The quest for New Physics at the Intensity Frontier

Paride Paradisi

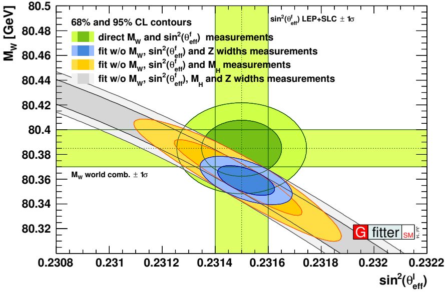
University of Padova and INFN

Corfu2018

2 September 2018, Corfu

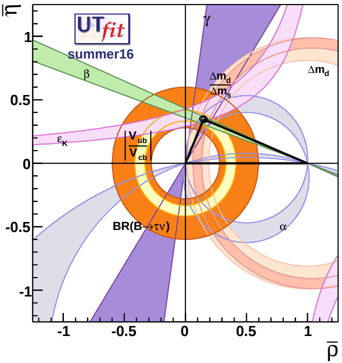
Plan of the talk

1. **Current status of the (very!) Standard Model**
2. **Strategies to look for New Physics at low-energy**
3. **Current anomalies and their interpretations**
   - The $g-2$ of the muon
   - LFUV in semileptonic B decays
4. **Conclusions and future prospects**



The LEP legacy

- Z-pole observables @ the 0.1% level
- Important constraints on many BSM



The B-factories legacy

- Confirmation of the CKM mechanism
- Important constraints on many BSM

Belle II + LHCb phase 2 upgrade: improvement in reach of factor 2.7-4
Like going from 8 TeV to 21-32 TeV!

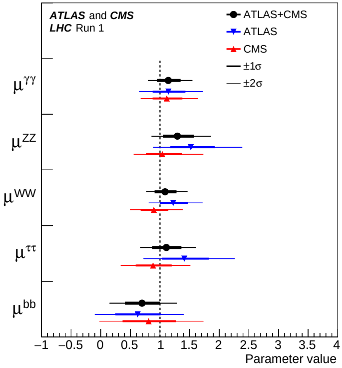
[Tim Gershon's summary talk @ Moriond 2017]

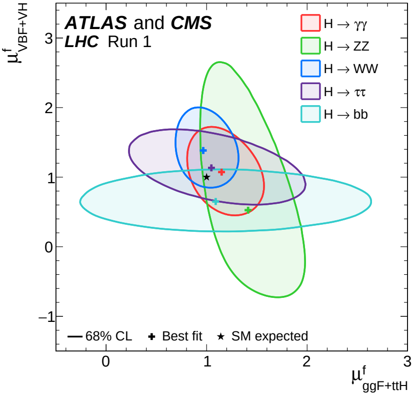
The LHC legacy

- **Higgs Boson mass** (combined LHC Run 1 results of ATLAS and CMS)

$$\mathbf{m_H} = \mathbf{125.09} \pm \mathbf{0.21}(\text{stat.}) \pm \mathbf{0.11}(\text{syst.})$$

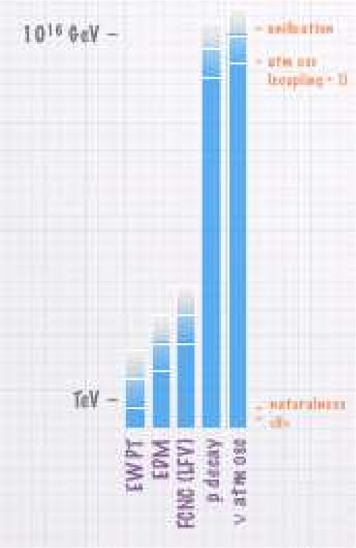
- **Higgs Boson couplings**: $\mu_i^f = \dfrac{\sigma_i Br^f}{(\sigma_i)_{SM}(Br^f)_{SM}}$ $\qquad (\mu_i^f \equiv \text{signal strengths})$





The NP “scale”

- **Gravity** $\Longrightarrow$ $\Lambda_{\text{Planck}} \sim 10^{18-19}\ \text{GeV}$
- **Neutrino masses** $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \text{GeV}$
- **BAU**: evidence of CPV beyond SM
  - Electroweak Baryogenesis $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \text{TeV}$
  - Leptogenesis $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \text{GeV}$
- **Hierarchy problem**: $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \text{TeV}$
- **Dark Matter (WIMP)** $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \text{TeV}$

