

# Impact of dimension-eight SMEFT operators in the EWPO and Triple Gauge Couplings analysis in Universal SMEFT



Peter Reimitz

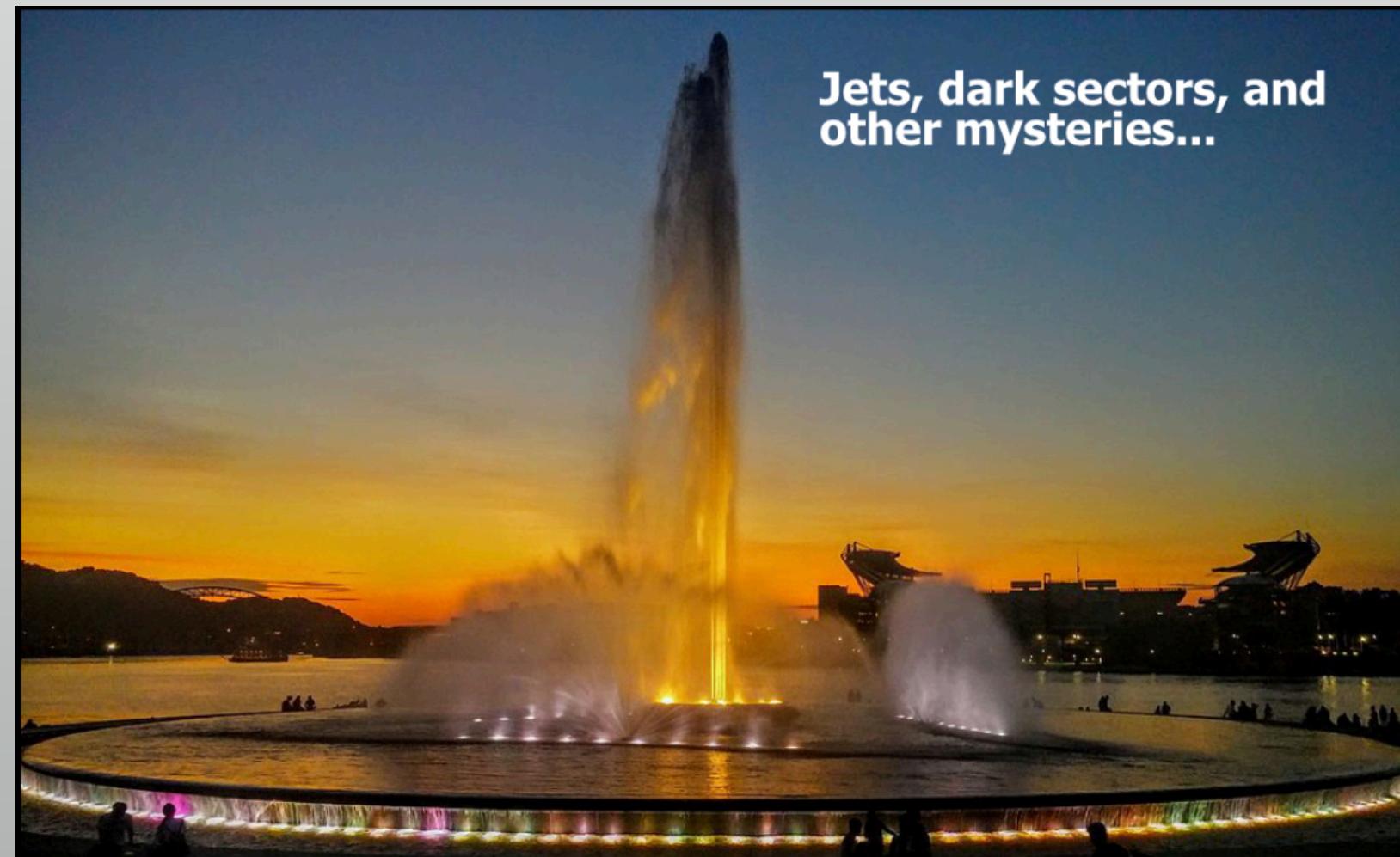
*Instituto de Física, Universidade de São Paulo (IFUSP)*

Based on:

arXiv 2304.03305

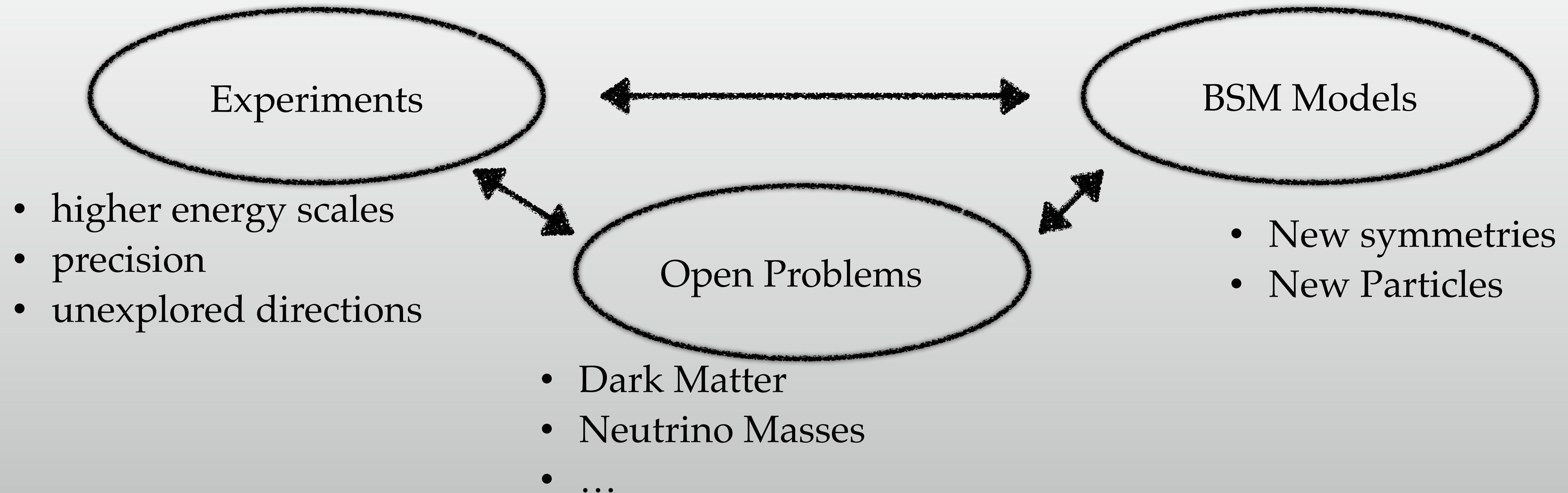


T. Corbett, J. Desai, O. Éboli, M.C. Gonzalez-Garcia, M. Martines, PR

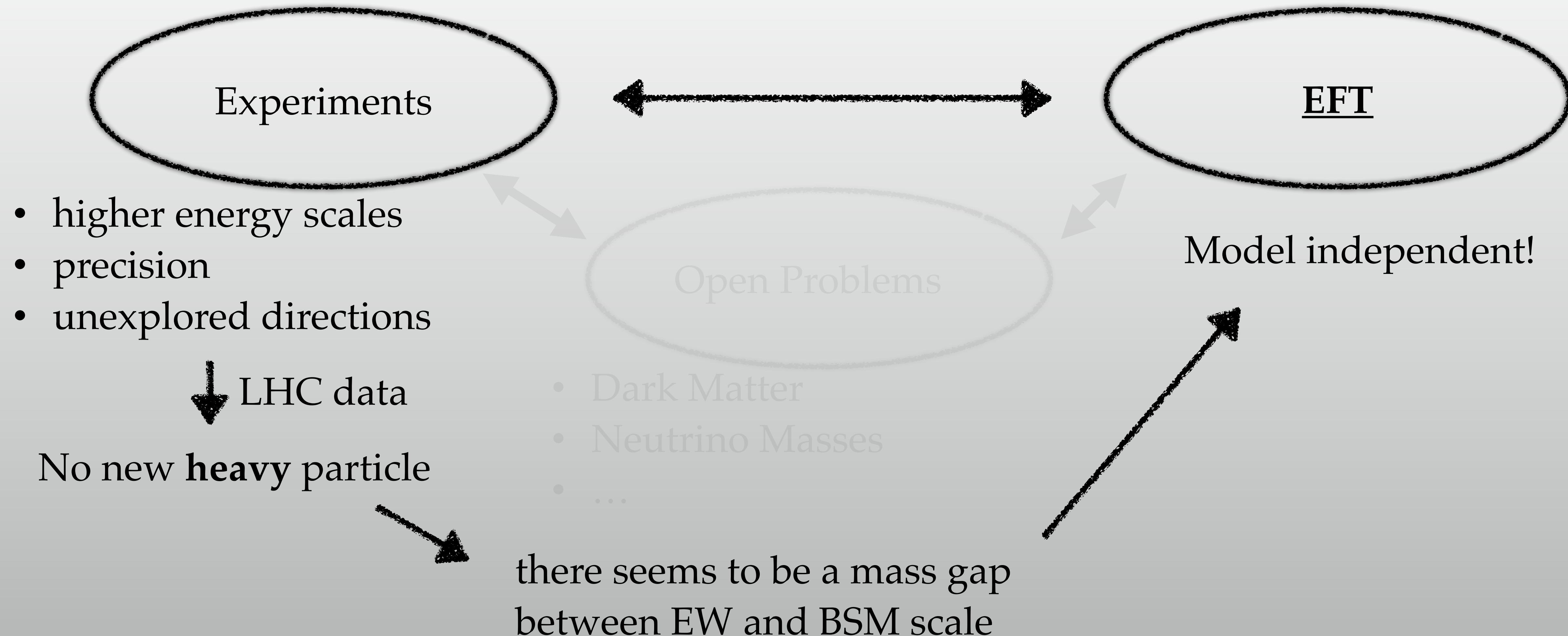


Pheno 2023, May 08-10, 2023

# Directions for Particle Physics



## Why EFTs?



*powerful framework to study BSM*

## About SMEFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n^{(6)} + \sum_n \frac{f_n}{\Lambda^4} \mathcal{O}_n^{(8)}$$

set constraints on  
coefficients

$$|M_{\text{SM}}|^2 + \mathcal{M}_{\text{SM}}^* \mathcal{M}^{(6)} + |\mathcal{M}^{(6)}|^2 + \mathcal{M}_{\text{SM}}^* \mathcal{M}^{(8)}$$

