EFT results in and beyond Higgs physics at the LHC

Aliya Nigamova (UHH) on behalf of ATLAS and CMS collaborations

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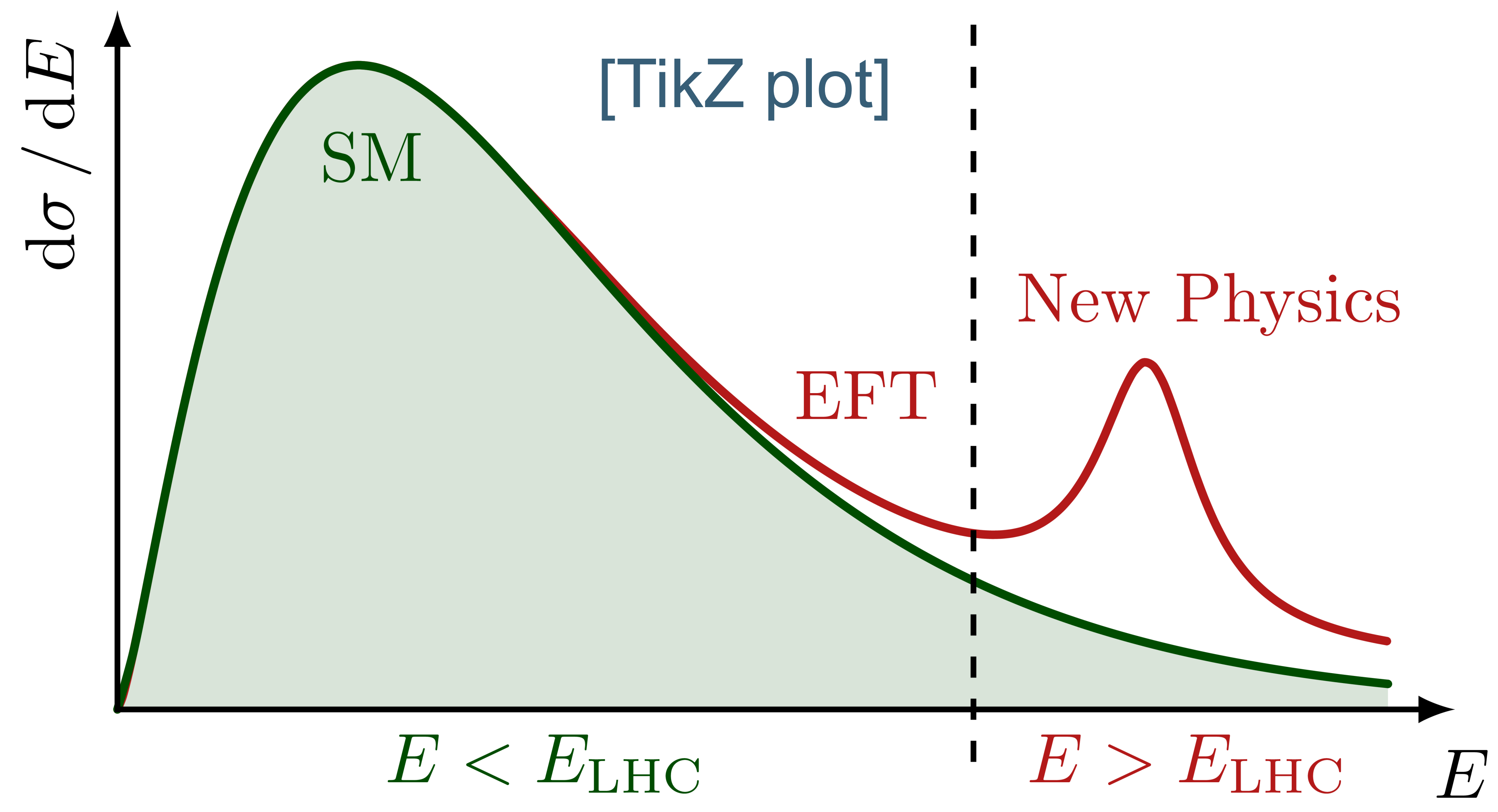
UHH CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

CMS Compact Muon Solenoid

ATLAS EXPERIMENT

Introduction



- Remarkable agreement with SM and ~TeV BSM exclusion limits motivate SMEFT
- Capture NP effects at the low energy by parametrizing them with additional terms $\mathscr{L}^{NP} \propto \dfrac{1}{\Lambda^2}$ (d=6) representing contact interactions
- Additional terms modify overall cross section of SM processes as well as kinematics distribution

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$+ \sum \frac{c_i}{\Lambda^2} O_i^{d=6} + \sum \frac{c_i}{\Lambda^4} O_i^{d=8} + \dots$$

Common framework - SMEFT

- SMEFT model is the most used and accepted theory [arxiv:2012.11343]
- Respects SM symmetries, constructed using SM operators
- Consider operators up to dim 6, and assume baryon and lepton-number conservation
- Number of parameters depends of flavor assumption, with `topU3l` relevant for Higgs operators:

$$\mathcal{L}_6^{(n)} = \frac{1}{\Lambda^2}\sum_\alpha C_\alpha Q_\alpha$$

$\mathcal{L}_6^{(3)} - H^4D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$
$\mathcal{L}_6^{(4)} - X^2H^2$	
Q_{HG}	$H^\dagger H\, G^a_{\mu\nu}G^{a\mu\nu}$
$Q_{H\tilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\, W^i_{\mu\nu}W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu}W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q_{H\tilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$H^\dagger\sigma^i H\, W^i_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu}B^{\mu\nu}$

$\mathcal{L}_6^{(5)} - \psi^2H^3$							
Q_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\tilde{H})$	Q_{dH}	$(H^\dagger H)(\bar{q}Y_d^\dagger dH)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		
Q_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$	Q_{bH}	$(H^\dagger H)(\bar{Q}Hb)$				
$\mathcal{L}_6^{(6)} - \psi^2XH$							
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\sigma^i HW^i_{\mu\nu}$	Q_{uW}	$(\bar{q}Y_u^\dagger\sigma^{\mu\nu}u)\sigma^i\tilde{H}W^i_{\mu\nu}$	Q_{uB}	$(\bar{q}Y_u^\dagger\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$	Q_{uG}	$(\bar{q}Y_u^\dagger\sigma^{\mu\nu}T^a u)\tilde{H}G^a_{\mu\nu}$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)HB_{\mu\nu}$	Q_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\sigma^i\tilde{H}W^i_{\mu\nu}$	Q_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\tilde{H}B_{\mu\nu}$	Q_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{H}G^a_{\mu\nu}$
Q_{dW}	$(\bar{q}Y_d^\dagger\sigma^{\mu\nu}d)\sigma^i HW^i_{\mu\nu}$	Q_{dB}	$(\bar{q}Y_d^\dagger\sigma^{\mu\nu}d)HB_{\mu\nu}$	Q_{dG}	$(\bar{q}Y_d^\dagger\sigma^{\mu\nu}T^a d)HG^a_{\mu\nu}$		
Q_{bW}	$(\bar{Q}\sigma^{\mu\nu}b)\sigma^i HW^i_{\mu\nu}$	Q_{bB}	$(\bar{Q}\sigma^{\mu\nu}b)HB_{\mu\nu}$	Q_{bG}	$(\bar{Q}\sigma^{\mu\nu}T^a b)HG^a_{\mu\nu}$		
$\mathcal{L}_6^{(7)} - \psi^2H^2D$							
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_r)$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$		
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$Q_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	$Q_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$	Q_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	Q_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$
Q_{Hud}	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}Y_uY_d^\dagger\gamma^\mu d)$	Q_{Htb}	$i(\tilde{H}^\dagger D_\mu H)(\bar{t}\gamma^\mu b)$				

Common framework

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$$\mathcal{L}_6^{(n)} = \frac{1}{\Lambda^2}\sum_\alpha C_\alpha Q_\alpha$$

$\mathcal{L}_6^{(5)} - \psi^2 H^3$					
Q_{uH}	$(H^\dagger H)(\bar q Y_u^\dagger u \tilde H)$	Q_{dH}	$(H^\dagger H)(\bar q Y_d^\dagger d H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r$
Q_{tH}	$(H^\dagger H)(\bar Q \tilde H t)$	[illegible]	[illegible]		
$\mathcal{L}_6^{(6)} - \psi^2 X H$					
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\sigma^i H W^i_{\mu\nu}$	Q_{uW}	$(\bar q Y_u^\dagger \sigma^{\mu\nu} u)\sigma^i H W^i_{\mu\nu}$	Q_{uB}	$(\bar q Y_u^\dagger \sigma^{\mu\nu} u)$
Q_{eB}	[illegible]	[illegible]	[illegible]	Q_{tB}	$(\bar Q \sigma^{\mu\nu} t)\tilde H B$
Q_{dW}	$(\bar q Y_d^\dagger \sigma^{\mu\nu} d)\sigma^i H W^i_{\mu\nu}$	Q_{dB}	$(\bar q Y_d^\dagger \sigma^{\mu\nu} d) H B_{\mu\nu}$	Q_{dG}	$(\bar q Y_d^\dagger \sigma^{\mu\nu} T^a$
Q_{bW}	$(\bar Q \sigma^{\mu\nu} b)\sigma^i H W^i_{\mu\nu}$	Q_{bB}	$(\bar Q \sigma^{\mu\nu} b) H B_{\mu\nu}$	Q_{bG}	$(\bar Q \sigma^{\mu\nu} T^a b)$
$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$					
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar l_p \sigma^i \gamma^\mu l_r)$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q \gamma^\mu q)$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar q \sigma^i \gamma^\mu q)$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)$
$Q_{HQ}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar Q \gamma^\mu Q)$	$Q_{HQ}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar Q \sigma^i \gamma^\mu Q)$	Q_{Ht}	$(H^\dagger i \overleftrightarrow{D}_\mu H)$
Q_{Hud}	$i(\tilde H^\dagger D_\mu H)(\bar u Y_u Y_d^\dagger \gamma^\mu d)$	Q_{Htb}	$i(\tilde H^\dagger D_\mu H)(\bar t \gamma^\mu b)$		

+ combination with other sectors provides access to 4 fermion operators

$\mathcal{L}_6^{(8a)} - (\bar L L)(\bar L L)$							
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q \gamma^\mu q)$	$Q_{lq}^{(3)}$	$(\bar l_p \sigma^i \gamma_\mu l_r)(\bar q \sigma^i \gamma^\mu q)$	Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$		
$Q_{lQ}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar Q \gamma^\mu Q)$	$Q_{lQ}^{(3)}$	$(\bar l_p \sigma^i \gamma_\mu l_r)(\bar Q \sigma^i \gamma^\mu Q)$	$Q_{QQ}^{(1)}$	$(\bar Q \gamma_\mu Q)(\bar Q \gamma^\mu Q)$	$Q_{QQ}^{(8)}$	$(\bar Q T^a \gamma_\mu Q)(\bar Q T^a \gamma^\mu Q)$
$Q_{qq}^{(1,1)}$	$(\bar q \gamma_\mu q)(\bar q \gamma^\mu q)$	$Q_{qq}^{(1,8)}$	$(\bar q T^a \gamma_\mu q)(\bar q T^a \gamma^\mu q)$	$Q_{qq}^{(3,1)}$	$(\bar q \sigma^i \gamma_\mu q)(\bar q \sigma^i \gamma^\mu q)$	$Q_{qq}^{(3,8)}$	$(\bar q \sigma^i T^a \gamma_\mu q)(\bar q \sigma^i T^a \gamma^\mu q)$
$Q_{Qq}^{(1,1)}$	$(\bar Q \gamma_\mu Q)(\bar q \gamma^\mu q)$	$Q_{Qq}^{(1,8)}$	$(\bar Q T^a \gamma_\mu Q)(\bar q T^a \gamma^\mu q)$	$Q_{Qq}^{(3,1)}$	$(\bar Q \sigma^i \gamma_\mu Q)(\bar q \sigma^i \gamma^\mu q)$	$Q_{Qq}^{(3,8)}$	$(\bar Q \sigma^i T^a \gamma_\mu Q)(\bar q \sigma^i T^a \gamma^\mu q)$
$\mathcal{L}_6^{(8b)} - (\bar R R)(\bar R R)$							
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u \gamma^\mu u)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d \gamma^\mu d)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$		
Q_{et}	$(\bar e_p \gamma_\mu e_r)(\bar t \gamma^\mu t)$	Q_{eb}	$(\bar e_p \gamma_\mu e_r)(\bar b \gamma^\mu b)$	Q_{tt}	$(\bar t \gamma_\mu t)(\bar t \gamma^\mu t)$	Q_{bb}	$(\bar b \gamma_\mu b)(\bar b \gamma^\mu b)$
$Q_{uu}^{(1)}$	$(\bar u \gamma_\mu u)(\bar u \gamma^\mu u)$	$Q_{uu}^{(8)}$	$(\bar u T^a \gamma_\mu u)(\bar u T^a \gamma^\mu u)$	$Q_{tu}^{(1)}$	$(\bar t \gamma_\mu t)(\bar u \gamma^\mu u)$	$Q_{tu}^{(8)}$	$(\bar t T^a \gamma_\mu t)(\bar u T^a \gamma^\mu u)$
$Q_{dd}^{(1)}$	$(\bar d \gamma_\mu d)(\bar d \gamma^\mu d)$	$Q_{dd}^{(8)}$	$(\bar d T^a \gamma_\mu d)(\bar d T^a \gamma^\mu d)$	$Q_{bd}^{(1)}$	$(\bar b \gamma_\mu b)(\bar d \gamma^\mu d)$	$Q_{bd}^{(8)}$	$(\bar b T^a \gamma_\mu b)(\bar d T^a \gamma^\mu d)$
$Q_{ud}^{(1)}$	$(\bar u \gamma_\mu u)(\bar d \gamma^\mu d)$	$Q_{ud}^{(8)}$	$(\bar u T^a \gamma_\mu u)(\bar d T^a \gamma^\mu d)$	$Q_{td}^{(1)}$	$(\bar t \gamma_\mu t)(\bar d \gamma^\mu d)$	$Q_{td}^{(8)}$	$(\bar t T^a \gamma_\mu t)(\bar d T^a \gamma^\mu d)$
$Q_{ub}^{(1)}$	$(\bar u \gamma_\mu u)(\bar b \gamma^\mu b)$	$Q_{ub}^{(8)}$	$(\bar u T^a \gamma_\mu u)(\bar b T^a \gamma^\mu b)$	$Q_{tb}^{(1)}$	$(\bar t \gamma_\mu t)(\bar b \gamma^\mu b)$	$Q_{tb}^{(8)}$	$(\bar t T^a \gamma_\mu t)(\bar b T^a \gamma^\mu b)$
$Q_{utbd}^{(1)}$	$(Y_u Y_d^\dagger)_{pr}(\bar u_p \gamma_\mu t)(\bar b \gamma^\mu d_r)$	$Q_{utbd}^{(8)}$	$(Y_u Y_d^\dagger)_{pr}(\bar u_p T^a \gamma_\mu t)(\bar b T^a \gamma^\mu d_r)$				
$\mathcal{L}_6^{(8c)} - (\bar L L)(\bar R R)$							
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u \gamma^\mu u)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d \gamma^\mu d)$	Q_{qe}	$(\bar q \gamma_\mu q)(\bar e_p \gamma^\mu e_r)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lt}	$(\bar l_p \gamma_\mu l_r)(\bar t \gamma^\mu t)$	Q_{lb}	$(\bar l_p \gamma_\mu l_r)(\bar b \gamma^\mu b)$	Q_{Qe}	$(\bar Q \gamma_\mu Q)(\bar e_p \gamma^\mu e_r)$		
$Q_{qu}^{(1)}$	$(\bar q \gamma_\mu q)(\bar u \gamma^\mu u)$	$Q_{Qu}^{(1)}$	$(\bar Q \gamma_\mu Q)(\bar u \gamma^\mu u)$	$Q_{qt}^{(1)}$	$(\bar q \gamma_\mu q)(\bar t \gamma^\mu t)$	$Q_{Qt}^{(1)}$	$(\bar Q \gamma_\mu Q)(\bar t \gamma^\mu t)$
$Q_{qu}^{(8)}$	$(\bar q T^a \gamma_\mu q)(\bar u T^a \gamma^\mu u)$	$Q_{Qu}^{(8)}$	$(\bar Q T^a \gamma_\mu Q)(\bar u T^a \gamma^\mu u)$	$Q_{qt}^{(8)}$	$(\bar q T^a \gamma_\mu q)(\bar t T^a \gamma^\mu t)$	$Q_{Qt}^{(8)}$	$(\bar Q T^a \gamma_\mu Q)(\bar t T^a \gamma^\mu t)$
$Q_{qd}^{(1)}$	$(\bar q \gamma_\mu q)(\bar d \gamma^\mu d)$	$Q_{Qd}^{(1)}$	$(\bar Q \gamma_\mu Q)(\bar d \gamma^\mu d)$	$Q_{qb}^{(1)}$	$(\bar q \gamma_\mu q)(\bar b \gamma^\mu b)$	$Q_{Qb}^{(1)}$	$(\bar Q \gamma_\mu Q)(\bar b \gamma^\mu b)$
$Q_{qd}^{(8)}$	$(\bar q T^a \gamma_\mu q)(\bar d T^a \gamma^\mu d)$	$Q_{Qd}^{(8)}$	$(\bar Q T^a \gamma_\mu Q)(\bar d T^a \gamma^\mu d)$	$Q_{qb}^{(8)}$	$(\bar q T^a \gamma_\mu q)(\bar b T^a \gamma^\mu b)$	$Q_{Qb}^{(8)}$	$(\bar Q T^a \gamma_\mu Q)(\bar b T^a \gamma^\mu b)$
$Q_{qQtu}^{(1)}$	$(Y_u^\dagger)_{pr}(\bar q_p \gamma_\mu Q)(\bar t \gamma^\mu u_r)$	$Q_{qQtu}^{(8)}$	$(Y_u^\dagger)_{pr}(\bar q_p T^a \gamma_\mu Q)(\bar t T^a \gamma^\mu u_r)$	$Q_{qQbd}^{(1)}$	$(Y_d^\dagger)_{pr}(\bar q_p \gamma_\mu Q)(\bar b \gamma^\mu d_r)$	$Q_{qQbd}^{(8)}$	$(Y_d^\dagger)_{pr}(\bar q_p T^a \gamma_\mu Q)(\bar b T^a \gamma^\mu d_r)$

EFT analysis strategies

I. Individual measurements

Derive sensitive to EFT observable

- Matrix element based observables ($\mathscr{P} \propto ME$) estimated with [MELA] based on kinematics and angular variables Ω

$$\mathcal{D}_{\mathrm{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\mathrm{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\mathrm{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\mathrm{alt}}(\mathbf{\Omega})}$$

- Optimal observable with [BIT] regression for a limited set of operators relevant for considered process; X = kinematics and angular variables

$$R(X|\vec{c}) = 1 + \sum_i R_i(X)c_i + \sum_{i,j} R_{i,j}(X)c_ic_j$$

II. Combinations

Input analyses are optimized to SM precision, model independent measurements considering up to 64 Wilson coefficients $\rightarrow$ PCA is used to identify non-flat directions

Parametrize (differential) cross section (and BR)

$$\mu_i^X(c_j) = \frac{(\sigma \times \mathcal{B})^{i,H\to X}}{(\sigma \times \mathcal{B})^{i,H\to X}_{\mathrm{SM}}} = \left(1 + \frac{\sigma^i_{\mathrm{int}}}{\sigma^i_{\mathrm{SM}}} + \frac{\sigma^i_{\mathrm{BSM}}}{\sigma^i_{\mathrm{SM}}}\right) \quad \ldots$$

$$\frac{\sigma^i_{\mathrm{int}}}{\sigma^i_{\mathrm{SM}}} = \sum_j A_j^{\sigma_i} c_j \qquad \frac{\sigma^i_{\mathrm{BSM}}}{\sigma^i_{\mathrm{SM}}} = \sum_{jk} B_{jk}^{\sigma_i} c_j c_k$$

EFT analysis strategies

I. Individual measurements

Derive sensitive to EFT observable based on event kinematics and angular variables

- ATLAS $H \to 4l$ [ATL-PHYS-PUB-2023-012]
- CMS VH($H \to bb$) EFT analysis [CMS-HIG-23-016]
- CMS EFT interpretation in $H \to WW$ MELA [Eur. Phys. J. C 84 (2024) 779]

II. Combinations

Input analyses are optimized to SM precision, model independent measurements considering up to 64 Wilson coefficients → PCA is used to identify non-flat directions

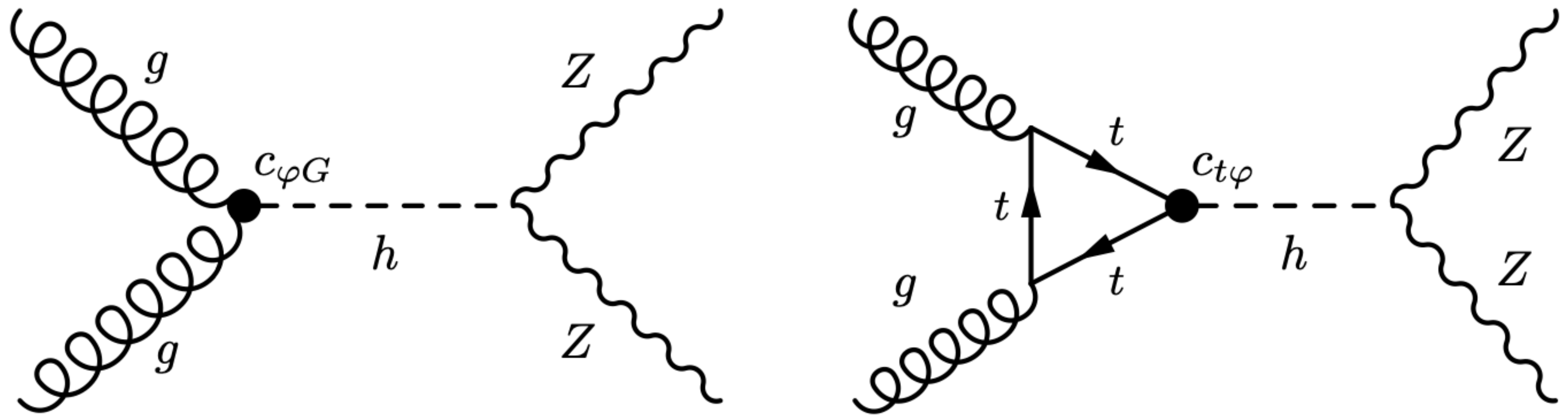
- ATLAS STXS + fiducial combination of Higgs channels [ANA-HIGG-2022-17-PAPER]
- CMS Higgs differential combination [CMS-HIG-23-013]
- ATLAS Higgs + EWK [ATL-PHYS-PUB-2022-037]
- CMS Higgs + EWK + Top [SMP-24-003]

I. Individual EFT measurements

H→(2l2ν) + (4l) ATLAS

[ATL-PHYS-PUB-2023-012]

