

Hunting New Physics in a Model-Independent Framework

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PRISMA+ Colloquium - 1 June 2022

My career path

Postdoc:
Durham



Undergrad:
Aachen

- Aachen
- Bonn
- Heidelberg
- Mainz



PhD: Heidelberg

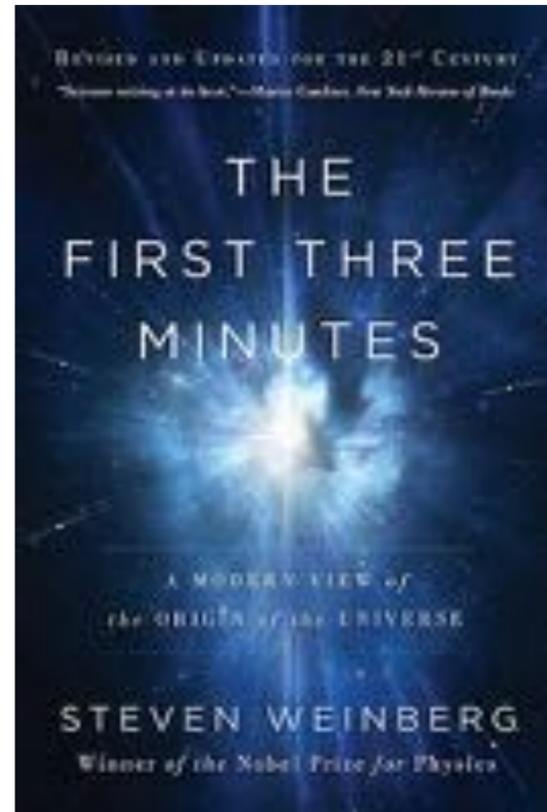


From October: Mainz



My career path

What got me into physics



+ many coincidences

What made me stay in physics

- freedom
- versatility
- physics

Outline

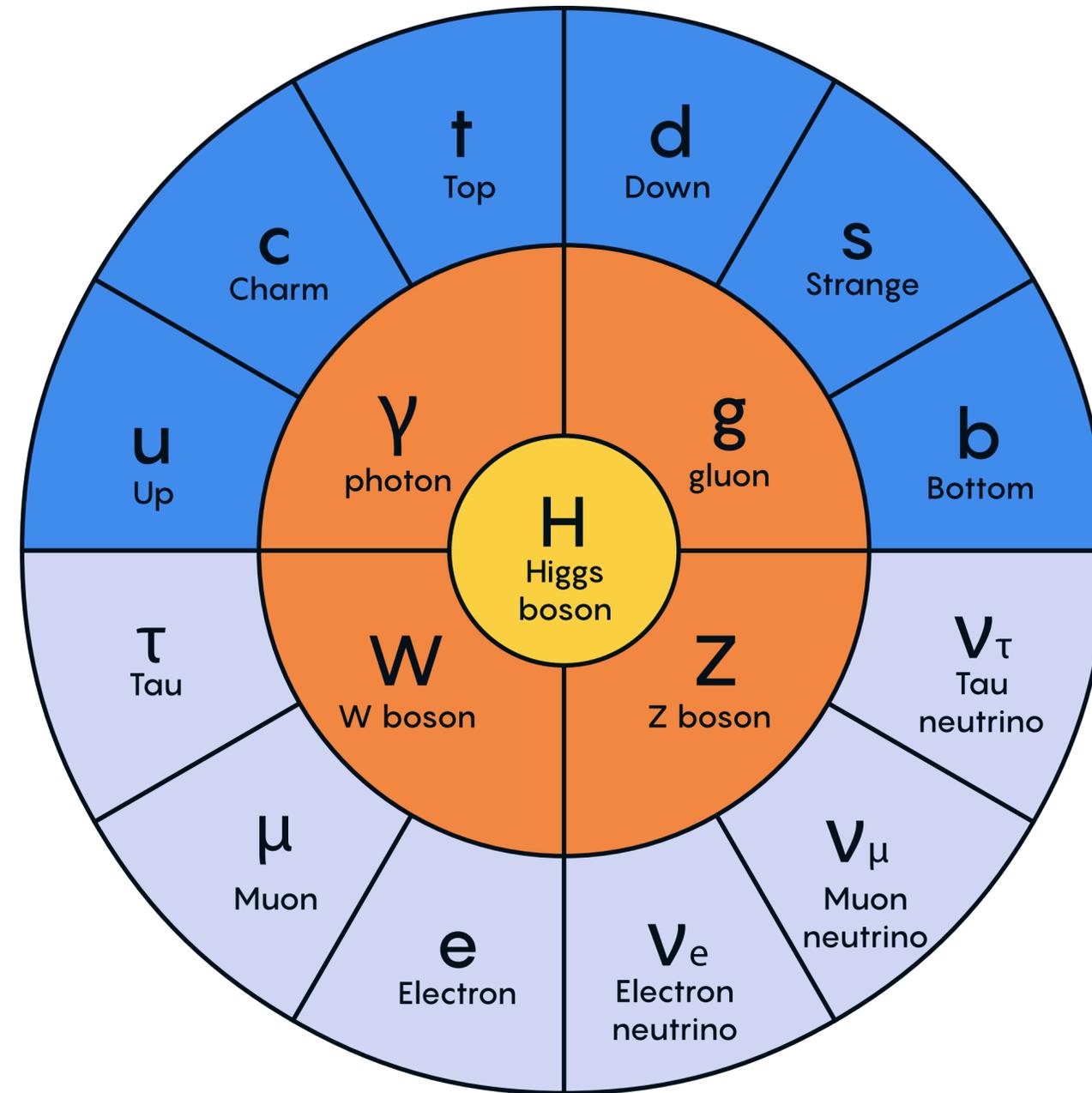
- Motivation: Why is the Standard Model incomplete?
- What is an effective field theory?
- How can EFTs help us to explore the new physics parameter space?
- Confronting EFTs with data: LHC global fits



PLEASE INTERRUPT ME

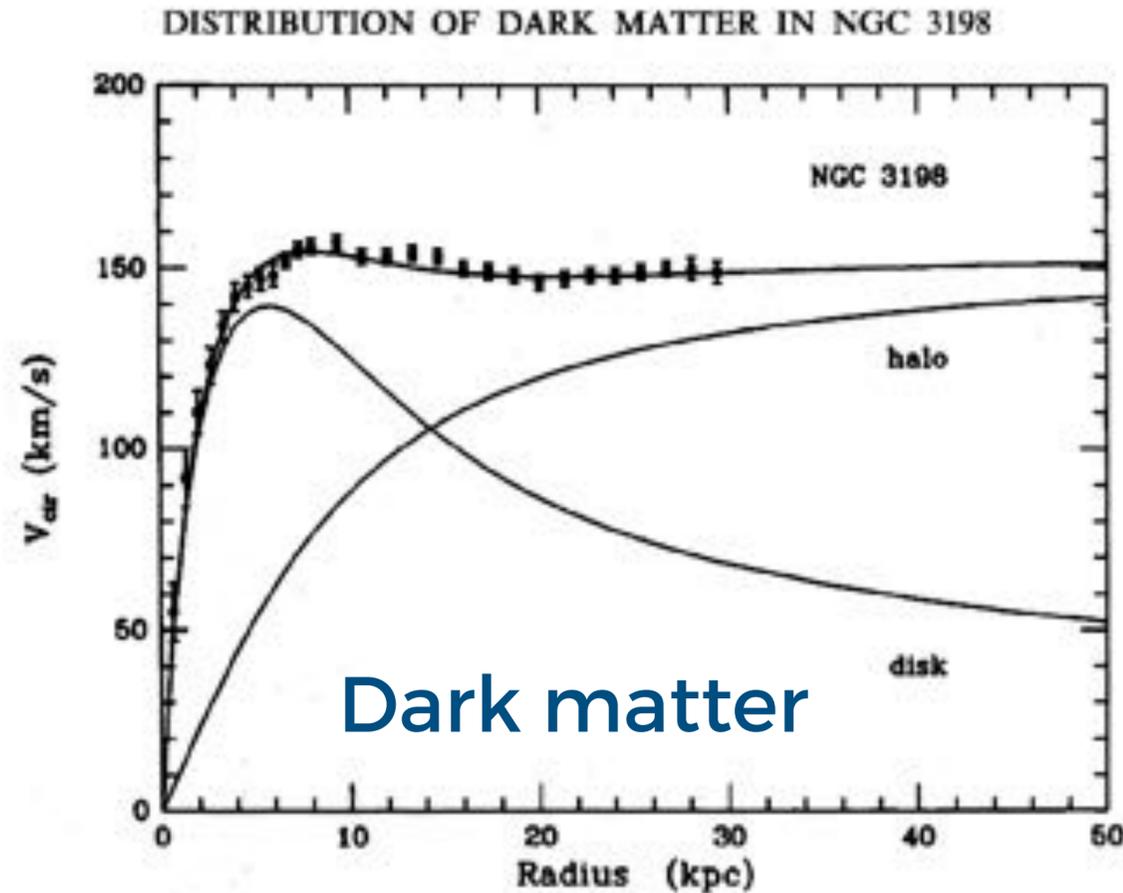
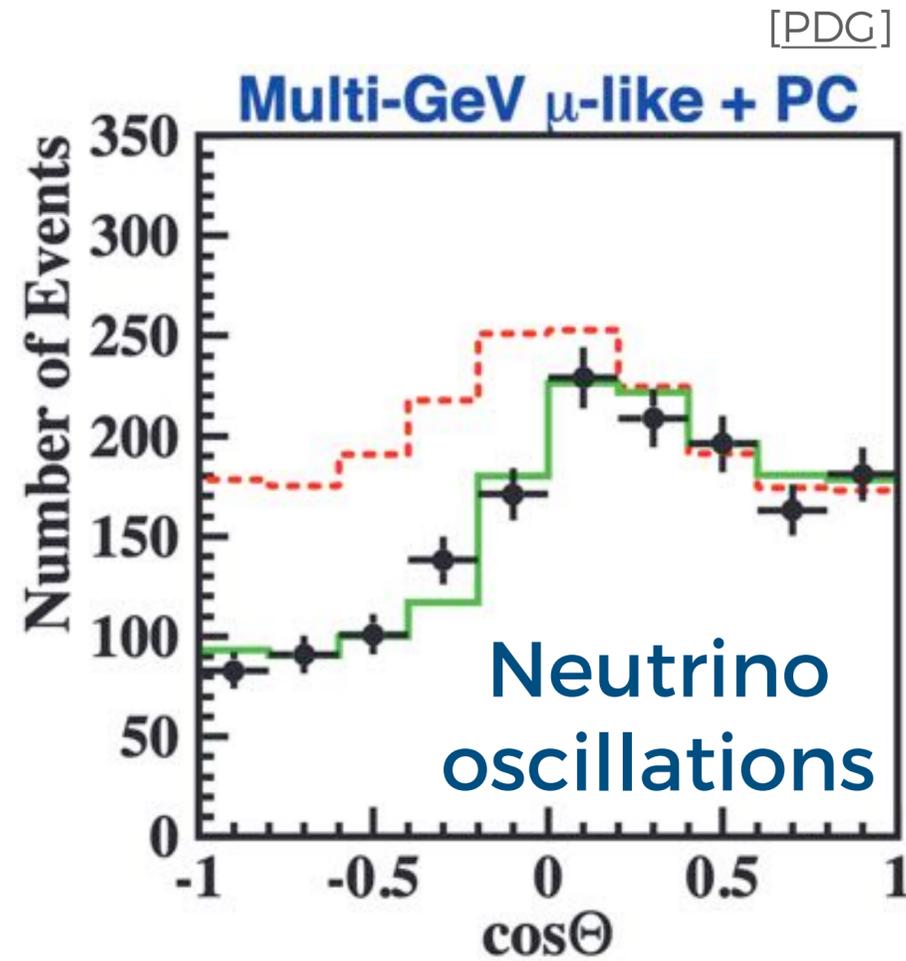
The Standard Model of particle physics

[quantamagazine.org]



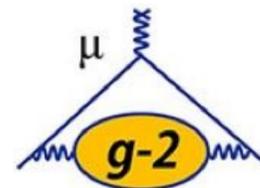
● QUARKS ● LEPTONS ● GAUGE BOSONS ● HIGGS BOSON

Physics beyond the Standard Model



[physicsanduniverse.com]

Muon $g-2$



W boson mass (?)



Physics beyond the SM?

Extra dimensions

Leptoquarks

Supersymmetry

Beyond Standard Model

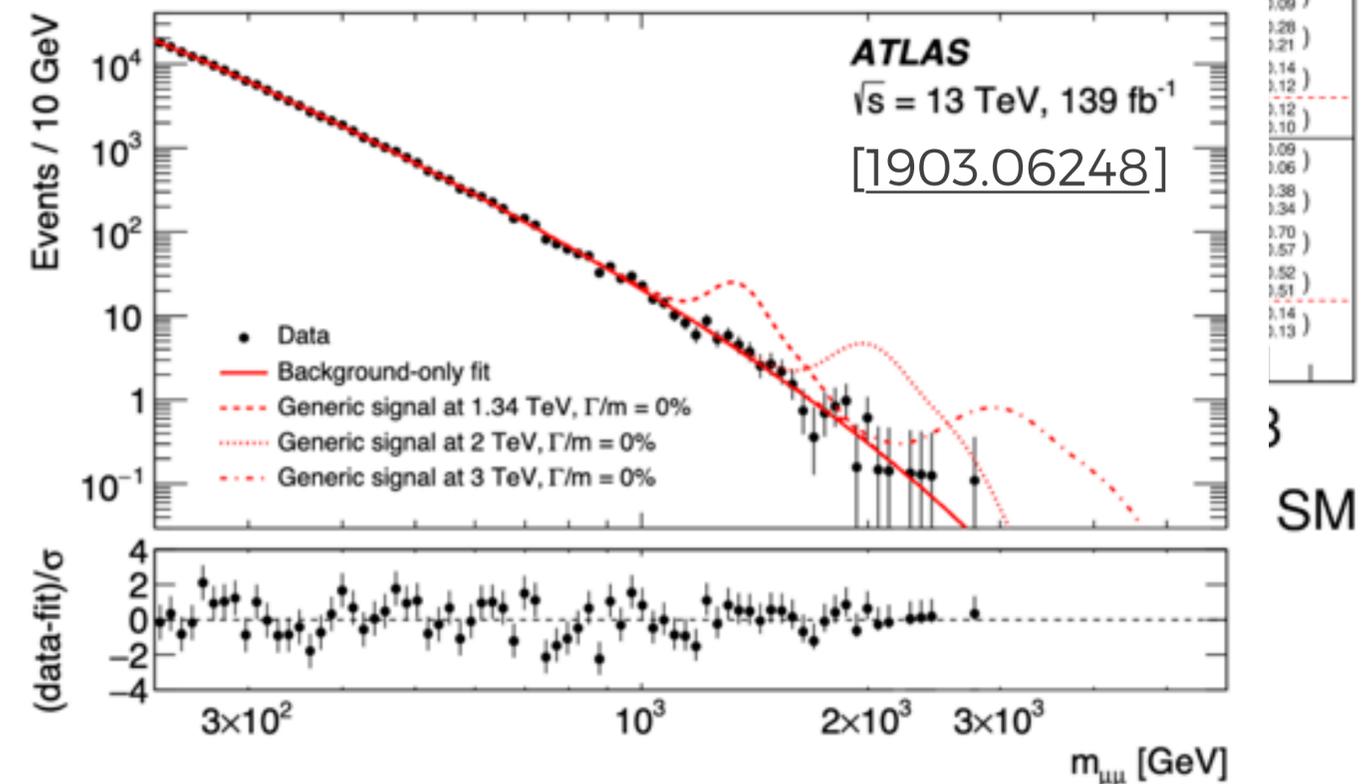
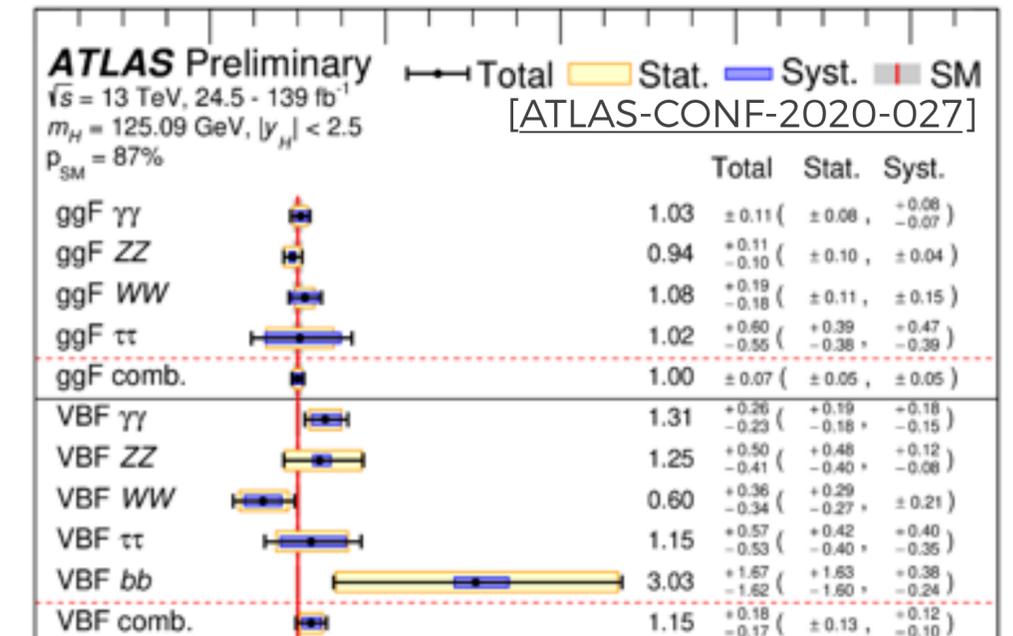
Axion-like particles