Why Dim-8 ?: convergence of expansion, negative cross-sections

Studies of Drell-Yan

ttH

EW pairs

Higgs

2003.11615 S. Alioli, R. Boughezal, E. Mereghetti, F. Petriello

2106.05337 R. Boughezal, E. Mereghetti, F. Petriello

2207.01703 R. Boughezal, Y. Huang, F. Petriello

2203.11976 T. Kim, A. Martin

2207.10714 L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch

EWPD

About SMEFT  
*powerful framework to study BSM*

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Why Dim-8 ?: convergence of expansion, negative cross-sections

Studies of Drell-Yan 2003.11615, 2106.05337, 2207.01703, 2207.10714, 2203.11976

ttH 2110.06929 S. Dawson, S. Homelier, M. Sullivan

EWPD

EW pairs

Higgs

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*powerful framework to study BSM*

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Studies of Drell-Yan 2003.11615, 2106.05337, 2207.01703, 2207.10714, 2203.11976

ttH 2110.06929

EWPD

EW pairs 2303.10493 C. Degrande, H.-L. Li

Higgs

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Studies of Drell-Yan [2003.11615](#), [2106.05337](#), [2207.01703](#), [2207.10714](#), [2203.11976](#)

ttH [2110.06929](#)

EWPD

EW pairs [2303.10493](#)

[2007.00565](#) C. Hays, A. Helset, A. Martin, M. Trott

Higgs [1808.00442](#) C. Hays, A. Martin, V. Sanz, J. Setford  
[2107.07470](#) T. Corbett, A. Martin, M. Trott

[2109.05595](#) A. Martin, M. Trott  
[2106.10284](#) T. Corbett

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Studies of Drell-Yan [2003.11615](#), [2106.05337](#), [2207.01703](#), [2207.10714](#), [2203.11976](#)

ttH [2110.06929](#)

EW pairs [2303.10493](#)

Higgs [1808.00442](#), [2107.07470](#), [2007.00565](#), [2109.05595](#), [2106.10284](#)

EWPD

[2007.00565](#) C. Hays, A. Helset, A. Martin, M. Trott

[2102.02812](#) T. Corbett, A. Helset, A. Martin, M. Trott

About SMEFT  
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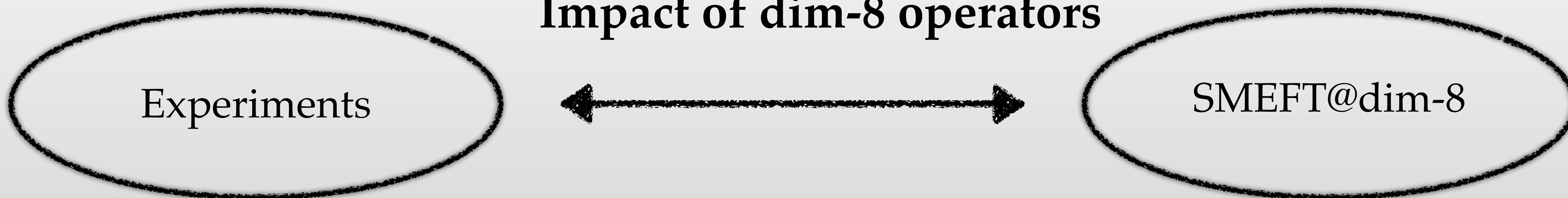
ttH [2110.06929](#)

EWPD [2007.00565](#), [2102.02812](#)

EW pairs [2303.10493](#) Impact of dim-8 operators on diboson production

Higgs [1808.00442](#), [2107.07470](#), [2007.00565](#), [2109.05595](#), [2106.10284](#)

## Setup for Study



- Z observables      } EWPO
- LEP2/Tevatron    }
- ATLAS              } EWDB
- CMS                }

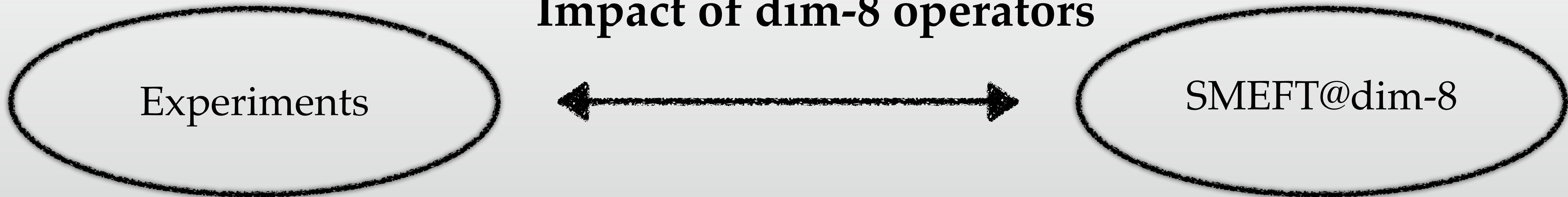
**sequential analysis**

1510.08462 J.D. Wells, Z. Zhang for dim-6 operators

→ **HISZ basis**

systematic study of SMEFT effects on:  
EWPO, TGC, input parameters,  
oblique parameters

## Setup for Study



- Z observables      } EWPO
- LEP2/Tevatron    }
- ATLAS              } EWDB
- CMS                }

**sequential analysis**

Universal SMEFT formalism

1510.08462 J.D. Wells, Z. Zhang for dim-6 operators

+ potential dim-8 operators

2005.00008 H-L. Li, Z. Ren, J. Shu, M.-L. Xiao, J.-H. Yu, Y.-H. Zhen

2005.00059 C. Murphy

## Set of operators (HISZ basis)

### Affecting kinetic terms:

dim-6

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

dim-8

$$\mathcal{O}_{W^2\Phi^4}^{(1)} = (\Phi^\dagger \Phi) \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{B^2\Phi^4}^{(1)} = (\Phi^\dagger \Phi) \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{BW\Phi^4}^{(1)} = (\Phi^\dagger \Phi) \Phi^\dagger \hat{W}_{\mu\nu} \Phi \hat{B}^{\mu\nu}$$

$$\mathcal{O}_{W^2\Phi^4}^{(3)} = \Phi^\dagger \hat{W}_{\mu\nu} \Phi \Phi^\dagger \hat{W}^{\mu\nu} \Phi$$

Canonically renormalise kinetic terms  
+ remove kinetic mixing term

## Set of operators (HISZ basis)

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$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

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$$\mathcal{O}_{BW\Phi^4}^{(1)} = (\Phi^\dagger \Phi) \Phi^\dagger \hat{W}_{\mu\nu} \Phi \hat{B}^{\mu\nu}$$

$$\mathcal{O}_{W^2\Phi^4}^{(3)} = \Phi^\dagger \hat{W}_{\mu\nu} \Phi \Phi^\dagger \hat{W}^{\mu\nu} \Phi$$

Absorbed by redefinition of coupling constants

## Set of operators

### Covariant derivative terms:

dim-6

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi)$$

dim-8

$$\mathcal{O}_{D^2 \Phi^6}^{(1)} = (\Phi^\dagger \Phi)^2 (D_\mu \Phi)^\dagger D^\mu \Phi$$

$$\mathcal{O}_{D^2 \Phi^6}^{(2)} = (\Phi^\dagger \Phi) (\Phi^\dagger \sigma^I \Phi) (D_\mu \Phi)^\dagger \sigma^I D^\mu \Phi$$

Contributing to Higgs vev corrections and  
gauge boson mass terms

## Set of operators

### Covariant derivative terms:

dim-6

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi)$$

$$\mathcal{O}_{D^2 \Phi^6}^{(1)} = (\Phi^\dagger \Phi)^2 (D_\mu \Phi)^\dagger D^\mu \Phi$$

$$\mathcal{O}_{D^2 \Phi^6}^{(2)} = (\Phi^\dagger \Phi) (\Phi^\dagger \sigma^I \Phi) (D_\mu \Phi)^\dagger \sigma^I D^\mu \Phi$$

dim-8

Corrections to Higgs vev and gauge boson mass term  
cancel each other

## Set of operators

Relevant for TGC:

dim-6

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

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

$$\mathcal{O}_{WWW} = \text{Tr} \left[ \hat{W}_\mu^\nu \hat{W}_\nu^\rho \hat{W}_\rho^\mu \right]$$

dim-8

$$\mathcal{O}_{W\Phi^4 D^2}^{(1)} = (\Phi^\dagger \Phi) (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{B\Phi^4 D^2}^{(1)} = (\Phi^\dagger \Phi) (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{W^3 \Phi^2}^{(1)} = (\Phi^\dagger \Phi) \text{Tr} \left[ \hat{W}_\mu^\nu \hat{W}_\nu^\rho \hat{W}_\rho^\mu \right]$$

$$\mathcal{O}_{W^2 B \Phi^2}^{(1)} = g^3 \frac{s_W}{8c_W} \varepsilon^{IJK} (\Phi^\dagger \sigma^I \Phi) B_\nu^\mu W_\rho^{J\nu} W_\mu^{K\rho}$$

Direct modifications to TGC

## Full Set of operators and input parameters

$$\begin{aligned}\mathcal{L}_{\text{eff}} = & \mathcal{L}_{SM} + \frac{f_{WWW}}{\Lambda^2} \mathcal{O}_{WWW} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_{BW}}{\Lambda^2} \mathcal{O}_{BW} + \frac{f_{\Phi,1}}{\Lambda^2} \mathcal{O}_{\Phi,1} + \frac{f_{4F}}{\Lambda^2} \mathcal{O}_{4F} \\ & + \frac{f_{D^2\Phi^6}^{(2)}}{\Lambda^4} \mathcal{O}_{D^2\Phi^6}^{(2)} + \frac{f_{W^3\Phi^2}^{(1)}}{\Lambda^4} \mathcal{O}_{W^3\Phi^2}^{(1)} + \frac{f_{W^2B\Phi^2}^{(1)}}{\Lambda^4} \mathcal{O}_{W^2B\Phi^2}^{(1)} + \frac{f_{B\Phi^4D^2}^{(1)}}{\Lambda^4} \mathcal{O}_{B\Phi^4D^2}^{(1)} \\ & + \frac{f_{W\Phi^4D^2}^{(1)}}{\Lambda^4} \mathcal{O}_{W\Phi^4D^2}^{(1)} + \frac{f_{W^2\Phi^4}^{(3)}}{\Lambda^4} \mathcal{O}_{W^2\Phi^4}^{(3)} + \frac{f_{BW\Phi^4}^{(1)}}{\Lambda^4} \mathcal{O}_{BW\Phi^4}^{(1)} + \frac{\Delta_{4F}^{(8)}}{\Lambda^4} \mathcal{O}_{4F}^{(8)}\end{aligned}$$

