Harnessing SMEFT for new physics exploration and the role of electroweak corrections

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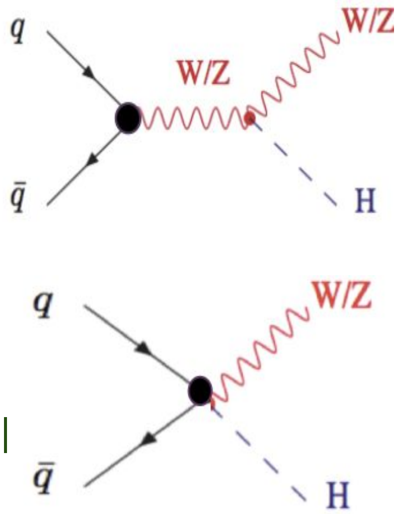
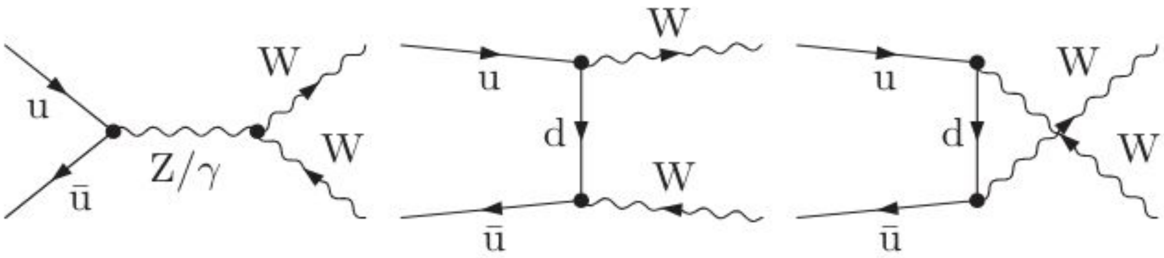
What is this talk about?

1. High-energy primaries and correlated processes

2. Zh as an example of constraining contact interactions

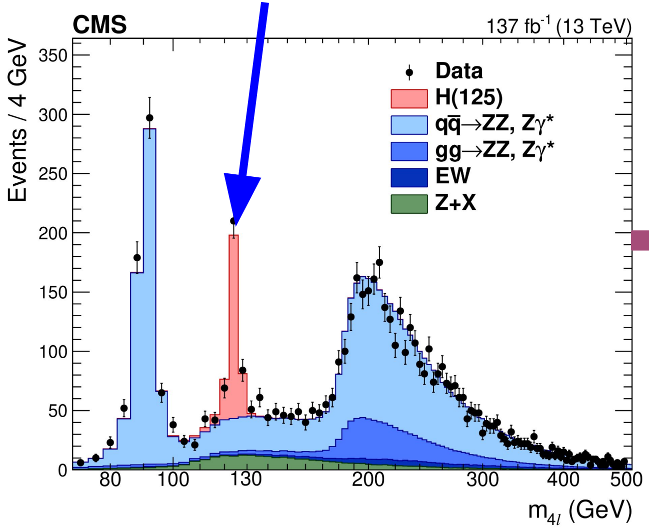
3. Importance of electroweak corrections: W^+W^- as an exampl





Particle physics discovery: the main types

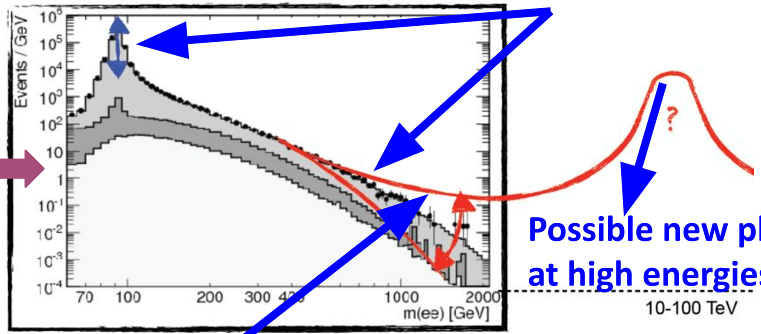
Discovery through resonance (the tested paradigm)



We are in the phase of no (new physics) resonance discoveries since the last ~12 years after the Higgs in 2012. What to do then?

New paradigm!

Discovery through precision



Possible new physics at high energies

%-level precision

Image: Francesco Riva

Possible to see hints of new physics through difference in heights, angular structure and tails of distributions without seeing the actual resonance

High-energy primaries

1. The four directions, *viz.*, Zh, $W^{\pm}h$, $W^{+}W^{-}$ and $W^{\pm}Z$ can be expressed (at high energies) respectively as $G^{0}h$, $G^{\pm}h$, $G^{+}G^{-}$ and $G^{\pm}G^{0}$ and the Higgs field can be written as

$$\begin{pmatrix} G^{+} \\ \frac{h+iG^{0}}{2} \end{pmatrix}$$

2. These four final states are **intrinsically connected by gauge symmetry** even though they are very different from a collider physics point of view

3. With the **Goldstone boson equivalence theorem** it is possible to compute amplitudes for various components of the Higgs in the unbroken phase

4. **Full *SU(2)* theory is manifest** [Franceschini, Panico,Pomarol, Riva, Wulzer, 2017]

High-energy primaries

Amplitude	High-energy primaries	Amplitude	High-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\frac{g^h_{Z d_L d_L} - g^h_{Z u_L u_L}}{\sqrt{2}}$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$g^h_{Z d_L d_L}$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$g^h_{Z u_L u_L}$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$\bar{f}_R f_R \to W_L W_L, Z_L h$	$g^h_{Z f_R f_R}$

