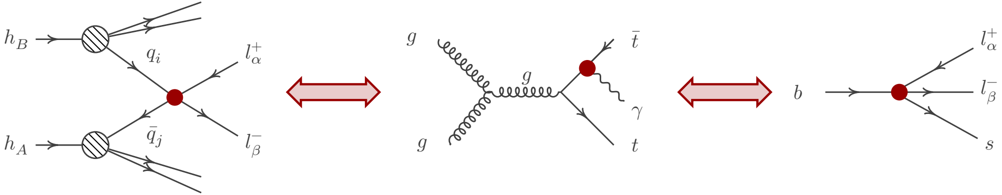

Synergies of Drell-Yan, top and beauty in global SMEFT-fits

Work in progress with Cornelius Grunwald, Gudrun Hiller and Kevin Kröninger

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15th International Workshop on Top Quark Physics

SMEFT approach to new physics

- Main objective of EFTs: compute low-energy observables without knowledge of full underlying theory
- SMEFT is constructed from all SM fields with the full SM symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Prerequisites:
  - Scale separation between the scale of the process and the scale Λ of new physics
  - Linearly realised EWSB

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

$O_n^{(j)}$: Local operators, IR-sensitive (SM-fields and symmetries)
$C_n^{(j)}$: Wilson coefficients, UV-sensitive (Effective couplings)

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- Dimension 6 operators: Warsaw Basis: 59 operators $\rightarrow$ 2499 free parameters

Minimal Flavour Violation

- Impose a $U(3)^3$ symmetry $G_F = U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$ [JHEP 05 (2021), 257]
- The SM Yukawa matrices are treated as spurions
  $\rightarrow$ Expand the quark bilinears, e.g.

$$\bar{Q}Q : a_1 \mathbb{1} + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + \ldots$$

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$$\bar{Q}Q : a_1 \mathbb{1} + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + \ldots$$

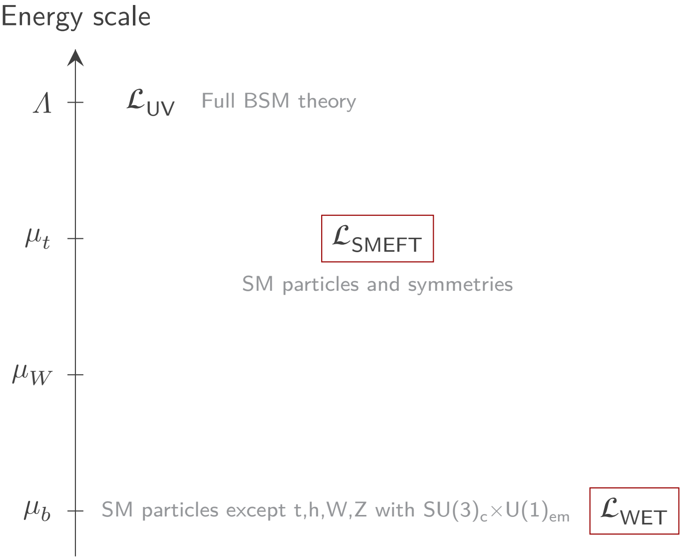
- Rotating to the mass basis and retaining only y_t yields:

$$C\,\bar{Q}Q \sim C\left[\bar{u}_L \begin{pmatrix} a_1 & 0 & 0 \\ 0 & a_1 & 0 \\ 0 & 0 & a_1 + a_2\, y_t^2 \end{pmatrix} u_L + \bar{d}_L \begin{pmatrix} a_1 + a_2\,|V_{td}|^2\, y_t^2 & a_2\, V_{td}^* V_{ts}\, y_t^2 & a_2\, V_{td}^* V_{tb}\, y_t^2 \\ a_2\, V_{ts}^* V_{td}\, y_t^2 & a_1 + a_2\,|V_{ts}|^2\, y_t^2 & a_2\, V_{ts}^* V_{tb}\, y_t^2 \\ a_2\, V_{tb}^* V_{td}\, y_t^2 & a_2\, V_{tb}^* V_{ts}\, y_t^2 & a_1 + a_2\,|V_{tb}|^2\, y_t^2 \end{pmatrix} d_L\right]$$

