Standard Model Effective Field Theory - Indirect constraints on fundamental physics

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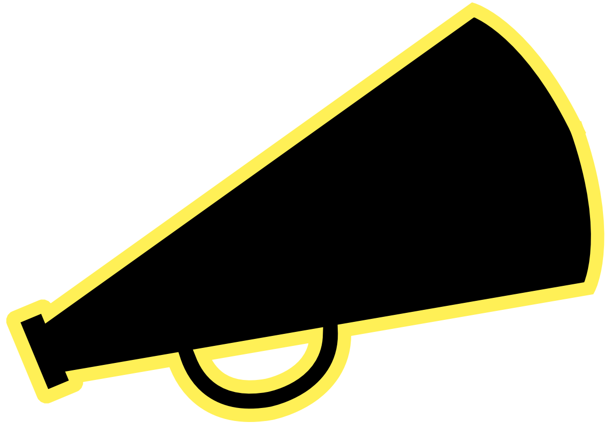
Virtual HET seminar Brookhaven National Laboratory - 9 June 2022

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?

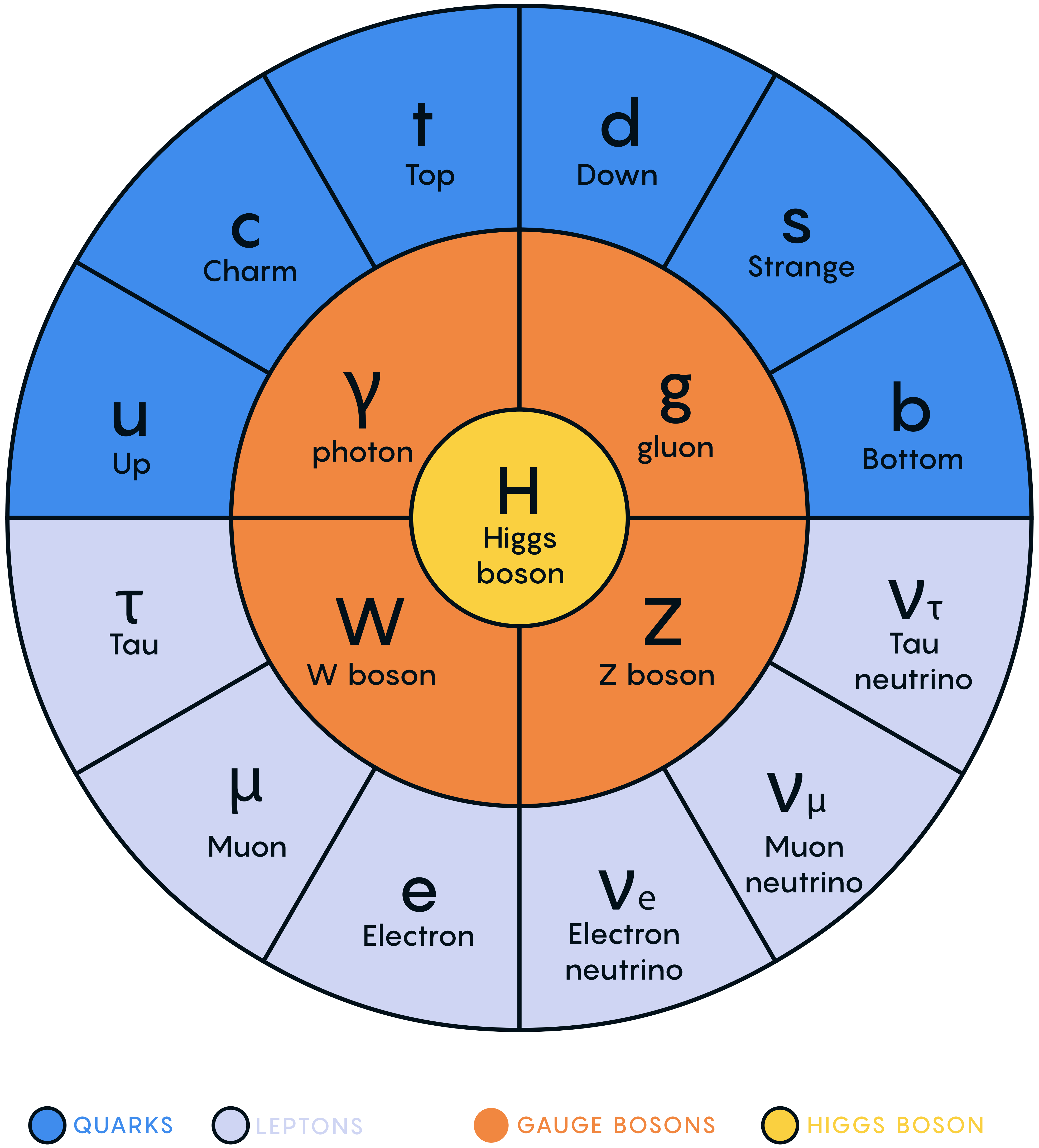
- Confronting EFTs with data: LHC global fits



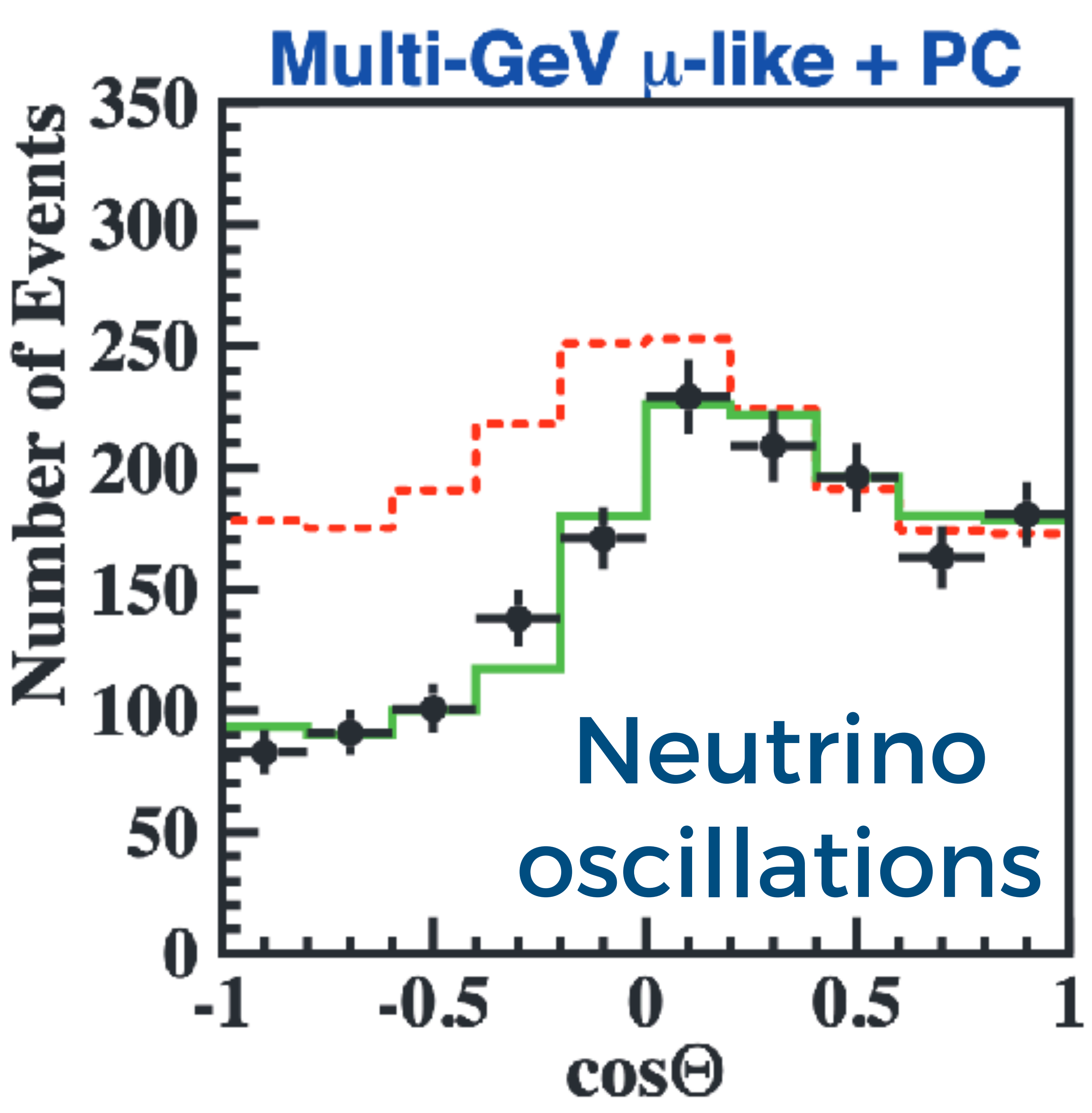
PLEASE INTERRUPT ME

The Standard Model of particle physics

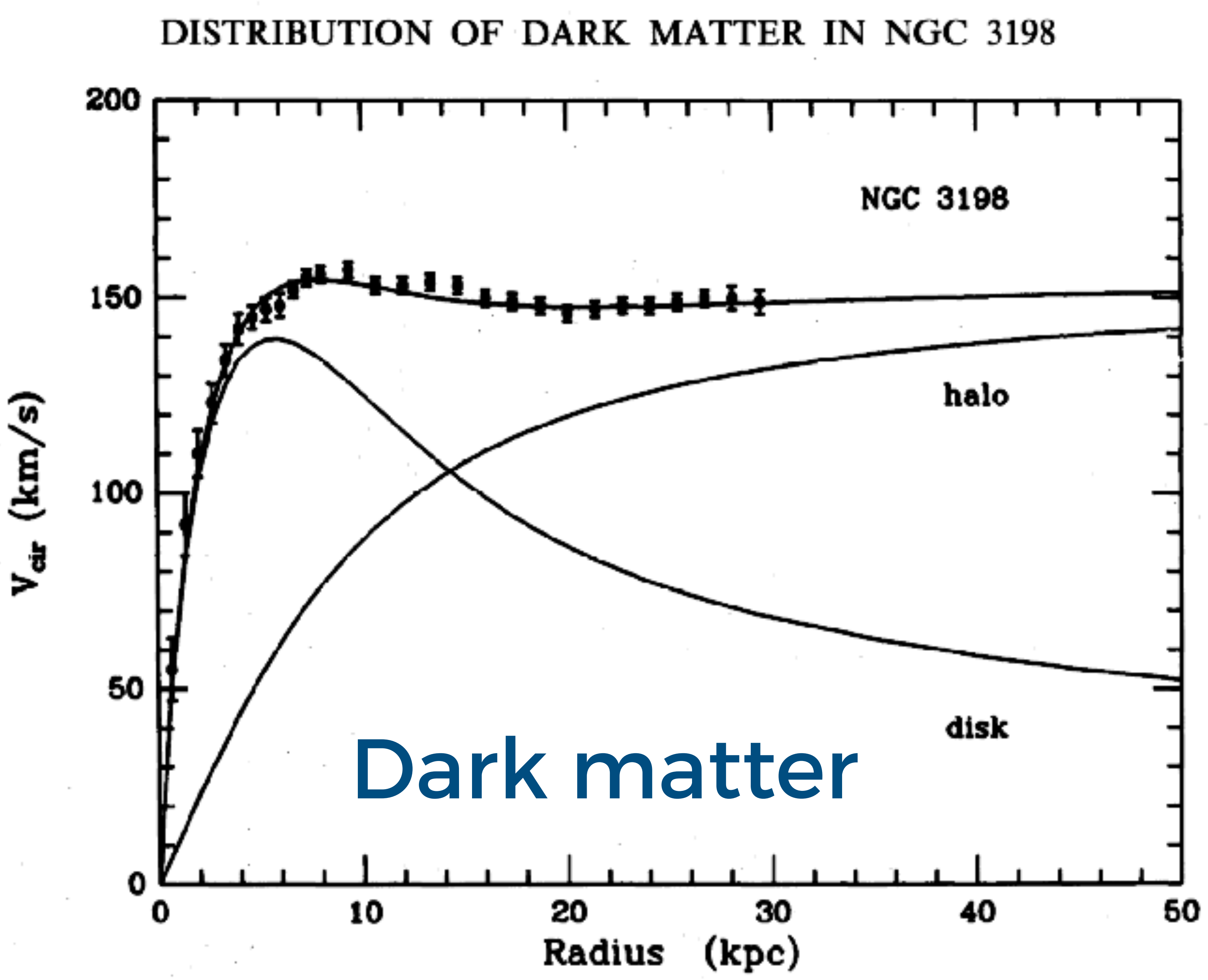
[quantamagazine.org]



Physics beyond the Standard Model



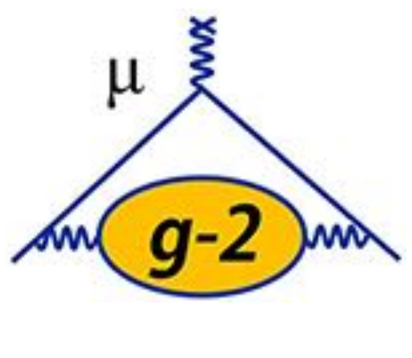
Neutrino oscillations



Dark matter

[physicsanduniverse.com]

Muon g-2



W boson mass (?)

Backup slide

Physics beyond the SM?

Extra dimensions

Leptoquarks

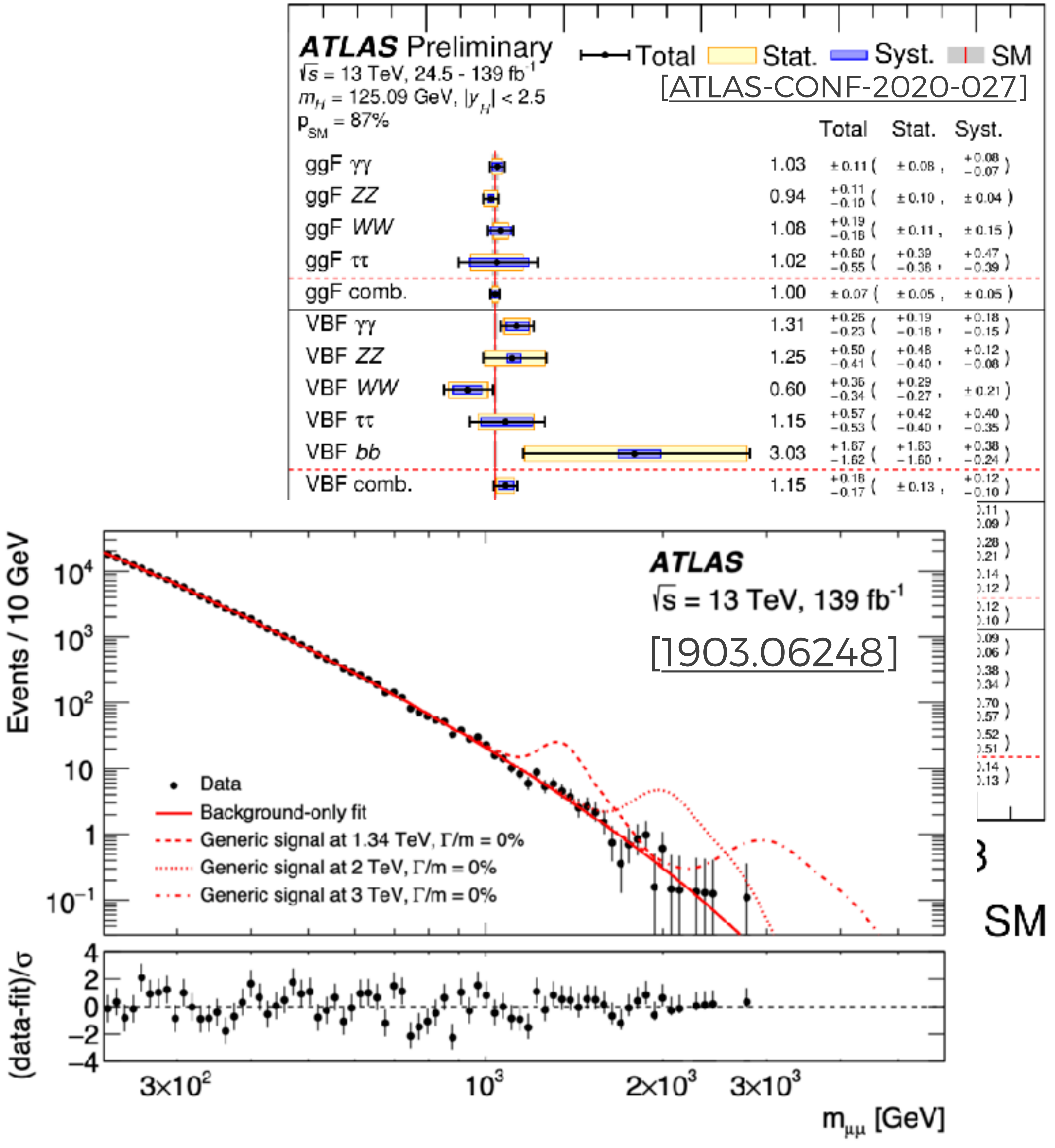
Supersymmetry

Beyond Standard Model

Axion-like particles

Z' bosons

4th generation



Is new physics hiding at the TeV scale?

