Effective field theory interpretations at the Large Hadron Collider

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on behalf of ATLAS and CMS Collaborations

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ATLAS EXPERIMENT

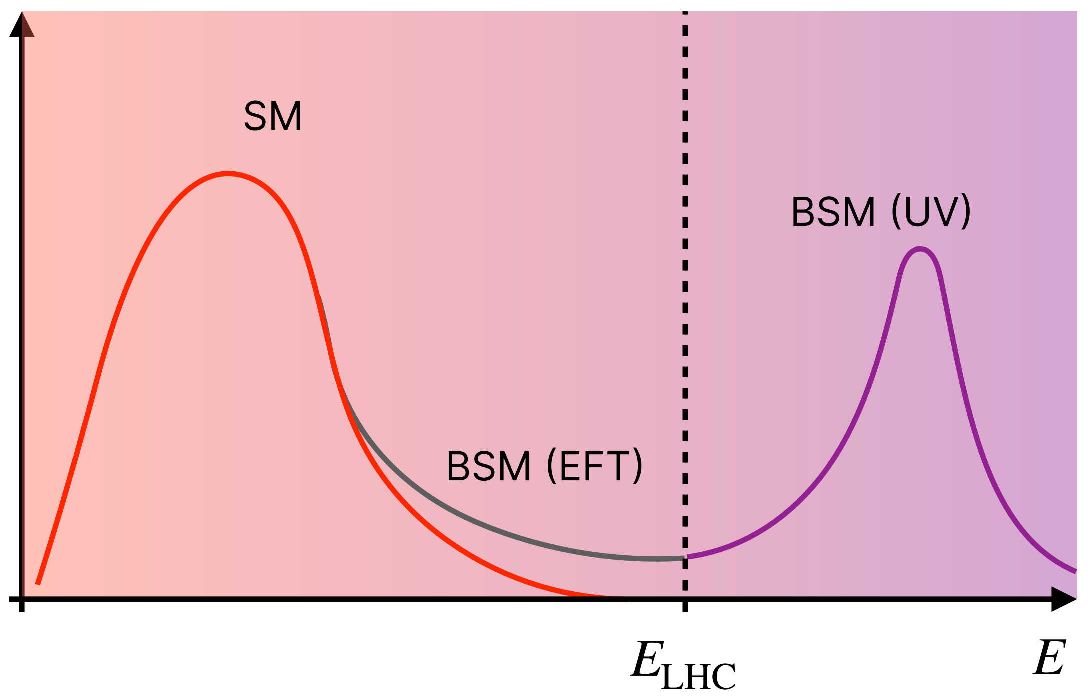
CMS

Physics at the Large Hadron Collider

- LHC is a powerful probe into high energy physics.
  - Measurements of Standard Model (SM) processes.
  - Searches for rare SM processes.
  - Searches for Beyond-SM (BSM) phenomena.
    - No direct observation reported by ATLAS & CMS.

Effective Field Theory frameworks

- Possible that BSM resonances are out of LHC reach.
- BSM physics at accessible energies described by EFT.
- Reduces to SM at low-energy.



Linear EFT

Standard Model Effective Field Theory (SMEFT)

- BSM phenomena as perturbations around SM:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \sum_{i,d>4} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- Expansion around (E/Λ).
  - E : energy scale of process.
  - Λ : BSM resonance mass scale.

Non-linear EFT

Higgs Effective Field Theory (HEFT)

- Higgs as a pseudo-Goldstone boson:

$$\mathcal{L}_{\text{HEFT}} = \mathcal{L}^{(4)} + \mathcal{L}_{Uh}$$

- Expansion around $(v/\Lambda)^2$.
  - $v = 246$ GeV : electroweak scale.

- Higher-dimension operators $\mathcal{O}_i$ consist of SM fields.
- Wilson coefficients (WC) c_i are free parameters.

Effective Field Theory frameworks

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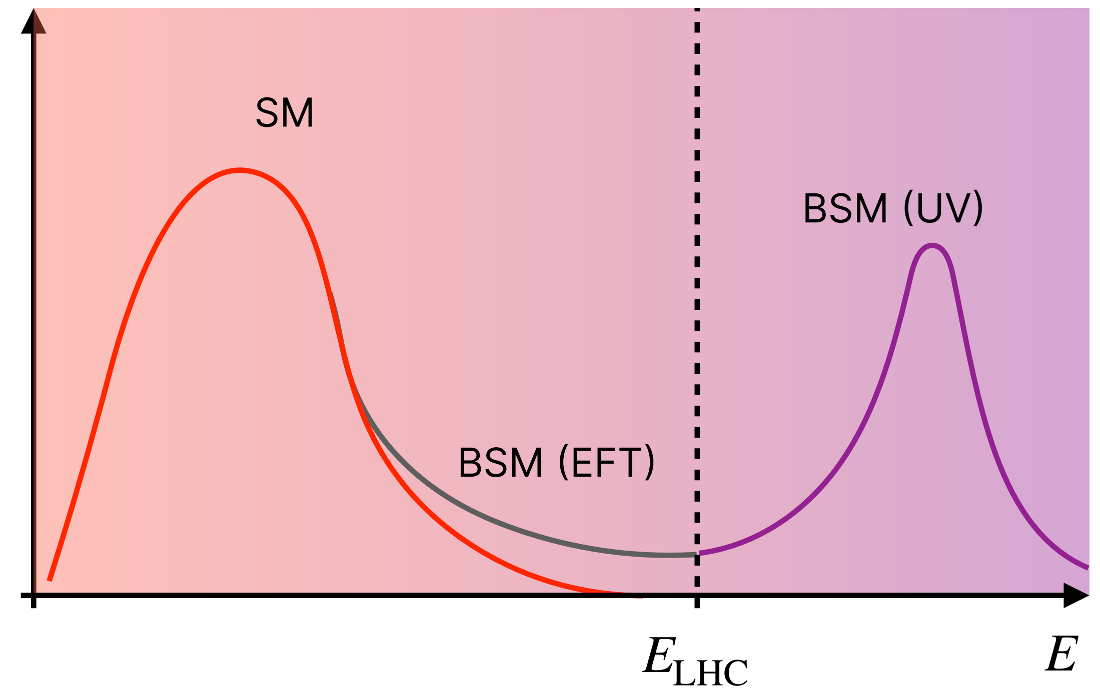


Linear EFT

Standard Model Effective Field Theory (SMEFT)

- Physical amplitudes:

$$|\mathcal{A}_{\text{SMEFT}}|^2 = |\mathcal{A}_{\text{SM}}|^2 + \sum_i \frac{c_i}{\Lambda^2} 2\text{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\text{SM}}^*\right) + \sum_{i,j} \frac{c_i c_j}{\Lambda^4}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right) + \sum_k \frac{c_k}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_i^{(8)} \mathcal{A}_{\text{SM}}^*\right) + \cdots$$

- $d = 6$: Warsaw basis.
- $d = 8$: Select operators identified.
  - Interference same Λ-order as $d = 6$ BSM.

Non-linear EFT

Higgs Effective Field Theory (HEFT)

- Higgs coupling:

$$\mathcal{F}_i\left(\frac{h}{v}\right) = 1 + \sum_{n=1}^{\infty} a_n \left(\frac{h}{v}\right)^n$$

- Couplings among different numbers of Higgs independent.

From measurements to interpretations

- Measurement/limits on **physical observable → Wilson coefficient** constraint.

$$\left\{ \begin{matrix} \sigma_{pp\to a} \\ \left(\frac{\mathrm{d}\sigma_{pp\to b}}{\mathrm{d}x}\right) \\ \vdots \end{matrix} \right\} \longmapsto \{c_i\}_{i=1,\ldots,N}$$

Measurement-side
Need more and more precise measurements.
- Differential information enhances sensitivity.
- Combination of multiple measurements.
- Parton/particle/detector-level?

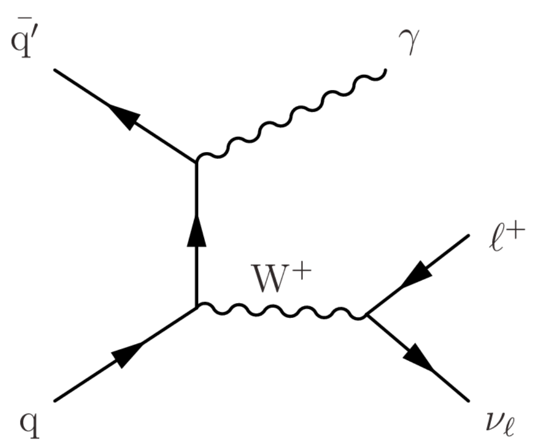
Interpretation-side
Many free parameters.
- Reduced by additional symmetry assumptions.
- Only a subset usually relevant for a process.
- One-at-a-time vs. simultaneous constraints.

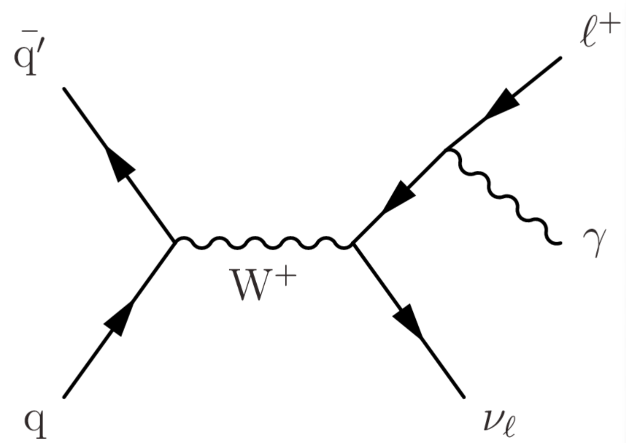
Presented in this talk
EFT interpretations performed by ATLAS and CMS Collaborations.
- Only select results.
- Limited details on analysis techniques.

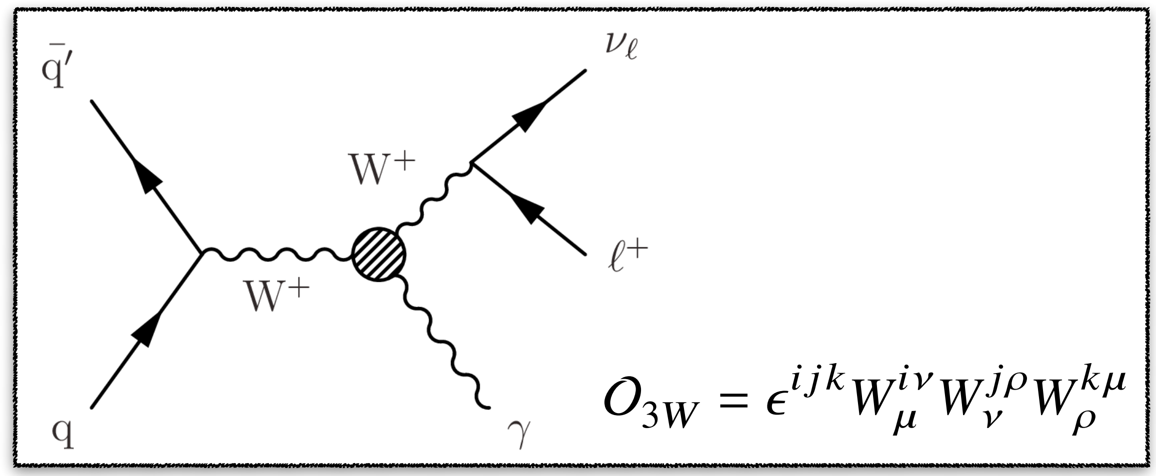
$W^{\pm}\gamma$ differential cross-section

PhysRevD.105.052003

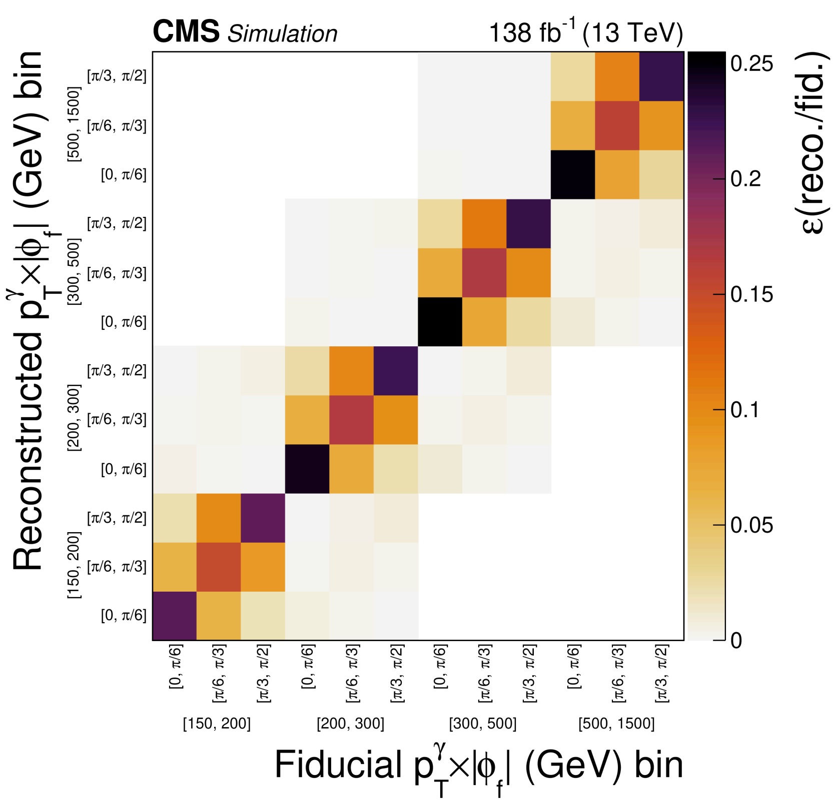
- Vector boson pair production sensitive to presence of anomalous triple gauge coupling (aTGC).
- SMEFT operator: CP-even modification of TGC.

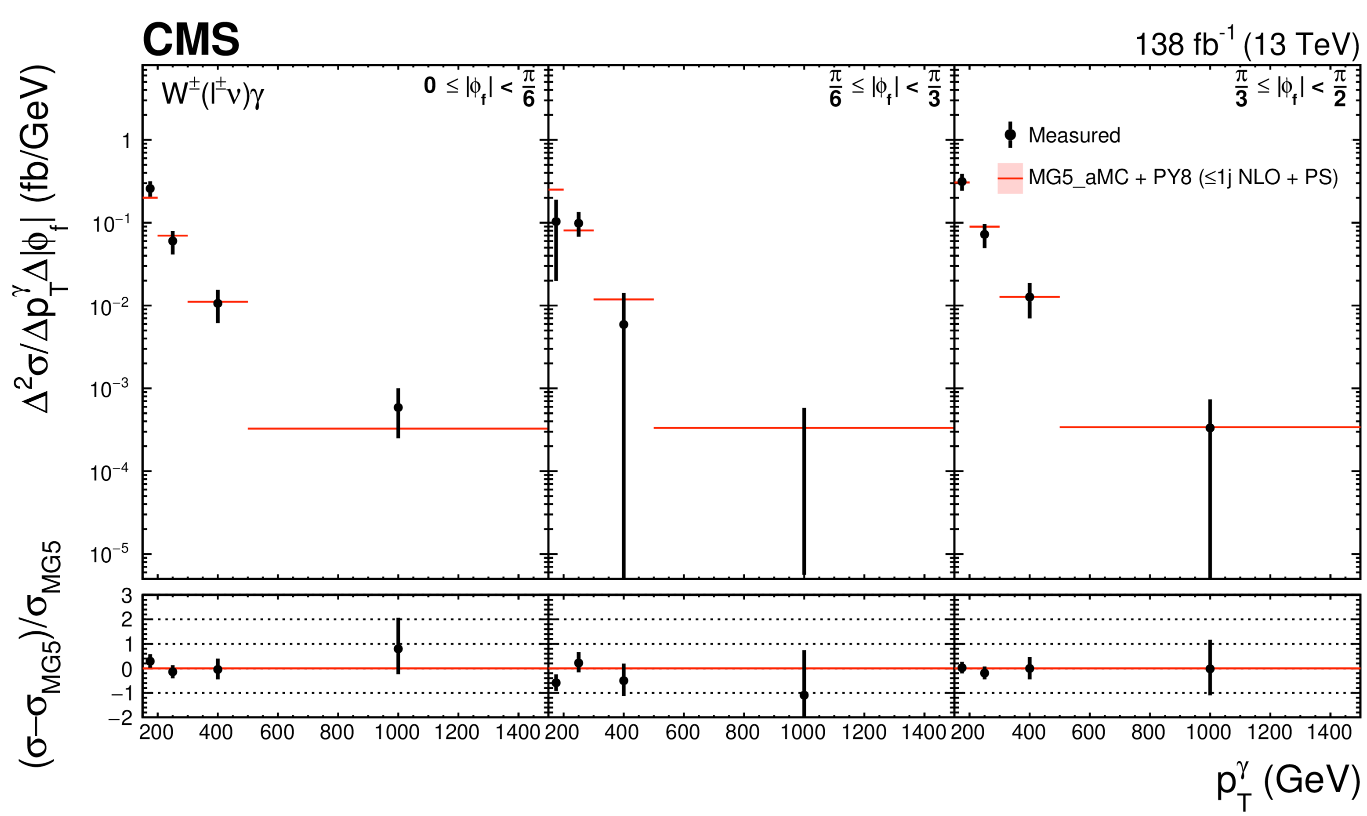






- Particle-level cross-section measured by unfolding detector effects.
- $(p_T^\gamma, |\phi_f|)$-differential spectrum provides sensitivity to interference effects.





