Electroweak Sector Under Scrutiny: A Combined Analysis of LHC and Electroweak Precision Data

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elusives
neutrinos, dark matter & dark energy physics

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Where are we standing?

- The search for direct NP did not show any new state.
- Probably they are heavy and there might exist a gap between them and the SM states.

The remarkable success of the SM and the lack of unexpected particles motivates to use a different approach to study NP.

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Two different conceptual routes to aproach the NP problem

Build a Model
Make predictions

Parametrize posible deviations
from SM by higher-dimension operators

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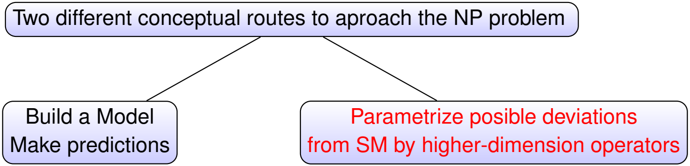
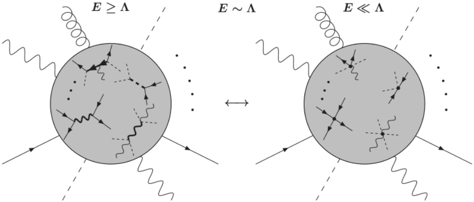


Effective Lagrangian: Linear realization

- We parametrize new physics in terms of a linear effective Lagrangian, with a light Higgs:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{n>4,j} \frac{f_{n,j}}{\Lambda^{n-4}} \mathcal{O}_{n,j}$$



Particle content: Same as the SM. No undiscovered particle at low energy.
Symmetries: The SM gauge symmetry $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ is linearly realized. The lepton and baryon numbers are conserved.

- There exist **59 Dimension-6 operators**.

[Grzadkowski et al. arXiv: 1008.4884]

# of relevant operators can be reduced by several considerations

Data-driven: **TGC, EWPD, Higgs**	**Operator basis HISZ** (EOM to eliminate redudant ones)	NP conserves **C and P symmetries**

Electroweak precision data (EWPD)

- The EWPD receives linear contribution from operators involving fermions, gauge bosons and the Higgs field:

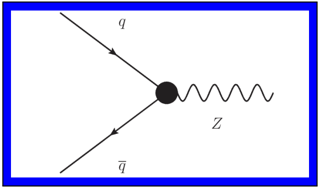
$$\mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_i\gamma^\mu L_j) \;, \qquad \mathcal{O}^{(3)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{L}_i\gamma^\mu T_a L_j) \;,$$

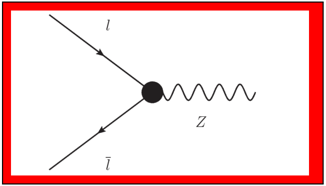
$$\mathcal{O}^{(1)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}_i\gamma^\mu Q_j) \;, \qquad \mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}_i\gamma^\mu T_a Q_j) \;,$$

$$\mathcal{O}^{(1)}_{\Phi u,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu u_{R_j}) \;, \qquad \mathcal{O}^{(1)}_{\Phi d,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{d}_{R_i}\gamma^\mu d_{R_j}) \;,$$

$$\mathcal{O}^{(1)}_{\Phi e,ij} = \Phi^\dagger(\overleftrightarrow{D}_\mu\Phi)(\bar{e}_{R_i}\gamma^\mu e_{R_j}) \;,$$

$$\Phi^\dagger\overleftrightarrow{D}_\mu\Phi = \Phi^\dagger D_\mu\Phi - (D_\mu\Phi)^\dagger\Phi \,, \quad \Phi^\dagger\overleftrightarrow{D}^a_\mu\Phi = \Phi^\dagger T^a D_\mu\Phi - (D_\mu\Phi)^\dagger T^a\Phi \,, \quad T^a = \sigma^a/2$$





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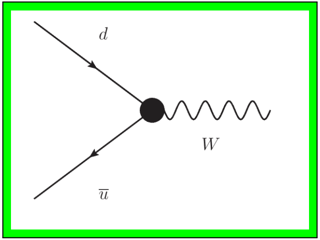
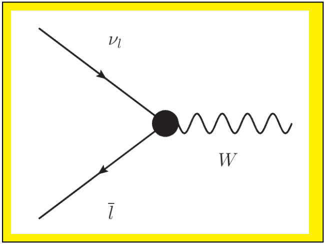




Electroweak precision data (EWPD)

- We also have the contribution of a purely fermion operator and bosonic operators to the EWPD:

$$\mathcal{O}_{BW} = \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \,, \quad \mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi) \quad \mathcal{O}_{LLLL} = (\bar{L}\gamma^\mu L)(\bar{L}\gamma^\mu L) \quad .$$

- $\mathcal{O}_{\Phi,1}$ and $\mathcal{O}_{BW}$ contributions are ubiquitous and stem from their effect on the finite renormalization of the SM fields and couplings once the lagrangian is canonically normalized (**corrections to the S and T oblique parameters**). $\mathcal{O}_{LLLL}$ gives a finite contribution to the Fermi constant.

