Characterizing new physics effects in gauge boson pair production

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Outline

- Motivation
- EFT for strongly-coupled EWSB
- New physics in $\bar{f}f \to W^+W^-, ZZ, \gamma Z$
- Phenomenology at large energies
- Conclusions

Motivation

- A priori, **ideal setting to test the triple gauge structure** [Hagiwara et al'86]. In strongly-coupled scenarios, sizeable deviations are expected (unitarity breaking). However, in weakly-coupled UV completions, deviations are less compelling but also possible (even with a SM Higgs).

- **Traditional analyses** rest on two assumptions:

  (i) TGVs corrections are the dominant new physics effect. Not supported by global LEP data EW fit [Han et al'04].

  (ii) Kinematic invariants promoted to form factors. Unitarity preserved but gauge symmetries not necessarily ensured.

- **EFT analysis** improves both points:

  (i) Model-independent, systematic and complete study of new physics effects.

  (ii) Unitarity and gauge symmetries automatically preserved.

  (iii) At the sub-TeV scale $\sqrt{s} \sim (0.6 - 1)$ TeV the picture becomes extremely simple (but nontrivial).

EFT for strongly-coupled EWSB

Main assumptions:

- **Strongly-coupled dynamics** at the TeV scale triggering EWSB [Longhitano'80,81; Appelquist et al'80,93]

- **Minimal EWSB pattern**: $SU(2)_L \times SU(2)_R \to SU(2)_V$. Most general with the minimal particle content (3 Goldstone bosons to account for the longitudinal modes of the W and Z). Collected in a nonlinear realization inside $U(x) \to g_L U(x) g_R^\dagger$.

- Natural cutoff of the theory **dynamically generated**: $\Lambda \sim 4\pi v \sim 3$ TeV. Nondecoupling scenario.

- **A light scalar field** can be added as a singlet (pseudo-Goldstone of a more general symmetry group) [Contino et al.'10]. It can always be tuned to the SM Higgs but more general.

Leading order Lagrangian:

$$\mathcal{L}_{LO} = -\frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\sum_j \bar{f}_j \not{D} f_j + \frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger\rangle + \mathcal{L}_Y(U, \bar{f}, f)$$

Power-counting: naive dimensional power-counting only applies to weakly-coupled (decoupling) scenarios. Requirements:

- Homogeneity of the LO Lagrangian (often overlooked!).
- Soft breaking of custodial symmetry: $\mathcal{O}_\beta = v^2 \langle \tau_L L_\mu \rangle^2$ subleading.

The **degree of divergence** of every diagram is [Buchalla, O.C.'13]

$$\Delta = v^2 (yv)^{\nu_f} (gv)^{\nu_g} \frac{p^d}{\Lambda^{2L}} \left(\frac{\Psi}{v}\right)^F \left(\frac{X_{\mu\nu}}{v}\right)^G \left(\frac{\varphi}{v}\right)^B$$

where $d = 2L + 2 - F/2 - G - \nu_f - \nu_g$. Bounded from above: number of counterterms finite (consistency check).

Operator building at every order: assemble building blocks (U, ψ, X and derivatives) according with the power-counting formula.

- NLO: 6 classes, denoted as UD^4, XUD^2, X^2U, $\psi^2 UD$, $\psi^2 UD^2$ and $\psi^4 U$.
- NNLO: 7 classes, UD^6, UXD^4, X^2UD^2, $\psi^2 UD^3$, X^3U, $\psi^2 UX$ and $\psi^2 UXD$.

New physics in $\bar{f}f \to W^+W^-$

Number of **independent EFT operators** [Buchalla, O.C. Rahn, Schlaffer'13]:

$$\mathcal{L}_{NLO} = \sum_j \lambda_j \mathcal{O}_{Xj} + \sum_j \eta_j \mathcal{O}_{Vj} + \beta \mathcal{O}_\beta + \eta_{4f} \mathcal{O}_{4f}$$

where $\mathcal{O}_\beta = v^2 \langle \tau_L L_\mu \rangle^2$ and

$$\mathcal{O}_{X1} = g' g B_{\mu\nu} \langle W^{\mu\nu} \tau_L \rangle \qquad \mathcal{O}_{X4} = g' g \epsilon^{\mu\nu\lambda\rho} \langle \tau_L W_{\mu\nu} \rangle B_{\lambda\rho}$$

