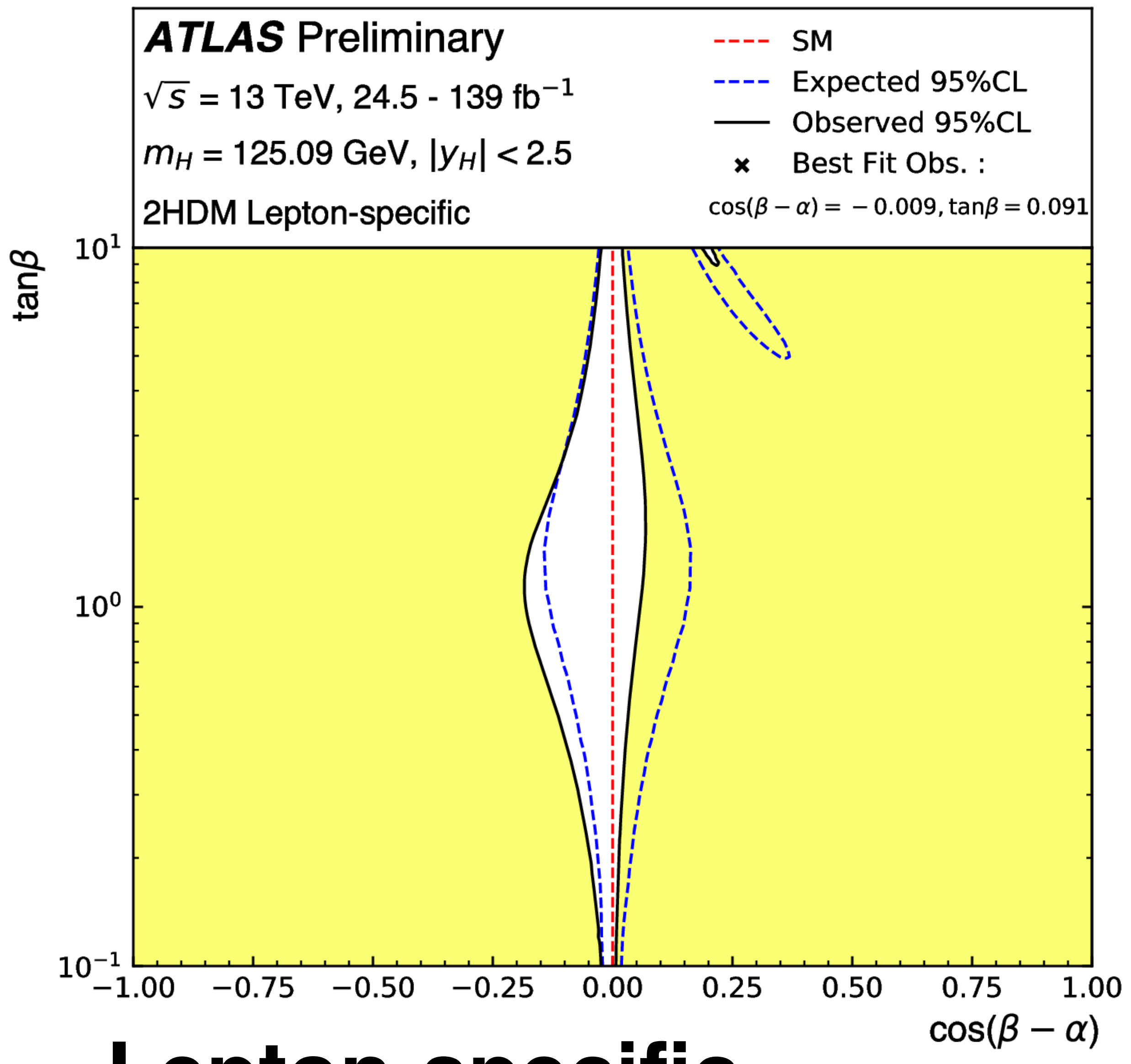
Constraints on Two Higgs Doublet Model (2HDM)



Type-I

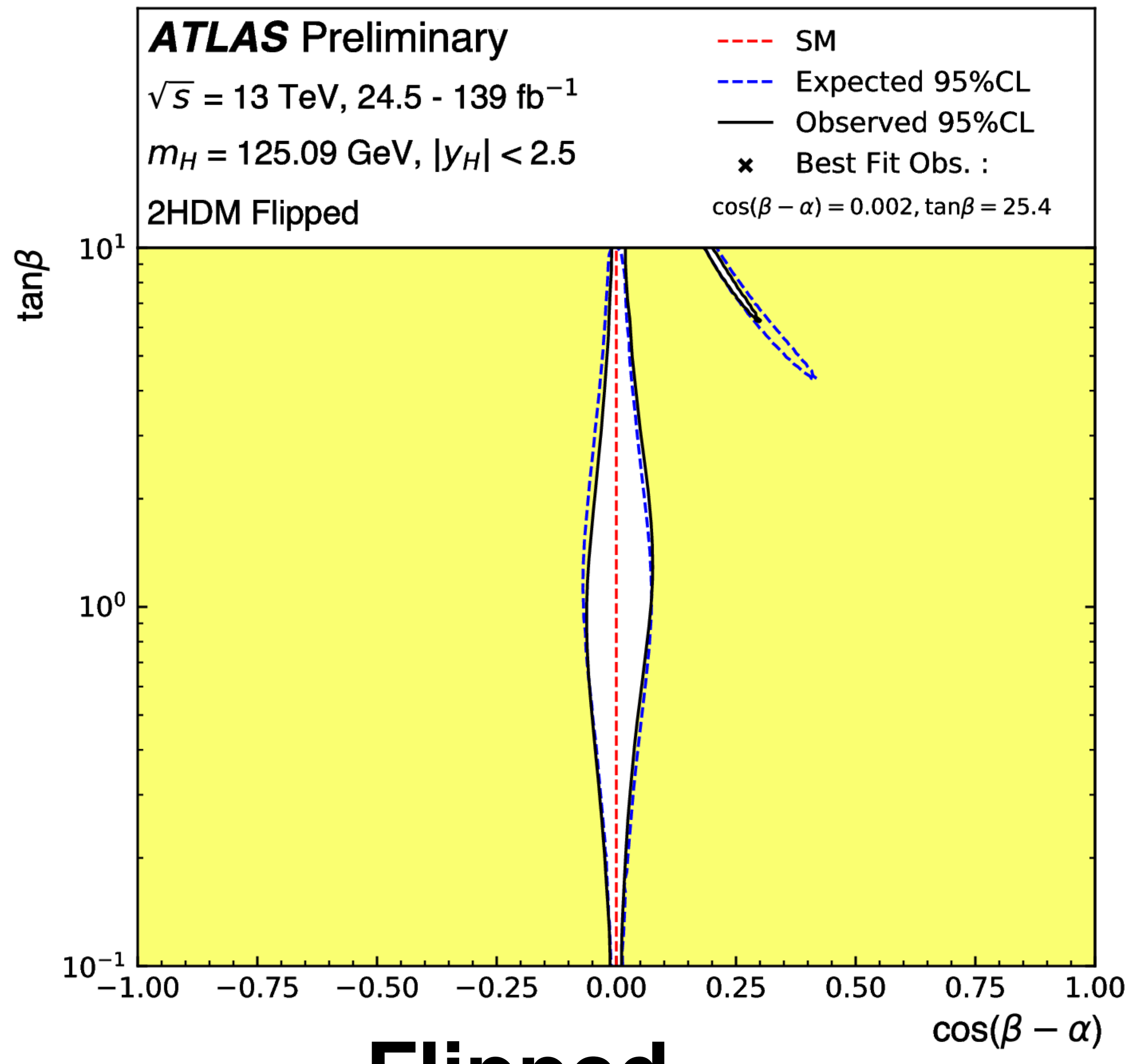


Type-II



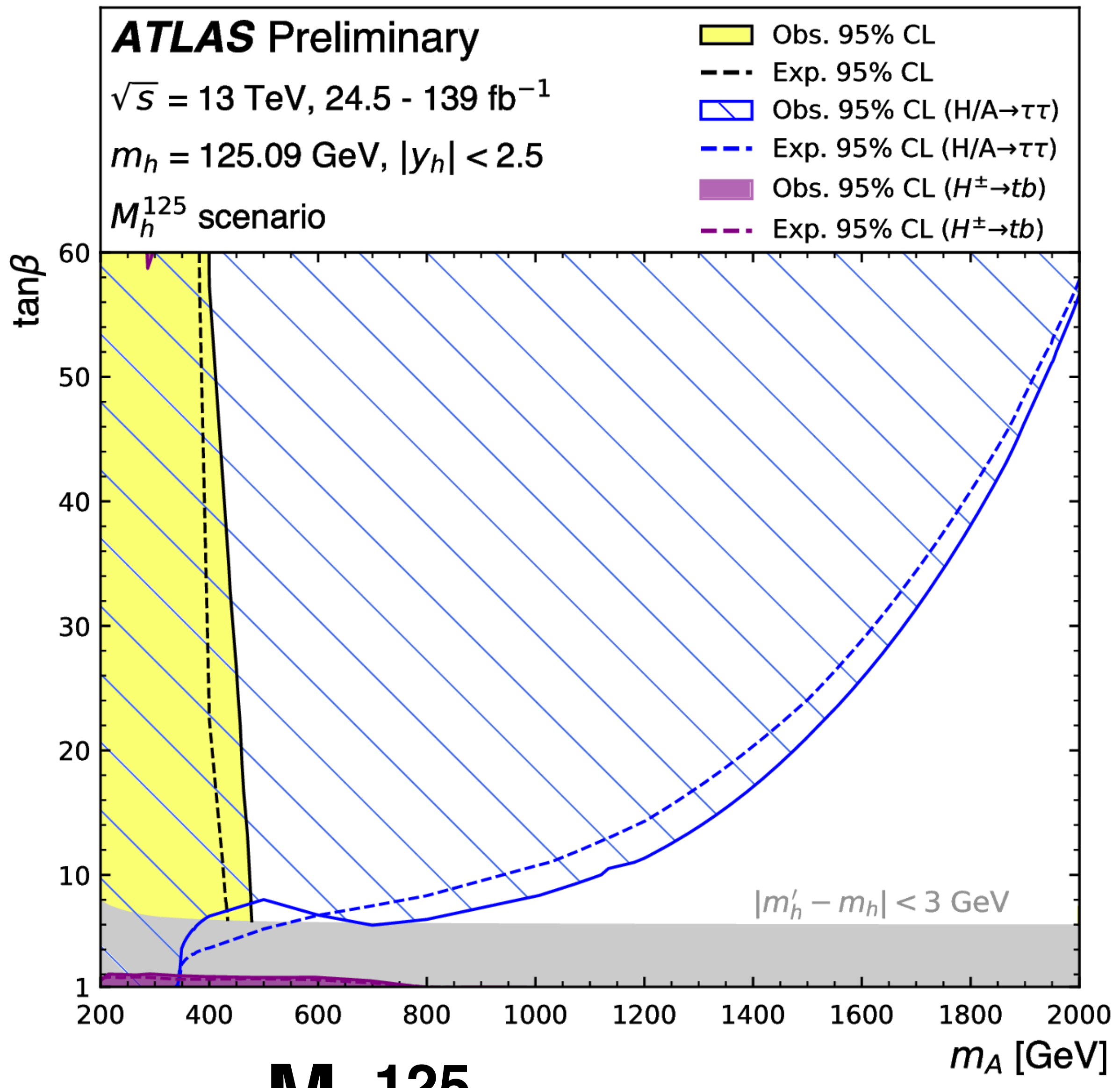
Lepton-specific

ATLAS-CONF-2020-027

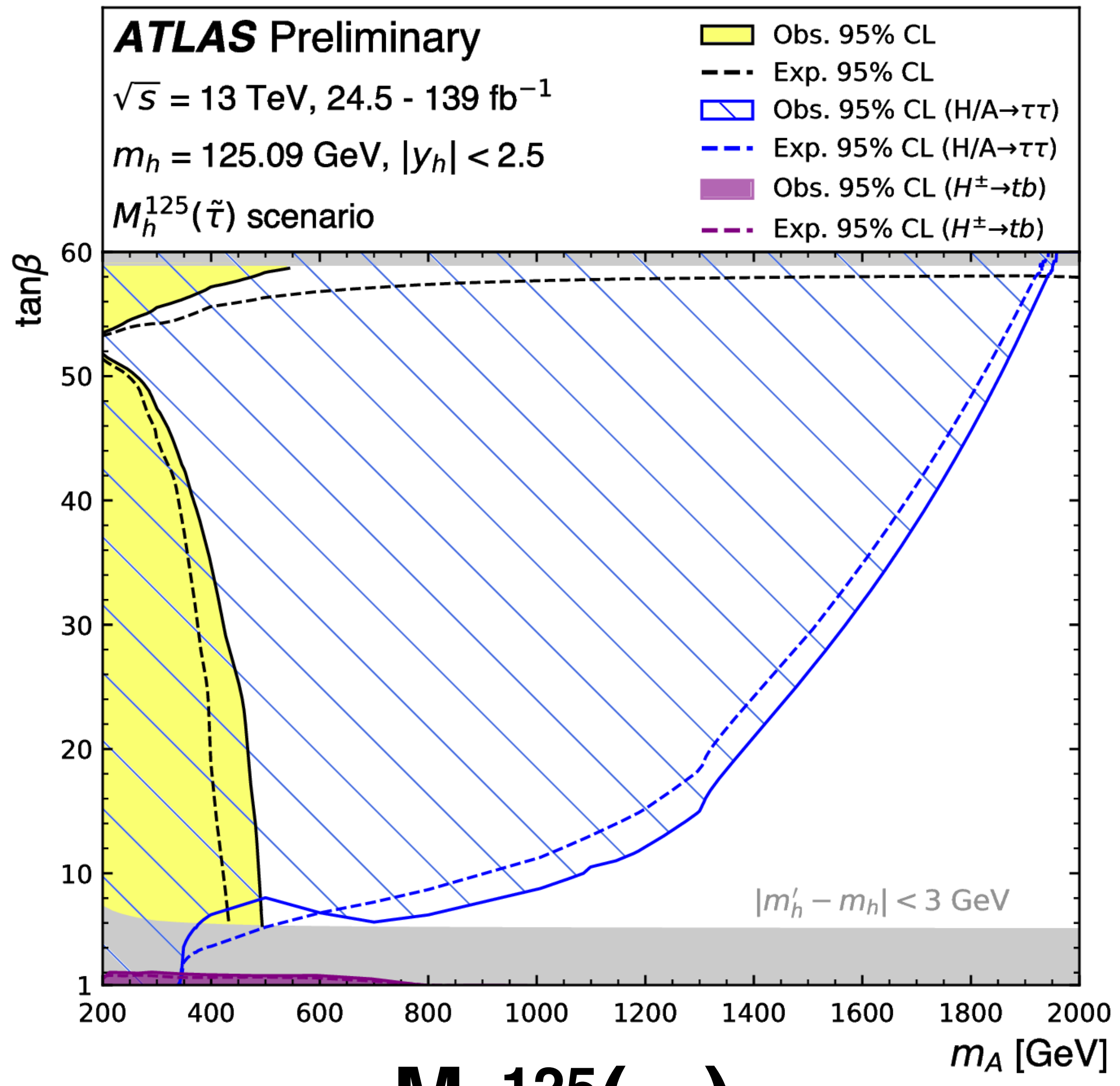


Flipped

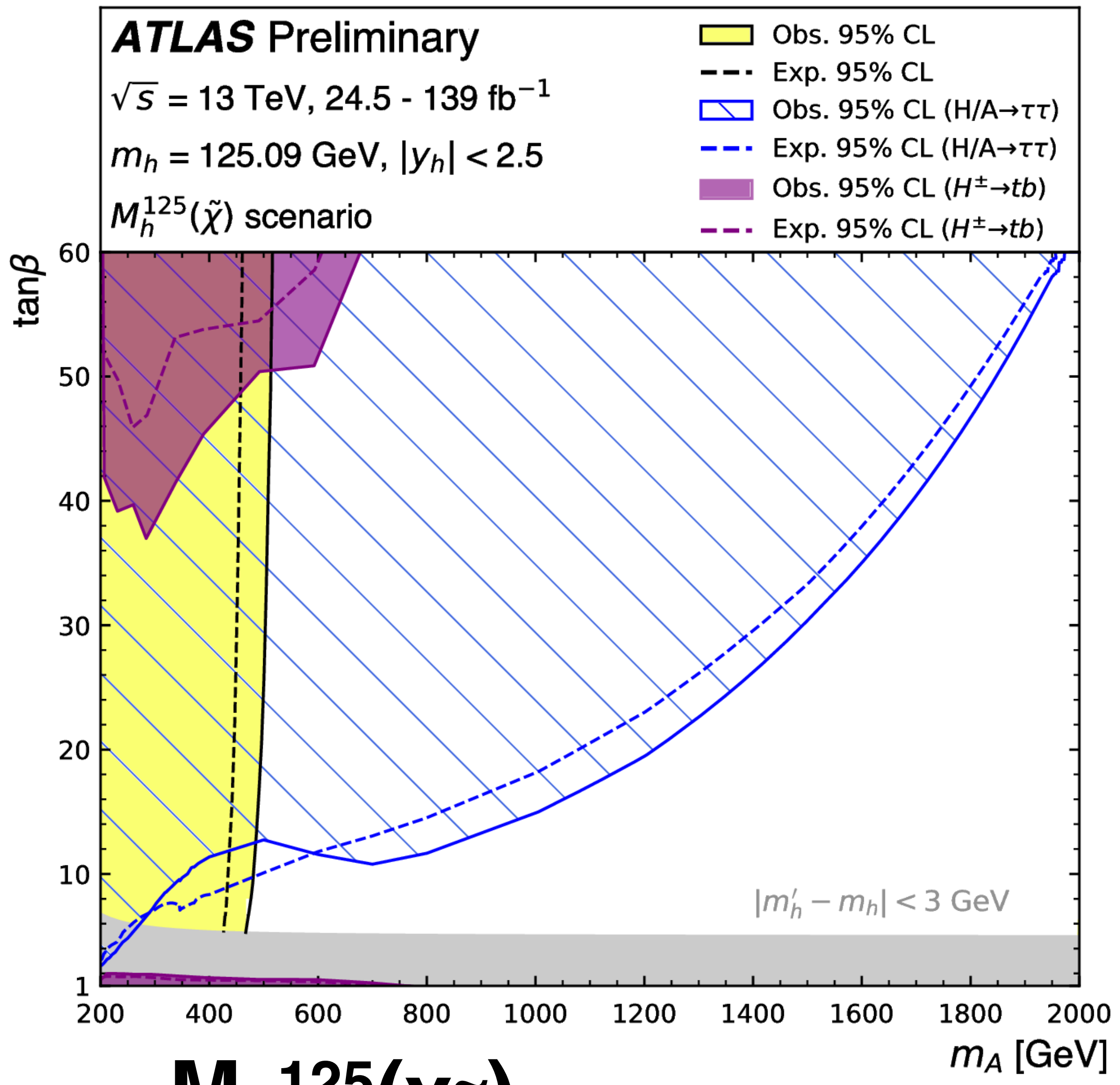
Constraints on Minimal Supersymmetric Standard Model (MSSM)



