Constraining Standard Model Effective Field Theory at colliders

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Unterstützt von / Supported by
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Outline

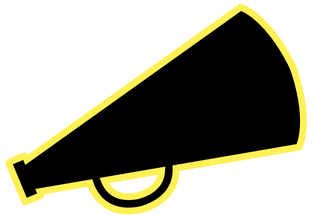
- Standard Model Effective Field Theory
- Global fits
  - CP-odd triple gauge interactions [AB, Gregg, Krauss, Schönherr (2102.01115)]
  - Global fits of the Higgs-gauge sector [AB, Corbett, Plehn (1812.07587)]

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (work in progress)]

Why do we need global fits?

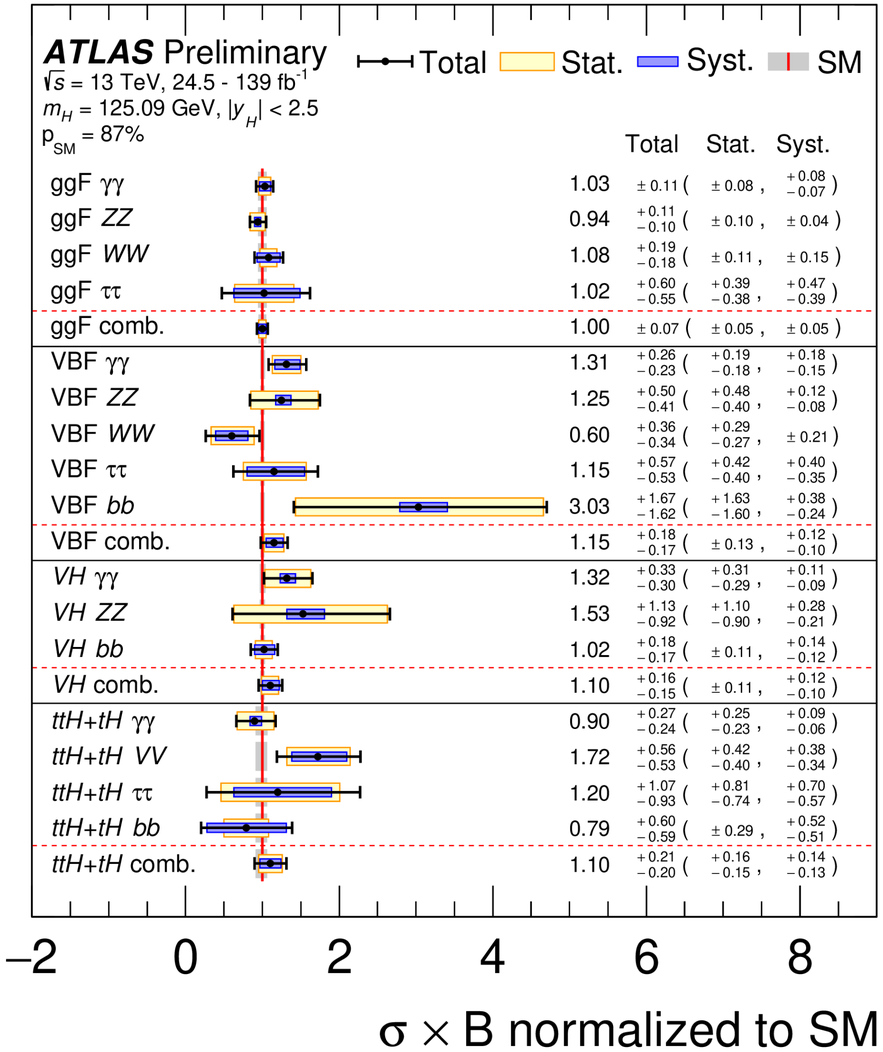
Why is Standard Model Effective Field Theory a good framework to perform them?

How do different sectors interact in global fits?



PLEASE INTERRUPT ME

Why do we need global fits?



[ATLAS-CONF-2020-027]

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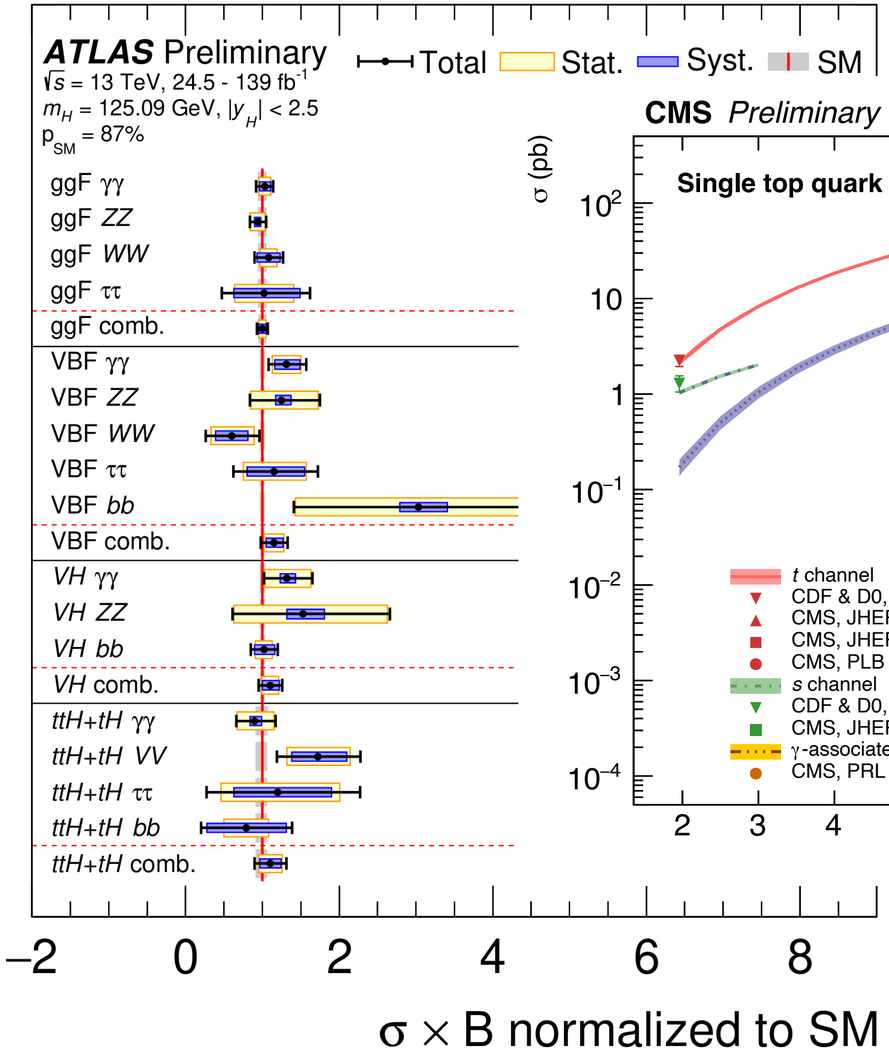
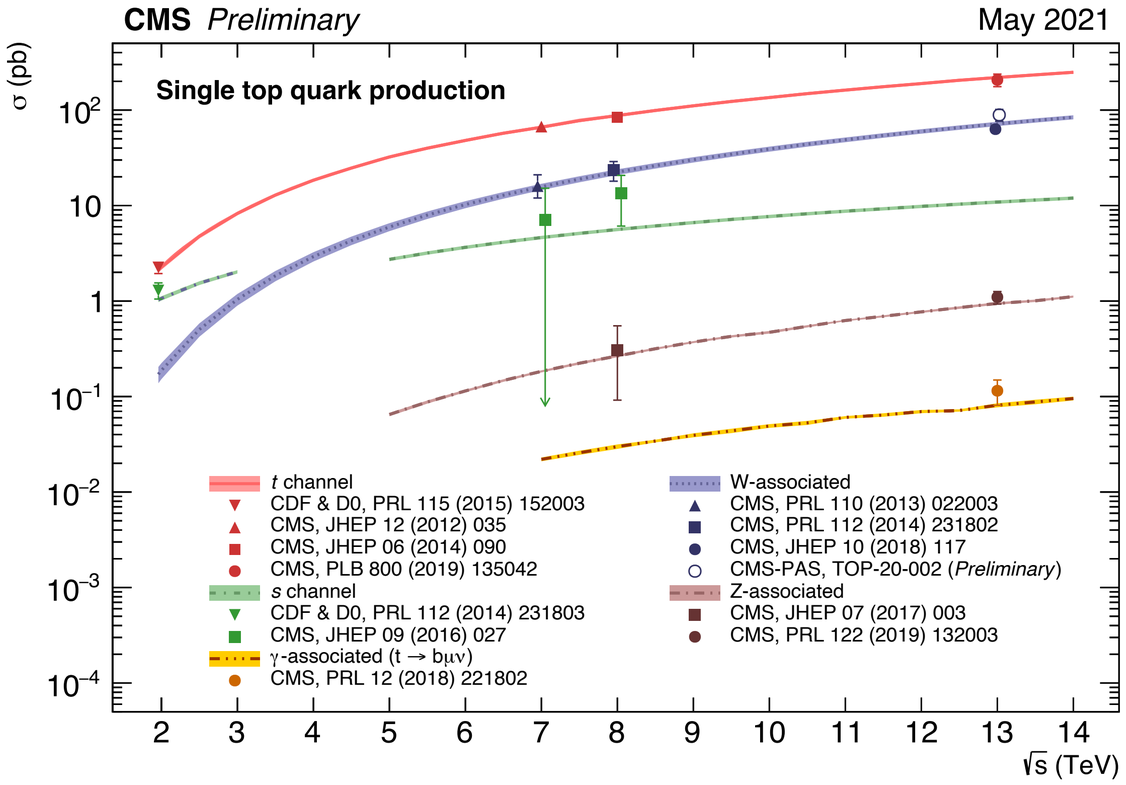
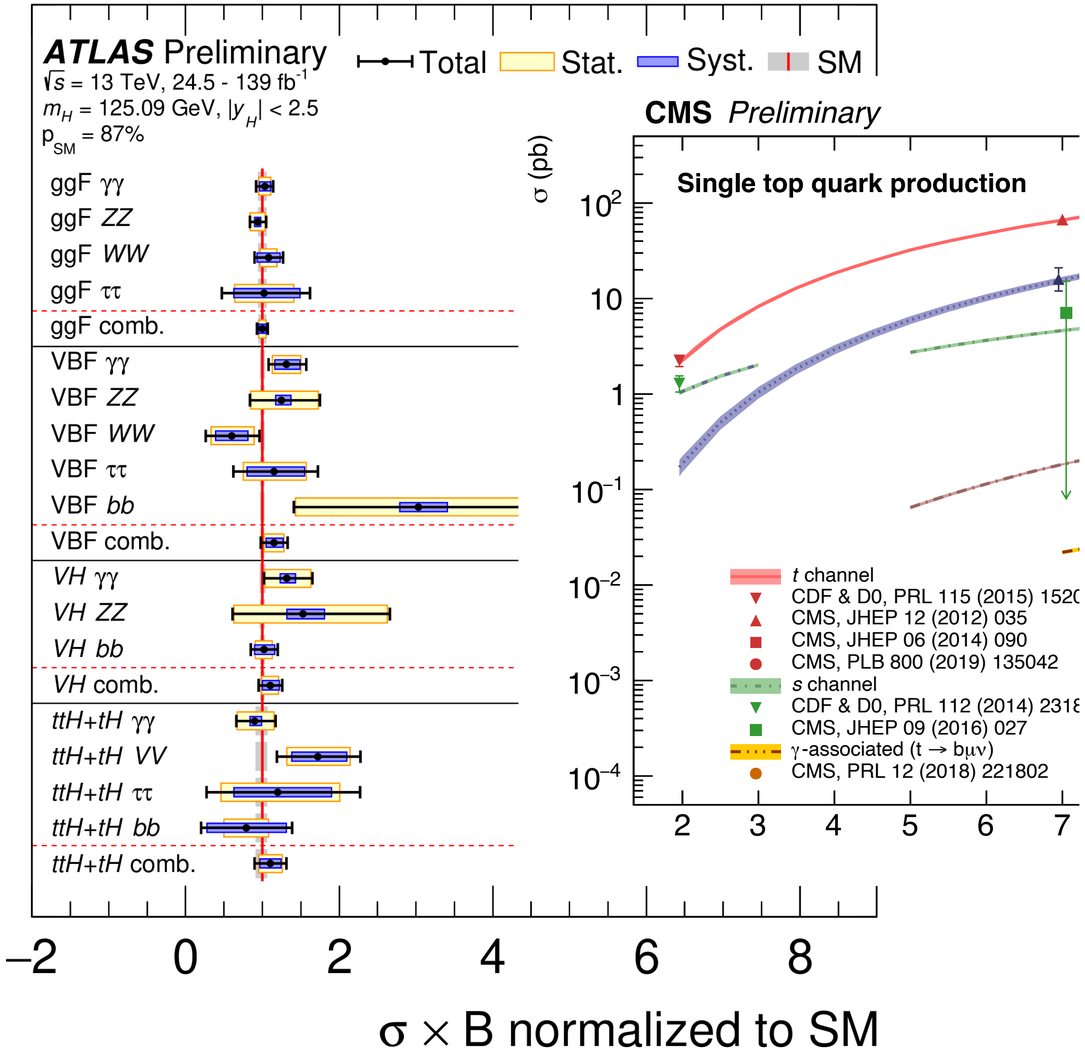


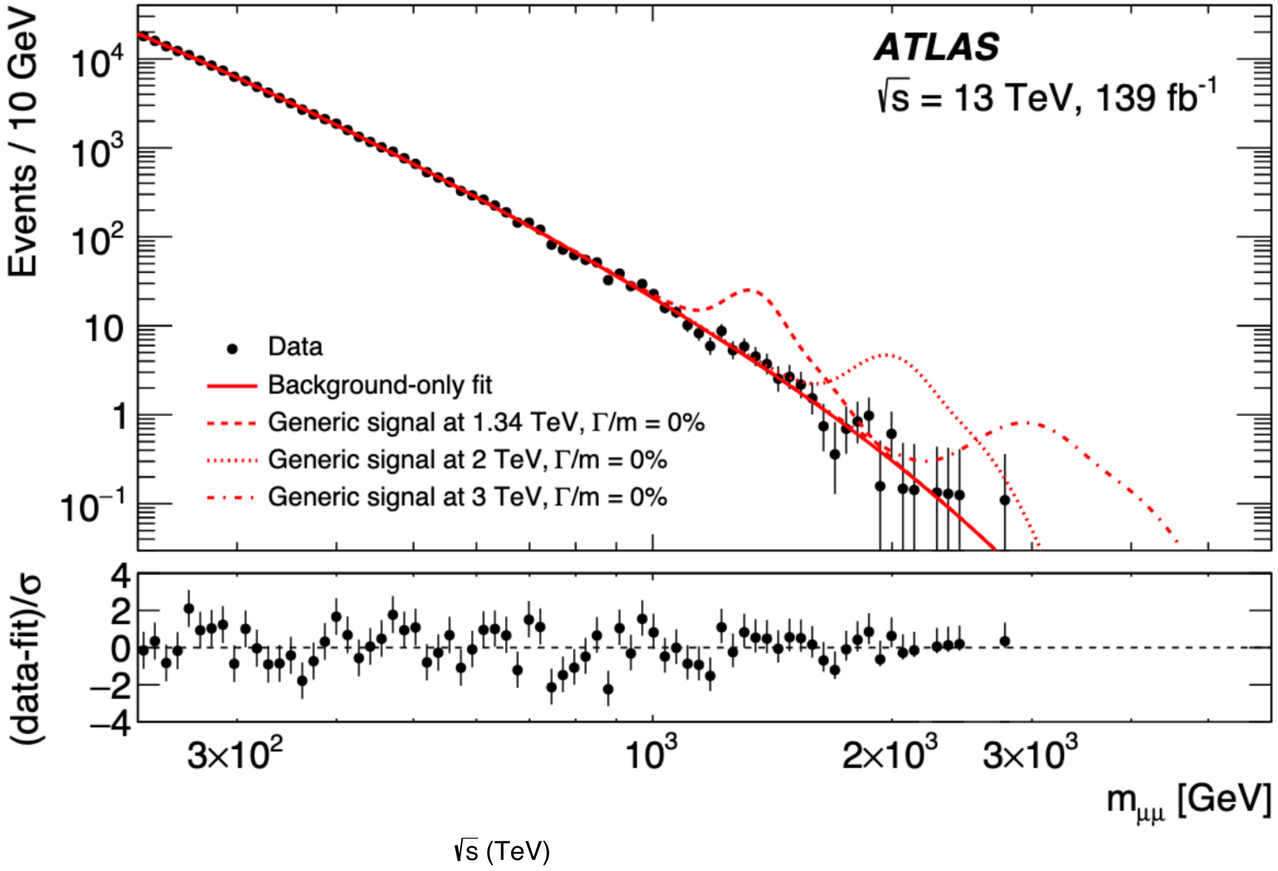


[ATLAS-CONF-2020-027]

Why do we need global fits?

[1903.06248]





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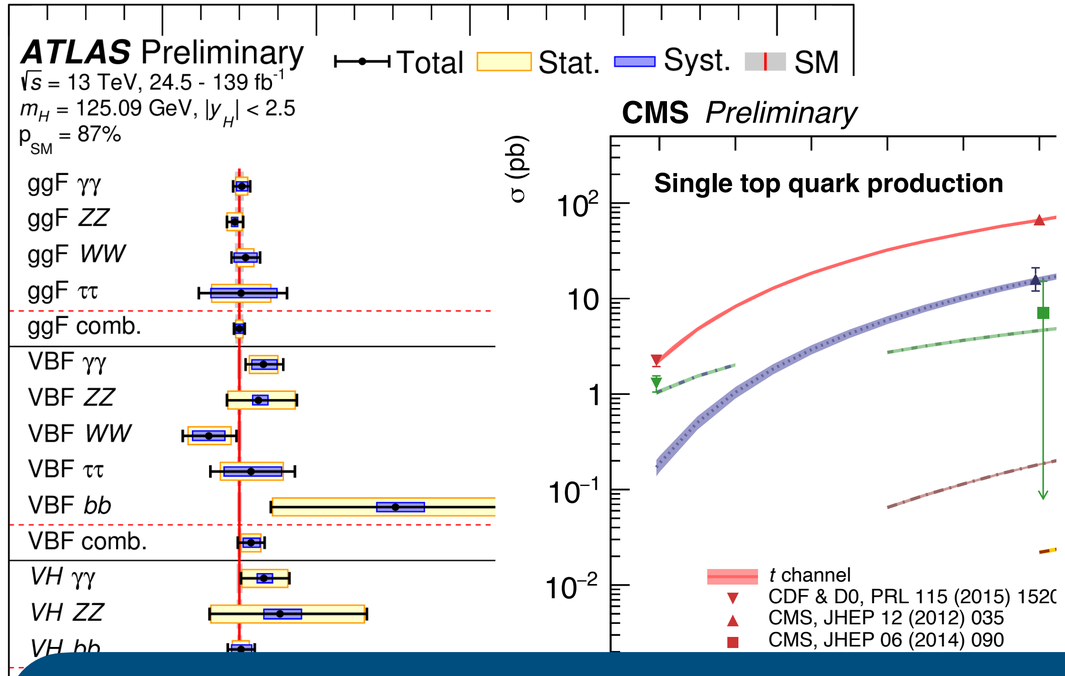
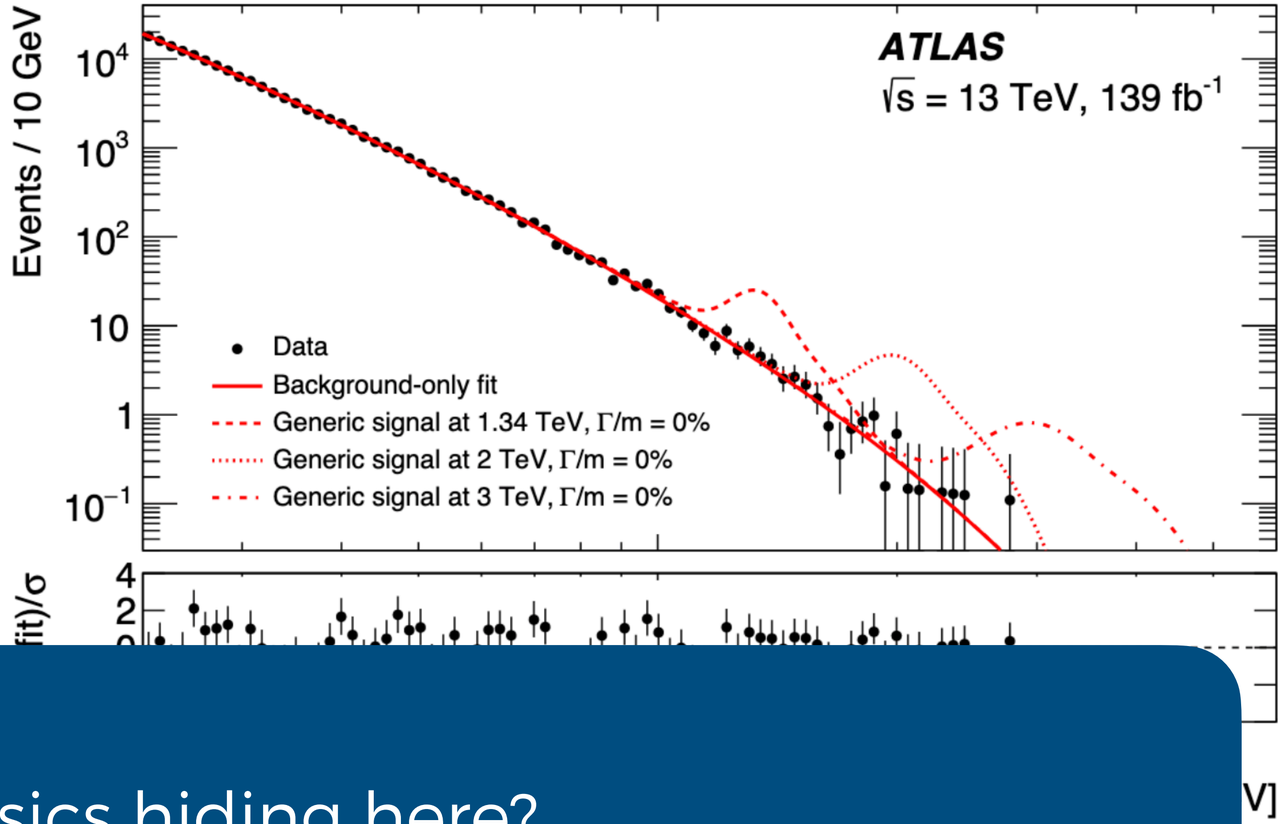




Is new physics hiding here?