Vh and *VV* channels are entwined by symmetry and they constrain the same set of observables at High energies but may have different directions [Franceschini, Panico,Pomarol, Riva, Wulzer, 2017, SB, Gupta, Seth, Reiness, Spannowsky, 2020]

High-energy primaries

Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g^Z_{uL} - \delta g^Z_{dL})/g - c^2_{\theta_W}\delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{dL}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{uL}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g^Z_{fR}/g\right]$

Vh and *VV* channels are entwined by symmetry and they constrain the same set of observables at High energies but may have different directions [Franceschini, Panico,Pomarol, Riva, Wulzer, 2017, SB, Gupta, Reiness, Seth, Spannowsky, 2020]

High-energy primaries

SILH basis	Warsaw basis
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B^a_{\mu\nu}$ $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$ $\mathcal{O}_{HB} = ig(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$ $\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$ $\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$	$\mathcal{O}_L^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$ $\mathcal{O}_L = (\bar{Q}_L \gamma^\mu Q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)$ $\mathcal{O}_R^u = (\bar{u}_R \gamma^\mu u_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$ $\mathcal{O}_R^d = (\bar{d}_R \gamma^\mu d_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$

Dimension-6 operators contributing to the high energy longitudinal diboson production channels in the SILH and Warsaw bases [Franceschini, Panico,Pomarol, Riva, Wulzer, 2017]

$$a_u = 4\frac{c_R^u}{\Lambda^2}, a_d = 4\frac{c_R^d}{\Lambda^2}, a_q^{(1)} = 4\frac{c_L^{(1)}}{\Lambda^2}, \text{ and } a_q^{(3)} = 4\frac{c_L^{(3)}}{\Lambda^2}$$

Relating the high-energy primaries with the Warsaw basis operators

Zh and *Wh* production at the LHC (example)

SM scaling κ-framework

$$\Delta\mathcal{L}_6 \supset \delta\hat{g}^h_{WW}\frac{2m_W^2}{v}hW^{+\mu}W^-_\mu + \boxed{\delta\hat{g}^h_{ZZ}\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2}} + \delta g^W_Q\left(W^+_\mu\bar{u}_L\gamma^\mu d_L + h.c.\right)$$
$$+ \delta g^W_L\left(W^+_\mu\bar{\nu}_L\gamma^\mu e_L + h.c.\right) + g^h_{WL}\frac{h}{v}\left(W^+_\mu\bar{\nu}_L\gamma^\mu e_L + h.c.\right)$$
$$+ g^h_{WQ}\frac{h}{v}\left(W^+_\mu\bar{u}_L\gamma^\mu d_L + h.c.\right) + \sum_f \delta g^Z_f Z_\mu\bar{f}\gamma^\mu f + \boxed{\sum_f g^h_{Zf}\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f}$$
$$+ \kappa_{WW}\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \tilde{\kappa}_{WW}\frac{h}{v}W^{+\mu\nu}\tilde{W}^-_{\mu\nu} + \boxed{\kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}}$$
$$+ \boxed{\tilde{\kappa}_{ZZ}\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}} + \kappa_{Z\gamma}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{Z\gamma}\frac{h}{v}A^{\mu\nu}\tilde{Z}_{\mu\nu} + \delta\hat{g}^h_{bb}\frac{\sqrt{2}m_b}{v}hb\bar{b}$$
$$+ \kappa_{\gamma\gamma}\frac{h}{v}A^{\mu\nu}A_{\mu\nu}$$

Contact interaction; no propagator; Energy growth

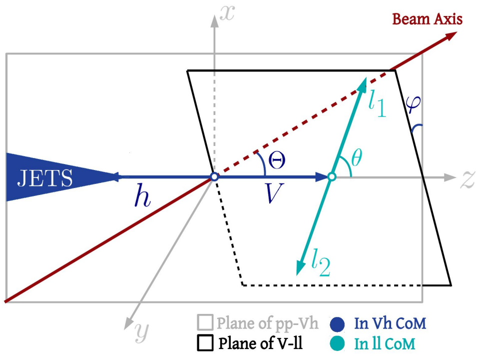
CP-even new Lorentz structure (angular deformation)

CP-odd new Lorentz structure (angular deformation)

Deformations written in broken phase after symmetry breaking

Vh production at *pp* colliders

- φ, Θ and $\{x, y, z\}$ in Vh CoM frame (z identified as direction of V-boson; y identified as normal to the plane of V and beam axis; x defined to complete the right-handed set), θ in V CoM frame
- Q: How much differential information can one extract from this process?
- For three body phase space, $3 \times 3 - 4 = 5$ kinematic variables completely define final state
- Barring boost factor, the variables are $\sqrt{s}, \Theta, \theta, \varphi$



SB, Gupta, Reiness, Seth, Spannowsky, 2020

Zh production (Helicity amplitude)