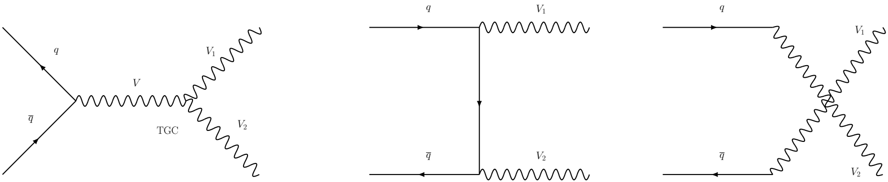
- Altogether the part of the dimension–six effective lagrangian that contributes to the EWPD is,

$$\begin{aligned} \Delta\mathcal{L}_{\rm eff}^{\rm EWPD} &= \frac{f_{\Phi Q}^{(1)}}{\Lambda^2}\mathcal{O}_{\Phi Q}^{(1)} + \frac{f_{\Phi Q}^{(3)}}{\Lambda^2}\mathcal{O}_{\Phi Q}^{(3)} + \frac{f_{\Phi u}^{(1)}}{\Lambda^2}\mathcal{O}_{\Phi u}^{(1)} + \frac{f_{\Phi d}^{(1)}}{\Lambda^2}\mathcal{O}_{\Phi d}^{(1)} + \frac{f_{\Phi e}^{(1)}}{\Lambda^2}\mathcal{O}_{\Phi e}^{(1)} \\ &+ \frac{f_{BW}}{\Lambda^2}\mathcal{O}_{BW} + \frac{f_{\Phi,1}}{\Lambda^2}\mathcal{O}_{\Phi,1} + \frac{f_{LLLL}}{\Lambda^2}\mathcal{O}_{LLLL} \quad . \end{aligned}$$

NO BLIND DIRECTIONS !!!! Fully advantage of the EWPD.

Triple Gauge Couplings (TGC) motivation

- The trilinear and quartic vector-boson couplings are completely determined by the gauge symmetry (SM).
- The scrutiny of these interactions can either lead to **an additional confirmation of the SM or give some hint on the existence of new phenomena at a higher scale**.
- TGC as well as fermion pair-gauge boson couplings contribute to WW and WZ productions.



Triple Gauge Couplings (TGC) parametrization

- The most general parametrization that describes the WWV vertices $(V = Z, \gamma)$ and it is Lorentz invariant can be cast as:

$$\mathcal{L}_{WWV} = -ig_{WWV} \Big[g_1^V \left(W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu} \right) V^\nu + k_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^+_{\lambda\mu} W^{-\mu}_\nu V^{\nu\lambda} \Big]$$

where $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$.

- Any departure from the SM can be parametrized as a shift of the dimensionless couplings,

$$g_i^V \to g_i^{V(SM)} + \Delta g_i^V .$$

Electromagnetic invariance $\Rightarrow g_1^\gamma = 1$

$$g_{WW\gamma} \equiv e = g \sin\theta \qquad g_1^{Z(SM)} = k_\gamma^{(SM)} = k_Z^{(SM)} = 1$$

$$g_{WWZ} = g \cos\theta$$

Triple Gauge Couplings and the d=6 dictionary

- The relevant subset of C and P even bosonic operators in the HISZ basis relevant to the TGC:

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger \widehat{W}^{\mu\nu}(D_\nu\Phi) \quad , \quad \mathcal{O}_B = (D_\mu\Phi)^\dagger \widehat{B}^{\mu\nu}(D_\nu\Phi) \quad ,$$

$$\mathcal{O}_{BW} = \Phi^\dagger \widehat{B}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi \quad , \qquad \mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger \Phi\Phi^\dagger (D^\mu\Phi)$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}[\widehat{W}_\mu^\nu \widehat{W}_\nu^\rho \widehat{W}_\rho^\mu] \quad .$$

$$\Delta g_1^Z = g_1^Z - 1 = \frac{g^2 v^2}{8c_W^2\Lambda^2}\left(f_W + 2\frac{s_\theta^2}{c_{2\theta}}f_{BW}\right) - 1\frac{1}{4c_{2\theta}}f_{\phi,1}\frac{v^2}{\Lambda^2} \ ,$$

$$\Delta k_\gamma = k_\gamma - 1 = \frac{g^2 v^2}{8\Lambda^2}\left(f_W - f_B - 2f_{BW}\right) \ ,$$

$$\Delta k_Z = k_Z - 1 = \frac{g^2 v^2}{8c_\theta^2\Lambda^2}\left(c_\theta^2 f_W - s_\theta^2 f_B + \frac{4s_\theta^2 c_\theta^2}{c_{2\theta}}f_{BW}\right) - \frac{1}{4c_{2\theta}}f_{\phi,1}\frac{v^2}{\Lambda^2} \ ,$$

$$\lambda_\gamma = \lambda_Z = \frac{3g^2 M_W^2}{2\Lambda^2}f_{WWW} \ .$$

Triple Gauge Couplings

- One extra operator that modifies the couplings of W to right-handed quark pairs and does not interfere with the SM contributions to the EWPD observables (linearly),

$$\mathcal{O}^{(1)}_{\Phi ud} = \tilde{\Phi}^\dagger (i\overleftrightarrow{D}_\mu \Phi)(\bar{u}_R \gamma^\mu d_R + \mathrm{h.c.}) \quad .$$

