Correlating lepton observables

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* **Rupert Coy, MF** - 1812.03165, to appear in PRD
Effective approach to lepton observables: the seesaw case

* **MF, Marco Nardecchia, Javi Serra, Luca Vecchi** – 1807.04279, JHEP10(2018)017
The bearable compositeness of leptons

(**Rupert Coy, MF, Federico Mescia, Olcyr Sumensari** - in preparation
EFT analysis of lepton flavour universality in b-to-s transitions)

Planck 2019 @ CAPFE, Granada, 3-7 June 2019

Outline

- Low energy lepton observables: great precision (vs a few anomalies)
- Imprint of UV new physics on the IR Effective Field Theory
- The case of the Seesaw Mechanism:
  general EFT treatment & consequent pattern of correlations
- The case of Partial Compositeness
  - The threat of flavour and CP violation:
    can one live with a compositeness scale close to TeV ?
  - General implications for neutrino mass generation
- Lepton anomalies in b-to-s transitions: unexpected ?

Precision frontiers in the lepton sector

- Assume only SM degrees of freedom below electroweak (EW) scale

ν oscillations

$$\frac{m_\nu}{v^2}\ell\ell HH \sim \frac{1}{10^{15}\mathrm{GeV}}\ell\ell HH$$

- Tiny neutrino masses: their contribution negligible in all other observables
- Lepton number violation frontier: searches for neutrino-less 2β decay

CUORE, GERDA, EXO,… ‘08

$$|(m_\nu)_{ee}| \lesssim 0.1 - 0.5\mathrm{eV}$$

- The electromagnetic dipole as the all-important dim-6 operator

$$\boxed{\frac{C^{e\gamma}_{ij}}{\Lambda^2}\overline{\ell_{Li}}\sigma^{\mu\nu}e_{Rj}F_{\mu\nu}H}$$

- Flavour violation frontier: μ-to-e transitions

$$\mu \to e\gamma \quad : \quad \frac{|C^{e\gamma}_{12,21}|}{\Lambda^2} < \frac{2.1\cdot 10^{-10}}{\mathrm{TeV}^2}$$

MEG ‘16

- CP violation frontier: electron Electric Dipole Moment (EDM)

$$d_e \quad : \quad \frac{\mathrm{Im}C^{e\gamma}_{11}}{\Lambda^2} < \frac{4.8\cdot 10^{-13}}{\mathrm{TeV}^2}$$

ACME ‘18

A plethora of constraints

ACME '18
update

	Upper bound on $\|C\|$ for $\Lambda = 1\,\mathrm{TeV}$	Observable
$C^{e\gamma}_{12,21}$	2.1×10^{-10}	$\mu \to e\gamma$
$C^{e\gamma}_{13,31}$	2.4×10^{-6}	$\tau \to e\gamma$
$C^{e\gamma}_{23,32}$	2.7×10^{-6}	$\tau \to \mu\gamma$
$\mathrm{Im}\, C^{e\gamma}_{11},\ \mathrm{Re}\, C^{e\gamma}_{11}$	0.48 $\cancel{3.8} \times 10^{-12},\ 2.4 \times 10^{-6}$	$d_e, \Delta a_e$
$\mathrm{Im}\, C^{e\gamma}_{22},\ \mathrm{Re}\, C^{e\gamma}_{22}$	$8.4 \times 10^{-3},\ 1.8 \times 10^{-5}$	$d_\mu, \Delta a_\mu$
$\mathrm{Im}\, C^{e\gamma}_{33},\ \mathrm{Re}\, C^{e\gamma}_{33}$	$4.4 \times 10^{-1},\ 3.2$	$d_\tau, \Delta a_\tau$
$C^{eH}_{12,21}$	3.5×10^{-5}	$\mu \to e\gamma$ (2-loop)
$C^{eH}_{13,31}$	3.0×10^{-1}	$\tau \to e\gamma$ (1- and 2-loop)
$C^{eH}_{23,32}$	3.4×10^{-1}	$\tau \to \mu\gamma$ (1- and 2-loop)
$\mathrm{Im}\, C^{eH}_{11},\ \mathrm{Re}\, C^{eH}_{11}$	0.82 $\cancel{6.5} \times 10^{-7},\ 8.4 \times 10^{-2}$	$d_e, \Delta a_e$ (2-loop)
C^{He}_{12}	$4.9(39) \times 10^{-6}$	$\mu\, Au \to e\, Au$ ($\mu \to eee$)
C^{He}_{13}	$1.5(1.8) \times 10^{-2}$	$\tau \to eee$ ($\tau \to e\mu^+\mu^-$)
C^{He}_{23}	$1.3(1.5) \times 10^{-2}$	$\tau \to \mu\mu\mu$ ($\tau \to \mu e^+ e^-$)
$C^{H\ell(1,3)}_{12}$	$4.9(37) \times 10^{-6}$	$\mu\, Au \to e\, Au$ ($\mu \to eee$)
$C^{H\ell(1,3)}_{13}$	$1.4(1.8) \times 10^{-2}$	$\tau \to eee(\tau \to e\mu^+\mu^-)$
$C^{H\ell(1,3)}_{23}$	$1.3(1.5) \times 10^{-2}$	$\tau \to \mu\mu\mu$ ($\tau \to \mu e^+ e^-$)