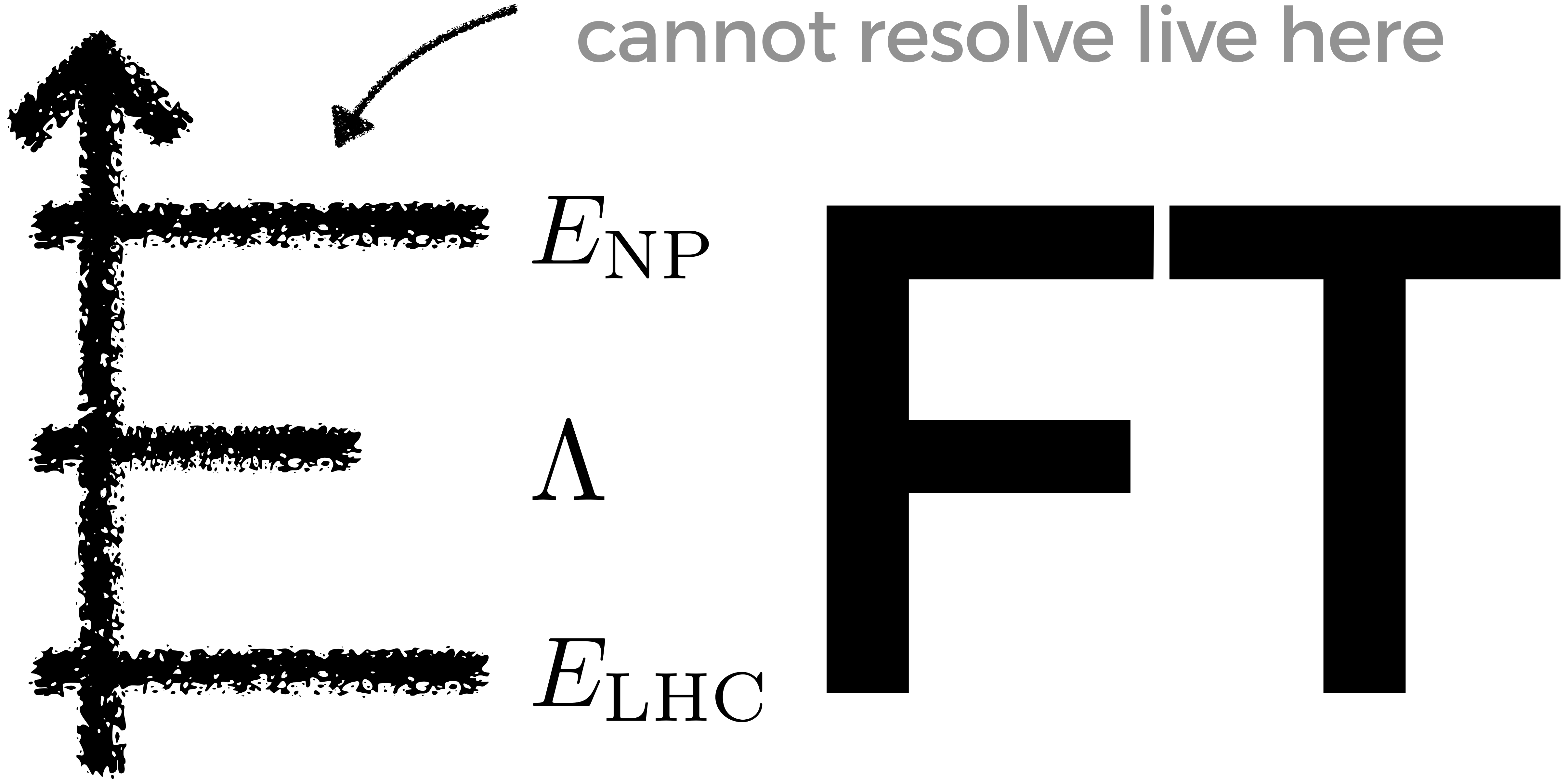
Can we test its effects at lower scales?