$W^{\pm}\gamma$ differential cross-section

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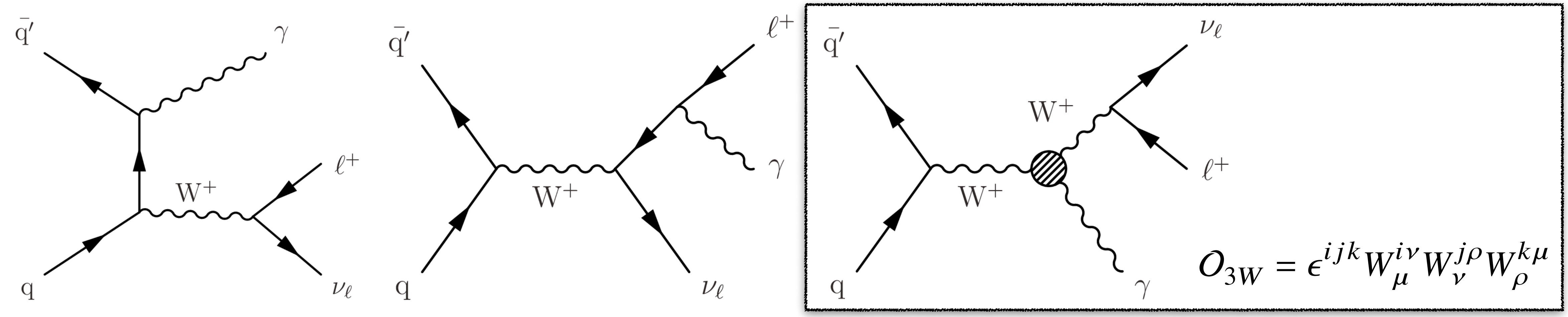
- SMEFT operator: CP-even modification of TGC.

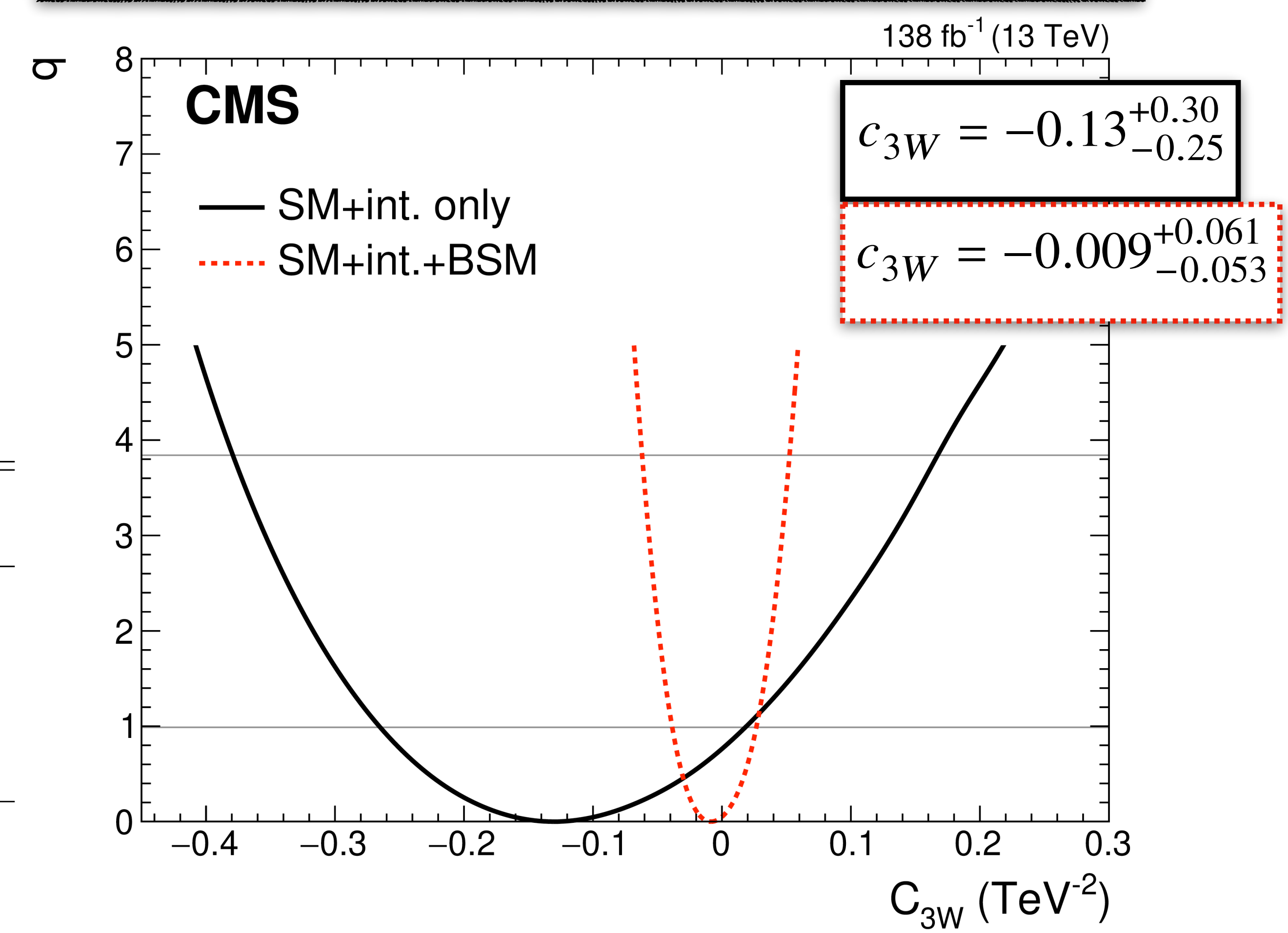


- Signal strength parametrization:

$$\sigma(c_{3W}) = \sigma_{\mathrm{SM}} + c_{3W}\sigma_{\mathrm{int}} + c_{3W}^2\sigma_{\mathrm{BSM}},$$

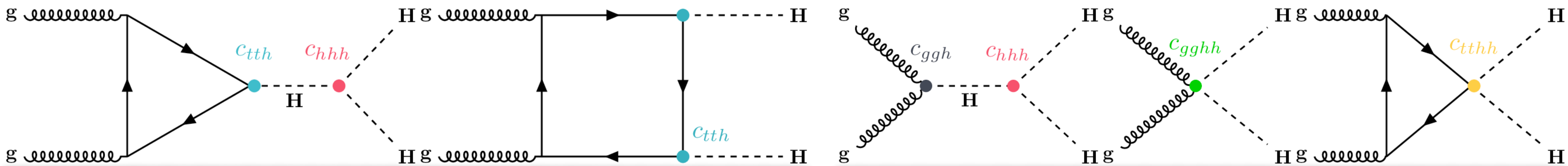
$$\mu(c_{3W}) = 1 + c_{3W}\left(\frac{\sigma_{\mathrm{int}}}{\sigma_{\mathrm{SM}}}\right) + c_{3W}^2\left(\frac{\sigma_{\mathrm{BSM}}}{\sigma_{\mathrm{SM}}}\right)$$

p_T^γ bin (GeV)	$0 \le \lvert\phi_f\rvert < \pi/6$		$\pi/6 \le \lvert\phi_f\rvert < \pi/3$		$\pi/3 \le \lvert\phi_f\rvert < \pi/2$	
	μ^{int}	μ^{BSM}	μ^{int}	μ^{BSM}	μ^{int}	μ^{BSM}
150–200	−0.19	0.52	0.03	0.50	0.23	0.44
200–300	−0.38	2.5	0.02	2.1	0.43	1.9
300–500	−0.95	10.7	0.06	10.3	1.0	11.0
500–800	−2.2	83.0	0.07	82.5	2.4	81.6
800–1500	−4.9	688.5	0.02	651.7	4.9	646.2



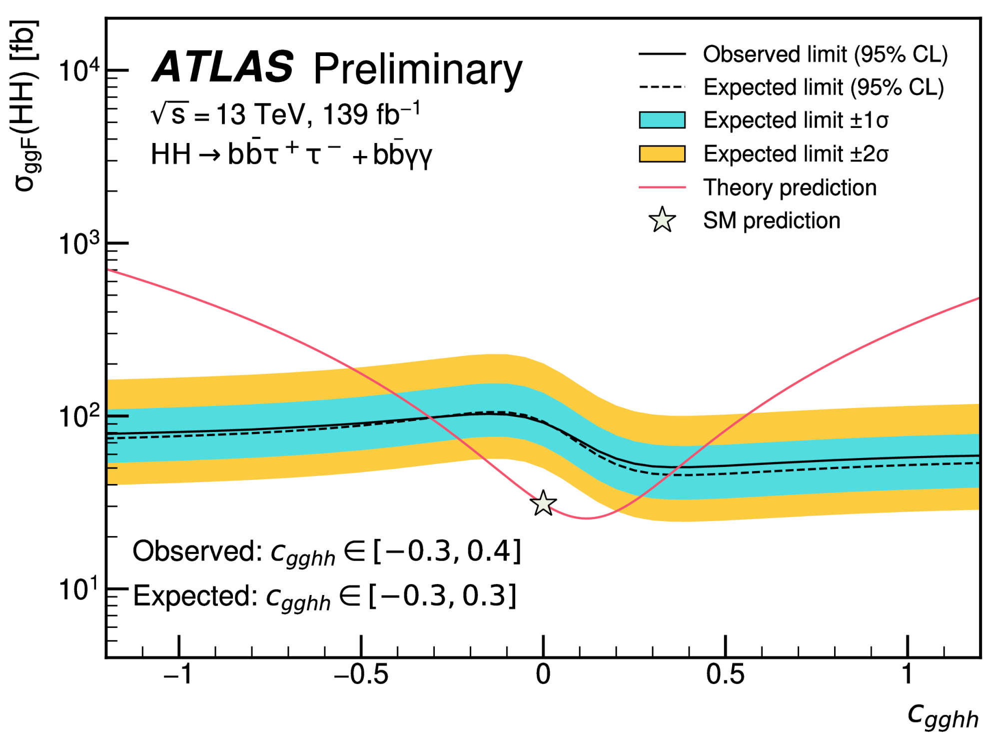
$HH \to bb\tau\tau, bb\gamma\gamma$ searches

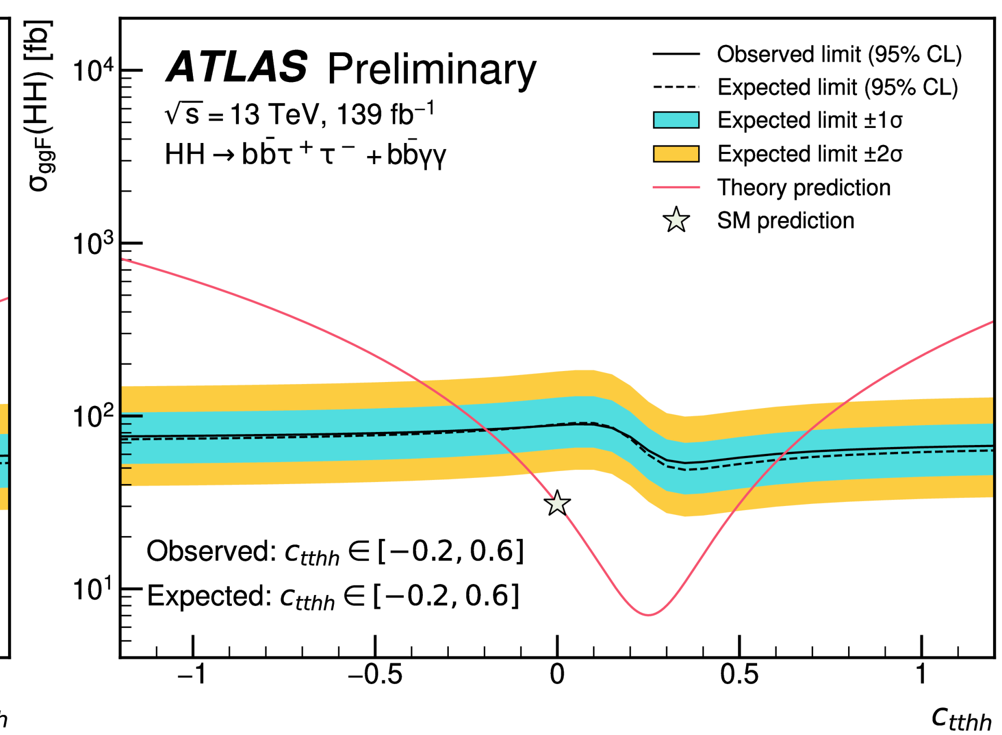
- Upper limit on Higgs pair production via gluon-fusion in $HH \to bb\tau\tau, bb\gamma\gamma$ decay channels.
  - HH uniquely sensitive to double-Higgs couplings c_{gghh} & c_{tthh}, de-correlated from others $(c_{tth}, c_{hhh}, c_{ggh})$ under HEFT.



SM-like	BSM
SM: $c_{tth}, c_{hhh} = 1$	SM: $c_{ggh}, c_{gghh}, c_{tthh} = 0$

- Existing limits on $\kappa_\lambda (\equiv c_{hhh}) \in (-1.0, 6.6)^{\text{exp}}, (-1.2, 7.2)^{\text{obs}}$ [ATLAS-CONF-2021-052]
- Constrain c_{gghh} & c_{tthh} with $(c_{tth}, c_{hhh}, c_{ggh})_{\text{SM}}$ fixed (one-at-a-time).

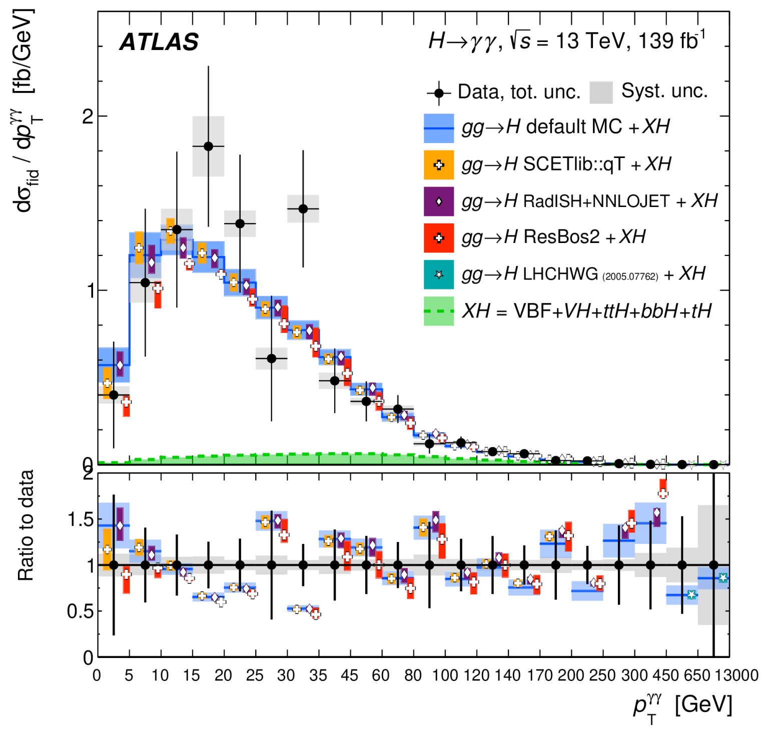


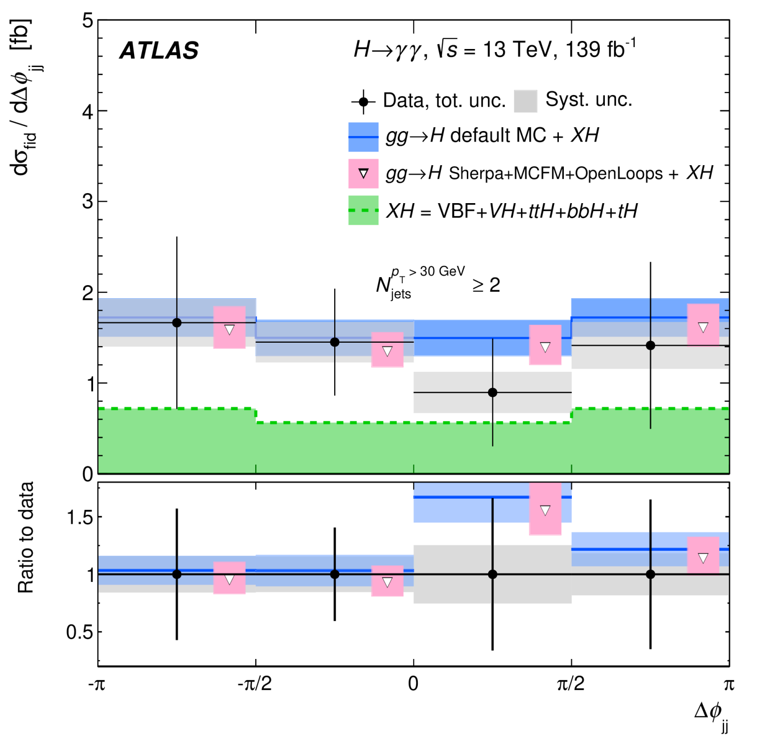


$H \to \gamma\gamma$ differential cross-section

JHEP08(2022)027

- Differential observables: $p_T^{\gamma\gamma}, N_{\text{jet}}, p_T^{j1}, m_{jj}, \Delta\phi_{jj}$.