- For a $2 \to 2$ process $f(\sigma)\bar{f}(-\sigma) \to Zh$, the helicity amplitudes are given by

$$\mathcal{M}_\sigma^{\lambda=\pm} = \sigma \frac{1+\sigma\lambda\cos\Theta}{\sqrt{2}} G_V \frac{m_V}{\boxed{\sqrt{\hat{s}}}} \left[\boxed{1} + \left(\frac{g^h_{Vf}}{g^V_f} + \hat{\kappa}_{VV} - i\lambda\hat{\tilde{\kappa}}_{VV} \right) \frac{\hat{s}}{2m_V^2} \right]$$

$$\mathcal{M}_\sigma^{\lambda=0} = -\frac{\sin\Theta}{2} G_V \left[\boxed{1} + \delta\hat{g}^h_{VV} + 2\hat{\kappa}_{VV} + \delta g^Z_f + \frac{g^h_{Vf}}{g^V_f} \left(-\frac{1}{2} + \frac{\hat{s}}{2m_V^2} \right) \right]$$

$$\begin{aligned} \hat{\kappa}_{WW} &= \kappa_{WW} \\ \hat{\kappa}_{ZZ} &= \kappa_{ZZ} + \frac{Q_f e}{g^Z_f}\kappa_{Z\gamma}, \\ \hat{\tilde{\kappa}}_{ZZ} &= \tilde{\kappa}_{ZZ} + \frac{Q_f e}{g^Z_f}\tilde{\kappa}_{Z\gamma} \end{aligned}$$

- $\lambda = \pm 1$ and $\sigma = \pm 1$ are, respectively, the helicities of the Z-boson and initial-state fermions, $g^Z_f = g(T^f_3 - Q_f s^2_{\theta_W})/c_{\theta_W}$
- Leading SM is longitudinal ($\lambda = 0$), Leading effect of $\kappa_{WW}, \kappa_{ZZ}, \tilde{\kappa}_{ZZ}$ is in the transverse-longitudinal (LT) interference, LT term vanishes if we aren't careful

SB, Englert, Gupta, Spannowsky, 2018

Vh production (Helicity amplitude)

- The differential cross-section for the process $pp \to Z(\ell^+\ell^-)/W(\ell\nu)h(b\bar{b})$ is a differential in four variables, *viz.*, $\frac{d\sigma}{dEd\Theta d\theta d\varphi}$
- The amplitude at the decay level can be written as

$$\mathcal{A}(\hat{s}, \Theta, \theta, \varphi) = \frac{-ig_\ell^V + \delta g_\ell^V}{\Gamma_V} \sum_\lambda \mathcal{M}_\sigma^\lambda(\hat{s}, \Theta) d_{\lambda,1}^{J=1}(\theta) e^{i\lambda\hat{\varphi}}$$

- $d_{\pm1,1}^{J=1} = \tau \frac{1 \pm \tau \cos\theta}{\sqrt{2}}$, $d_{0,1}^{J=1} = \sin\theta$ are the Wigner functions, τ is lepton helicity, Γ_V is the V-width and $g_f^Z = g(T_3^f - Q_f s_{\theta_W}^2)/c_{\theta_W}$ and $g_f^W = g/\sqrt{2}$
- $\hat{\varphi} \to$ azimuthal angle of positive helicity lepton, $\hat{\theta} \to$ its polar angle in Z-rest frame
- Polarisation of lepton is experimentally not accessible

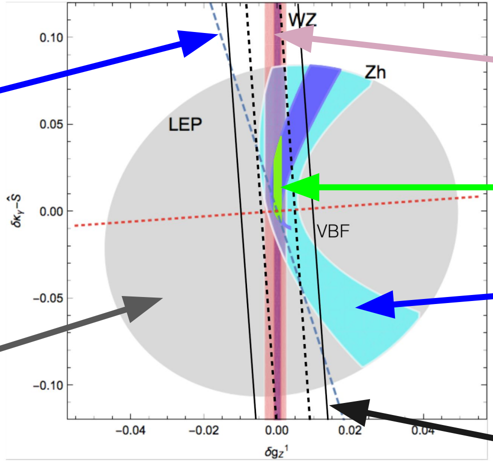
$$\mathcal{A}_0 \sim \sin\Theta \sin\theta$$
$$\mathcal{A}_+ \sim (1 + \cos\Theta)(1 + \cos\theta) e^{i\varphi}$$
$$\mathcal{A}_- \sim (1 - \cos\Theta)(1 - \cos\theta) e^{-i\varphi}$$

SB, Englert, Gupta, Spannowsky, 2018

Differential in energy: constraining the contact terms

Accidental cancellation of interference terms

LEP exclusion region



Exclusion from WZ [Franceschini et al, 2017]

Zh + WZ combined

Exclusion from Zh [SB, Englert, Gupta, Spannowsky, 2018]

WBF analysis in diphoton channel [Araz, SB, Gupta, Spannowsky, 2020]

$\sigma_{Zh}^{SM}/\sigma_{Zbb}$ without cuts ~ 4.6/165

With regular cut-based analysis ~ 0.26

With BDT optimisation ~ 0.50

Differential in energy: constraining the contact terms

	Our 100 TeV Projection	Our 14 TeV projection	LEP Bound
$\delta g^Z_{u_L}$	± 0.0003 (± 0.0001)	± 0.002 (± 0.0007)	-0.0026 ± 0.0032
$\delta g^Z_{d_L}$	± 0.0003 (± 0.0001)	± 0.003 (± 0.001)	0.0023 ± 0.002
$\delta g^Z_{u_R}$	± 0.0005 (± 0.0002)	± 0.005 (± 0.001)	-0.0036 ± 0.0070
$\delta g^Z_{d_R}$	± 0.0015 (± 0.0006)	± 0.016 (± 0.005)	0.016 ± 0.0104
δg^Z_1	± 0.0005 (± 0.0002)	± 0.005 (± 0.001)	$-0.009^{+0.043}_{-0.042}$
$\delta \kappa_\gamma$	± 0.0035 (± 0.0015)	± 0.032 (± 0.009)	$-0.016^{+0.085}_{-0.096}$
$\hat{S}$	± 0.0035 (± 0.0015)	± 0.032 (± 0.009)	0.0004 ± 0.0007
W	± 0.0004 (± 0.0002)	± 0.003 (± 0.001)	-0.0003 ± 0.0006
Y	± 0.0035 (± 0.0015)	± 0.032 (± 0.009)	0.0000 ± 0.0006