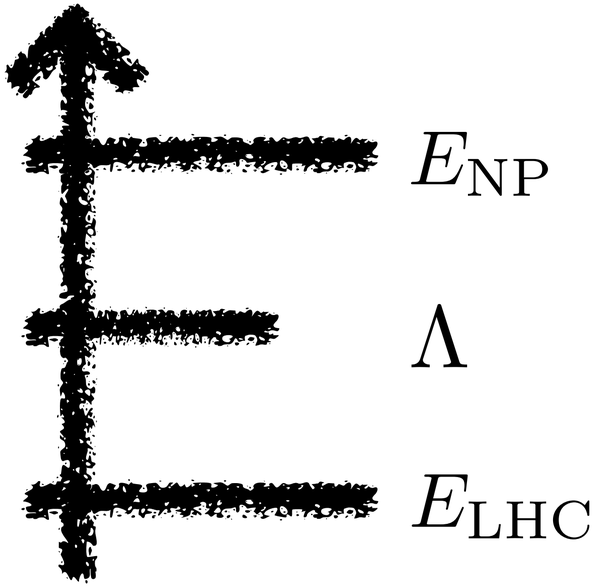
σ × B normalized to SM

[ATLAS-CONF-2020-027]

Effective field theory - EFT

EFT

Effective field theory - EFT

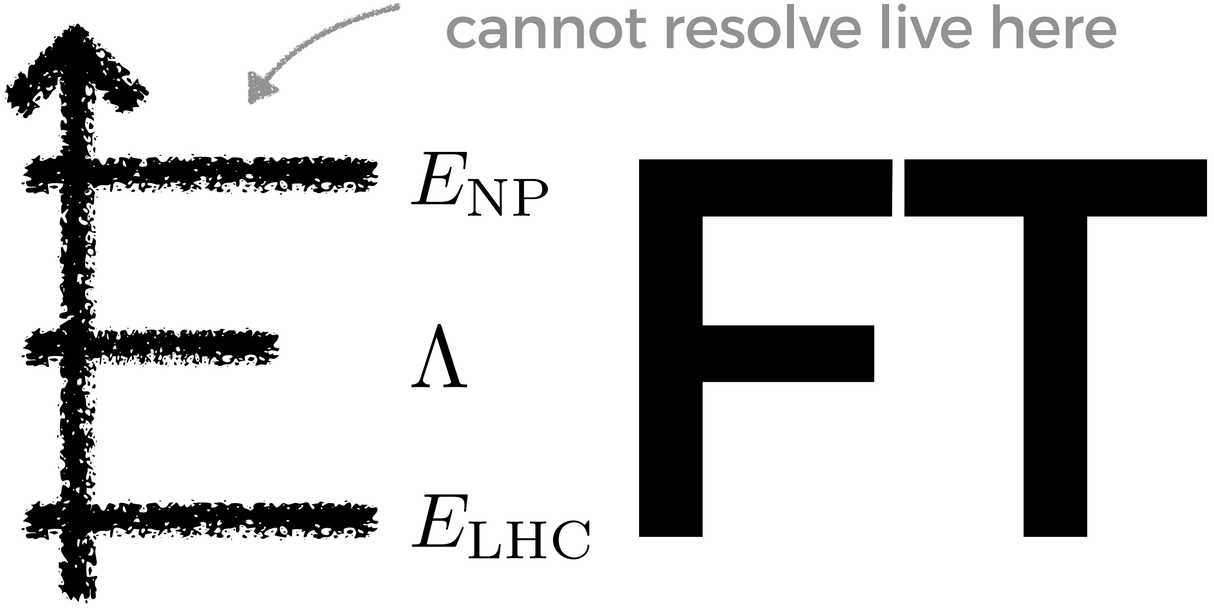


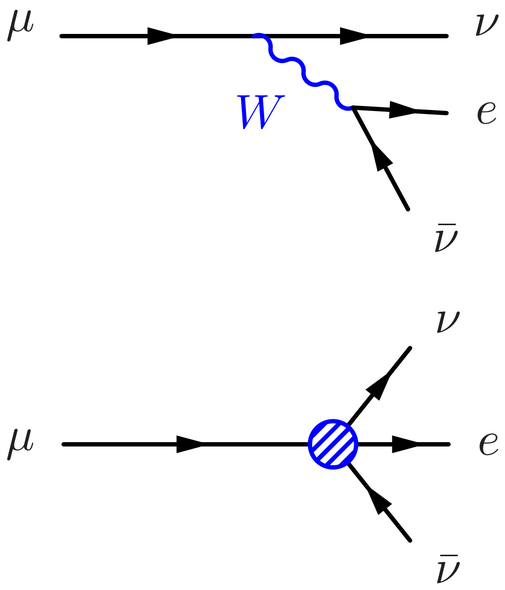
FT

Hierarchy of scales

Effective field theory - EFT

Heavy particles that we cannot resolve live here





Describe NP by higher-order interactions of SM fields

Hierarchy of scales

New kinematic structures

(in contrast to kappa framework)

SM effective field theory - SMEFT

[review: Brivio, Trott (1706.08945)]

- SMEFT: SM fields only, SM symmetries respected
- Higgs doublet structure (in contrast to HEFT)
- Different bases: **Warsaw**, HISZ, SILH, ...

[Grzadkowski et al. (1008.4884)]
[Hagiwara, Ishihara, Szalapski, Zeppenfeld]
[Giudice et al. (hep-ph/0703164)]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_x \frac{c_x}{\Lambda^2} \mathcal{O}_x^{(6)}$$

59 operators (MFV)

Not all of them contribute to Higgs/diboson/top physics

Fit c_x/Λ^2

Odd dimensions violate lepton or baryon number

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}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
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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}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
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Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

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Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
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Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

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

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Plus another 24 four-fermion operators

A 2D example:

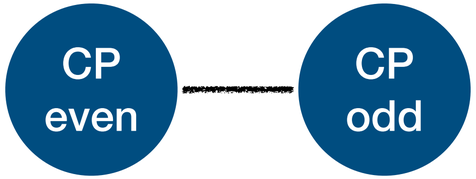
CP-odd triple gauge couplings

CP-odd dimension-6 operators

- Linear effect of CP-odd operators on the total cross section is very small

  (zero before kinematic cuts)

- Influence of CP-odd operators on CP-even+CP-odd fit often negligible [Ethier et al (2101.03180)]



- Need dedicated observables

- Only few fits of CP-odd SMEFT operators

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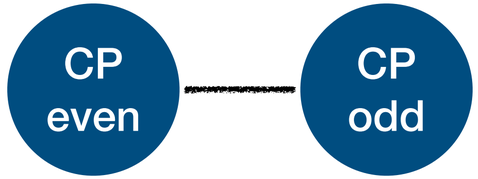


- Need dedicated observables

- Only few fits of CP-odd SMEFT operators
  - Higgs production and decay

    [Brehmer et al (1712.02350)]

    [Bernlochner et al (1808.06577)]

    [Englert et al (1901.05982)]

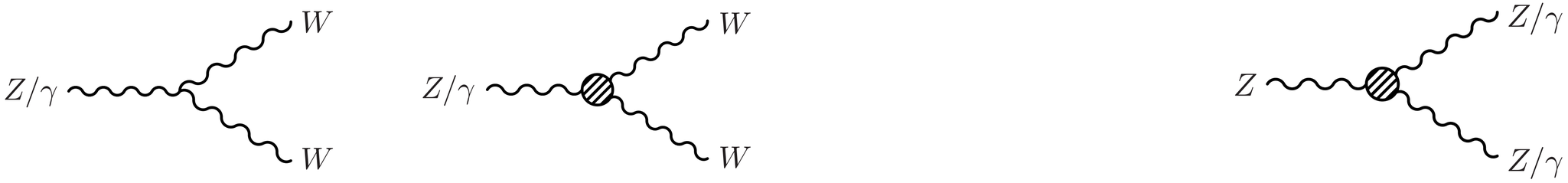
  - Low-energy experiments (EDMs + LEP+ $B \to X_s \gamma$)

    [Cirigliano et al (1903.03625)]

  - Diboson production

    [Bakshi et al (2009.13394)]
    [Ethier et al (2101.03180)] (distributions)

CP-odd triple gauge couplings



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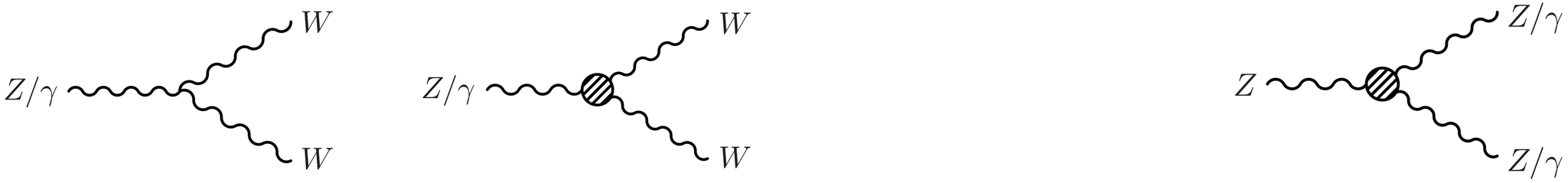

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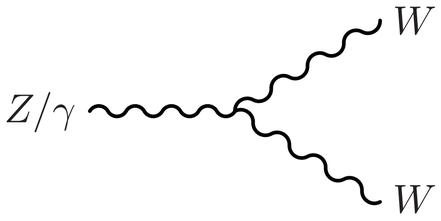

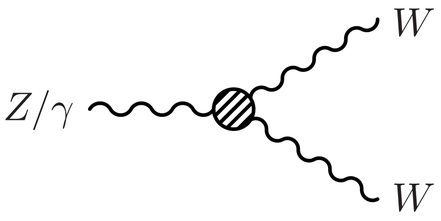

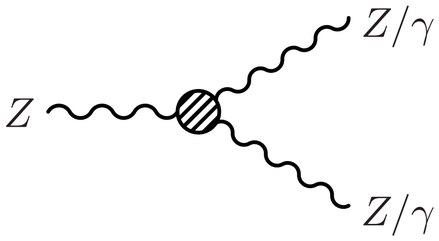

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Does not exist in the SM

First contribution appears at dim-8

Luckily only two dim-6 operators contribute

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_{\tilde{W}}}{\Lambda^2}\,\mathcal{O}_{\tilde{W}} + \frac{c_{H\tilde{W}B}}{\Lambda^2}\,\mathcal{O}_{H\tilde{W}B}$$

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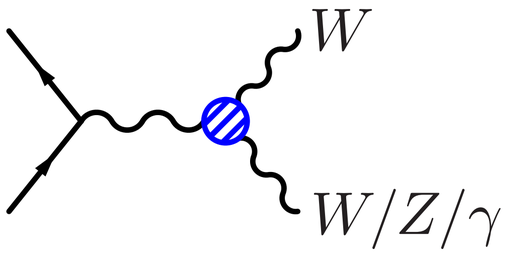
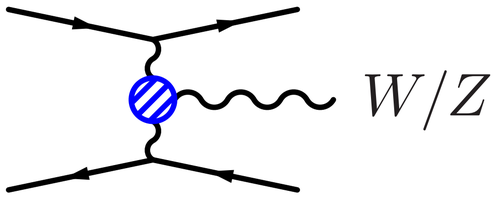
Triple gauge couplings

[AB, Gregg, Krauss, Schönherr (2102.01115)]





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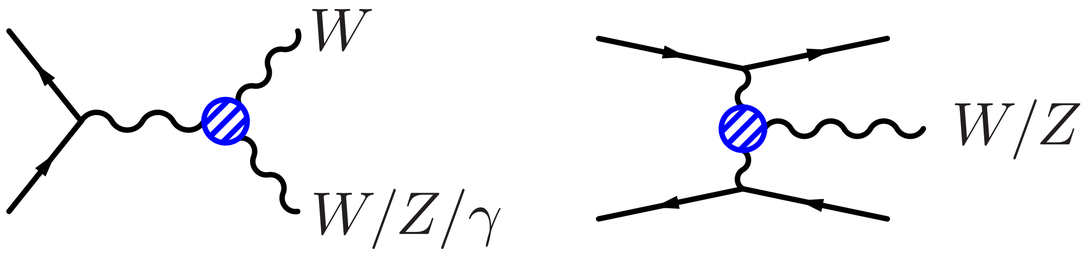

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Interactions involve epsilon tensor

Triple gauge couplings

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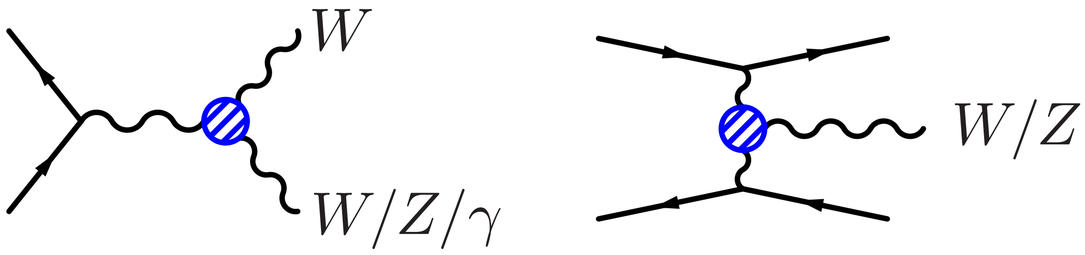

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Interactions involve epsilon tensor

→ triple products on the momenta

Triple gauge couplings

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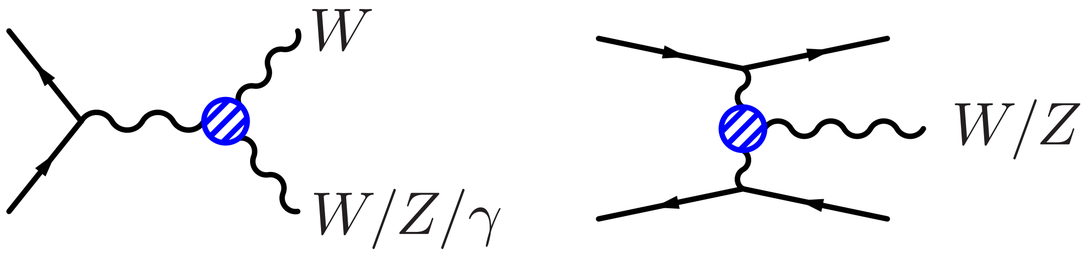

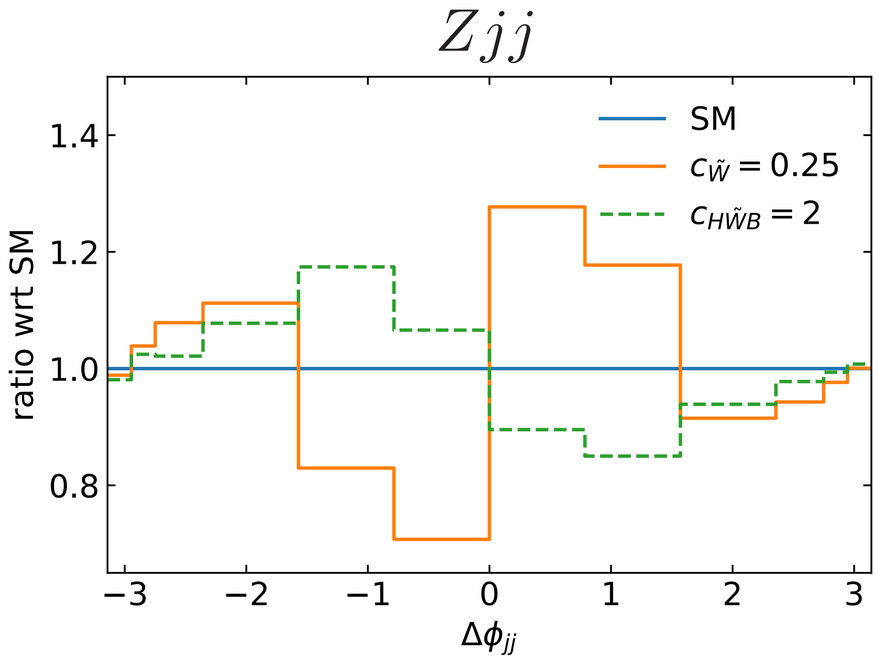

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Interactions involve epsilon tensor

→ triple products on the momenta

→ Modulation of $\Delta\phi$ distributions

$$\Delta\phi_{kl} \propto \sin^{-1}\left((\vec{p}_k - \vec{p}_l)_z\, (\vec{p}_k \times \vec{p}_l)_z\right)$$

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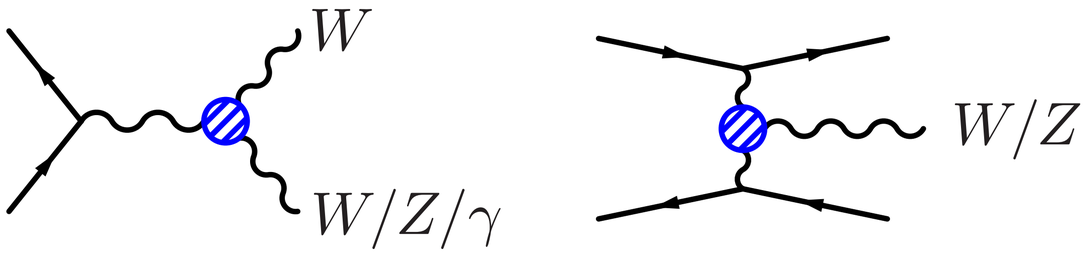

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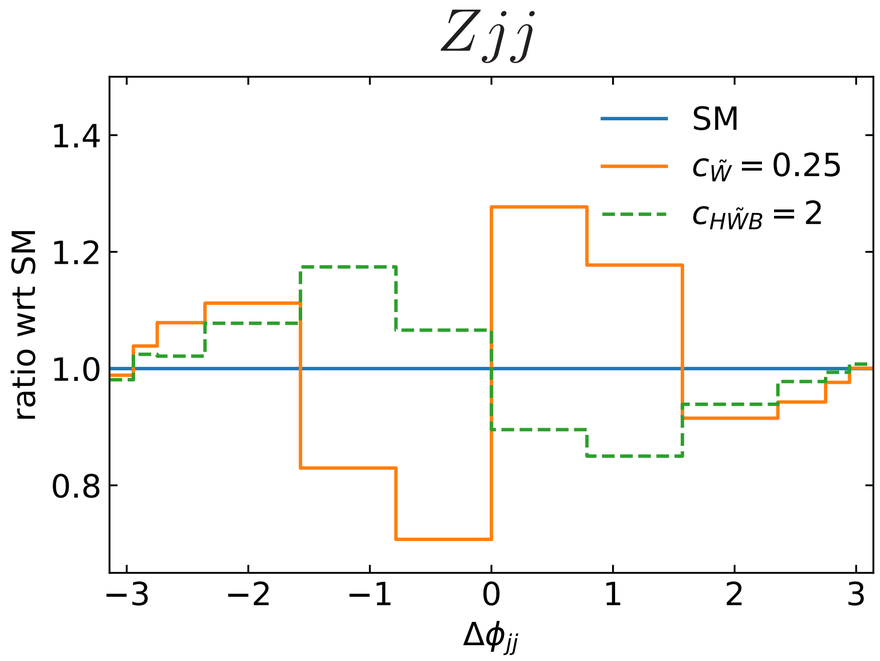
Interactions involve epsilon tensor

→ **triple products on the momenta**

→ **Modulation of $\Delta\phi$ distributions**

$$\Delta\phi_{kl} \propto \sin^{-1}\left((\vec{p}_k - \vec{p}_l)_z\, (\vec{p}_k \times \vec{p}_l)_z\right)$$