- Analysis considering SMEFT effects in H production only →limited set of WC

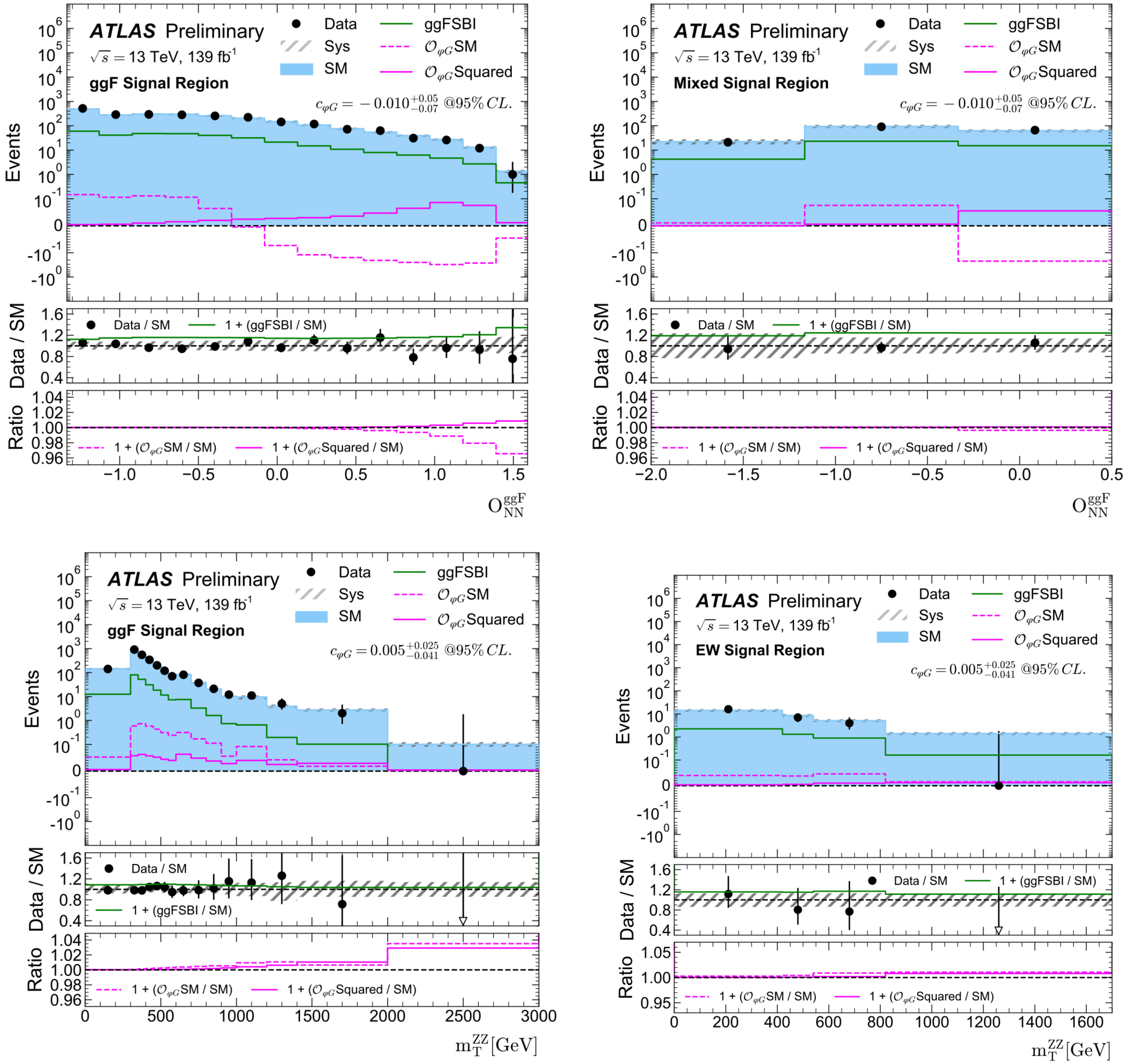


- Using NN observable in H → 4 lepton channel

$$O_{\rm NN} = \log_{10}\frac{P_{\rm S}}{P_{\rm B}+P_{\rm NI}}$$

- In H→$2l2\nu$ lepton channel:

$$m_{\rm T}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2+(p_{\rm T}^{\ell\ell})^2}+\sqrt{m_Z^2+(E_{\rm T}^{\rm miss})^2}\right]^2-\left|\vec{p}_{\rm T}^{\,\ell\ell}+\vec{E}_{\rm T}^{\rm miss}\right|^2}$$



H→$(2l2\nu)$ + $(4l)$ ATLAS

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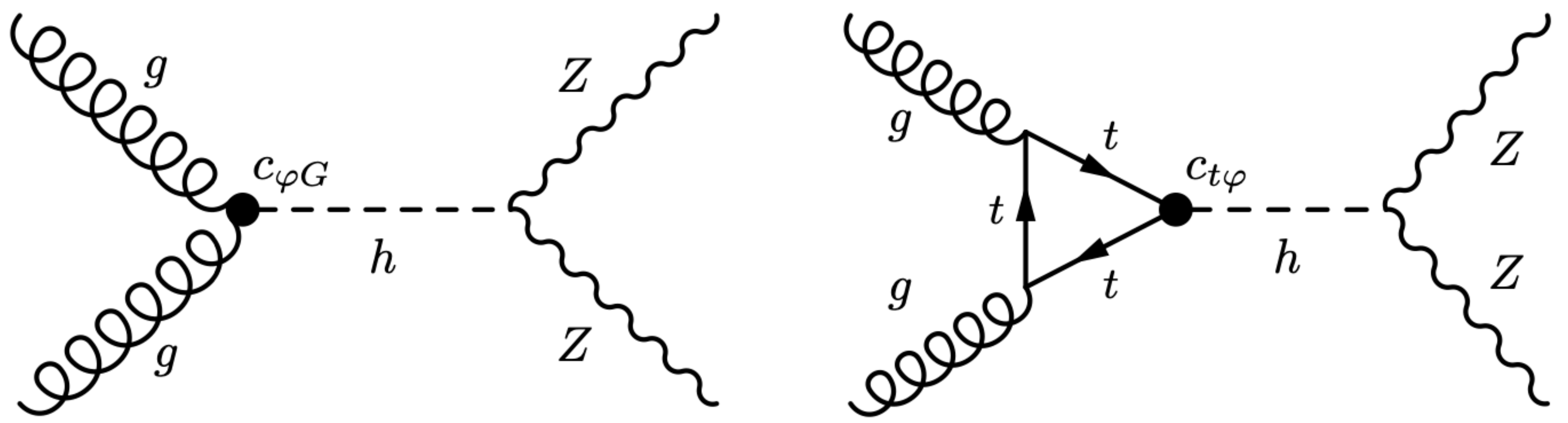
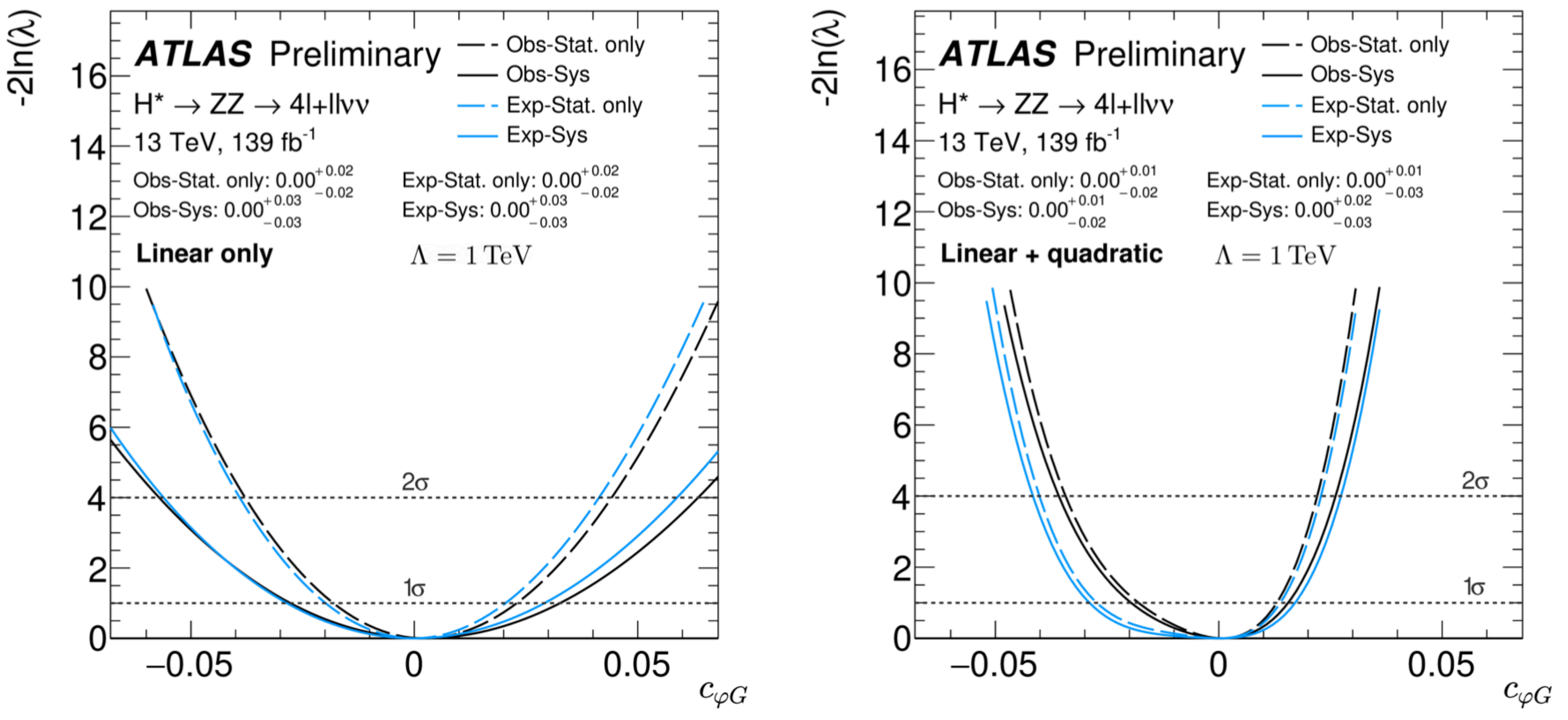


- Using NN observable in H → 4 lepton channel

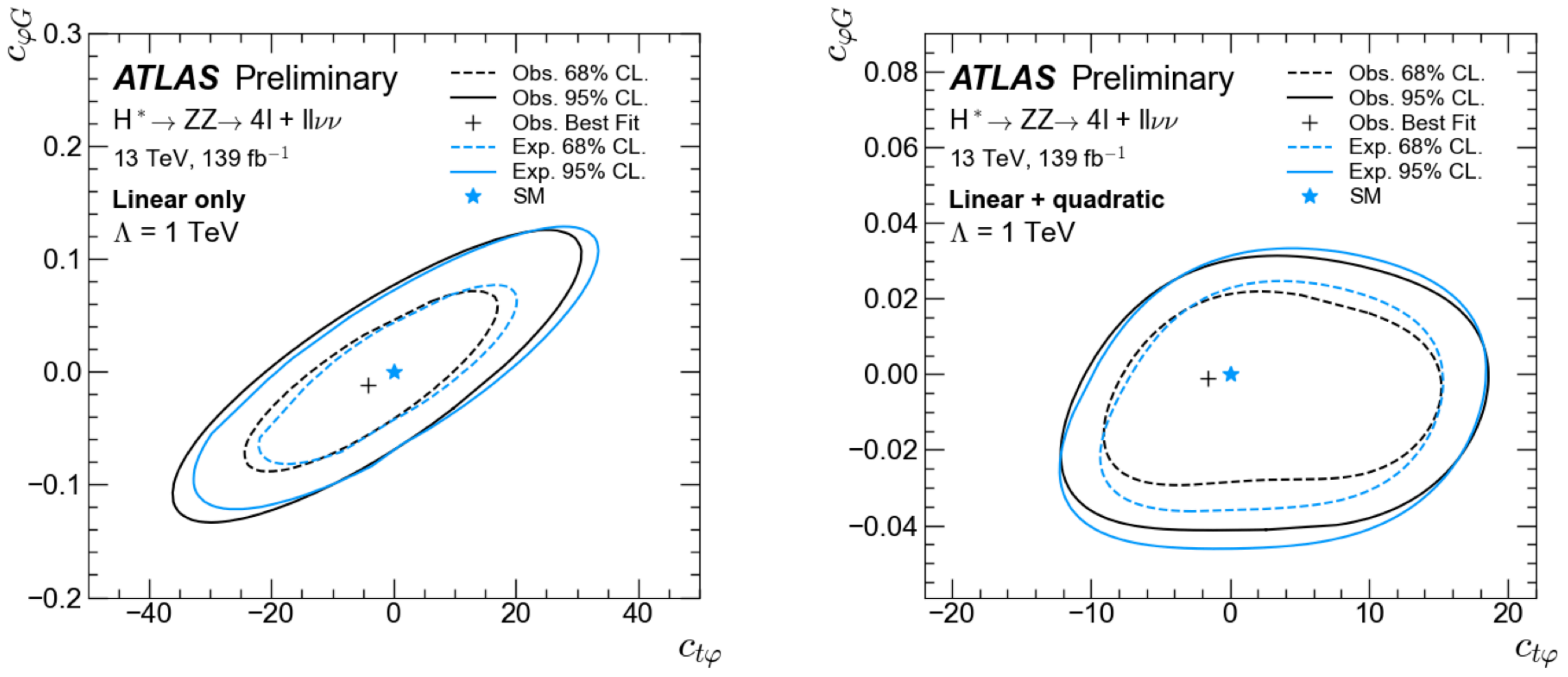
$$O_{NN} = \log_{10} \frac{P_S}{P_B + P_{NI}}$$

- In H→$2l2\nu$ lepton channel:

$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{miss})^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2}$$



(a) (b)



(a) (b)

VH(H→bb) EFT analysis (CMS)

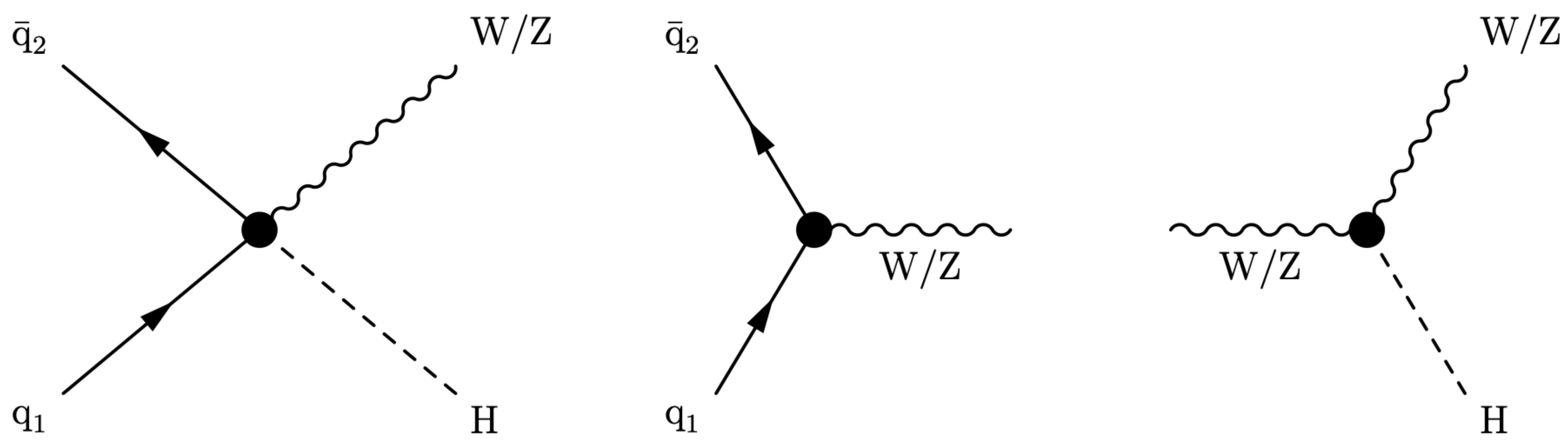
[talk by Vasilije Perovic]

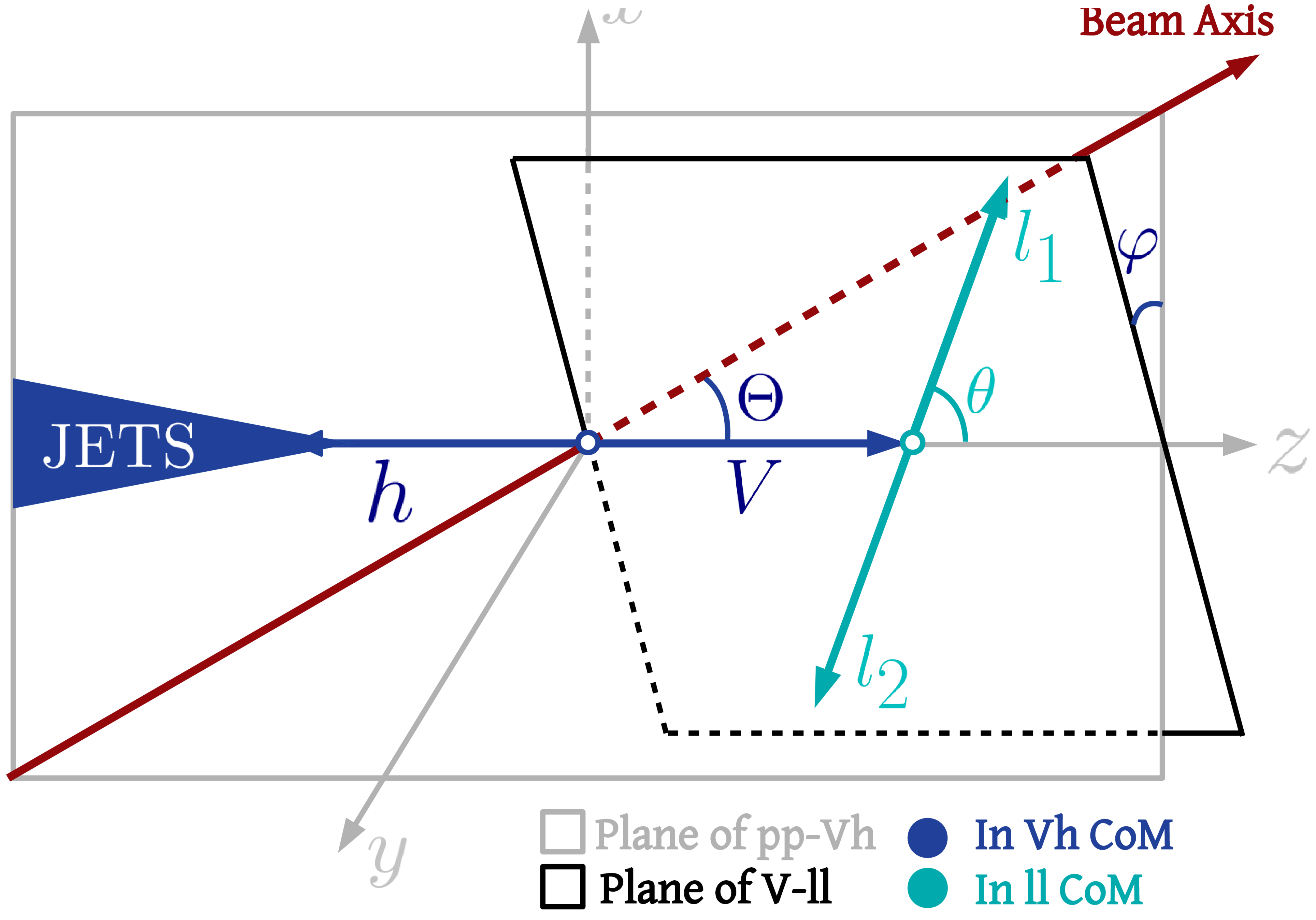
CMS-HIG-23-016

- New Run 2 analysis designed to gain sensitivity to EFT effects specifically extending STXS parametrization approach to constrain $c_{Hq}^{(3)}$, $c_{Hq}^{(1)}$, c_{Hu}, c_{Hd} and linear combinations of c_{HW}, c_{HWB}, c_{HB} (+ CP-odd) = g_2^{ZZ}, g_4^{ZZ}
- Angular information to improve sensitivity to CP-even vs. CP-odd HVV couplings g_2^{ZZ}, g_4^{ZZ}

$$g_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{\rm HB} + c_w^2 c_{\rm HW} + s_w c_w c_{\rm HWB}\right)$$

$$g_4^{ZZ} = \tilde{g}_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{\rm H\tilde{B}} + c_w^2 c_{\rm H\widetilde{W}} + s_w c_w c_{\rm H\widetilde{W}B}\right)$$





VH(H→bb) EFT analysis (CMS)

[talk by Vasilije Perovic]

CMS-HIG-23-016

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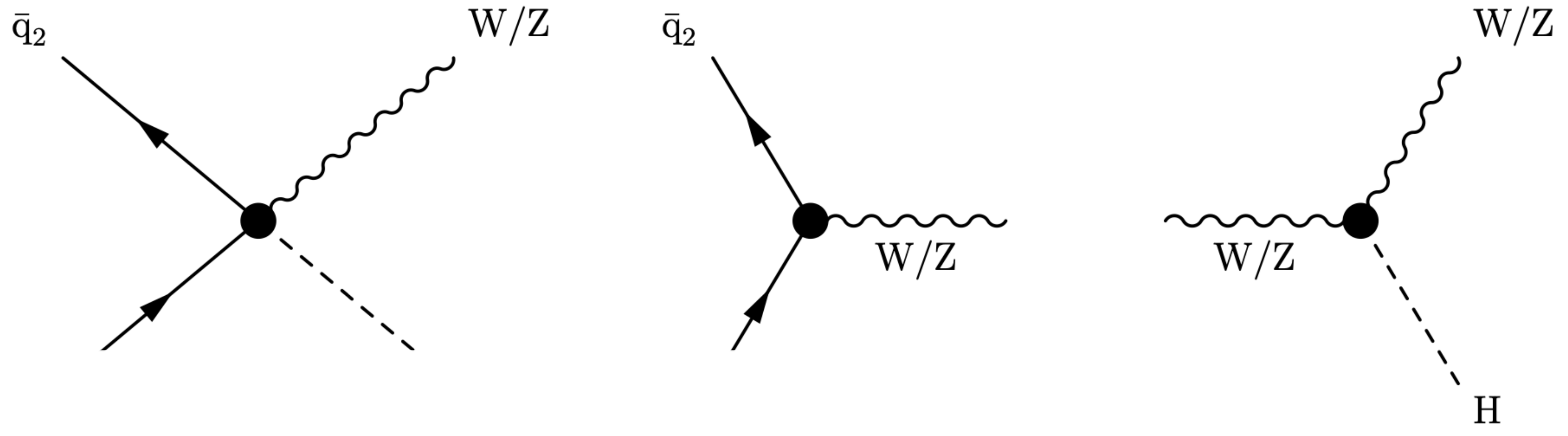
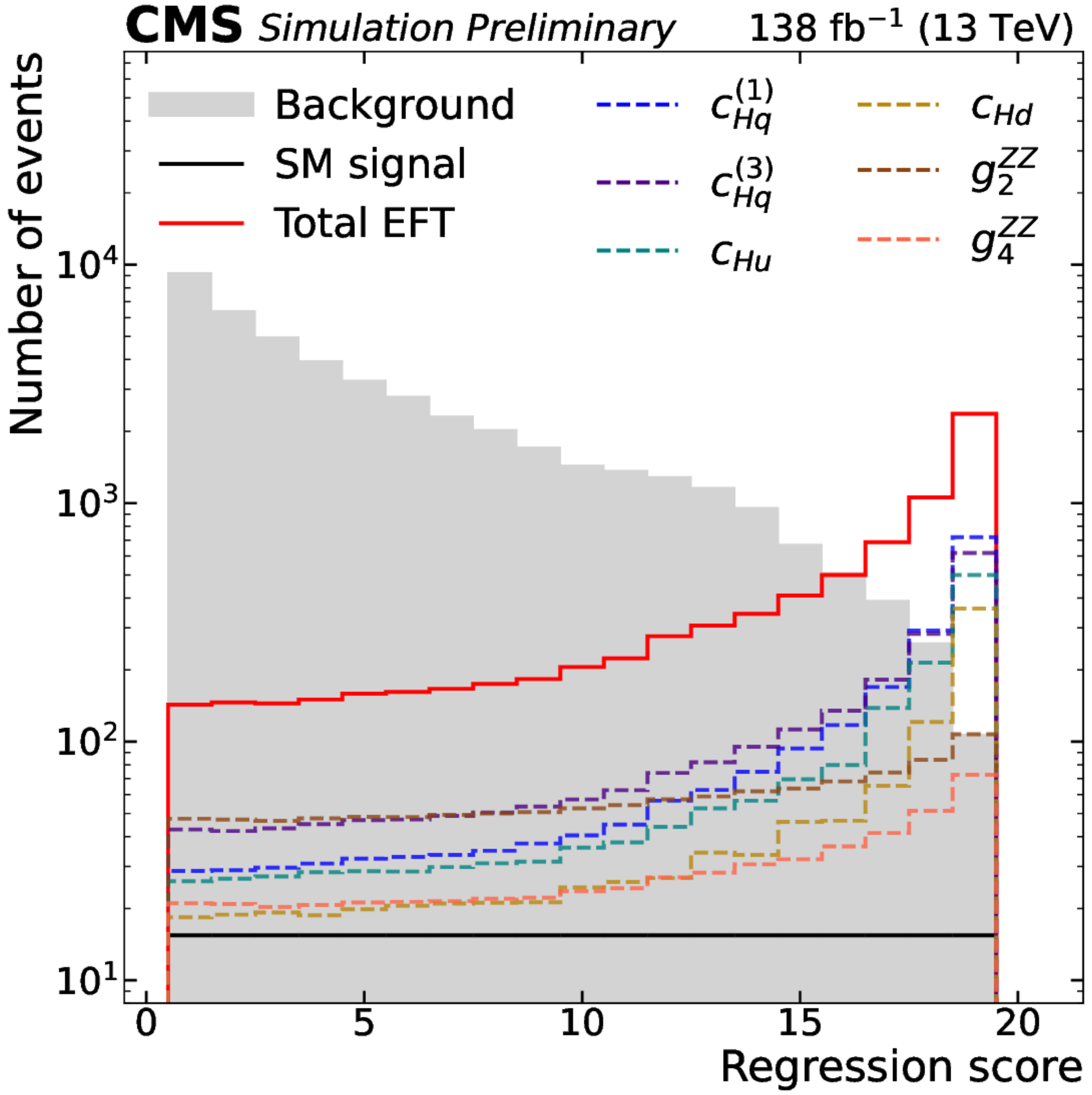
- Angular information to improve sensitivity to CP-even vs. CP-odd HVV couplings g_2^{ZZ}, g_4^{ZZ}
- Likelihood ratio observable estimated with [BIT] regression as optimal observable (kinematics + angular variables used in the training)
- Iterative approach to find an observable that performs optimally for each Wilson coefficient