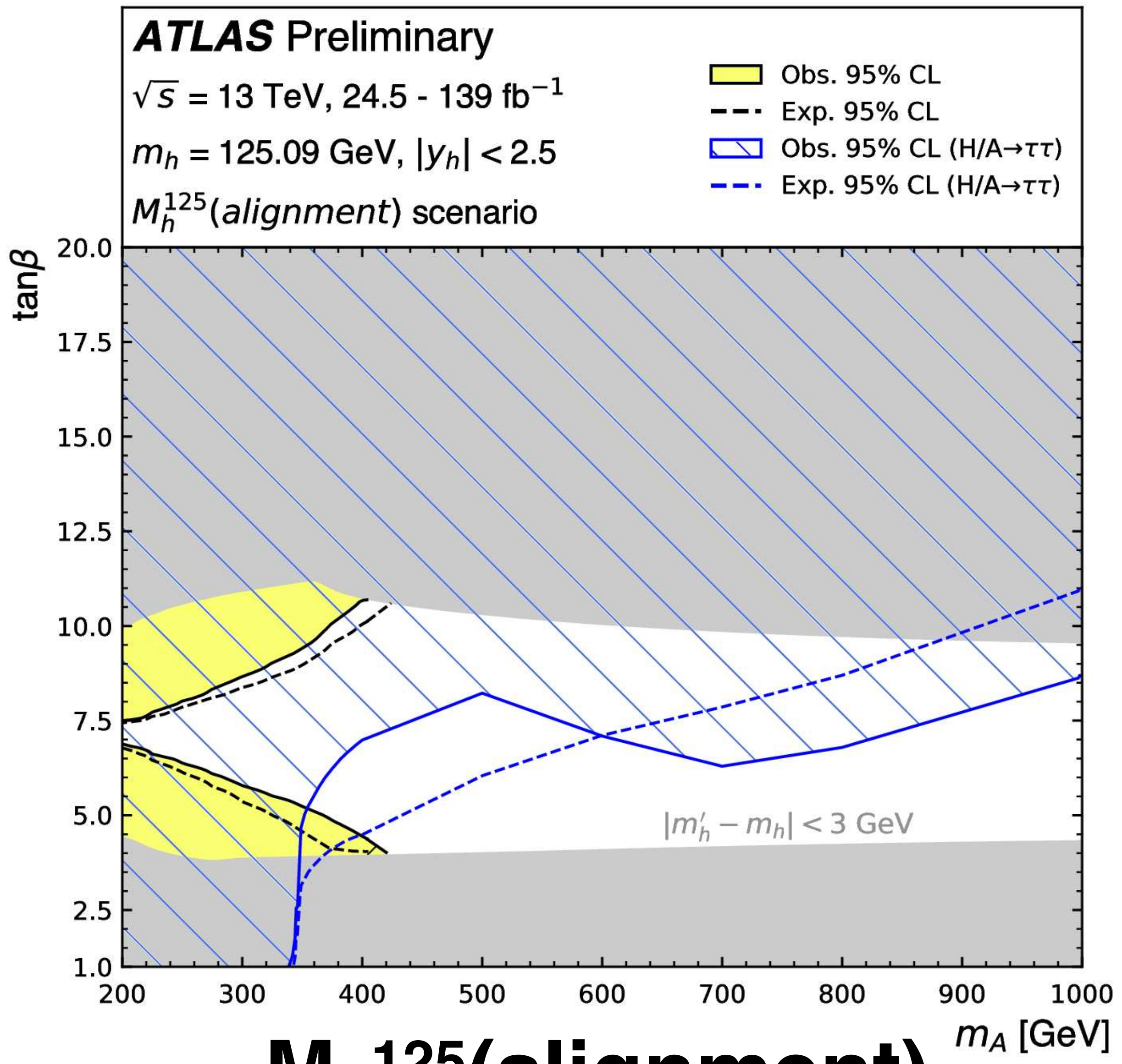
M_h^{125}



$M_h^{125}(\tau^{\sim})$



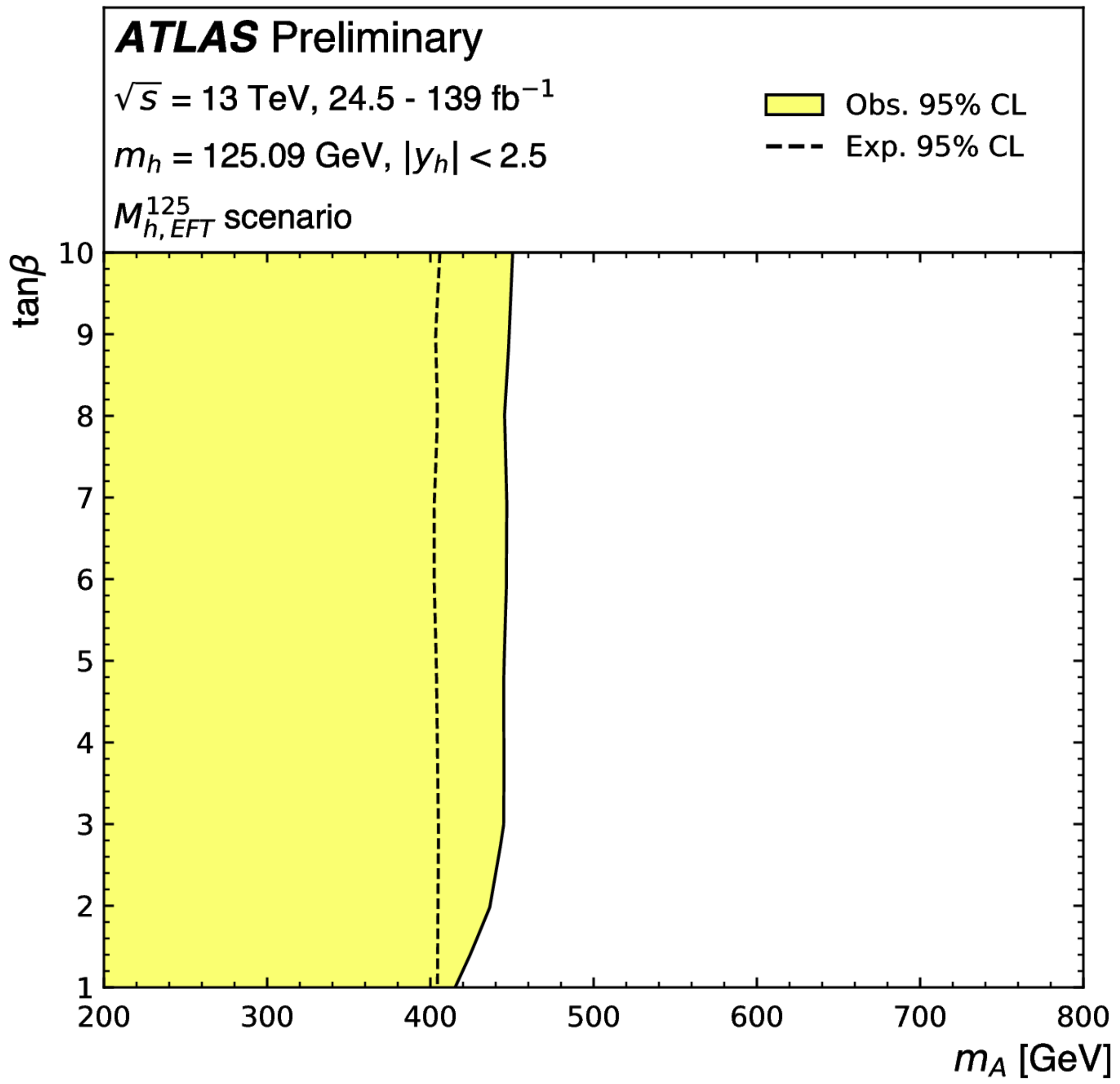
$M_h^{125}(\chi^{\sim})$



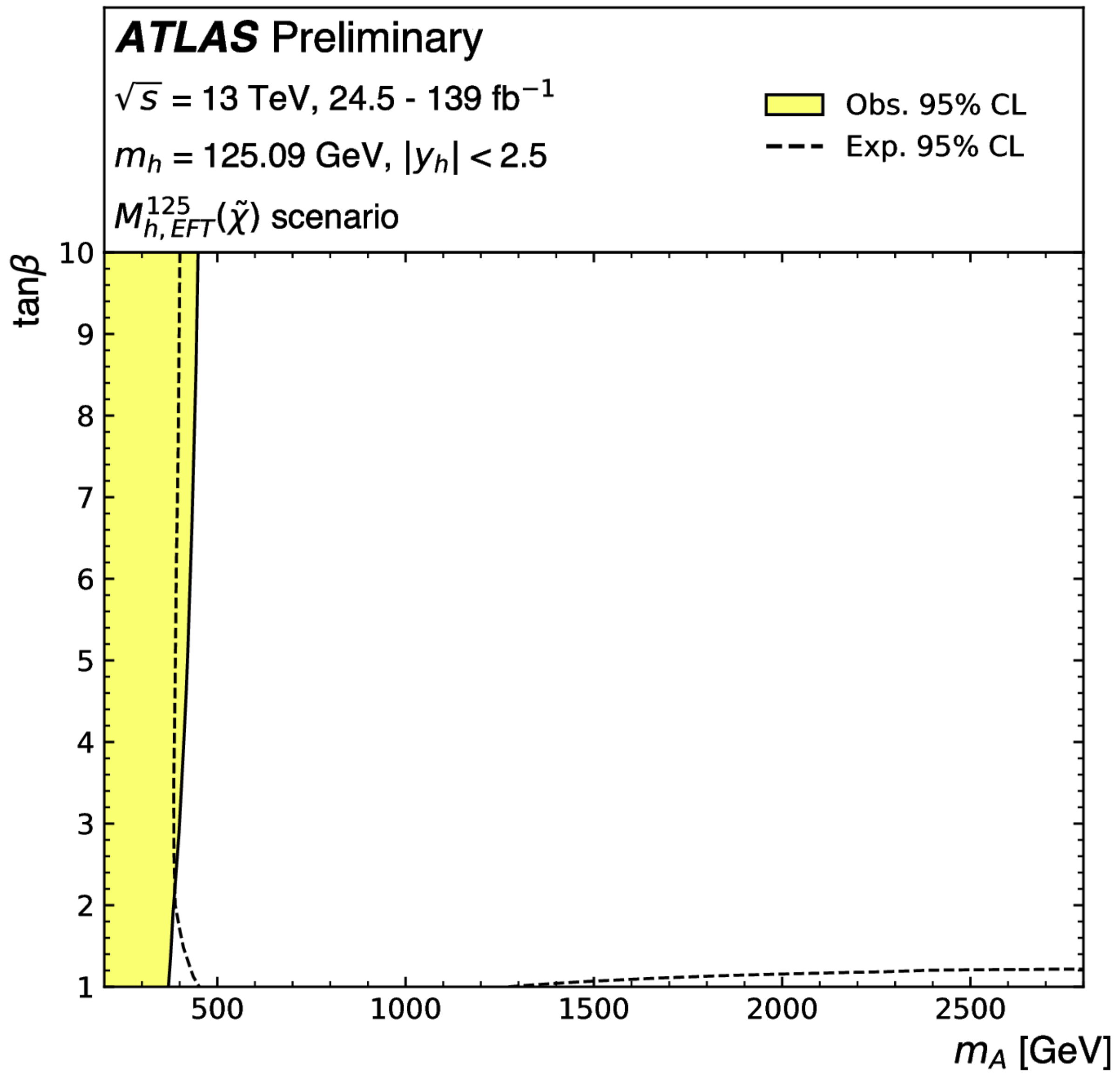
M_h^{125}(alignment)

ATL-PHYS-CONF-2020-053

Constraints on Minimal Supersymmetric Standard Model (MSSM)



$M_{h,EFT}^{125}$



$M_{h,EFT}^{125}(\tilde{\chi})$

ATL-PHYS-CONF-2020-053

CMS Slides

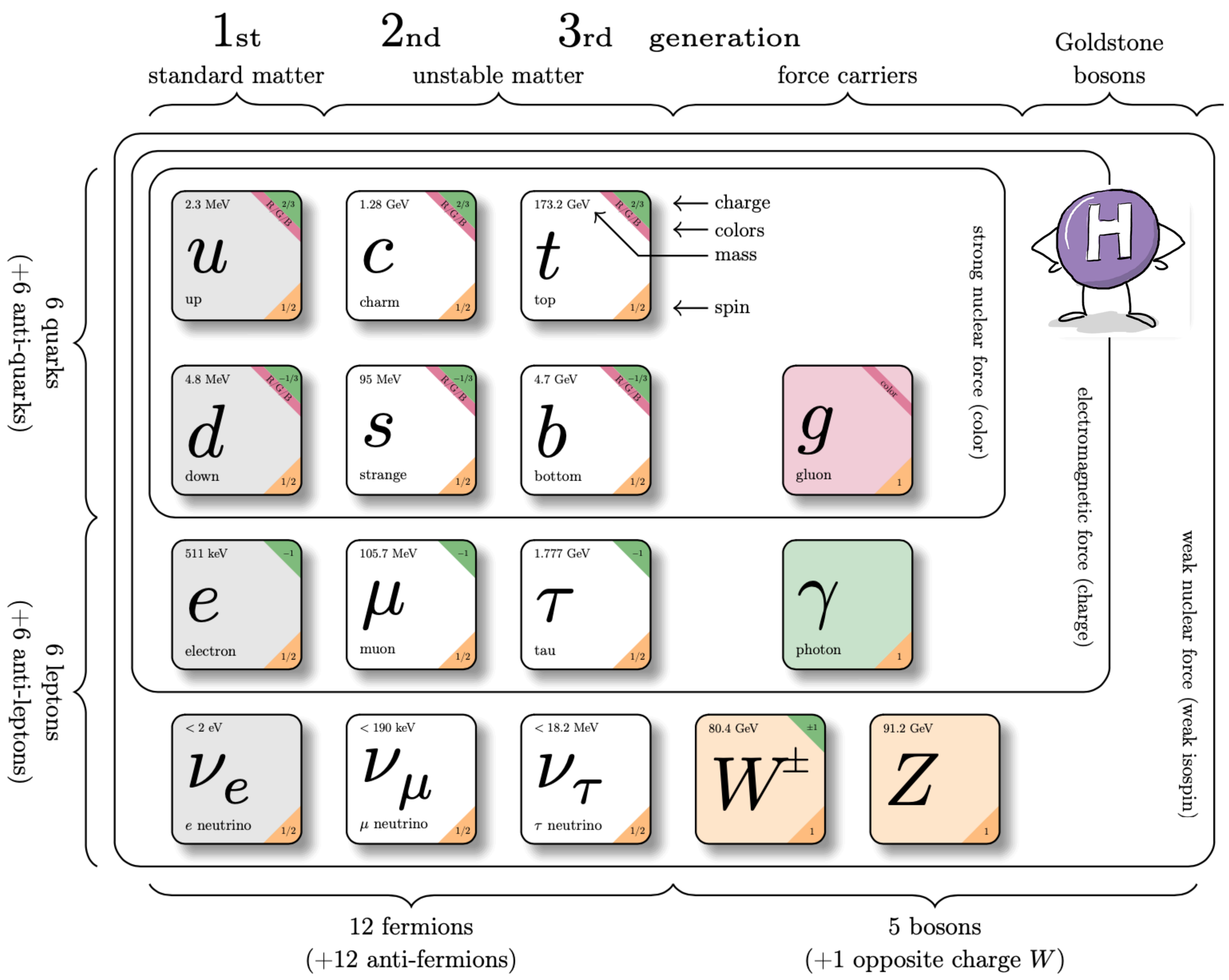
Higgs Hunting
21/09/2021

CMS Higgs Combination

Matteo Bonanomi
(LLR, Ecole Polytechnique, CNRS)
On behalf of the CMS Collaboration

The Higgs sector

The **Higgs boson** is a **scalar particle**, regulates the **EWSB mechanism**, and it couples with:



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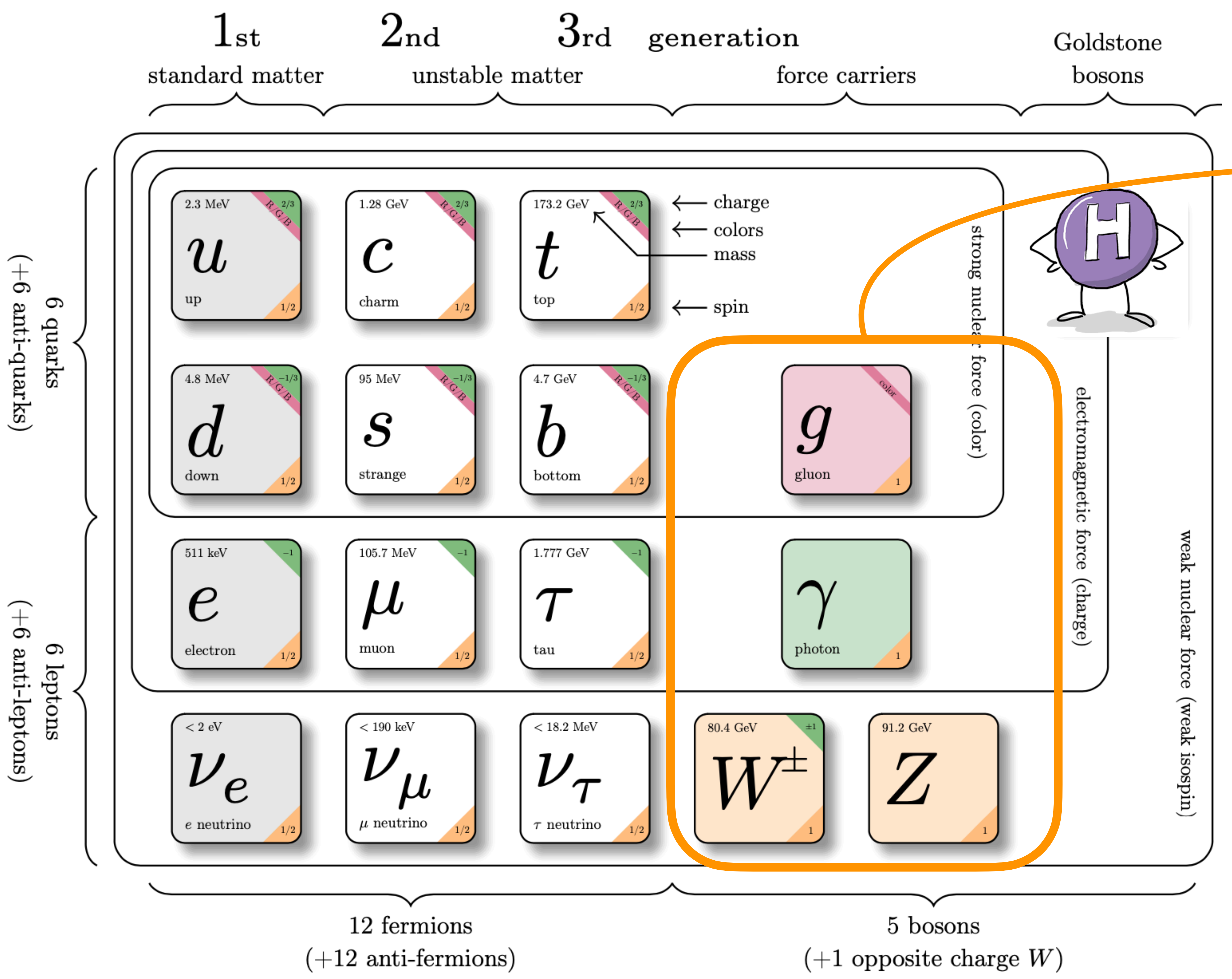
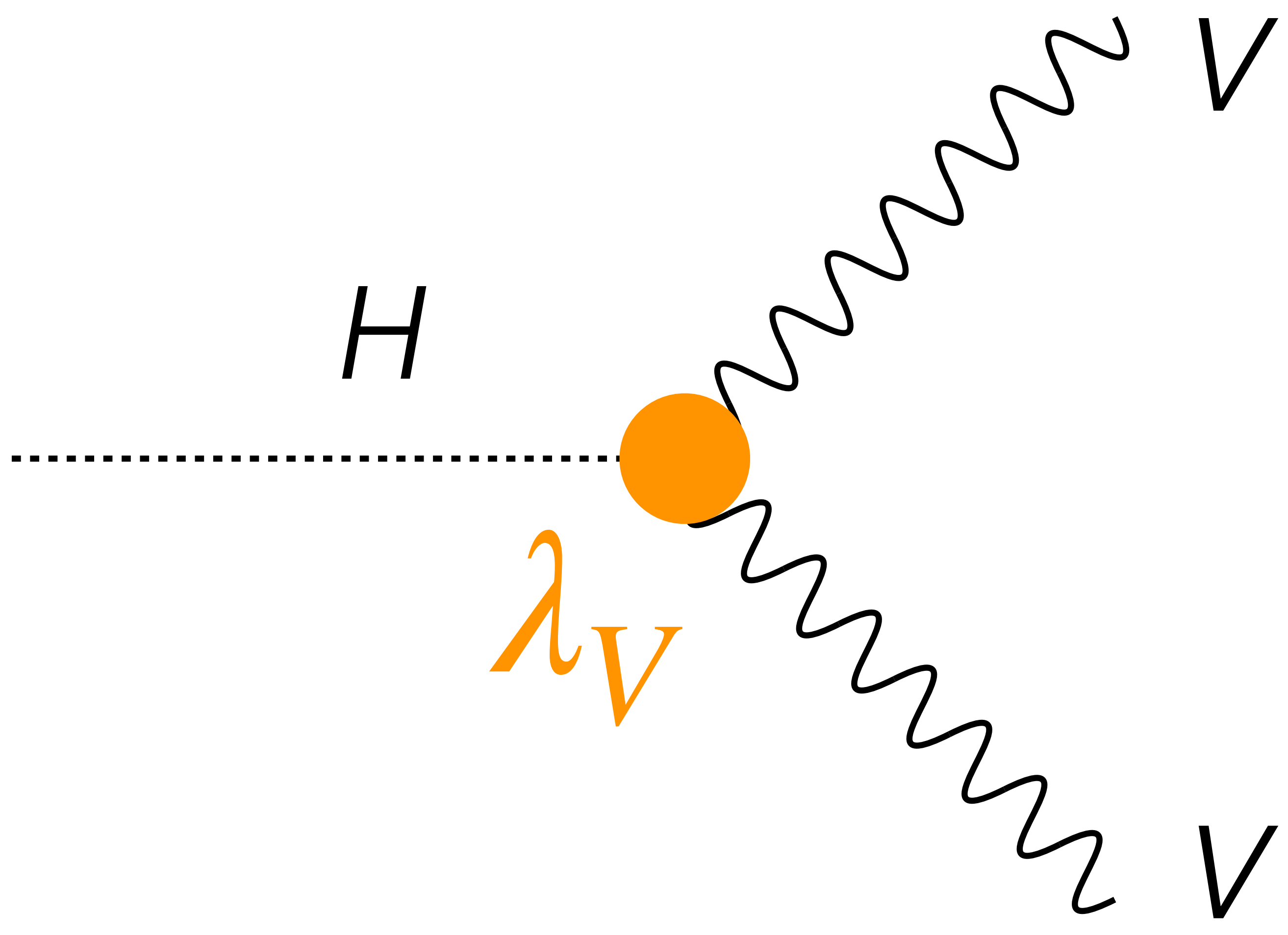


Couplings to gauge bosons: $\lambda_V = \frac{2}{v} m_V^2$



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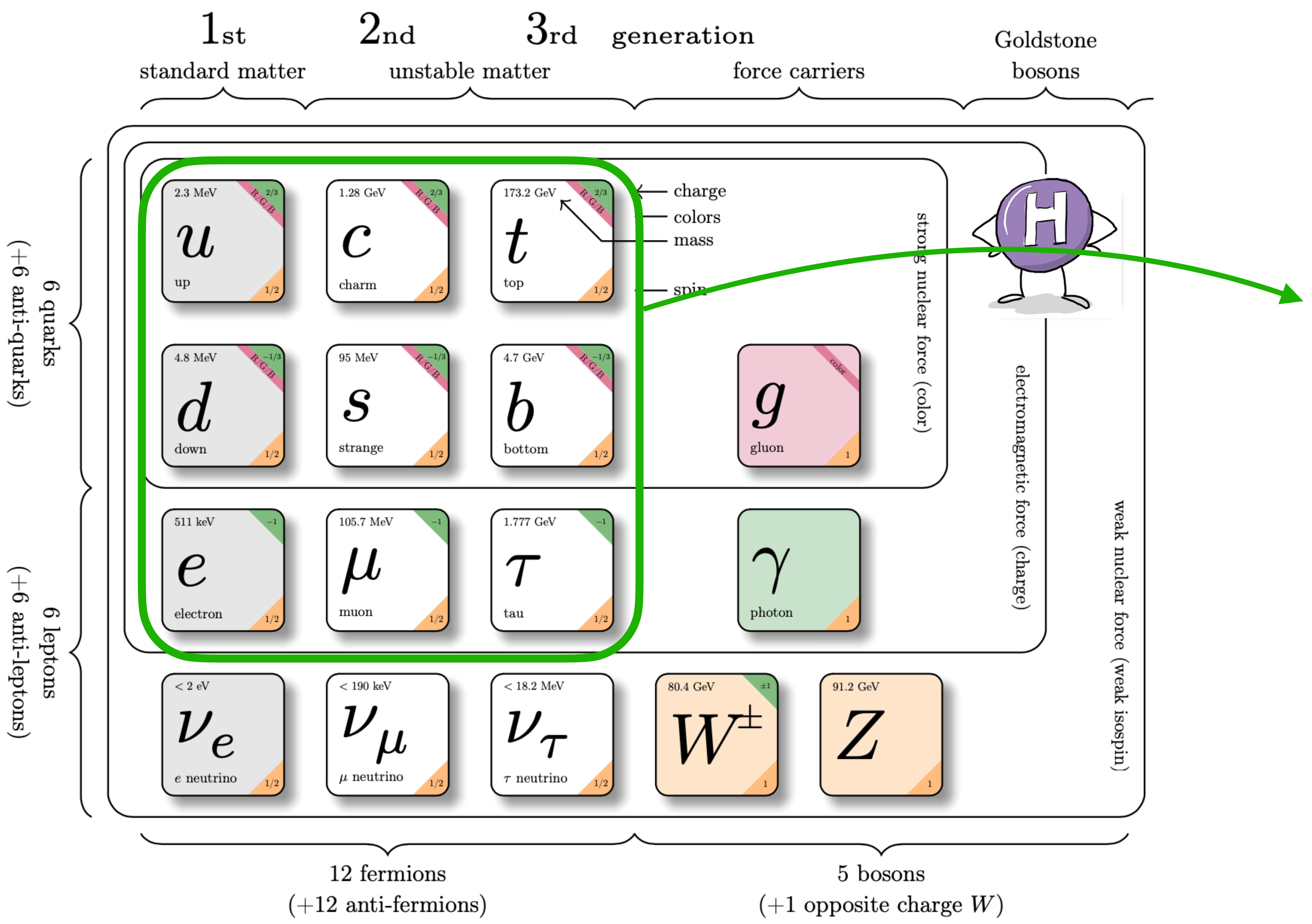
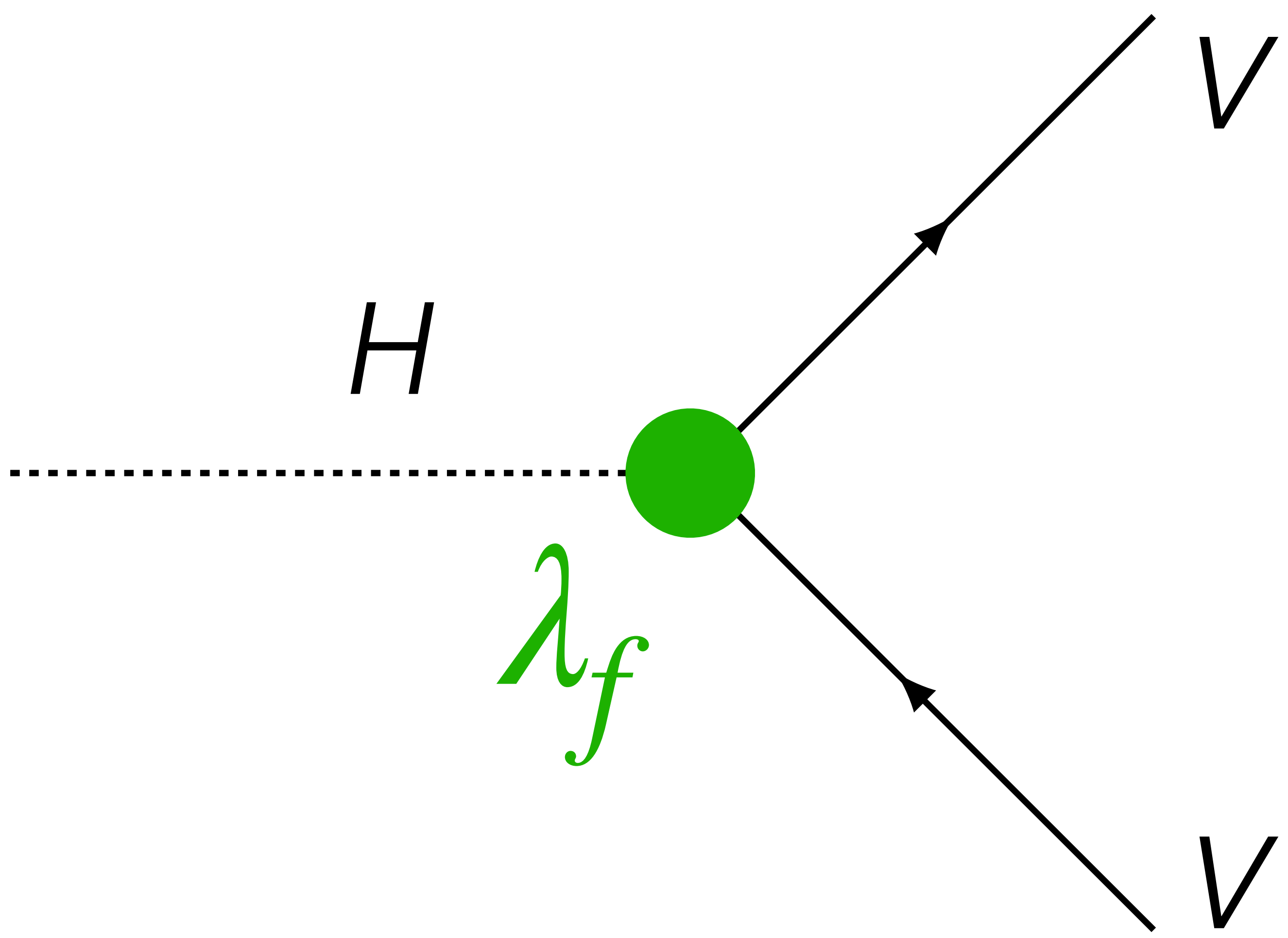