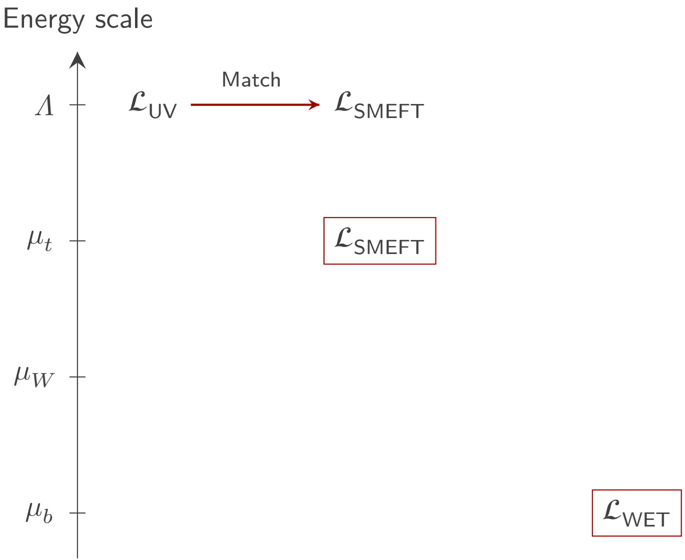
$t\bar{t}$ Drell-Yan $b \rightarrow sll$

- Imposes **correlations** among flavour entries and allows for **down-type FCNCs**

Running and Matching

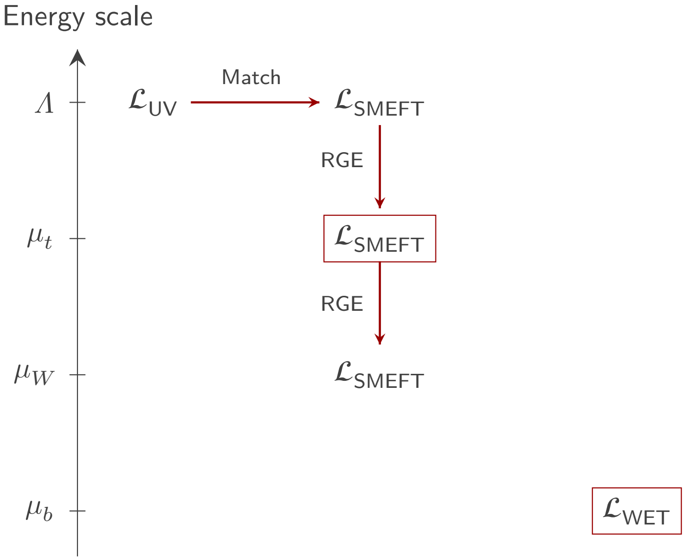


Running and Matching



- Match a possible UV theory onto the SMEFT at the matching scale Λ

Running and Matching



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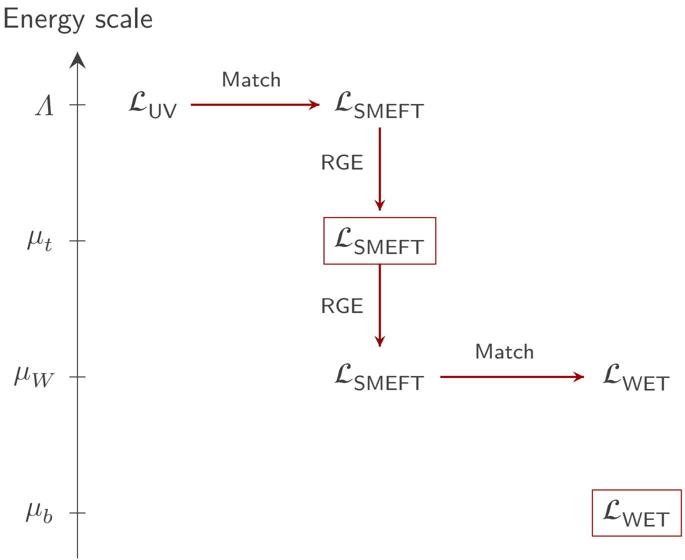
- Apply the SMEFT RGE to evolve the Wilson coefficients to lower energy scales
- Compute top and collider observables at the scale μ_t