- The effective lagrangian of the operators that contribute to TGC (plus the ones from EWPD):

$$\Delta\mathcal{L}^{\mathrm{TGC}}_{\mathrm{eff}} = \frac{f_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f^{(1)}_{\Phi ud}}{\Lambda^2}\mathcal{O}^{(1)}_{\Phi ud} \quad .$$

Higgs interactions

- The following operators change the Yukawa couplings of the Higgs boson, $\mathcal{L}_{Hff} = g^f_{Hij}\bar{f}_{L_i} f_{R_j} h$

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger\Phi)(\bar{L}_i \Phi e_{R,j}) \quad , \quad \mathcal{O}_{u\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i \tilde{\Phi} u_{R,j}) \quad ,$$

$$\mathcal{O}_{d\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i \Phi d_{R,j}) \quad , \quad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu \left(\Phi^\dagger\Phi\right) \partial_\mu \left(\Phi^\dagger\Phi\right) \quad ,$$

with the respective effective Lagrangian,

$$\Delta\mathcal{L}^{\rm Yuk}_{\rm eff} = \frac{f_\mu m_\mu}{\Lambda^2 v}\mathcal{O}_{e\Phi,22} + \frac{f_\tau m_\tau}{\Lambda^2 v}\mathcal{O}_{e\Phi,33} + \frac{f_b m_b}{\Lambda^2 v}\mathcal{O}_{d\Phi,33} + \frac{f_t m_t}{\Lambda^2 v}\mathcal{O}_{u\Phi,33} + \text{ h.c.}$$

- It is basically a shift in the couplings,

$$g^f_{Hij} = -\frac{m^f_i}{v}\delta_{ij}\left[1 - \frac{v^2}{4\Lambda^2}\left(f_{\phi,1} + 2 f_{\phi,2}\right)\right] + \frac{v^2}{\sqrt{2}\Lambda^2} f_{f\phi,ij} \; .$$

- We consider only **the diagonal couplings, the third family and also muon pairs**, i.e., the ones that being currently tested at LHC.

- The couplings to the Higgs boson are also modified by the following bosonic operators,

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi \; G^a_{\mu\nu} G^{a\mu\nu} \; , \; \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \; , \; \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

Higgs interactions

- The parametrization that describes the HVV vertices and it is Lorentz invariant can be cast as:

$$\mathcal{L}_{HVV} = g_{Hgg} G^a_{\mu\nu} G^{a\mu\nu} + g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} h + g^{(1)}_{HZ\gamma} A_{\mu\nu} Z^{\mu} \partial^{\nu} h + g^{(2)}_{HZ\gamma} A_{\mu\nu} Z^{\mu\nu} h$$
$$+ g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu} \partial^{\nu} h + g^{(2)}_{HZZ} Z_{\mu\nu} Z^{\mu\nu} h + g^{(3)}_{HZZ} Z_{\mu} Z^{\mu} h$$
$$+ g^{(1)}_{HWW} \left(W^+_{\mu\nu} W^{-\mu} \partial^{\nu} h + \text{h.c.} \right) + g^{(2)}_{HWW} W^+_{\mu\nu} W^{-\mu\nu} h + g^{(3)}_{HWW} W^+_{\mu} W^{-\mu} h$$

where the shift to the SM values is $\left(g^{(3)SM}_{HZZ} = \frac{m_Z^2}{v} \; , \quad g^{(3)SM}_{HWW} = \frac{2 m_Z^2 c_\theta^2}{v} \right)$:

$$\Delta g_{Hgg} = -g_s^2 f_{GG} \frac{v}{\Lambda^2} \; , \qquad \Delta g_{H\gamma\gamma} = -\frac{e^2}{4} \left[(f_{BB} + f_{WW}) + f_{BW} \right] \frac{v}{\Lambda^2} \; ,$$

$$\Delta g^{(1)}_{HZ\gamma} = \frac{e^2}{2 s_{2\theta}} (f_W - f_B) \frac{v}{\Lambda^2} \; , \quad \Delta g^{(2)}_{HZ\gamma} = \frac{e^2 c_\theta}{4 s_\theta} \left[2 \frac{s_\theta^2}{c_\theta^2} f_{BB} - 2 f_{WW} + \frac{c_{2\theta}}{c_\theta^2} f_{BW} \right] \frac{v}{\Lambda^2} \; ,$$