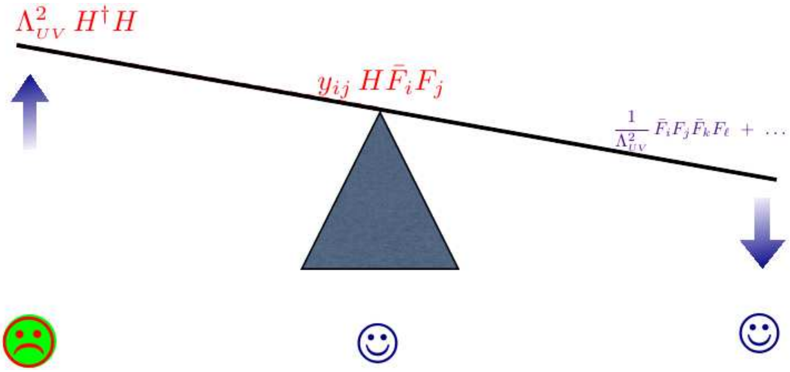


SM = effective theory at the EW scale

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d\geq 5} \frac{c_{ij}^{(d)}}{\Lambda_{NP}^{d-4}}\, O_{ij}^{(d)}$$

- $\mathcal{L}_{\text{eff}}^{d=5} = \dfrac{y_\nu^{ij}}{\Lambda_{\text{see-saw}}} L_i L_j \phi\phi,$
- $\mathcal{L}_{\text{eff}}^{d=6}$ generates FCNC operators

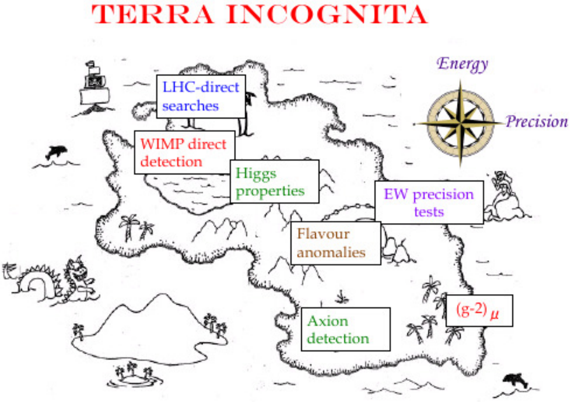
Hierarchy see-saw



[Rattazzi @ ppLHCb2013, Genova]

- **Hierarchy problem**: $\Lambda_{\text{NP}} \lesssim \text{TeV}$
- **SM Yukawas**: $M_W \lesssim \Lambda_{\text{NP}} \lesssim M_P$
- **Flavor problem**: $\Lambda_{\text{NP}} \gg \text{TeV}$

(Desperately) Looking for NP



[Casas @ Moriond 2017]

- We do not have a cross in the map to know where the BSM treasure is, as we had for the Higgs boson: we have to explore the whole territory!
- Is the BSM treasure is in the territory to be explored? Does it exist at all?
- The content of the BSM treasure is also a mystery: SUSY, new strong interactions, extra dimensions, something unexpected, ... ?

High-intensity frontier

Where to look for New Physics at low-energy?

- **Processes very suppressed or even forbidden in the SM**
  - LFV processes ($\mu \to e\gamma$, $\mu \to e$ in N, $\tau \to \mu\gamma$, $\tau \to 3\mu$, $\cdots$)
  - CPV effects in the electron/neutron EDMs
  - FCNC & CPV in $B_{s,d}$ & D decay/mixing amplitudes

- **Processes predicted with high precision in the SM**
  - EWPO as $(g-2)_\mu$: $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} \approx (3 \pm 1) \times 10^{-9}$ (3σ discrepancy!)
  - LFUV in $M \to \ell\nu$ (with $M = \pi, K, B$), $B \to D^{(*)}\ell\nu$, $B \to K\ell\ell'$, τ and Z decays

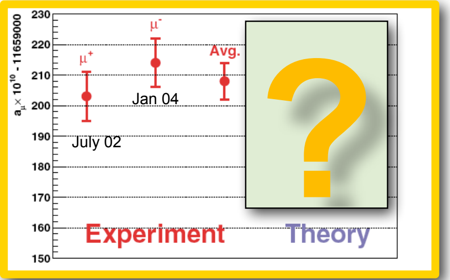
Experimental status

Process	Present	Experiment	Future	Experiment
$\mu \to e\gamma$	4.2×10^{-13}	MEG	$\approx 4 \times 10^{-14}$	MEG II
$\mu \to 3e$	1.0×10^{-12}	SINDRUM	$\approx 10^{-16}$	Mu3e
μ^- Au $\to e^-$ Au	7.0×10^{-13}	SINDRUM II	?	
μ^- Ti $\to e^-$ Ti	4.3×10^{-12}	SINDRUM II	?	
μ^- Al $\to e^-$ Al	–		$\approx 10^{-16}$	COMET, MU2e
$\tau \to e\gamma$	3.3×10^{-8}	Belle & BaBar	$\sim 10^{-9}$	Belle II
$\tau \to \mu\gamma$	4.4×10^{-8}	Belle & BaBar	$\sim 10^{-9}$	Belle II
$\tau \to 3e$	2.7×10^{-8}	Belle & BaBar	$\sim 10^{-10}$	Belle II
$\tau \to 3\mu$	2.1×10^{-8}	Belle & BaBar	$\sim 10^{-10}$	Belle II
$d_e(\mathrm{e\ cm})$	8.7×10^{-29}	ACNE	?	
$d_\mu(\mathrm{e\ cm})$	1.9×10^{-19}	Muon (g-2)	?	

