PIKIMO 2026: Adding tree-level SMEFT corrections to EWPOs to GRIFFIN

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SMEFT Basics

- Effective Field Theory extension of the Standard Model [1008.4884]
- Add operators that obey the SM symmetries, corresponding to physics at higher scale Λ

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=5} \frac{1}{\Lambda^{d-4}} C_i^{(d)} \mathcal{O}_i^{(d)}$$

- C_i are Wilson coefficients, $\mathcal{O}$ are in the Warsaw basis

Why SMEFT

- Non-model dependent way to analyze BSM physics
- Treats SM as a low-energy approximation with new physics at a higher scale
- Can perform global fits on experimental data on Wilson coefficients
- Lots of interesting phenomenology in all areas of particle physics

GRIFFIN Basics

- Interested in measuring $f\bar{f} \to f'\bar{f}'$ scattering (often) near the Z boson resonance.
- Interpret results through Electroweak Pseudo-Observables (EWPOs) plus additional effects
- GRIFFIN (Gauge-invariant Resonance In Four-Fermion INteractions) [2211.16272] is a C++ package providing these values for calculating four-fermion processes
- Easily modifiable to add higher-order corrections

GRIFFIN Structure

- Chiral structure:

$$\mathcal{M} = [M_{VV}\gamma^{\mu}\otimes\gamma_{\mu} - M_{VA}\gamma^{\mu}\otimes\gamma_{\mu}\gamma^{5} - M_{AV}\gamma^{\mu}\gamma^{5}\otimes\gamma_{\mu} + M_{AA}\gamma^{\mu}\gamma^{5}\otimes\gamma_{\mu}\gamma^{5}]$$

- Differential cross-section:

$$\begin{aligned}\frac{d\sigma}{d\cos\theta} = \frac{N_c s}{32\pi}\Big[&(1+c_\theta^2)\left(|M_{VV}|^2 + |M_{VA}|^2 + |M_{AV}|^2 + |M_{AA}|^2\right) \\ &+ 4c_\theta \mathrm{Re}\{M_{VV}M_{AA}^* + M_{VA}M_{AA}^*\} \\ &- 2P_f(1+c_\theta^2)\mathrm{Re}\{M_{VV}M_{AV}^* + M_{VA}M_{AA}^*\} \\ &- 4P_f c_\theta \mathrm{Re}\{M_{VV}M_{VA}^* + M_{AV}M_{AA}^*\}\Big]\end{aligned}$$

Z-pole Expansion

- Near Z resonance, expand matrix element as

$$M_{ij} = \frac{R_{ij}}{s - s_0} + S_{ij} + S'_{ij}(s - s_0)$$

$i, j = V, A$ and $s_0 = M_Z^2 - iM_Z\Gamma_Z$

- Can write the pole coefficient in terms of form factors F_V^f, F_A^f, and the effective weak mixing angle $\sin^2\theta_{\text{eff}}^f$.

Form Factors

$$\sin^2\theta^f_{\text{eff}} = \frac{1}{4|Q_f|}\left[1 - \text{Re}\frac{Z_{Vf}}{Z_{Af}}\right]_{s=M_Z^2}$$

$$F_A^f = \left[\frac{|Z_{Af}|^2}{1+\text{Re}\Sigma'_Z} - \frac{1}{2}M_Z\Gamma_Z|a^Z_{f(0)}|^2\text{Im}\Sigma''_Z\right]_{s=M_Z^2} + \mathcal{O}(\alpha^3)$$

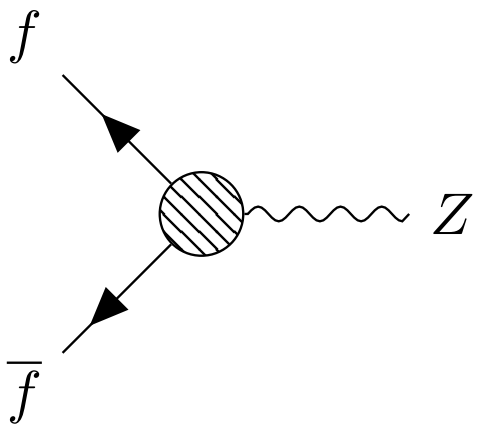
$$F_V^f = F_A^f\left[(1-4|Q_f|\sin^2\theta^f_{\text{eff}})^2 + \left(\text{Im}\frac{Z_{Vf}}{Z_{Af}}\right)^2\right]$$