Observables: asymmetries

Systematic uncertainties cancel out

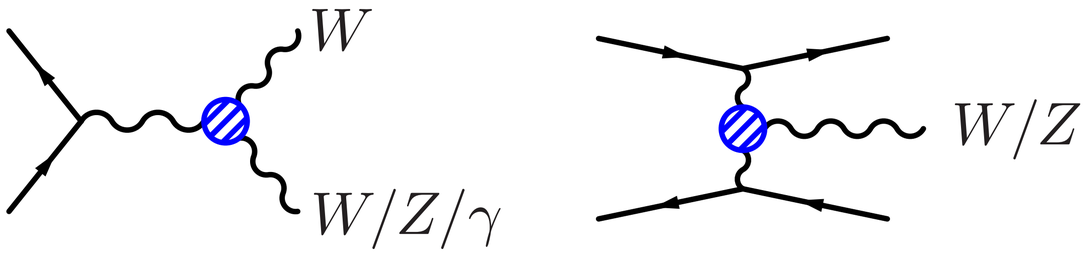
$$A_{ij} = \frac{N_{i,-j} - N_{i,+j}}{N_{i,-j} + N_{i,+j}}$$

$$i = WW,\, WZ,\, W\gamma,\, Zjj,\, Wjj$$

$$j = 1,\, \ldots,\, 6$$

Triple gauge couplings

[AB, Gregg, Krauss, Schönherr (2102.01115)]



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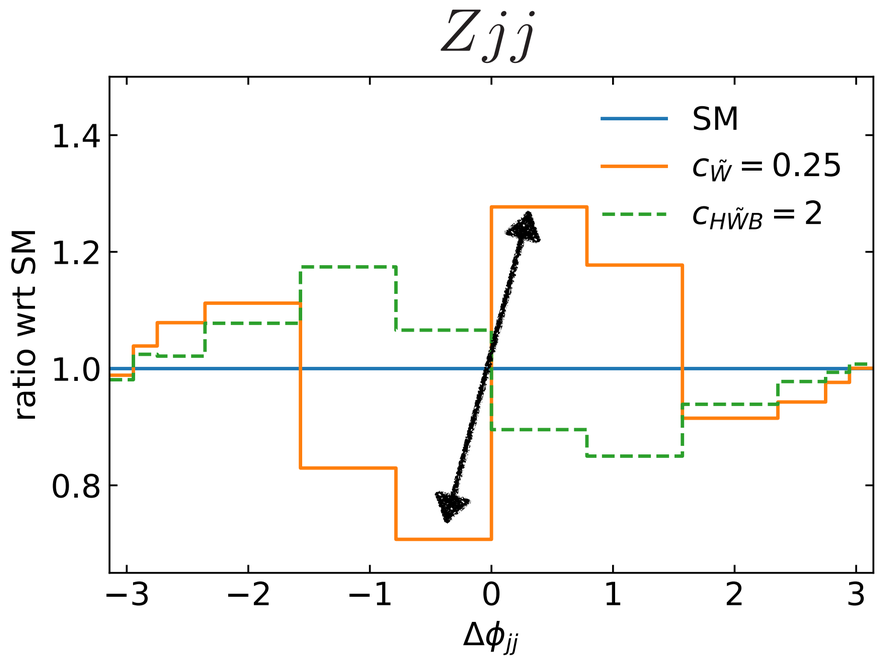

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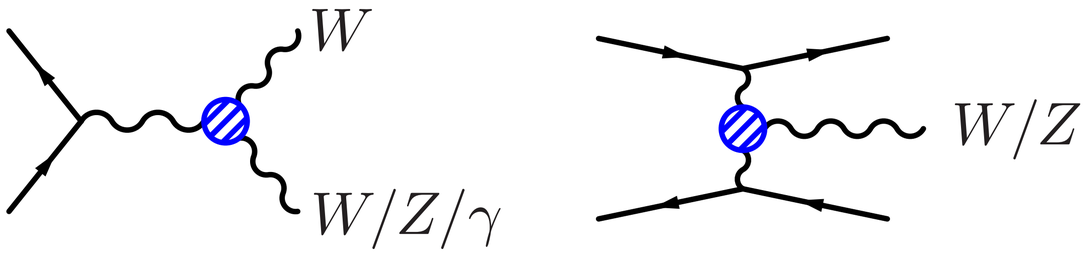

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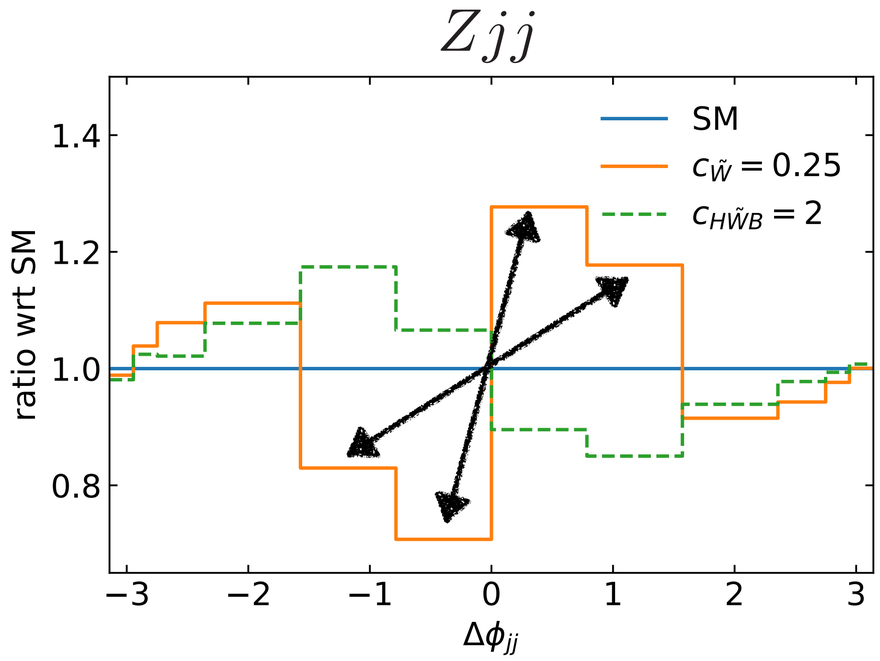

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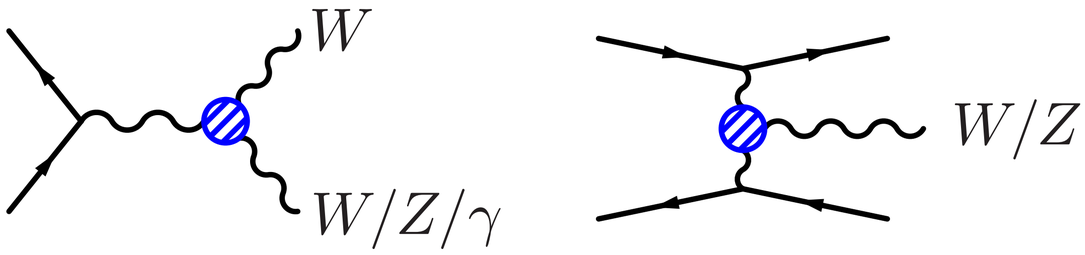

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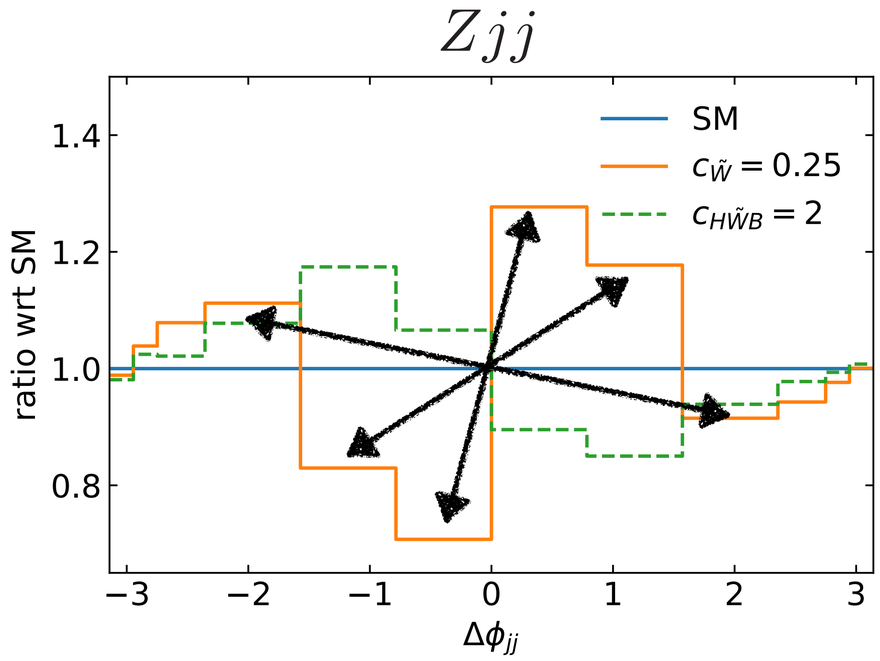

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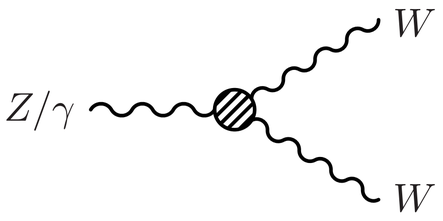
Triple gauge couplings - results



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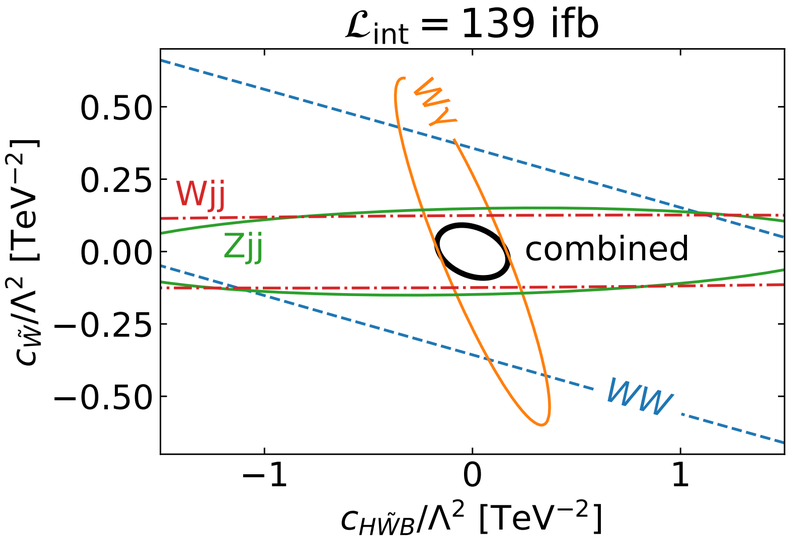

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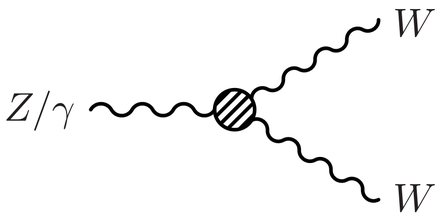

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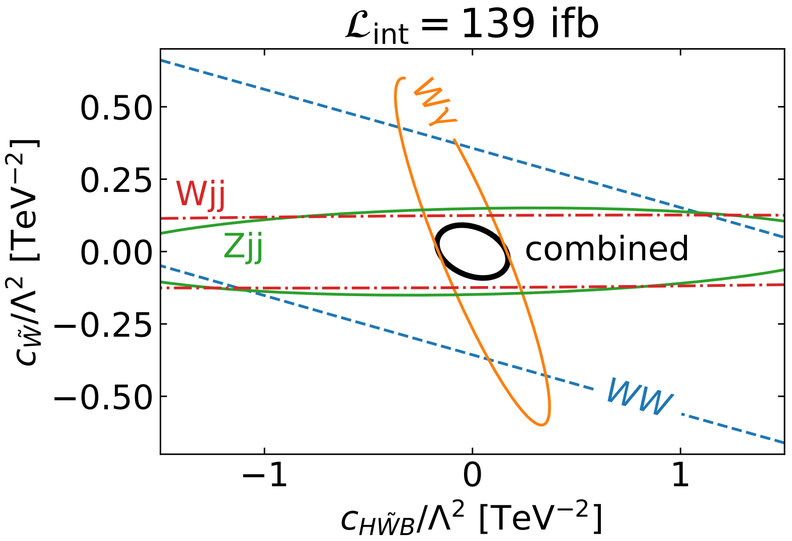

WZ limits too weak to appear on plots

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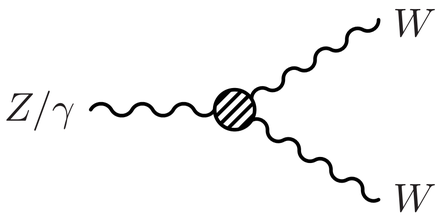

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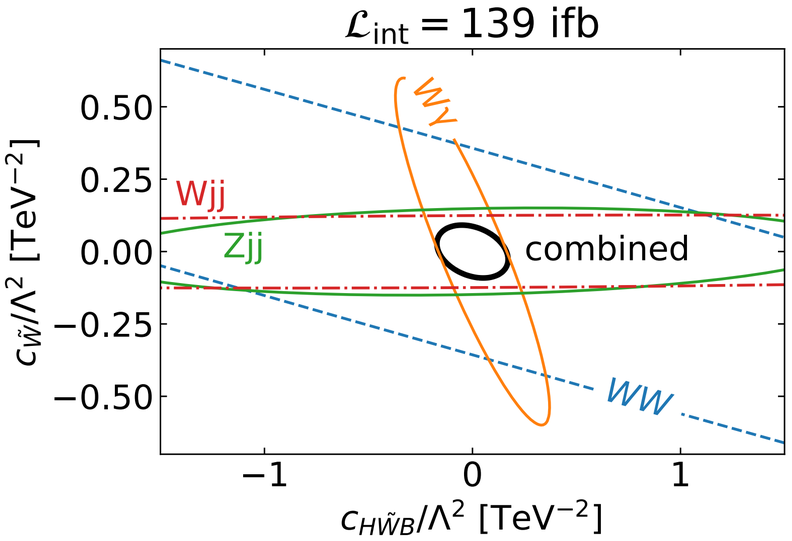

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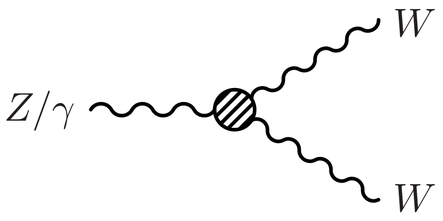

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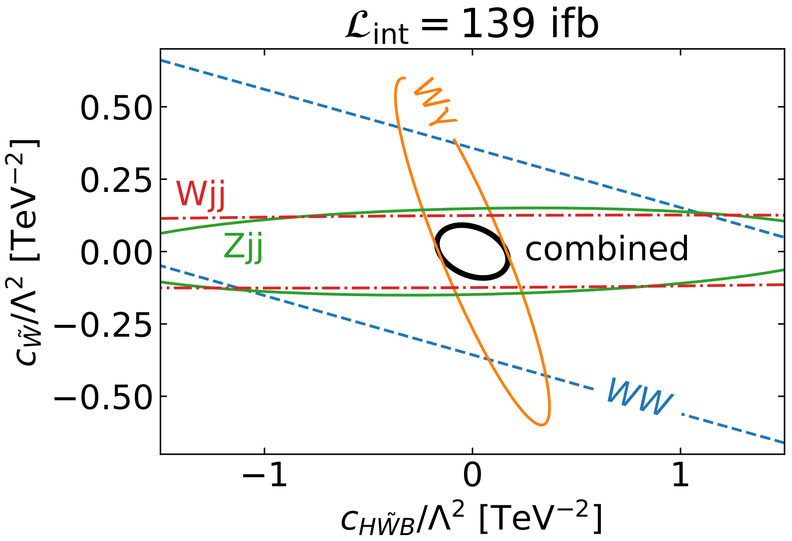

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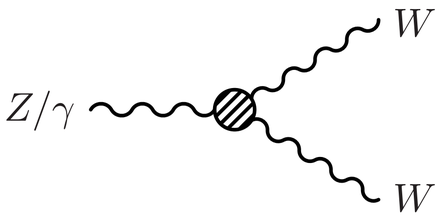

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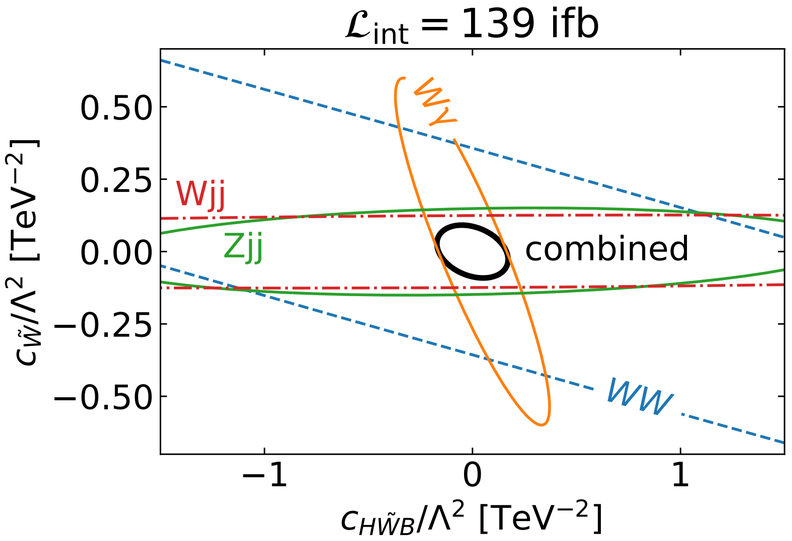

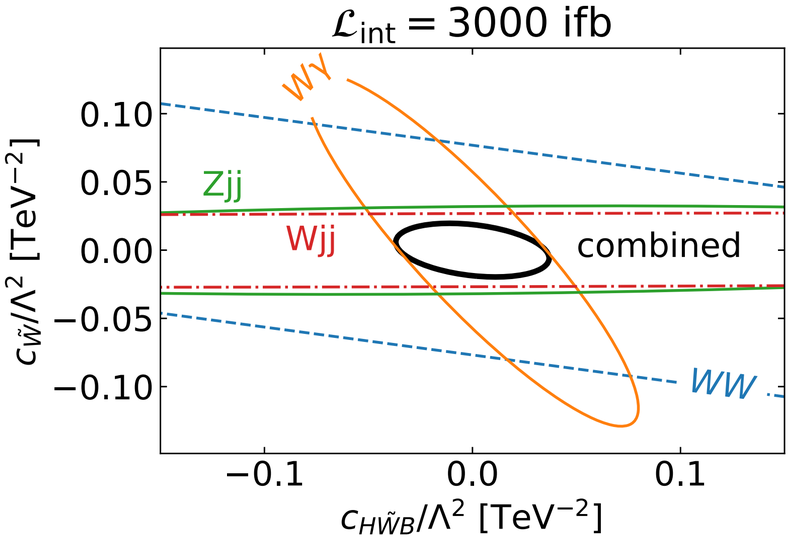

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Limits for 3 iab at $\mathcal{O}(10^{-2})$

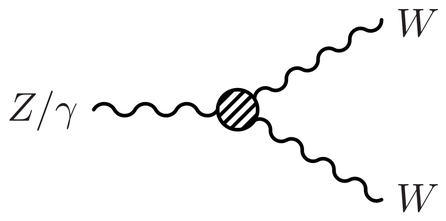
$$|c_{H\tilde{W}B}|/\Lambda^2 < 3.1\ \text{TeV}^{-2}\ \text{Higgs WBF}+\gamma$$

$$|c_{H\tilde{W}B}|/\Lambda^2 < 1.5\ \text{TeV}^{-2}\ \text{Higgs production}$$

[AB et al (2003.06379)]

[Bernlochner et al (1808.06577)]

Triple gauge couplings - results



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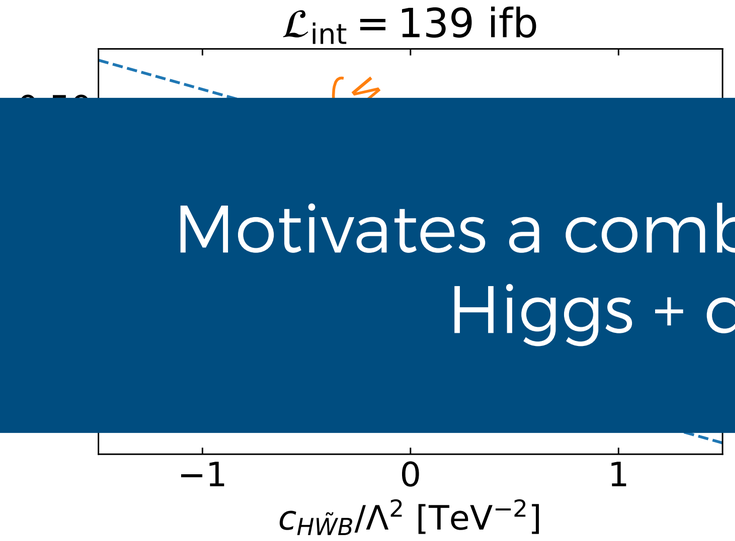

