Constraining New Physics with Combined Low and High Energy Observables

A combined effective operator analysis of precision data

James Jenkins

Theoretical Division, T-2
Los Alamos National Laboratory

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   - Observables
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Operator Set

$U(3)^5$ Invariant Operators

$$\mathcal{O}_{WB} = (h^\dagger \sigma^a h) W^a_{\mu\nu} B^{\mu\nu}, \mathcal{O}_h = |h^\dagger D_\mu h|^2$$

$$\mathcal{O}^s_{\ell\ell} = \frac{1}{2}(\bar{\ell}\gamma^\mu \ell)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}^s_{\ell q} = (\bar{\ell}\gamma^\mu \ell)(\bar{q}\gamma_\mu q), \quad \mathcal{O}^t_{\ell q} = (\bar{\ell}\gamma^\mu \sigma^a \ell)(\bar{q}\gamma_\mu \sigma^a q),$$

$$\mathcal{O}_{\ell e} = (\bar{\ell}\gamma^\mu \ell)(\bar{e}\gamma_\mu e), \quad \mathcal{O}_{qe} = (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e), \quad \mathcal{O}_{\ell u} = (\bar{\ell}\gamma^\mu \ell)(\bar{u}\gamma_\mu u), \quad \mathcal{O}_{\ell d} = (\bar{\ell}\gamma^\mu \ell)(\bar{d}\gamma_\mu d),$$

$$\mathcal{O}_{ee} = \frac{1}{2}(\bar{e}\gamma^\mu e)(\bar{e}\gamma_\mu e), \quad \mathcal{O}_{eu} = (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u), \quad \mathcal{O}_{ed} = (\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d).$$

$$\mathcal{O}^s_{h\ell} = i(h^\dagger D^\mu h)(\bar{\ell}\gamma_\mu \ell) + \text{h.c.}, \quad \mathcal{O}^t_{h\ell} = i(h^\dagger D^\mu \sigma^a h)(\bar{\ell}\gamma_\mu \sigma^a \ell) + \text{h.c.},$$

$$\mathcal{O}^s_{hq} = i(h^\dagger D^\mu h)(\bar{q}\gamma_\mu q) + \text{h.c.}, \quad \mathcal{O}^t_{hq} = i(h^\dagger D^\mu \sigma^a h)(\bar{q}\gamma_\mu \sigma^a q) + \text{h.c.},$$

$$\mathcal{O}_{hu} = i(h^\dagger D^\mu h)(\bar{u}\gamma_\mu u) + \text{h.c.}, \quad \mathcal{O}_{hd} = i(h^\dagger D^\mu h)(\bar{d}\gamma_\mu d) + \text{h.c.}, \quad \mathcal{O}_{he} = i(h^\dagger D^\mu h)(\bar{e}\gamma_\mu e) + \text{h.c.}$$

$$\mathcal{O}_W = \epsilon^{abc} W^{a\nu}_\mu W^{b\lambda}_\nu W^{c\mu}_\lambda$$

These interfere with dominant Standard Model processes

Operator Anatomy

Each operator is associated with a *dimensionless* coupling constant $\frac{a_i}{v^2}\mathcal{O}_i$

$$a_i = \frac{v^2}{\Lambda_i^2} \times T^{\text{flavor}}_{a,b\ldots}$$

- Operators will shift parameters ($\alpha, \; M_Z, \; G_F$...) and contribute to physical processes directly.
- Goal is to calculate corrections to observables (linear in a_i) and bound operators:
  - Globally
  - Using individual operators

We Use $v = 174\ \mathrm{GeV}$

Precision Observables

Included Measurements

- Weak charge in Cs and Tl (Atomic Parity Violation)
- Neutrino Deep Inelastic Scattering (DIS) data (NuTeV)
- Z-Pole Observables
- LEP2 fermion pair production
- W pair production differential cross-sections
- W mass measurements

From this, we create a χ^2 function quadratic in a_i parameters. This contains 237 (generally correlated) terms!

