北京大学 PEKING UNIVERSITY 高能物理研究中心

Operator Correlations in Electroweak Scatterings at LHC

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Standard Model Effective Field Theory

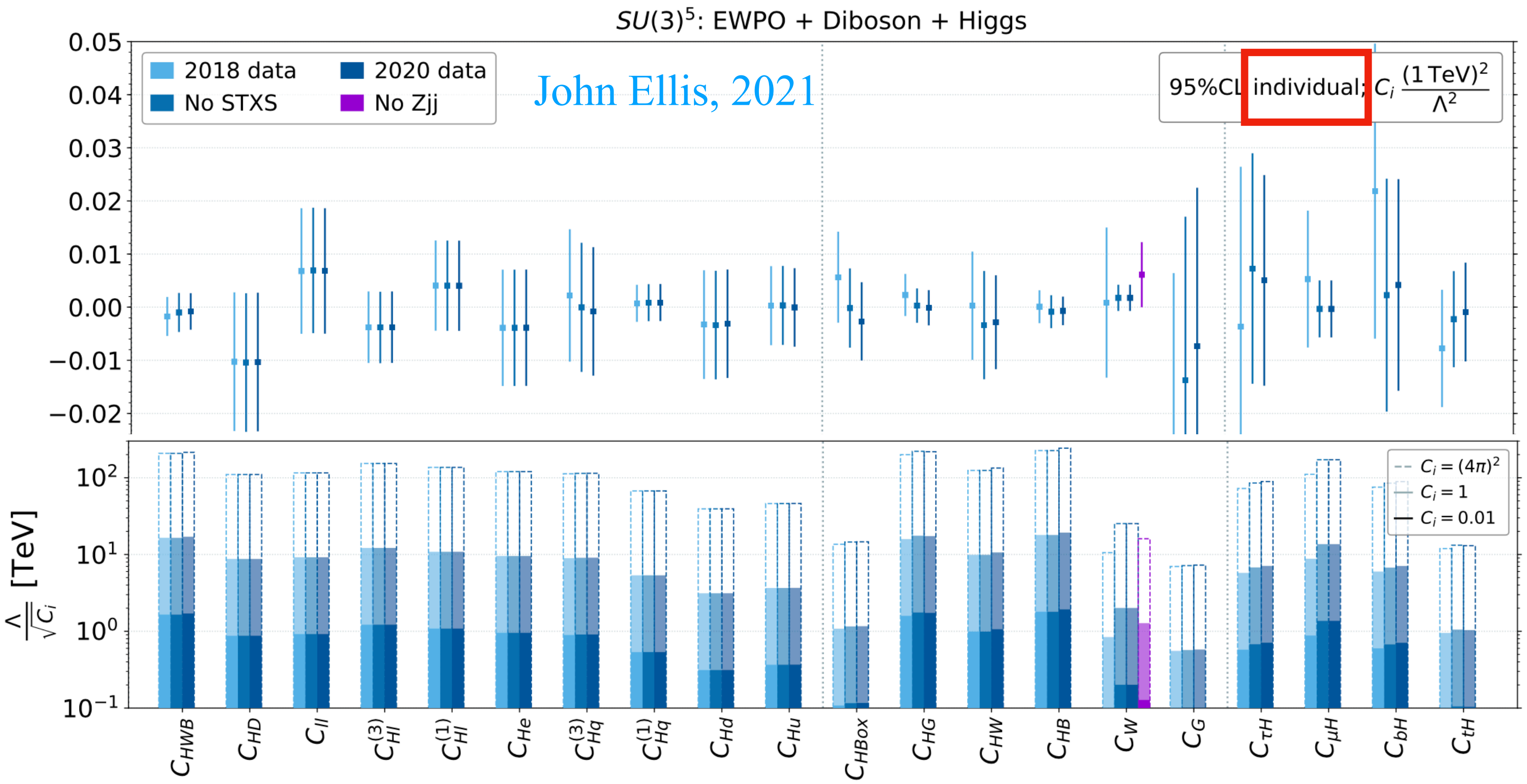
- Physics beyond the Standard Model:

Hierarchy problem	Matter anti-matter asymmetry	Dark matter
SUSY…	**Baryogenesis…**	**WIMPs**

- The absence of evidence for new particles suggests that the new resonances may be too heavy to be probed at LHC.

- Their quantum effects can be described by higher dimensional operators:

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}(\frac{1}{\Lambda^4}),$$



$$\Delta\sigma \simeq 0 \quad \rightarrow \quad C_i/\Lambda^2 \simeq 0$$

$$C_i \rightarrow 0 \quad \text{or} \quad \Lambda \rightarrow \infty$$

New physics decouples from the SM.

Operator Correlations in SMEFT

- When different operators originate from the same heavy resonance, they are likely correlated.

$$\Delta\mathcal{L}_{\text{EFT}} \supset -\frac{1}{32\pi^2 M^2}\left[\frac{1}{90}G'_{\mu\nu}G'_{\nu\rho}G'_{\rho\mu} + \frac{1}{12}U G'_{\mu\nu}G'_{\mu\nu}\right],$$

$G'_{\mu\nu} = [D_\mu, D_\nu]$

D_μ : covariant derivative of heavy resonance

$$\mathcal{O}_W = \epsilon^{IJK} W_\mu^{I\,\nu} W_\nu^{J\,\rho} W_\rho^{K\,\mu} \qquad \mathcal{O}_{HW} = H^\dagger H\, W^I_{\mu\nu} W^{I\,\mu\nu}$$

$\mathcal{O}_{HW}$ must exist together with $\mathcal{O}_W$.

sufficient & necessary

sufficient

Operators are correlated.

Heavy resonance is charged under $SU(2)_L$

$(D_\mu \supset W_\mu$ and $G'_{\mu\nu} \supset W^I_{\mu\nu})$

The aim of EFT analysis is to discover the nontrivial correlations of operators!

- Their Wilson coefficients may depend on the same new parameters, the operator correlations can provide insights into UV complete models.

We investigate the correlations of operators in electroweak scattering channels.