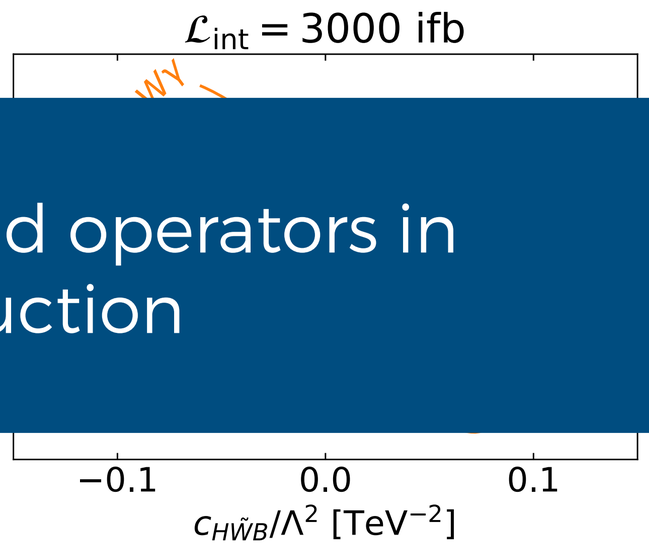

Motivates a combined fit of CP-odd operators in Higgs + diboson + X production

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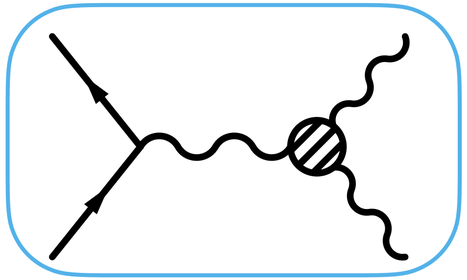
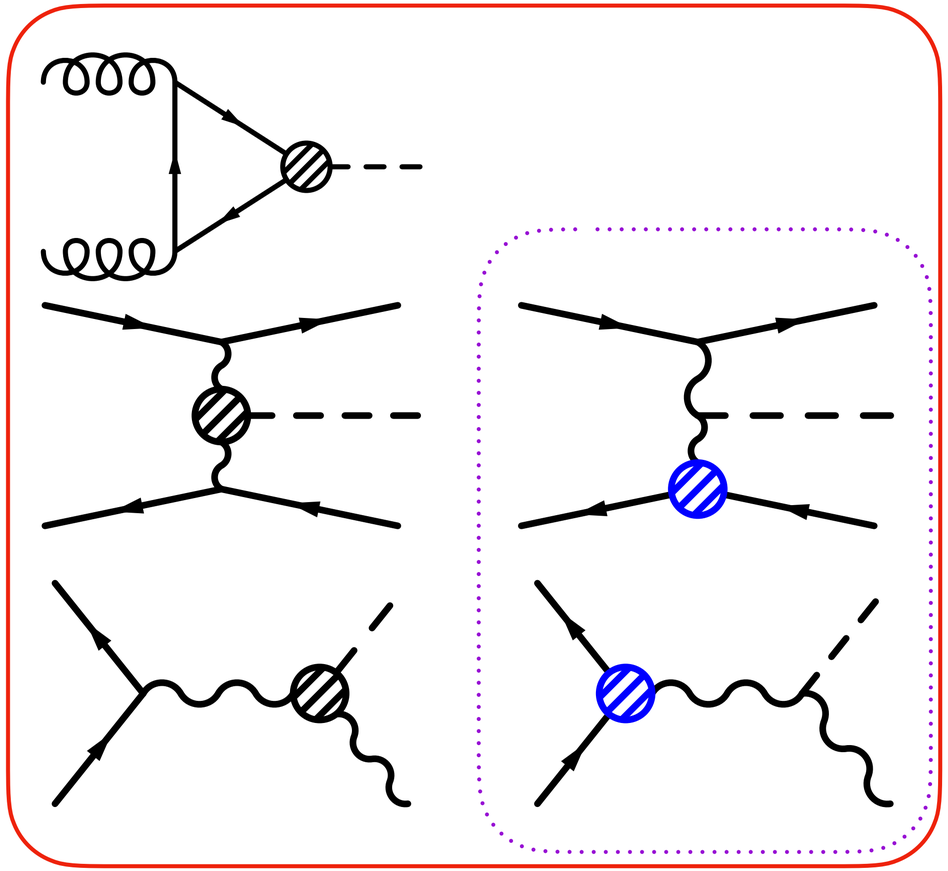
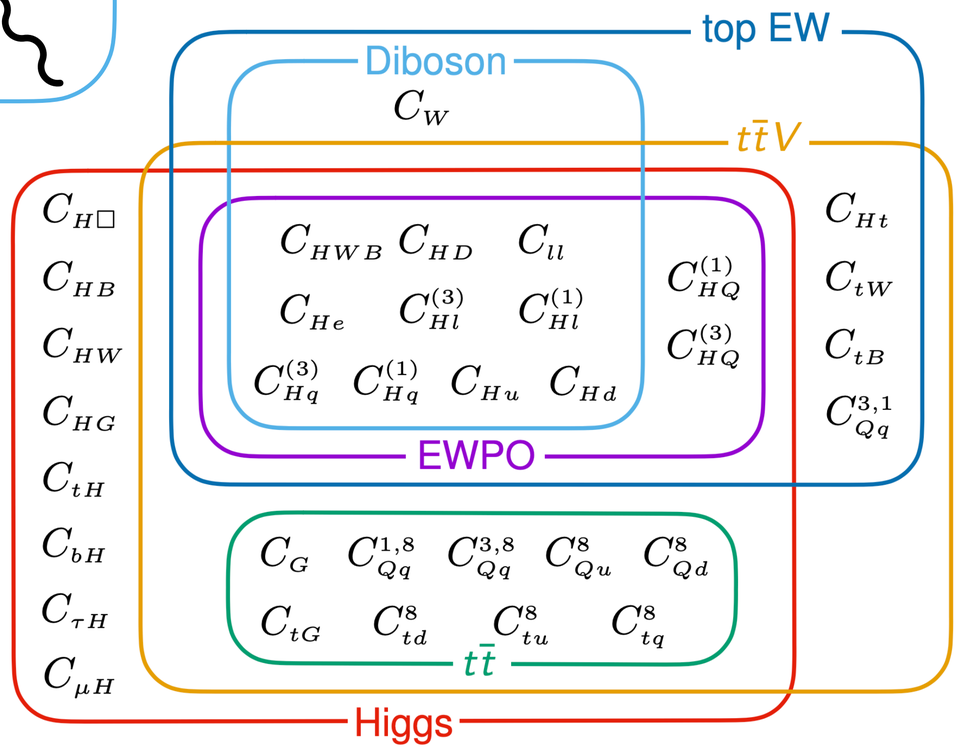
CP-even interactions

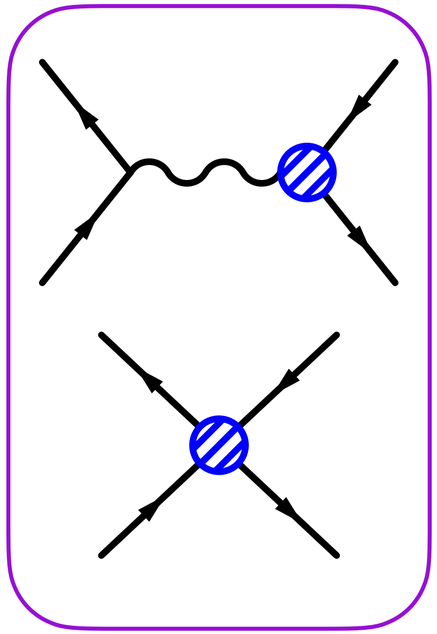
CP even fit (of the Higgs-gauge sector)







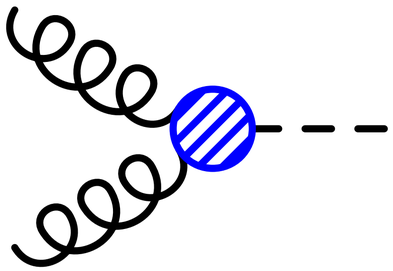
[Ellis, Madigan, Mimasu, Sanz, You (2012.02779)]



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

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

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 $\mathcal{O}_{HG}$

Affects total cross section only

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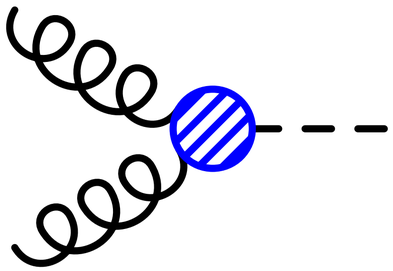

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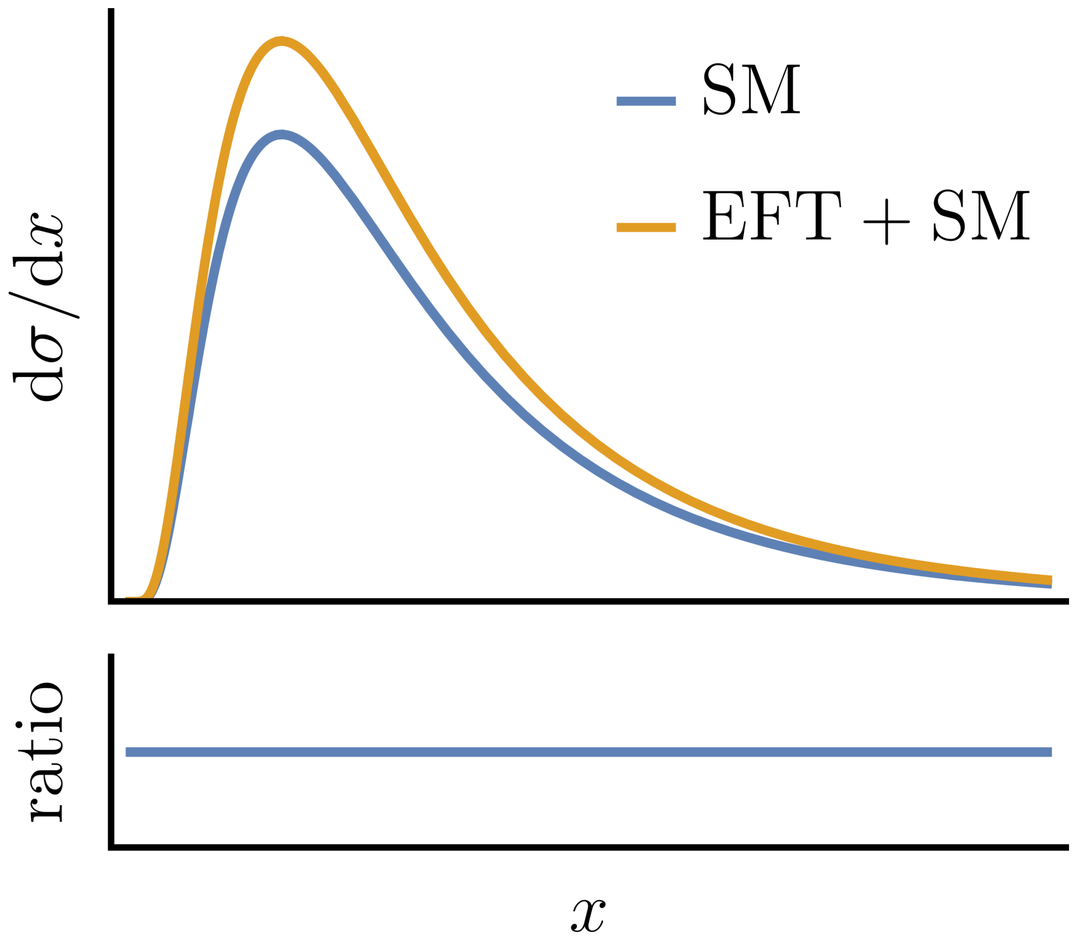

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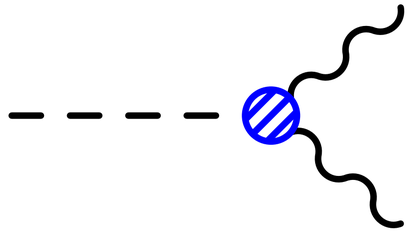
Feynman rules



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

EFT: $g_{hZZ}^{\rm EFT}\left[p_{Z_1}^\mu p_{Z_2}^\nu - \eta^{\mu\nu}\, p_{Z_1}\cdot p_{Z_2}\right]$

EFT contribution has additional momentum dependence

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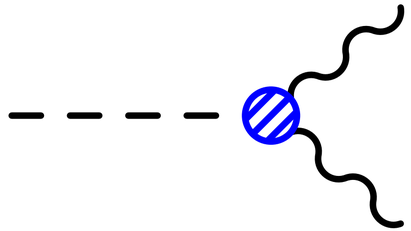

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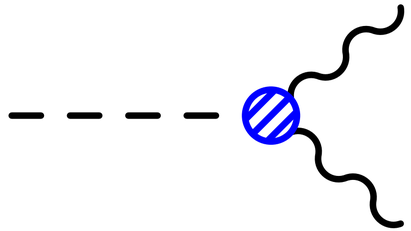

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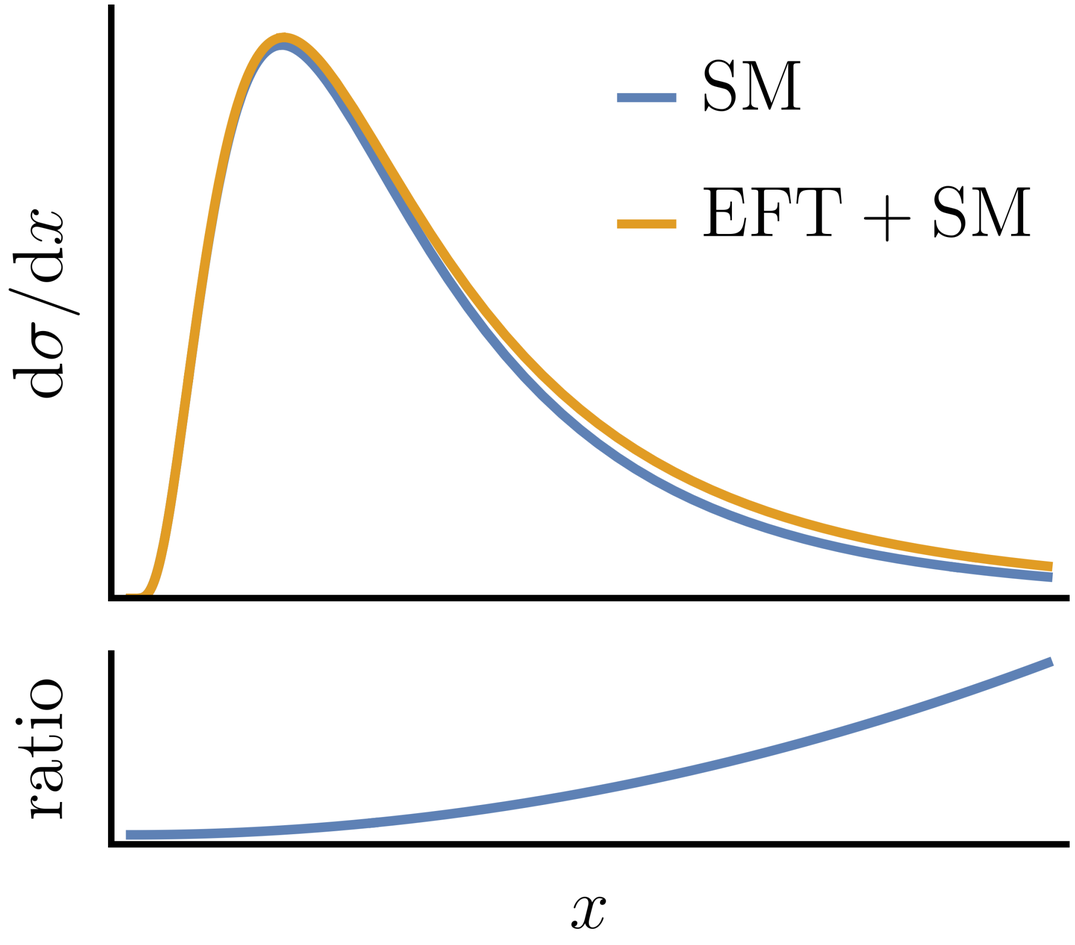
EFT contribution has additional momentum dependence

Affects distributions



e.g. m_{Zh} in HZ production

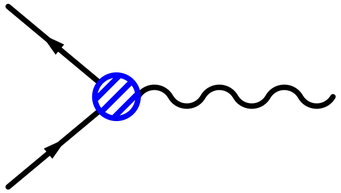
The operator $\mathcal{O}_{Hu}$

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

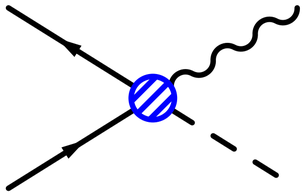
Feynman rules

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

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



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



New contact interaction

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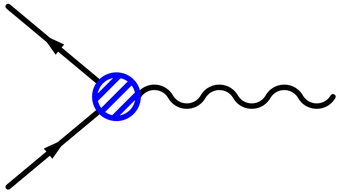
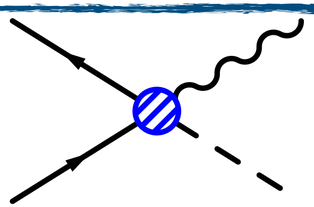
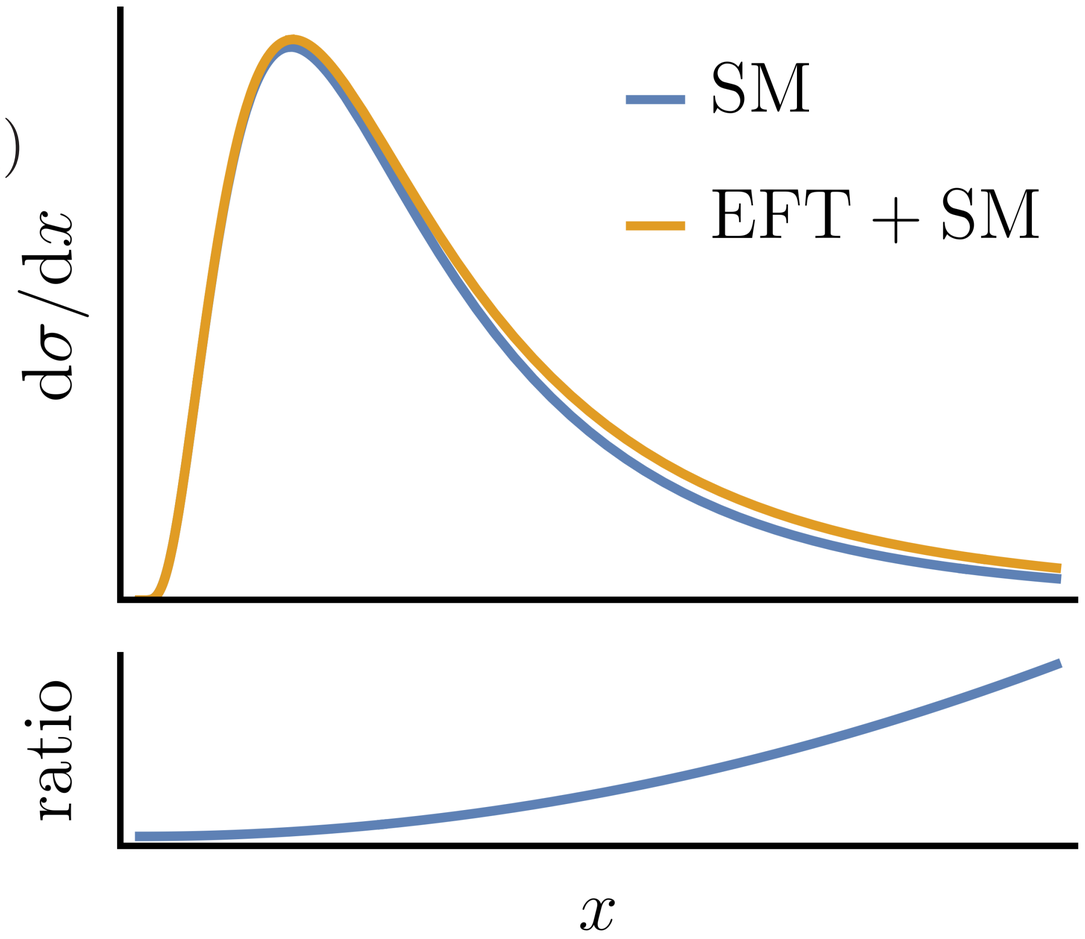


EFT Zhuu: $g_{Zuu}^{\rm EFT}/v\,\gamma^\mu\,P_R$

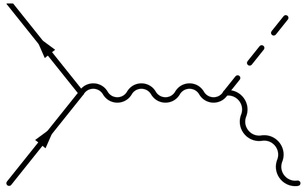


New contact interaction

Affects distributions



SM: propagator suppression

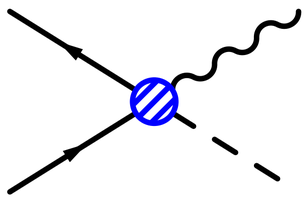


Dimension-six operators - effects

- 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

Validity?

