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USING FLAVOUR TO SIMPLIFY RUNNING IN THE LEFT

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(based on WIP w/ S. Renner, D. Sutherland)

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Effective field theory valid below the electroweak scale.

$$\mathcal{L}_{LEFT} = \mathcal{L}_{\mathrm{QCD+QED}} + \sum_{k,D>4} c_k^{(D)} \mathcal{O}_k^{(D)},$$

where $c_k^{(D)}$ have an implicit suppression of $\frac{1}{\Lambda_{EW}^{D-4}}$.

RUNNING AT ONE LOOP IN THE LEFT

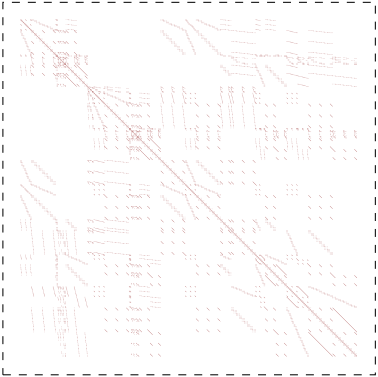
Running first calculated at one-loop in (Jenkins, Manohar, and Stoffer 2018)

Focus on vectorial operators

$$(\overline{\psi}\,\gamma_\mu P_{L/R}\,\psi)\,(\overline{\chi}\,\gamma^\mu P_{L/R}\,\chi) \qquad \psi,\chi \in \{d,e,u\}$$

RUNNING AT ONE LOOP IN THE LEFT

$$(4\pi)^2 \frac{\mathrm{d}}{\mathrm{d}t} c_V(t) = \boxed{\gamma(t)}\, c_V(t) \qquad (t \equiv \ln \mu)$$



DSixTools basis (Fuentes-Martin, Ruiz-Femenia, Vicente, and Virto 2021)

THE LEFT HAS A LARGE (BROKEN) FLAVOUR SYMMETRY

$$(U(3)_{d_L} \times U(3)_{d_R} \rtimes \mathbb{Z}_{2,d}) \times (U(3)_{e_L} \times U(3)_{e_R} \rtimes \mathbb{Z}_{2,e}) \\ \times (U(2)_{u_L} \times U(2)_{u_R} \rtimes \mathbb{Z}_{2,u}) \times U(3)_{\nu_L}$$

Kinetic terms invariant under $d_L^i \to U_{d_L}^{ij} d_L^j$, $d_R^i \to U_{d_R}^{ij} d_R^j$, $d_L \leftrightarrow d_R$, ...

Masses and other operators break this — their components are *charged* under the flavour group.

$$\mathcal{L} = i\overline{d}_L^i D d_L^i + i\overline{d}_R^i D d_R^i + [\text{sim. for } u_L, u_R, e_L, e_R, \nu_L] \\ - [M^d]_{ij}\overline{d}_L^i d_R^j + \text{h.c.} + [\text{sim. for } M^u, M^e] \\ + c_{ijkl}\left(\overline{d}_L^i \gamma d_L^j\right)\left(\overline{e}_L^k \gamma e_L^l\right) + [\text{other ops}]$$

(Neglecting purely gluonic operators)

WE USE A SMALLER LARGE (BROKEN) FLAVOUR SYMMETRY

$$SU(3)_d \times SU(3)_e \times SU(2)_u \times \mathbb{Z}_2$$

Kinetic terms invariant under $d_L^i \to U_d^{ij} d_L^j$, $d_R^i \to U_d^{ij} d_R^j$, ..., $(d_L, e_L, u_L) \leftrightarrow (d_R, e_R, u_R)$.