Operator Correlations in Electroweak Scatterings

- Assuming that the quadratic contributions of operators can be neglected.

$$\sigma_{tot} = \sigma_{SM} + \frac{C_i}{\Lambda^2}\sigma_i + \left(\frac{C_i}{\Lambda^2}\right)^2 \sigma_i^{(2)}$$

- The deviations in the total cross section of various electroweak scattering channels:

$$\Delta\sigma_{pp\to ZW^\pm} = \left[-0.927\, C_W + 1.191\, C_{HWB}\right] \left(\frac{\text{TeV}}{\Lambda}\right)^2 \text{ pb},$$

$$\Delta\sigma^{\text{VBF}[h]}_{pp\to jjh} = \left[-0.308\, C_{HW} + 0.172\, C_{HWB}\right] \left(\frac{\text{TeV}}{\Lambda}\right)^2 \text{ pb},$$

$$\Delta\sigma^{\text{VBS(WW)}}_{pp\to jjW^\pm W^\pm} = \left[0.010\, C_W + 0.011\, C_{HW} + 0.002\, C_{HWB}\right] \left(\frac{\text{TeV}}{\Lambda}\right)^2 \text{ pb},$$

$$\mathcal{O}_W = \epsilon^{IJK}\, W_\mu^{I\,\nu} W_\nu^{J\,\rho} W_\rho^{K\,\mu},$$

$$\mathcal{O}_{HW} = H^\dagger H\; W^I_{\mu\nu} W^{I\,\mu\nu},$$

$$\mathcal{O}_{HWB} = H^\dagger \tau^I H\; W^I_{\mu\nu} B^{\mu\nu},$$

- When these electroweak operators originate from the same heavy resonance, they are correlated.

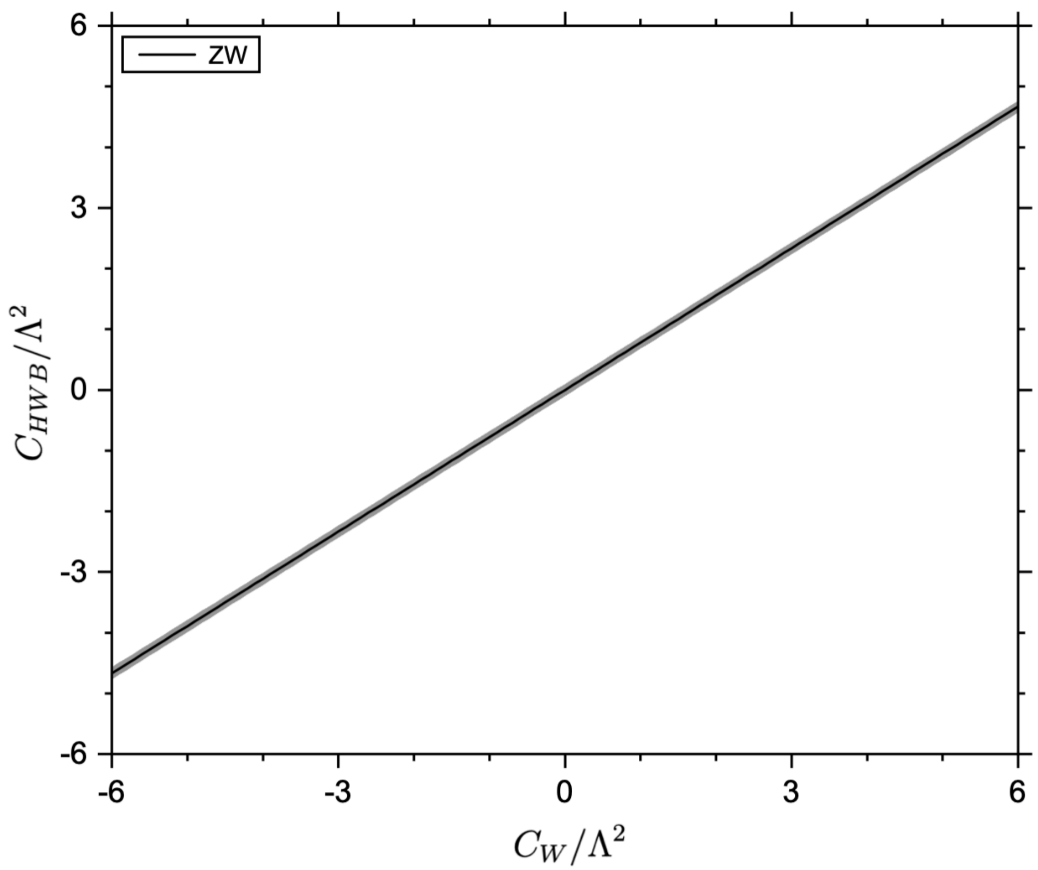
Blind Direction in ZW Production

- If total cross section of ZW production is consistent with the SM prediction, it can be attributed to a coherent cancellation of correlated operators.

$$\Delta\sigma_{pp\to ZW^\pm} = \frac{-0.927\, C_W + 1.191\, C_{HWB}}{\Lambda^2} \simeq 0.$$

- This correlated behavior will determine a nontrivial relationship between these Wilson coefficients, leading to a blind direction for these coefficients.

Blind direction in ZW production: $-0.307\, C_W + 1.191\, C_{HWB} = 0$



The Wilson coefficients of correlated operators may depend on the same parameters of UV completion:

$$C_W = C_W(g,\, g',\, g_1^{UV},\, g_2^{UV},\, \ldots)$$
$$C_{HWB} = C_{HWB}(g,\, g',\, g_1^{UV},\, g_2^{UV},\, \ldots)$$

Blind direction can provide insights into UV completion.