$$\mathcal{O}_{X2} = g^2 \langle W^{\mu\nu} \tau_L \rangle^2 \qquad \mathcal{O}_{X5} = g^2 \epsilon^{\mu\nu\lambda\rho} \langle \tau_L W_{\mu\nu} \rangle \langle \tau_L W_{\lambda\rho} \rangle$$

$$\mathcal{O}_{X3} = g \epsilon^{\mu\nu\lambda\rho} \langle W_{\mu\nu} L_\lambda \rangle \langle \tau_L L_\rho \rangle \qquad \mathcal{O}_{X6} = g \langle W_{\mu\nu} L^\mu \rangle \langle \tau_L L^\nu \rangle$$

are oblique and triple-gauge corrections ($L_\mu = iUD_\mu U^\dagger$, $\tau_L = UT_3U^\dagger$),

$$\mathcal{O}_{V1} = -\bar{q}\gamma^\mu q \ \langle L_\mu \tau_L \rangle; \qquad \mathcal{O}_{V7} = -\bar{l}\gamma^\mu l \ \langle L_\mu \tau_L \rangle$$

$$\mathcal{O}_{V2} = -\bar{q}\gamma^\mu \tau_L q \ \langle L_\mu \tau_L \rangle; \qquad \mathcal{O}_{V8} = -\bar{l}\gamma^\mu \tau_L l \ \langle L_\mu \tau_L \rangle$$

$$\mathcal{O}_{V4} = -\bar{u}\gamma^\mu u \ \langle L_\mu \tau_L \rangle; \qquad \mathcal{O}_{V9} = -\bar{l}\gamma^\mu \tau_{12} l \ \langle L_\mu \tau_{21} \rangle$$

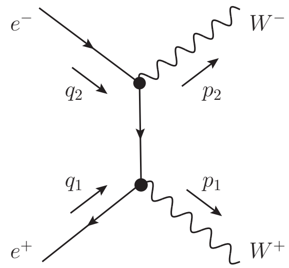
$$\mathcal{O}_{V5} = -\bar{d}\gamma^\mu d \ \langle L_\mu \tau_L \rangle; \qquad \mathcal{O}_{V10} = -\bar{e}\gamma^\mu e \ \langle L_\mu \tau_L \rangle$$

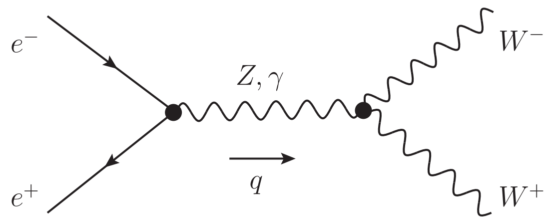
are gauge-fermion new physics contributions ($\tau_{12,21} = T_1 \pm iT_2$) and

$$\mathcal{O}_{4f} = \frac{1}{2}(\mathcal{O}_{LL5} - 4\mathcal{O}_{LL15}) = (\bar{e}_L \gamma_\rho \mu_L)(\bar{\nu}_\mu \gamma^\rho \nu_e)$$

General structure of the corrections: direct vs indirect.

- Direct: corrections to gauge-fermion and triple-gauge vertices (process-dependent).





(i) **Gauge-fermion**: $\mathcal{O}_{V1-5,9}$ are the 5 direct contributions to gauge-fermion vertices in pp collisions ($\bar{u}dW$, $\bar{u}uZ$ and $\bar{d}dZ$); $\mathcal{O}_{V9,10}$ and the combination $\frac{1}{2}\mathcal{O}_{V7} - \mathcal{O}_{V8}$ for e^+e^- ($\bar{e}eZ$ and $\bar{\nu}eW$).

$$\mathcal{L}_f = e\bar{f}\gamma_\mu A^\mu f + e\sum_{j=L,R}\left[\zeta_j^{(0)} + \delta\zeta_j\right]\bar{f}_j\gamma_\mu Z^\mu f_j - \frac{g}{\sqrt{2}}\left[1 + \delta\phi_L\right]\bar{\nu}_L\gamma^\mu W_\mu^+ f_L + \mathrm{h.c.}$$

Common to charge and neutral production.