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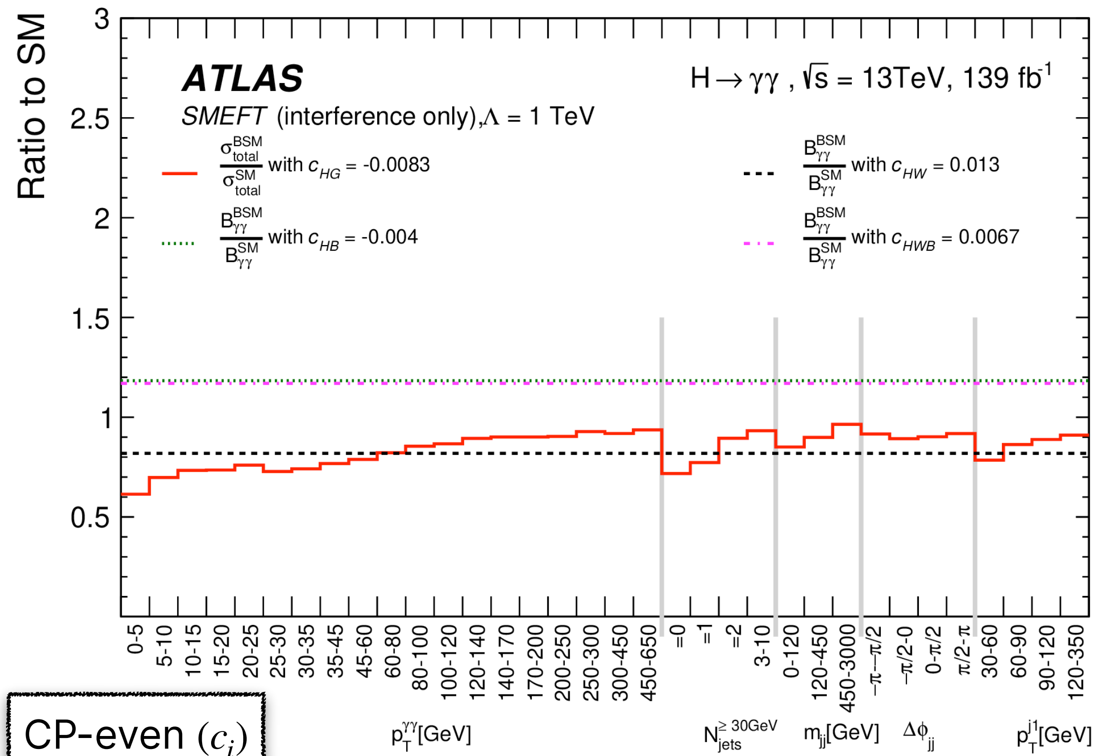
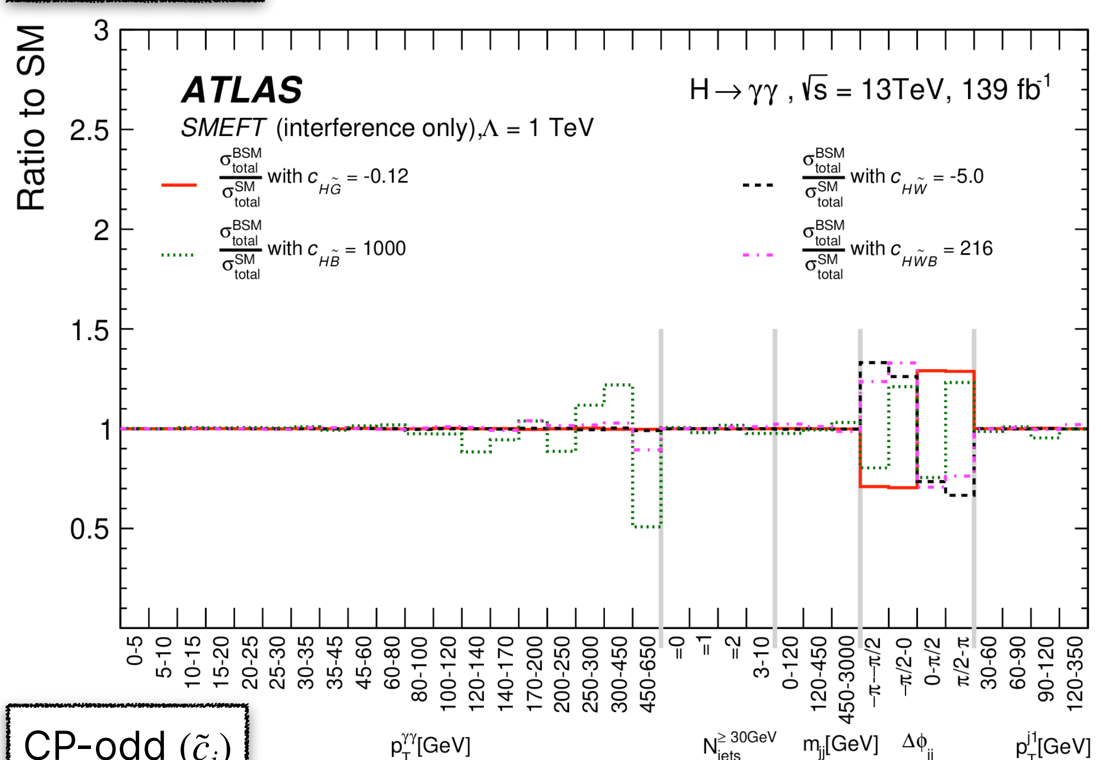


CP-even (c_i)



CP-odd ($\tilde{c}_i$)

$H \rightarrow \gamma\gamma$ differential cross-section

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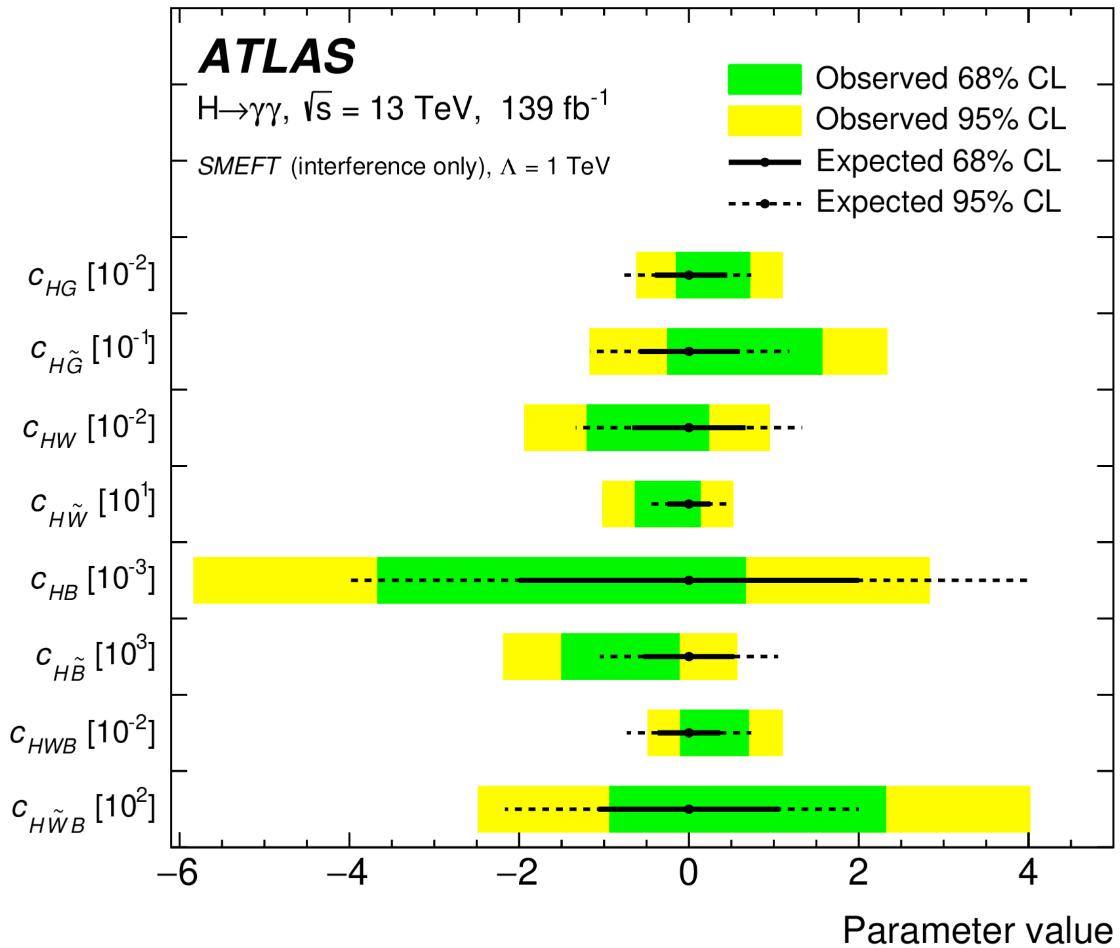
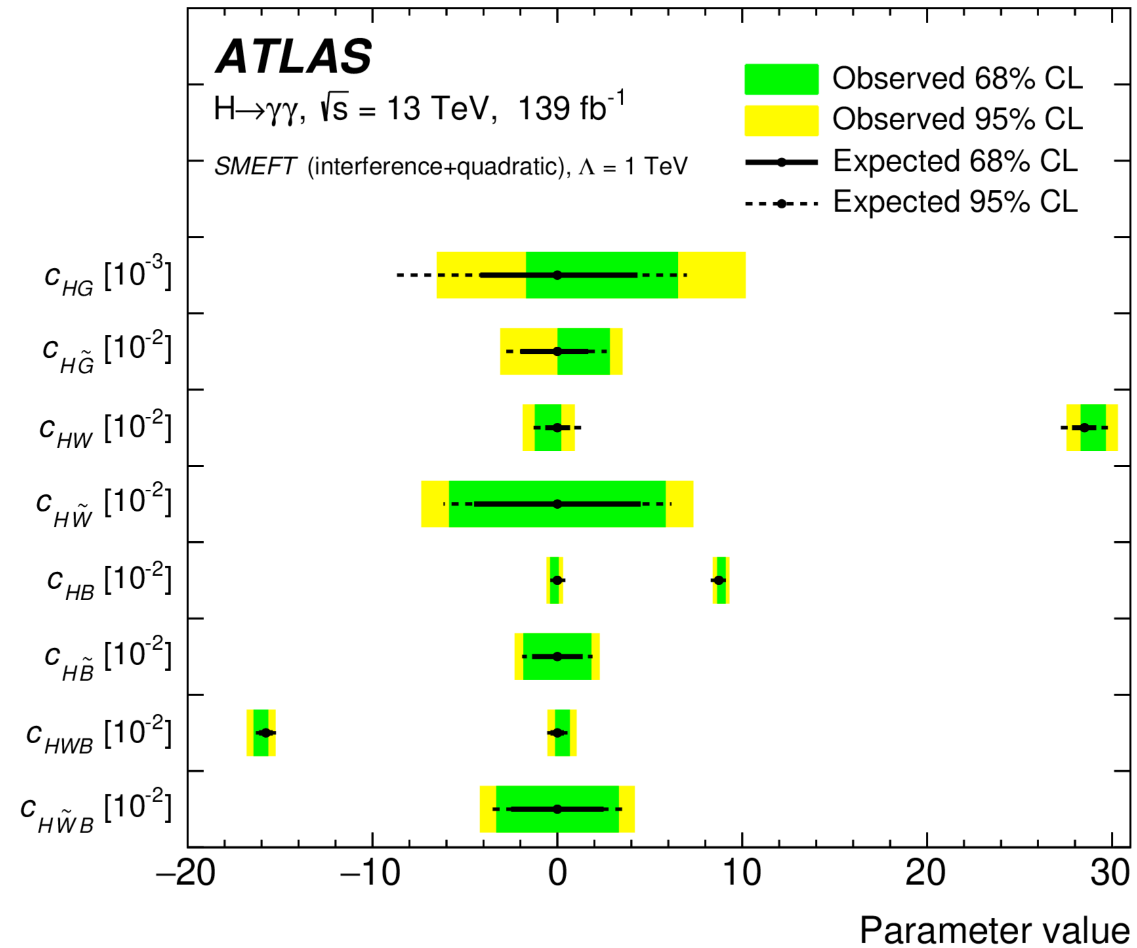
- CP-even & -odd WCs constrained (one-at-a-time).