Explore UV Completion via Blind Direction

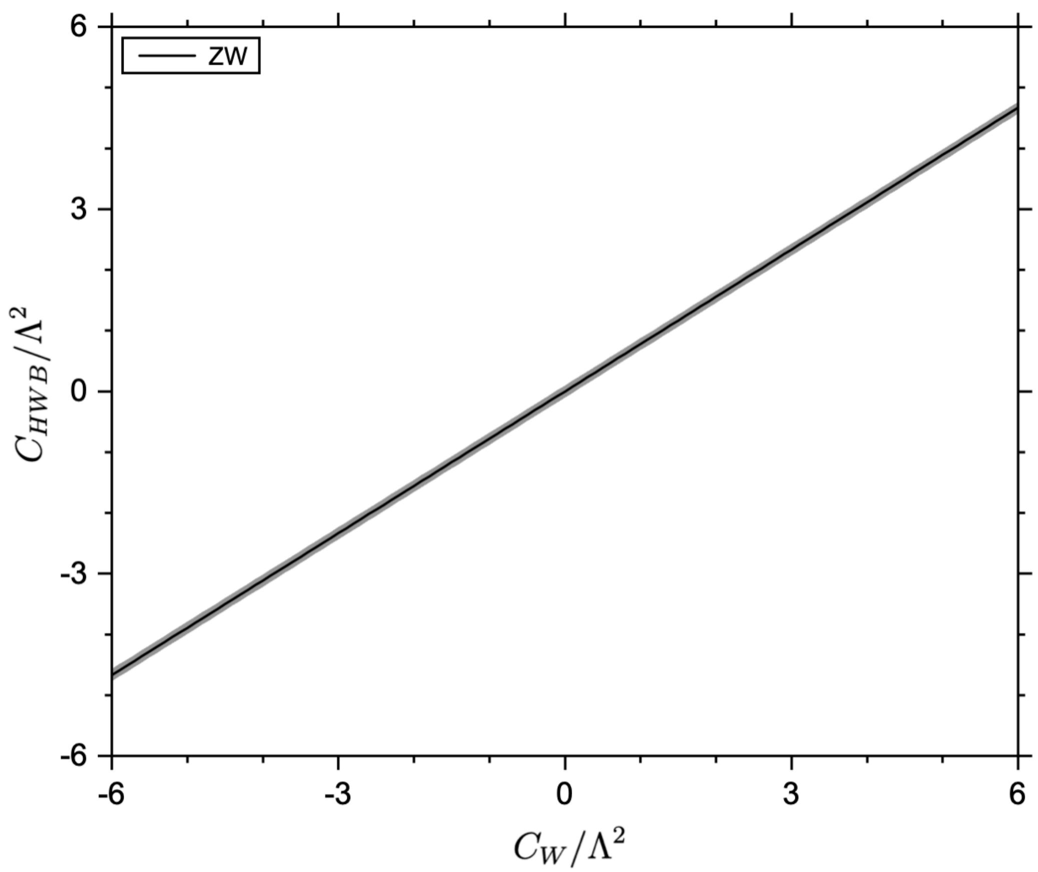
- Suppose these correlated operators originate from the 2HDM.

$$\Delta\mathcal{L}_{\rm 2HDM}=(D_\mu\varphi)^\dagger(D^\mu\varphi)-M^2\varphi^\dagger\varphi-\frac{\lambda_\varphi}{4}(\varphi^\dagger\varphi)^2 + (\eta_H H^\dagger H+\eta_\varphi\varphi^\dagger\varphi)(\tilde{H}^\dagger\varphi+\varphi^\dagger\tilde{H}) - \lambda_1(\tilde{H}^\dagger H)(\varphi^\dagger\varphi)-\lambda_2(\tilde{H}^\dagger\varphi)^\dagger(\tilde{H}^\dagger\varphi)-\lambda_3((\tilde{H}^\dagger\varphi)^2+(\varphi^\dagger\tilde{H})^2),$$

T. D. Lee, 1973; John F. Gunion et al., 2003; G. C. Branco et al., 2012

Operator	Wilson Coefficients
$\mathcal{O}_W$	$\frac{C_W}{\Lambda^2}=\frac{g^3}{5760\pi^2\Lambda^2}$
$\mathcal{O}_{HW}$	$\frac{C_{HW}}{\Lambda^2}=\frac{g^2}{768\pi^2\Lambda^2}(2\lambda_1+\lambda_2)$
$\mathcal{O}_{HWB}$	$\frac{C_{HWB}}{\Lambda^2}=\frac{gg'\lambda_2}{384\pi^2\Lambda^2}$

Blind direction in ZW production: $-0.307\,C_W+1.191\,C_{HWB}=0$



The blind direction in ZW production determines nontrivial relations between UV parameters and SM couplings:

$$\lambda_2=-\frac{g^2}{15g'}\frac{\sigma_W}{\sigma_{HWB}}=0.0625,$$

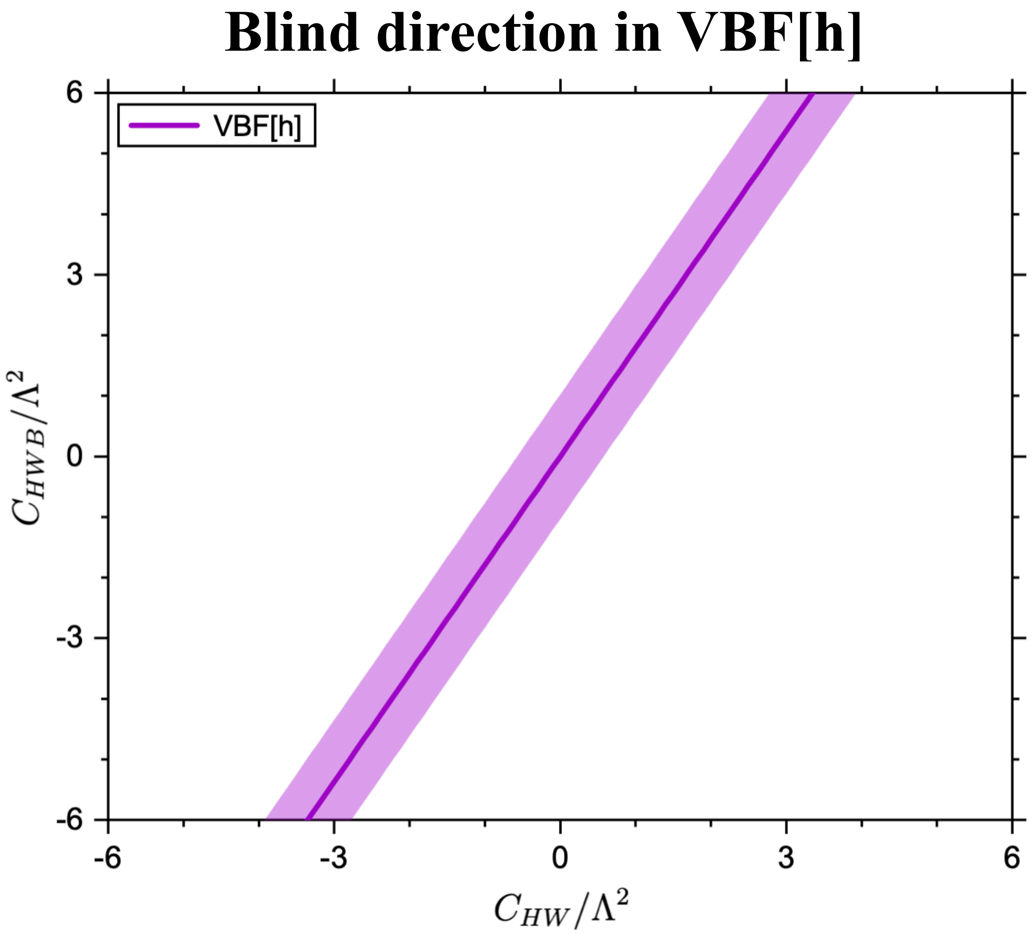
Independent of cutoff scale Λ.