Input data

- Electroweak precision observables
- Single Higgs data
  - Signal strength
  - Simplified template cross sections

    (Differential information)
- Diboson distributions
- Dihiggs signal strength

[ATLAS-CONF-2020-053]

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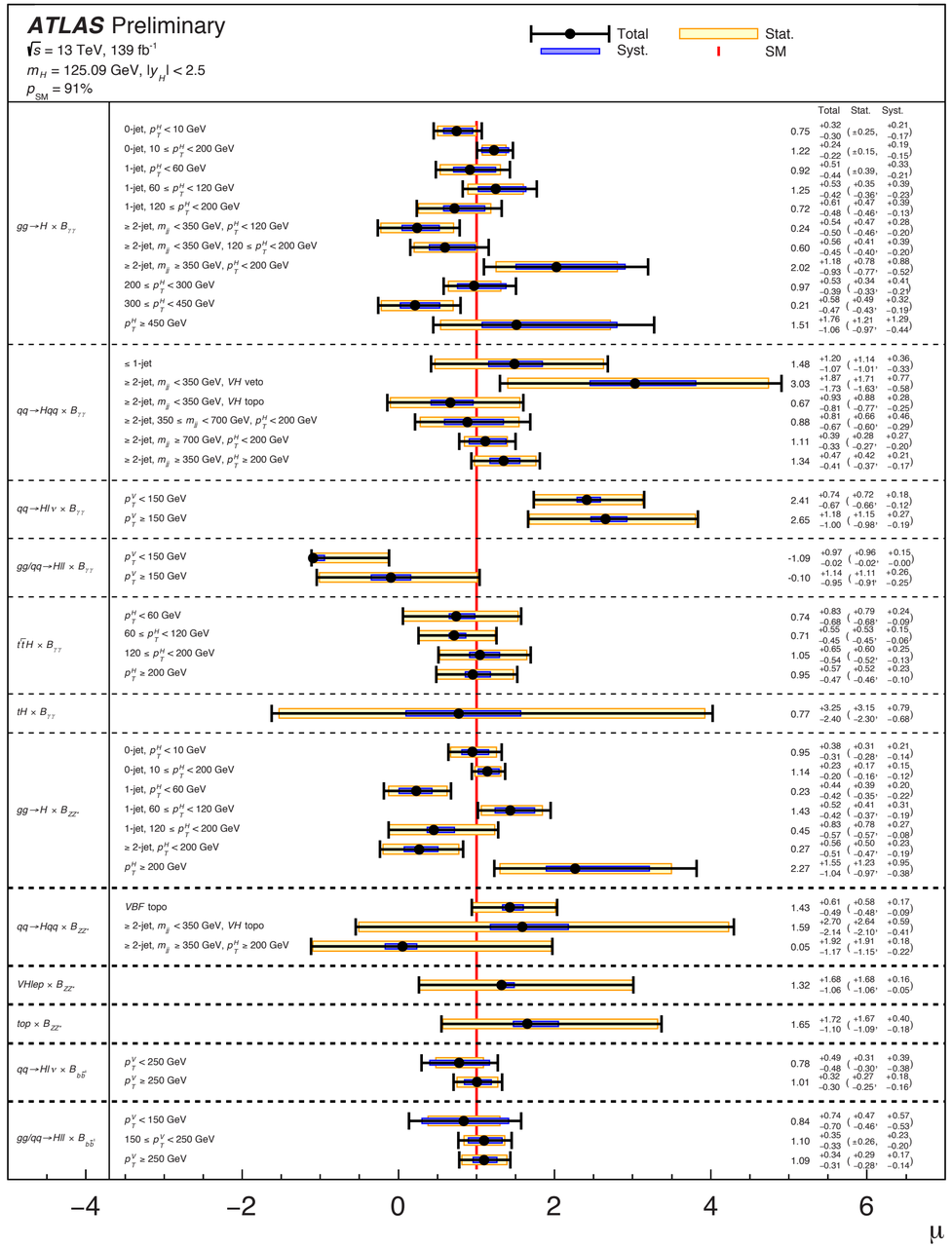

[CERN-EP-2018-327]

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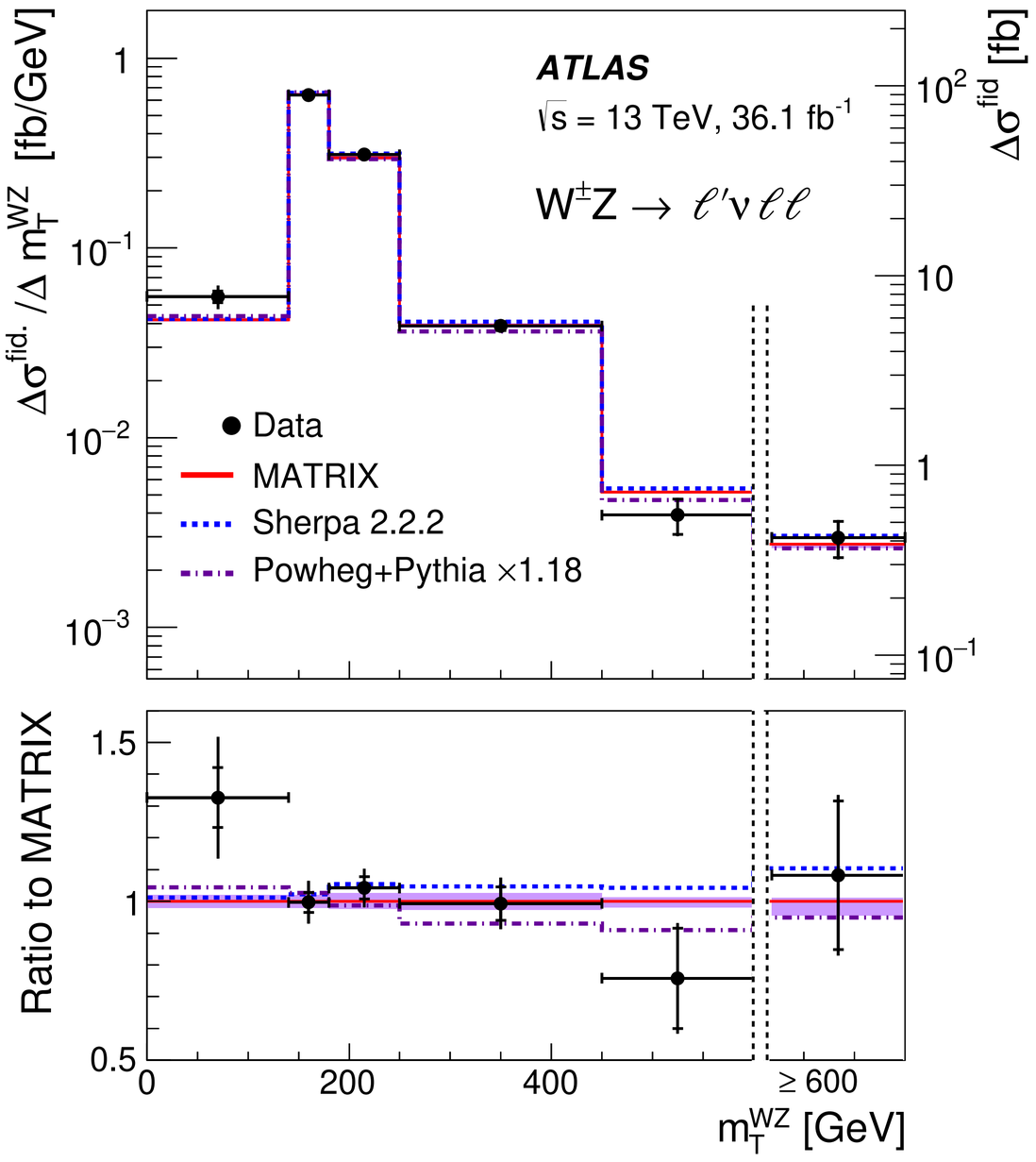

Dihiggs

- Constrains $\mathcal{O}_H = (H^\dagger H)^3$ which appear in many scalar extensions
- gg->HH at NLO in Powheg [Heinrich, Jones, Kerner, Scyboz (2006.16877)]
- Considered channels from ATLAS and CMS

$$HH \to b\bar{b}b\bar{b}$$
$$HH \to b\bar{b}\gamma\gamma$$
$$HH \to b\bar{b}\tau\tau$$

[AB, Corbett, Plehn (1812.07587)]

LHC Run II fit - without fermion-gauge operators

[HISZ basis]

$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu}$$
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Only operators involving the Higgs or TGCs

[SFitter Run I: Butter et al. (1604.03105)]

[Ellis, (Madigan), (Mimasu), (Murphy), Sanz, You (1803.03252, 2012.02779)],
[da Silva Almeida, Alves, (Rosa Agostinho), Éboli, Gonzalez-Garcia (1812.01009, 2108.04828)]

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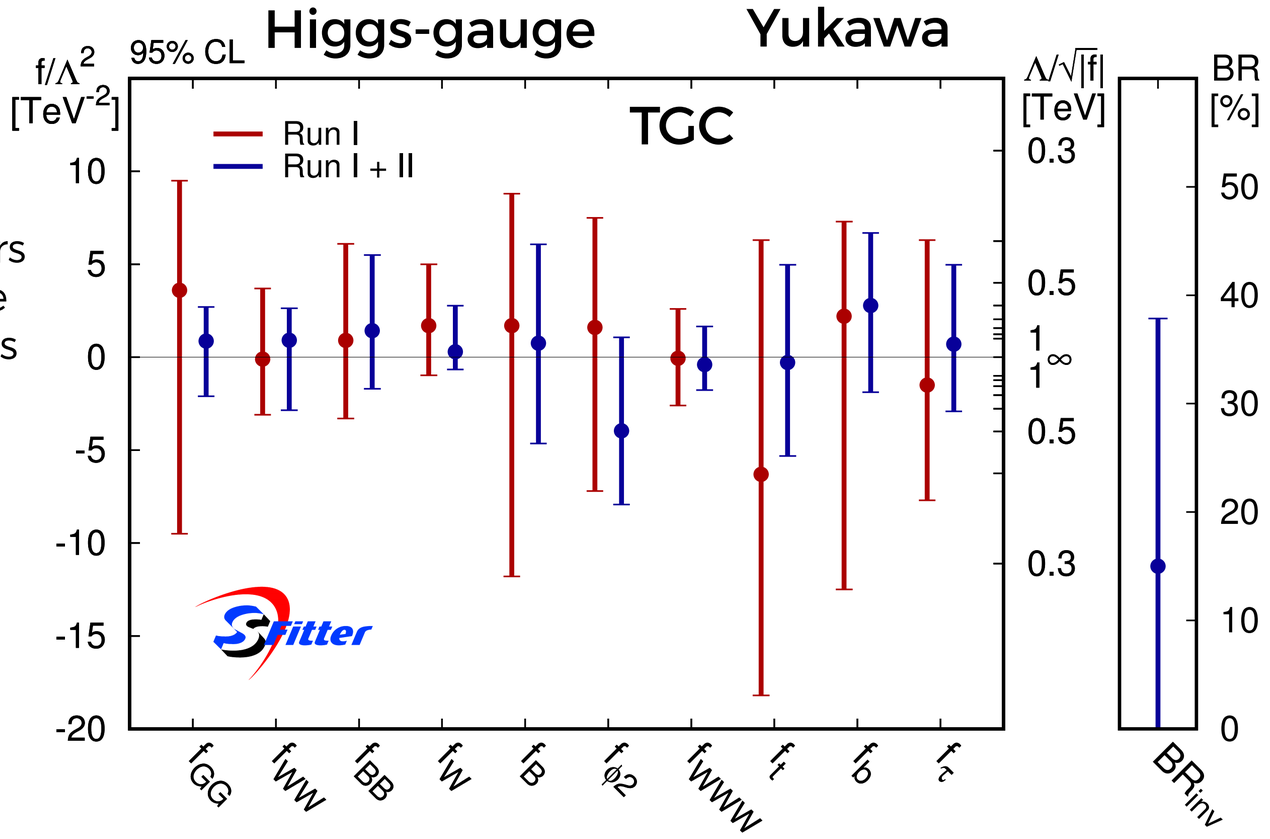

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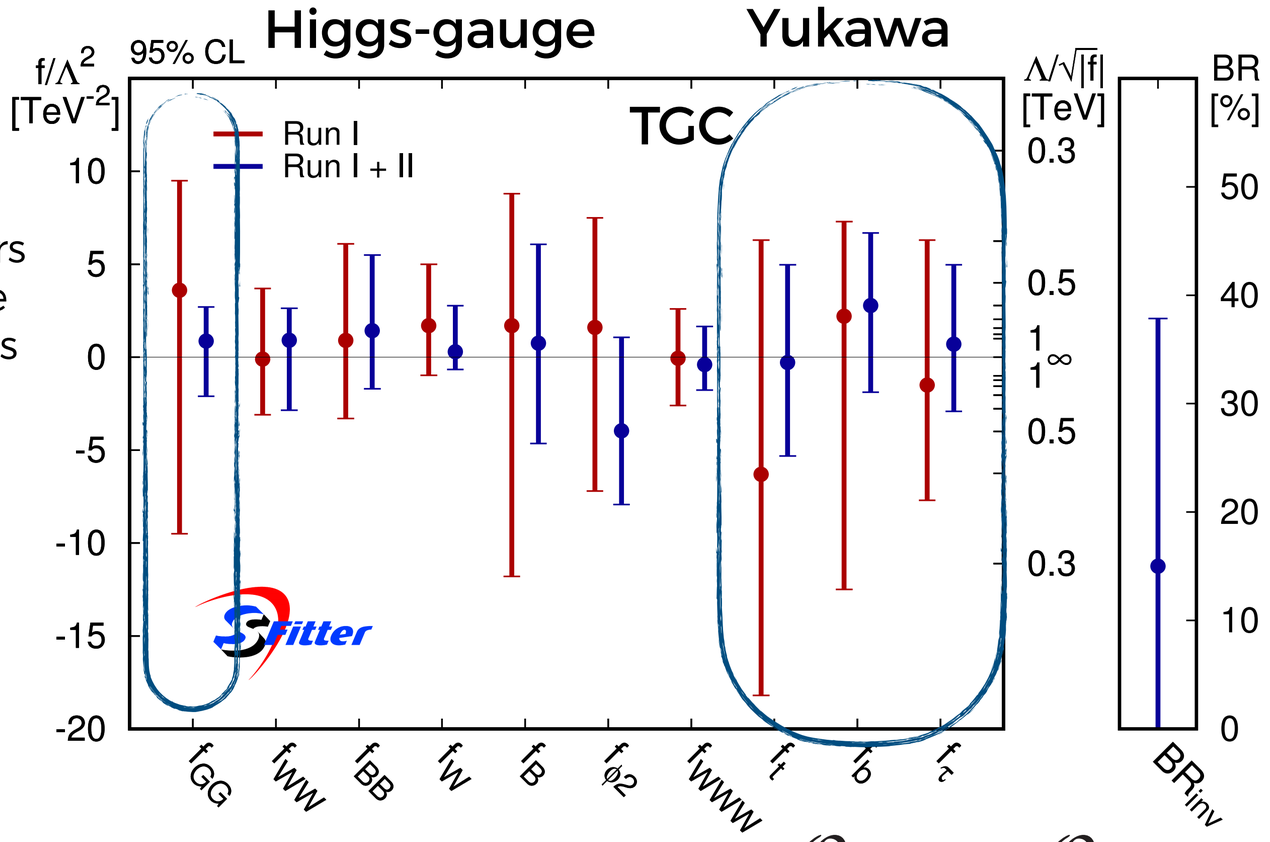

tth measurements disentangle $\mathcal{O}_{GG}$ and $\mathcal{O}_t$

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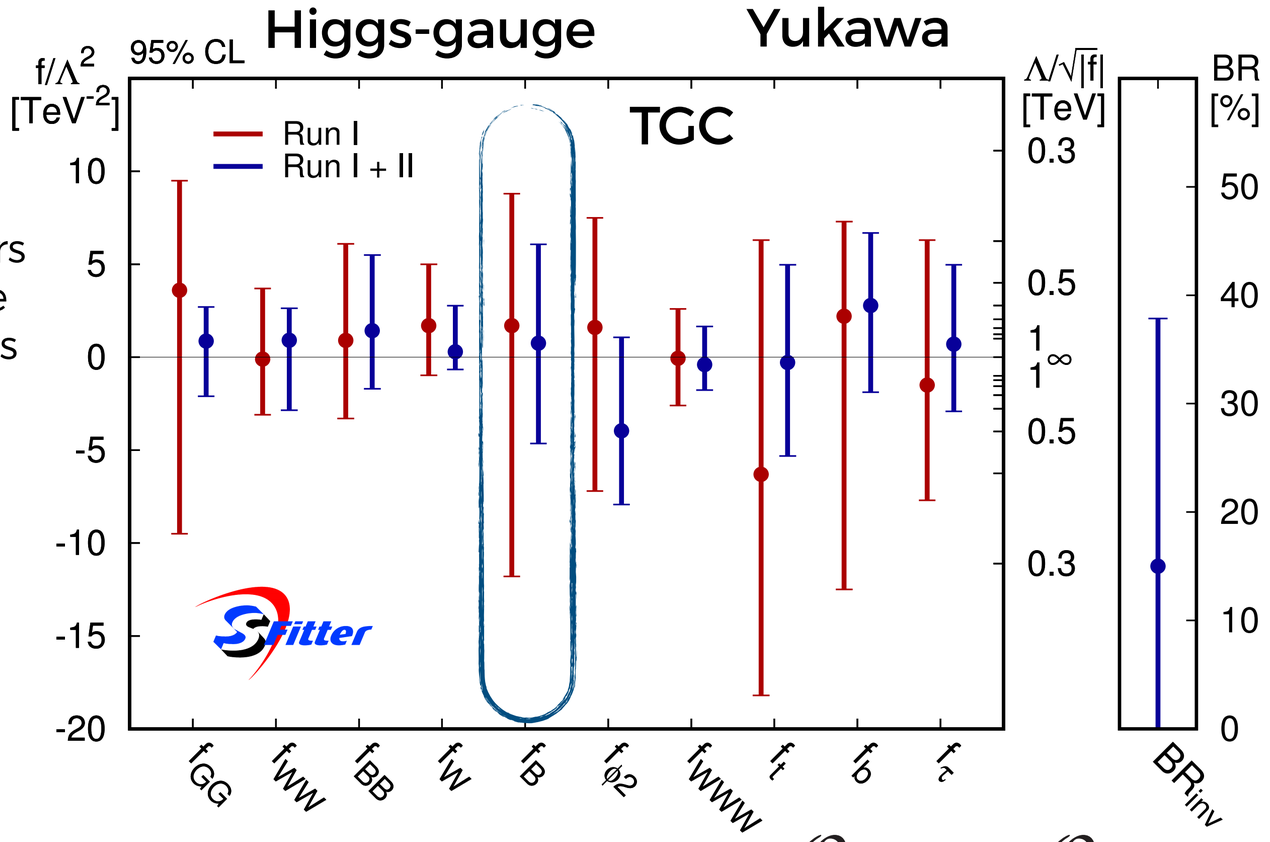