2-lepton operators: flavour violation & dipoles

Another analogous table for 4-lepton operators

Also, electroweak precision tests in the lepton sector

To interpret the low energy remnants of each given UV theory, need to systematically match to the associated Effective Field Theory (EFT)

Seesaw EFT

Coy Frigerio '18

Name	Operator
$Q_{W,\alpha\beta}$	$(\overline{l^c_{L\alpha}}\tilde{H}^*)(\tilde{H}^\dagger l_{L\beta})$
$Q^{(1)}_{Hl,\alpha\beta}$	$(\overline{l_{L\alpha}}\gamma_\mu l_{L\beta})(H^\dagger i\overleftrightarrow{D^\mu} H)$
$Q^{(3)}_{Hl,\alpha\beta}$	$(\overline{l_{L\alpha}}\gamma_\mu \sigma^A l_{L\beta})(H^\dagger i\overleftrightarrow{D^\mu}\sigma^A H)$
$Q_{eB,\alpha\beta}$	$(\overline{l_{L\alpha}}\sigma_{\mu\nu} e_{R\beta})HB^{\mu\nu}$
$Q_{eW,\alpha\beta}$	$(\overline{l_{L\alpha}}\sigma_{\mu\nu} e_{R\beta})\sigma^A HW^{A\mu\nu}$

Add any number of sterile neutrinos to the SM:

$$\mathcal{L}_N = i\overline{N_R}\gamma^\mu\partial_\mu N_R - \left(\frac{1}{2}\overline{N_R}M{N_R}^c + \overline{N_R}Y\tilde{H}^\dagger l_L + h.c.\right)$$

M

$$\mathcal{L}^{eff}_M = \frac{1}{2}(Y^T M^{-1} Y)Q_W + \frac{1}{4}(Y^\dagger M^{-1*}M^{-1}Y)(Q^{(1)}_{H\ell} - Q^{(3)}_{H\ell}) + \frac{1}{192\pi^2}(Y^\dagger M^{-1*}M^{-1}Y)Y_e^\dagger(g_2 Q_{eW} - g_1 Q_{eB})$$

Minkowski '77 ++ Broncano-Gavela-Jenkins '02

One-loop matching needed to catch the leading contribution to dipoles

Running of Wilson Coefficients (WCs) for dim-5 and dim-6 operators:

$$\frac{dC^W}{d\log\mu} = \gamma_W C^W \qquad \frac{dC^i}{d\log\mu} = \gamma^i_j C^j + \gamma^i_W C^{W\dagger}C^W$$

Davidson-Gorbahn-Leak '18 and references therein

New loop-suppressed, but log-enhanced operators arise at EW scale

m_W

Electromagnetic dipole: additional one-loop matching needed, involving Q_W twice

$$\mathcal{L}^{eff}_{m_W} \supset -\frac{e}{32\pi^2}\left[\frac{1}{3}\left(Y^\dagger M^{-1*}M^{-1}Y\right) + \frac{v^2}{8m_W^2}(Y^T M^{-1}Y)^\dagger(Y^T M^{-1}Y)\right] Y_e^\dagger\frac{v}{\sqrt{2}}(\overline{e_L}\sigma_{\mu\nu}e_R)F^{\mu\nu}$$

→ ***compute observables measured at electroweak scale***

Negligible QED running

m_μ

→ ***compute observables measured at charged-lepton scale***

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$$\mathcal{L}_M^{eff} = \cancel{\frac{1}{2}(Y^T M^{-1} Y)Q_W} + \frac{1}{4}(Y^\dagger M^{-1*}M^{-1}Y)(Q^{(1)}_{H\ell} - Q^{(3)}_{H\ell}) + \frac{1}{192\pi^2}(Y^\dagger M^{-1*}M^{-1}Y)Y_e^\dagger(g_2 Q_{eW} - g_1 Q_{eB})$$

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→ *compute observables measured at electroweak scale*

Negligible QED running

m_μ

→ *compute observables measured at charged-lepton scale*

Approximate lepton number conservation (e.g. inverse seesaw): Then dim-6 operators can have observable effects !