Couplings to gauge bosons: $\lambda_V = \frac{2}{v} m_V^2$

Couplings to fermions: $\lambda_f = \frac{\sqrt{2}}{v} m_f$



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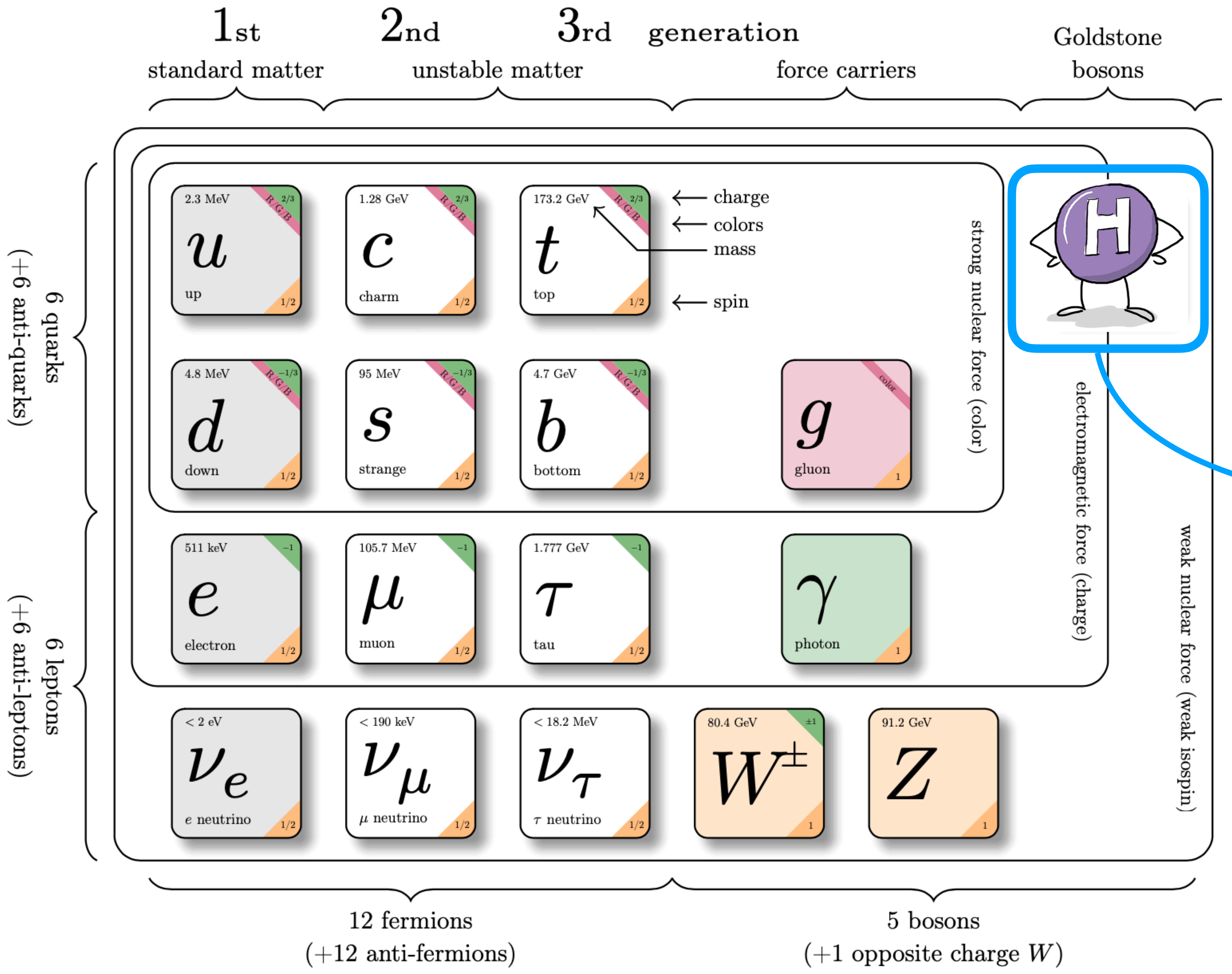
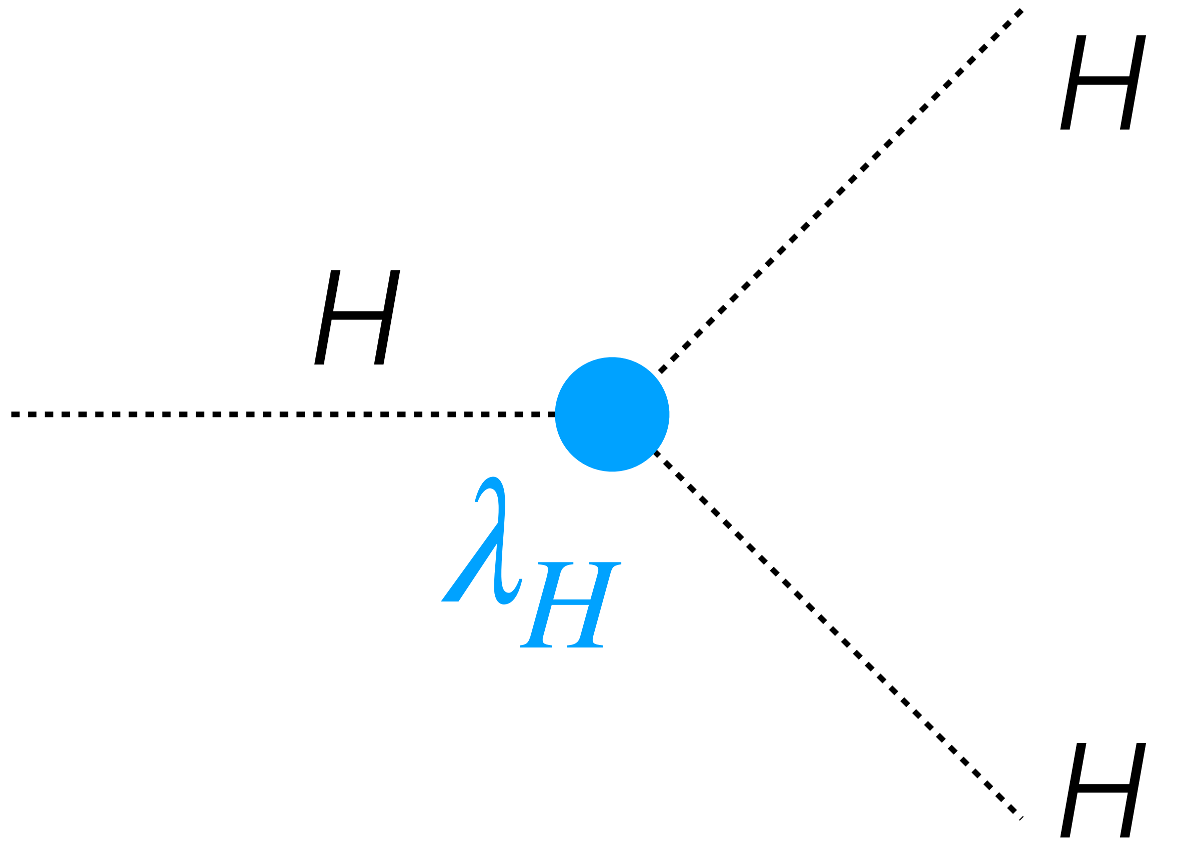


Couplings to gauge bosons: $\lambda_V = \frac{2}{v} m_V^2$

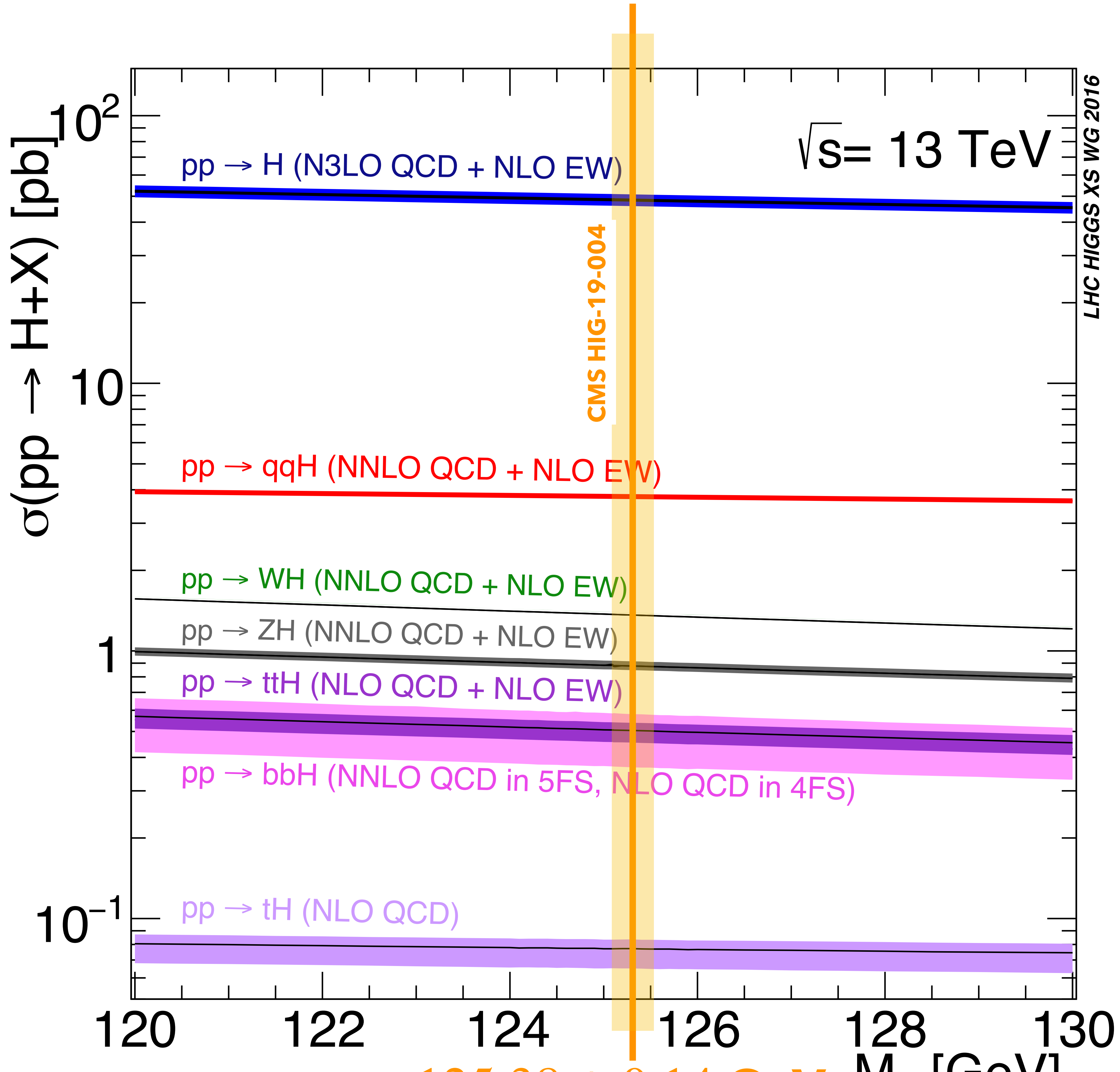
Couplings to fermions: $\lambda_f = \frac{\sqrt{2}}{v} m_f$

Higgs boson self-coupling: $\lambda_H = \frac{m_H^2}{v^2}$



The Higgs sector at the LHC

In 2015 LHC started the **Run II** phase, opening the doors for the ***precision physics era***, with the goal of **precision measurements** of the **Higgs** boson **couplings**



$m_H = 125.38 \pm 0.14$ **GeV**

The large statistics and combination of different decay channels provide comprehensive assessment of H boson properties:

Production and decay rates

Higgs boson self coupling

EFT interpretations in STXS

Results from partial Run-II CMS Combination shown

The input analyses

References in Backup

Decay channel	Luminosity (fb^{-1})	ggH	VBF	VH	ttH
$H \rightarrow \gamma\gamma$	77	✓	✓		✓
$H \rightarrow ZZ^* \rightarrow 4\ell$	137	✓	✓	✓	✓
$H \rightarrow WW$	36	✓	✓	✓	
$H \rightarrow bb$	36 (ggH) - 77 (others)	✓		✓	✓
$H \rightarrow \tau\tau$	77	✓	✓	✓	
ttH multilepton	77				✓
$H \rightarrow \mu\mu$	36	✓	✓		

The input analyses

References in Backup

Decay channel	Luminosity (fb^{-1})	ggH	VBF	VH	ttH
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$H \rightarrow bb$	36 (ggH) - 77 (others)	✓		✓	✓
$H \rightarrow \tau\tau$	77	✓	✓	✓	
ttH multilepton	77				✓
$H \rightarrow \mu\mu$	36	✓	✓		

Partial Run-II dataset(s), yet **comprehensive study** of the **H boson properties**.

Currently **working** on **full Run-II combination**

Signal strength modifiers

Scaling of production (*i*) or decay (*f*) of the SM Higgs boson as:

$$\mu_i = \frac{\sigma_i}{\left(\sigma_i\right)_{\mathrm{SM}}} \qquad \mu^f = \frac{B^f}{\left(B^f\right)_{\mathrm{SM}}}$$

The combined signal strength modifier is measured to be

$$\mu = 1.02 \pm 0.04(\mathrm{th}) \ \pm 0.04(\mathrm{exp}) \ \pm 0.04(\mathrm{stat})$$

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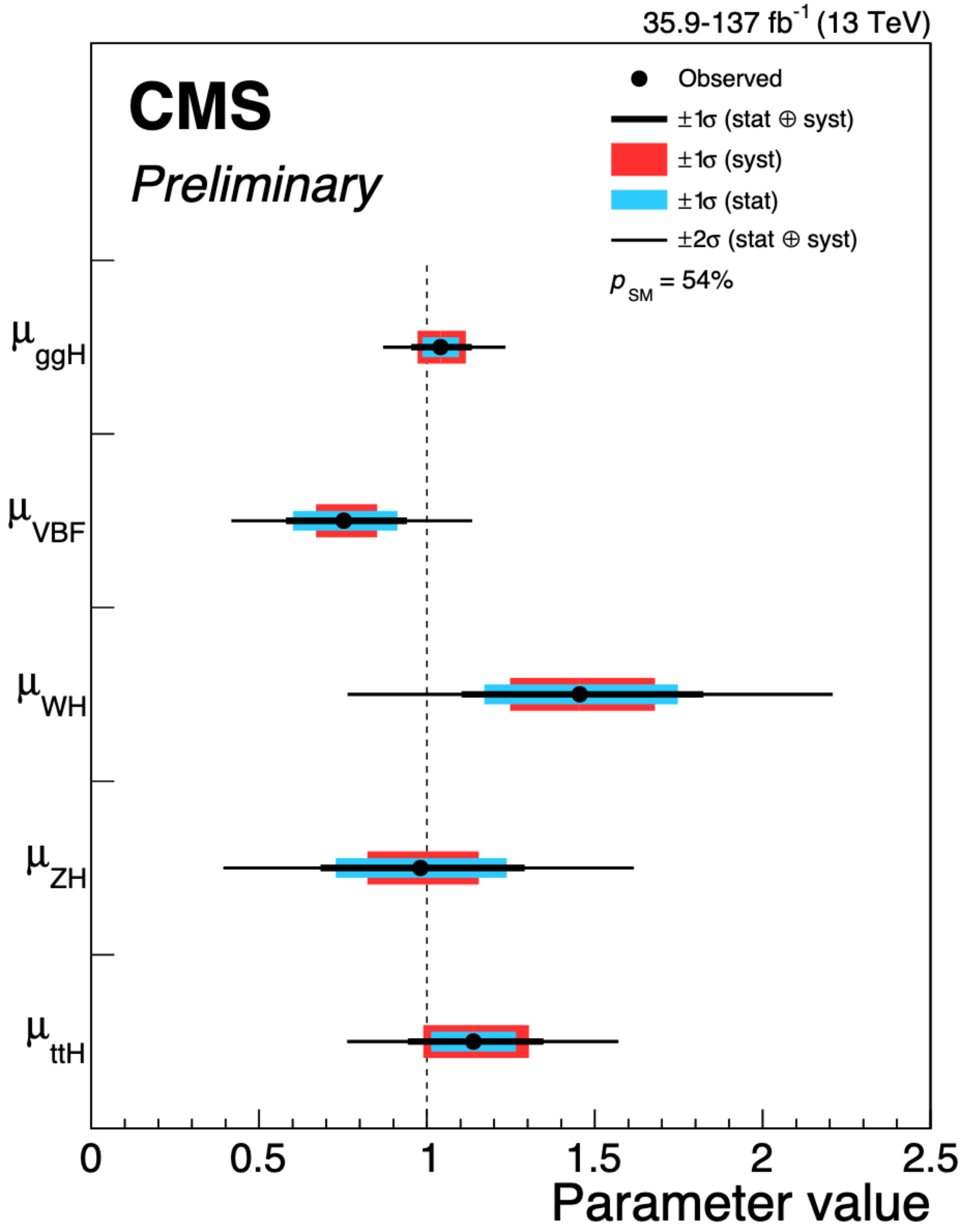
The combined signal strength modifier is measured to be

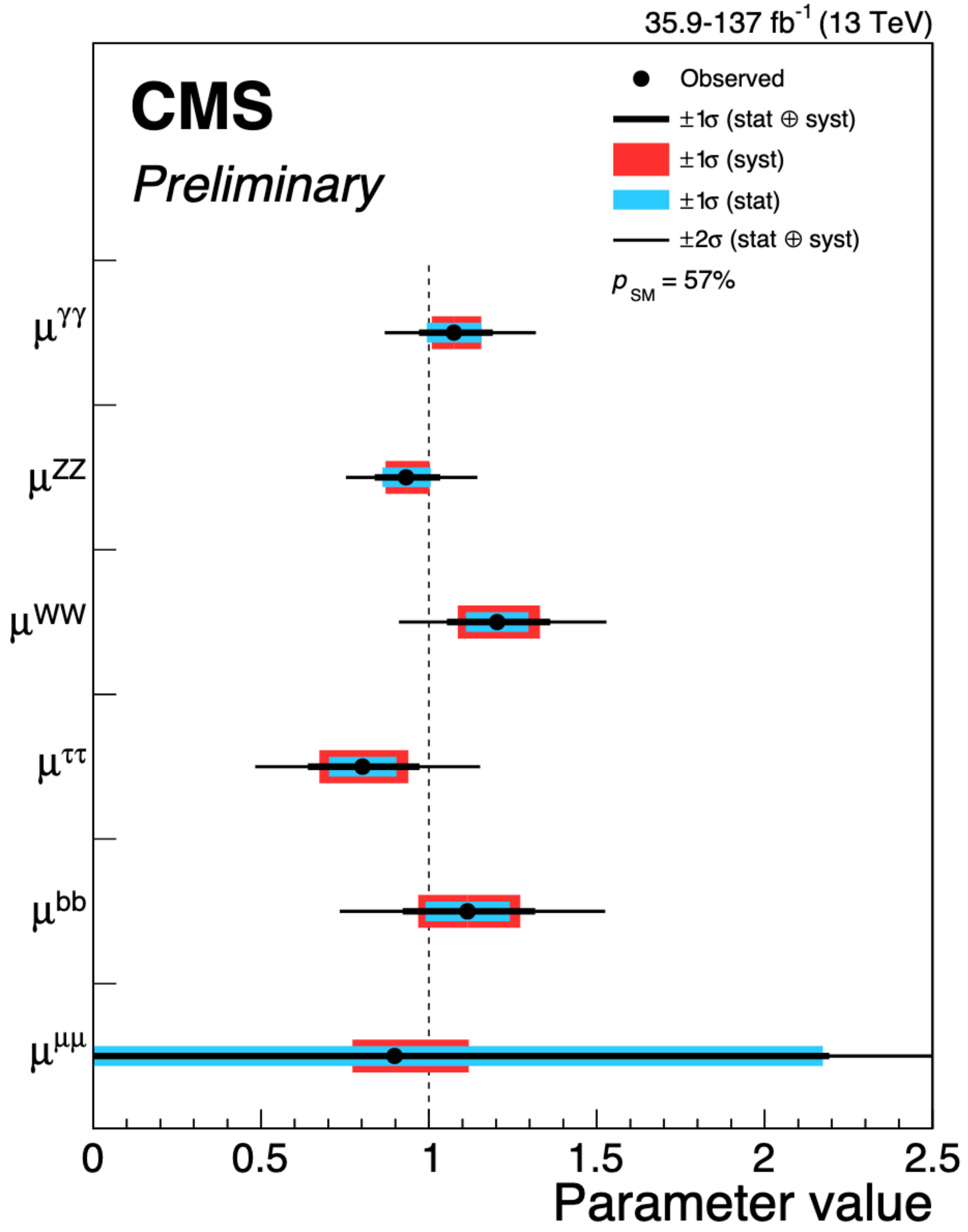
$$\mu = 1.02 \pm 0.04(\mathrm{th}) \pm 0.04(\mathrm{exp}) \pm 0.04(\mathrm{stat})$$

With the increasing statistics available from Run-II, the systematic uncertainties are becoming the **limiting factor for the ultimate precision** of the measurements, while statistical uncertainties are substantially **reduced in many decay channels**

Signal strength modifiers

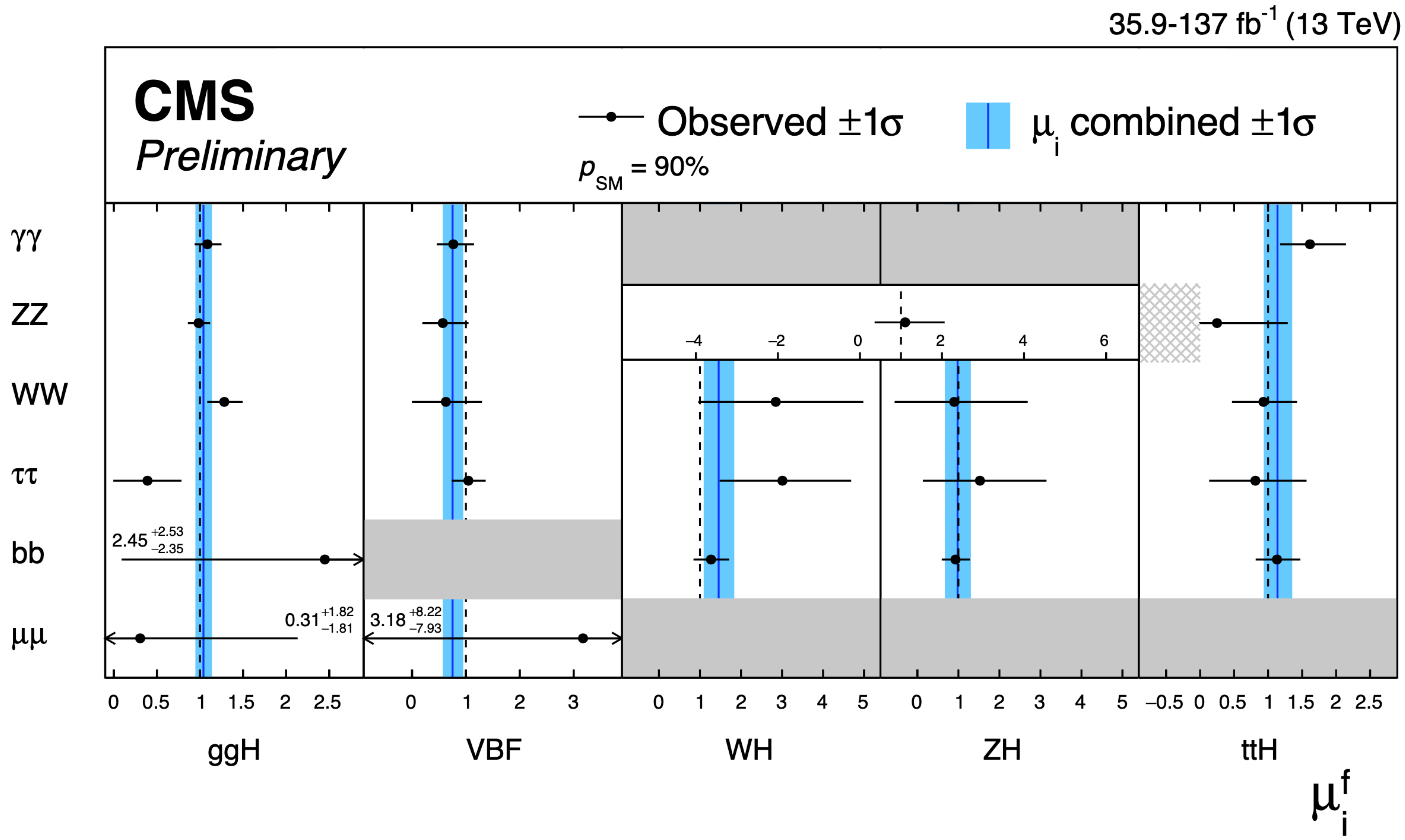
Simultaneous measurement of all the **production** and **decay signal strengths**





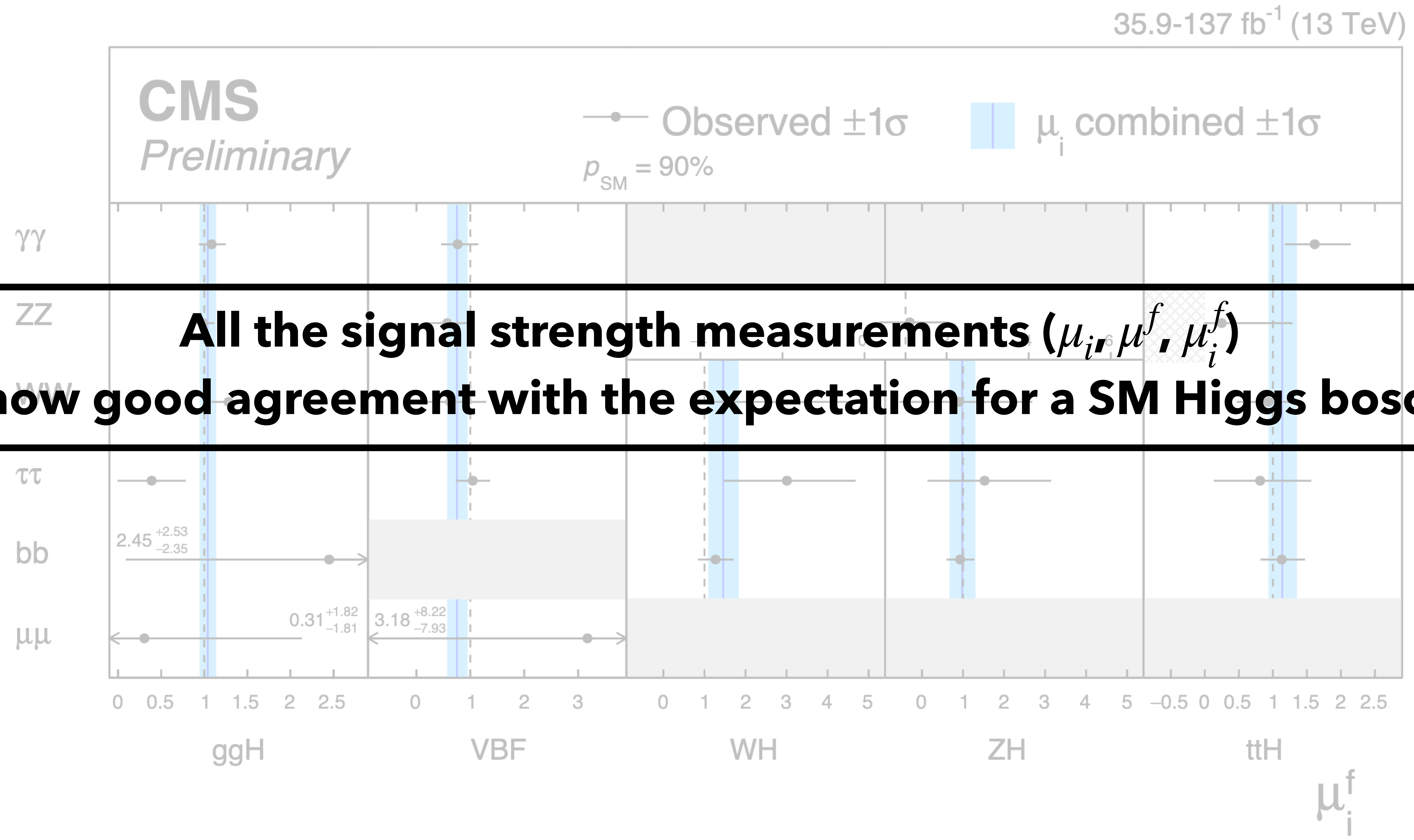
Signal strength modifiers

Measurement of **production times decay** μ_i^f from combination across decay channels