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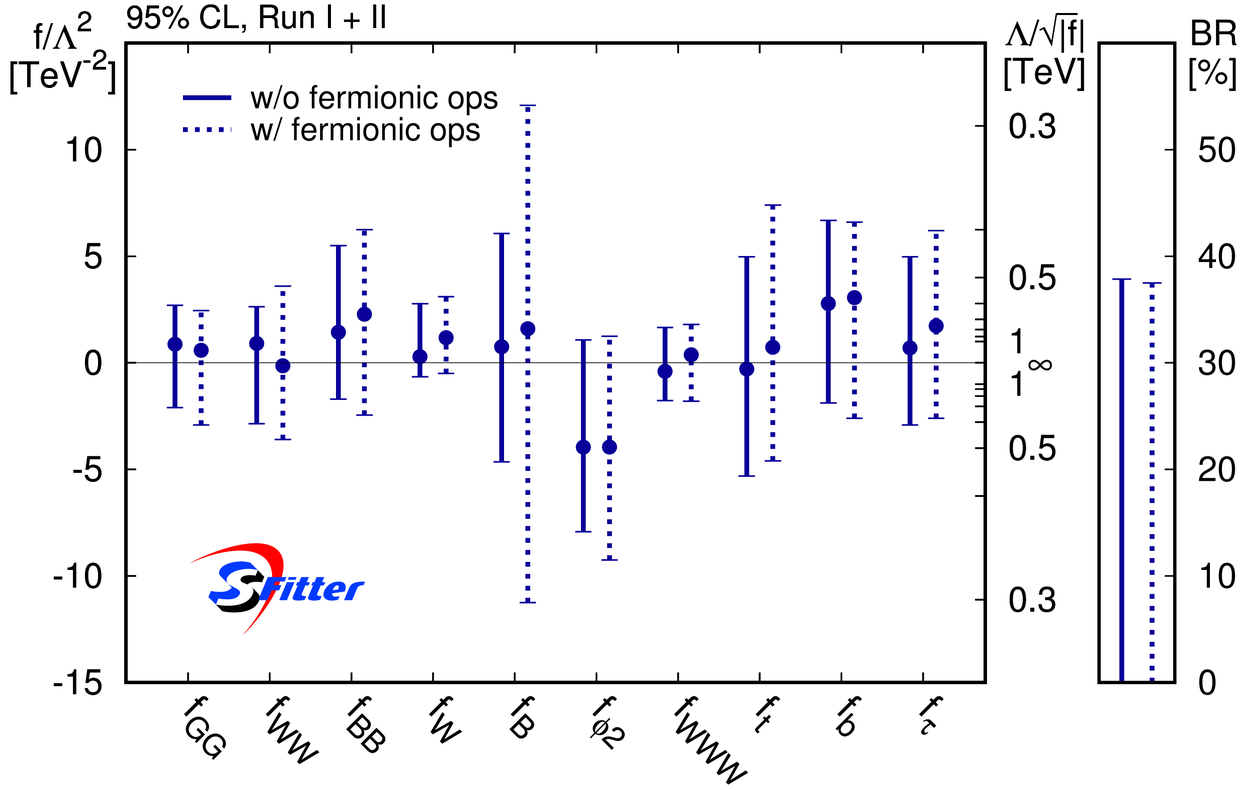
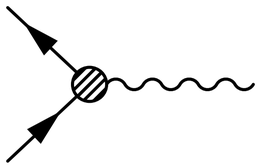
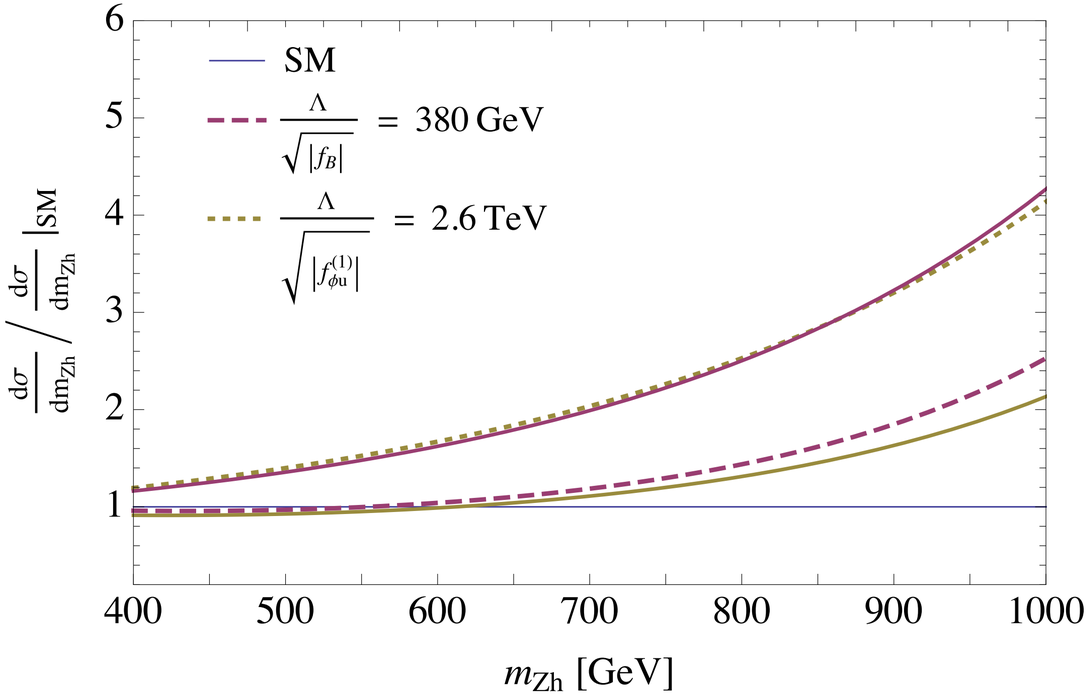


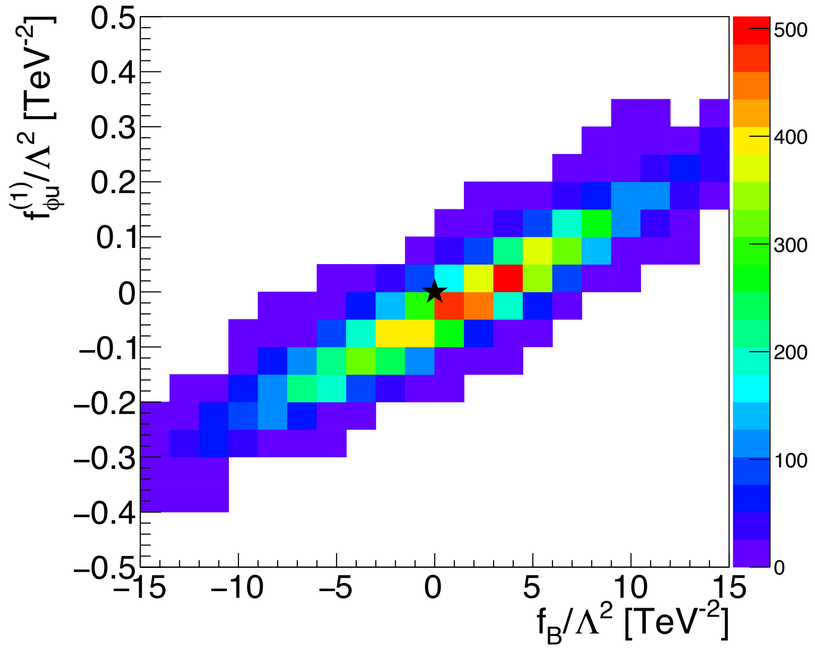
Adding more freedom



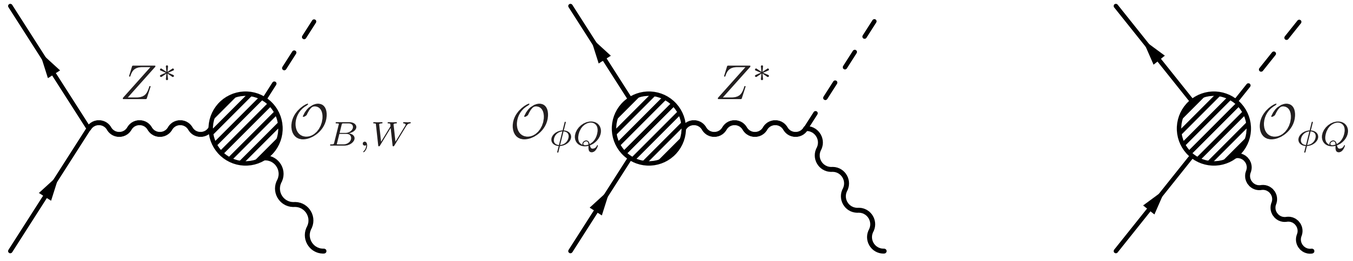
$$\mathcal{O}_{\phi 1} = (D_\mu\phi)^\dagger\ \phi\phi^\dagger\ (D^\mu\phi) \qquad \mathcal{O}_{BW} = \phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\phi$$
$$\mathcal{O}^{(1)}_{\phi Q} = \phi^\dagger(i\overleftrightarrow{D}_\mu\phi)(\bar{Q}\gamma^\mu Q) \qquad \mathcal{O}^{(3)}_{\phi Q} = \phi^\dagger(i\overleftrightarrow{D}^a{}_\mu\phi)(\bar{Q}\gamma^\mu\sigma^a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

LHC Run II fit - correlations





Contributions to Zh production



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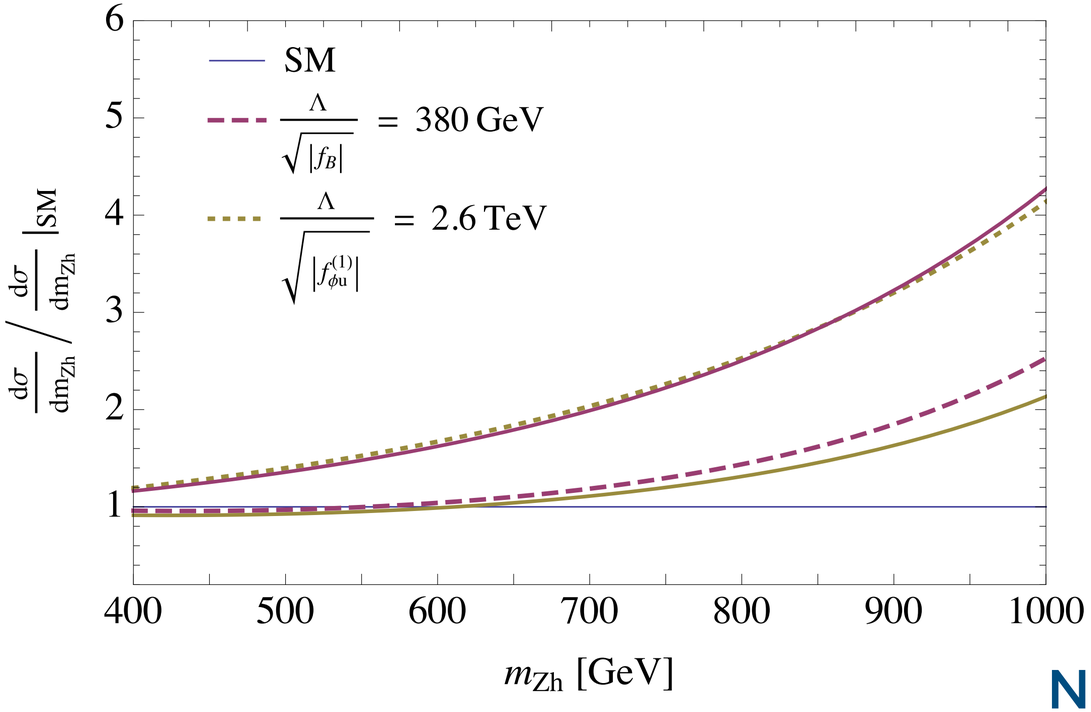

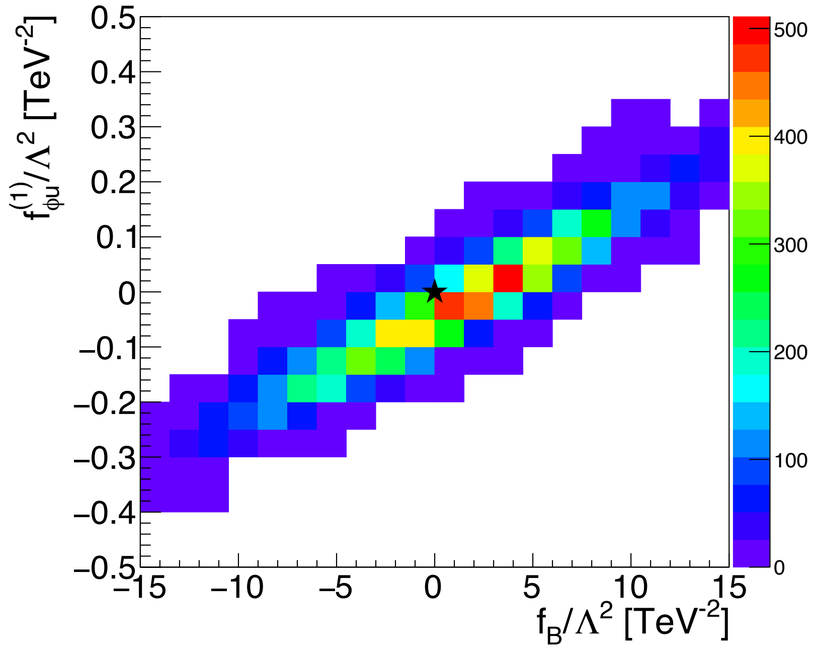

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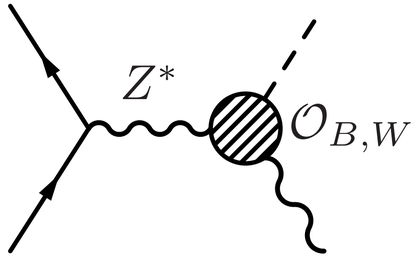
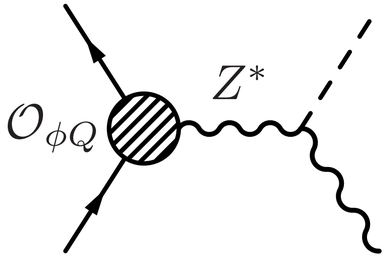
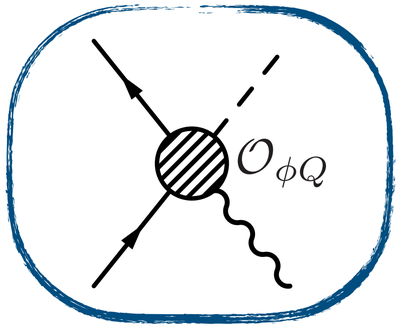




No propagator suppression



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SMEFT fits - a global effort!

	Eboli, Gonzalez-Garcia et al	Fitmaker	SFitter	HEPfit	SMEFit	Dawson et al.	Chakrabortty et al.
Linear/quadratic	Both	Linear	Both (Higgs quadratic)	Linear	Both	Linear	Linear
Basis	HISZ	Warsaw	HISZ (Higgs) Warsaw (top)	Warsaw	Warsaw	Warsaw	Warsaw
NLO QCD included	LO	Top only	Top only	LO	Top only	Vh, diboson, EWPO	EWPO only
Fitting procedure	χ^2	Bayesian	Toy MC, χ^2	Bayesian	Toy MC	χ^2	Bayesian
Uncertainties	Gaussian, correlated theory uncertainties	All Gauss	Gauss, Poisson, flat	(Asymmetric) Gauss, flat	All Gauss	All Gauss, uncorrelated	All Gauss
UV complete model fits	✘	✔	In preparation	✔	✘	✔	✔
EW scheme	Alpha	Alpha	Alpha	Alpha	mW	mW	Alpha
References	1211.4580, 1509.01585, 1805.11108, 1812.01009, 2108.04828	1404.3667, 1803.03252, 2012.02779	1505.05516, 1604.03105, 1812.07587	1710.05402, 1910.14012	1901.05965, 1906.05296, 2101.03180, 2105.00006	2007.01296	2009.13394, 2010.04088, 2012.03839

Filled to my best knowledge - apologies for any mistakes

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UV complete model fits	✘	✔	In preparation	✔	✘	✔	✔
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DY + diboson

Higgs + diboson + top

Distributions

Projections

VBS

CP odd

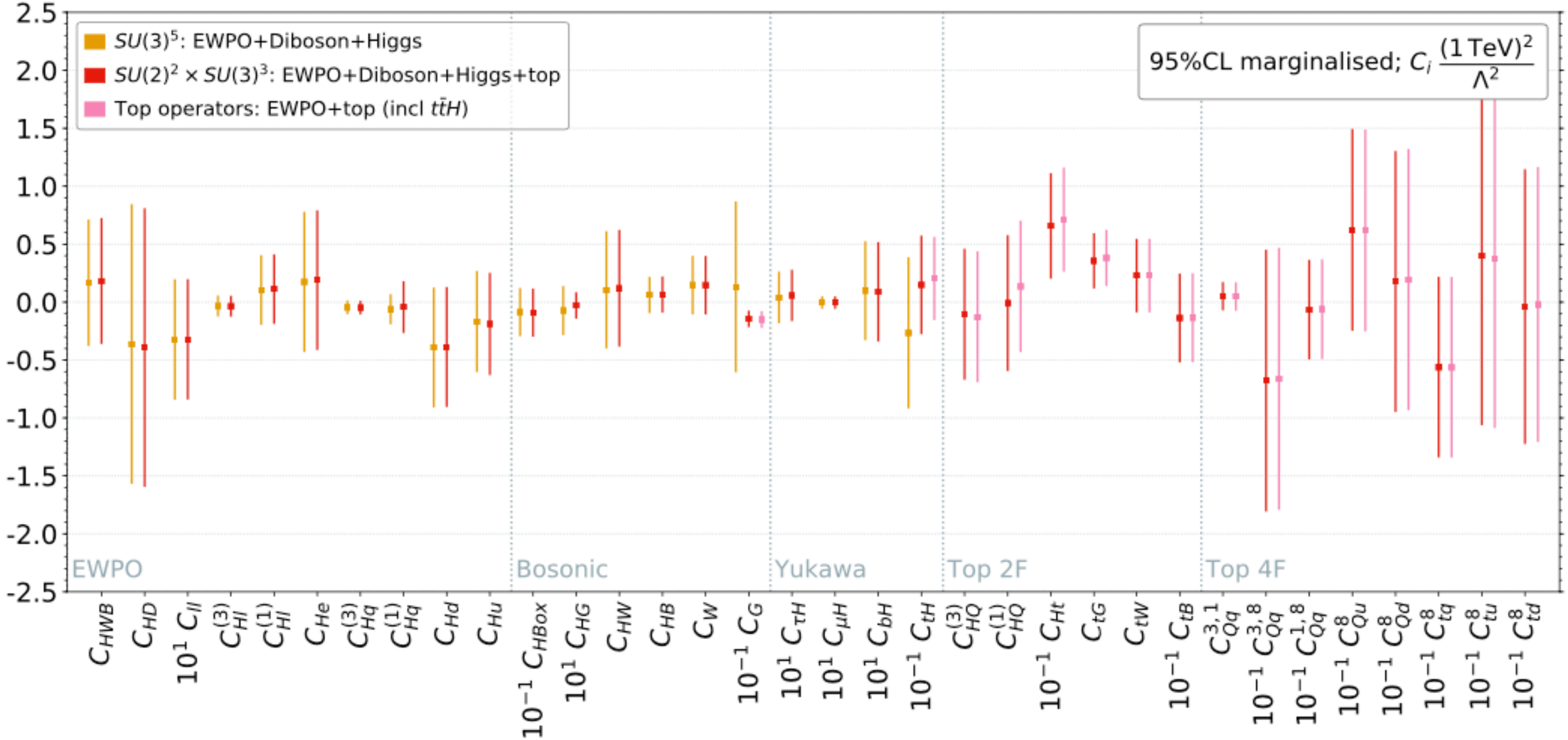
Filled to my best knowledge - apologies for any mistakes

Higgs-top combination

[see also: Ethier et al. (2105.00006)]

Combining different sectors, e.g. top + Higgs

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



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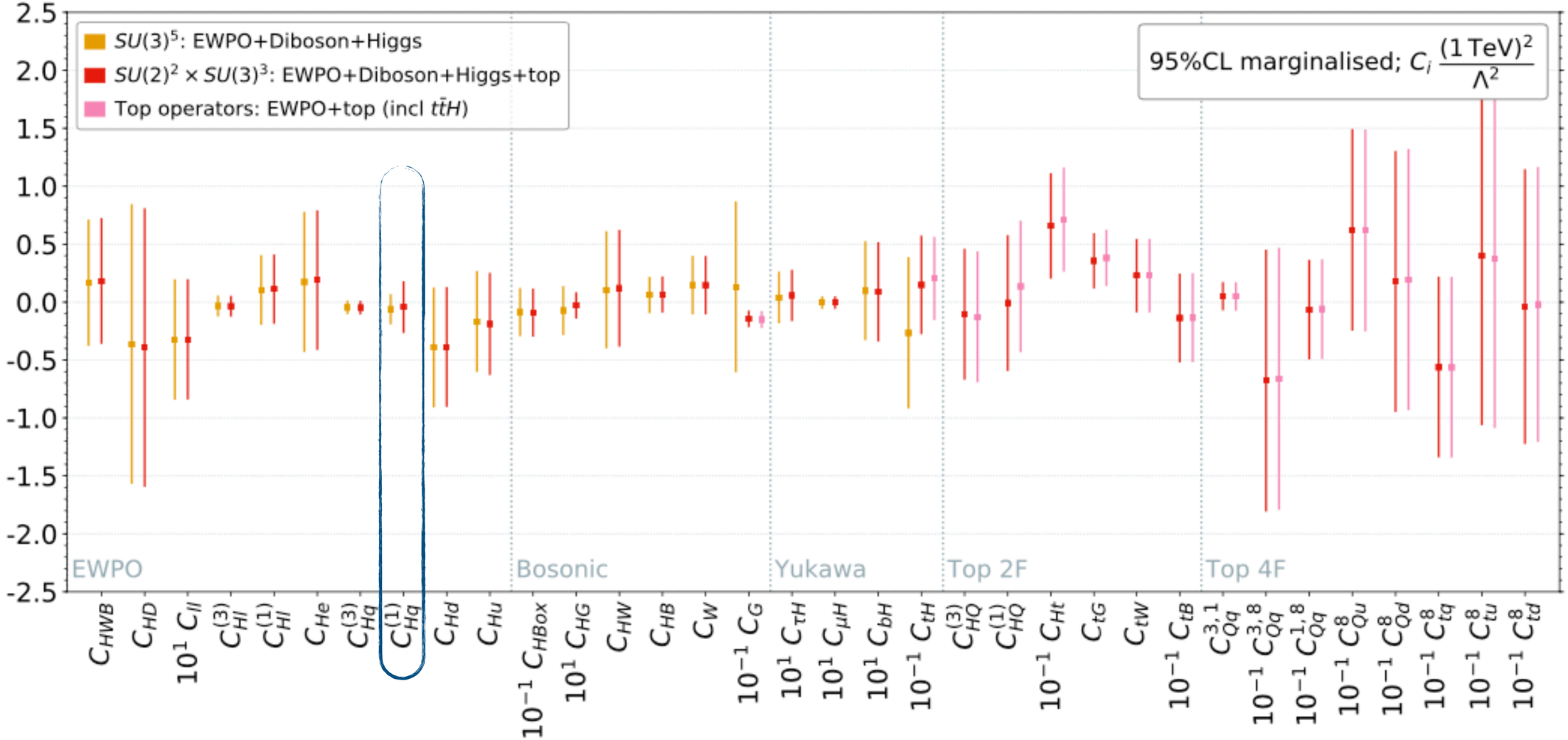