Coy-Frigerio '18

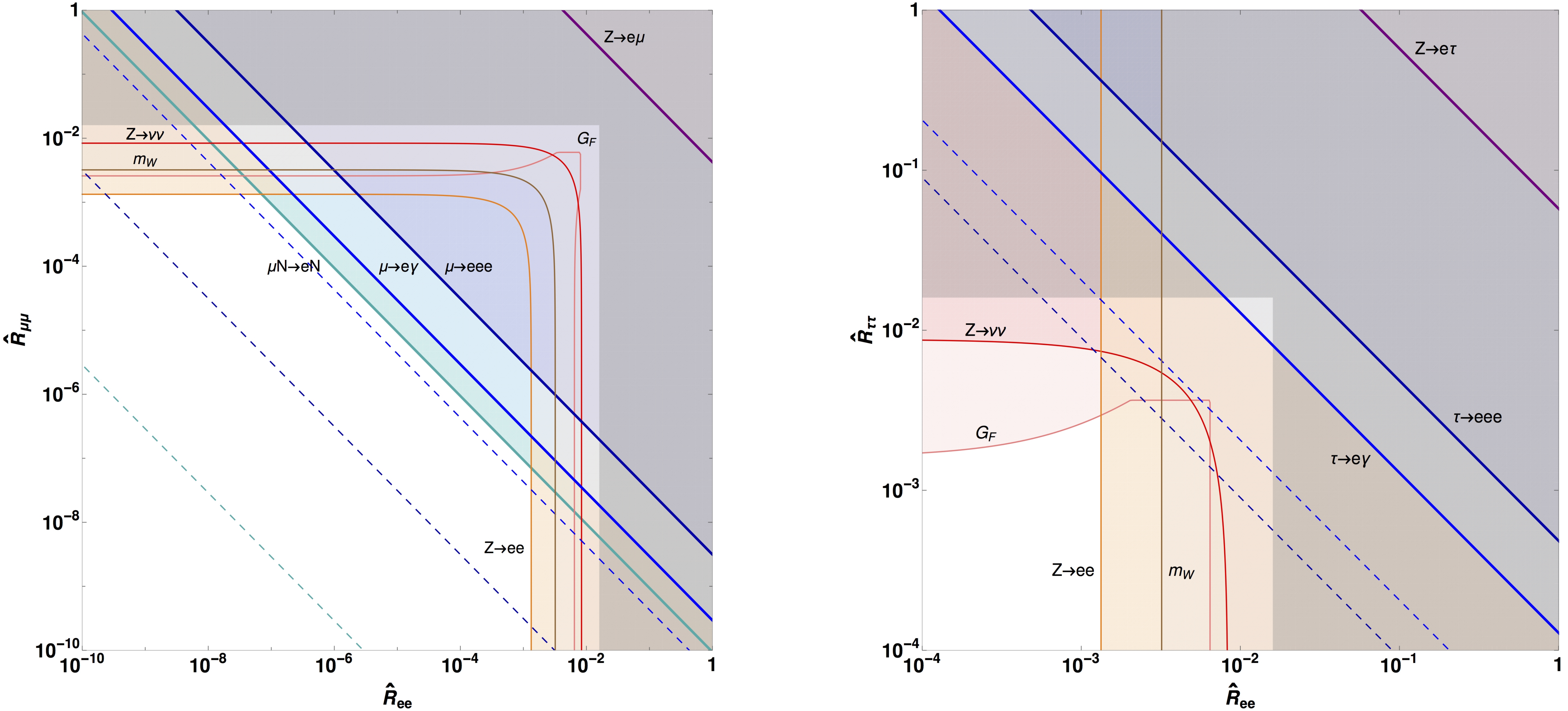
Seesaw footprints at low energy

Replacing $(Y^T M^{-1} Y)_{\alpha\beta} \simeq 0$ strongly constrains $(Y^\dagger M^{-1*} M^{-1} Y)_{\alpha\beta}$

$$\hat{R}_{\alpha\beta} \equiv m_W^2 \left(Y^\dagger M^{-1*} \log \frac{M}{m_W} M^{-1} Y \right)_{\alpha\beta} = \sum_i Y^*_{i\alpha} Y_{i\beta} \frac{m_W^2}{M_i^2} \log \frac{M_i}{m_W}$$

$$\hat{R}_{\alpha\beta} = \sqrt{\hat{R}_{\alpha\alpha}\hat{R}_{\beta\beta}} \quad \text{for } n_s \leq 3$$

$$|\hat{R}_{\alpha\beta}| \leq \sqrt{\hat{R}_{\alpha\alpha}\hat{R}_{\beta\beta}} \quad \text{for } n_s > 3$$



e.g. Falkowski-Riva '15

Electroweak precision tests often overcome flavour-violation searches!