Effective field theory - EFT

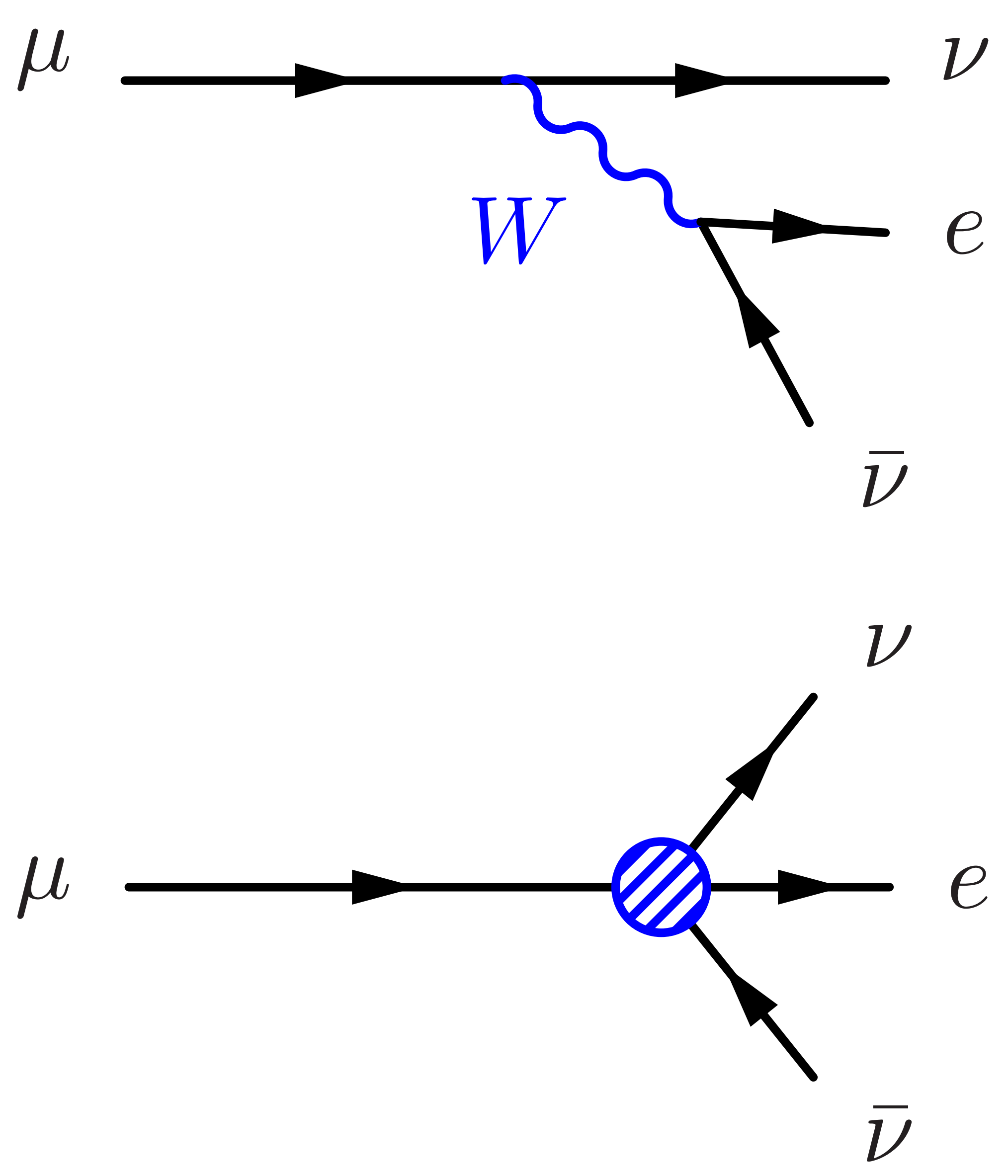
EFT

Effective field theory - EFT

Heavy particles that we cannot resolve live here

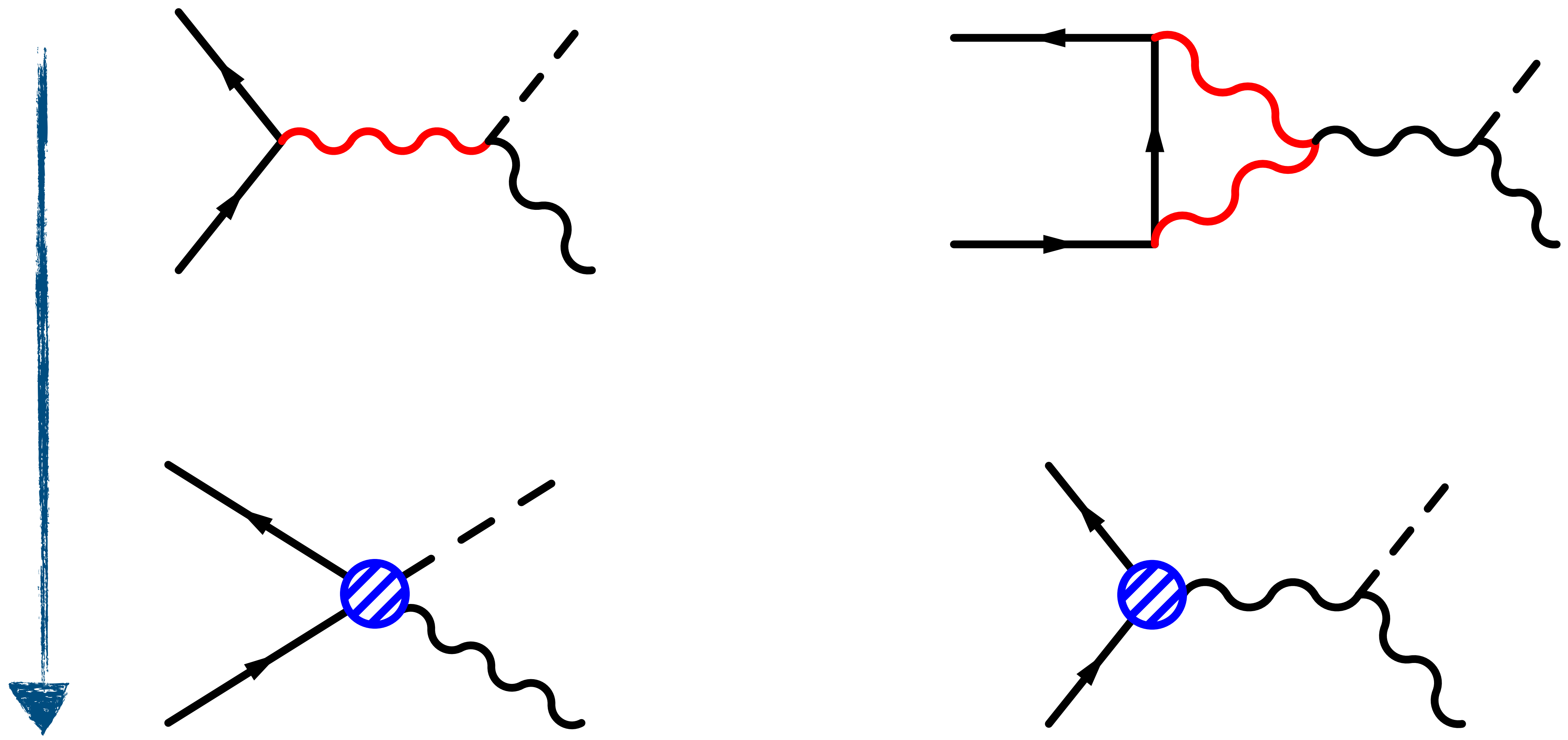


Hierarchy of scales



Describe NP by higher-order interactions of SM fields

Top down - matching of a new model

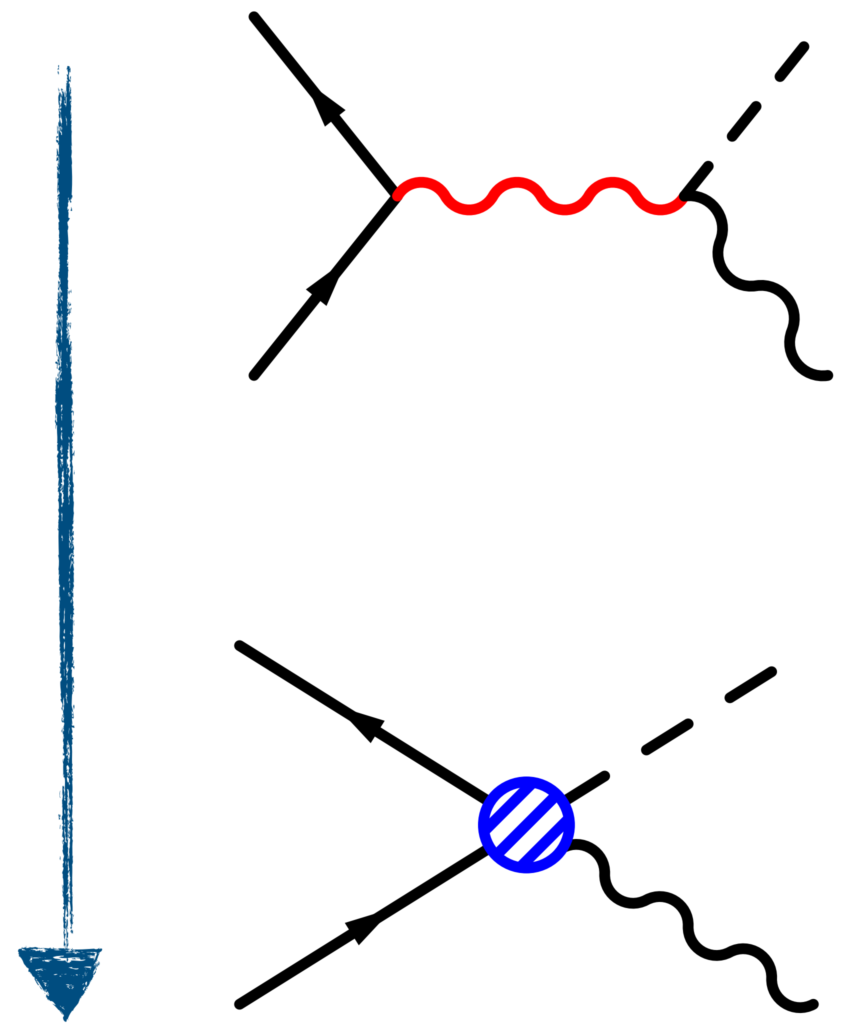


Tree level One loop

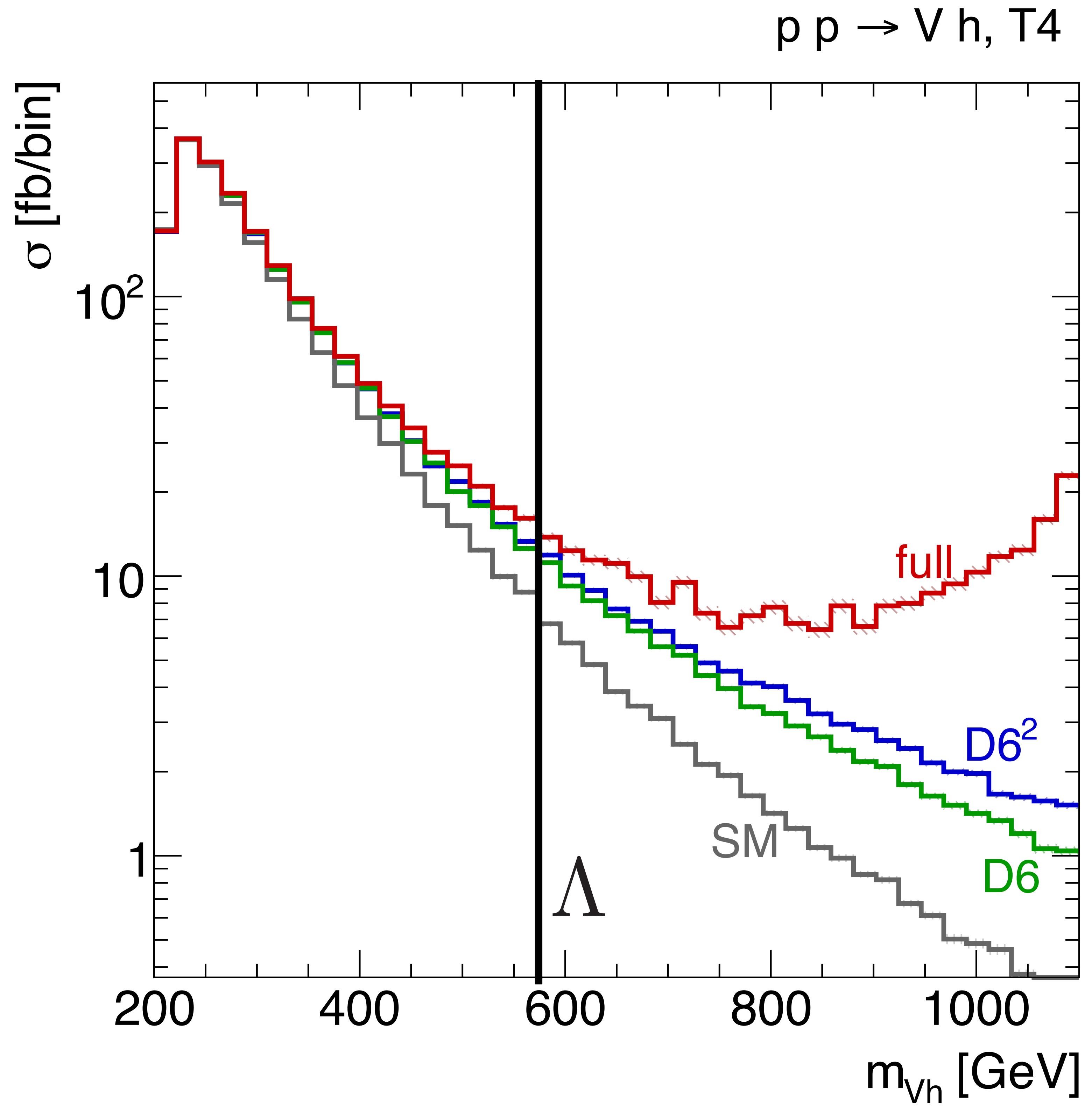
Model with new heavy vector boson

Start from full UV-complete model and match onto EFT

Top down - matching of a new model



Tree level

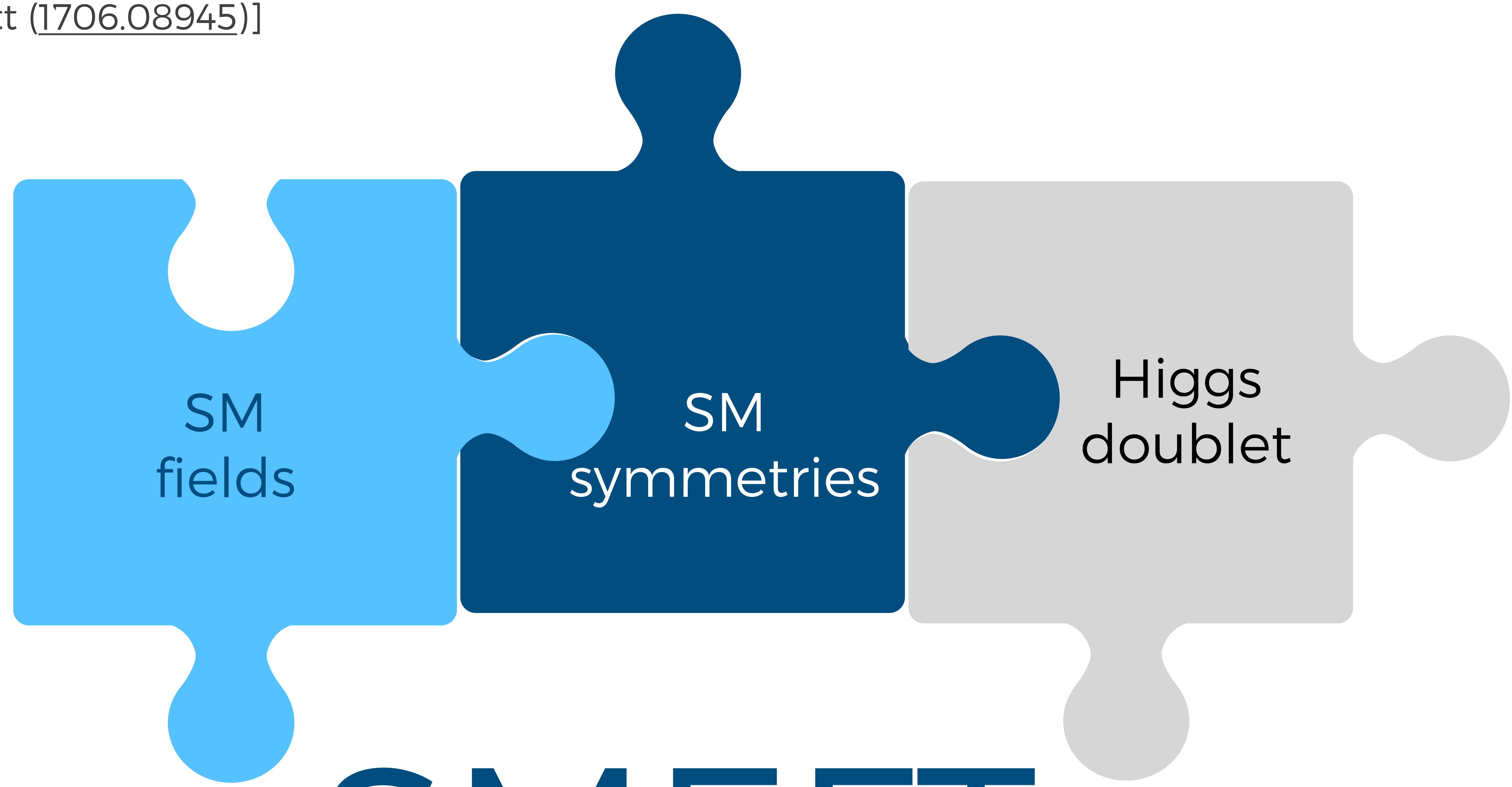


Model with new heavy vector boson

Start from full UV-complete model and match onto EFT

EFTs from the bottom-up

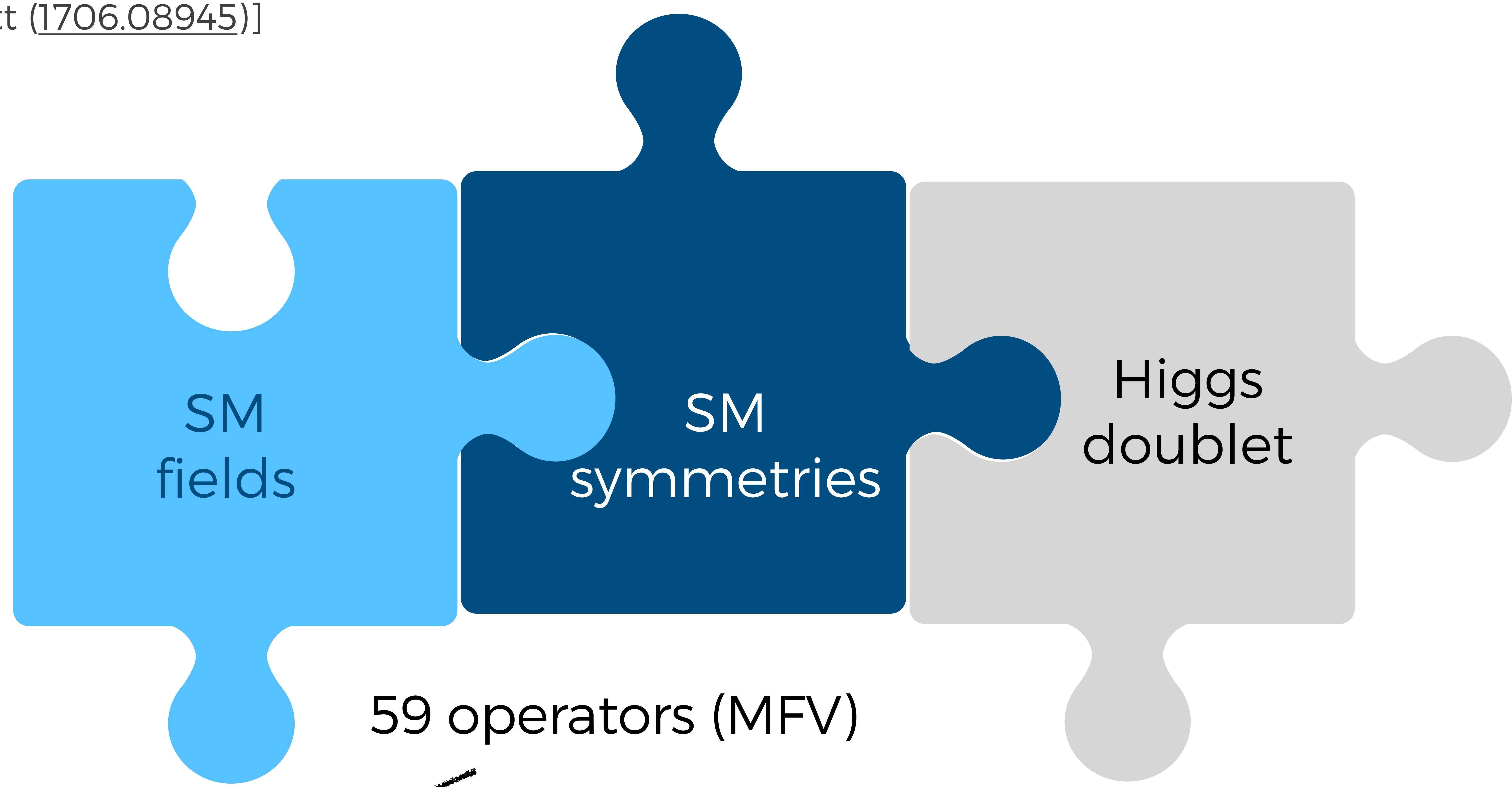
[review: Brivio, Trott (1706.08945)]



SMEFT

EFTs from the bottom-up

[review: Brivio, Trott (1706.08945)]



59 operators (MFV)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

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)]

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

Plus another 24 four-fermion operators

This talk:

CP even fits

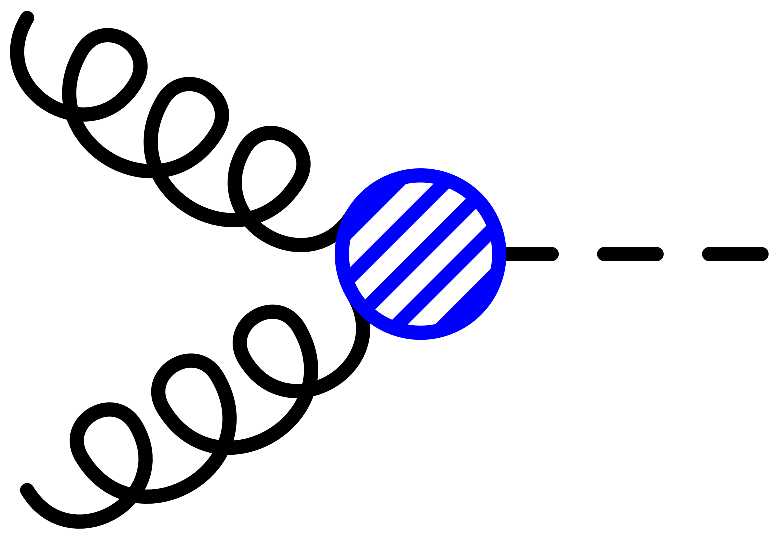
Backup: CP odd

The operator $\mathcal{O}_{HG}$

Affects total cross section only

$$\mathcal{O}_{HG} = H^\dagger H\, G^A_{\mu\nu} G^{A,\mu\nu} \to vh\, G^A_{\mu\nu} G^{A\mu\nu}$$

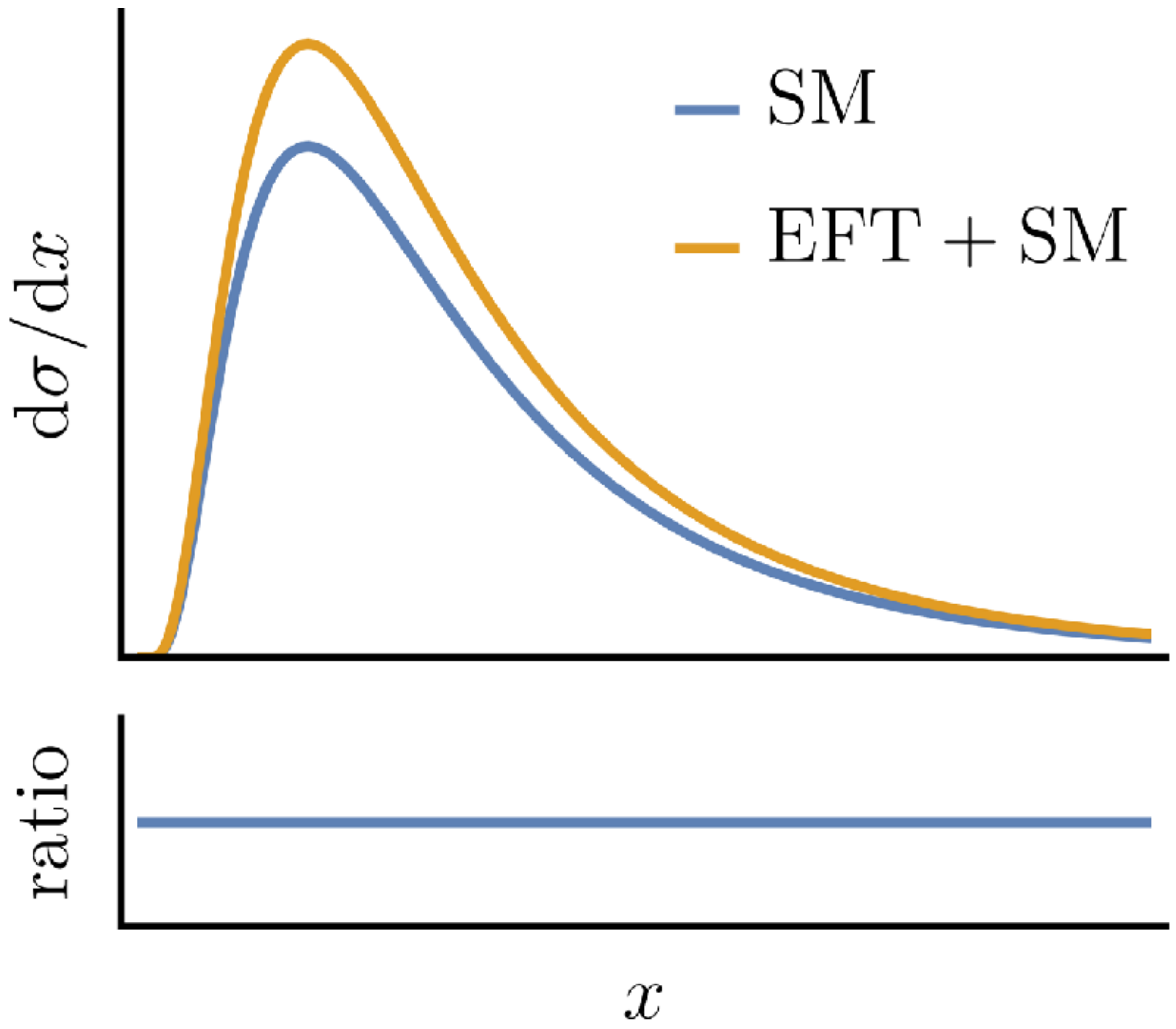
Feynman rules



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

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

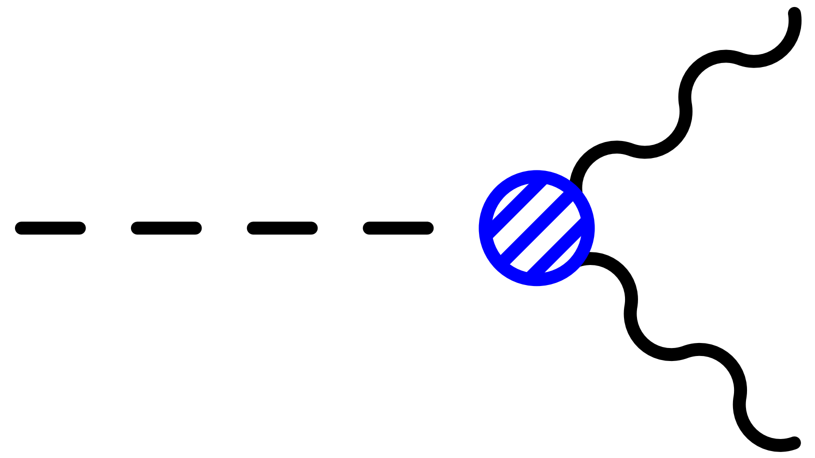
Structurally the same



The operator $\mathcal{O}_{HB}$

$$\mathcal{O}_{HB} = H^\dagger H\, B_{\mu\nu} B^{\mu\nu} \to c^{\rm EFT}_{HZZ}\, h\, Z_{\mu\nu} Z^{\mu\nu}$$

Feynman rules

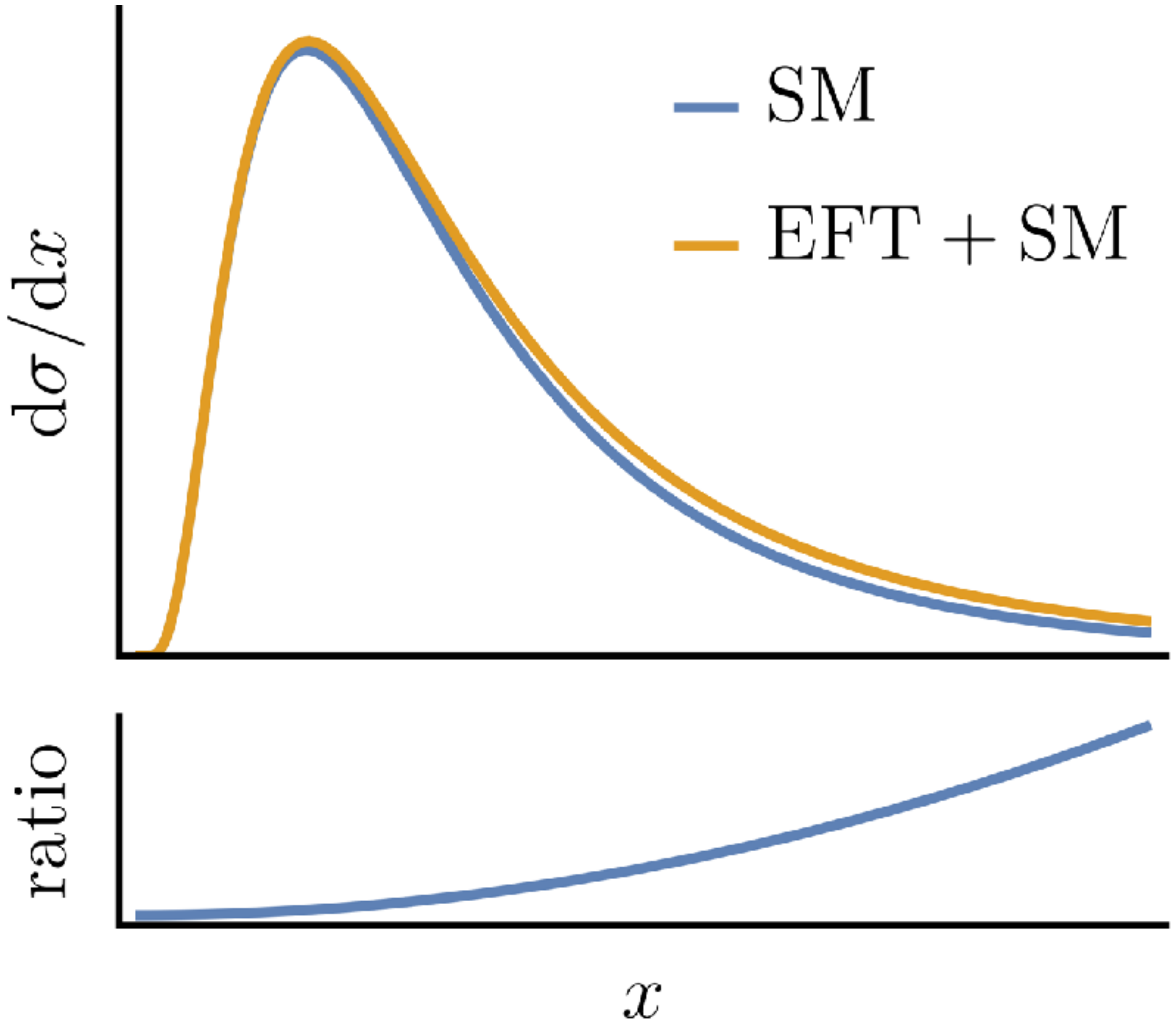


SM: $g^{\rm SM}_{ZZh}\, \eta^{\mu\nu}$

EFT: $g^{\rm EFT}_{hZZ}\, \left[p^\mu_{Z_1} p^\nu_{Z_2} - \eta^{\mu\nu}\, p_{Z_1} \cdot p_{Z_2}\right]$