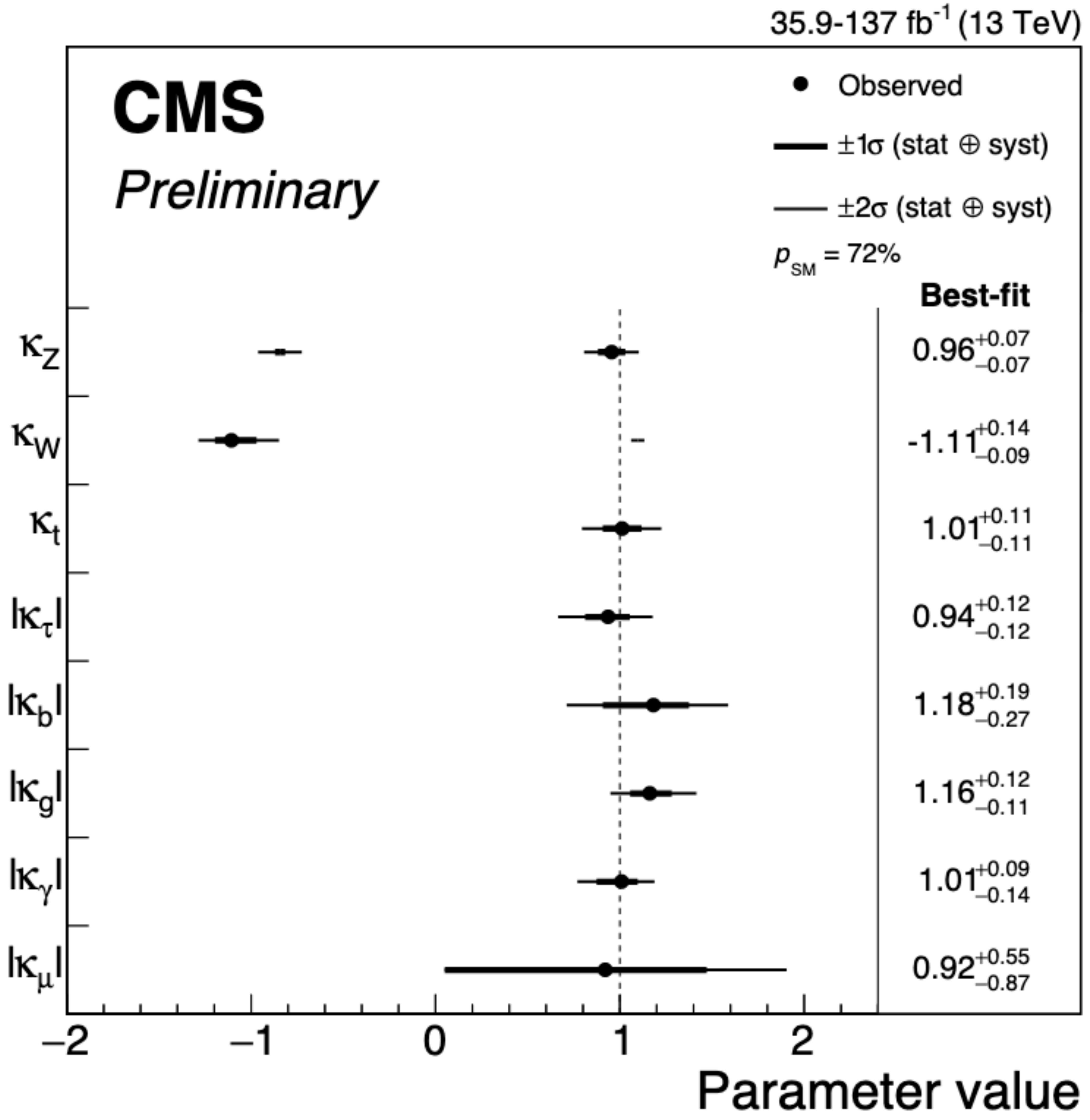
Signal strength modifiers

Measurement of **production times decay** μ_i^f from combination across decay channels



All the signal strength measurements (μ_i, μ^f, μ_i^f) show good agreement with the expectation for a SM Higgs boson

H boson couplings: κ-framework



Assuming only SM Higgs boson decays:

$$\sigma_i B^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$$

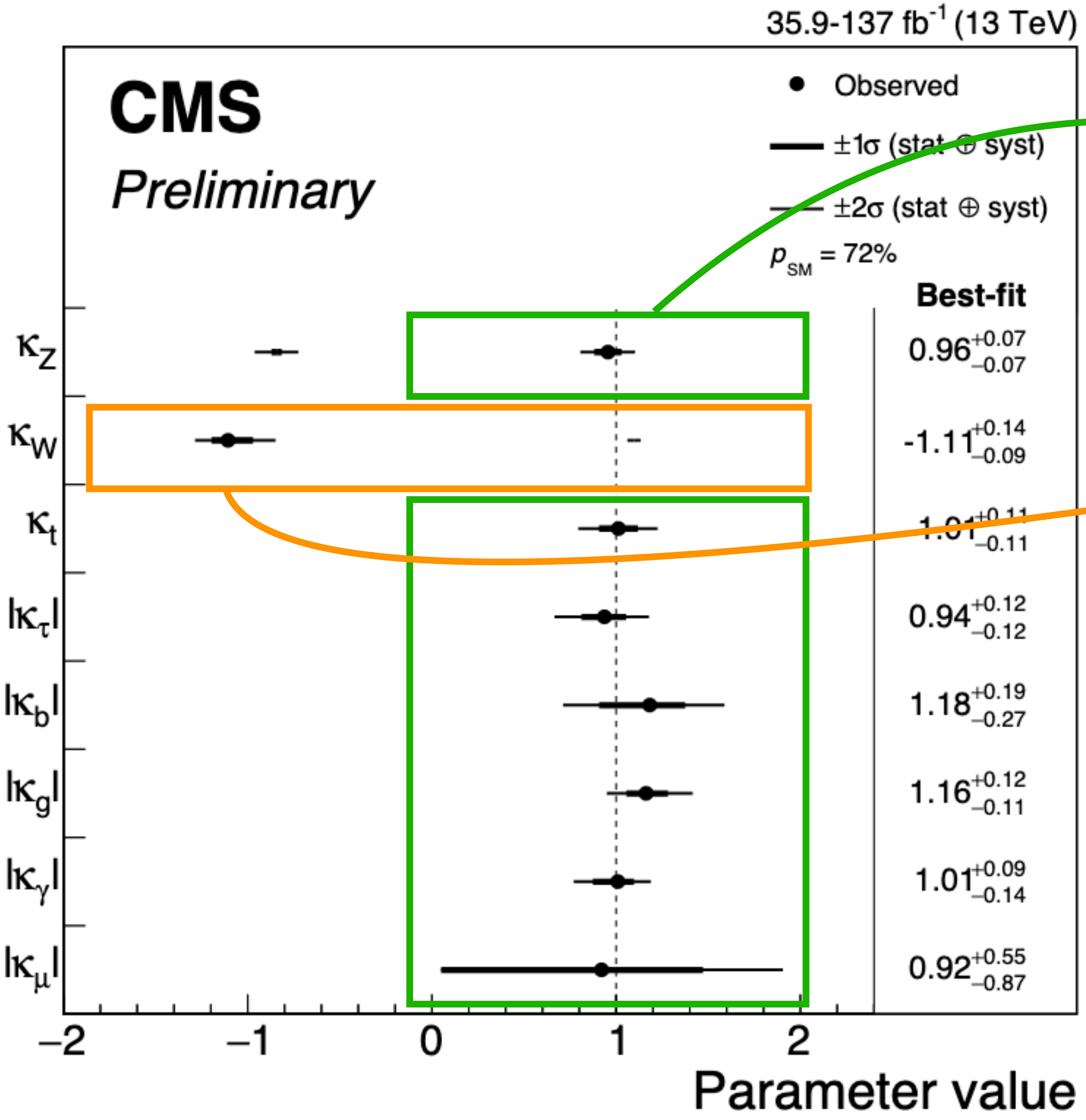
$\Gamma_H(\vec{\kappa})$: total width of the Higgs boson

$\Gamma^f(\vec{\kappa})$: partial width of the decay to the final state f

Coupling modifiers $\vec{\kappa}$ to parametrize deviations in HVV and Hff couplings from the SM predictions:

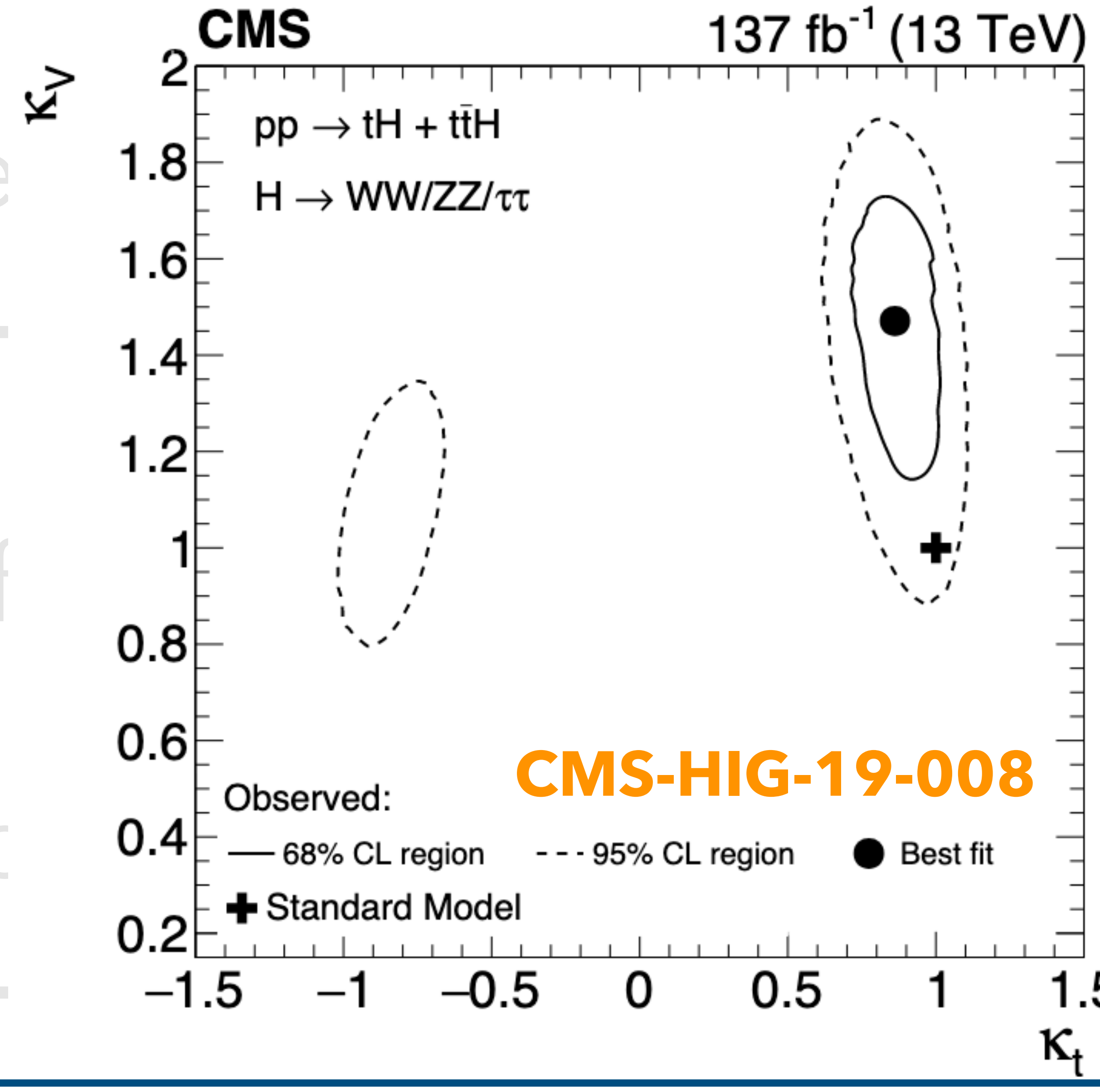
$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

H boson couplings: κ-framework

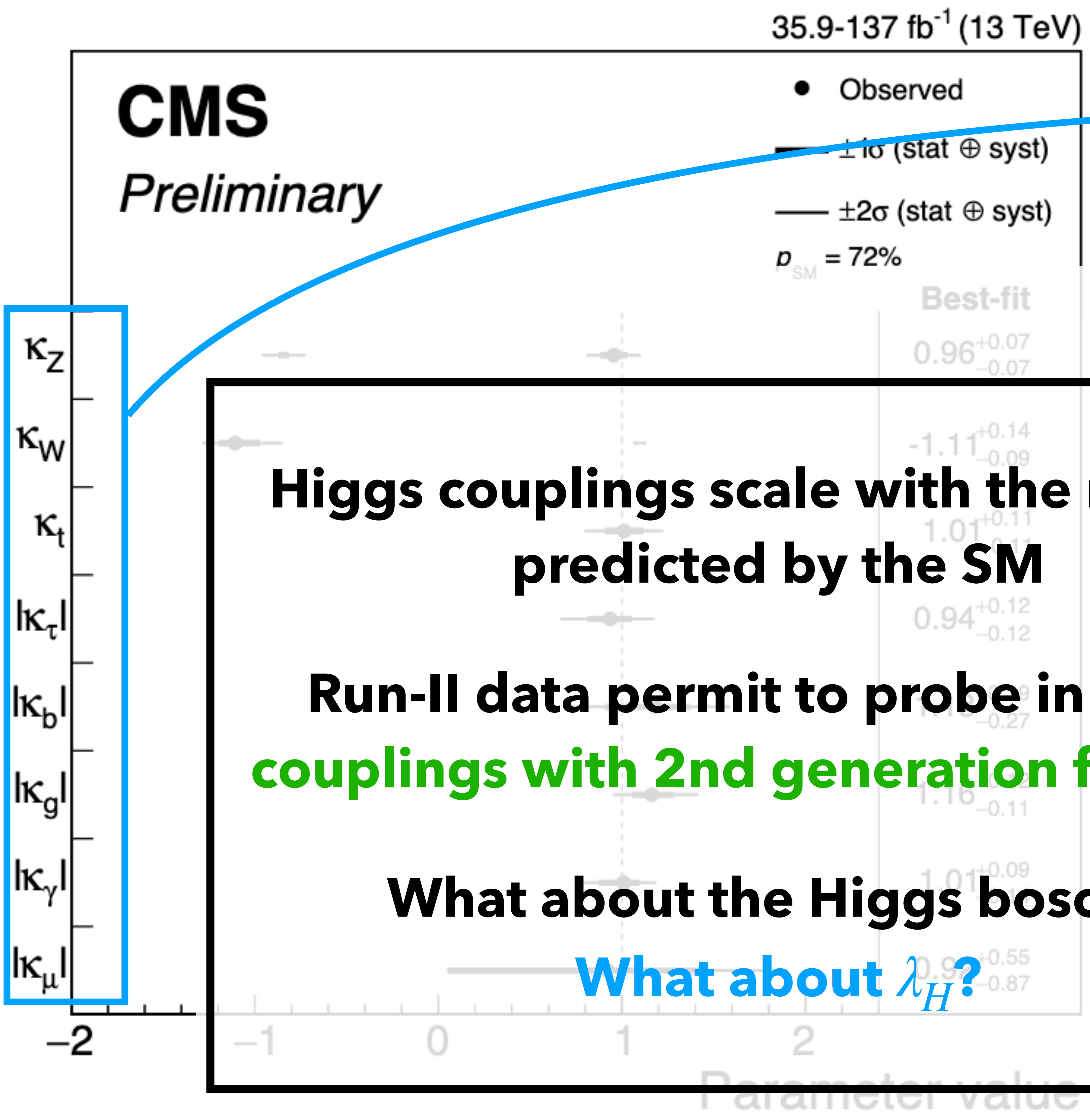


All the measurements agree with the SM expectations ($\kappa_j = 1$)

The κ_{W} best-fit value is negative due to the interference between tH production diagrams



H boson couplings: κ-framework

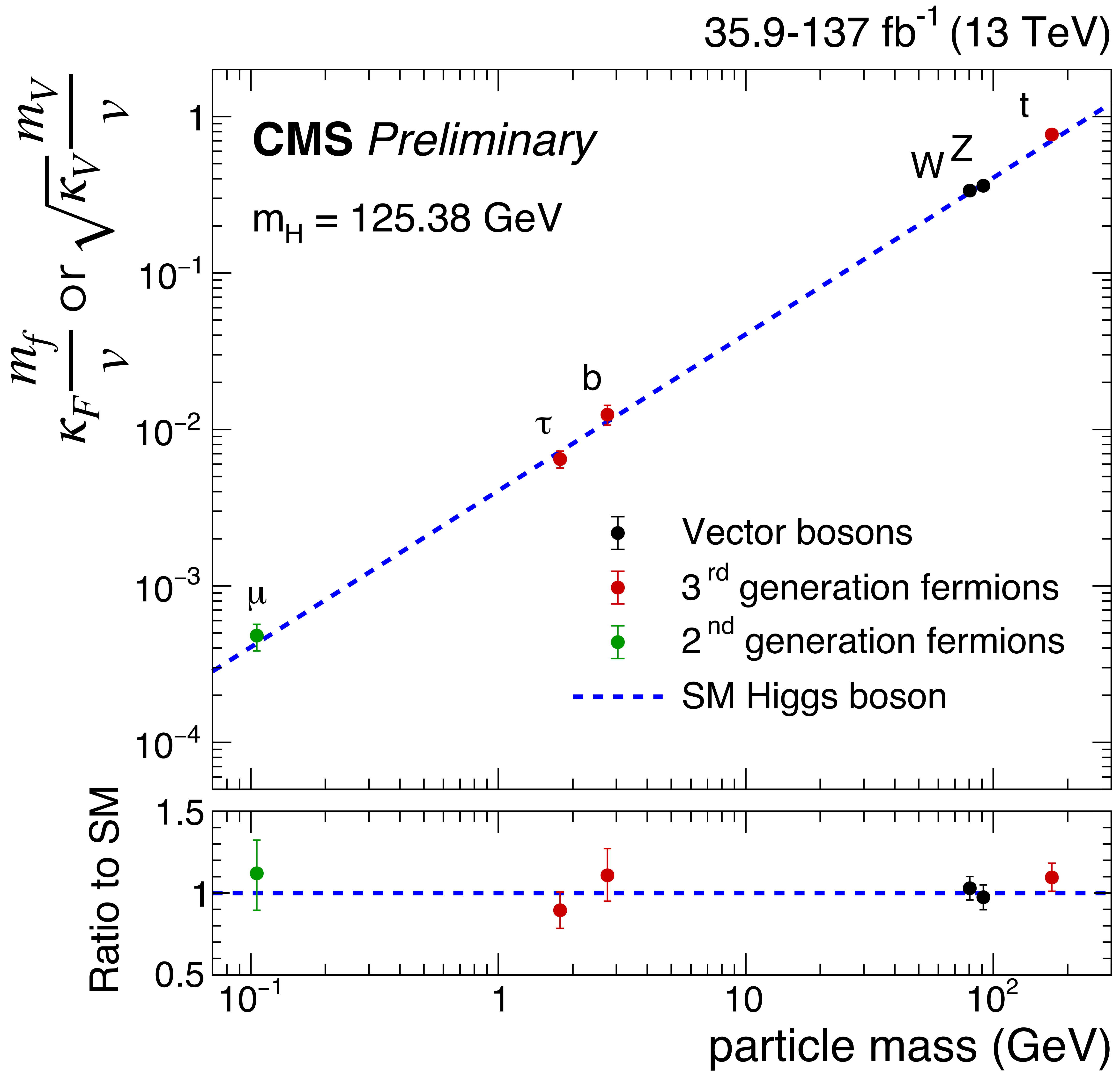


Higgs couplings scale with the mass as predicted by the SM

Run-II data permit to probe in detail couplings with 2nd generation fermions

What about the Higgs boson?

What about λ_H?



H boson self-coupling

Constraint on $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$ from single-Higgs decay channels via modifications of the production cross sections and decay widths from NLO electroweak corrections

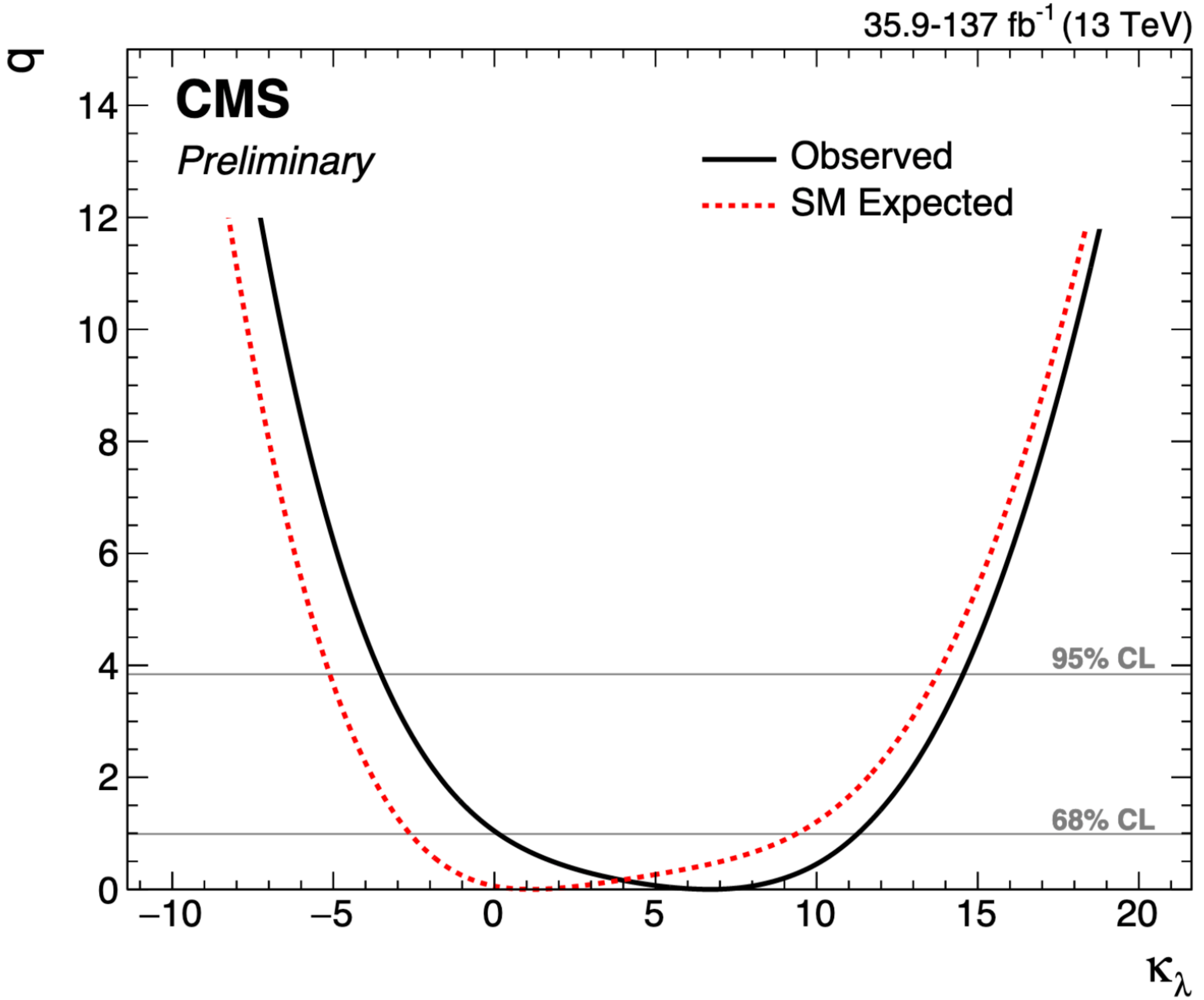
Inclusive production and decay rates scale as[1]

$$\mu_i(\kappa_V, \kappa_F, \kappa_\lambda) = Z_H^{BSM}(\kappa_\lambda)\left[S_i(\kappa_V, \kappa_F) + K_{BSM}(1-\kappa_\lambda)\right].$$

$$\mu^f(\kappa_V, \kappa_F, \kappa_\lambda) = \frac{S_f(\kappa_V, \kappa_F) + (\kappa_\lambda - 1)C^f}{\sum_d \Gamma_d^{SM}\left(S_d(\kappa_V, \kappa_F) + (\kappa_\lambda - 1)C^d\right)}$$

Limits on κ_λ with $\kappa_V = \kappa_F = 1$:

$[-3.5, 14.5]$ @95% CL
([-5.1,13.7])



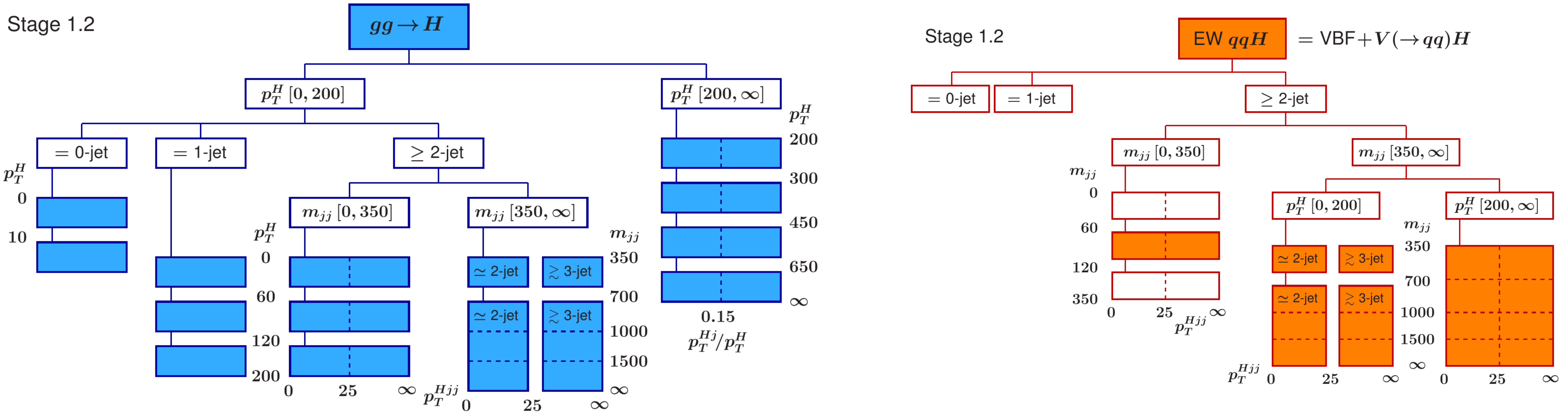
Additional scans with κ_V or κ_F floating in backup