Z' bosons

4th generation

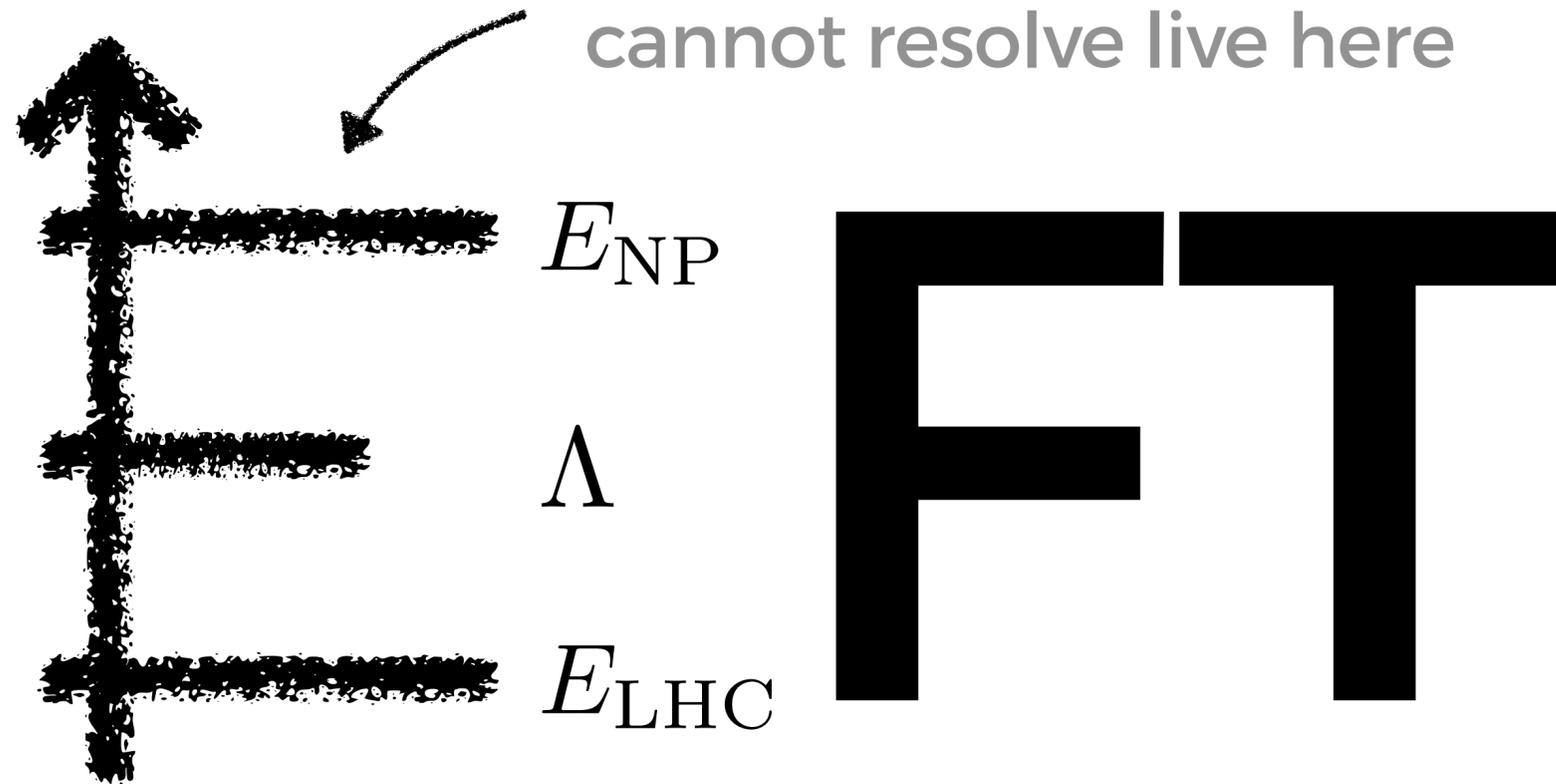
Is new physics hiding at the TeV scale?

Can we test its effects at lower scales?

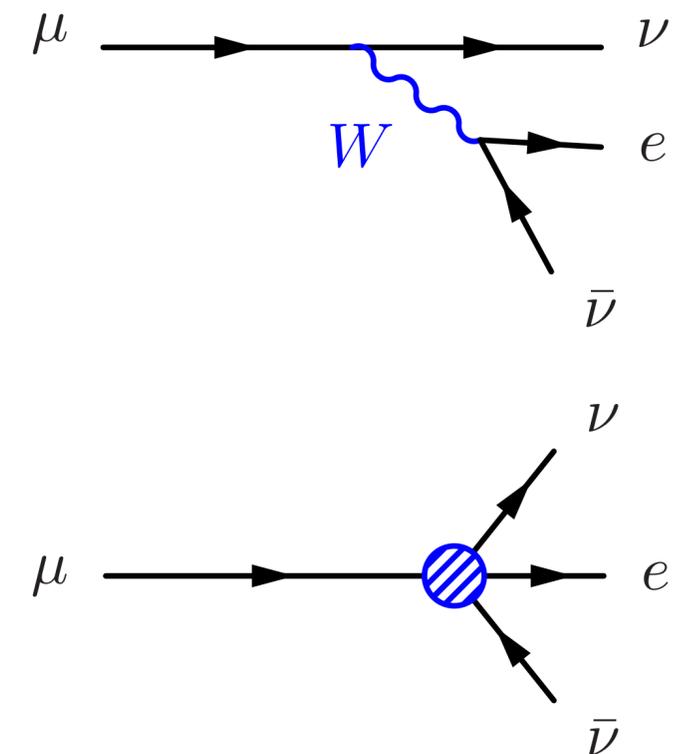


Effective field theory - EFT

Heavy particles that we cannot resolve live here

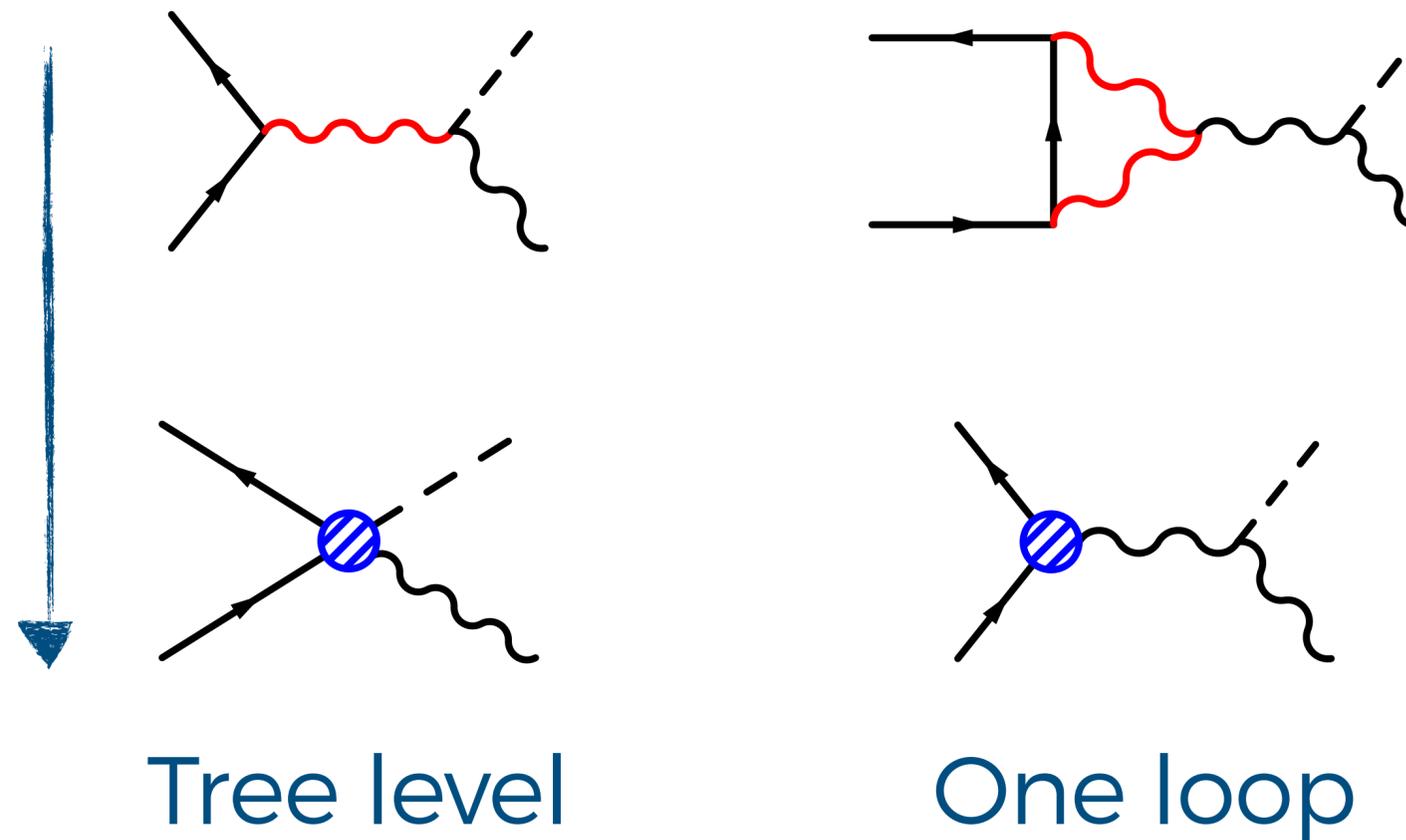


Hierarchy of scales



Describe NP by higher-order interactions of SM fields

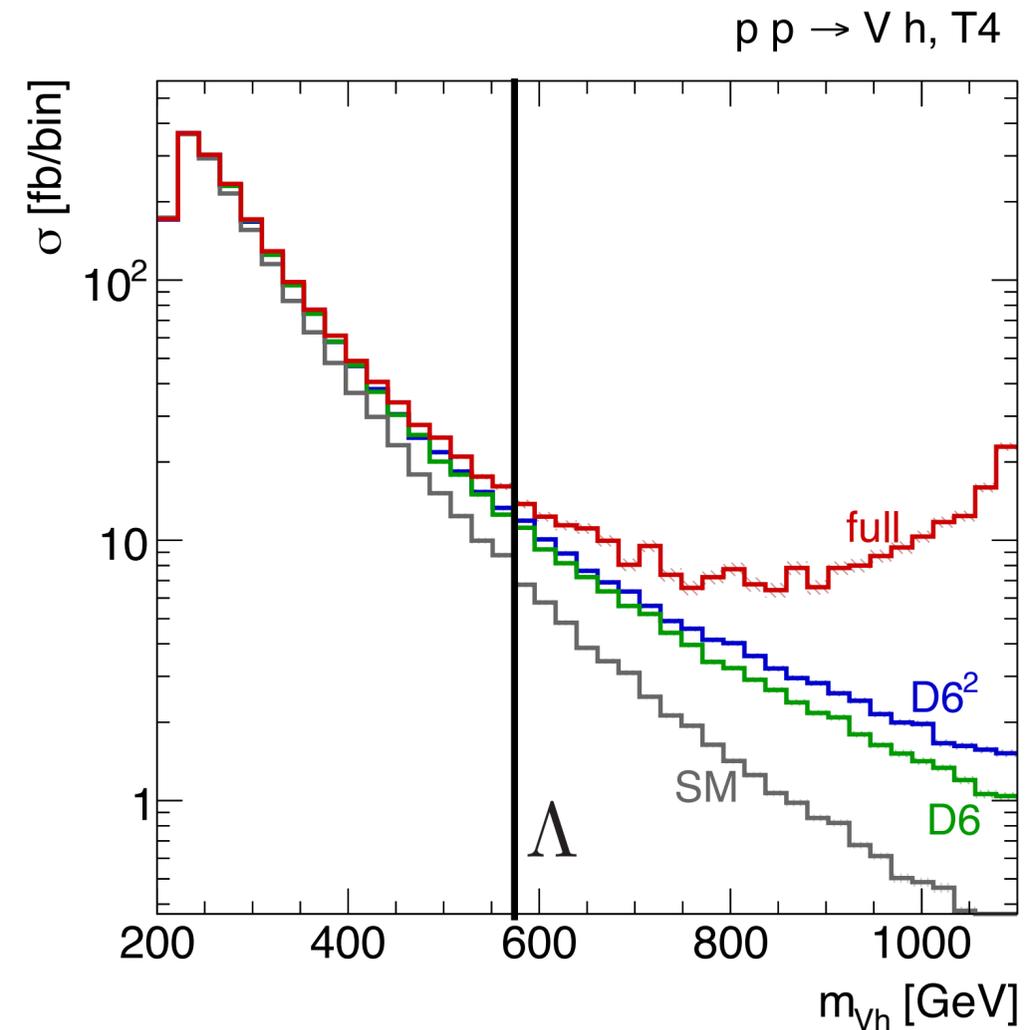
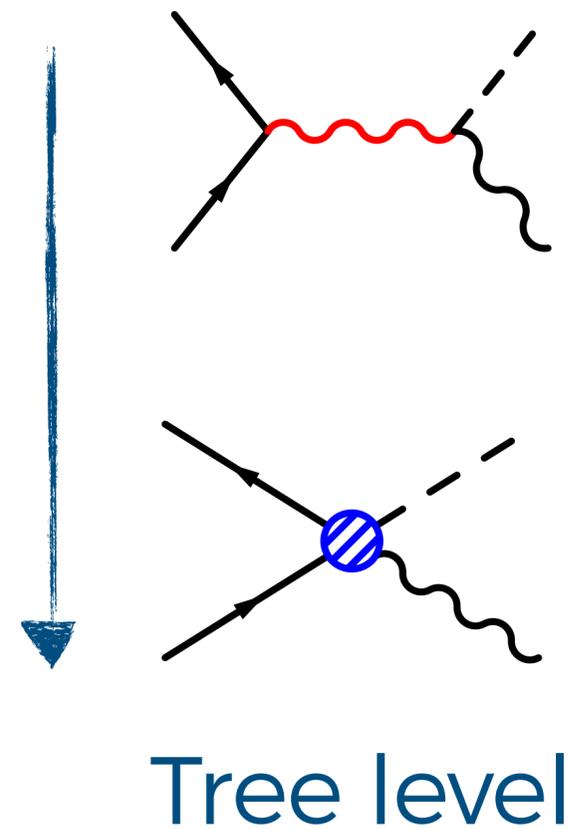
Top down - matching of a new model