Running and Matching



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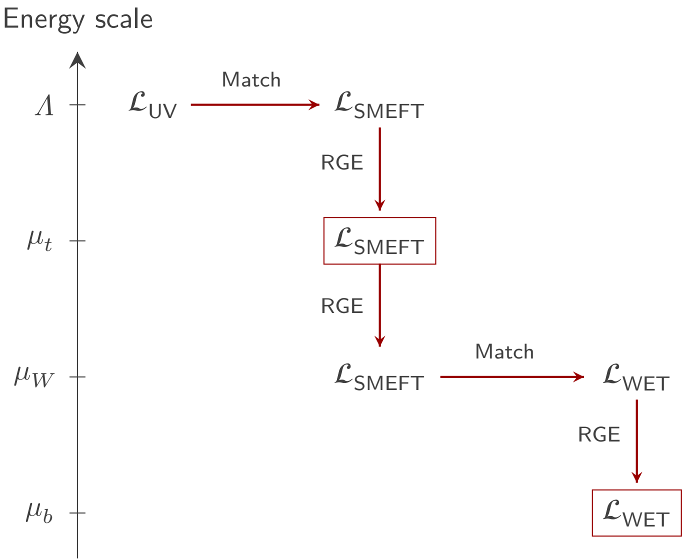
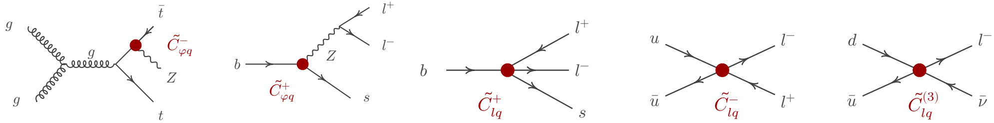
Running and Matching



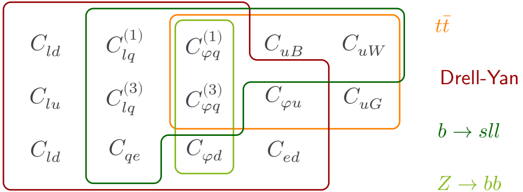
- Match a possible UV theory onto the SMEFT at the matching scale Λ
- Apply the SMEFT RGE to evolve the Wilson coefficients to lower energy scales
- Compute top and collider observables at the scale μ_t
- Match the SMEFT onto the WET at the scale μ_W
- Use the WET RGE to compute the Wilson coefficients at the scale μ_b of flavour-observables

Synergies of top, beauty and Drell-Yan

- Extension of Bißmann et al. [JHEP 06 (2021), 010] with DY and MFV instead of top-philic
- Individual observables always leave unconstrained (flat) directions in parameter space

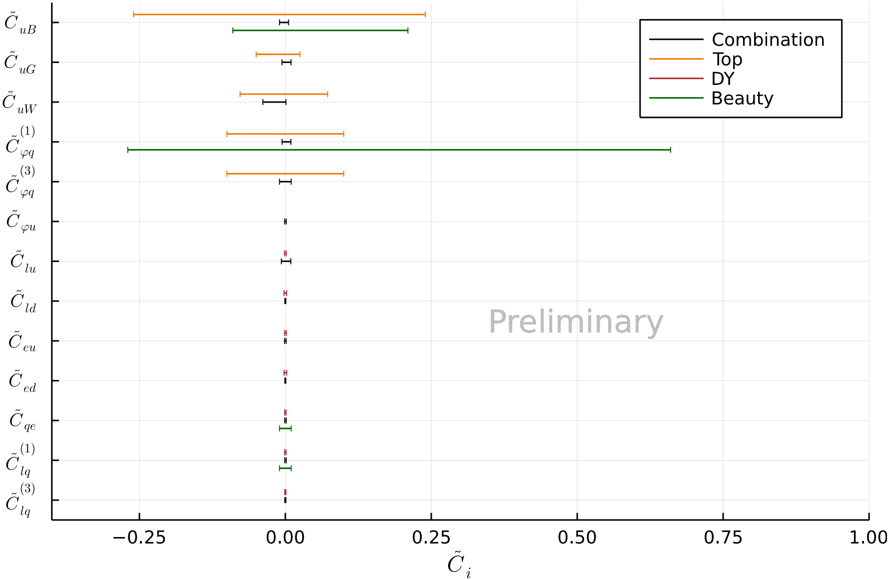


- Top, beauty and Drell-Yan probe different linear combinations
  $\rightarrow$ Combination breaks flat directions and thus strongly improves the fit



