

# Perturbative calculations for the Z-Penguin

Based on work in collaboration with:  
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# Content

Introduction: Flavour Sector and Effective Theories

Phenomenology:  $K^+ \rightarrow \pi^+ \bar{\nu} \nu$  and  $\mu \rightarrow 3e$

Renormalisation of Z-Penguin for  
Generic Perturbative Theories

# Flavour Symmetry

The standard model gauge sector is CP conserving and has a large global flavour symmetry

$$\mathcal{L}_g = \sum_f \bar{\psi}_f D\psi_f + \sum_i \frac{1}{4} g_i \vec{F}_{\mu\nu}^i \vec{F}^{i\mu\nu}$$

$$f \in \{u, d, e, Q, L\}$$

$$G_{\text{flavour}} = \prod_f \text{SU}(3)_f \times \prod_x \text{U}(1)_x$$

[Chivukula, Georgi '87]

Only Higgs Yukawa couplings break this symmetry in the SM

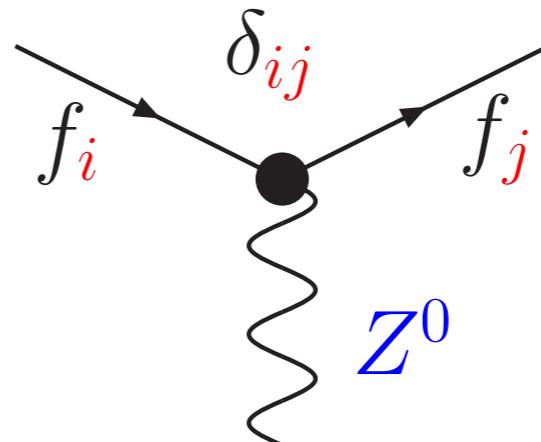
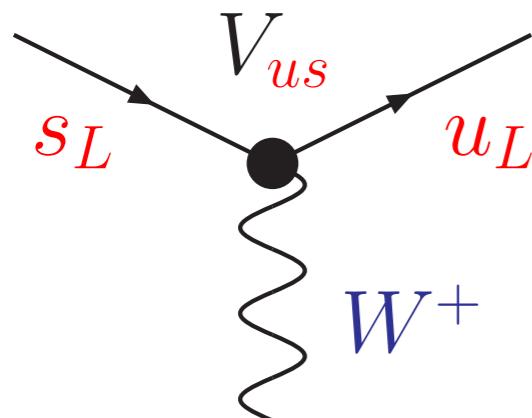
$$-\mathcal{L}_Y^q = \bar{u}_R Y_u \tilde{\phi}^\dagger Q_L + \bar{d}_R Y_d \phi^\dagger Q_L$$

Mass eigenstates  $\neq$  flavour eigenstates

for diagonal  $Y_d$ :  $Y_u = \frac{1}{v} \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

# Neutral & Charged Current Interactions

Mass  $\neq$  flavour eigenstates



SM: Only charged currents  
change the flavour ( $\propto V_{us}$ )

SM: Neutral currents do not  
change the flavour ( $i=j$ ) at tree-level

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM matrix parametrises CP and flavour violation in the SM

Standard Model: Higgs sector<sub>4</sub> is the source of flavour violation

# Flavour Problem

New physics like Supersymmetry, Extra Dimensions ...  
will have new sources of flavour violation,

while flavour observables agree well with in current precision.

If we will have new physics at a scale  $\Lambda$  we will generate

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Lambda^2 \phi^\dagger \phi + \frac{1}{\Lambda^2} (\bar{s} d_L)(\bar{s} d_R) + \dots$$

From the  $\Lambda^2$  term we expect  $\Lambda = \mathcal{O}(M_Z)$

From the  $\frac{1}{\Lambda^2}$  term we expect  $\Lambda \gg M_Z$

# New Physics sensitivity

The New Physics (**NP**) and the Standard Model (**SM**) compete

$$\delta\mathcal{L} = \frac{C_{NP}}{\Lambda_{NP}^2} (\bar{s}d_L)(\bar{s}d_R) + \frac{C_{SM}}{v_{EW}^2} (\bar{s}d_L)(\bar{s}d_R) \dots$$

Since we have no particle physics evidence of new physics

- \* Calculate the **SM** flavour violation as precisely as possible.
- \* Understand the origin and correlation of **NP** flavour violation to be able to interpret small deviations.