[SB, Englert, Gupta, Spannowsky, 2018, 2019]

Directions from *VBF*, *Zh*, *Wh*, and *WZ*

$$|(-0.04\ c^1_Q + 1.4\ c^{(3)}_Q + 0.1\ c_{uR} - 0.03\ c_{dR})\xi| < 0.003 \qquad [VBF]$$

$$|(-0.18\ c^1_Q + 1.3\ c^{(3)}_Q + 0.3\ c_{uR} - 0.1\ c_{dR})\xi| < 0.0005 \qquad [Zh]$$

$$|c^{(3)}_Q \xi| < 0.0004 \qquad [Wh]$$

$$-0.0004 < c^{(3)}_Q \xi < 0.0003 \qquad [WZ]$$

[Araz, SB, Gupta, Spannowsky, 2020]

The W^+W^- channel

$$
\begin{aligned}
\Delta\mathcal{L}_{\rm BSM} = {} & \delta g^Z_{uL}\left[Z^\mu \bar{u}_L\gamma_\mu u_L + \frac{\cos\theta_W}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.}) + \ldots\right] + \delta g^Z_{uR}\left[Z^\mu \bar{u}_R\gamma_\mu u_R\right] \\
& + \delta g^Z_{dL}\left[Z^\mu \bar{d}_L\gamma_\mu d_L - \frac{\cos\theta_W}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.}) + \ldots\right] + \delta g^Z_{dR}\left[Z^\mu \bar{d}_R\gamma_\mu d_R\right] \\
& + ig\cos\theta_W \delta g^Z_1\left[Z^\mu(W^{+\nu}W^-_{\mu\nu} - \text{h.c.}) + Z^{\mu\nu}W^+_\mu W^-_\nu + \ldots\right] \\
& + ie\delta\kappa_\gamma[(A_{\mu\nu} - \tan\theta_W Z_{\mu\nu})W^{+\mu}W^{-\nu} + \ldots],
\end{aligned}
$$

with $Z_{\mu\nu} \equiv \hat{Z}_{\mu\nu} - iW^+_{[\mu}W^-_{\nu]}$, $A_{\mu\nu} \equiv \hat{A}_{\mu\nu}$, $W^\pm_{\mu\nu} \equiv \hat{W}^\pm_{\mu\nu} \pm iW^\pm_{[\mu}(A+Z)_{\nu]}$, where $\hat{V}_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, and θ_W is the Weinberg angle

Electroweak corrections

We include approximate electroweak (EW) corrections in Sherpa which includes infrared subtracted EW 1-loop corrections as additional weights to the respective Born cross sections. In those the event weight is calculated based on the expression

$$\mathrm{d}\sigma_{\mathrm{NLO,EW}_{\mathrm{approx}}} = \left[B(\Phi) + V_{\mathrm{EW}}(\Phi) + I_{\mathrm{EW}}(\Phi)\right]\mathrm{d}\Phi$$

B = Born contribution also entering the uncorrected QCD cross Section

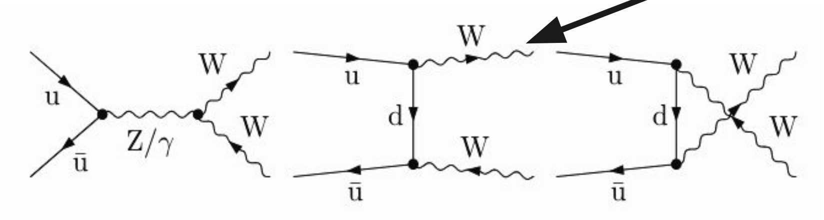
V_{EW} = electroweak virtual corrections at 1-loop accuracy

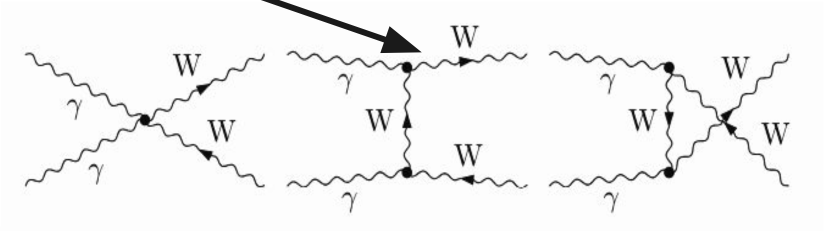
I_{EW} = generalised Catani-Seymour insertion operator for EW NLO calculations.

Latter subtracts all infrared singularities of the virtual corrections. This fundamentally arbitrary procedure should provide a good approximation if electroweak Sudakov logarithms are dominant.