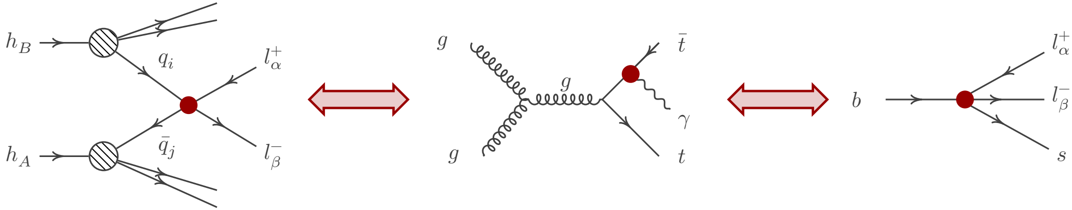
See also e.g. Greljo et al. [JHEP 11 (2020) 080] for DY in SMEFT

Preliminary Results



Conclusion

- EFTs allow for a systematic and model-independent search for BSM physics
- Flavour assumptions link top, beauty and Drell-Yan
- A consistent combination requires RGE running and matching
- Complementarity allows to break flat directions
- The combination of top-quark, flavour and collider observables strongly enhances global fits of SMEFT Wilson coefficients



Extra Slides

Collider measurements included in the fit

Process	Observable	Experiment	$\sqrt{s}$	Int. luminosity
$t\bar{t}\gamma$	$\sigma^{\text{fid}}(t\bar{t}\gamma, 1\ell)$, $\sigma^{\text{fid}}(t\bar{t}\gamma, 2\ell)$	ATLAS	13 TeV	36.1 fb^{-1}
$t\bar{t}Z$	$\sigma^{\text{inc}}(t\bar{t}Z)$	CMS	13 TeV	77.5 fb^{-1}
$t\bar{t}$	$\sigma^{\text{inc}}(t\bar{t})$	ATLAS	13 TeV	36.1 fb^{-1}
$t\bar{t}$	F_0 , F_L	ATLAS	8 TeV	20.2 fb^{-1}
$t\bar{t}$	Γ_t	ATLAS	8 TeV	20.2 fb^{-1}
$Z \to bb$	$A_{FB}^{0,b}$, R_b	ALEPH, DELPHI, L3, OPAL, SLD	/	/
$pp \to e^+e^-$	Events, 68 bins	CMS	13 TeV	137 fb^{-1}
$pp \to \mu^+\mu^-$	Events, 36 bins	CMS	13 TeV	140 fb^{-1}
$pp \to \tau^+\tau^-$	Events, 17 bins	ATLAS	13 TeV	139 fb^{-1}
$pp \to e\nu$	Events, 40 bins	ATLAS	13 TeV	139 fb^{-1}
$pp \to \mu\nu$	Events, 35 bins	ATLAS	13 TeV	139 fb^{-1}
$pp \to \tau\nu$	Events, 10 bins	ATLAS	13 TeV	139 fb^{-1}

Flavour measurements included in the fit

Process	Observable	Experiment	q^2 bin [GeV^2]
$\bar{B} \to X_s \gamma$	$\mathrm{BR}_{E_\gamma > 1.6\ \mathrm{GeV}}$	HFLAV	/
$B^0 \to K^* \gamma$	BR	HFLAV	/
$B^+ \to K^{*+} \gamma$	BR	HFLAV	/
$\bar{B} \to X_s \ell^+ \ell^-$	BR	BaBar	$[1, 6]$
	A_{FB}	Belle	$[1, 6]$
$B_s \to \mu^+ \mu^-$	BR	LHCb	/
$B^0 \to K^* \mu^+ \mu^-$	F_L, P_1, P_2, P_3, P_4', P_5', P_6', P_8'	LHCb	$[1.1, 6]$
$B^0 \to K \mu^+ \mu^-$	$d\mathrm{BR}/dq^2$	LHCb	$[1, 6]$
$B^+ \to K^+ \mu^+ \mu^-$	$d\mathrm{BR}/dq^2$	LHCb	$[1, 6]$
$B^+ \to K^{+*} \mu^+ \mu^-$	$d\mathrm{BR}/dq^2$	LHCb	$[1, 6]$
$B_s \to \phi \mu^+ \mu^-$	F_L, S_3, S_4, S_7	LHCb	$[1, 6]$
$\Lambda_b \to \Lambda \mu^+ \mu^-$	$d\mathrm{BR}/dq^2$	LHCb	$[15, 20]$
$B_s - \bar{B}_s$ mixing	ΔM_s	HFLAV	/