# Symmetry Classification Of New Physics Contributions

Standard model:  $SU(3)_C \otimes SU(2)_W \otimes U(1)_Y$  gauge symmetry

Above weak scale  $SU(2) \otimes U(1)$  will be a good symmetry

Use the  $SU(2) \otimes U(1)$  invariant fields ( $Q_L, d_R, u_R$ ) to write

$$i(\bar{B}_L \gamma^\mu S_L)(\phi^\dagger \overset{\leftrightarrow}{D}_\mu \phi)$$

for example –  $B_L$  &  $S_L$  denote 3rd & 2nd generation doublets.

# Symmetry Classification

$$i(\bar{B}_L \gamma^\mu S_L)(\Phi^\dagger \overset{\leftrightarrow}{D}_\mu \Phi)$$

After electroweak symmetry breaking

$$\rightarrow -v M_Z Z_\mu (\bar{b}_L \gamma^\mu s_L) + \text{up-type quarks}$$

Effective Z-penguin vertex  $\propto v^2$

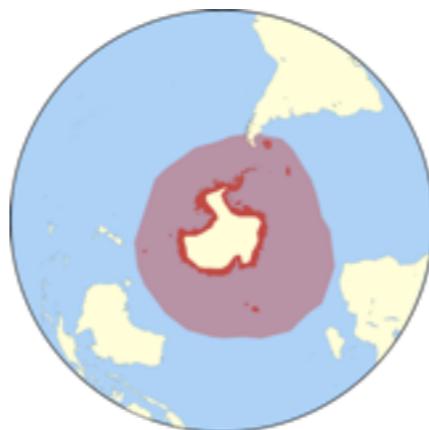
→ sensitive to e.w. symmetry breaking

Similar for other fermions, e.g. in

$$i(\bar{e}_L \gamma^\mu \mu_L)(\Phi^\dagger D_\mu \Phi), i(\bar{e}_L \gamma^\mu \tau^a \mu_L)(\Phi^\dagger \tau^a D_\mu \Phi),$$
$$i(\bar{s}_L \gamma^\mu d_L)(\Phi^\dagger D_\mu \Phi) \dots$$

# Phenomenology of the Z-Penguin

Penguins Contribute to Different Observables

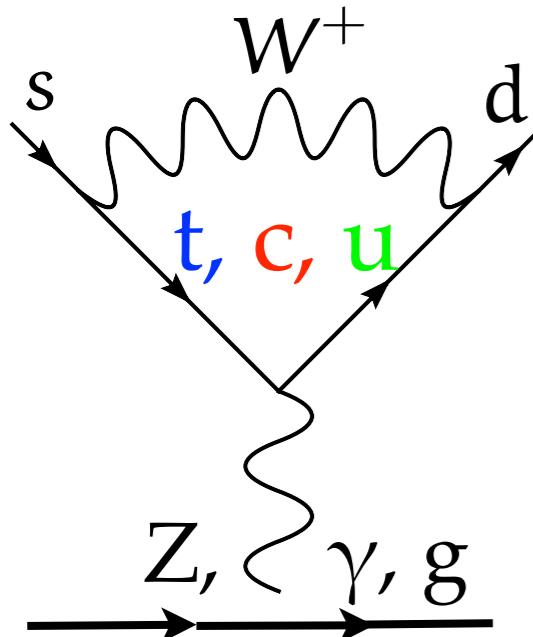


The Z-Penguin plays an important role in:

$B_{(s)} \rightarrow \mu^+ \mu^-$ ,  $B \rightarrow K^{(*)} l^+ l^-$ ,  $B \rightarrow K^{(*)} \pi$ ,  $K^+ \rightarrow \pi^+ \bar{\nu} \nu$ ,  $\varepsilon' / \varepsilon, \dots$   
 $\mu \rightarrow e$ ,  $\mu \rightarrow 3e$ ,  $\mu \rightarrow e \gamma$