$$Z_{Vf}(s) = v_f^Z(s) + v_f^\gamma(s)\frac{\Sigma_{\gamma Z}(s)}{1+\Sigma_{\gamma\gamma}(s)} \quad \Sigma_Z(s) = \Sigma_{ZZ}(s) - \frac{[\Sigma_{\gamma Z}(s)]^2}{s+\Sigma_{\gamma\gamma}(s)}$$

$$Z_{Af}(s) = a_f^Z(s) + a_f^\gamma(s)\frac{\Sigma_{\gamma Z}(s)}{1+\Sigma_{\gamma\gamma}(s)}$$

Zff vertex

- $v_f^Z(s)$ and $a_f^Z(s)$ are the Zff vertex form factors.
- $\mathcal{L}_{Zff} = Z_\mu \bar{f} \gamma^\mu (v_f^Z - a_f^Z \gamma_5) f$
- At tree level,
  $\mathcal{L}_{Zff(0)} = Z_\mu \bar{f} \frac{e}{s_W c_W} \left((I_3^f - Q^f s_w^2) \frac{1-\gamma^5}{2} - Q^f s_w^2 \frac{1+\gamma^5}{2} \right)$
- $v_{f(0)}^Z = \frac{e}{2 s_w c_w} \left(I_3^f - 2 Q^f \sin^2 \theta_W \right)$, $a_{f(0)}^Z = \frac{e I_3^f}{2 s_w c_w}$



Tree level SMEFT in GRIFFIN

- Due to modular nature, easy to add code for SMEFT corrections
- Allows for studying BSM corrections to EWPOs [1909.02000, 1502.02570]
- Can perform global fits now with high precision in the SM
- Starting just by adding tree-level SMEFT-SM interference

SMEFT Contributions to GRIFFIN

- Three general classes of contributions
- Operators contribute to Zff vertex: $\mathcal{O}_{\varphi WB}$, $\mathcal{O}_{\varphi D}$, $\mathcal{O}_{\varphi l}^{(1)}$, $\mathcal{O}_{\varphi l}^{(3)}$, $\mathcal{O}_{\varphi e}$.
- Operators contribute to non-resonant: $\mathcal{O}_{ll}$, $\mathcal{O}_{lq}^{(1)}$, $\mathcal{O}_{lq}^{(3)}$, $\mathcal{O}_{ee}$, $\mathcal{O}_{eu}$, $\mathcal{O}_{ed}$, $\mathcal{O}_{le}$, $\mathcal{O}_{lu}$, $\mathcal{O}_{ld}$, $\mathcal{O}_{qe}$
- In addition, some contribute again G_μ: $[\mathcal{O}_{ll}]_{1221}$, $[\mathcal{O}_{ll}]_{2112}$, $[\mathcal{O}_{\varphi l}^{(3)}]_{11}$, $[\mathcal{O}_{\varphi l}^{(3)}]_{22}$, $\mathcal{O}_{\varphi WB}$, $\mathcal{O}_{\varphi D}$
  - Relevant because GRIFFIN accepts M_W or G_μ as inputs, then calculates

$$G_\mu = \frac{\pi\alpha}{\sqrt{2}M_W^2(1 - M_W^2/M_Z^2)}(1 + \Delta r)$$

SMEFT Contributions to Form Factors

- At leading order, SMEFT corrections to form factors simplify greatly

$$Z_{Vf}(s) = v^Z_{f(0)}(s) + \delta v^Z_{f,\mathrm{SMEFT}}(s) \quad Z_{Af}(s) = a^Z_{f(0)}(s) + \delta a^Z_{f,\mathrm{SMEFT}}(s)$$

$$\sin^2\theta^f_{\mathrm{eff}} = \frac{1}{4|Q_f|}\left[1 - \mathrm{Re}\frac{v^Z_{f(0)}(s) + \delta v^Z_{f,\mathrm{SMEFT}}(s)}{a^Z_{f(0)}(s) + \delta a^Z_{f,\mathrm{SMEFT}}(s)}\right]_{s=M_Z^2}$$