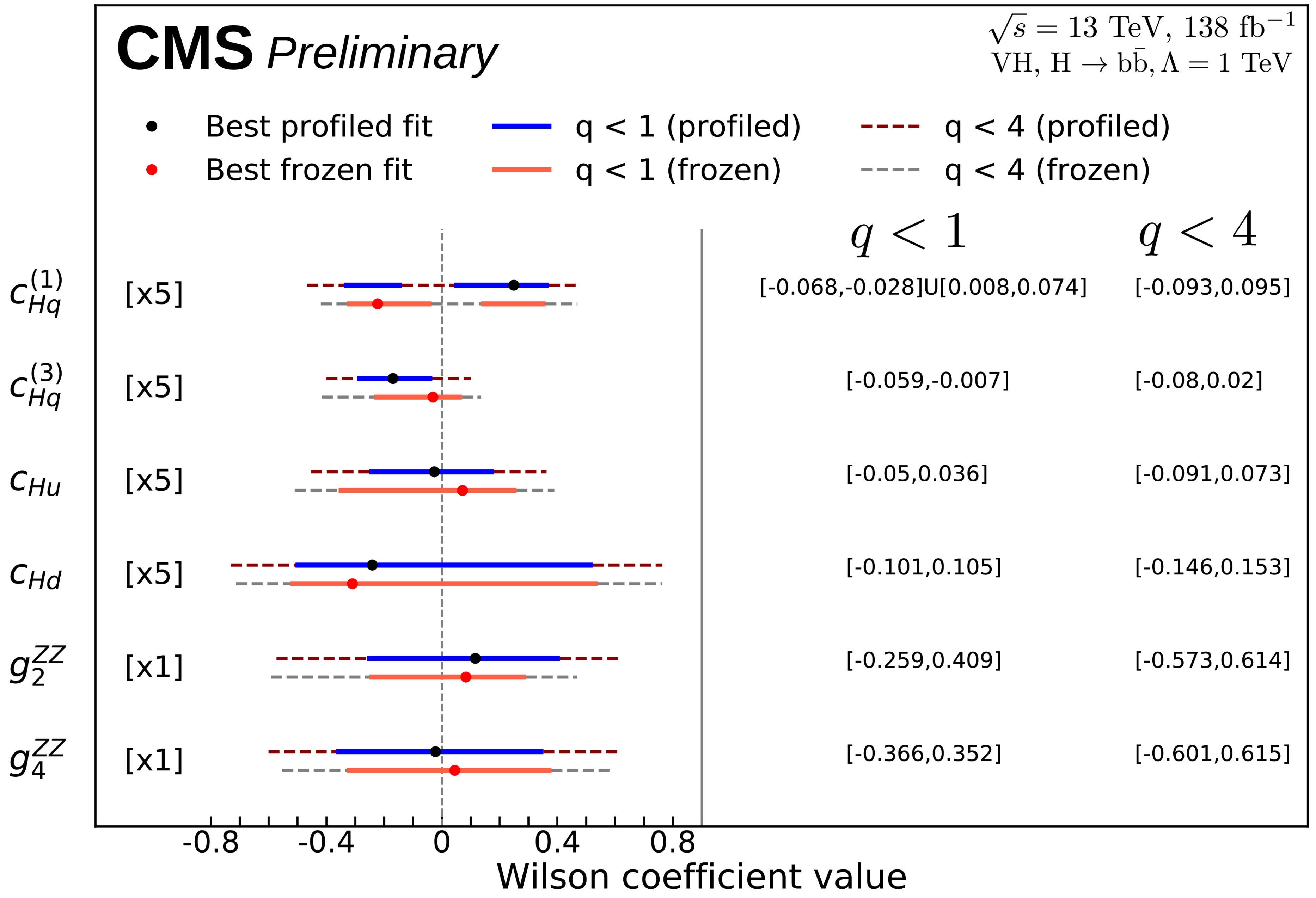
Method learns detector-level kinematics and propagates it to the output score

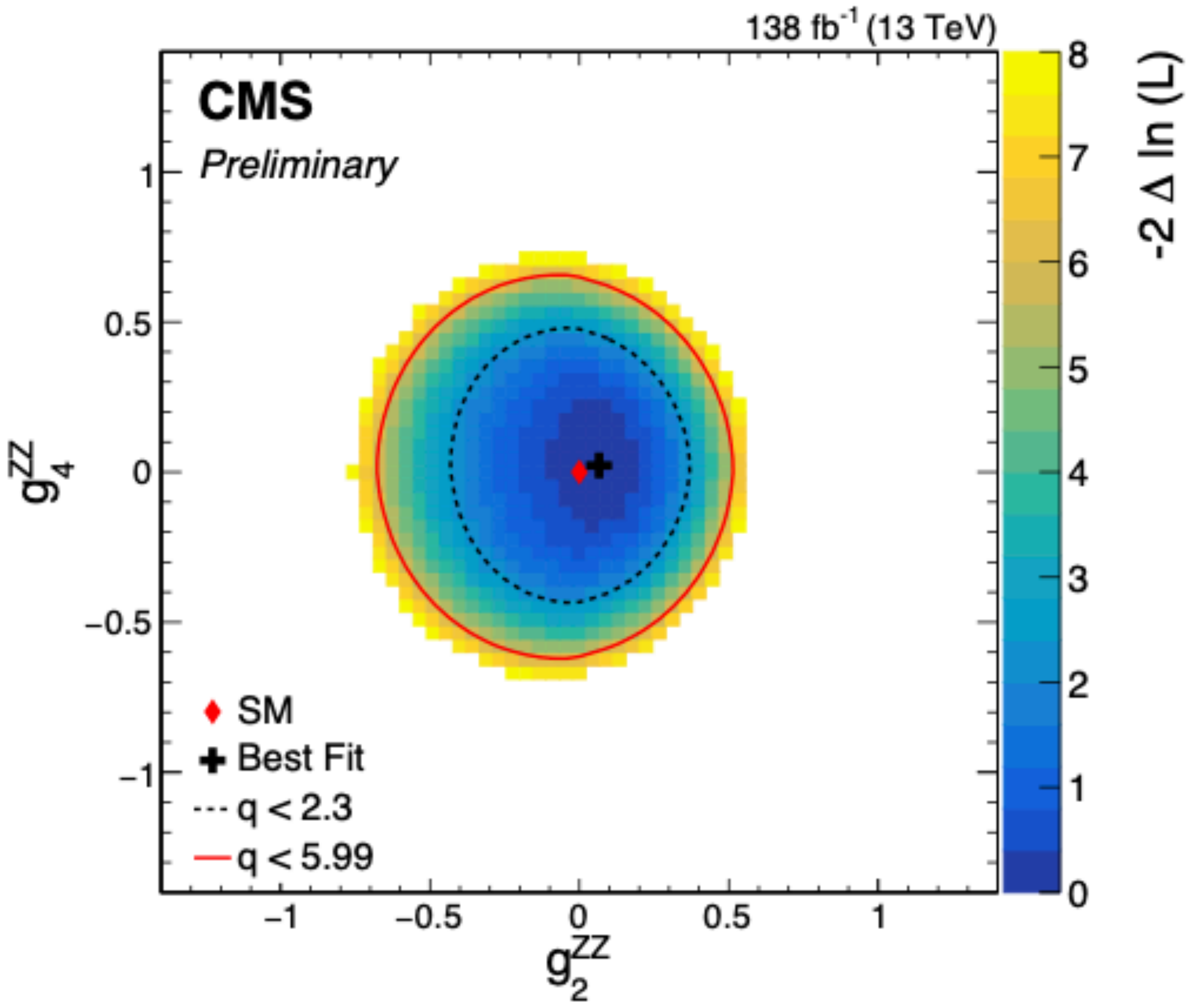
$$R(X|\vec{c}) = 1 + \sum_i R_i(X)c_i + \sum_{i,j} R_{i,j}(X)c_ic_j$$

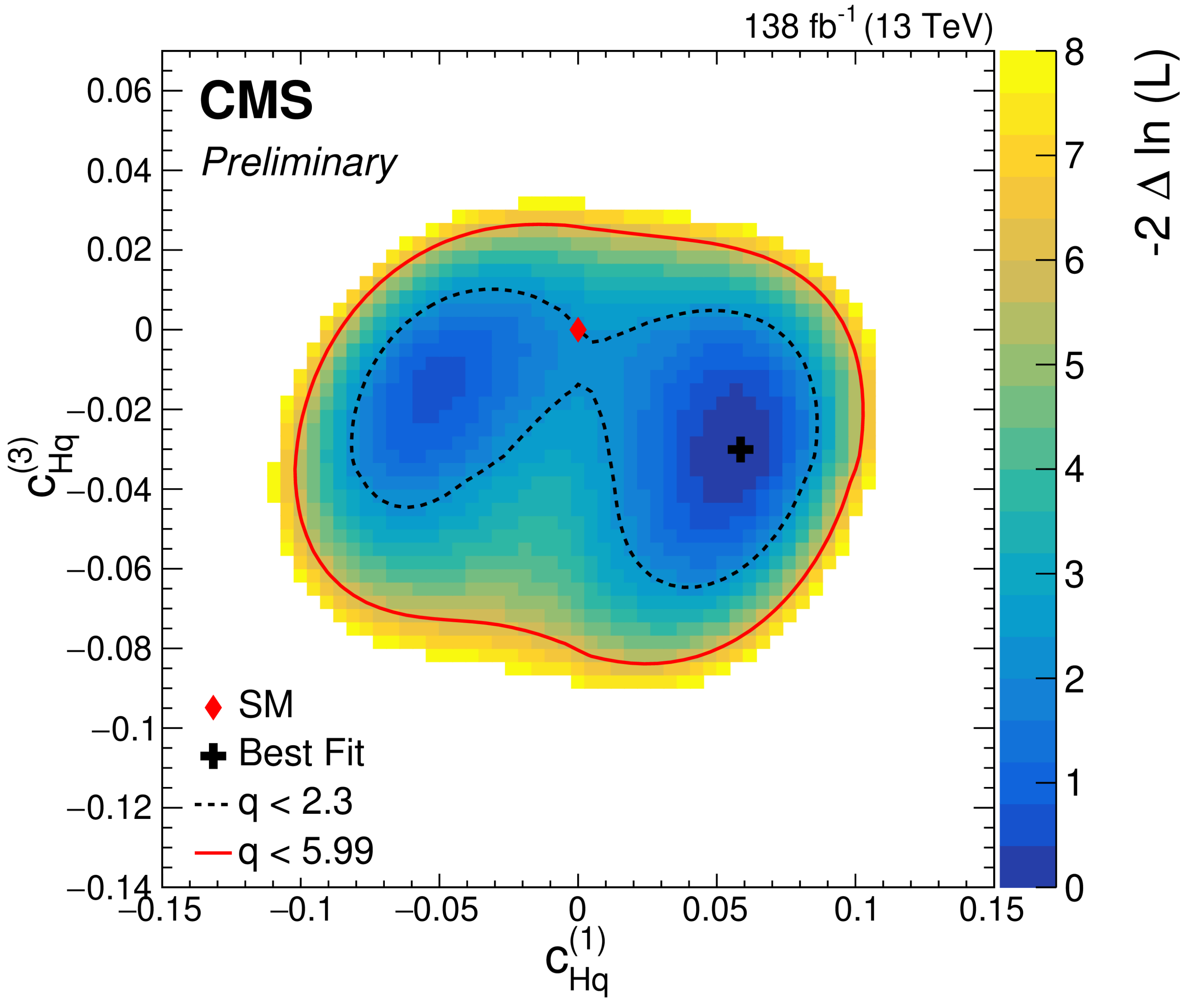
VH(H→bb) EFT analysis (CMS)

[talk by Vasilije Perovic]

CMS-HIG-23-016







- Negligible loss in the sensitivity from profiling the all parameters due to the optimized analysis observable

- Addition of CP-sensitive variables → access to the linear combination of CP-odd SMEFT WC

$$g_4^{ZZ} = \tilde{g}_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{H\tilde{B}} + c_w^2 c_{H\widetilde{W}} + s_w c_w c_{H\widetilde{W}B}\right)$$

H→WW MELA analyses (CMS)

[talk by Federica De Riggi]

[Eur. Phys. J. C 84 (2024) 779]

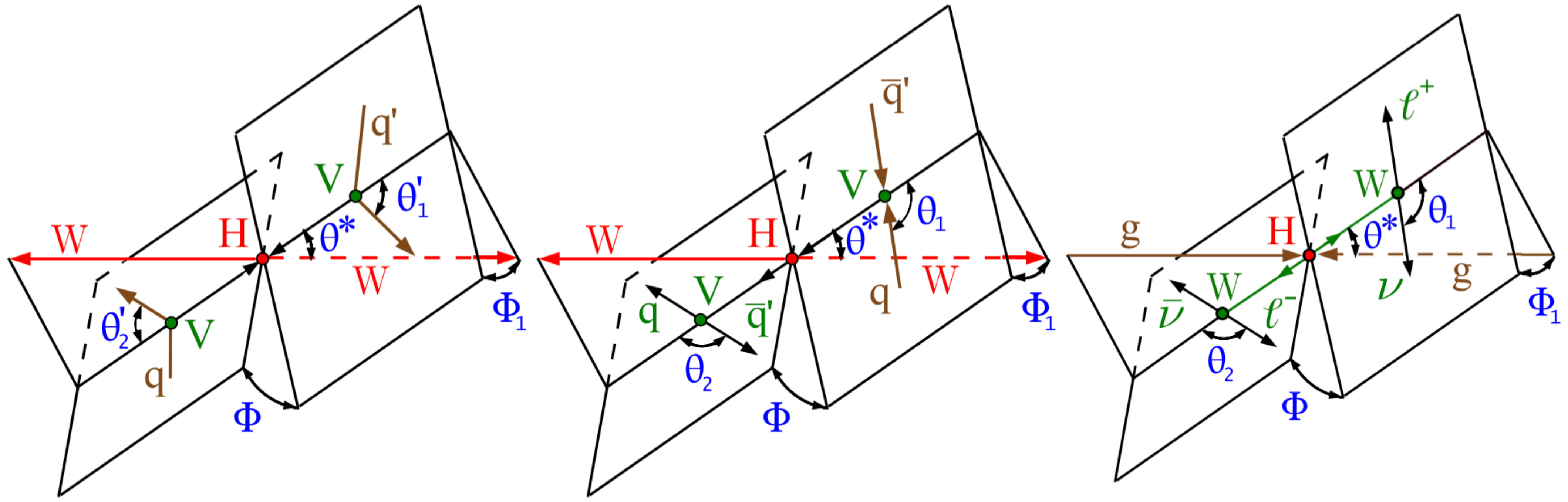
- Use MELA method to construct an observable sensitive to the modifications to Higgs production

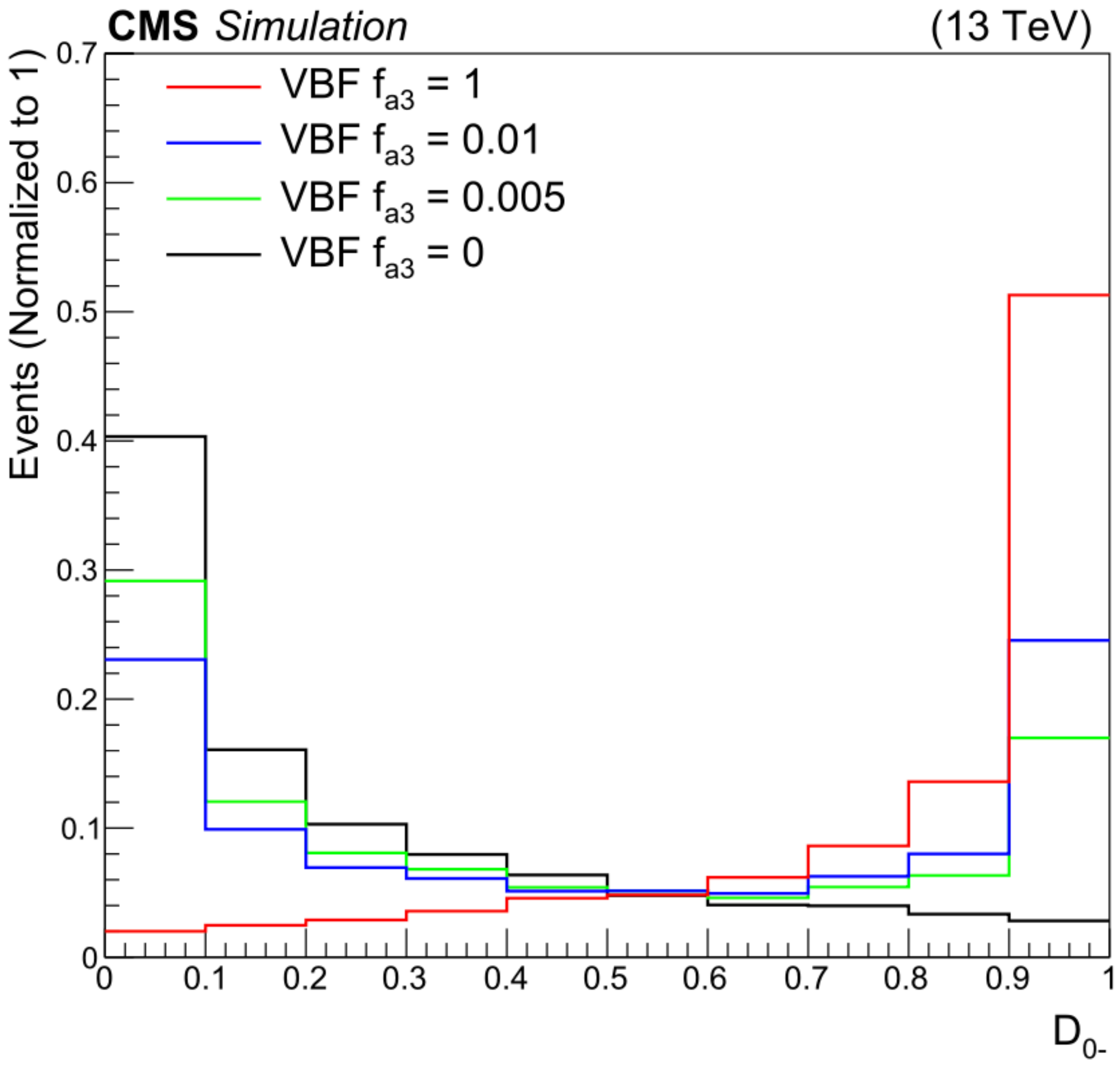
$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

- Granular fit to $[D_{VBF}, D_{0-}, m_{ll}]$

$$\mathcal{D}_{\mathrm{BSM}} = \frac{\mathcal{P}_{\mathrm{BSM}}(\Omega)}{\mathcal{P}_{\mathrm{BSM}}(\Omega) + \mathcal{P}_{\mathrm{SM}}(\Omega)}$$

- D_{VBF} - optimal observable to VBF production, D_{0-} - CP sensitive, m_{ll} observable is used to gain sensitivity to decay vertex





The output score is based on gen-level ME, better suited for leptonic final states

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[talk by Federica De Riggi]

[Eur. Phys. J. C 84 (2024) 779]

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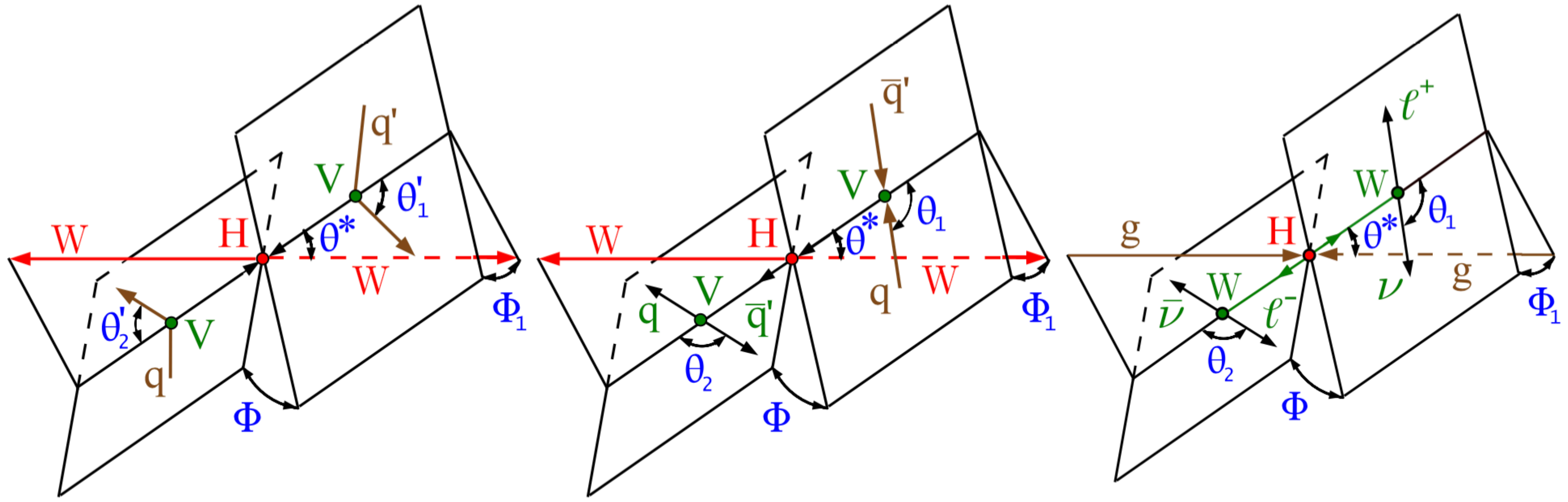

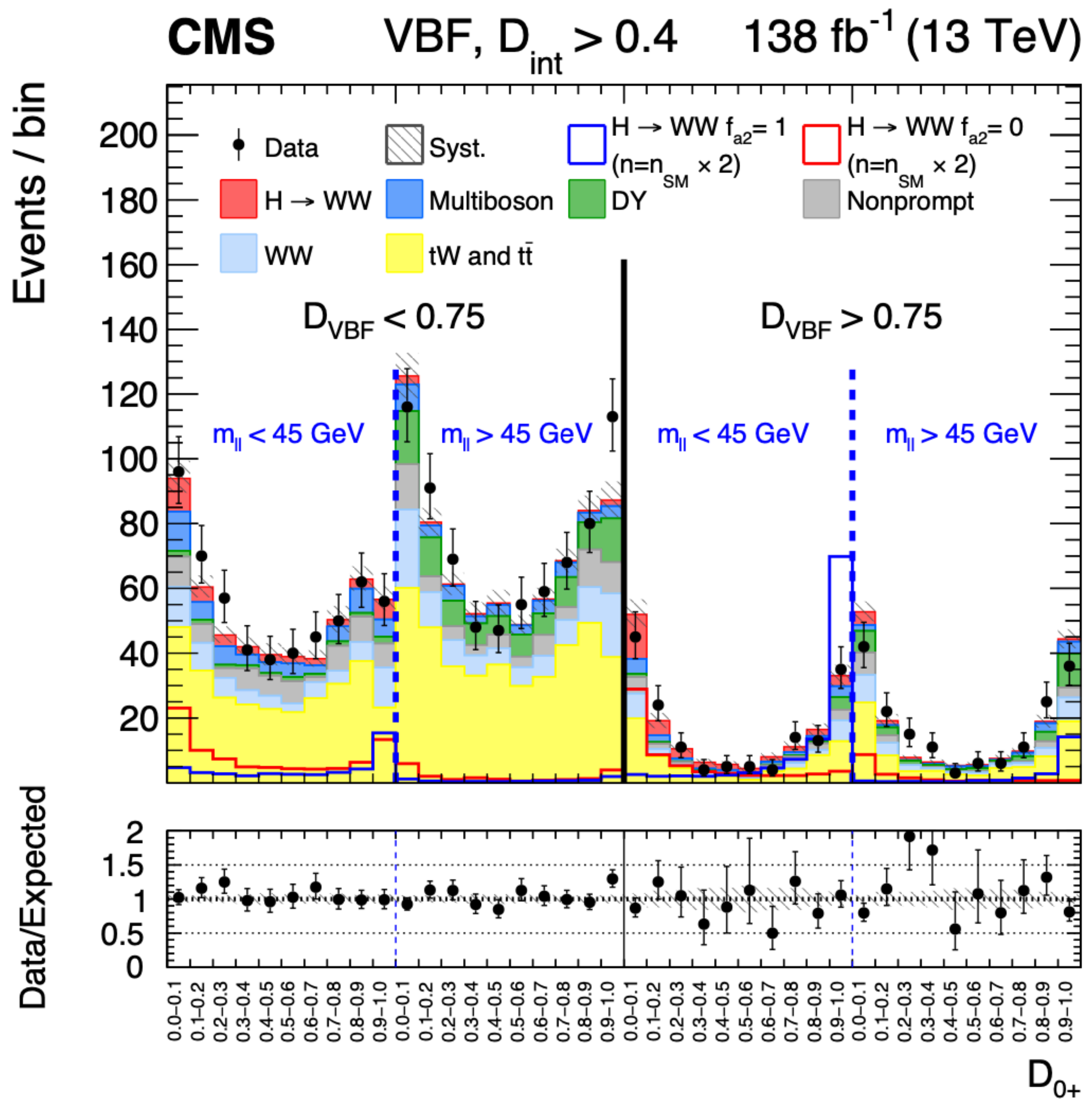

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H→WW MELA analyses (CMS)