## Input parameters:

$$\hat{e} = \sqrt{4\pi\hat{\alpha}_{\text{em}}} ,$$

$$\hat{v}^2 = \frac{1}{\sqrt{2}\hat{G}_F} ,$$

$$\hat{c}^2\hat{s}^2 = \frac{\pi\hat{\alpha}_{\text{em}}}{\sqrt{2}\hat{G}_F\hat{M}_Z^2}$$

# Part 1: Electroweak Precision Observables

[hep-ex/0509008](#)

SLD, DELPHI, ALEPH, L3, OPAL, LEP

## Z observables

$$\Gamma_Z, \sigma_h^0, \mathcal{A}_\ell(\tau^{\text{pol}}), R_\ell^0, \mathcal{A}_\ell(\text{SLD}), A_{\text{FB}}^{0,l}, R_c^0, R_b^0, \mathcal{A}_c, \mathcal{A}_b, A_{\text{FB}}^{0,c}, \text{ and } A_{\text{FB}}^{0,b} \text{ (SLD/LEP-I)},$$

## Average W-boson mass + width (LEP2/Tevatron):

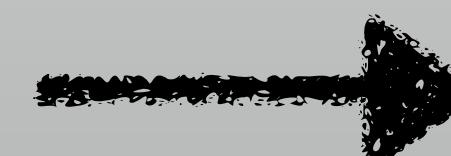
$$M_W, \Gamma_W$$

PDG Chin. Phys. C40, 100001 (2016)

LEP2/Tevatron

$$\chi^2_{\text{EWPO}} \equiv \chi^2_{\text{EWPO}} \left( f_{BW}, f_{\Phi,1}, \Delta_{4F}, f_{BW\Phi^4}^{(1)}, f_{D^2\Phi^6}^{(2)}, \Delta_{4F}^{(8)}, f_{W^2\Phi^4}^{(3)} \right)$$

We cannot constrain all coefficients



$$\begin{aligned}\tilde{\Delta}_{4F} &= \Delta_{4F} + \frac{\hat{v}^2}{\Lambda^2} \Delta_{4F}^{(8)}, \\ \tilde{f}_{BW} &= f_{BW} + \frac{\hat{v}^2}{2\Lambda^2} f_{BW\Phi^4}^{(1)}, \\ \tilde{f}_{\Phi,1} &= f_{\Phi,1} + \frac{\hat{v}^2}{\Lambda^2} f_{D^2\Phi^6}^{(2)}\end{aligned}$$

# Part 1: Electroweak Precision Observables

[hep-ex/0509008](#)

SLD, DELPHI, ALEPH, L3, OPAL, LEP

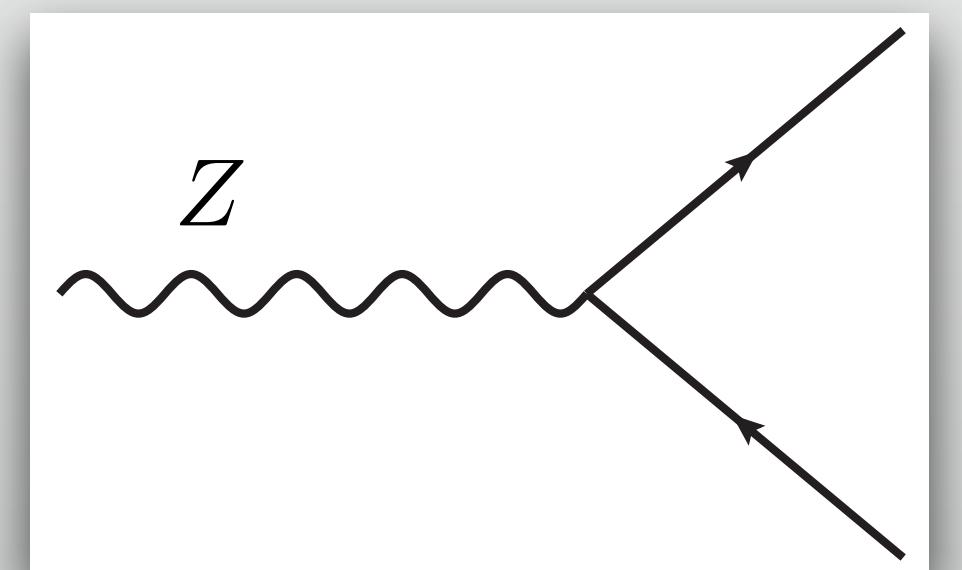
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## Z coupling to fermions

$$\frac{\hat{e}}{\hat{s}\hat{c}} (\hat{g}^f (1 + \Delta g_1) + Q^f \Delta g_2)$$

$$\Delta g_1 \simeq -\frac{1}{4} \frac{\hat{v}^2}{\Lambda^2} \left[ 2\tilde{\Delta}_{4F} + \tilde{f}_{\Phi,1} \right] - \frac{1}{32} \frac{\hat{v}^4}{\Lambda^4} \left[ -12(\tilde{\Delta}_{4F})^2 + 4\tilde{\Delta}_{4F}\tilde{f}_{\Phi,1} - 3(\tilde{f}_{\Phi,1})^2 \right]$$



$$\Delta g_2 = \frac{\hat{v}^2}{\Lambda^2} \frac{1}{2\hat{c}_2} \left[ -\hat{s}^2\hat{c}^2 \left( 2\tilde{\Delta}_{4F} + \tilde{f}_{\Phi,1} \right) + \frac{\hat{e}^2}{2} \tilde{f}_{BW} \right]$$

$$+ \frac{\hat{v}^4}{\Lambda^4} \frac{1}{8\hat{c}_2^3} \left\{ \frac{\hat{s}_2^2}{4} \left[ (1 + 3\hat{c}_4) \left( (\tilde{\Delta}_{4F})^2 + \frac{1}{4}(\tilde{f}_{\phi,1})^2 \right) - (3 + \hat{c}_4)\tilde{\Delta}_{4F}\tilde{f}_{\phi,1} \right] \right.$$

$$\left. - \frac{\hat{e}^2}{2} \left( \hat{c}_4\tilde{f}_{BW}\tilde{f}_{\phi,1} - 2\tilde{\Delta}_{4F}\tilde{f}_{BW} + \hat{e}^2(\tilde{f}_{BW})^2 \right) \right\}$$

Cancellations for

$$\tilde{f}_{\Phi,1} = -2\tilde{\Delta}_{4F} = \frac{\hat{e}^2}{2\hat{s}^2} \frac{\hat{v}^2}{\Lambda^2} f_{W^2\Phi^4}^{(3)}$$

# Part 1: Electroweak Precision Observables

## Average W-boson mass + width (LEP2/Tevatron):

$$M_W \quad , \quad \Gamma_W$$

PDG Chin. Phys. C40, 100001 (2016)

LEP2/Tevatron

$$\begin{aligned} \frac{\Delta M_W}{\hat{M}_W} = & \frac{1}{4\hat{c}_2} \frac{\hat{v}^2}{\Lambda^2} \left[ \hat{e}^2 \tilde{f}_{BW} - 2\hat{s}^2 \tilde{\Delta}_{4F} - \hat{c}^2 \tilde{f}_{\Phi,1} \right] + \frac{\hat{e}^2}{8\hat{s}^2} \frac{\hat{v}^4}{\Lambda^4} f_{W^2\Phi^4}^{(3)} \\ & + \frac{1}{8\hat{c}_2^3} \frac{\hat{v}^4}{\Lambda^4} \left[ -\hat{s}^4 (2 + 3\hat{c}_2) (\tilde{\Delta}_{4F})^2 + \frac{1}{4} \hat{c}^4 (-2 + 5\hat{c}_2) (\tilde{f}_{\Phi,1})^2 - \frac{1}{16} \hat{e}^4 \frac{(7 - 6\hat{c}_2 + 3\hat{c}_4)}{\hat{s}^2} (\tilde{f}_{BW})^2 \right. \\ & \left. - \frac{\hat{c}^2}{4} (9 - 6\hat{c}_2 + 5\hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{\Phi,1} + \frac{1}{4} \hat{e}^2 (7 - 2\hat{c}_2 + 3\hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{BW} - \frac{1}{2} \hat{e}^2 \hat{c}^2 (-2 + 3\hat{c}_2) \tilde{f}_{\Phi,1} \tilde{f}_{BW} \right] \end{aligned}$$

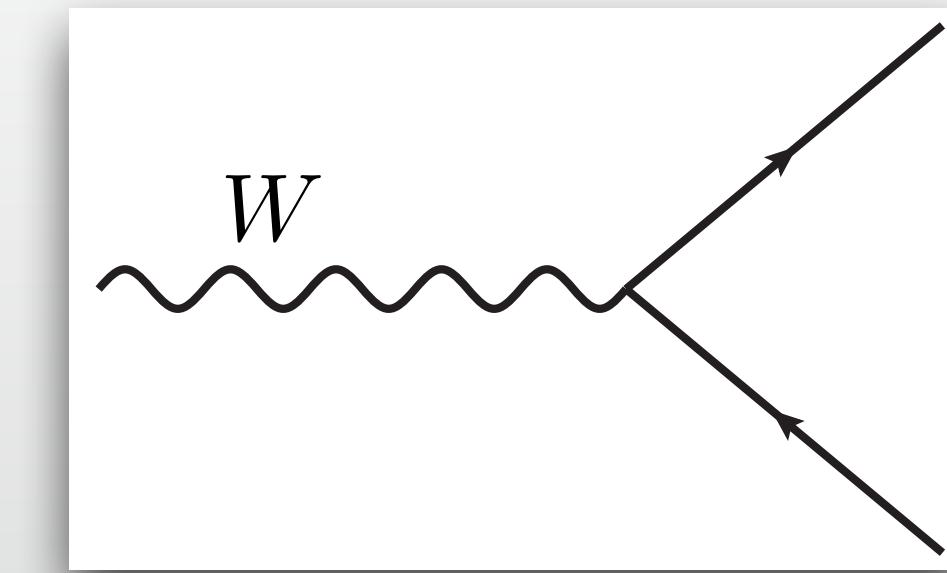
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# Part 1: Electroweak Precision Observables