Table: Present and future experimental sensitivities for relevant low-energy observables.

- So far, only upper bounds. Still excellent prospects for exp. improvements.
- We can expect a NP signal in all above observables below the current bounds.

On the muon $g - 2$



- **Today:** $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].
- **Future:** new muon g-2 experiments at:
  - **Fermilab E989:** aims at $\pm 16 \times 10^{-11}$, ie 0.14ppm. Beam expected next year. First result expected in 2018 with a precision comparable to that of BNL E821.
  - **J-PARC proposal:** aims at phase 1 start with 0.37ppm (2016 revised TDR).
- **Are theorists ready for this (amazing) precision? Not yet**

[courtesy of M. Passera]

Comparisons of the SM predictions with the measured g-2 value:

$a_\mu^{EXP} = 116592091\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072 with latest value of $\lambda = \mu_\mu/\mu_p$ from CODATA'10

$a_\mu^{\mathrm{SM}} \times 10^{11}$	$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}}$	σ
116 591 761 (57)	$330\ (85) \times 10^{-11}$	3.9 [1]
116 591 818 (51)	$273\ (81) \times 10^{-11}$	3.4 [2]
116 591 841 (58)	$250\ (86) \times 10^{-11}$	2.9 [3]

with the recent "conservative" hadronic light-by-light $a_\mu^{HNLO}(lbl) = 102\ (39) \times 10^{-11}$ of F. Jegerlehner arXiv:1511.04473, and the hadronic leading-order of:

[1] Jegerlehner, arXiv:1511.04473.
[2] Davier, arXiv:1612:02743.
[3] Hagiwara et al, JPG38 (2011) 085003.

[courtesy of M. Passera]

On leptonic dipoles: $\ell \to \ell' \gamma$

- **NP effects are encoded in the effective Lagrangian**

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R \sigma_{\mu\nu} A_{\ell\ell'} \ell'_L + \bar{\ell}'_L \sigma_{\mu\nu} A^\star_{\ell\ell'} \ell_R\right) F^{\mu\nu} \qquad \ell, \ell' = e, \mu, \tau\,,$$

  - **Branching ratios of $\ell \to \ell' \gamma$**

$$\frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell' \nu_\ell \bar{\nu}_{\ell'})} = \frac{48\pi^3 \alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right).$$

  - **Δa_ℓ and leptonic EDMs**

$$\Delta a_\ell = 2 m_\ell^2\, \mathrm{Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\, \mathrm{Im}(A_{\ell\ell})\,.$$

  - **“Naive scaling”:**

$$\Delta a_\ell / \Delta a_{\ell'} = m_\ell^2 / m_{\ell'}^2, \qquad d_\ell / d_{\ell'} = m_\ell / m_{\ell'}\,.$$

Model-independent predictions

- $\mathrm{BR}(\ell_i \to \ell_j \gamma)$ **vs.** $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\ell\tau}}{10^{-2}}\right)^2$$

- **EDMs assuming "Naive scaling"** $d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-28} \left(\frac{\phi_e^{CPV}}{10^{-4}}\right) \; e\,\mathrm{cm}\,,$$

$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 2 \times 10^{-22}\, \phi_\mu^{CPV} \; e\,\mathrm{cm}\,.$$

Main message: the explanation of the anomaly $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ requires a NP scenario nearly flavor and CP conserving

[Giudice, P.P., & Passera, '12]

Testing new physics with the electron $g-2$

- **Longstanding muon $g-2$ anomaly**

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \approx (3 \pm 1) \times 10^{-9}$$

$$\Delta a_\mu \approx a_\mu^{\rm EW} = \frac{m_\mu^2}{(4\pi v)^2}\left(1 - \frac{4}{3}s_{\rm W}^2 + \frac{8}{3}s_{\rm W}^4\right) \approx 2 \times 10^{-9}.$$

- **How could we check if the a_μ discrepancy is due to NP?**

- **Testing NP effects in a_e** [Giudice, P.P, & Passera, '12]: $\Delta a_e/\Delta a_\mu = m_e^2/m_\mu^2$

$$\Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}.$$

  - a_e has never played a role in testing NP effects. From $a_e^{\rm SM}(\alpha) = a_e^{\rm EXP}$, we extract α which is is the most precise value of α available today!
  - The situation has now changed thanks to th. and exp. progresses.

The Standard Model prediction of the electron $g-2$

- **Using the second best determination of α from atomic physics $\alpha(^{87}\mathrm{Rb})$**

$$\Delta a_e = a_e^{\mathrm{EXP}} - a_e^{\mathrm{SM}} = -9.2\,(8.1) \times 10^{-13},$$

  - Beautiful test of QED at four-loop level!
  - $\delta\Delta a_e = 8.1 \times 10^{-13}$ is dominated by δa_e^{SM} through $\delta\alpha(^{87}\mathrm{Rb})$.