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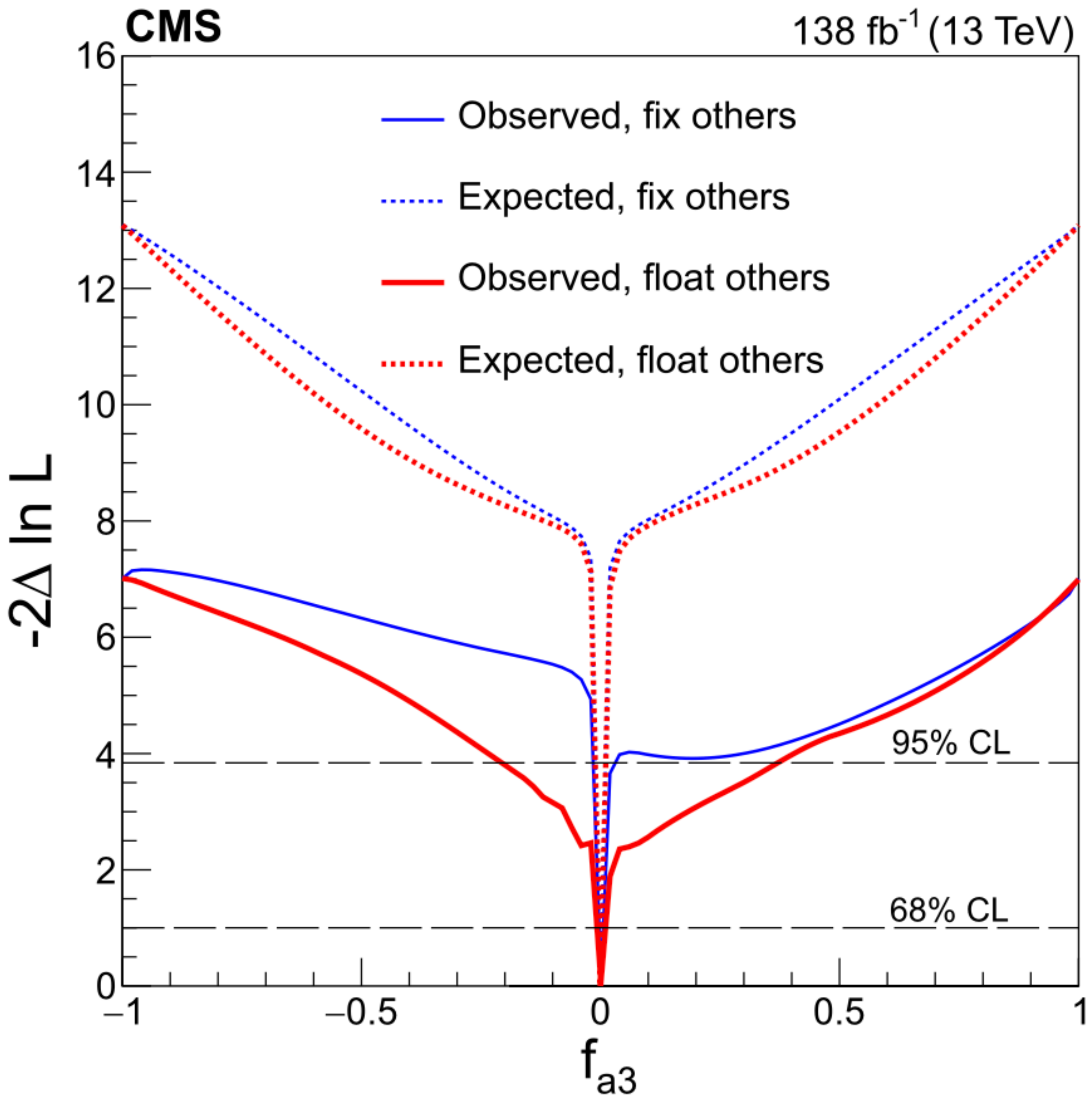
[Eur. Phys. J. C 84 (2024) 779]



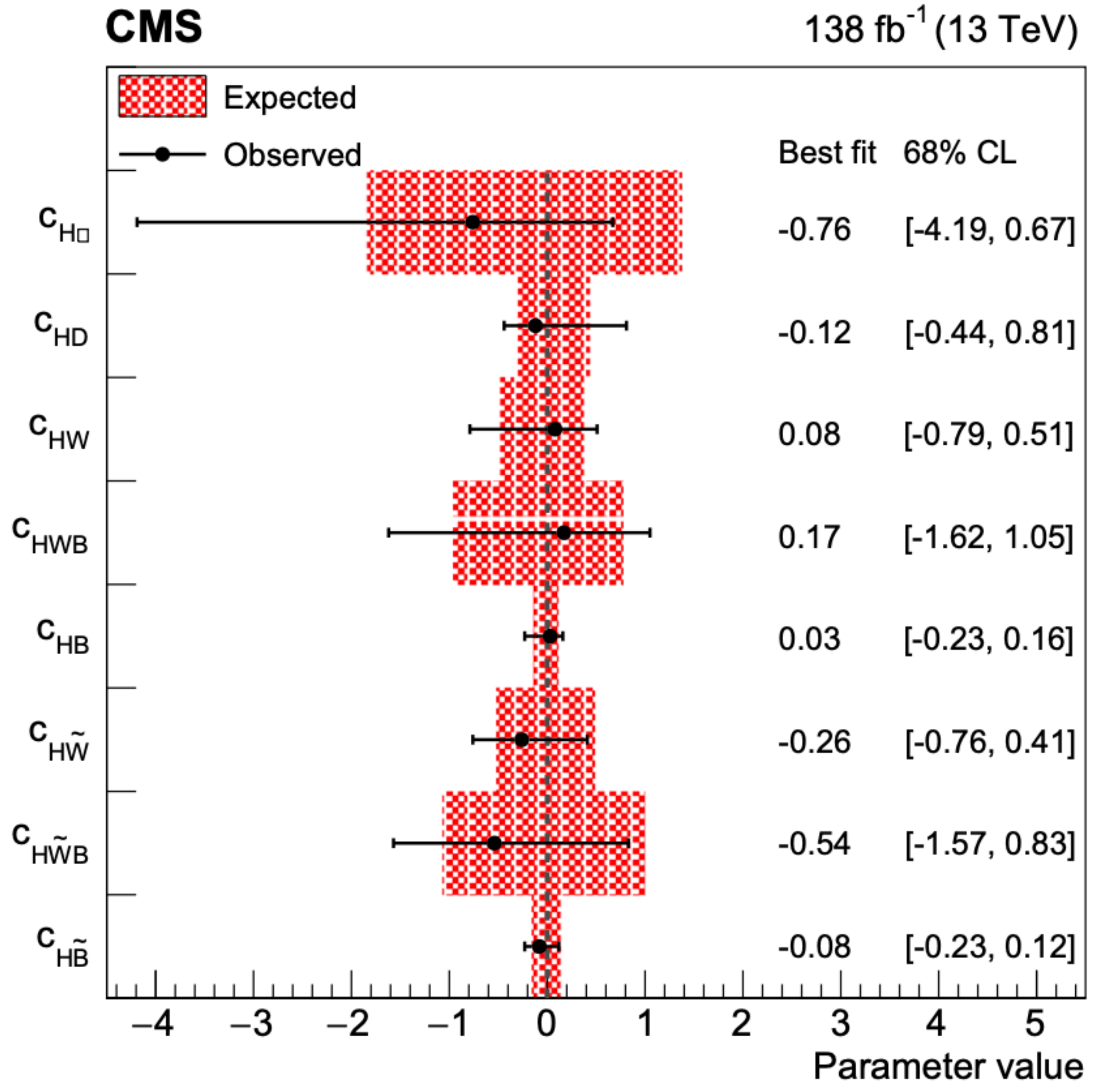
$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \, \mathrm{sign}\left(\frac{a_i}{a_1}\right)$$

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

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

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

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



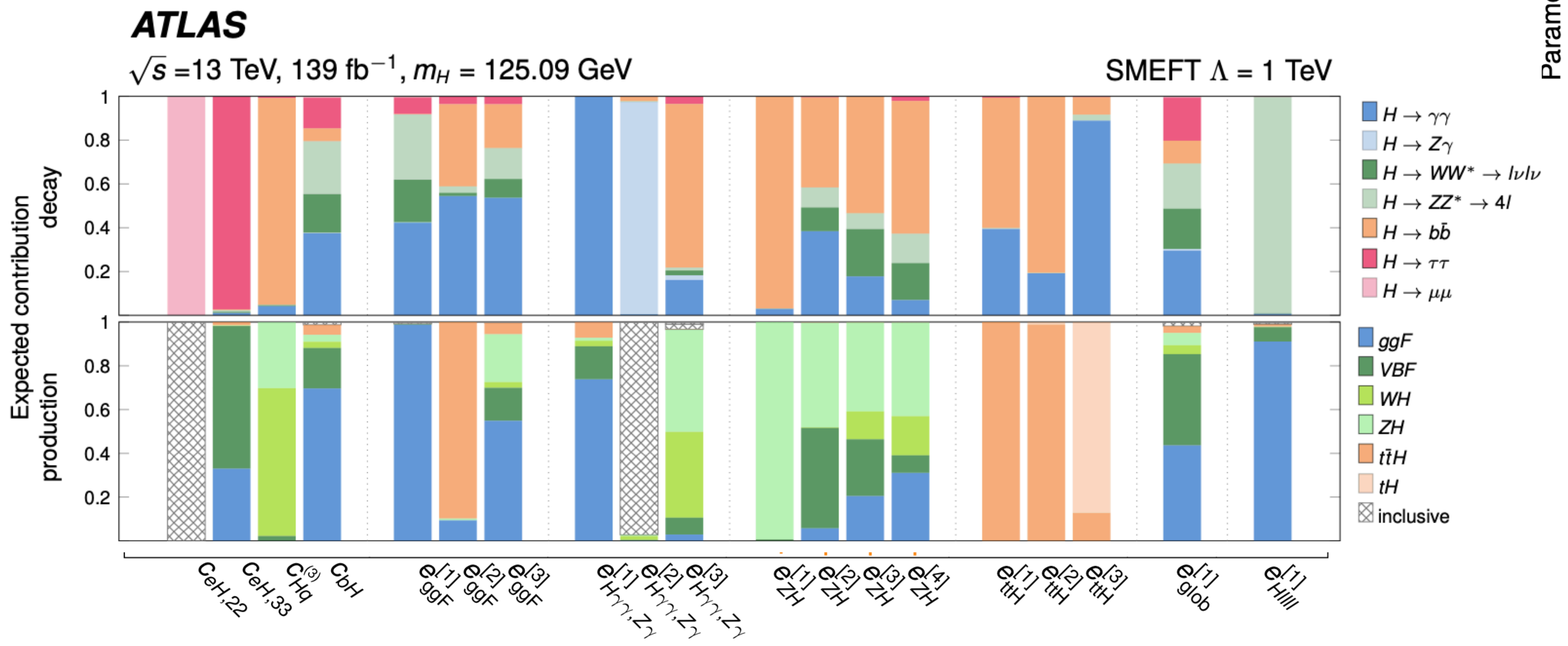
- Results extracted for HVV anomalous couplings, the most stringent to date
- Translated HVV constraints to SMEFT Higgs and Warsaw basis, all in agreement with the SM.

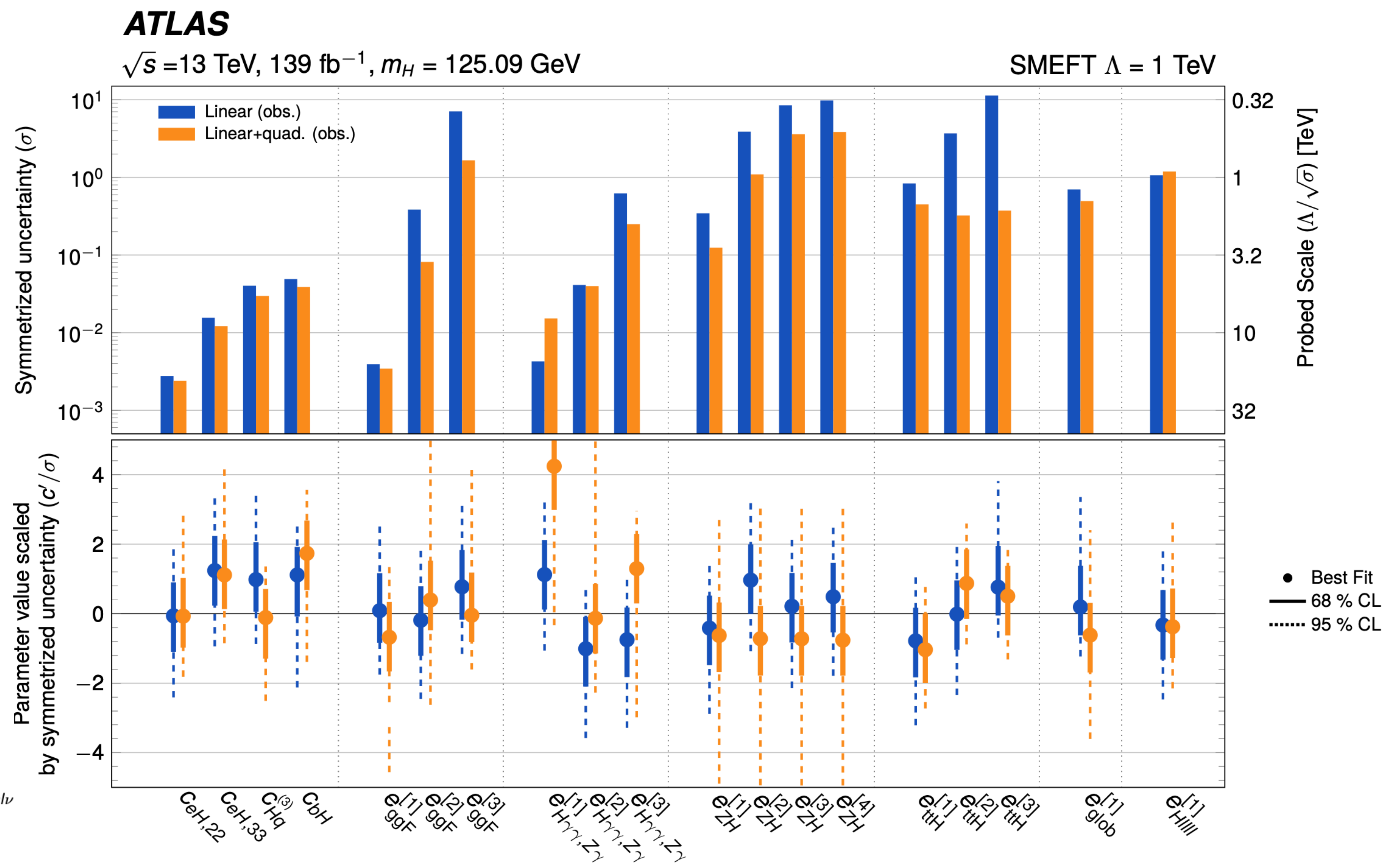
II. SMEFT combination

Higgs STXS combination in ATLAS [talk by Oliver Rieger]

[ANA-HIGG-2022-17-PAPER]

- STXS combination + SMEFT interpretation $H \to \gamma\gamma$, $H \to W^+W^-$, $H \to ZZ^{(*)}$, $H \to \tau^+\tau^-$, $H \to b\bar{b}$, $H \to \mu^+\mu^-$, $H \to Z\gamma$
- Starting with 46 WC identified 15 linear combinations and 4 single coefficients
- Sensitivity from different channels in the combination





- Results agree with the SM at 95% CL
- Interpretation in 2HDM and MSSM models by matching SMEFT parameters to 2HDM

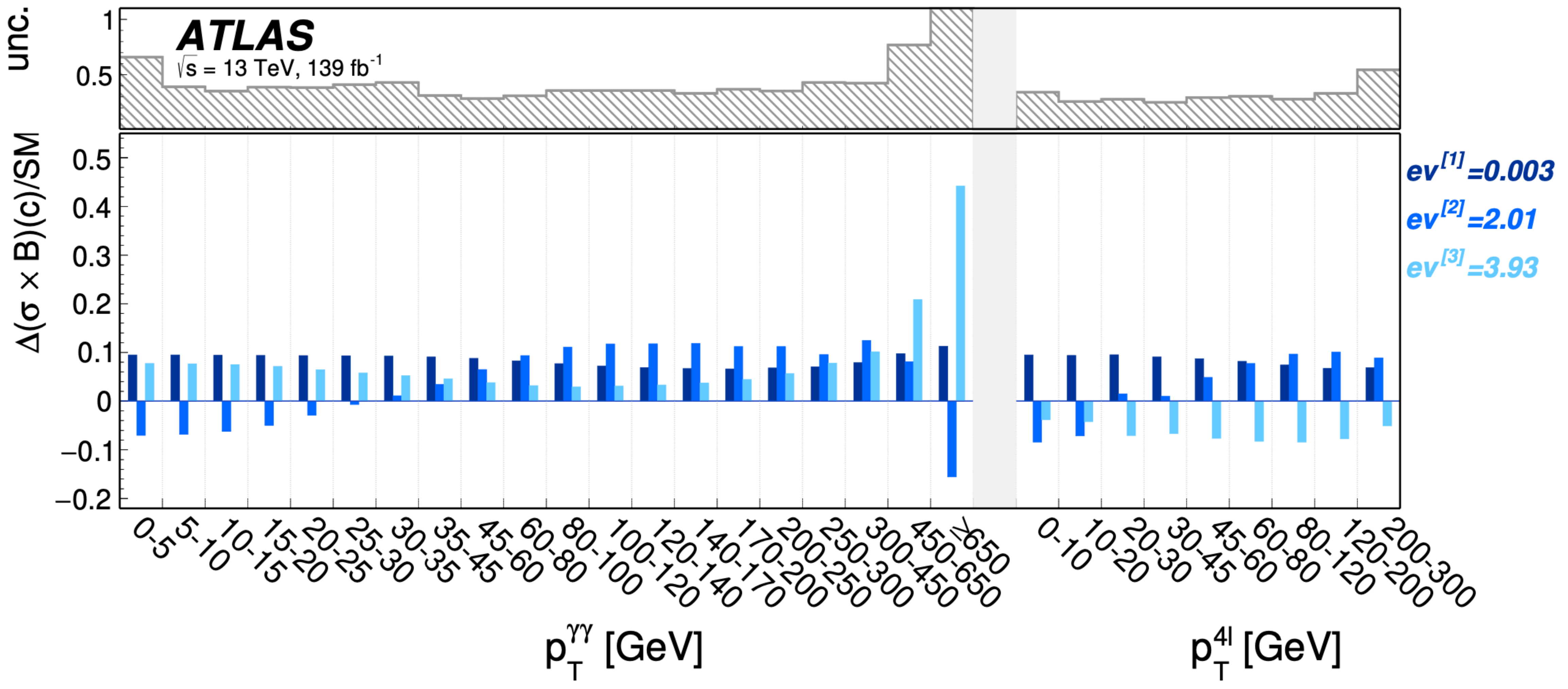
Higgs differential combination in ATLAS

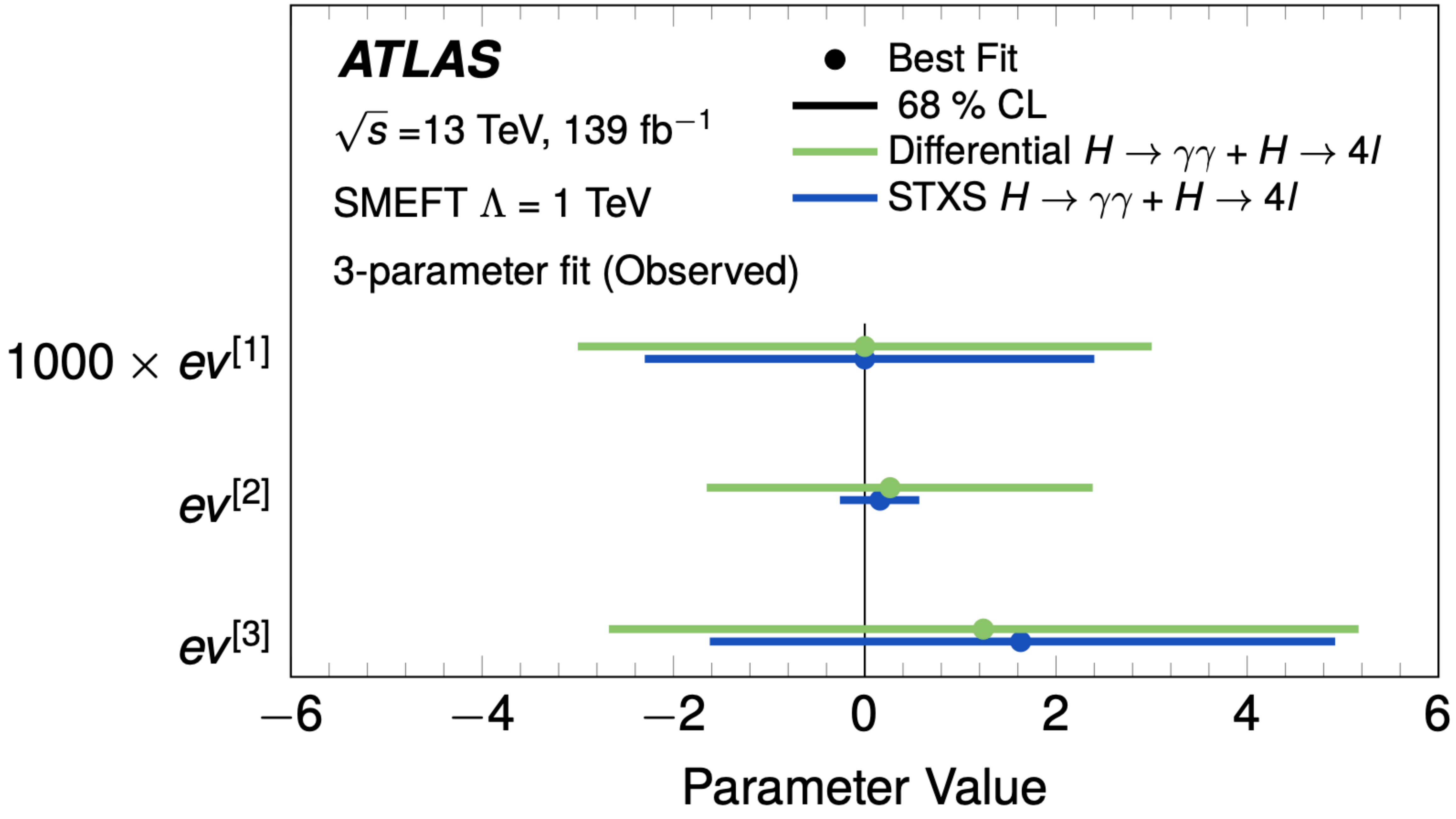
[ANA-HIGG-2022-17-PAPER]