Consider two examples:  $K^+ \rightarrow \pi^+ \bar{\nu} \nu$  (SM) and  $\mu \rightarrow 3e$  (SMEFT)

# Rare Kaon Decays



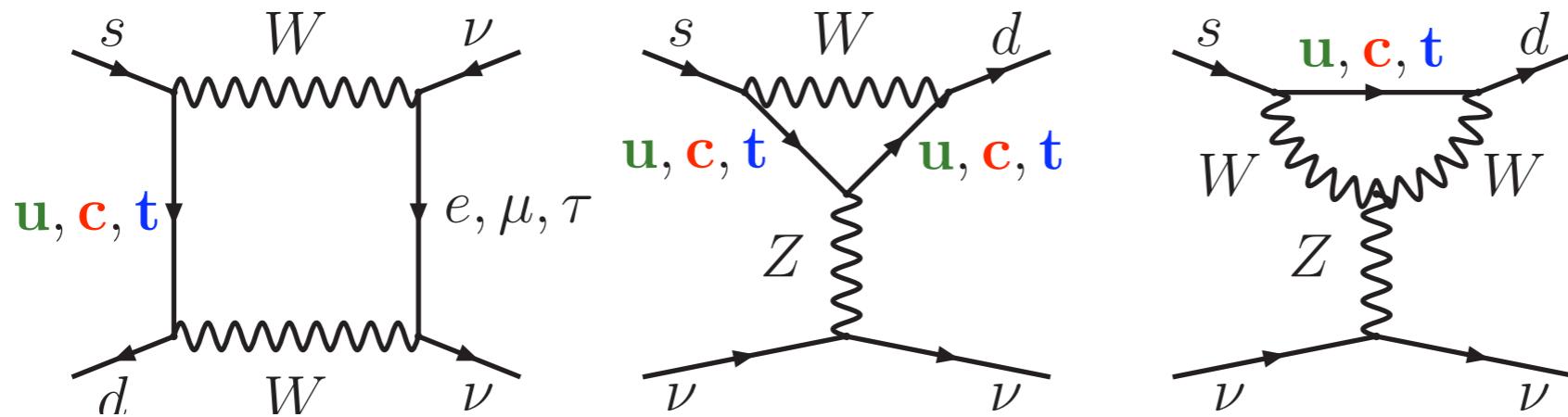
Using the GIM mechanism,  
we can eliminate either  $V_{cs}^* V_{cd}$  or  
 $V_{us}^* V_{ud} \rightarrow -V_{cs}^* V_{cd} - V_{ts}^* V_{td}$

$\text{Im} V_{ts}^* V_{td} = -\text{Im} V_{cs}^* V_{cd} = \mathcal{O}(\lambda^5)$	$\text{Im} V_{us}^* V_{ud} = 0$
$\text{Re} V_{us}^* V_{ud} = -\text{Re} V_{cs}^* V_{cd} = \mathcal{O}(\lambda^1)$	$\text{Re} V_{ts}^* V_{td} = \mathcal{O}(\lambda^5)$

Z-Penguin and Boxes (high virtuality):  
power expansion in:  $A_c - A_u \propto 0 + \mathcal{O}(m_c^2/M_W^2)$

$\gamma/g$ -Penguin (momentum expansion + e.o.m.):  
power expansion in:  $A_c - A_u \propto \mathcal{O}(\text{Log}(m_c^2/m_u^2))$

# $K^+ \rightarrow \pi^+ \bar{\nu} \nu$ at $M_W$



$$x_i = \frac{m_i^2}{M_W^2}$$

$$\sum_i V_{is}^* V_{id} F(x_i) = V_{ts}^* V_{td} (F(x_t) - F(x_u)) + V_{cs}^* V_{cd} (F(x_c) - F(x_u))$$

Quadratic GIM:  $\lambda^5 \frac{m_t^2}{M_W^2}$

$$\lambda \frac{m_c^2}{M_W^2} \ln \frac{M_W}{m_c}$$

$$\lambda \frac{\Lambda_{\text{QCD}}^2}{M_W^2}$$

Matching (NLO + EW):

$$Q_\nu = (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_L \gamma^\mu \nu_L)$$