The seesaw shifts μ decay at tree-level → This affects G_F universality , m_W , Z decays

A bit of spurion analysis

- Different UV models can be discerned by the way they break flavour symmetries

$$SU(3)_{l_L} \times U(1)_{l_L} \times SU(3)_{e_R} \times U(1)_{e_R}$$

- Seesaw introduces an extra spurion for each sterile neutrino N_i

$$\boxed{(Y_e)_{\alpha\beta} \sim (\overline{\mathbf{3}}_{-1}, \mathbf{3}_1) \quad Y_{i\alpha} \sim (\overline{\mathbf{3}}_{-1}, \mathbf{1}_0)}$$

- Spurions cannot tell gauge/Lorentz accidents, log vs finite, …

$$Q_{H\ell}^{(1)} - Q_{H\ell}^{(3)} \ \text{shifts}$$
$$Z \to \nu\bar{\nu} \ , \ \text{not} \ \ Z \to e^+e^-$$

- For flavour/CP structure, spurions very useful even at higher orders: e.g. finite 2-loop seesaw contribution to e-EDM from a dim-10 operator

$$|d_e| \sim \frac{2e}{(16\pi^2)^2} \left(\frac{v}{\sqrt{2}}\right)^4 \frac{\mathrm{Im}\left(\left[\hat{S}Y_e^\dagger Y_e \hat{S}, \hat{S}\right]_{ee}\right)}{m_W^6} m_e$$
$$\simeq 5.7 \times 10^{-28}\, \mathrm{Im}\left(\hat{S}_{e\tau}\hat{S}_{\tau\mu}\hat{S}_{\mu e}\right) e \ \mathrm{cm}$$

$$[\ \hat{S} \equiv m_W^2 Y^\dagger M^{-1*} M^{-1} Y \ ]$$

Coy-Frigerio '18

- With the EFT approach, one can tell the seesaw from other UV models with different spurions → different correlations

$$\boxed{S_6 \sim (\overline{\mathbf{6}}_{-2}, \mathbf{1}_0) \ , \quad S_3 \sim (\overline{\mathbf{3}}_{-1}, 1_0) \ \text{with} \ L[S_3] \neq -1 \ , \quad \ldots}$$

Partial Compositeness as a theory of flavour

D.B.Kaplan '91
Contino-Pomarol '04
++

- *Mixing SM fermions with a strongly-coupled, scale-invariant sector may induce hierarchy at IR scale m* from anarchy at UV scale Λ*
  - ✓ *hierarchy in fermion masses and mixing*
  - ✓ *suppression of flavour/CP violating operators*
- *Composite coupling $1 < g^* < 4\pi$*
- *Each SM fermion ψ_i acquires degree of partial compositeness $0 < \epsilon_i < 1$*
- *If m* is as low as a few TeVs, electroweak scale may arise naturally, via a composite Higgs*

$$\mathcal{L}_{PC} = \lambda_{ij}\psi_i\psi_j O^H_{ij} + \lambda_i\psi_i O^\Psi_i + \ldots$$

$$\lambda_{ij}(m_*) \simeq \lambda_{ij}(\Lambda)\left(\frac{m_*}{\Lambda}\right)^{\Delta^H_{ij}-1}$$

Bilinear mixing 'irrelevant':
λ's power-suppressed in the IR,
as Δ^H > ~2 for a 'composite Higgs'

$$\lambda_i(m_*) \simeq \lambda_i(\Lambda)\left(\frac{m_*}{\Lambda}\right)^{\Delta^\Psi_i-5/2} \equiv g^*\epsilon_i$$

Linear mixing can be 'relevant'
as $\Delta^\Psi \geq 3/2$ allowed by unitarity.
Slightly different Δ^Ψ_i induce hierarchical ϵ_i at m*

Partial compositeness (PC) for leptons

- ***Challenges in the lepton sector:***
  - *Can PC close to TeV face the great precision of low-energy experiments?*
  - *Can PC accommodate (small, but non-hierarchical) neutrino parameters?*
- ***Naive Dimensional Analysis (NDA) of Wilson coefficients:***

$$\mathcal{L}_{m_*} \supset y^e_{ij}\overline{\ell_{Li}}e_{Rj}H + \frac{C^{e\gamma}_{ij}}{\Lambda^2}\overline{\ell_{Li}}\sigma^{\mu\nu}e_{Rj}F_{\mu\nu}H$$