Interference

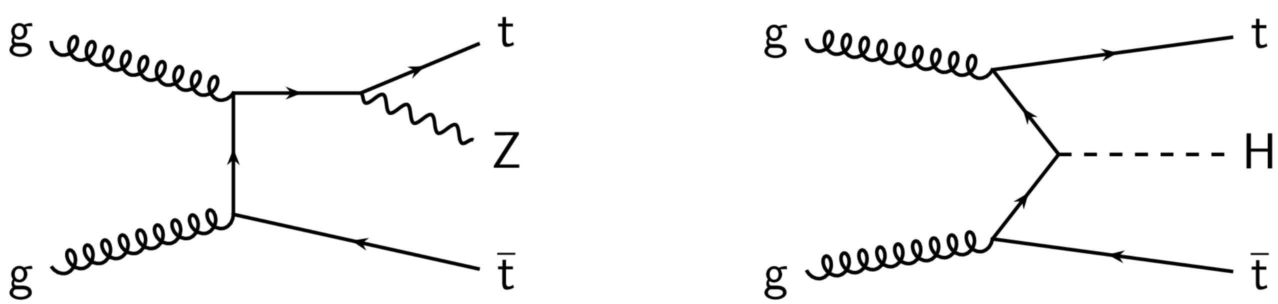


Interference+BSM

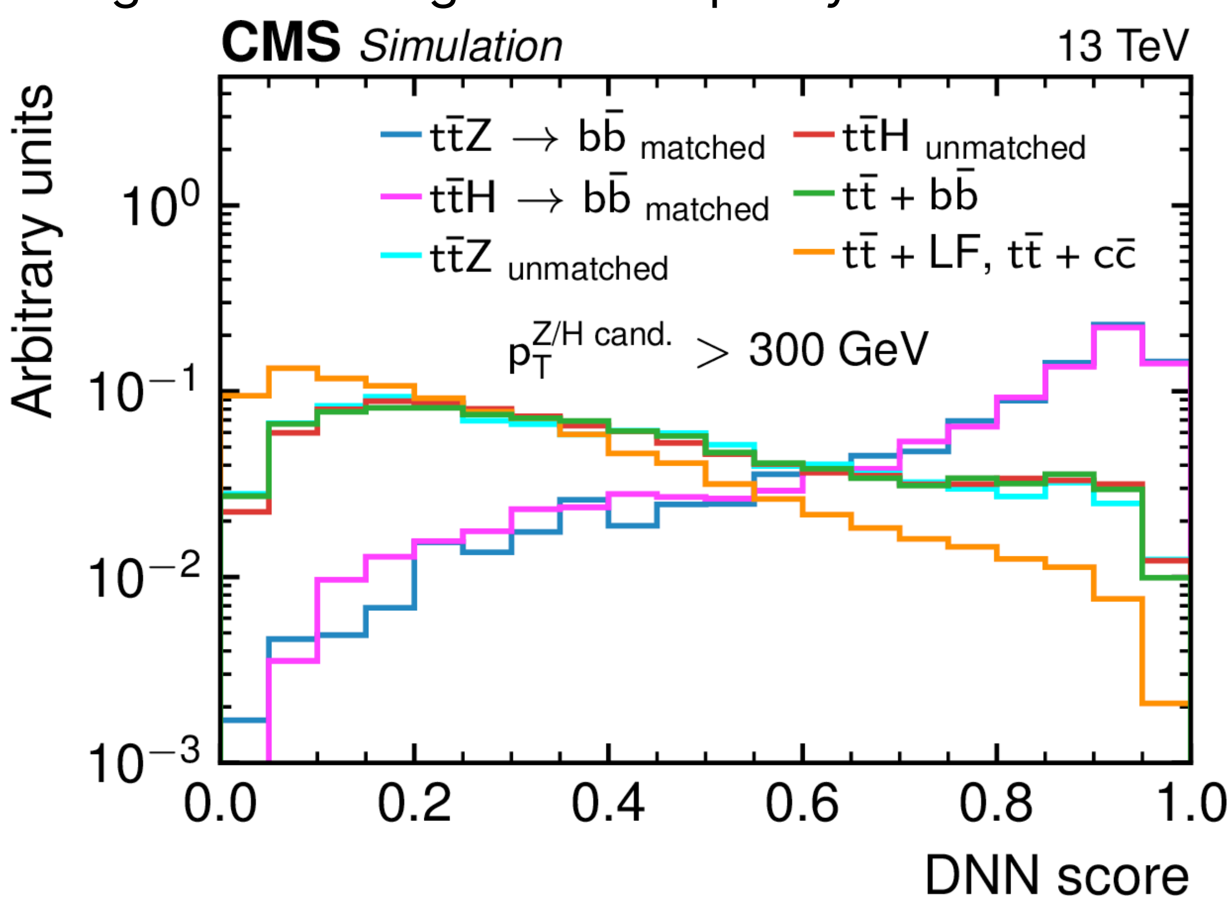
Top quark pair + boosted *Z/H*

arXiv:2208.12837

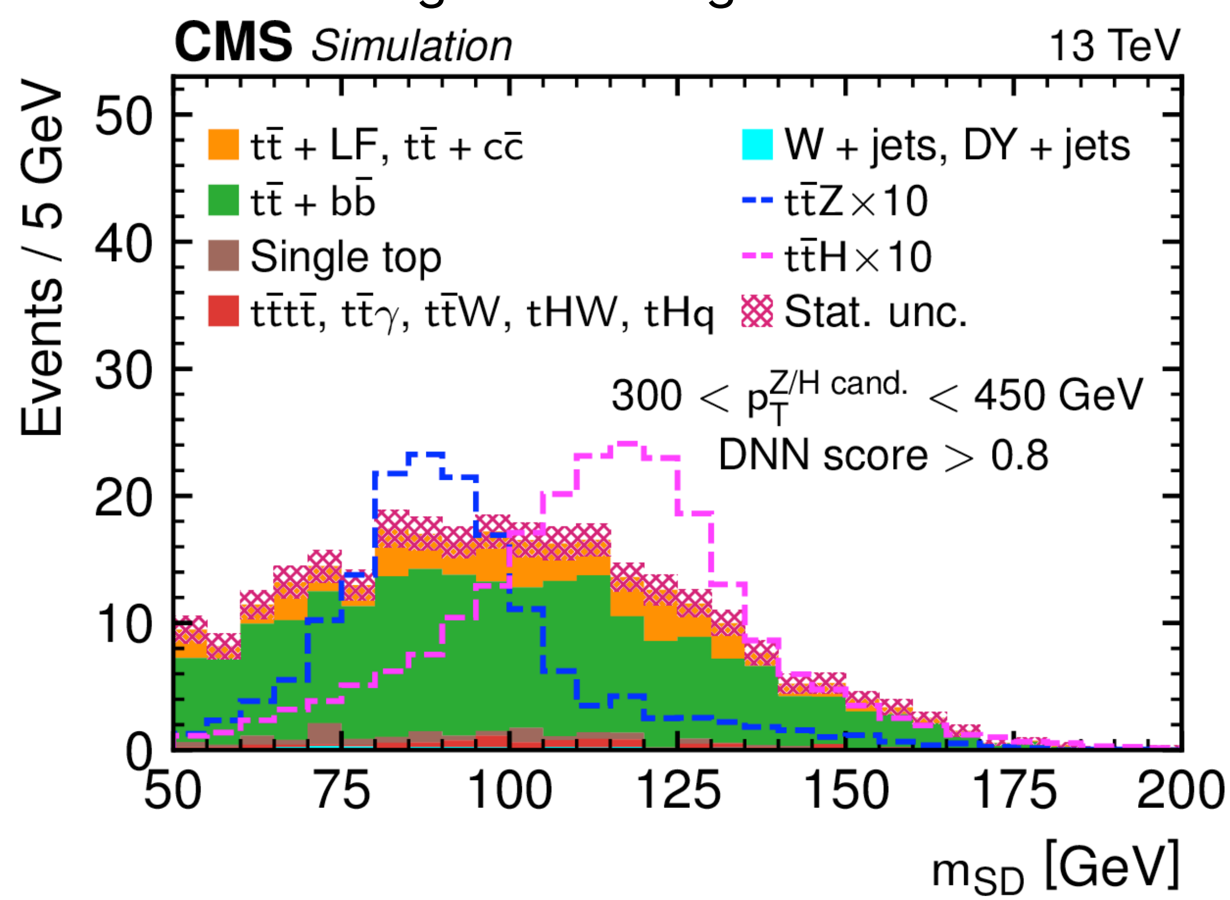
- Measurement of $t\bar{t} + Z/H$ with high p_{T}.
  - One large-radius, $b\bar{b}$-tagged jet from Z/H.
  - Jets from $t\bar{t}$.
  - One e/μ, presence of $p_{\mathrm{T}}^{\mathrm{miss}}$ from W.



- Deep neural network used to obtain signal regions with high $t\bar{t} + Z/H$ purity.



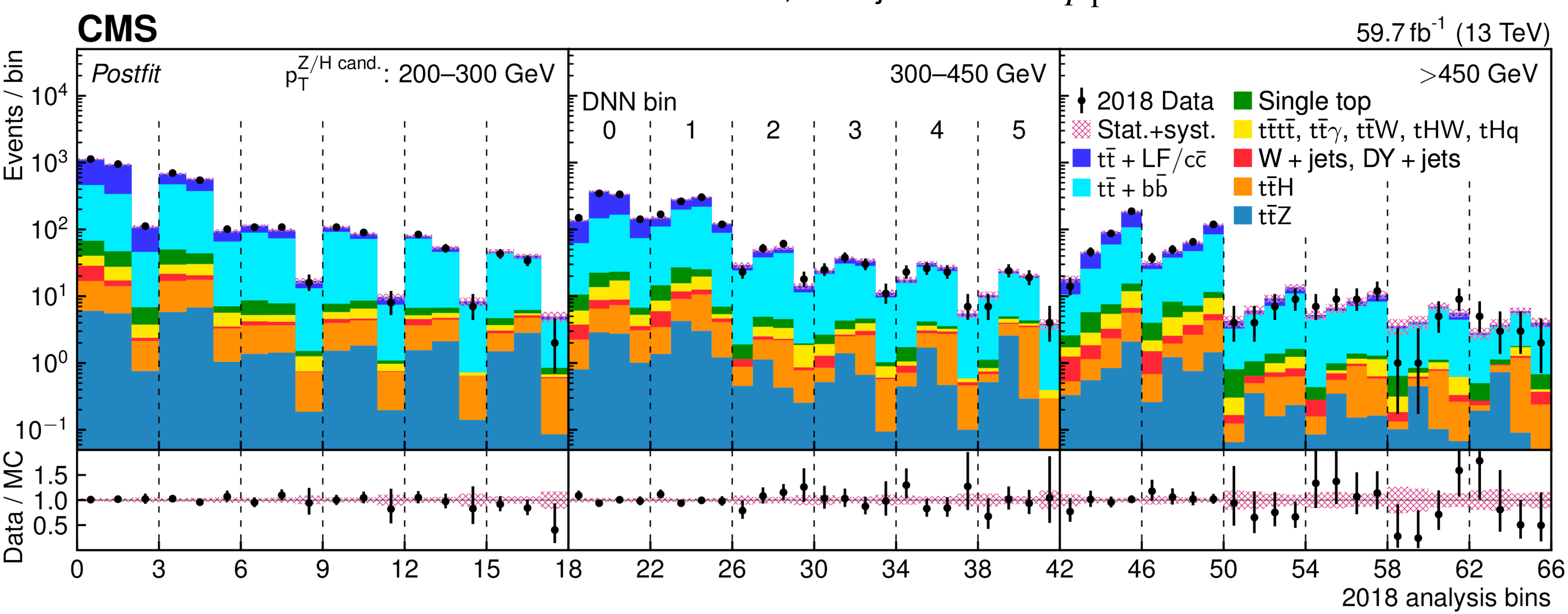
- Z/H jet mass windows used to further discriminate against backgrounds.



Top quark pair + boosted Z/H

arXiv:2208.12837

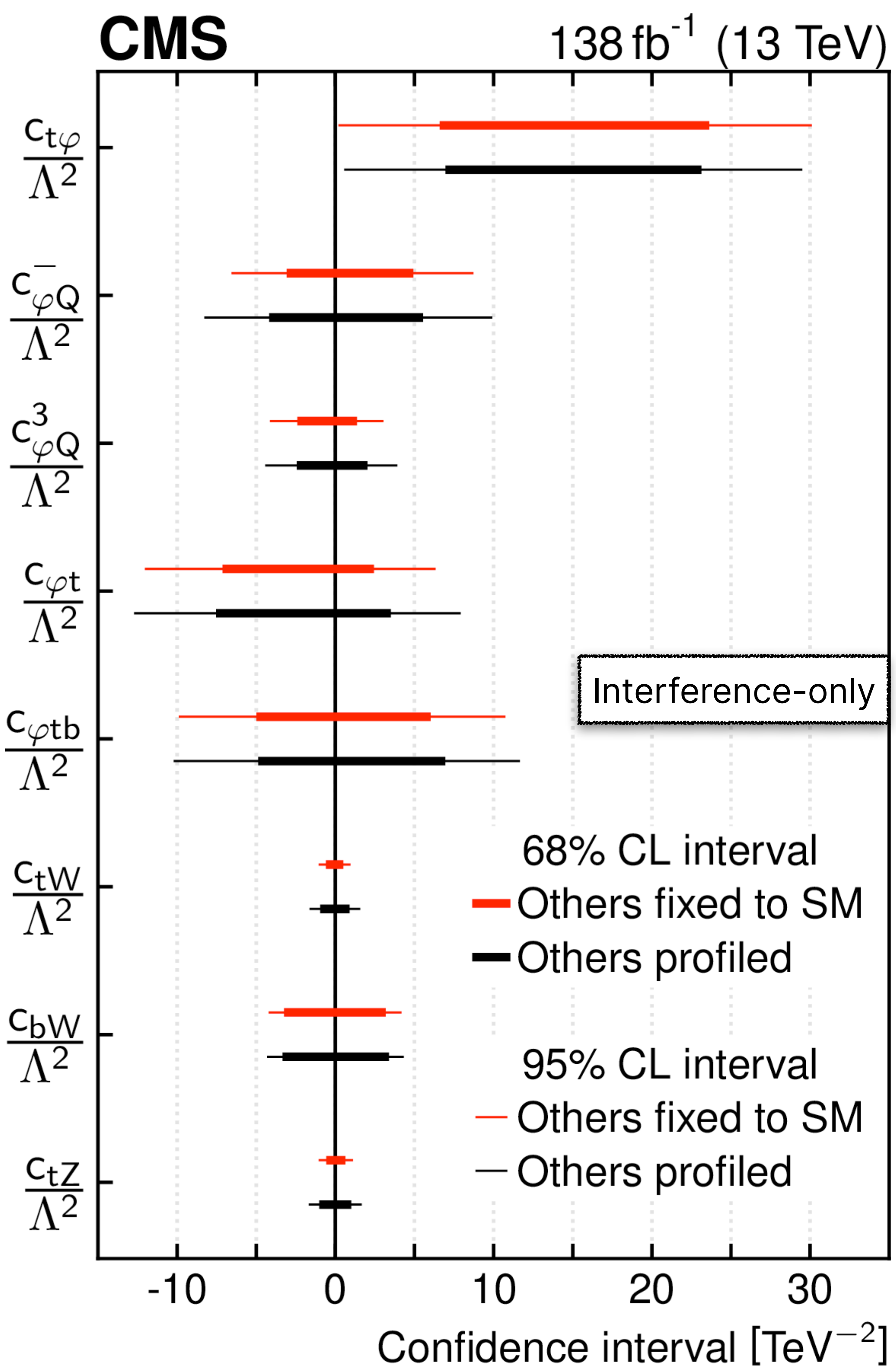
- Differential cross-section as a function of NN score, Z/H jet mass and p_{T}.



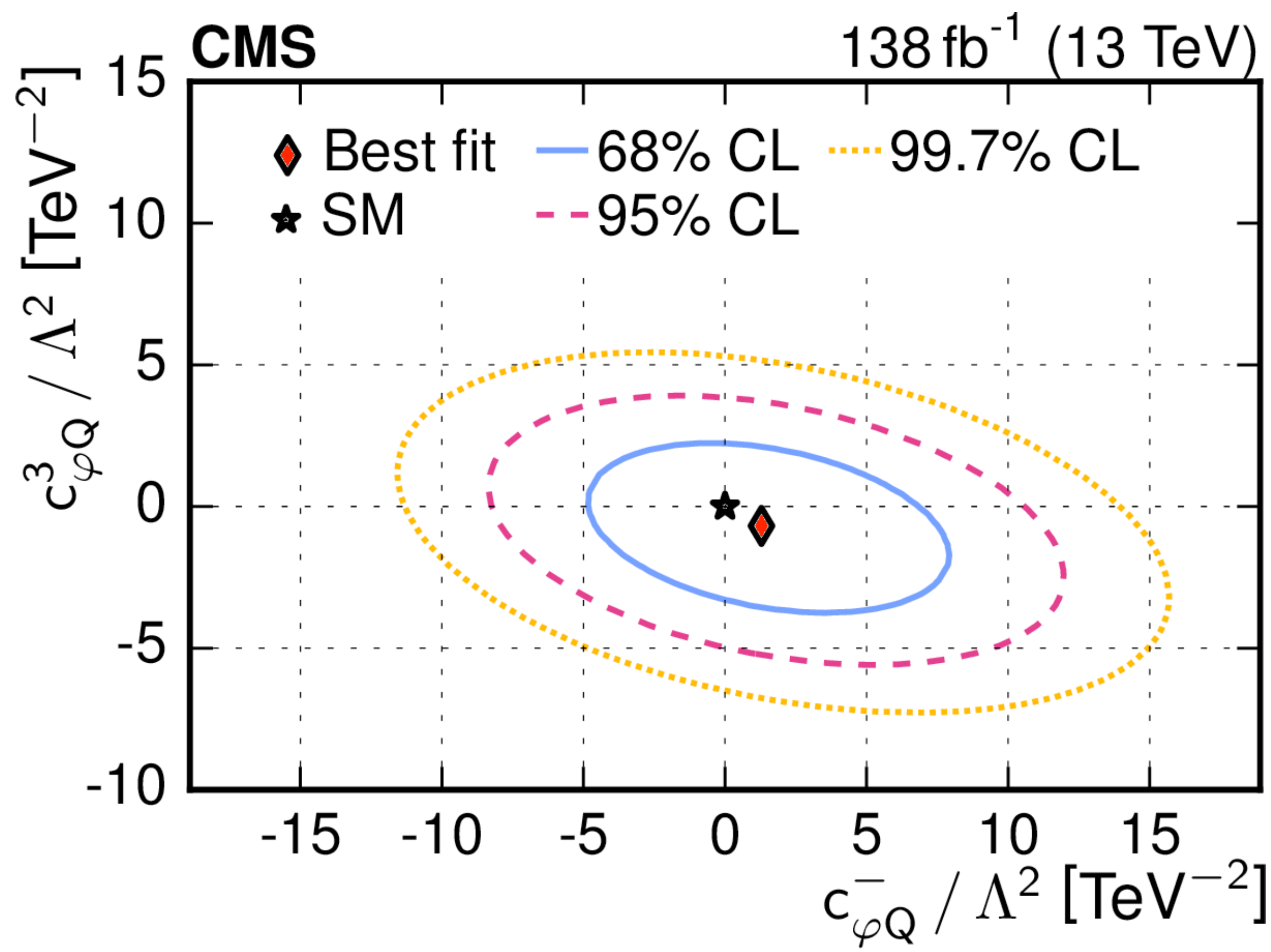
- Both $t\bar{t}+Z/H$ signal & $t\bar{t}+b\bar{b}$ background varied with WCs, with detector effects accounted for in simulation.

Top quark pair + boosted *Z*/*H*

arXiv:2208.12837



- Constrain 8 SMEFT WCs.



- Simultaneous & 1D limits comparable due to absence of significant correlations.