$$\Delta g^{(1)}_{HZZ} = \frac{e^2}{4 c_\theta^2} \left[\frac{c_\theta^2}{s_\theta^2} f_W + f_B \right] \frac{v}{\Lambda^2} \; , \; \Delta g^{(2)}_{HZZ} = \frac{e^2 c_\theta^2}{4 s_\theta^2} \left[\frac{s_\theta^4}{c_\theta^4} f_{BB} + f_{WW} + \frac{s_\theta^2}{c_\theta^2} f_{BW} \right] \frac{v}{\Lambda^2} \; ,$$

$$\Delta g^{(3)}_{HZZ} = \frac{m_Z^2}{4} \left[f_{\phi,1} - 2 f_{\phi,2} \right] \frac{v}{\Lambda^2} \; , \; \Delta g^{(1)}_{HWW} = \frac{e^2}{4 s_\theta^2} f_{WW} \frac{v}{\Lambda^2} \; ,$$

$$\Delta g^{(2)}_{HWW} = -\frac{e^2}{2 s_\theta^2} f_{WW} \frac{v}{\Lambda^2} \; , \qquad \Delta g^{(3)}_{HWW} = \frac{m_Z^2 c_\theta^2}{4} \left[\frac{-2 \left(3 c_\theta^2 - s_\theta^2 \right)}{c_{2\theta}} f_{\phi,1} - 4 f_{\phi,2} + \frac{4 e^2}{c_{2\theta}} f_{BW} \right] \frac{v}{\Lambda^2} \; ,$$

$$\boxed{\Delta \mathcal{L}^{\rm HVV}_{\rm eff} = -\frac{\alpha_s}{8\pi} \frac{f_{GG}}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}}$$

Analysis framework

- In the EWPD analysis we take into account 15 observables of which 12 are Z observables and 3 W observables:

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

$$M_W\ ,\ \Gamma_W\ \text{ and }\ \text{Br}(W\to\ell\nu).$$

- We construct a χ^2 function for the EWPD to perform the statistical analysis,

$$\chi^2_{\rm EWPD}(f_{BW}, f_{\Phi,1}, f^{(3)}_{\Phi,Q}, f^{(1)}_{\Phi,Q}, f^{(1)}_{\Phi,u}, f^{(1)}_{\Phi,d}, f^{(1)}_{\Phi,e}, f_{LLLL})\ .$$

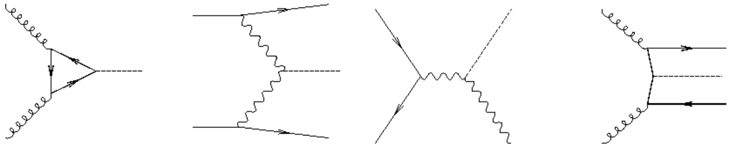
- As for the analysis of TGC, we use the kinematic distribuitions data from W^+W^- and $W^\pm Z$ from ATLAS and CMS collaborations:

Channel (a)	Distribution	# bins	Data set	Int Lum
$WW\to\ell^+\ell'^- + \not{E}_T\ (0j)$	$p_T^{\rm leading,lepton}$	3	ATLAS 8 TeV,	20.3 fb^{-1}
$WW\to\ell^+\ell^{(\prime)-} + \not{E}_T\ (0j)$	$m_{\ell\ell^{(\prime)}}$	8	CMS 8 TeV,	19.4 fb^{-1}
$WZ\to\ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}	6	ATLAS 8 TeV,	20.3 fb^{-1}
$WZ\to\ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	10	CMS 8 TeV,	19.6 fb^{-1}
$WW\to e^\pm\mu^\mp + \not{E}_T\ (0j)$	m_T	17	ATLAS 13 TeV,	36.1 fb^{-1}
$WZ\to\ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}	6	ATLAS 13 TeV,	36.1 fb^{-1}

$$\chi^2_{\rm EWPD+EWDBD}(f_B, f_W, f_{WWW}, f_{BW}, f_{\Phi,1}, f^{(3)}_{\Phi,Q}, f^{(1)}_{\Phi,Q}, f^{(1)}_{\Phi,u}, f^{(1)}_{\Phi,d}, f^{(1)}_{\Phi,ud}, f^{(1)}_{\Phi,e}, f_{LLLL})\ .$$

Analysis framework

- As for Higgs processes, we use the available data from Runs 1 and 2. The main production processes are, $\boldsymbol{ggF}$, $\boldsymbol{VBF}$, $\boldsymbol{VH}$, and $\boldsymbol{t\bar{t}H}$.