Model with **new heavy vector boson**

Start from **full** UV-complete model and match onto **EFT**

Top down - matching of a new model

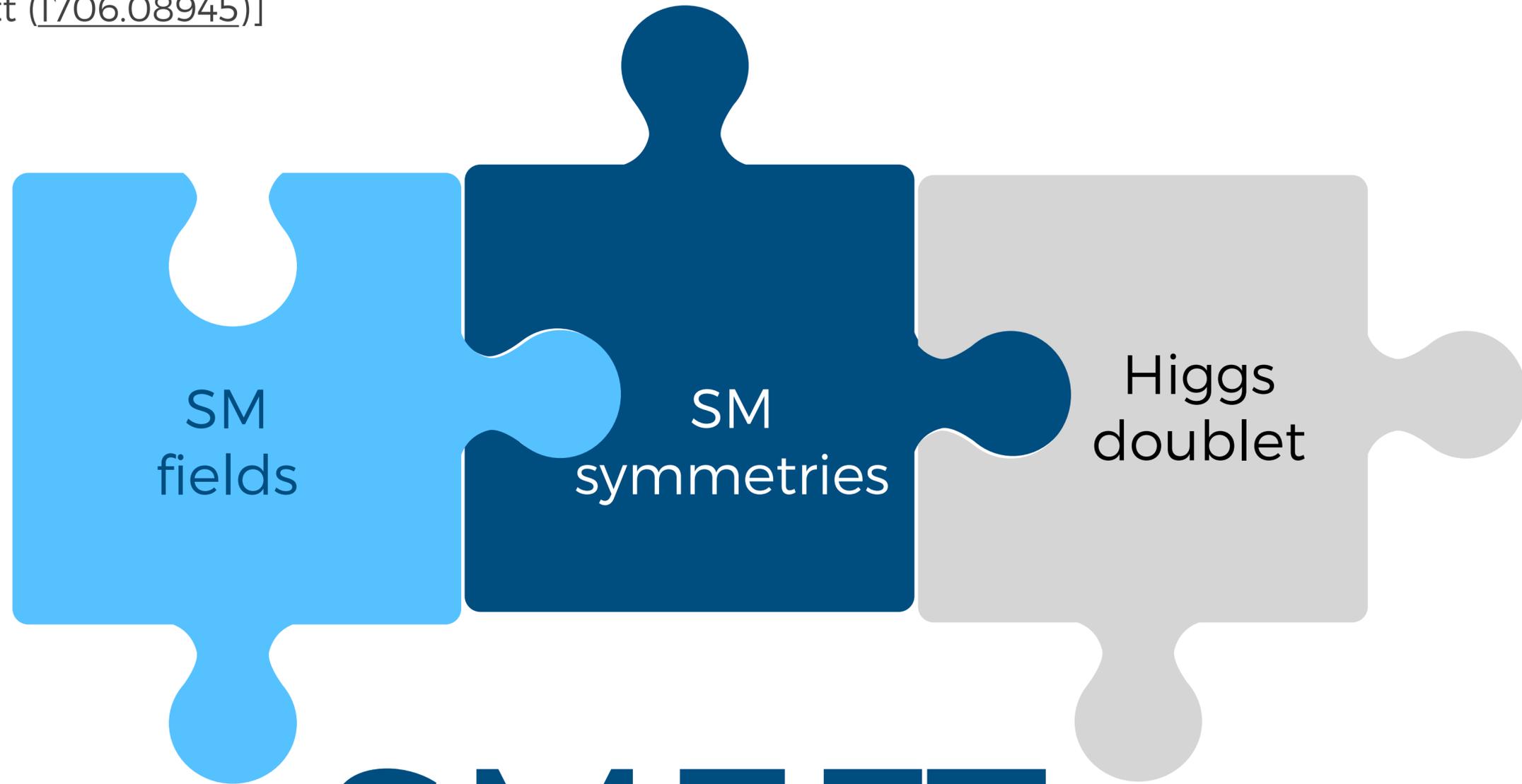


Model with **new heavy vector boson**

Start from **full** UV-complete model and match onto **EFT**

EFTs from the bottom-up

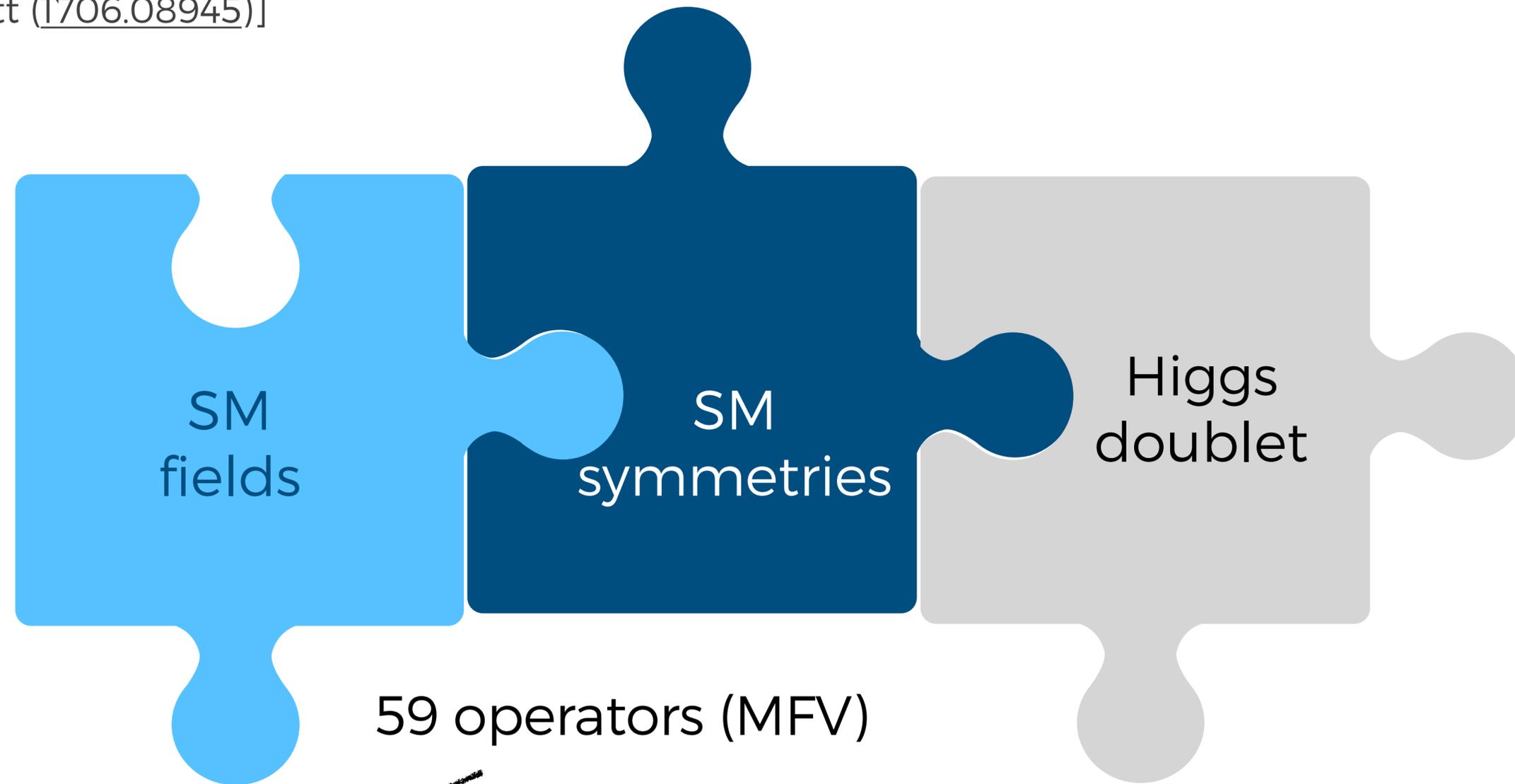
[review: Brivio, Trott ([1706.08945](#))]



SMEFT

EFTs from the bottom-up

[review: Brivio, Trott ([1706.08945](#))]



$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^2} \mathcal{O}_j^{(8)} + \dots$$

Odd dimensions violate lepton or baryon number

SMEFT advantages

- Proper, renormalizable **quantum field theory**
- **Minimal assumptions** on UV completion
- **Universal language** for data interpretation
- Allows combination of data from multiple experiments

Systematic program for indirect searches!

Warsaw basis

[Grzadkowski et al. (1008.4884)]

1 : X^3		2 : H^6		3 : $H^4 D^2$		5 : $\psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_\tau H)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_\tau \tilde{H})$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_\tau H)$
$Q_{\tilde{W}}$	$\epsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						
4 : $X^2 H^2$		6 : $\psi^2 X H + \text{h.c.}$		7 : $\psi^2 H^2 D$			
Q_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_\tau) \tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_\tau)$		
$Q_{H\tilde{G}}$	$H^\dagger H \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_\tau) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_\tau)$		
Q_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_\tau) \tilde{H} G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_\tau)$		
$Q_{H\tilde{W}}$	$H^\dagger H \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_\tau) \tau^I \tilde{H} W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_\tau)$		
Q_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_\tau) \tilde{H} B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_\tau)$		
$Q_{H\tilde{B}}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_\tau) H G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_\tau)$		
Q_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_\tau) \tau^I H W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_\tau)$		
$Q_{H\tilde{W}B}$	$H^\dagger \tau^I H \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_\tau) H B_{\mu\nu}$	$Q_{Hud} + \text{h.c.}$	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_\tau)$		
8 : $(\bar{L}L)(\bar{L}L)$							
Q_{ll}	$(\bar{l}_p \gamma_\mu l_\tau)(\bar{l}_s \gamma^\mu l_t)$						

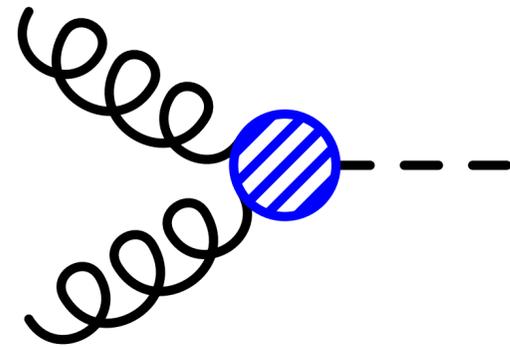
Plus another 24 four-fermion operators

The operator \mathcal{O}_{HG}

Affects total cross section only

$$\mathcal{O}_{HG} = H^\dagger H G_{\mu\nu}^A G^{A,\mu\nu} \rightarrow v h G_{\mu\nu}^A G^{A,\mu\nu}$$

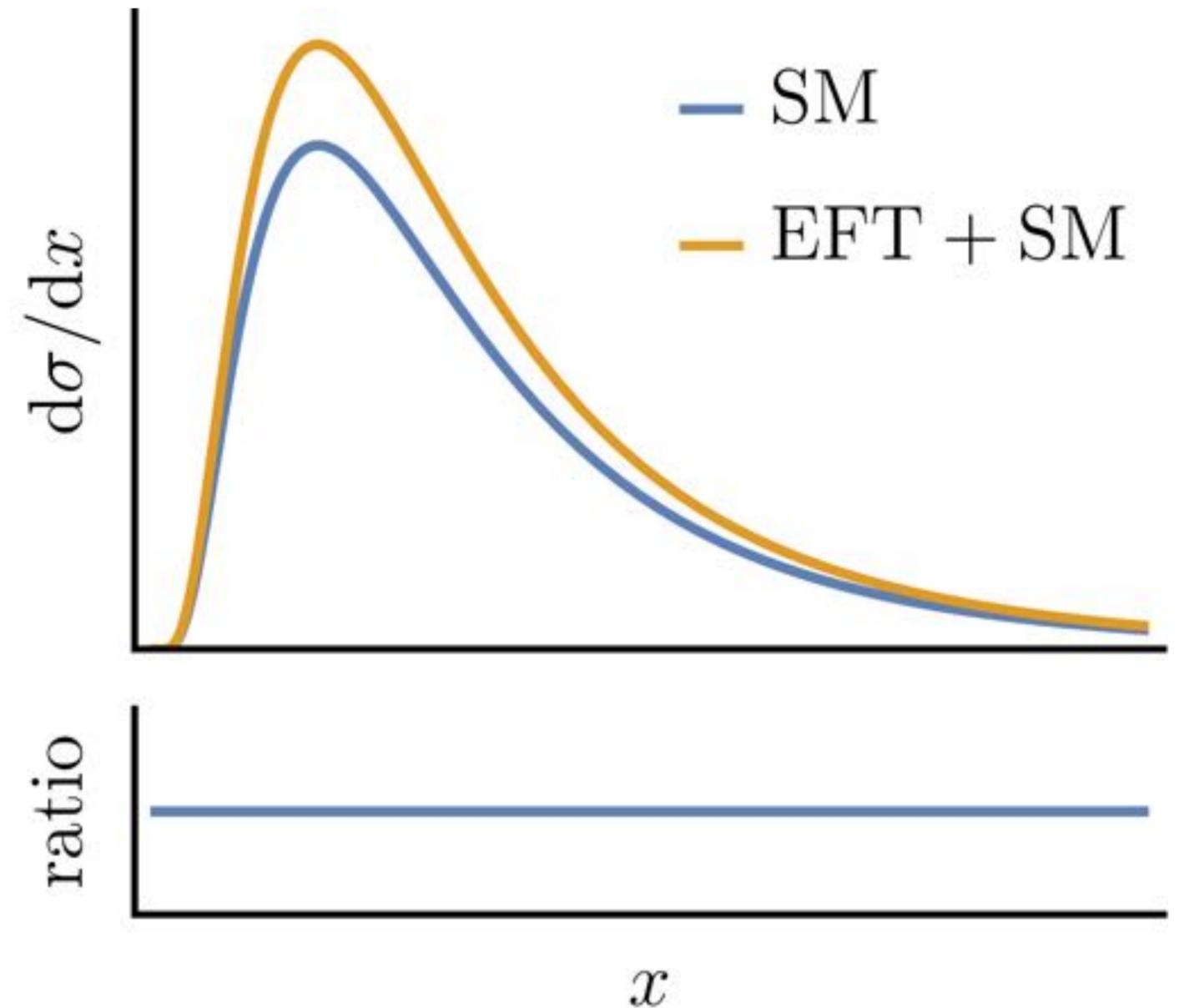
Feynman rules



SM: $-i G_H \delta_{a_1, a_2} (p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2)$

EFT: $-i v \delta_{a_1, a_2} (p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2)$

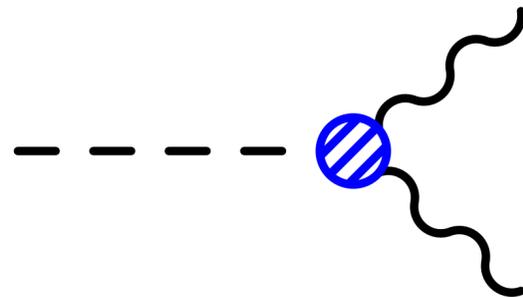
Structurally the same



The operator \mathcal{O}_{HB}

$$\mathcal{O}_{HB} = H^\dagger H B_{\mu\nu} B^{\mu\nu} \rightarrow c_{HZZ}^{\text{EFT}} h Z_{\mu\nu} Z^{\mu\nu}$$

Feynman rules

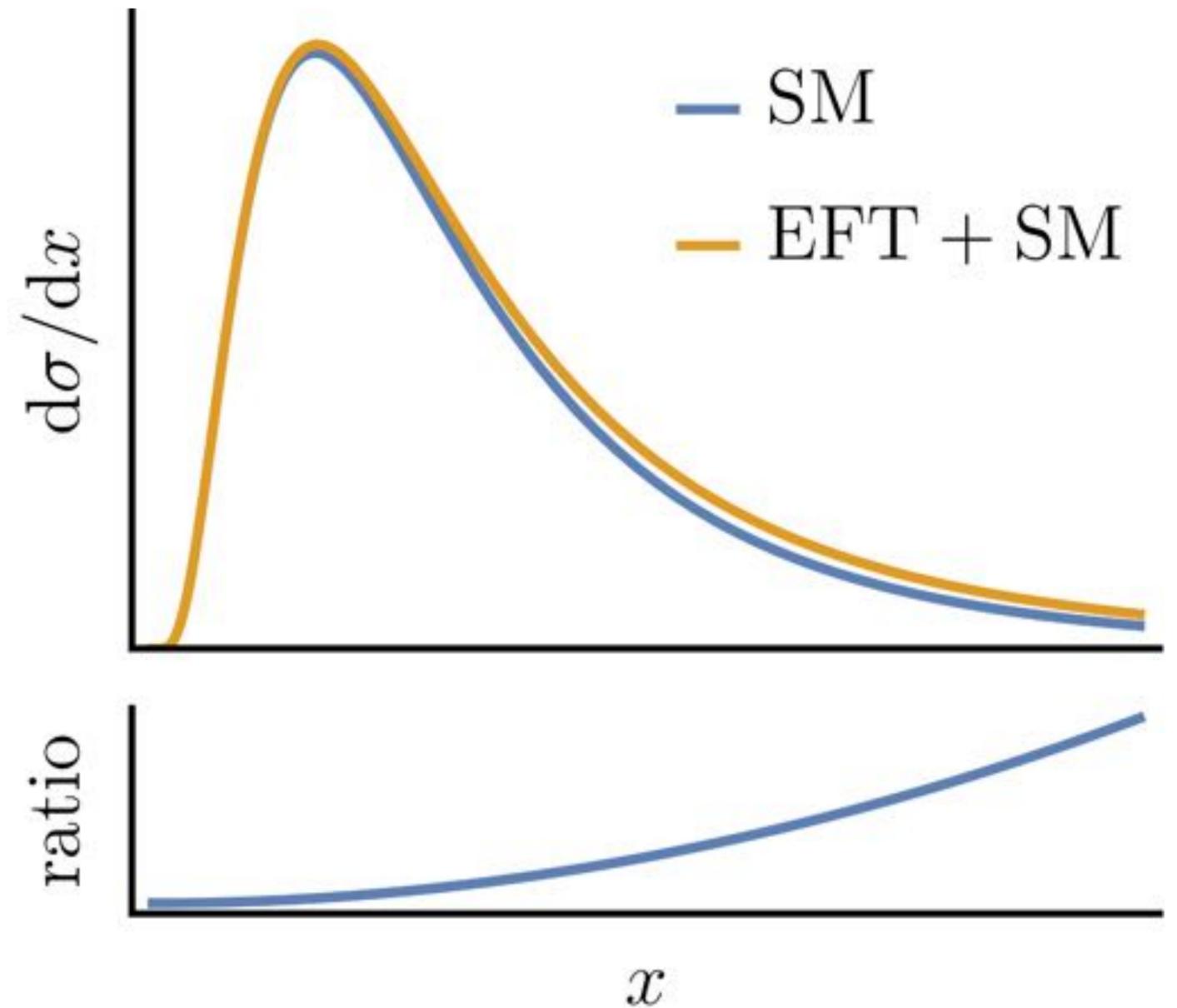


SM: $g_{ZZh}^{\text{SM}} \eta^{\mu\nu}$

EFT: $g_{hZZ}^{\text{EFT}} [p_{Z_1}^\mu p_{Z_2}^\nu - \eta^{\mu\nu} p_{Z_1} \cdot p_{Z_2}]$

EFT contribution has additional momentum dependence

Affects distributions



e.g. m_{Zh} in HZ production

The operator \mathcal{O}_{Hu}

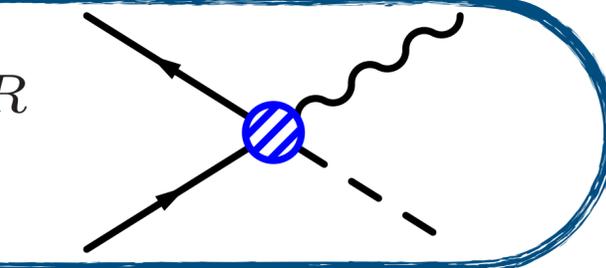
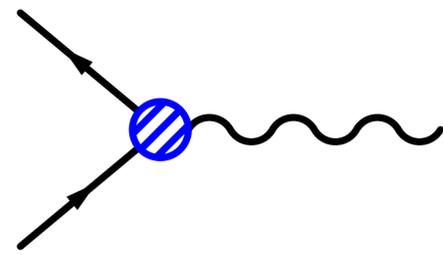
$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{u}_R \gamma^\mu u_R) \rightarrow (h + v) Z_\mu (\bar{u}_R \gamma^\mu u_R)$$