- **Future improvements in the determination of Δa_e**

$$\underbrace{(0.2)_{\mathrm{QED4}},\ \ (0.2)_{\mathrm{QED5}},\ \ \ (0.2)_{\mathrm{HAD}}}_{(0.4)_{\mathrm{TH}}},\ \ (7.6)_{\delta\alpha},\ \ (2.8)_{\delta a_e^{\mathrm{EXP}}}.$$

  - The errors from QED4 and QED5 will be reduced soon to 0.1×10^{-13} [Kinoshita]
  - Experimental uncertainties from $\delta a_e^{\mathrm{EXP}}$ and $\delta\alpha$ dominate!
  - We expect a reduction of $\delta a_e^{\mathrm{EXP}}$ to a part in 10^{-13} (or better). [Gabrielse]
  - Work is also in progress for a significant reduction of $\delta\alpha$. [Nez]

- **Δa_e at the 10^{-13} (or below) is not too far! This will bring a_e to play a pivotal role in probing new physics in the leptonic sector.** [Giudice, P.P, & Passera, '12]

Not only $\mu \to e\gamma$...

- **LFV** operators **@ dim-6**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2_{\bf LFV}}\,\mathcal{O}^{\bf dim-6} + \ldots .$$

$$\mathcal{O}^{\rm dim-6} \ni \;\; \bar\mu_R\,\sigma^{\mu\nu}\,H\,e_L\,F_{\mu\nu}\,,\;\; (\bar\mu_L\gamma^\mu e_L)\left(\bar f_L\gamma^\mu f_L\right)\,,\;\; (\bar\mu_R e_L)\left(\bar f_R f_L\right)\,,\; f = e,u,d$$

- $\ell \to \ell'\gamma$ probe ONLY the dipole-operator (at tree level)
- $\ell_i \to \ell_j\bar\ell_k\ell_k$ and $\mu \to e$ in Nuclei probe dipole and 4-fermion operators
- When the dipole-operator is dominant:

$$\mathrm{BR}(\ell_i \to \ell_j\ell_k\bar\ell_k) \approx \alpha \times \mathrm{BR}(\ell_i \to \ell_j\gamma)$$
$$\mathrm{CR}(\mu \to e \text{ in N}) \approx \alpha \times \mathrm{BR}(\mu \to e\gamma)$$

$$\frac{\mathrm{BR}(\mu \to \mathbf{3e})}{\mathbf{3 \times 10^{-15}}} \approx \frac{\mathrm{BR}(\mu \to \mathbf{e}\gamma)}{\mathbf{5 \times 10^{-13}}} \approx \frac{\mathrm{CR}(\mu \to \mathbf{e} \text{ in N})}{\mathbf{3 \times 10^{-15}}}$$

- **Ratios like $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma)$ probe the NP flavor structure**
- **Ratios like $Br(\mu \to e\gamma)/Br(\mu \to eee)$ probe the NP operator at work**

Hints of LFUV in semileptonic B decays

- **LFUV in CC $b \to c$ transitions** (tree-level in the SM) @ 3.9σ

$$R_D^{\tau/\ell} = \frac{\mathcal{B}(B \to D\tau\bar{\nu})_{\rm exp}/\mathcal{B}(B \to D\tau\bar{\nu})_{\rm SM}}{\mathcal{B}(\bar{B} \to D\ell\bar{\nu})_{\rm exp}/\mathcal{B}(B \to D\ell\bar{\nu})_{\rm SM}} = 1.34 \pm 0.17$$

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^*\tau\bar{\nu})_{\rm exp}/\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})_{\rm SM}}{\mathcal{B}(B \to D^*\ell\bar{\nu})_{\rm exp}/\mathcal{B}(B \to D^*\ell\bar{\nu})_{\rm SM}} 1.23 \pm 0.07$$

[HFAG averages of BaBar '13, Belle '15, LHCb '15, Fajfer, Kamenik and Nisandzic '12]

- **LFUV in NC $b \to s$ transitions** (1-loop in the SM) @ 2.6σ

$$R_K^{\mu/e} = \left.\frac{\mathcal{B}(B \to K\mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B \to Ke\bar{e})_{\rm exp}}\right|_{q^2\in[1,6]{\rm GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036$$ [LHCb '14]

$$R_{K^*}^{\mu/e} = \left.\frac{\mathcal{B}(B \to K^*\mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B \to K^*e\bar{e})_{\rm exp}}\right|_{q^2\in[1.1,6]{\rm GeV}^2} = 0.685^{+0.113}_{-0.069} \pm 0.047$$ [LHCb '17]

while $(R_K^{\mu/e})_{SM} = 1$ up to few % corrections [Hiller et al,'07, Bordone, Isidori and Pattori, '16].