SMEFT Operators in Warsaw basis

$$O_{uG} = (\bar{q}_L \sigma^{\mu\nu} T^A u_R)\, \tilde{\varphi} G^A_{\mu\nu}\,,$$

$$O_{uB} = (\bar{q}_L \sigma^{\mu\nu} u_R)\, \tilde{\varphi} B_{\mu\nu}\,,$$

$$O^{(1)}_{lq} = \left(\bar{l}_L \gamma_\mu l_L\right) \left(\bar{q}_L \gamma^\mu q_L\right)\,,$$

$$O_{eu} = \left(\bar{e}_R \gamma_\mu e_R\right) \left(\bar{u}_R \gamma^\mu u_R\right)\,,$$

$$O_{lu} = \left(\bar{l}_L \gamma_\mu l_L\right) \left(\bar{u}_R \gamma^\mu u_R\right)\,,$$

$$O^{(1)}_{\varphi q} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right) \left(\bar{q}_L \gamma^\mu q_L\right)\,,$$

$$O_{\varphi u} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right) \left(\bar{u}_R \gamma^\mu u_R\right)\,,$$

$$O_{uW} = (\bar{q}_L \sigma^{\mu\nu} u_R)\, \tau^I \tilde{\varphi} W^I_{\mu\nu}\,,$$

$$O_{qe} = \left(\bar{q}_L \gamma_\mu q_L\right) \left(\bar{e}_R \gamma^\mu e_R\right)\,,$$

$$O^{(3)}_{lq} = \left(\bar{l}_L \gamma_\mu \tau^I l_L\right) \left(\bar{q}_L \gamma^\mu \tau^I q_L\right)\,,$$

$$O_{ed} = \left(\bar{e}_R \gamma_\mu e_R\right) \left(\bar{d}_R \gamma^\mu d_R\right)\,,$$

$$O_{ld} = \left(\bar{l}_L \gamma_\mu l_L\right) \left(\bar{d}_R \gamma^\mu d_R\right)\,,$$

$$O^{(3)}_{\varphi q} = \left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right) \left(\bar{q}_L \tau^I \gamma^\mu q_L\right)\,,$$

$$O_{\varphi d} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right) \left(\bar{d}_R \gamma^\mu d_R\right)\,,$$

Weak Effective Theory for $b \to sll$

Effective Lagrangian for $b \to sll$

$$\mathcal{L}_{\text{WET}}^{bs} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) Q_i(\mu)$$

$$Q_1 = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L)\,, \qquad Q_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)\,,$$

$$Q_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q}\gamma^\mu q)\,, \qquad Q_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q}\gamma^\mu T^a q)\,,$$

$$Q_5 = (\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\sigma b_L) \sum_q (\bar{q}\gamma^\mu \gamma^\nu \gamma^\sigma q)\,, \qquad Q_6 = (\bar{s}_L \gamma_\mu \gamma_\nu \gamma_\sigma T^a b_L) \sum_q (\bar{q}\gamma^\mu \gamma^\nu \gamma^\sigma T^a q)\,,$$

$$Q_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}\,, \qquad Q_8 = \frac{g_s}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu}\,,$$

$$Q_9^{ij} = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}^i \gamma^\mu \ell^j)\,, \qquad Q_{10}^{ij} = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}^i \gamma^\mu \gamma_5 \ell^j)\,,$$

Weak Effective Theories for $b \to s\nu\nu$ and B_s mixing

Effective Lagrangian for $b \to s\nu\nu$

$$\mathcal{L}^{\nu}_{\mathrm{WET}} = \frac{4G_F}{\sqrt{2}} V^*_{ts} V_{tb} \sum_{i,j=1}^{3} \left(C^{ij}_L(\mu) Q^{ij}_L(\mu) + C^{ij}_R(\mu) Q^{ij}_R(\mu) \right)$$

$$Q^{ij}_L = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}^i \gamma^\mu (1-\gamma_5) \nu^j) \,, \quad Q^{ij}_R = \frac{e^2}{16\pi^2} (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}^i \gamma^\mu (1-\gamma_5) \nu^j) \,.$$