- We predict the expected signal strengths in the presence of the new operators, for several final states of the Higgs decay, like $h \to \gamma\gamma, h \to \bar{t}t, h \to \bar{b}b, h \to VV, h \to \gamma Z, h \to \tau\tau, h \to \mu\mu$.

$$\sigma_Y^{ano} = \left.\frac{\sigma_Y^{ano}}{\sigma_Y^{SM}}\right|_{tree} \left.\sigma_Y^{SM}\right|_{soa}, \quad \Gamma^{ano}(h \to X) = \left.\frac{\Gamma^{ano}(h \to X)}{\Gamma^{SM}(h \to X)}\right|_{tree} \left.\Gamma^{SM}(h \to X)\right|_{soa}$$

$$\mu_F = \frac{\epsilon_{gg}^F \sigma_{gg}^{ano}(1+\xi_g) + \epsilon_{VBF}^F \sigma_{VBF}^{ano}(1+\xi_{VBF}) + \epsilon_{WH}^F \sigma_{WH}^{ano}(1+\xi_{VH}) + \epsilon_{ZH}^F \sigma_{ZH}^{ano}(1+\xi_{VH}) + \epsilon_{t\bar{t}H}^F \sigma_{t\bar{t}H}^{ano}}{\epsilon_{gg}^F \sigma_{gg}^{SM} + \epsilon_{VBF}^F \sigma_{VBF}^{SM} + \epsilon_{WH}^F \sigma_{WH}^{SM} + \epsilon_{ZH}^F \sigma_{ZH}^{SM} + \epsilon_{t\bar{t}H}^F \sigma_{t\bar{t}H}^{SM}} \otimes \frac{\mathrm{Br}^{ano}[h \to F]}{\mathrm{Br}^{SM}[h \to F]}$$

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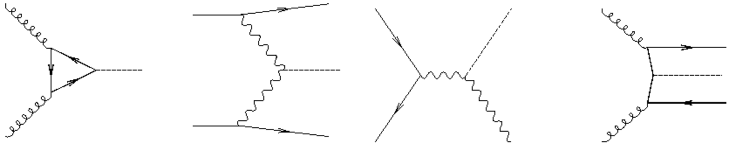

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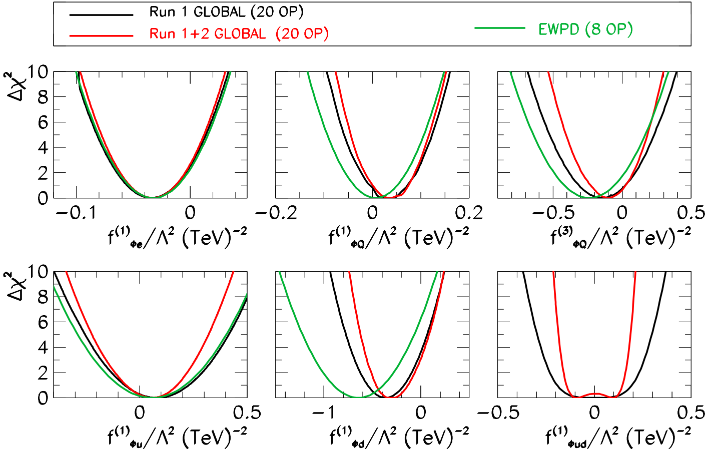
- The statistical comparison of our effective theory predictions with the LHC Runs 1 and 2 data is made by means of a $\chi^2_{\rm Higgs}$ function based on these 22 (Run 1) + 35 (Run 2) data points. Adding to the previous ones, we get:

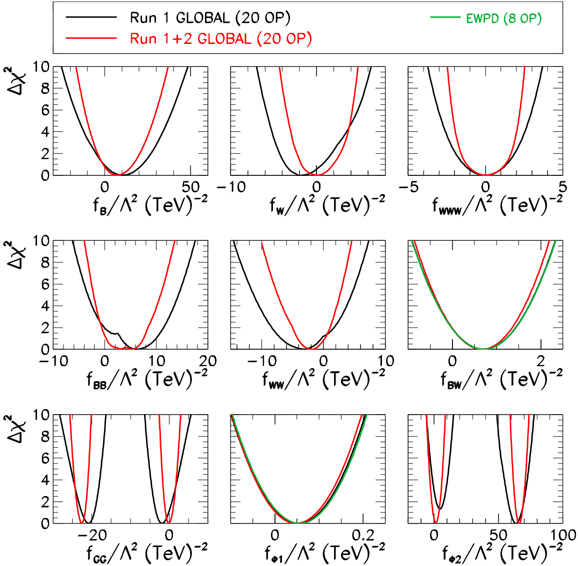
$$\chi^2_{\rm EWPD+EWDBD+Higgs}(f_B, f_W, f_{WWW}, f_{BB}, f_{WW}, f_{BW}, f_{GG}, f_{\Phi,1}, f_{\Phi,2}, f^{(3)}_{\Phi,Q}, f^{(1)}_{\Phi,Q}, f^{(1)}_{\Phi,u}, f^{(1)}_{\Phi,d}, f^{(1)}_{\Phi,ud}, f^{(1)}_{\Phi,e}, f_{LLLL}, f_b, f_t, f_\tau, f_\mu)$$