Hints of LFUV in semileptonic B decays

Coeff.	best fit	1σ	pull
C_9^μ	-1.56	$[-2.87, -0.71]$	4.1σ
C_{10}^μ	$+1.20$	$[+0.58, +2.00]$	4.2σ
C_9^e	$+1.54$	$[+0.76, +2.48]$	4.3σ
C_{10}^e	-1.27	$[-2.08, -0.61]$	4.3σ
$C_9^\mu = -C_{10}^\mu$	-0.63	$[-0.98, -0.32]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.76$	$[+0.36, +1.27]$	4.3σ
$C_9^e = C_{10}^e$	-1.91	$[-2.71, -1.10]$	3.9σ
$C_9'^{\,\mu}$	-0.05	$[-0.57, +0.46]$	0.2σ
$C_{10}'^{\,\mu}$	$+0.03$	$[-0.44, +0.51]$	0.1σ
$C_9'^{\,e}$	$+0.07$	$[-0.49, +0.69]$	0.2σ
$C_{10}'^{\,e}$	-0.04	$[-0.57, +0.45]$	0.2σ

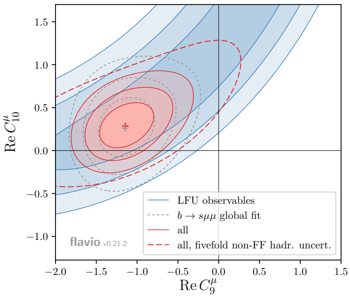
$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

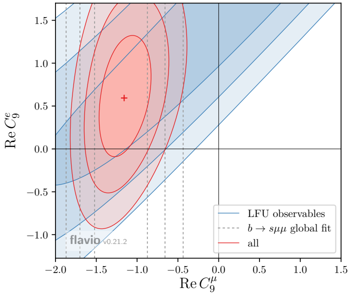
$$O_9'^{\,\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

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

$$O_{10}'^{\,\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

[Altmannshofer, Stangl, & Straub, '17]





High-energy effective Lagrangian

- **A simultaneous explanation of both $R_K^{\mu/e}$ and $R_D^{\tau/\ell}$ anomalies naturally selects a left-handed operator $(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$ which is related to $(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$ by the $SU(2)_L$ gauge symmetry** [Bhattacharya et al., '14].

- **Global fits** of $B \to K^*\ell\ell$ data favour (not exclusively) an effective 4-fermion operator involving left-handed currents $(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$, i.e. the $C_9 = -C_{10}$ solution [Hiller et al., '14, Hurth et al.,'14, Altmannshofer and Straub '14, Descotes-Genon et al., '15, ...].

- **This picture can work only if NP couples much more strongly to the third generation than to the first two.** Two interesting scenarios are:

  - **Lepton Flavour Violating case:** NP couples in the interaction basis only to third generations. Couplings to lighter generations are generated by the misalignment between the mass and the interaction bases [Glashow, Guadagnoli and Lane, '14] .

  - **Lepton Flavour Conserving case:** NP couples dominantly to third generations but LFV does not arise if the groups $U(1)_e \times U(1)_\mu \times U(1)_\tau$ are unbroken [Alonso et al., '15].

LFV case: high-energy effective Lagrangian

- In the energy window between the EW scale v and the NP scale Λ, NP effects are described by $\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}$ with $\mathcal{L}$ invariant under $SU(2)_L \otimes U(1)_Y$.

$$\mathcal{L}_{\rm NP} = \frac{C_1}{\Lambda^2} \left(\bar{q}_{3L}\gamma^\mu q_{3L}\right)\left(\bar{\ell}_{3L}\gamma_\mu \ell_{3L}\right) + \frac{C_3}{\Lambda^2} \left(\bar{q}_{3L}\gamma^\mu \tau^a q_{3L}\right)\left(\bar{\ell}_{3L}\gamma_\mu \tau^a \ell_{3L}\right).$$

- After EWSB we move to the mass basis through the unitary transformations

$$u_L \to V_u u_L \qquad d_L \to V_d d_L \qquad \nu_L \to U_e \nu_L \qquad e_L \to U_e e_L\,,$$

$$\begin{aligned}
\mathcal{L}_{\rm NP} = \frac{1}{\Lambda^2}[&(C_1 + C_3)\,\lambda^d_{ij}\lambda^e_{kl}\,(\bar{d}_{Li}\gamma^\mu d_{Lj})(\bar{e}_{Lk}\gamma_\mu e_{Ll}) \ + && B \to K^{(*)}\ell\ell' \\
&(C_1 - C_3)\,\lambda^d_{ij}\lambda^e_{kl}\,(\bar{d}_{Li}\gamma^\mu d_{Lj})(\bar{\nu}_{Lk}\gamma_\mu \nu_{Ll})] \ + && B \to K^{(*)}\nu\nu \\
&2C_3(V\lambda^d)_{ij}\lambda^e_{kl}\,(\bar{u}_{Li}\gamma^\mu d_{Lj})(\bar{e}_{Lk}\gamma_\mu \nu_{Ll}) + h.c.] && B \to D^{(*)}\ell\nu
\end{aligned}$$

