Flavour aspects of model building

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Flavour puzzle of the SM

Quark Sector

$$\theta_{23}^Q \approx 2.5^\circ\,, \theta_{13}^Q \approx 0.2^\circ\,, \theta_{12}^Q \approx 13^\circ$$

$$m_u \approx 2.2\,\text{MeV},\, m_c \approx 1.2\,\text{GeV},\, m_t \approx 173\,\text{GeV}$$

$$m_d \approx 4.7\,\text{MeV},\, m_s \approx 95\,\text{MeV},\, m_b \approx 4.18\,\text{GeV}$$

Lepton Sector

$$\theta_{23}^L \approx 47.2^\circ\,, \theta_{13}^L \approx 8.5^\circ\,, \theta_{12}^L \approx 33.6^\circ$$

$$m_e \approx 0.51\,\text{MeV},\, m_\mu \approx 105.6\,\text{MeV},\, m_\tau \approx 1.77\,\text{GeV}$$

$$\Delta m_{21}^2 \approx 7.40\times 10^{-5}\, eV^2,\, \Delta m_{31}^2 \approx 2.49\times 10^{-3}\, eV^2$$

Additional questions for neutrinos

- Mass generation : new physics scale ?
- Dirac or Majorana
- Neutrino hierarchy : normal versus inverted

- Could this flavour structure be understood better in more fundamental theory ?
- Does it has simpler structure at high energy ?

What flavour physics taught us by now?

Predicted new particles before direct discovery

- **Precision measurements of flavour changing processes in the quark and lepton sector**
- Charged lepton flavour violating processes (clean channels)

Recent measurements involving flavour structure

Flavour violation in

- Higgs decay : $h \to \mu\tau$
- Top decay : $t \to cV(= \gamma, Z, g)$ etc.
- Bottom-sector : rare B decays

Flavour puzzle and hierarchy problem are connected ?

Current anomalies

$b \to s l^+ l^-$[LHCb, JHEP **1708** (2017) 055]

$$R_K^{[1,6]} = \frac{\Gamma(B \to K \mu^+ \mu^-)}{\Gamma(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_{K^*}^{[0.045,1.1]} = \frac{\Gamma(B \to K^* \mu^+ \mu^-)}{\Gamma(B^+ \to K^* e^+ e^-)} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}^{[1.1,6]} = \frac{\Gamma(B \to K^* \mu^+ \mu^-)}{\Gamma(B^+ \to K^* e^+ e^-)} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

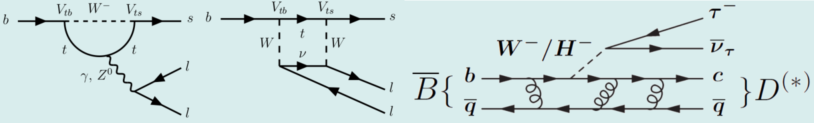
$b \to c \tau \nu$[LHCb, Phys. Rev. Lett. **115** (2015), 111803]

$$R_D = \frac{\Gamma(B \to D \tau \bar{\nu})}{\Gamma(B \to D l \bar{\nu})} = 0.388 \pm 0.047 \quad R_D^* = \frac{\Gamma(B \to D^* \tau \bar{\nu})}{\Gamma(B \to D^* l \bar{\nu})} = 0.321 \pm 0.021$$

Lepton flavour universality violation !! (accidental global symmetry in the SM)

SM predictions

- Flavor changing neutral currents are absent at tree level (GIM mechanism)



Model building to address anomalies

- Model independent EFT analysis
- Simplified models : just look for mediator
- UV complete models

- Tree level mediator : leptoquarks (natural existence in GUTs) and new vector boson Z'/W' (extended gauge sector)
- New Physics at loop level
- RH currents
- Composite models

Incomplete list of references :

1703.09226,1704.05340,1704.05446,1704.06659,1706.06100,1706.07779,1708.08450,1710.06363

+ many more..

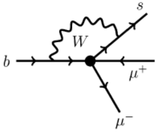
Model independent EFT analysis

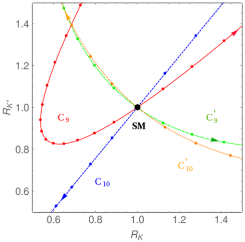
$$H_{eff}^{NP} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i,l} (C_i^l O_i^l + C_i^{\prime} O_i^{\prime l}) + h.c.$$

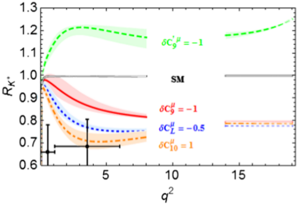
Semileptonic four Fermi operators :

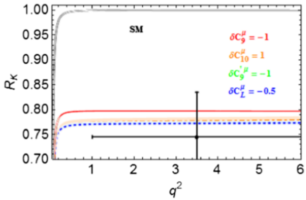
$$O_9^l = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l) \quad O_{10}^l = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma_5 l)$$

$$O_9^{\prime l} = (\bar{s}\gamma_\mu P_R b)(\bar{l}\gamma^\mu l) \quad O_{10}^{\prime l} = (\bar{s}\gamma_\mu P_R b)(\bar{l}\gamma^\mu \gamma_5 l)$$