Operator  
Mixing (RGE)

ChiPT &  
Lattice

NNLO involves 3-loop massive tadpoles. Compare result with similar calculation of  $B \rightarrow \mu^+ \mu^-$  [Cerda-Sevilla, Gorbahn, Leek]

Matrix element from  $K_{l3}$  decays (Isospin symmetry:  $K^+ \rightarrow \pi^0 e^+ \nu$ )

[Mescia, Smith]

# Expressions for $K \rightarrow \pi \bar{\nu} \nu$

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa_+ (1 + \Delta_{\text{EM}}) \cdot \left[ \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda_c}{\lambda} P_c(X) + \frac{\text{Re} \lambda_t}{\lambda^5} X(x_t) \right)^2 \right]$$

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = \kappa_L \cdot \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2$$

New Physics without extra light degrees of freedom  
can be absorbed into  
 $X(x_t) \rightarrow X(x_t) + X_{\text{NP}}$

# $K \rightarrow \pi \bar{v} v$ : Error Budget

Updating old analysis [Brod et.al. '11] using input from CKMfitter '16

$B_L \cdot 10^{11}$	Central:	2.874	$B_+ \cdot 10^{11}$	Central:	8.345
Error:	-0.195	0.161	Error:	-0.468	0.409
A	-0.152	0.1	A	-0.308	0.202
$x_t$	-0.07	0.071	$\delta P_{cu}$	-0.243	0.247
$\eta$	-0.099	0.104	$\rho$	-0.093	0.089
$\kappa_1$	-0.017	0.002	$P_c$	-0.183	0.185
$\lambda$	0.	0.	$x_t$	-0.142	0.143
			$\kappa_+$	-0.04	0.04
			$\eta$	-0.023	0.024
			$\lambda$	-0.001	0.001

# Lepton Sector

Dimension-5 Operator Generate Neutrino Masses

$$\begin{aligned}\delta\mathcal{L} = & +\frac{C_5^{\alpha\beta}}{2\Lambda}(\bar{\ell}_\alpha\varepsilon H_1^*)(\ell_\beta^c\varepsilon H_1^*) + \frac{C_5^{\alpha\beta*}}{2\Lambda}(\bar{\ell}_\beta^c\varepsilon H_1)(\ell_\alpha\varepsilon H_1) \\ & +\frac{C_{21}^{\alpha\beta}}{2\Lambda}\left((\bar{\ell}_\alpha\varepsilon H_2^*)(\ell_\beta^c\varepsilon H_1^*) + (\bar{\ell}_\beta\varepsilon H_1^*)(\ell_\alpha^c\varepsilon H_2^*)\right) + \text{h.c.} \\ & +\frac{C_{22}^{\alpha\beta}}{2\Lambda}(\bar{\ell}_\alpha\varepsilon H_2^*)(\ell_\beta^c\varepsilon H_2^*) + \frac{C_{22}^{\alpha\beta*}}{2\Lambda}(\bar{\ell}_\beta^c\varepsilon H_2)(\ell_\alpha\varepsilon H_2) \\ & -\frac{C_A^{\alpha\beta}}{2\Lambda}(\bar{\ell}_\alpha\varepsilon\ell_\beta^c)(H_1^\dagger\varepsilon H_2^*) - \frac{C_A^{\alpha\beta*}}{2\Lambda}(\bar{\ell}_\beta^c\varepsilon\ell_\alpha)(H_2\varepsilon H_1)\end{aligned}$$

These operators mix into the Z-Penguin and  
other dimension 6-Operators.