(ii) **Triple-gauge**:

$$\Gamma_{\mu\nu\lambda}^{WWV}(p_1, p_2; q) = f_1 Q_\lambda g_{\mu\nu} + f_2(p_{1\nu}g_{\mu\lambda} - p_{2\mu}g_{\nu\lambda}) + if_3(p_{1\nu}g_{\mu\lambda} + p_{2\mu}g_{\nu\lambda}) + f_4 p_{1\nu}p_{2\mu}Q_\lambda + if_5\epsilon_{\mu\nu\lambda\rho}Q_\rho + f_6\epsilon_{\mu\nu\lambda\rho}q_\rho + f_7 Q_\lambda\epsilon_{\mu\nu\alpha\rho}p_{1\alpha}p_{2\rho}$$

Indirect contributions

Shifts in gauge propagators and standard model parameters.

- Kinetic terms ($\mathcal{O}_{X1,2}$):

$$\mathcal{L}_K = -\frac{1}{4}(1-2\Delta_Z)Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}(1-2\Delta_A)A_{\mu\nu}A^{\mu\nu} + \frac{1}{2}\Delta_{AZ}A_{\mu\nu}Z^{\mu\nu}$$

- SM parameters ($\mathcal{O}_\beta$, $\mathcal{O}_{V9}$, $\mathcal{O}_{4j}$): $m_Z \to (1+\delta_M)m_Z$ and $G_F \to (1+2\delta_G)G_F$.

- Common to charged and neutral production.

Best strategy: reabsorb shifts into direct contributions [Holdom'90] through

$$Z_\mu = (1+\Delta_Z)\hat{Z}_\mu; \qquad A_\mu = (1+\Delta_A)\hat{A}_\mu + \Delta_{AZ}\hat{Z}_\mu$$
$$m_Z = (1-\delta_M-\Delta_Z)\,\hat{m}_Z; \qquad G_F = (1-2\delta_G)\,\hat{G}_F; \qquad e = (1-\Delta_A)\,\hat{e}$$

Net effect: Shifts on the vertices. For instance

$$\delta\zeta_L = \frac{2e^2\lambda_1 - c_{2W}\eta_L + \hat{\beta}}{s_{2W}c_{2W}}; \qquad \delta\zeta_R = \frac{2e^2\lambda_1 - c_{2W}\eta_R + 2s_W^2\hat{\beta}}{s_{2W}c_{2W}}$$

and similar expressions for triple-gauge vertex parameters.

Phenomenology at large energies

Main motivation for EFT: large energy gap between the electroweak and new physics scales. For LHC and linear colliders, aimed energy window: $\sqrt{s} \sim (0.6 - 1)$ TeV. In this energy regime $v^2 \ll s \ll \Lambda^2$ and

- Cross sections can be expanded in powers of v^2/s;
- Good convergence of the EFT expansion (in s/Λ^2) is expected.

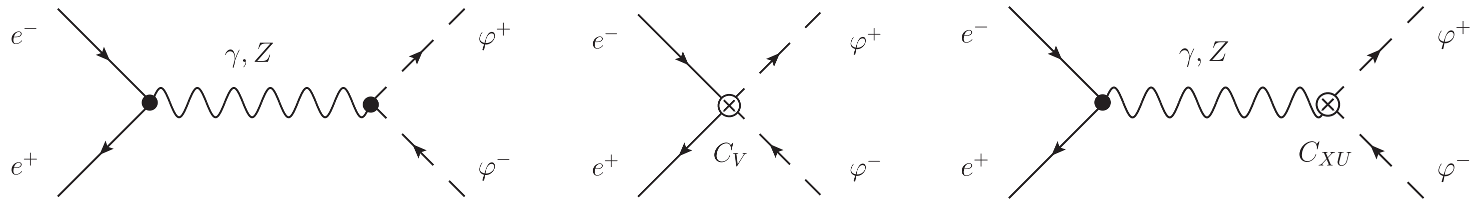
For $e^+e^- \to W^+W^-$ one finds [Buchalla, O.C., Rahn, Schlaffer'13]:

$$\frac{d\sigma_{WW}^R}{d\cos\theta} = \frac{\pi\alpha^2 \sin^2\theta}{8s_W^2 c_W^2}\frac{1}{m_W^2}\eta_R; \qquad \frac{d\sigma_{WW}^L}{d\cos\theta} = \frac{\pi\alpha^2 \sin^2\theta}{16c_W^2 s_W^4}\frac{1}{m_W^2}\eta_L$$

New physics signals dominated by gauge-fermion operators!...