Our global analysis is extended from a Mathematica Notebook by Han & Skiba, 2005

Added low energy observable: Δ_{CKM}

Consider the unitarity of the CKM matrix. We write:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \equiv 1 + \Delta_{CKM},$$

where the deviation from unitarity receives contributions as

$$\Delta_{CKM} = 2\left[(a_{hq3} - a_{hl3}) - (a_{lq3} - a_{ll3})\right].$$

This is experimentally constrained to be
$\Delta_{CKM} = (-2 \pm 6) \times 10^{-4}$ (Dominant Superallowed Modes)

Δ_{CKM} constrains operators

$$\mathcal{O}^{s}_{\ell\ell} = \frac{1}{2}(\bar{\ell}\gamma^{\mu}\ell)(\bar{\ell}\gamma_{\mu}\ell), \quad \mathcal{O}^{t}_{\ell q} = (\bar{\ell}\gamma^{\mu}\sigma^{a}\ell)(\bar{q}\gamma_{\mu}\sigma^{a}q),$$

$$\mathcal{O}^{t}_{h\ell} = i(h^{\dagger}D^{\mu}\sigma^{a}h)(\bar{\ell}\gamma_{\mu}\sigma^{a}\ell) + \mathrm{hc.}, \quad \mathcal{O}^{t}_{hq} = i(h^{\dagger}D^{\mu}\sigma^{a}h)(\bar{q}\gamma_{\mu}\sigma^{a}q) + \mathrm{hc.}$$

Simple Error Propagation

Maximum deviation of a quantity composed of *n* observables:

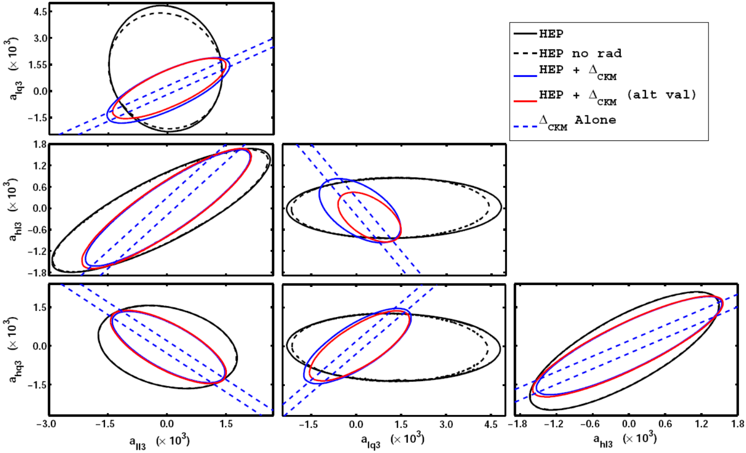
$$(\delta\Delta_{CKM}))^2 = \sum_{i,j}^{n} \frac{\partial\Delta_{CKM}}{\partial a_i}\frac{\partial\Delta_{CKM}}{\partial a_j} M_{ij}\delta a_i \delta a_j.$$

Plugging in numbers from precision data yields

$$\delta\Delta_{CKM} = 2.94 \times 10^{-3}.$$

This is 4.8 times larger than the experimentally extracted Δ_{CKM} uncertainty of 6×10^{-4}!