Simplified Template Cross Section framework

The primary goal of **STXS** framework is to **minimise the measurement dependence on theory predictions without losing sensitivity**

Coverage of the entire phase space and **specific regions** designed **to detect BSM effects**

In this analysis STXS bins used to set constraints on Effective Field Theory (EFT) operators



EFT couplings

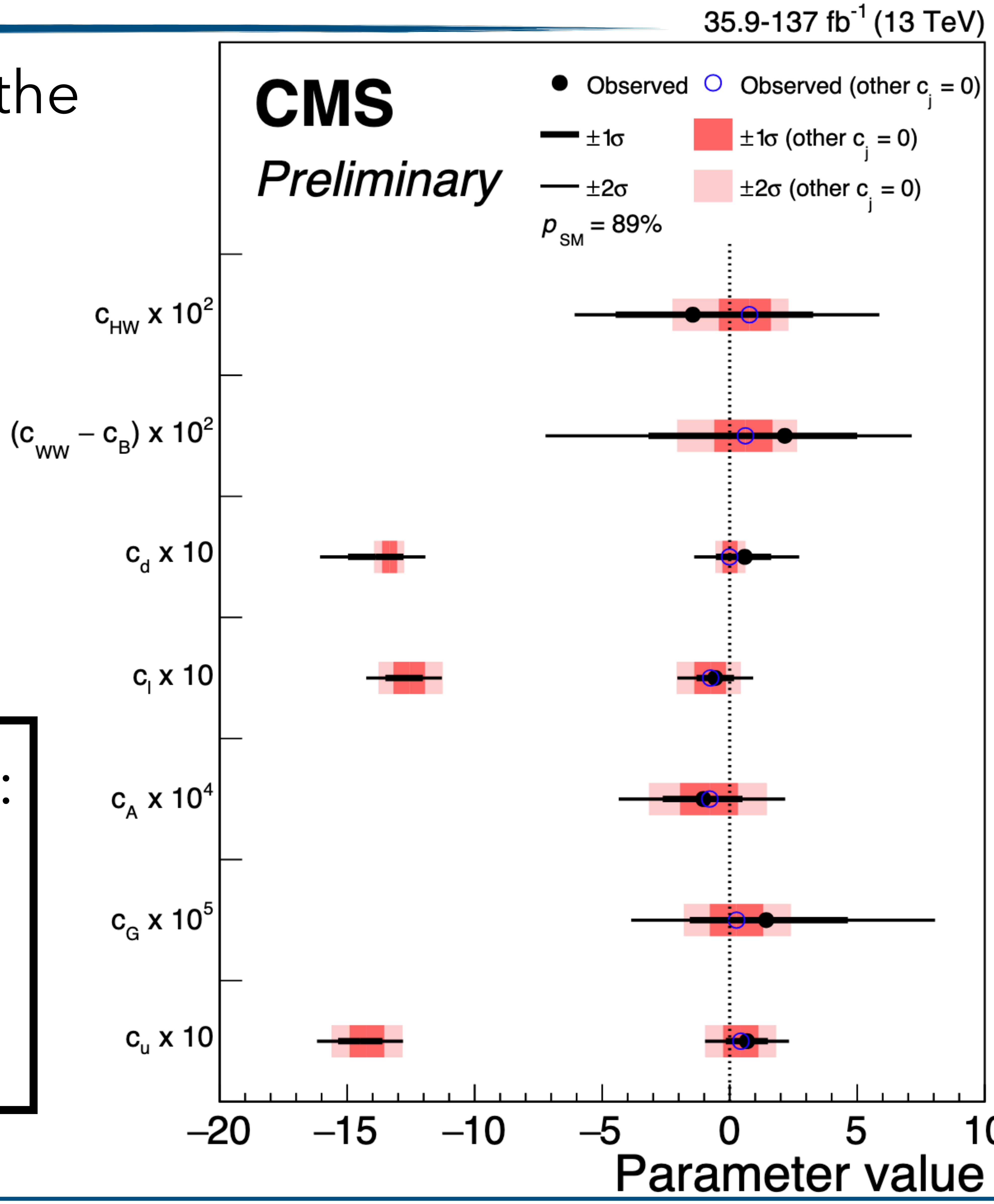
Extend SM Lagrangian with higher-dim operators in the **HEL[1] model:**

$$\mathcal{L}_{\mathrm{HEL}} = \mathcal{L}_{\mathrm{SM}} + \sum_j \mathcal{O}_j f_j / \Lambda^2$$

$$\sigma_i^{\mathrm{EFT}} = \sigma_i^{\mathrm{SM}} + \sigma_i^{\mathrm{int}} + \sigma_i^{\mathrm{BSM}}$$

Scaling depending on $c_j = f_j/\Lambda^2$ for each STXS bin:

$$\mu_i(c_j) = \frac{\sigma_i^{\mathrm{EFT}}}{\sigma_i^{\mathrm{SM}}} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$



[1]: Higgs Effective Lagrangian

EFT couplings

Extend SM Lagrangian with higher-dim operators in the **HEL[1] model:**

$$\mathcal{L}_{\mathrm{HEL}} = \mathcal{L}_{\mathrm{SM}} + \sum_j \mathcal{O}_j f_j/\Lambda^2$$

$H \to \mu\mu$ and boosted $H \to bb$ analyses not considered

Eight EFT parameters measured simultaneously

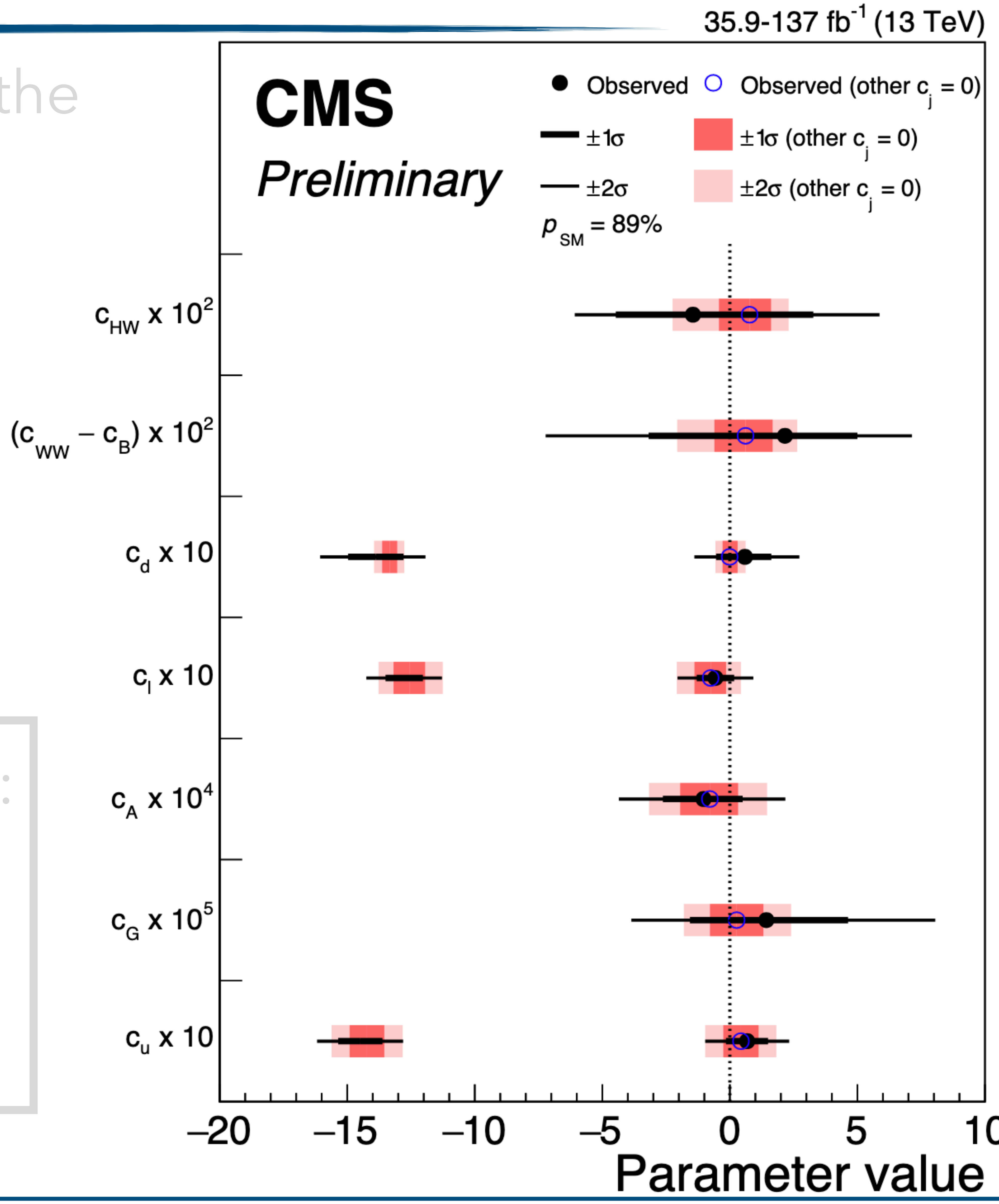
$$\sigma_i^{\mathrm{EFT}} = \sigma_i^{\mathrm{SM}} + \sigma_i^{\mathrm{int}} + \sigma_i^{\mathrm{BSM}}$$

Parameters related to **leading CP-even terms**

Scaling depending on $c_j = f_j/\Lambda^2$ for each STXS bin:

Stringent constraints on HEL parameters

$$\mu_i(c_j) = \frac{\sigma_i^{\mathrm{EFT}}}{\sigma_i^{\mathrm{SM}}} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$



1: Higgs Effective Lagrangian

Conclusions

The large statistics collected during Run-II opens the doors to *precision measurements era*

- Partial Run-II datasets used here, full Run-II analyses are ongoing and will be included in a future study
- Similar **statistical** and **systematic components of the uncertainty**, results will soon be limited by latter

Comprehensive characterization of the Higgs boson properties from combination of all decay channels

- Signal strength modifiers $\mu = 1.02 \pm 0.04(\mathrm{th}) \pm 0.04(\mathrm{exp}) \pm 0.04(\mathrm{stat})$
- Study Higgs couplings from κ-framework measurements and expected scaling with the mass is observed
- Interpretation of STXS measurements in EFT: most powerful constraints on HEL parameters to date

Full Run-II combination (from CMS and ATLAS+CMS) will enhance the precision of these results…

Conclusions

The large statistics collected during Run-II opens the doors to *precision measurements era*

- Partial Run-II datasets used here, full Run-II analyses are ongoing and will be included in a future study
- Similar **statistical** and **systematic components of the uncertainty**, results will soon be limited by latter

Comprehensive characterization of the Higgs boson properties from combination of all decay channels

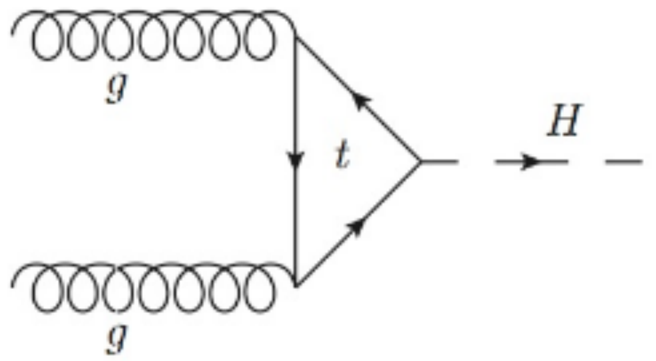
- Signal strength modifiers $\mu = 1.02 \pm 0.04(\mathrm{th}) \pm 0.04(\mathrm{exp}) \pm 0.04(\mathrm{stat})$
- Study Higgs couplings from κ-framework measurements and expected scaling with the mass is observed
- Interpretation of STXS measurements in EFT: most powerful constraints on HEL parameters to date

Full Run-II combination (from CMS and ATLAS+CMS) will enhance the precision of these results…

… and possibly unveil new physics!

BACKUP SLIDES

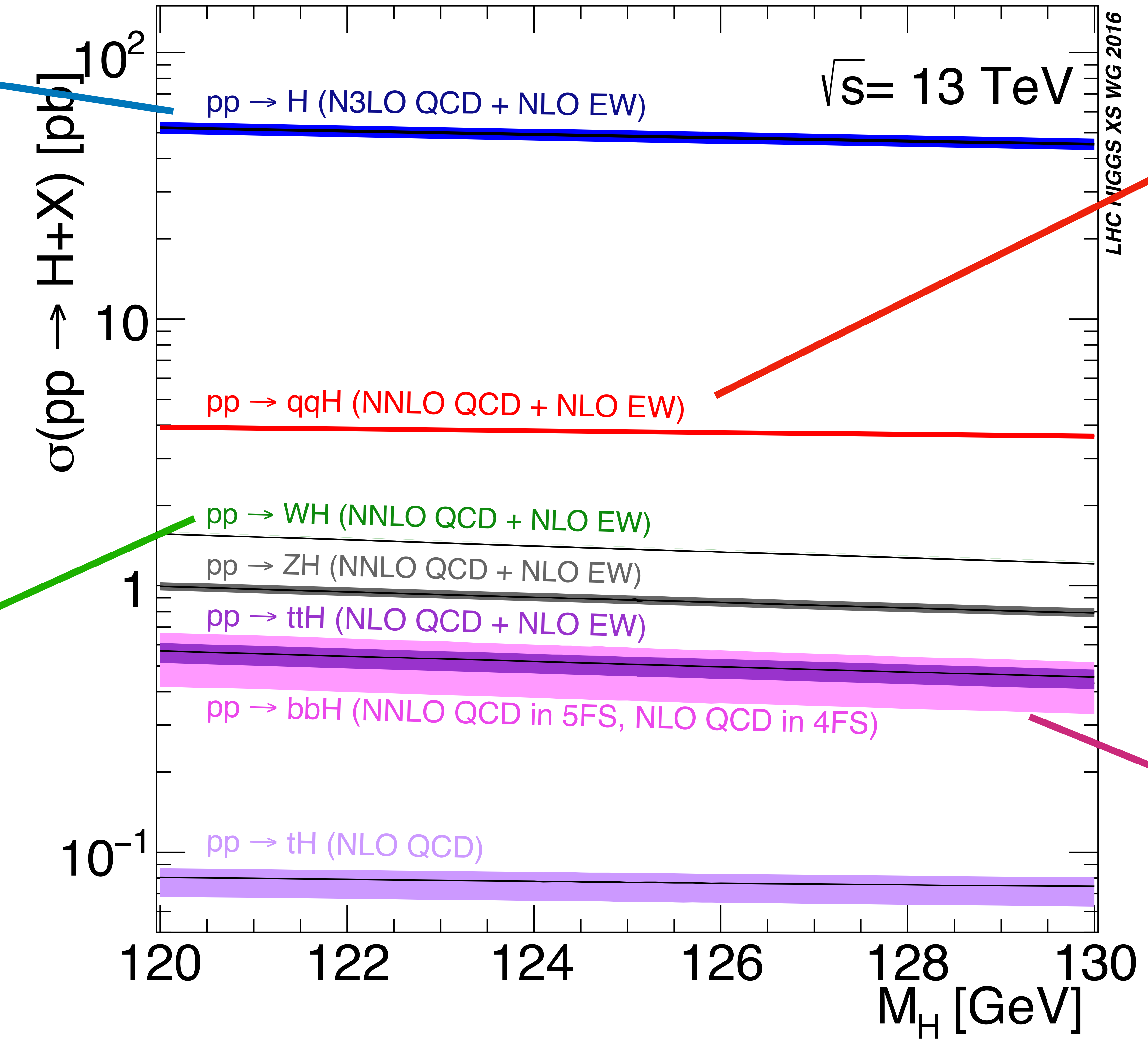
Higgs boson production at LHC

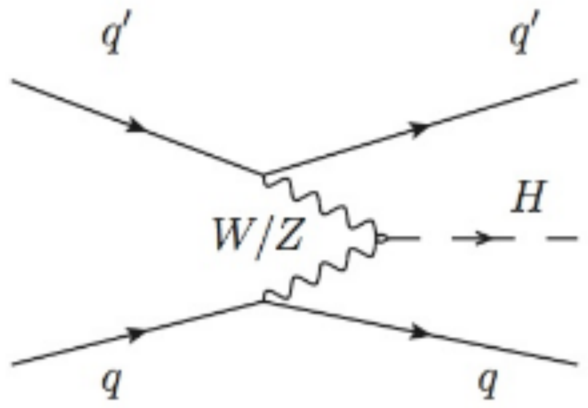


ggH

$\sigma \times \mathcal{B}(H \to WW) = 9.5$ pb

$\sigma \times \mathcal{B}(H \to ZZ) = 1.27$ pb

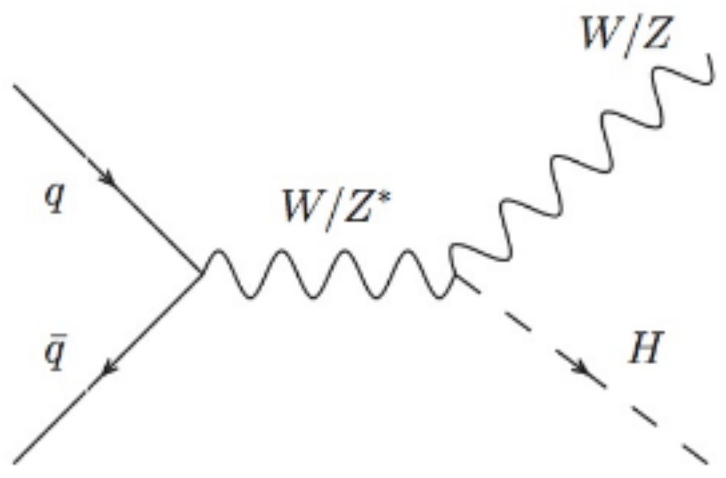




qqH, VBF

$\sigma \times \mathcal{B}(H \to WW) = 0.8$ pb

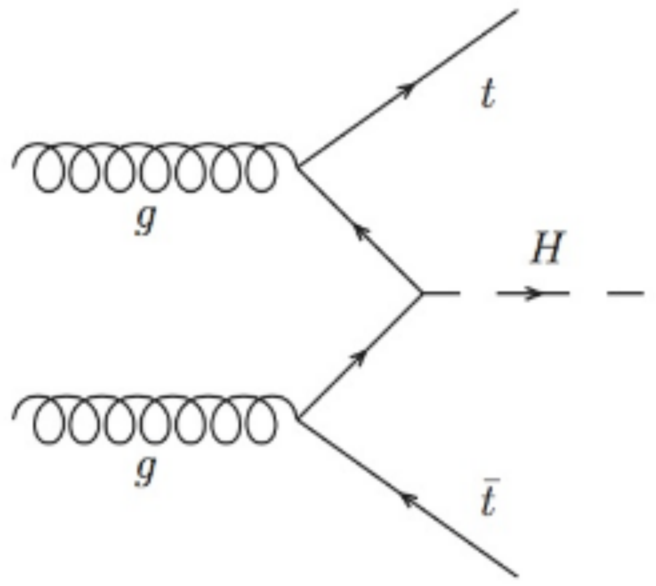
$\sigma \times \mathcal{B}(H \to ZZ) = 0.1$ pb



VH

$\sigma \times \mathcal{B}(H \to WW) = 0.5$ pb

$\sigma \times \mathcal{B}(H \to ZZ) = 0.06$ pb



ttH

$\sigma \times \mathcal{B}(H \to WW) = 0.1$ pb

$\sigma \times \mathcal{B}(H \to ZZ) = 0.01$ pb

The input analyses & categories

References in Backup

Analysis	Decay tags	Production tags	Luminosity (fb^{-1})	References
$H \to \gamma\gamma$	$\gamma\gamma$	ggH, $p_T(H) \times$ N-jet bins VBF, $p_T(H\ jj)$ bins	77.4	[53]
		ttH	35.9, 41.5	[54], [55]
$H \to ZZ^{(*)} \to 4\ell$	4μ, $2e2\mu/2\mu 2e$, 4e	ggH, $p_T(H) \times$ N-jet bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH	137	[56]
$H \to WW^{(*)} \to \ell\nu\ell\nu$	$e\mu/\mu e$ ee+$\mu\mu$ $e\mu$+jj 3ℓ 4ℓ	ggH $\leq$ 2-jets VBF ggH $\leq$ 1-jet VH hadronic WH leptonic ZH leptonic	35.9	[57]
$H \to \tau\tau$	$e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$	ggH, $p_T(H) \times$ N-jet bins VH hadronic VBF	77.4	[58]
		VH, high-$p_T(V)$	35.9	[59]
$H \to bb$	$W(\ell\nu)H(bb)$ $Z(\nu\nu)H(bb)$, $Z(\ell\ell)H(bb)$	WH leptonic ZH leptonic	35.9, 41.5	[60], [61]
	bb	ttH, $t\bar{t} \to 0, 1, 2\ell +$ jets	77.4	[62]
		ggH, high-$p_T(H)$ bins	35.9	[63]
ttH production with $H \to$ leptons	$2\ell ss$, 3ℓ, 4ℓ, $1\ell+2\tau_h$, $2\ell ss+1\tau_h$, $3\ell+1\tau_h$	ttH	35.9, 41.5	[64], [65]
$H \to \mu\mu$	$\mu\mu$	ggH VBF	35.9	[66]

	Luminosity (fb^{-1})	References
$H \to \gamma\gamma$	77	CMS-PAS-HIG-18-029 CMS-PAS-HIG-18-018
$H \to ZZ^* \to 4\ell$	137	CMS-PAS-HIG-19-001
$H \to WW$	36	Phys. Lett. B 791 (2019) 96
$H \to bb$	36 (ggH) - 77 (others)	Phys. Rev. Lett. 121, 121801 (2018) CMS-PAS-HIG-18-030 Phys.Rev. Lett. 120, 071802 (2018)
$H \to \tau\tau$	77	CMS-PAS-HIG-18-032 JHEP 06 (2019) 093
ttH multilepton	77	CMS-PAS-HIG-18-019
$H \to \mu\mu$	36	Phys. Rev. Lett. 122, 021801 (2019)

Signal strength modifiers

Production μ_i		Uncertainty	
Parameters	Best-fit	Stat.	Syst.
μ_{ggH}	$1.04^{+0.09}_{-0.09}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.05}_{-0.05}$ $\left(^{+0.05}_{-0.05}\right)$	$^{+0.08}_{-0.07}$ $\left(^{+0.07}_{-0.07}\right)$
μ_{VBF}	$0.75^{+0.19}_{-0.17}$ $\left(^{+0.20}_{-0.19}\right)$	$^{+0.16}_{-0.15}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.10}_{-0.08}$ $\left(^{+0.11}_{-0.10}\right)$
μ_{WH}	$1.46^{+0.37}_{-0.35}$ $\left(^{+0.35}_{-0.34}\right)$	$^{+0.29}_{-0.28}$ $\left(^{+0.29}_{-0.28}\right)$	$^{+0.22}_{-0.21}$ $\left(^{+0.20}_{-0.19}\right)$
μ_{ZH}	$0.98^{+0.31}_{-0.30}$ $\left(^{+0.30}_{-0.29}\right)$	$^{+0.26}_{-0.25}$ $\left(^{+0.25}_{-0.25}\right)$	$^{+0.17}_{-0.16}$ $\left(^{+0.17}_{-0.15}\right)$
μ_{ttH}	$1.14^{+0.21}_{-0.20}$ $\left(^{+0.20}_{-0.18}\right)$	$^{+0.13}_{-0.13}$ $\left(^{+0.12}_{-0.12}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.15}_{-0.13}\right)$

Decay μ^f		Uncertainty	
Parameters	Best-fit	Stat.	Syst.
$\mu^{\gamma\gamma}$	$1.07^{+0.12}_{-0.10}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.08}_{-0.08}\right)$	$^{+0.08}_{-0.07}$ $\left(^{+0.07}_{-0.06}\right)$
μ^{ZZ}	$0.93^{+0.10}_{-0.09}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.07}_{-0.07}$ $\left(^{+0.08}_{-0.07}\right)$	$^{+0.07}_{-0.06}$ $\left(^{+0.07}_{-0.06}\right)$
μ^{WW}	$1.20^{+0.16}_{-0.15}$ $\left(^{+0.14}_{-0.13}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.13}_{-0.12}$ $\left(^{+0.11}_{-0.10}\right)$
$\mu^{\tau\tau}$	$0.80^{+0.17}_{-0.16}$ $\left(^{+0.18}_{-0.17}\right)$	$^{+0.10}_{-0.10}$ $\left(^{+0.10}_{-0.10}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.15}_{-0.14}\right)$
μ^{bb}	$1.11^{+0.20}_{-0.19}$ $\left(^{+0.20}_{-0.19}\right)$	$^{+0.13}_{-0.13}$ $\left(^{+0.12}_{-0.12}\right)$	$^{+0.16}_{-0.15}$ $\left(^{+0.15}_{-0.14}\right)$
$\mu^{\mu\mu}$	$0.90^{+1.29}_{-1.28}$ $\left(^{+1.27}_{-1.26}\right)$	$^{+1.28}_{-1.27}$ $\left(^{+1.25}_{-1.26}\right)$	$^{+0.22}_{-0.13}$ $\left(^{+0.24}_{-0.06}\right)$