Results



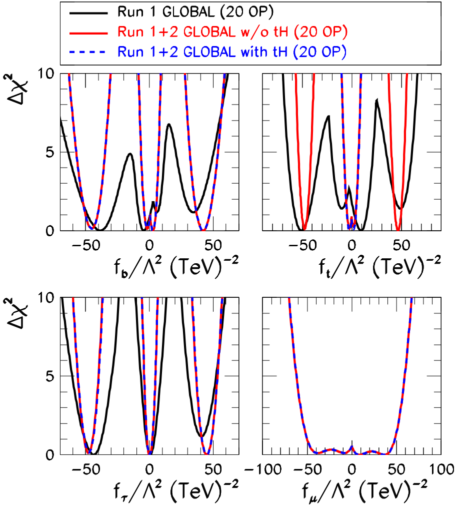
- The EWPD analysis favors non-vanishing value for $f^{(1)}_{\Phi d}/\Lambda^2$ at 2σ, a result driven by the 2.7σ discrepancy between the observed $A^{0,b}_{\mathrm{FB}}$ and the SM.
- No significant discrepancy is observed between the relevant LHC observables, but not negligible, in particular for $f^{(1)}_{\Phi d}/\Lambda^2$.

Results



- We can see that Run 2 data is essential to better constrain these Wilson coefficients, and study the TGC.

Results



- Both ttH and tH (including tHW and tHj) contribute to the cross section ratio.
- It is not possible to determine the relative contribution of tH vs ttH. We show the results for two extreme assumptions.

Ongoing work

- Study the operators which include dipole-like couplings for the quarks.

$$\mathcal{O}_{uW,ij} = i\bar{Q}_i\sigma^{\mu\nu}u_{R,j}\hat{W}_{\mu\nu}\tilde{\Phi}\ , \qquad \mathcal{O}_{uB,ij} = i\bar{Q}_i\sigma^{\mu\nu}u_{R,j}\hat{B}_{\mu\nu}\tilde{\Phi}\ ,$$
$$\mathcal{O}_{dW,ij} = i\bar{Q}_i\sigma^{\mu\nu}d_{R,j}\hat{W}_{\mu\nu}\Phi\ , \qquad \mathcal{O}_{dB,ij} = i\bar{Q}_i\sigma^{\mu\nu}d_{R,j}\hat{B}_{\mu\nu}\Phi$$

$$\mathcal{L} = -\frac{ev}{\sqrt{2}\Lambda^2}\left[F_{f\gamma}\bar{f}\gamma^{\mu\nu}f\partial_\mu A_\nu + F_{fZ}\bar{f}\gamma^{\mu\nu}f\partial_\mu Z_\nu + \left(\bar{f}\sigma^{\mu\nu}\left(F^L_{ff'W}L + F^R_{ff'W}R\right)f'\partial_\mu W^+_\nu + h.c.\right)\right]$$

$$F_{u\gamma} = f_{uW} + f_{uB}\ ,\ F_{d\gamma} = f_{dW} - f_{dB}$$

$\Rightarrow$ **Anomalous magnetic moment**

$$F^R_{udW} = \frac{1}{s_W}f_{uW}\ ,\ F^L_{udW} = \frac{1}{s_W}f_{dW}$$

$\Rightarrow$ **W boson width decay**

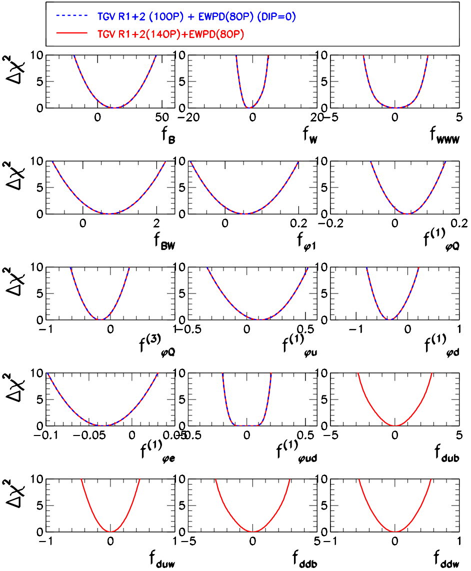
$$F_{uZ} = \frac{c_W}{s_W}f_{uW} - \frac{s_W}{c_W}f_{uB}\ ,\ F_{dZ} = \frac{c_W}{s_W}f_{dW} - \frac{s_W}{c_W}f_{dB}$$

$\Rightarrow$ **Z boson width decay**

- Can be constrainted by the fit to the LEP observables.