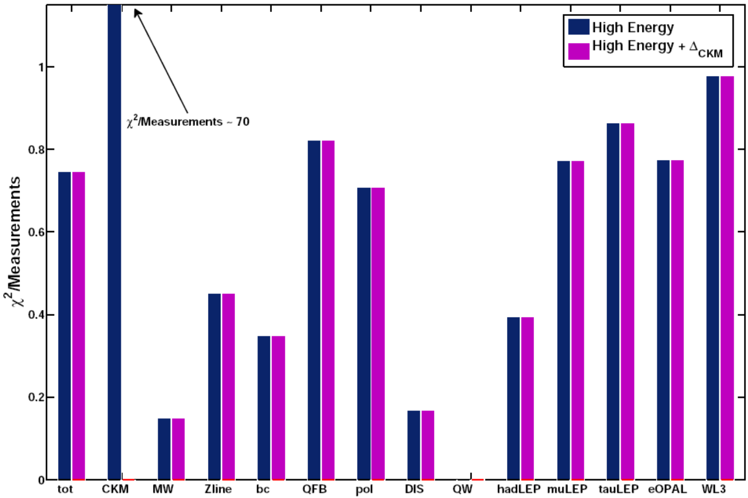
Allowed Contours



Alternate value: $\Delta_{CKM} = -0.0025 \pm 0.0006$

Pseudo-Pull Plot

Contributions from various measurement types



Observable Correlations

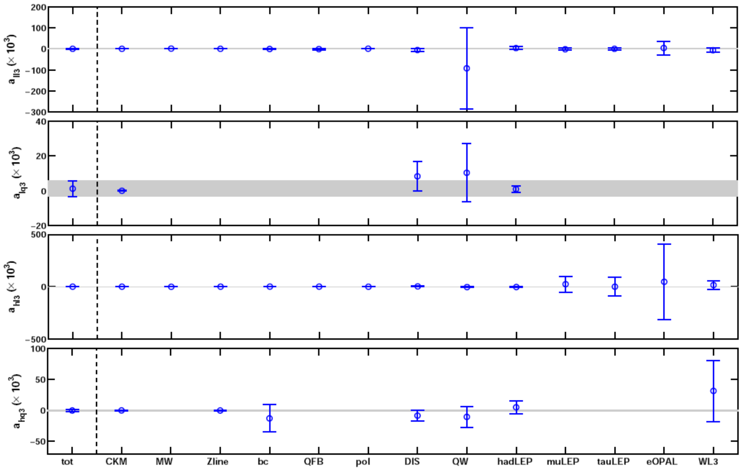
Assuming the dominance of a single operator $\mathcal{O}_i$, we substitute a_i for Δ_{CKM} using $a_i = \pm\frac{1}{2}\Delta_{CKM}$

This leads to direct correlations between any two observables!

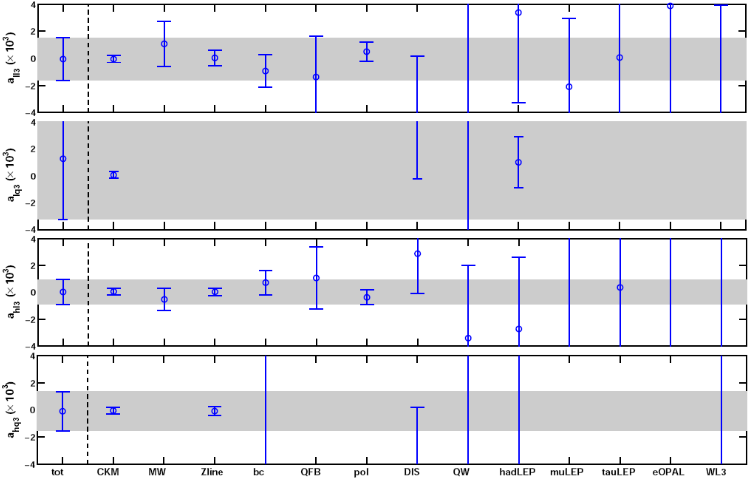
In particular, the χ^2 functions become simple quadratics:

Measurement	χ^2_{SM}	$\mathcal{O}^s_{\ell\ell}$	$\mathcal{O}^t_{\ell q}$	$\mathcal{O}^t_{h\ell}$	$\mathcal{O}^t_{hq}$
Δ_{CKM}	0.11	$1.2e3\Delta + 2.8e6\Delta^2$	$1.2e3\Delta + 2.8e6\Delta^2$	$1.2e3\Delta + 2.86\Delta^2$	$1.2e3\Delta + 2.8e6\Delta^2$
MW	0.65	$-2.4e2\Delta + 2.7e3\Delta^2$		$-4.7e2\Delta + 1.1e5\Delta^2$	
Zline	0.96	$-2.2e1\Delta + 6.8e4\Delta^2$		$6.9e1\Delta + 3.3e5\Delta^2$	$1.5e2\Delta + 2.2e5\Delta^2$
bc	0.90	$3.6e2\Delta + 6.8e3\Delta^2$		$4.7e2\Delta + 8.1e3\Delta^2$	$8.0e0\Delta + 8.2e1\Delta^2$
pol	0.98	$-3.3e2\Delta + 8.2e4\Delta^2$		$-4.3e2\Delta + 1.4e5\Delta^2$	
QFB	0.57	$2.1e2\Delta + 1.8e4\Delta^2$		$2.6e2\Delta + 3.1e4\Delta^2$	
DIS	1.27	$9.1e1\Delta + 1.9e3\Delta^2$	$6.1e1\Delta + 9.6e2\Delta^2$	$1.9e2\Delta + 8.2e3\Delta^2$	$6.1e1\Delta + 9.6e2\Delta^2$
QW	0.54	$1.3e0\Delta + 1.8e0\Delta^2$	$2.6e1\Delta + 3.1e2\Delta^2$	$-7.9e1\Delta + 2.9e3\Delta^2$	$2.6e1\Delta + 3.1e2\Delta^2$
hadLEP	0.66	$-3.5e1\Delta + 1.3e3\Delta^2$	$1.2e2\Delta + 1.6e4\Delta^2$	$-4.3e1\Delta + 2.0e3\Delta^2$	$-2.2e1\Delta + 5.4e2\Delta^2$
μLEP	0.85	$2.2e1\Delta + 1.3e3\Delta^2$		$1.1e0\Delta + 5.4e0\Delta^2$	
τLEP	0.85	$-4.1e - 1\Delta + 8.2e2\Delta^2$		$9.1e - 3\Delta + 3.3e0\Delta^2$	
eOPAL	0.77	$-7.4e - 1\Delta + 2.4e1\Delta^2$		$9.1e - 1\Delta + 1.9e - 1\Delta^2$	
WL3	1.09	$7.2e0\Delta + 1.3e2\Delta^2$		$9.1e - 1\Delta + 6.8e0\Delta^2$	$-1.6e0\Delta + 6.3e0\Delta^2$
tot	0.86	$7.4e0\Delta + 1.8e4\Delta^2$	$1.3e1\Delta + 1.2e4\Delta^2$	$7.8e0\Delta + 3.0e4\Delta^2$	$1.7e1\Delta + 1.9e4\Delta^2$