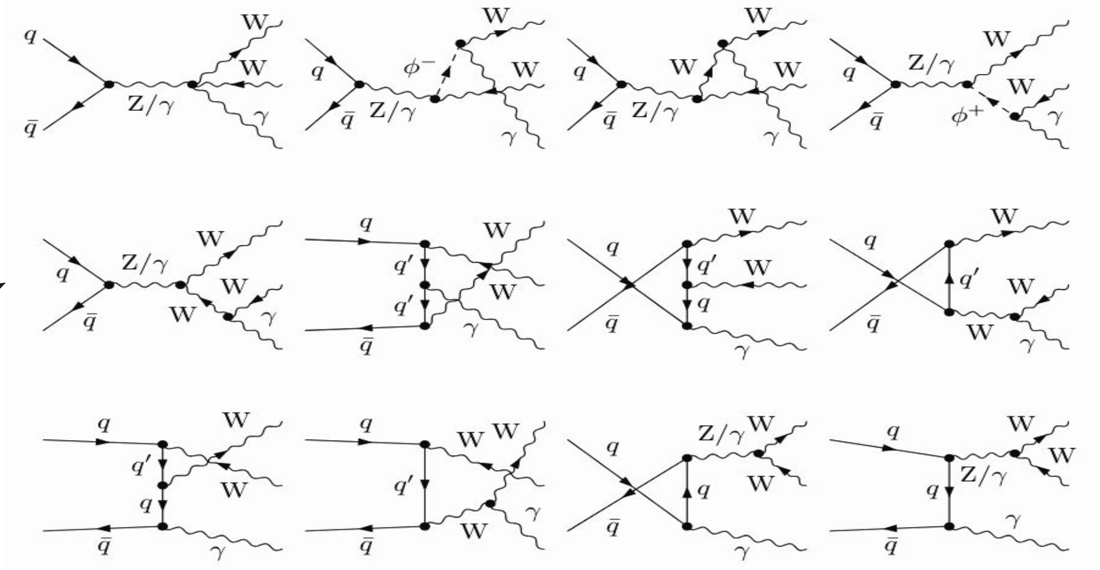
Electroweak corrections in W^+W^-

Leading order



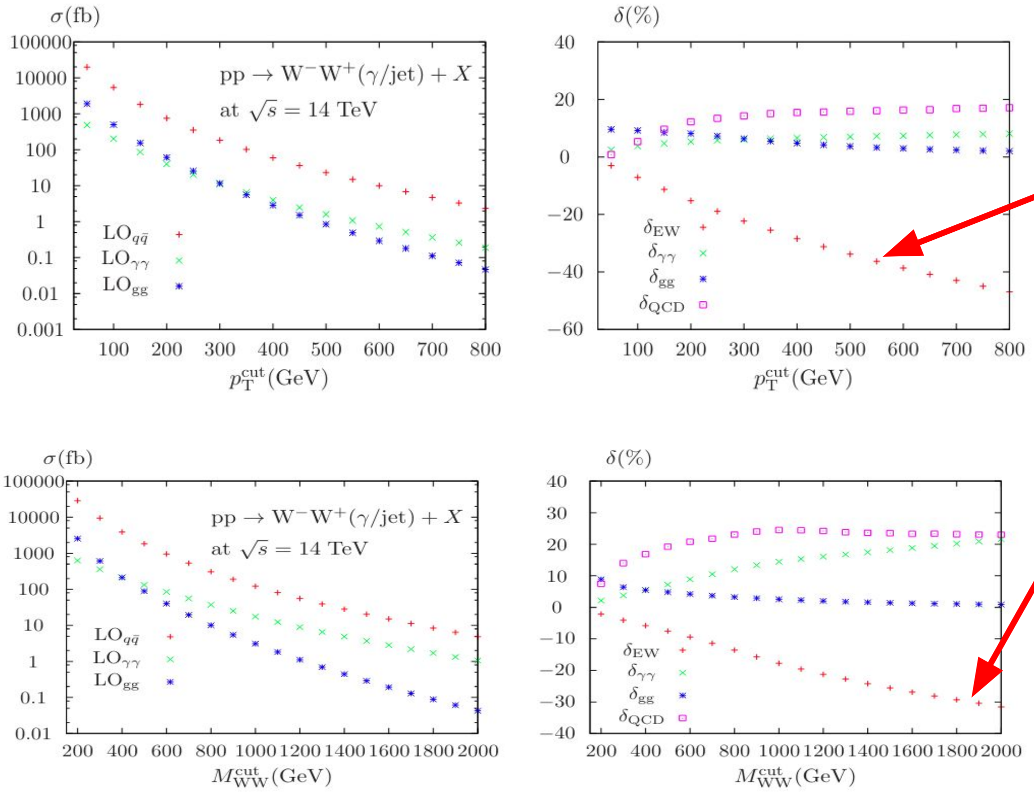


[Bierweiler et al, 2012]



Real bremsstrahlung diagrams

Electroweak corrections in W^+W^-



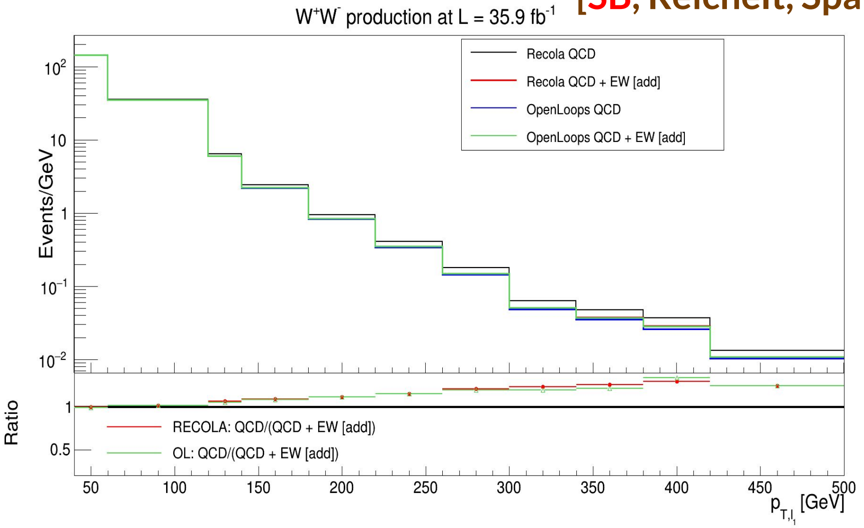
Large electroweak corrections!

