Higgs physics highlights at the LHC

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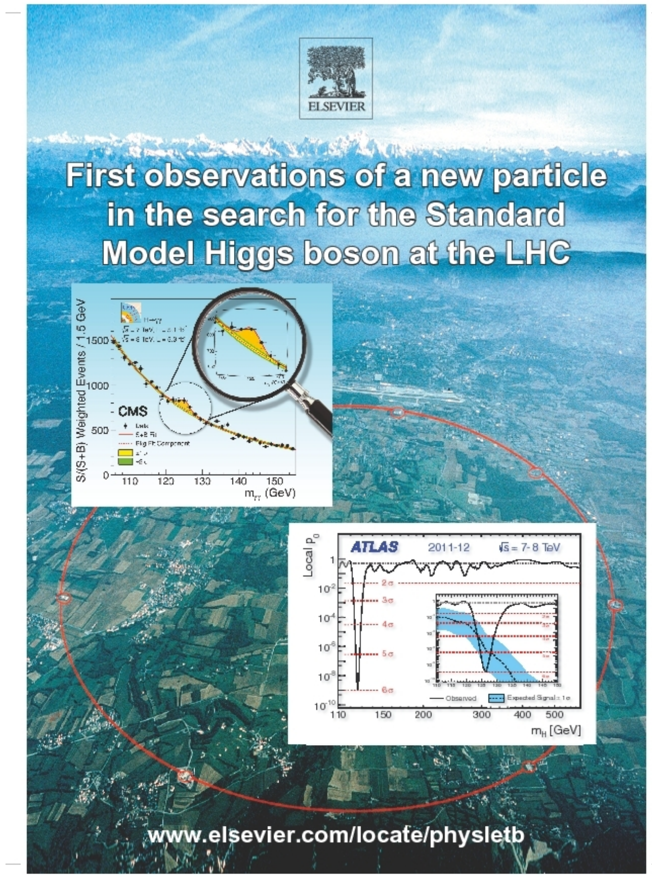
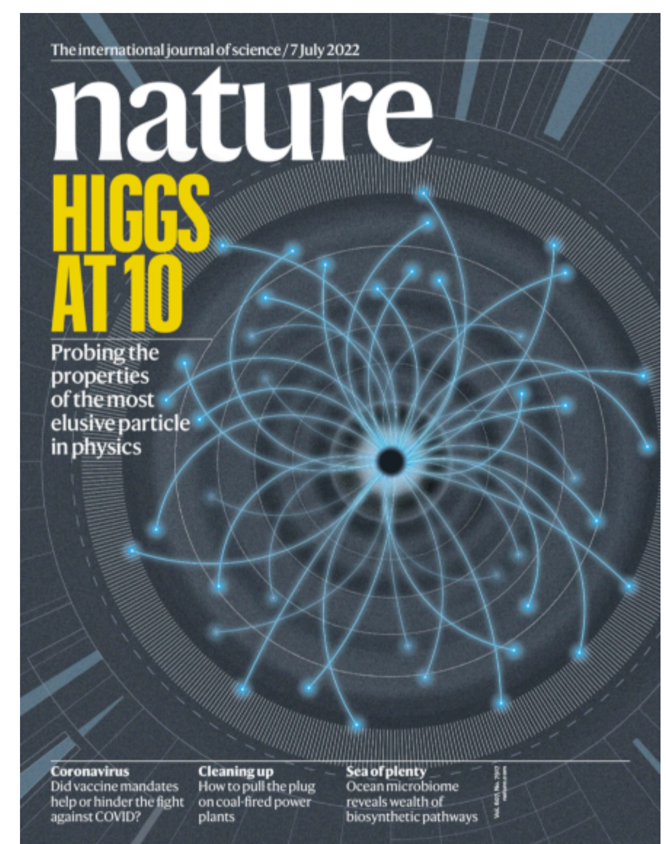
The Higgs boson

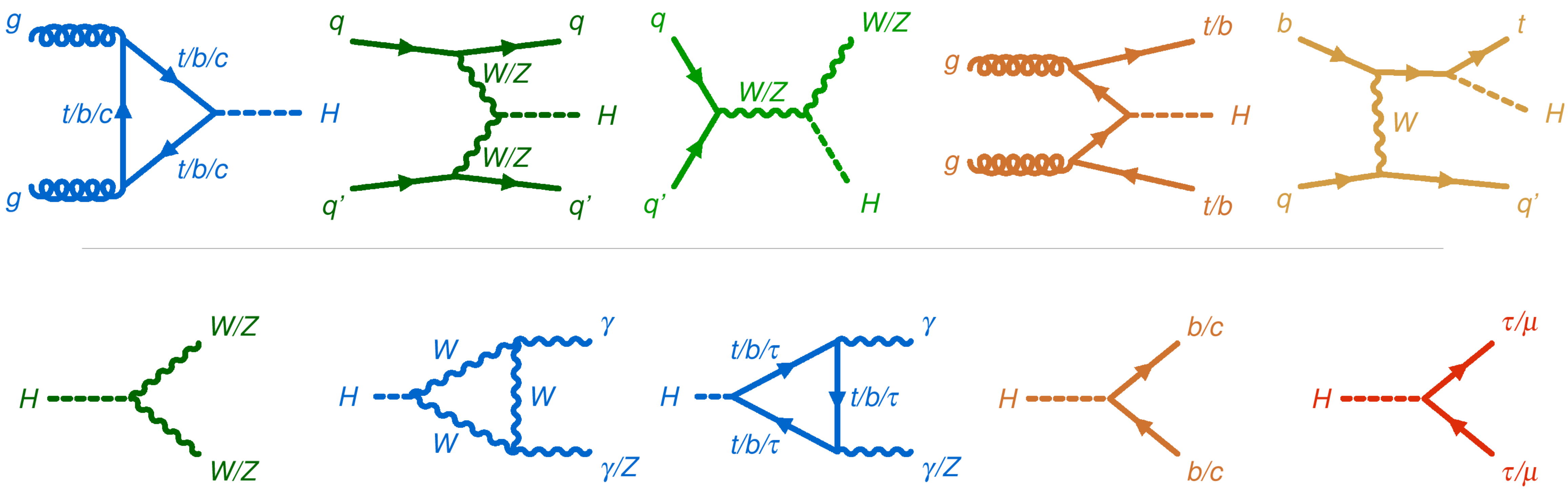
- **The Higgs boson** was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) in 2012
  - a major milestone for particle physics
- It opened a new way to refine our understanding of the electroweak sector
  - many studies of **Higgs boson properties** have been performed
  - deviation from the Standard Model (SM) predictions on Higgs boson properties would provide clue for new physics





Measurements of Higgs coupling properties

Higgs coupling property measurements

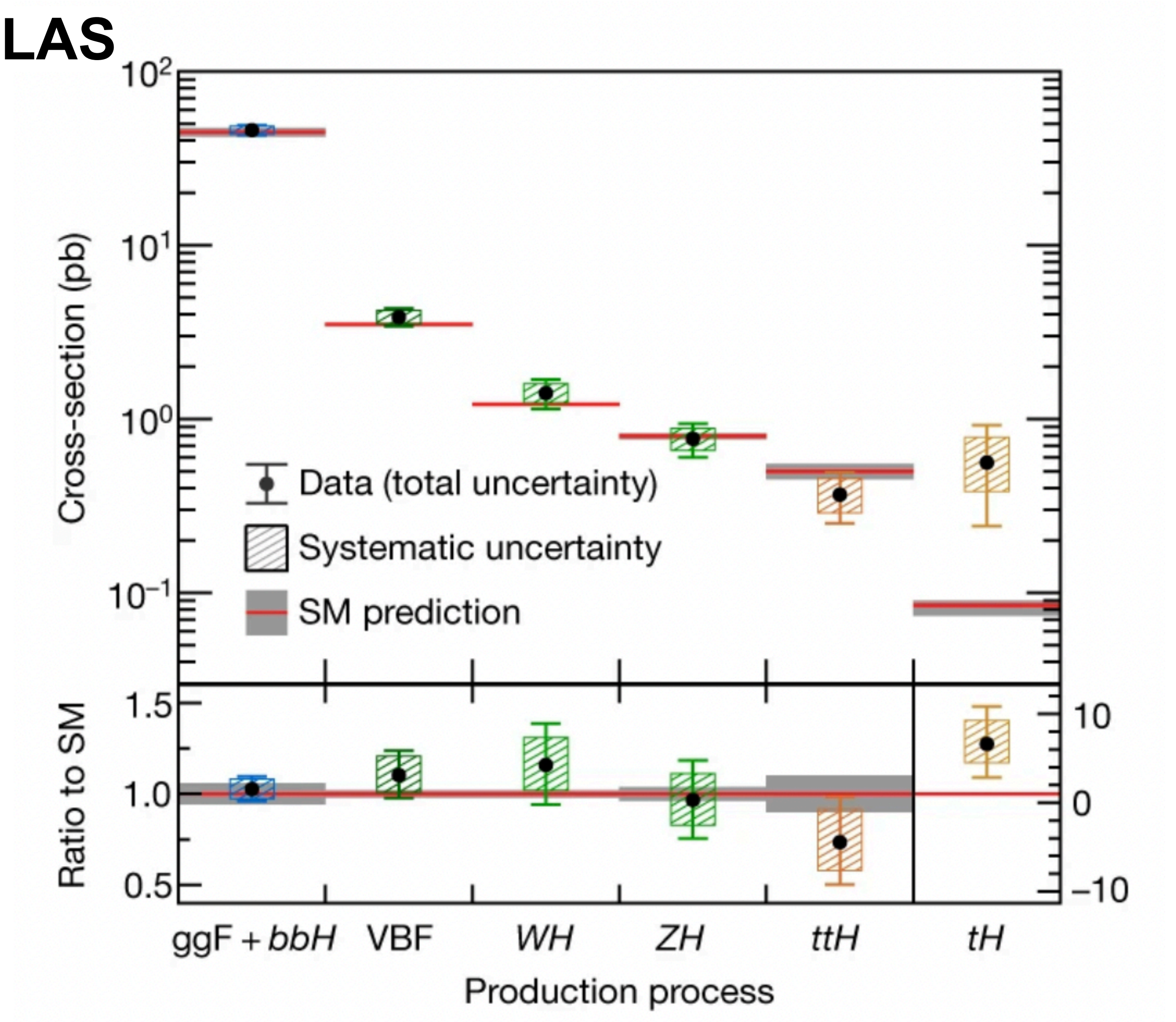


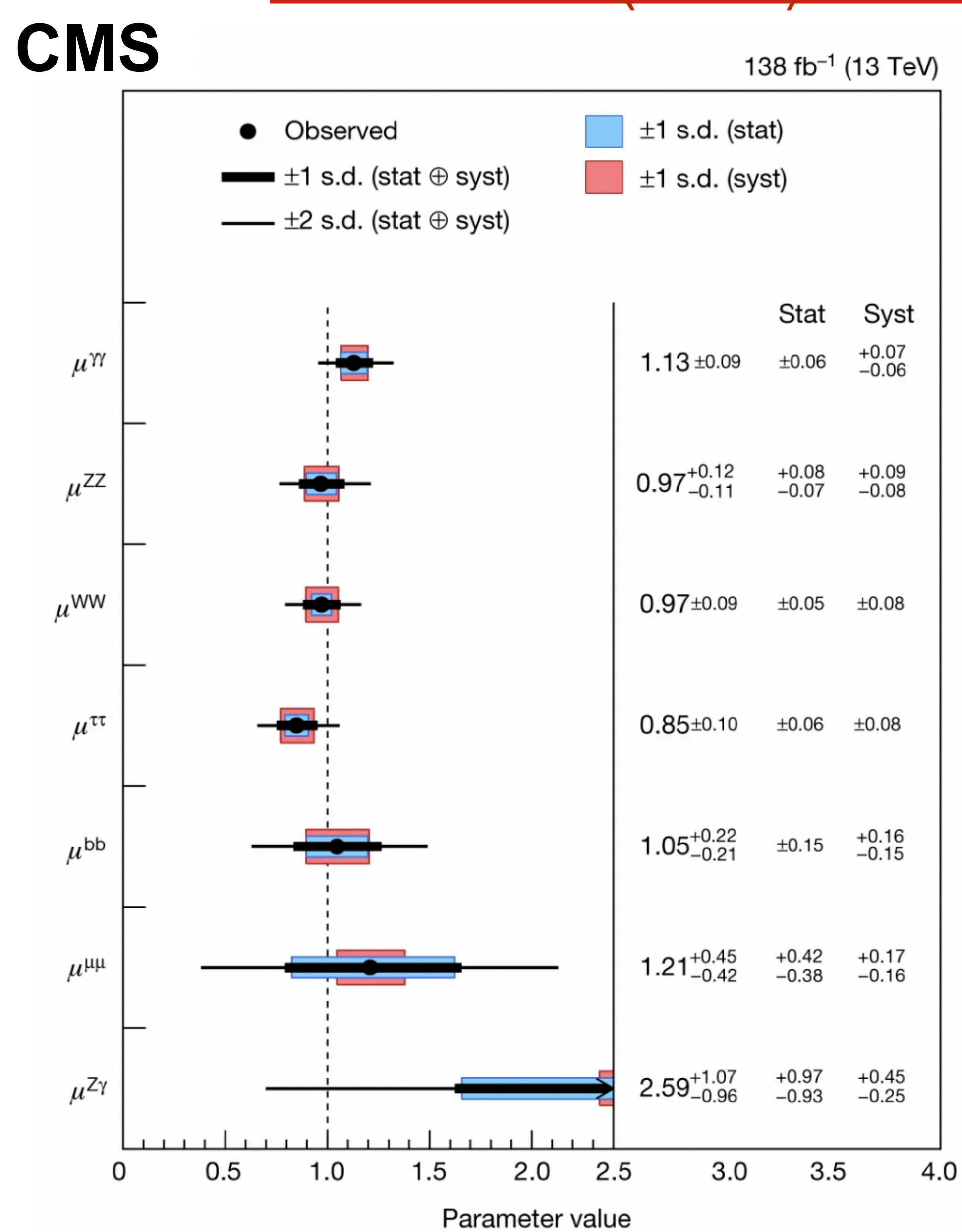
- ATLAS & CMS combine various Higgs production channels and various Higgs decay channels

Higgs production and decay rates

Nature 607 (2022) 52-59

Nature 607 (2022) 60-68

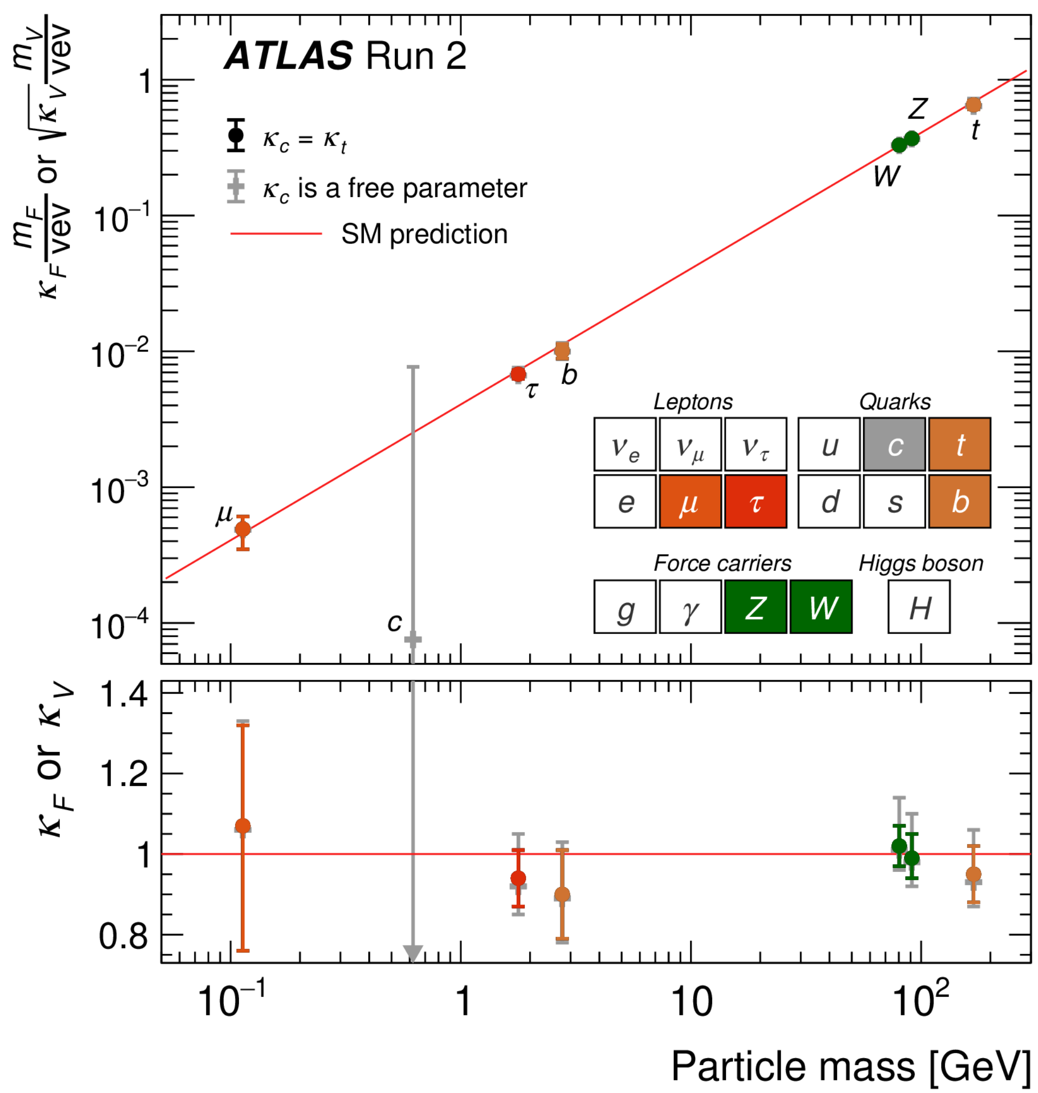




- ggF cross section is now measured with 7% precision
  - Precision of N3LO cross section prediction: 5%
- All major production modes (ggF, VBF, WH, ZH, ttH) and decay modes (H→γγ, H→ZZ, H→WW, H→ττ, H→bb) are observed

Higgs boson couplings with “kappa”

ATLAS Nature 607 (2022) 52-59



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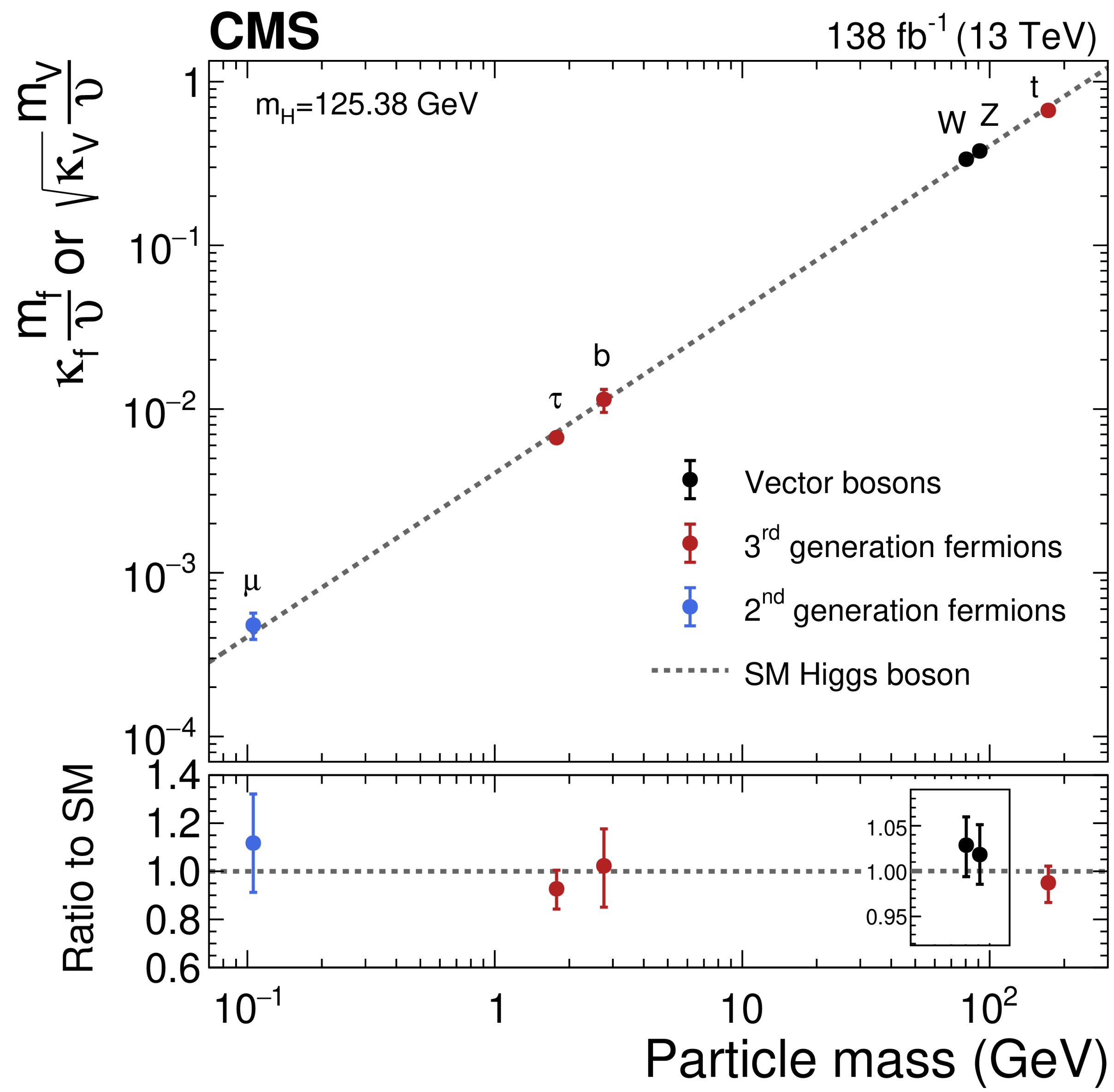
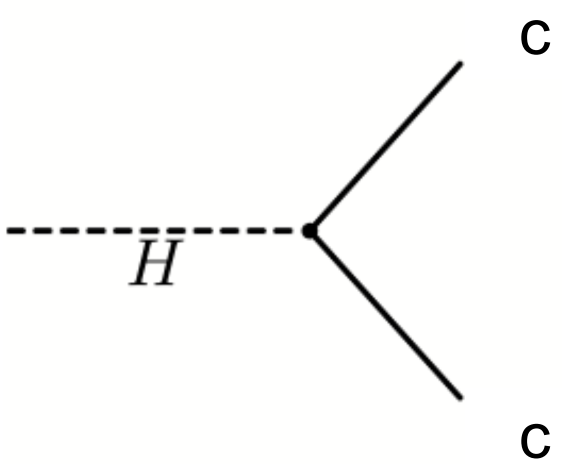
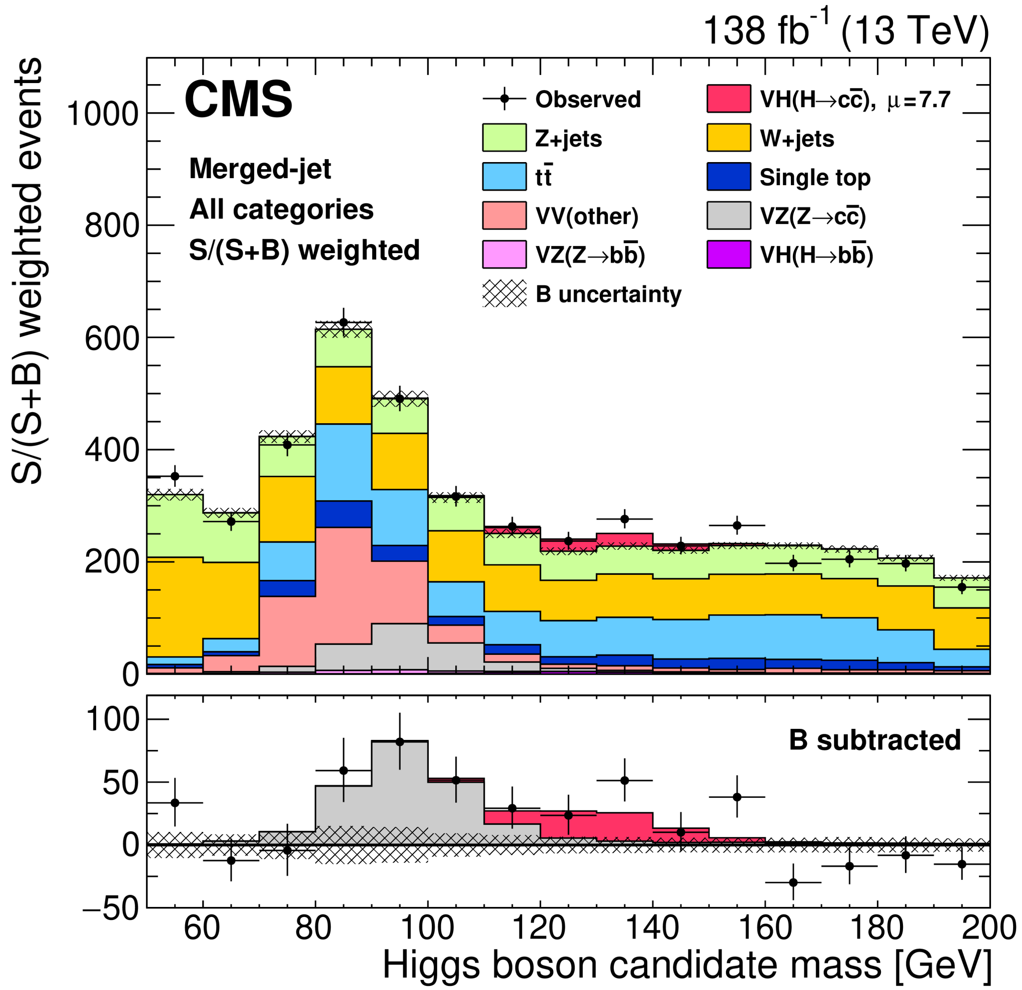


- “Kappa” framework: assign coupling modifier to each interaction vertex (e.g. κ_W, κ_t…)
- Good agreement with the SM across 3 orders of magnitude of particle mass
- One of the most prominent achievements to date at the LHC

Higgs couplings to c quarks

- **H→cc̄ decay** is currently the main channel to probe Higgs coupling to c quarks
  - branching ratio in SM: 2.8%