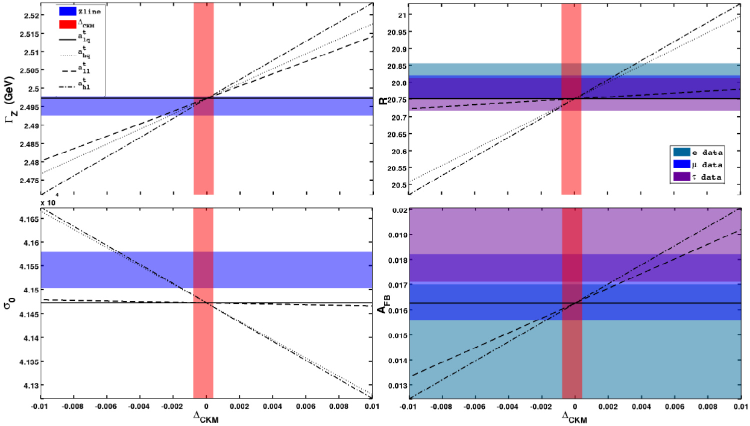
Individual Operator Constraints



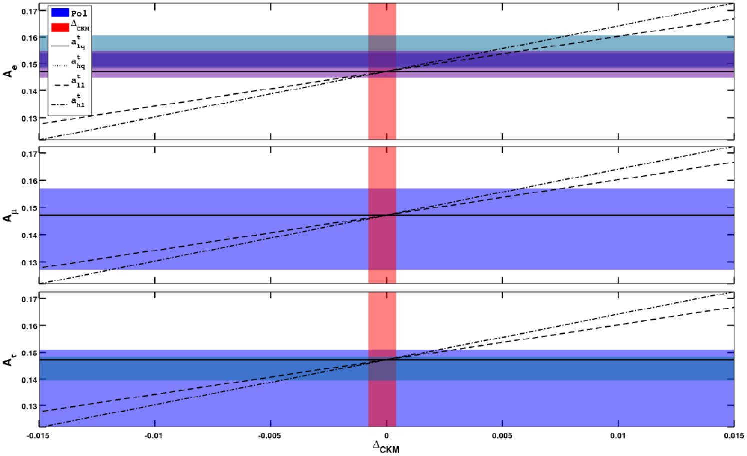
Individual Operator Constraints



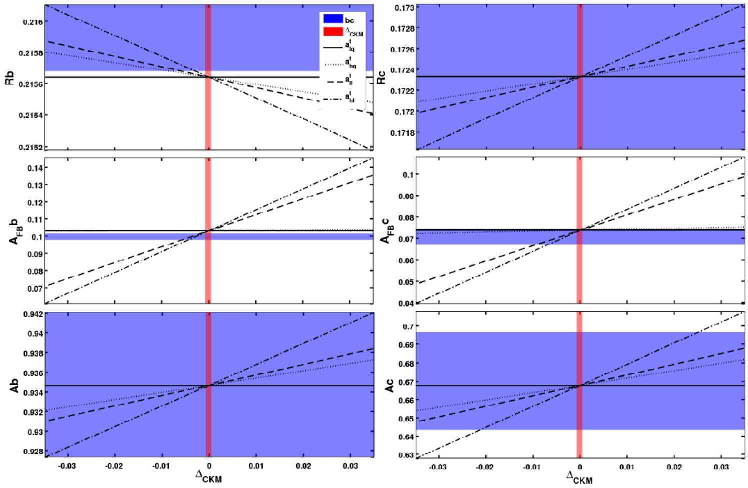
Z-Line Correlations (Light Fermions)



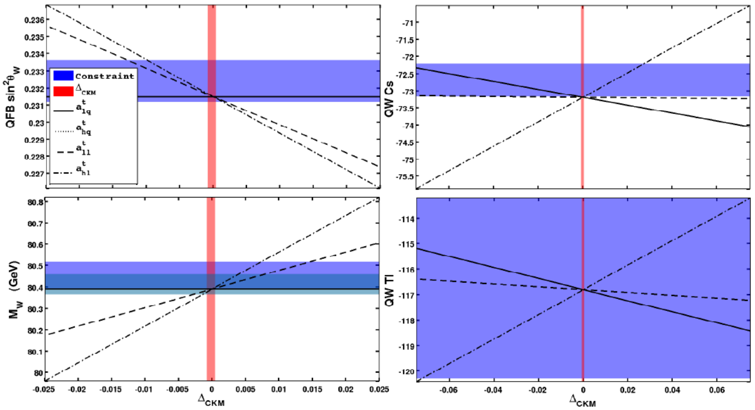
Z-Pole Polarized Lepton Asymmetries



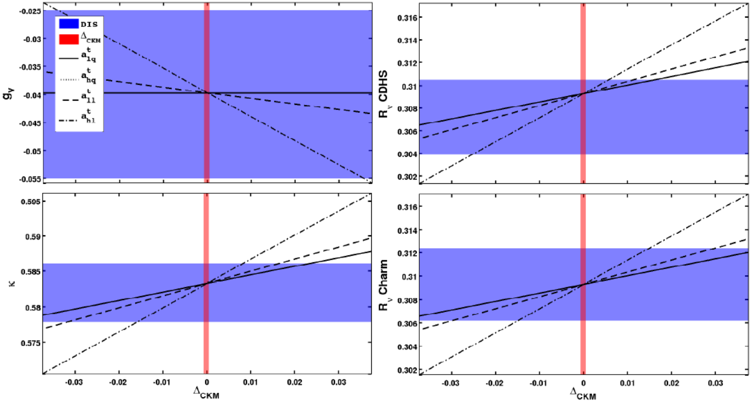
Z-Pole Heavy Fermion Observables



Other Correlations



DIS Correlation (without NuTeV)



The NuTeV Anomaly

The Standard Model Lagrangian may be written as:

$$\mathcal{L} = -4\sqrt{2}G_F\left[g_L^\nu\bar{\nu}\gamma_\mu P_L\nu + g_R^\nu\bar{\nu}\gamma_\mu P_R\nu\right]\left[g_L^f\bar{f}\gamma^\mu P_L f + g_R^f\bar{f}\gamma^\mu P_R f\right].$$

NuTeV constrains the coupling combinations

$$g_L^2 = (2g_L^\nu g_L^u)^2 + (2g_L^\nu g_L^d)^2$$
$$g_R^2 = (2g_L^\nu g_R^u)^2 + (2g_L^\nu g_R^d)^2$$