The insights of UV completion can be directly derived from the blind direction with correlated operators.

Blind Direction in Vector Boson Fusion

- When precise measurements of VBF[h] also consistent with the SM prediction, the correlation of electroweak operators exhibits as

$$\Delta\sigma^{\mathrm{VBF}[h]}_{pp\to jjh} = \frac{-0.308\,C_{HW} + 0.172\,C_{HWB}}{\Lambda^2} \simeq 0.$$



The blind direction implies:

$$\frac{C_{HWB}}{C_{HW}} = \frac{2g'\lambda_2}{2\lambda_1+\lambda_2} = \frac{\sigma_{HW}}{\sigma_{HWB}} = 1.79$$

$$\lambda_1 = -0.20\,\lambda_2 = -0.0125.$$

Operator	Wilson Coefficients
$\mathcal{O}_W$	$\frac{C_W}{\Lambda^2} = \frac{g^3}{5760\pi^2\Lambda^2}$
$\mathcal{O}_{HW}$	$\frac{C_{HW}}{\Lambda^2} = \frac{g^2}{768\pi^2\Lambda^2}(2\lambda_1+\lambda_2)$
$\mathcal{O}_{HWB}$	$\frac{C_{HWB}}{\Lambda^2} = \frac{gg'\lambda_2}{384\pi^2\Lambda^2}$

EFT analysis within operator correlations

$$\lambda_2 = -\frac{g^2}{15g'}\frac{\sigma_W}{\sigma_{HWB}} = 0.0625,$$

$$\lambda_1 = -0.20\,\lambda_2 = -0.0125.$$

Vital to examine or rule out the UV complete models

EFT analysis within individual approximation

$$\frac{C_W}{\Lambda^2} \in [-0.13, 0.13]$$
$$\frac{C_{HW}}{\Lambda^2} \in [-0.57, 0.57]$$
$$\frac{C_{HWB}}{\Lambda^2} \in [-0.10, 0.10]$$

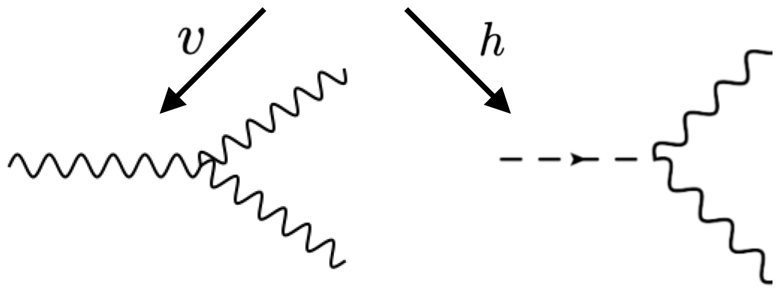
Validating Operator Correlations in Complementary

- When the total cross section is consistent with the SM prediction, it can also be attributed to the contributions of operators are individually suppressed.

$$\Delta\sigma \simeq 0 \quad \begin{cases} C_1\,\sigma_1 + C_2\,\sigma_2 + \cdots \simeq 0 \\ C_i \to 0 \quad \text{or} \quad \Lambda \to \infty \end{cases}$$

Explore the non-vanishing contributions of correlated operators in complementary.

$$\mathcal{O}_{HWB} = H^\dagger \tau^I H\, W^I_{\mu\nu} B_{\mu\nu}$$



The correlated cancellation in one channel can be broken in another one.