- Performed the differential combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ measurements
- Constraining 3 linear combinations of Wilson coefficients

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

- While fiducial measurements is more granular than STXS, sensitivity is lower
  - Inclusive in Higgs production modes
  - Demonstrates importance of STXS





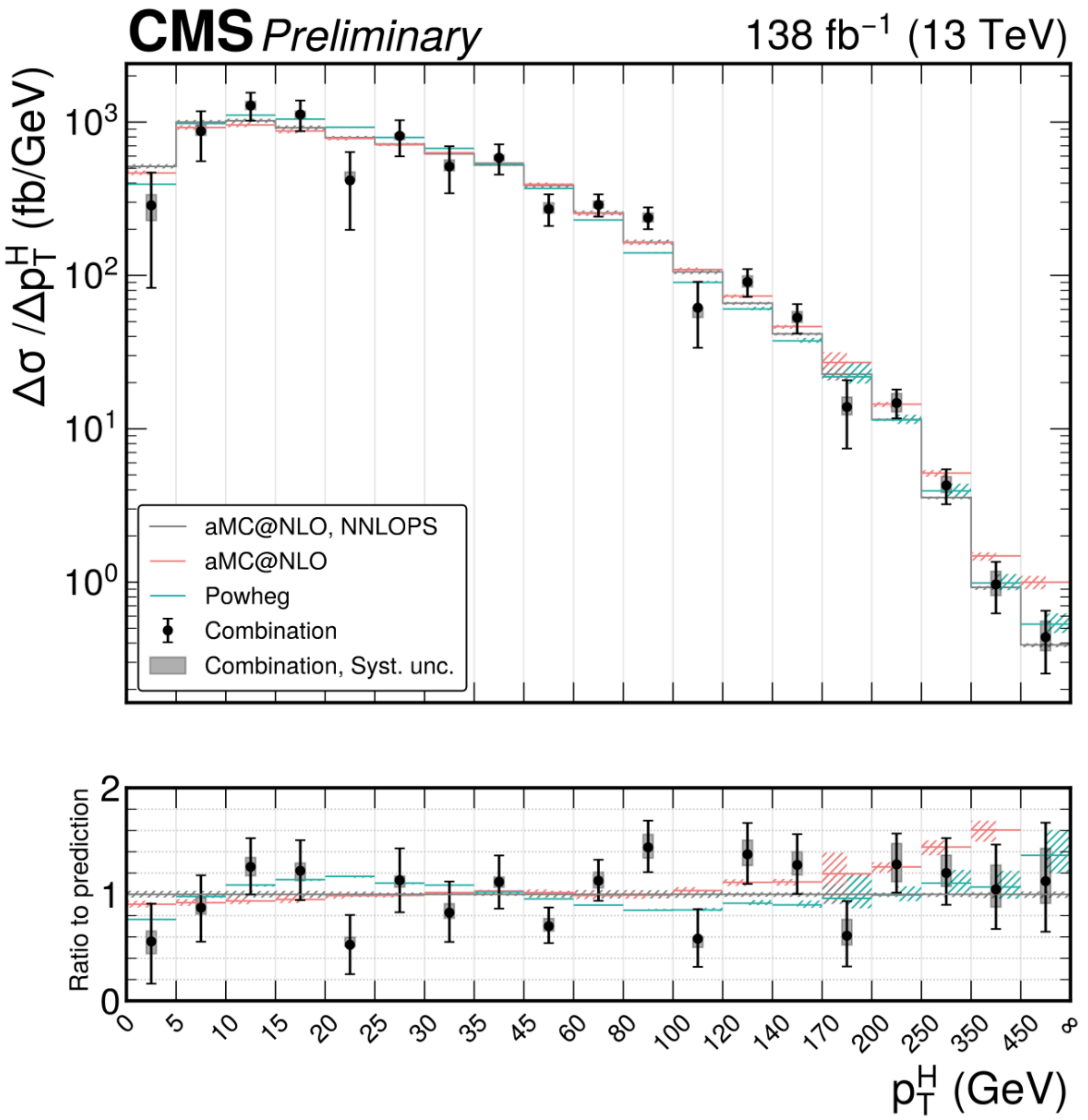
Higgs differential combination in CMS

[talk by Massimiliano Galli] [CMS-HIG-23-013]

- Interpretation of differential combination
  - $H \to \gamma\gamma, H \to W^+W^-, H \to ZZ^{(*)} \to 4l,$ $H \to \tau^+\tau^-, H \to \tau^+\tau^-$ (boosted)

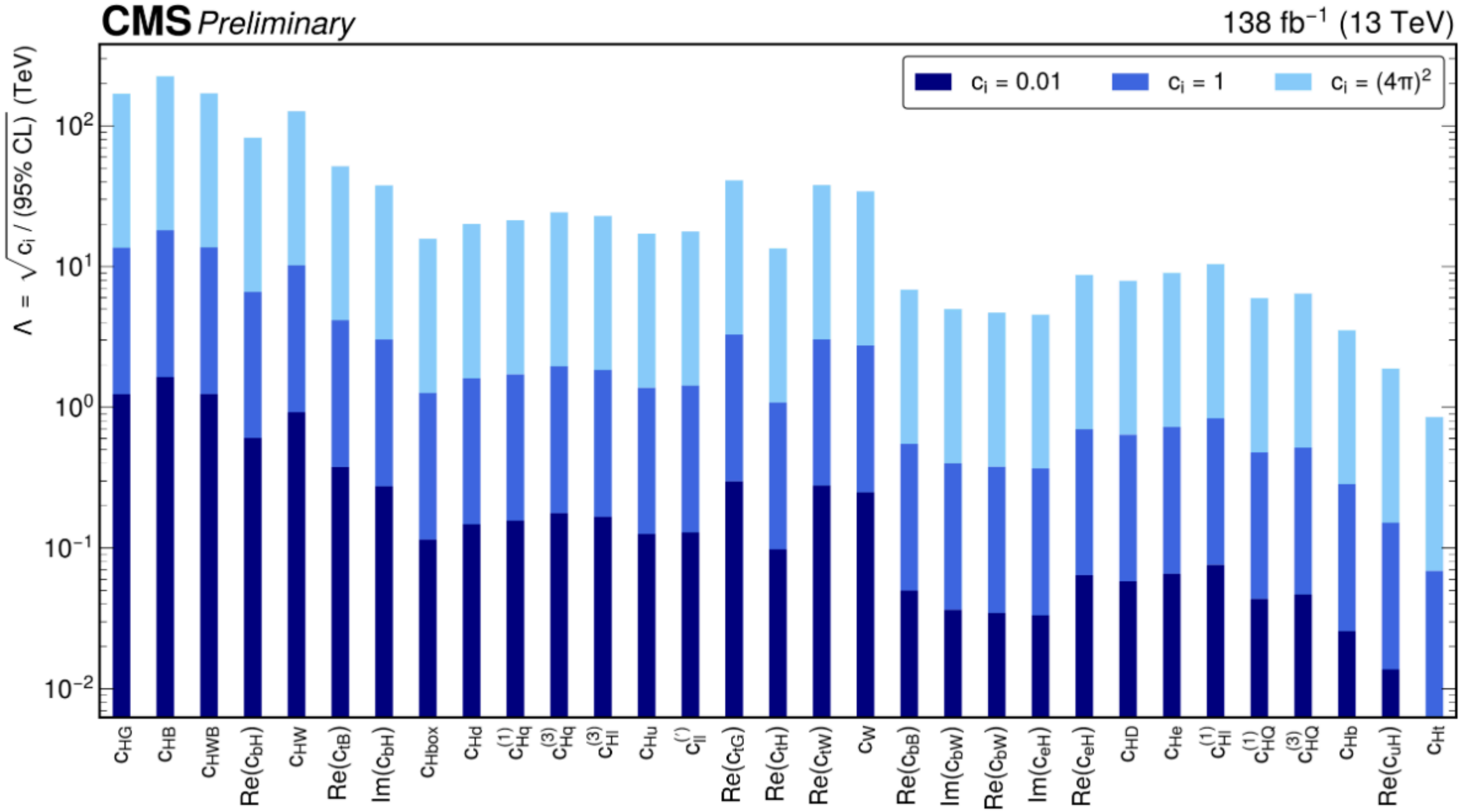
$$\mu_i^X(c_j) = \frac{(\sigma \times \mathcal{B})^{i,H\to X}}{(\sigma \times \mathcal{B})^{i,H\to X}_{\text{SM}}} = \left(1 + \frac{\sigma^i_{\text{int}}}{\sigma^i_{\text{SM}}} + \frac{\sigma^i_{\text{BSM}}}{\sigma^i_{\text{SM}}}\right) \left(\frac{1 + \frac{\Gamma^{H\to X}_{\text{int}}}{\Gamma^{H\to X}_{\text{SM}}} + \frac{\Gamma^{H\to X}_{\text{BSM}}}{\Gamma^{H\to X}_{\text{SM}}}}{1 + \frac{\Gamma^{H}_{\text{int}}}{\Gamma^{H}_{\text{SM}}} + \frac{\Gamma^{H}_{\text{BSM}}}{\Gamma^{H}_{\text{SM}}}}\right)$$

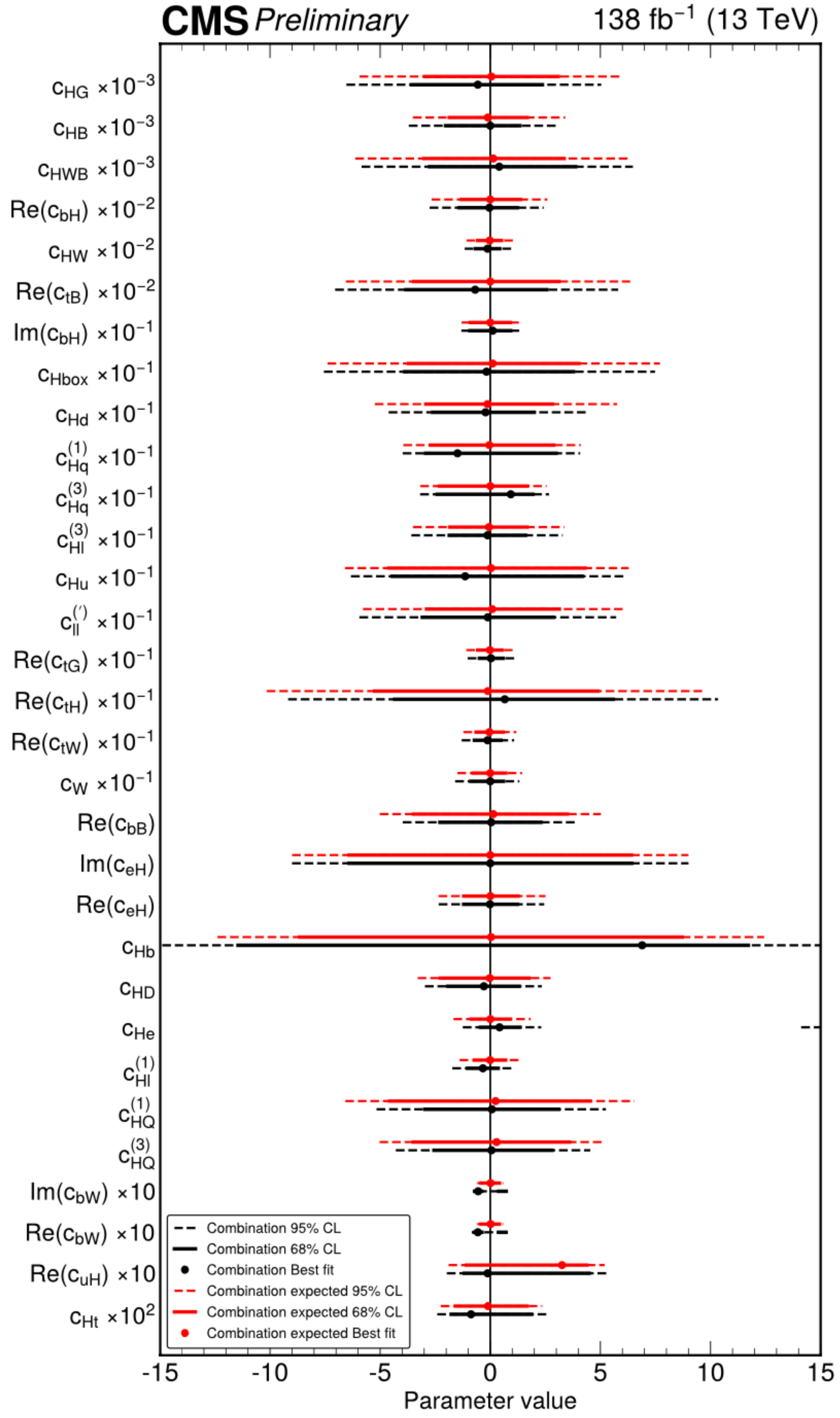
  - p_T^H (+ studied $\Delta\phi_{jj}$ in $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4l$, for CP-odd) used for SMEFT interpretation
  - Parametrization is derived in fiducial regions



Higgs differential combination in CMS

[CMS-HIG-23-013]

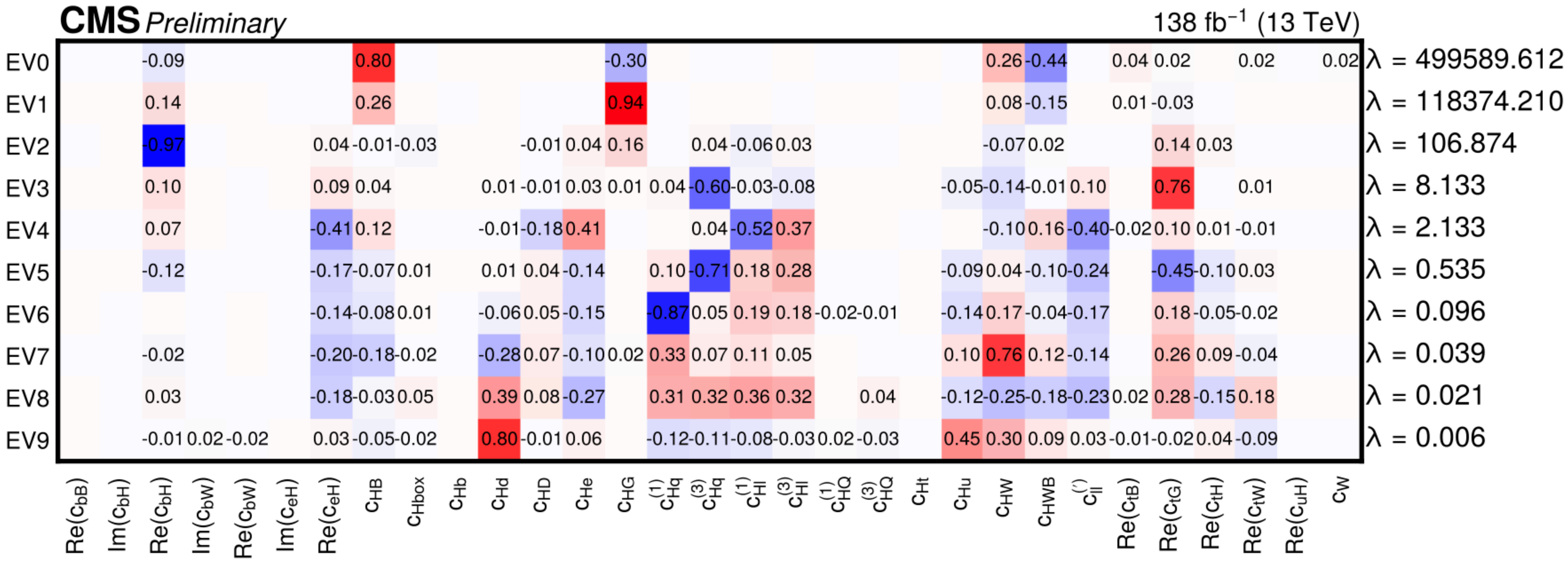


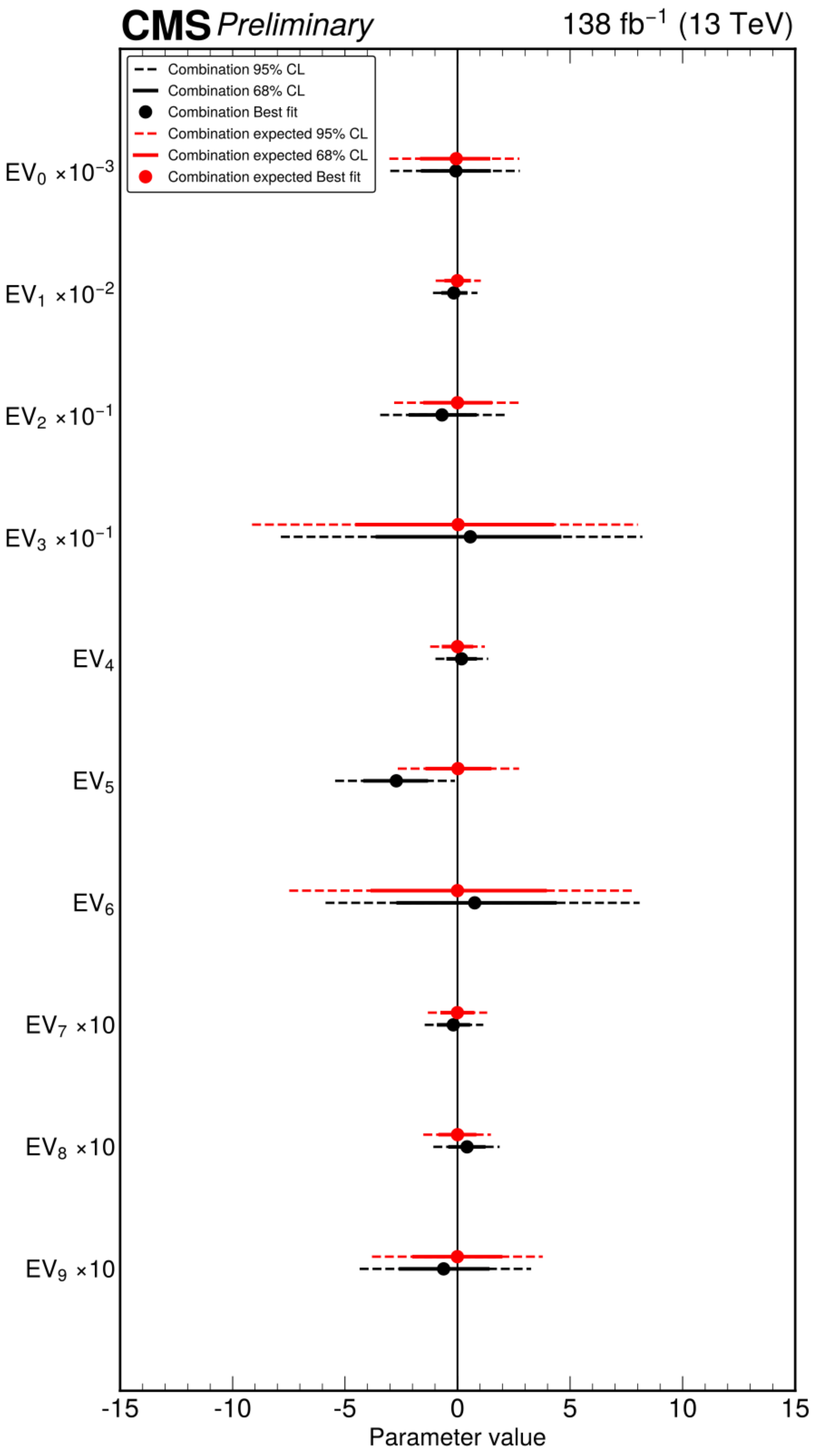


- 31 operators are considered (including CP-odd)
- Individual measurements for each c_i (other fixed $c_j = 0,\ i \neq j$)

Higgs differential combination in CMS

[CMS-HIG-23-013]

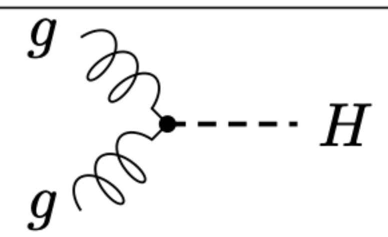
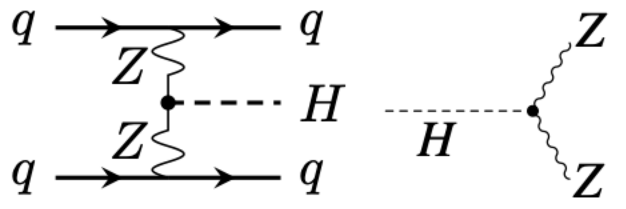
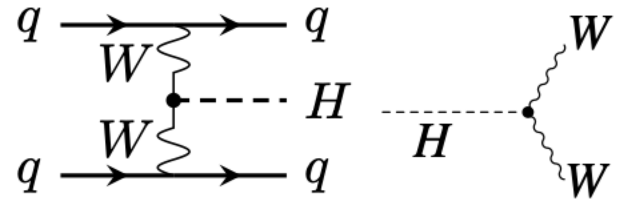
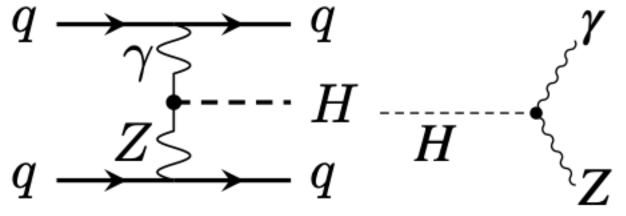




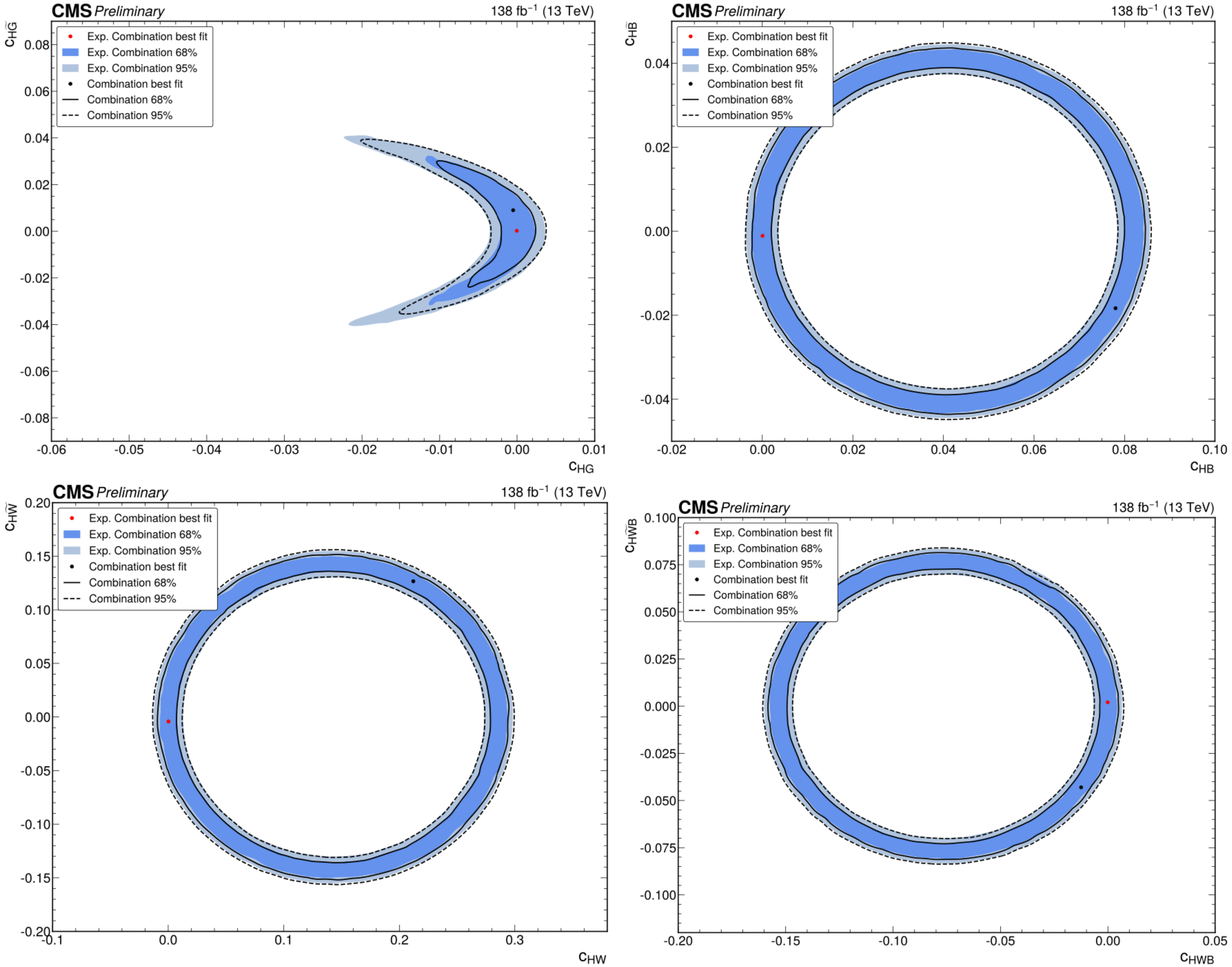
- 31 operators are considered (including CP-odd)
- PCA is applied to identify 10 linear combinations that can be constrained simultaneously
- All results are in agreement with the SM ($c_i = 0$) at 95%CL