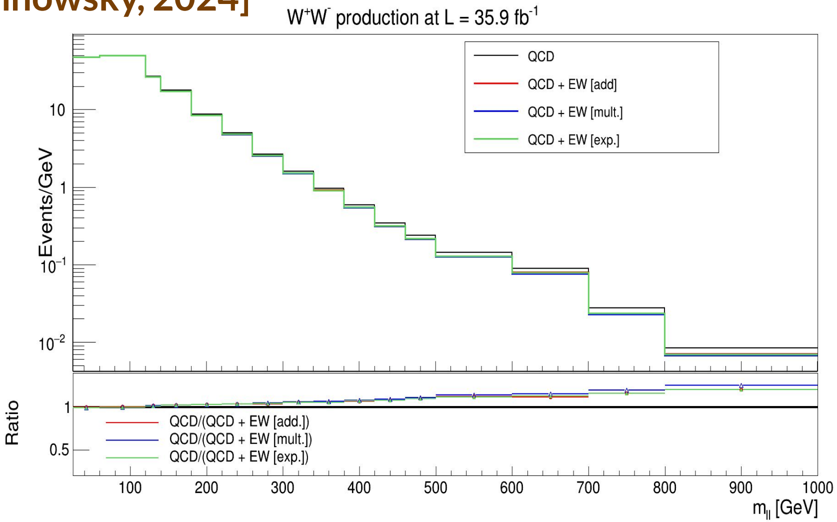
[Bierweiler et al, 2012]

Event generation

$$pp \to W^+(l^+\nu)W^-(l^-\nu) \qquad \mu_R^2 = \mu_F^2 = M_{\perp,W^+}^2 + M_{\perp,W^-}^2$$

[SB, Reichelt, Spannowsky, 2024]





Signal: SMEFT+SM interference; Backgrounds: $\text{Drell-Yan}\ (pp \to \ell^+\ell^-), VZ, t\bar{t} + tW, W\ell\ell$

χ^2 analysis

$$\chi^2 = \sum_i \sum_j \frac{[\mathcal{O}^{\text{theo.}}_{ij}(p) - \mathcal{O}^{\text{exp., SM}}_{ij}]^2}{\sigma^2_{ij}}$$

$$\mathcal{O}^{\text{theo.}}_{ij}(p) = \mathcal{O}^{\text{SM}}_{ij} + p \times \mathcal{O}^{\text{SMEFT}}_{ij}$$

$$p = \delta g^Z_{d_R}, \delta g^Z_{u_R}, \delta g^Z_{u_L}, \text{ or } \delta g^Z_{d_L}$$

$$\sigma_{ij} = \sqrt{(\sigma^{\text{exp.}}_{ij,\text{stat.}})^2 + (\sigma^{\text{theo.}}_{ij,\text{stat.}})^2 + (\sigma^{\text{exp.}}_{ij,\text{syst.}})^2 + (\sigma^{\text{theo.}}_{ij,\text{syst.}})^2}$$

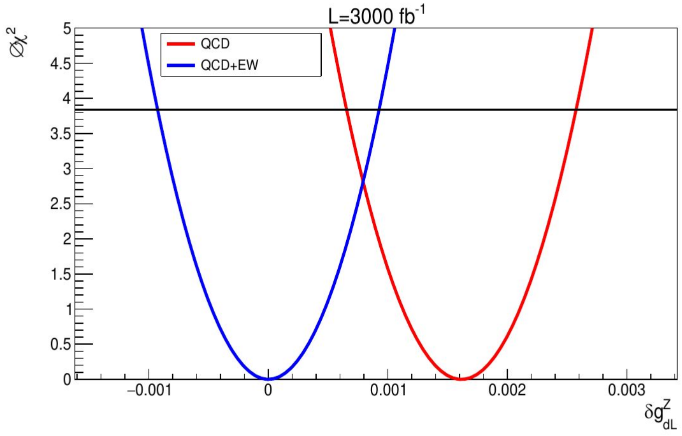
6 sub-categories: $e\mu - 0, e\mu - 1, ee - 0, ee - 1, \mu\mu - 0,$ and $\mu\mu - 1$
`0' and `1' refer to the jet multiplicity