Yukawa coupling vs e.g. dipole operator

$$y^e_{ij} = c^e_{ij}\,\epsilon^\ell_i\,\epsilon^e_j\,g_*$$

Higgs coupling

order one coefficients

lepton composite fraction

careful Yukawa diagonalisation to derive WCs in flavour basis

$$\frac{C^{e\gamma}_{ij}}{\Lambda^2} = \frac{c^{e\gamma}_{ij}}{m_*^2}\left(\frac{g_*}{4\pi}\right)^2\epsilon^\ell_i\,\epsilon^e_j\,e\,g_*$$

scale dimension

strong loop-factor

photon coupling

Other lepton operators in PC framework

Effective operator	Wilson coefficient
$Q_{eW}^{ij} = \left(\bar{\ell}_L^i \sigma^{\mu\nu} e_R^j\right) \sigma^I H W_{\mu\nu}^I$	$\frac{C_{ij}^{eW}}{\Lambda^2} = \frac{1}{16\pi^2} \frac{g_*^3}{m_*^2} \epsilon_i^\ell \epsilon_j^e g\, c_{ij}^{eW} = \frac{1}{16\pi^2} \frac{g_*^2}{m_*^2} \frac{\epsilon_i^\ell}{\epsilon_j^\ell} \frac{\sqrt{2} m_j^e}{v} g\, c_{ij}^{eW}$
$Q_{eB}^{ij} = \left(\bar{\ell}_L^i \sigma^{\mu\nu} e_R^j\right) H B_{\mu\nu}$	$\frac{C_{ij}^{eB}}{\Lambda^2} = \frac{1}{16\pi^2} \frac{g_*^3}{m_*^2} \epsilon_i^\ell \epsilon_j^e g'\, c_{ij}^{eB} = \frac{1}{16\pi^2} \frac{g_*^2}{m_*^2} \frac{\epsilon_i^\ell}{\epsilon_j^\ell} \frac{\sqrt{2} m_j^e}{v} g'\, c_{ij}^{eB}$
$Q_{eH}^{ij} = (H^\dagger H)\left(\bar{\ell}_L^i e_R^j H\right)$	$\frac{C_{ij}^{eH}}{\Lambda^2} = \frac{g_*^3}{m_*^2} \epsilon_i^\ell \epsilon_j^e\, c_{ij}^{eH} = \frac{g_*^2}{m_*^2} \frac{\epsilon_i^\ell}{\epsilon_j^\ell} \frac{\sqrt{2} m_j^e}{v}\, c_{ij}^{eH}$
$Q_{H\ell}^{(1)ij} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{\ell}_L^i \gamma^\mu \ell_L^j\right)$	$\frac{C_{ij}^{H\ell(1)}}{\Lambda^2} = \frac{g_*^2}{m_*^2} \epsilon_i^\ell \epsilon_j^\ell\, c_{ij}^{H\ell(1)}$
$Q_{H\ell}^{(3)ij} = \left(H^\dagger \sigma^I i \overleftrightarrow{D}_\mu H\right)\left(\bar{\ell}_L^i \sigma^I \gamma^\mu \ell_L^j\right)$	$\frac{C_{ij}^{H\ell(3)}}{\Lambda^2} = \frac{g_*^2}{m_*^2} \epsilon_i^\ell \epsilon_j^\ell\, c_{ij}^{H\ell(3)}$
$Q_{He}^{ij} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{e}_R^i \gamma^\mu e_R^j\right)$	$\frac{C_{ij}^{He}}{\Lambda^2} = \frac{g_*^2}{m_*^2} \epsilon_i^e \epsilon_j^e\, c_{ij}^{He} = \frac{1}{m_*^2} \frac{2 m_i^e m_j^e}{v^2} \frac{1}{\epsilon_i^\ell \epsilon_j^\ell}\, c_{ij}^{He}$
$Q_{\ell\ell}^{ijmn} = \left(\bar{\ell}_L^i \gamma_\mu \ell_L^j\right)\left(\bar{\ell}_L^m \gamma^\mu \ell_L^n\right)$	$\frac{C_{ijmn}^{\ell\ell}}{\Lambda^2} = \frac{g_*^2}{m_*^2} \epsilon_i^\ell \epsilon_j^\ell \epsilon_m^\ell \epsilon_n^\ell\, c_{ijmn}^{\ell\ell}$
$Q_{\ell e}^{ijmn} = \left(\bar{\ell}_L^i \gamma_\mu \ell_L^j\right)\left(\bar{e}_R^m \gamma^\mu e_R^n\right)$	$\frac{C_{ijmn}^{\ell e}}{\Lambda^2} = \frac{g_*^2}{m_*^2} \epsilon_i^\ell \epsilon_j^\ell \epsilon_m^e \epsilon_n^e\, c_{ijmn}^{\ell e} = \frac{1}{m_*^2} \frac{2 m_m^e m_n^e}{v^2} \frac{\epsilon_i^\ell \epsilon_j^\ell}{\epsilon_m^\ell \epsilon_n^\ell}\, c_{ijmn}^{\ell e}$
$Q_{ee}^{ijmn} = \left(\bar{e}_R^i \gamma_\mu e_R^j\right)\left(\bar{e}_R^m \gamma^\mu e_R^n\right)$	$\frac{C_{ijmn}^{ee}}{\Lambda^2} = \frac{g_*^2}{m_*^2} \epsilon_i^e \epsilon_j^e \epsilon_m^e \epsilon_n^e\, c_{ijmn}^{ee} = \frac{1}{g_*^2 m_*^2} \frac{4 m_i^e m_j^e m_m^e m_n^e}{v^4 \epsilon_i^\ell \epsilon_j^\ell \epsilon_m^\ell \epsilon_n^\ell}\, c_{ijmn}^{ee}$