[Calibbi, Crivellin, Ota, '15]

$$\lambda^d_{ij} = V^*_{d3i}V_{d3j} \qquad \lambda^e_{ij} = U^*_{e3i}U_{e3j} \qquad V_u^\dagger V_d = V_{\rm CKM} \equiv V$$

- Assumption for the flavor structure: $\lambda^{d,e}_{33} \approx 1, \quad \lambda^{d,e}_{22} = |\lambda^{d,e}_{23}|^2, \quad \lambda^{d,e}_{13} = 0.$

Semileptonic observables

- $B \to K\ell\bar{\ell}$

$$R_K^{\mu/e} \approx 1 - 0.28\,\frac{(C_1 + C_3)}{\Lambda^2(\mathrm{TeV})}\,\frac{\lambda_{23}^d\,|\lambda_{23}^e|^2}{10^{-3}} \qquad (R_K^{\mu/e})_{exp} < 1$$

- $R_{D^{(*)}}^{\tau/\ell}$

$$R_{D^{(*)}}^{\tau/\ell} \approx 1 - \frac{0.12\,C_3}{\Lambda^2(\mathrm{TeV})}\left(1 + \frac{\lambda_{23}^d}{V_{cb}}\right)\lambda_{33}^e \qquad (R_{D^{(*)}}^{\tau/\ell})_{exp} > 1$$

- $B \to K\nu\bar{\nu}$

$$R_K^{\nu\nu} \approx 1 + \frac{0.6\,(C_1 - C_3)}{\Lambda^2(\mathrm{TeV})}\left(\frac{\lambda_{23}^d}{0.01}\right) + \frac{0.3\,(C_1 - C_3)^2}{\Lambda^4(\mathrm{TeV})}\left(\frac{\lambda_{23}^d}{0.01}\right)^2$$

$$R_K^{\nu\nu} = \frac{\mathcal{B}(B \to K\nu\bar{\nu})}{\mathcal{B}(B \to K\nu\bar{\nu})_{\mathrm{SM}}} \leq 4.3$$

  - The correct pattern of deviation from the SM is reproduced for $C_3 < 0$, $\lambda_{23}^d < 0$ and $|\lambda_{23}^d/V_{cb}| \lesssim 1$. For $|C_3| \sim \mathcal{O}(1)$, we need $\Lambda \sim 1$ TeV and $|\lambda_{23}^e| \gtrsim 0.1$.

[Calibbi, Crivellin and Ota, '15]

Construction of the low-energy effective Lagrangian: running and matching

- We use the renormalization group equations (RGEs) to evolve the effective lagrangian $\mathcal{L}_{\rm NP}$ from $\mu \sim \Lambda$ down to $\mu \sim 1$ GeV. This is done is three steps:
  - First step: the RGEs in the unbroken $SU(2)_L \otimes U(1)_Y$ theory [Manohar et al.,'13] are used to compute the coefficients in the effective lagrangian down to a scale $\mu \sim m_Z$.
  - Second step: the coefficients are matched to those of an effective lagrangian for the theory in the broken symmetry phase of $SU(2)_L \otimes U(1)_Y$, that is $U(1)_{el}$.
  - Third step: the coefficients of this effective lagrangian are computed at $\mu \sim 1$ GeV using the RGEs for the theory with the only $U(1)_{el}$ gauge group.
- Then we take matrix elements of the relevant operators. The scale dependence of the RGE contributions cancels with that of the matrix elements.

[Feruglio, P.P., Pattori, PRL '16, '17]

Leptonic Z-coupling modifications

- $\mathcal{L}_{\rm NP}$ **induces modification of the** W, Z **couplings**

$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda^2}[(C_1 + C_3)\,\lambda^u_{ij}\lambda^e_{kl}\,(\bar{u}_{Li}\gamma^\mu u_{Lj})(\bar{\nu}_{Lk}\gamma_\mu \nu_{Ll}) + (C_1 - C_3)\,\lambda^u_{ij}\lambda^e_{kl}\,(\bar{u}_{Li}\gamma^\mu u_{Lj})(\bar{e}_{Lk}\gamma_\mu e_{Ll}) \; + \ldots]$$

$$\mathcal{L}_Z = \frac{g_2}{c_W}\bar{e}_i\left(\not{Z} g^{ij}_{\ell L} P_L + \not{Z} g^{ij}_{\ell R} P_R\right) e_j + \frac{g_2}{c_W}\bar{\nu}_{Li}\,\not{Z}\, g^{ij}_{\nu L}\,\nu_{Lj}$$

$$\Delta g^{ij}_{\ell L} \simeq \frac{v^2}{\Lambda^2}\left(3y_t^2(C_1 - C_3)\lambda^u_{33} + g_2^2 C_3\right)\log\left(\frac{\Lambda}{m_Z}\right)\frac{\lambda^e_{ij}}{16\pi^2}$$

$$\Delta g^{ij}_{\nu L} \simeq \frac{v^2}{\Lambda^2}\left(3y_t^2(C_1 + C_3)\lambda^u_{33} - g_2^2 C_3\right)\log\left(\frac{\Lambda}{m_Z}\right)\frac{\lambda^e_{ij}}{16\pi^2}$$