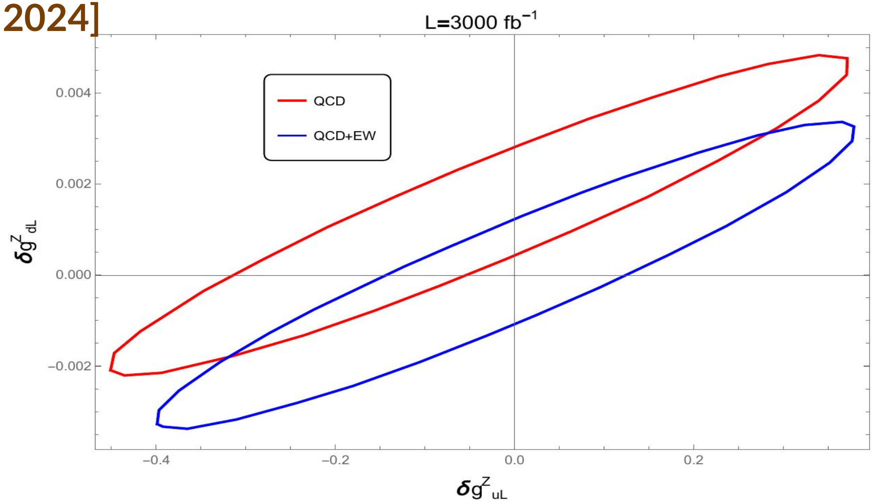
Theo. calculated at either SM@NLO-QCD+approximate-NLO-EW + SMEFT@LO or SM@NLO-QCD + SMEFT@LO

Exp. calculated at SM@NLO-QCD+approximate-NLO-EW

Results (95% C.L. bounds) - 1 and 2 parameter fits

[SB, Reichelt, Spannowsky, 2024]





Coupling	QCD: $\mathcal{L} = 300$ fb^{-1}	QCD+EW: $\mathcal{L} = 300$ fb^{-1}	QCD: $\mathcal{L} = 3$ ab^{-1}	QCD+EW: $\mathcal{L} = 3$ ab^{-1}
$\delta g^Z_{d_R}$	[-0.2744 0.0531]	[-0.1569, 0.1569]	[-0.1611, -0.0421]	[-0.0567, 0.0567]
$\delta g^Z_{u_R}$	[-0.0180, 0.0818]	[-0.0474, 0.0474]	[0.0111, 0.0463]	[-0.0167, 0.0167]
$\delta g^Z_{d_L}$	[-0.0008, 0.0039]	[-0.0023, 0.0023]	[0.0006, 0.0026]	[-0.0010, 0.0010]
$\delta g^Z_{u_L}$	[-0.3910, 0.0927]	[-0.2383, 0.2383]	[-0.2969, -0.0702]	[-0.1104, 0.1104]

Summary

1. EFT's essence shows that many anomalous Higgs couplings were already constrained by LEP through *Z*-pole and di-boson measurements

2. *Zh*, *Wh*, *WW* and *WZ* are important channels to disentangle various directions in the EFT space. They are intrinsically correlated

3. Multiple dimensions come about from the various correlated EFT coefficients. Blind directions need to be broken.

4. Inclusion of electroweak corrections to the backgrounds can change the bounds on the SMEFT couplings considerably as what we may perceive to be a change owing to SMEFT deformations might be owing to higher-order corrections

5. The next step would include considering mixed NLO electroweak + NLO QCD to the SMEFT interference terms (ongoing!)

Thank you!!!

Backup slides

Four directions in the EFT space (Warsaw Basis)

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(c^1_L - c^3_L) \\
g^h_{Zd_Ld_L} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(c^1_L + c^3_L) \\
g^h_{Zu_Ru_R} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}c^u_R \\
g^h_{Zd_Rd_R} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}c^d_R
\end{aligned}
$$

Four directions in the EFT space (SILH Basis)

$$g^h_{Zu_Lu_L} = \frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_W + c_{HW} - c_{2W} - \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B}))$$

$$g^h_{Zd_Ld_L} = -\frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_W + c_{HW} - c_{2W} + \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B}))$$

$$g^h_{Zu_Ru_R} = -\frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})$$

$$g^h_{Zd_Rd_R} = \frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})$$

Four directions in the EFT space (Higgs primaries)

$$g^h_{Zu_Lu_L} = 2\delta g^Z_{Zu_Lu_L} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}}$$

$$g^h_{Zd_Ld_L} = 2\delta g^Z_{Zd_Ld_L} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}}$$

$$g^h_{Zu_Ru_R} = 2\delta g^Z_{Zu_Ru_R} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}}$$

$$g^h_{Zd_Rd_R} = 2\delta g^Z_{Zd_Rd_R} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}}$$

Four directions in the EFT space (Universal model)

$$g^h_{Zu_Lu_L} = -\frac{g}{c_{\theta_W}}\left((c^2_{\theta_W} + \frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W + \frac{t^2_{\theta_W}}{3}(\hat{S} - \delta\kappa_\gamma - Y)\right)$$

$$g^h_{Zd_Ld_L} = \frac{g}{c_{\theta_W}}\left((c^2_{\theta_W} - \frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W - \frac{t^2_{\theta_W}}{3}(\hat{S} - \delta\kappa_\gamma - Y)\right)$$

$$g^h_{Zu_Ru_R} = -\frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S} - \delta\kappa_\gamma + c^2_{\theta_W}\delta g^Z_1 - Y)$$

$$g^h_{Zd_Rd_R} = \frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S} - \delta\kappa_\gamma + c^2_{\theta_W}\delta g^Z_1 - Y)$$