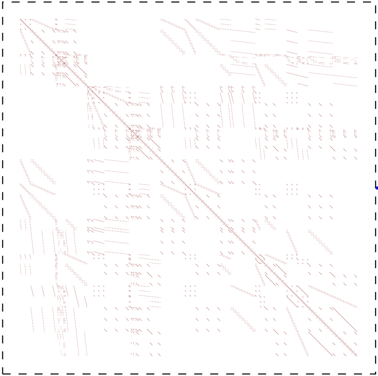
Masses and other operators break this — their components are *charged* under the flavour group.

$$\mathcal{L} = i\overline{d}_L^i D d_L^i + i\overline{d}_R^i D d_R^i + [\text{sim. for } u_L, u_R, e_L, e_R, \nu_L]$$
$$- [M^d]_{ij} \overline{d}_L^i d_R^j + \text{h.c.} + [\text{sim. for } M^u, M^e]$$
$$+ c_{ijkl} \left(\overline{d}_L^i \gamma d_L^j\right) \left(\overline{e}_L^k \gamma e_L^l\right) + [\text{other ops}]$$

(Neglecting purely gluonic operators)

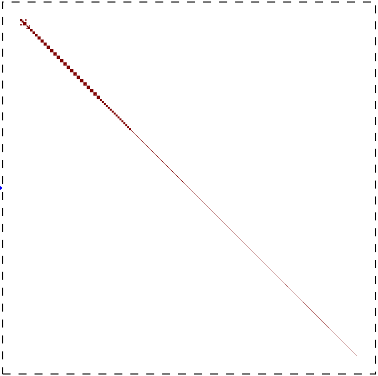
EFFECT ON ANOMALOUS DIMENSION MATRIX

$$(4\pi)^2 \frac{\mathrm{d}}{\mathrm{d}t} c_V(t) = \boxed{\gamma(t)}\, c_V(t) \qquad (t \equiv \ln \mu)$$



DSixTools/San Diego basis

→



Flavour & parity basis

$$(4\pi)^2 \frac{\mathrm{d}}{\mathrm{d}t} c_V(t) = \gamma(t) c_V(t) \qquad (t \equiv \ln \mu)$$

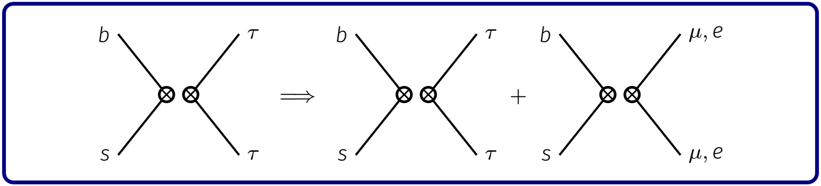
Solve for

$$c_V(t_b) = U(t_b, t_W) c_V(t_W)$$

$$(S^{-1}US)_{ij} = \left(\frac{m_b}{m_W}\right)^{\frac{\hat{\gamma}_i}{(4\pi)^2}} \delta_{ij}$$

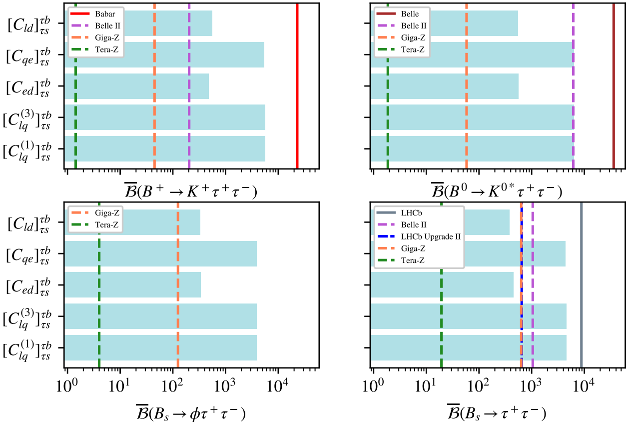
No mixing, directions with +ve $\hat{\gamma}$ shrink, -ve $\hat{\gamma}$ grow.

PHENO EXAMPLE



τ only at M_W scale $\implies$ τ, and some e and μ, at m_b scale

$bs\mu\mu$ (teal bars) can be better than current/projected $bs\tau\tau$ (solid/dashed lines)



Also (Cornella, Faroughy, Fuentes-Martin, Isidori, and Neubert 2021)

SUMMARY

- Flavour and parity simplify running in the LEFT
- γ can be block diagonalised to all orders
- The map $M_W \to m_b$ is fully understandable in terms of eigenvalues and eigenvectors
- Many possible pheno applications!