Average W-boson mass + widths (LEP2/Tevatron):

$$M_W , \Gamma_W$$



$$\begin{aligned} \Delta g_W = & \frac{1}{4\hat{c}_2} \frac{\hat{v}^2}{\Lambda^2} \left[ \hat{e}^2 \tilde{f}_{BW} - 2\hat{c}^2 \tilde{\Delta}_{4F} - \hat{c}^2 \tilde{f}_{\Phi,1} \right] \\ & + \frac{1}{8\hat{c}_2^3} \frac{\hat{v}^4}{\Lambda^4} \left[ \hat{e}^2 \frac{\hat{c}_2^3}{\hat{s}^2} f_{W^2\Phi^4}^{(3)} + \hat{c}^4 (-2 + 5\hat{c}_2)(\tilde{\Delta}_{4F})^2 - \frac{1}{16} \frac{(7 - 6\hat{c}_2 + 3\hat{c}_4)}{\hat{s}^2} \hat{e}^4 (\tilde{f}_{BW})^2 \right. \\ & + \frac{1}{4} \hat{c}^4 (-2 + 5\hat{c}_2)(\tilde{f}_{\Phi,1})^2 - \frac{1}{4} \hat{c}^2 (7 - 6\hat{c}_2 + 3\hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{\Phi,1} + \frac{1}{4} \hat{e}^2 (5 - 2\hat{c}_2 + \hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{BW} \\ & \left. - \frac{1}{2} \hat{e}^2 \hat{c}^2 (-2 + 3\hat{c}_2) \tilde{f}_{\Phi,1} \tilde{f}_{BW} \right] \end{aligned}$$

Breaks correlation



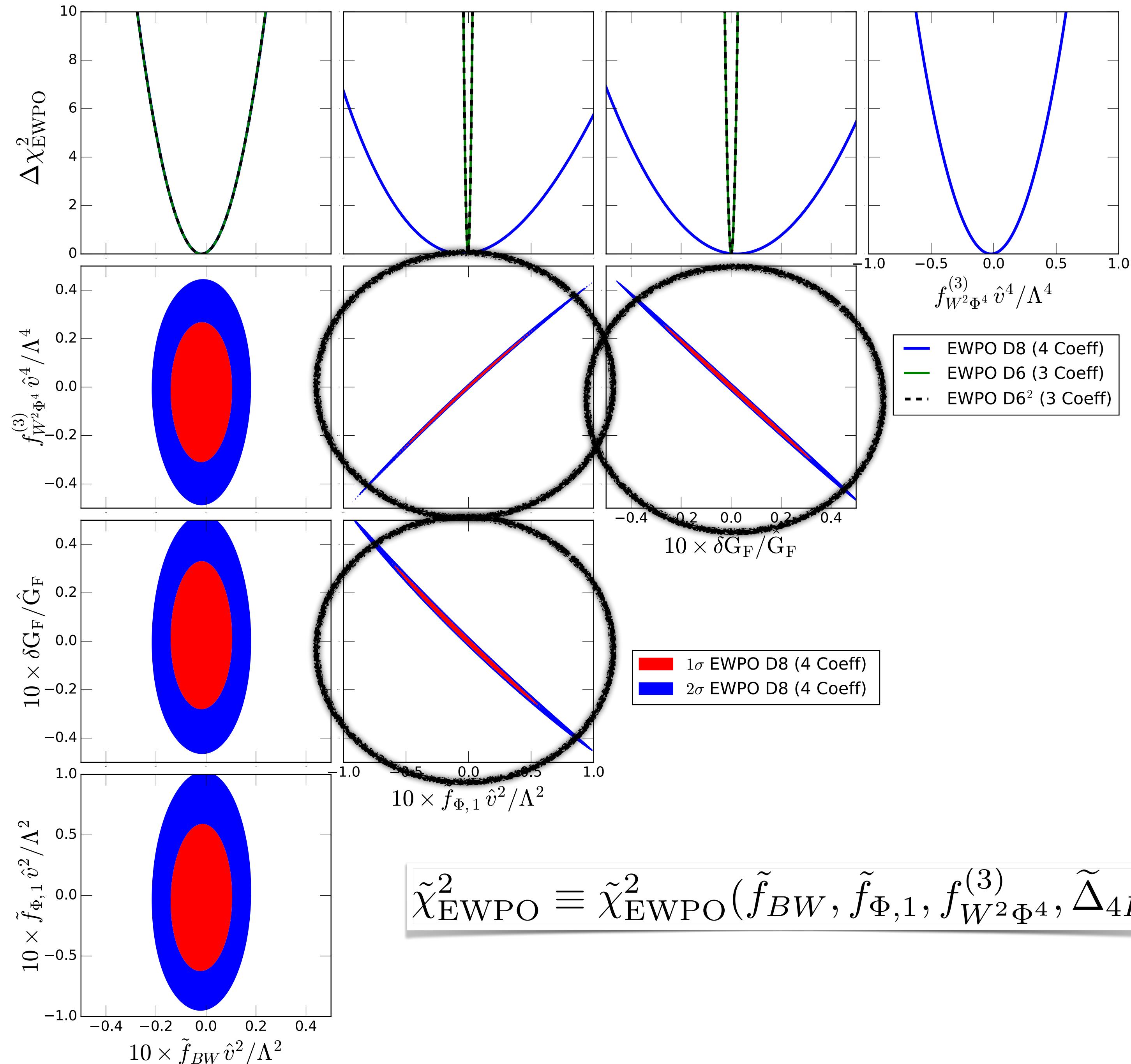
$\Gamma_W$  sets constraints

# Part 1: EWPO

dim-8  
weakens bounds by at  
least a factor 10

$$\tilde{f}_{\Phi,1}, \frac{\delta G_F}{\hat{G}_F}$$

	EWPO 95% CL allowed range	
Coupling	dimension 6	dimension 8
$\frac{\hat{v}^2}{\Lambda^2} \tilde{f}_{BW}$	[-0.018, 0.014]	[-0.018, 0.014]
$\frac{\hat{v}^2}{\Lambda^2} \tilde{f}_{\Phi,1}$	[-0.0028, 0.0018]	[-0.080, 0.081]
$\frac{\delta G_F}{\hat{G}_F}$	[-0.0016, 0.0017]	[-0.038, 0.044]
$\frac{\hat{v}^4}{\Lambda^4} f_{W^2\Phi^4}^{(3)}$	—	[-0.40, 0.36]



## Part 2: Diboson Data

$$\begin{aligned} \mathcal{L}_{WWV} = & -ig_{WWV} \left\{ g_1^V \left( W_{\mu\nu}^+ W^{-\mu} V^\nu - W_\mu^+ V_\nu W^{-\mu\nu} \right) \right. \\ & \left. + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{\hat{M}_W^2} W_{\mu\nu}^+ W^{-\nu\rho} V_\rho^\mu \right\} \end{aligned}$$

	Channel ( <i>a</i> )	Distribution	# bins	Data set	Int Lum
EWDB data	$WZ \rightarrow \ell^+ \ell^- \ell'^\pm$	$M(WZ)$	7	CMS 13 TeV,	$137.2 \text{ fb}^{-1}$ [46]
	$WW \rightarrow \ell^+ \ell'^{-} + 0/1j$	$M(\ell^+ \ell'^{-})$	11	CMS 13 TeV,	$35.9 \text{ fb}^{-1}$ [47]
	$W\gamma \rightarrow \ell\nu\gamma$	$\frac{d^2\sigma}{dp_T d\phi}$	12	CMS 13 TeV,	$137.1 \text{ fb}^{-1}$ [48]
	$WW \rightarrow e^\pm \mu^\mp + E_T (0j)$	$m_T$	17 (15)	ATLAS 13 TeV,	$36.1 \text{ fb}^{-1}$ [49]
	$WZ \rightarrow \ell^+ \ell^- \ell'^\pm$	$m_T^{WZ}$	6	ATLAS 13 TeV,	$36.1 \text{ fb}^{-1}$ [50]
	$Zjj \rightarrow \ell^+ \ell^- jj$	$\frac{d\sigma}{d\phi}$	12	ATLAS 13 TeV,	$139 \text{ fb}^{-1}$ [51]
	$WW \rightarrow \ell^+ \ell'^{-} + E_T (1j)$	$\frac{d\sigma}{dm_{\ell^+\ell^-}}$	10	ATLAS 13 TeV,	$139 \text{ fb}^{-1}$ [52]

e.g.:

$$\begin{aligned} g_1^Z = & 1 + \frac{1}{2} \frac{\hat{v}^2}{\Lambda^2} \left[ \frac{\hat{e}^2}{4\hat{s}^2\hat{c}^2} \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4D^2}^{(1)} \right) - \left[ \frac{1}{\hat{c}_2} \tilde{\Delta}_{4F} + \frac{1}{2} \frac{\hat{e}^2}{\hat{c}^2\hat{c}_2} \tilde{f}_{BW} - \frac{1}{2\hat{c}_2} \tilde{f}_{\Phi,1} \right] \right. \\ & + \frac{1}{16\hat{c}_2^3} \frac{\hat{v}^4}{\Lambda^4} \left[ (1 + 2\hat{c}_2 + 3\hat{c}_4) \left( (\tilde{\Delta}_{4F})^2 + \frac{1}{4} (\tilde{f}_{\Phi,1})^2 \right) - \frac{\hat{e}^4}{\hat{c}^2} (\tilde{f}_{BW})^2 \right. \\ & \left. + 2 \frac{\hat{e}^2}{\hat{c}^2} \tilde{\Delta}_{4F} \tilde{f}_{BW} - (3 - 2\hat{c}_2 + \hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{\Phi,1} - \hat{e}^2 \frac{\hat{c}_4}{\hat{c}^2} \tilde{f}_{BW} \tilde{f}_{\Phi,1} \right] \\ & \left. - \frac{\hat{e}^2}{4\hat{s}\hat{c}\hat{s}_4} \frac{\hat{v}^4}{\Lambda^4} \left( \tilde{\Delta}_{4F} - \hat{e}^2 \tilde{f}_{BW} + \frac{1}{2} (1 + 2\hat{c}_2) \tilde{f}_{\Phi,1} \right) f_W \right] \end{aligned}$$

Most of it constrained by EWPD

## Part 2: Diboson Data

$$\begin{aligned} \mathcal{L}_{WWV} = & -ig_{WWV} \left\{ g_1^V \left( W_{\mu\nu}^+ W^{-\mu} V^\nu - W_\mu^+ V_\nu W^{-\mu\nu} \right) \right. \\ & \left. + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{\hat{M}_W^2} W_{\mu\nu}^+ W^{-\nu\rho} V_\rho^\mu \right\} \end{aligned}$$