Effective Lagrangian for B_s mixing

$$\mathcal{L}^{\mathrm{mix}}_{\mathrm{WET}} = \frac{G_F^2 m_W^2}{16\pi^2} Q^{\mathrm{mix}}_1 \left| V_{tb} V^*_{ts} \right|^2 C^{\mathrm{mix}}_{1,tt} \,,$$

$$Q^{\mathrm{mix}}_1 = \left(\bar{s}_L \gamma_\mu b_L \right) \left(\bar{s}_L \gamma^\mu b_L \right) \,.$$

Tree-level Matching

$$\Delta C_9^{\text{tree}} = \frac{\pi}{\alpha}\left[\tilde{C}_{lq}^{(1)} + \tilde{C}_{lq}^{(3)} + \tilde{C}_{qe} + \left(-1 + 4\sin^2\theta_w\right)\left(\tilde{C}_{\varphi q}^{(1)} + \tilde{C}_{\varphi q}^{(3)}\right)\right]\frac{\gamma_A}{1+\gamma_A}$$
$$= \left[430.5 \cdot \left(\tilde{C}_{qe} + \tilde{C}_{lq}^{(1)} + \tilde{C}_{lq}^{(3)}\right) - 45.86 \cdot \left(\tilde{C}_{\varphi q}^{(1)} + \tilde{C}_{\varphi q}^{(3)}\right)\right]\frac{\gamma_A}{1+\gamma_A},$$

$$\Delta C_{10}^{\text{tree}} = \frac{\pi}{\alpha}\left[-\tilde{C}_{lq}^{(1)} - \tilde{C}_{lq}^{(3)} + \tilde{C}_{qe} + \tilde{C}_{\varphi q}^{(1)} + \tilde{C}_{\varphi q}^{(3)}\right]\frac{\gamma_A}{1+\gamma_A}$$
$$= \left[430.5 \cdot \left(\tilde{C}_{\varphi q}^{(1)} + \tilde{C}_{\varphi q}^{(3)} + \tilde{C}_{qe} - \tilde{C}_{lq}^{(1)} - \tilde{C}_{lq}^{(3)}\right)\right]\frac{\gamma_A}{1+\gamma_A},$$

$$\Delta C_L^{\text{tree}} = \frac{\pi}{\alpha}\left[\tilde{C}_{lq}^{(1)} - \tilde{C}_{lq}^{(3)} + \tilde{C}_{\varphi q}^{(1)} + \tilde{C}_{\varphi q}^{(3)}\right]\frac{\gamma_A}{1+\gamma_A}$$
$$= \left[430.5 \cdot \left(\tilde{C}_{\varphi q}^{(1)} + \tilde{C}_{\varphi q}^{(3)} + \tilde{C}_{lq}^{(1)} - \tilde{C}_{lq}^{(3)}\right)\right]\frac{\gamma_A}{1+\gamma_A}$$