Including NLO QCD corrections

[MG: Degrande et al. (2008.11743)]
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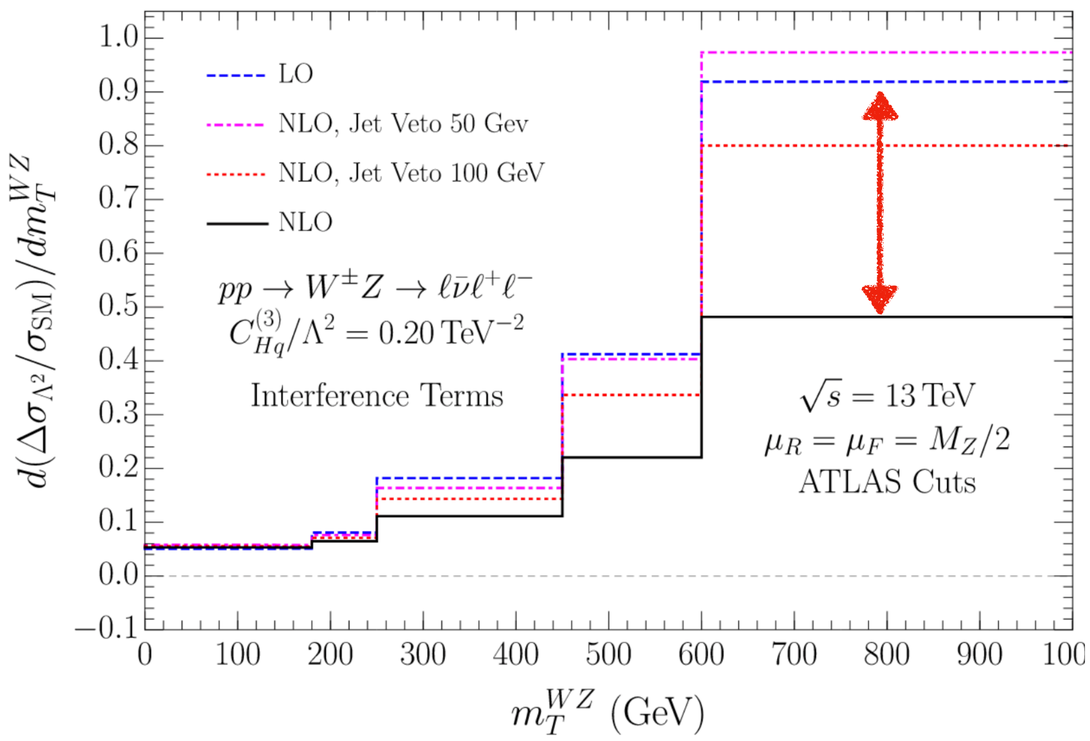
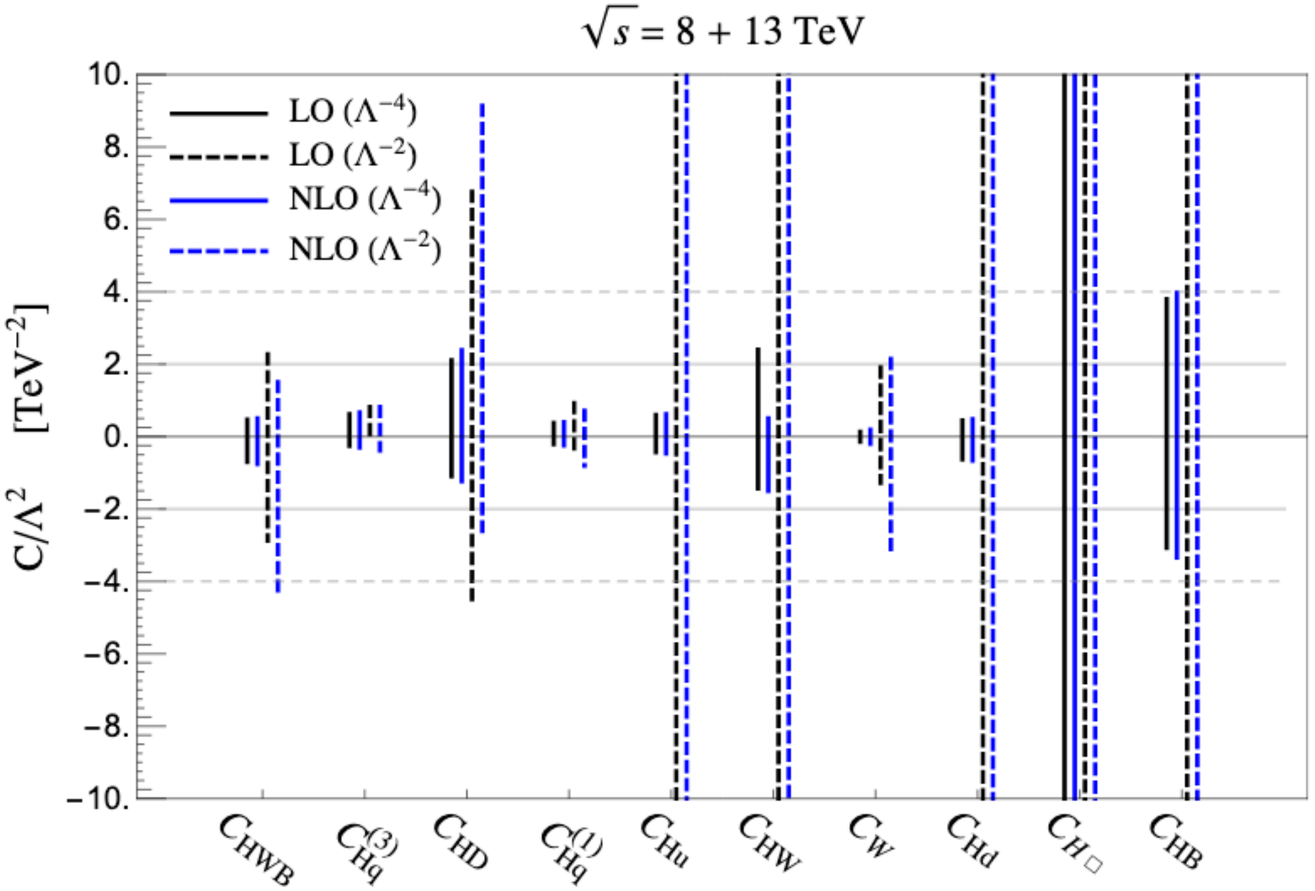
SMEFT @ NLO, e.g. NLO QCD for diboson + Vh





[Baglio et al (1909.11576, 2003.07862)]

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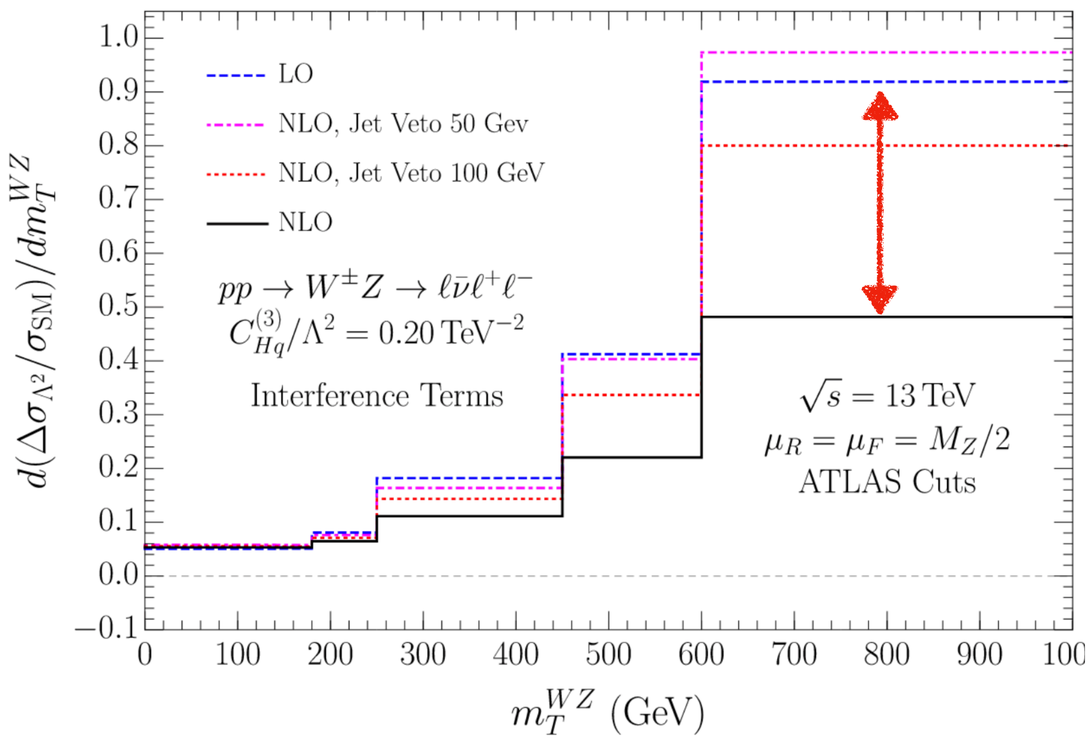

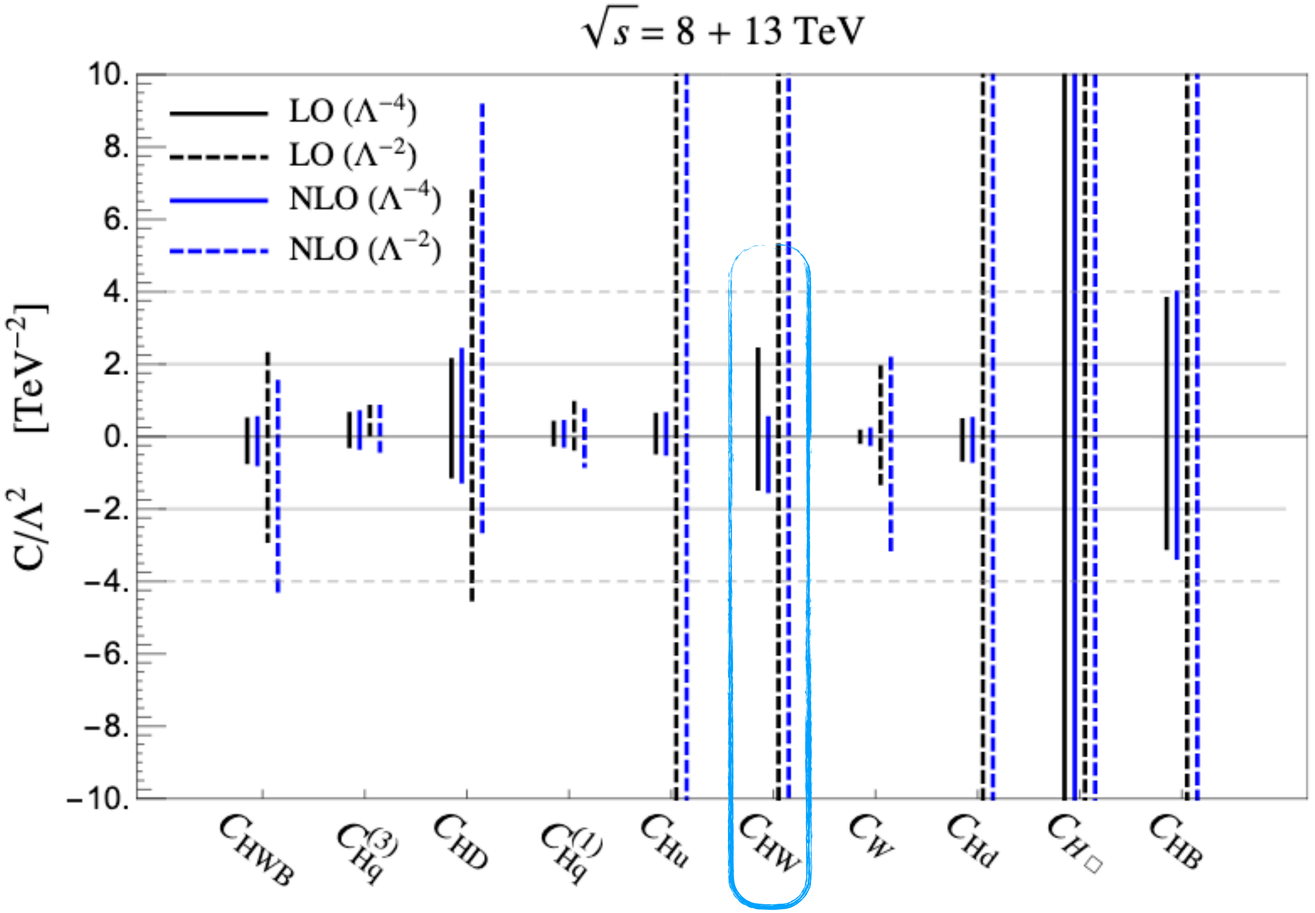

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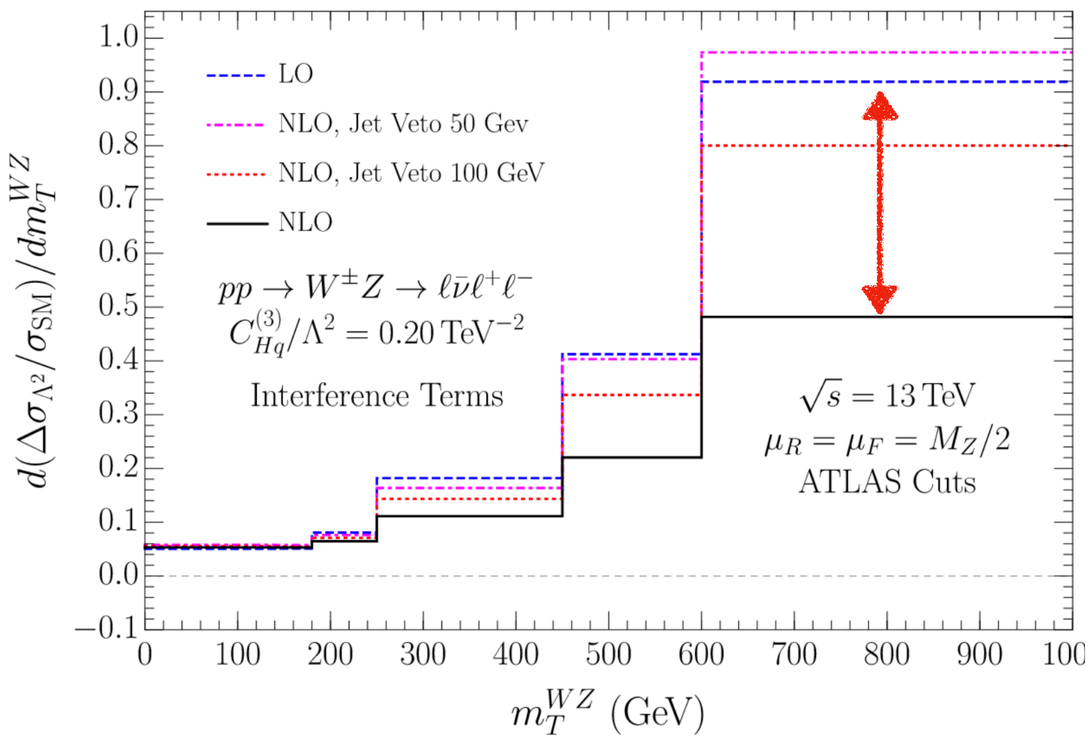
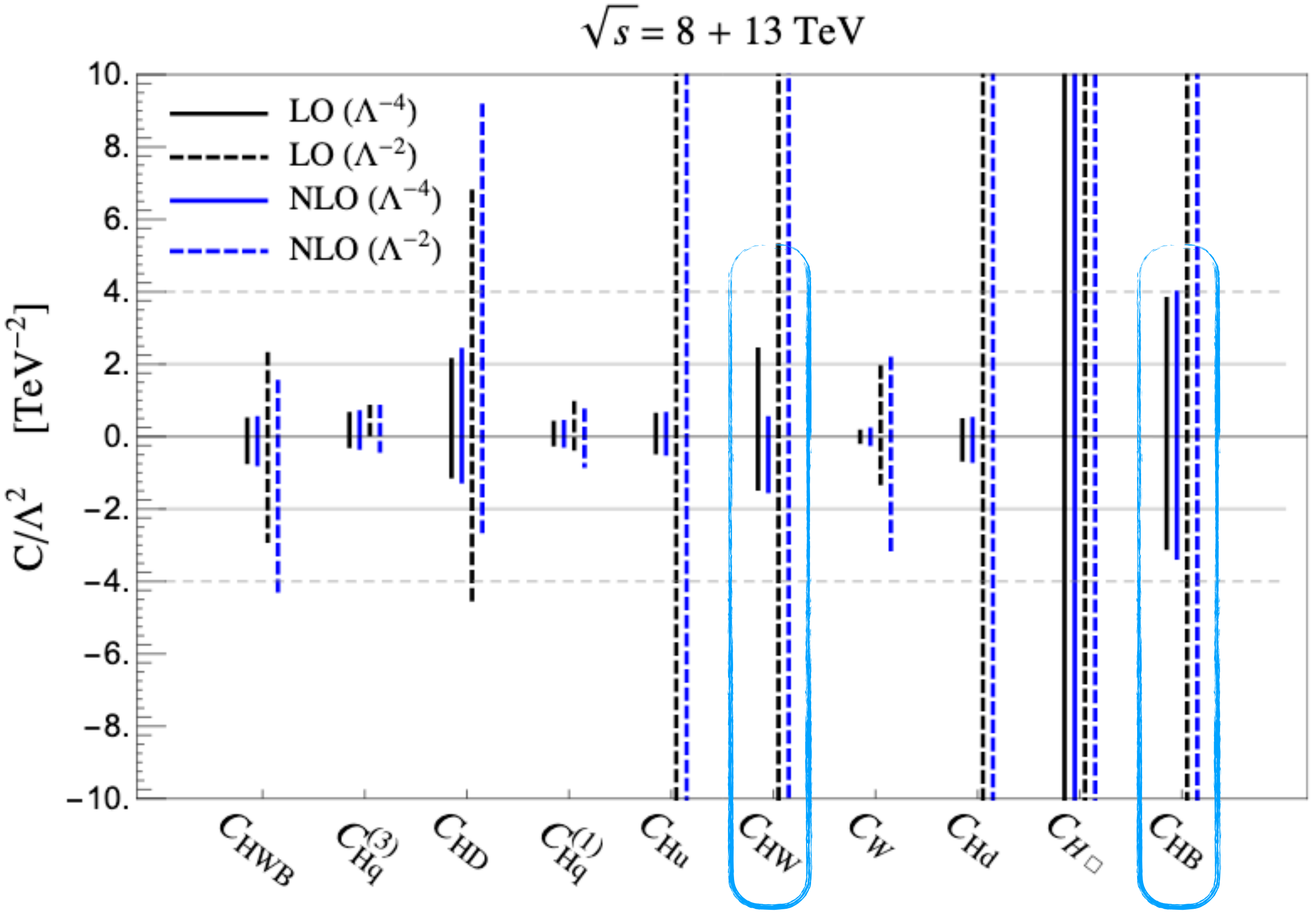
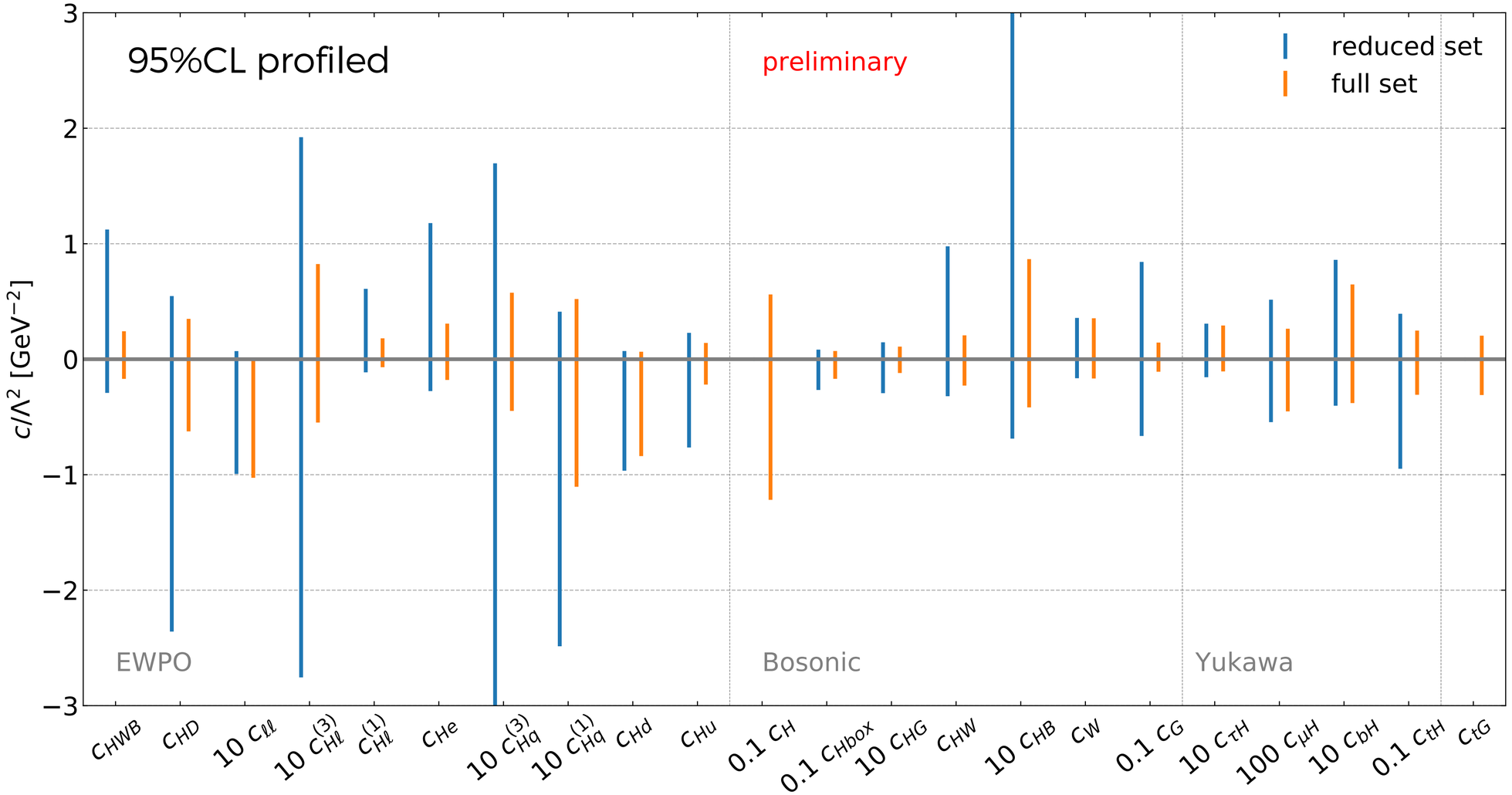