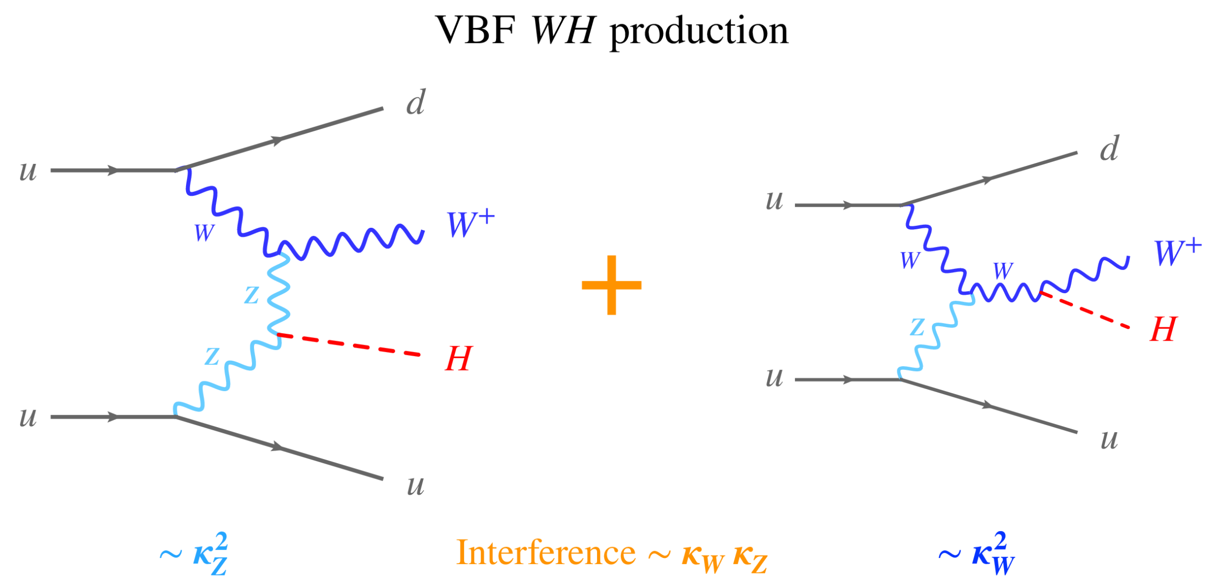
Phys. Rev. Lett. 131 (2023) 061801

Eur. Phys. J. C 82 (2022) 717

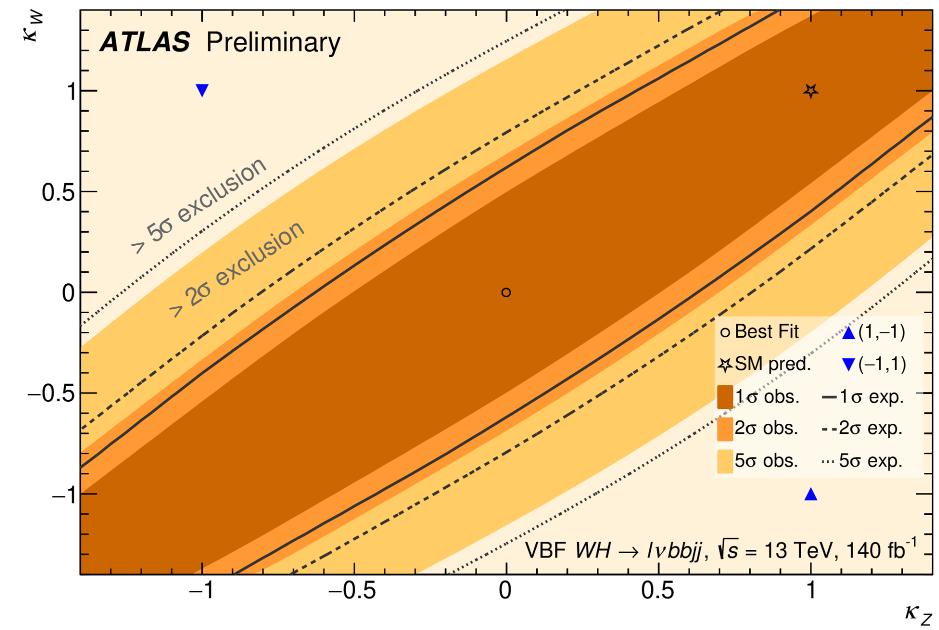
VH H→cc̄

- Tag leptonically decaying W/Z boson
- Observed limit at 95% CL on H→cc̄ signal strength: 14 (CMS) and 26 (ATLAS) times SM prediction
- Constraint on Higgs-charm Yukawa coupling modifier: **1.1 < |Kc| < 5.5 (CMS) and |Kc| < 8.5 (ATLAS)**

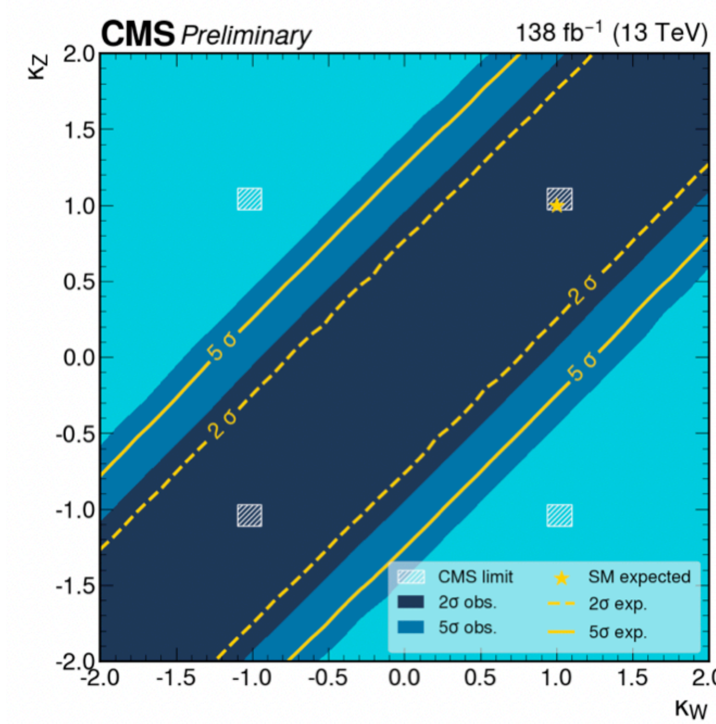
Relative sign of κ_W and κ_Z



$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z\,\kappa_W\,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$



ATLAS-CONF-2023-057

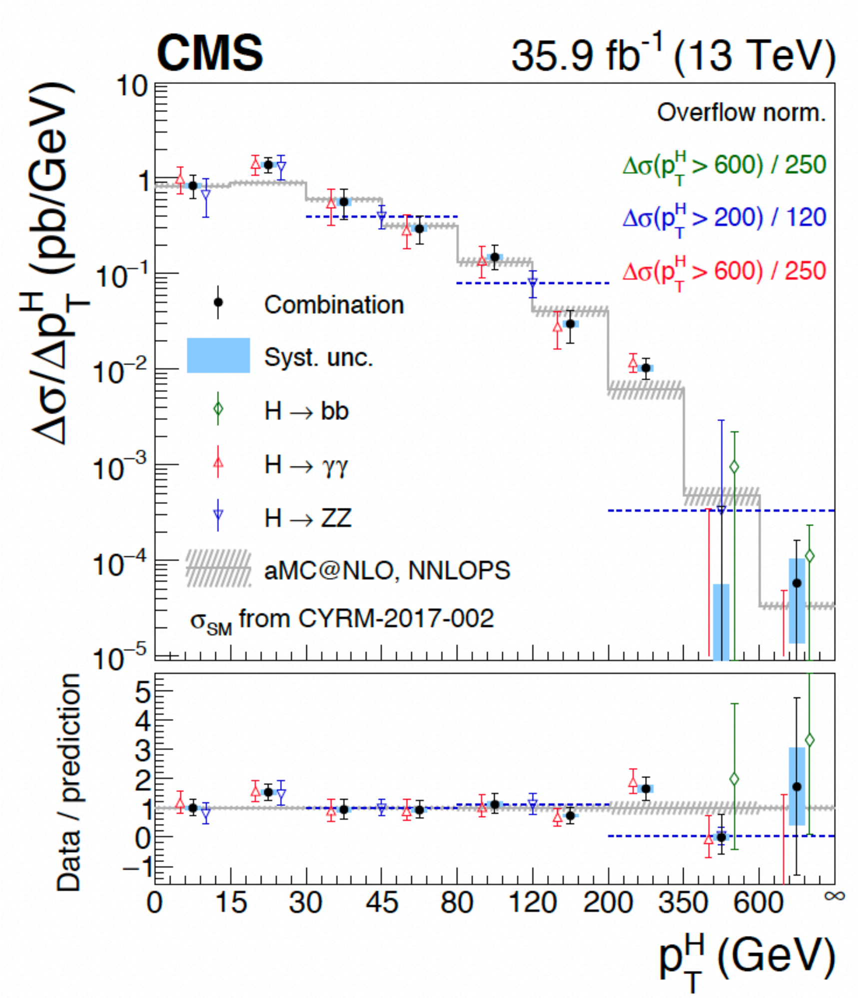


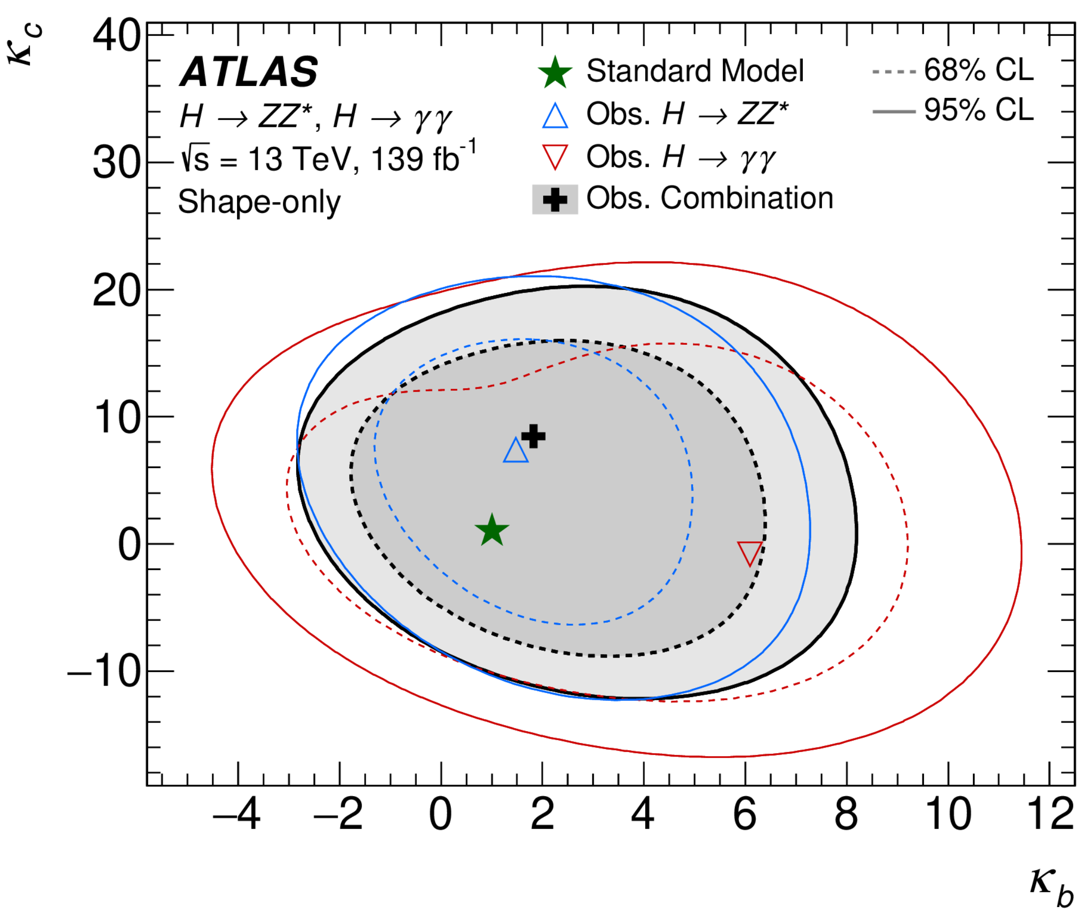
- VBF WH production mode offers sensitivity to the relative sign of κ_W and κ_Z
- Studied using Higgs decays to b-quarks and W decays with a lepton
- Opposite-sign coupling hypothesis is excluded with significance greater than 5σ by both ATLAS and CMS

CMS-PAS-HIG-23-007 (NEW)

Fiducial cross sections

- Define fiducial phase space and measure cross section inclusively or differentially to minimize dependence on theoretical uncertainties and provide sensitivity to BSM effects
  - Measured in different decay modes ($H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$, $H\to\tau\tau$, $H\to bb$) and in combination
  - Results are **currently in agreement with the SM predictions** and can be interpreted using kappa models





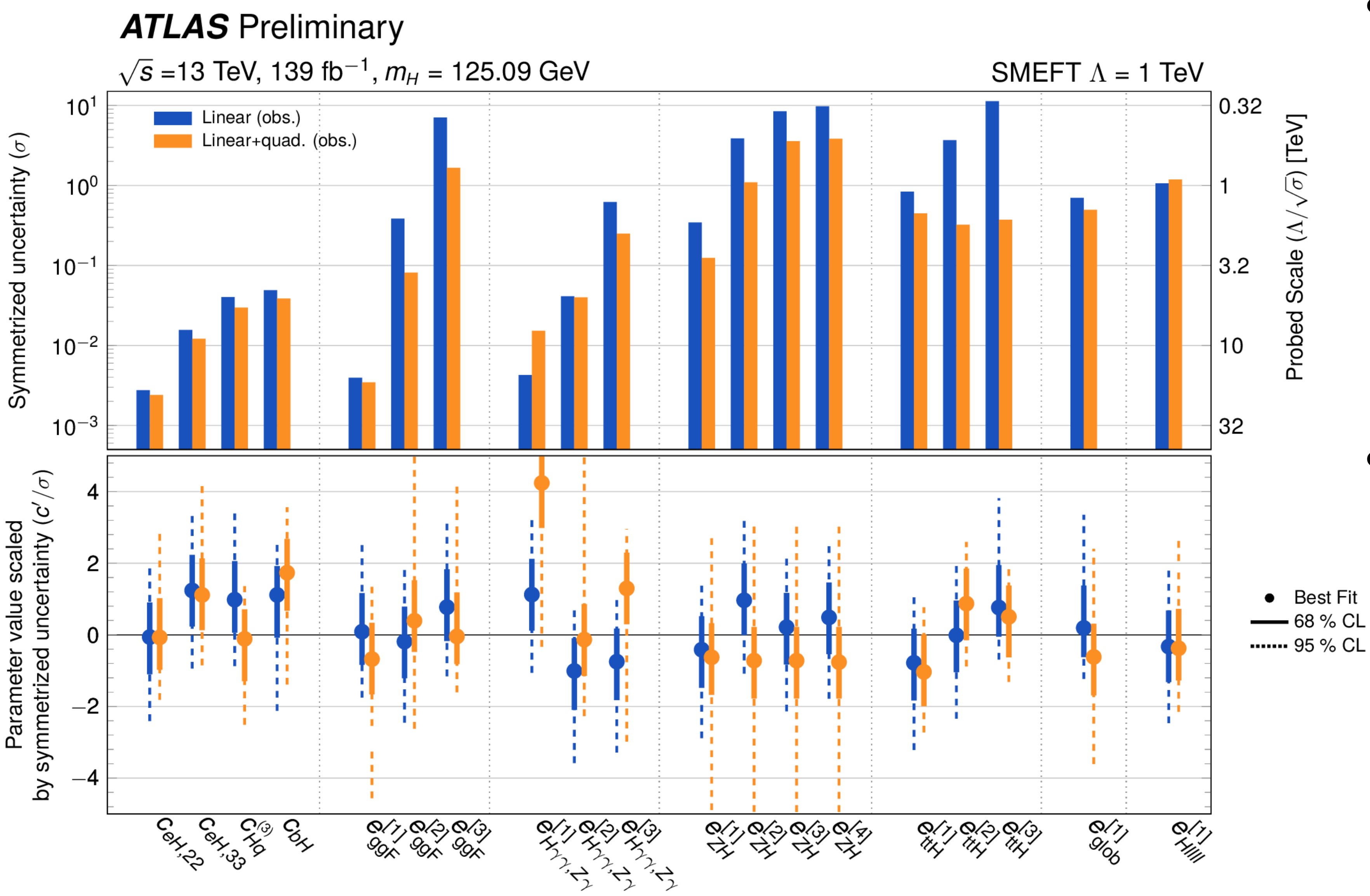
[Phys. Lett. B 792 (2019) 369]
[JHEP05(2023)028]

Interpretation with EFT

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

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

- Rotate the SMEFT basis cj to eigenvector cj' and fit sensitive eigenvectors simultaneously

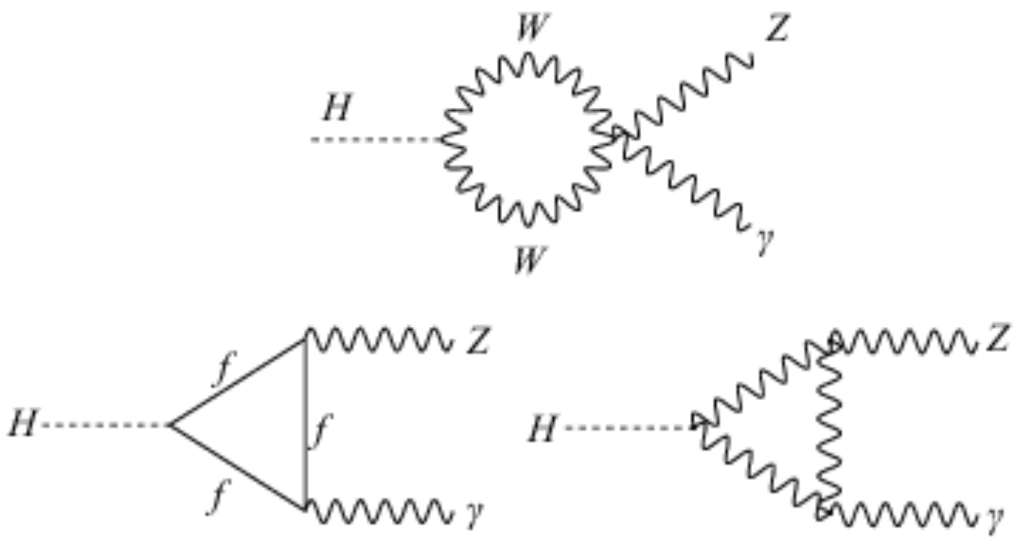


- All measured parameters are consistent with the SM expectation within their uncertainties
- Comparison of the linear model and the linear+quadratic model shows sizeable sensitivity to operators suppressed by Λ^4

ATLAS-CONF-2023-052

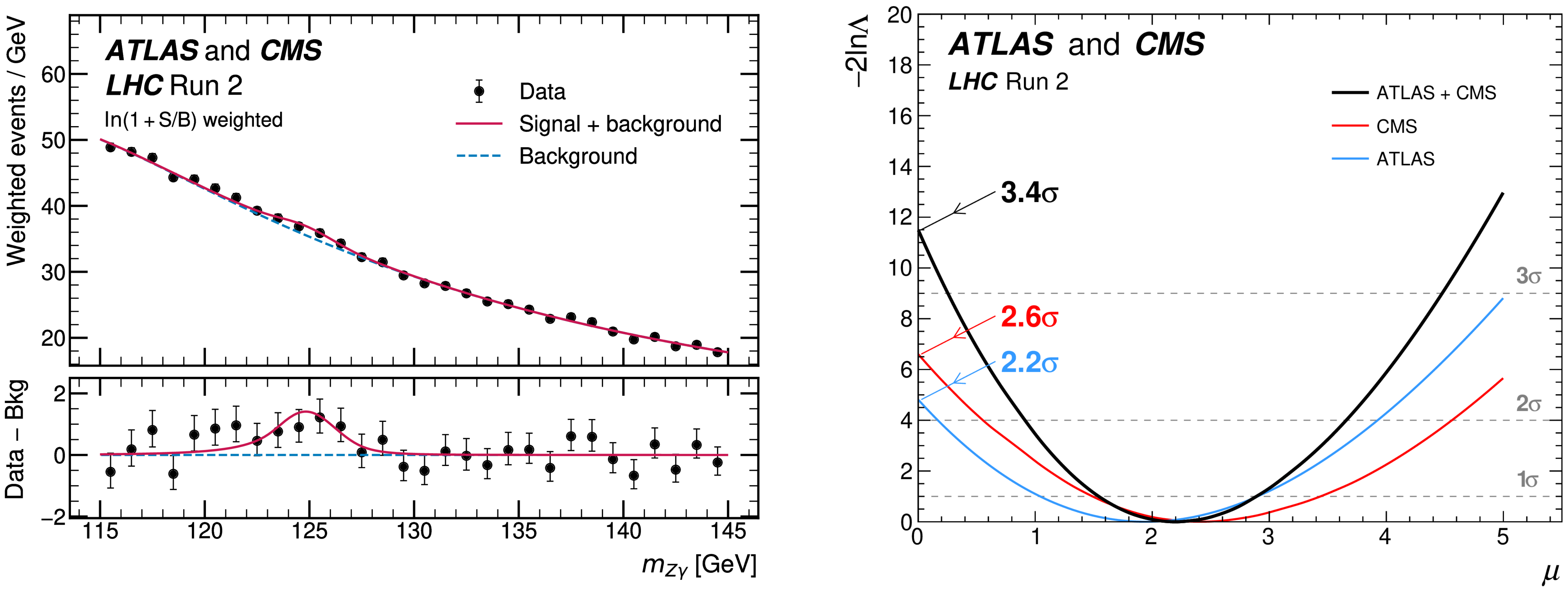
H→Zγ decay

- BSM particles & couplings could be present in the quantum loops
- Difference between H→Zγ decay and H→γγ/H→ZZ decay sensitive to new physics
  - (e.g. Qing-Hong Cao et al. *Phys. Lett. B* 789 (2019) 233)
  - Small branching ratio in SM (1.6×10^{-3}); main bkg: non-Higgs Zγ, Z+jets
- Select events with two leptons (mll ~90 GeV) and one photon and separate them to multiple categories to target various production modes
- Fit in llγ mass distribution over all categories



H→Zγ decay

Phys. Rev. Lett. 132 (2024) 021803, Featured in Physics



- The observed H→Zγ significance in ATLAS+CMS combined result is **3.4σ** (expected 1.6σ)
  - **First evidence** of the H→Zγ decay
- Signal strength is 2.2 ± 0.7: agrees with theoretical expectation within **1.9σ**
- With the ongoing Run3 of the LHC, we will be able to improve the precision of this rare Higgs decay

Measurement of Higgs mass/width, spin/CP

Higgs mass/width

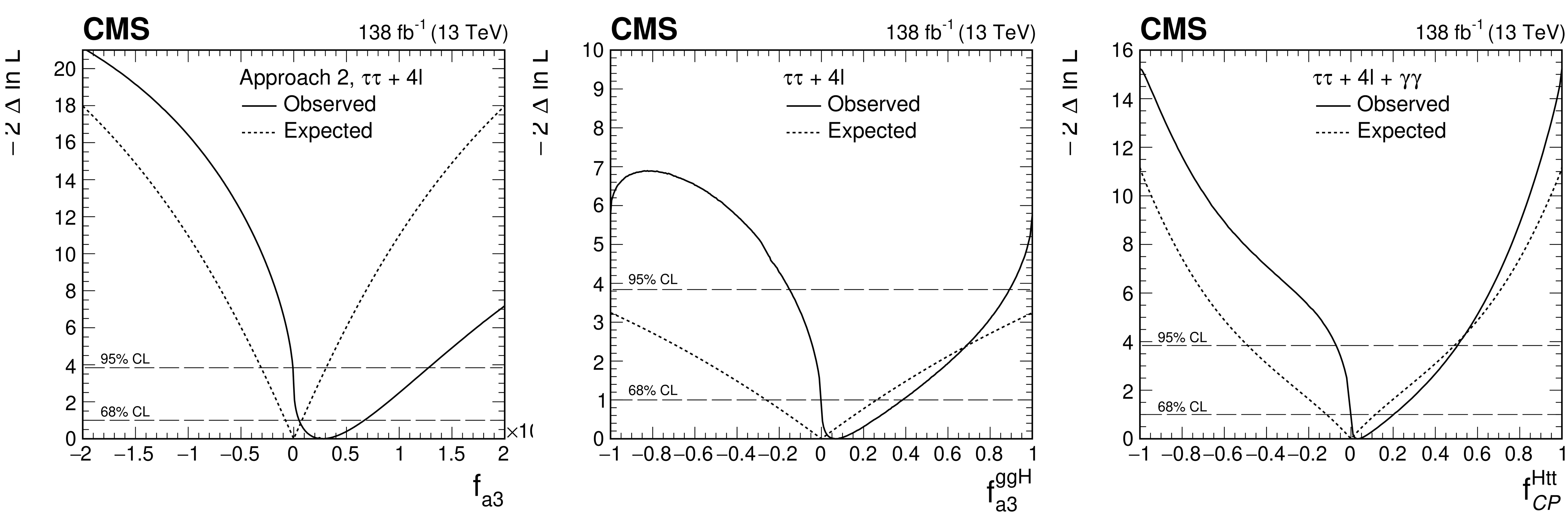
- **Higgs mass** is the only free parameter in the SM Higgs sector. Measured in channels with best resolution: $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$
  - ATLAS+CMS Run 1: 125.09 ± 0.24 GeV
  - CMS Run 1+partial Run 2: 125.38 ± 0.14 GeV
  - ATLAS Run 1+full Run 2: 125.11 ± 0.11 GeV
- SM prediction of **Higgs width**: 4.1 MeV
  - direct measurement limited by detector resolution
- Constrain Higgs width by comparing on-shell and off-shell Higgs rates using $H \to ZZ^* \to 4l$ and $H \to ZZ^* \to 2l2\nu$
  - determined to be $3.2^{+2.4}_{-1.7}$ MeV
- In $\gamma\gamma$ channel, interference between Higgs signal and continuous background can cause Higgs mass shift
  - this effect can also constrain Higgs width

Higgs spin/CP

- The SM Higgs boson is a scalar: **spin**-zero, **CP**-even
  - The observed boson was verified to be spin-zero in Run 1
- Non-CP-even couplings of the Higgs boson were searched
  - Data disfavor the pure CP-odd scenario, stringent constraints on CP mixing are given

Phys. Rev. D 108 (2023) 032013

HVV vertices **Hgg vertices** **Htt vertices**

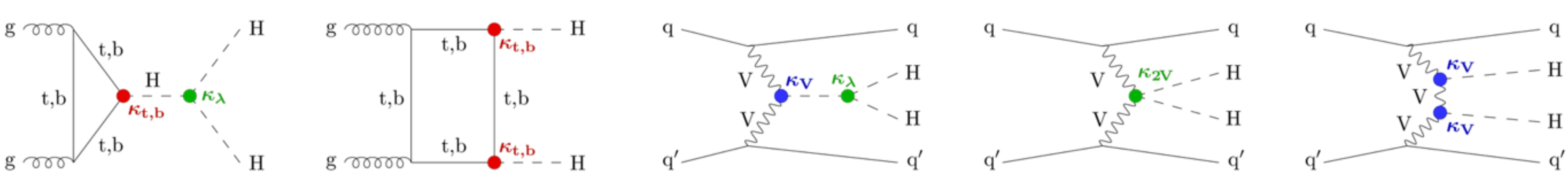


Higgs boson self-couplings

Higgs boson self-couplings

- **Higgs self-coupling is one of the deepest questions of SM and may provide a portal to new physics beyond it**
  - Vacuum stability, early universe evolvement, …
- **Double Higgs production is the way to directly probe Higgs self-couplings at the LHC**
  - Extremely low cross-section in the SM
  - Non-SM self-coupling strength can change cross-section and kinematics of double Higgs production