Signal strength modifiers

Decay mode	Production Process														
	ggH			VBF			WH			ZH			ttH		
	Best-fit	Uncertainty Stat.	Uncertainty Syst.	Best-fit	Uncertainty Stat.	Uncertainty Syst.	Best-fit	Uncertainty Stat.	Uncertainty Syst.	Best-fit	Uncertainty Stat.	Uncertainty Syst.	Best-fit	Uncertainty Stat.	Uncertainty Syst.
$H \rightarrow bb$	2.45 $^{+2.53}_{-2.35}$ ($^{+2.11}_{-1.95}$)	$^{+2.04}_{-2.01}$ ($^{+1.92}_{-1.91}$)	$^{+1.51}_{-1.22}$ ($^{+0.86}_{-0.34}$)	— (—)			1.27 $^{+0.42}_{-0.40}$ ($^{+0.42}_{-0.41}$)	$^{+0.32}_{-0.31}$ ($^{+0.33}_{-0.32}$)	$^{+0.27}_{-0.25}$ ($^{+0.27}_{-0.26}$)	0.93 $^{+0.33}_{-0.31}$ ($^{+0.32}_{-0.31}$)	$^{+0.27}_{-0.26}$ ($^{+0.26}_{-0.26}$)	$^{+0.19}_{-0.17}$ ($^{+0.19}_{-0.17}$)	1.13 $^{+0.33}_{-0.30}$ ($^{+0.32}_{-0.30}$)	$^{+0.16}_{-0.16}$ ($^{+0.16}_{-0.16}$)	$^{+0.29}_{-0.25}$ ($^{+0.28}_{-0.25}$)
$H \rightarrow \tau\tau$	0.39 $^{+0.38}_{-0.39}$ ($^{+0.39}_{-0.36}$)	$^{+0.16}_{-0.16}$ ($^{+0.16}_{-0.16}$)	$^{+0.35}_{-0.35}$ ($^{+0.36}_{-0.33}$)	1.05 $^{+0.30}_{-0.29}$ ($^{+0.31}_{-0.30}$)	$^{+0.25}_{-0.24}$ ($^{+0.25}_{-0.25}$)	$^{+0.18}_{-0.17}$ ($^{+0.18}_{-0.17}$)	3.01 $^{+1.65}_{-1.51}$ ($^{+1.52}_{-1.40}$)	$^{+1.37}_{-1.27}$ ($^{+1.27}_{-1.16}$)	$^{+0.92}_{-0.81}$ ($^{+0.82}_{-0.78}$)	1.53 $^{+1.60}_{-1.37}$ ($^{+1.45}_{-1.25}$)	$^{+1.41}_{-1.25}$ ($^{+1.32}_{-1.17}$)	$^{+0.75}_{-0.55}$ ($^{+0.59}_{-0.46}$)	0.81 $^{+0.74}_{-0.67}$ ($^{+0.72}_{-0.64}$)	$^{+0.57}_{-0.53}$ ($^{+0.57}_{-0.53}$)	$^{+0.46}_{-0.40}$ ($^{+0.43}_{-0.36}$)
$H \rightarrow WW$	1.28 $^{+0.20}_{-0.19}$ ($^{+0.17}_{-0.16}$)	$^{+0.11}_{-0.11}$ ($^{+0.11}_{-0.10}$)	$^{+0.17}_{-0.15}$ ($^{+0.14}_{-0.12}$)	0.63 $^{+0.65}_{-0.61}$ ($^{+0.61}_{-0.58}$)	$^{+0.58}_{-0.54}$ ($^{+0.55}_{-0.52}$)	$^{+0.30}_{-0.29}$ ($^{+0.27}_{-0.26}$)	2.85 $^{+2.11}_{-1.87}$ ($^{+1.48}_{-1.20}$)	$^{+1.78}_{-1.60}$ ($^{+1.33}_{-1.09}$)	$^{+1.13}_{-0.96}$ ($^{+0.64}_{-0.51}$)	0.90 $^{+1.77}_{-1.43}$ ($^{+1.67}_{-1.37}$)	$^{+1.70}_{-1.41}$ ($^{+1.61}_{-1.36}$)	$^{+0.50}_{-0.24}$ ($^{+0.43}_{-0.21}$)	0.93 $^{+0.48}_{-0.45}$ ($^{+0.45}_{-0.41}$)	$^{+0.37}_{-0.36}$ ($^{+0.35}_{-0.35}$)	$^{+0.30}_{-0.26}$ ($^{+0.27}_{-0.22}$)
$H \rightarrow ZZ$	0.98 $^{+0.12}_{-0.11}$ ($^{+0.13}_{-0.12}$)	$^{+0.09}_{-0.09}$ ($^{+0.10}_{-0.09}$)	$^{+0.08}_{-0.07}$ ($^{+0.08}_{-0.07}$)	0.57 $^{+0.46}_{-0.36}$ ($^{+0.57}_{-0.47}$)	$^{+0.44}_{-0.35}$ ($^{+0.52}_{-0.44}$)	$^{+0.15}_{-0.09}$ ($^{+0.23}_{-0.14}$)	1.10 $^{+0.96}_{-0.74}$ ($^{+0.99}_{-0.73}$)	$^{+0.94}_{-0.74}$ ($^{+0.96}_{-0.72}$)	$^{+0.19}_{-0.10}$ ($^{+0.21}_{-0.11}$)				0.25 $^{+1.03}_{-0.25}$ ($^{+1.12}_{-0.67}$)	$^{+1.00}_{-0.25}$ ($^{+1.10}_{-0.67}$)	$^{+0.21}_{-0.00}$ ($^{+0.22}_{-0.06}$)
$H \rightarrow \gamma\gamma$	1.09 $^{+0.15}_{-0.14}$ ($^{+0.14}_{-0.13}$)	$^{+0.11}_{-0.11}$ ($^{+0.11}_{-0.11}$)	$^{+0.10}_{-0.08}$ ($^{+0.09}_{-0.07}$)	0.77 $^{+0.37}_{-0.29}$ ($^{+0.41}_{-0.36}$)	$^{+0.32}_{-0.27}$ ($^{+0.33}_{-0.32}$)	$^{+0.18}_{-0.09}$ ($^{+0.25}_{-0.18}$)	— (—)			— (—)			1.62 $^{+0.52}_{-0.43}$ ($^{+0.41}_{-0.35}$)	$^{+0.44}_{-0.40}$ ($^{+0.39}_{-0.35}$)	$^{+0.27}_{-0.14}$ ($^{+0.15}_{-0.07}$)
$H \rightarrow \mu\mu$	0.31 $^{+1.82}_{-1.81}$ ($^{+1.78}_{-1.79}$)	$^{+1.80}_{-1.80}$ ($^{+1.76}_{-1.79}$)	$^{+0.22}_{-0.22}$ ($^{+0.28}_{-0.07}$)	3.18 $^{+8.22}_{-7.93}$ ($^{+8.13}_{-7.95}$)	$^{+7.99}_{-7.90}$ ($^{+8.01}_{-7.88}$)	$^{+1.93}_{-0.76}$ ($^{+1.41}_{-1.05}$)	— (—)			— (—)			— (—)		

H boson couplings: κ-framework

Parameters	Best-fit	Uncertainty Stat.	Uncertainty Syst.
	Coupling modifiers κ_i		
κ_Z	$0.96^{+0.07}_{-0.07}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.05}$
	$\left(^{+0.08}_{-0.08}\right)$	$\left(^{+0.06}_{-0.06}\right)$	$\left(^{+0.05}_{-0.05}\right)$
κ_W	$-1.11^{+0.14}_{-0.09}$	$^{+0.13}_{-0.07}$	$^{+0.05}_{-0.06}$
	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.07}_{-0.07}\right)$	$\left(^{+0.06}_{-0.06}\right)$
κ_t	$1.01^{+0.11}_{-0.11}$	$^{+0.06}_{-0.06}$	$^{+0.09}_{-0.08}$
	$\left(^{+0.10}_{-0.10}\right)$	$\left(^{+0.06}_{-0.06}\right)$	$\left(^{+0.08}_{-0.08}\right)$
κ_τ	$0.94^{+0.12}_{-0.12}$	$^{+0.08}_{-0.11}$	$^{+0.09}_{-0.06}$
	$\left(^{+0.12}_{-0.11}\right)$	$\left(^{+0.08}_{-0.07}\right)$	$\left(^{+0.09}_{-0.08}\right)$
κ_b	$1.18^{+0.19}_{-0.27}$	$^{+0.14}_{-0.13}$	$^{+0.13}_{-0.24}$
	$\left(^{+0.17}_{-0.16}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.11}_{-0.11}\right)$
κ_g	$1.16^{+0.12}_{-0.11}$	$^{+0.08}_{-0.08}$	$^{+0.08}_{-0.08}$
	$\left(^{+0.11}_{-0.10}\right)$	$\left(^{+0.07}_{-0.07}\right)$	$\left(^{+0.08}_{-0.07}\right)$
κ_γ	$1.01^{+0.09}_{-0.14}$	$^{+0.07}_{-0.07}$	$^{+0.06}_{-0.12}$
	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.07}_{-0.07}\right)$	$\left(^{+0.05}_{-0.05}\right)$
κ_μ	$0.92^{+0.55}_{-0.87}$	$^{+0.54}_{-0.87}$	$^{+0.10}_{-0.01}$
	$\left(^{+0.52}_{-0.96}\right)$	$\left(^{+0.51}_{-0.95}\right)$	$\left(^{+0.08}_{-0.08}\right)$

Assuming only SM Higgs boson decays:

$$\sigma_i B^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$$

$\Gamma_H(\vec{\kappa})$: total width of the Higgs boson

$\Gamma^f(\vec{\kappa})$: partial width of the decay to the final state f

Coupling modifiers $\vec{\kappa}$ to parametrize deviations in HVV and Hff couplings from the SM predictions:

$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

Extract $\mu_{i,j}\left(\kappa_\lambda\right)$

$$\mu^{\text{prod}}\left(\kappa_\lambda, C1\right) = \frac{\sigma^{\text{NLO}}}{\sigma^{\text{NLO}}_{\text{SM}}} = \frac{1+\kappa_\lambda C_1 + \delta Z_H}{\left(1-\left(\kappa_\lambda^2-1\right)\delta Z_H\right)\left(1+C_1+\delta Z_H\right)}$$

$$\mu_i^f = \mu_i \times \mu^f$$

$$\mu^{\text{decay}}\left(\kappa_\lambda, C_1^{\Gamma_{ZZ}}\right) = \frac{BR(H\to ZZ)}{BR(H\to ZZ)} = 1 + \frac{\left(\kappa_\lambda - 1\right)\left(C_1^{\Gamma_{ZZ}} - C_1^{\Gamma_{tot}}\right)}{1+\left(\kappa_\lambda-1\right)C_1^{\Gamma_{tot}}}$$

Extract $\mu_{i,j}\left(\kappa_\lambda\right)$

$$\mu_i^f = \mu_i \times \mu^f$$

$$\mu^{\text{prod}}\left(\kappa_\lambda, C1\right) = \frac{\sigma^{\text{NLO}}}{\sigma^{\text{NLO}}_{\text{SM}}} = \frac{1 + \kappa_\lambda C_1 + \delta Z_H}{\left(1 - \left(\kappa_\lambda^2 - 1\right)\delta Z_H\right)\left(1 + C_1 + \delta Z_H\right)}$$

$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

$$C_1^{\Gamma_{tot}} = \sum_j \text{BR}_j^{\text{SM}} C_1^\Gamma(j) = 2.5 \times 10^{-3}$$

$$\mu^{\text{decay}}\left(\kappa_\lambda, C_1^{\Gamma_{ZZ}}\right) = \frac{BR(H \to ZZ)}{BR(H \to ZZ)} = 1 + \frac{\left(\kappa_\lambda - 1\right)\left(C_1^{\Gamma_{ZZ}} - C_1^{\Gamma_{tot}}\right)}{1 + \left(\kappa_\lambda - 1\right)C_1^{\Gamma_{tot}}}$$

Extract $\mu_{i,j}(\kappa_\lambda)$

$$\mu^{\text{prod}}(\kappa_\lambda, C1) = \frac{\sigma^{\text{NLO}}}{\sigma^{\text{NLO}}_{\text{SM}}} = \frac{1 + \kappa_\lambda C_1 + \delta Z_H}{\left(1 - (\kappa_\lambda^2 - 1)\,\delta Z_H\right)(1 + C_1 + \delta Z_H)}$$

$$\mu_i^f = \mu_i \times \mu^f$$

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

$$C_1(p_n) = \frac{2\Re\left(\mathscr{M}^{0*}\mathscr{M}^1_{\lambda_3^{SM}}\right)}{\left|\mathscr{M}^0\right|^2}$$

$$\delta Z_H = -1.536 \times 10^{-3}$$

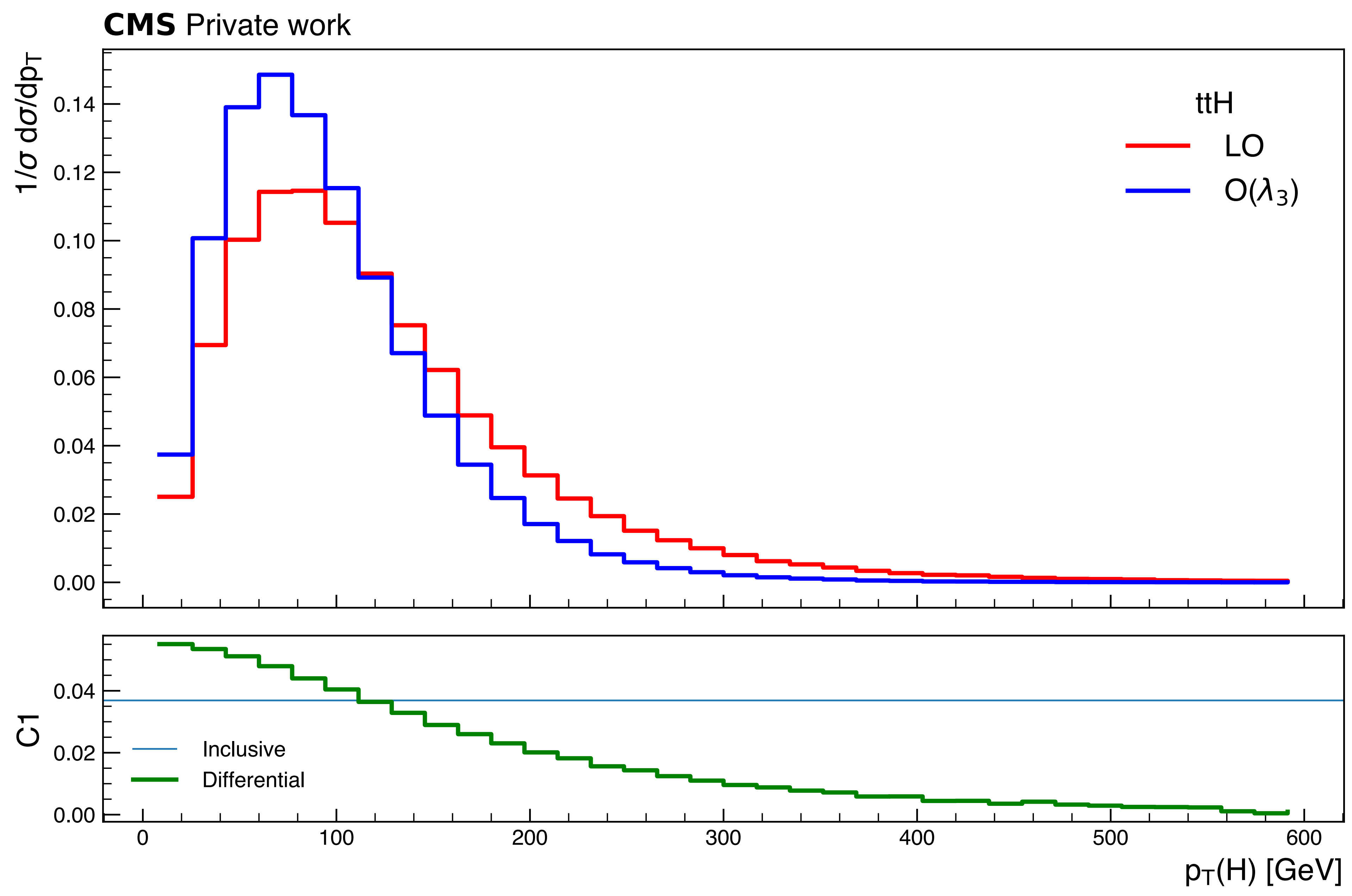
Depends both on the H boson production mode and on the kinematics

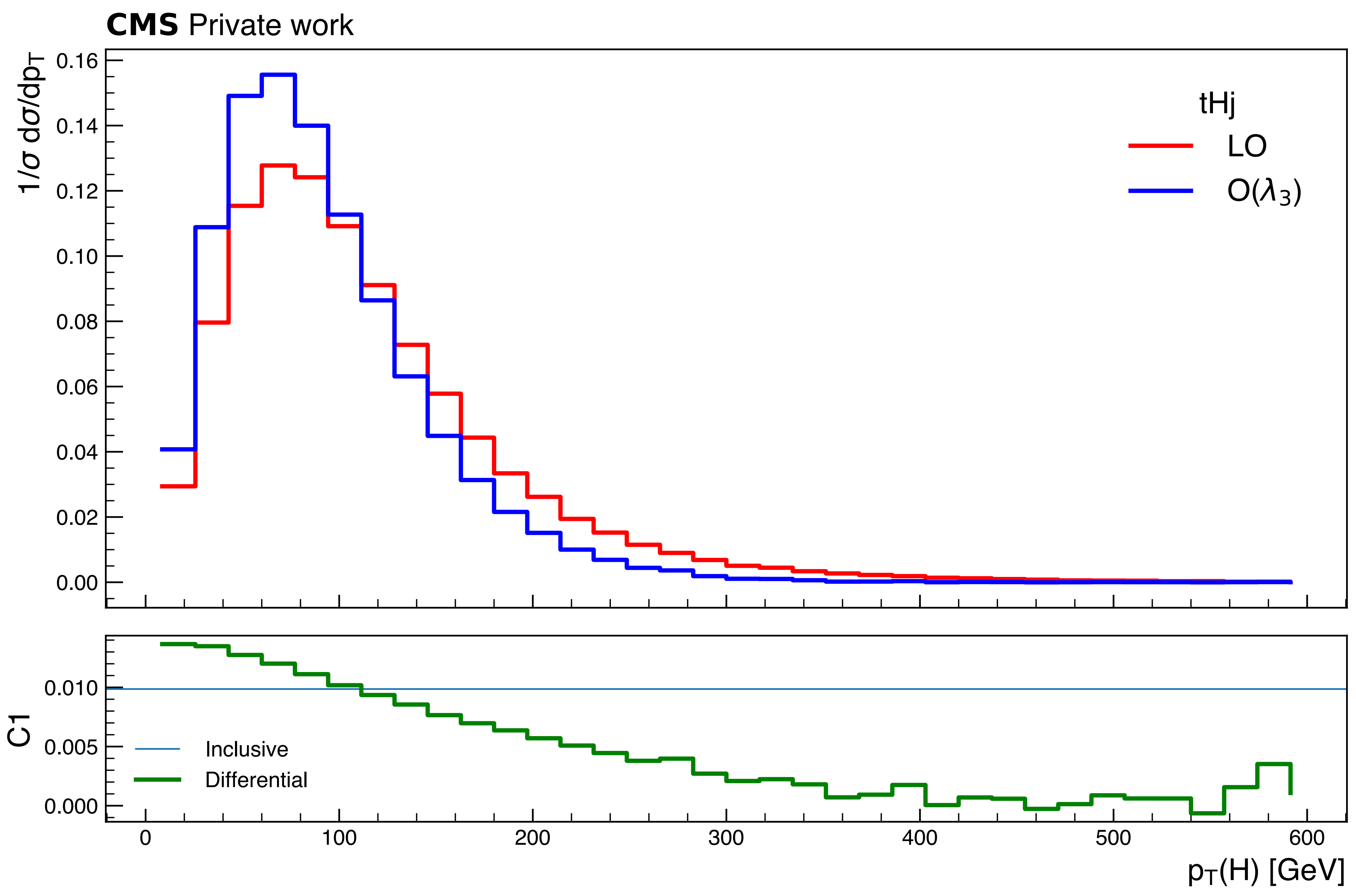
$$\mu^{\text{decay}}(\kappa_\lambda, C_1^{\Gamma_{ZZ}}) = \frac{BR(H \to ZZ)}{BR(H \to ZZ)} = 1 + \frac{(\kappa_\lambda - 1)\left(C_1^{\Gamma_{ZZ}} - C_1^{\Gamma_{tot}}\right)}{1 + (\kappa_\lambda - 1)\,C_1^{\Gamma_{tot}}}$$

Compute $C_1(p_n)$

While δZ_H is a universal quantity, $C_1(p_n)$ is process and kinematics dependent

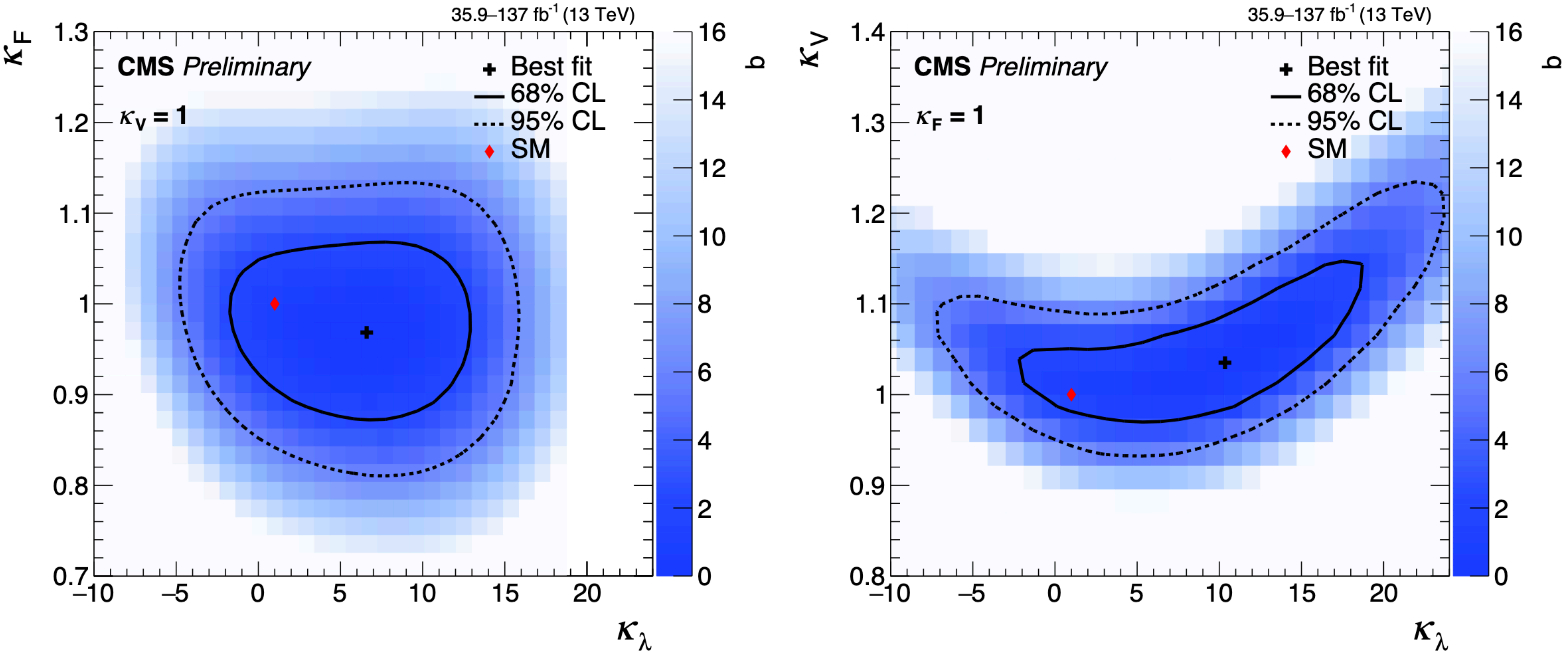
- MadGraph5 dedicated hhh-model and reweighing tool available
- Generate LO events (for each prod. mode) and reweigh to take into account NLO EW corrections
  - Extracted on an event-by-event basis: $C_1 = \mathrm{xsec}_{\mathcal{O}(\lambda_3)}/\mathrm{xsec}_{\mathrm{LO}}$