EFT contribution has additional momentum dependence

Affects distributions



e.g. m_{Zh} in HZ production

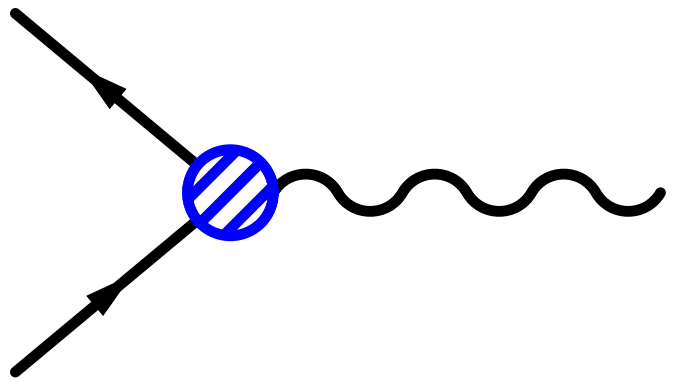
The operator $\mathcal{O}_{Hu}$

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

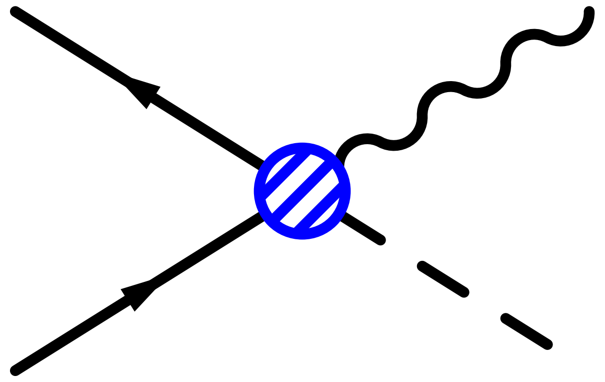
Feynman rules

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

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

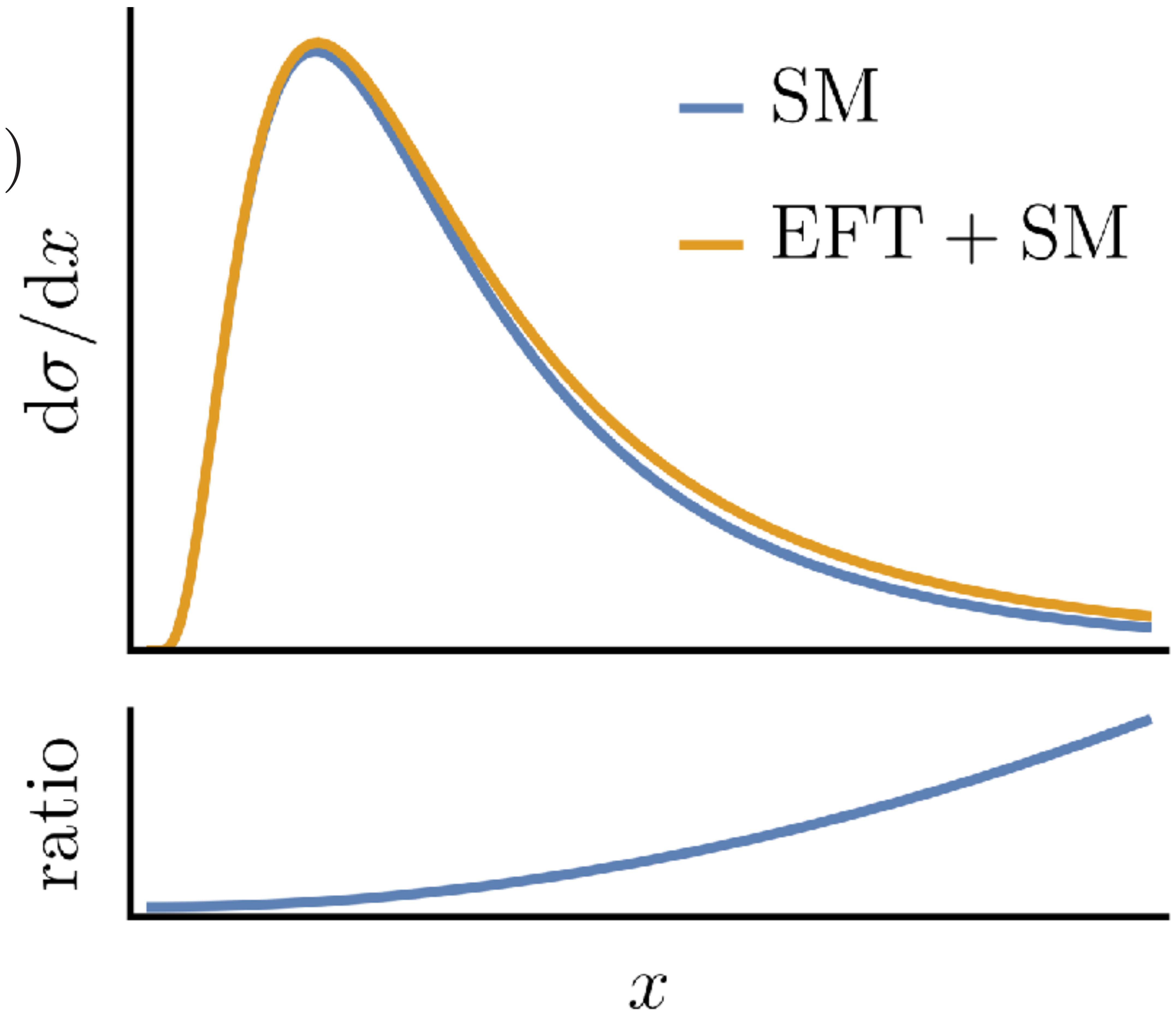


EFT Zhuu: $g_{Zuu}^{\mathrm{EFT}}/v\,\gamma^\mu\,P_R$

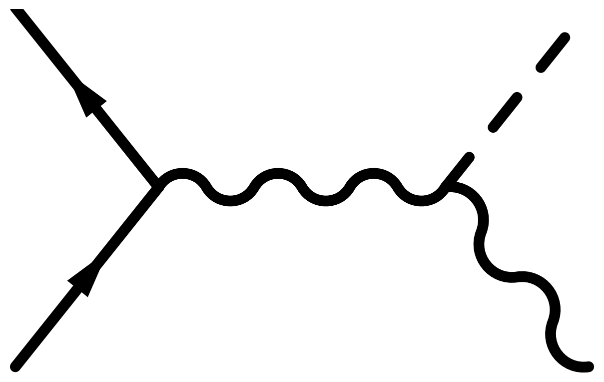


New contact interaction

Affects distributions



SM: propagator suppression

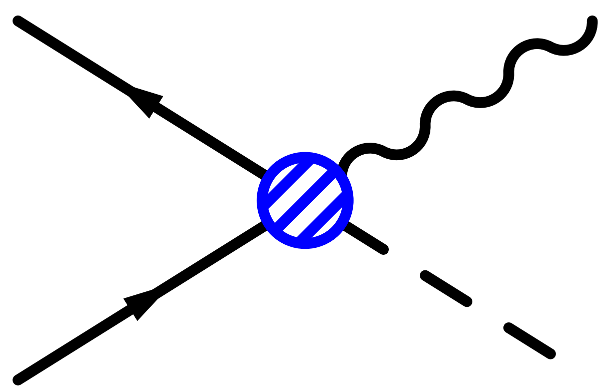


Dimension-six operators - effects

- 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)

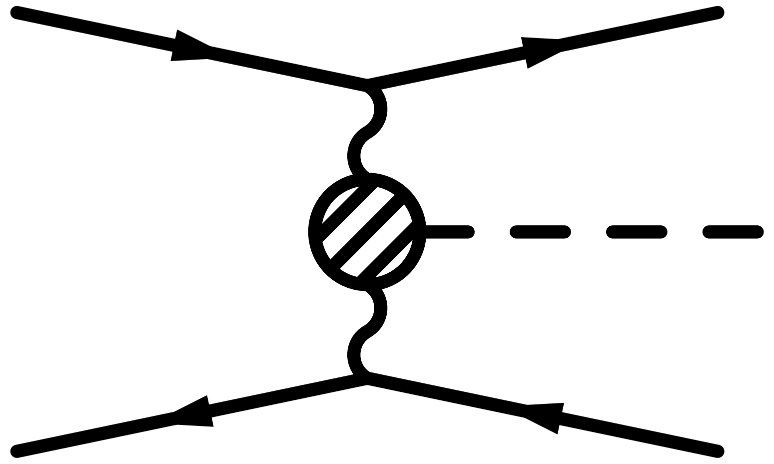


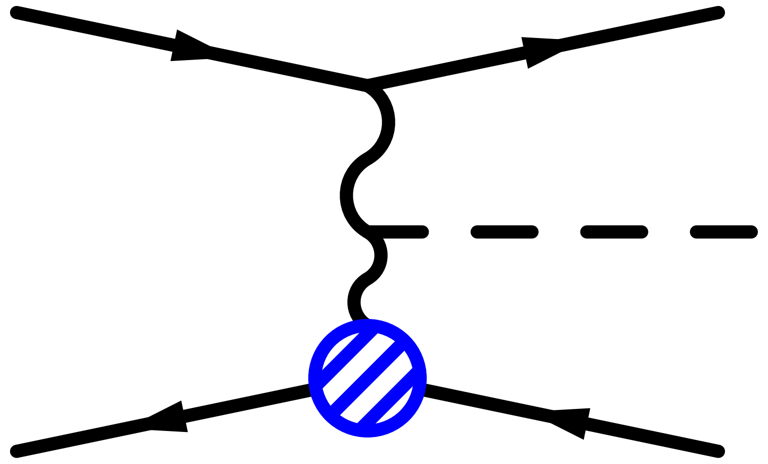
distributions affected

Global SMEFT fits

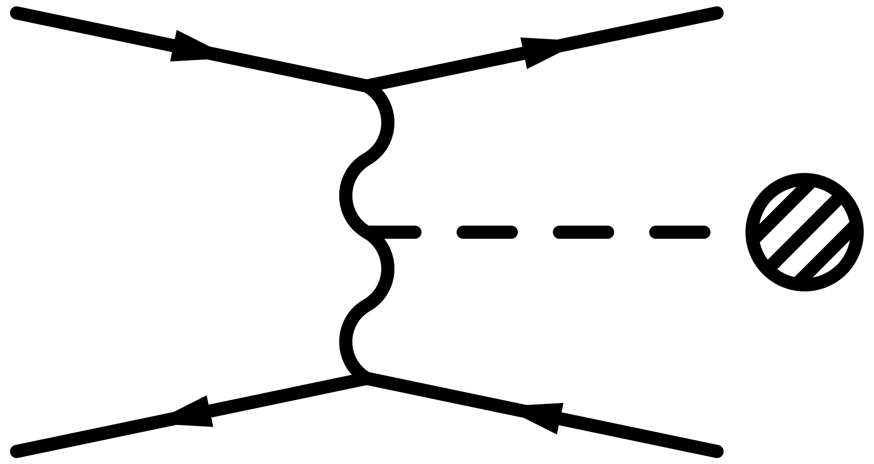
Why global fits?

One observable can be influenced by many operators

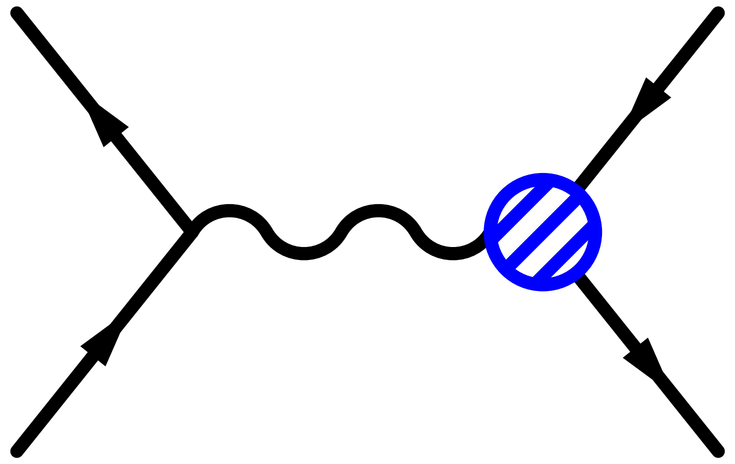




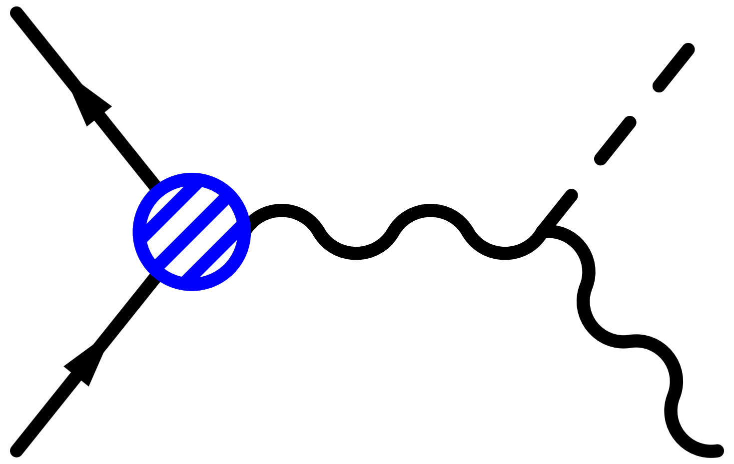
Higgs decay



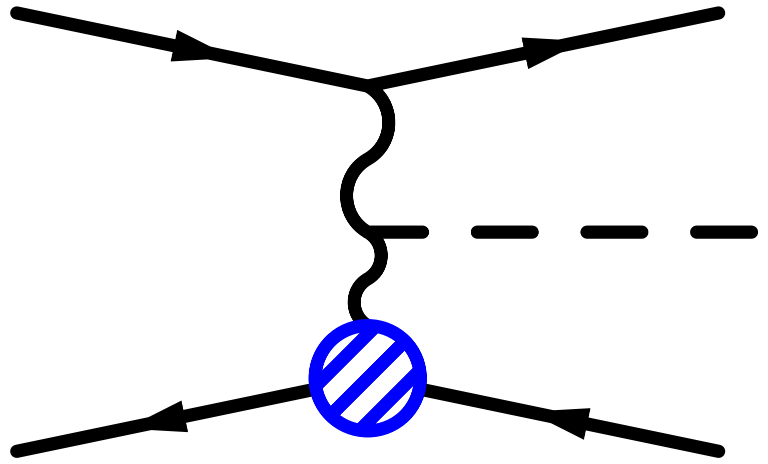
One operator can contribute to many different observables



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



Zh production



Weak boson fusion
Higgs production

How to do global fits?
Backup slide

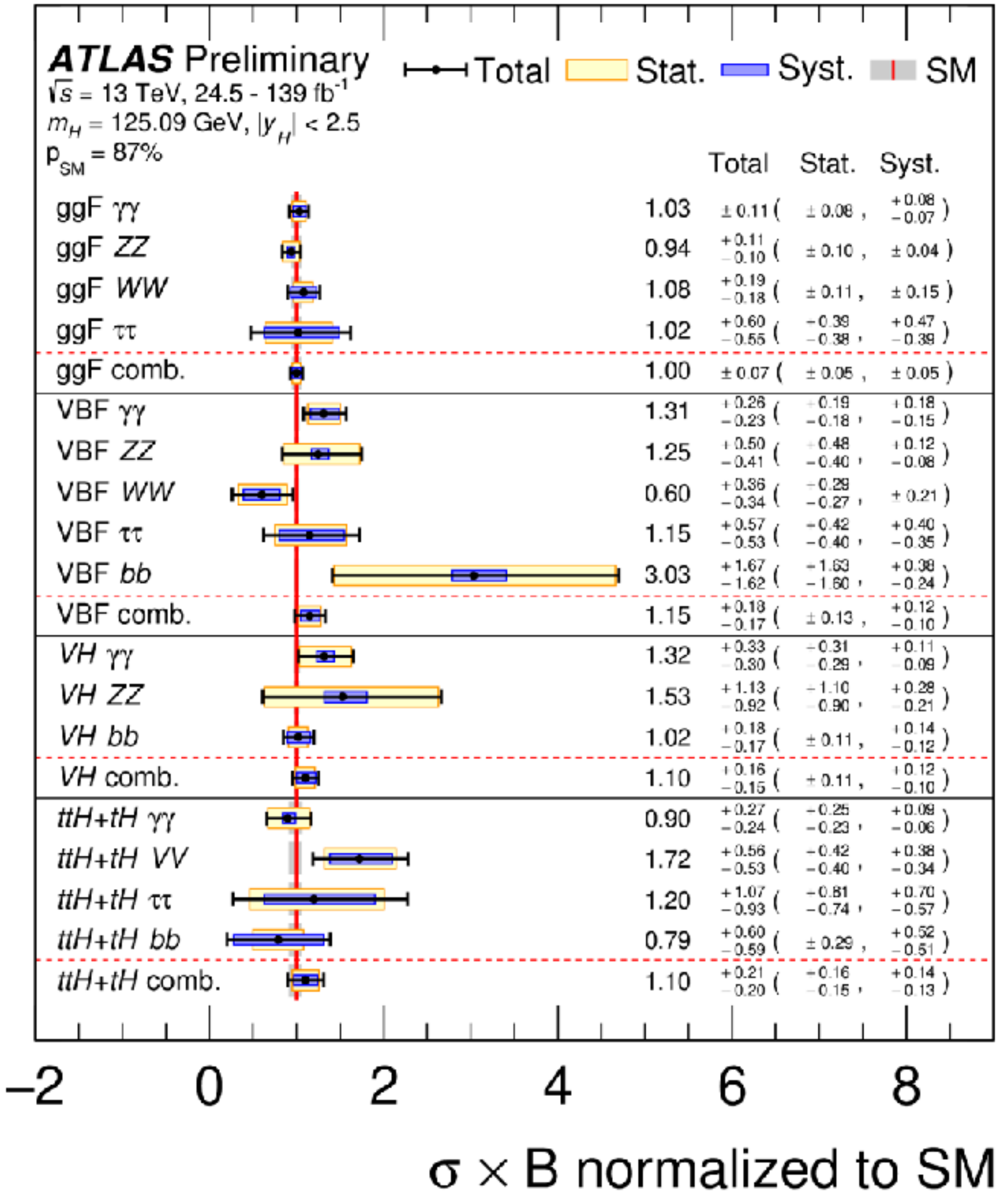
Why global fits?