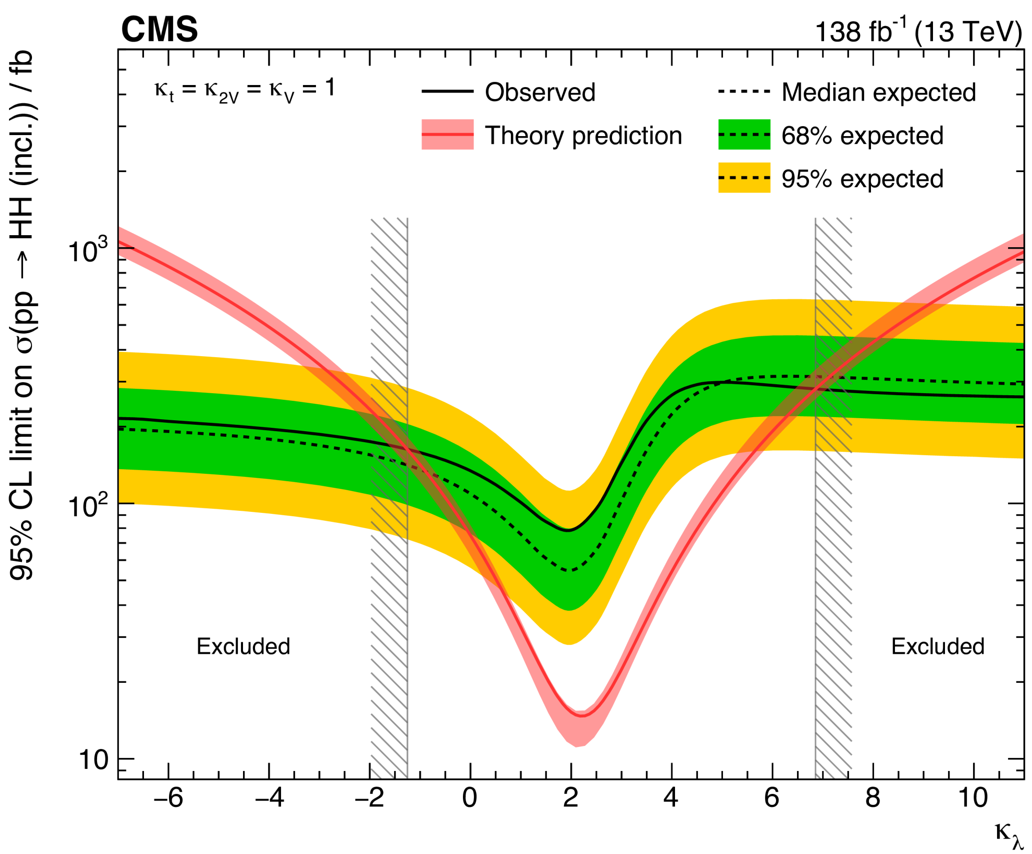
Higgs boson pair production

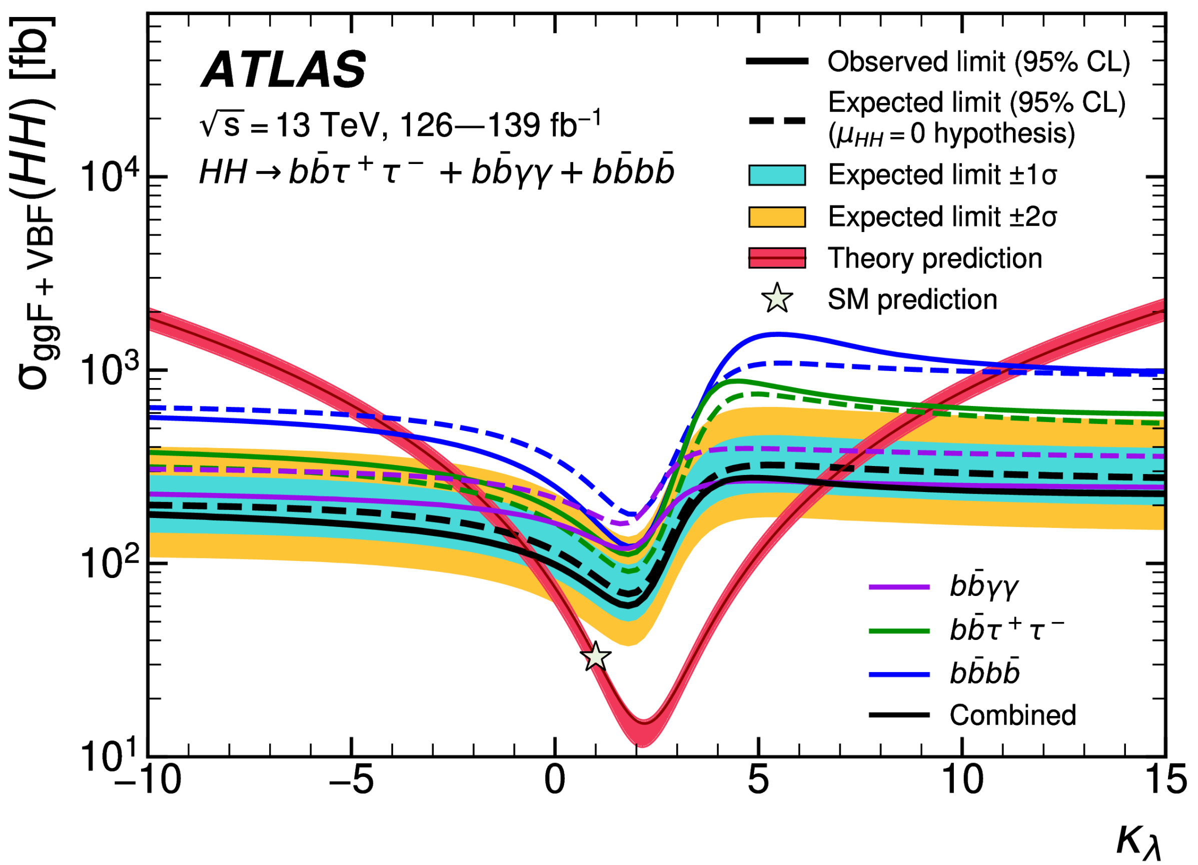


Double Higgs production combination

Nature 607 (2022) 60-68

Phys. Lett. B 843 (2023) 137745





- HHH trilinear self-coupling modifier: $-1.2<\kappa_\lambda<6.5$ (CMS); $-0.6<\kappa_\lambda<6.6$ (ATLAS)

Double Higgs production combination

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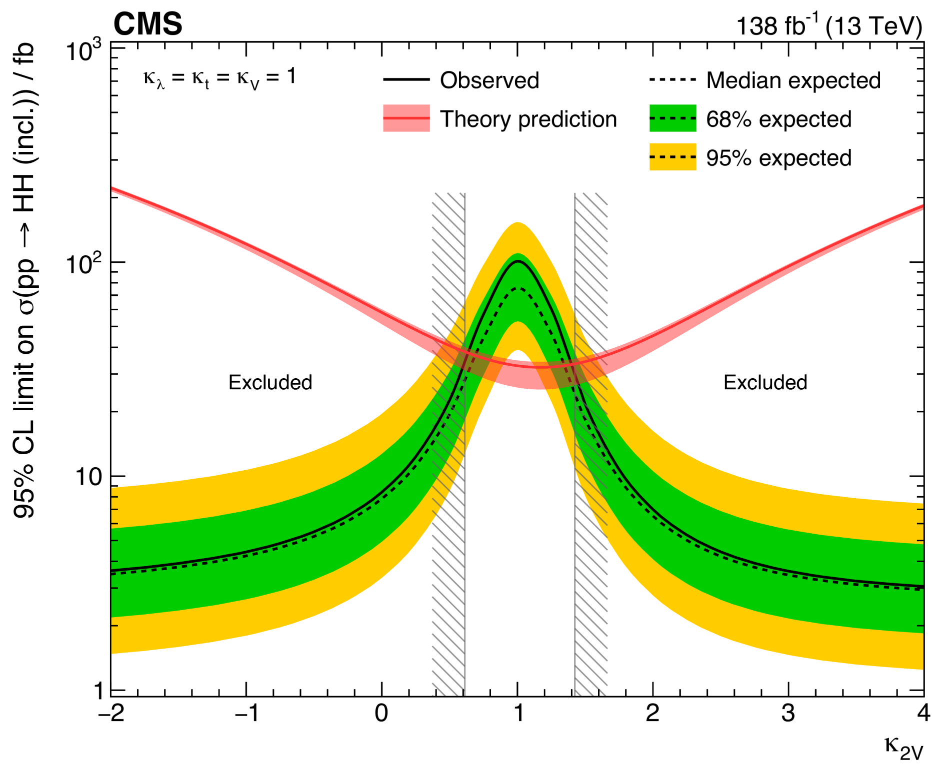

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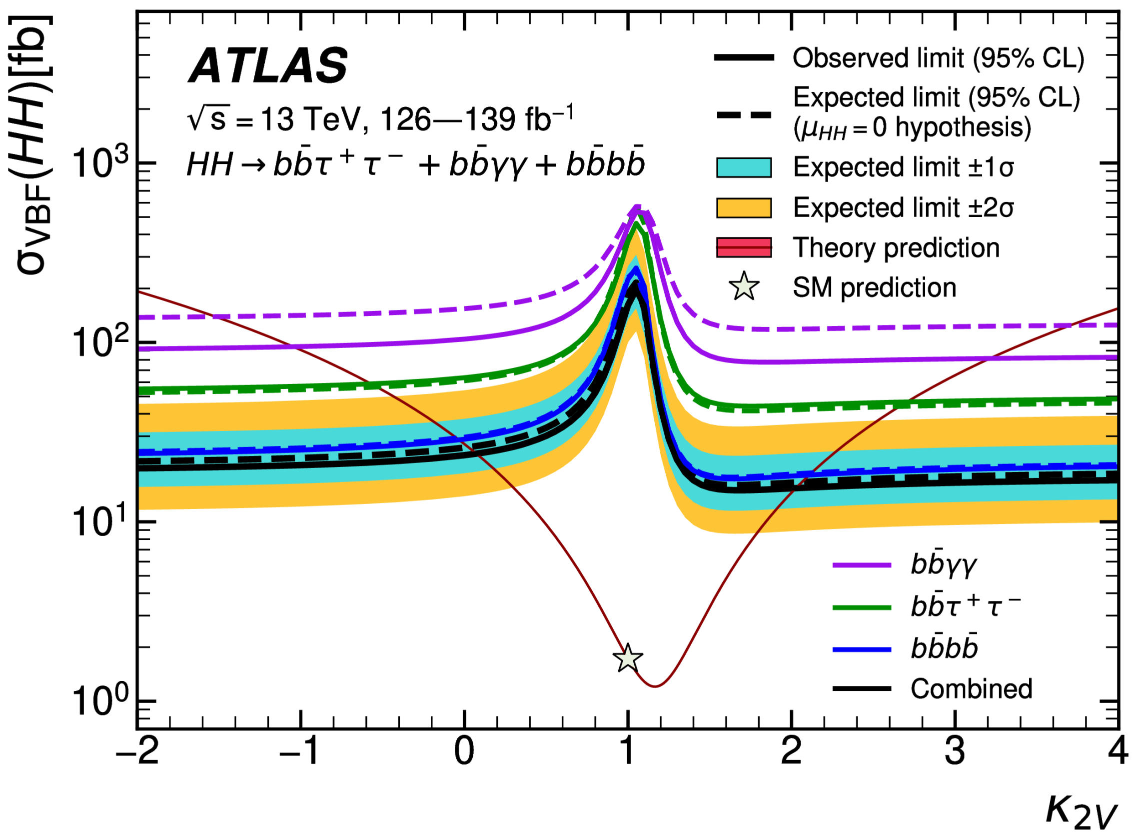
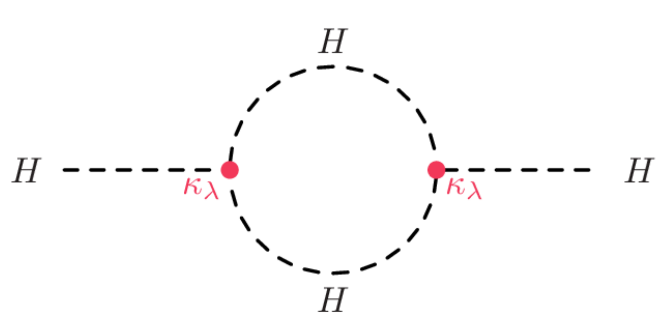
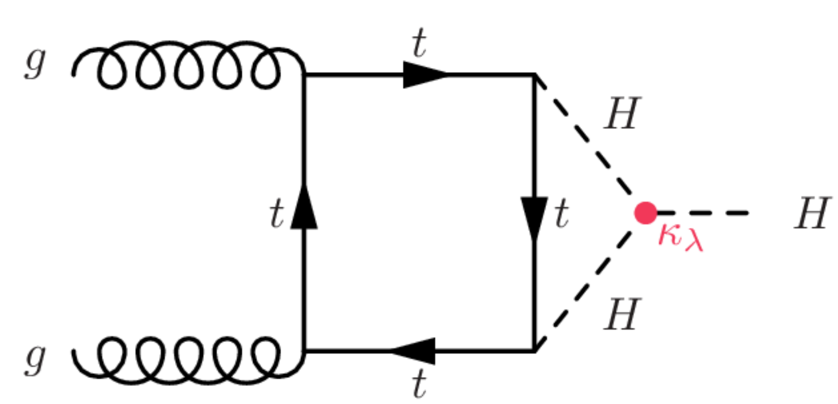
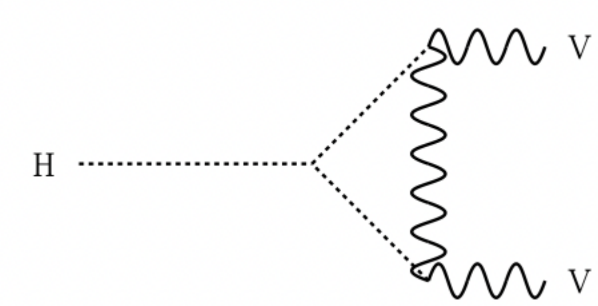


- HHVV quartic coupling modifier: $0.7<\kappa_{2V}<1.4$ (CMS); $0.1<\kappa_{2V}<2.0$ (ATLAS)

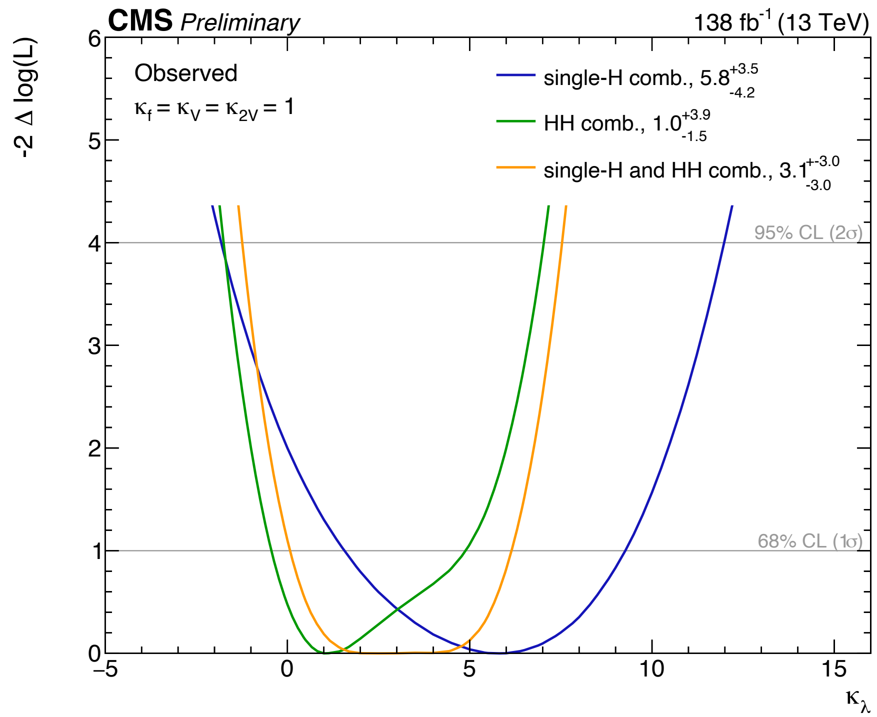
- Single Higgs boson production and decays can be modified by self-coupling modifier through NLO EW correction

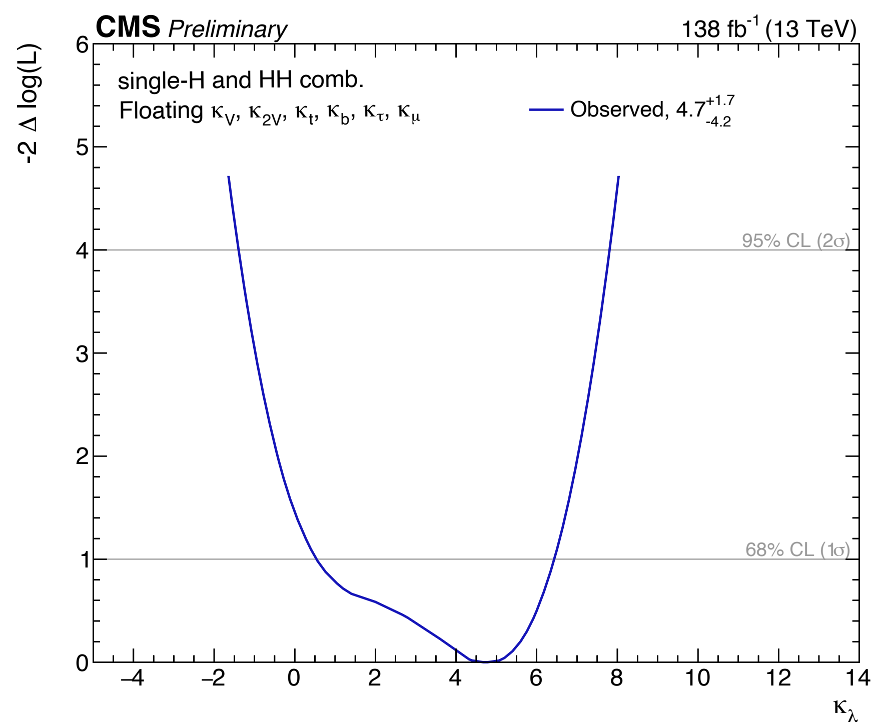


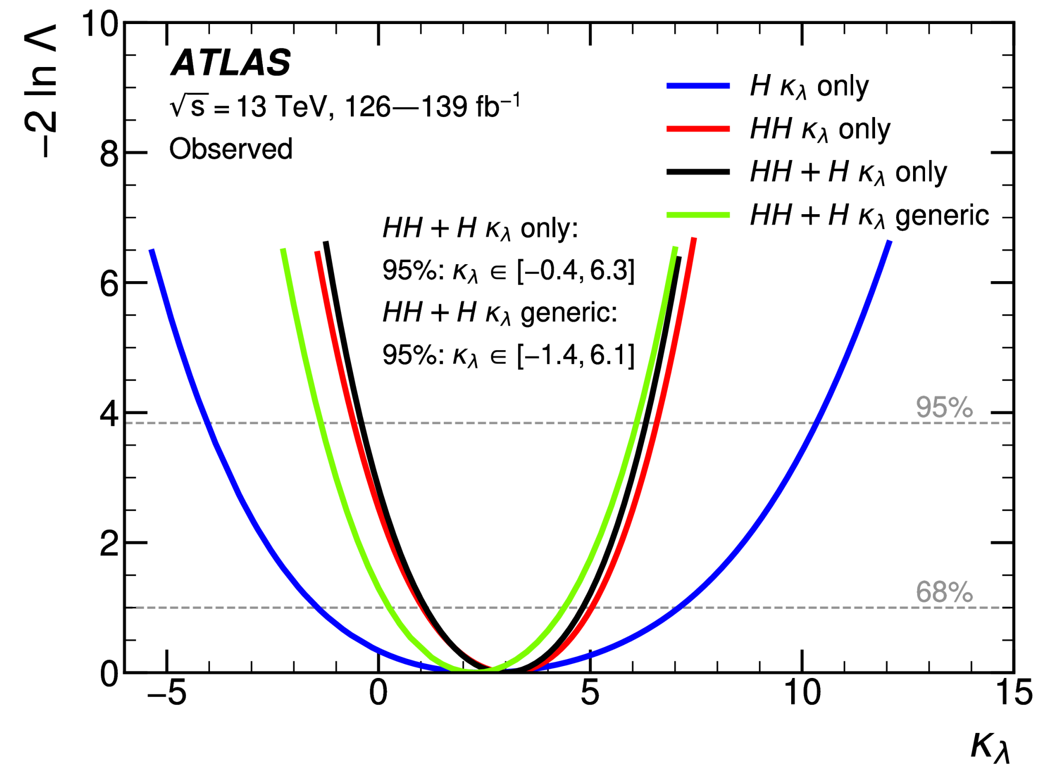




Double Higgs + Single Higgs Combination





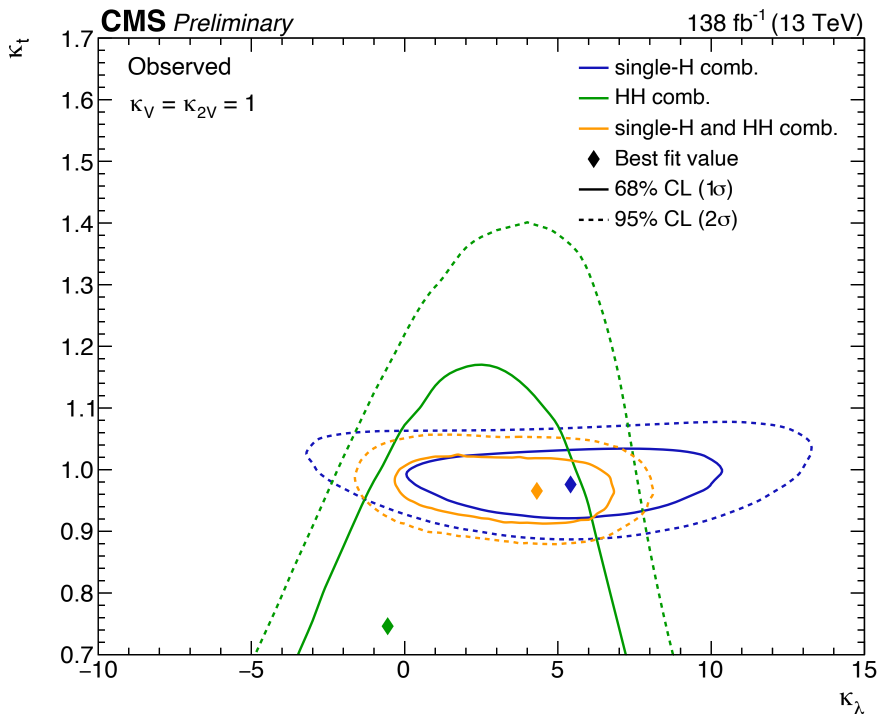


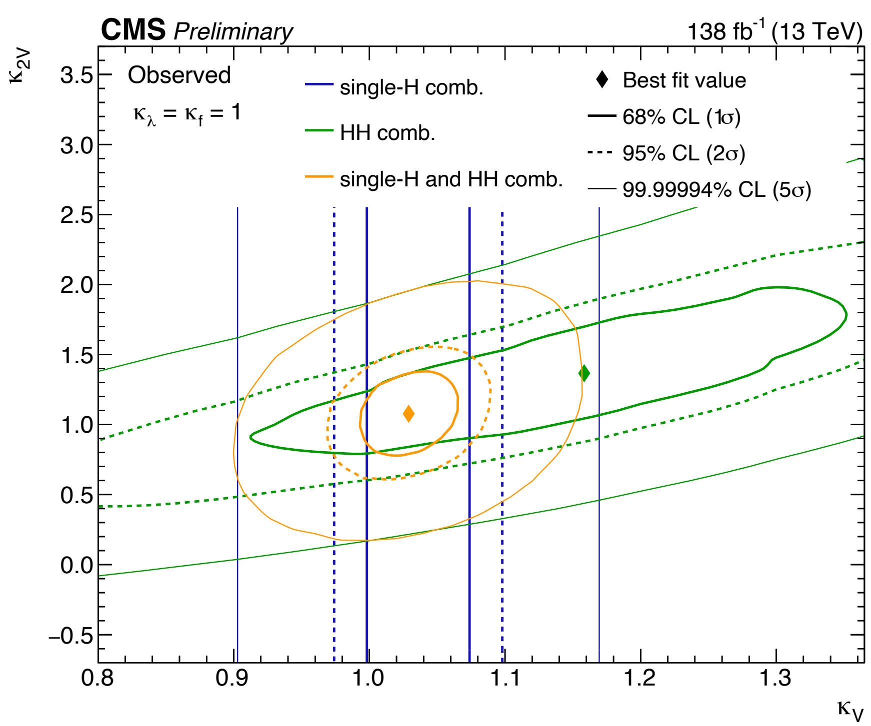
Phys. Lett. B 843 (2023) 137745

CMS-PAS-HIG-23-006 (NEW)

- Single Higgs measurements provide additional sensitivity to trilinear self-coupling

Double Higgs + Single Higgs Combination





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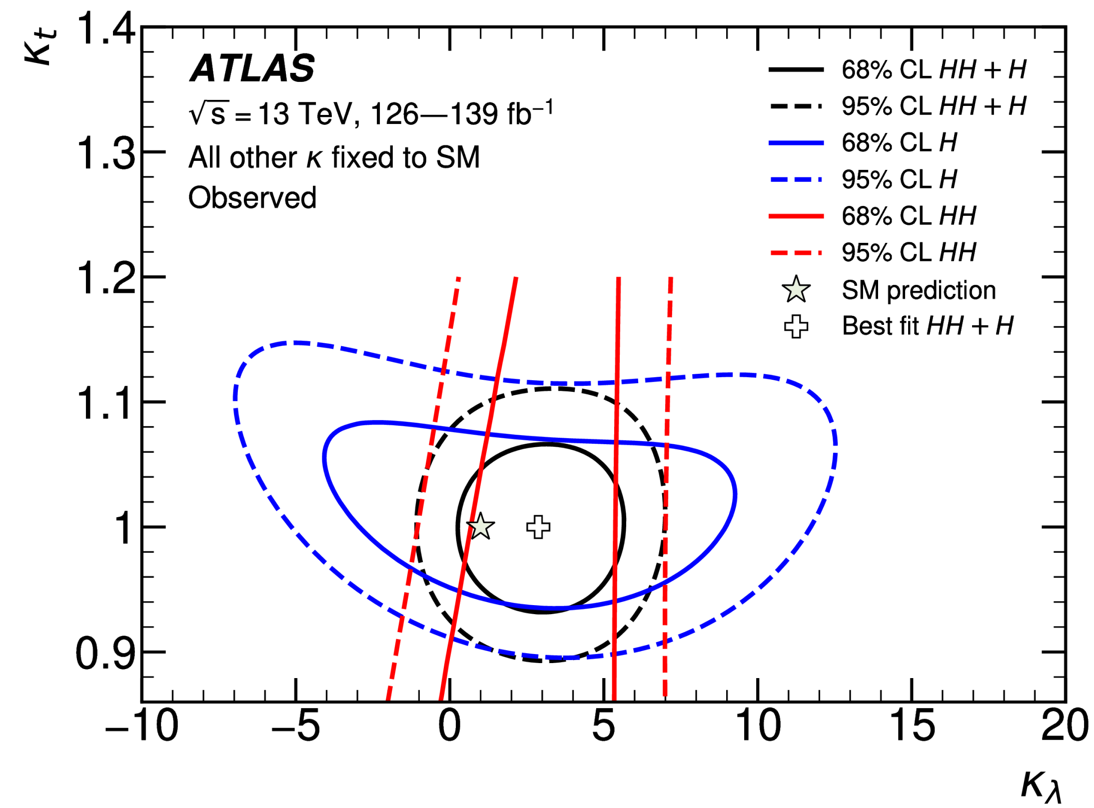


Phys. Lett. B 843 (2023) 137745

- Combined single-Higgs and double-Higgs analyses provide results with fewer assumptions

Summary

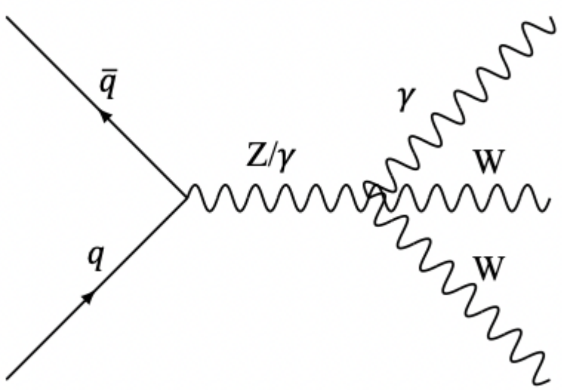
- LHC experiments continue to **deliver many interesting Higgs physics results**
  - a portrait of the Higgs boson
  - first evidence of $H \to Z\gamma$ decay
  - etc.
- **Run 3 has started** and LHC experiments are taking good quality data with high efficiency
  - please stay tuned!