Two observations to understand the result:

- The dominant piece above comes entirely from $W_L^+W_L^-$ polarizations. The result should be equivalent to $e^+e^- \to \varphi^+\varphi^-$ in Landau gauge.



- Elimination of redundancies: the dominant triple-gauge operators are not independent.

$$\mathcal{O}_{X7} = ig' B_{\mu\nu} \langle \tau_L [L^\mu, L^\nu] \rangle = f_1^{(7)}(\mathcal{O}_{X1}, \mathcal{O}_\beta) + f_2^{(7)}(\mathcal{O}_{Vj})$$
$$\mathcal{O}_{X8} = ig \langle W_{\mu\nu} [L^\mu, L^\nu] \rangle = f_1^{(8)}(\mathcal{O}_{X1}) + f_2^{(8)}(\mathcal{O}_{Vj})$$
$$\mathcal{O}_{X9} = ig \langle W_{\mu\nu} \tau_L \rangle \langle \tau_L [L^\mu, L^\nu] \rangle = f_1^{(9)}(\mathcal{O}_{X2}, \mathcal{O}_\beta) + f_2^{(9)}(\mathcal{O}_{Vj})$$

Actually, at large energies,

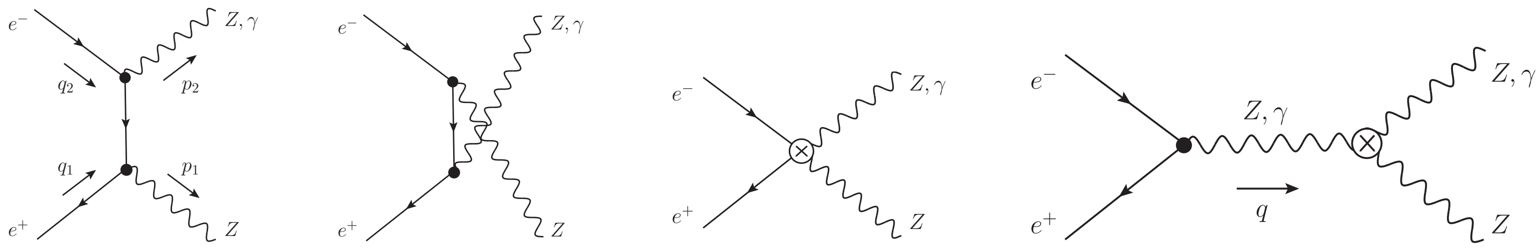
$$\lim_{s \gg v^2} \mathcal{O}_{X7} = f_2^{(7)}(\mathcal{O}_{Vj})$$
$$\lim_{s \gg v^2} \mathcal{O}_{X8} = f_2^{(8)}(\mathcal{O}_{Vj})$$
$$\lim_{s \gg v^2} \mathcal{O}_{X9} = f_2^{(9)}(\mathcal{O}_{Vj})$$

Bottomline:

- Neglecting gauge-fermion corrections is inconsistent. However, for e^+e^- they can be exactly eliminated without approximations. Probably not the most convenient basis choice if one does a global fit.

- Probing triple-gauge corrections is not well-defined. Triple gauge vertex defined up to field redefinitions...

New physics in $\bar{f}f \to ZZ, \gamma Z$



- **Indirect contributions** already considered.

- **Gauge-fermion**: no new structures.