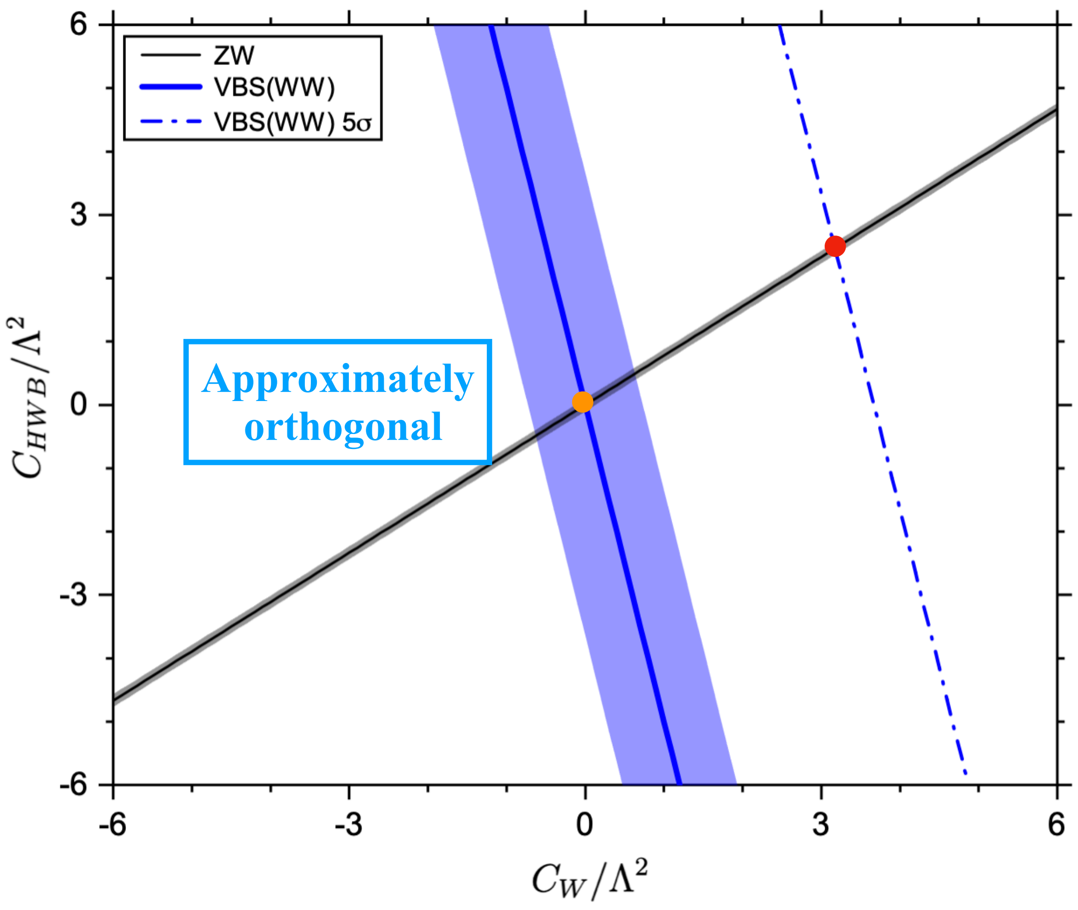
- The correlated cancellation of these electroweak operators in ZW production and VBF[h] can be validated by exploring their correlations in VBS(WW).

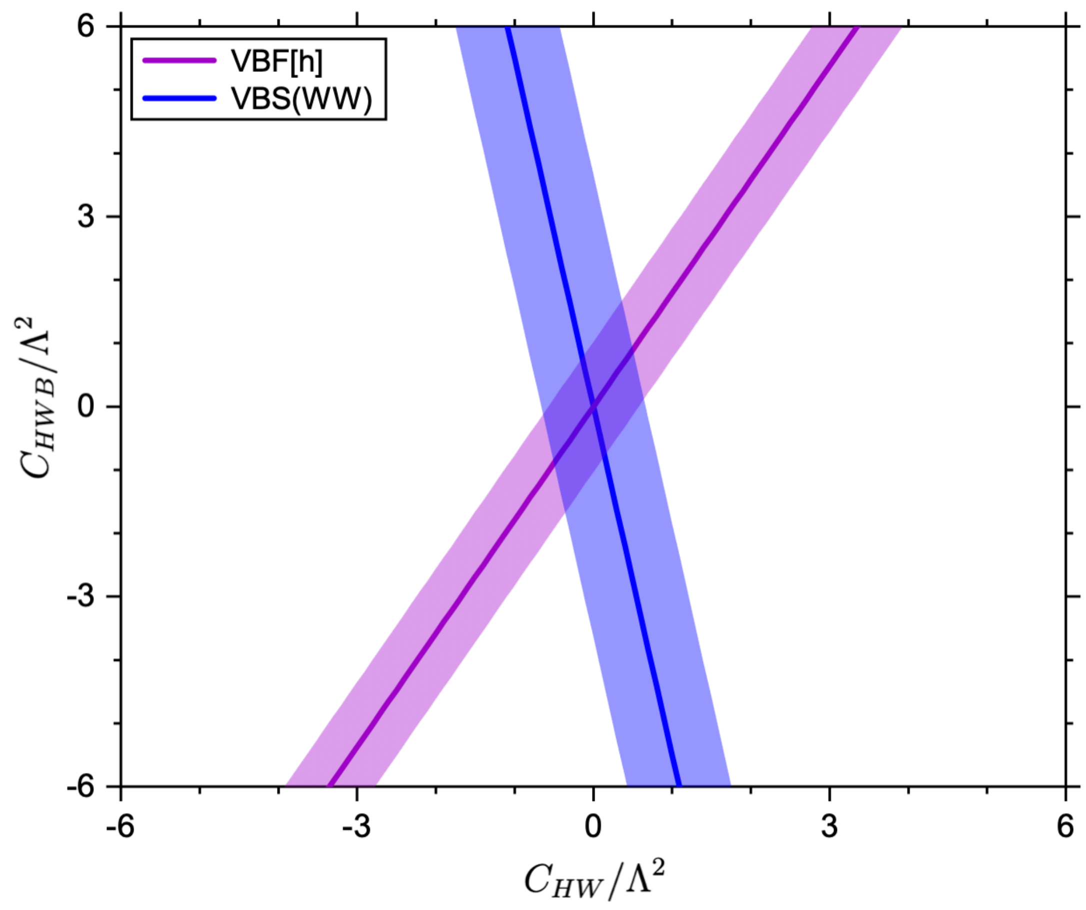
$$\Delta\sigma_{pp\to ZW^\pm} = \left[-0.927\,C_W + 1.191\,C_{HWB}\right]$$

$$\Delta\sigma^{\mathrm{VBF}[h]}_{pp\to jjh} = \left[-0.308\,C_{HW} + 0.172\,C_{HWB}\right]$$

$$\Delta\sigma^{\mathrm{VBS(WW)}}_{pp\to jjW^\pm W^\pm} = \left[0.010\,C_W + 0.011\,C_{HW} + 0.002\,C_{HWB}\right]$$

Validating Operator Correlations in Complementary





- If a deviation is observed in VBS(WW), it validates the operators exhibit correlated cancellation in other scattering channels.

$$C_1\,\sigma_1 + C_2\,\sigma_2 + \cdots \simeq 0$$ ✅

- If VBS(WW) also consistent with SM prediction, the heavy resonance decouples from the SM.