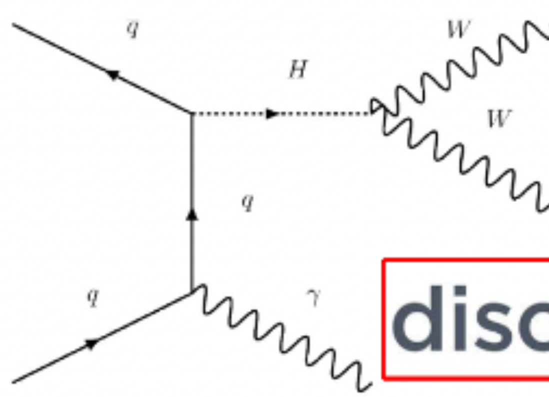
Higgs physics studies in electroweak and top measurements

First observation of WWγ production

arxiv:2310.05164   submitted to PRL

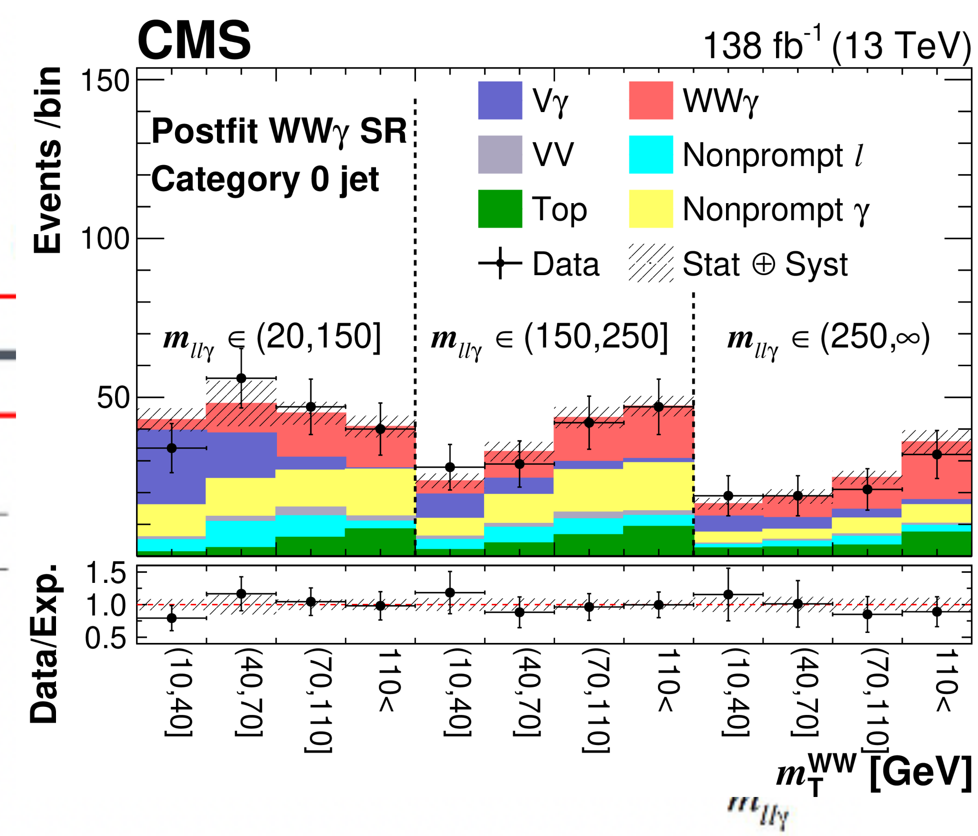
- First observation (**5.6σ**) of WWγ production
  - Provide the best sensitivity for Yukawa couplings between Higgs and light quarks



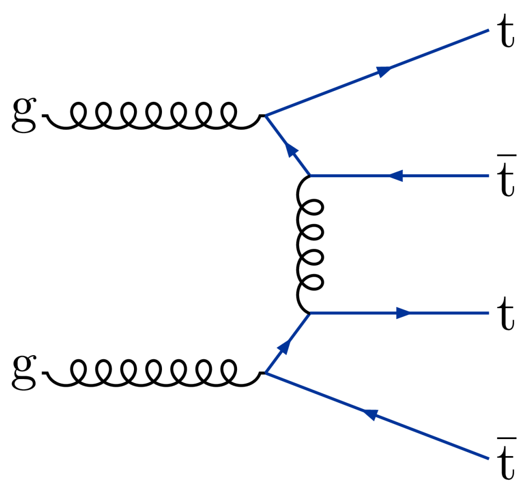


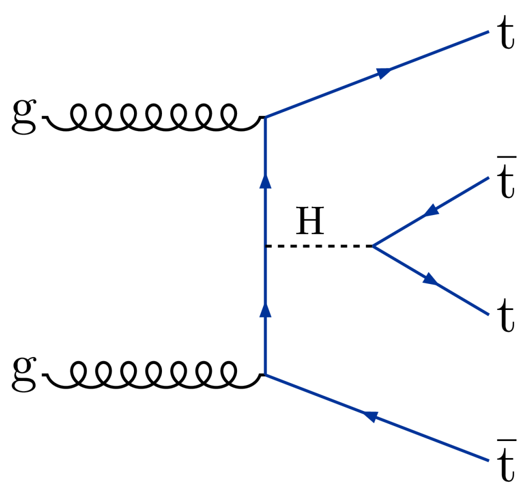
discovery+

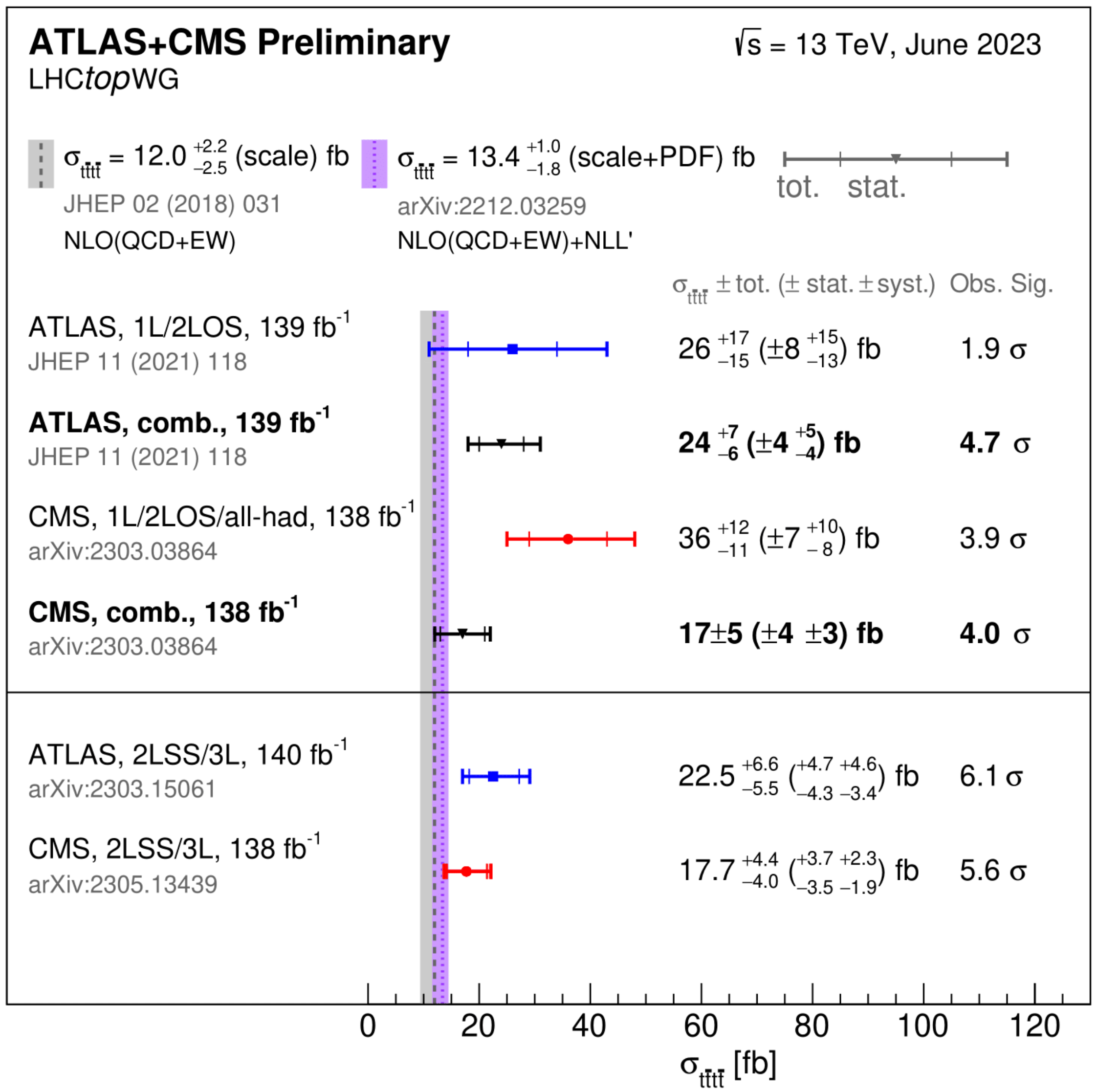
Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \lesssim 13000$ (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \lesssim 14000$ (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \lesssim 1300$ (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \lesssim 110$(200)



Observation of four top production







Eur. Phys. J. C 83 (2023) 496

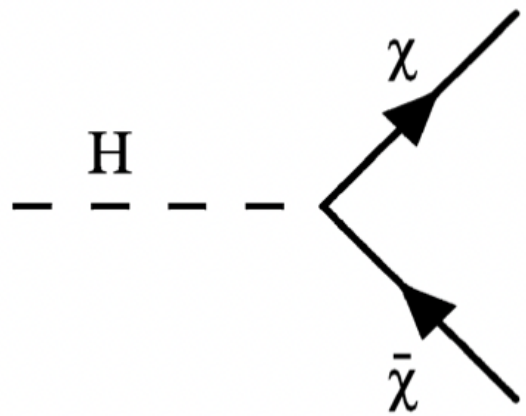
Phys. Lett. B 847 (2023) 138290

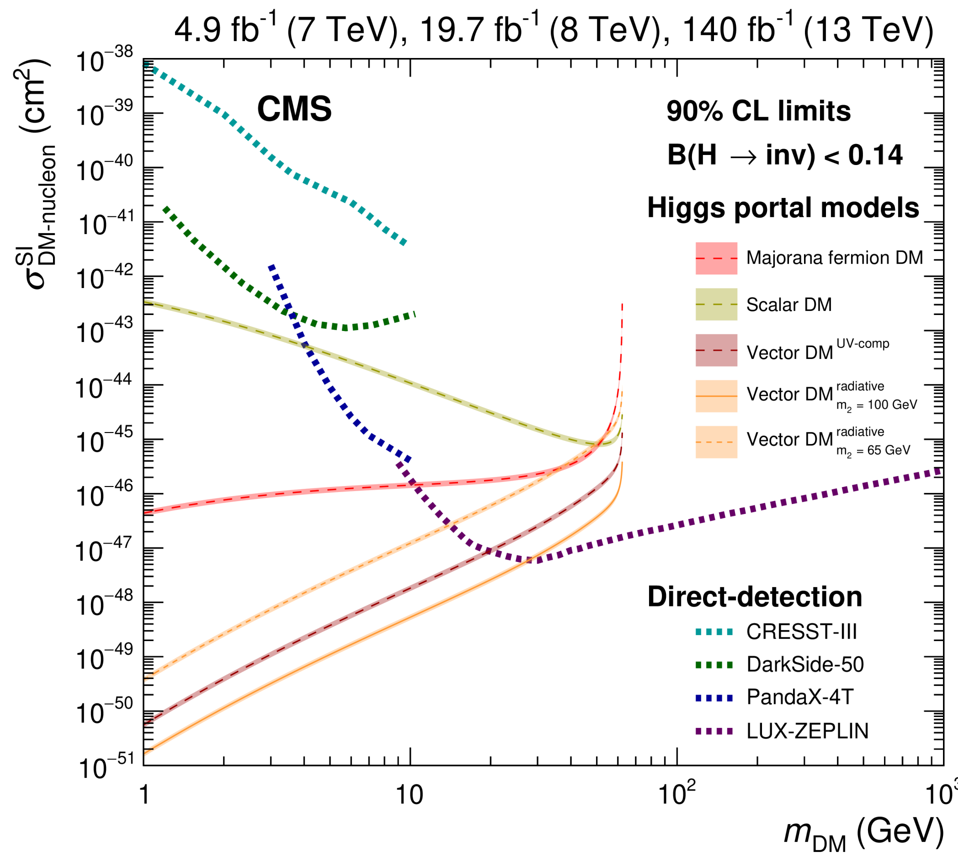
- Observation by ATLAS and CMS experiments independently
  - this process is extremely rare compared to top-pair production, but it is already a measurement limited by systematics
- Results provides sensitivity to the Higgs-top Yukawa coupling

Search for BSM Higgs production and decay

Search for Higgs→invisible decay

- Higgs→invisible decay is favored by so-called "Higgs portal" model
  - where Dark Matter interacts with known particles through the Higgs boson
- Run 2 Higgs→invisible results:
  - ATLAS: BR<11% (Phys. Lett. B 842 (2023) 137963)
  - CMS: BR<15% (EPJC 83 (2023) 933)
- Results are interpreted as limit on DM-nucleon scattering in Higgs portal model





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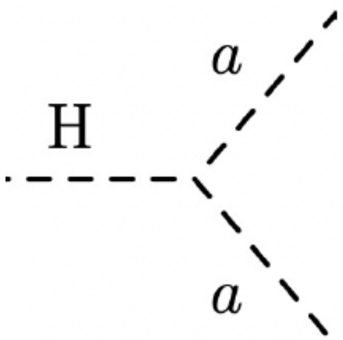
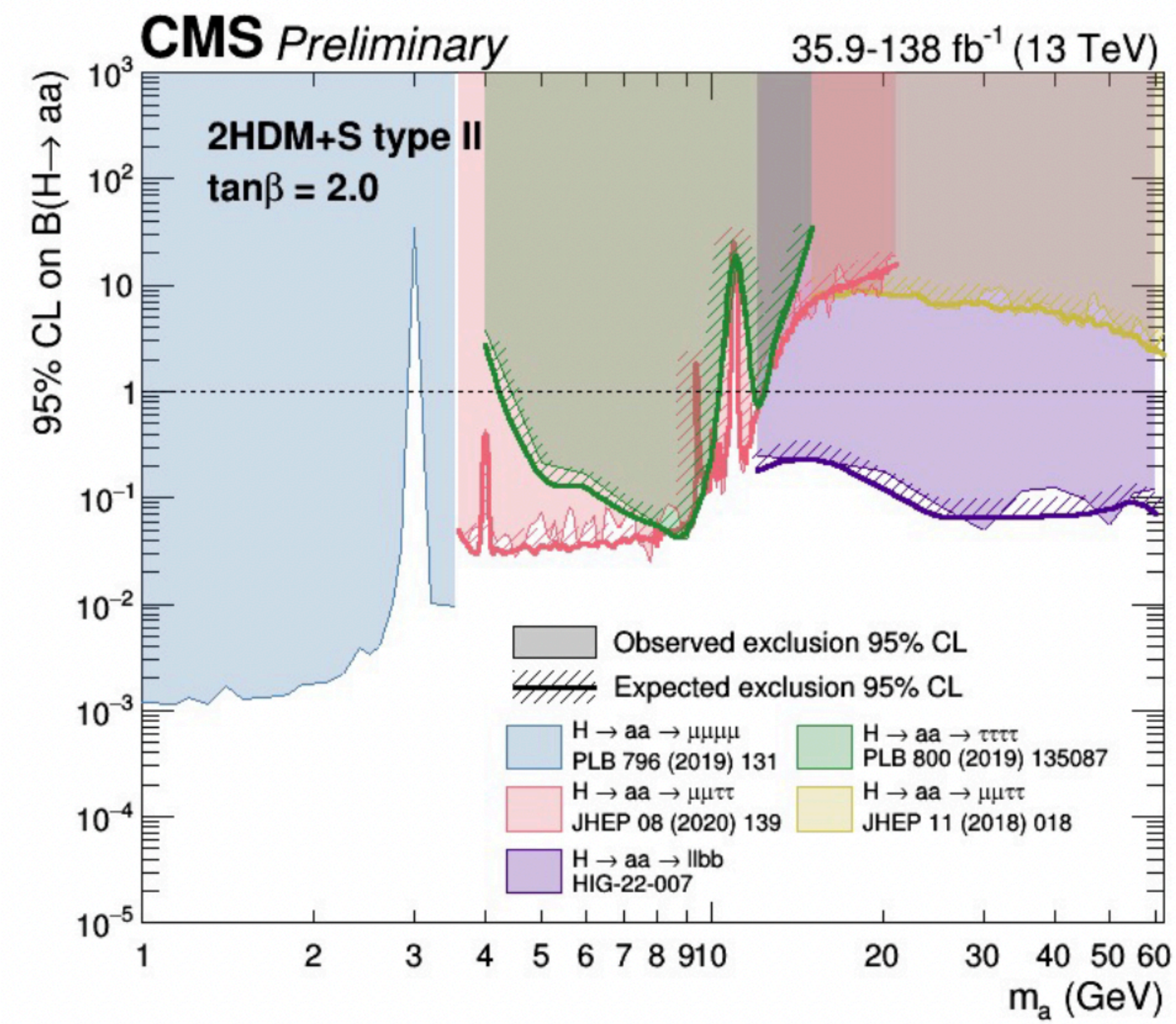
Search for Higgs exotic decay

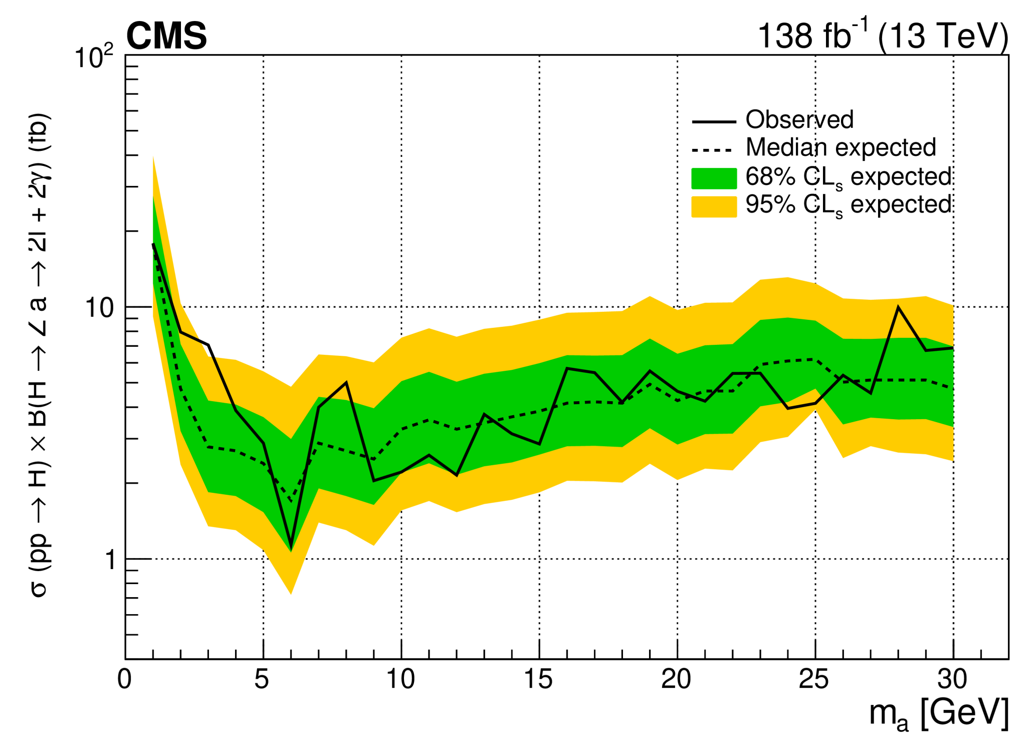


Higgs decays to exotic particles predicted by various BSM models: additional SM-neutral singlet, minimal composite Higgs models, two-Higgs-doublet-like models, axion-like particle, etc.



H→Za→llγγ

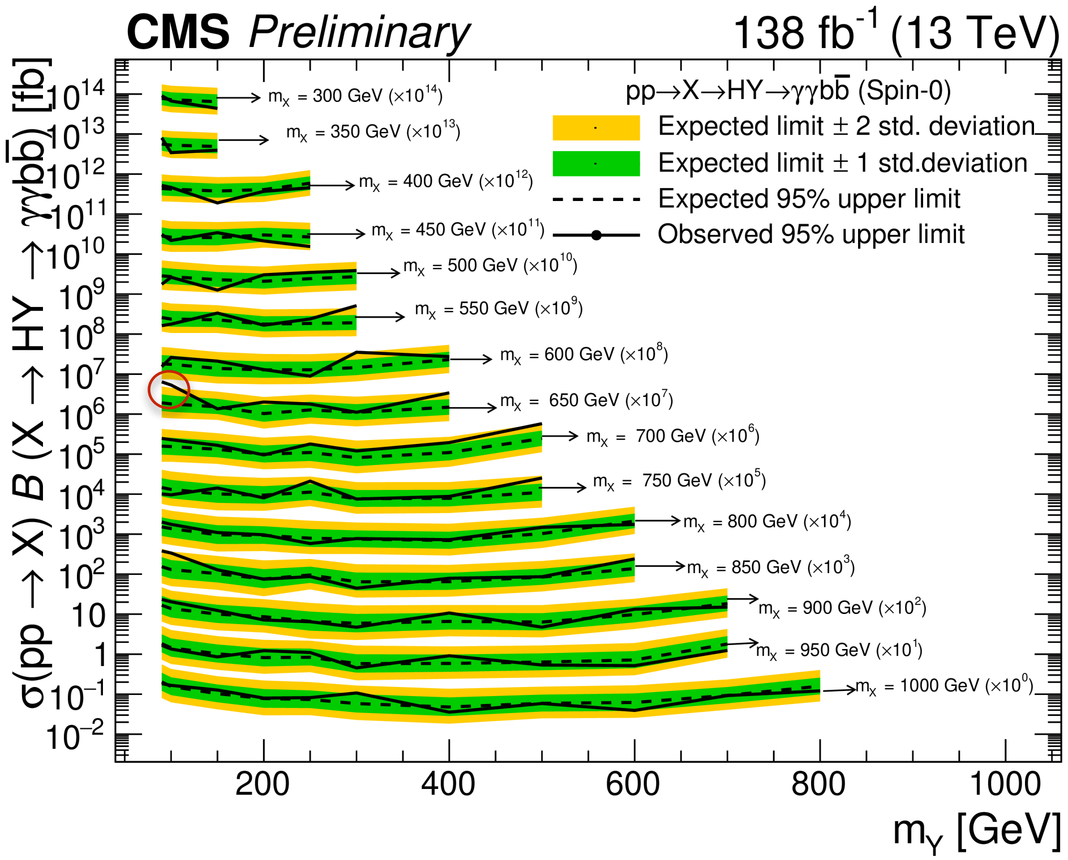
Low-mass pseudoscalar a decays to two merged photons

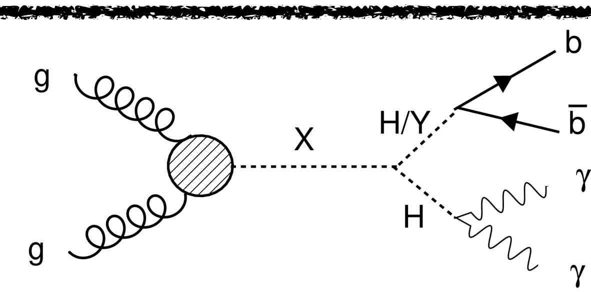


arxiv:2311.00130

Search for heavy resonances

CMS-PAS-HIG-21-011





Search for resonance X decay to H/Y+H

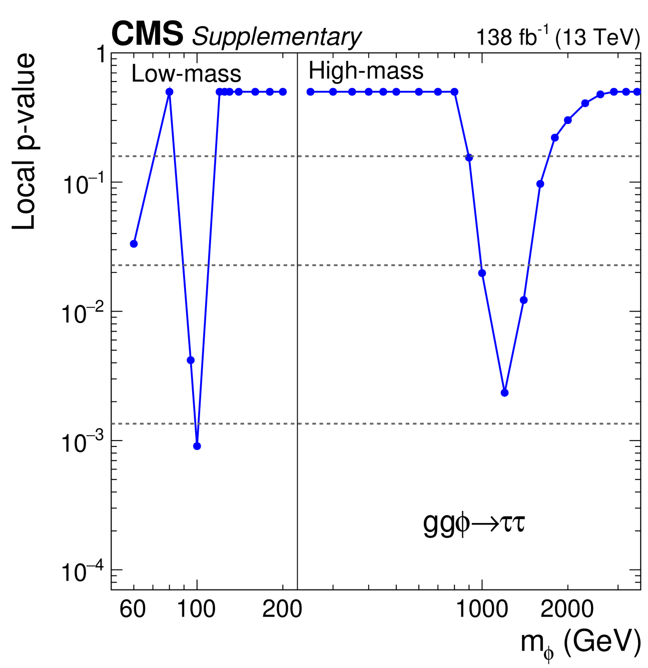
- motivated by extended H sector, extra dimensions, etc.

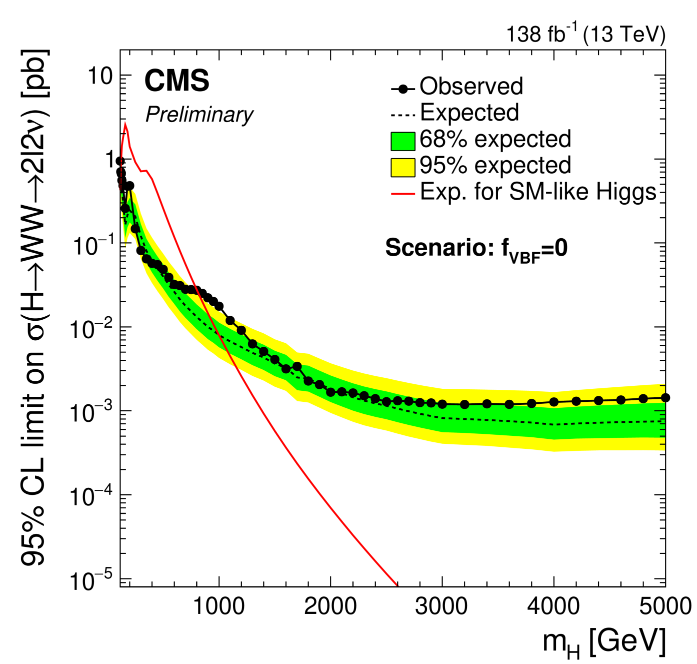
Excess of X→Y(bb)+H(γγ) at mX=650 GeV and mY=90 GeV

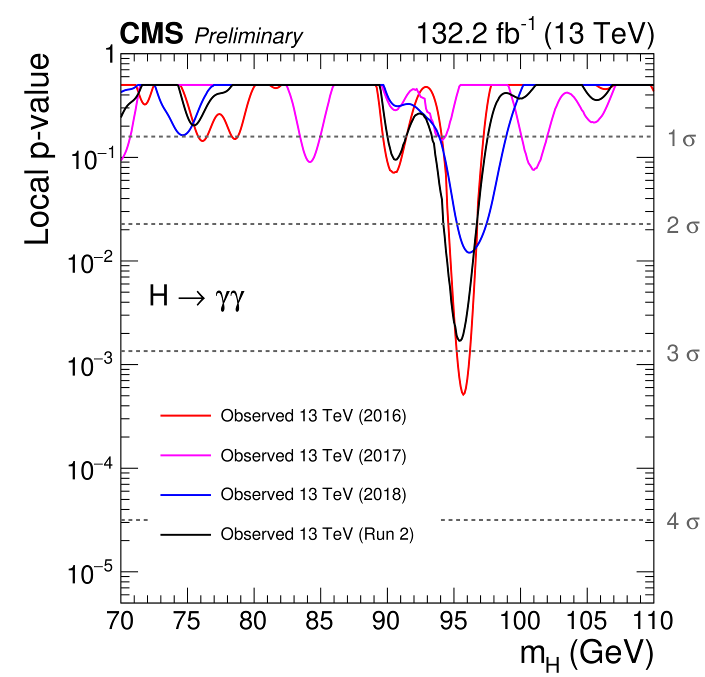
- 3.8σ local, 2.8σ global

Interesting numbers from other searches

- X→$\tau\tau$: 90-100 GeV excess, 3.1σ local, 2.7σ global
- X→WW: 650 GeV excess, 3.8σ local, 2.6σ global
- X→γγ: 95 GeV excess, 2.9σ local, 1.3σ global







arxiv:2208.02717 CMS-PAS-HIG-20-016 CMS-PAS-HIG-20-002

Thank you!