Experimental bounds on WCs translate into
constraints on the PC parameters: m*, g*, and the ε's

Minimal PC under pressure

Frigerio, Nardecchia, Serra, Vecchi '18

Flavour-violation frontier (μ → e γ)

$$|C^{e\gamma}_{12,21}| < 2\cdot 10^{-8}\left(\frac{\Lambda}{10\ \mathrm{TeV}}\right)^2 \longrightarrow |c^{e\gamma}_{12,21}|\left(\frac{g_*}{4\pi}\right)^2\left(\frac{10\ \mathrm{TeV}}{m_*}\right)^2 \boxed{< 2\cdot 10^{-3}}$$

from
generic EFT
to
anarchic PC

CP-violation frontier (electron EDM)

$$|\mathrm{Im}C^{e\gamma}_{11}| < 0.5\cdot 10^{-10}\left(\frac{\Lambda}{10\ \mathrm{TeV}}\right)^2 \longrightarrow |\mathrm{Im}c^{e\gamma}_{11}|\left(\frac{g_*}{4\pi}\right)^2\left(\frac{10\ \mathrm{TeV}}{m_*}\right)^2 \boxed{< 0.5\cdot 10^{-4}}$$

PC strongly relaxes the constraints. Nonetheless flavour anarchy (c_{ij} of order one) is incompatible with natural compositeness scale (m_* ~ a few TeV and g_* ~ a few)

The ratio $m_*/g_* \sim f$ is the decay constant of the composite Goldstone Higgs.

v^2/f^2 measures the tuning needed for the EW scale.

Precision data require $v^2/f^2 < 0.1$

$$\frac{v^2}{f^2} \sim \frac{(g_* v)^2}{m_*^2} \simeq 0.1\left(\frac{g_*}{4\pi}\right)^2\left(\frac{10\ \mathrm{TeV}}{m_*}\right)^2$$

review by Panico Wulzer '15

Two approaches to relax the bounds

Frigerio, Nardecchia, Serra, Vecchi '18

[A] Strong dynamics is not flavour-anarchic

Assume it preserves flavour numbers $U(1)_e \times U(1)_\mu \times U(1)_\tau$ as well as CP.

Note the PC explanation for $y_e << y_\mu << y_\tau$ is preserved.

In this case c_{ij} are not generic, and flavour/CP violation resides only in the external couplings λ's

Flavour-violation frontier (μ → e γ)

$$|c^{e\gamma}_{12,21}| \left(\frac{g_*}{4\pi}\right)^2 \left(\frac{10\ \text{TeV}}{m_*}\right)^2 \boxed{< 0.03}$$

CP-violation frontier (electron EDM)

$$|\text{Im} c^{e\gamma}_{11}| \left(\frac{g_*}{4\pi}\right)^2 \left(\frac{10\ \text{TeV}}{m_*}\right)^2 \boxed{< 0.01}$$

[B] Strong dynamics allows for multiple scales

$$m_* \sim 10\ \text{TeV} \ll m_*^\tau \ll m_*^\mu \ll m_*^e$$

Panico, Pomarol '16

Operators $O_{e,\mu,\tau}$ decouple at different scales, explaining Yukawa hierarchies (even for $\varepsilon_{e,\mu,\tau} \sim 1$).