Calculation in SMEFT completes ADMs up to dimension 6

# Anomalous Dimensions

$$Q_{HL(1)} = i (\bar{e}_L \gamma^\mu \mu_L) (\Phi^\dagger D_\mu \Phi), Q_{HL(3)} = i (\bar{e}_L \gamma^\mu \tau^a \mu_L) (\Phi^\dagger \tau^a D_\mu \Phi)$$

$$\begin{aligned} (\vec{C}[\tilde{\gamma}] \vec{C}^\dagger)_{H\ell(1)}^{\beta\alpha} &= -C_5^{\beta\rho} \frac{3\delta_{\rho\sigma}}{2} C_5^{*\sigma\alpha} \\ &\quad -C_{21}^{\beta\rho} \frac{3\delta_{\rho\sigma}}{2} C_{21}^{*\sigma\alpha} + C_A^{\beta\rho} \frac{\delta_{\rho\sigma}}{2} C_A^{*\sigma\alpha} \\ (\vec{C}[\tilde{\gamma}] \vec{C}^\dagger)_{H\ell(3)}^{\beta\alpha} &= C_5^{\beta\rho} \delta_{\rho\sigma} C_5^{*\sigma\alpha} \\ &\quad + C_{21}^{\beta\rho} \delta_{\rho\sigma} C_{21}^{*\sigma\alpha} + C_A^{\beta\rho} \frac{\delta_{\rho\sigma}}{2} C_{21}^{*\sigma\alpha} - C_{21}^{\beta\rho} \frac{\delta_{\rho\sigma}}{2} C_A^{*\sigma\alpha} \end{aligned}$$

RGE govern mixing into the Z-Penguin:

$$(16\pi^2)\mu \frac{d}{d\mu} \tilde{C} = \tilde{C}\hat{\gamma} + \vec{C}[\tilde{\gamma}] \vec{C}^\dagger$$

And then e.g. constrained by  $\text{Br}(\mu \rightarrow 3e) < 10^{-10}$

$$|C_{\ell\ell}^{e\mu ee} + C_{\ell\ell}^{eee\mu} + g_L^e [C_{H\ell(1)}^{e\mu} + C_{H\ell(3)}^{e\mu}] - \delta C_{penguin}^{e\mu}| < 7.1 \times 10^{-7}$$

# Sensitivity

$$|C_{\ell\ell}^{e\mu ee} + C_{\ell\ell}^{eee\mu} + g_L^e [C_{H\ell(1)}^{e\mu} + C_{H\ell(3)}^{e\mu}] - \delta C_{penguin}^{e\mu}| < 7.1 \times 10^{-7}$$

From the left-handed contribution to  $\text{Br}(\mu \rightarrow 3e) < 10^{-10}$

This results in a sensitivity to the dimension 5-operator Wilson coefficients:

$$\left| C_{21}^{ee} C_{21}^{e\mu*} + 0.5 C_{22}^{ee} C_{22}^{e\mu*} + 0.1 \sum_{\sigma} (C_A^{e\sigma} - C_{21}^{e\sigma}) (C_A^{\sigma\mu*} + C_{21}^{\sigma\mu*}) \right| < \frac{1}{5.2 \ln (\Lambda/m_{22})} \left( \frac{\Lambda}{10 \text{TeV}} \right)^2$$

# Generic Lagrangian for the Z-Penguin

We only need cubic interactions of scalars  $h$ , fermions  $f$  and vectors  $V$ .

$$\begin{aligned}\mathcal{L}_3 = & \sum_{f_1 f_2 s_1 L/R} y_{s_1 \bar{f}_1 f_2}^{L/R} h_{s_1} \bar{\Psi}_{f_1} P_{L/R} \Psi_{f_2} + \sum_{f_1 f_2 v_1 L/R} g_{v_1 \bar{f}_1 f_2}^{L/R} V_{v_1, \mu} \bar{\Psi}_{f_1} \gamma^\mu P_{L/R} \Psi_{f_2} \\ & + \frac{i}{6} \sum_{v_1 v_2 v_3} g_{v_1 v_2 v_3} \left( V_{v_1, \mu} V_{v_2, \nu} \partial^{[\mu} V_{v_3}^{\nu]} + \dots \right) \\ & - \frac{i}{2} \sum_{v_1 s_1 s_2} g_{v_1 s_1 s_2} V_{v_1}^\mu \left( h_{s_1} \partial_\mu h_{s_2} - (\partial_\mu h_{s_1}) h_{s_2} \right).\end{aligned}$$

- ▶ We can add  $SU(3) \times U(1) \rightarrow$  higher orders
- ▶ Perturbative Unitary  $\rightarrow$  massive vectors from SSB
- ▶ Add  $R_\xi$  gauge-fixing