$$C_i \to 0 \quad \text{or} \quad \Lambda \to \infty$$ ✅

Summary

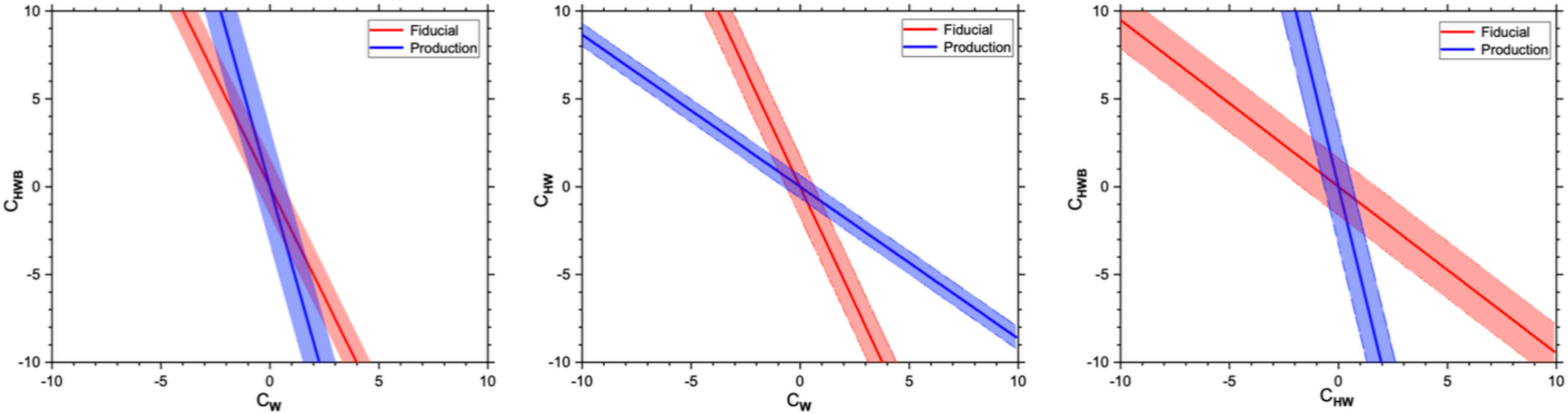
- We emphasize that the correlations of different operators can be crucial for exploring new physics in a bottom-up approach.
- We investigate the operator correlations in various electroweak scattering channels, and found that the operator correlations can provide insights into UV completions.
- To validate the operators exhibit correlated cancellation in ZW production and VBF[h] in complementary, the precise measurements of VBS(WW) are vital.

Thanks for your attention !

Back Up

Fiducial Level vs Parton Level

- $p_T(\ell) > 20\text{GeV}$, $|\eta(\ell)| < 2.5$, $m_{\ell\ell} > 20\text{GeV}$; CMS collaboration, 2020
- $p_T(j) > 50\text{GeV}$, $|\eta(j)| < 4.7$, $\Delta R_{\ell j} > 0.4$;
- $m_{jj} > 500\text{GeV}$, $|\Delta\eta_{jj}| > 2.5$;



UV correspondence in 3-dimension correlation

$$\Delta\mathcal{L}_{\rm 2HDM}=(D_\mu\varphi)^\dagger(D^\mu\varphi)-M^2\varphi^\dagger\varphi-\frac{\lambda_\varphi}{4}(\varphi^\dagger\varphi)^2$$
$$+(\eta_H H^\dagger H+\eta_\varphi\varphi^\dagger\varphi)(\tilde{H}^\dagger\varphi+\varphi^\dagger\tilde{H})$$
$$-\lambda_1(\tilde{H}^\dagger H)(\varphi^\dagger\varphi)-\lambda_2(\tilde{H}^\dagger\varphi)^\dagger(\tilde{H}^\dagger\varphi)-\lambda_3((\tilde{H}^\dagger\varphi)^2+(\varphi^\dagger\tilde{H})^2),$$

Operator	Wilson Coefficients
$\mathcal{O}_W$	$\frac{C_W}{\Lambda^2}=\frac{g^3}{5760\pi^2\Lambda^2}$
$\mathcal{O}_{HW}$	$\frac{C_{HW}}{\Lambda^2}=\frac{g^2}{768\pi^2\Lambda^2}(2\lambda_1+\lambda_2)$
$\mathcal{O}_{HWB}$	$\frac{C_{HWB}}{\Lambda^2}=\frac{gg'\lambda_2}{384\pi^2\Lambda^2}$
$\mathcal{O}_{H\Box}$	$\frac{C_{H\Box}}{\Lambda^2}=-\frac{g^4}{7680\pi^2\Lambda^2}+\frac{2\lambda_3^2-\lambda_1^2-\lambda_1\lambda_2}{96\pi^2\Lambda^2}$

$$\Delta\sigma_{pp\to ZW^\pm}=\left[-0.927\,C_W+1.191\,C_{HWB}\right]\left(\frac{\rm TeV}{\Lambda}\right)^2\ {\rm pb},$$
$$\Delta\sigma^{\rm VBF[h]}_{pp\to jjh}=\left[-0.308\,C_{HW}+0.172\,C_{HWB}+0.458\,C_{H\Box}\right]\left(\frac{\rm TeV}{\Lambda}\right)^2\ {\rm pb},$$
$$\Delta\sigma^{\rm VBS(WW)}_{pp\to jjW^\pm W^\pm}=\left[0.010\,C_W+0.011\,C_{HW}+0.002\,C_{HWB}+0.001\,C_{H\Box}\right]\left(\frac{\rm TeV}{\Lambda}\right)^2\ {\rm pb},$$
$$\Delta\sigma_{pp\to Zh}=\left[0.541\,C_{HW}+0.296\,C_{HWB}+0.978\,C_{H\Box}\right]\left(\frac{\rm TeV}{\Lambda}\right)^2\ {\rm pb},$$

- If no deviation exist in di-boson production, vector boson fusion and ZH associated production:

$$\lambda_1=-0.0296,\quad \lambda_2=0.0632,\quad \lambda_3=0.0057$$

- If no deviation exist in di-boson production, vector boson fusion and vector boson scattering:

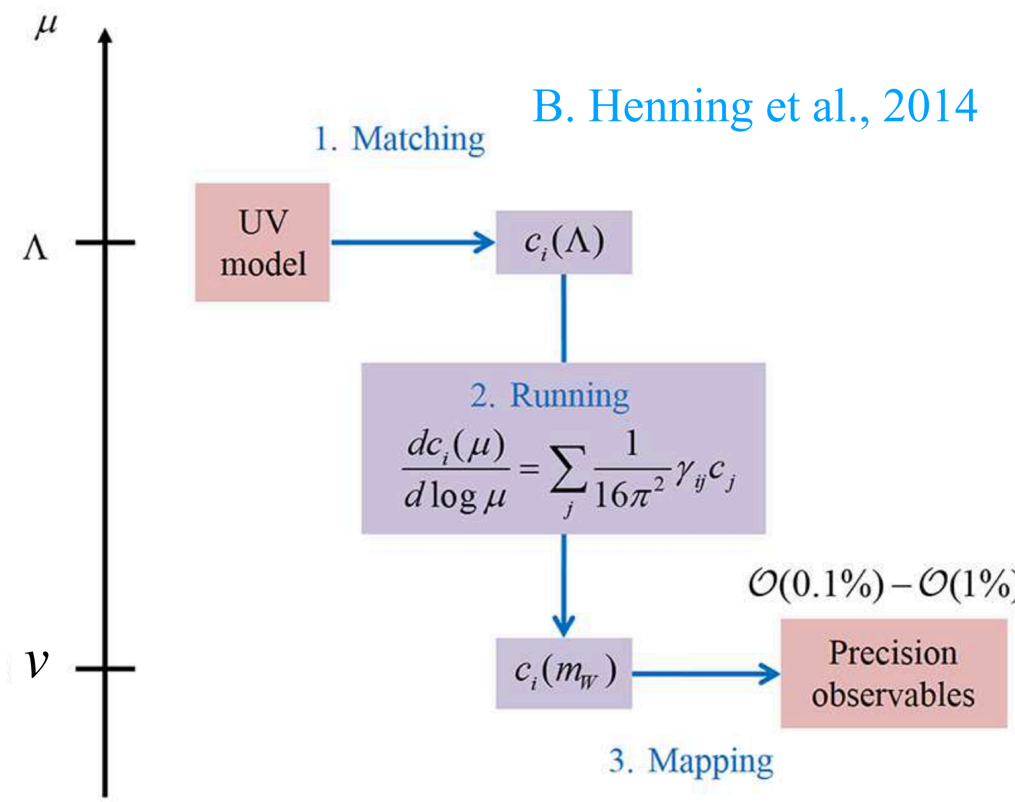
$$\lambda_1=-0.0360,\quad \lambda_2=0.0632,\quad \lambda_3=0.0138\,i$$

Operator Correlations within RGE

- The total cross sections are measured around electroweak scale $v = 246$ GeV, while the matching of effective operators is conducted at cutoff scale Λ.

$$C_i(v) = C_i(\Lambda) - \sum_j \frac{1}{16\pi^2}\gamma_{ij}\, C_j(\Lambda) \log\frac{\Lambda}{v}$$

The RGE of Wilson coefficients can alter the operator correlations, potentially modify the interpretation on UV completion.



- The operator correlations at electroweak scale:

$$\frac{C_{HWB}(v)}{C_W(v)} = 0.78, \qquad \frac{C_{HWB}(v)}{C_{HW}(v)} = 1.79.$$

- The operator correlations at cutoff scale $\Lambda = 1$ TeV:

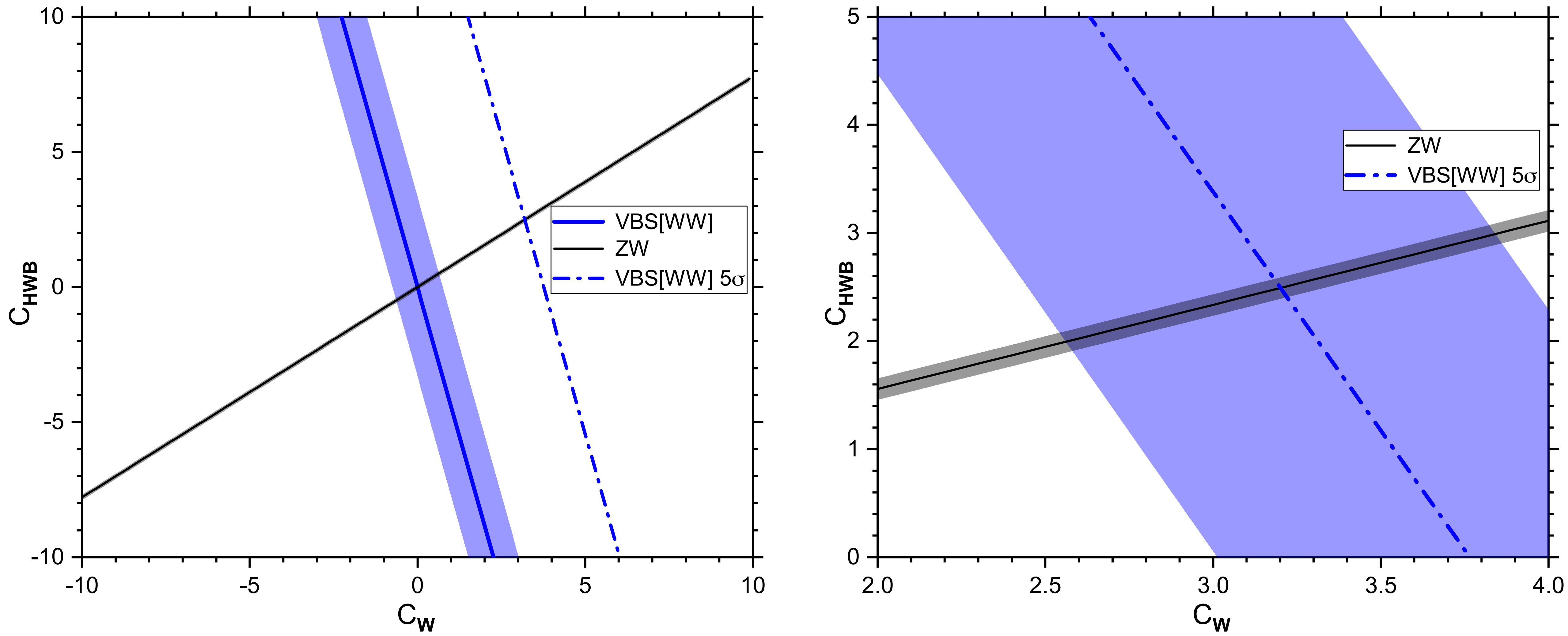
$$\frac{C_{HWB}(\Lambda)}{C_W(\Lambda)} = 0.75, \qquad \frac{C_{HWB}(\Lambda)}{C_{HW}(\Lambda)} = 2.16.$$

