The Bearable Compositeness of Leptons

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Outline

→ Fermion partial compositeness (PC):

a theoretical framework to address the flavour problem

→ General implications for neutrino mass and mixing

→ The threat of charged-lepton flavour and CP violation:

can one live with a compositeness scale close to TeV ?

Partial compositeness as a theory for flavour

D.B.Kaplan '91

- *Classical flavour questions*
  - *Why SM fermion masses and mixing are hierarchical, except for neutrinos?*
  - *New physics close to TeV is motivated by the hierarchy problem: why flavour and CP violations are so small?*
- *Partial Compositeness (PC) answers*
  - *If the SM fermions mix with a strongly-coupled sector, the dynamics may induce hierarchy from anarchy*
  - *In turn flavour/CP violating effects can be suppressed by this hierarchy*

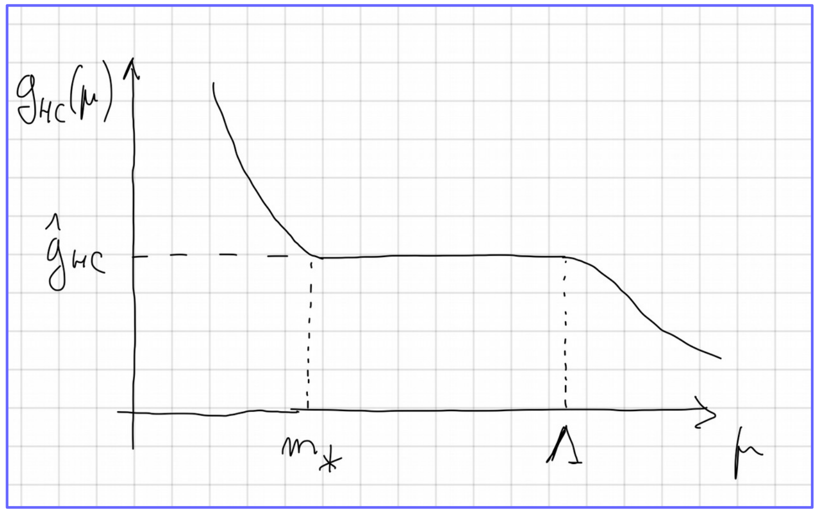
  (if the new dynamics is close to the TeV, the Higgs may be composite)
- *Challenges in the lepton sector*
  - *Can PC accommodate (predict) neutrino parameters?*
  - *Can PC close to TeV bear the great precision of low-energy experiments?*

Partial Compositeness (I)

- SM fermions ψ weakly mix with composite operators O's at some UV scale Λ

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

- O's belong to an (approximately) scale-invariant sector, that eventually confines at scale m* << Λ



- If this sector is strongly-coupled, O's may have large anomalous dimensions:

$$\mu\frac{d}{d\mu}\lambda_{ij} \simeq (\Delta^H_{ij} - 1)\lambda_{ij} + \mathcal{O}(\lambda^3)\ ,\quad \Delta^H_{ij} \geq 1\ ,\quad \Delta^H_{ij} \gtrsim 2$$

To avoid hierarchy problem: $\Delta[O^{H\dagger}O^H] \sim 2\,\Delta^H > 4$

Luty, Okui '04
Rattazzi, Rychkov, Tonni, Vichi '08

Unitarity Bounds

Mack '77

$$\mu\frac{d}{d\mu}\lambda_i \simeq (\Delta^\Psi_i - 5/2)\lambda_i + \mathcal{O}(\lambda^3)\ ,\quad \Delta^\Psi_i \geq 3/2$$

Partial Compositeness (II)

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

Bilinear mixing 'irrelevant':
λ's are power-suppressed in the IR ($\Delta^H - 1 > 1$)
[tension between large (top) Yukawa couplings and quark flavour-violation bounds]

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

Linear mixing more 'relevant' ($\Delta^\Psi - 5/2 > -1$).
slightly different anomalous dimensions induce large hierarchies among λ's in the IR

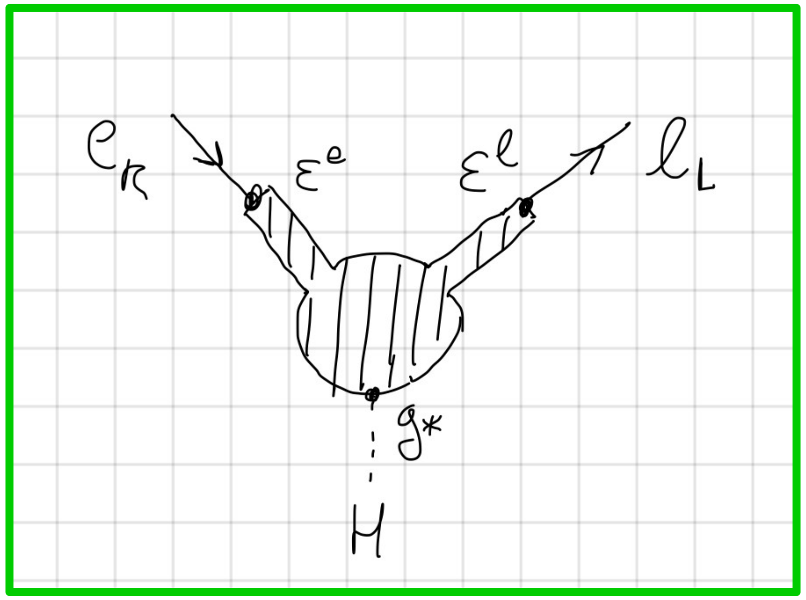
- Composite states have characteristic strong coupling, $1 < g^* < 4\pi$
- Partially composite states have degree of compositeness $0 < \varepsilon_i < 1$
- SM Yukawa couplings are controlled by the product of left- and right-handed ε's