# Finite Z-Penguin?

- ▶ Can we derive a general finite one-loop result for FCNC Z penguin?
- ▶ In the loops we need the correct high-energy behaviour
  - ▶ Gauge-structure of Greens functions determined by Slavnov-Taylor identities
  - ▶ Traditionally used in high-energy scattering (“Goldstone-boson Equivalence Theorem”)
  - ▶ At the same time, UV behaviour controls renormalization properties

# Remnants of Gauge Symmetry

- We assume that the massive vector bosons originate from a spontaneously broken gauge symmetry
- Fix the gauge for massive vector ( $\sigma_{V^\pm} = \pm i$ ,  $\sigma_V = 1$ )

$$\mathcal{L}_{\text{fix}} = - \sum_v (2\xi_v)^{-1} F_{\bar{v}} F_v, \quad F_v = \partial_\mu V_v^\mu - \sigma_v \xi_v M_v \phi_v,$$

- From  $s\bar{u}_v = -F_v/\xi_v$  obtain 3-point STIs:

$$g_{v_1 \Phi_2 \Phi_3} = \sigma_{v_2} \sigma_{v_3} \frac{M_{v_2}^2 + M_{v_3}^2 - M_{v_1}^2}{2M_{v_2} M_{v_3}} g_{v_1 v_2 v_3}, \quad g_{v_1 \Phi_2 s_1} = -i \sigma_{v_2} \frac{1}{2M_{v_2}} g_{v_1 v_2 s_1},$$

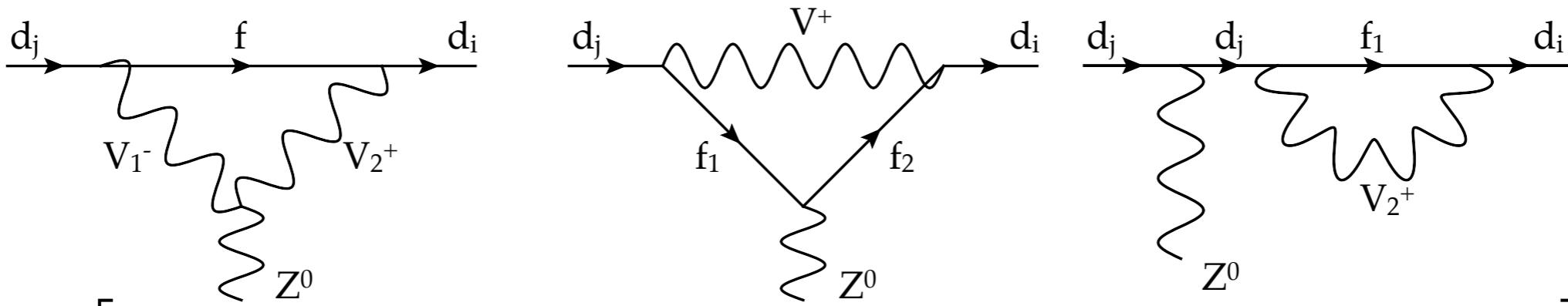
$$g_{v_1 v_2 \Phi_3} = -i \sigma_{v_3} \frac{M_{v_1}^2 - M_{v_2}^2}{M_{v_3}} g_{v_1 v_2 v_3}, \quad g_{\Phi_1 s_1 s_2} = i \sigma_{v_1} \frac{M_{s_1}^2 - M_{s_2}^2}{M_{v_1}} g_{v_1 s_1 s_2},$$

$$g_{\Phi_1 \Phi_2 s_1} = -\sigma_{v_1} \sigma_{v_2} \frac{M_{s_1}^2}{2M_{v_1} M_{v_2}} g_{v_1 v_2 s_1}, \quad g_{\Phi_1 \Phi_2 \Phi_3} = 0,$$

$$y_{\Phi_1 \bar{f}_1 f_2}^\sigma = -i \sigma_{v_1} \frac{1}{M_{v_1}} (m_{f_1} g_{v_1 \bar{f}_1 f_2}^\sigma - g_{v_1 \bar{f}_1 f_2}^{\bar{\sigma}} m_{f_2}).$$