	C_W	C_{HB}	C_{HW}	C_{HWB}
γ_W	$\frac{29}{2}g^2$	0	0	0
γ_{HB}	0	$-\frac{9}{2}g^2 - \frac{79}{6}g'^2$	0	$3gg'$
γ_{HW}	$-15g^2$	0	$-\frac{3}{2}g'^2 - \frac{53}{6}g^2$	gg'
γ_{HWB}	$3g^2g'$	$2gg'$	$2gg'$	$\frac{19}{3}g'^2 + \frac{4}{3}g^2$

R. Alonso et.al., 2014

The measured operator correlations can effectively capture information about the UV completion, when the new resonance is not excessively heavy.

Coupled channels Analysis with Large Deviation



John Ellis, 2021

	C_{HWB}	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{Hq}^{(3)}$	$C_{Hq}^{(1)}$	C_{Hd}	C_{Hu}	C_{HBox}	C_{HG}	C_{HW}	C_{HB}	C_W
C_{HW}	+98	-98	+14	+3.0	+97	+98	-31	-43	+26	-77	-61	+2.0	+100	+93	+8.4
C_{HG}	+2.2	-1.5	+1.3	-7.0	+1.4	+1.5	-7.1	+0.8	+2.3	-3.7	-1.4	+100	+2.0	+2.3	-1.1
C_{HBox}	-58	+59	-6.8	-16	-59	-59	+3.7	+32	-13	+40	+100	-1.4	-61	-54	-8.0
C_{Hu}	-78	+76	-22	+20	-75	-76	+19	+32	-6.1	+100	+40	-3.7	-77	-77	-7.4
C_{Hd}	+27	-24	+9.8	-34	+22	+23	-5.5	+6.5	+100	-6.1	-13	+2.3	+26	+26	+2.0
$C_{Hq}^{(1)}$	-43	+42	-11	+6.7	-42	-42	+14	+100	+6.5	+32	+32	+0.8	-43	-43	-5.4
$C_{Hq}^{(3)}$	-32	+26	-5.1	+57	-26	-26	+100	+14	-5.5	+19	+3.7	-7.1	-31	-31	+14
C_{He}	+100	-100	+13	+12	+100	+100	-26	-42	+23	-76	-59	+1.5	+98	+98	+9.6
$C_{Hl}^{(1)}$	+99	-100	+7.4	+11	+100	+100	-26	-42	+22	-75	-59	+1.4	+97	+98	+9.4
$C_{Hl}^{(3)}$	+2.7	-12	+12	+100	+11	+12	+57	+6.7	-34	+20	-16	-7.0	+3.0	+3.1	+13
C_{ll}	+15	-13	+100	+12	+7.4	+13	-5.1	-11	+9.8	-22	-6.8	+1.3	+14	+14	+3.9
C_{HD}	-100	+100	-13	-12	-100	-100	+26	+42	-24	+76	+59	-1.5	-98	-98	-9.6
C_{HWB}	+100	-100	+15	+2.7	+99	+100	-32	-43	+27	-78	-58	+2.2	+98	+98	+8.5

2-dimension

$$\rho = \begin{bmatrix} \rho_W & \rho_{W\text{-}HWB} \\ \rho_{W\text{-}HWB} & \rho_{\varphi WB} \end{bmatrix} = \begin{bmatrix} 1 & 0.98 \\ 0.98 & 1 \end{bmatrix}.$$

3-dimension

$$\rho = \begin{bmatrix} \rho_W & \rho_{W\text{-}HW} & \rho_{W\text{-}HWB} \\ \rho_{W\text{-}HW} & \rho_{HW} & \rho_{HW\text{-}HWB} \\ \rho_{W\text{-}HWB} & \rho_{HW\text{-}HWB} & \rho_{HWB} \end{bmatrix} = \begin{bmatrix} 1 & -0.27 & 0.98 \\ -0.27 & 1 & -0.25 \\ 0.98 & -0.25 & 1 \end{bmatrix}.$$

4-dimension

$$\rho = \begin{bmatrix} \rho_W & \rho_{W\text{-}HW} & \rho_{W\text{-}HWB} & \rho_{W\text{-}H\Box} \\ \rho_{W\text{-}HW} & \rho_{HW} & \rho_{HW\text{-}HWB} & \rho_{HW\text{-}H\Box} \\ \rho_{W\text{-}HWB} & \rho_{HW\text{-}HWB} & \rho_{HWB} & \rho_{HWB\text{-}H\Box} \\ \rho_{W\text{-}H\Box} & \rho_{HW\text{-}H\Box} & \rho_{HWB\text{-}H\Box} & \rho_{H\Box} \end{bmatrix} = \begin{bmatrix} 1 & -0.34 & 0.98 & -0.54 \\ -0.34 & 1 & -0.33 & -0.58 \\ 0.98 & -0.33 & 1 & -0.56 \\ -0.54 & -0.58 & -0.56 & 1 \end{bmatrix}$$

$$\Delta\mathcal{L}_{\text{EFT}} \supset -\frac{1}{32\pi^2 M^2}\left[\underbrace{\frac{1}{90} G'_{\mu\nu} G'_{\nu\rho} G'_{\rho\mu}}_{\mathcal{O}_W} + \underbrace{\frac{1}{12} U G'_{\mu\nu} G'_{\mu\nu}}_{\mathcal{O}_{HW}\ \mathcal{O}_{HWB}}\right],$$

$$\mathcal{O}_W = \epsilon^{IJK} W^I_{\mu\nu} W^J_{\nu\rho} W^K_{\rho\mu}$$

$$\mathcal{O}_{HW} = H^\dagger H\, W^I_{\mu\nu} W^I_{\mu\nu}$$

$$\mathcal{O}_{HWB} = H^\dagger \tau^I H\, W^I_{\mu\nu} B_{\mu\nu}$$