Even if c_{ij} are generic, flavour/CP violation in the i,j channel are strongly suppressed by $\mathbf{m_*^{i,j}}$

The contributions to μ → e γ and electron EDM are suppressed, relatively to scenario [A],

by a factor $$\frac{m_\mu m_\tau}{g_*^2 v^2} \lesssim 10^{-6}$$ effectively solving the flavour/CP problem

Neutrino mass from compositeness

Below compositeness scale:

$$\mathcal{L}_{m_*} \supset \frac{m_\nu}{v^2}\ell\ell HH + h.c.$$

Weinberg '79

If lepton number $U(1)_L$ is broken by strong dynamics, then NDA gives

$$m_\nu \simeq \frac{(g_* \epsilon^\ell v)^2}{m_*} \gtrsim \frac{m_\tau^2}{m_*}$$

Multi-TeV strong dynamics must preserve lepton number:

$U(1)_L$ should be broken only by weak, external couplings, with $\Delta L \neq 0$

$\mathcal{L}_{PC}$	spurion
$\lambda_\ell \ell\, O_{L=-1}$	λ_ℓ
$\tilde{\lambda}\, O_{L=\Delta L}$	$\tilde{\lambda}$
$\tilde{\lambda}_\ell \ell\, O_{L=\Delta L-1}$	$\tilde{\lambda}_\ell$
$\tilde{\lambda}_{\ell\ell} \ell\ell\, O_{L=\Delta L-2}$	$\tilde{\lambda}_{\ell\ell}$
$\dots$	$\dots$

Vecchi et al. '12, '15

$$\tilde{\lambda}(m_*) \simeq \tilde{\lambda}(\Lambda_L)\left(\frac{m_*}{\Lambda_L}\right)^{\gamma_{O_L}}$$

can be easily very small in the IR !

m_ν requires a combination of spurions with a total $\Delta L = -2$

Assuming flavour anarchy in the UV (all λ's of the same order), one can show that only 3 flavour structures for m_ν can emerge from Partial Compositeness

3 neutrino flavour structures from PC

Frigerio, Nardecchia, Serra, Vecchi '18

m^ν quadratic in ϵ_k^ℓ : $\quad m_{ij}^\nu = \epsilon_i^\ell \epsilon_j^\ell \tilde{\epsilon} \, \dfrac{(g_* v)^2}{m_*} \propto \begin{pmatrix} (\epsilon_1^\ell)^2 & \epsilon_1^\ell \epsilon_2^\ell & \epsilon_1^\ell \epsilon_3^\ell \\ \dots & (\epsilon_2^\ell)^2 & \epsilon_2^\ell \epsilon_3^\ell \\ \dots & \dots & (\epsilon_3^\ell)^3 \end{pmatrix}$

m_ν linear in ϵ_k^ℓ : $\quad m_{ij}^\nu = (\epsilon_i^\ell \tilde{\epsilon}_j + \epsilon_j^\ell \tilde{\epsilon}_i) \, \dfrac{(g_* v)^2}{m_*} \propto \begin{pmatrix} \epsilon_1^\ell & \epsilon_2^\ell & \epsilon_3^\ell \\ \epsilon_2^\ell & \epsilon_2^\ell & \epsilon_3^\ell \\ \epsilon_3^\ell & \epsilon_3^\ell & \epsilon_{3,2}^\ell \end{pmatrix}$

Large neutrino mixing implies that 2 (or even 3) lepton doublets have similar degree of PC

$\boxed{|\epsilon_1^\ell| \lesssim |\epsilon_2^\ell| \sim |\epsilon_3^\ell|}$ → correlation with charged-lepton flavour/CP violation

m_ν independent from ϵ_k^ℓ : $\quad m_{ij}^\nu = \tilde{\epsilon}_{ij} \, \dfrac{(g_* v)^2}{m_*} \propto \mathcal{O} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$

Large mixing is automatic, as all mass matrix entries scale from UV to IR with the same anomalous dimension.