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School of Physics, PKU, Beijing, China
19–22 April, 2024
Workshop on Mμon Physics
at the Intensity and Precision Frontiers
SCIENTIFIC PROGRAMME
1. Muon Sources R&D
2. Muon Precision Measurements
3. Muon Rare Process Searches
4. Muon Applications
5. Theoretical Muon Physics
6. Future Experiments & Muon Colliders
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北京大学物理学院
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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

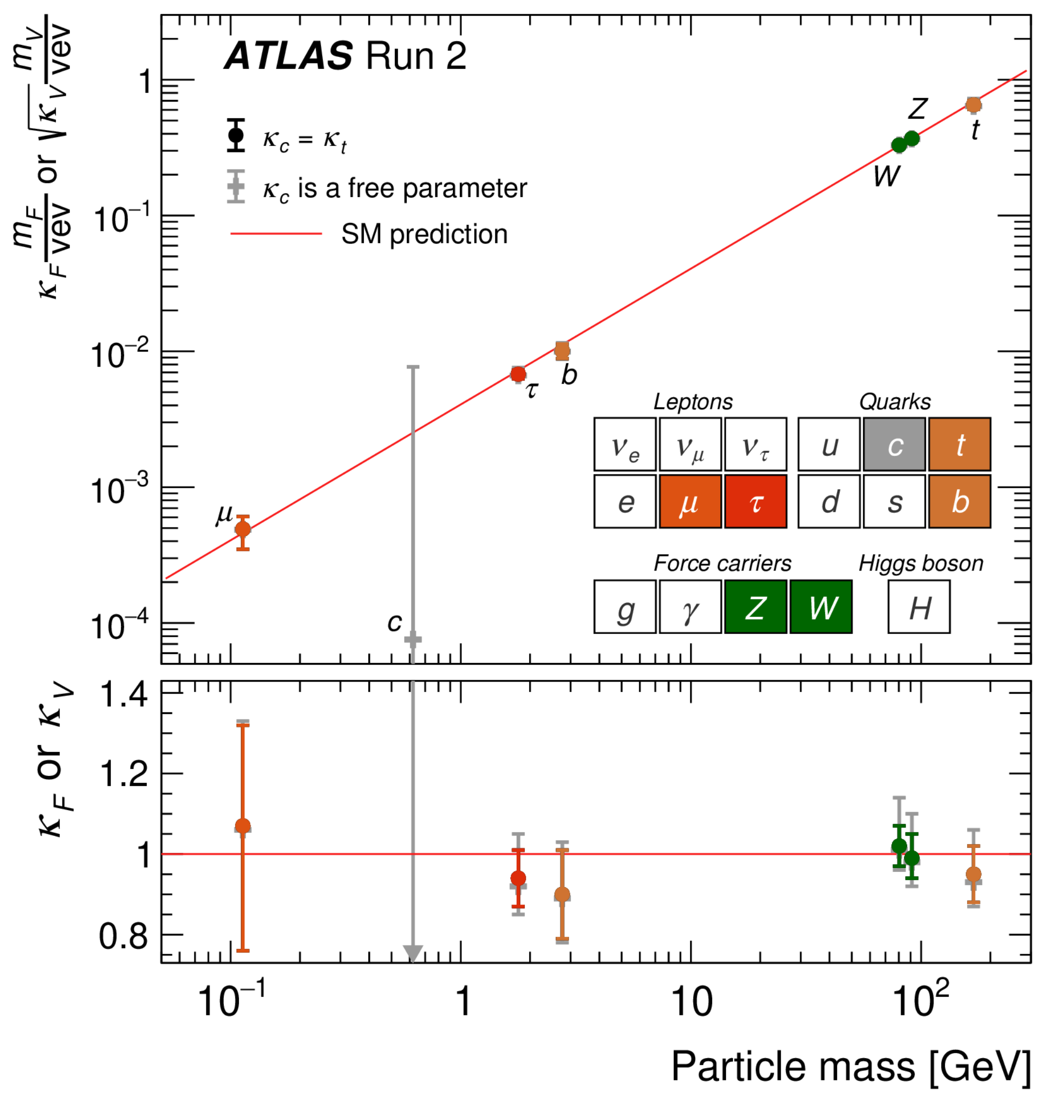
$$\Gamma_H(\boldsymbol{\kappa}, B_{\text{i.}}, B_{\text{u.}}) = \kappa_H^2(\boldsymbol{\kappa}, B_{\text{i.}}, B_{\text{u.}})\, \Gamma_H^{\text{SM}}$$

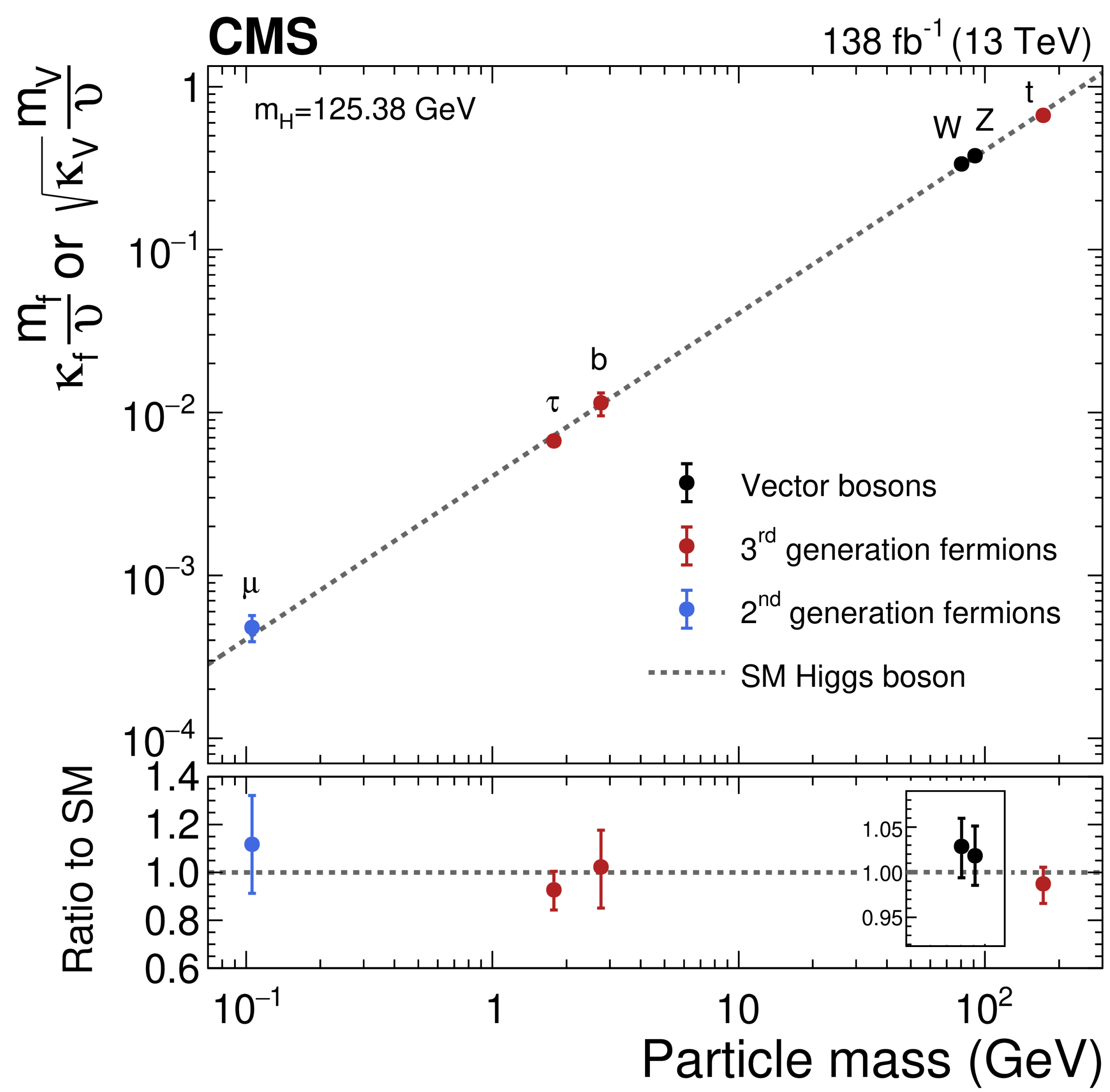
$B_{i.}$= BSM contribution to BR of invisible decays which are identified through a missing transverse momentum signature

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

Higgs boson couplings with “kappa”

ATLAS [Nature 607 (2022) 52-59] [Nature 607 (2022) 60-68]

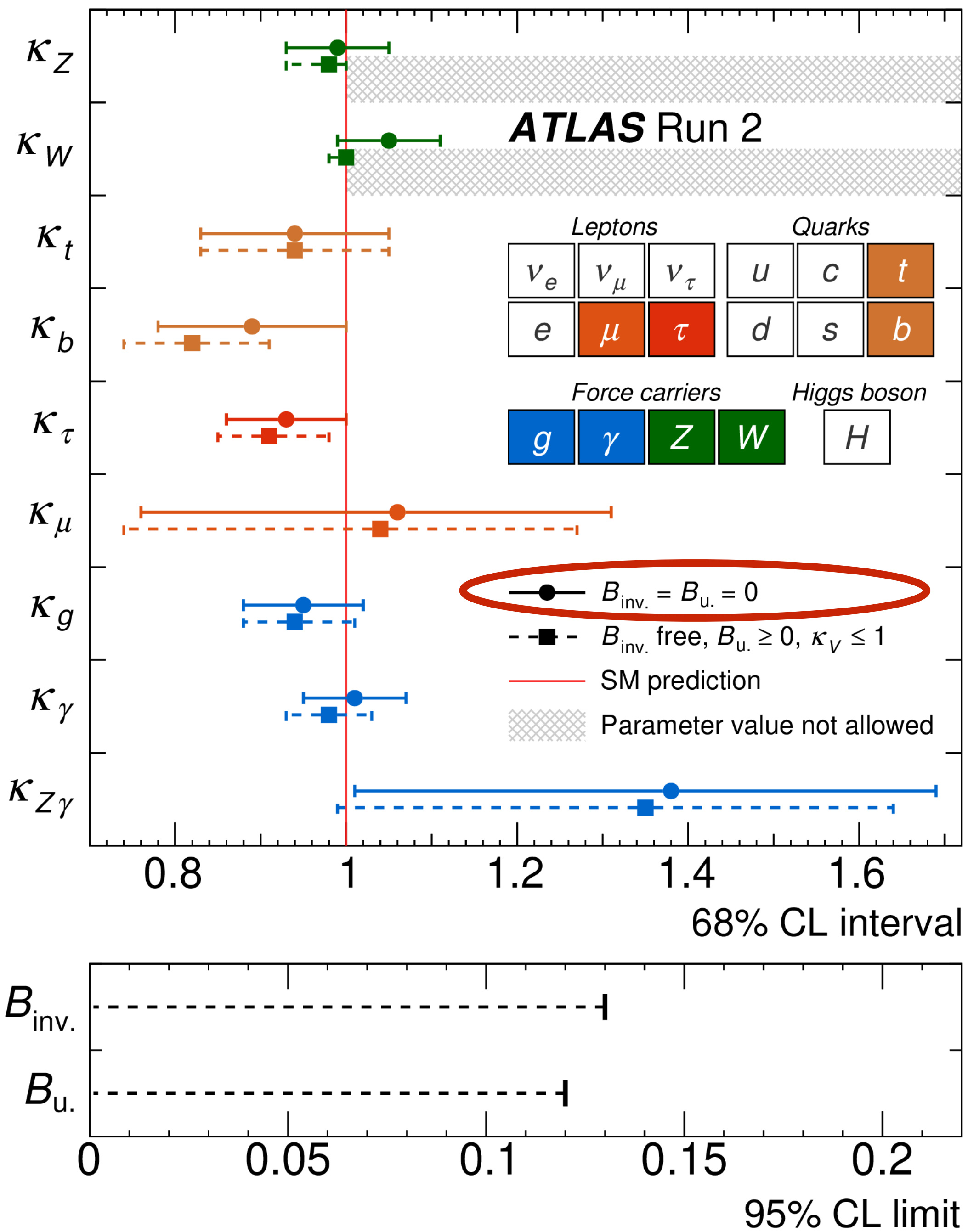




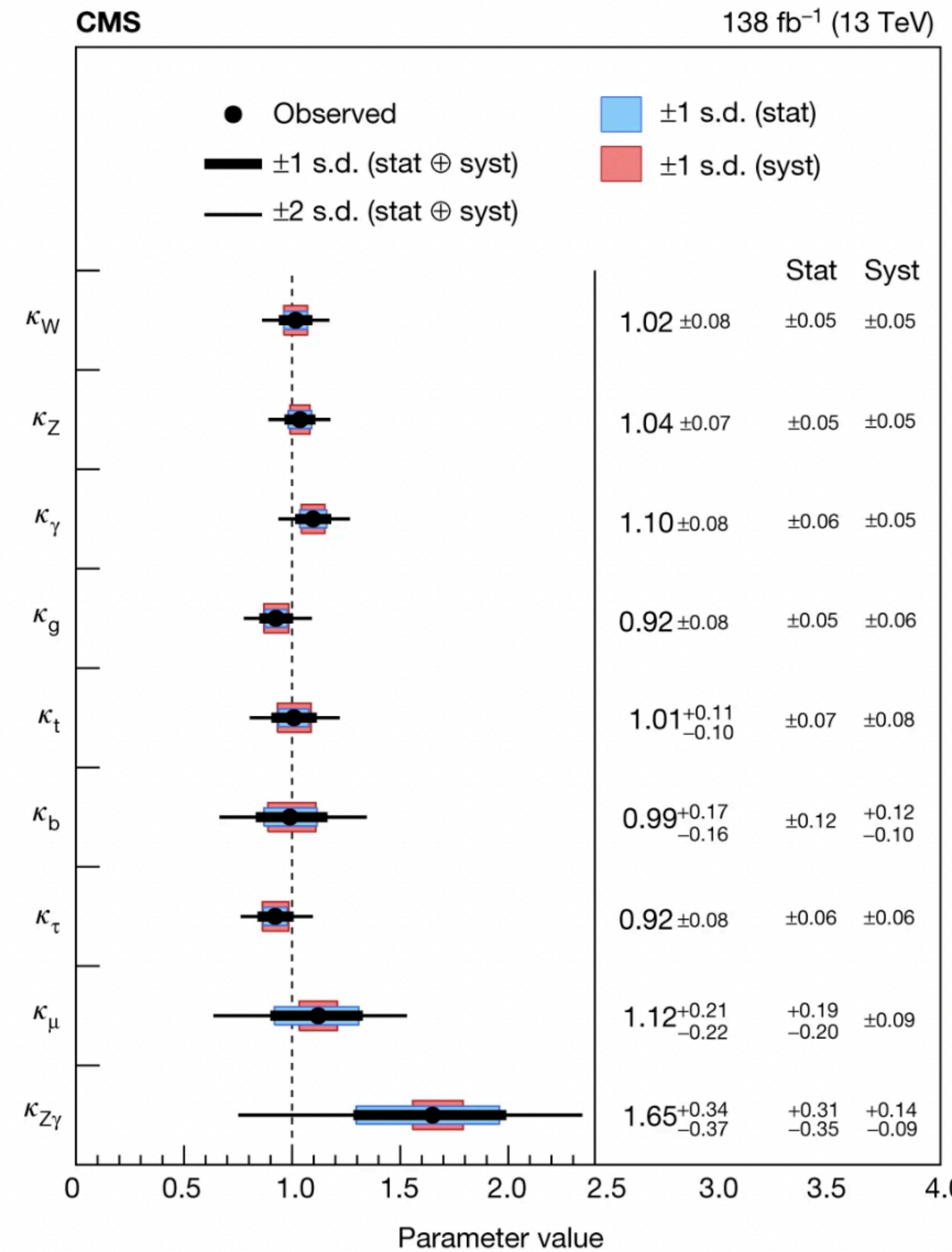
- Assume no BSM contribution in loop-induced processes (ggF, H→γγ, etc.) or total width. Resolve ggF and Hγγ effective vertices
- Good agreement with the SM across 3 orders of magnitude of particle mass

Higgs boson couplings with “kappa”

ATLAS Nature 607 (2022) 52-59

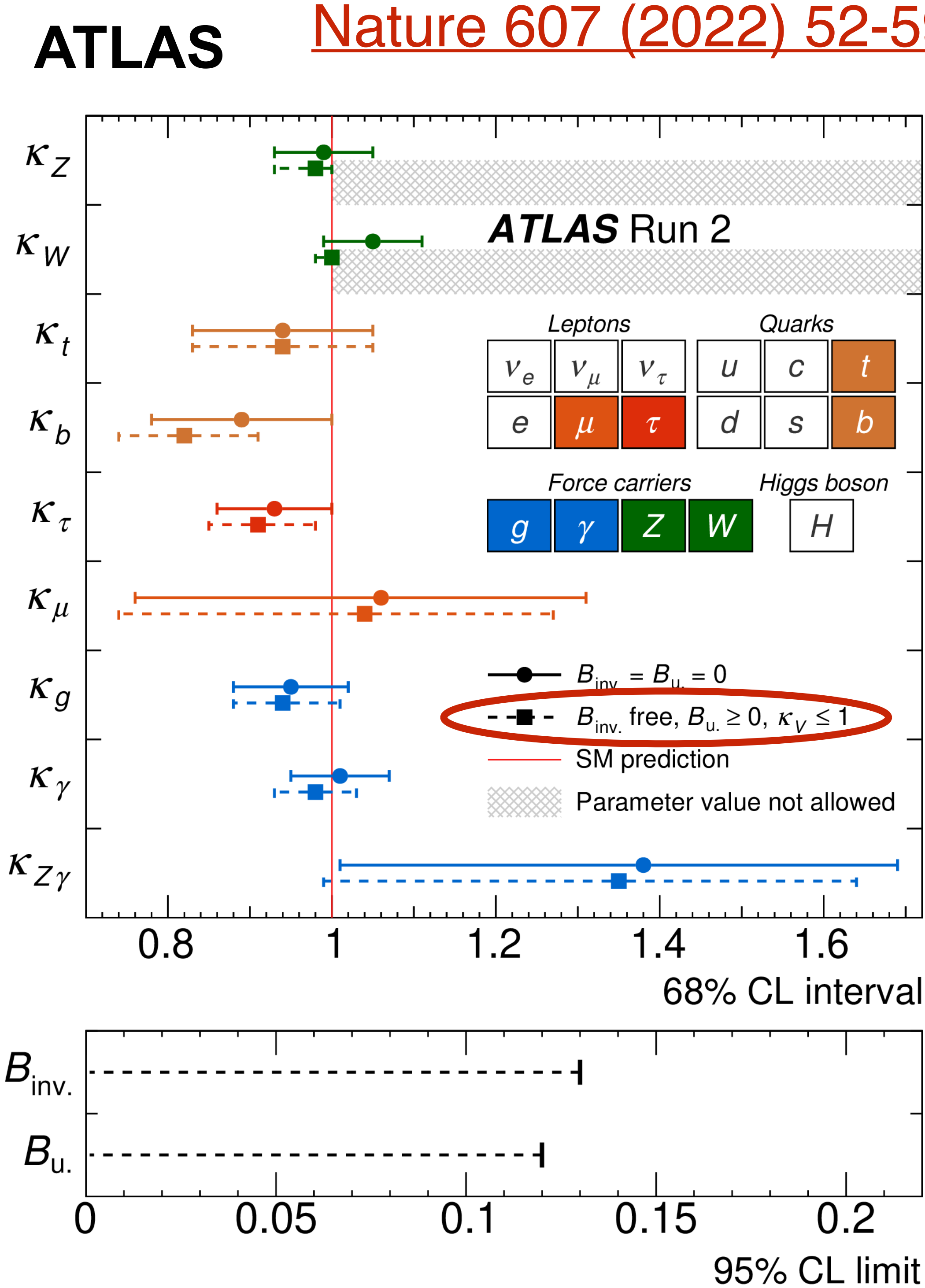


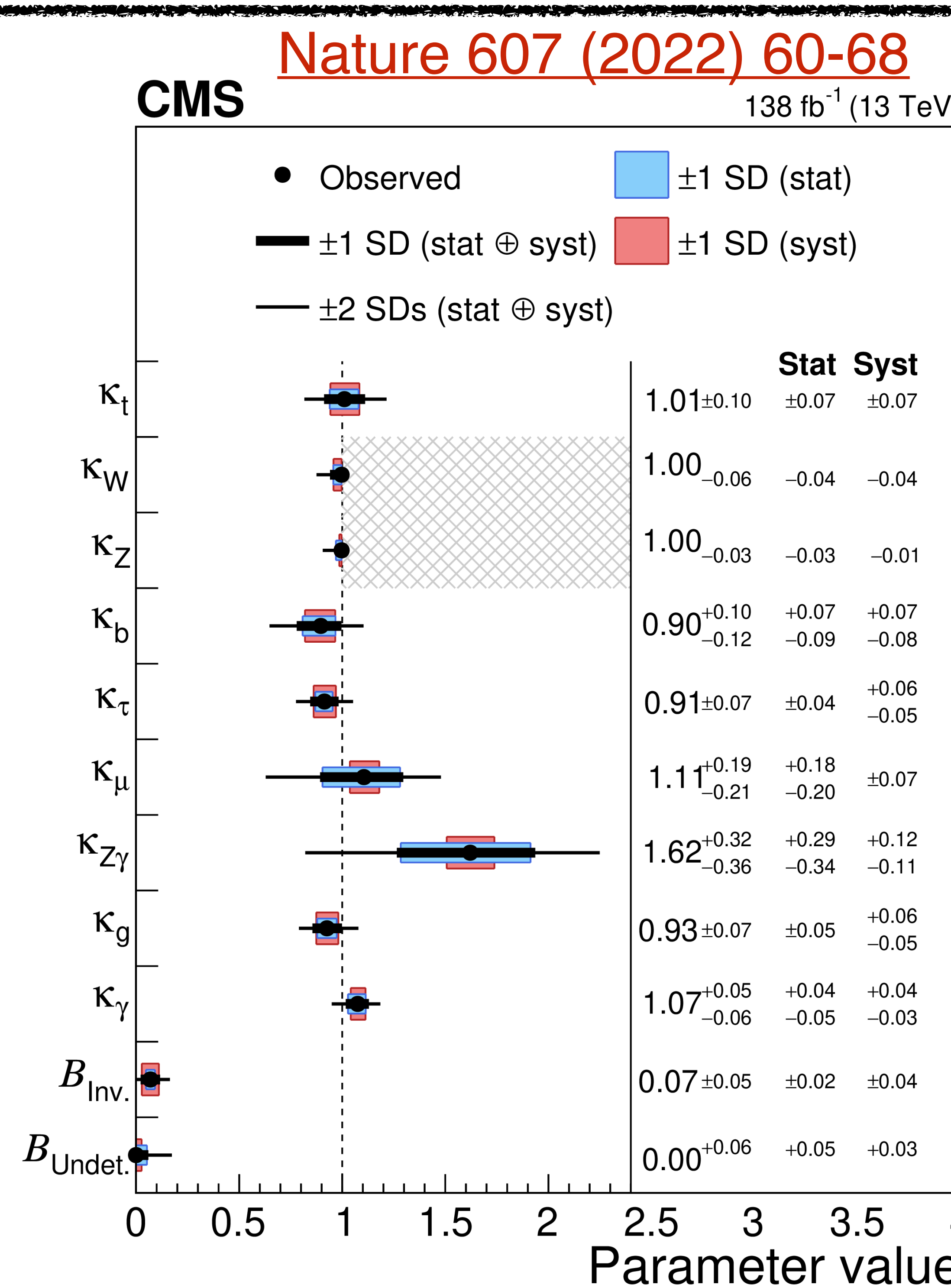
Nature 607 (2022) 60-68



- Not resolving ggF and Hγγ effective vertices (and introducing coupling modifiers κ_g, κ_γ)
  - assume $B_{invisible}$=$B_{undetected}$=0
- All coupling modifiers are measured to be compatible with the SM

Higgs boson couplings with "kappa"



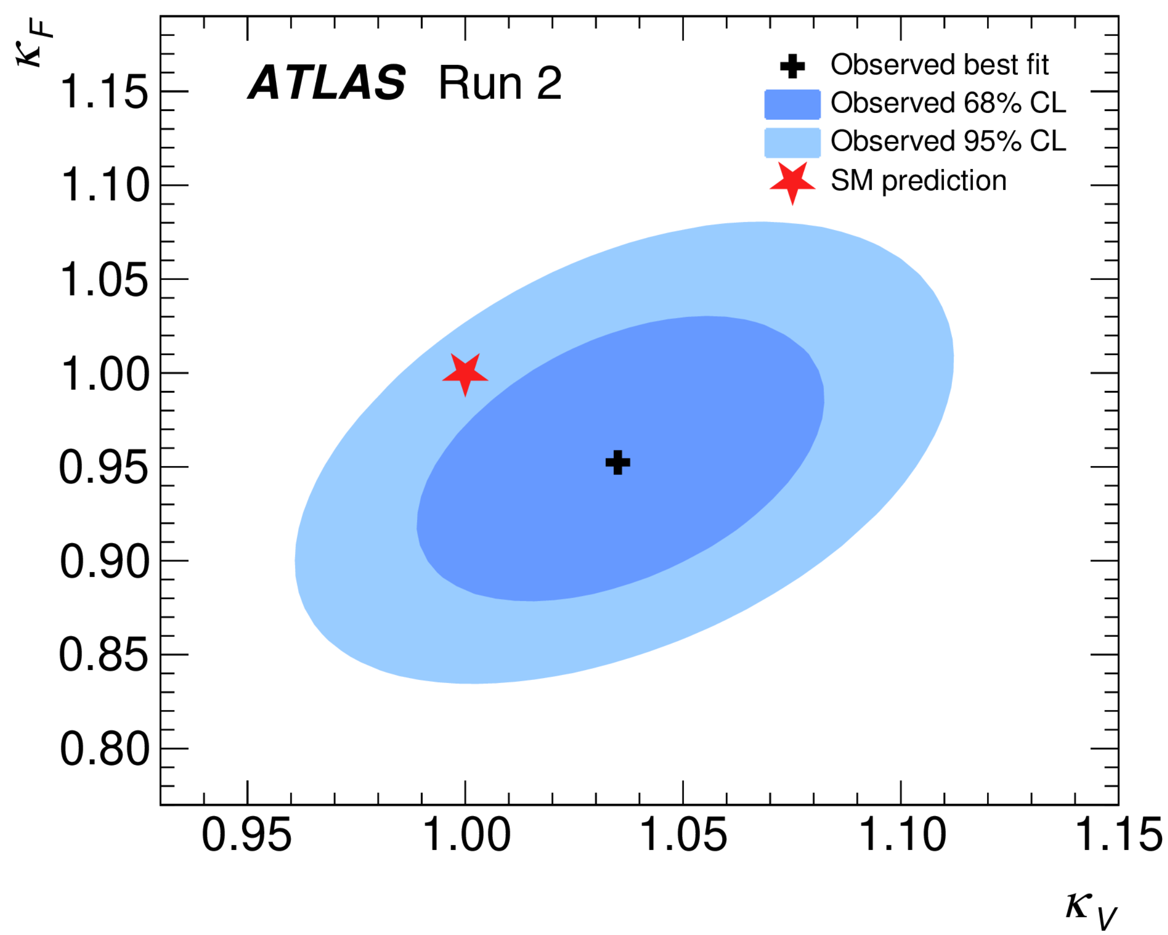


- Not resolving ggF and Hγγ effective vertices (and introducing coupling modifiers κ_g, κ_γ)
  - constrain $B_{invisible}$ and $B_{undetected}$ using H→invisible analysis and $\kappa_V < 1$
- Both invisible and undetected BR's are compatible with zero