EFT space directions

- δg_f^Z and δg_{ZZ}^h $\rightarrow$ deviations in SM amplitude
- These do not grow with energy and are suppressed by $\mathcal{O}(m_Z^2/\hat{s})$ w.r.t. g_{Vf}^h
- Five directions: g_{Zf}^h with $f = u_L, u_R, d_L, d_R$ and g_{Wud}^h $\rightarrow$ only four operators in Warsaw basis $g_{Wud}^h = c_{\theta_W} \frac{g_{Zu_L}^h - g_{Zd_L}^h}{\sqrt{2}}$
- Knowing proton polarisation is not possible and hence in reality there are two directions Also, upon only considering interference terms, we have

$$g_{\mathbf{u}}^Z = g_{Zu_L}^h + \frac{g_{u_R}^Z}{g_{u_L}^Z} g_{Zu_R}^h$$

$$g_{\mathbf{d}}^Z = g_{Zd_L}^h + \frac{g_{d_R}^Z}{g_{d_L}^Z} g_{Zd_R}^h \qquad g_{\mathbf{p}}^Z = g_{\mathbf{u}}^Z + \frac{\mathcal{L}_d(\hat{s})}{\mathcal{L}_u(\hat{s})} g_{\mathbf{d}}^Z$$

$$g_{\mathbf{p}}^Z = g_{Zu_L}^h - 0.76\; g_{Zd_L}^h - 0.45\; g_{Zu_R}^h + 0.14\; g_{Zd_R}^h$$

$$g_{Z\mathbf{p}}^h = 2\delta g_{Zu_L}^h - 1.52\; g_{Zd_L}^h - 0.90\; g_{Zu_R}^h + 0.28\; g_{Zd_R}^h - 0.14\; \delta\kappa_\gamma - 0.89\; \delta g_1^Z$$

$$g_{Z\mathbf{p}}^h = -0.14\; (\delta\kappa_\gamma - \hat{S} + Y) - 0.89\; \delta g_1^Z - 1.3\; W$$

EFT Validity

- Till now, we have dropped the $gg \to Zh$ contribution which is $\sim 15\%$ of the qq rate
- It doesn't grow with energy in presence of the anomalous couplings
- We estimate the scale of new physics for a given δg^h_{Zf}
- Example: Heavy $SU(2)_L$ triplet (singlet) vector W'^a (Z') couples to SM fermion current $\bar{f}\sigma^a\gamma_\mu f$ ($\bar{f}\gamma_\mu f$) with g_f and to the Higgs current $iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H$ ($iH^\dagger \overleftrightarrow{D}_\mu H$) with g_H

$$g^h_{Zu_L,d_L} \sim \frac{g_H g^2 v^2}{2\Lambda^2},$$

$$g^h_{Zf} \sim \frac{g_H g g_f v^2}{\Lambda^2} \qquad g^h_{Zu_R,d_R} \sim \frac{g_H g g' Y_{u_R,d_R} v^2}{\Lambda^2}$$

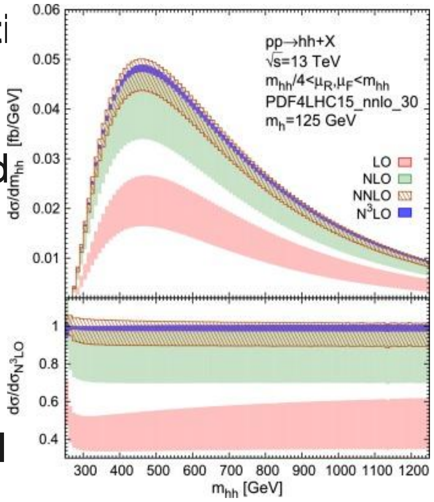
- $\Lambda \to$ mass scale of vector and thus cut-off for low energy EFT
- Assumed g_f to be a combination of $g_B = g' Y_f$ and $g_W = g/2$ for universal case

Types of uncertainties in particle physics

- **Systematic (experimental):** includes instrumental uncertainties, uncertainties due to calibration of energy scales and resolution of detectors, uncertainti
detector efficiencies, etc.

- **Statistical (experimental):** stem from finite number of events record

- **Modelling of signal and backgrounds (theoretical)**



- **Luminosity:** uncertainty on precise determination of the rate of coll

Theory precision ⟷ Experimental precision

Curiosity: How to propagate all of these uncertainties consistently in an ML algorithm?

Catani-Seymour

The Catani-Seymour subtraction method, including the use of the insertion operator $\mathbf{I}(\epsilon)$, was originally developed for handling infrared (IR) divergences in Quantum Chromodynamics (QCD) calculations. However, the principles behind the subtraction method can be extended and applied to other gauge theories, including electroweak (EW) theory, for next-to-leading-order (NLO) calculations.

Application to Electroweak Calculations

When dealing with NLO corrections in electroweak (EW) theory, similar challenges arise due to IR divergences from soft and collinear photons (and sometimes Z bosons in specific processes). The Catani-Seymour subtraction method can be adapted to manage these divergences as follows:

1. **Photon Emission**: Just as gluons can be soft or collinear in QCD, photons can be emitted in a soft or collinear manner, leading to IR divergences. The subtraction terms in the Catani-Seymour method can be modified to account for the specific kinematics and coupling structures of photon emissions.

Catani Seymour

2. **Universal Structures**: The structure of IR divergences has universal properties that apply across different gauge theories. The key idea of constructing counterterms that locally approximate the behavior of the matrix elements in singular regions remains valid.

3. **Insertion Operators**: In the EW context, the insertion operator \(\mathbf{I}(\epsilon) \) must be redefined to include the contributions from the EW interactions. This involves recalculating the kinematic factors \(\mathcal{V}_{ij}(\epsilon) \) to reflect the dynamics of photons (and possibly other weak bosons).

4. **Mixed QCD-EW Corrections**: In processes involving both QCD and EW corrections, a combined subtraction scheme can be employed. This involves constructing subtraction terms that handle both QCD and EW singularities simultaneously, ensuring a consistent treatment of all IR divergences.