Higgs differential combination in CMS

[CMS-HIG-23-013]

Class	Operator	Wilson coefficient	Example process
$\mathcal{L}_6^{(4)} - X^2H^2$	$H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$	c_{HG}	
	$H^\dagger H \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$	$\tilde{c}_{HG}$	
	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	c_{HB}	
	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\tilde{c}_{HB}$	
	$H^\dagger H W^i_{\mu\nu} W^{i\mu\nu}$	c_{HW}	
	$H^\dagger H \tilde{W}^i_{\mu\nu} W^{i\mu\nu}$	$\tilde{c}_{HW}$	
	$H^\dagger \sigma^i H W^i_{\mu\nu} B^{i\mu\nu}$	c_{HWB}	
	$H^\dagger \sigma^i H \tilde{W}^i_{\mu\nu} B^{i\mu\nu}$	$\tilde{c}_{HWB}$	

- 2D scans CP-odd vs. CP even Wilson coefficients
- All results are in agreement with the SM ($c_i = 0$) at 95%CL



EFT Constraints from Higgs + EWK (ATLAS)

[ATL-PHYS-PUB-2022-037]

LHC measurements:

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]

+

Diboson

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]

[ATL-PHYS-PUB-2022-037]

EW precision measurements (LEP):

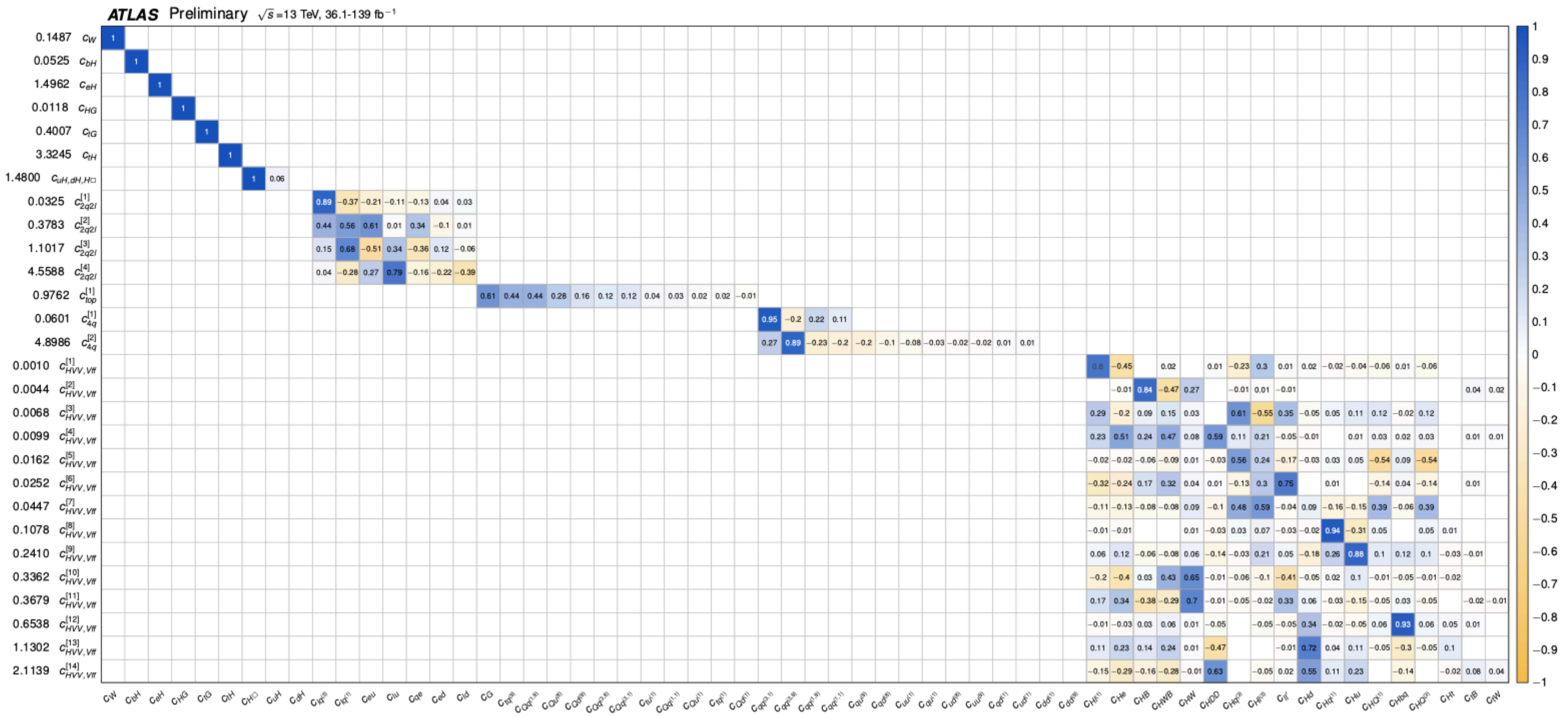
Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R_ℓ^0	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R_c^0	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R_b^0	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010	0.01718 ± 0.00037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

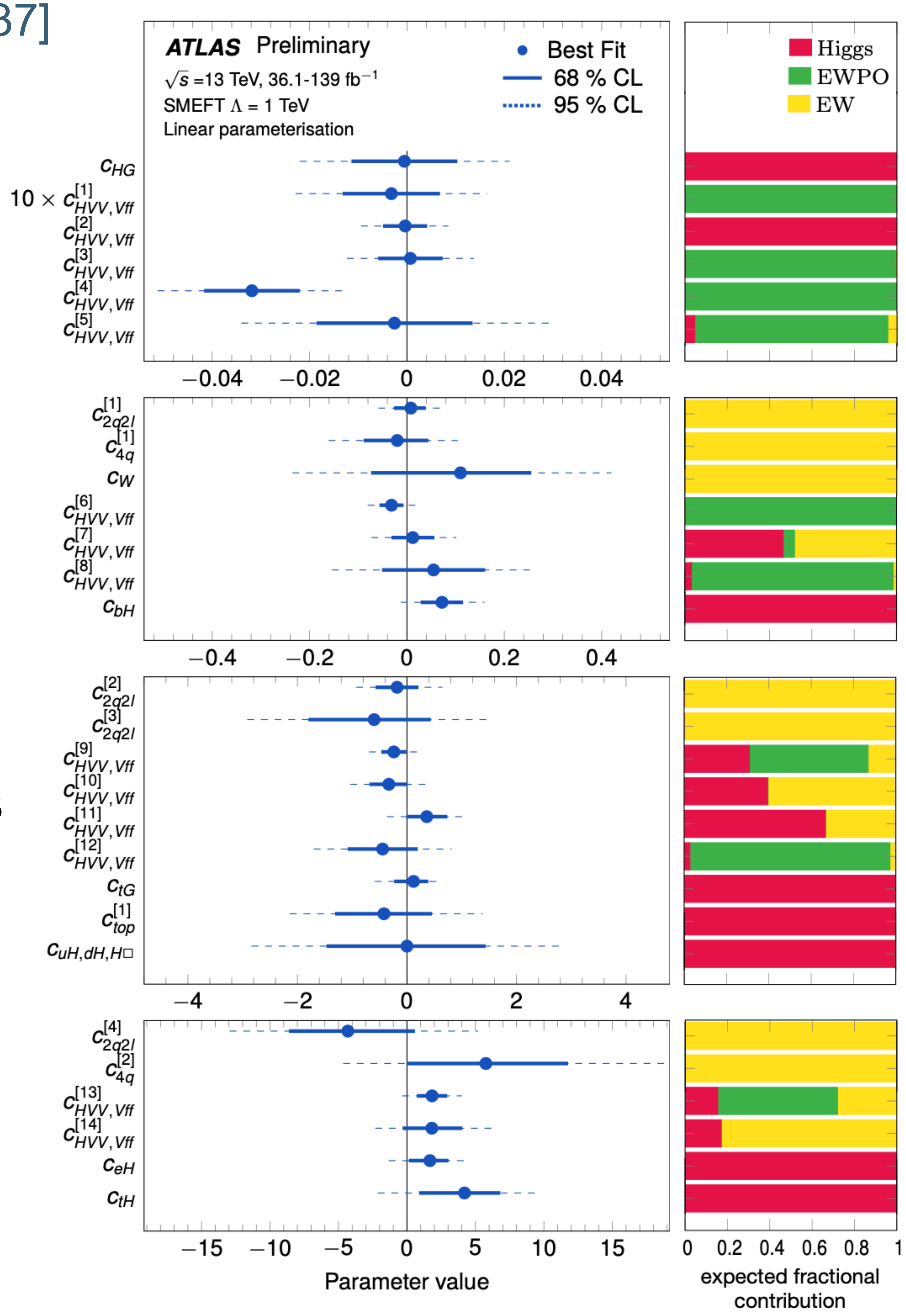
+

Input parameters	Value	Ref.
m_Z [GeV]	91.1876 ± 0.0021	[43]
m_W [GeV]	80.387 ± 0.016	[42]
m_h [GeV]	125.10 ± 0.14	[43]
m_t [GeV]	172.4 ± 0.7	[43]
m_b [GeV]	4.18 ± 0.03	[43]
m_c [GeV]	1.27 ± 0.02	[43]
m_τ [GeV]	1.77686 ± 0.00012	[43]
G_F [GeV^{-2}]	$1.1663787 \cdot 10^{-5}$	[43]
α_{EW}	1/137.03599084(21)	[43]
α_s	0.1179 ± 0.0010	[43]
$\Delta\alpha$	0.0576 ± 0.0008	[45]

EFT Constraints from Higgs + EWK (ATLAS)

[ATL-PHYS-PUB-2022-037]





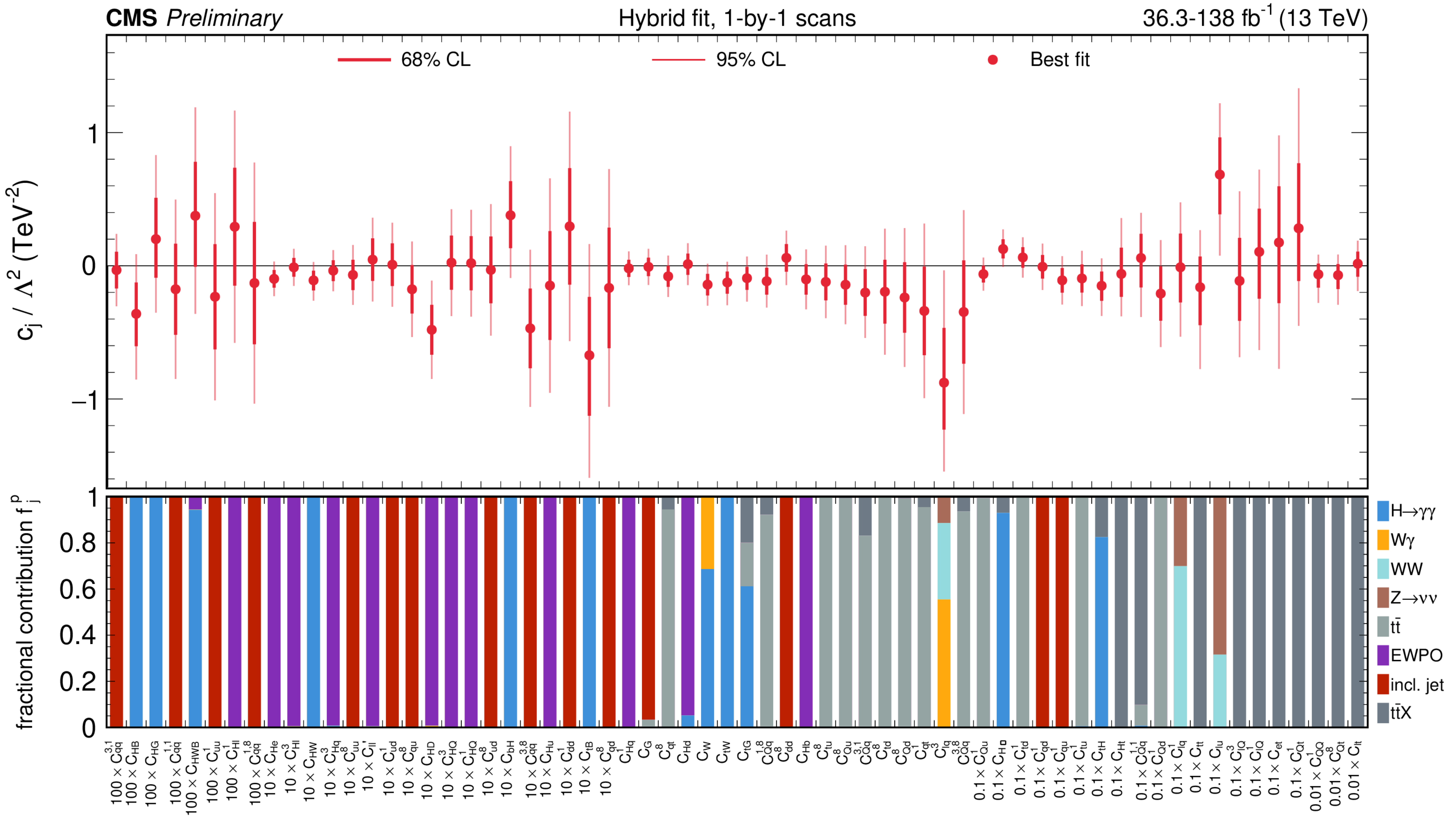
- Performing PCA on subgroups of WC to remove flat directions
  → constraints for 22 linear combinations and 6 WC
- Many LC benefit from Higgs + EWK combination
- Compatible with the SM at 95% CL

Higgs + EWK + Top combination in CMS

[CMS-SMP-24-003]

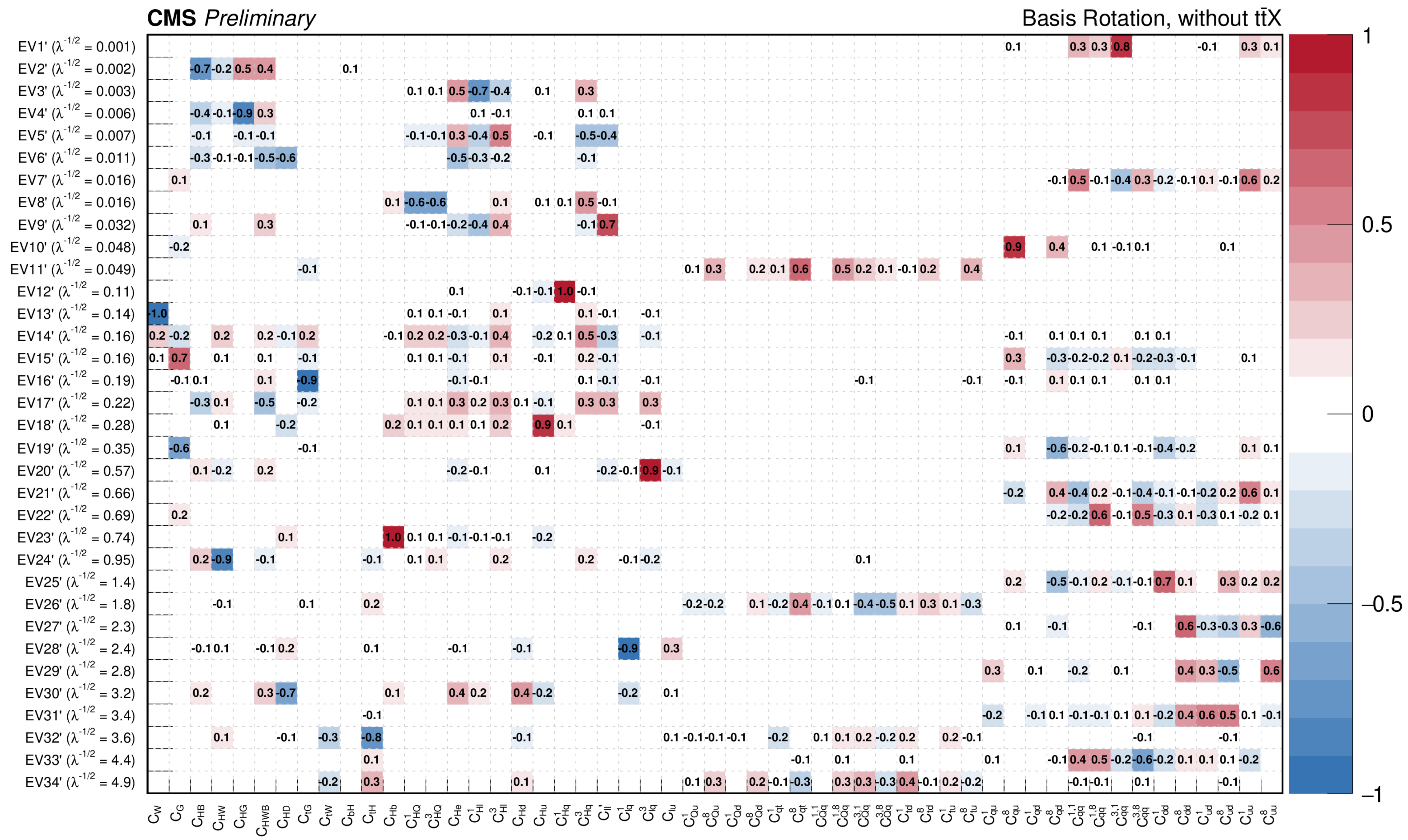
Analysis	Type of measurement	Observables used	Experimental likelihood
$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]	✓
$W\gamma$	Fid. diff. cross sections	$p_T^\gamma \times \|\phi_f\|$	✓
WW	Fid. diff. cross sections	$m_{\ell\ell}$	✓
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^Z	✓
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$	×
EWPO	Pseudo-observables	$\Gamma_Z,\ \sigma^0_{had},\ R_\ell,\ R_c,\ R_b,\ A^{0,\ell}_{FB},\ A^{0,c}_{FB},\ A^{0,b}_{FB}$	×
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \|y^{jet}\|$	×
$t\bar{t}X$	Direct EFT	Yields in regions of interest	✓

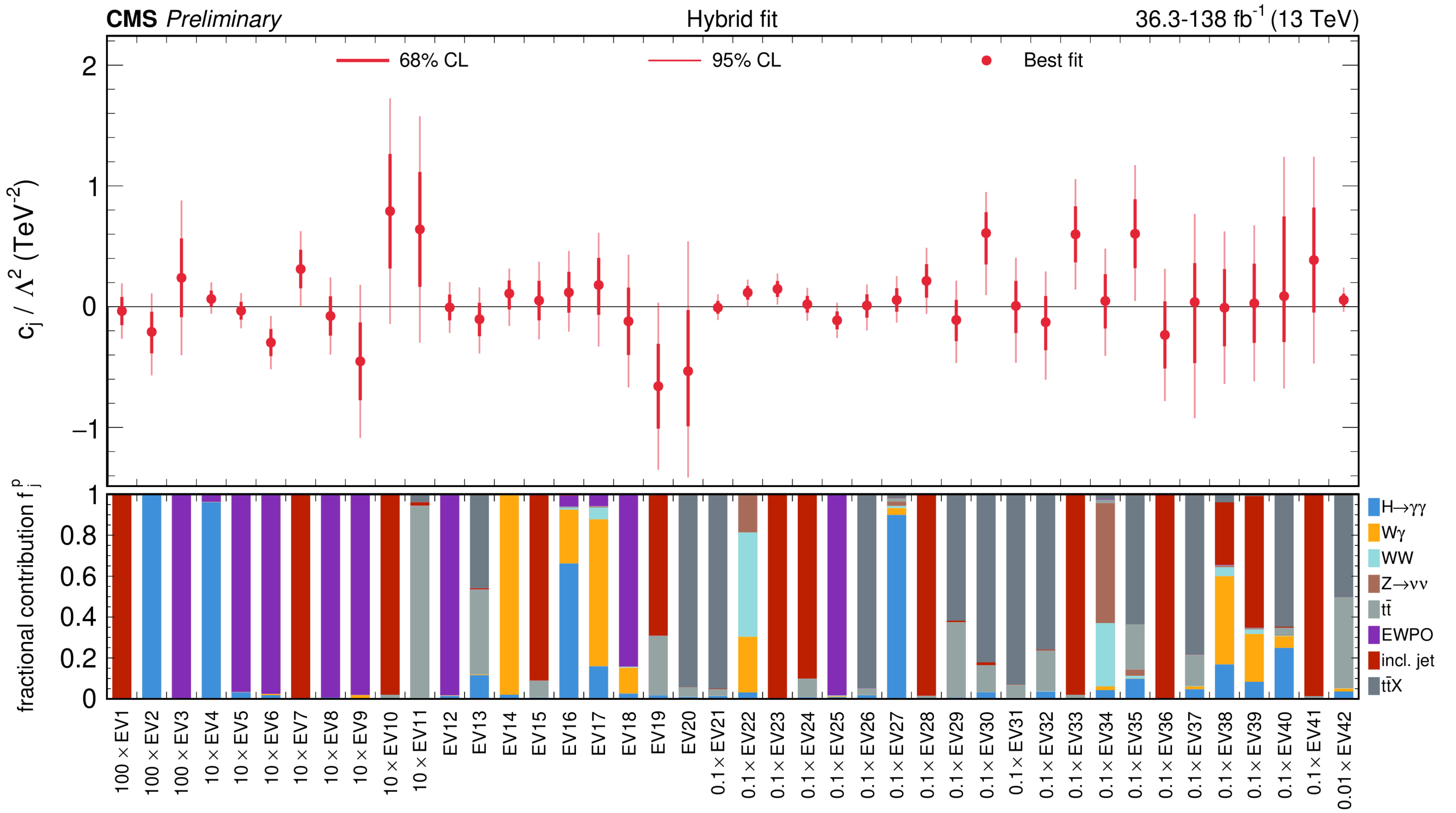
- Similar measurement from CMS where 64 WC are considered
- Achieved by selecting input analysis to target various groups of WC
  - from Higgs sector: $H \to \gamma\gamma$ is selected as the one with highest STXS granularity