- 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

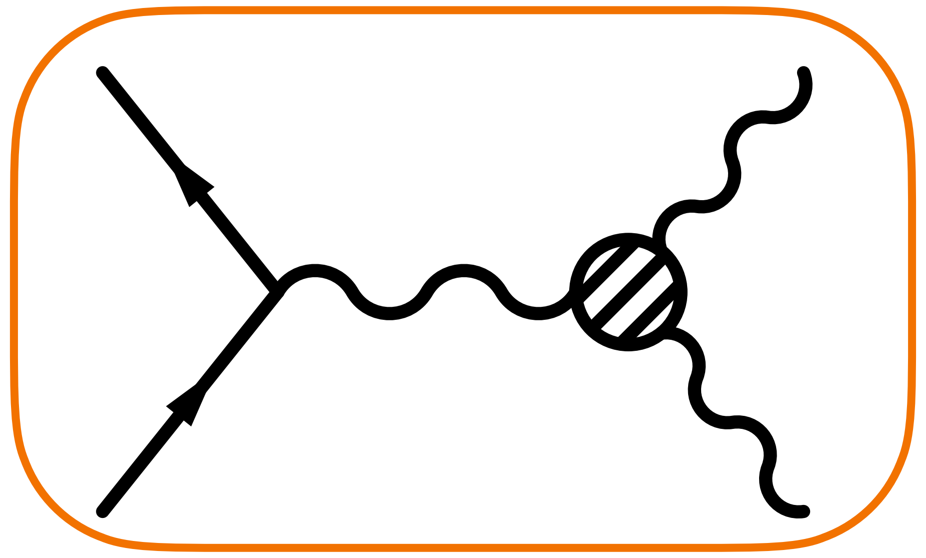
Need a global analysis of all EFT coefficients to map all direction of new fundamental physics

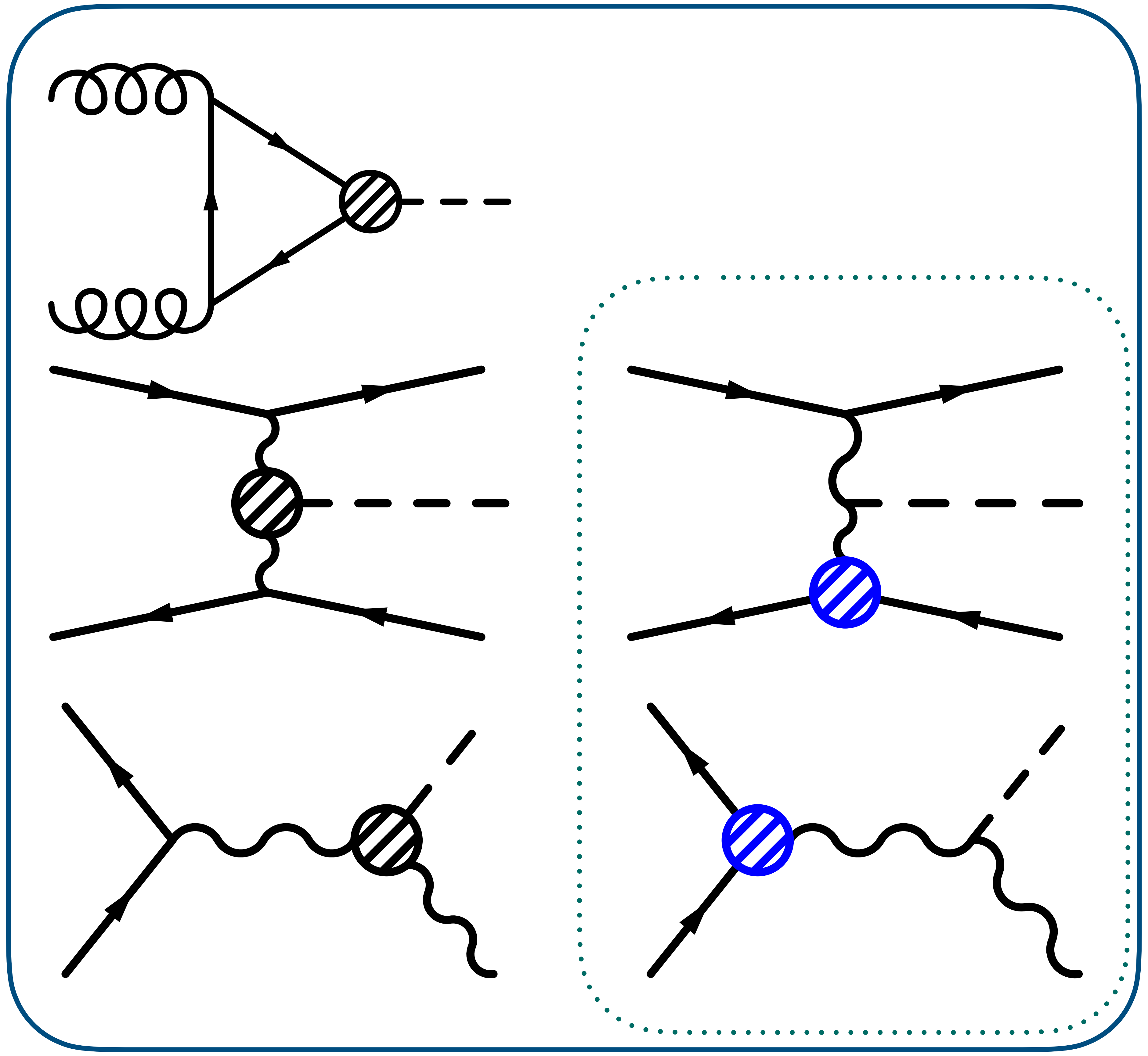
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

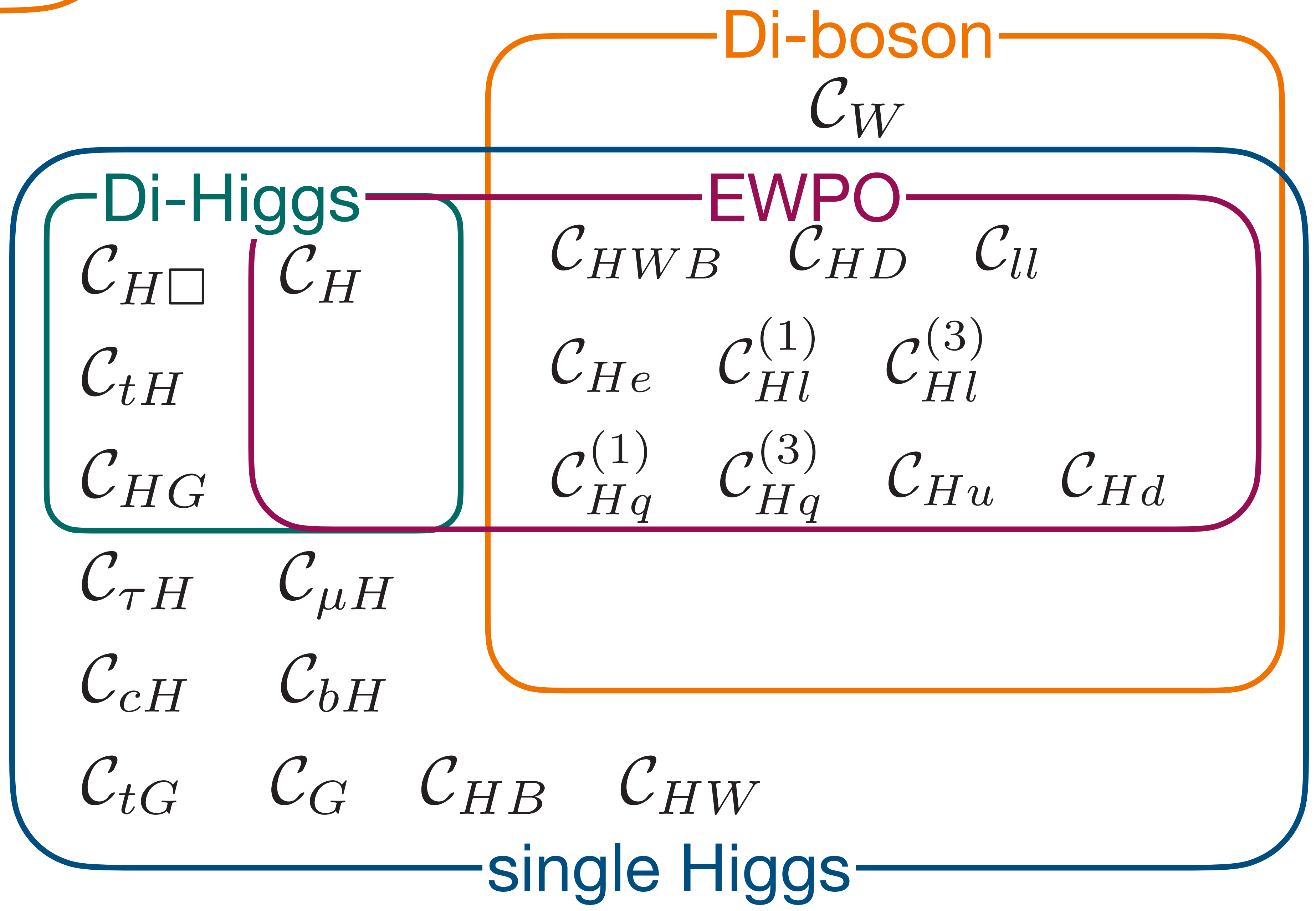
[ATLAS-CONF-2020-027]



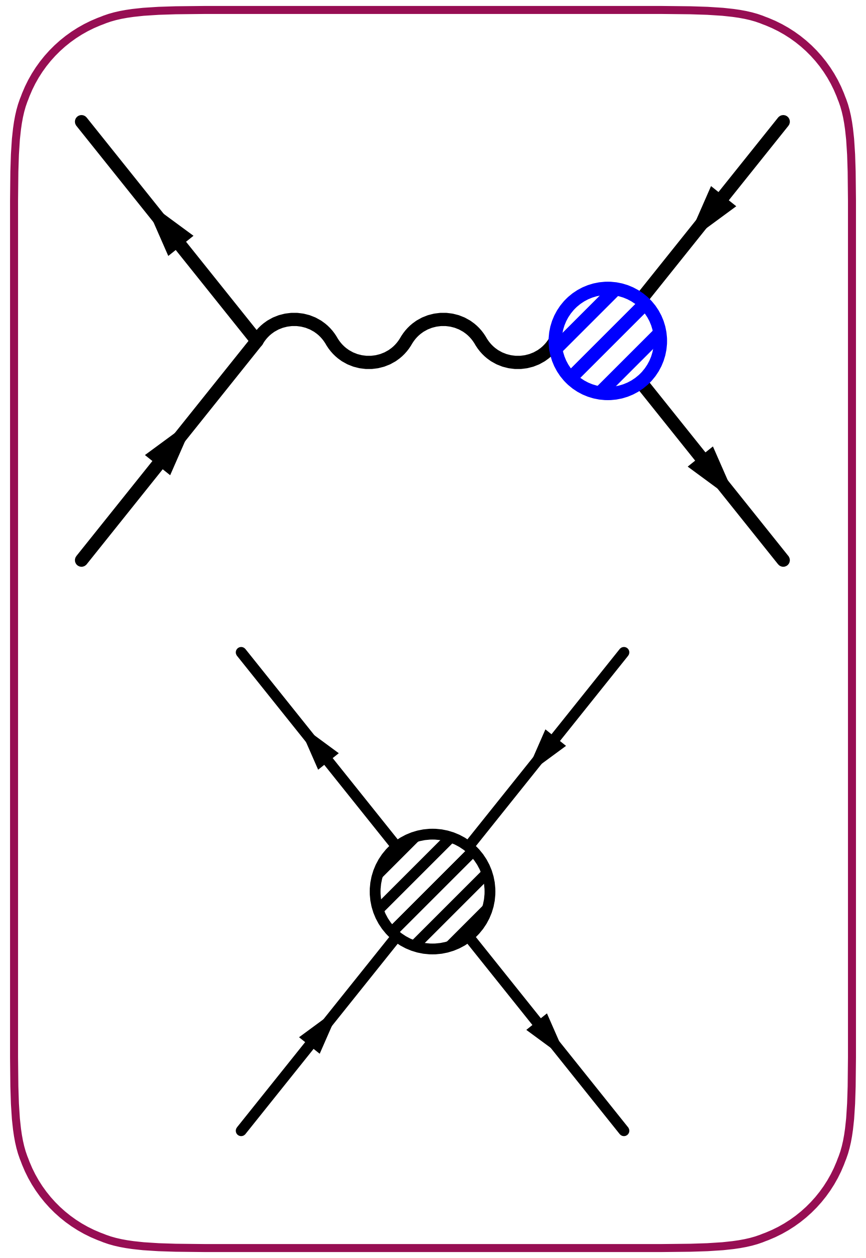
The Higgs and electroweak sector







EWPO: Electroweak precision observables (LEP)



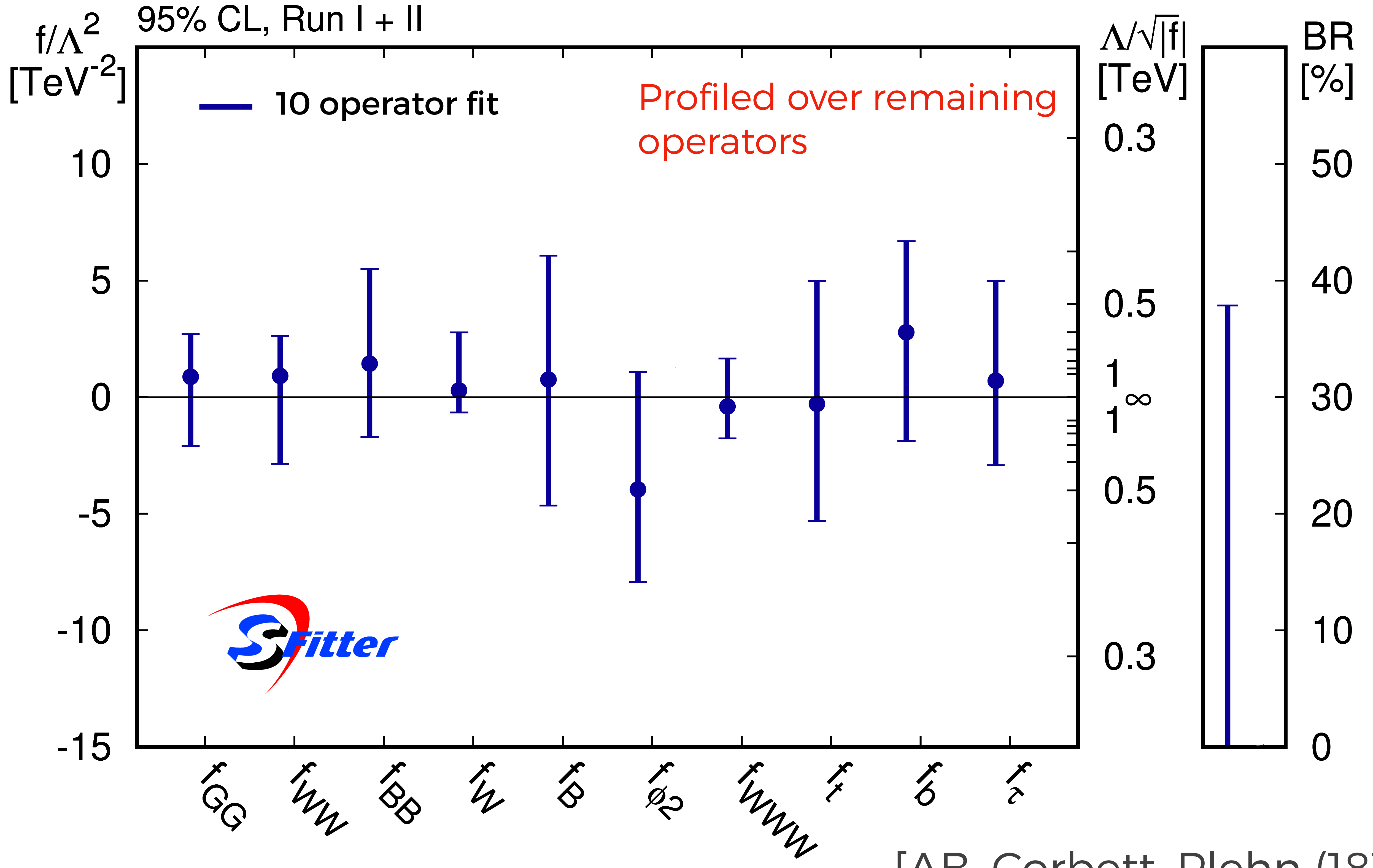
How do different sectors interact in a global fit? [Baglio, Dawson, Lewis, (1708.03332)]

LHC 2018 fit - fermion-gauge operators

[Hagiwara-Ishihara-Szalapski-Zeppenfeld basis]

Higgs only

$$\mathcal{O}_{GG} = \phi^\dagger \phi \, G^a_{\mu\nu} G^{a\mu\nu}$$
$$\mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$
$$\mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi$$
$$\mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi)$$
$$\mathcal{O}_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi)$$
$$\mathcal{O}_{\phi 2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi)$$
$$\mathcal{O}_{WWW} = \mathrm{Tr} \left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^{\mu}_{\rho} \right)$$
$$\mathcal{O}_{\tau} = \phi^\dagger \phi \, \bar{L}_3 \phi e_{R,3}$$
$$\mathcal{O}_{t} = \phi^\dagger \phi \, \bar{Q}_3 \tilde{\phi} u_{R,3}$$
$$\mathcal{O}_{b} = \phi^\dagger \phi \, \bar{Q}_3 \phi d_{R,3}$$



[AB, Corbett, Plehn (1812.07587)]

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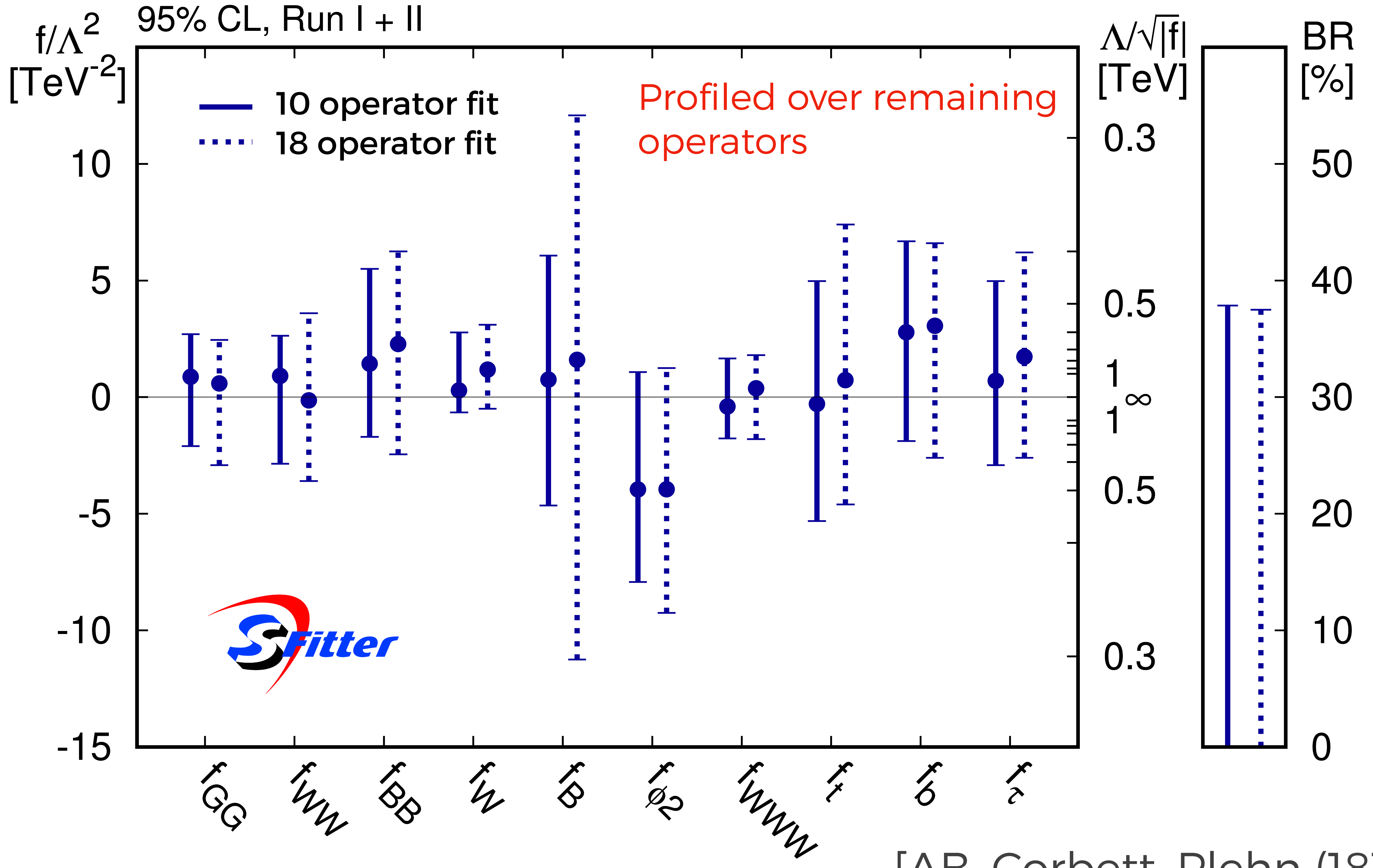
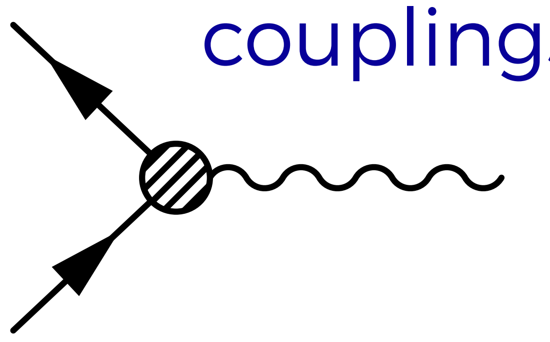