One-loop Matching

$$
\begin{aligned}
C_7 &= -2.351\,\tilde{C}_{uB} + 0.09273\,\tilde{C}_{uW} - 0.09457\,\tilde{C}^{(1)}_{\varphi q} + 0.7948\,\tilde{C}^{(3)}_{\varphi q} \\
C_8 &= -0.6638\,\tilde{C}_{uG} + 0.2706\,\tilde{C}_{uW} + 0.2837\,\tilde{C}^{(1)}_{\varphi q} + 0.7565\,\tilde{C}^{(3)}_{\varphi q} \\
C_9 &= 2.506\,\tilde{C}_{uB} + 2.137\,\tilde{C}_{uW} + 0.2134\,\tilde{C}_{\varphi u} - 1.108\,\tilde{C}^{(1)}_{\varphi q} + 4.374\,\tilde{C}^{(3)}_{\varphi q} \\
&\quad + 2.003 \cdot \left(-\tilde{C}_{eu} - \tilde{C}_{qe} + \tilde{C}^{(1)}_{lq}\right) - 3.163\,\tilde{C}^{(3)}_{lq} \\
C_{10} &= -7.515\,\tilde{C}_{uW} + 2.003\left(-\tilde{C}_{\varphi u} + \tilde{C}^{(1)}_{\varphi q} - \tilde{C}_{eu} + \tilde{C}_{lu} + \tilde{C}_{qe} - \tilde{C}^{(1)}_{lq}\right) \\
&\quad - 17.88\,\tilde{C}^{(3)}_{\varphi q} + 3.163\,\tilde{C}^{(3)}_{lq} \\
C_L &= 12.89\,\tilde{C}_{uW} + 2.003 \cdot \left(-\tilde{C}_{\varphi u} + \tilde{C}^{(1)}_{\varphi q} - \tilde{C}_{lu} + \tilde{C}^{(1)}_{lq}\right) - 22.83\,\tilde{C}^{(3)}_{\varphi q} - 16.28\,\tilde{C}^{(3)}_{lq} \\
C_{\text{mix}} &= 4.129\,\tilde{C}_{uW} + 3.579\,\tilde{C}^{(1)}_{\varphi q} - 10.1\,\tilde{C}^{(1)}_{\varphi q} + 12.95\,\tilde{C}^{(3)}_{\varphi q}
\end{aligned}
$$

MFV Spurion Expansion

$$\bar{Q}Q :\sim a_1\mathbb{1} + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + \ldots \quad \bar{U}U :\sim b_1\mathbb{1} + b_2 Y_u^\dagger Y_u + \ldots \quad \bar{D}D :\sim e_1\mathbb{1} + e_2 Y_d^\dagger Y_d + \ldots$$

$$\bar{Q}U :\sim (c_1\mathbb{1} + c_2 Y_u Y_u^\dagger + \ldots)Y_u \qquad \bar{Q}D :\sim (d_1\mathbb{1} + d_2 Y_u Y_u^\dagger + \ldots)Y_d$$

After rotation to mass basis:

$$\begin{aligned}
\bar{Q}Q :\ & \bar{d}_{Li} d_{Lj} \to a_1 \delta_{ij} + a_2 y_t^2 V_{ti}^* V_{tj} \\
& \bar{u}_{Li} u_{Lj} \to a_1 \delta_{ij} + a_2 y_t^2 \delta_{3i}\delta_{3j} \\
& \bar{u}_{Li} d_{Lj} \to a_1 V_{ij} + a_2 y_t^2 \delta_{3i} V_{tj} \\
& \bar{d}_{Li} u_{Lj} \to a_1 V_{ji}^* + a_2 y_t^2 V_{ti}^* \delta_{3j} \\
\bar{U}U :\ & \bar{u}_{Ri} u_{Rj} \to b_1 \delta_{ij} + b_2 y_t^2 \delta_{3i}\delta_{3j} \\
\bar{D}D :\ & \bar{d}_{Ri} d_{Rj} \to e_1 \delta_{ij}
\end{aligned}$$

$$\begin{aligned}
\bar{Q}U :\ & \bar{u}_{Li} u_{Rj} \to (c_1 + c_2 y_t^2) y_t \delta_{3i}\delta_{3j}\,, \\
& \bar{d}_{Li} u_{Rj} \to (c_1 + c_2 y_t^2) y_t V_{ti}^* \delta_{3j}\,, \\
\bar{Q}D :\ & \simeq 0 \\
\bar{D}D :\ & \bar{d}_{Ri} d_{Rj} \to e_1 \delta_{ij}
\end{aligned}$$

EFT cross section and Simulation Chain

$$\mathcal{M} = \mathcal{M}^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i \mathcal{M}_i^{\text{BSM}} \xrightarrow{\sigma \propto |\mathcal{M}|^2} \sigma = \sigma^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i \sigma_i^{\text{int}} + \frac{1}{\Lambda^4}\sum_{i \leq j} C_i C_j \sigma_{ij}^{\text{BSM}}$$

model definition	FeynRules 2.0 (arXiv:1310.1921)
parton level Monte Carlo	MadGraph5 (arXiv:1405.0301)
hadronisation and parton shower	Pythia8 (arXiv:1410.3012)
detector simulation	Delphes3 (arXiv:1307.6346)

Constraints on semileptonic four-fermion Operators (preliminary)