Higgs + EWK + Top combination in CMS

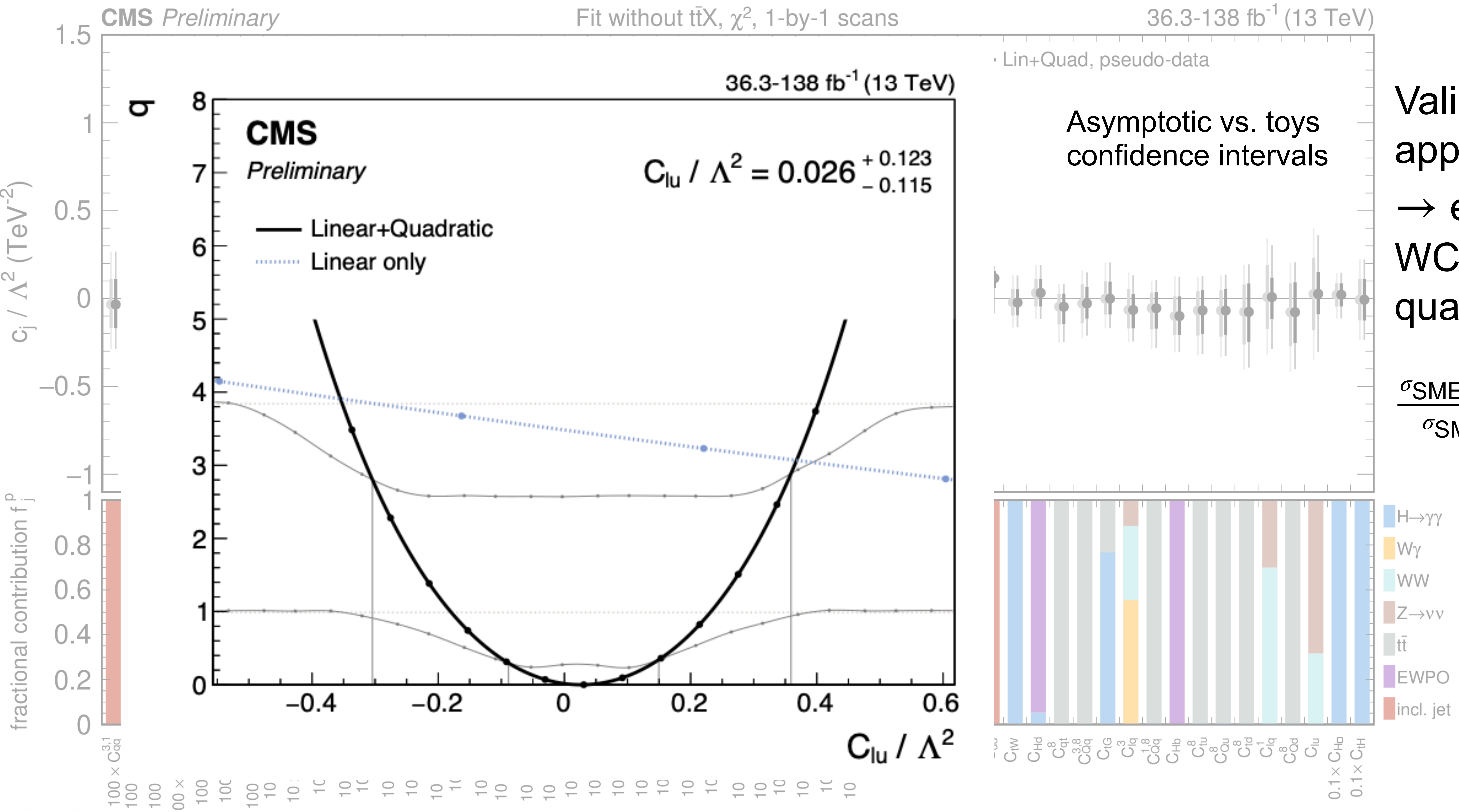
[CMS-SMP-24-003]





- Global PCA is performed to identify 42 linear combinations of WC that can be constrained simultaneously, 9 of which clearly benefit from including non Higgs channels (EWK and Top)
- The results are in agreement with the SM at the level of 1.7 %

Higgs + EWK + Top combination in CMS



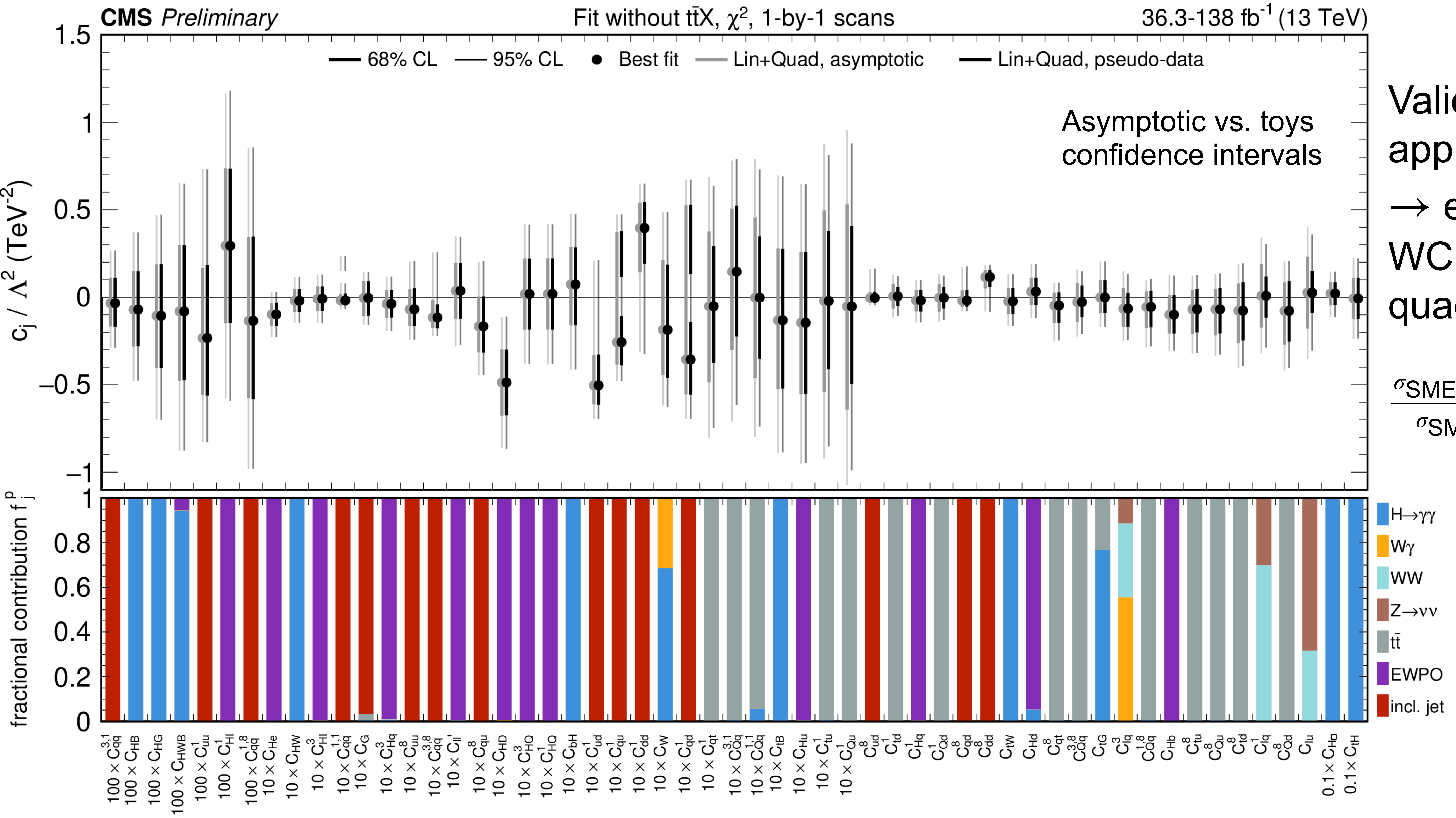
[CMS-SMP-24-003]

Validity of asymptotic approximation was studied → effect is important for the WC with significant quadratic contribution

$$\frac{\sigma_{\text{SMEFT}}}{\sigma_{\text{SM}}} = 1 + \sum_j A^i_{p,j} \frac{c_j}{\Lambda^2} + \boxed{\sum_{j,k} B^i_{p,jk} \frac{c_j c_k}{\Lambda^4}}$$

Higgs + EWK + Top combination in CMS

[CMS-SMP-24-003]



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$$\frac{\sigma_{\mathrm{SMEFT}}}{\sigma_{\mathrm{SM}}} = 1 + \sum_j A^i_{p,j} \frac{c_j}{\Lambda^2} + \boxed{\sum_{j,k} B^i_{p,jk} \frac{c_j c_k}{\Lambda^4}}$$

Summary

- ATLAS and CMS both have a reach program of indirect NP searches with SMEFT framework
- Exploring equally important approaches:
  - Optimal observables with individual analyses, e.g. CP-odd vs. CP-even

    ATLAS H→4l [ATL-PHYS-PUB-2023-012]

    CMS VH(H→bb) EFT analysis [CMS-HIG-23-016]

    CMS EFT interpretation in H→WW MELA [Eur. Phys. J. C 84 (2024) 779]
  - Global combinations allow to consider O(10) - making interpretations more model-independent

    ATLAS STXS + fiducial combination of Higgs channels [ANA-HIGG-2022-17-PAPER]

    CMS Higgs differential combination [CMS-HIG-23-013]

    ATLAS Higgs + EWK [ATL-PHYS-PUB-2022-037]

    CMS Higgs + EWK + Top [SMP-24-003]

Thank you!

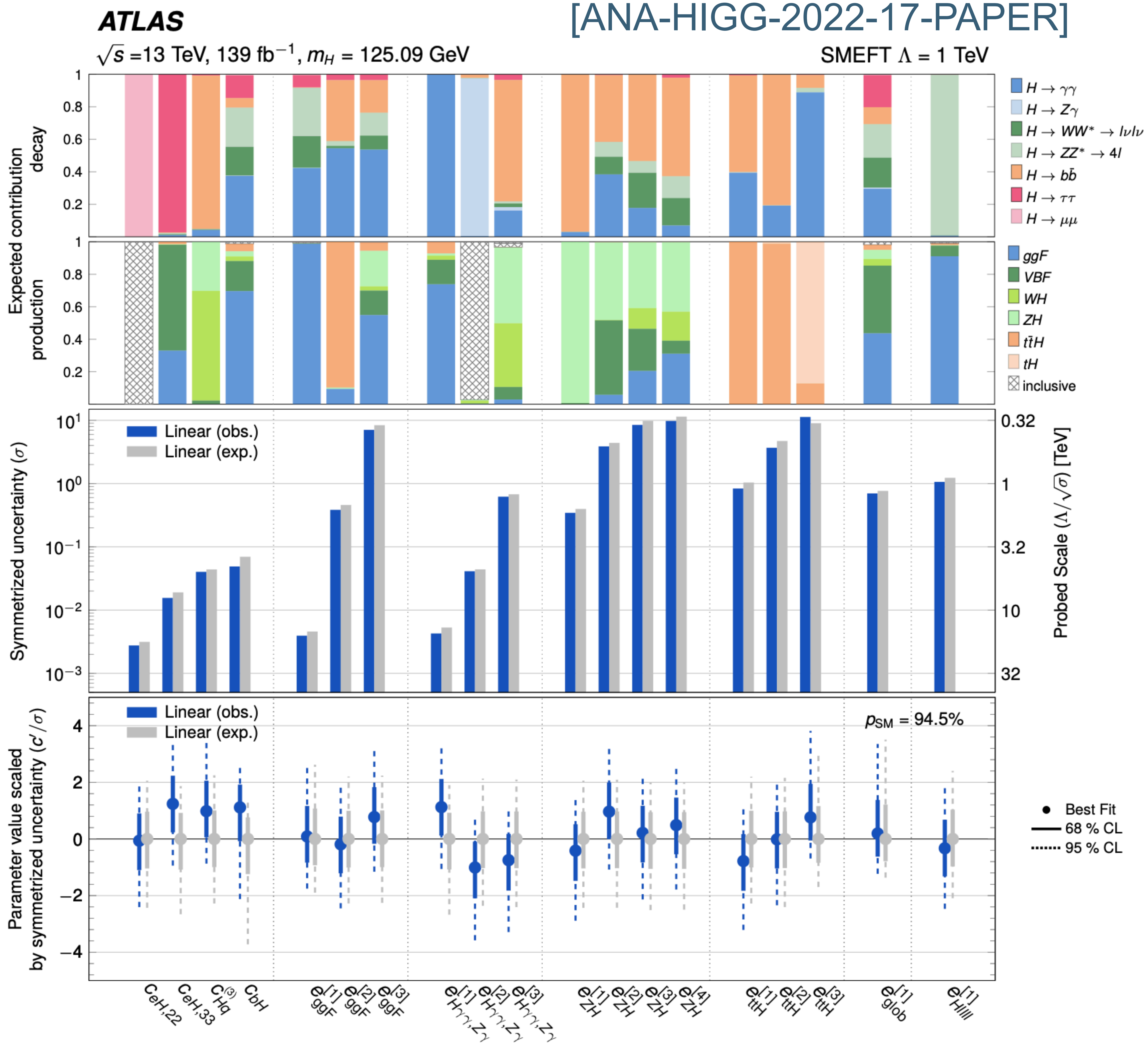
Backup

Higgs STXS combination ATLAS

- STXS combination + SMEFT interpretation $H \to \gamma\gamma$, $H \to W^+W^-$, $H \to ZZ^{(*)}$, $H \to \tau^+\tau^-$, $H \to b\bar{b}$, $H \to \mu^+\mu^-$, $H \to Z\gamma$
- Starting with 46 WC identified 15 linear combinations and 4 single coefficients by applying PCA on the following groups:

$$
\begin{aligned}
\boldsymbol{c} = \{c_{eH,22}\} \cup \quad & & \boldsymbol{c}' = \{c_{eH,22}\} \cup \\
\{c_{eH,33}\} \cup \quad & & \{c_{eH,33}\} \cup \\
\{c^{(3)}_{Hq}\} \cup \quad & & \{c^{(3)}_{Hq}\} \cup \\
\{c_{bH}\} \cup \quad & & \{c_{bH}\} \cup \\
\{c_{HG}, c_{tG}, c_{tH}\} \cup \quad & \rightarrow & \{e^{[1]}_{\text{ggF}}, e^{[2]}_{\text{ggF}}, e^{[3]}_{\text{ggF}}\} \cup \\
\{c_{HB}, c_{HW}, c_{HWB}, c_{tB}, c_{tW}\} \cup \quad & \rightarrow & \{e^{[1]}_{H\gamma\gamma,Z\gamma}, e^{[2]}_{H\gamma\gamma,Z\gamma}, e^{[3]}_{H\gamma\gamma,Z\gamma}\} \cup \\
\{c_{Hu}, c^{(1)}_{Hq}, c_{Hd}, c^{(3)}_{Hl,33}, & & \\
c_{Ht}, c_{He,33}, c^{(1)}_{Hl,33}, c_{Hb}\} \cup \quad & \rightarrow & \{e^{[1]}_{ZH}, e^{[2]}_{ZH}, e^{[3]}_{ZH}, e^{[4]}_{ZH}\} \cup \\
\{c_G, c^{(1,8)}_{Qq}, c^{(3,1)}_{Qq}, c^{(8)}_{tq}, c^{(8)}_{Qu}, c^{(8)}_{tu}, c^{(8)}_{td}, & & \\
c^{(8)}_{Qd}, c^{(3,8)}_{Qq}, c^{(1,1)}_{Qq}, c^{(1)}_{tu}, c^{(1)}_{tq}, c^{(1)}_{Qu}, c^{(1)}_{Qd}\} \cup \quad & \rightarrow & \{e^{[1]}_{\text{ttH}}, e^{[2]}_{\text{ttH}}, e^{[3]}_{\text{ttH}}\} \cup \\
\{c_{H\Box}, c^{(3)}_{Hl,11}, c^{(3)}_{Hl,22}, c_{ll,1221}\} \cup \quad & \rightarrow & \{e^{[1]}_{\text{glob}}\} \cup \\
\{c^{(1)}_{Hl,11}, c^{(1)}_{Hl,22}, c_{He,11}, c_{He,22}, c_{HDD}, c^{(3)}_{HQ}, c^{(1)}_{HQ}\} \quad & \rightarrow & \{e^{[1]}_{Hllll}\}.
\end{aligned}
$$

[ANA-HIGG-2022-17-PAPER]

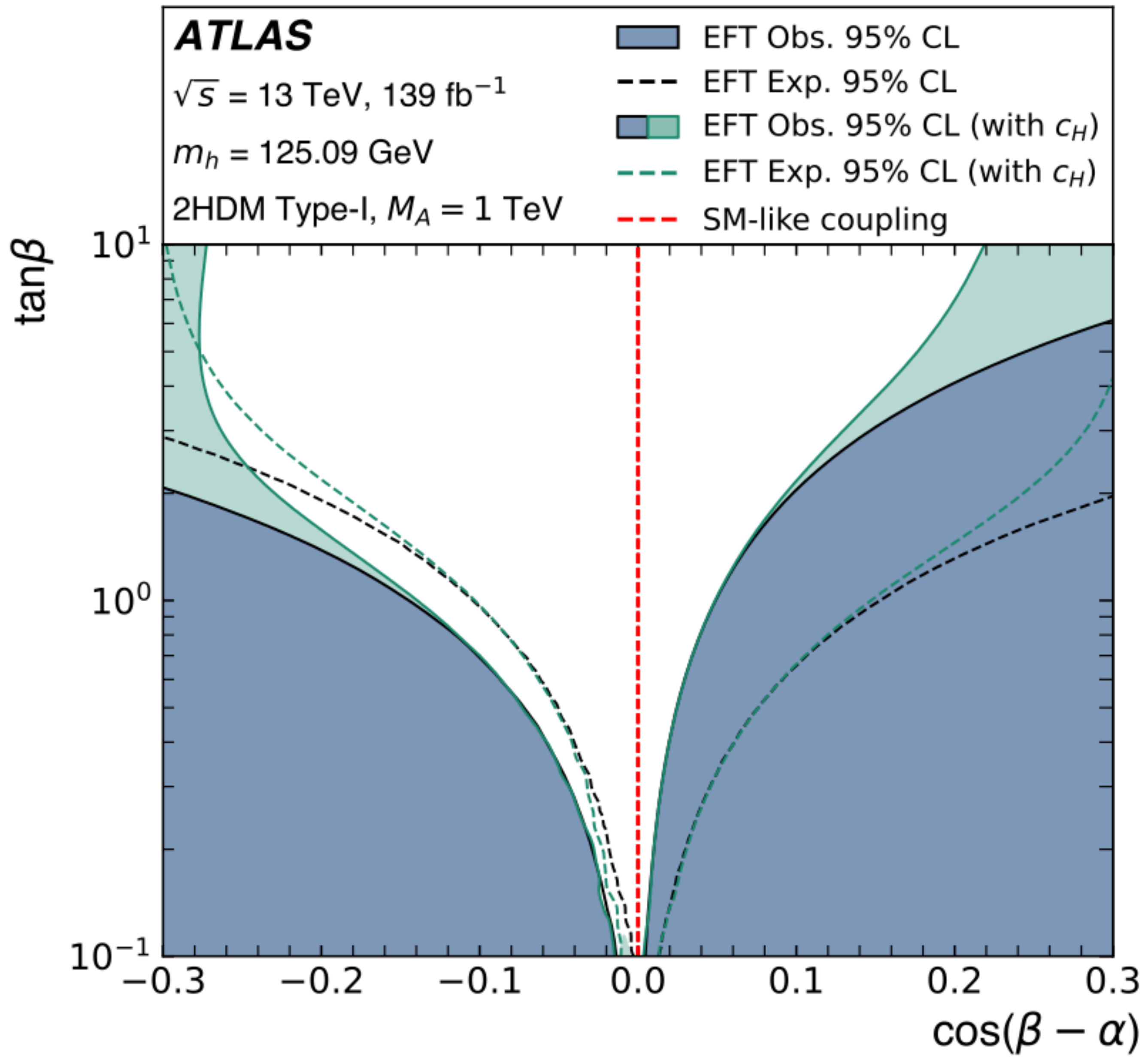


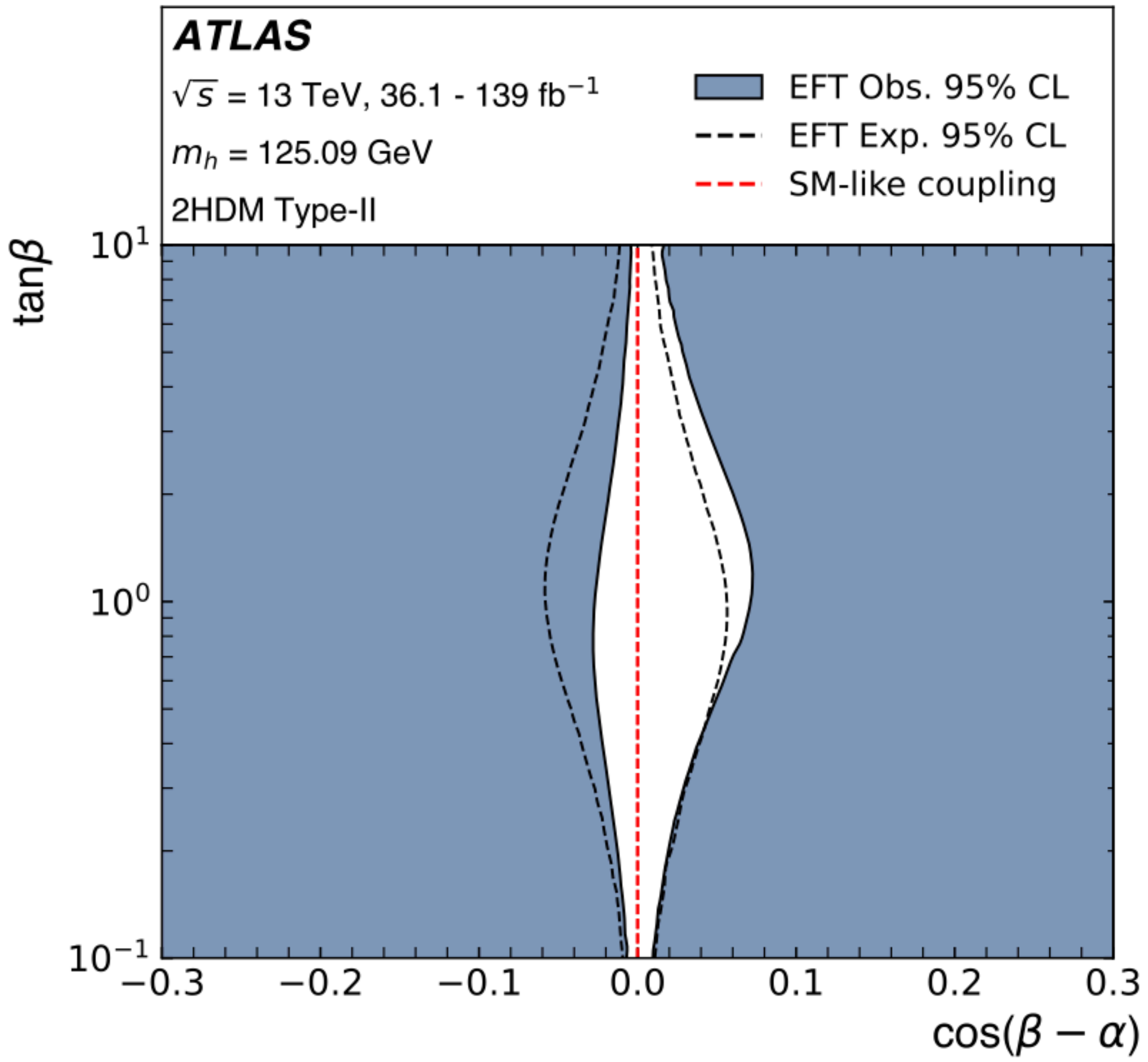
Higgs STXS combination ATLAS

[ANA-HIGG-2022-17-PAPER]

- STXS combination + SMEFT interpretation $H \to \gamma\gamma$, $H \to W^+W^-$, $H \to ZZ^{(*)}$, $H \to \tau^+\tau^-$, $H \to b\bar{b}$, $H \to \mu^+\mu^-$, $H \to Z\gamma$
- 2HDM interpretation:

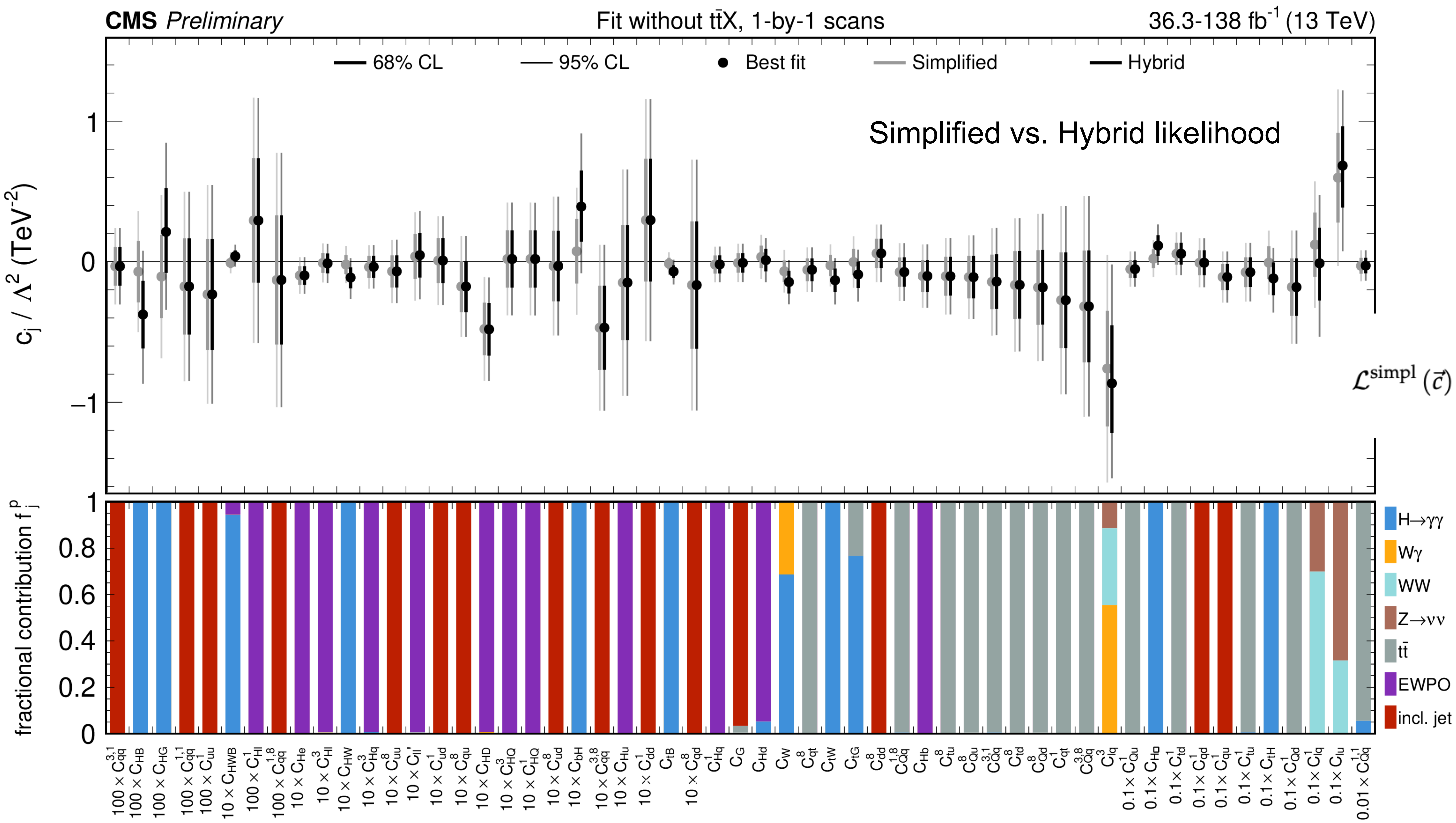
$$\frac{v^2 c_{iH}}{\Lambda^2} = -Y_i \eta_i \frac{\cos(\beta - \alpha)}{\tan\beta}$$





Higgs + EWK + Top combination in CMS

[CMS-SMP-24-003]



+ Studied validity of simplified likelihood

$$\mathcal{L}^{\text{simpl}}(\vec{c}) = \frac{\exp\left(-\frac{1}{2}\left(\vec{\mu}(\vec{c})-\hat{\vec{\mu}}\right)^T V^{-1}\left(\vec{\mu}(\vec{c})-\hat{\vec{\mu}}\right)\right)}{\sqrt{(2\pi)^m \det(V)}}$$

Higgs + EWK + Top combination in CMS

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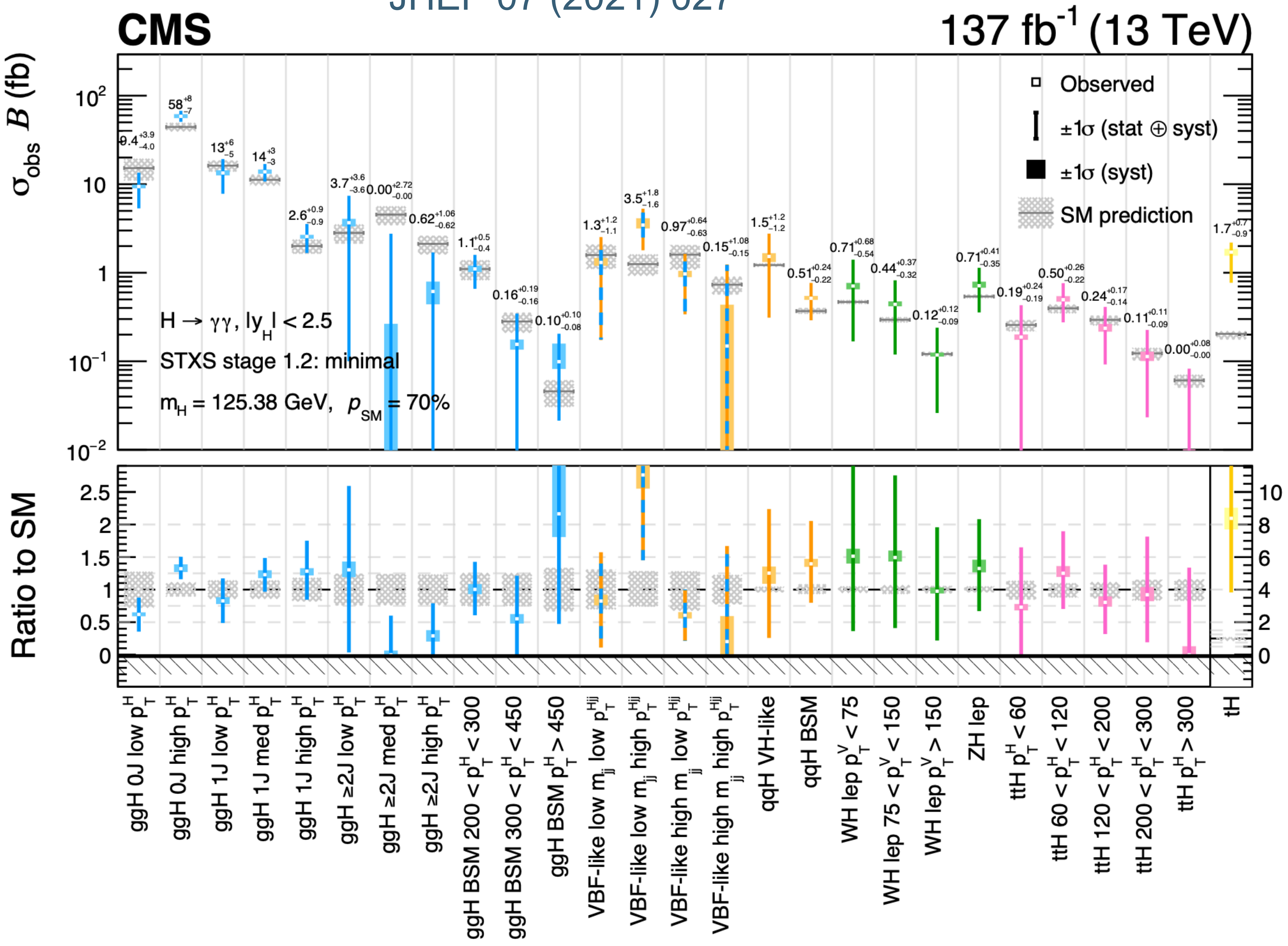
[CMS-SMP-24-003]



Analysis	Type of measurement	Observables used	Experi likeliho
$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]	✓
$W\gamma$	Fid. diff. cross sections	$p_T^\gamma \times \|\phi_f\|$	✓
WW	Fid. diff. cross sections	$m_{\ell\ell}$	✓
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^Z	✓
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$	×
EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A^{0,\ell}_{FB}$, $A^{0,c}_{FB}$, $A^{0,b}_{FB}$	×
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \|y^{jet}\|$	×
$t\bar{t}X$	Direct EFT	Yields in regions of interest	✓

Higgs + EWK + Top hybrid likelihood (CMS)

[CMS-SMP-24-003]

The likelihood in this combination is expressed as

$$\mathcal{L}\left(\text{data}\,;\,\vec{c},\vec{v}\right) = \mathcal{L}^{\text{expt}}\left(\vec{c},\vec{v}\right)\mathcal{L}^{\text{simpl}}\left(\vec{c}\right), \tag{9}$$

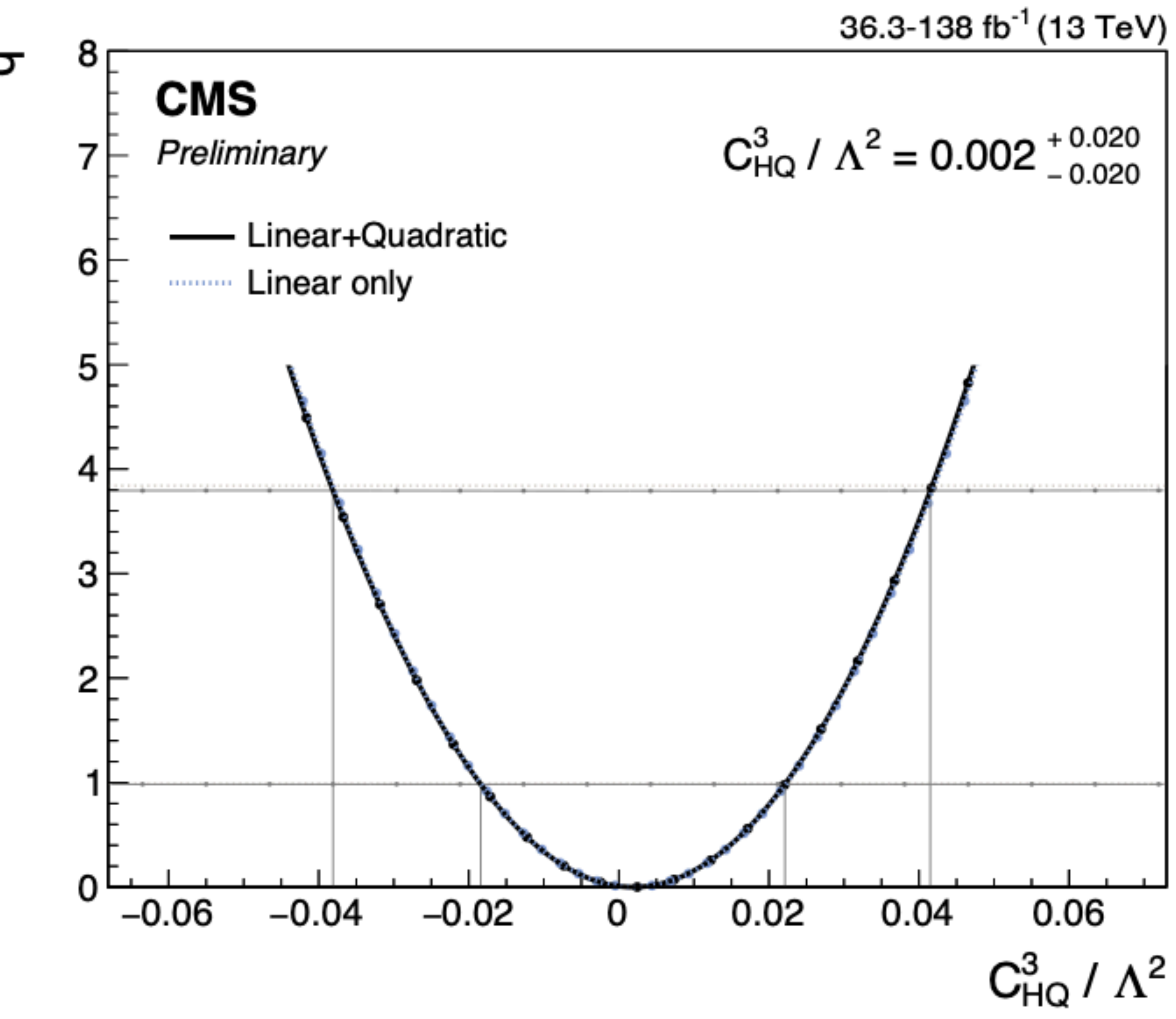
where

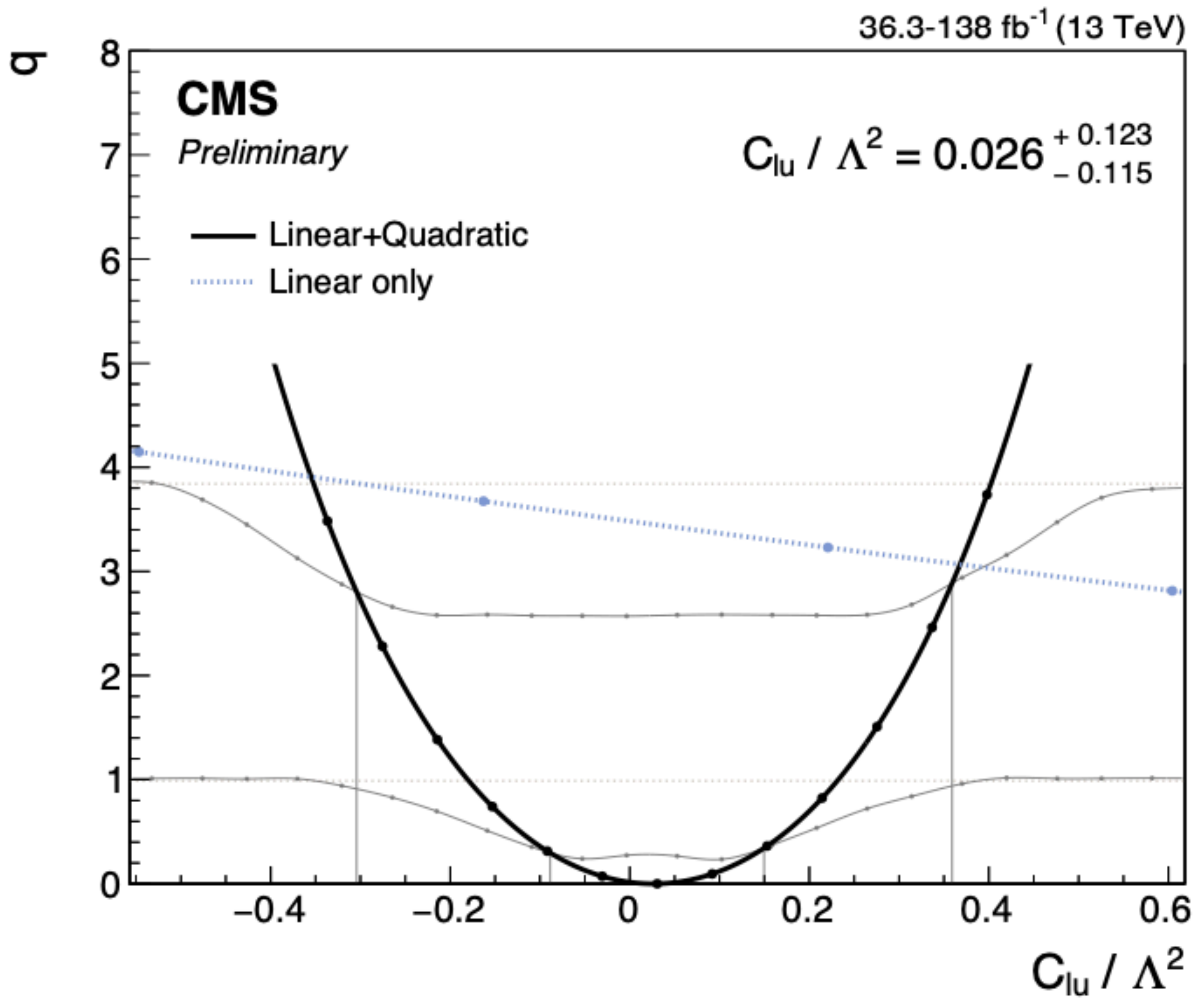
$$\mathcal{L}^{\text{expt}}\left(\vec{c},\vec{v}\right) = \prod_i \text{Poisson}\left(n_i\,;\,\sum_j \mu'^j(\vec{c})s_i^j(\vec{v}) + b_i(\vec{v})\right)\prod_k p_k\left(y_k\,;\,\nu_k\right); \tag{10}$$

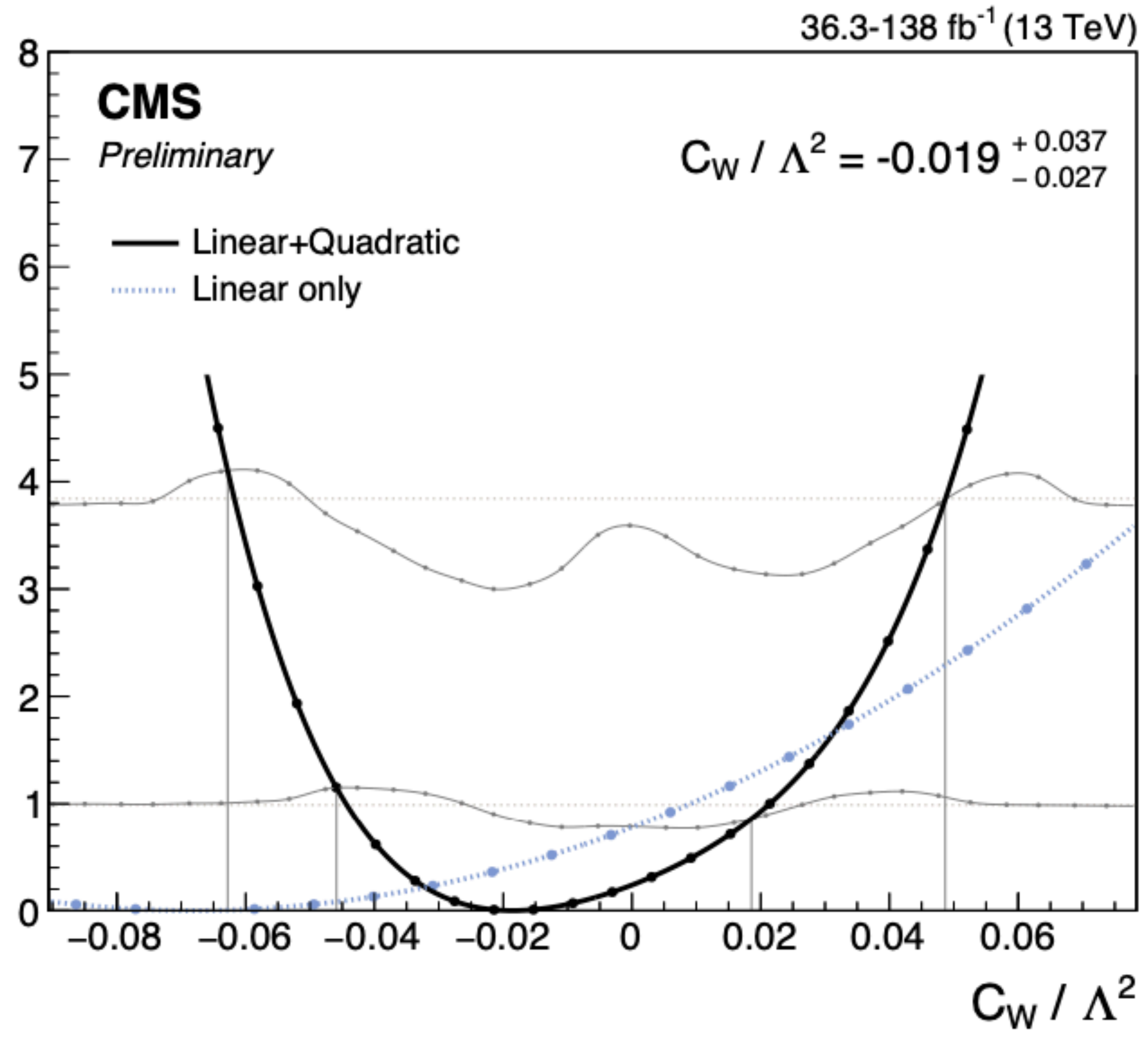
$$\mathcal{L}^{\text{simpl}}\left(\vec{c}\right) = \frac{\exp\left(-\frac{1}{2}\left(\vec{\mu}(\vec{c}) - \hat{\vec{\mu}}\right)^T V^{-1}\left(\vec{\mu}(\vec{c}) - \hat{\vec{\mu}}\right)\right)}{\sqrt{(2\pi)^m \det(V)}}. \tag{11}$$

Higgs + EWK + Top asymptotic approximation(CMS)

[CMS-SMP-24-003]

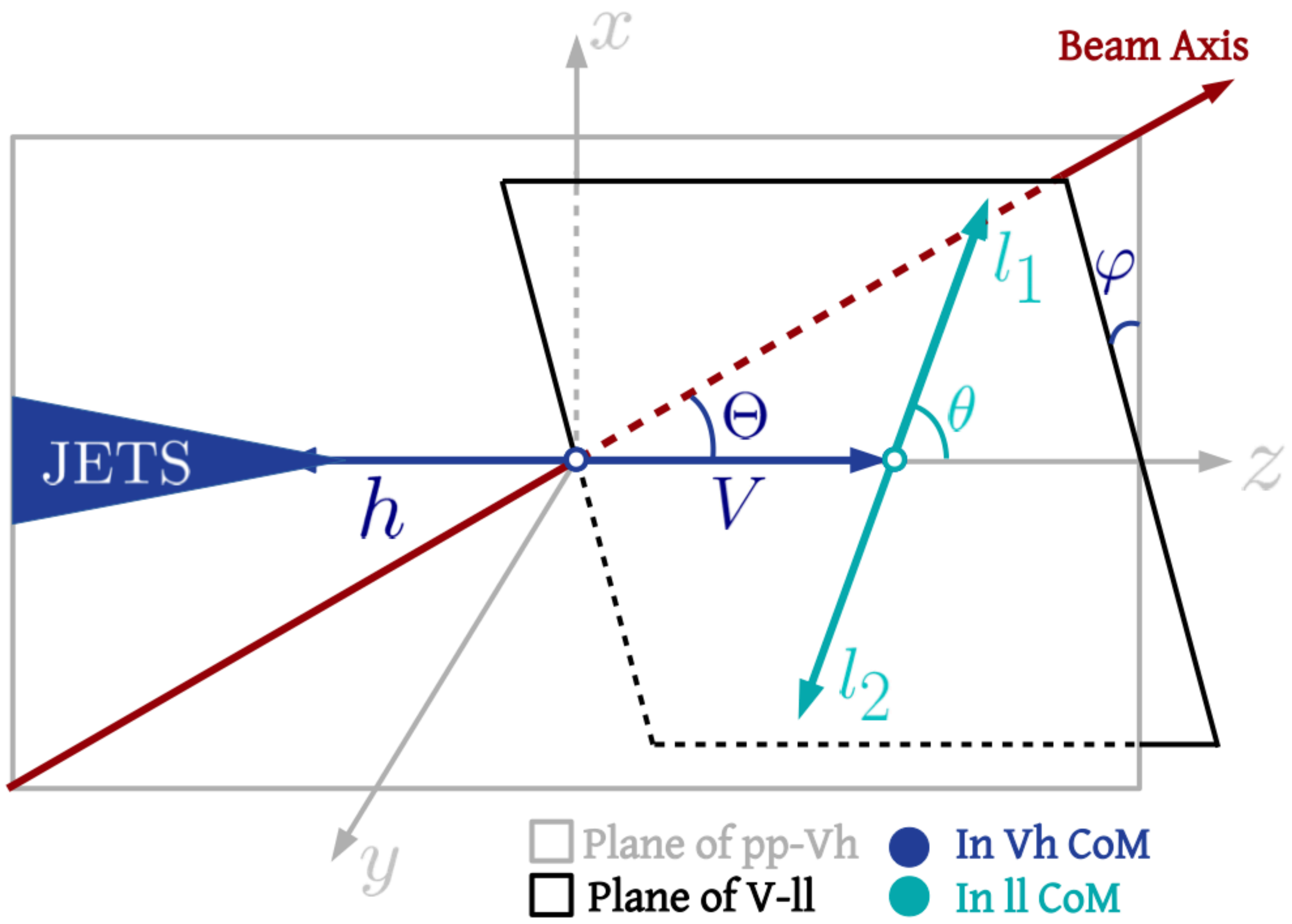






VH(H→bb) EFT analysis (angular variables)

CMS-HIG-23-016



$$|\mathcal{M}(\hat{s},\Theta,\theta,\varphi)|^2 = \sum_i a_i(\hat{s})\, f_i(\Theta,\theta,\varphi)$$

$$f_1 = f_{LL} = \sin^2\Theta \sin^2\theta$$
$$f_2 = f^1_{TT} = \cos\Theta\cos\theta$$
$$f_3 = f^2_{TT} = (1+\cos^2\Theta)(1+\cos^2\theta)$$
$$f_4 = f^1_{LT} = \cos\varphi\sin\Theta\sin\theta$$
$$f_5 = f^2_{LT} = \cos\varphi\sin\Theta\sin\theta\cos\Theta\cos\theta$$
$$f_6 = \tilde{f}^1_{LT} = \sin\varphi\sin\Theta\sin\theta$$
$$f_7 = \tilde{f}^2_{LT} = \sin\varphi\sin\Theta\sin\theta\cos\Theta\cos\theta$$
$$f_8 = f_{TT'} = \cos^2\varphi\sin^2\Theta\sin^2\theta$$
$$f_9 = \tilde{f}_{TT'} = \sin^2\varphi\sin^2\Theta\sin^2\theta,$$