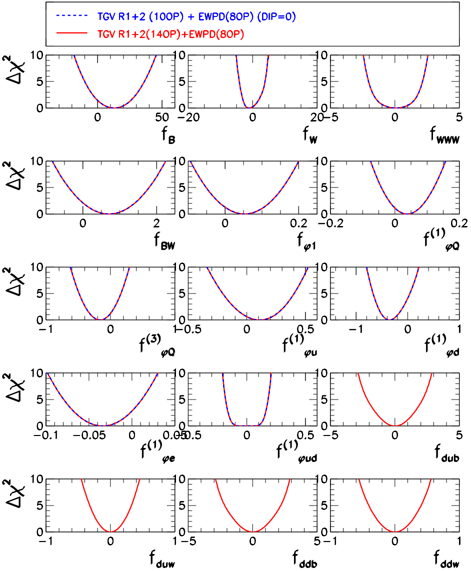
Have these operators any impact on the TGV analysis?

Impact of the dipole operators on the TGV



- The impact of the dipoles is minimum.
- Neverthless the TGV can impose strong bounds on the dipole operators!

Impact of the dipole operators on the TGV



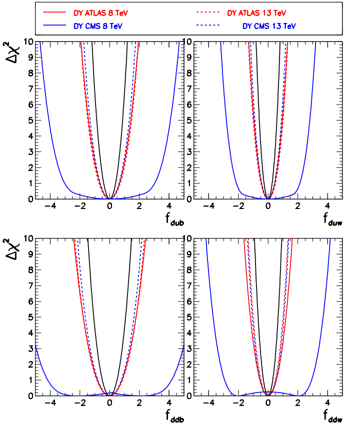
- The impact of the dipoles is minimum.
- Neverthless the TGV can impose strong bounds on the dipole operators!

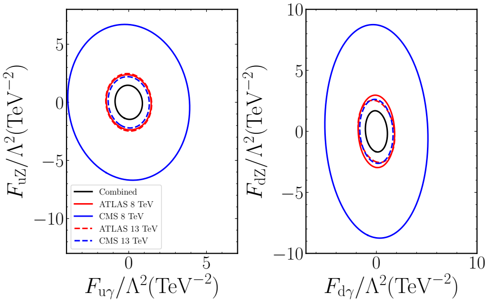
How these bounds are comparable with other data set?

Other bounds on the dipole operators

- Drell-Yan cross section at CMS and ATLAS can also impose bounds on these operators.

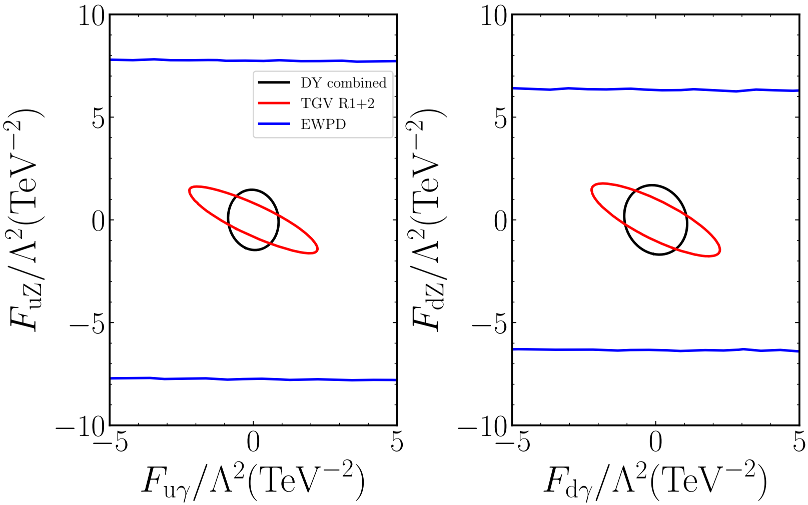
	Int.Luminosity (fb^{-1})	$m_{\ell\ell}$	# Data points
ATLAS 13 TeV	36 fb^{-1}	250–6000 GeV	6+6
CMS 13 TeV	36 fb^{-1}	200–3000 GeV	6+6
ATLAS 8 TeV	20.3 fb^{-1}	200–1500 GeV	8
CMS 8 TeV	19.7 fb^{-1}	200-2000 GeV	11





Comparison with other bounds

- DY is better than EWPD: larger energy and DY has conttributions from both $\boldsymbol{F_{qZ}}$ and $\boldsymbol{F_{q\gamma}}$ couplings.



Summary

- Altogether the analyses **show no statistically significant source of tension with the SM.**
- The impact of the inclusion of the LHC results is still minor **but not negligible** for the EWPD bounded operators involving gauge couplings to quarks.
- The combined Run 2 data constrains the operator coefficients **with a bit better precision** to that of the full Run 1 analysis.
- For the dipole operators, we see that the **TGV data already puts some good bounds.**
- **Drell-Yan process does a better job than EWPD.**

Thank you very much!!!