Higgs + Electroweak combination

ATL-PHYS-PUB-2022-037

ATLAS Higgs STXS + ATLAS Electroweak + LEP/SLD EW Precision Observables

Complementary measurements

Combined SMEFT interpretation

Group	Wilson coefficient	Operator	LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
Individual	c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$		✓	
	c_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$		✓	✓
	c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		✓	
	c_{bH}	$(H^\dagger H)(\bar{Q} H b)$		✓	
	c_{tH}	$(H^\dagger H)(\bar{Q} \tilde{H} t)$		✓	
	c_{tG}	$(\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{H}\, G^A_{\mu\nu}$		✓	
Higgs overall rate	$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	
	c_{uH}	$(H^\dagger H)(\bar{q} Y_u^\dagger u \tilde{H})$		✓	
2-lepton, 2-quark	$c_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$			✓
	$c_{lq}^{(3)}$	$(\bar{l}\gamma_\mu \tau^I l)(\bar{q}\gamma^\mu \tau^I q)$			✓
	c_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$			✓
	c_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$			✓
	c_{lu}	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$			✓
	c_{ld}	$(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$			✓
	c_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$			✓
Top quark couplings	c_G	$f^{abc} G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho$		✓	✓
	$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$		✓	
	$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$		✓	
	$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$		✓	
	$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$		✓	
	$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$		✓	
	$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$		✓	
	$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$		✓	
	$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$		✓	
	$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$		✓	
	$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$		✓	
	$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$		✓	

Group	Wilson coefficient	Operator	LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
4-light-quark	$c_{qq}^{(1,1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$			✓
	$c_{qq}^{(1,8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$			✓
	$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$			✓
	$c_{qq}^{(3,8)}$	$(\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$			✓
	$c_{uu}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$			✓
	$c_{uu}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$			✓
	$c_{dd}^{(1)}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$			✓
	$c_{dd}^{(8)}$	$(\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$			✓
	$c_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$			✓
	$c_{ud}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$			✓
	$c_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$			✓
	$c_{qu}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$			✓
	$c_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$			✓
	$c_{qd}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$			✓
$H \to \gamma\gamma + \mathrm{EWPO}$	c_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$		✓	✓
	c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		✓	
	c_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$		✓	
	c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	✓	✓	✓
	$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓
	$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓
	c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	✓	✓	✓
	$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓
	$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓
	c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓
	c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓
	$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	✓	✓	
	$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$	✓	✓	
	c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	✓		
	c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	✓	✓	
	c_{tW}	$(\bar{Q}\sigma^{\mu\nu} t)\tau^I \tilde{H}\, W^I_{\mu\nu}$		✓	
	c_{tB}	$(\bar{Q}\sigma^{\mu\nu} t)\tilde{H}\, B_{\mu\nu}$		✓	
	c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓		✓

Higgs + Electroweak combination

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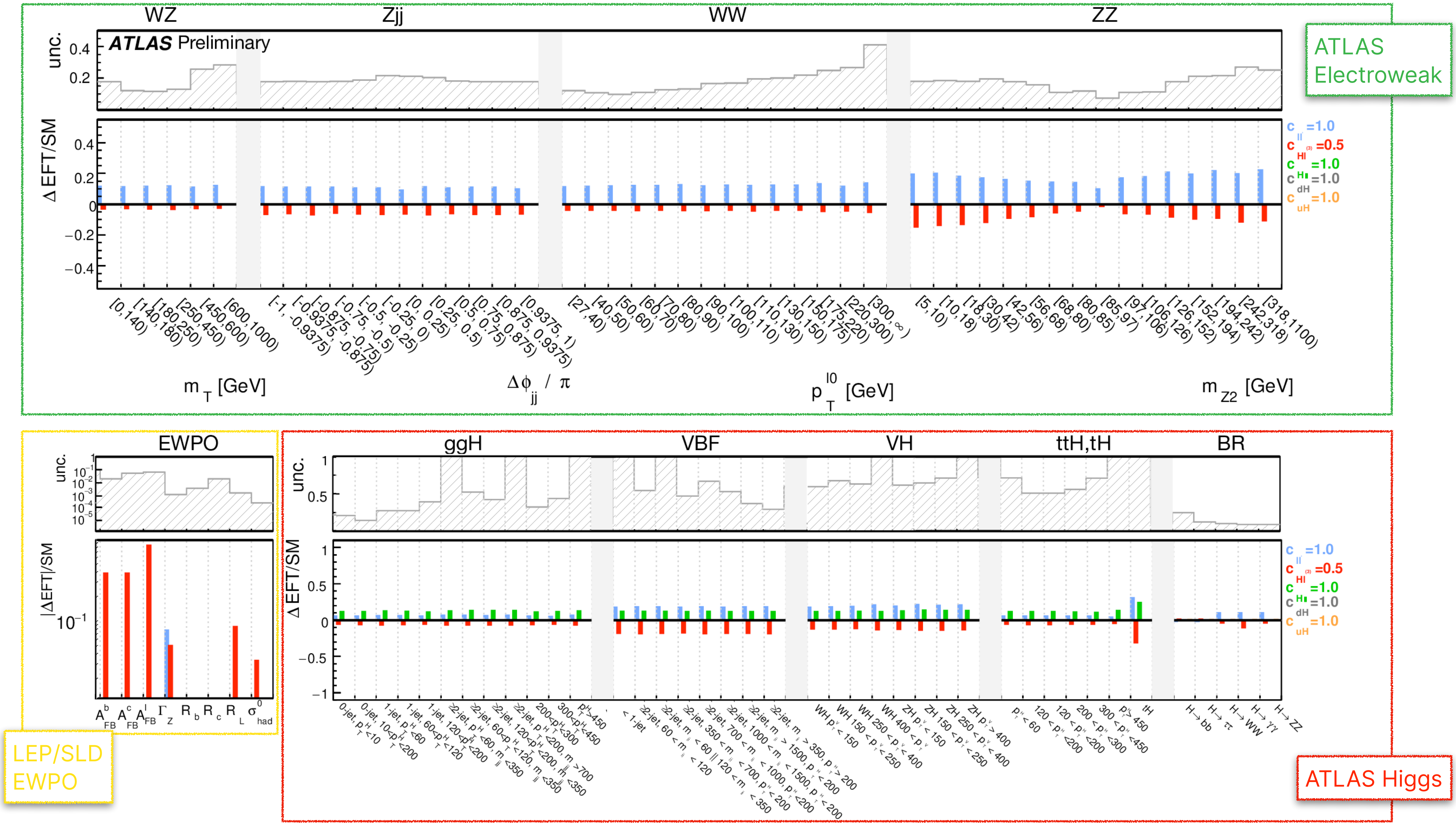
- Impact of select SMEFT WCs on different measurements.



Higgs + Electroweak combination

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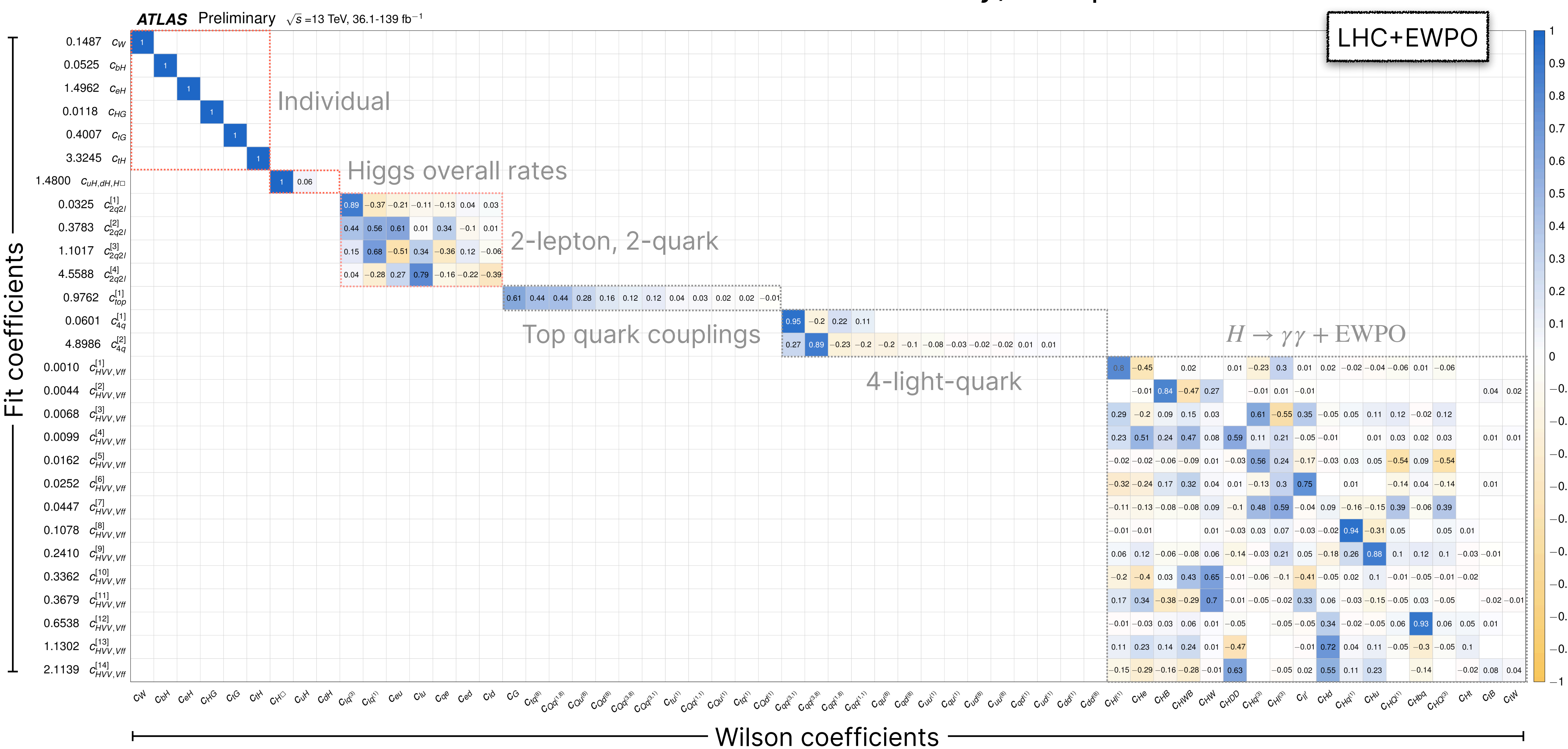
- Sensitivity optimized with Gaussian approximation:

$$H_{\text{SMEFT}} = A^{\text{T}} H_{\mu} A$$

  - A : SMEFT parametrization
  - H_{μ} : Signal strength information.
- 28(24) fit coefficients constrained in LHC+EWPO(ATLAS-only) interpretation.



Higgs + Electroweak combination

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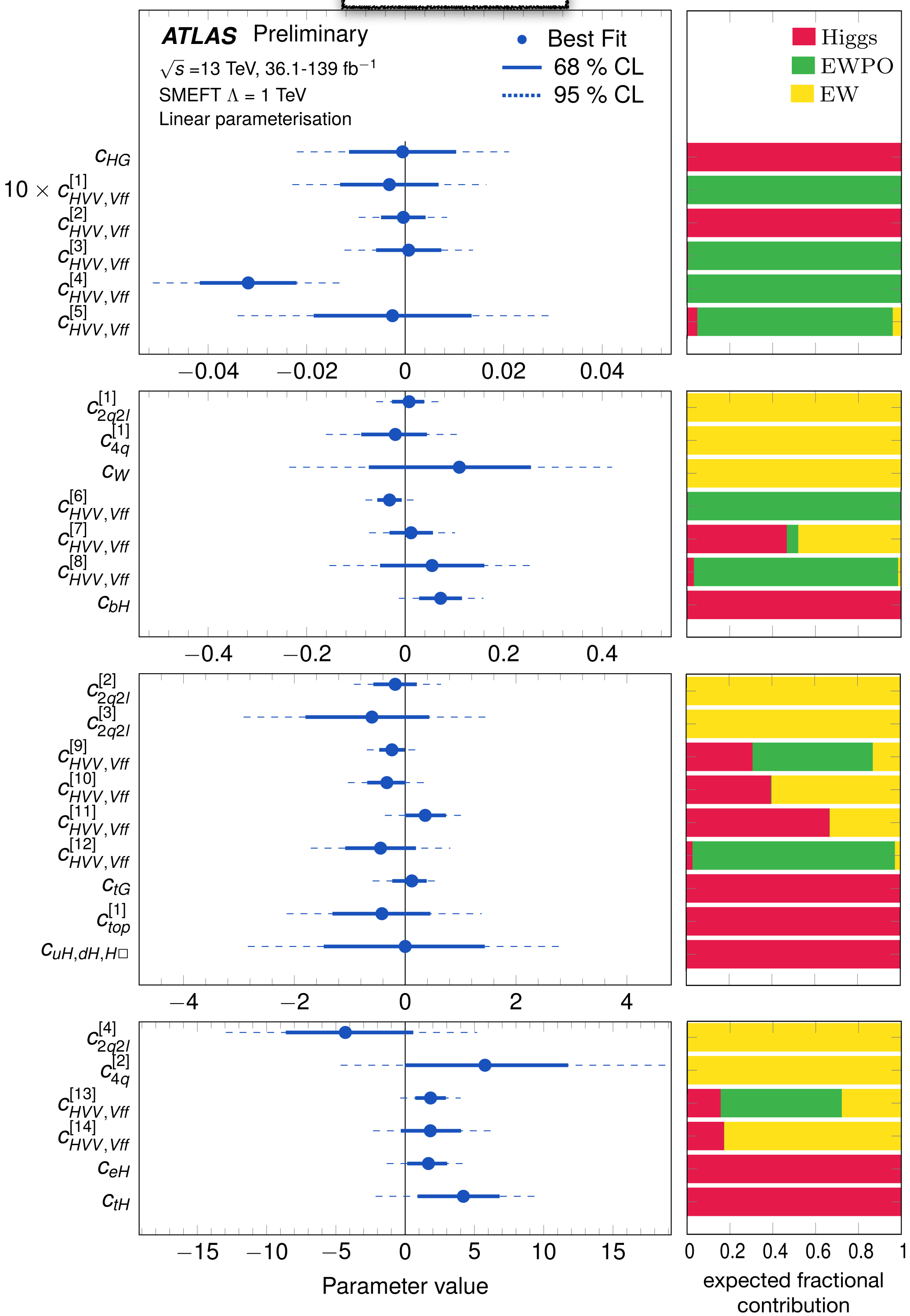
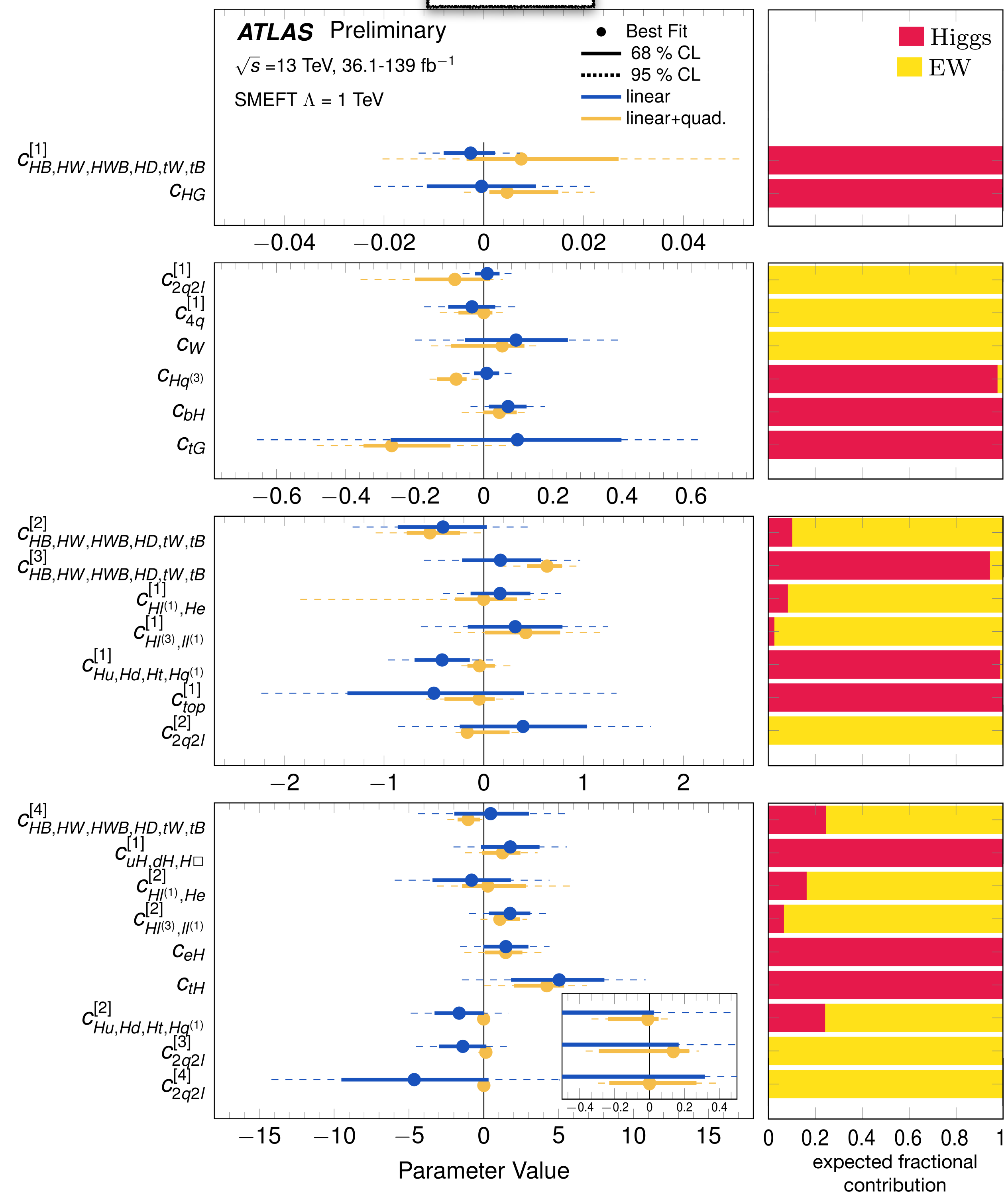
LHC+EWPO (Simplified likelihood model available)



LHC-only



Summary

- EFTs enable a theoretically consistent, systematic characterization of deviations from SM.
- Increasing body of interpretations from ATLAS & CMS.
- Future considerations:
  - Coherent treatment of EFT effects on background & signal processes.
  - Inclusion of more measurements & operators.
  - Availability of information for re-interpretations.
- All presented results consistent with the SM.
  - $W^{\pm}\gamma$ differential cross section: PhysRevD.105.052003
  - $HH \to bb\tau\tau, bb\gamma\gamma$ searches: ATL-PHYS-PUB-2022-019
  - $H \to \gamma\gamma$ differential cross-section: JHEP08(2022)027
  - Top quark pair + boosted *Z/H*: arXiv:2208.12837
  - Higgs+electroweak combination: ATL-PHYS-PUB-2022-037

Backup

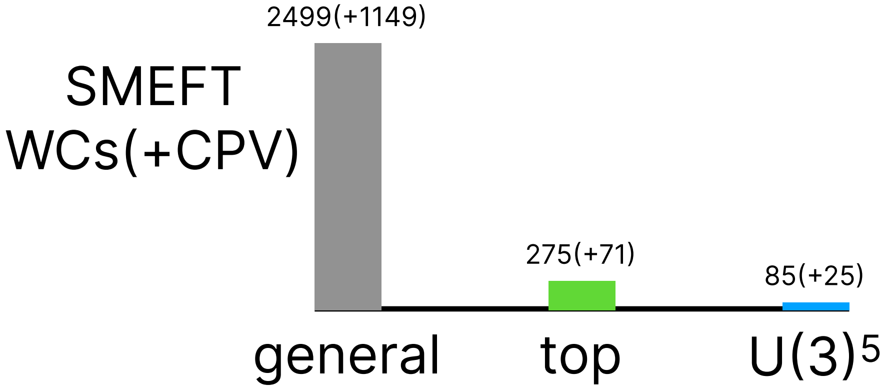
SMEFT

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r) \varepsilon_{jk} (\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r) \varepsilon_{jk} (\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jn} \varepsilon_{km} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r) \varepsilon_{jk} (\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} \left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar q_s^k \sigma^{\mu\nu} u_t)$				

Table 3: Four-fermion operators.