Feynman rules

SM Zuu : $g_{Zuu}^{\text{SM}} \gamma^\mu P_R$

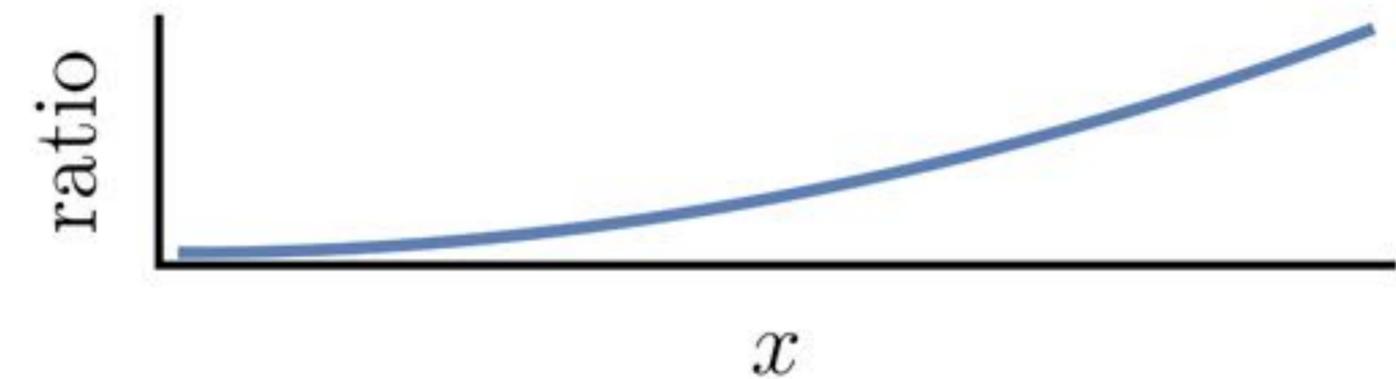
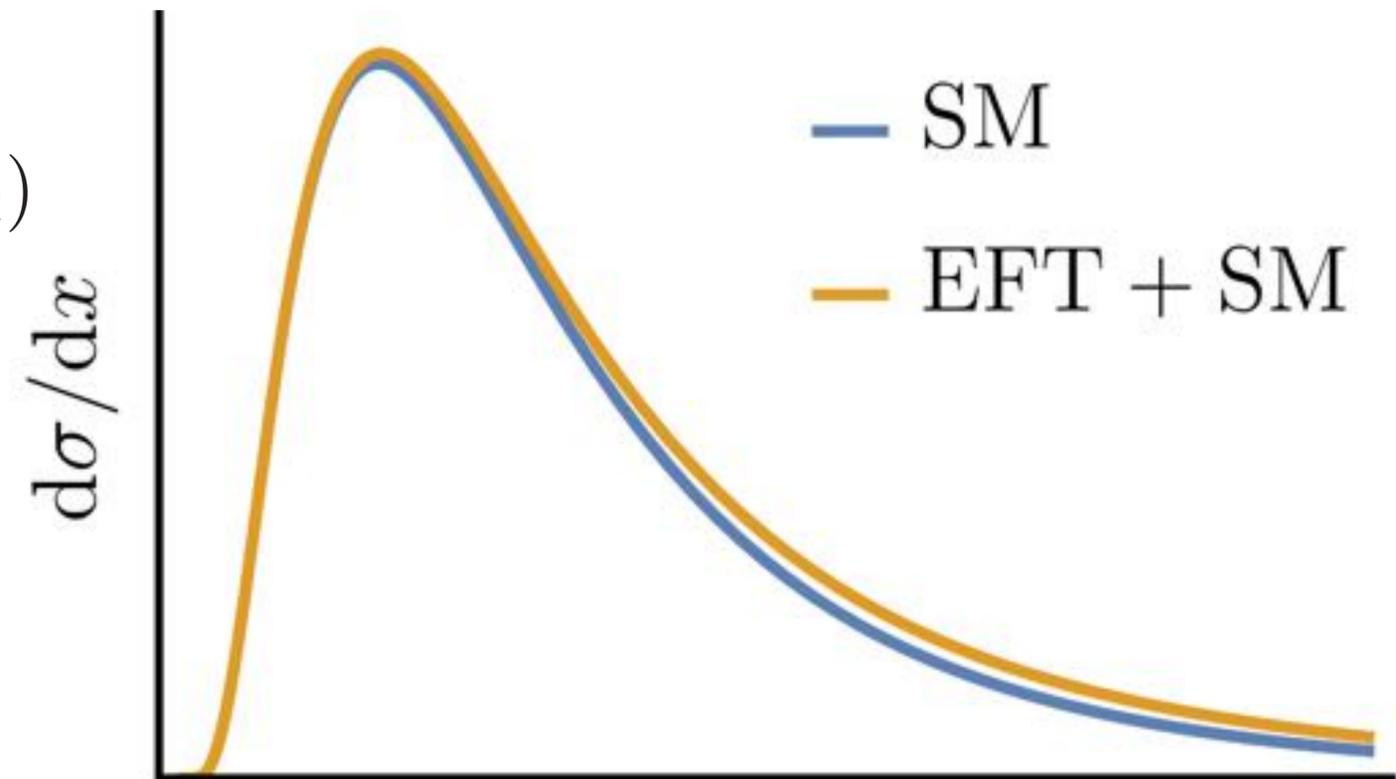
EFT Zuu : $g_{Zuu}^{\text{EFT}} \gamma^\mu P_R$

EFT $Zhuu$: $g_{Zuu}^{\text{EFT}} / v \gamma^\mu P_R$

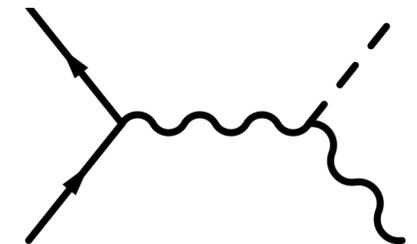


New contact interaction

Affects distributions



SM: propagator suppression

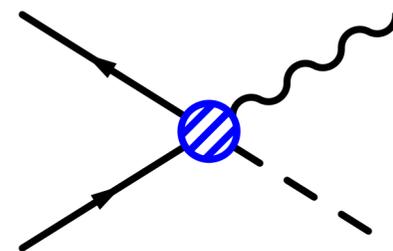


Dimension-six operators - effects

- Contribution to SM-like structures
(same Lorentz structure as in SM)

Only total cross section affected

- Interactions with new Lorentz structures
- New contact interactions
(not present in the SM)

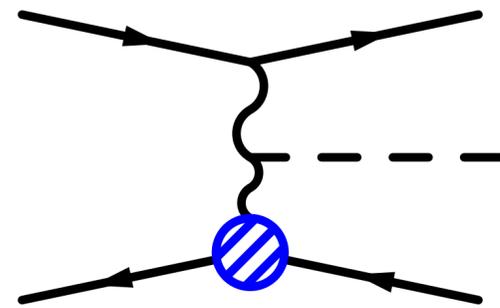
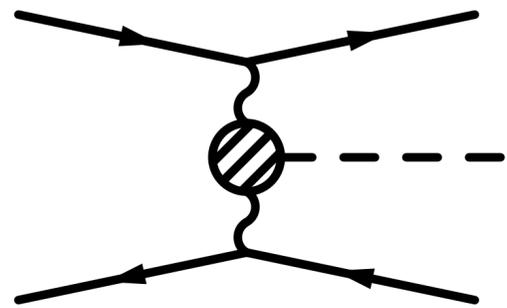


distributions affected

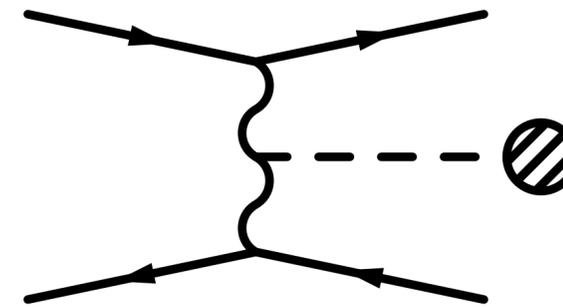
Global SMEFT fits

Why global fits?

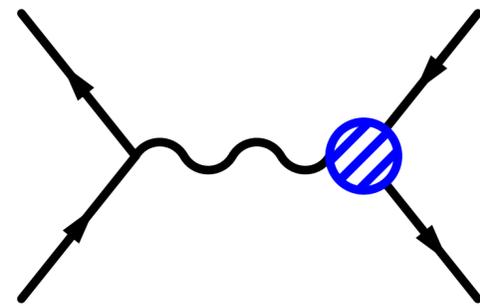
One observable can be influenced by many operators



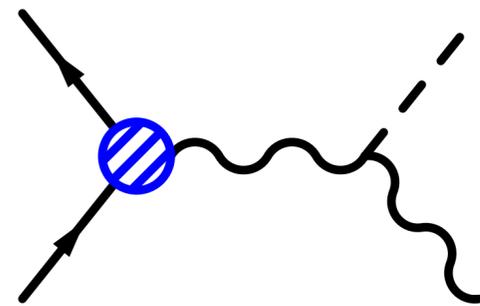
Higgs decay



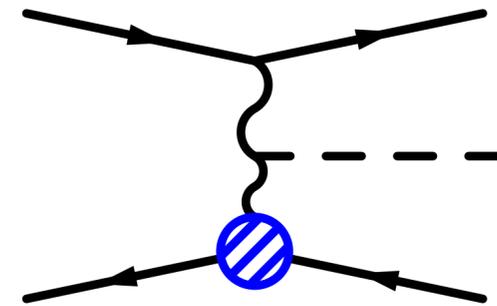
One operator can contribute to many different observables



$$e^+ e^- \rightarrow f \bar{f}$$



Zh production



Weak boson fusion
Higgs production

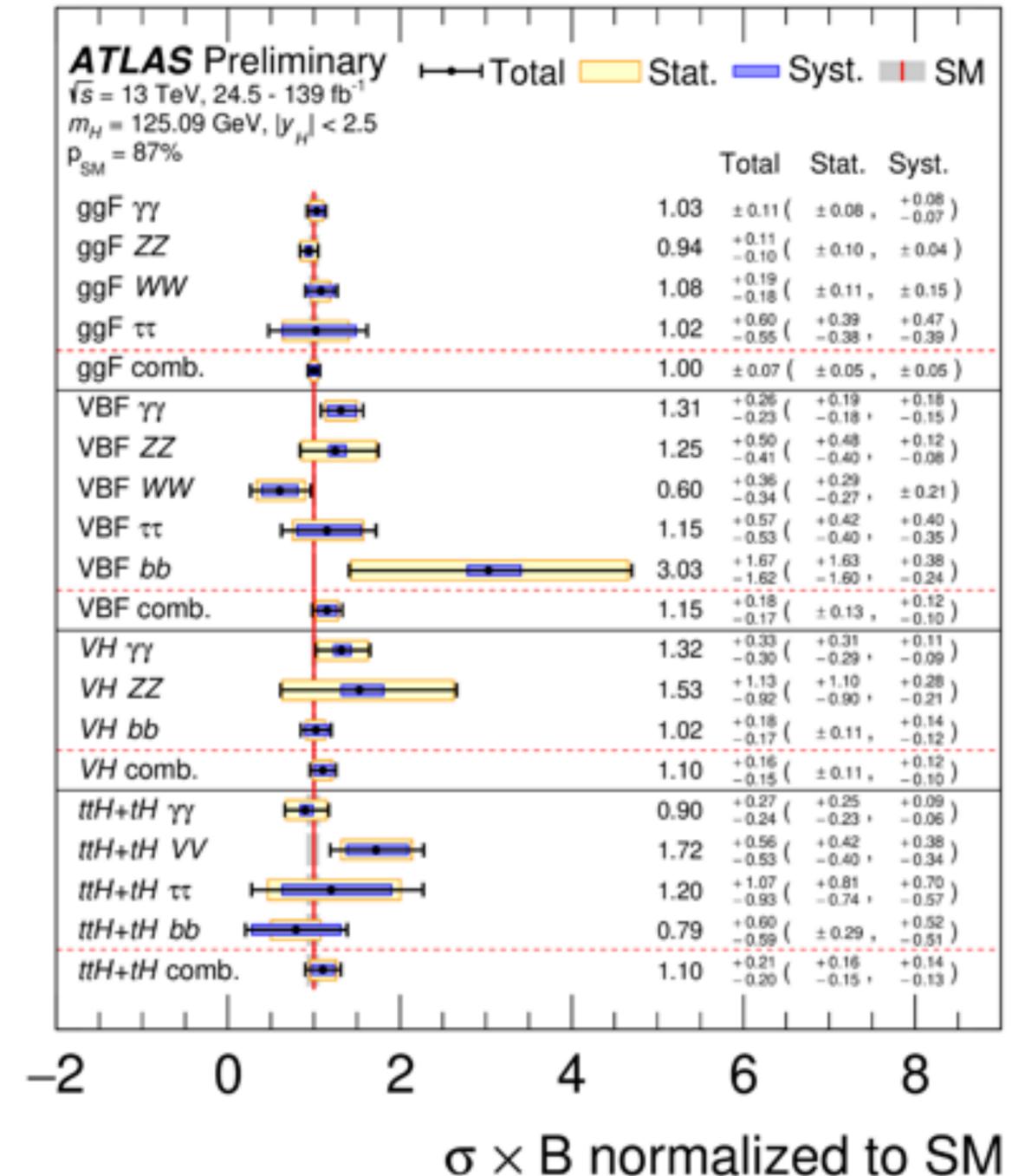
Why global fits?

- Lots of measurements (without a clear deviation from the SM)
- One observable can be influenced by many operators
- One operator can contribute to many different observables

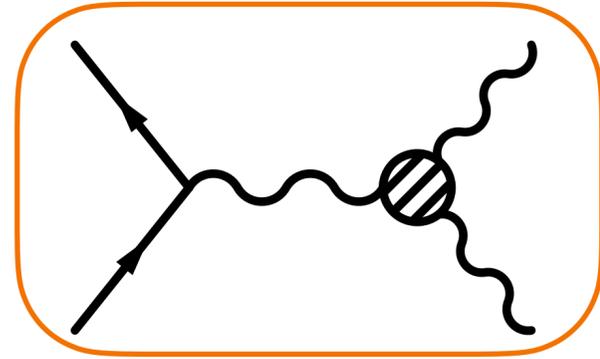
Need a global analysis of all EFT coefficients to map all direction of new fundamental physics

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j}{\Lambda^2} \mathcal{O}_j^{(8)} + \dots$$

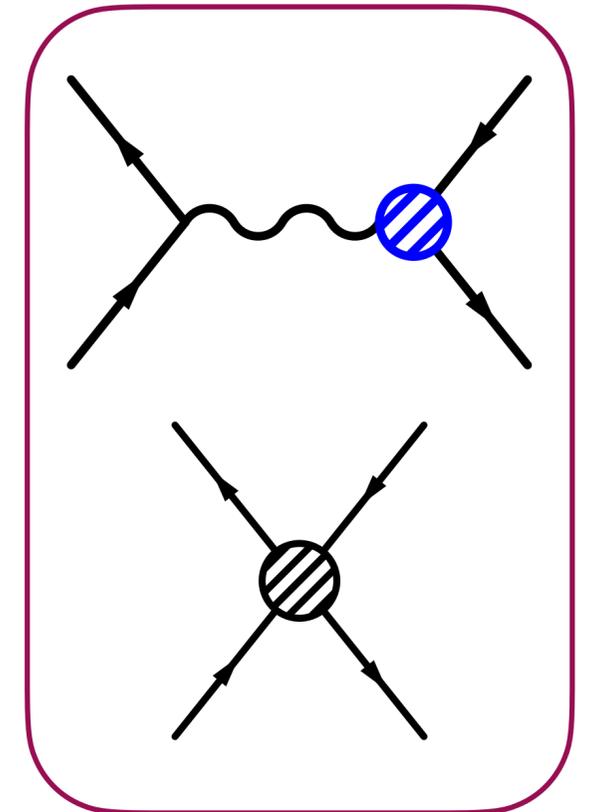
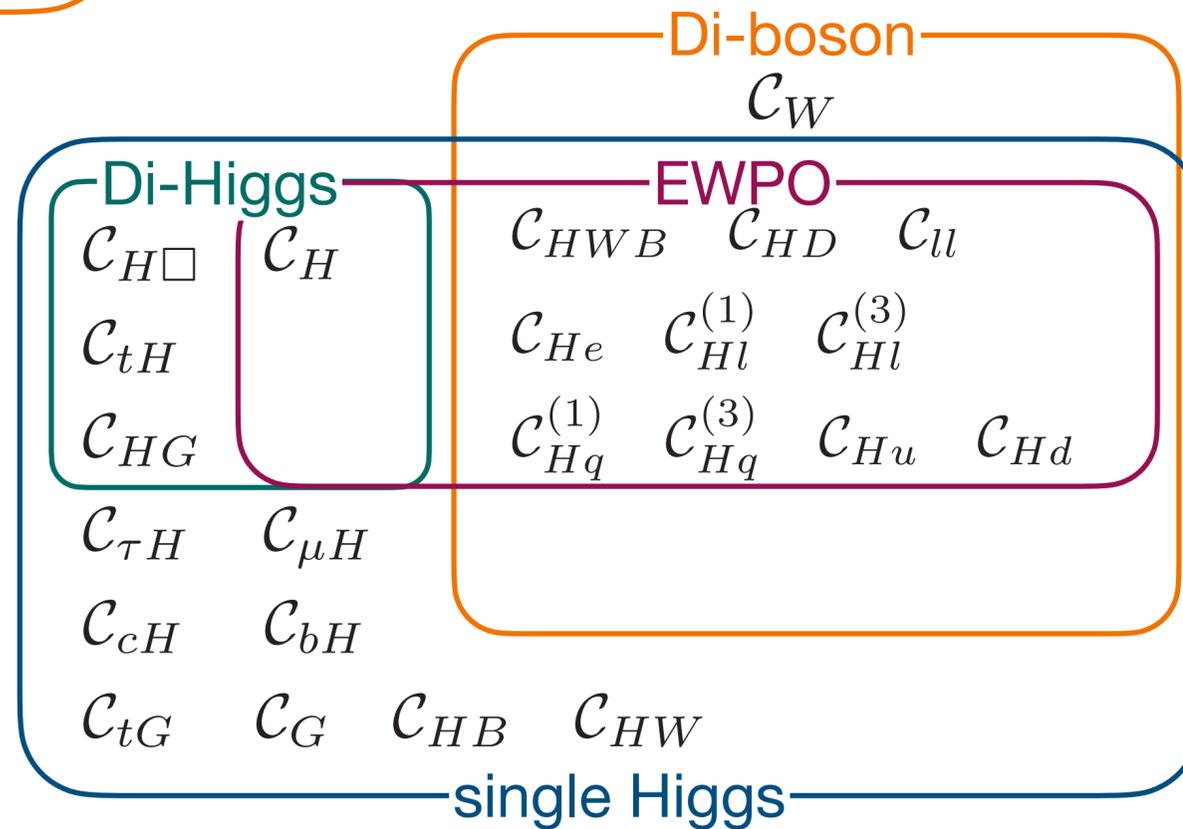
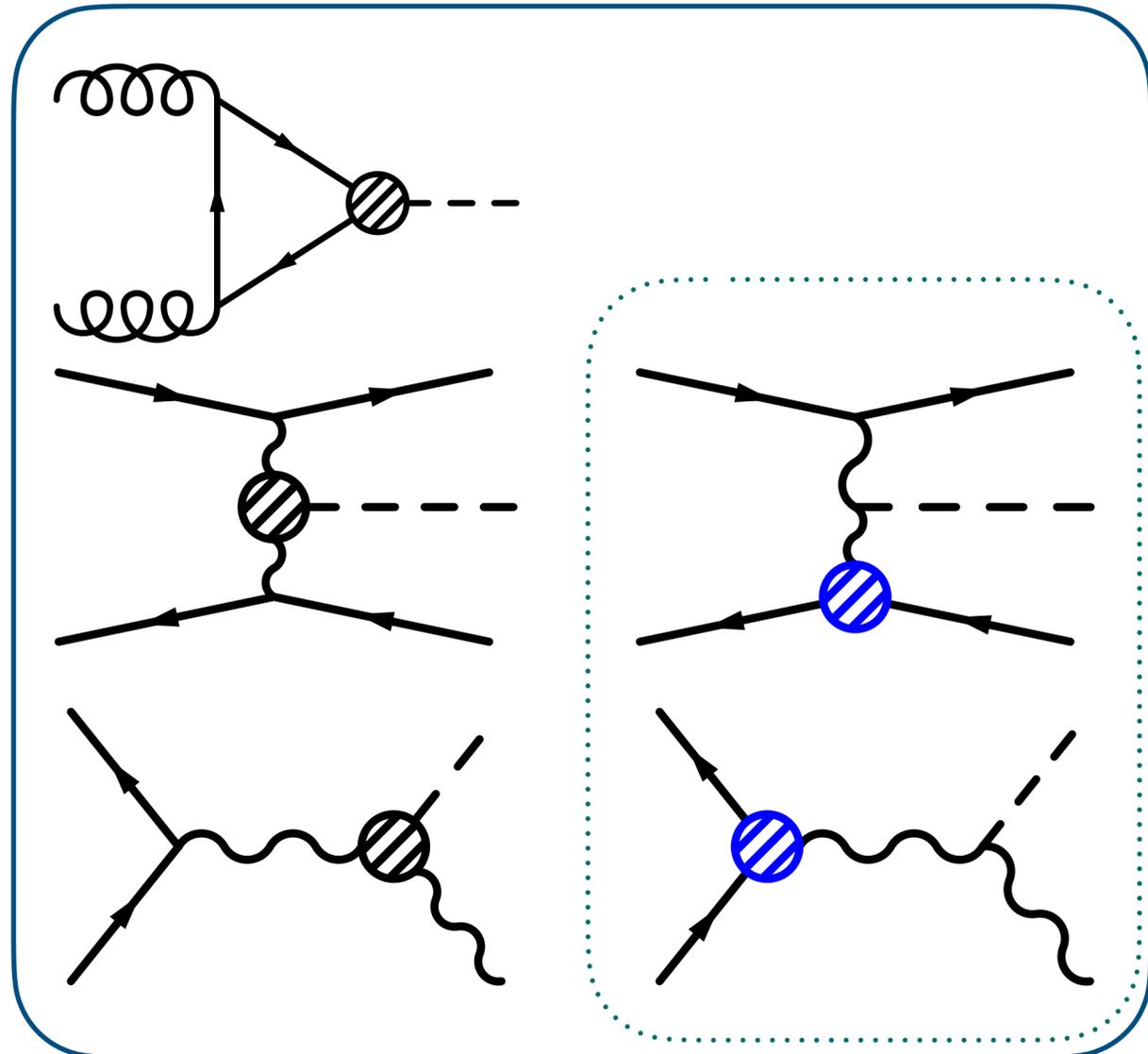
[ATLAS-CONF-2020-027]