One Wilson coefficient at a time, NP only for the muon sector, $O^{\prime}_{9,10}$ are disfavoured[1]

[1] L. S. Geng, B. Grinstein, S. Jaeger, J. Martin Camalich, X. L. Ren and R. X. Shi, Phys. Rev. D **96** (2017), 093006

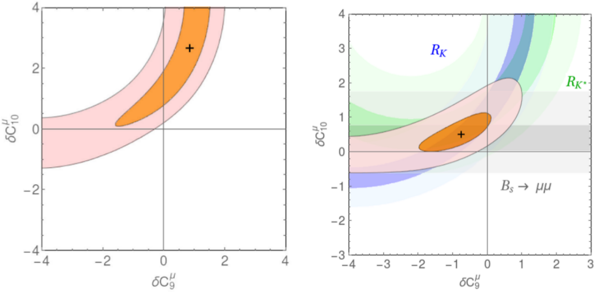


Figure: Phys. Rev. D **96** (2017), 093006

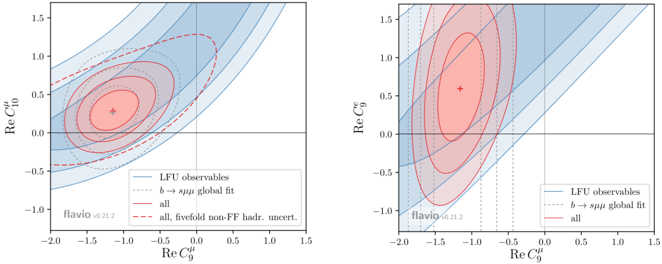


Figure: W. Altmannshofer, P. Stangl and D. M. Straub, Phys. Rev. D **96** (2017), 055008

SMEFT framework : new physics in top sector[2]

- TeV scale mediator couples to right handed top quark and muons

$$L_{SMEFT} = L_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i$$

$$O_{eu} = (\bar{\mu}\gamma^\mu \mu)(\bar{t}_R \gamma_\mu t_R) \quad ; \quad O_{lu} = (\bar{l}_\alpha \gamma^\mu l_\alpha)(\bar{t}_R \gamma_\mu t_R)$$

Modify Z boson couplings to the muon (LEP measurements)

$$L = \frac{g}{2c_W} \bar{\mu}(\delta g_L P_L + \delta g_R P_R)\mu Z^\alpha$$

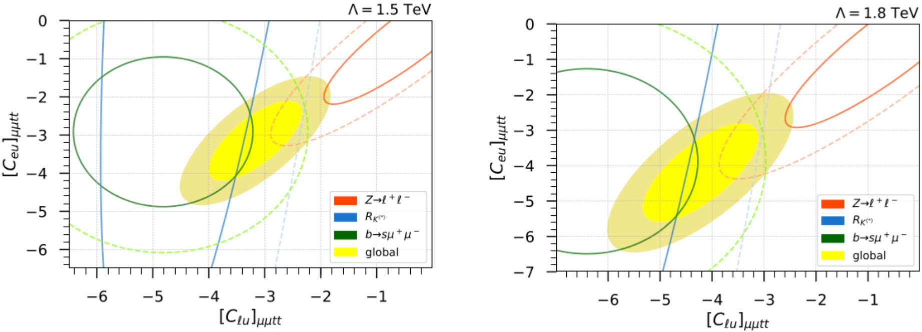
Below EW scale :

$$H_{eff}^{NP} = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{ts}^* V_{tb} \left(C_9 (\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha \mu) + C_{10} (\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}\gamma^\alpha \gamma_5 \mu) \right) + h.c.$$

$$C_9^{ij,\mu} \simeq \frac{x_t v^2}{8 s_{\theta_W}^2 \Lambda^2} \left[\log\left(\frac{\Lambda}{M_W}\right) + I_0(x_t) \right] (C_{lu} + C_{eu})$$

$$C_{10}^{ij,\mu} \simeq \frac{-x_t v^2}{8 s_{\theta_W}^2 \Lambda^2} \left[\log\left(\frac{\Lambda}{M_W}\right) + I_0(x_t) \right] (C_{lu} - C_{eu})$$

[2] J. E. Camargo-Molina, A. Celis and D. A. Faroughy, Phys. Lett. B **784** (2018) 284



Preferred direction $C_{lu} \sim C_{eu}$[3]

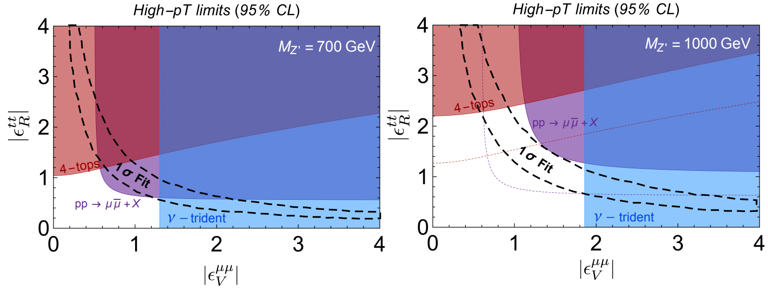
[3] 1805.04917

Mediators and high p_T phenomenology[4]