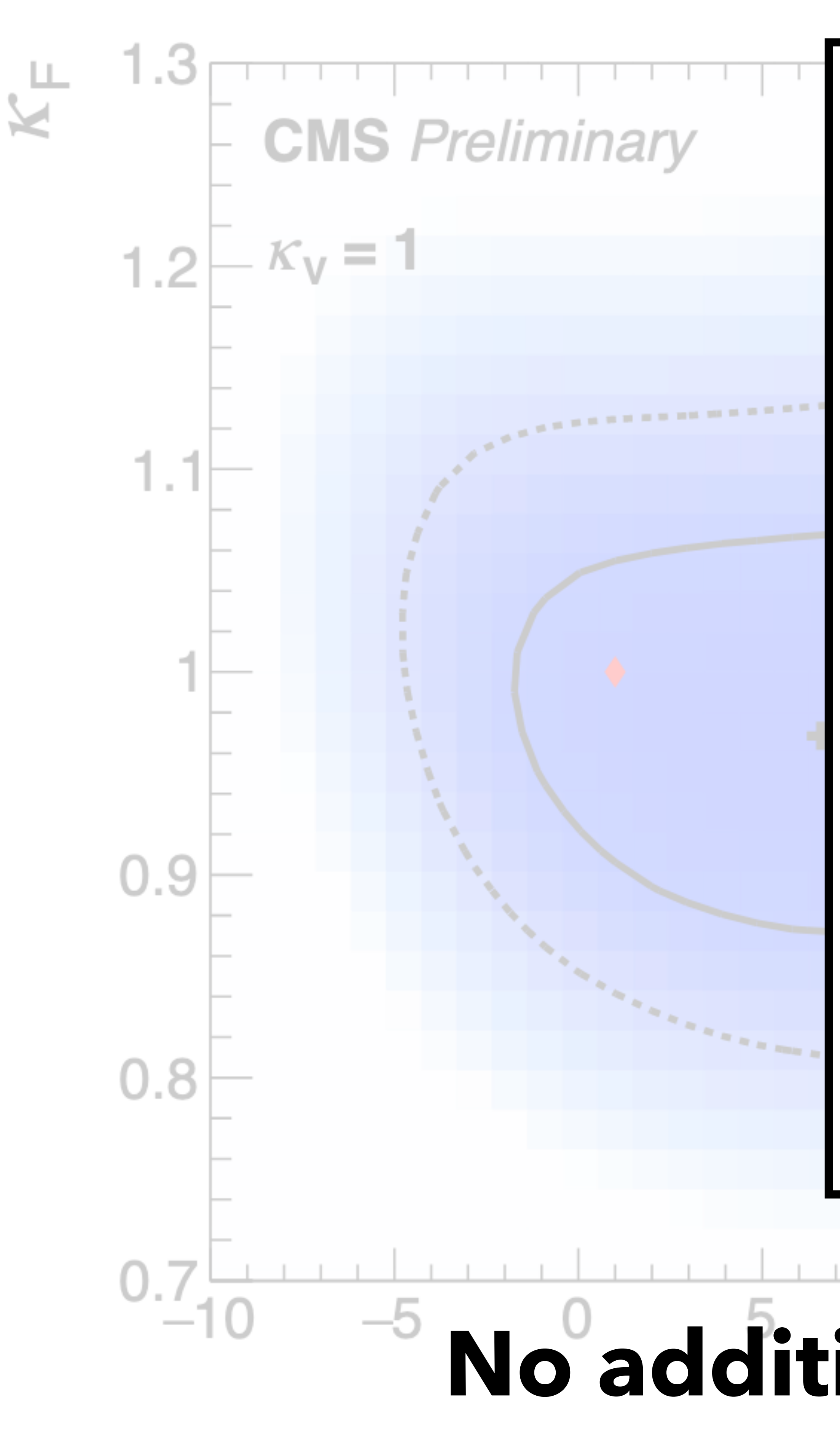
H boson self-coupling

Constraint on $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$ from single-Higgs decay channels via modifications of the production cross sections and decay widths from NLO electroweak corrections

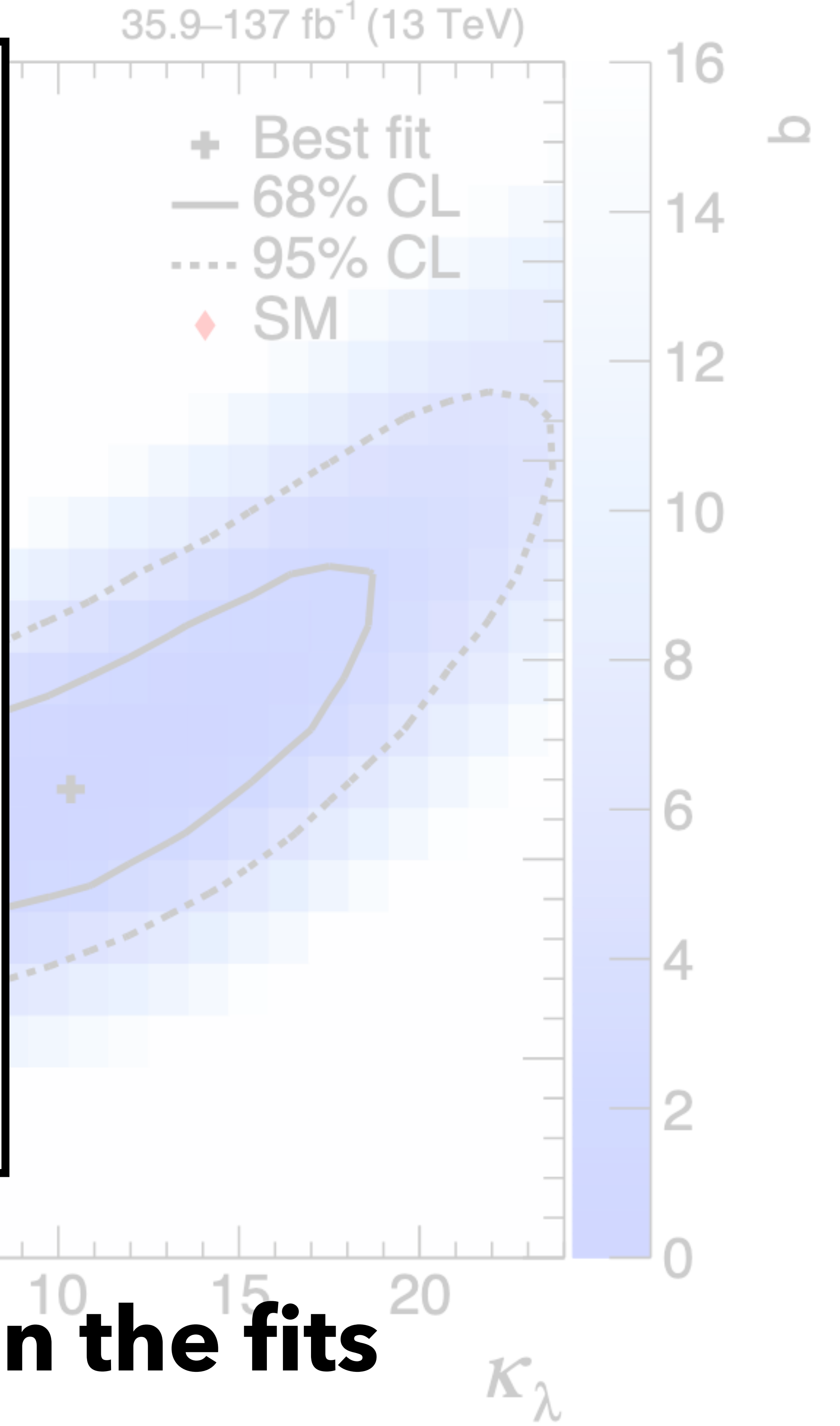


H boson self-coupling

Constraint on $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$ from single-Higgs decay channels via modifications of the production cross sections and decay widths from NLO electroweak corrections



Assumption	Best fit κ_λ	95% CL interval
$\kappa_F = \kappa_V = 1$	$6.7^{+4.6}_{-6.6}$ $\left(^{+8.3}_{-3.8}\right)$	$[-3.5, 14.5]$ $([-5.1, 13.7])$
$\kappa_F = 1$	$10.3^{+6.1}_{-10.0}$ $\left(^{+8.8}_{-5.0}\right)$	$[-5.5, 21.7]$ $([-7.4, 17.2])$
$\kappa_V = 1$	$6.6^{+4.5}_{-6.1}$ $\left(^{+8.2}_{-4.0}\right)$	$[-3.3, 14.4]$ $([-5.5, 13.8])$

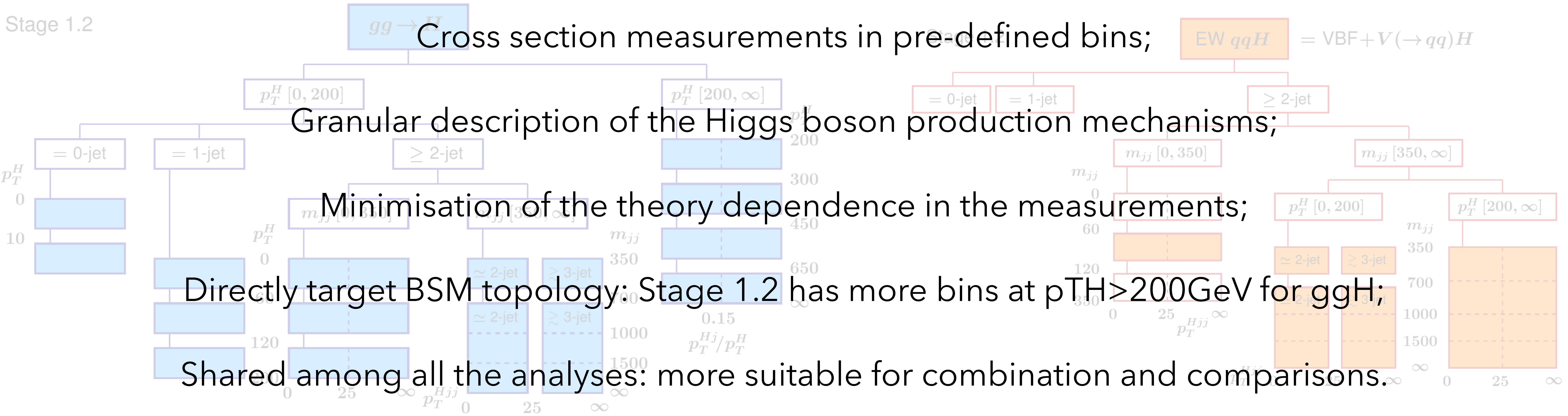


No additional constrain power with κ_V, κ_F profiled in the fits

Simplified Template Cross Section framework

The primary goal of **STXS** framework is to **minimise the measurement dependence on theory predictions without losing sensitivity**

Coverage of the entire phase space and **specific regions** designed **to detect BSM effects**



Cross section measurements in pre-defined bins;

Granular description of the Higgs boson production mechanisms;

Minimisation of the theory dependence in the measurements;

Directly target BSM topology: Stage 1.2 has more bins at pTH>200GeV for ggH;

Shared among all the analyses: more suitable for combination and comparisons.

EFT parametrization of STXS bins

STXS region (stage 0)	A_j
gg → H	$8.73 \times 10^3\, c_G$
qq → Hqq	$9.02\, c_{WW} + 0.6\, c_B - 0.797\, c_{HW} + 0.399\, c_A$
qq → Hℓν	$42.5\, c_{WW} + 19.9\, c_{HW}$
qq → Hℓℓ	$36.6\, c_{WW} + 10.5\, c_B + 15\, c_{HW} + 5.14\, c_A$
gg/qq → ttH	$2.95\, c_u + 115\, c_G$

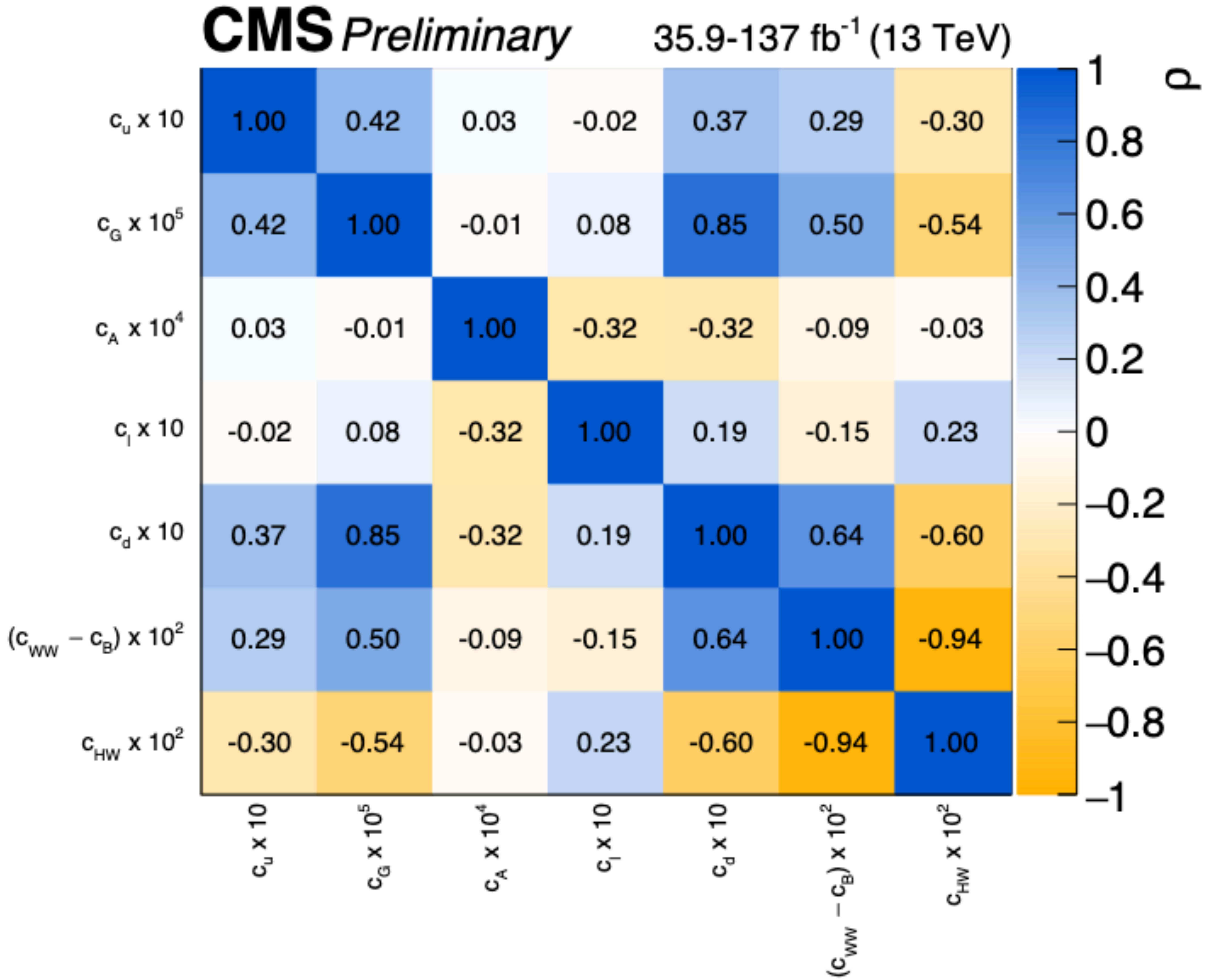
STXS region (stage 0)	B_{jk}
gg → H	$1.95 \times 10^7\, {c_G}^2$
qq → Hqq	$171\, {c_{WW}}^2 + 3.42\, {c_B}^2 + 114\, {c_{HW}}^2 + 0.874\, {c_A}^2 + 23.1\, c_{WW}\, c_B + 233\, c_{WW}\, c_{HW} + 6.22\, c_{WW}\, c_A + 15.3\, c_B\, c_{HW} + 2.02\, c_B\, c_A + 0.681\, c_{HW}\, c_A$
qq → Hℓν	$912\, {c_{WW}}^2 + 558\, {c_{HW}}^2 + 1.3 \times 10^3\, c_{WW}\, c_{HW}$
qq → Hℓℓ	$602\, {c_{WW}}^2 + 51.7\, {c_B}^2 + 321\, {c_{HW}}^2 + 10.7\, {c_A}^2 + 350\, c_{WW}\, c_B + 772\, c_{WW}\, c_{HW} + 102\, c_{WW}\, c_A + 227\, c_B\, c_{HW} + 31.4\, c_B\, c_A + 29.7\, c_{HW}\, c_A$
gg/qq → ttH	$2.14\, {c_u}^2 + 6.13\, {c_{WW}}^2 + 1\, {c_B}^2 + 5.87\, {c_{HW}}^2 + 2.97 \times 10^4\, {c_G}^2 + 167\, c_u\, c_G - 0.31\, c_{WW}\, c_B + 11.9\, c_{WW}\, c_{HW} - 0.318\, c_B\, c_{HW}$

STXS Stage 1.0 and Stage 1.1 parametrizations in CMS-HIG-19-005

Limits on EFT parameters

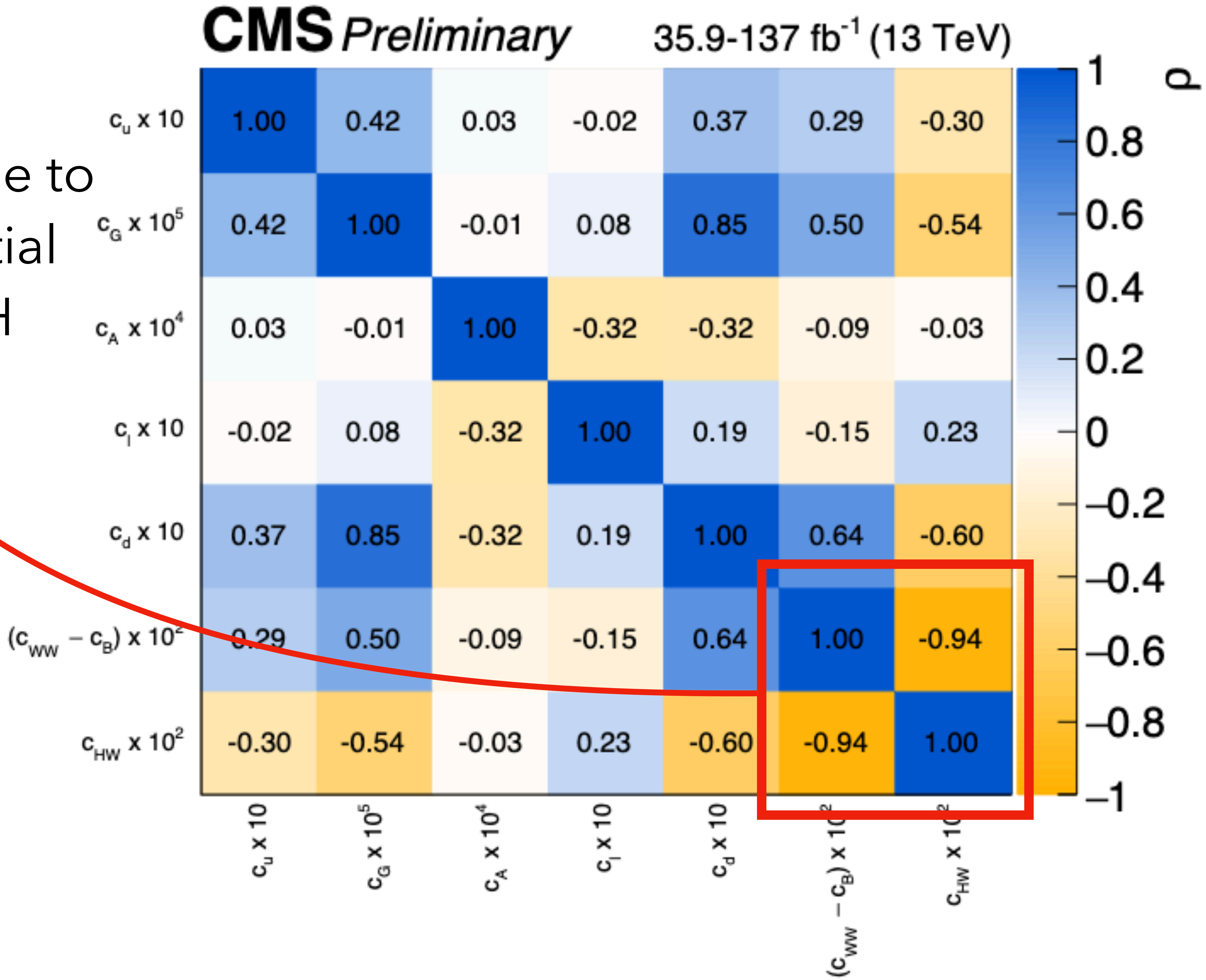
HEL Parameters	Definition	Others profiled	Fix others to SM
$c_A \times 10^4$	$c_A = \frac{m_W^2}{g'^2} \frac{f_A}{\Lambda^2}$	$-1.03^{+1.53}_{-1.59}$ $\left(^{+1.59}_{-1.56}\right)$	$-0.78^{+1.11}_{-1.16}$ $\left(^{+1.10}_{-1.11}\right)$
$c_G \times 10^5$	$c_G = \frac{m_W^2}{g_s^2} \frac{f_G}{\Lambda^2}$	$1.43^{+3.20}_{-3.00}$ $\left(^{+3.13}_{-2.74}\right)$	$0.27^{+1.05}_{-1.05}$ $\left(^{+1.03}_{-1.01}\right)$
$c_u \times 10$	$c_u = -v^2 \frac{f_u}{\Lambda^2}$	$0.68^{+0.82}_{-0.83}$ $\left(^{+0.83}_{-0.79}\right)$	$0.43^{+0.69}_{-0.69}$ $\left(^{+0.68}_{-0.67}\right)$
$c_d \times 10$	$c_d = -v^2 \frac{f_d}{\Lambda^2}$	$0.59^{+1.03}_{-1.13}$ $\left(^{+1.08}_{-1.05}\right)$	$-0.01^{+0.31}_{-0.28}$ $\left(^{+0.30}_{-0.28}\right)$
$c_\ell \times 10$	$c_\ell = -v^2 \frac{f_\ell}{\Lambda^2}$	$-0.57^{+0.74}_{-0.73}$ $\left(^{+0.72}_{-0.77}\right)$	$-0.75^{+0.60}_{-0.64}$ $\left(^{+0.58}_{-0.60}\right)$
$c_{HW} \times 10^2$	$c_{HW} = \frac{m_W^2}{2g} \frac{f_{HW}}{\Lambda^2}$	$-1.45^{+4.72}_{-3.03}$ $\left(^{+3.93}_{-3.27}\right)$	$0.77^{+0.84}_{-1.20}$ $\left(^{+1.04}_{-1.38}\right)$
$(c_{WW} - c_B) \times 10^2$	$c_{WW} = \frac{m_W^2}{g} \frac{f_{WW}}{\Lambda^2}, c_B = \frac{2m_W^2}{g'} \frac{f_B}{\Lambda^2}$	$2.16^{+2.84}_{-5.35}$ $\left(^{+3.46}_{-5.00}\right)$	$0.62^{+1.06}_{-1.22}$ $\left(^{+1.09}_{-1.23}\right)$