	Channel ( <i>a</i> )	Distribution	# bins	Data set	Int Lum
EWDB data	$WZ \rightarrow \ell^+ \ell^- \ell'^\pm$	$M(WZ)$	7	CMS 13 TeV,	$137.2 \text{ fb}^{-1}$ [46]
	$WW \rightarrow \ell^+ \ell'^{-} + 0/1j$	$M(\ell^+ \ell'^{-})$	11	CMS 13 TeV,	$35.9 \text{ fb}^{-1}$ [47]
	$W\gamma \rightarrow \ell\nu\gamma$	$\frac{d^2\sigma}{dp_T d\phi}$	12	CMS 13 TeV,	$137.1 \text{ fb}^{-1}$ [48]
	$WW \rightarrow e^\pm \mu^\mp + E_T (0j)$	$m_T$	17 (15)	ATLAS 13 TeV,	$36.1 \text{ fb}^{-1}$ [49]
	$WZ \rightarrow \ell^+ \ell^- \ell'^\pm$	$m_T^{WZ}$	6	ATLAS 13 TeV,	$36.1 \text{ fb}^{-1}$ [50]
	$Zjj \rightarrow \ell^+ \ell^- jj$	$\frac{d\sigma}{d\phi}$	12	ATLAS 13 TeV,	$139 \text{ fb}^{-1}$ [51]
	$WW \rightarrow \ell^+ \ell'^{-} + E_T (1j)$	$\frac{d\sigma}{dm_{\ell^+\ell^-}}$	10	ATLAS 13 TeV,	$139 \text{ fb}^{-1}$ [52]

$$\Delta g_1^Z = \frac{\hat{e}^2}{\hat{s}^2 \hat{c}^2} \left[ \frac{1}{8} \frac{\hat{v}^2}{\Lambda^2} \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4 D^2}^{(1)} \right) \right] ,$$

$$\Delta \kappa_\gamma = \frac{\hat{e}^2}{\hat{s}^2} \left[ \frac{1}{8} \frac{\hat{v}^2}{\Lambda^2} \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4 D^2}^{(1)} + f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4 D^2}^{(1)} \right) \right] ,$$

$$\Delta \kappa_Z = \frac{\hat{e}^2}{\hat{s}^2} \left[ \frac{1}{8} \frac{\hat{v}^2}{\Lambda^2} \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4 D^2}^{(1)} \right) - \frac{\hat{s}^2}{8\hat{c}^2} \frac{\hat{v}^2}{\Lambda^2} \left( f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4 D^2}^{(1)} \right) \right] ,$$

$$\lambda_\gamma = \frac{3\hat{e}^2}{2\hat{s}^2} \frac{\hat{M}_W^2}{\Lambda^2} \left[ f_{WWW} + \frac{\hat{v}^2}{2\Lambda^2} f_{W^3 \Phi^2}^{(1)} \right] - \frac{\hat{M}_W^4}{2\Lambda^4} f_{W^2 B\Phi^2}^{(1)} ,$$

$$\lambda_Z = \frac{3\hat{e}^2}{2\hat{s}^2} \frac{\hat{M}_W^2}{\Lambda^2} \left[ f_{WWW} + \frac{\hat{v}^2}{2\Lambda^2} f_{W^3 \Phi^2}^{(1)} \right] + \frac{\hat{M}_W^4}{2\Lambda^4} \frac{\hat{s}^2}{\hat{c}^2} f_{W^2 B\Phi^2}^{(1)}$$

Consider only direct contributions

## Part 2: Diboson Data

effective coefficients

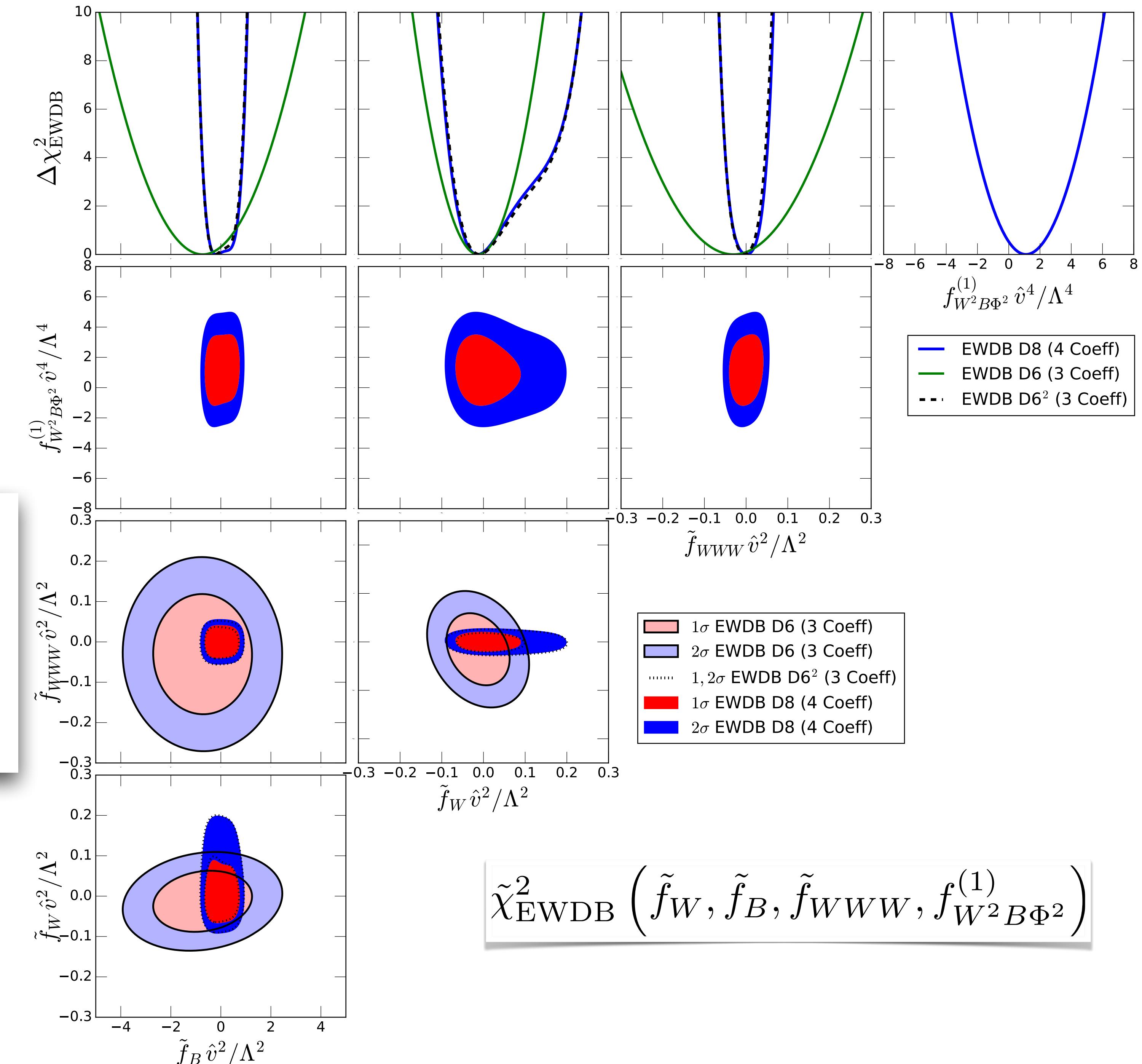
$$\tilde{f}_W = f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4 D^2}^{(1)},$$

$$\tilde{f}_B = f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4 D^2}^{(1)},$$

$$\tilde{f}_{WWW} = f_{WWW} + \frac{\hat{v}^2}{2} f_{W^3 \Phi^2}^{(1)}$$

EWDB 95% CL allowed range			
Coupling	dimension 6	$(\text{dimension 6})^2$	dimension 8
$\frac{\hat{v}^2}{\Lambda^2} \tilde{f}_B$	[-3.3, 1.8]	[-0.75, 0.83]	[-0.73, 0.86]
$\frac{\hat{v}^2}{\Lambda^2} \tilde{f}_W$	[-0.11, 0.085]	[-0.079, 0.16]	[-0.080, 0.16]
$\frac{\hat{v}^2}{\Lambda^2} \tilde{f}_{WWW}$	[-0.22, 0.16]	[-0.049, 0.045]	[-0.048, 0.049]
$\frac{\hat{v}^4}{\Lambda^4} f_{W^2 B \Phi^2}^{(1)}$	—	—	[-1.9, 4.2]

$\mathcal{O}(1/\Lambda^4)$  contributions  
strengthen bounds on  
 $\mathcal{O}_B, \mathcal{O}_{WWW}$



$$\tilde{\chi}_{\text{EWDB}}^2 \left( \tilde{f}_W, \tilde{f}_B, \tilde{f}_{WWW}, f_{W^2 B \Phi^2}^{(1)} \right)$$