[AB, Corbett, Plehn (1812.07587)]

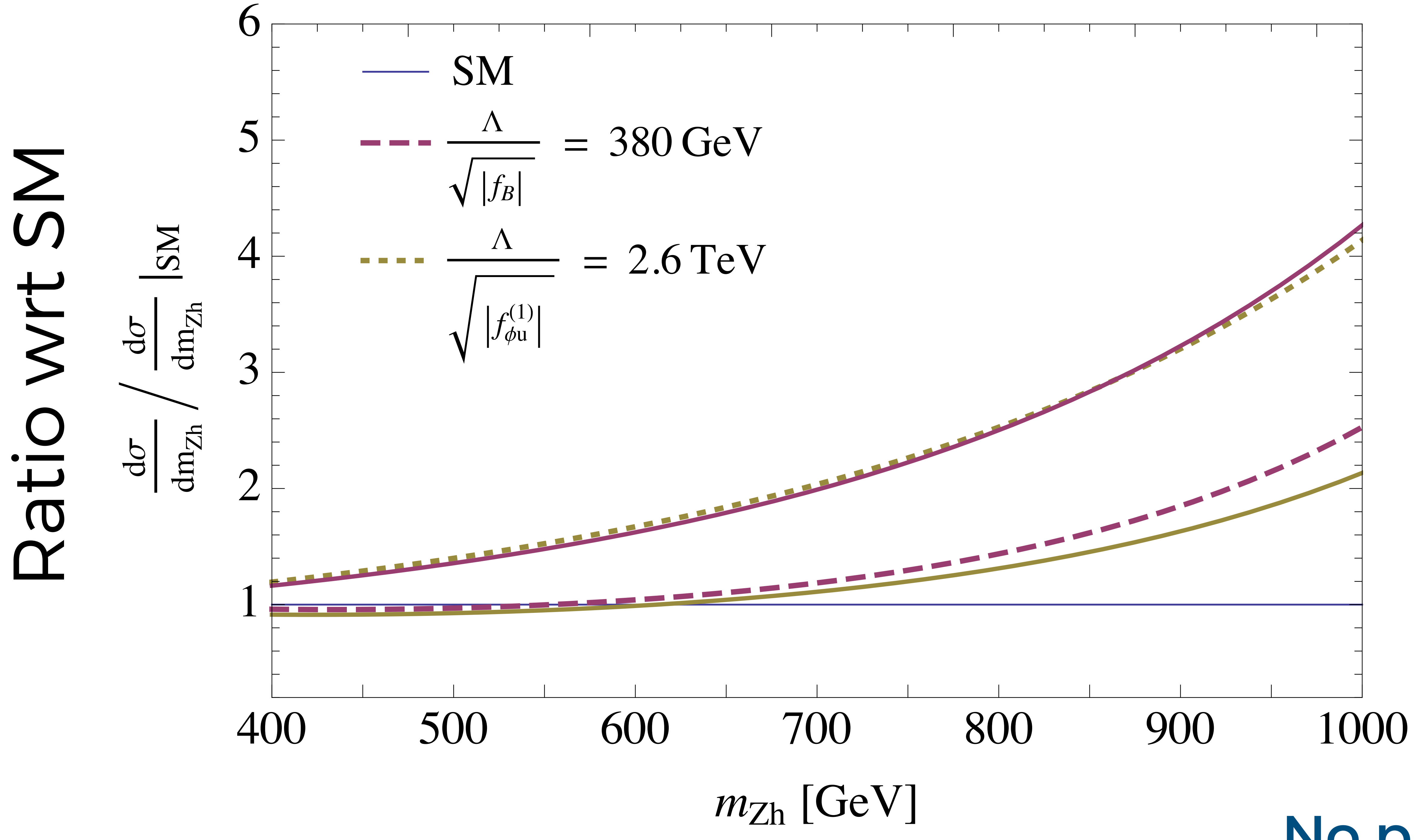
Fermion-gauge couplings

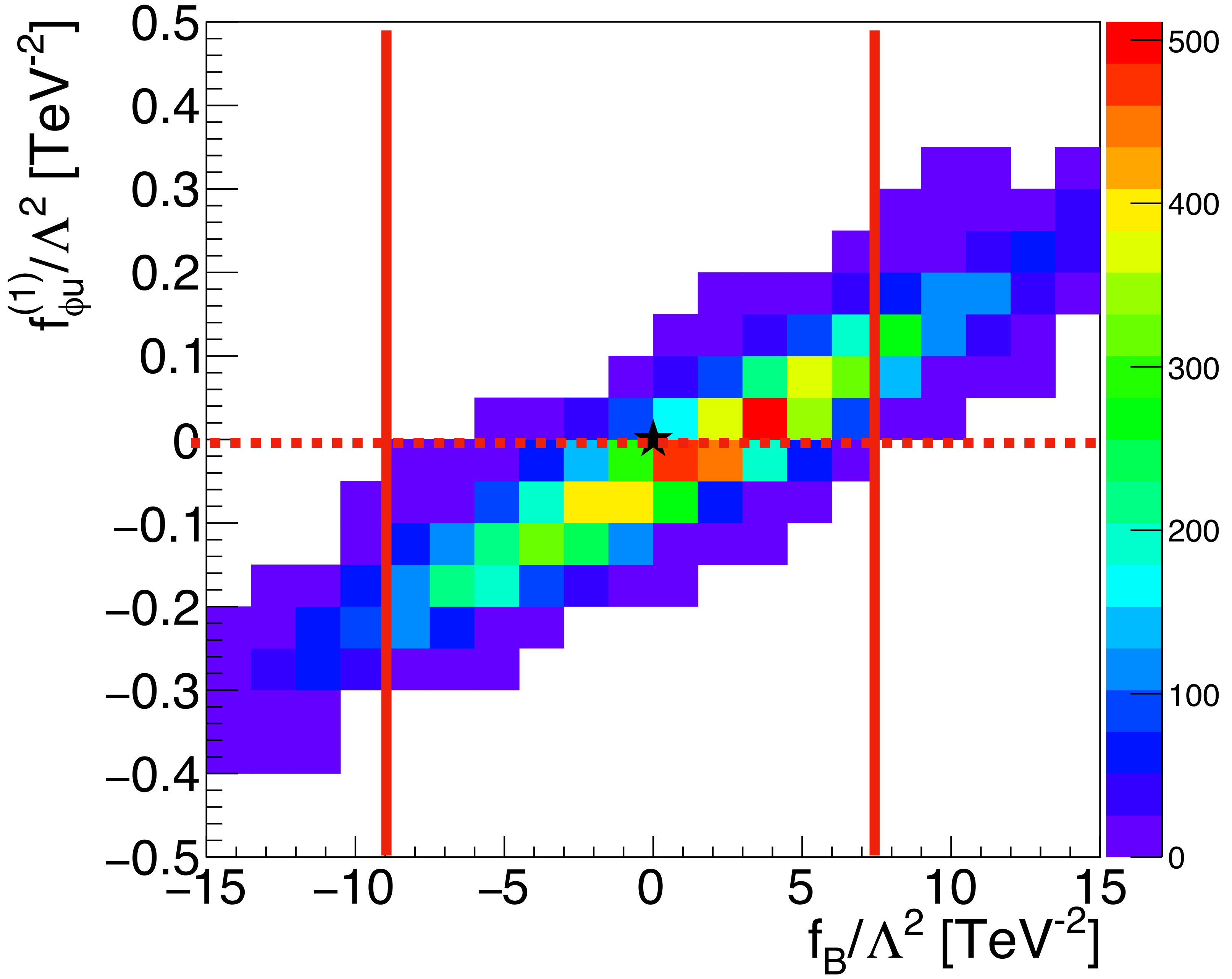


$$\mathcal{O}_{\phi 1} = (D_\mu \phi)^\dagger \; \phi \phi^\dagger \; (D^\mu \phi) \qquad \mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$
$$\mathcal{O}^{(1)}_{\phi Q} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{Q} \gamma^\mu Q) \qquad \mathcal{O}^{(3)}_{\phi Q} =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

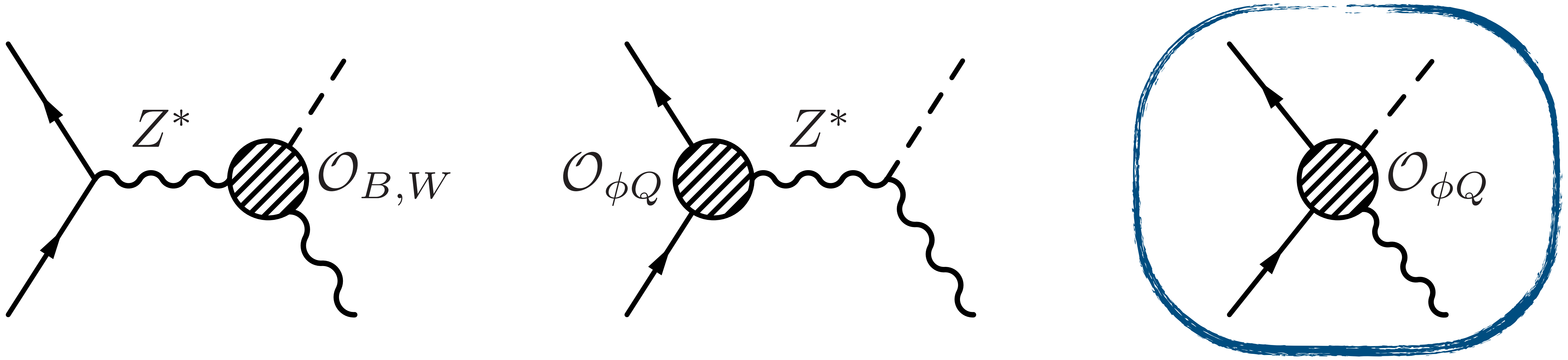
LHC 2018 fit - correlations

[Banerjee et al (1807.01796)]
[AB, Corbett, Plehn (1812.07587)]





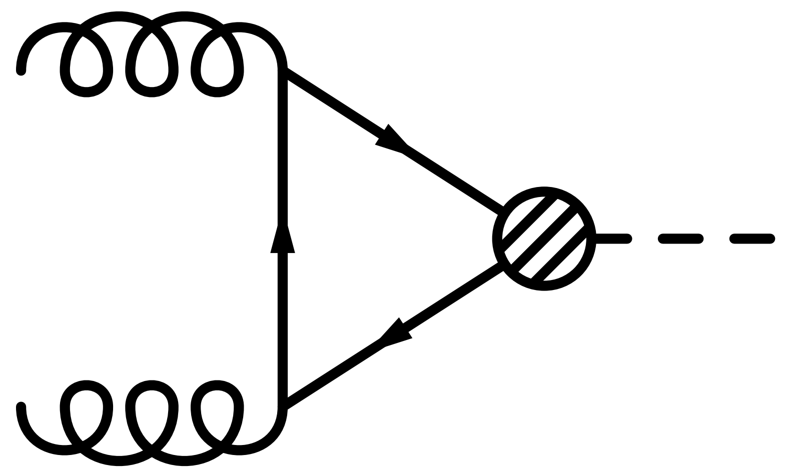
Contributions to Zh production



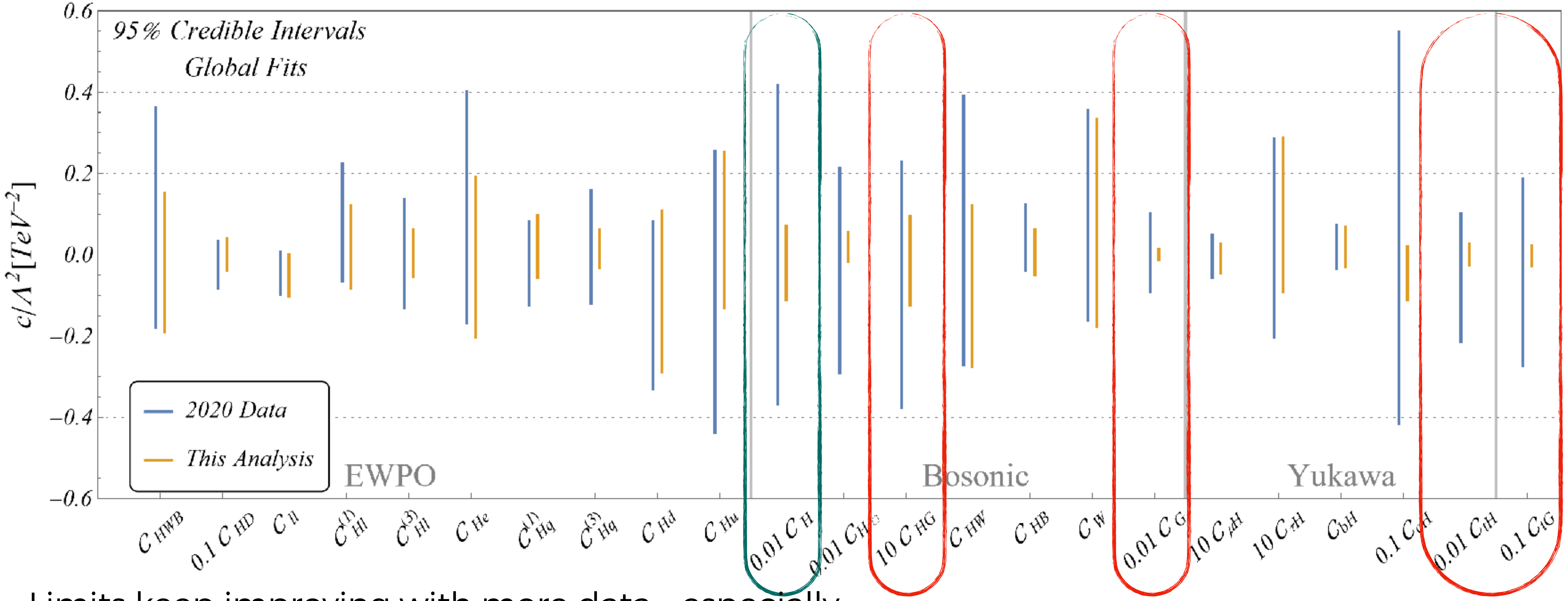
No propagator suppression

$$\mathcal{O}_B = (D_\mu\phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\phi)$$
$$\mathcal{O}_W = (D_\mu\phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\phi)$$
$$\mathcal{O}_{\phi Q}^{(1)} = \phi^\dagger(i\overleftrightarrow{D}_\mu\phi)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{O}_{\phi Q}^{(3)} = \phi^\dagger(i\overleftrightarrow{D}^a{}_\mu\phi)(\bar{Q}\gamma^\mu\sigma^a Q)$$

LHC 2021 fit



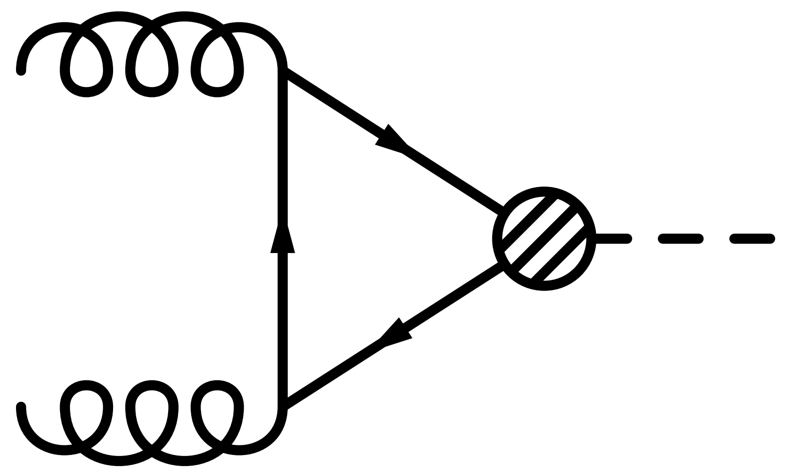
Di-Higgs production



Limits keep improving with more data - especially with more differential measurements

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

LHC 2021 fit



Di-Higgs production

So what have we learned about new physics now?