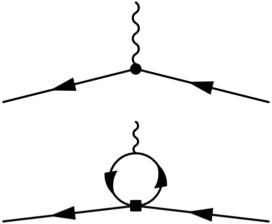


Figure: Z couplings with fermions. Upper: RGE induced coupling. Lower: one-loop diagram.

- Approximate LO results obtained adding to the **RGE** contributions from gauge and top yukawa interactions the **one-loop matrix element**.

- The **scale dependence** of the **RGE** contribution cancels with that of the **matrix element** dominated by a quark loop.

Z-pole observables

- **Non-universal leptonic vector and axial-vector Z couplings** [PDG]

$$\frac{v_\tau}{v_e} \approx 1 - 0.05\,\frac{[(C_1 - C_3)\lambda^u_{33} + 0.2\,C_3]}{\Lambda^2(\mathrm{TeV})}$$
$$\frac{a_\tau}{a_e} \approx 1 - 0.004\,\frac{[(C_1 - C_3)\lambda^u_{33} + 0.2\,C_3]}{\Lambda^2(\mathrm{TeV})}\,,$$

to be compared with the LEP result [PDG]

$$\frac{v_\tau}{v_e} = 0.959 \pm 0.029\,, \qquad \frac{a_\tau}{a_e} = 1.0019 \pm 0.0015$$

- **Number of neutrinos N_ν from the invisible Z decay width**

$$N_\nu \approx 3 + 0.008\,\frac{[(C_1 + C_3)\lambda^u_{33} - 0.2\,C_3]}{\Lambda^2(\mathrm{TeV})}$$

to be compared with the LEP result [PDG]

$$N_\nu = 2.9840 \pm 0.0082$$

Purely leptonic effective Lagrangian

- **Quantum effects generate a purely leptonic effective Lagrangian**:

$$\mathcal{L}_{\rm eff}^{\rm NC} = -\frac{4G_F}{\sqrt{2}}\lambda^e_{ij}\left[(\bar{e}_{Li}\gamma_\mu e_{Lj})\sum\nolimits_\psi \bar{\psi}\gamma^\mu\psi\,(2g^Z_\psi \mathbf{c}^{\mathbf{e}}_{\mathbf{t}} - Q_\psi \mathbf{c}^{\mathbf{e}}_{\gamma}) + h.c.\right]$$

$$\mathcal{L}_{\rm eff}^{\rm CC} = -\frac{4G_F}{\sqrt{2}}\lambda^e_{ij}\left[\mathbf{c}^{\mathbf{cc}}_{\mathbf{t}}(\bar{e}_{Li}\gamma_\mu \nu_{Lj})(\bar{\nu}_{Lk}\gamma^\mu e_{Lk} + \bar{u}_{Lk}\gamma^\mu V_{kl} d_{Ll}) + h.c.\right]$$

$\psi = \{\nu_{Lk}, e_{Lk,Rk}, u_{L,R}, d_{L,R}, s_{L,R}\}$ $\qquad g^Z_\psi = T_3(\psi) - Q_\psi \sin^2\theta_W$

$$\mathbf{c}^{\mathbf{e}}_{\mathbf{t}} = \mathbf{y}^2_{\mathbf{t}}\frac{3}{32\pi^2}\frac{v^2}{\Lambda^2}(C_1 - C_3)\lambda^u_{33}\log\frac{\Lambda^2}{m_t^2}$$

$$\mathbf{c}^{\mathbf{cc}}_{\mathbf{t}} = \mathbf{y}^2_{\mathbf{t}}\frac{3}{16\pi^2}\frac{v^2}{\Lambda^2}C_3\,\lambda^u_{33}\log\frac{\Lambda^2}{m_t^2}$$

$$\mathbf{c}^{\mathbf{e}}_{\gamma} = \frac{\mathbf{e}^2}{48\pi^2}\frac{v^2}{\Lambda^2}\left[(3C_3 - C_1)\log\frac{\Lambda^2}{\mu^2} + \ldots\right]$$

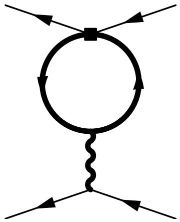


Figure: Diagram generating a four-lepton process.