## Part 2: Diboson Data

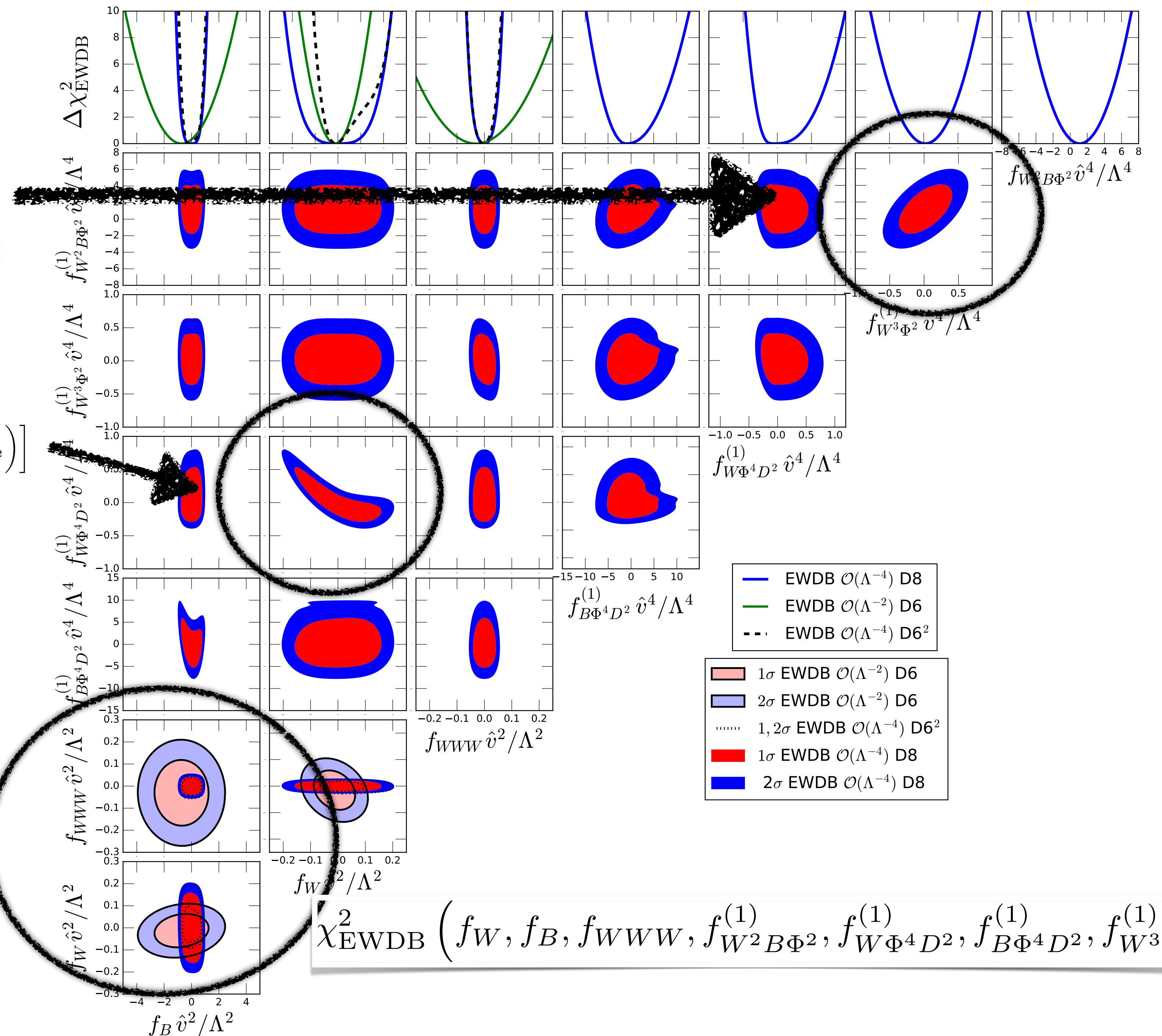
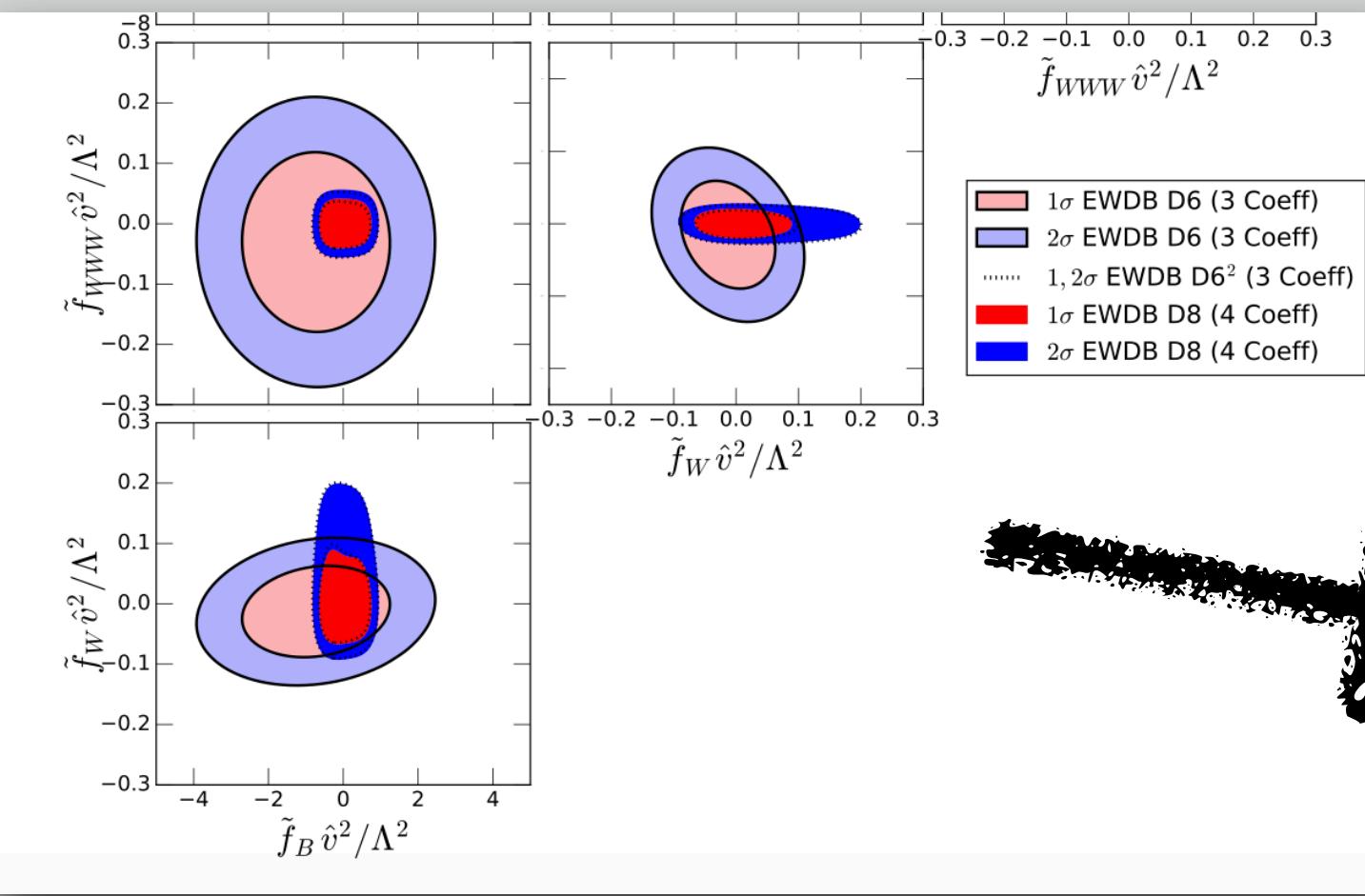
$$\lambda_\gamma = \frac{3\hat{e}^2}{2\hat{s}^2} \frac{\hat{M}_W^2}{\Lambda^2} \left[ f_{WWW} + \frac{\hat{v}^2}{2\Lambda^2} f_{W^3\Phi^2}^{(1)} \right] - \frac{\hat{M}_W^4}{2\Lambda^4} f_{W^2B\Phi^2}^{(1)},$$

$$\lambda_Z = \frac{3\hat{e}^2}{2\hat{s}^2} \frac{\hat{M}_W^2}{\Lambda^2} \left[ f_{WWW} + \frac{\hat{v}^2}{2\Lambda^2} f_{W^3\Phi^2}^{(1)} \right] + \frac{\hat{M}_W^4}{2\Lambda^4} \frac{\hat{s}^2}{\hat{c}^2} f_{W^2B\Phi^2}^{(1)}$$

$$\Delta g_1^Z = \frac{\hat{e}^2}{\hat{s}^2 \hat{c}^2} \left[ \frac{1}{8} \frac{\hat{v}^2}{\Lambda^2} \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4D^2}^{(1)} \right) \right],$$

$$\Delta \kappa_\gamma = \frac{\hat{e}^2}{\hat{s}^2} \left[ \frac{1}{8} \frac{\hat{v}^2}{\Lambda^2} \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4D^2}^{(1)} + f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4D^2}^{(1)} \right) \right],$$

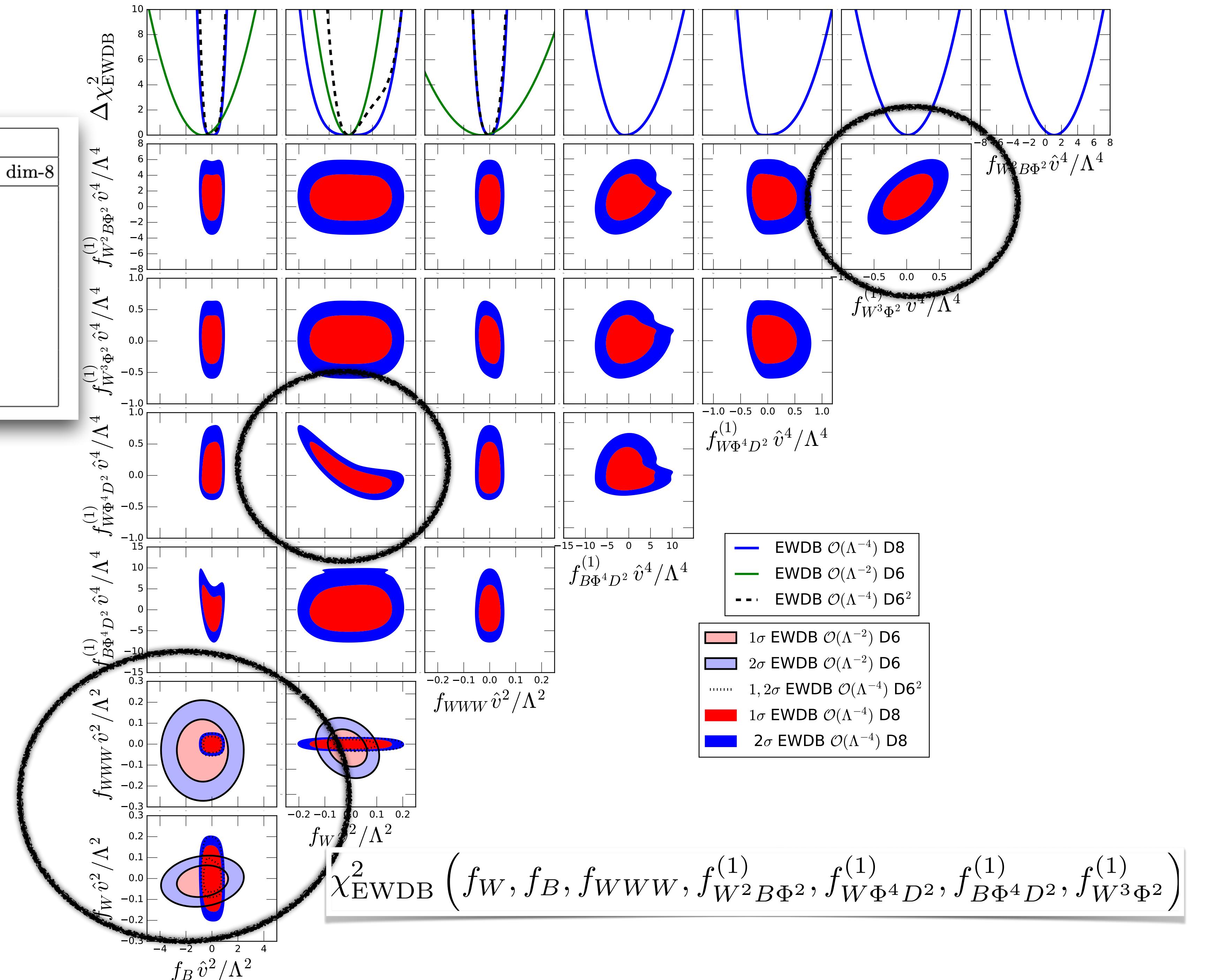
$$\Delta \kappa_Z = \frac{\hat{e}^2}{\hat{s}^2} \left[ \frac{1}{8} \frac{\hat{v}^2}{\Lambda^2} \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4D^2}^{(1)} \right) - \frac{\hat{s}^2}{8\hat{c}^2} \frac{\hat{v}^2}{\Lambda^2} \left( f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4D^2}^{(1)} \right) \right]$$