The Higgs and electroweak sector



EWPO: Electroweak precision observables (LEP)



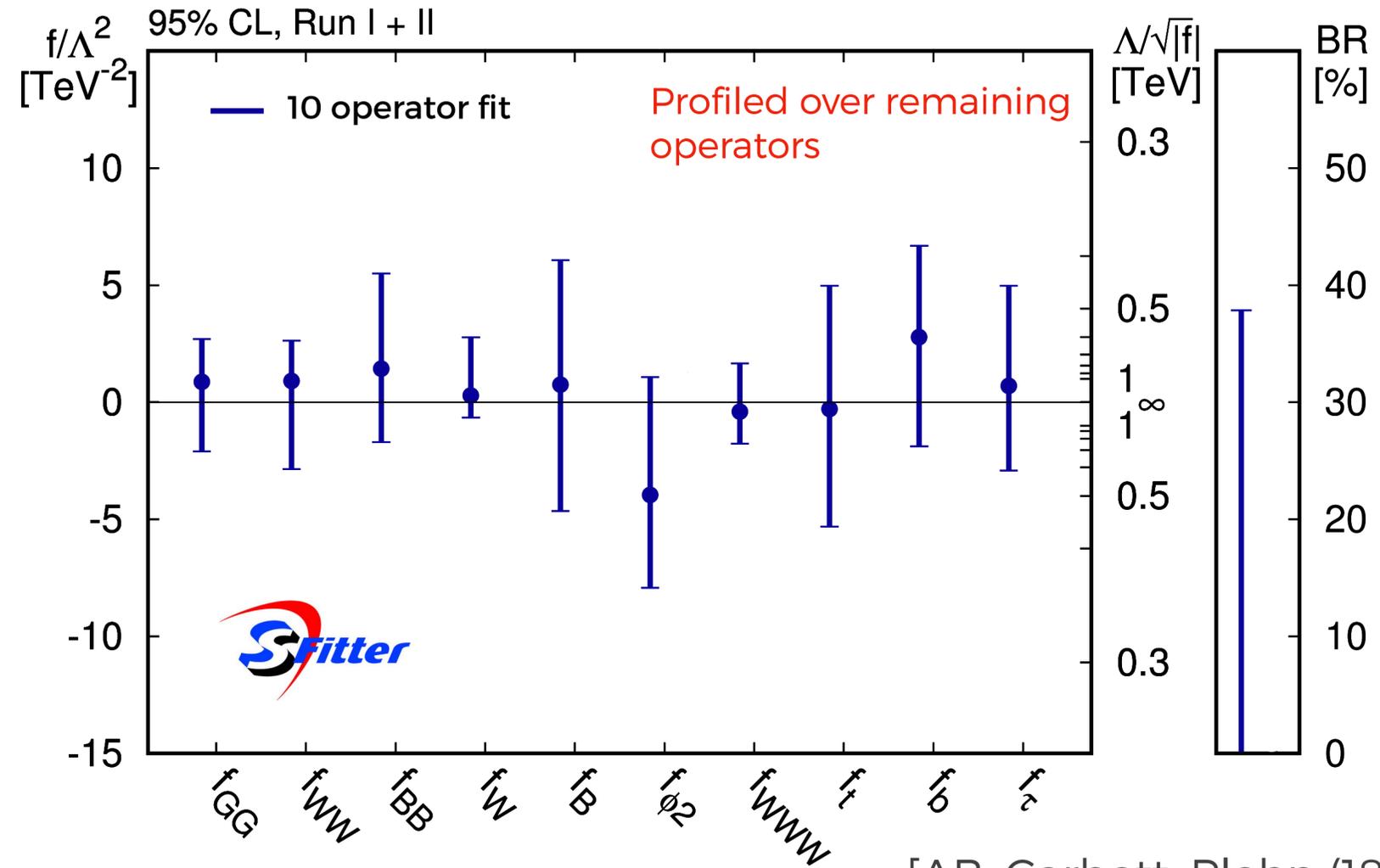
How do different sectors interact in a global fit?

LHC 2018 fit - fermion-gauge operators

[Hagiwara-Ishihara-Szalapski-Zeppenfeld basis]

Higgs only

$$\begin{aligned} \mathcal{O}_{GG} &= \phi^\dagger \phi G_{\mu\nu}^a G^{a\mu\nu} \\ \mathcal{O}_{WW} &= \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \\ \mathcal{O}_{BB} &= \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi \\ \mathcal{O}_W &= (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \\ \mathcal{O}_B &= (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \\ \mathcal{O}_{\phi 2} &= \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) \\ \mathcal{O}_{WWW} &= \text{Tr} \left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu \right) \\ \mathcal{O}_\tau &= \phi^\dagger \phi \bar{L}_3 \phi e_{R,3} \\ \mathcal{O}_t &= \phi^\dagger \phi \bar{Q}_3 \tilde{\phi} u_{R,3} \\ \mathcal{O}_b &= \phi^\dagger \phi \bar{Q}_3 \phi d_{R,3} \end{aligned}$$



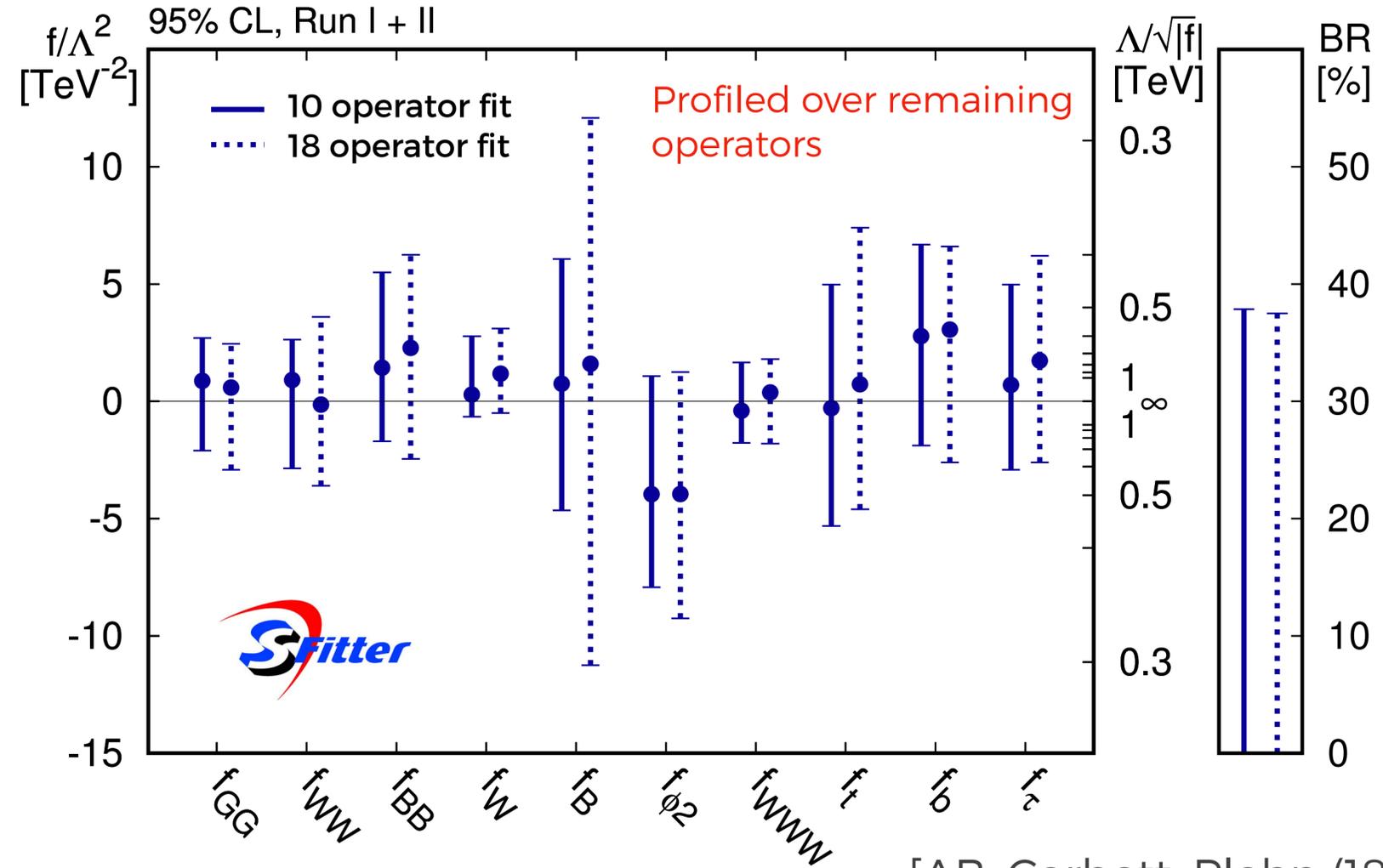
[AB, Corbett, Plehn (1812.07587)]

LHC 2018 fit - fermion-gauge operators

[Hagiwara-Ishihara-Szalapski-Zeppenfeld basis]

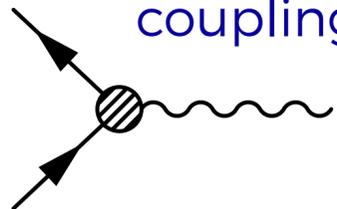
Higgs only

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[AB, Corbett, Plehn (1812.07587)]

Fermion-gauge couplings

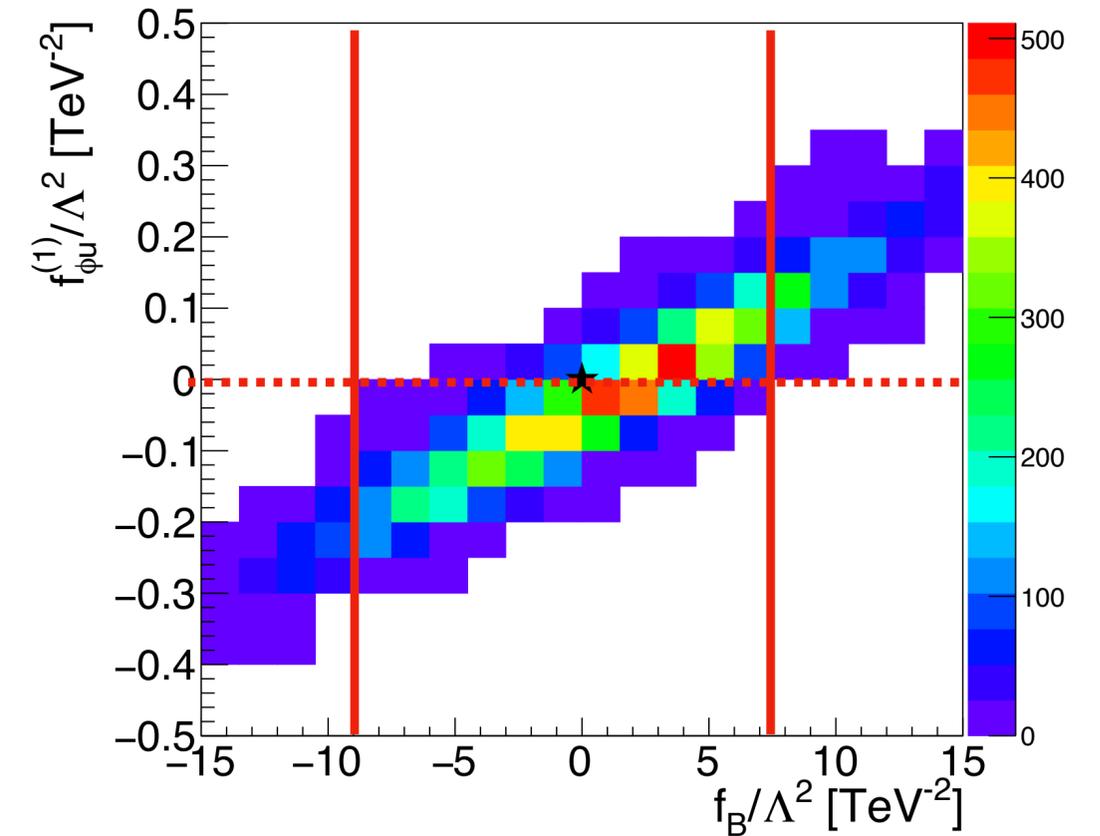
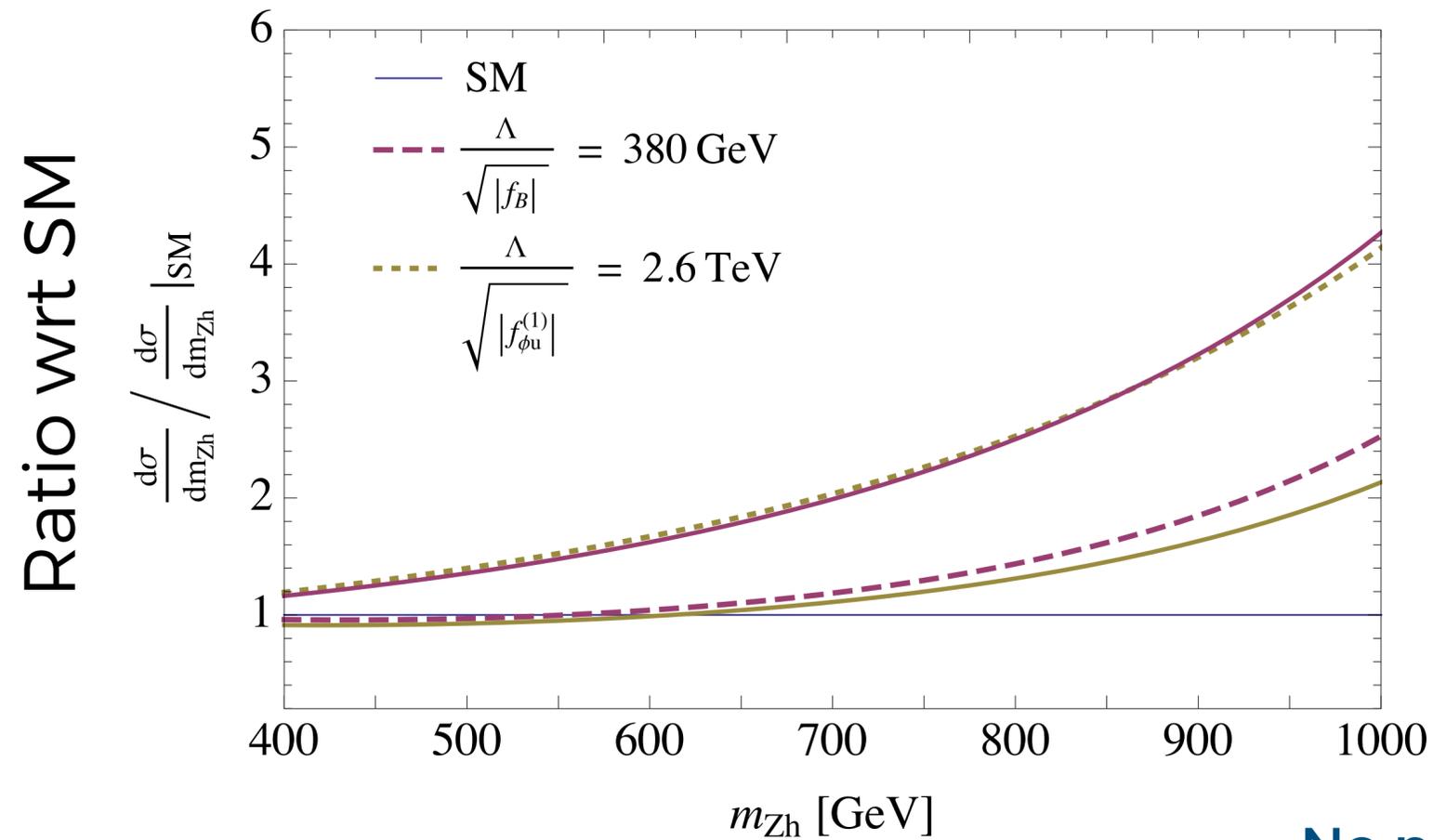


$$\begin{aligned} \mathcal{O}_{\phi 1} &= (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi) & \mathcal{O}_{BW} &= \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \\ \mathcal{O}_{\phi Q}^{(1)} &= \phi^\dagger (i \overleftrightarrow{D}_\mu \phi) (\bar{Q} \gamma^\mu Q) & \mathcal{O}_{\phi Q}^{(3)} &= \phi^\dagger (i \overleftrightarrow{D}_\mu^a \phi) (\bar{Q} \gamma^\mu \sigma^a Q) & \mathcal{O}_{\phi u}^{(1)} &= \phi^\dagger (i \overleftrightarrow{D}_\mu \phi) (\bar{u}_R \gamma^\mu u_R) \\ \mathcal{O}_{\phi d}^{(1)} &= \phi^\dagger (i \overleftrightarrow{D}_\mu \phi) (\bar{d}_R \gamma^\mu d_R) & \mathcal{O}_{\phi e}^{(1)} &= \phi^\dagger (i \overleftrightarrow{D}_\mu \phi) (\bar{e}_R \gamma^\mu e_R) & \mathcal{O}_{LLLL} &= (\bar{L} \gamma_\mu L) (\bar{L} \gamma^\mu L) \end{aligned}$$