- **Triple-gauge**: gauge invariance and Bose symmetry further reduce the number of parameters to [Hagiwara et al'86]

$$\Gamma^{ZZV}_{\mu\nu\lambda}(p_1, p_2; q) = i\mu_1^V(p_{1\nu}g_{\mu\lambda} + p_{2\mu}g_{\nu\lambda}) + i\mu_2^V\epsilon_{\mu\nu\lambda\rho}Q_\rho$$

and

$$\Gamma^{Z\gamma V}_{\mu\nu\lambda}(p_1, p_2; q) = i\beta_1^V\,(p_{2\lambda}g_{\mu\nu} - p_{2\mu}g_{\nu\lambda}) + i\beta_2^V\epsilon_{\mu\nu\lambda\rho}p_{2\rho} + i\frac{\beta_3^V}{\Lambda^2}p_{2\mu}(p_1\cdot p_2 g_{\nu\lambda} - p_{1\nu}p_{2\lambda}) + i\frac{\beta_4^V}{\Lambda^2}Q_\lambda\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta$$

$$\Gamma^{ZZV}_{\mu\nu\lambda}(p_1,p_2;q) = i\mu_1^V(p_{1\nu}g_{\mu\lambda} + p_{2\mu}g_{\nu\lambda}) + i\mu_2^V\epsilon_{\mu\nu\lambda\rho}Q_\rho$$

$$\Gamma^{Z\gamma V}_{\mu\nu\lambda}(p_1,p_2;q) = i\beta_1^V\,(p_{2\lambda}g_{\mu\nu} - p_{2\mu}g_{\nu\lambda}) + i\beta_2^V\epsilon_{\mu\nu\lambda\rho}p_{2\rho}$$
$$+\,i\frac{\beta_3^V}{\Lambda^2}p_{2\mu}(p_1\cdot p_2 g_{\nu\lambda} - p_{1\nu}p_{2\lambda}) + i\frac{\beta_4^V}{\Lambda^2}Q_\lambda\epsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta$$

Observations:

- None of the parameters is generated by the SM at tree level. Corrections come from 1-loop fermion triangle loops with rapid fall-off $\ln s/s^2$ (anomaly) [Gounaris et al'00]

- All parameters are either CP or P violating. Only the P violating can interfere with the SM.

- To a very good approximation, $\beta_{3,4}$ can be neglected (extra Λ^2 suppression).

- Gauge invariance implies that $\beta_i, \mu_i \sim (s - m_V^2)$: (i) the amplitudes vanish when all the particles are on-shell; (ii) NNLO operators needed; (iii) points at redundancies...

The operators contributing to nTGV are [O.C.'13]:

$$\mathcal{L}_{nTGV} = \sum_{j=L,R} \left\{ \frac{c_{jW}}{\Lambda^2} J_\mu^{(j)} \langle W^{\mu\nu} L_\nu \rangle + \frac{c_{jB}}{\Lambda^2} J_\mu^{(j)} B^{\mu\nu} \langle \tau_L L_\nu \rangle \right.$$
$$\left. + \frac{\tilde{c}_{jW}}{\Lambda^2} J_\mu^{(j)} \langle \tilde{W}^{\mu\nu} L_\nu \rangle + \frac{\tilde{c}_{jB}}{\Lambda^2} J_\mu^{(j)} \tilde{B}^{\mu\nu} \langle \tau_L L_\nu \rangle \right\}$$

Alternatively, using the equations of motion for the gauge fields one can eliminate the fermion bilinears (only for e^+e^-!) and

$$\mathcal{L}_{nTGV} = \frac{\lambda_{ZZ}}{\Lambda^2} \partial_\lambda Z^{\lambda\mu} Z^\nu Z_{\mu\nu} + \frac{\lambda_{\gamma\gamma}}{\Lambda^2} \partial_\lambda F^{\lambda\mu} Z^\nu F_{\mu\nu} + \frac{\lambda_{Z\gamma}}{\Lambda^2} \partial_\lambda Z^{\lambda\mu} Z^\nu F_{\mu\nu} + \frac{\lambda_{\gamma Z}}{\Lambda^2} \partial_\lambda F^{\lambda\mu} Z^\nu Z_{\mu\nu}$$