$$\delta\sin^2\theta^f_{\mathrm{eff}} \approx \frac{-1}{4|Q_f|}\left[\mathrm{Re}\frac{v^Z_{f(0)}}{a^Z_{f(0)}}\left(\frac{\delta v^Z_{f,\mathrm{SMEFT}}}{v^Z_{f(0)}} - \frac{\delta a^Z_{f,\mathrm{SMEFT}}}{a^Z_{f(0)}}\right)\right]$$

$$F^f_A = \left[|a^Z_{f(0)} + \delta a^Z_{f,\mathrm{SMEFT}}|^2\right]_{s=M_Z^2}, \qquad \delta F^f_A \approx 2a^Z_{f(0)}\delta a^Z_{f,\mathrm{SMEFT}}$$

$$F^f_V = F^f_A\left[(1 - 4|Q_f|\sin^2\theta^f_{\mathrm{eff}})^2\right].$$

Form Factors (cont.)

- Can get these shifts from the SMEFT Lagrangian [1704.03888]

$$\delta v^Z_{f,\mathrm{SMEFT}} = \frac{e}{2 s_W c_W}\left(\delta g_L^{Zf} + \delta g_R^{Zf}\right), \delta a^Z_{f,\mathrm{SMEFT}} = \frac{e}{2 s_W c_W}\left(\delta g_L^{Zf} - \delta g_R^{Zf}\right)$$

$$\delta g_L^{Zf} = -\frac{C_{\varphi D}}{\Lambda^2}\frac{M_W^2}{8\pi\alpha}\left(2\left(I_{3f} - Q_f\right) - 2\left(2I_{3f} - Q_f\right)\frac{M_W^2}{M_Z^2}\right) - \frac{C^{(1)}_{\varphi f}}{\Lambda^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)\frac{M_W^2}{2\pi\alpha} +$$
$$I_{3f}\frac{C^{(3)}_{\varphi f}}{\Lambda^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)\frac{M_W^2}{\pi\alpha} + I_{3f}\frac{C_{\varphi WB}}{\Lambda^2}\frac{M_W^2}{\pi\alpha}\frac{M_W}{M_Z^2}\sqrt{M_Z^2 - M_W^2}$$

$$\delta g_R^{Zf} = -\frac{C_{\varphi f}}{\Lambda^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)\frac{M_W^2}{2\pi\alpha} + Q_f\frac{C_{\varphi D}}{\Lambda^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)\frac{M_W^2}{4\pi\alpha}$$

SMEFT Contributions to W Mass

- G_μ picks up corrections from the SMEFT due to corrections to muon decay

$$G_\mu = \frac{1}{\sqrt{2}v^2} - \frac{1}{\sqrt{2}} C_{ll} + \sqrt{2} C_{\varphi l}^{(3)}$$

- Additional shifts in M_Z lead to the following corrections to M_W^2 ($c_W^2 s_W^2 = \frac{\pi\alpha}{\sqrt{2} G_\mu M_Z^2}$)

$$\delta M_W^2 = \frac{1}{2\Lambda^2 G_\mu} \frac{M_Z^2 c_W^2 s_W^2}{\sqrt{\frac{1}{4} - c_W^2 s_W^2}} \left(\frac{C_{ll}}{\sqrt{2}} - \sqrt{2} C_{\phi l}^{(3)} \right.$$

$$\left. - \frac{\sqrt{2} C_{\phi WB} c_W s_W}{\frac{1}{2} - \sqrt{\frac{1}{4} - c_W^2 s_W^2}} + \frac{C_{\phi D}}{2\sqrt{2}} \left(1 - \frac{\sqrt{\frac{1}{4} - c_W^2 s_W^2} + \frac{1}{2}}{c_W^2 s_W^2} \right) \right)$$

SMEFT Non-Resonant Contributions

- Non-resonant contributions to $f\bar{f} \to f'\bar{f}'$ scattering from four-fermion SMEFT operators
- Similarly, can find quickly from chiral structure, then rewrite in terms of GRIFFIN's vector/axial vector structure