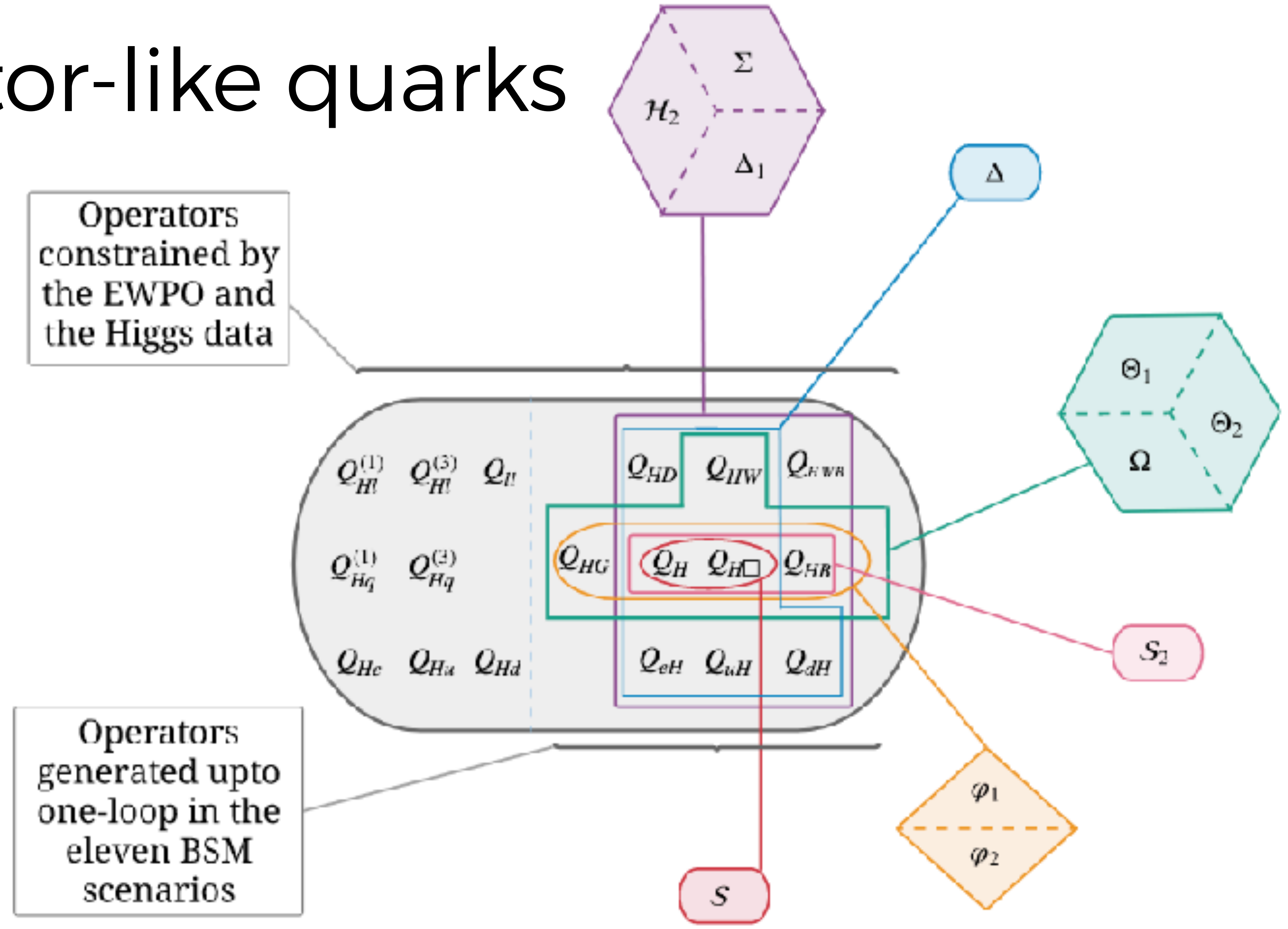
Limits keep improving with more data - especially with more differential measurements

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

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, Chakrabortty, 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, Chakrabortty, (Englert), Spannowsky, (Stylianou) (2009.13394), (2012.03839)]
[Krämer, Summ, Voigt (1908.04798)]
[Brivio, Brugisser, Geoffray, Kilian, Krämer (2108.01094)]
[...]



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

Two Higgs doublet model

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

CoDEx [Bakshi, Chakrabortty, Patra (1808.04403)]

$$Q_{\rm HB} \to \frac{g_Y^2\lambda_{\mathcal{H}_2,1}}{384\pi^2 m^2_{\mathcal{H}_2}} + \frac{g_Y^2\lambda_{\mathcal{H}_2,2}}{768\pi^2 m^2_{\mathcal{H}_2}}$$

$$Q_{\rm HW} \to \frac{g_W^2\lambda_{\mathcal{H}_2,1}}{384\pi^2 m^2_{\mathcal{H}_2}} + \frac{g_W^2\lambda_{\mathcal{H}_2,2}}{768\pi^2 m^2_{\mathcal{H}_2}}$$

$$Q_{\rm HWB} \to \frac{g_W g_Y\lambda_{\mathcal{H}_2,2}}{384\pi^2 m^2_{\mathcal{H}_2}}$$

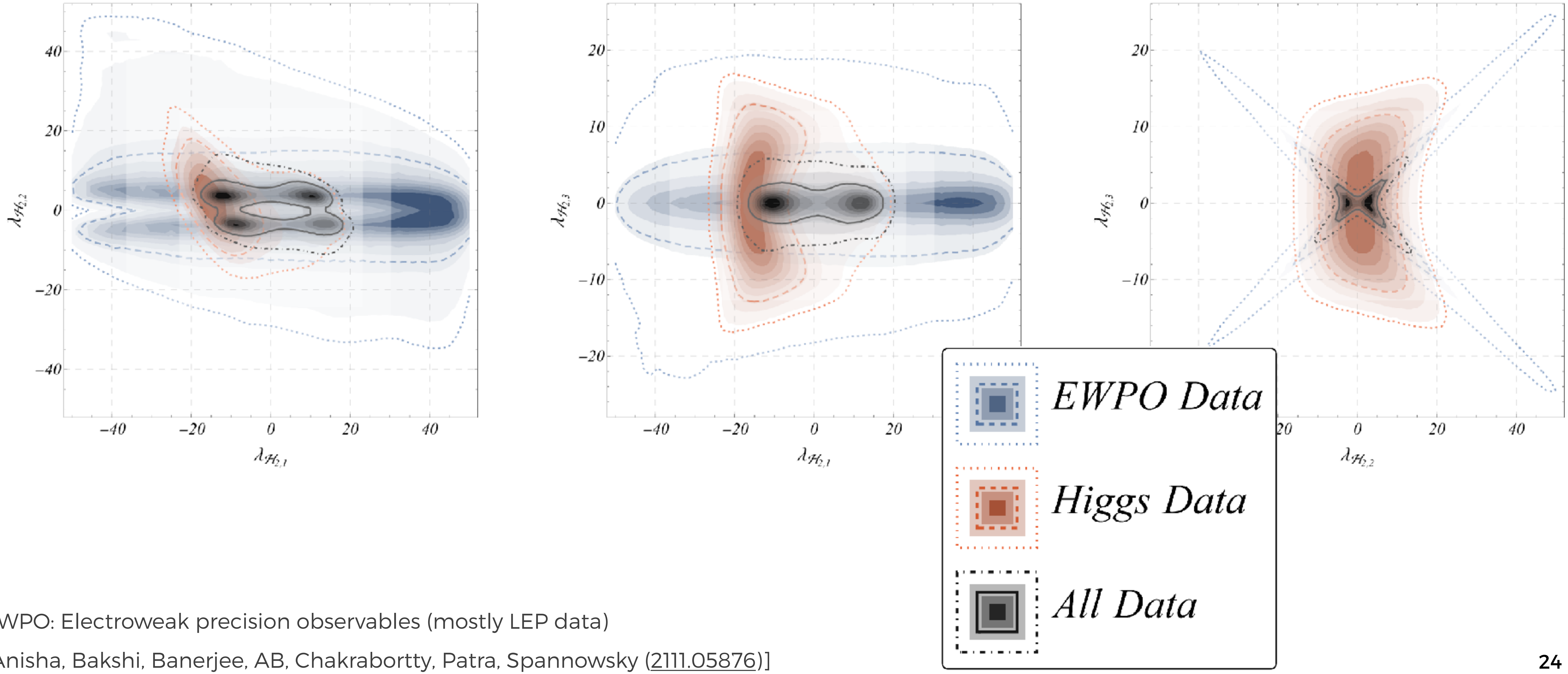
Table 3: Warsaw basis effective operators and the associated WCs that emerge after integrating-out the heavy field $\mathcal{H}_2 : (1, 2, -\frac{1}{2})$. Operators highlighted in red do not affect our current set of observables and are thus absent from our analysis. Operators highlighted in blue are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

Dim-6 Ops.	Wilson coefficients
$Q_{\rm dH}$	$\frac{\eta_H^2 Y_d^{\rm SM}}{16\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_H\eta_{\mathcal{H}_2}Y_d^{\rm SM}}{16\pi^2 m^2_{\mathcal{H}_2}} - \frac{\eta_H Y^{(d)}_{\mathcal{H}_2}}{m^2_{\mathcal{H}_2}} - \frac{3\eta_H\lambda_{\mathcal{H}_2}Y^{(d)}_{\mathcal{H}_2}}{32\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_H\lambda_{\mathcal{H}_2,1}Y^{(d)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,1}Y^{(d)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} \frac{\eta_H\lambda_{\mathcal{H}_2,2}Y^{(d)}_{\mathcal{H}_2}}{4\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,2}Y^{(d)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,2}Y_d^{\rm SM}}{192\pi^2 m^2_{\mathcal{H}_2}} \frac{5\eta_H\lambda_{\mathcal{H}_2,3}Y^{(d)}_{\mathcal{H}_2}}{8\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,3}Y_d^{\rm SM}}{48\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm eH}$	$\frac{\eta_H^2 Y_e^{\rm SM}}{16\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_H\eta_{\mathcal{H}_2}Y_e^{\rm SM}}{16\pi^2 m^2_{\mathcal{H}_2}} - \frac{\eta_H Y^{(e)}_{\mathcal{H}_2}}{m^2_{\mathcal{H}_2}} - \frac{3\eta_H\lambda_{\mathcal{H}_2}Y^{(e)}_{\mathcal{H}_2}}{32\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_H\lambda_{\mathcal{H}_2,1}Y^{(e)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,1}Y^{(e)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} \frac{\eta_H\lambda_{\mathcal{H}_2,2}Y^{(e)}_{\mathcal{H}_2}}{4\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,2}Y^{(e)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,2}Y_e^{\rm SM}}{192\pi^2 m^2_{\mathcal{H}_2}} \frac{5\eta_H\lambda_{\mathcal{H}_2,3}Y^{(e)}_{\mathcal{H}_2}}{8\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,3}Y_e^{\rm SM}}{48\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm uH}$	$\frac{\eta_H^2 Y_u^{\rm SM}}{16\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_H\lambda_{\mathcal{H}_2}Y^{(u)}_{\mathcal{H}_2}}{32\pi^2 m^2_{\mathcal{H}_2}} + \frac{\eta_H Y^{(u)}_{\mathcal{H}_2}}{m^2_{\mathcal{H}_2}} - \frac{3\eta_H\eta_{\mathcal{H}_2}Y_u^{\rm SM}}{16\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_H\lambda_{\mathcal{H}_2,1}Y^{(u)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,1}Y^{(u)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} - \frac{\eta_H\lambda_{\mathcal{H}_2,2}Y^{(u)}_{\mathcal{H}_2}}{4\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,2}Y^{(u)}_{\mathcal{H}_2}}{16\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,2}Y_u^{\rm SM}}{192\pi^2 m^2_{\mathcal{H}_2}} \frac{\lambda^2_{\mathcal{H}_2,3}Y_u^{\rm SM}}{48\pi^2 m^2_{\mathcal{H}_2}} - \frac{5\eta_H\lambda_{\mathcal{H}_2,3}Y^{(u)}_{\mathcal{H}_2}}{8\pi^2 m^2_{\mathcal{H}_2}}$
Q_H	$\frac{3\eta_H^2\lambda_{\mathcal{H}_2}}{32\pi^2 m^2_{\mathcal{H}_2}} + \frac{17\eta_H^2\lambda_H^{\rm SM}}{16\pi^2 m^2_{\mathcal{H}_2}} + \frac{\eta_H^2}{m^2_{\mathcal{H}_2}} - \frac{3\eta_H^2\lambda_{\mathcal{H}_2,1}}{4\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_H\eta_{\mathcal{H}_2}\lambda_H^{\rm SM}}{8\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_H\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,1}}{8\pi^2 m^2_{\mathcal{H}_2}} - \frac{13\eta_H^2\lambda_{\mathcal{H}_2,2}}{16\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_H\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,2}}{8\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda^3_{\mathcal{H}_2,1}}{48\pi^2 m^2_{\mathcal{H}_2}} \frac{\lambda_H^{\rm SM}\lambda^2_{\mathcal{H}_2,2}}{96\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda^2_{\mathcal{H}_2,1}\lambda_{\mathcal{H}_2,2}}{32\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda_{\mathcal{H}_2,1}\lambda^2_{\mathcal{H}_2,2}}{32\pi^2 m^2_{\mathcal{H}_2}} - \frac{7\eta_H^2\lambda_{\mathcal{H}_2,3}}{4\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda_H^{\rm SM}\lambda^2_{\mathcal{H}_2,3}}{24\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda^3_{\mathcal{H}_2,2}}{96\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda_{\mathcal{H}_2,1}\lambda^2_{\mathcal{H}_2,3}}{8\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda_{\mathcal{H}_2,2}\lambda^2_{\mathcal{H}_2,3}}{8\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{H\Box}$	$-\frac{g_W^4}{7680\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\eta_H^2}{32\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda^2_{\mathcal{H}_2,1}}{96\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda_{\mathcal{H}_2,1}\lambda_{\mathcal{H}_2,2}}{96\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,2}}{384\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,3}}{96\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm HD}$	$-\frac{g_Y^4}{1920\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda^2_{\mathcal{H}_2,2}}{96\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,3}}{24\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm HB}$	$\frac{g_Y^2\lambda_{\mathcal{H}_2,1}}{384\pi^2 m^2_{\mathcal{H}_2}} + \frac{g_Y^2\lambda_{\mathcal{H}_2,2}}{768\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm HW}$	$\frac{g_W^2\lambda_{\mathcal{H}_2,1}}{384\pi^2 m^2_{\mathcal{H}_2}} + \frac{g_W^2\lambda_{\mathcal{H}_2,2}}{768\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm HWB}$	$\frac{g_W g_Y\lambda_{\mathcal{H}_2,2}}{384\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm Hl}{}^{(1)}$	$\frac{g_Y^4}{3840\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm Hq}{}^{(1)}$	$-\frac{g_Y^4}{11520\pi^2 m^2_{\mathcal{H}_2}}$

Dim-6 Ops.	Wilson coefficients
$Q_{\rm Hd}$	$\frac{g_Y^4}{5760\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm He}$	$\frac{g_Y^4}{1920\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm Hu}$	$-\frac{g_Y^4}{2880\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm Hl}{}^{(3)}$	$-\frac{g_W^4}{1920\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm Hq}{}^{(3)}$	$-\frac{g_W^4}{1920\pi^2 m^2_{\mathcal{H}_2}}$
Q_W	$\frac{g_W^3}{5760\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm ll}$	$-\frac{g_W^4}{7680\pi^2 m^2_{\mathcal{H}_2}} - \frac{g_Y^4}{7680\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm ud}{}^{(1)}$	$\frac{g_Y^4}{4320\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm lq}{}^{(3)}$	$-\frac{g_W^4}{3840\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm qq}{}^{(3)}$	$-\frac{g_W^4}{7680\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm dd}$	$-\frac{g_Y^4}{17280\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm ed}$	$-\frac{g_Y^4}{2880\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm ee}$	$-\frac{g_Y^4}{1920\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm eu}$	$\frac{g_Y^4}{1440\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm uu}$	$-\frac{g_Y^4}{4320\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm lu}$	$\frac{g_Y^4}{2880\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm qe}$	$\frac{g_Y^4}{5760\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm ld}$	$-\frac{g_Y^4}{5760\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm qq}{}^{(1)}$	$-\frac{g_Y^4}{69120\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm le}$	$-\frac{g_Y^4}{1920\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\lambda_{\mathcal{H}_2}Y^{(e)2}_{\mathcal{H}_2}}{128\pi^2 m^2_{\mathcal{H}_2}} - \frac{Y^{(e)2}_{\mathcal{H}_2}}{4m^2_{\mathcal{H}_2}}$
$Q_{\rm qd}{}^{(1)}$	$\frac{g_Y^4}{17280\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\lambda_{\mathcal{H}_2}Y^{(d)2}_{\mathcal{H}_2}}{128\pi^2 m^2_{\mathcal{H}_2}} - \frac{Y^{(d)2}_{\mathcal{H}_2}}{4m^2_{\mathcal{H}_2}}$
$Q_{\rm qu}{}^{(1)}$	$-\frac{g_Y^4}{8640\pi^2 m^2_{\mathcal{H}_2}} - \frac{3\lambda_{\mathcal{H}_2}Y^{(u)2}_{\mathcal{H}_2}}{128\pi^2 m^2_{\mathcal{H}_2}} - \frac{Y^{(u)2}_{\mathcal{H}_2}}{4m^2_{\mathcal{H}_2}}$
$Q_{\rm quqd}{}^{(1)}$	$-\frac{3\lambda_{\mathcal{H}_2}Y^{(d)}_{\mathcal{H}_2}Y^{(u)}_{\mathcal{H}_2}}{64\pi^2 m^2_{\mathcal{H}_2}} - \frac{Y^{(d)}_{\mathcal{H}_2}Y^{(u)}_{\mathcal{H}_2}}{2m^2_{\mathcal{H}_2}}$
$Q_{\rm lequ}{}^{(1)}$	$\frac{3\lambda_{\mathcal{H}_2}Y^{(e)}_{\mathcal{H}_2}Y^{(u)}_{\mathcal{H}_2}}{64\pi^2 m^2_{\mathcal{H}_2}} + \frac{Y^{(e)}_{\mathcal{H}_2}Y^{(u)}_{\mathcal{H}_2}}{2m^2_{\mathcal{H}_2}}$
$Q_{\rm lq}{}^{(1)}$	$\frac{g_Y^4}{11520\pi^2 m^2_{\mathcal{H}_2}}$
$Q_{\rm ledq}$	$\frac{3\lambda_{\mathcal{H}_2}Y^{(d)}_{\mathcal{H}_2}Y^{(e)}_{\mathcal{H}_2}}{64\pi^2 m^2_{\mathcal{H}_2}} + \frac{Y^{(d)}_{\mathcal{H}_2}Y^{(e)}_{\mathcal{H}_2}}{2m^2_{\mathcal{H}_2}}$

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

Constraints on two Higgs doublet model



EWPO: Electroweak precision observables (mostly LEP data)

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

Future directions in SMEFT (fits)

Future directions in SMEFT (fits)