Below compositeness scale:

$$\mathcal{L}_{m_*} = y^e_{ij}\overline{\ell_L}_i e_{Rj} H + h.c. \qquad y^e_{ij} \simeq g^*\epsilon^\ell_i\epsilon^e_j$$

[up to order-one coefficients in each Yukawa coupling entry]

$$\theta^\ell_{ij} \sim \epsilon^\ell_i/\epsilon^\ell_j$$



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 Naive Dimensional Analysis (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:

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

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

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 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

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

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

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

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

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

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]

Charged-lepton flavour and CP violation

Among dim-6 operators involving leptons, let us focus on the electromagnetic dipole:

$$\mathcal{L}_{D=6} \supset \frac{C^{e\gamma}_{ij}}{\Lambda^2} \overline{e_{Li}} \sigma^{\mu\nu} e_{Rj} F_{\mu\nu} \frac{v}{\sqrt{2}}$$

Flavour-violation frontier

MEG '16

ACME '18

	Upper bound on $\lvert C\rvert$ for $\Lambda = 1$ 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}	$\tau \to \mu\gamma$
$\mathrm{Im}\, C^{e\gamma}_{11}$, $\mathrm{Re}\, C^{e\gamma}_{11}$	~~3.8~~ 0.48 $\times 10^{-12}$, 2.4×10^{-6}	$d_e, \Delta a_e$
$\mathrm{Im}\, C^{e\gamma}_{22}$, $\mathrm{Re}\, C^{e\gamma}_{22}$	8.4×10^{-3}, 1.8×10^{-5}	$d_\mu, \Delta a_\mu$
$\mathrm{Im}\, C^{e\gamma}_{33}$, $\mathrm{Re}\, C^{e\gamma}_{33}$	4.4×10^{-1}, 3.2	$d_\tau, \Delta a_\tau$

CP-violation frontier

(severe bounds on many other lepton operators, especially from various μ-to-e transitions and e-EDM)

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

Dipole operator in PC framework

$$\mathcal{L}_{D=6} \supset \frac{C_{ij}^{e\gamma}}{\Lambda^2} \overline{e_{Li}} \sigma^{\mu\nu} e_{Rj} F_{\mu\nu} \frac{v}{\sqrt{2}}$$

As in the case of Yukawa couplings and neutrino masses, the Wilson coefficient can be estimated by Naive Dimensional Analysis (NDA):

order one coefficient

strong loop-factor

Higgs coupling

$$\frac{C_{ij}^{e\gamma}}{\Lambda^2} \frac{v}{\sqrt{2}} = \frac{c_{ij}^{e\gamma}}{m_*^2} \left(\frac{g_*}{4\pi}\right)^2 \epsilon_i^{\ell} \epsilon_j^{e} \, e \, \frac{g_* v}{\sqrt{2}} = \frac{c_{ij}^{e\gamma}}{m_*^2} \left(\frac{g_*}{4\pi}\right)^2 \frac{\epsilon_i^{\ell}}{\epsilon_j^{\ell}} m_j \, e$$

scale dimension

photon coupling

relevant ratio of PC parameters

lepton composite fraction

Minimal PC under pressure

Flavour-violation frontier ($\mu \to e\,\gamma$)

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

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 not compatible with the most natural compositeness scale (m_* a few TeV, 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 $v^2/f^2 < 0.1$

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

Panico Wulzer '15

Two approaches to relax the bounds

[A] Strong dynamics is not flavour-anarchic. Besides $U(1)_L$, it also preserves flavour numbers $U(1)_e \times U(1)_\mu \times U(1)_\tau$ as well as CP. The PC explanation for $y_e \ll y_\mu \ll y_\tau$ is preserved.

(note QCD has a large flavour symmetry)

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

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

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

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

Conclusions

- Precision lepton observables are exploring the multi-TeV scale
- Partial compositeness explain fermion mass hierarchies, and thus mitigates the flavour problem
- Three specific neutrino flavour patterns emerge from the composite dynamics
- Flavor and CP constraints push the compositeness scale above the range preferred by naturalness
- A symmetry $U(1)^3$ x CP greatly reduces the tension. Alternative solution is to allow for multiple flavour scales above m_*
- *Comment on current anomalies* (muon g-2, B semi-leptonic decays): they are flavor and CP conserving !
  But, they require composite states below m_*, except for the b-to-s violation of lepton universality...