$f = e/\mu/\tau, f' = e/\mu/\tau$:

$$M_{LL} = -\frac{1}{\Lambda^2}\left(2[C_{ll}]_{fff'f'} + 2[C_{ll}]_{ff'f'f}\right)$$

$$M_{RR} = -\frac{1}{\Lambda^2} 4[C_{ee}]_{fff'f'}$$

$$M_{LR} = -\frac{1}{\Lambda^2}[C_{le}]_{fff'f'}$$

$$M_{RL} = -\frac{1}{\Lambda^2}[C_{le}]_{f'f'ff}$$

Future Steps

- Still more work that needs to be done to incorporate same-fermion scattering (additional M_{SS}, M_{PP} contributions)
- Include higher-order contributions
- Include dimension 8 operators

Conclusion

- The SMEFT is a powerful framework for evaluating model-independent impacts of BSM physics on (e.g.) EWPOs
- GRIFFIN is a useful package for gauge-invariant, modular higher-order corrections to four-fermion scattering
- Now, can perform more accurate SMEFT fits
- Two great tastes that taste great together

Backup

SMEFT Operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

Table: dimension 6 SMEFT Operators in the Warsaw basis

Form Factors (cont.)

These factors, in addition to higher-order imaginary corrections, combine to form R (at NNLO):

$$R_{ij}^{(0+1+2)} = 4 I_3^f I_3^{f'} \sqrt{F_A^f F_A^{f'}} \Big[\tilde{Q}_i^f \tilde{Q}_j^{f'} \left(1 + i r_{AA}^I - \frac{1}{2}(r_{AA}^I)^2 + \frac{1}{2}\delta\overline{X}_{(2)} \right) + (\tilde{Q}_i^f I_{j,f'} + \tilde{Q}_j^{f'} I_{i,f})(i - r_{AA}^I) - I_{i,f} I_{j,f'} \Big] + M_Z \Gamma_Z Z_{if(0)} Z'_{jf'(0)} x_{ij}^I$$

$$\tilde{Q}_V^f = 1 - 4|Q_f| \sin^2 \theta_{\text{eff}}^f \qquad \tilde{Q}_A^f = 1$$

$$I_{V,f} = \frac{1}{(a_{f(0)})^2} \left[a_{f(0)}^Z \text{Im} Z_{Vf(1)} - v_{f(0)}^Z \text{Im} Z_{Af(1)} \right] \qquad I_{A,f} = 0$$

$$r_{AA}^I = \frac{\text{Im} Z_{Af(1)}}{a_{f(0)}^Z} + \frac{\text{Im} Z_{Af'(1)}}{a_{f'(0)}^Z} - \text{Im}\Sigma'_{Z(1)} \qquad \delta\overline{X}_{(2)} = -(\text{Im}\Sigma'_{Z(1)})^2 + 2\frac{B_{\gamma Z,ij(1)}^R}{R_{ij}^{(0)}}$$

$$x_{ij}^I = \frac{\text{Im} Z'_{if(1)}}{Z_{if(0)}} + \frac{\text{Im} Z'_{jf'(1)}}{Z_{jf'(0)}} - \frac{1}{2}\text{Im}\Sigma''_{Z(1)}$$

GRIFFIN Framework

- Two base classes: `invals` and `psobs`
- An `invals` object takes boson masses and widths, fermion masses, and couplings
- Two child classes for SM inputs: one for (α, M_Z, M_W) couplings and one for (α, M_Z, G_μ)
- All EWPOs are calculated with M_W; for latter inputs calculate via

$$G_\mu = \frac{\pi\alpha}{\sqrt{2}M_W^2(1 - M_W^2/M_Z^2)}(1 + \Delta r)$$

GRIFFIN Framework (cont.)

- A `psobs` object returns a value used to calculate an matrix element
- Has child classes for $F^f_{V,A}$, $\sin^2\theta^f_{\text{eff}}$ with corrections up to complete NNLO ($\mathcal{O}(\alpha^2) + \mathcal{O}(\alpha\alpha_s)$)
- Child class for matrix elements, from complex-pole expansion (up to NNLO) and off-resonance (up to NLO, for now)

Non-resonant

$f = e/\mu/\tau, f' = \nu_e/\nu_\mu/\nu_\tau$:

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{ll}]_{fff'f'} + [C_{ll}]_{ff'f'f}\right)$$
$$M_{RR} = M_{LR} = 0$$
$$M_{RL} = -\frac{1}{\Lambda^2}[C_{le}]_{f'f'ff}$$

$f = \nu_e/\nu_\mu/\nu_\tau, f' = e/\mu/\tau$:

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$$M_{RR} = M_{RL} = 0$$
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Non-resonant

$f = \nu_e/\nu_\mu/\nu_\tau, f' = \nu_e/\nu_\mu/\nu_\tau$:

$$M_{LL} = -\frac{1}{\Lambda^2}\left(2[C_{ll}]_{fff'f'} + 2[C_{ll}]_{ff'f'f}\right)$$

$$M_{RR} = M_{LR} = M_{RL} = 0$$

$f = e/\mu/\tau, f' = u/c$:

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{lq}^{(1)}]_{fff'f'} - [C_{lq}^{(3)}]_{fff'f'}\right)$$

$$M_{RR} = -\frac{1}{\Lambda^2}[C_{eu}]_{fff'f'}$$

$$M_{LR} = -\frac{1}{\Lambda^2}[C_{lu}]_{fff'f'}$$

$$M_{RL} = -\frac{1}{\Lambda^2}[C_{qe}]_{f'f'ff}$$

Non-resonant

$f = u/c, f' = e/\mu/\tau$:

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{lq}^{(1)}]_{f'f'ff} - [C_{lq}^{(3)}]_{f'f'ff}\right)$$

$$M_{RR} = -\frac{1}{\Lambda^2}[C_{eu}]_{f'f'ff}$$

$$M_{LR} = -\frac{1}{\Lambda^2}[C_{qe}]_{fff'f'}$$

$$M_{RL} = -\frac{1}{\Lambda^2}[C_{lu}]_{f'f'ff}$$

Non-resonant

$f = e/\mu/\tau, f' = s/d/b$:

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{lq}^{(1)}]_{fff'f'} + [C_{lq}^{(3)}]_{fff'f'}\right)$$

$$M_{RR} = -\frac{1}{\Lambda^2}[C_{ed}]_{fff'f'}$$

$$M_{LR} = -\frac{1}{\Lambda^2}[C_{ld}]_{fff'f'}$$

$$M_{RL} = -\frac{1}{\Lambda^2}[C_{qe}]_{f'f'ff}$$

Non-resonant

$f = d/s/b, f' = e/\mu/\tau$:

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{lq}^{(1)}]_{f'f'ff} + [C_{lq}^{(3)}]_{f'f'ff}\right)$$

$$M_{RR} = -\frac{1}{\Lambda^2}[C_{ed}]_{f'f'ff}$$

$$M_{LR} = -\frac{1}{\Lambda^2}[C_{qe}]_{fff'f'}$$

$$M_{RL} = -\frac{1}{\Lambda^2}[C_{ld}]_{f'f'ff}$$

Non-resonant

$$f = \nu_e/\nu_\mu/\nu_\tau, f' = u/c:$$

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{lq}^{(1)}]_{fff'f'} + [C_{lq}^{(3)}]_{fff'f'}\right)$$

$$M_{RR} = M_{RL} = 0$$

$$M_{LR} = -\frac{1}{\Lambda^2}[C_{lu}]_{fff'f'}$$

$$f = u/c, f' = \nu_e/\nu_\mu/\nu_\tau:$$

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{lq}^{(1)}]_{f'f'ff} + [C_{lq}^{(3)}]_{f'f'ff}\right)$$

$$M_{RR} = M_{LR} = 0$$

$$M_{RL} = -\frac{1}{\Lambda^2}[C_{lu}]_{f'f'ff}$$

Non-resonant

$$f = \nu_e/\nu_\mu/\nu_\tau, f' = s/d/b:$$

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{lq}^{(1)}]_{fff'f'} - [C_{lq}^{(3)}]_{fff'f'}\right)$$

$$M_{RR} = M_{RL} = 0$$

$$M_{LR} = -\frac{1}{\Lambda^2}[C_{ld}]_{fff'f'}$$

$$f = d/s/b, f' = \nu_e/\nu_\mu/\nu_\tau:$$

$$M_{LL} = -\frac{1}{\Lambda^2}\left([C_{lq}^{(1)}]_{f'f'ff} - [C_{lq}^{(3)}]_{f'f'ff}\right)$$

$$M_{RR} = M_{LR} = 0$$

$$M_{RL} = -\frac{1}{\Lambda^2}[C_{ld}]_{f'f'ff}$$