LHC 2018 fit - correlations

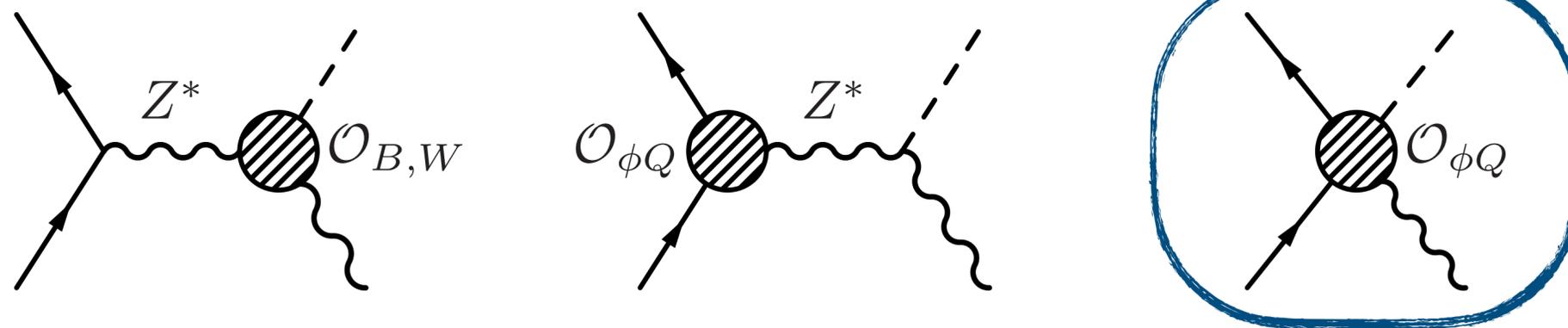
[Banerjee et al (1807.01796)]

[AB, Corbett, Plehn (1812.07587)]



Contributions to Zh production

No propagator suppression



$$\mathcal{O}_B = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi)$$

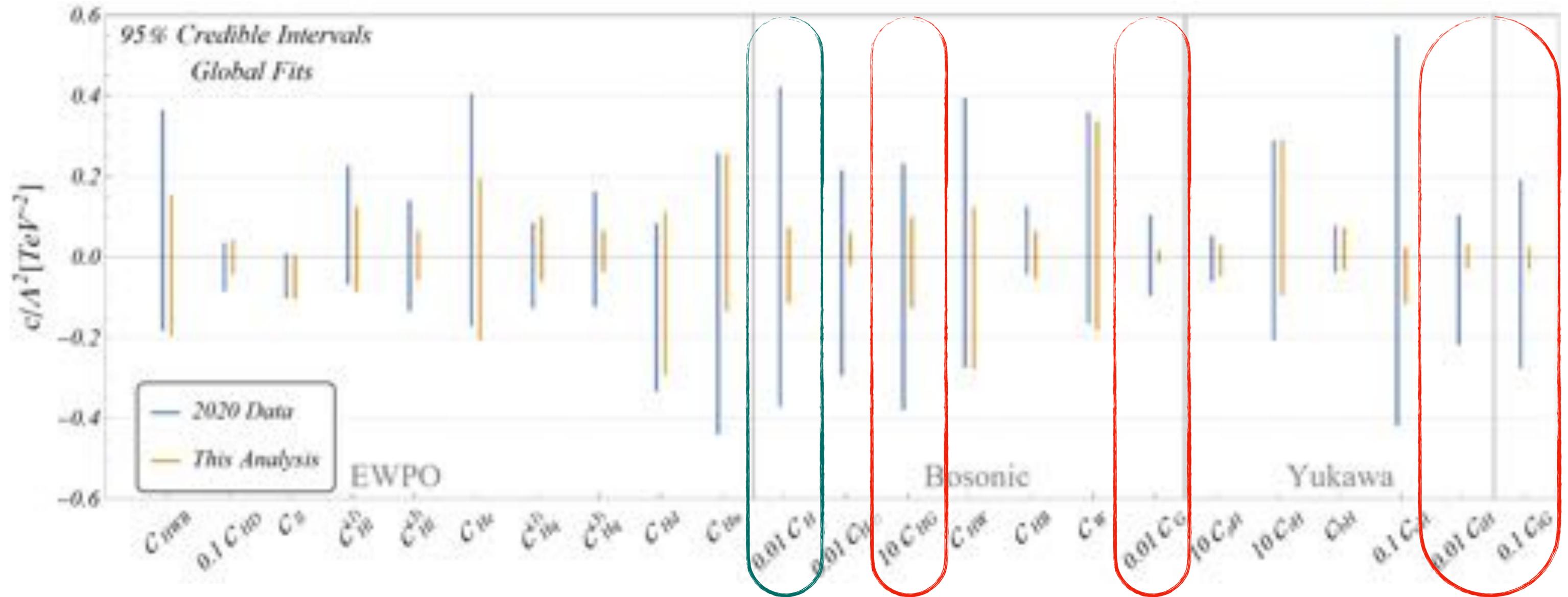
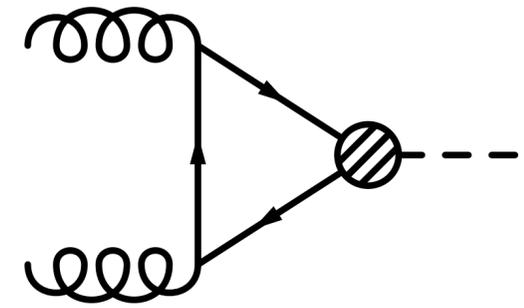
$$\mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi)$$

$$\mathcal{O}_{\phi Q}^{(1)} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi) (\bar{Q} \gamma^\mu Q)$$

$$\mathcal{O}_{\phi Q}^{(3)} = \phi^\dagger (i \overleftrightarrow{D}_\mu^a \phi) (\bar{Q} \gamma^\mu \sigma^a Q)$$

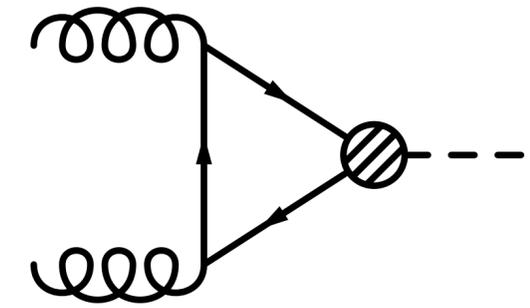
LHC 2021 fit

Di-Higgs production



LHC 2021 fit

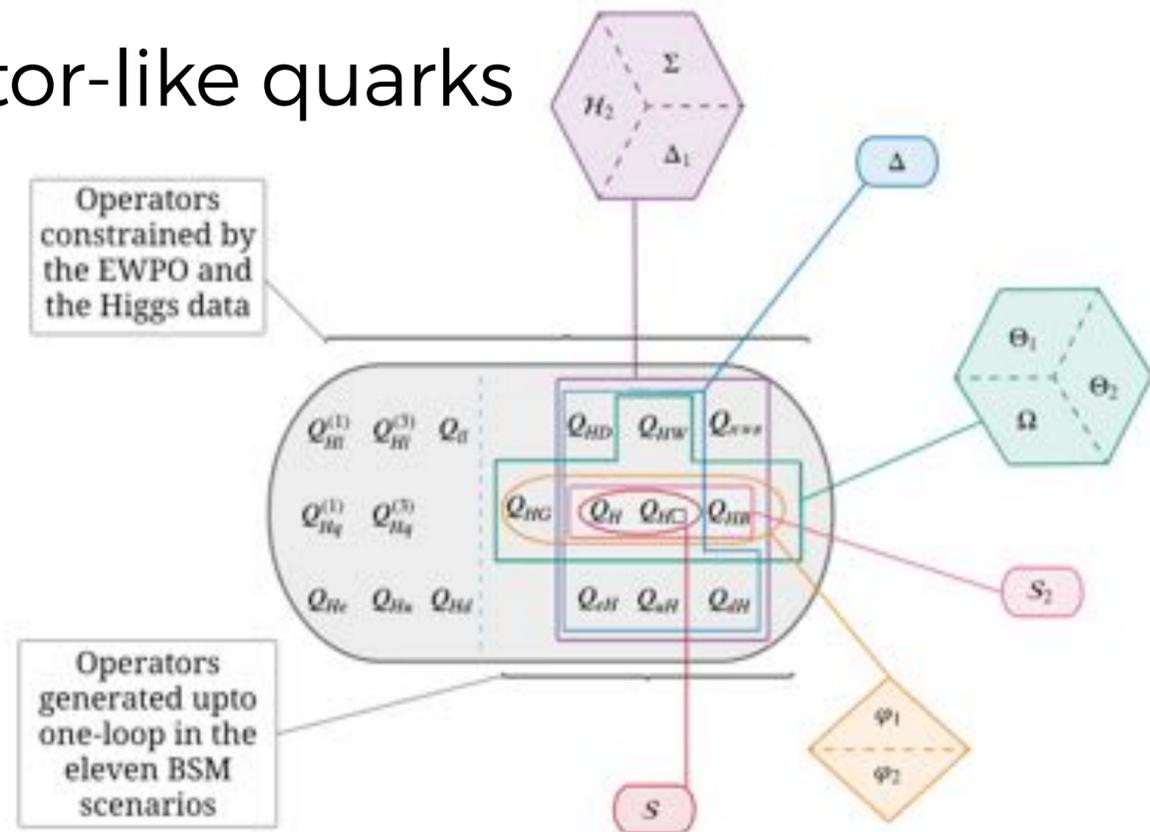
Di-Higgs production



So what have we learned about new physics now?

UV complete model fits

- Map UV complete models onto EFT
- Extended scalar sectors
- Quark bidoublet model
- Vector-singlet pair model
- Vector-like quarks
- ...



[Anisha, Bakshi, Chakraborty, Kumar Patra (2010.04088)]

[Gorbahn, No, Sanz (1502.07352)]

[Drozd, Ellis, Quevillon, You (1504.02409)]

[Ellis, (Madigan, Mimasu, Murphy), Sanz, You (1803.03252), (2012.02779)]

[Dawson, Homiller, Lane (2007.01296), (2102.02823)]

[Bakshi, Chakraborty, (Englert), Spannowsky, (Stylianou) (2009.13394), (2012.03839)]

[Krämer, Summ, Voigt (1908.04798)]

[Brivio, Brugisser, Geoffray, Kilian, Krämer (2108.01094)]

[...]

Model	C_{HD}	C_U	$C_{H\Box}^3$	$C_{H\Box}^1$	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						-1			
S_1		1							
Σ			$\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_t}{4}$		
Σ_1			$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_t}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$		
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_t}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_t}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_t}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_t}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_t	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_t}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_t$	$-y_t$	$-y_b$
$\{B, B_1\}$						1	y_t	y_t	y_b
$\{Q_1, Q_7\}$								y_t	

Two Higgs doublet model

$$\begin{aligned}
 \mathcal{L}_{\mathcal{H}_2} = & \mathcal{L}_{\text{SM}}^{d \leq 4} + |\mathcal{D}_\mu \mathcal{H}_2|^2 - m_{\mathcal{H}_2}^2 |\mathcal{H}_2|^2 - \frac{\lambda_{\mathcal{H}_2}}{4} |\mathcal{H}_2|^4 \\
 & - (\eta_H |\tilde{H}|^2 + \eta_{\mathcal{H}_2} |\mathcal{H}_2|^2) (\tilde{H}^\dagger \mathcal{H}_2 + \mathcal{H}_2^\dagger \tilde{H}) \\
 & - \lambda_{\mathcal{H}_2,1} |\tilde{H}|^2 |\mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,2} |\tilde{H}^\dagger \mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,3} \left[(\tilde{H}^\dagger \mathcal{H}_2)^2 + (\mathcal{H}_2^\dagger \tilde{H})^2 \right] \\
 & - \left\{ Y_{\mathcal{H}_2}^{(e)} \bar{l}_L \tilde{\mathcal{H}}_2 e_R + Y_{\mathcal{H}_2}^{(u)} \bar{q}_L \mathcal{H}_2 u_R + Y_{\mathcal{H}_2}^{(d)} \bar{q}_L \tilde{\mathcal{H}}_2 d_R + \text{h.c.} \right\}.
 \end{aligned}$$

CoDEX [Bakshi, Chakraborty, Patra (1808.04403)]

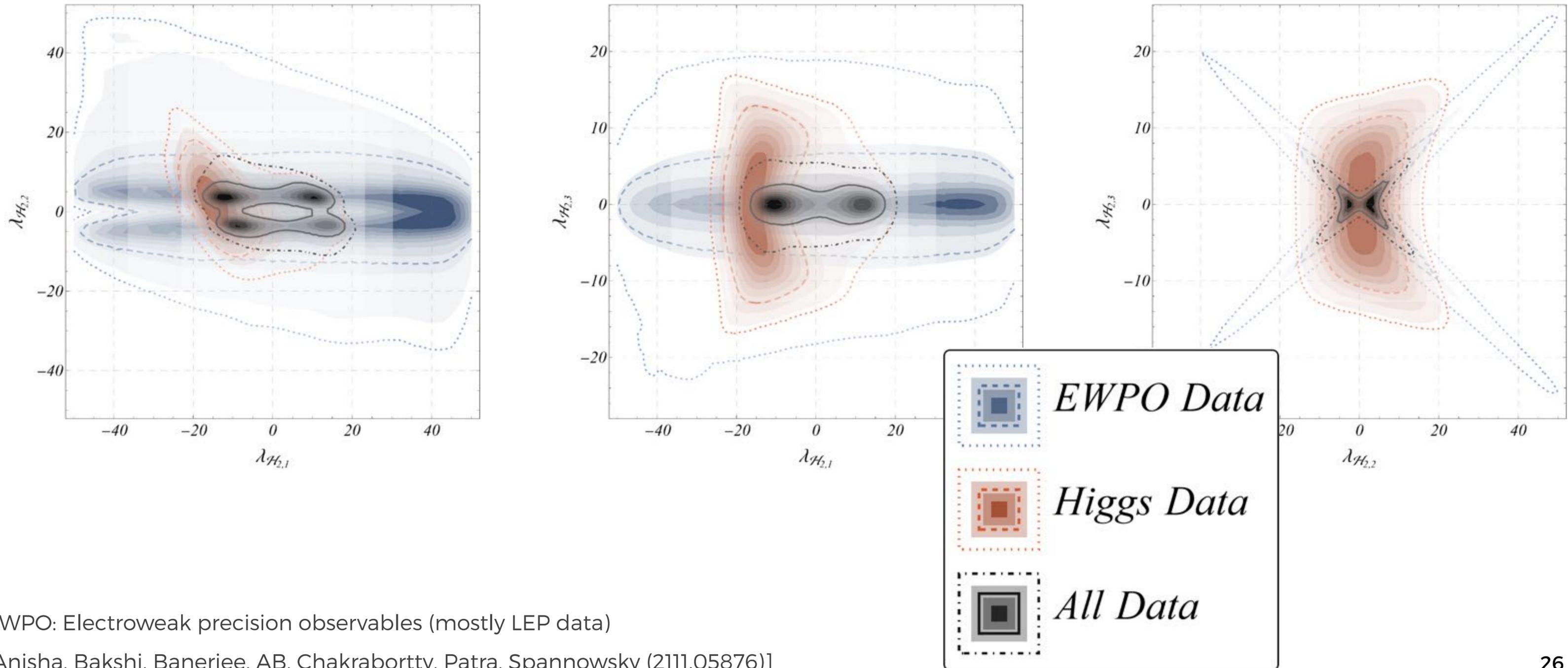
$$\begin{aligned}
 Q_{\text{HB}} & \rightarrow \frac{g_Y^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{g_Y^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}^2} \\
 Q_{\text{HW}} & \rightarrow \frac{g_W^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{g_W^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}^2} \\
 Q_{\text{HWB}} & \rightarrow \frac{g_W g_Y \lambda_{\mathcal{H}_2,2}}{384\pi^2 m_{\mathcal{H}_2}^2}
 \end{aligned}$$

[Anisha, Bakshi, Banerjee, AB, Chakraborty, Patra, Spannowsky (2111.05876)]

Table 3: Warsaw basis effective operators and the associated WCs that emerge after integrating-out the heavy field $\mathcal{H}_2 : (1, 2, -\frac{1}{2})$. Operators highlighted in red do not affect our current set of observables and are thus absent from our analysis. Operators highlighted in blue are functions of SM parameters only, while the red coloured ones do not contribute to our observables.