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

Generality

Relax (flavor) assumptions

Dim6^2 effects

Dim8 effects

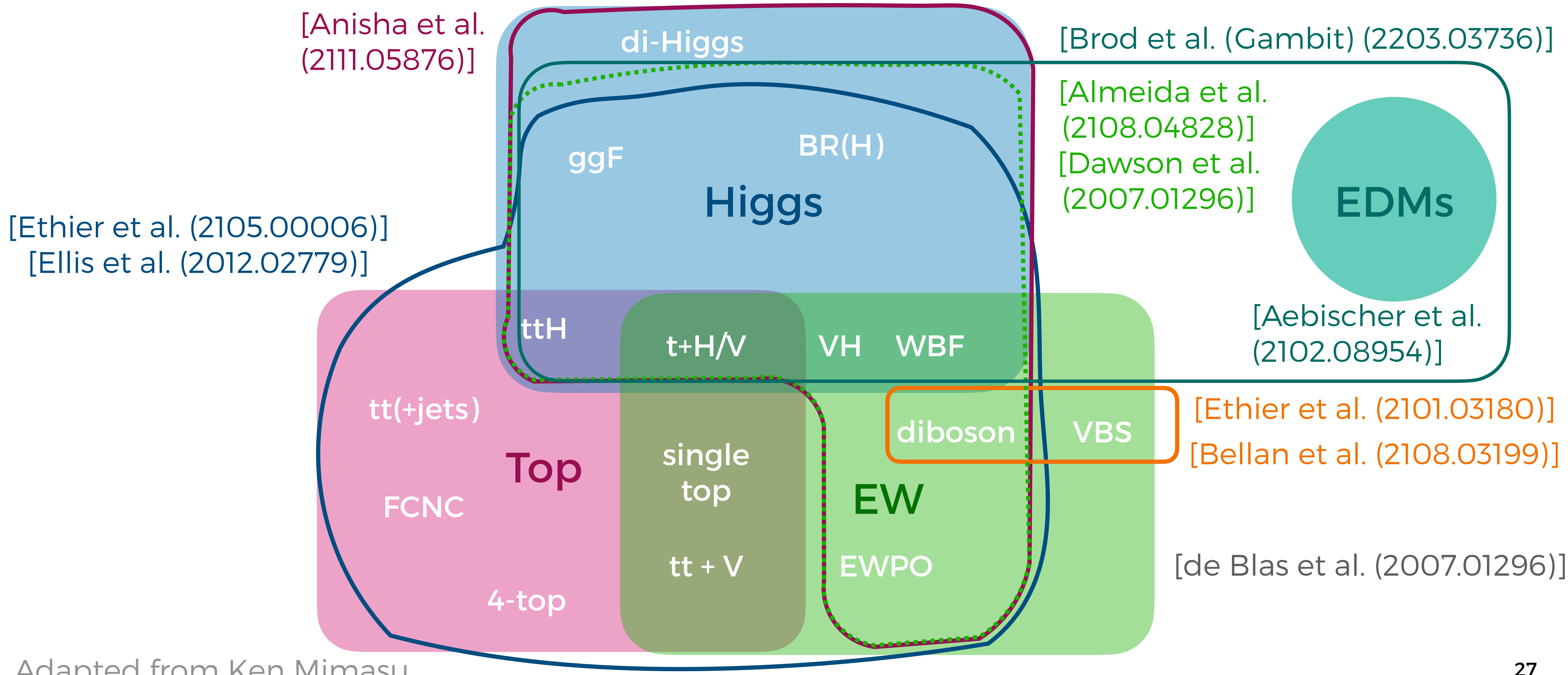
Combine more sectors

Add more data

SMEFT@NLO

Precision

Global fits



Adapted from Ken Mimasu

$1/\Lambda^4$ 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)]

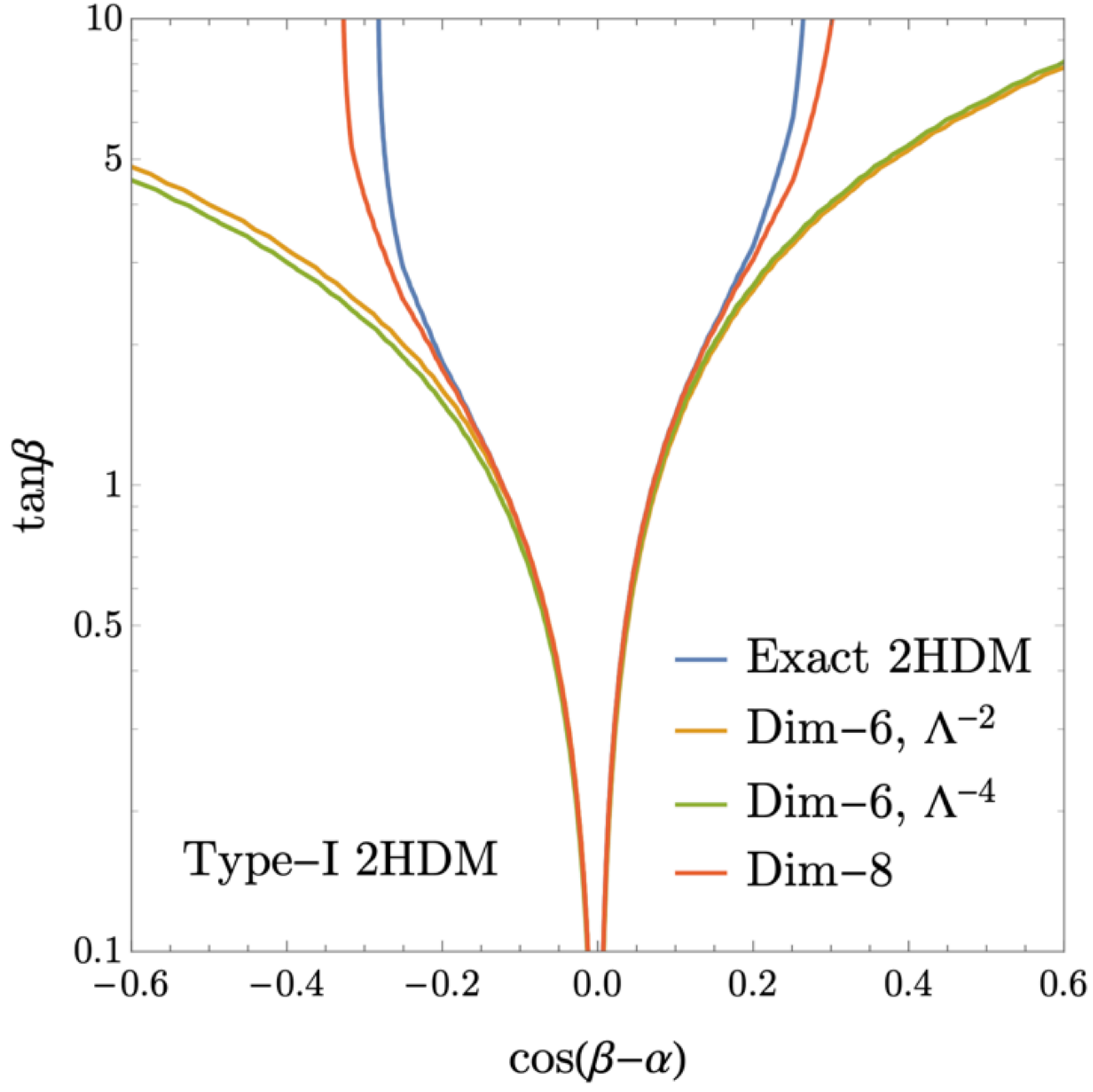
- vector-like top partner contribution to tth: O(1%)

  [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)]

[Dawson et al. (2205.01561)] 95% CL



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!

SMEFT fits - a global effort!

Filled to my best knowledge

	Eboli, Gonzalez-Garcia et al	Fitmaker	SFitter	TopFitter	HEPfit	SMEFit	Dawson et al.	Chakrabortty et al.
Input	EWPD+Higgs+VV, DY +VV	EWPD+Higgs+VV + top	EWPD+Higgs+VV, top	top	EWPD+Higgs+VV Flavor	EWPD+Higgs+VV, VBS + diboson, top	EWPD+Higgs+VV	EWPD + Higgs
Linear/ quadratic	Both	Linear	Both	Linear	Linear	Both	Linear	Linear
Basis	HISZ	Warsaw	HISZ (Higgs) Warsaw (top)	Warsaw	Warsaw	Warsaw	Warsaw	Warsaw
EW scheme	Alpha	Alpha	Alpha	-	Alpha	mW	mW	Alpha
Flavor assumptions	$SU(3)^5$	$SU(3)^5$ $SU(2)^2 \times SU(3)^3$	$SU(3)^5$ $SU(2)^2 \times SU(3)^3$	$SU(3)^5$	$SU(3)^5$ general	$SU(2)^2 \times SU(3)^3$	$SU(2)^2 \times SU(3)^3$	$SU(3)^5$
NLO QCD included	LO	Top only	Top only	LO	LO	Top only	Vh, diboson, EWPO	EWPO only
Fitting procedure	Chi2	Bayesian	Toy MC, Chi2, Bayesian	Chi2	Bayesian	Toy MC	Chi2	Bayesian
Uncertainties	Gaussian, theory correlated	Gauss	Gauss, Poisson, flat	Gauss	(Asymmetric) Gauss, flat	Gauss	Gauss, uncorrelated	Gauss
UV complete model fits	✗	✓	✓	✓	✓	✗	✓	✓
Specialties	VV + DY	Higgs + EWPO + top + diboson	Correlation of uncertainty classes	Top	Projections	CP odd operators VBS	NLO for VV and Vh	UV complete models
References	1211.4580, 1509.01585, 1805.11108, 1812.01009, 2108.04828	1404.3667, 1803.03252, 2012.02779	1308.1979, 1505.05516, 1604.03105, 1812.07587, 1910.03606	1506.08845, 1512.03360, 1901.03164	1710.0540, 1905.03764, 1907.04311, 1910.14012	1901.05965, 1906.05296, 2101.03180	2007.01296	2009.13394, 2010.04088, 2012.03839, 2111.05876

SMEFT fits - a global effort!

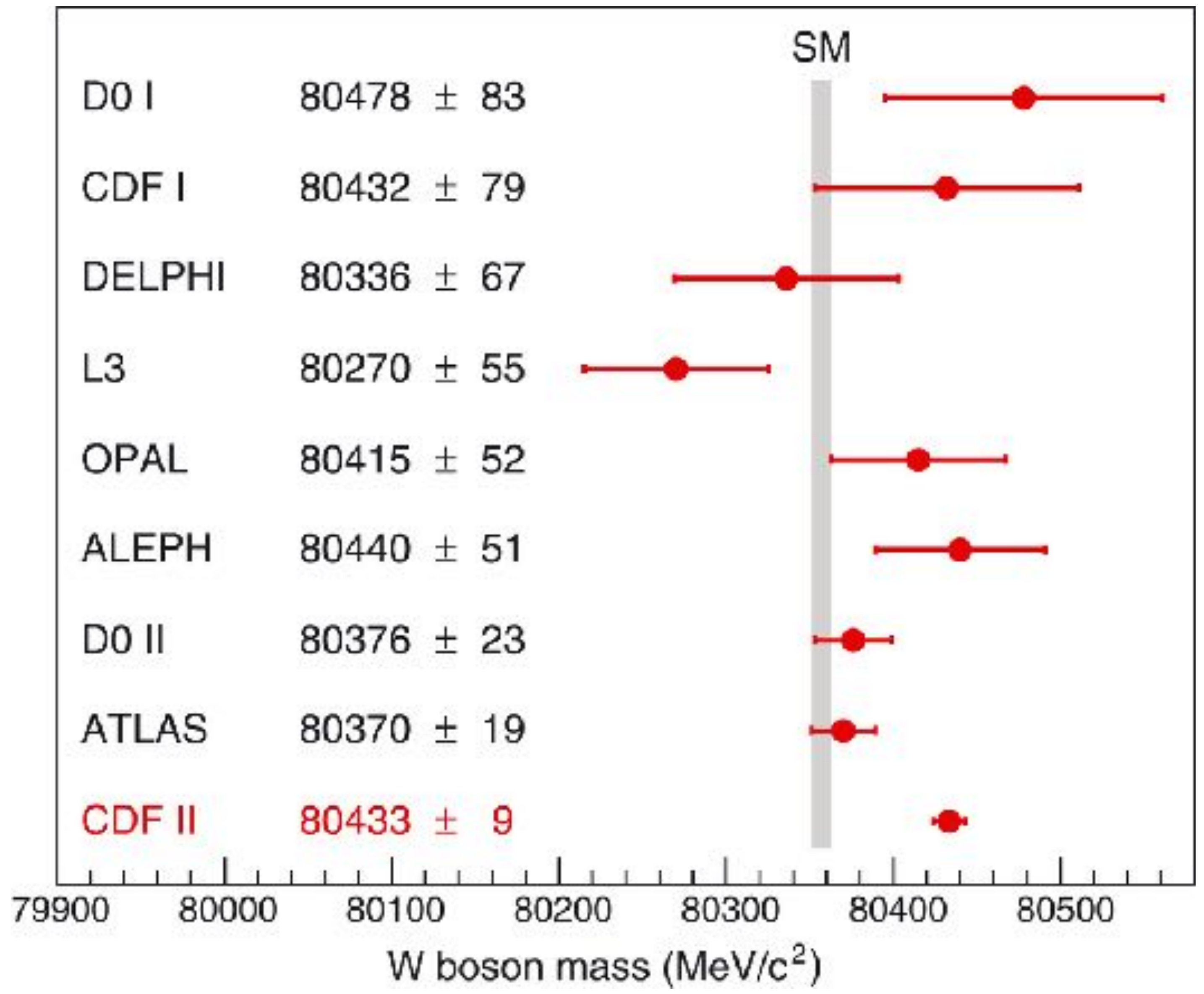
Filled to my best knowledge

	Eboli, Gonzalez-Garcia et al	Fitmaker	SFitter	TopFitter	HEPfit	SMEFit	Dawson et al.	Chakrabortty et al.
Input	EWPD+Higgs+VV, DY +VV	EWPD+Higgs+VV + top	EWPD+Higgs+VV, top	top	EWPD+Higgs+VV Flavor	EWPD+Higgs+VV, VBS + diboson, top	EWPD+Higgs+VV	EWPD + Higgs
Linear/ quadratic	Both	Linear	Both	Linear	Linear	Both	Linear	Linear
Basis	HISZ	Warsaw	HISZ (Higgs) Warsaw (top)	Warsaw	Warsaw	Warsaw	Warsaw	Warsaw
Uncertainties	Gaussian, theory correlated	Gauss	Gauss, Poisson, flat	Gauss	(Asymmetric) Gauss, flat	Gauss	Gauss, uncorrelated	Gauss
UV complete model fits	✗	✓	✓	✓	✓	✗	✓	✓
Specialties	VV + DY	Higgs + EWPO + top + diboson	Correlation of uncertainty classes	Top	Projections	CP odd operators VBS	NLO for VV and Vh	UV complete models
References	1211.4580, 1509.01585, 1805.11108, 1812.01009, 2108.04828	1404.3667, 1803.03252, 2012.02779	1308.1979, 1505.05516, 1604.03105, 1812.07587, 1910.03606	1506.08845, 1512.03360, 1901.03164	1710.0540, 1905.03764, 1907.04311, 1910.14012	1901.05965, 1906.05296, 2101.03180	2007.01296	2009.13394, 2010.04088, 2012.03839, 2111.05876

Many groups contribute to the field.
Each of them has their own strength.

W boson mass - SMEFT interpretations

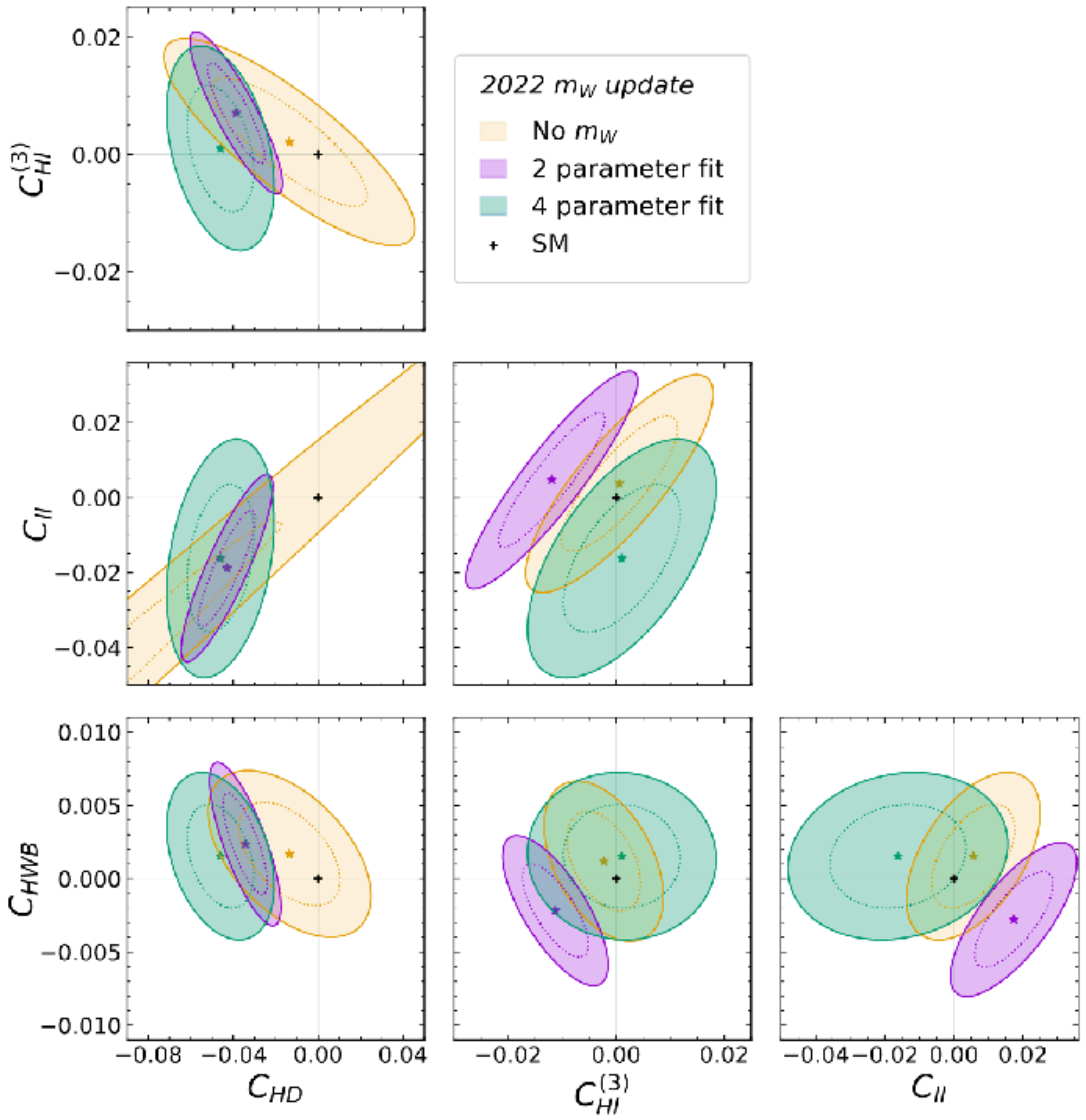
[CDF II (Science)]



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

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