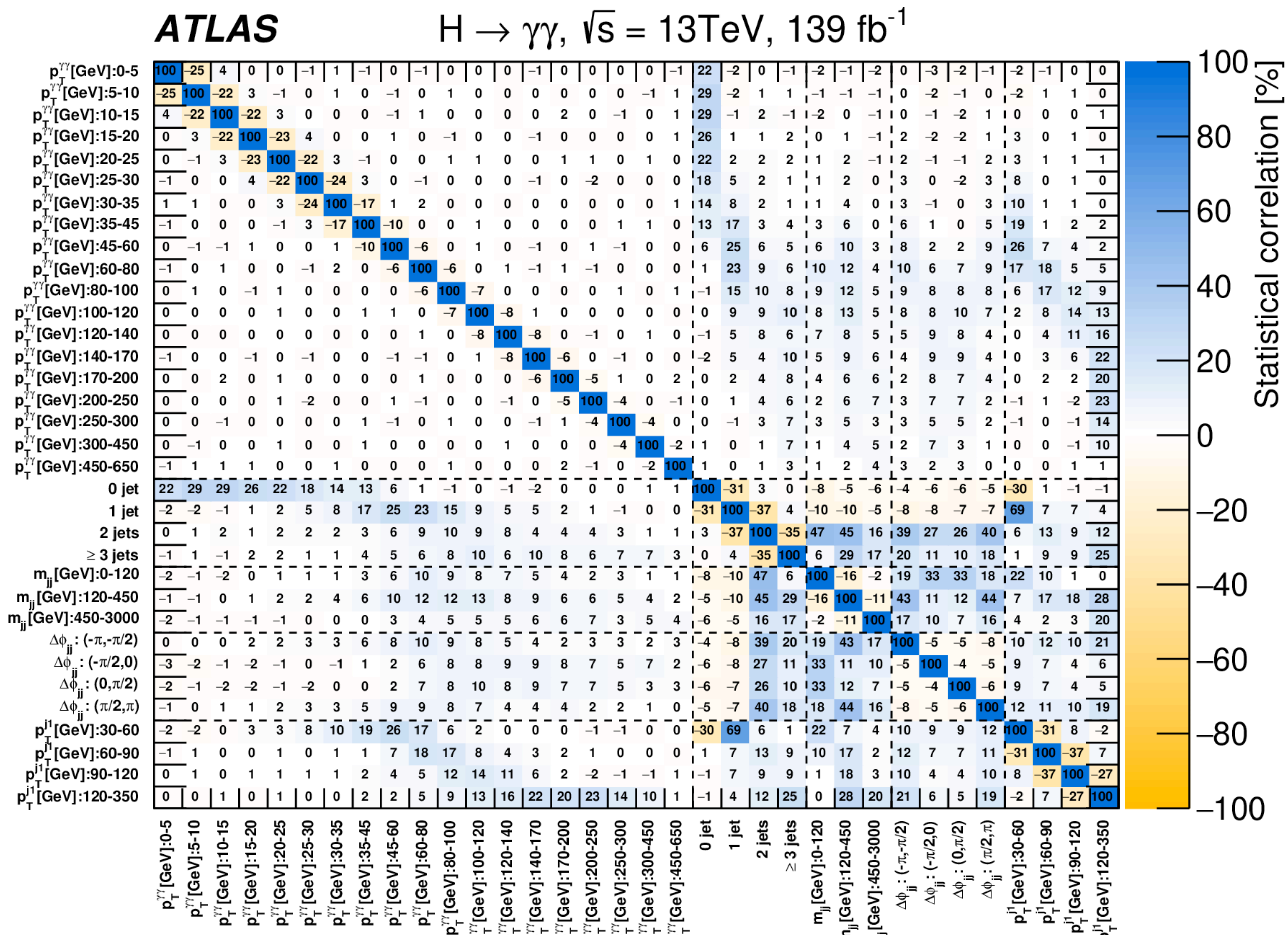


2499(+1149)
SMEFT
WCs(+CPV)
275(+71)
85(+25)
general
top
U(3)5

$H \to \gamma\gamma$ differential cross-section

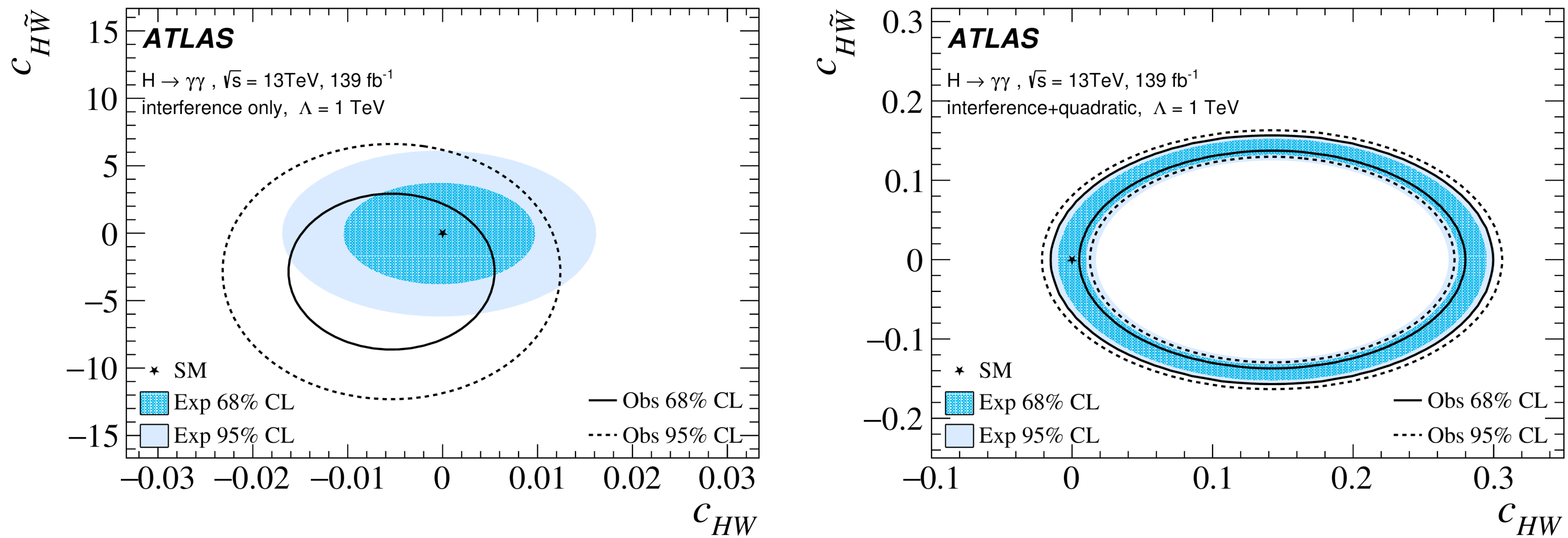
arXiv:2202.00487

- The observed statistical correlations, evaluated with a bootstrapping technique.



$H \to \gamma\gamma$ differential cross-section

arXiv:2202.00487



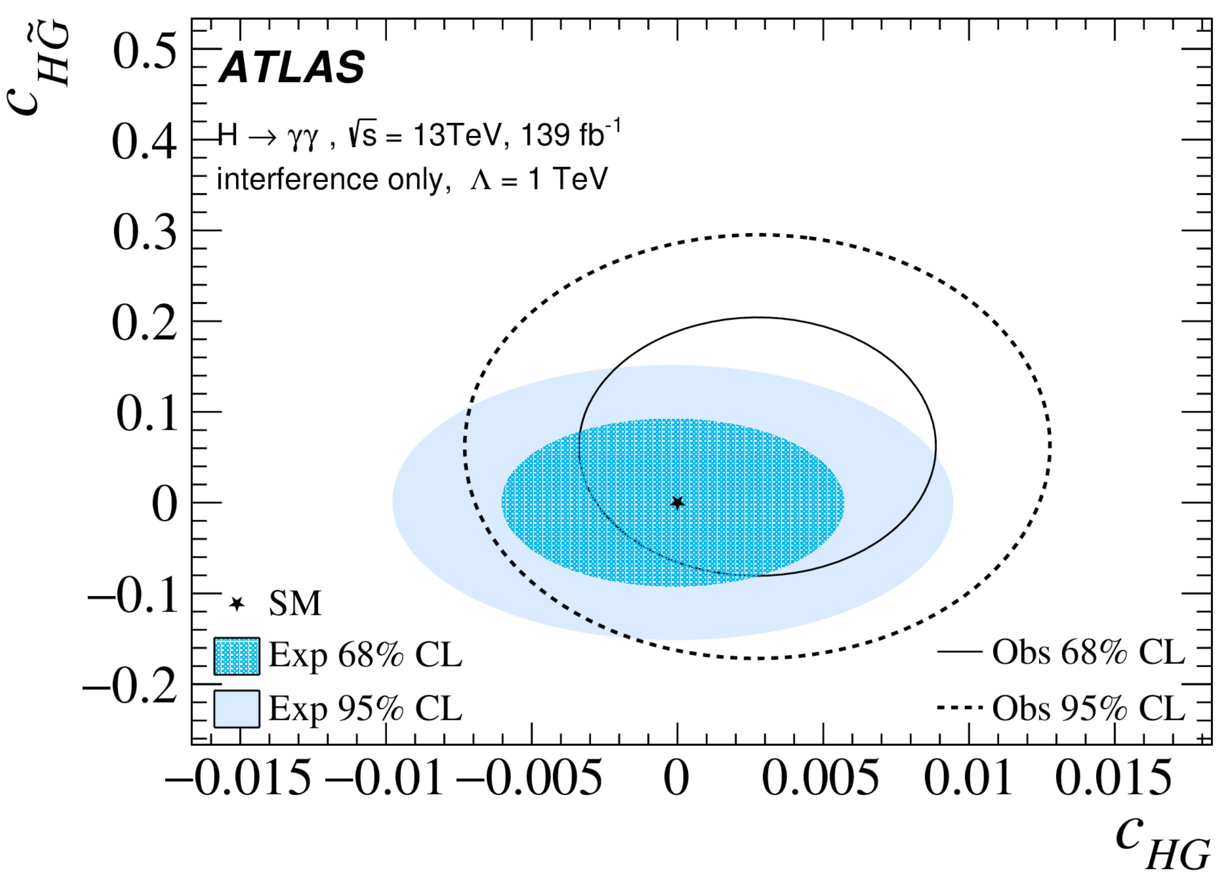
Interference

Interference+BSM

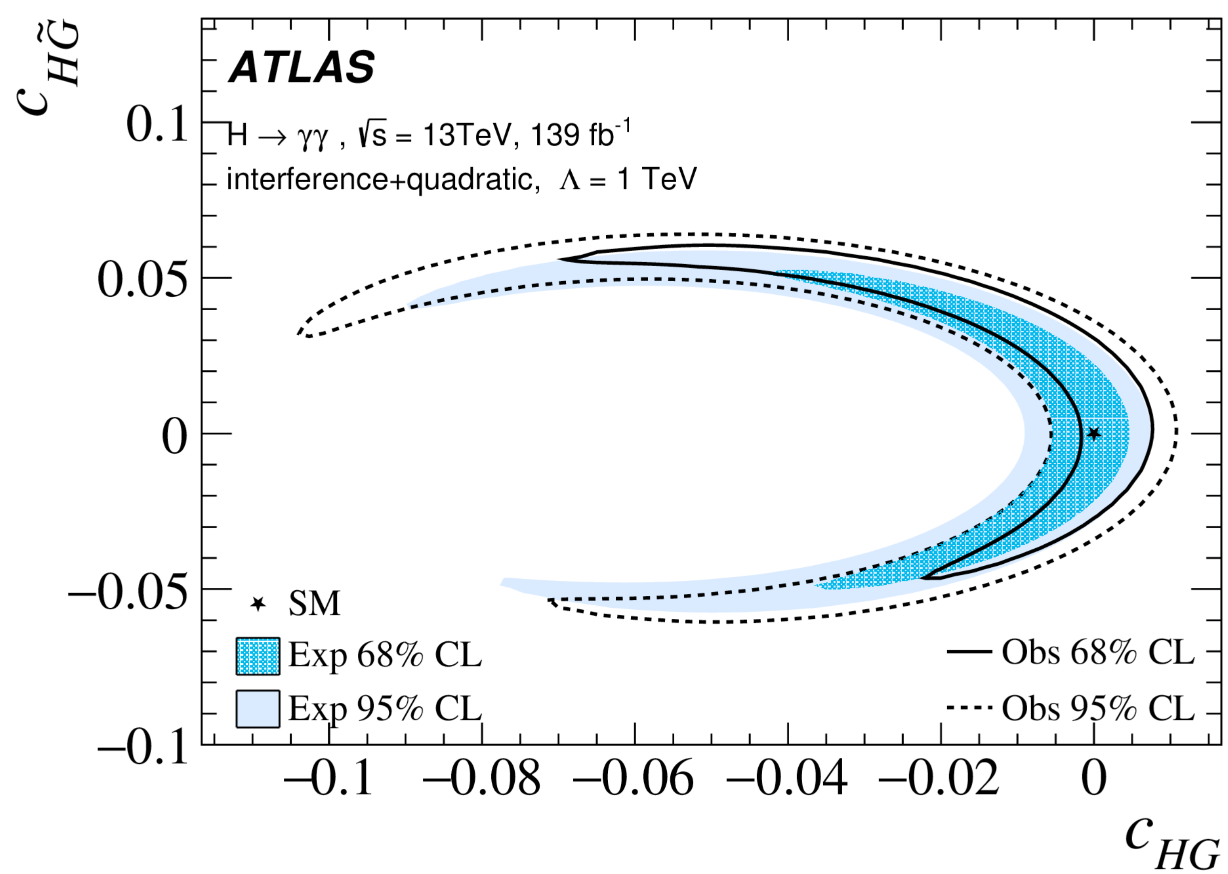
$H \to \gamma\gamma$ differential cross-section

JHEP08(2022)027

- CP-even & -odd WCs constrained (two-at-a-time).