[Baglio et al (1909.11576, 2003.07862)]

Global fit

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (work in progress)]



No diboson data

Reduced set: EWPO + 2020 Higgs data (incl. ATLAS STXS data)
Full set: EWPO + 2021 Higgs data + Dihiggs

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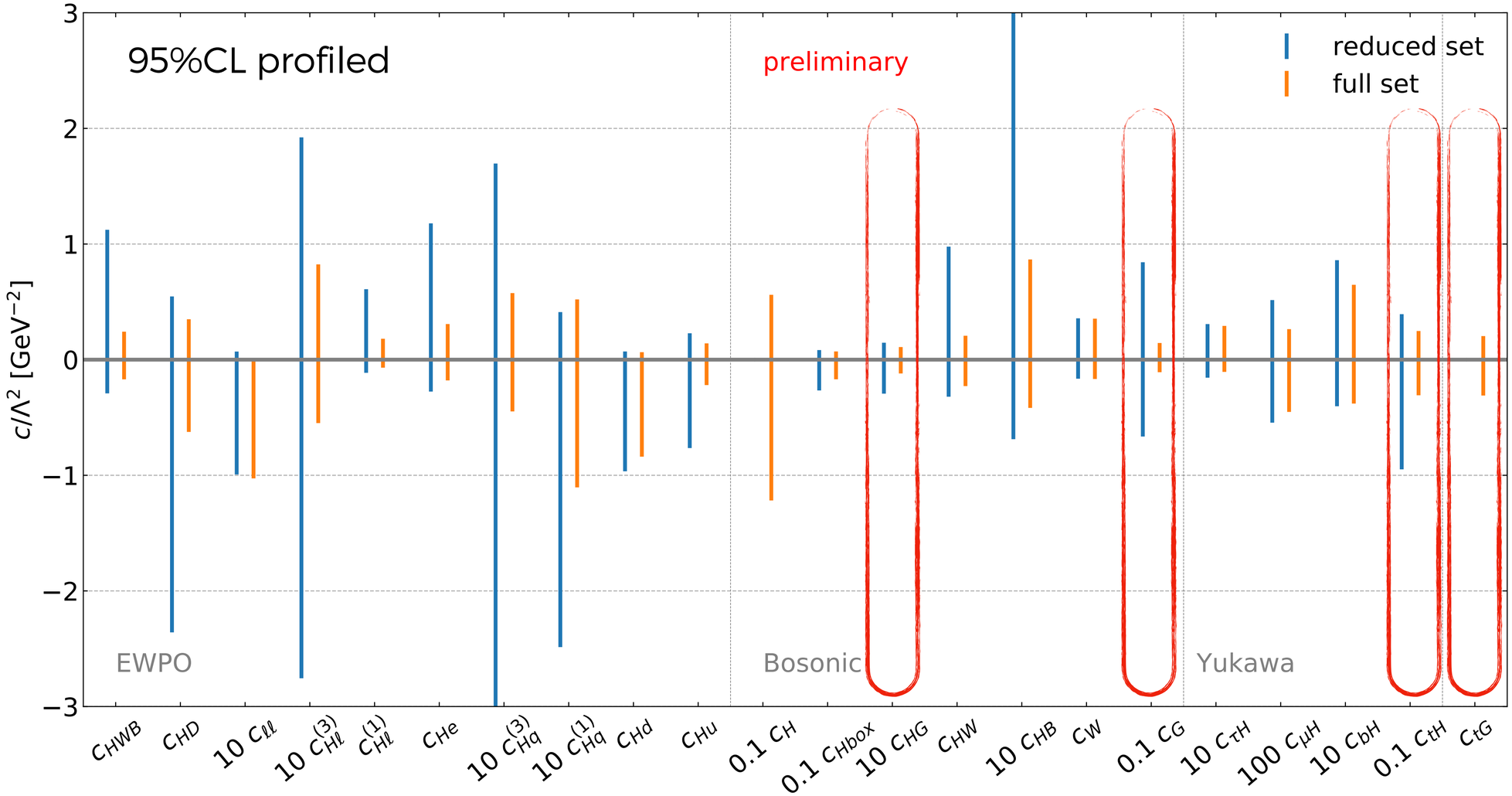

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UV complete model fits

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

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (work in progress)]
[Gorbahn, No, Sanz (1502.07352)]
[Drozd, Ellis, Quevillon, You (1504.02409)]
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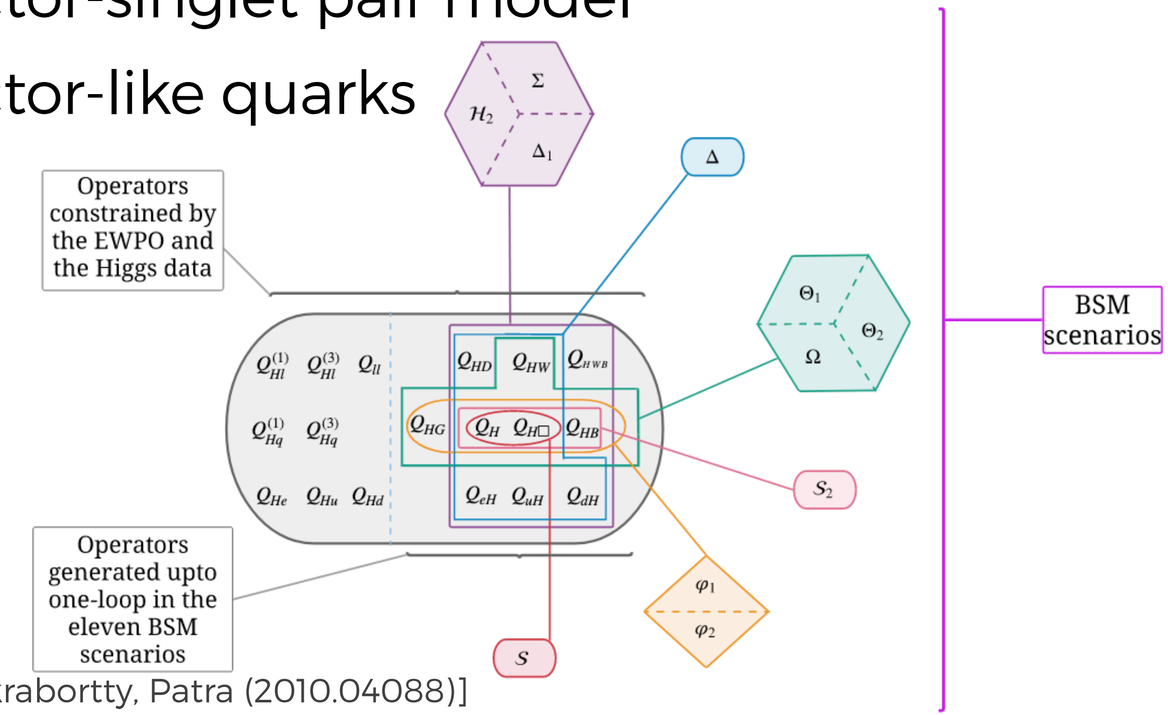
[Bakshi, Chakrabortty, (Englert), Spannowsky, (Stylianou) (2009.13394), (2012.03839)]



[Anisha, Bakshi, Chakrabortty, Patra (2010.04088)]

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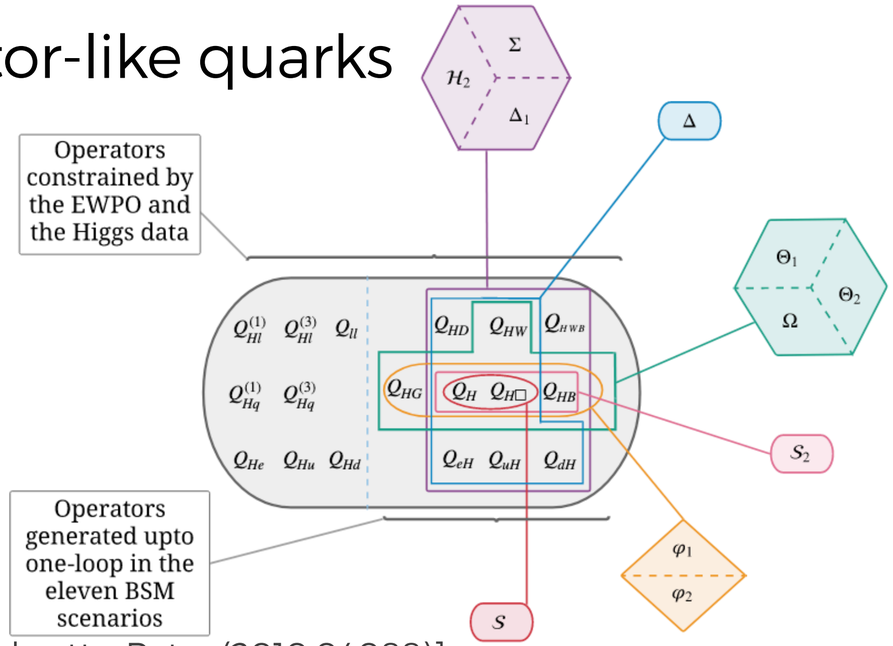

Model	C_{HD}	C_{ll}	C_{Hl}^3	C_{Hl}^1	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						-1			
S_1		1							
Σ			$\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
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	

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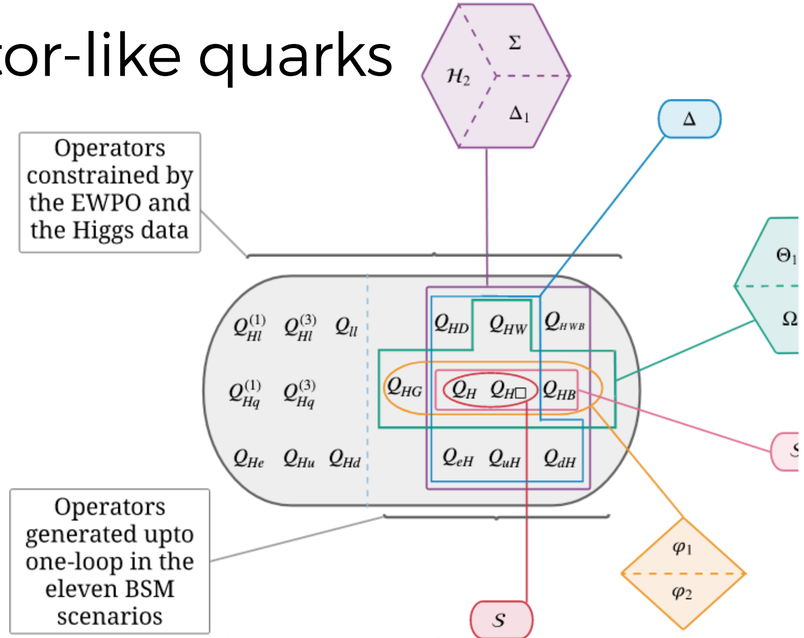

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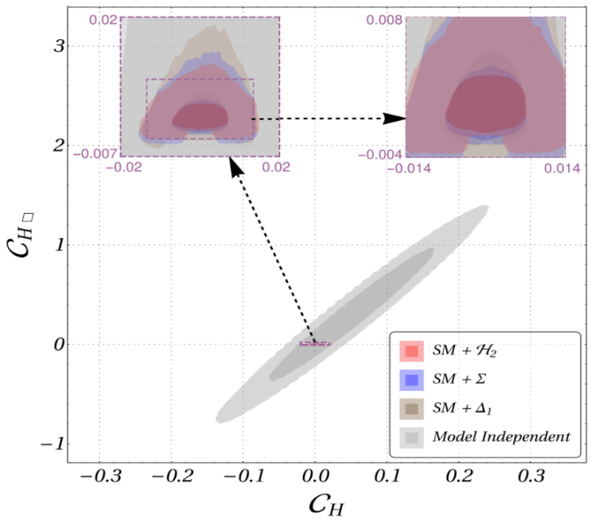
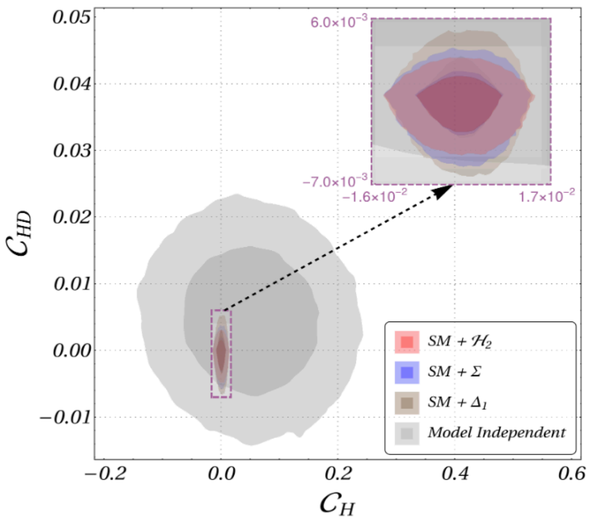
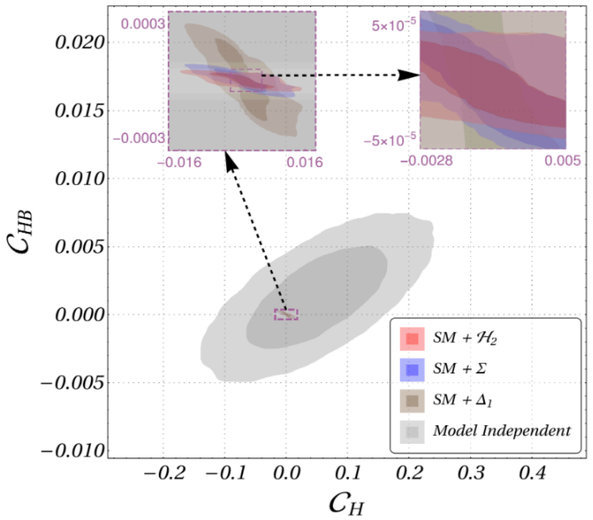


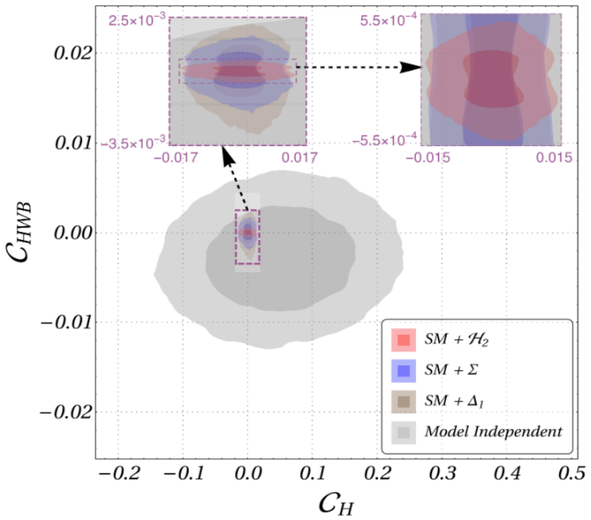
(a) $\mathcal{C}_H$ - $\mathcal{C}_{H\Box}$



(b) $\mathcal{C}_H$ - $\mathcal{C}_{HD}$



(c) $\mathcal{C}_H$ - $\mathcal{C}_{HB}$



(d) $\mathcal{C}_H$ - $\mathcal{C}_{HWB}$

[Anisha, Bakshi, Chakrabortty, Patra (2010.04088)]

Summary

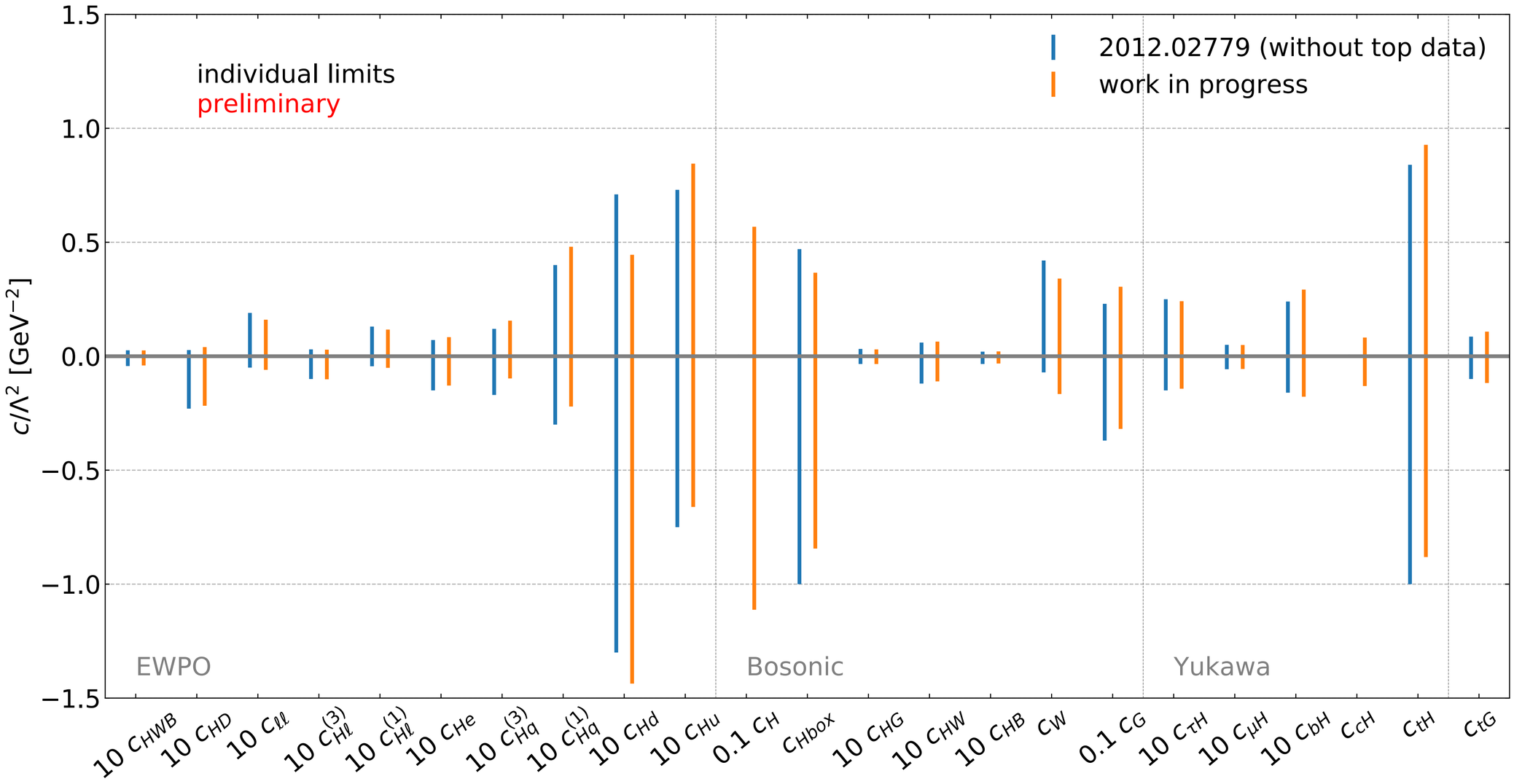
- **CP-odd interactions** in diboson and Vjj production
  - Charged TGC: (almost) orthogonal limits from $W\gamma$ and Vjj

- **Global fit for LHC run II**
  - Combinations of different sectors

    Higgs + diboson + EWPO + top + X
  - SMEFT is the framework, but not the answer

Thank you for your attention!

Individual limits



Profiled limits