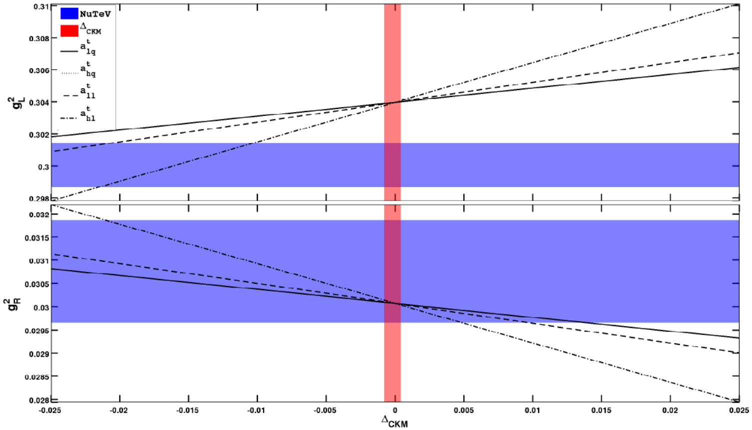
They find

$g_L^2 = 0.30005 \pm 0.00137$ (EW Fit : 0.3042)

$g_R^2 = 0.03076 \pm 0.00011$ (EW Fit : 0.0301)

Usually interpreted as a 3σ deviation in $\sin^2\theta_w$

NuTeV Correlations



NuTeV: More Details

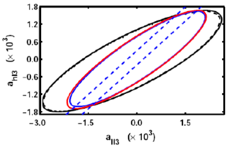
$$
\begin{aligned}
\delta g_L^2 &= \frac{1}{18(2s^2-1)}\Big\{6s^2(2s^2-1)(a_{lq1}+a_{hq1}) + 2s^2(20s^4-28s^2+9)(a_{lq3}-a_{hq3}) \\
&+ 2s^2(10s^4-19s^2+9)(2a_{hl3}-a_{ll3}) - 2a_{hl1}(20s^6-46s^4+36s^2-9) \\
&- a_h(10s^6-27s^4+27s^2-9) + 2sca_{WB}(9-10s^2)\Big\}
\end{aligned}
$$

Substituting Δ_{CKM}

$$
\delta g_L^2 = \frac{s^2(10s^2-9)}{9}\left\{\frac{-\Delta_{CKM}}{2} + \frac{1}{2s^2-1}\left(s^2 a_{ll3} - a_{hl3}\right)\right\}.
$$

Plugging in the observed δg_L^2 and Δ_{CKM} yields the relationship

$$
a_{hl3} - 0.231 a_{ll3} = (7.7 - 7.9) \times 10^{-3}
$$



This band is outside of the allowed $a_{hl3} - a_{ll3}$ contour!

Comments on Non-$U(3)^5$ Invariant Operators

Non-$U(3)^5$ Invariant Operators

$$\mathcal{O}qde = (\bar{\ell}e)(\bar{d}q) + \text{h.c.}, \quad \mathcal{O}_{\ell q} = (\bar{\ell}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$
$$\mathcal{O}^t_{\ell q} = (\bar{\ell}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}, \quad \mathcal{O}_{hh} = i(h^T \epsilon D_\mu h)(\bar{u}\gamma^\mu d) + \text{h.c.}$$

These affect a disjoint set of observables (almost).

Treating the flavor structure

- Minimal Flavor Violation (MFV) Mass suppressions
- Two Higgs Doublet Model $\tan\beta$ enhancement
- R Parity Violating SUSY Complete freedom

A full extension to include these operators is not trivial!

Summary

We combine bounds from high energy precision measurements and low energy observables to constrain new physics.

- Δ_{CKM} constraints are important
  - Should be included in future fits
  - Non-trivially modify the allowed global parameter space
  - Yields observable correlations (individual operator approach)
- The NuTeV Anomaly
  - Can't be resolved by a single operator
  - Can't be resolved by the (four) Δ_{CKM} operators
  - Can be resolved using all operators
- Non-$U(3)^5$ invariant analysis is hard and results are forthcoming!