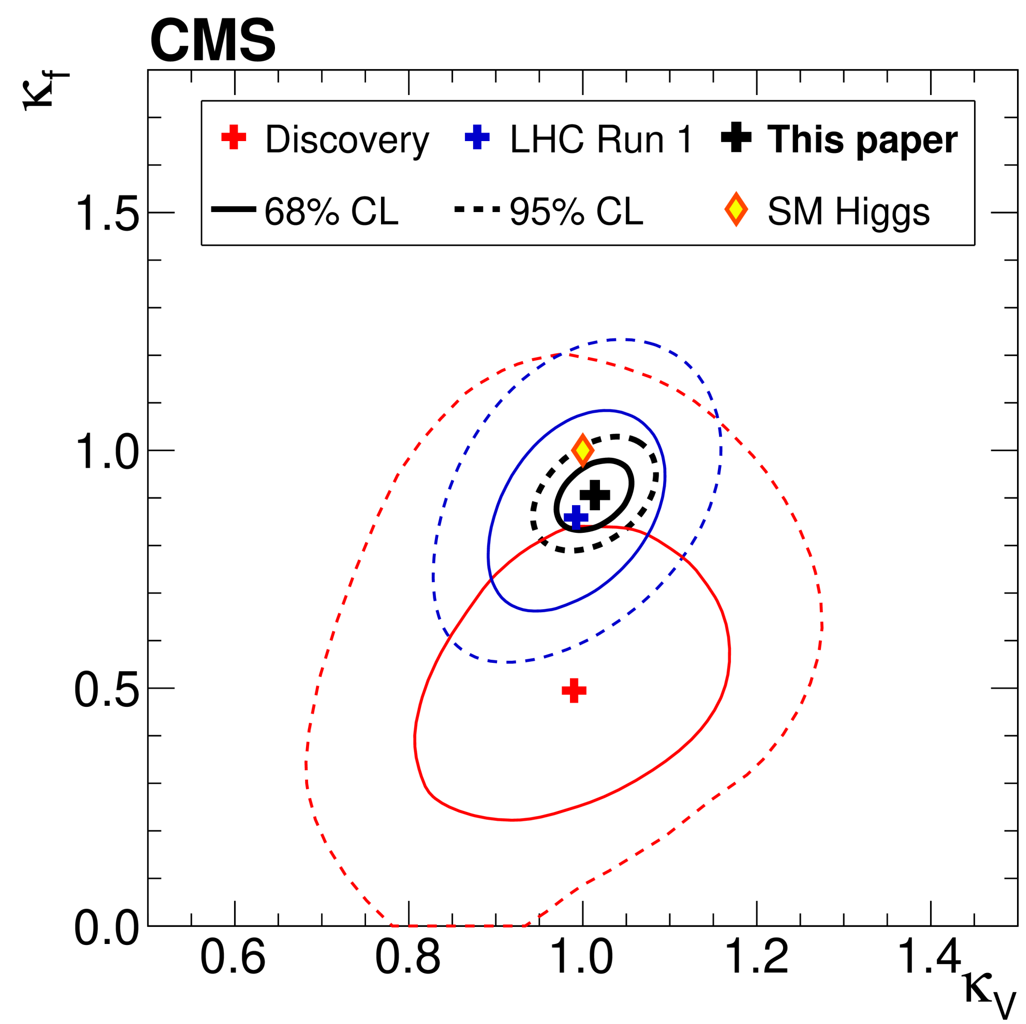
Higgs boson couplings with "kappa"

ATLAS Nature 607 (2022) 52-59

Nature 607 (2022) 60-68



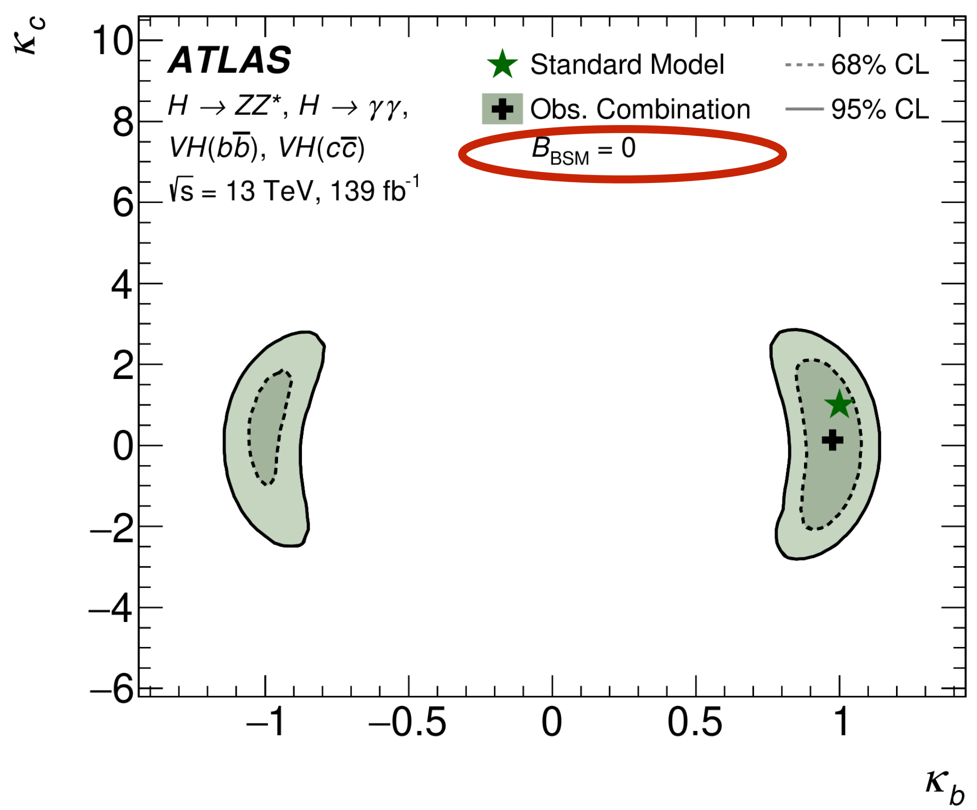
$\kappa_V = 1.035 \pm 0.031$ and $\kappa_F = 0.95 \pm 0.05$

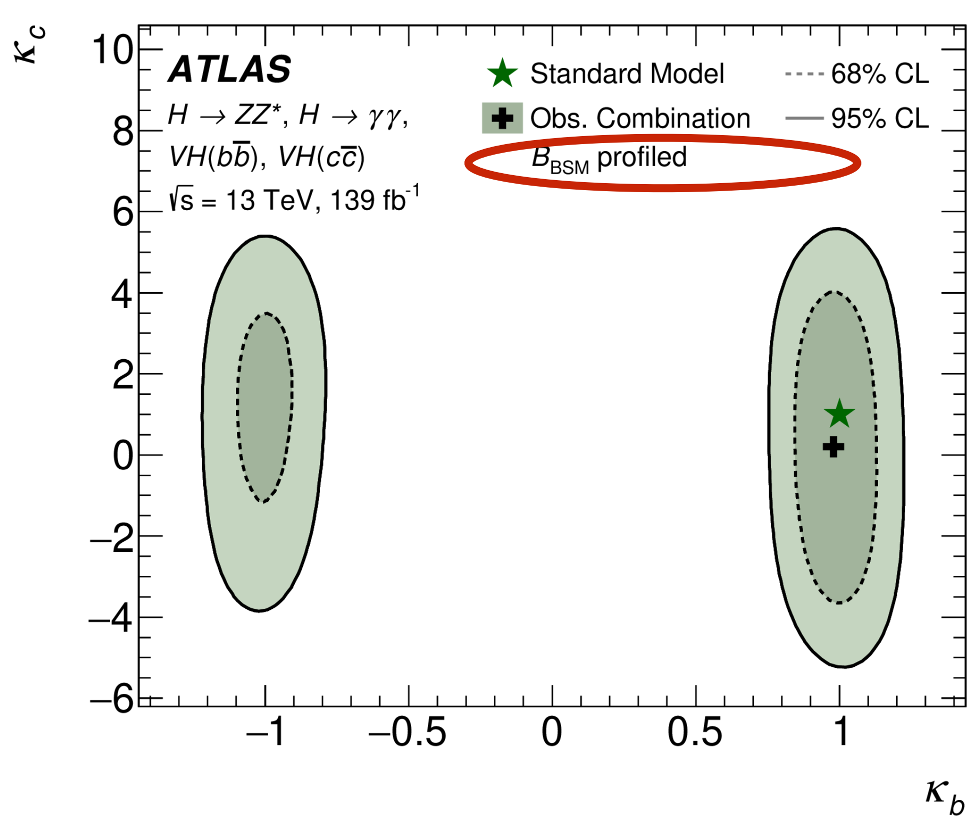


- κ_V for all vector bosons and κ_F for all heavy fermions are measured
- SM prediction is within 95% CL contour of measurement result

Higgs couplings to c quarks

- Constraints from ATLAS combination of VH(bb) & VH(cc), and Higgs p_T differential XS of H→γγ & H→ZZ:
  - $-1.61<\kappa_c<1.70$ ($B_{BSM}=0$)
  - $-2.63<\kappa_c<3.01$ (B_{BSM} profiled)

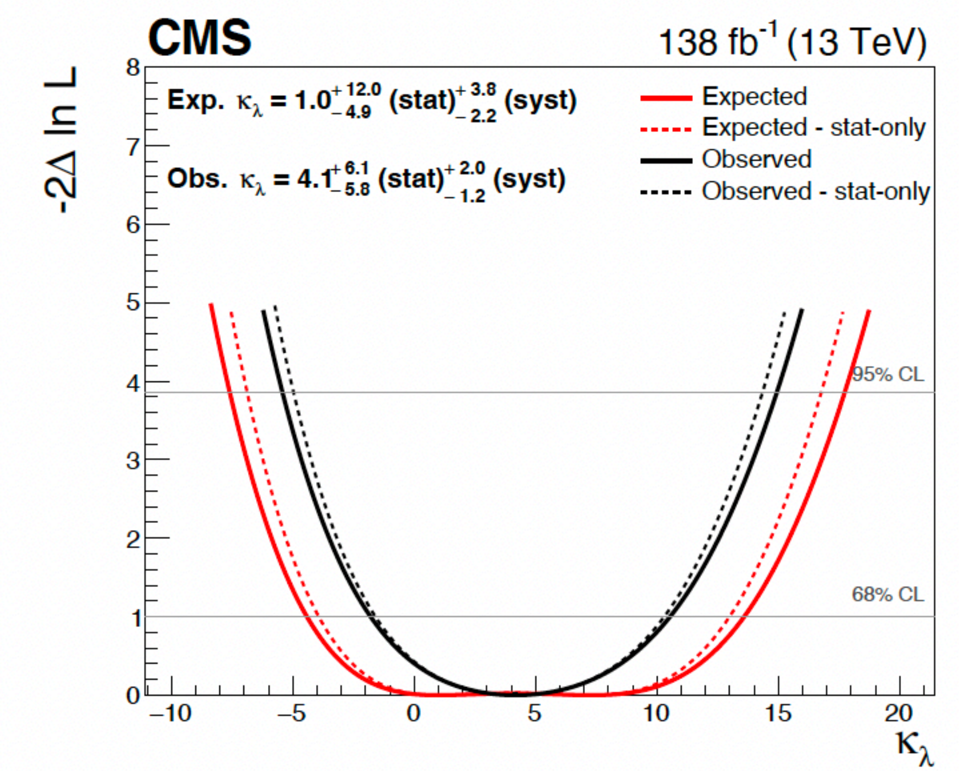


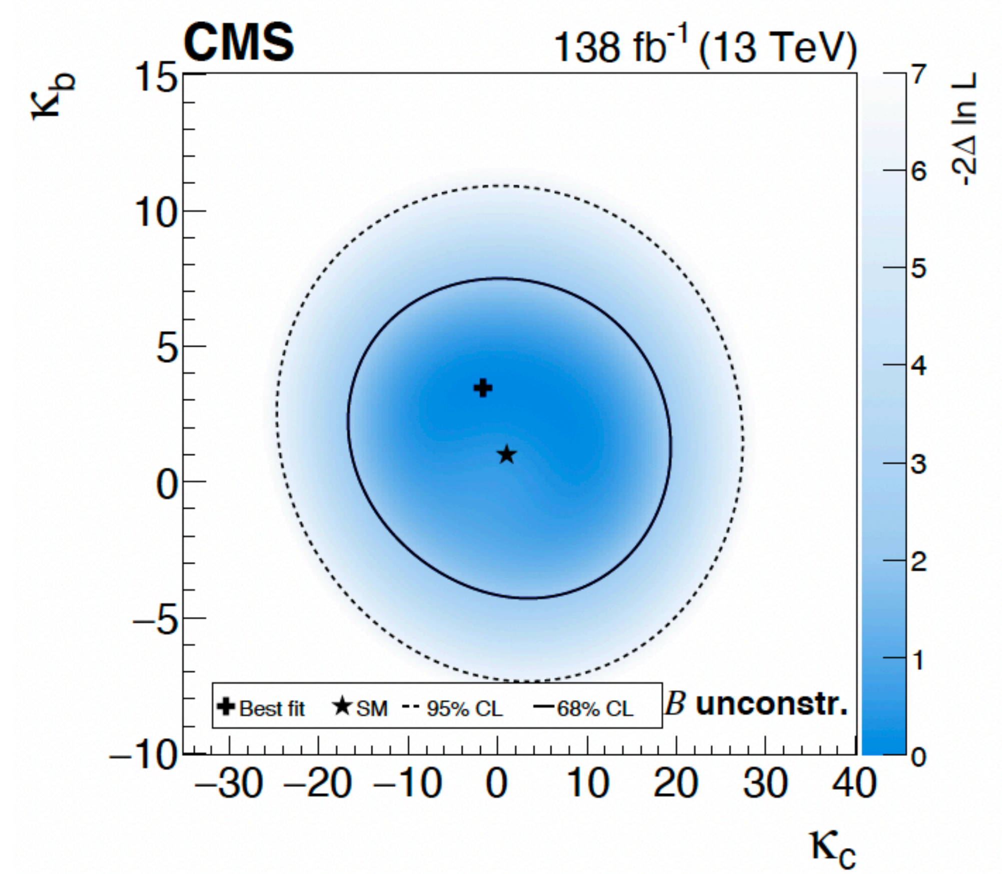


JHEP05(2023)028

Interpretation with coupling modifiers

- Interpretation from transverse momentum distribution:
  - Constraints on the trilinear self-coupling of the Higgs boson (κ_λ):
    - $-5.4<\kappa_\lambda<14.9$
    - can be used in future single and double Higgs boson combinations
  - Constraints on the Higgs boson couplings to b and c quarks (k_b and k_c):
    - $-5.6<\kappa_b<8.9$; $-20<\kappa_c<23$ (using only shape information)
    - complementary with constraints from H→cc decay





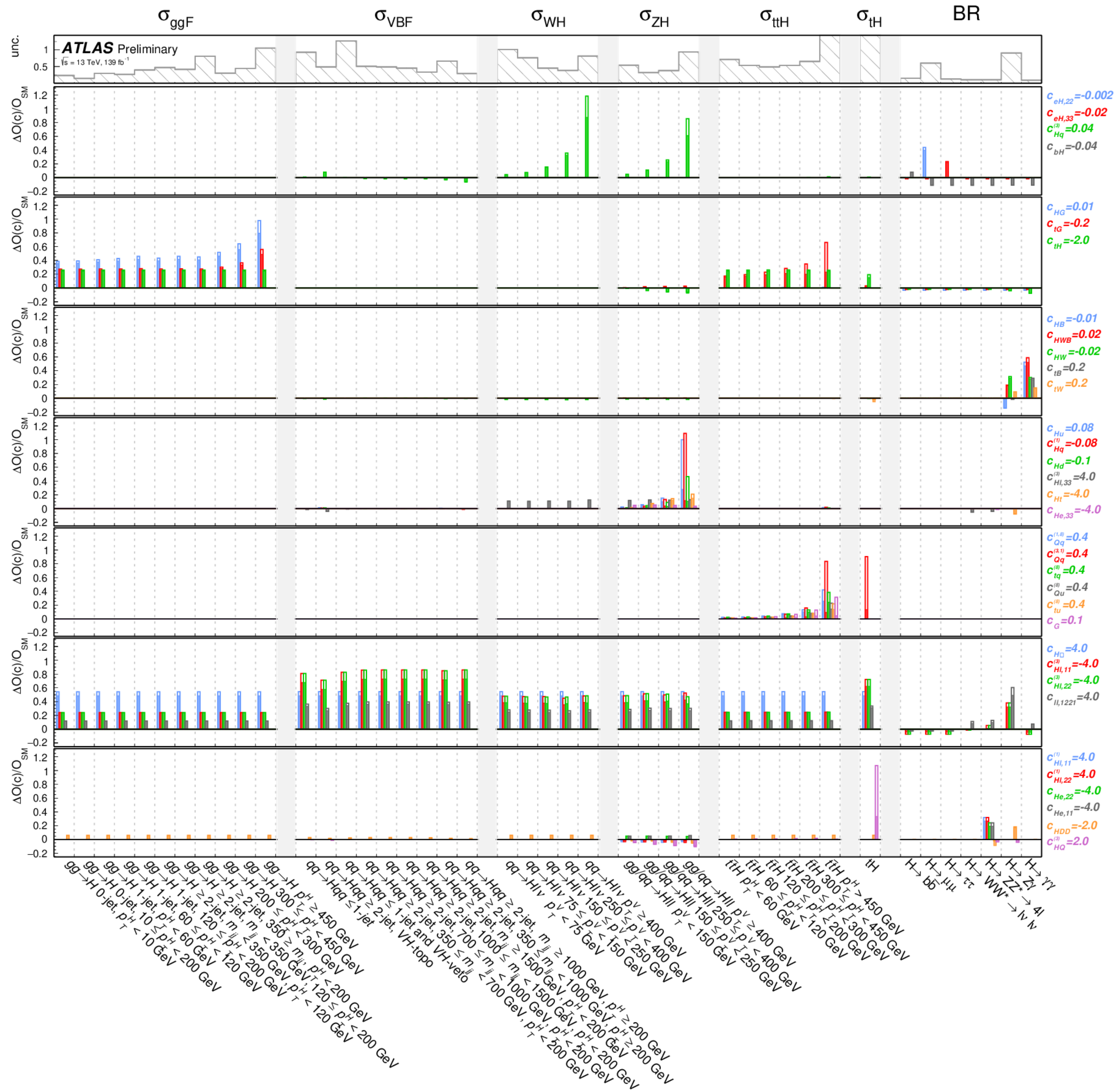
JHEP 08 (2023) 040

EFT interpretation from Higgs measurements

Interpretation of STXS with EFT

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

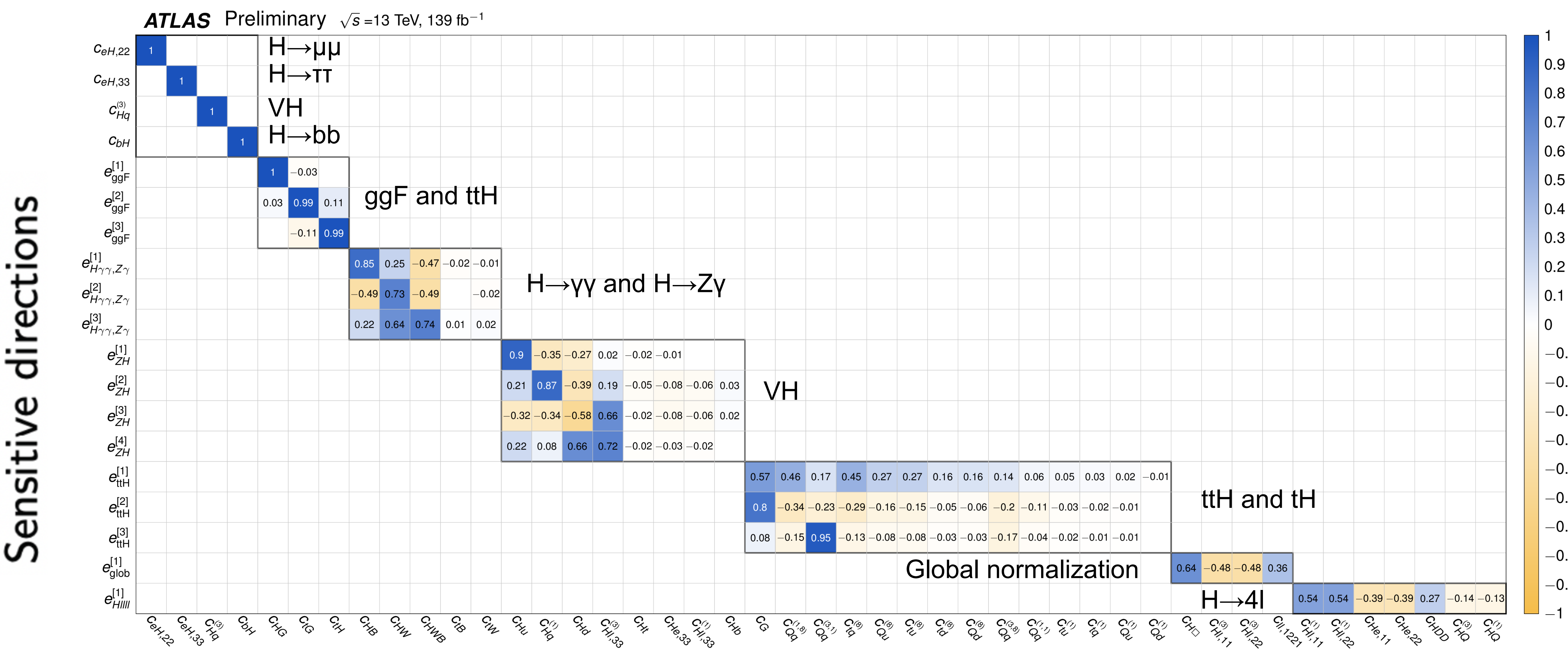
- Parameterize the signal strengths, $(XS*BR)_{meas}$/ $(XS*BR)_{SM}$, directly with Wilson coefficients of d=6 SMEFT operators



[ATLAS-CONF-2023-052]

Interpretation of STXS with EFT

- Rotate the SMEFT basis cj to eigenvector cj' and fit 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



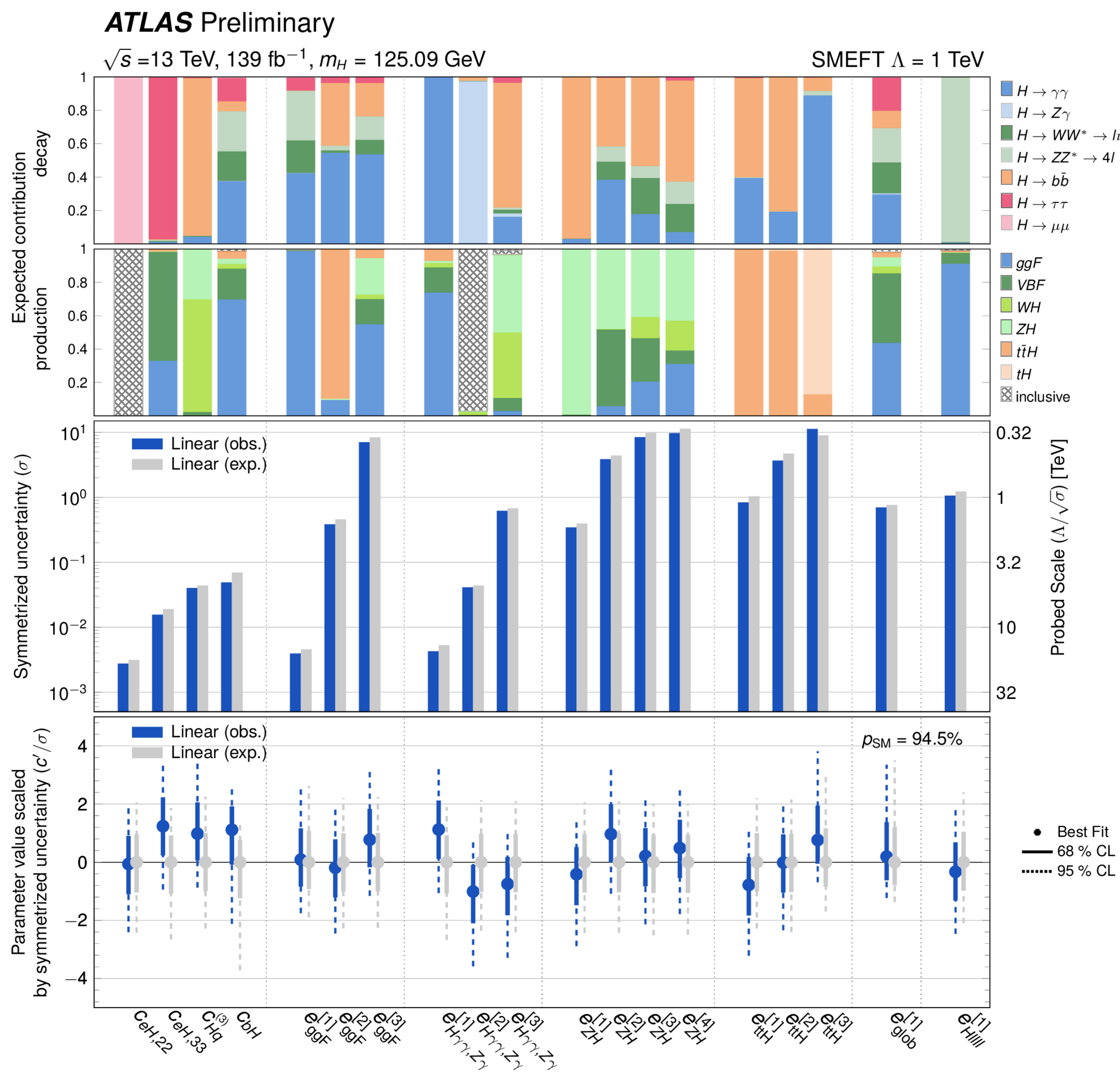
ATLAS-CONF-2023-052 Wilson coefficients

Interpretation of STXS with EFT

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

- Six (five) parameters are almost exclusively measured by a single decay (production) mode

From a simultaneous fit; linear only results



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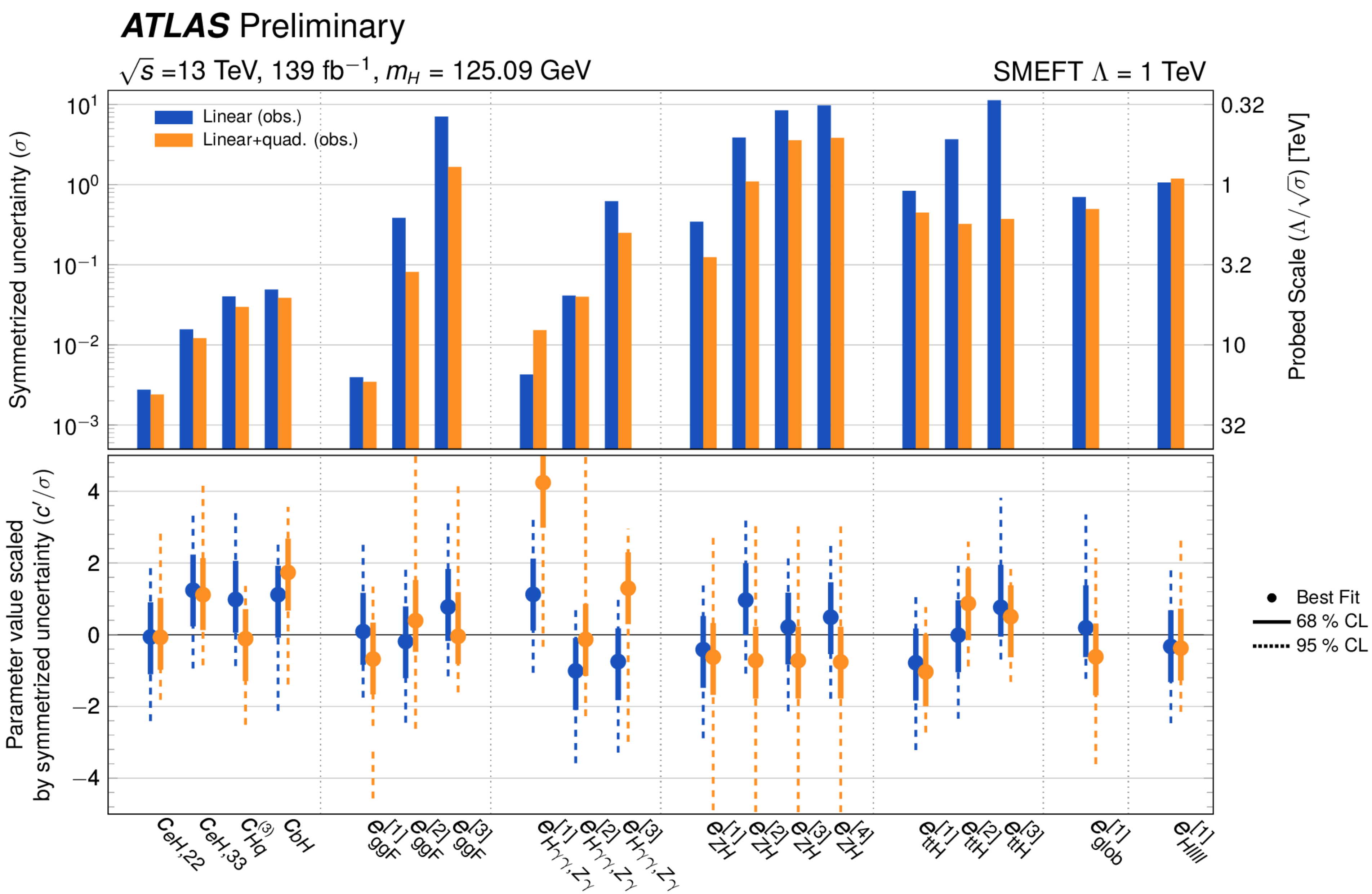
Interpretation of STXS with EFT