Correlations of EFT parameters

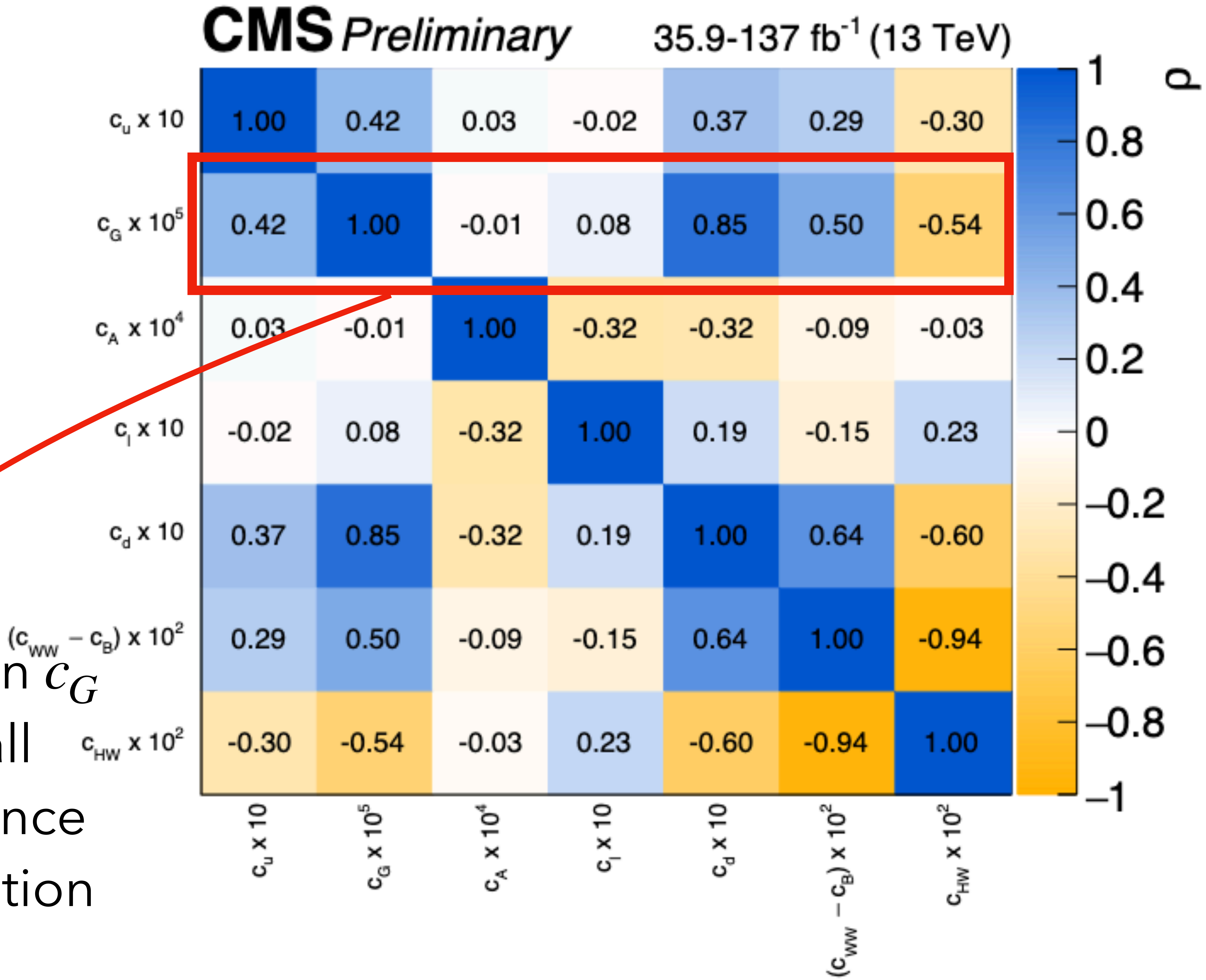


Correlations of EFT parameters

Large correlations due to the limited differential information for VH production



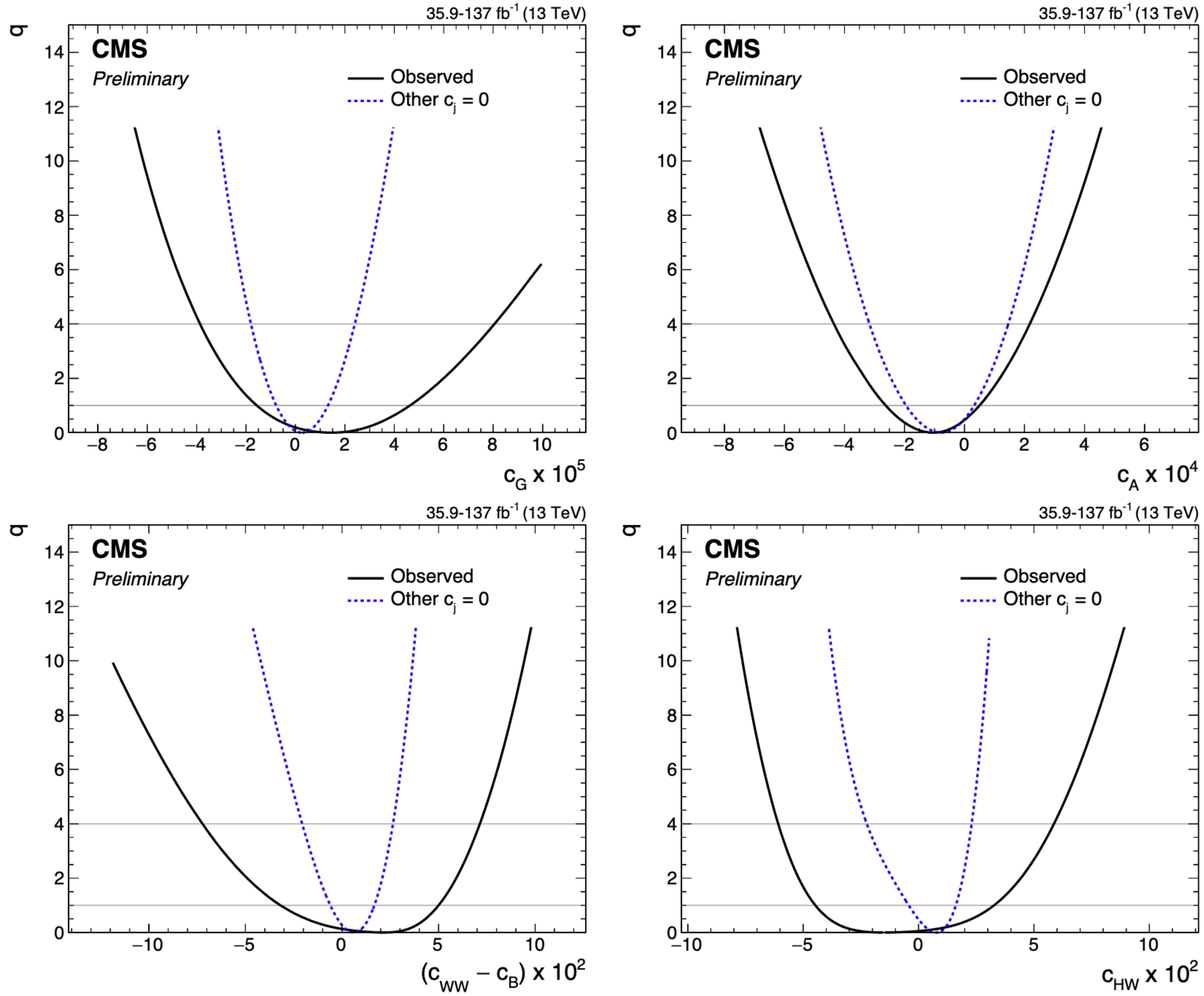
Correlations of EFT parameters



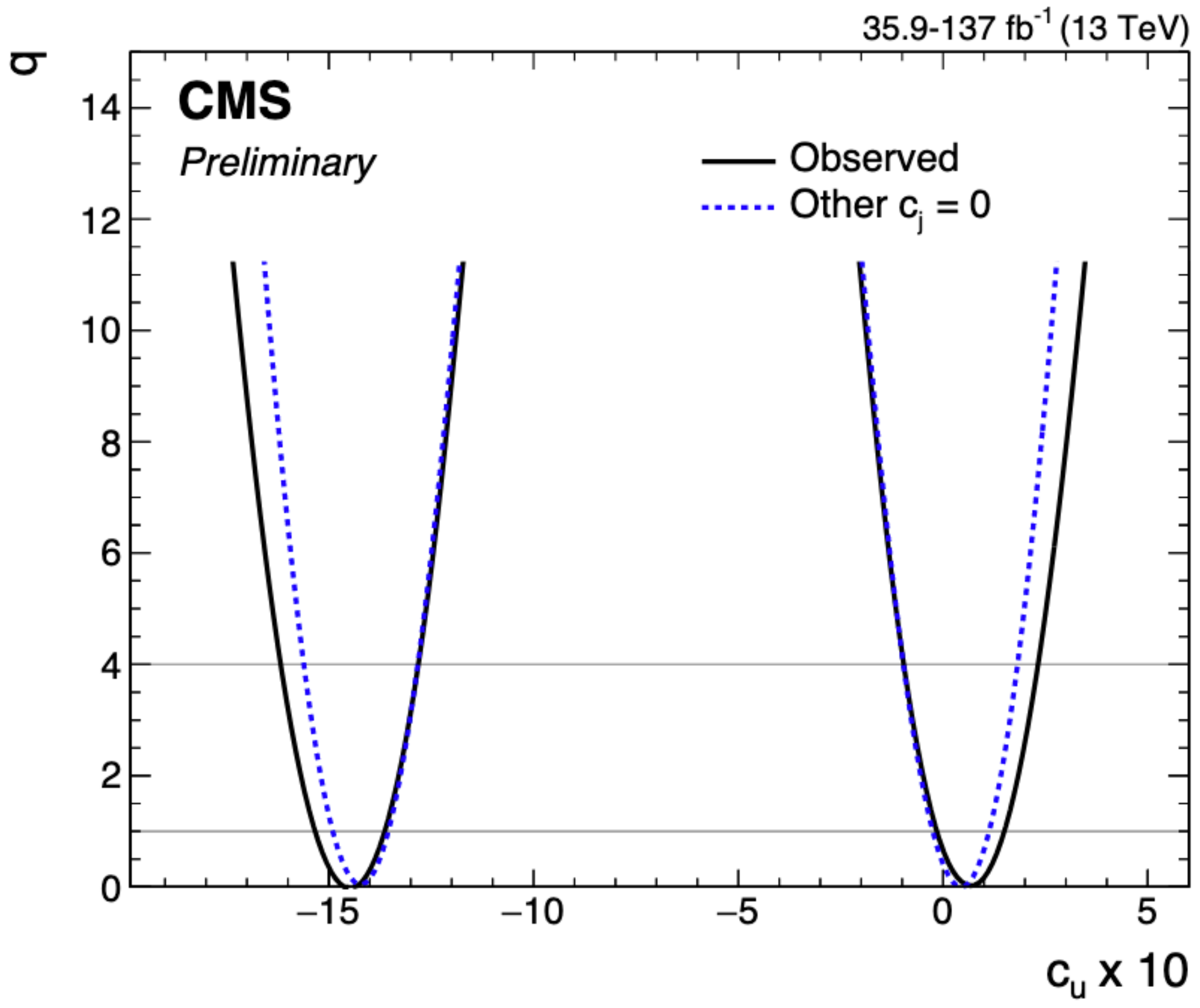
	$c_u \times 10$	$c_G \times 10^5$	$c_A \times 10^4$	$c_l \times 10$	$c_d \times 10$	$(c_{WW} - c_B) \times 10^2$	$c_{HW} \times 10^2$
$c_u \times 10$	1.00	0.42	0.03	-0.02	0.37	0.29	-0.30
$c_G \times 10^5$	0.42	1.00	-0.01	0.08	0.85	0.50	-0.54
$c_A \times 10^4$	0.03	-0.01	1.00	-0.32	-0.32	-0.09	-0.03
$c_l \times 10$	-0.02	0.08	-0.32	1.00	0.19	-0.15	0.23
$c_d \times 10$	0.37	0.85	-0.32	0.19	1.00	0.64	-0.60
$(c_{WW} - c_B) \times 10^2$	0.29	0.50	-0.09	-0.15	0.64	1.00	-0.94
$c_{HW} \times 10^2$	-0.30	-0.54	-0.03	0.23	-0.60	-0.94	1.00

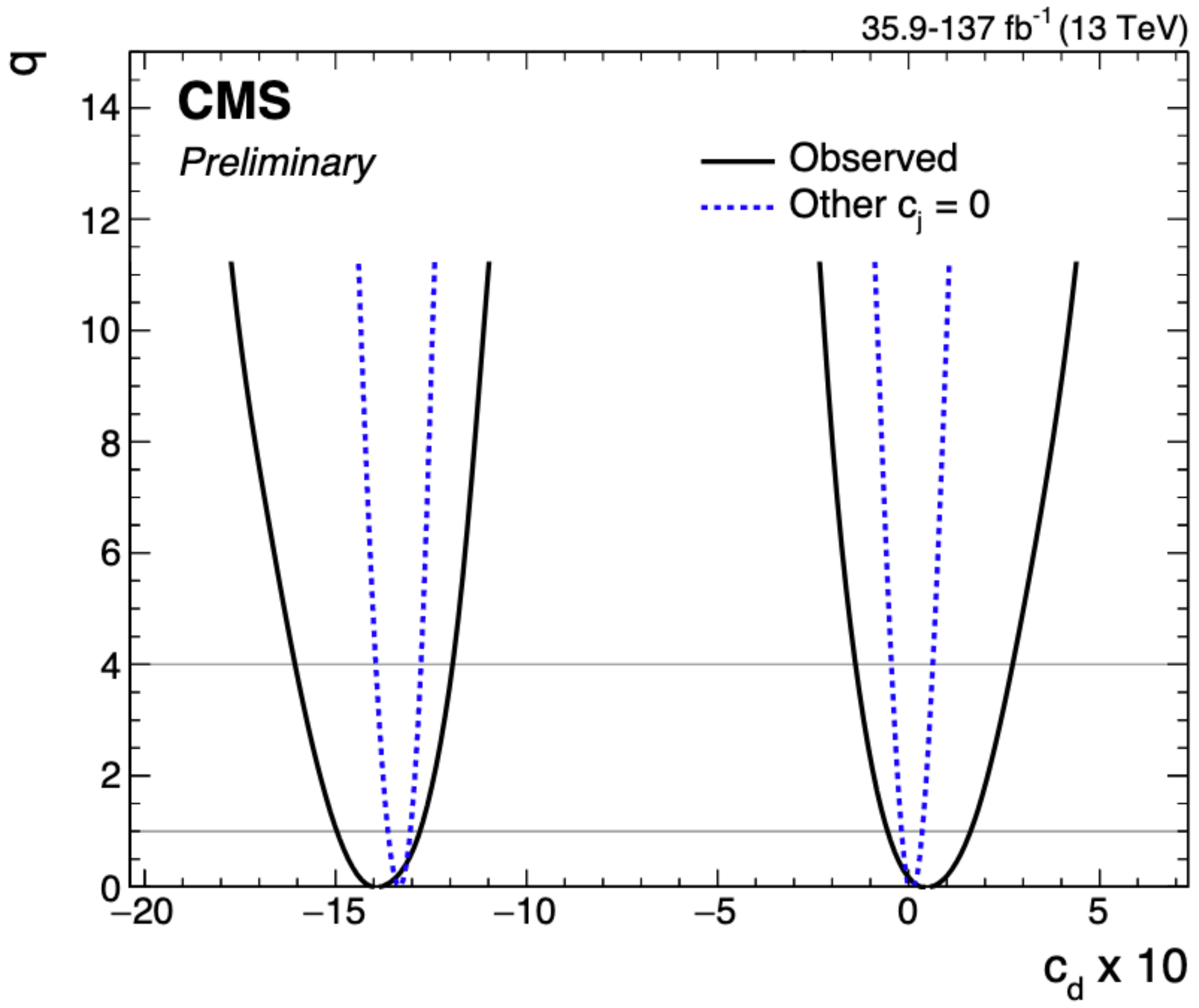
Large correlations on c_G coming from small kinematic dependence in STXS parametrization

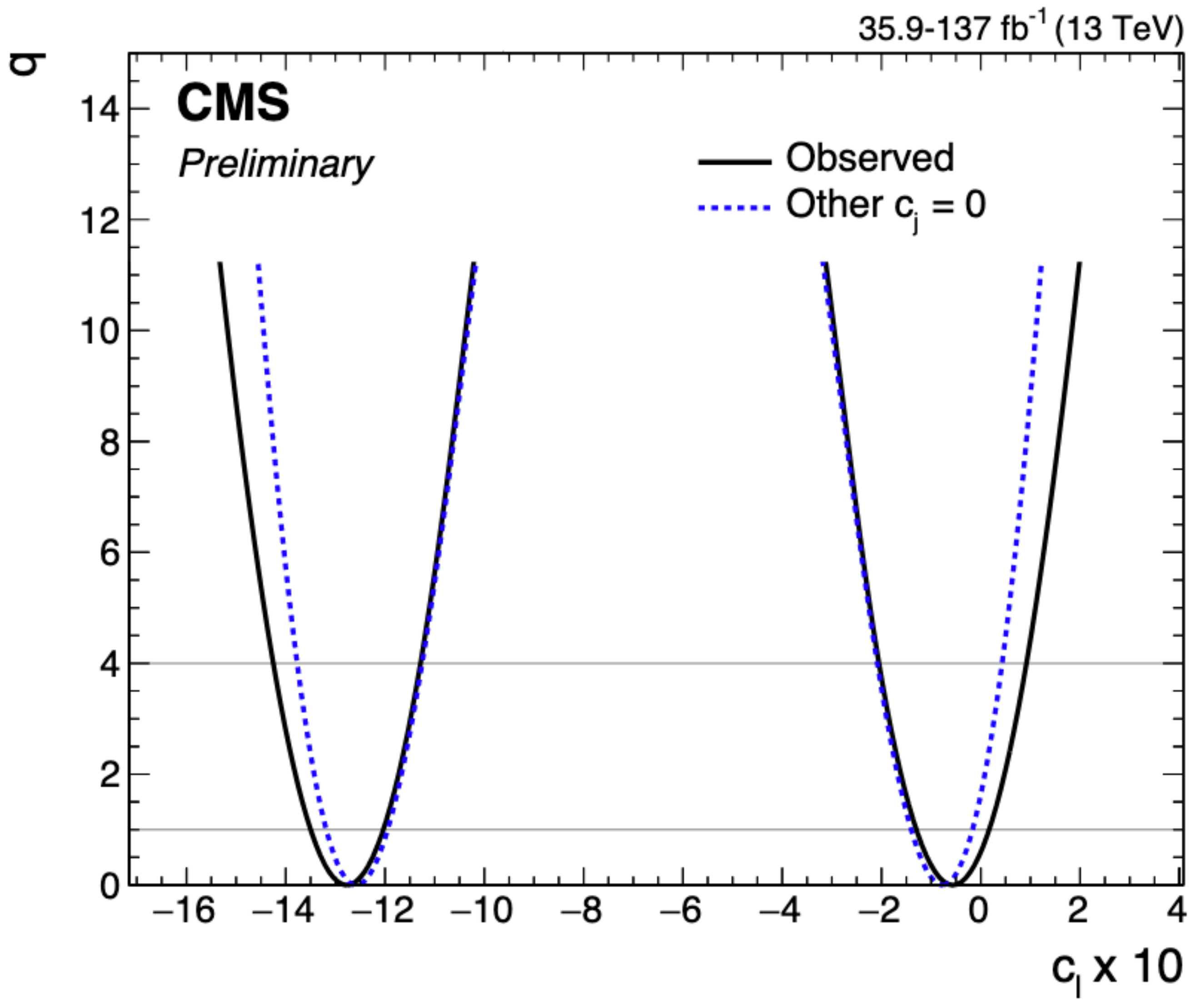
EFT parameters: likelihood scans



EFT parameters: likelihood scans

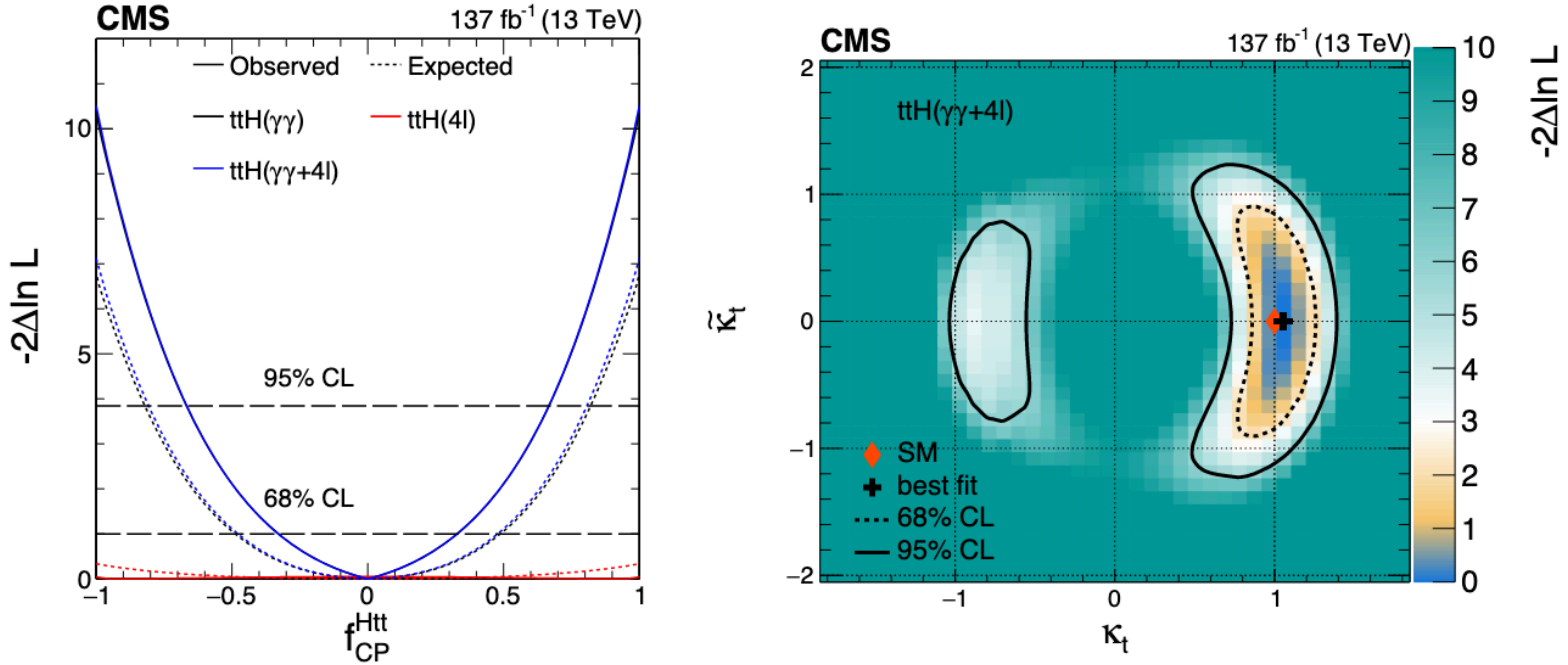




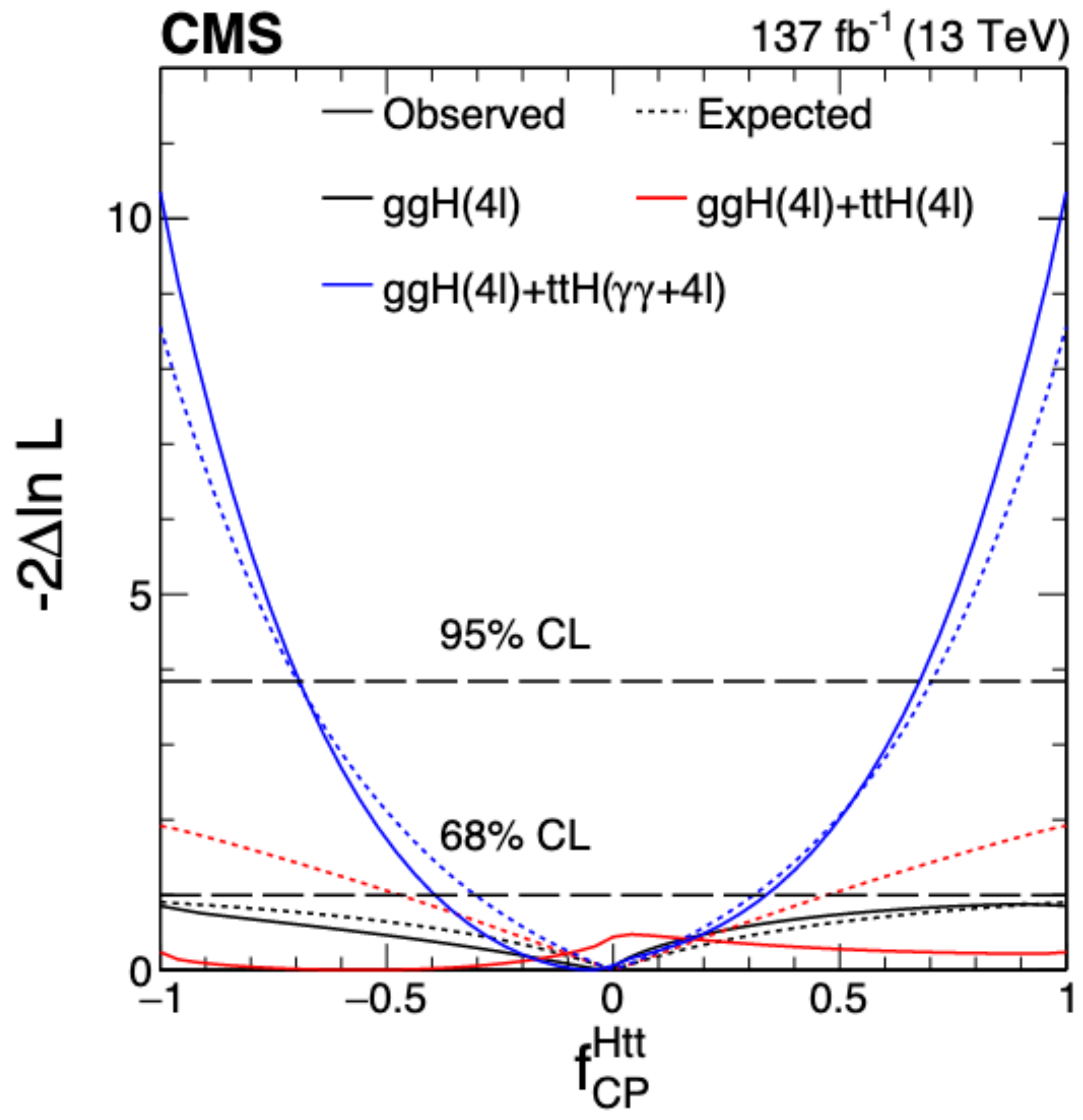


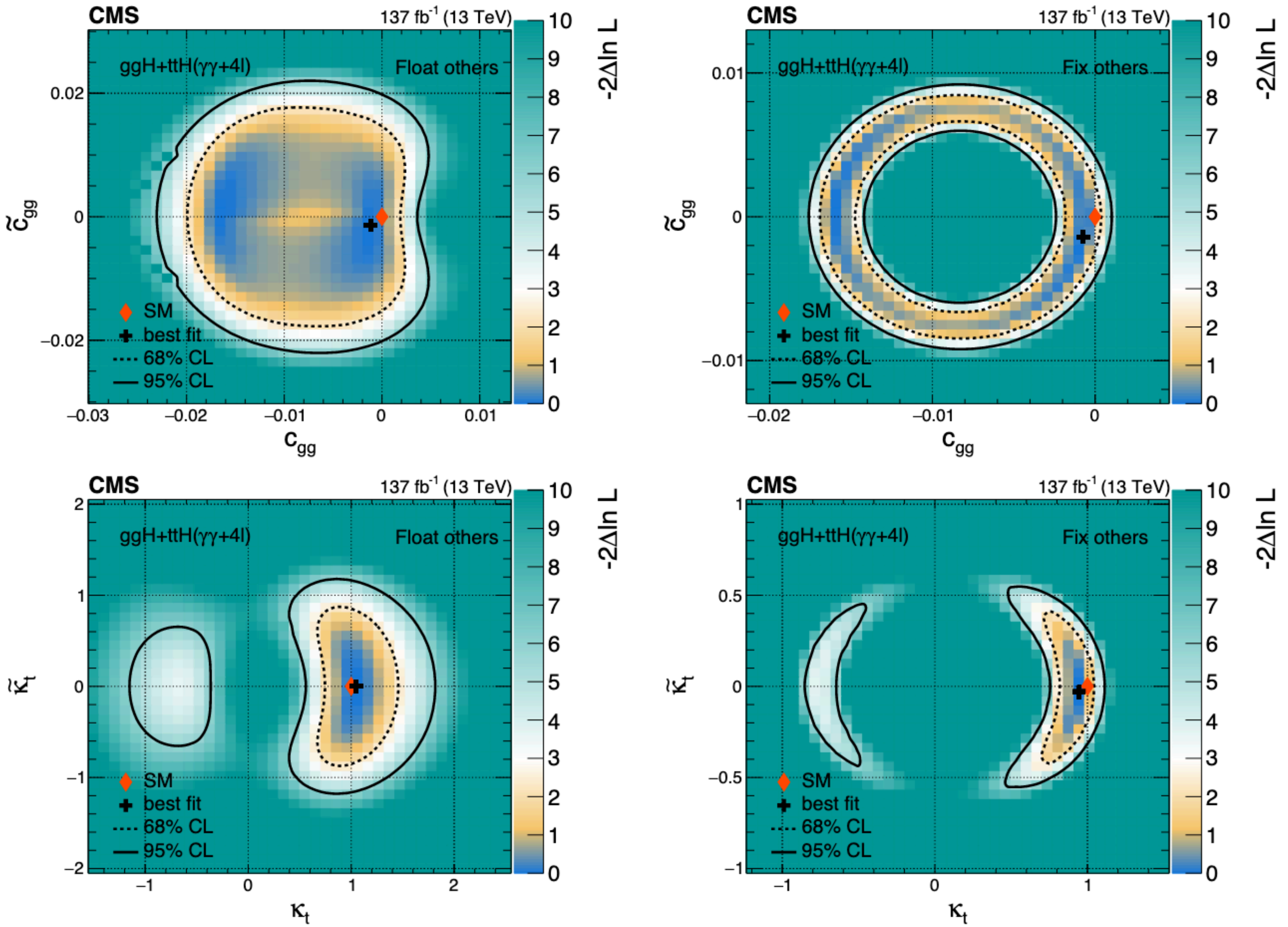
Htt couplings & EFT interpretation

$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} \operatorname{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$



Htt couplings & EFT interpretation





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