- Allows us to eliminate all Goldstone couplings

# Results in terms of physical parameters



$$\sum_{f_1 f_2 v_1} \left[ \tilde{k}_{f_1 f_2 v_1}^L \left( \tilde{C}_0(m_{f_1}, m_{f_2}, M_{v_1}) - \frac{1}{2} \right) + k_{f_1 f_2 v_1}^L C_0(m_{f_1}, m_{f_2}, M_{v_1}) + k'_{f_1 f_2 v_1}^L \right]$$

$$+ \sum_{f_1 v_1 v_2} \left[ \tilde{k}_{f_1 v_1 v_2}^L \left( \tilde{C}_0(m_{f_1}, M_{v_1}, M_{v_2}) + \frac{1}{2} \right) + k_{f_1 v_1 v_2}^L C_0(m_{f_1}, M_{v_1}, M_{v_2}) + k'_{f_1 v_1 v_2}^L \right]$$

The divergent loop functions  $\tilde{C}_0$  are multiplied with:

$$\tilde{k}_{f_1 f_2 v_1}^L = \left( g_{Z \bar{f}_2 f_1}^L + \frac{m_{f_1} m_{f_2}}{2M_{v_1}^2} g_{Z \bar{f}_2 f_1}^R \right) g_{\bar{v}_1 \bar{d}_i f_2}^L g_{v_1 \bar{f}_1 d_j}^L,$$

$$\tilde{k}_{f_1 v_1 v_2}^L = - \left( 3 + \frac{m_{f_1}^2 (M_{v_1}^2 + M_{v_2}^2 - M_Z^2)}{4M_{v_1}^2 M_{v_2}^2} \right) g_{Z v_1 \bar{v}_2} g_{\bar{v}_1 \bar{d}_i f_1}^L g_{v_2 \bar{f}_1 d_j}^L$$

$$- \frac{1}{2} \left( 1 + \frac{m_{f_1}^2}{2M_{v_1}^2} \right) \left( g_{Z \bar{d}_i d_i}^\sigma g_{v_1 \bar{d}_i f_1}^\sigma g_{\bar{v}_1 \bar{f}_1 d_j}^\sigma + g_{v_1 \bar{d}_i f_1}^\sigma g_{\bar{v}_1 \bar{f}_1 d_j}^\sigma g_{Z \bar{d}_j d_j}^\sigma \right) \delta_{v_1 v_2},$$

# Consider SM fermions and extra $W^\pm$

Derive STIs for  $f - f - V - V$  function:

- Relations between products of trilinear couplings

$$\sum_{v_3} g_{v_3 \bar{f}_1 f_2}^{L/R} g_{v_1 v_2 \bar{v}_3} = \sum_{f_3} (g_{v_1 \bar{f}_1 f_3}^{L/R} g_{v_2 \bar{f}_3 f_2}^{L/R} - g_{v_2 \bar{f}_1 f_3}^{L/R} g_{v_1 \bar{f}_3 f_2}^{L/R})$$

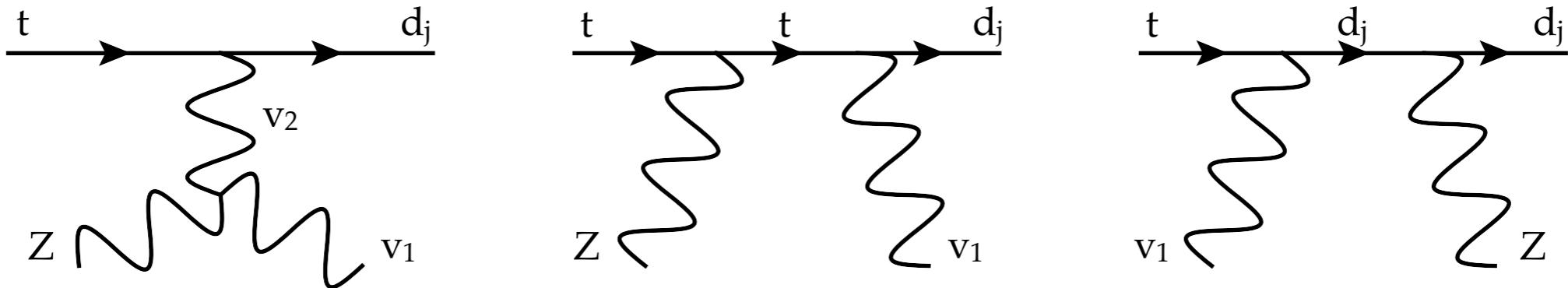
- For  $v_1 \rightarrow W_1^+, v_2 \rightarrow W_2^-, f_1 \rightarrow d_i, f_2 \rightarrow d_j$  and using  $g_{Z \bar{d}_i d_j} = 0$  implies CKM unitarity for SM fermions:

$$0 = \sum_{f_3} g_{W_2^- \bar{s} f_3}^L g_{W_1^+ \bar{f}_3 d}^L$$

- We still obtain a divergence proportional to

$$\sum_{v_1, v_2} \left( \frac{1}{2M_{v_1}^2} (g_{Z \bar{t} t}^R - g_{Z \bar{d} d}^L) \delta_{v_1 v_2} - \frac{(M_{v_1}^2 + M_{v_2}^2 - M_Z^2)}{4M_{v_1}^2 M_{v_2}^2} g_{Z v_1 \bar{v}_2} \right) g_{\bar{v}_1 \bar{d}_i t}^L g_{v_2 \bar{t} d_j}^L$$

## Two additional STIs:



Setting  $v_3 = Z, f_2 = d_j$  there are two additional STIs:

$$g_{Z\bar{t}t}^L g_{v_1^+ \bar{t}d_j}^L = g_{v_1^+ \bar{t}d_j}^L g_{Z\bar{d}_j d_j}^L + \sum_{v_2} g_{Z v_1^+ v_2^-} g_{v_2^+ \bar{t}d_j}^L$$

$$g_{Z\bar{t}t}^R g_{v_1^+ \bar{t}d_j}^L = \frac{1}{2} g_{v_1^+ \bar{t}d_j}^L \left( g_{Z\bar{t}t}^L + g_{Z\bar{d}_j d_j}^L \right) + \sum_{v_2} \frac{M_{v_1}^2 - M_Z^2}{2M_{v_2}^2} g_{Z v_1^+ v_2^-} g_{v_2^+ \bar{t}d_j}^L$$

Which can be used to eliminate  $g_{Z\bar{t}t}^{L/R}$  from the expression

# Results for extra $W^\pm$

The resulting expression comprises less parameters

$$\hat{C}_{d_j d_i Z}^L = \sum_{v_1 v_2} f_V(m_t, M_{v_1}, M_{v_2}) g_{Z v_2^+ v_1^-} g_{v_1^+ \bar{t} d_j}^L g_{v_2^- \bar{d}_i t}^L$$

and a finite loop function

$$\begin{aligned} f_V(m_i, m_j, m_k) &= m_i^2 C_0(m_i, m_k, m_k) - \frac{m_i^2 (m_j^2 + m_k^2 - M_Z^2)}{4m_j^2 m_k^2} \\ &+ \frac{m_i^2 (-3m_j^2 + m_k^2 - M_Z^2) + 4m_k^2 (m_j^2 - m_k^2 + M_Z^2)}{4m_j^2 m_k^2} m_i^2 C_0(m_i, m_i, m_k) \\ &+ \frac{-M_Z^2 (3m_j^2 + 4m_k^2) - 13m_j^2 m_k^2 + 3m_j^4 + 4m_k^4}{4m_j^2 m_k^2} m_i^2 C_0(m_i, m_j, m_k) . \end{aligned}$$

- ▶ Can be applied to models with extra gauge bosons
- ▶ Can be extended to models with arbitrary scalars and fermions
- ▶ Agrees with explicit calculations in the SM, MSSM, LR-Model, multi Higgs models \ vector-like quarks
- ▶ For heavy new physics reproduces the logs of an EFT calculation

# Conclusions

Flavour Physics provide precision probes of new effective interactions

Requires higher order calculations in the SM

SMEFT parameterises heavy new physics

Can also consider generic new physics

- Use STIs/unitarity to renormalise
- and to reduce number of input parameters