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

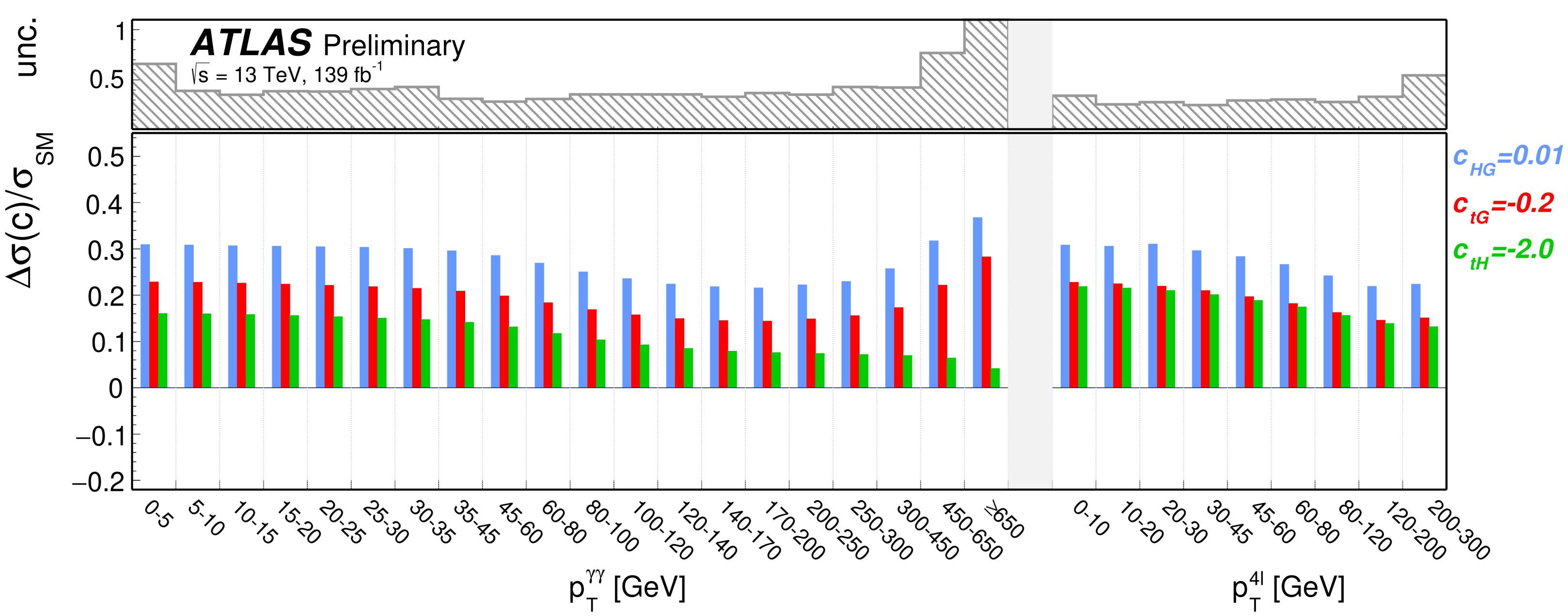
- Comparison of the linear model and the linear+quadratic model shows sizeable sensitivity to operators suppressed by Λ^4



ATLAS-CONF-2023-052

Interpretation of fiducial differential XS with EFT

- Differential distribution of Higgs transverse momentum are also affected by a few SMEFT operators (e.g. c_{HG}, c_{tG}, c_{tH})
  - H→γγ and H→ZZ channels are used for the pT(H) interpretation
- A rotation in the parameter space is performed to define a new set of coefficients which are decorrelated



$$ev^{[1]} = 0.999c_{HG} - 0.035c_{tG} - 0.003c_{tH},$$
$$ev^{[2]} = 0.035c_{HG} + 0.978c_{tG} + 0.205c_{tH},$$
$$ev^{[3]} = -0.005c_{HG} - 0.205c_{tG} + 0.979c_{tH}.$$

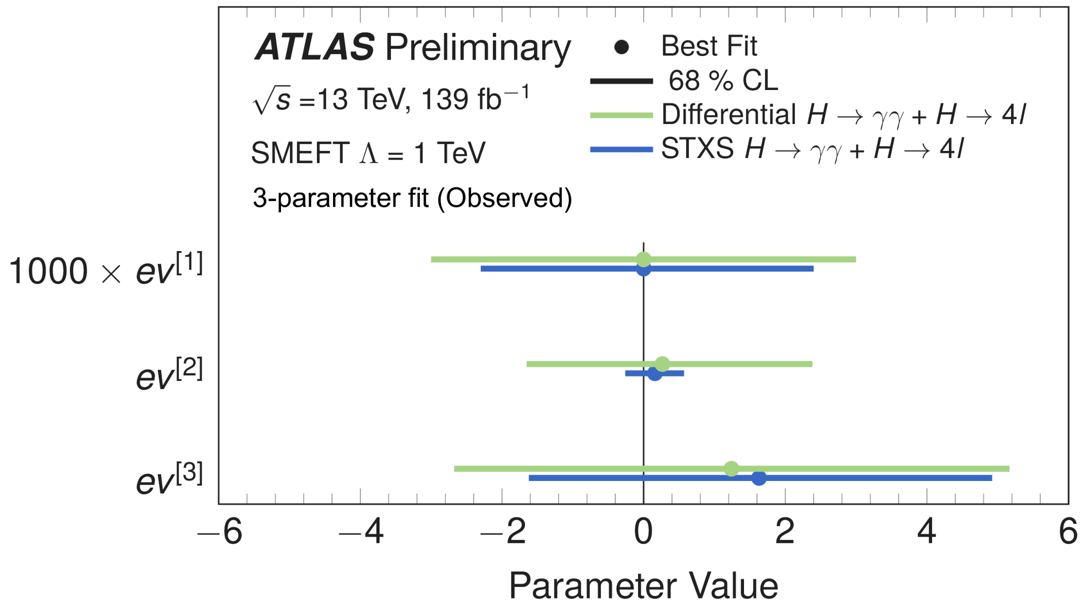
ATLAS-CONF-2023-052

Interpretation of fiducial differential XS with EFT

From 3 fits with one parameter of interest

Parameter	Observed 68% CL interval		Expected 68% CL interval	
	stat. + syst.	stat. only	stat. + syst.	stat. only
c_{HG}	$0.000^{+0.003}_{-0.003}$	$0.000^{+0.002}_{-0.002}$	$0.000^{+0.003}_{-0.003}$	$0.000^{+0.002}_{-0.002}$
c_{tG}	$0.00^{+0.08}_{-0.09}$	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.08}_{-0.09}$	$0.00^{+0.05}_{-0.05}$
c_{tH}	$0.1^{+1.0}_{-1.1}$	$0.1^{+0.7}_{-0.7}$	$0.0^{+1.0}_{-1.1}$	$0.0^{+0.7}_{-0.7}$

From a simultaneous fit



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- Using the same decay channels, the constraints from differential XS are weaker than STXS
  - differential measurements are inclusive in production mode
  - STXS separate different production modes whose cross-sections are affected in different ways by the different operators

Interpretation of STXS with EFT

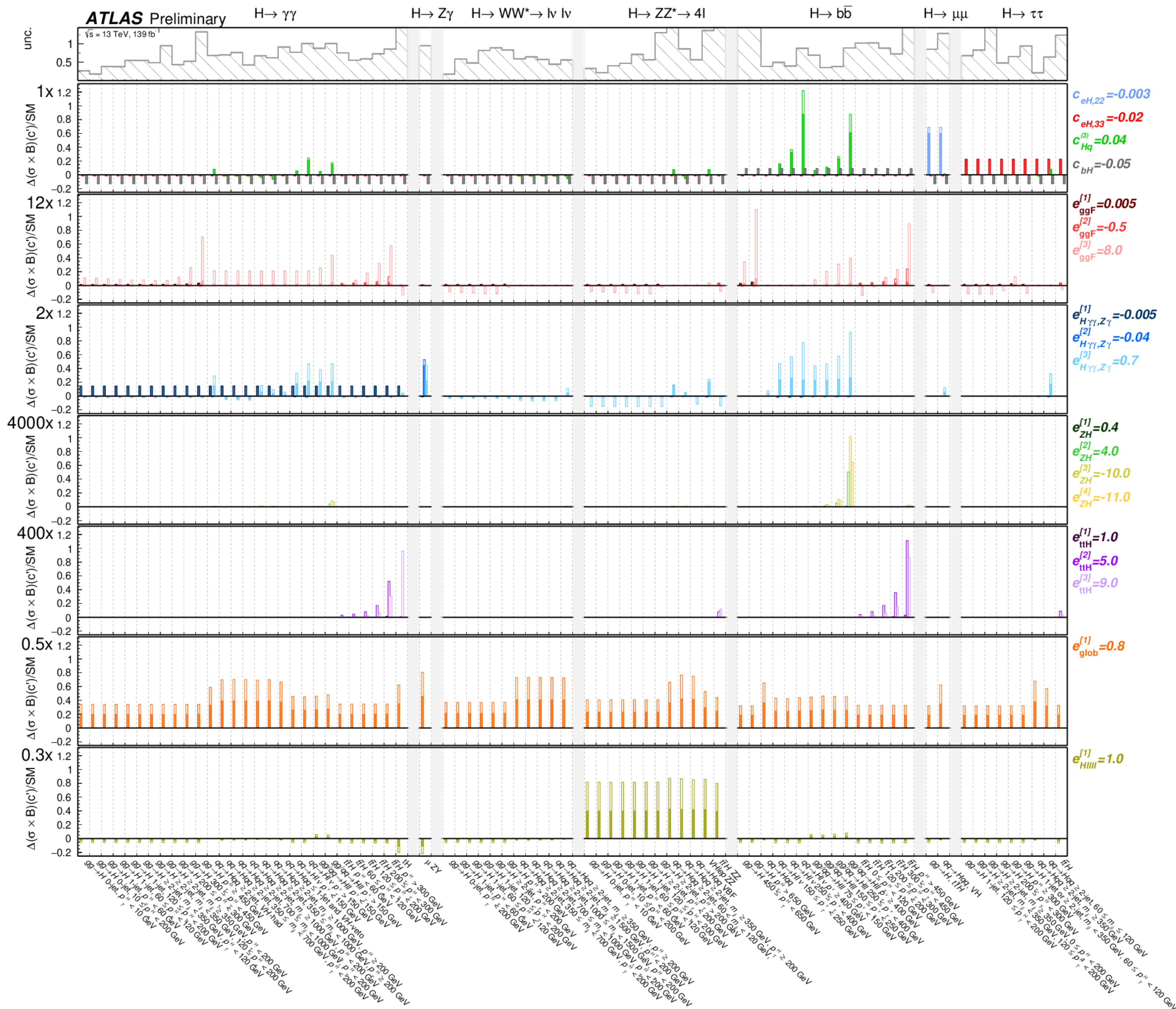
Wilson coefficient	Operator	Wilson coefficient	Operator
c_H	$(H^\dagger H)^3$	$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$	$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$c_{tu}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$c_{td}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$
c_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$c_{td}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$
$c_{Hl,11}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_1\gamma^\mu l_1)$	$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
$c_{Hl,22}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_2\gamma^\mu l_2)$	$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$c_{Hl,33}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_3\gamma^\mu l_3)$	$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
$c_{Hl,11}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_1\tau^I\gamma^\mu l_1)$	$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$
$c_{Hl,22}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_2\tau^I\gamma^\mu l_2)$	$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$
$c_{Hl,33}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_3\tau^I\gamma^\mu l_3)$	$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$
$c_{He,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_1\gamma^\mu e_1)$	$c_{eH,22}$	$(H^\dagger H)(\bar{l}_2 e_2 H)$
$c_{He,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_2\gamma^\mu e_2)$	$c_{eH,33}$	$(H^\dagger H)(\bar{l}_3 e_3 H)$
$c_{He,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_3\gamma^\mu e_3)$	c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\widetilde{H})$
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H}t)$
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$	c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\,G_{\mu\nu}^A$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\,W_{\mu\nu}^I$
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\,B_{\mu\nu}$
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{Q}\tau^I\gamma^\mu Q)$	$c_{ll,1221}$	$(\bar{l}_1\gamma_\mu l_2)(\bar{l}_2\gamma^\mu l_1)$
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$		
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$		

ATLAS-CONF-2023-052

Interpretation of STXS with EFT

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

- Parameterize the signal strengths, $(XS*BR)_{meas}/(XS*BR)_{SM}$, directly with Wilson coefficients of d=6 SMEFT operators



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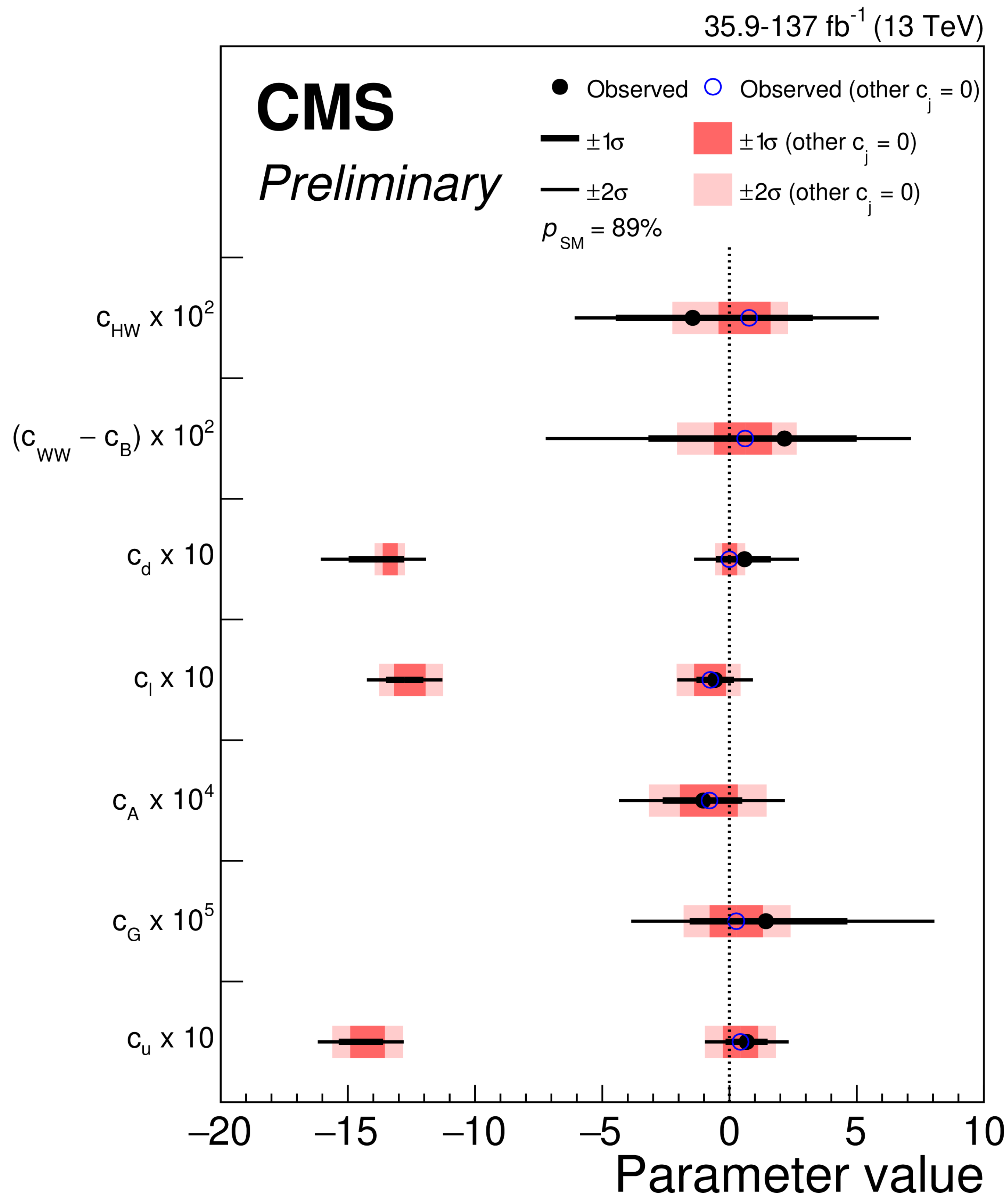
Interpretation of STXS with EFT

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

- CMS provided constraints on the parameters of the Higgs Effective Lagrangian model

- For many of the parameters these results represented the strongest constraints



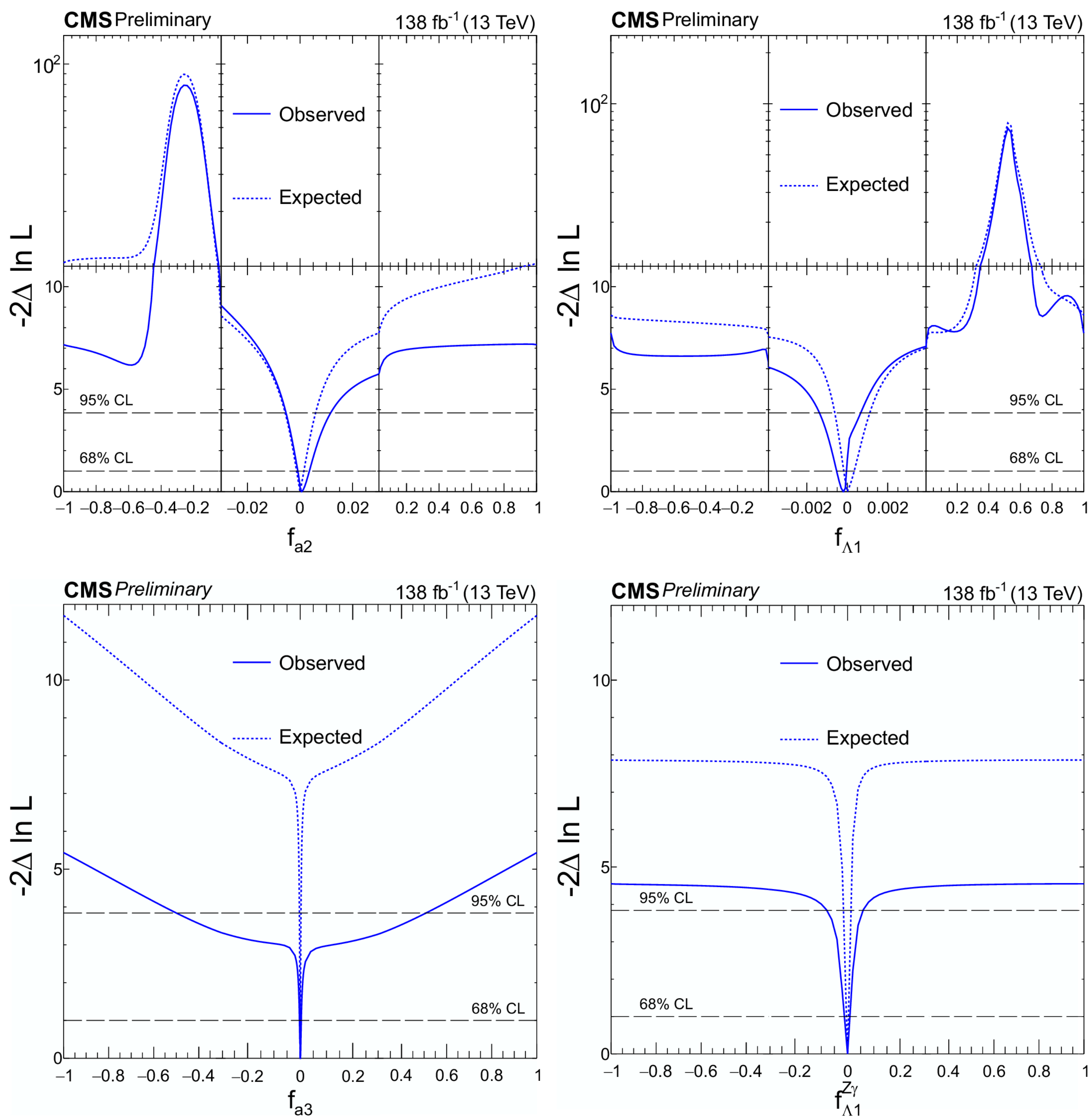
CMS-PAS-HIG-19-005

Higgs anomalous coupling

$H \rightarrow WW^*$

CMS-PAS-HIG-22-008

HVV vertex
Approach 1
$a_i^{ZZ} = a_i^{WW}$



$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_j |a_j|^2\sigma_j}\,\mathrm{sign}\left(\frac{a_i}{a_1}\right),$$

- Studied individually
- Significant interference effects for certain values is evident

Higgs anomalous coupling

CMS-PAS-HIG-22-008

HVV vertex SMEFT (Warsaw basis)

$$\delta a_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(2c_{H\Box} + \frac{6e^2}{s_w^2}c_{HWB} + (\frac{3c_w^2}{2s_w^2} - \frac{1}{2})c_{HD}\right),$$

$$\kappa_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_w^2}c_{HWB} + (1 - \frac{1}{2s_w^2})c_{HD}\right),$$

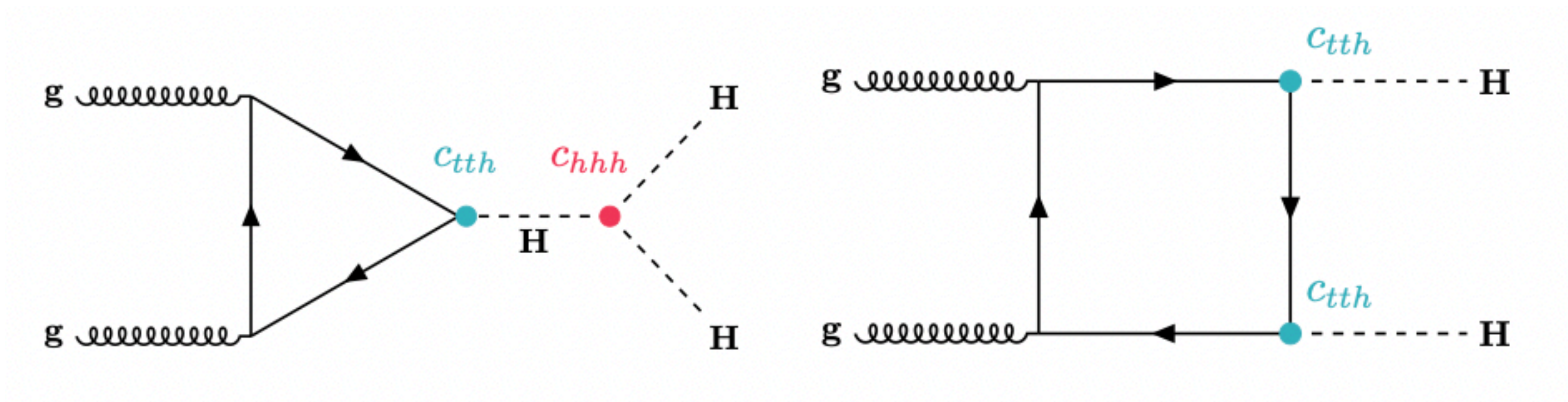
$$a_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{HB} + c_w^2 c_{HW} + s_w c_w c_{HWB}\right),$$

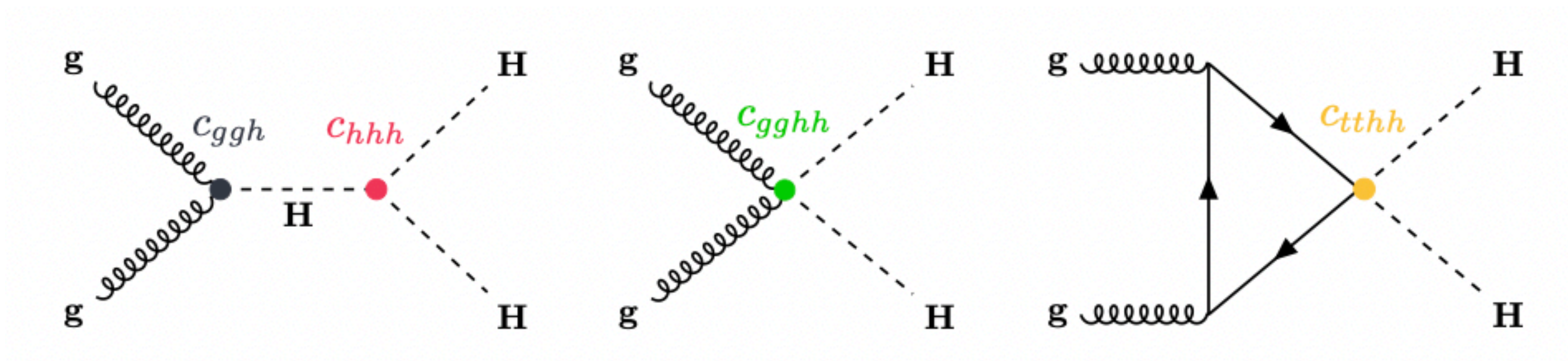
$$a_3^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{H\tilde{B}} + c_w^2 c_{H\tilde{W}} + s_w c_w c_{H\tilde{W}B}\right),$$

Coupling	Observed	Expected
$c_{H\Box}$	$-0.76^{+1.43}_{-3.43}$	$0.0^{+1.37}_{-1.84}$
c_{HD}	$-0.12^{+0.93}_{-0.32}$	$0.0^{+0.43}_{-0.30}$
c_{HW}	$0.08^{+0.43}_{-0.87}$	$0.0^{+0.37}_{-0.48}$
c_{HWB}	$0.17^{+0.88}_{-1.79}$	$0.0^{+0.77}_{-0.96}$
c_{HB}	$0.03^{+0.13}_{-0.26}$	$0.0^{+0.11}_{-0.14}$
$c_{H\tilde{W}}$	$-0.26^{+0.67}_{-0.50}$	$0.0^{+0.48}_{-0.52}$
$c_{H\tilde{W}B}$	$-0.54^{+1.37}_{-1.03}$	$0.0^{+0.99}_{-1.07}$
$c_{H\tilde{B}}$	$-0.08^{+0.20}_{-0.15}$	$0.0^{+0.15}_{-0.16}$