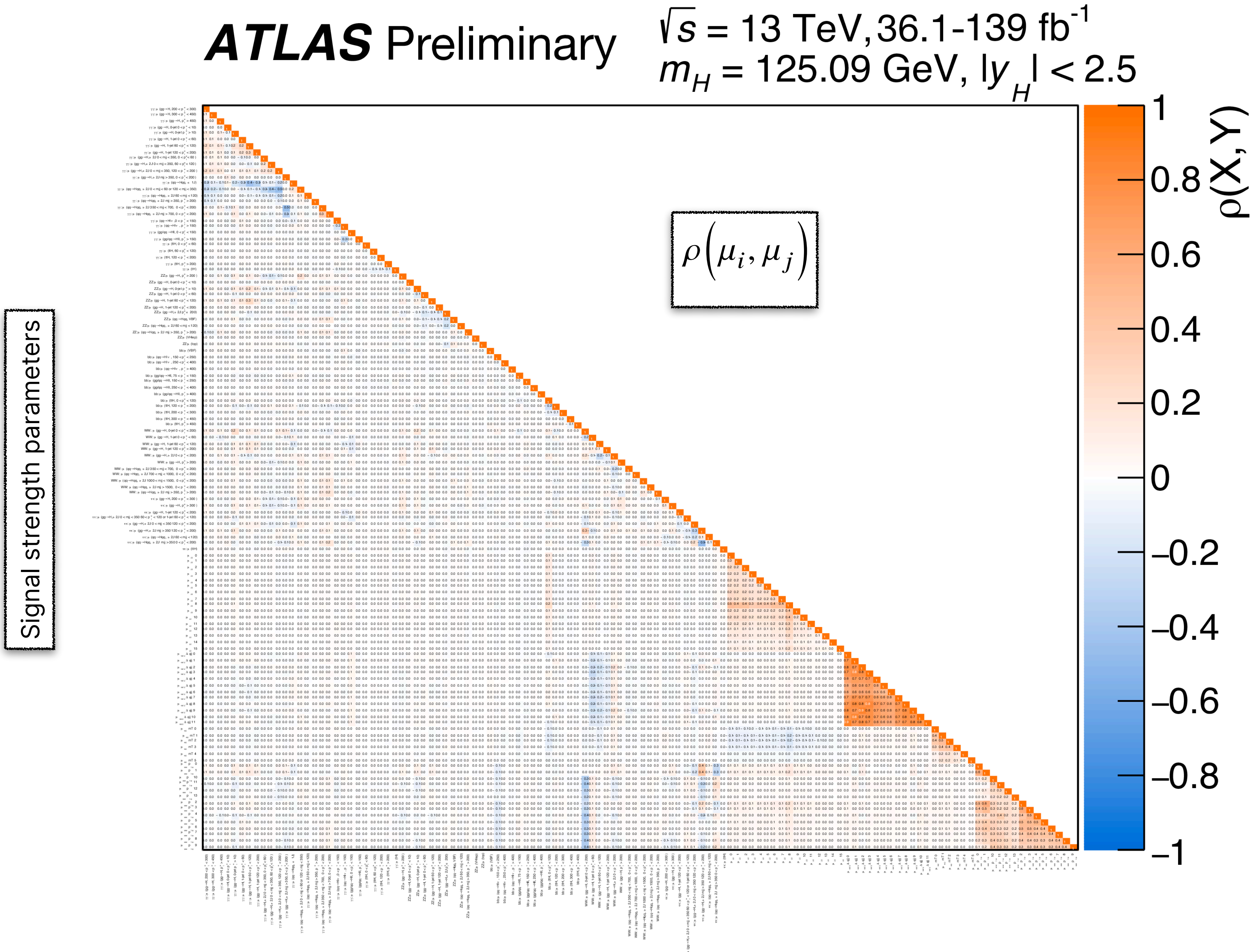


Interference



Interference+BSM

Higgs + Electroweak combination



Higgs + Electroweak combination

ATL-PHYS-PUB-2022-037

ATLAS Higgs STXS

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[10]
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H (4\ell)$	139	[11]
$H \to WW^*$	ggF, VBF	139	[12]
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H (\tau_{\text{had}}\tau_{\text{had}})$	139	[13]
	WH, ZH	139	[14,15,16]
$H \to b\bar{b}$	VBF	126	[17]
	$t\bar{t}H$	139	[18]

+

ATLAS EW

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]	Ref.
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55\,GeV$, $p_T^{\text{jet}} < 35\,GeV$	$p_T^{\text{lead. lep.}}$	36	[19]
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)\,GeV$	m_T^{WZ}	36	[20]
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180\,GeV$	m_{Z2}	139	[21]
$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000\,GeV$, $m_{\ell\ell} \in (81, 101)\,GeV$	$\Delta\phi_{jj}$	139	[22]

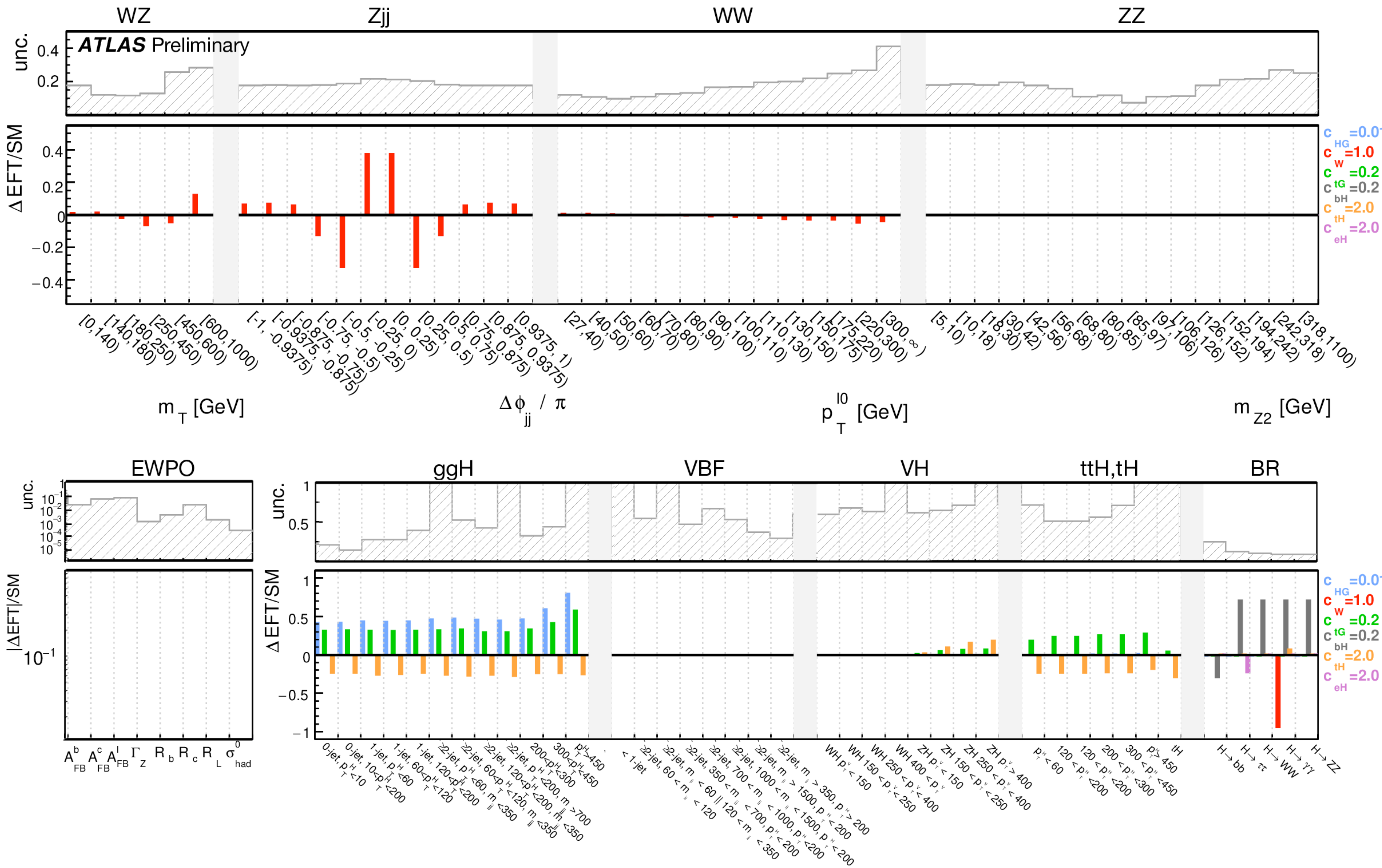
+

LEP/SLD EWPO

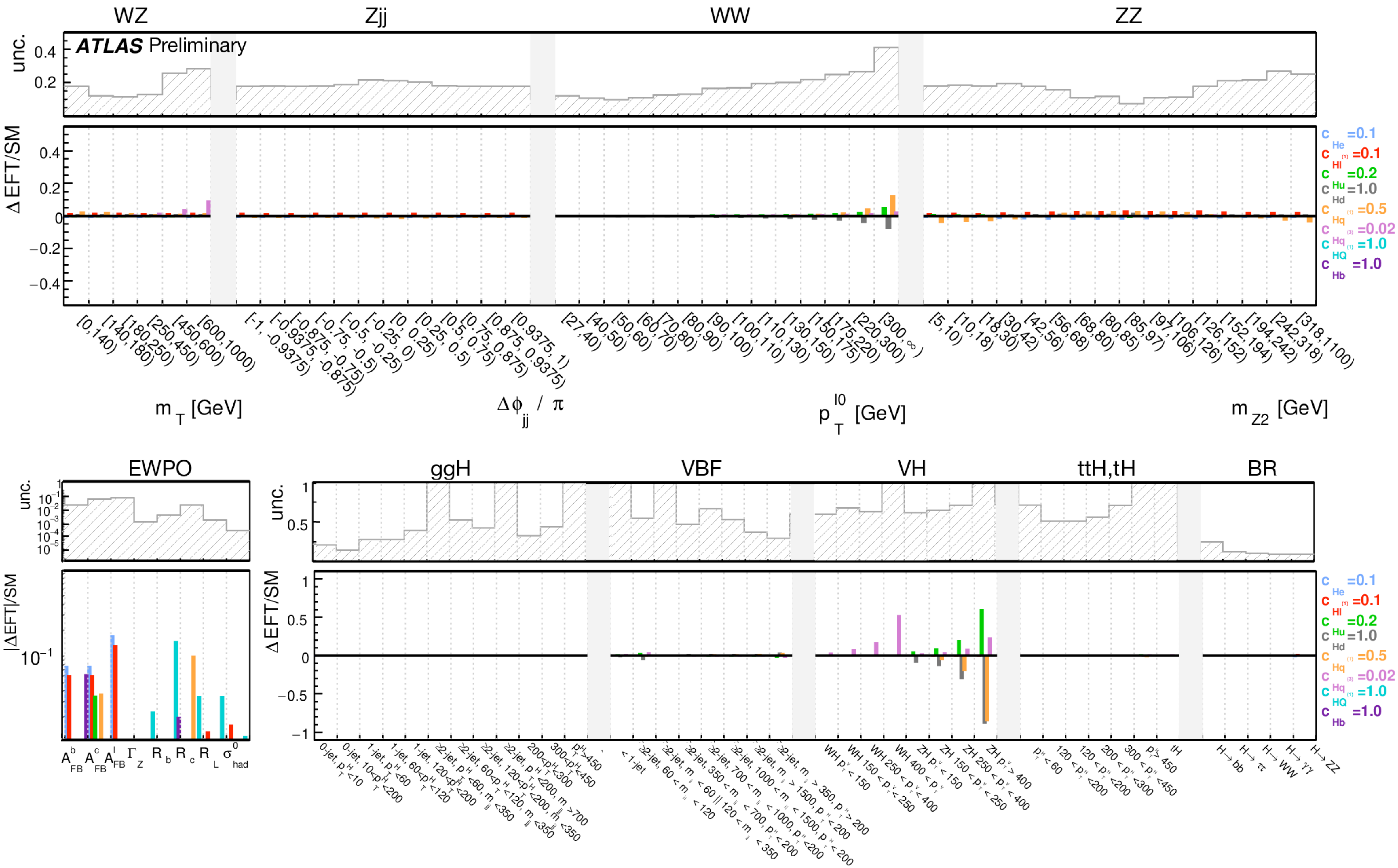
Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R^0_ℓ	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