## Part 2: Diboson Data

Coefficient	EWPB 95% CL allowed range		
	$\mathcal{O}(\Lambda^{-2})$	$\mathcal{O}(\Lambda^{-4}) (\text{dim-6})^2$	$\mathcal{O}(\Lambda^{-4}) (\text{dim-6})^2 + \text{dim-8}$
$\frac{\hat{v}^2}{\Lambda^2} f_B$	[-3.3, 1.8]	[-0.75, 0.83]	[-0.89, 0.89]
$\frac{\hat{v}^2}{\Lambda^2} f_W$	[-0.11, 0.085]	[-0.079, 0.16]	[-0.18, 0.18]
$\frac{\hat{v}^2}{\Lambda^2} f_{WWW}$	[-0.22, 0.16]	[-0.049, 0.045]	[-0.05, 0.05]
$\frac{\hat{v}^4}{\Lambda^4} f_{W^2 B \Phi^2}^{(1)}$	—	—	[-2.6, 5.0]
$\frac{\hat{v}^4}{\Lambda^4} f_{B \Phi^4 D^2}$	—	—	[-6.48, 7.8]
$\frac{\hat{v}^4}{\Lambda^4} f_{W \Phi^4 D^2}$	—	—	[-0.33, 0.66]
$\frac{\hat{v}^4}{\Lambda^4} f_{W^3 \Phi^2}$	—	—	[-0.47, 0.51]

$\mathcal{O}(1/\Lambda^4)$  contributions  
strengthen bounds on  
 $\mathcal{O}_B, \mathcal{O}_{WWW}$



## Summary and Conclusion

- Study of impact of  $1/\Lambda^4$  corrections in EWPO and EWDB
- Inclusion of dim-8 operators in universal theory, CP conservation
- EWPO study with effective coefficients
- TGC analysis mostly impacted by dim-6 squared
- Energy dependence allows to constrain all coefficients independently

Future: We expect stronger bounds on TGC in the future

→ combined analysis:

Inclusion of indirect contributions, possible anomalous fermionic couplings

Backup

# Energy dependence of amplitudes

$$\begin{aligned} \mathcal{M}(d_- \bar{d}_+ \rightarrow W_0^+ W_0^-) &= -i \frac{\hat{e}^2}{24\hat{s}^2\hat{c}^2} \frac{\hat{S}}{\Lambda^2} \sin \theta \left[ 3\hat{c}^2 f_W - \hat{s}^2 f_B + \frac{\hat{v}^2}{2\Lambda^2} \left( 3\hat{c}^2 f_{W\Phi^4D^2}^{(1)} - \hat{s}^2 f_{B\Phi^4D^2}^{(1)} \right) \right], \\ \mathcal{M}(d_+ \bar{d}_- \rightarrow W_\pm^+ W_\pm^-) &= i \frac{\hat{e}^2}{48\hat{s}^2\hat{c}^2} \frac{\hat{S}}{\Lambda^2} \sin \theta \frac{\hat{v}^2}{\Lambda^2} f_{W^2B\Phi^2}^{(1)}, \\ \mathcal{M}(d_- \bar{d}_+ \rightarrow W_\pm^+ W_\pm^-) &= -i \frac{3\hat{e}^4}{8\hat{s}^4} \frac{\hat{S}}{\Lambda^2} \sin \theta \left[ f_{WWW} + \frac{\hat{v}^2}{2\Lambda^2} \left( f_{W^3\Phi^2}^{(1)} + \frac{\hat{s}^2}{18\hat{c}^2} f_{W^2B\Phi^2}^{(1)} \right) \right], \\ \mathcal{M}(d_+ \bar{d}_- \rightarrow W_0^+ W_0^-) &= -i \frac{\hat{e}^2}{12\hat{c}^2} \frac{\hat{S}}{\Lambda^2} \sin \theta \left( f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4D^2}^{(1)} \right), \\ \mathcal{M}(u_- \bar{u}_+ \rightarrow W_0^+ W_0^-) &= i \frac{\hat{e}^2}{24\hat{s}^2\hat{c}^2} \frac{\hat{S}}{\Lambda^2} \sin \theta \left[ 3\hat{c}^2 f_W + \hat{s}^2 f_B + \frac{\hat{v}^2}{2\Lambda^2} \left( 3\hat{c}^2 f_{W\Phi^4D^2}^{(1)} + \hat{s}^2 f_{B\Phi^4D^2}^{(1)} \right) \right], \\ \mathcal{M}(u_+ \bar{u}_- \rightarrow W^+ W^-) &= i \frac{\hat{e}^2}{6\hat{c}^2} \frac{\hat{S}}{\Lambda^2} \sin \theta \left( f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4D^2}^{(1)} \right), \\ \mathcal{M}(u_+ \bar{u}_- \rightarrow W_\pm^+ W_\pm^-) &= -i \frac{\hat{e}^4}{24\hat{s}^2\hat{c}^2} \frac{\hat{S}}{\Lambda^2} \sin \theta \frac{\hat{v}^2}{\Lambda^2} f_{W^2B\Phi^2}^{(1)}, \\ \mathcal{M}(u_+ \bar{u}_- \rightarrow W^+ W^-) &= i \frac{\hat{e}^2}{6\hat{c}^2} \frac{\hat{S}}{\Lambda^2} \sin \theta \left( f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4D^2}^{(1)} \right), \\ \mathcal{M}(u_+ \bar{u}_- \rightarrow W_\pm^+ W_\pm^-) &= -i \frac{\hat{e}^4}{24\hat{s}^2\hat{c}^2} \frac{\hat{S}}{\Lambda^2} \sin \theta \frac{\hat{v}^2}{\Lambda^2} f_{W^2B\Phi^2}^{(1)}, \\ \mathcal{M}(u_- \bar{u}_+ \rightarrow W_\pm^+ W_\pm^-) &= i \frac{3\hat{e}^4}{8\hat{s}^4} \frac{\hat{S}}{\Lambda^2} \sin \theta \left[ f_{WWW} + \frac{\hat{v}^2}{2\Lambda^2} \left( f_{W^3\Phi^2}^{(1)} - \frac{\hat{s}^2}{18\hat{c}^2} f_{W^2B\Phi^2}^{(1)} \right) \right] \end{aligned}$$

$$\mathcal{M}\left(d_{-}\bar{u}_{+} \rightarrow Z_{\pm}W_{\pm}^{-}\right) = i\frac{3\hat{c}\hat{e}^4}{4\sqrt{2}\hat{s}^4}\frac{\hat{S}}{\Lambda^2}\sin\theta\left[f_{WWW}+\frac{\hat{v}^2}{2\Lambda^2}\left(f^{(1)}_{W^3\Phi^2}+\frac{\hat{s}^2}{6\hat{c}^2}f^{(1)}_{W^2B\Phi^2}\right)\right]\,,$$

$$\mathcal{M}\left(d_{-}\bar{u}_{+} \rightarrow Z_0W_0^{-}\right) = i\frac{\hat{e}^2}{4\sqrt{2}\hat{s}^2}\frac{\hat{S}}{\Lambda^2}\sin\theta\left(f_W+\frac{\hat{v}^2}{2\Lambda^2}f^{(1)}_{W\Phi^4D^2}\right)\,,$$

$$\mathcal{M}\left(d_{-}\bar{u}_{+} \rightarrow \gamma_{\pm}W_{\pm}^{-}\right) = i\frac{3\hat{e}^4}{4\sqrt{2}\hat{s}^3}\frac{\hat{S}}{\Lambda^2}\sin\theta\left[f_{WWW}+\frac{\hat{v}^2}{2\Lambda^2}\left(f^{(1)}_{W^3\Phi^2}-\frac{1}{6}f^{(1)}_{W^2B\Phi^2}\right)\right]$$

# Corrections to the Z and W couplings

$$\begin{aligned}
\Delta g_1 = & -\frac{1}{4} \frac{\hat{v}^2}{\Lambda^2} \left[ 2 \left( \Delta_{4F} + \frac{\hat{v}^2}{\Lambda^2} \Delta_{4F}^{(8)} \right) + f_{\Phi,1} + \frac{\hat{v}^2}{\Lambda^2} f_{D^2 \Phi^6}^{(2)} \right] \\
& - \frac{1}{32} \frac{\hat{v}^4}{\Lambda^4} \left[ -12(\Delta_{4F})^2 + 4\Delta_{4F}f_{\Phi,1} - 3(f_{\Phi,1})^2 \right] \\
\simeq & -\frac{1}{4} \frac{\hat{v}^2}{\Lambda^2} \left[ 2\tilde{\Delta}_{4F} + \tilde{f}_{\Phi,1} \right] - \frac{1}{32} \frac{\hat{v}^4}{\Lambda^4} \left[ -12(\tilde{\Delta}_{4F})^2 + 4\tilde{\Delta}_{4F}\tilde{f}_{\Phi,1} - 3(\tilde{f}_{\Phi,1})^2 \right] \\
\Delta g_2 = & \frac{\hat{v}^2}{\Lambda^2} \frac{1}{2\hat{c}_2} \left[ -\hat{s}^2 \hat{c}^2 \left( 2\tilde{\Delta}_{4F} + \tilde{f}_{\Phi,1} \right) + \frac{\hat{e}^2}{2} \tilde{f}_{BW} \right] \\
& + \frac{\hat{v}^4}{\Lambda^4} \frac{1}{8\hat{c}_2^3} \left\{ \frac{\hat{s}_2^2}{4} \left[ (1+3\hat{c}_4) \left( (\tilde{\Delta}_{4F})^2 + \frac{1}{4}(\tilde{f}_{\phi,1})^2 \right) - (3+\hat{c}_4)\tilde{\Delta}_{4F}\tilde{f}_{\phi,1} \right] \right. \\
& \left. - \frac{\hat{e}^2}{2} \left( \hat{c}_4 \tilde{f}_{BW} \tilde{f}_{\phi,1} - 2\tilde{\Delta}_{4F}\tilde{f}_{BW} + \hat{e}^2(\tilde{f}_{BW})^2 \right) \right\}
\end{aligned}$$