Interpretation of HH with EFT

HEFT currently used for most interpretations of HH

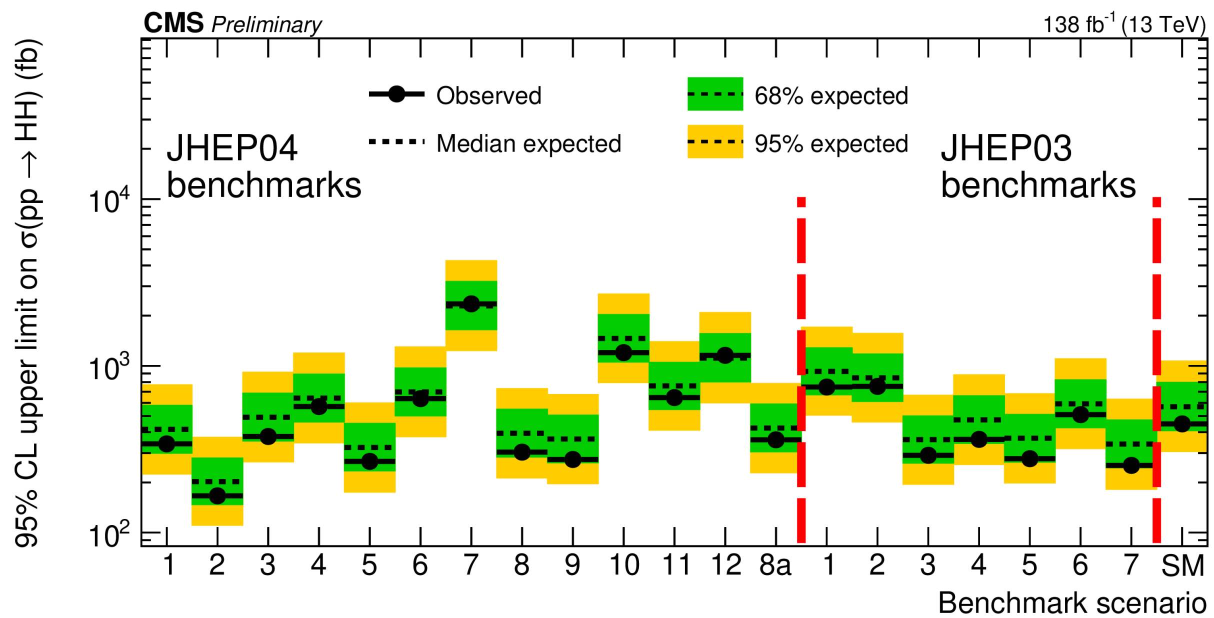


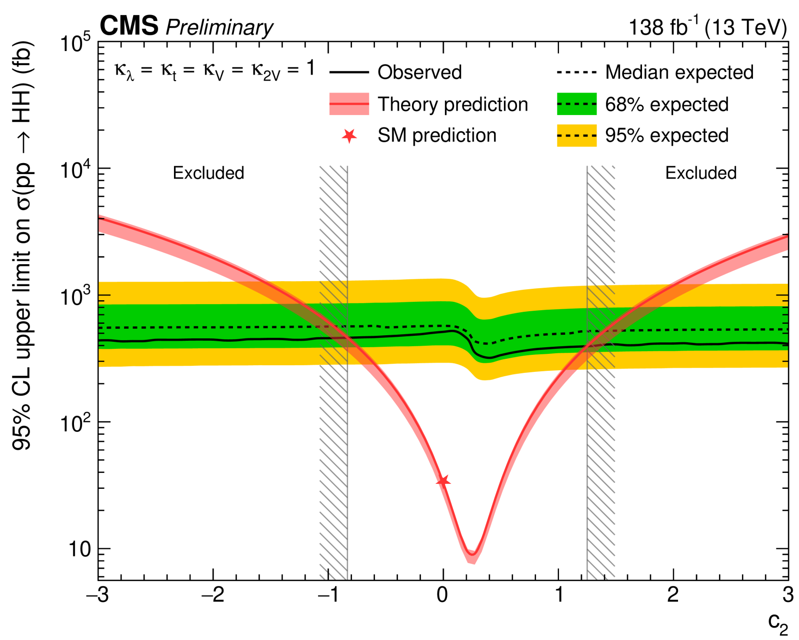


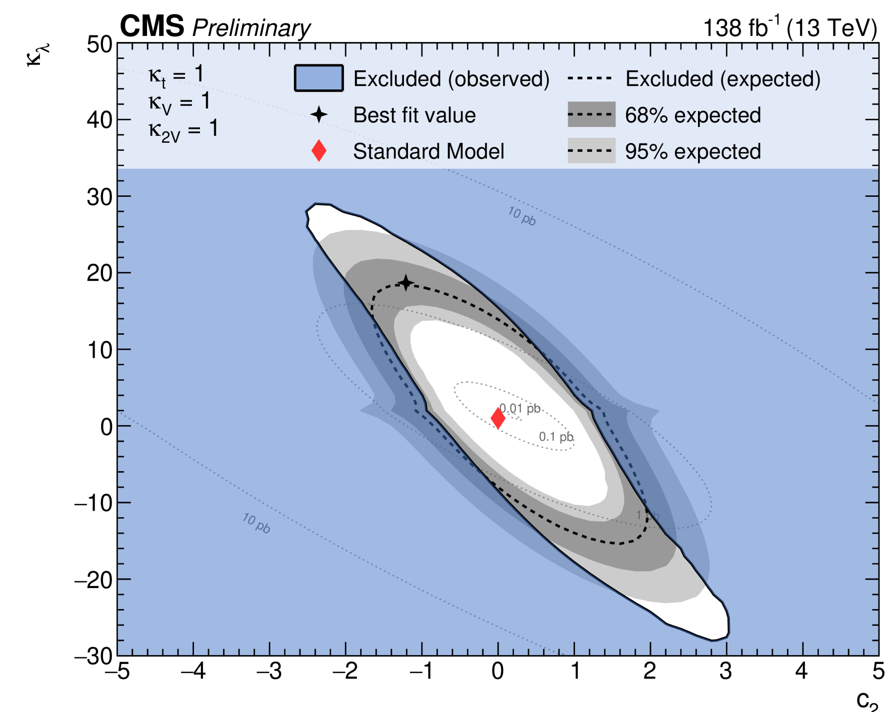
ATL-PHYS-PUB-2022-019

CMS HH→bbWW

CMS-PAS-HIG-21-005



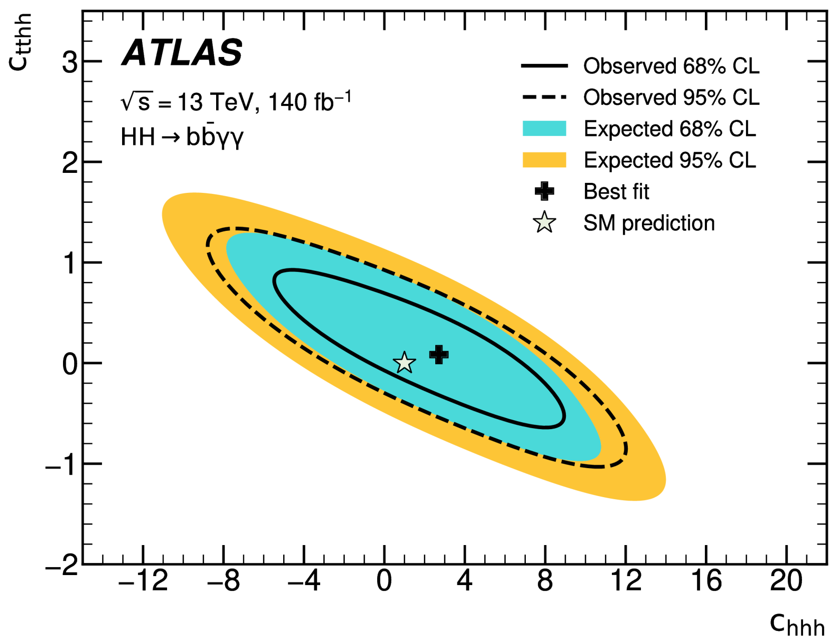


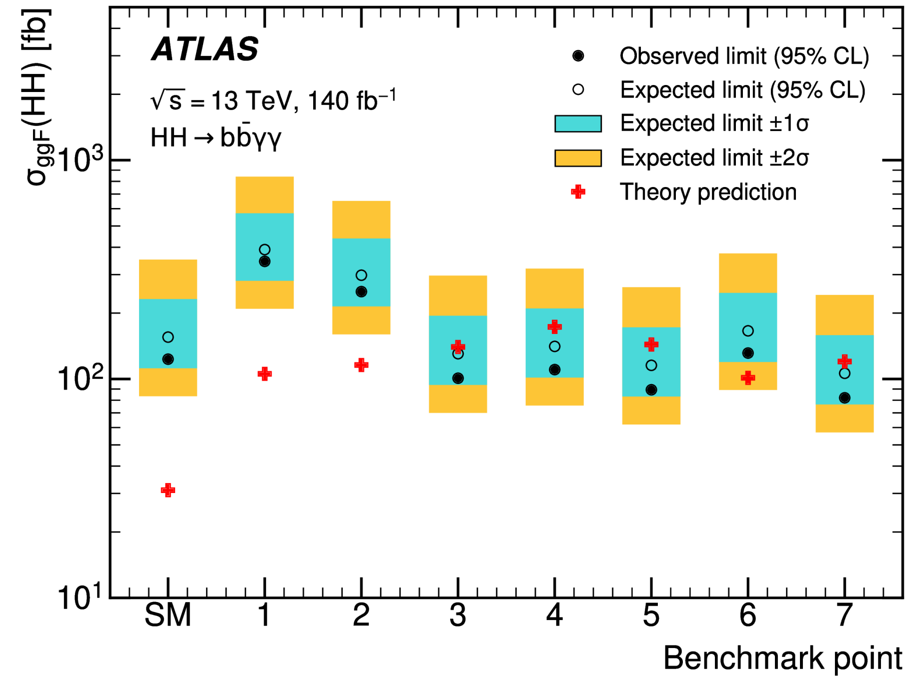


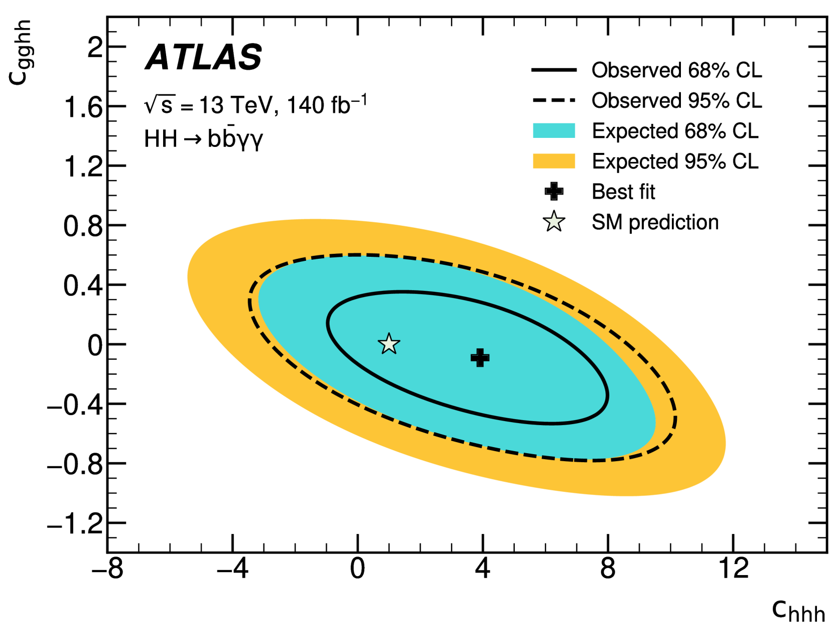
- Results are interpreted in HEFT
- BSM coupling c_2(=c_{ttHH}) is constrained between -0.8 and 1.3

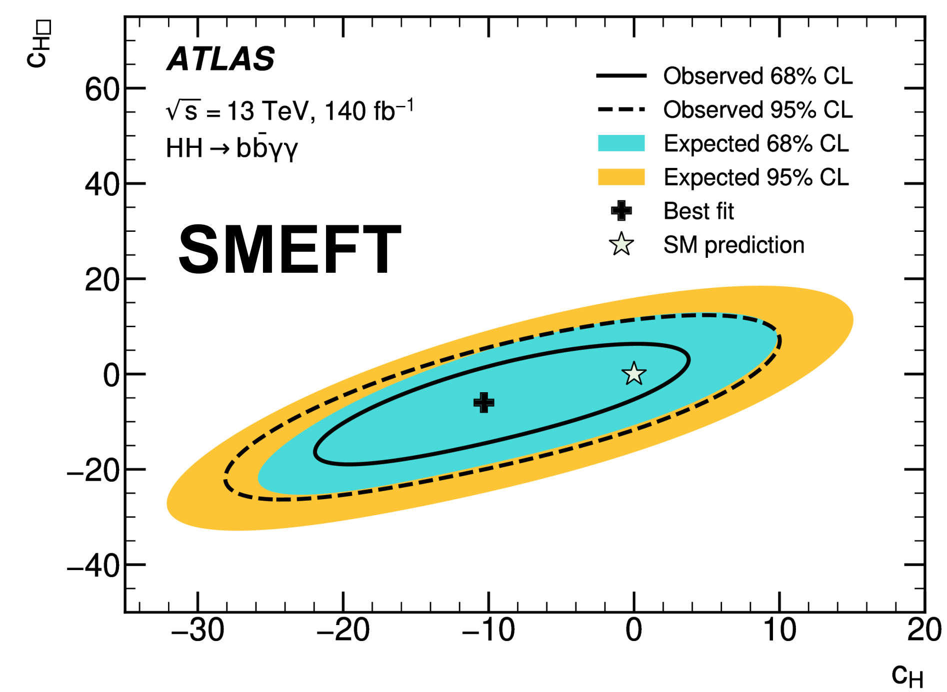
ATLAS HH→bbγγ

arxiv:2310.12301





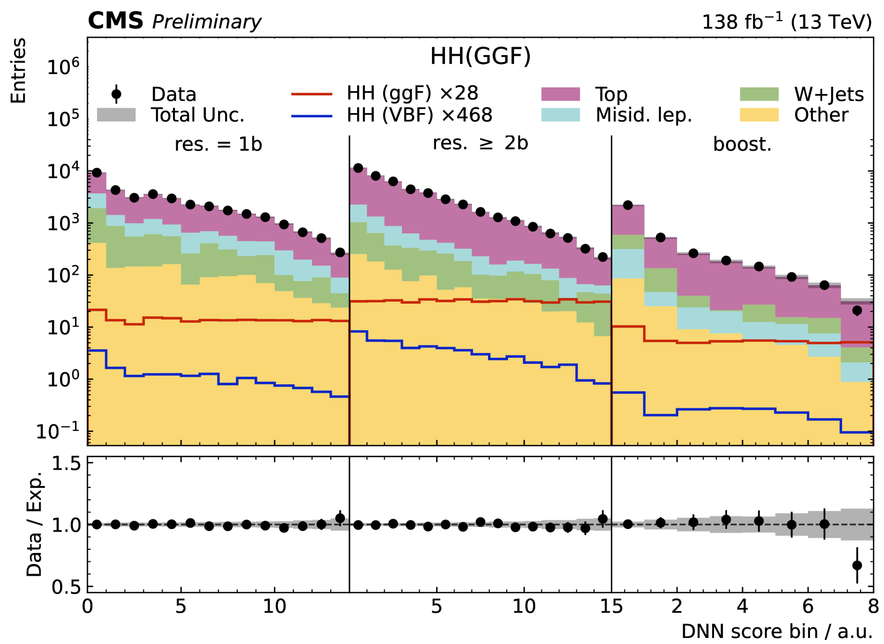


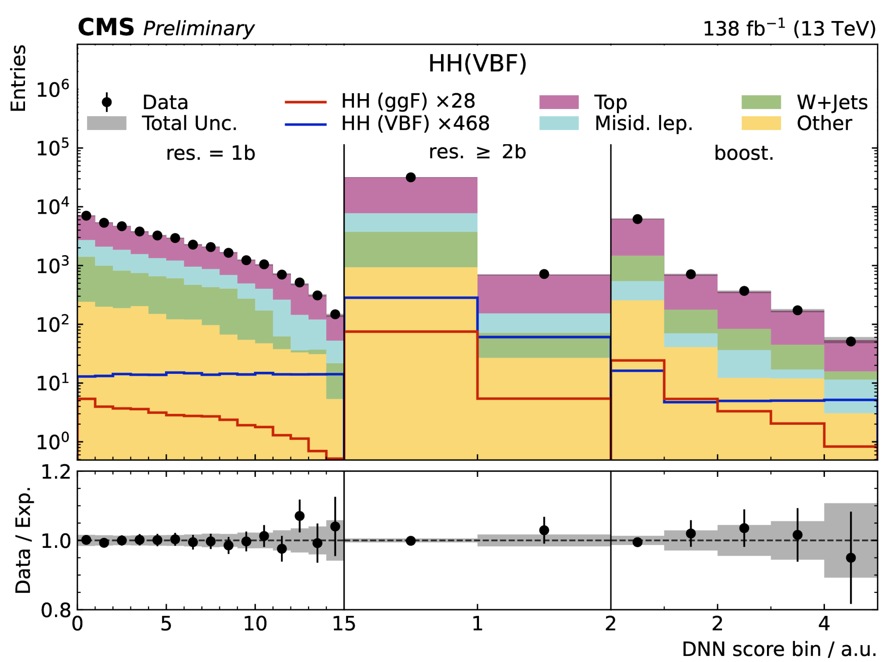


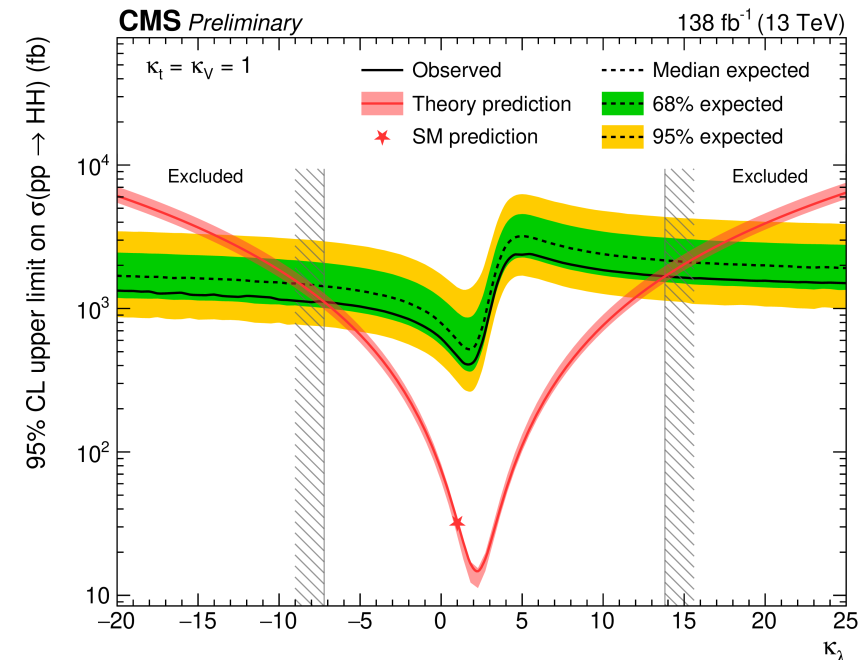
- Results are interpreted in both HEFT and SMEFT
- Excluded four of the considered seven HEFT benchmark points

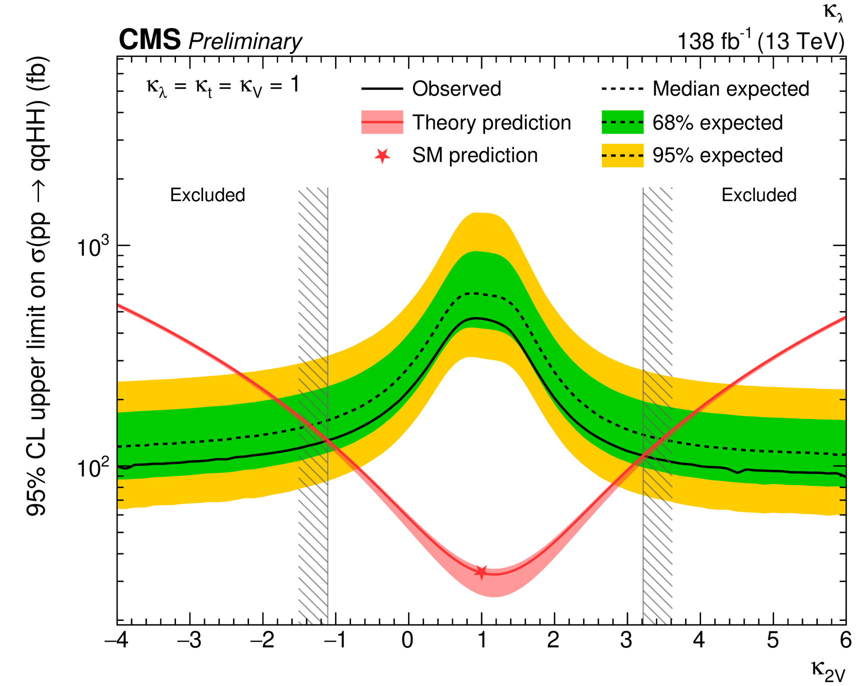
CMS HH→bbWW

[CMS-PAS-HIG-21-005]





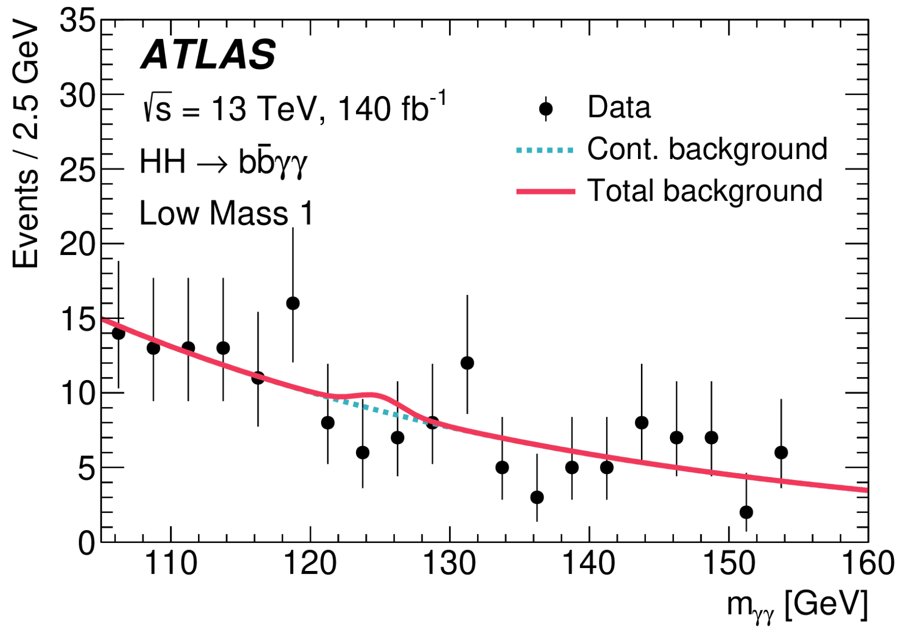


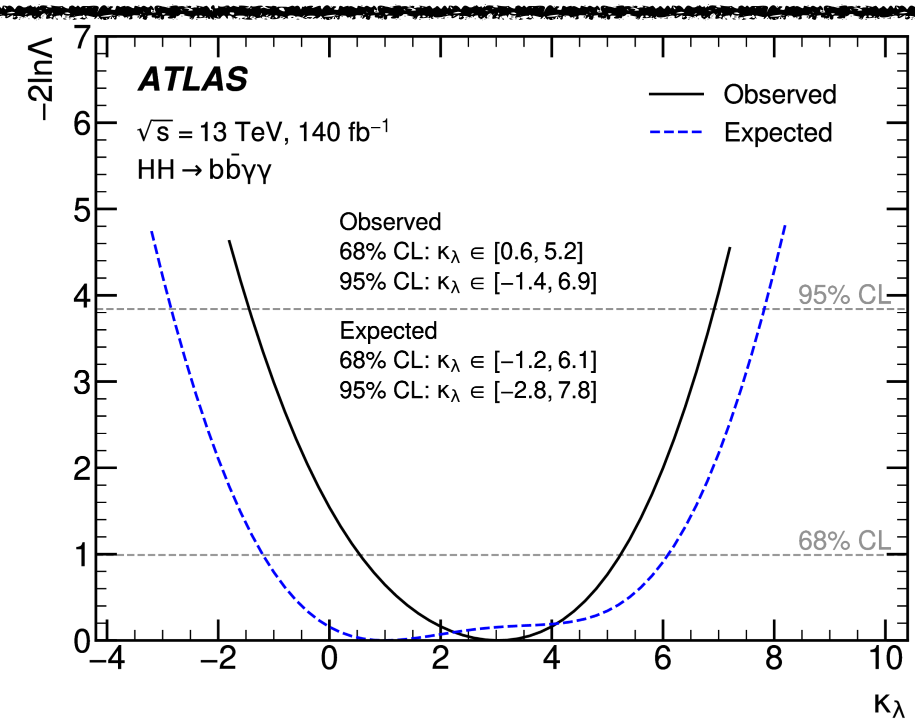


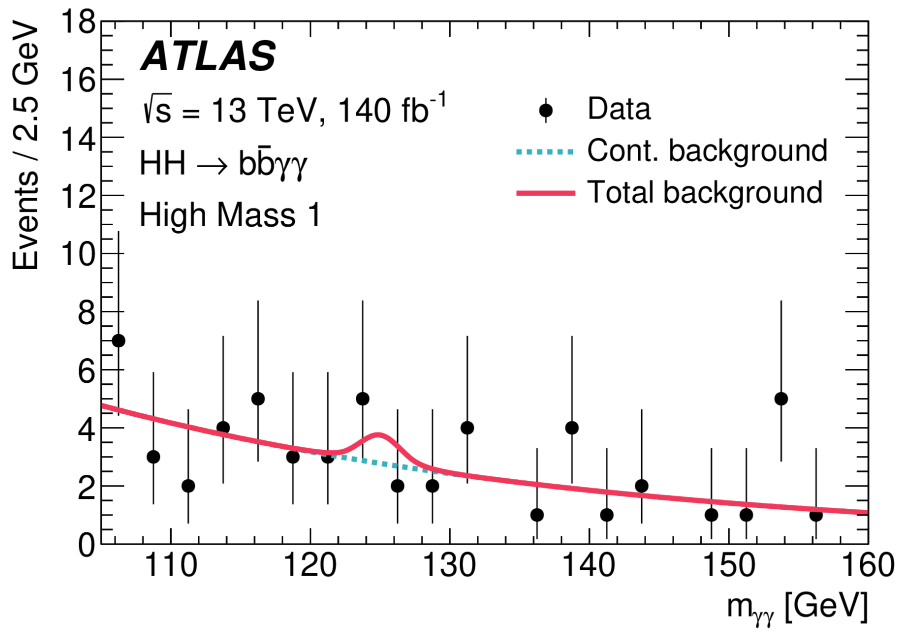
- CMS released HH→bbWW search result (with significant improvement from the partial run-2 result)

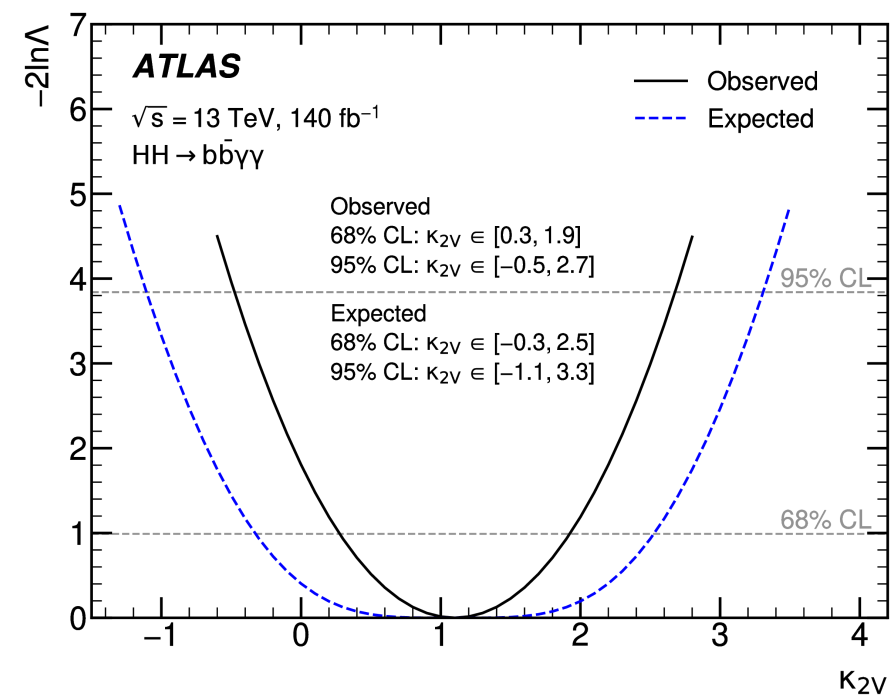
ATLAS HH→bbγγ

arxiv:2310.12301









- ATLAS reoptimize HH→bbγγ to optimize both HHH and HHVV couplings