Forward-backward b-quark asymmetry at the Z pole

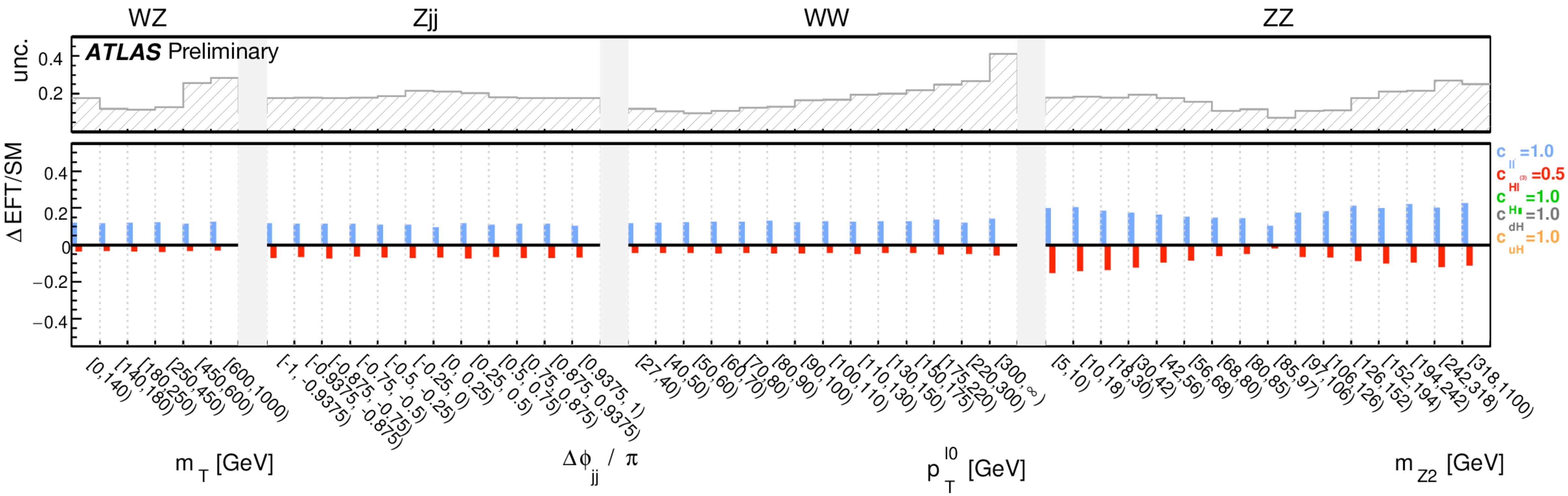
Higgs + Electroweak combination

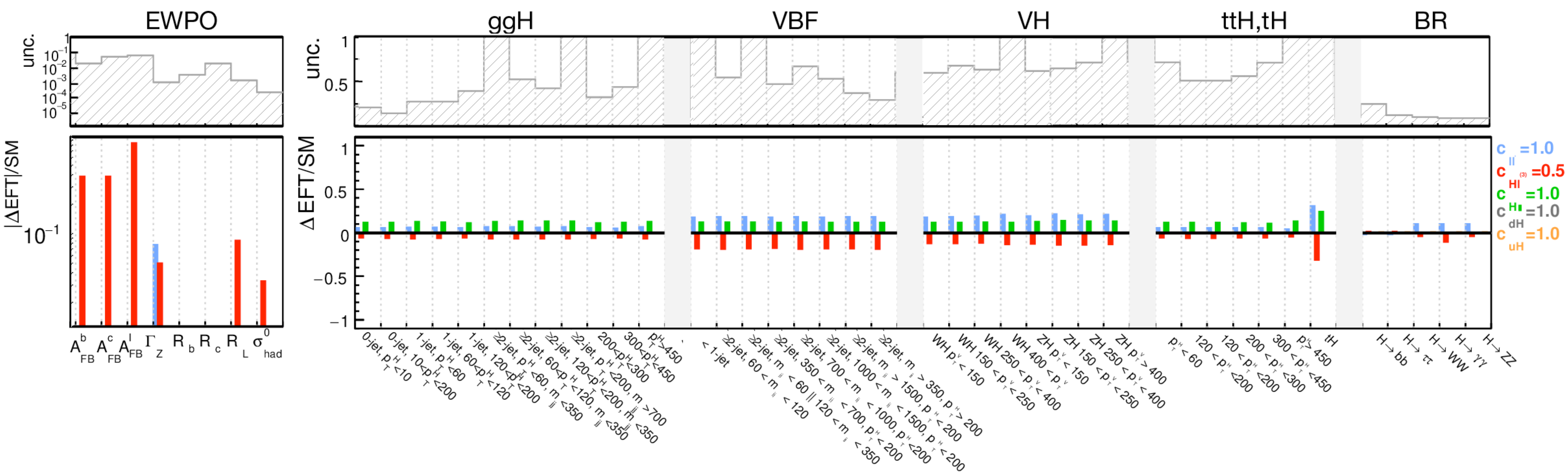


Higgs + Electroweak combination

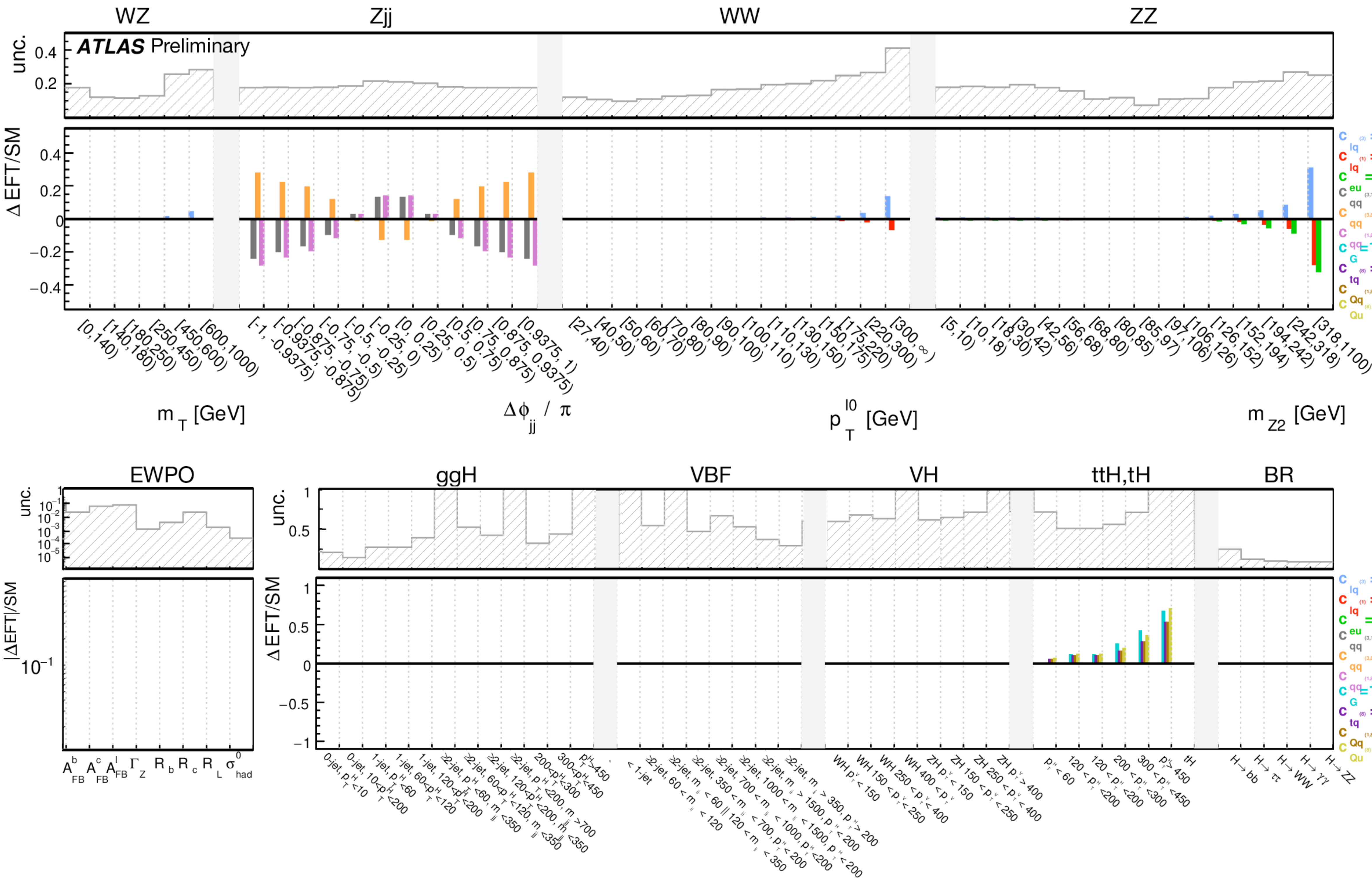


Higgs + Electroweak combination

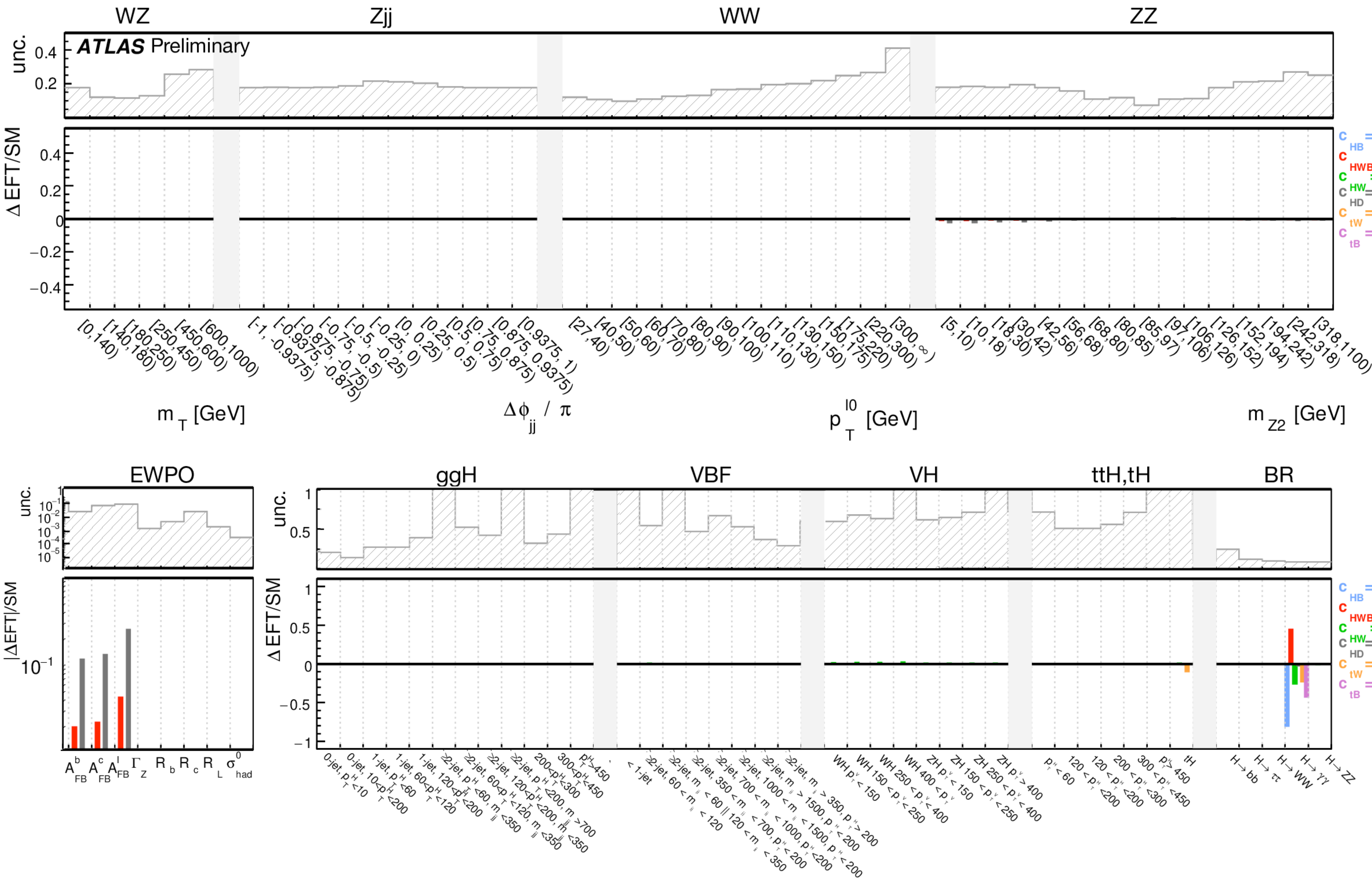




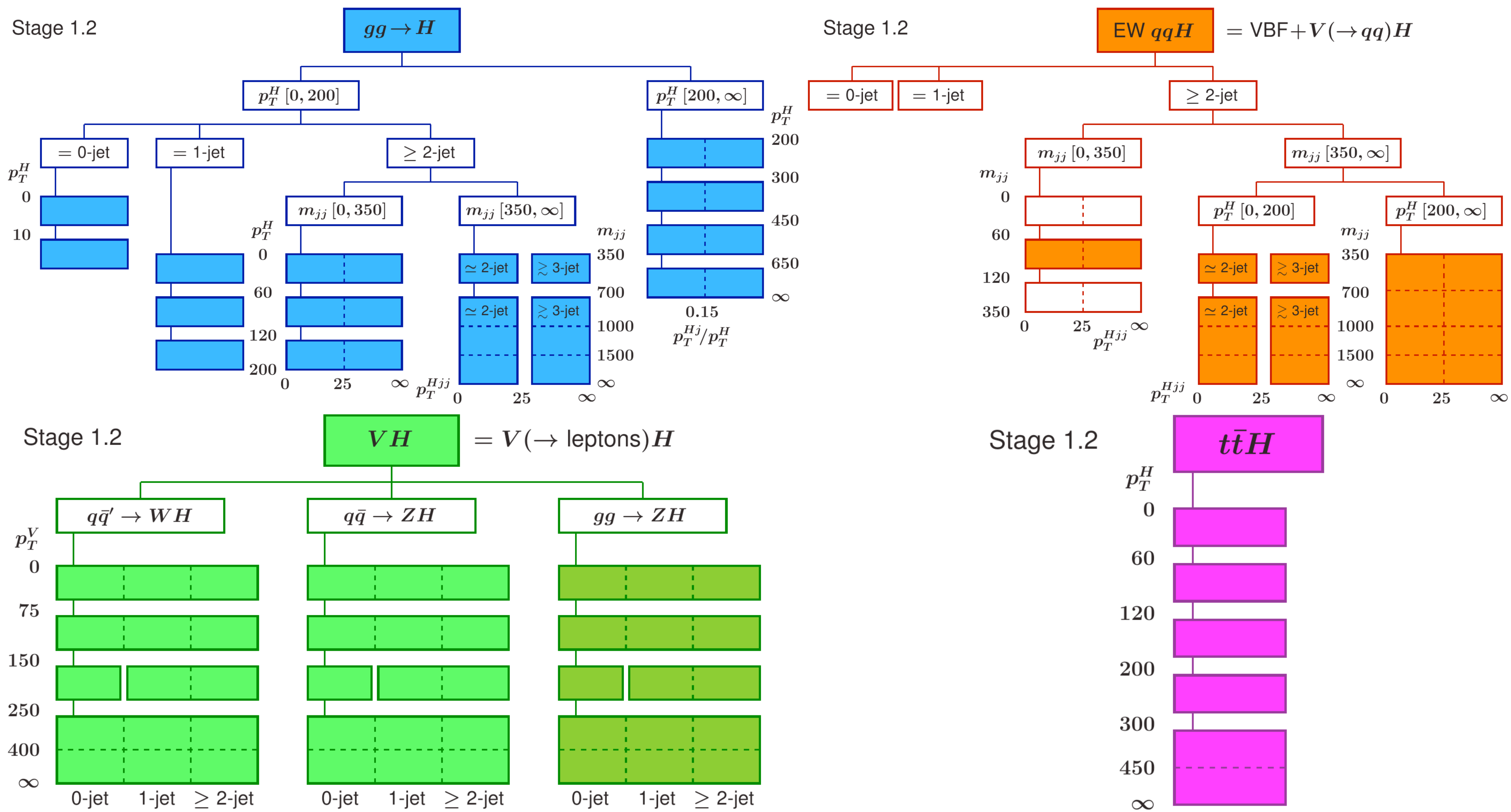
Higgs + Electroweak combination



Higgs + Electroweak combination



Simplified Template Cross-sections



$HH \to bb\tau\tau, bb\gamma\gamma$ searches

2.2.3 Parametrisation of the total cross section

To parametrise the deviations of the total cross section from the one in the SM, we write the LO cross section in terms of the 15 coefficients $A_1, \ldots, A_{15}$, following Refs. [31, 71].

$$\begin{aligned}\sigma/\sigma_{SM} = {} & A_1\, c_t^4 + A_2\, c_{tt}^2 + A_3\, c_t^2 c_{hhh}^2 + A_4\, c_{ggh}^2 c_{hhh}^2 + A_5\, c_{gghh}^2 + A_6\, c_{tt} c_t^2 + A_7\, c_t^3 c_{hhh} \\ & + A_8\, c_{tt} c_t\, c_{hhh} + A_9\, c_{tt} c_{ggh} c_{hhh} + A_{10}\, c_{tt} c_{gghh} + A_{11}\, c_t^2 c_{ggh} c_{hhh} + A_{12}\, c_t^2 c_{gghh} \\ & + A_{13}\, c_t c_{hhh}^2 c_{ggh} + A_{14}\, c_t c_{hhh} c_{gghh} + A_{15}\, c_{ggh} c_{hhh} c_{gghh}\,. \end{aligned} \tag{2.7}$$

$HH \to bb\tau\tau, bb\gamma\gamma$ searches

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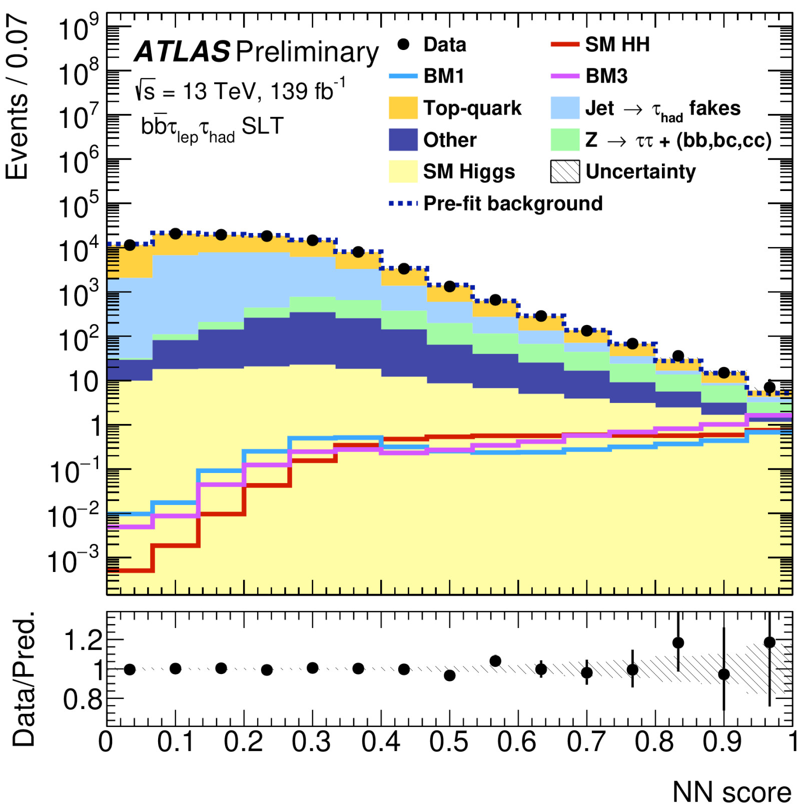

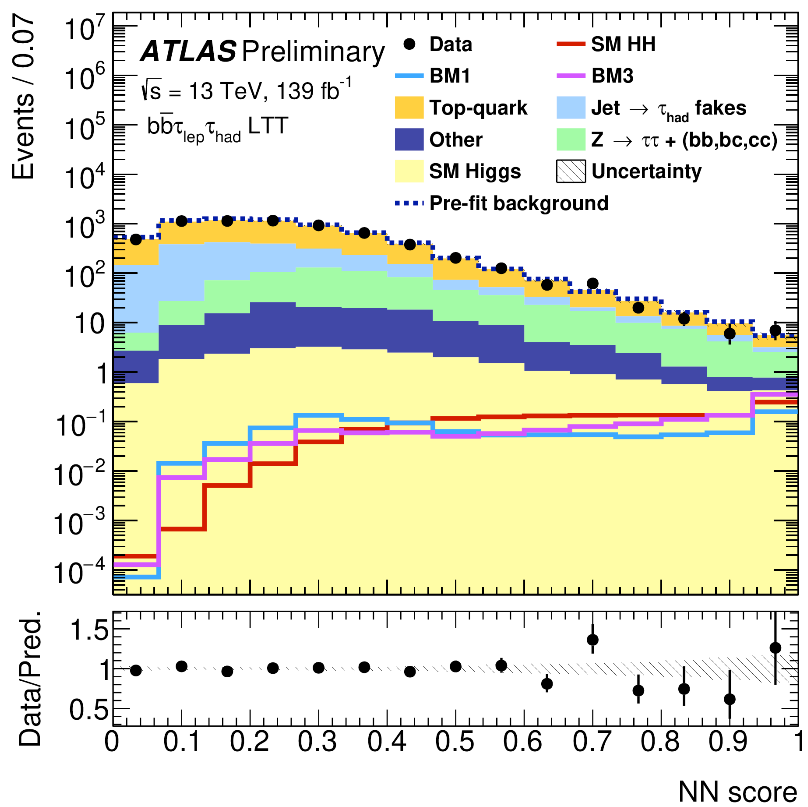

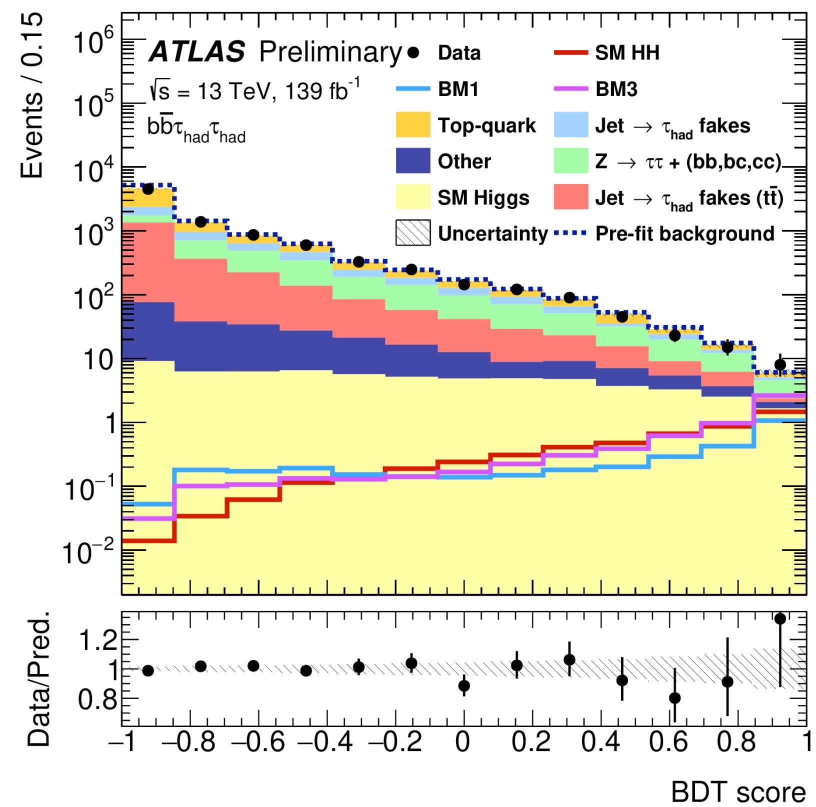

$W^{\pm}\gamma$ differential cross section

- At high-energy limit, no EFT effects over inclusive decay angles.
  - Boost to $W\gamma$ centre-of-mass frame (neutrino four-momentum reconstructed following approximation).