→ NO correlation with charged-lepton flavour/CP violation

[for all 3 neutrino flavor structures, anarchic PC predicts large CP-violating phases]

Current anomalies with leptons

- μ magnetic dipole moment (3 to 4 σ discrepancy), presently data-taking @ Fermilab

$$a_\mu^{exp} - a_\mu^{SM} \simeq (31 \pm 8)10^{-10} \sim \mathrm{Re}\, C_{22}^{e\gamma}$$

review e.g. Knecht '14, Jegerlehner '18

- B-meson charged-current semi-leptonic decays (R_{D,D^*}): violation of Lepton Flavour Universality (LFU) at ~ 4 σ combining 3 experiments

$$-\frac{1}{v^2} V_{cb} C_{bc\nu_\tau\tau} (\overline{b_L}\gamma^\mu c_L)(\overline{\nu_{\tau L}}\gamma^\mu \tau_L)$$

$$C_{bc\nu_\tau\tau} = 0.12 \pm 0.03$$

e.g. Freytsis, Ligeti, Ruderman '15
Buttazzo, Greljo, isidori, Marzocca '17

- B-meson neutral-current semi-leptonic decays: violation of LFU at > 4 σ from LHCb clean observables only (R_{K,K^*}, $B_s \to \mu\mu$)

$$\frac{4}{v^2} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{bs\mu\mu} (\overline{b_L}\gamma^\mu s_L)(\overline{\mu_L}\gamma^\mu \mu_L)$$

$$C_{bs\mu\mu} = -0.53 \pm 0.09$$

e.g. Aebischer-Altmannshofer-
Guadagnoli-Reboud-Stangl-Straub '19

Violation of LFU in *b-to-s* transitions

In Partial Compositeness :

$$\frac{C^{\ell q}_{ijkl}}{\Lambda^2}(\overline{q_{Li}}\gamma^\mu q_{Lj})(\overline{\ell_{Lk}}\gamma^\mu \ell_{Ll})$$

$$\boxed{\frac{C^{\ell q}_{ijkl}}{\Lambda^2} = c^{\ell q}_{ijkl}\,\frac{g_*^2}{m_*^2}\,\epsilon^q_i\,\epsilon^q_j\,\epsilon^\ell_k\,\epsilon^\ell_l}$$

To fit the anomalies:

$$c^{\ell q}_{bs\mu\mu} \simeq \left(\frac{4\pi}{g_*}\right)^2\left(\frac{m_*}{10\ \mathrm{TeV}}\right)^2\left(\frac{0.1}{\epsilon^q_3\epsilon^\ell_2}\right)^2$$

A number of constraints from other semi-leptonic b-to-s transitions:

$$X^\ell_{ij} \equiv \frac{\mathcal{A}^\ell_{b\to s l^+_i l^-_j}}{\mathcal{A}^\ell_{b\to s\mu\mu}} \sim \frac{\mathcal{A}^\ell_{b\to s\overline{\nu}_i\nu_j}}{\mathcal{A}^\ell_{b\to s\overline{\nu}_\mu\nu_\mu}}$$

$$|X^\ell| \le \begin{pmatrix} 0.8 & 2.5 & 55 \\ 3.0 & 1 & 56 \\ 32 & 44 & 30 \end{pmatrix}$$

Frigerio, Nardecchia, Serra, Vecchi ‘18

Scenarios consistent with all lepton observables exist, e.g.

$$\boxed{U(1)^3 \text{ with } \epsilon^\ell_i \sim \epsilon^e_i}$$

$$\boxed{m^\ell_{1*} \gg m^\ell_{2*} \sim m^\ell_{3*} \ge m_*}$$

Several non-standard lepton (and quark) processes predicted close to current sensitivity

In model-independent EFT :

Coy, Frigerio, Mescia, Sumensari - PRELIMINARY

Several WCs fit well at tree-level, with Λ ~ 10 TeV

A few WCs fit well via an EW loop, with Λ ~ 1 TeV

$$\boxed{\frac{C^{\ell u}_{2223}}{\Lambda^2} \sim \frac{3}{\mathrm{TeV}^2} \quad \text{or} \quad \frac{C^{\ell q(1)}_{1133}}{\Lambda^2} \sim \frac{-0.3}{\mathrm{TeV}^2} \quad \text{or} \quad \ldots}$$

Consistent with W/Z couplings, LEP contact interactions, other LFU tests, LHC dilepton searches, ...

→ Minimal TeV mediator models have large pull w.r.t. the SM

Summary

- The lepton EFT can be probed far beyond the TeV scale
- A given UV theory predicts specific pattern of highly-correlated WCs
- Seesaw below 10^6 GeV: EW precision tests compete with LFV
- Partial Compositeness: flavour and CP constraints push m_* well above the most natural range
- Flavour symmetry $U(1)^3$ x CP greatly reduces the tension; radical solution is to allow for multiple flavour scales above m_*
- 3 specific neutrino flavour patterns from composite dynamics
- b-to-s violation of LFU as a ‘natural’ anomaly ?
  i) no need of flavour/CP violation
  ii) within PC, no need of new states below m_*
  iii) weakly-coupled, ad-hoc, TeV-scale new physics still possible