# Corrections to the Z and W couplings

$$\begin{aligned} \frac{\Delta M_W}{\hat{M}_W} = & \frac{1}{4\hat{c}_2} \frac{\hat{v}^2}{\Lambda^2} \left[ \hat{e}^2 \tilde{f}_{BW} - 2\hat{s}^2 \tilde{\Delta}_{4F} - \hat{c}^2 \tilde{f}_{\Phi,1} \right] + \frac{\hat{e}^2}{8\hat{s}^2} \frac{\hat{v}^4}{\Lambda^4} f_{W^2\Phi^4}^{(3)} \\ & + \frac{1}{8\hat{c}_2^3} \frac{\hat{v}^4}{\Lambda^4} \left[ -\hat{s}^4 (2 + 3\hat{c}_2) (\tilde{\Delta}_{4F})^2 + \frac{1}{4} \hat{c}^4 (-2 + 5\hat{c}_2) (\tilde{f}_{\Phi,1})^2 - \frac{1}{16} \hat{e}^4 \frac{(7 - 6\hat{c}_2 + 3\hat{c}_4)}{\hat{s}^2} (\tilde{f}_{BW})^2 \right. \\ & \left. - \frac{\hat{c}^2}{4} (9 - 6\hat{c}_2 + 5\hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{\Phi,1} + \frac{1}{4} \hat{e}^2 (7 - 2\hat{c}_2 + 3\hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{BW} - \frac{1}{2} \hat{e}^2 \hat{c}^2 (-2 + 3\hat{c}_2) \tilde{f}_{\Phi,1} \tilde{f}_{BW} \right] \end{aligned}$$

$$\begin{aligned} \Delta g_W = & \frac{1}{4\hat{c}_2} \frac{\hat{v}^2}{\Lambda^2} \left[ \hat{e}^2 \tilde{f}_{BW} - 2\hat{c}^2 \tilde{\Delta}_{4F} - \hat{c}^2 \tilde{f}_{\Phi,1} \right] \\ & + \frac{1}{8\hat{c}_2^3} \frac{\hat{v}^4}{\Lambda^4} \left[ \hat{e}^2 \frac{\hat{c}_2^3}{\hat{s}^2} f_{W^2\Phi^4}^{(3)} + \hat{c}^4 (-2 + 5\hat{c}_2) (\tilde{\Delta}_{4F})^2 - \frac{1}{16} \frac{(7 - 6\hat{c}_2 + 3\hat{c}_4)}{\hat{s}^2} \hat{e}^4 (\tilde{f}_{BW})^2 \right. \\ & + \frac{1}{4} \hat{c}^4 (-2 + 5\hat{c}_2) (\tilde{f}_{\Phi,1})^2 - \frac{1}{4} \hat{c}^2 (7 - 6\hat{c}_2 + 3\hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{\Phi,1} + \frac{1}{4} \hat{e}^2 (5 - 2\hat{c}_2 + \hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{BW} \\ & \left. - \frac{1}{2} \hat{e}^2 \hat{c}^2 (-2 + 3\hat{c}_2) \tilde{f}_{\Phi,1} \tilde{f}_{BW} \right] \end{aligned}$$

$$\frac{\hat{e}}{\hat{s}} (1 + \Delta g_W)$$

# Corrections to TGC

$$\begin{aligned}
g_1^Z = & 1 + \frac{1}{2} \frac{\hat{v}^2}{\Lambda^2} \left[ \frac{\hat{e}^2}{4\hat{s}^2\hat{c}^2} \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4D^2}^{(1)} \right) - \frac{1}{\hat{c}_2} \tilde{\Delta}_{4F} + \frac{1}{2} \frac{\hat{e}^2}{\hat{c}^2\hat{c}_2} \tilde{f}_{BW} - \frac{1}{2\hat{c}_2} \tilde{f}_{\Phi,1} \right] \\
& + \frac{1}{16\hat{c}_2^3} \frac{\hat{v}^4}{\Lambda^4} \left[ (1 + 2\hat{c}_2 + 3\hat{c}_4) \left( (\tilde{\Delta}_{4F})^2 + \frac{1}{4} (\tilde{f}_{\Phi,1})^2 \right) - \frac{\hat{e}^4}{\hat{c}^2} (\tilde{f}_{BW})^2 \right. \\
& \left. + 2 \frac{\hat{e}^2}{\hat{c}^2} \tilde{\Delta}_{4F} \tilde{f}_{BW} - (3 - 2\hat{c}_2 + \hat{c}_4) \tilde{\Delta}_{4F} \tilde{f}_{\Phi,1} - \hat{e}^2 \frac{\hat{c}_4}{\hat{c}^2} \tilde{f}_{BW} \tilde{f}_{\Phi,1} \right] \\
& - \frac{\hat{e}^2}{4\hat{s}\hat{c}\hat{s}_4} \frac{\hat{v}^4}{\Lambda^4} \left( \tilde{\Delta}_{4F} - \hat{e}^2 \tilde{f}_{BW} + \frac{1}{2} (1 + 2\hat{c}_2) \tilde{f}_{\Phi,1} \right) f_W
\end{aligned}$$

$$\begin{aligned}
\kappa_\gamma = & 1 + \frac{1}{8} \frac{\hat{e}^2}{\hat{s}^2} \frac{\hat{v}^2}{\Lambda^2} \left[ \left( f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4D^2}^{(1)} \right) + \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4D^2}^{(1)} \right) - 2\tilde{f}_{BW} \right] \\
& - \frac{\hat{e}^2}{32} \frac{\hat{v}^4}{\Lambda^4} \frac{1}{\hat{s}^2\hat{c}_2} \left( 2(1 - \hat{c}_2) \tilde{\Delta}_{4F} - 2\hat{e}^2 \tilde{f}_{BW} + (1 + \hat{c}_2) \tilde{f}_{\Phi,1} \right) (f_B + f_W - 2\tilde{f}_{BW}) \\
& + \frac{\hat{e}^2}{4\hat{s}^2} \frac{\hat{v}^4}{\Lambda^4} f_{W^2\Phi^4}^{(3)}
\end{aligned}$$

# Corrections

## to TGC

$$\kappa_Z = 1 + \frac{1}{8} \frac{\hat{e}^2}{\hat{s}^2} \frac{\hat{v}^2}{\Lambda^2} \left[ \left( f_W + \frac{\hat{v}^2}{2\Lambda^2} f_{W\Phi^4D^2}^{(1)} \right) - \frac{\hat{s}^2}{\hat{c}^2} \left( f_B + \frac{\hat{v}^2}{2\Lambda^2} f_{B\Phi^4D^2}^{(1)} \right) + \frac{4\hat{s}^2}{\hat{c}_2} \tilde{f}_{BW} - \frac{4\hat{s}^2}{\hat{e}^2 \hat{c}_2} \tilde{\Delta}_{4F} - \frac{2\hat{s}^2}{\hat{e}^2 \hat{c}_2} \tilde{f}_{\Phi,1} \right]$$

$$+ \frac{1}{16\hat{s}^2 \hat{c}_2^3} \frac{\hat{v}^4}{\Lambda^4} \left[ \hat{s}^2 (1 + 2\hat{c}_2 + 3\hat{c}_4) \left( (\tilde{\Delta}_{4F})^2 + \frac{1}{4} (\tilde{f}_{\Phi,1})^2 \right) - \hat{e}^4 (2 - 2\hat{c}_2 + \hat{c}_4) (\tilde{f}_{BW})^2 \right.$$

$$+ \hat{s}^2 (3 - 2\hat{c}_2 + \hat{c}_4) \left( 2\hat{e}^2 \tilde{\Delta}_{4F} \tilde{f}_{BW} - \tilde{\Delta}_{4F} \tilde{f}_{\phi,1} \right) - \hat{e}^2 \hat{s}^2 (-1 + 2\hat{c}_2 + \hat{c}_4) \tilde{f}_{BW} \tilde{f}_{\Phi,1}$$

$$+ f_W \left( \hat{e}^2 \hat{c}_2^2 (-2 + \hat{c}_2) \tilde{\Delta}_{4F} + \hat{e}^2 \frac{\hat{c}_2^2}{2} (2 + \hat{c}_2) \left( \frac{\hat{e}^2}{\hat{c}^2} \tilde{f}_{BW} - \tilde{f}_{\Phi,1} \right) \right)$$

$$\left. + f_B \hat{e}^2 \frac{\hat{s}^2 \hat{c}_2^3}{2\hat{c}^2} \left( \tilde{f}_{\Phi,1} - 2\tilde{\Delta}_{4F} + \frac{\hat{e}^2}{\hat{s}^2} \tilde{f}_{BW} \right) + 4\hat{e}^2 \hat{c}_2^3 f_{W^2\Phi^4}^{(3)} \right]$$

$$\lambda_\gamma = \frac{3}{2} \frac{\hat{e}^2}{\hat{s}^2} \frac{\hat{M}_W^2}{\Lambda^2} \left[ \left( f_{WWW} + \frac{\hat{v}^2}{2\Lambda^2} f_{W^3\Phi^2}^{(1)} \right) \right.$$

$$\left. + \frac{1}{2\hat{c}_2} \frac{\hat{v}^2}{\Lambda^2} f_{WWW} \left( \hat{e}^2 \tilde{f}_{BW} - (2\tilde{\Delta}_{4F} + \tilde{f}_{\Phi,1}) \hat{c}^2 \right) \right] - \frac{\hat{M}_W^4}{2\Lambda^4} f_{W^2B\Phi^2}^{(1)} ,$$

$$\lambda_Z = \frac{3}{2} \frac{\hat{e}^2}{\hat{s}^2} \frac{\hat{M}_W^2}{\Lambda^2} \left[ \left( f_{WWW} + \frac{\hat{v}^2}{2\Lambda^2} f_{W^3\Phi^2}^{(1)} \right) \right.$$

$$\left. - \frac{\hat{v}^2}{\Lambda^2} \frac{\hat{s}^2 (2 + \hat{c}_2)}{\hat{s}_2 \hat{s}_4} f_{WWW} \left( 4\tilde{\Delta}_{4F} \hat{c}^2 + 2\tilde{f}_{\Phi,1} \hat{c}^2 - 2\hat{e}^2 \tilde{f}_{BW} \right) \right] + \frac{\hat{M}_W^4}{2\Lambda^4} \frac{\hat{s}^2}{\hat{c}^2} f_{W^2B\Phi^2}^{(1)}$$