	Z'	S_1	R_2	$\widetilde{U}_1$	$\widetilde{V}_2$
$[\mathcal{O}_{\ell u}]_{\mu\mu tt}$	✓	✗	✓	✗	✓
$[\mathcal{O}_{eu}]_{\mu\mu tt}$	✓	✓	✗	✓	✗
$\mathcal{C}_{\ell u}, \mathcal{C}_{eu} < 0$	✓	✗	✓	✓	✗

$R_2 \sim (3,2,7/6) \quad \widetilde{U}_{1\alpha} \sim (3,1,5/3)$

$S_1 \sim (3^*,1,1/3) \quad \widetilde{V}_{2\alpha} \sim (3^*,2,-1/6)$

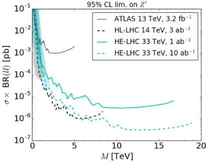


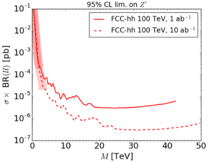
$$\mathcal{L} = Z'_\alpha \left[\bar{\mu}\gamma^\alpha(\epsilon_L^{\mu\mu}P_L + \epsilon_R^{\mu\mu}P_R)\mu + \epsilon_R^{tt}\,\bar{t}\gamma^\alpha P_R t\right]$$

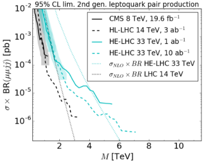
$$C_{lu} = -\epsilon_R^{tt}\epsilon_L^{\mu\mu} \qquad C_{eu} = -\epsilon_R^{tt}\epsilon_R^{\mu\mu}$$

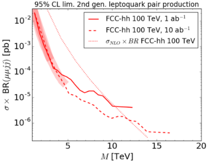
[4] 1805.04917

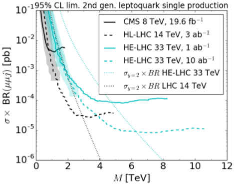
Z' and LQ based models[5]

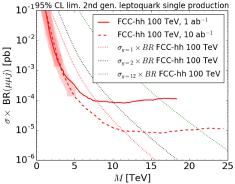


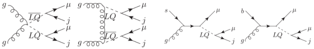












[5] B. C. Allanach, B. Gripaios and T. You, JHEP **1803** (2018) 021

Combined explanation[6]

- New physics couples dominantly to third generation left handed quarks and leptons
- Flavour symmetry $U(2)_q \times U(2)_l$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

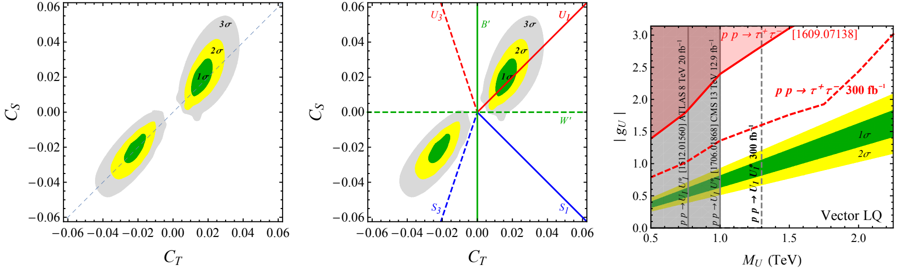
Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\bar\nu}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}C^{\rm SM}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
$\lvert g^W_\tau/g^W_\ell\rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
$\mathcal{B}(\tau \to 3\mu)$	$(0.0 \pm 0.6) \times 10^{-8}$	$2.5 \times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$

[6] D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, JHEP **1711** (2017) 044, [arXiv:1706.07808 [hep-ph]].

$$\mathcal{L}_U = -\frac{1}{2} U^{\dagger}_{1,\mu\nu} U^{1,\mu\nu} + M_U^2 U^{\dagger}_{1,\mu} U_1^{\mu} + g_U (J_U^{\mu} U_{1,\mu} + \mathrm{h.c.})$$

$$J_U^{\mu} \equiv \beta_{i\alpha}\ \bar{Q}_i \gamma^{\mu} L_{\alpha} \qquad U_1^{\mu} \equiv (\mathbf{3}, \mathbf{1}, 2/3)$$

1706.07808



Does same new physics answer multiple questions?

- DM and B-physics anomalies
- Neutrino masses and B physics anomalies
- DM, neutrino masses and B physics anomalies
- Top and bottom (correlation between $R_{D^{(*)}}$ and top quark FCNC decays in leptoquark models, arXiv:1812.08484)
- Correlating lepton flavor universality violation in B decays with $\mu \to e\gamma$ using leptoquarks, arXiv:1706.08511

Summary and outlook

- Model independent analysis for R_K/R_K^* requires new physics in the left sector
- Simplified models with LQ are particularly interesting
- Flavour physics is complementary to other direct searches for new physics
- **Future measurements in the flavour sector may guide us towards the actual fundamental theory ?**

Thank you