with

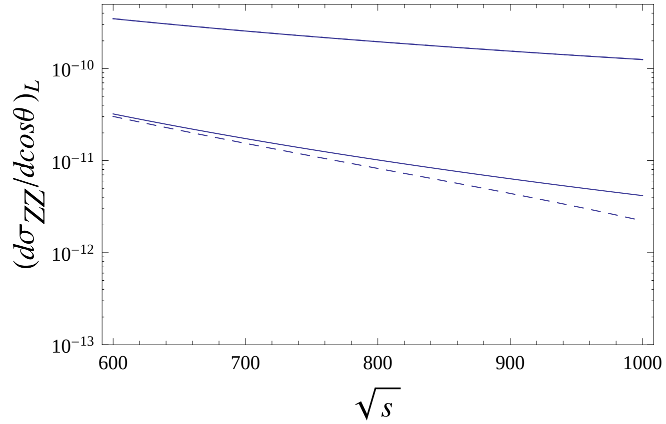
$$\lambda_{ZZ} = -c_W c_{LW} + s_W c_{LB} + c_W c_{RW} - s_W c_{RB}$$
$$\lambda_{\gamma\gamma} = -\frac{s_W^2}{c_W} c_{LW} - s_W c_{LB} - \frac{s_W}{t_{2W}} c_{RW} - \frac{c_W}{t_{2W}} c_{RB}$$
$$\lambda_{Z\gamma} = -s_W c_{LW} - c_W c_{LB} + s_W c_{RW} + c_W c_{RB}$$
$$\lambda_{\gamma Z} = -s_W c_{LW} + \frac{s_W^2}{c_W} c_{LB} - \frac{c_W}{t_{2W}} c_{RW} + \frac{s_W}{t_{2W}} c_{RB}$$

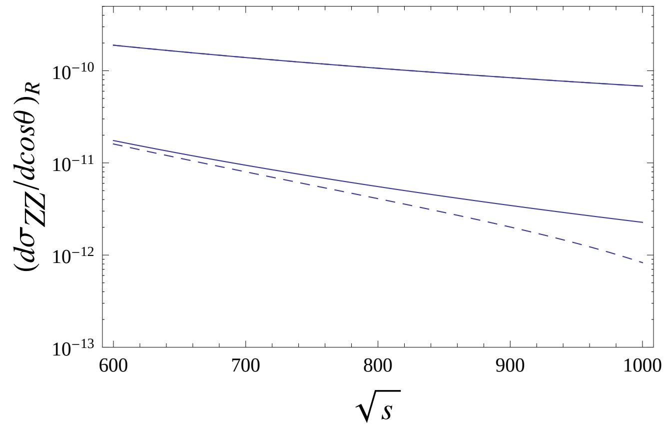
Phenomenology at large energies

The cross sections for $e^+e^- \to ZZ, \gamma Z$ read [O.C.'13]:

$$\frac{d\sigma^j_{Z_T^\pm Z_T^\mp}}{d\cos\theta} = \frac{2\pi\alpha^2}{s}\frac{1\pm\cos\theta}{1\mp\cos\theta}\zeta_j^4; \qquad \frac{d\sigma^j_{Z_L Z_T^\pm}}{d\cos\theta} = -\frac{\pi\alpha^2(1\mp\cos\theta)\zeta_j^2}{\Lambda^2}\frac{c_W\tilde{c}_{jW} - s_W\tilde{c}_{jB}}{e s_{2W}}$$

$$\frac{d\sigma^j_{\gamma^\mp Z_T^\pm}}{d\cos\theta} = \frac{2\pi\alpha^2}{s}\frac{1\pm\cos\theta}{1\mp\cos\theta}\zeta_j^2; \qquad \frac{d\sigma^j_{\gamma^\pm Z_L}}{d\cos\theta} = -\frac{\pi\alpha^2(1\mp\cos\theta)\zeta_j}{\Lambda^2}\frac{s_W\tilde{c}_{jW} + c_W\tilde{c}_{jB}}{e s_{2W}}$$





Final-state polarization analysis unfolds nTGV. **Initial-state polarization** analysis to determine the EFT coefficients.

Charged vs neutral

- TGV: SM contributions at tree level **vs** SM contributions at one loop.
- TGV: NLO operators **vs** NNLO operators.
- New physics signatures: energy-based **vs** polarization-based.
- LL enhancement (constant cross section) **vs** LL suppression $(1/s^3)$.
- For different reasons, both processes end up being dominated by gauge-fermion vertex corrections.

Conclusions

- The combination of EFT at collider energies brings a very simple picture of new physics effects in boson pair production.

- Colliders as magnifying lens: tiny new physics effects get dramatically enhanced.

- The complete analysis ends up in a very reduced number of relevant parameters. Partial EW fits can be very informative.

- Nature of the Higgs largely irrelevant for these processes. Conclusions qualitatively unchanged for a weakly-coupled scenario.