Dim-6 Ops.	Wilson coefficients	Dim-6 Ops.	Wilson coefficients
Q_{dH}	$\frac{\eta_H^2 Y_d^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} Y_d^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{\eta_H Y_{\mathcal{H}_2}^{(d)}}{m_{\mathcal{H}_2}^2} - \frac{3\eta_H \lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(d)}}{32\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(d)}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(d)}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\eta_H \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(d)}}{4\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(d)}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,2}^2 Y_d^{\text{SM}}}{192\pi^2 m_{\mathcal{H}_2}^2} + \frac{5\eta_H \lambda_{\mathcal{H}_2,3} Y_{\mathcal{H}_2}^{(d)}}{8\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2 Y_d^{\text{SM}}}{48\pi^2 m_{\mathcal{H}_2}^2}$	Q_{Hd}	$\frac{g_Y^4}{5760\pi^2 m_{\mathcal{H}_2}^2}$
Q_{eH}	$\frac{\eta_H^2 Y_e^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} Y_e^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{\eta_H Y_{\mathcal{H}_2}^{(e)}}{m_{\mathcal{H}_2}^2} - \frac{3\eta_H \lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(e)}}{32\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(e)}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(e)}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\eta_H \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(e)}}{4\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(e)}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,2}^2 Y_e^{\text{SM}}}{192\pi^2 m_{\mathcal{H}_2}^2} + \frac{5\eta_H \lambda_{\mathcal{H}_2,3} Y_{\mathcal{H}_2}^{(e)}}{8\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2 Y_e^{\text{SM}}}{48\pi^2 m_{\mathcal{H}_2}^2}$	Q_{He}	$\frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2}$
Q_{uH}	$\frac{\eta_H^2 Y_u^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \lambda_{\mathcal{H}_2} Y_u^{\text{SM}}}{32\pi^2 m_{\mathcal{H}_2}^2} + \frac{\eta_H Y_{\mathcal{H}_2}^{(u)}}{m_{\mathcal{H}_2}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} Y_u^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H \lambda_{\mathcal{H}_2,1} Y_u^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y_u^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{\eta_H \lambda_{\mathcal{H}_2,2} Y_u^{\text{SM}}}{4\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y_u^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,2}^2 Y_u^{\text{SM}}}{192\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2 Y_u^{\text{SM}}}{48\pi^2 m_{\mathcal{H}_2}^2} - \frac{5\eta_H \lambda_{\mathcal{H}_2,3} Y_u^{\text{SM}}}{8\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,3}^2 Y_u^{\text{SM}}}{8\pi^2 m_{\mathcal{H}_2}^2}$	Q_{Hu}	$-\frac{g_Y^4}{2880\pi^2 m_{\mathcal{H}_2}^2}$
Q_{H}	$\frac{3\eta_H^2 \lambda_{\mathcal{H}_2}}{32\pi^2 m_{\mathcal{H}_2}^2} + \frac{17\eta_H^2 \lambda_{\mathcal{H}_2}^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\eta_H^2}{m_{\mathcal{H}_2}^2} - \frac{3\eta_H^2 \lambda_{\mathcal{H}_2,1}}{4\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2}^{\text{SM}}}{8\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1}}{8\pi^2 m_{\mathcal{H}_2}^2} - \frac{13\eta_H^2 \lambda_{\mathcal{H}_2,2}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2}}{8\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1}^3}{48\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2}^{\text{SM}} \lambda_{\mathcal{H}_2,2}^2}{96\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1}^2 \lambda_{\mathcal{H}_2,2}}{32\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1} \lambda_{\mathcal{H}_2,2}^2}{32\pi^2 m_{\mathcal{H}_2}^2} - \frac{7\eta_H^2 \lambda_{\mathcal{H}_2,3}}{4\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2}^{\text{SM}} \lambda_{\mathcal{H}_2,3}^2}{24\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,2}^3}{96\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1} \lambda_{\mathcal{H}_2,3}^2}{8\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,2} \lambda_{\mathcal{H}_2,3}^2}{8\pi^2 m_{\mathcal{H}_2}^2}$	$Q_{\text{Hq}}^{(3)}$	$-\frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\text{H}\square}$	$-\frac{g_W^4}{7680\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H^2}{32\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1}^2}{96\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1} \lambda_{\mathcal{H}_2,2}}{96\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,2}^2}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2}{96\pi^2 m_{\mathcal{H}_2}^2}$	Q_{W}	$\frac{g_W^3}{5760\pi^2 m_{\mathcal{H}_2}^2}$
Q_{HD}	$-\frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,2}^2}{96\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2}{24\pi^2 m_{\mathcal{H}_2}^2}$	Q_{ll}	$-\frac{g_W^4}{7680\pi^2 m_{\mathcal{H}_2}^2} - \frac{g_Y^4}{7680\pi^2 m_{\mathcal{H}_2}^2}$
Q_{HB}	$\frac{g_Y^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{g_Y^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}^2}$	$Q_{\text{ud}}^{(1)}$	$\frac{g_Y^4}{4320\pi^2 m_{\mathcal{H}_2}^2}$
Q_{HW}	$\frac{g_W^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{g_W^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}^2}$	$Q_{\text{ld}}^{(3)}$	$-\frac{g_Y^4}{3840\pi^2 m_{\mathcal{H}_2}^2}$
Q_{HWB}	$\frac{g_W g_Y \lambda_{\mathcal{H}_2,2}}{384\pi^2 m_{\mathcal{H}_2}^2}$	$Q_{\text{qq}}^{(3)}$	$-\frac{g_Y^4}{7680\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\text{Hl}}^{(1)}$	$\frac{g_Y^4}{3840\pi^2 m_{\mathcal{H}_2}^2}$	Q_{dd}	$-\frac{g_Y^4}{17280\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\text{Hq}}^{(1)}$	$-\frac{g_Y^4}{11520\pi^2 m_{\mathcal{H}_2}^2}$	Q_{ed}	$-\frac{g_Y^4}{2880\pi^2 m_{\mathcal{H}_2}^2}$
		Q_{ee}	$-\frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2}$
		Q_{eu}	$\frac{g_Y^4}{1440\pi^2 m_{\mathcal{H}_2}^2}$
		Q_{uu}	$-\frac{g_Y^4}{4320\pi^2 m_{\mathcal{H}_2}^2}$
		Q_{lu}	$\frac{g_Y^4}{2880\pi^2 m_{\mathcal{H}_2}^2}$
		Q_{qe}	$\frac{g_Y^4}{5760\pi^2 m_{\mathcal{H}_2}^2}$
		Q_{ld}	$-\frac{g_Y^4}{5760\pi^2 m_{\mathcal{H}_2}^2}$
		$Q_{\text{qq}}^{(1)}$	$-\frac{g_Y^4}{69120\pi^2 m_{\mathcal{H}_2}^2}$
		Q_{le}	$-\frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(e)2}}{128\pi^2 m_{\mathcal{H}_2}^2} - \frac{Y_{\mathcal{H}_2}^{(e)2}}{4m_{\mathcal{H}_2}^2}$
		$Q_{\text{qd}}^{(1)}$	$\frac{g_Y^4}{17280\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(d)2}}{128\pi^2 m_{\mathcal{H}_2}^2} - \frac{Y_{\mathcal{H}_2}^{(d)2}}{4m_{\mathcal{H}_2}^2}$
		$Q_{\text{qu}}^{(1)}$	$-\frac{g_Y^4}{8640\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(u)2}}{128\pi^2 m_{\mathcal{H}_2}^2} - \frac{Y_{\mathcal{H}_2}^{(u)2}}{4m_{\mathcal{H}_2}^2}$
		$Q_{\text{quqd}}^{(1)}$	$-\frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(d)} Y_{\mathcal{H}_2}^{(u)}}{64\pi^2 m_{\mathcal{H}_2}^2} - \frac{Y_{\mathcal{H}_2}^{(d)} Y_{\mathcal{H}_2}^{(u)}}{2m_{\mathcal{H}_2}^2}$
		$Q_{\text{lequ}}^{(1)}$	$\frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(e)} Y_{\mathcal{H}_2}^{(u)}}{64\pi^2 m_{\mathcal{H}_2}^2} + \frac{Y_{\mathcal{H}_2}^{(e)} Y_{\mathcal{H}_2}^{(u)}}{2m_{\mathcal{H}_2}^2}$
		$Q_{\text{ld}}^{(1)}$	$\frac{g_Y^4}{11520\pi^2 m_{\mathcal{H}_2}^2}$
		Q_{ledq}	$\frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(d)} Y_{\mathcal{H}_2}^{(e)}}{64\pi^2 m_{\mathcal{H}_2}^2} + \frac{Y_{\mathcal{H}_2}^{(d)} Y_{\mathcal{H}_2}^{(e)}}{2m_{\mathcal{H}_2}^2}$

Constraints on two Higgs doublet model



Future directions in SMEFT (fits)

Future directions in SMEFT (fits)

$$\mathcal{A} = \mathcal{A}_{\text{SM}} + a_i \frac{C_i^{(6)}}{\Lambda^2} + \boxed{b_{jk} \frac{C_j^{(6)} C_k^{(6)}}{\Lambda^4} + c_l \frac{C_l^{(8)}}{\Lambda^4}} + \frac{1}{16\pi^2} \left[\boxed{d_m \frac{C_m^{(6)}}{\Lambda^2} + e_n \frac{C_n^{(6)}}{\Lambda^2} \log \left(\frac{\mu^2}{\Lambda^2} \right)} \right] + \dots$$

Generality

Relax (flavor) assumptions

Dim6² effects
Dim8 effects

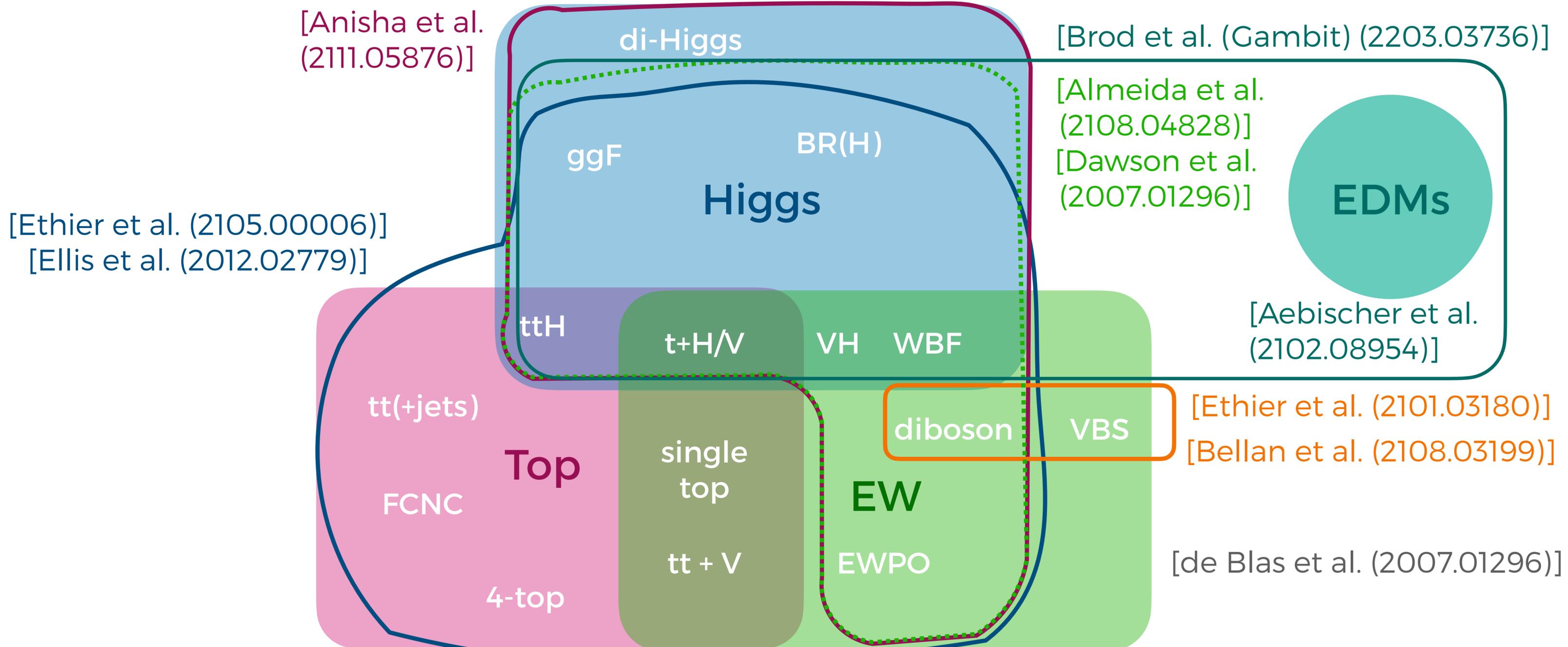
Combine more sectors

Add more data

SMEFT@NLO

Precision

Global fits



$1/\Lambda^4$ effects

- Large number of dim8 operators
(Wh production: 66 dim8 operators)
- Focus on dim8 operators induced in matching of specific UV-complete models in a specific process
(few parameters, relation between WCs)
- Or: all dim8 operators have the same magnitude
Wh: $O(10\%)$ effect

[Hays, Martin, Sanz, Setford (1808.00442)]

Dim-8 effects in specific UV models

- Heavy U(1) boson mixing with B, vector-triplet model contributions to EWPD

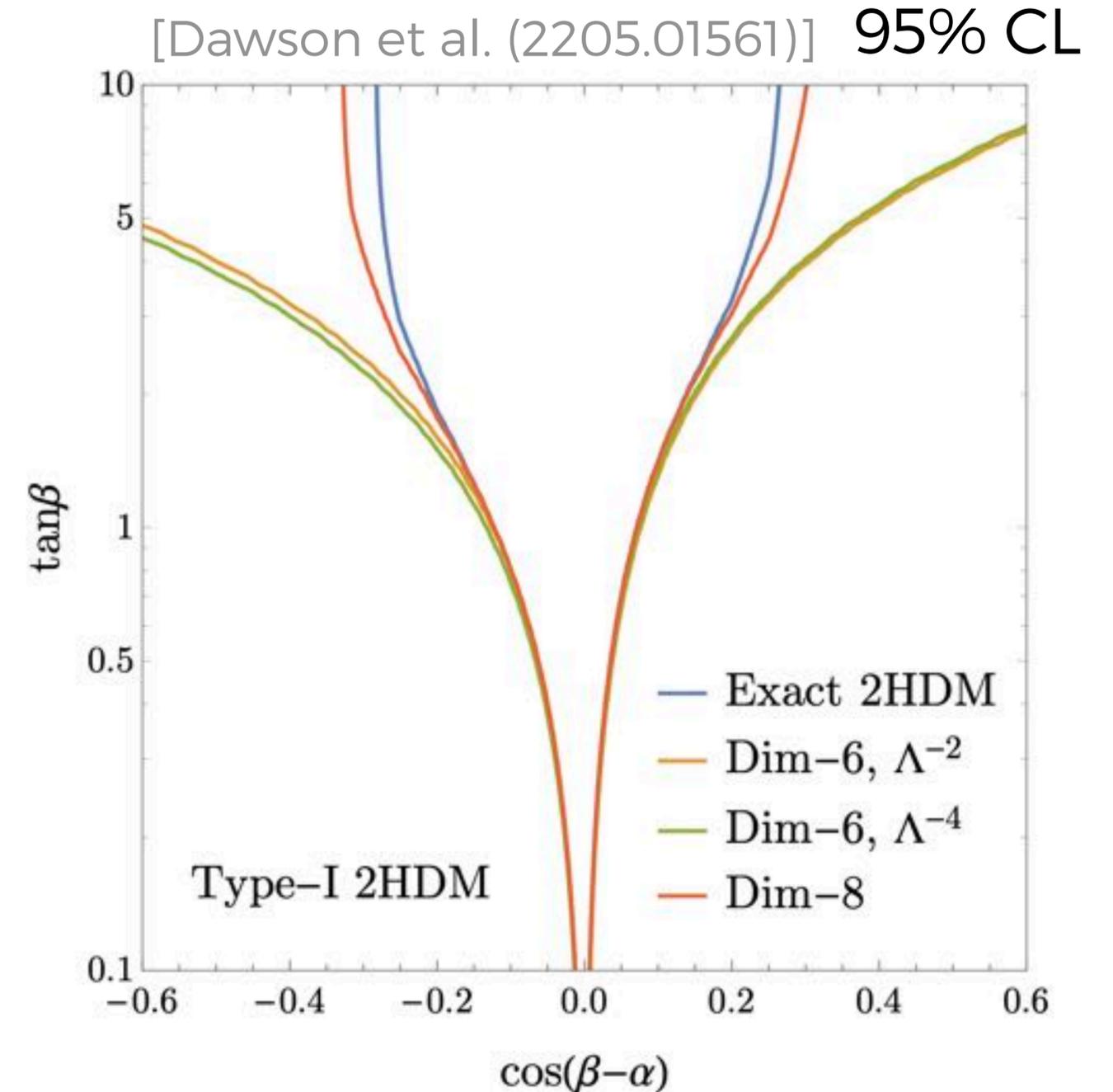
[Corbett, Helset, Martin, Trott (2102.02819)]

- vector-like top partner contribution to $t\bar{t}h$: $O(1\%)$

[Dawson, Homiller, Sullivan (2110.06929)]

- Size of effects depends on input parameter shifts
- 2HDM: improved description of UV limits when including dim8

[Dawson, Fontes, Homiller, Sullivan (2205.01561)]



Summary

We are on the way towards a truly global EFT fit!