BACKUP SLIDES

RUNNING AT ONE LOOP IN THE LEFT

Schematically (Jenkins, Manohar, and Stoffer 2018)

$$
\begin{aligned}
\text{masses} \to (4\pi)^2\,\dot{M} &= (e^2+g^2)M + (e+g)dM^2 + c_S M^3 + c_V M^3 + d^2 M^3\,,\\
\text{QED} \to (4\pi)^2\,\dot{e} &= e^3 + e^2 dM + d^2 M^2\,,\\
\text{QCD} \to (4\pi)^2\,\dot{g} &= g^3 + g^2 dM + d^2 M^2\,,\\
\text{dipoles} \to (4\pi)^2\,\dot{d} &= (e^2+g^2+eg)d + eM(c_S+c_T) + (e+g)d^2 M\,,\\
\text{4f scalar} \to (4\pi)^2\,\dot{c}_S &= (e^2+g^2)(c_S+c_T) + (e^2+g^2+eg)d^2\,,\\
\text{4f tensor} \to (4\pi)^2\,\dot{c}_T &= (e^2+g^2)(c_S+c_T)\,,\\
\text{4f vector} \to (4\pi)^2\,\dot{c}_V &= (e^2+g^2)c_V + (e^2+g^2+eg)d^2\,,
\end{aligned}
$$

Neglect operators in grey at $O(0.1\%)$ accuracy.

$\{c_S, c_T\}$ and c_V do not mix due to helicity selection rules. (Cheung and Shen 2015)

SOLVING RUNNING

$$\gamma(t) = e^2(t)\hat{\gamma}_e + g^2(t)\hat{\gamma}_g.$$

$$\begin{aligned}\ln U(t_b, t_W) = & \frac{1}{(4\pi)^2}\int \gamma(t_1) + \frac{1}{2\,(4\pi)^4}\int_{t_1>t_2}[\gamma(t_1), \gamma(t_2)] \\ & + \frac{1}{6\,(4\pi)^6}\int_{t_1>t_2>t_3}([\gamma(t_1), [\gamma(t_2), \gamma(t_3)]] + [\gamma(t_3), [\gamma(t_2), \gamma(t_1)]]) + \dots, \\ = & -\hat{\gamma}_e \times 1.803 \times 10^{-3} - \hat{\gamma}_g \times 3.783 \times 10^{-2} - \frac{1}{2}[\hat{\gamma}_e, \hat{\gamma}_g] \times 7.379 \times 10^{-6} + \dots\end{aligned}$$

Neglecting higher order terms matches fully numerical solution to $\mathcal{O}(0.0001\%)$ accuracy for lepton universal $b \to s$ block.

Cheung, Clifford and Chia-Hsien Shen (2015). "Nonrenormalization Theorems without Supersymmetry". In: *Phys. Rev. Lett.* 115.7, p. 071601. DOI: 10.1103/PhysRevLett.115.071601. arXiv: 1505.01844 [hep-ph].

Cornella, Claudia et al. (2021). "Reading the footprints of the B-meson flavor anomalies". In: *JHEP* 08, p. 050. DOI: 10.1007/JHEP08(2021)050. arXiv: 2103.16558 [hep-ph].

Fuentes-Martin, Javier et al. (2021). "DsixTools 2.0: The Effective Field Theory Toolkit". In: *Eur. Phys. J. C* 81.2, p. 167. DOI: 10.1140/epjc/s10052-020-08778-y. arXiv: 2010.16341 [hep-ph].

Jenkins, Elizabeth E., Aneesh V. Manohar, and Peter Stoffer (2018). "Low-Energy Effective Field Theory below the Electroweak Scale: Anomalous Dimensions". In: *JHEP* 01. [Erratum: JHEP 12, 042 (2023)], p. 084. DOI: 10.1007/JHEP01(2018)084. arXiv: 1711.05270 [hep-ph].