Backup: Discrete (quasi-)degeneracies in the parameter space

- Antecipating the presence of discrete (quasi-)degeneracies in the parameter space will be useful in terms of computing a χ^2 with **20** parameters.

$$HW^+_\mu W^{-\mu} \text{ coefficient : } \left(\frac{g^2 v}{2}\right)\left[1 - \frac{v^2}{4}\left(\frac{f_{\Phi,1}}{\Lambda^2} + 2\frac{f_{\Phi,2}}{\Lambda^2}\right)\right]$$

$$\underbrace{\frac{f_{\Phi,1}}{\Lambda^2}}_{\text{Stringent bound from EWPD}} \Rightarrow \underbrace{\frac{f_{\Phi,2}}{\Lambda^2} = 0 \;\vee\; \frac{f_{\Phi,2}}{\Lambda^2} = \frac{4}{v^2} \sim 65\text{TeV}^{-2}}_{\text{Degeneracy with the SM results}}$$

$$H\bar{f}f \text{ coefficient : } -\frac{m_f}{v}\left[1 - \frac{v^2}{2}\left(\frac{f_{\Phi,2}}{\Lambda^2} + \sqrt{2}\frac{f_f}{\Lambda^2}\right)\right]$$

$$\underbrace{\frac{f_{\Phi,2}}{\Lambda^2}}_{\text{2 different values} \to \text{flipping the sign of the SM } HVV} \Rightarrow \underbrace{\frac{f_f}{\Lambda} = 0\,,\; \frac{f_f}{\Lambda} = \pm 2\sqrt{2}/v^2 \sim 45\text{TeV}^{-2}}_{2\times 2 \text{ degenerate SM-like solutions}}$$

Backup: Discrete (quasi-)degeneracies in the parameter space

$$HG^a_{\mu\nu}G^{a,\mu\nu}\ \text{coefficient}:\ -\frac{1}{4}G^{gg}_{\rm SM} - \frac{\alpha_S v}{8\pi}\frac{f_{GG}}{\Lambda^2}$$

$$\underbrace{G^{gg}_{\rm SM} \sim -5.3\times 10^{-2}\text{TeV}^{-1}}_{\text{Flipping the sign}} \quad \Rightarrow \quad \underbrace{\frac{f_{GG}}{\Lambda^2} \sim \frac{-4\pi}{v\alpha_s}G_{gg,\rm SM} \sim 25\text{TeV}^{-2}}_{\text{SM like solution}}$$

$$HG^a_{\mu\nu}G^{a,\mu\nu}\ \text{coefficient}:\ -\frac{1}{4}G^{\gamma\gamma}_{\rm SM} + \frac{e^2 v}{4}\frac{f_{WW}+f_{BB}-f_{BW}}{\Lambda^2}$$

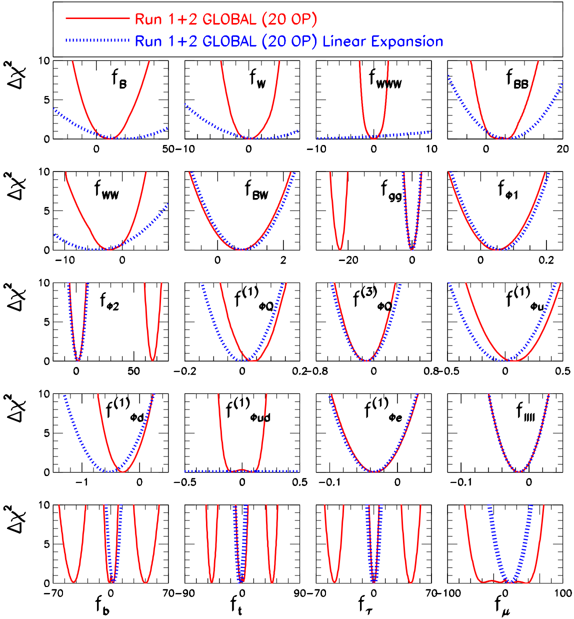
$$\underbrace{G^{\gamma\gamma}_{\rm SM} \sim 3.3\times 10^{-2}\text{TeV}^{-1}}_{\text{Flipping the sign}} \quad \Rightarrow \quad \underbrace{\frac{(f_{WW}+f_{BB}-f_{BW})}{\Lambda^2} \sim \frac{2}{v\,e^2}G_{\gamma\gamma,\rm SM} \sim 3\text{TeV}^{-2}}_{\text{SM like solution}}$$

Measurement of the effective photon-Z-coupling $HF_{\mu\nu}Z^{\mu\nu}$ bounds a different combination of f_{WW}, f_{BB} and f_{BW}

EWPD independently constrains f_{BW}

Aproximate degeneracy

Backup:Linear vs non Linear



Backup: How the old analysis change when we introduce the dipole operators