SMEFT

- Model-independent parametrisation of new fundamental physics

Outlook

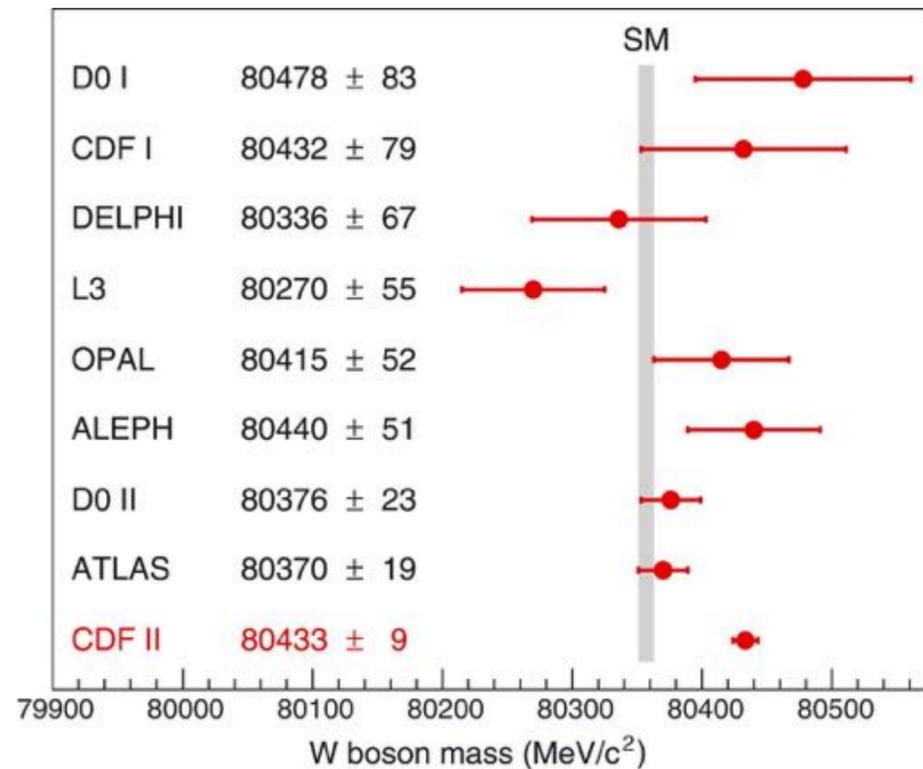
- Combining more sectors
- Precision
 - SMEFT@NLO
 - Dimension-8

Thank you for your attention!

See you in October!

W boson mass - SMEFT interpretations

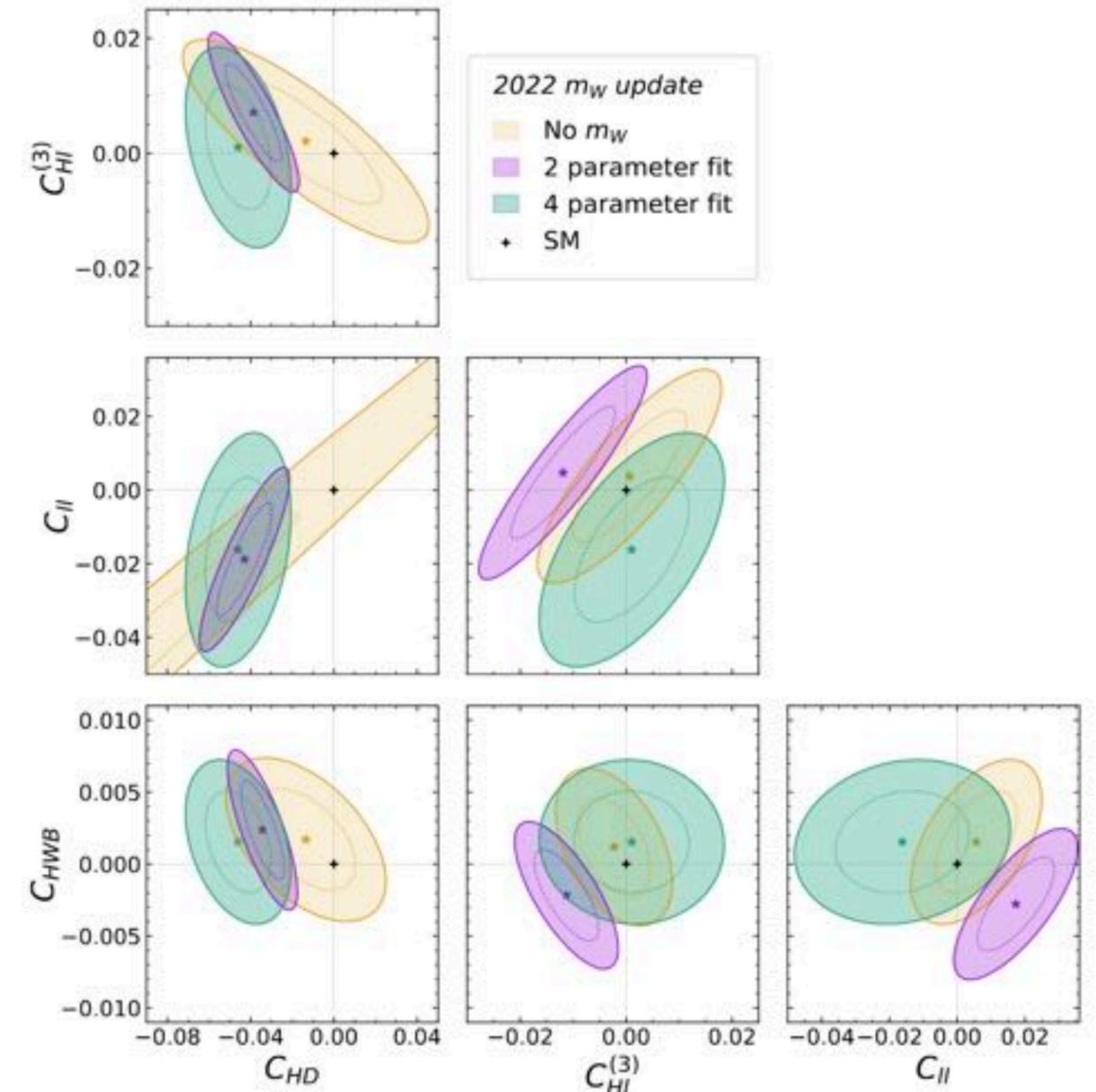
[CDF II (Science)]



global fits and SMEFT studies

[de Blas et al. (2204.04204)]
 [Bagnaschi et al. (2204.05260)]
 [Balkin, Madge et al. (2204.05992)]
 [Almeida et al. (2204.10130)]
 [many more (...)]

[Bagnaschi et al. (2204.05260)]



$\{\alpha_{EW}, G_F, M_Z\}$ scheme

$$\frac{\delta m_W^2}{m_W^2} = -\frac{s_{2W}}{4c_{2W}} \frac{v^2}{\Lambda^2} \left(\frac{c_W}{s_W} C_{HD} + \frac{s_W}{c_W} \left(4C_{HI}^{(3)} - 2C_{II} \right) + 4C_{HWB} \right)$$

$1/\Lambda^4$ effects

- Large number of dim8 operators
(Wh production: 66 dim8 operators)
- Focus on dim8 operators induced in matching of specific UV-complete models in a specific process
(few parameters, relation between WCs)
- Or: all dim8 operators have the same magnitude

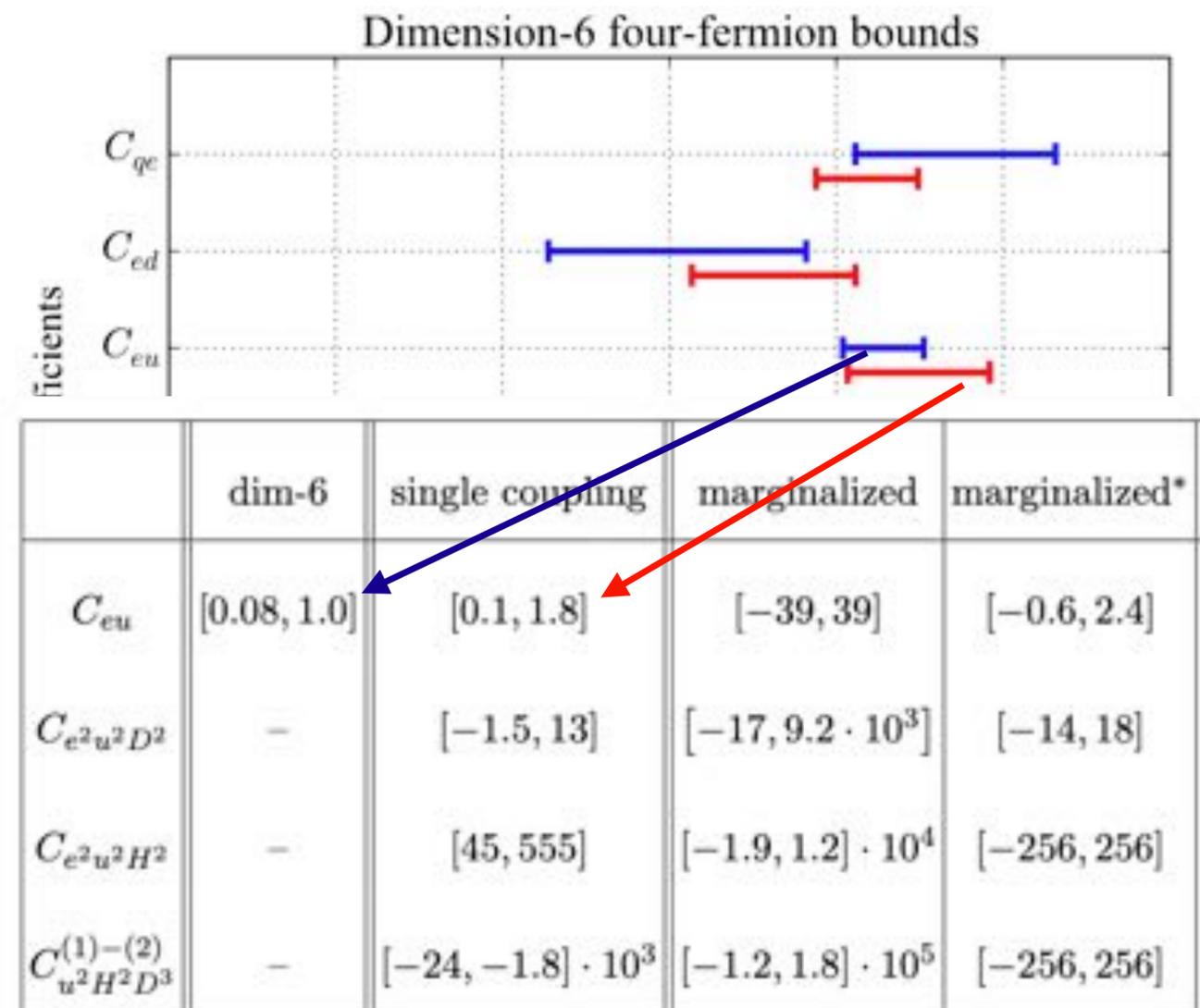
Wh: O(10%) effect

[Hays, Martin, Sanz, Setford (1808.00442)]

Global fit
with 4 operators

[Bougheza, Mereghetti, Petriello (2106.05337)]

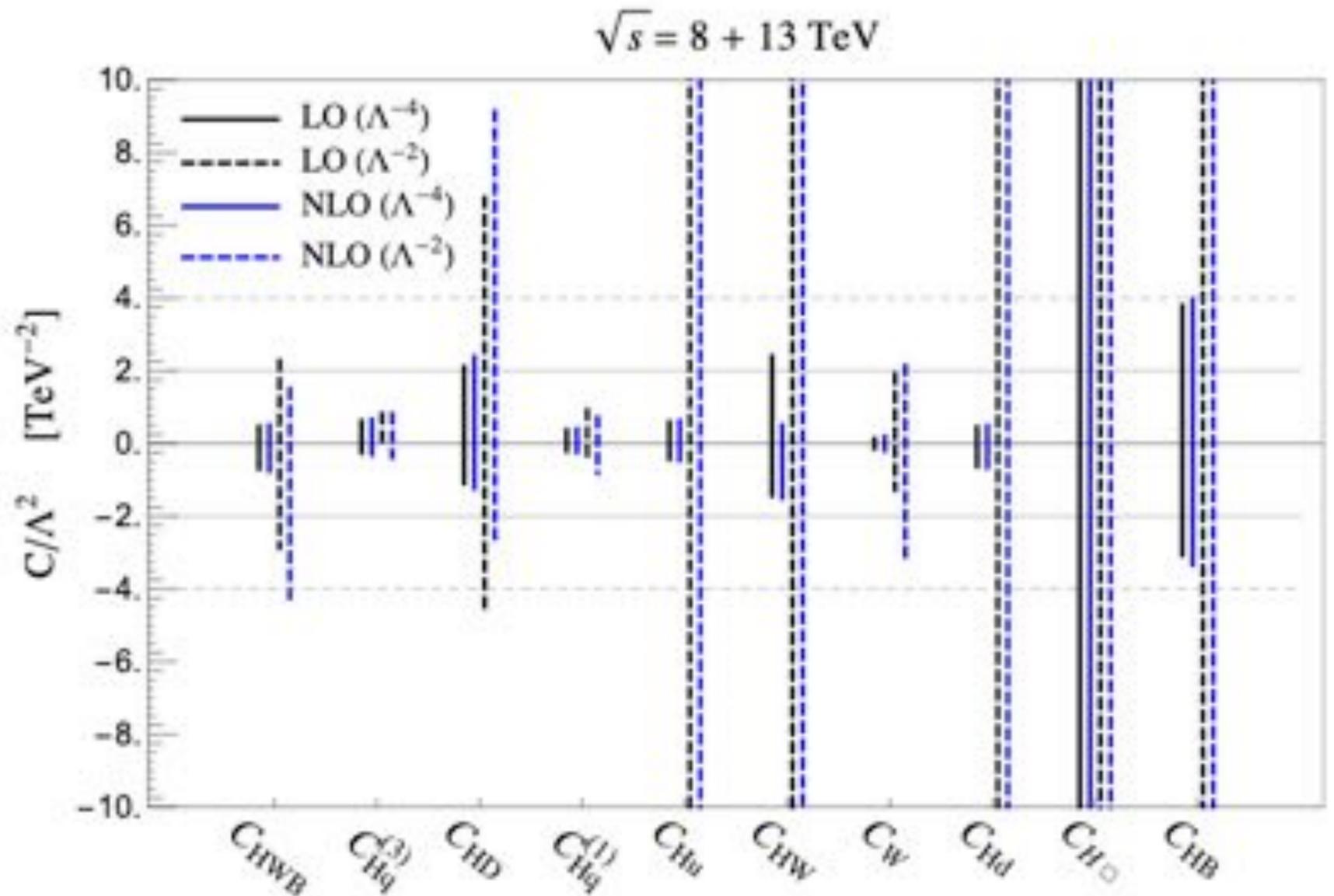
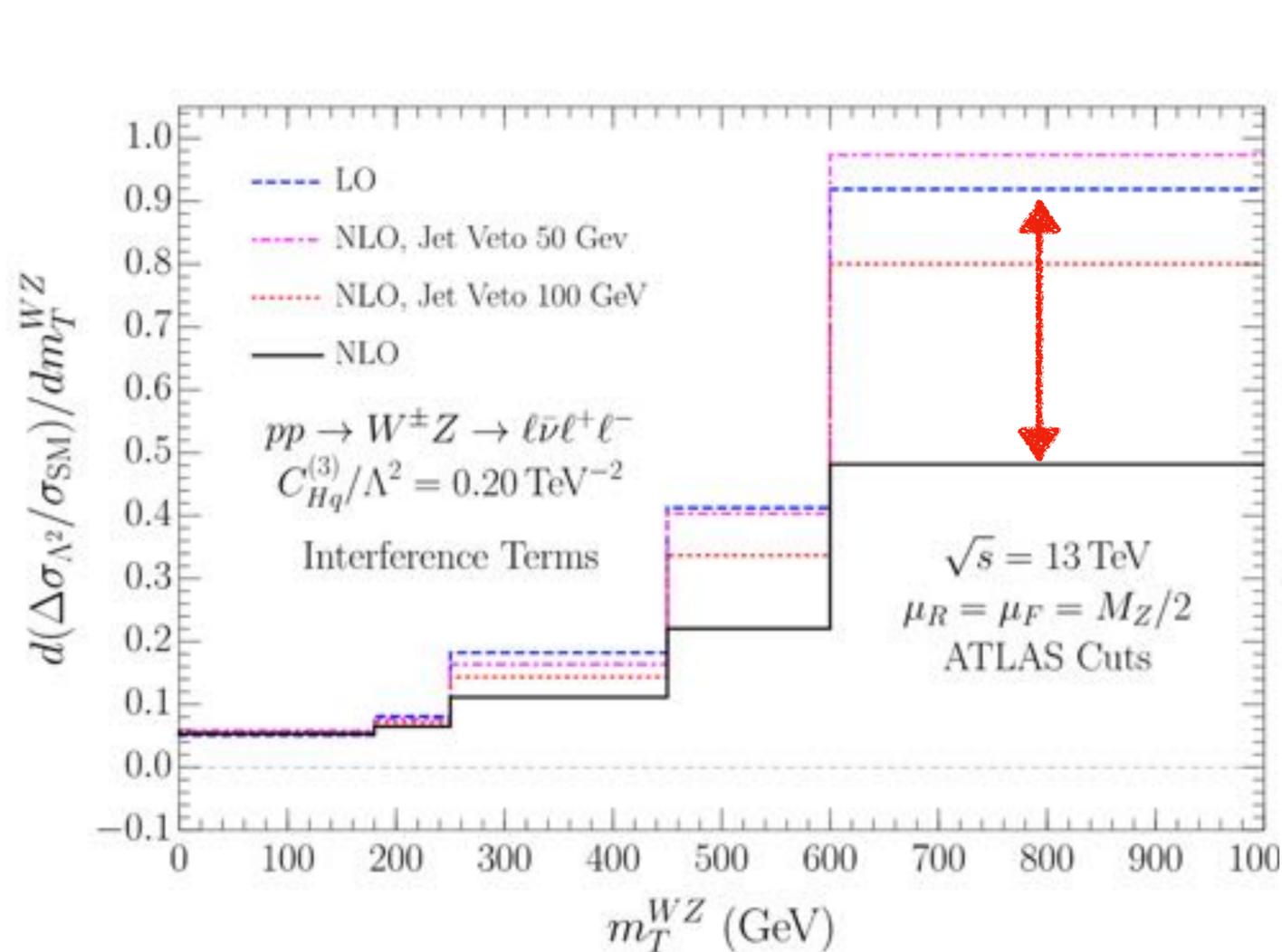
Dilepton production,
single operator fits,
inclusion of dim6 squared terms



Including NLO QCD corrections

SMEFT @ NLO, e.g. NLO QCD for diboson + Vh

[MG: Degrande et al. (2008.11743)]
 Top sector fits including NLO QCD:
 [Hartland et al (1901.05965)]
 [Ellis et al. (2012.02779)]
 [Brivio et al. (1910.03606)]



[Baglio et al (1909.11576, 2003.07862)]