- Top-quark yukawa interactions affect both neutral and charged currents.
- Gauge interactions are proportional to e^2 and to the e.m. current.

- **LFU breaking effects in $\tau \to \ell\bar{\nu}\nu$**

$$R_\tau^{\tau/e} = \frac{\mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm SM}}$$

$$R_\tau^{\tau/\mu} = \frac{\mathcal{B}(\tau \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau \to e\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm SM}}$$

- $R_\tau^{\tau/\ell}$: experiments vs. theory

$$R_\tau^{\tau/\mu} = 1.0022 \pm 0.0030\,, \quad R_\tau^{\tau/e} = 1.0060 \pm 0.0030$$ [HFAG, '14]

$$R_\tau^{\tau/\ell} \approx 1 + \frac{0.01\, C_3}{\Lambda^2(\mathrm{TeV})}\, \lambda^u_{33}\lambda^e_{33}$$

- $R_{D^{(*)}}^{\tau/\ell}$: experiments vs. theory

$$R_D^{\tau/\ell} = 1.37 \pm 0.17, \qquad R_{D^*}^{\tau/\ell} = 1.28 \pm 0.08$$

$$R_{D^{(*)}}^{\tau/\ell} \approx 1 - \frac{0.12\, C_3}{\Lambda^2(\mathrm{TeV})} \left(1 + \frac{\lambda^d_{23}}{V_{cb}}\right) \lambda^e_{33}$$

Strong tension between $R_\tau^{\tau/\ell}$ and $R_D^{\tau/\ell}$

LFV decays

- **LFV τ decays (1-loop)**

$$\mathcal{B}(\tau \to 3\mu) \approx 5 \times 10^{-8} \, \frac{(C_1 - C_3)^2}{\Lambda^4(\mathrm{TeV})} \left(\frac{\lambda^e_{23}}{0.3}\right)^2$$

$$\mathcal{B}(\tau \to 3\mu) \approx \mathcal{B}(\tau \to \mu\rho) \approx \mathcal{B}(\tau \to \mu\pi)$$

- **LFV B decays (tree-level)**

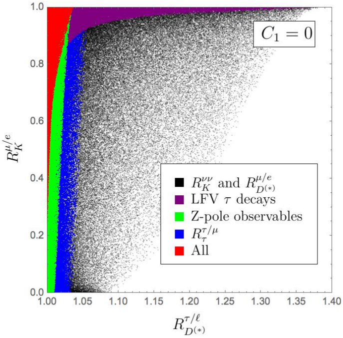
$$\mathcal{B}(B \to K\tau\mu) \approx 4 \times 10^{-8} \left|C_9^{\mu\tau}\right|^2 \approx 10^{-7} \left|\frac{C_9^{\mu\mu}}{0.5}\right|^2 \left|\frac{0.3}{\lambda^e_{23}}\right|^2 ,$$

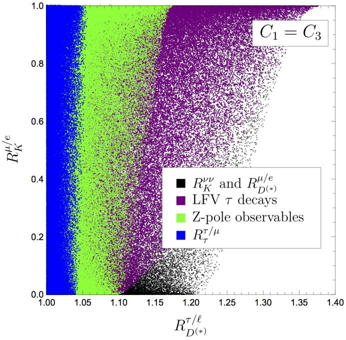
since $C_9^{\mu\mu}/C_9^{\mu\tau} \approx \lambda^e_{23}$ and $|C_9^{\mu\mu}| \approx 0.5$ from $R_K^{e/\mu} \approx 0.75$.

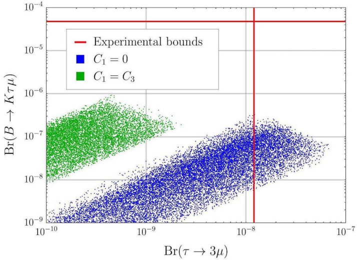
- **Experimental bounds** [HFAG]:

$$\mathcal{B}(\tau \to 3\mu)_{\rm exp} \leq 2.1 \times 10^{-8}$$
$$\mathcal{B}(\tau \to \mu\rho)_{\rm exp} \leq 1.2 \times 10^{-8}$$
$$\mathcal{B}(\tau \to \mu\pi)_{\rm exp} \leq 2.7 \times 10^{-8}$$
$$\mathcal{B}(B \to K\tau\mu)_{\rm exp} \leq 4.8 \times 10^{-5}$$

B anomalies







[Feruglio, P.P., Pattori, PRL ’16, ’17]

Discussion

- **Question: are there ways out to the EWPT bounds discussed here?**
  - Log effects can be cancelled/suppressed by finite terms, not captured by our RGE-based approach, which require the knowledge of the complete UV theory.
  - Our starting point can be generalized by allowing more operators at the scale Λ, making it possible cancellation/suppression of log effects [Barbieri et al,'16, Isidori et al,'17]
  - EWPT constraints are relaxed if $\lambda^d_{23} \gg V_{cb}$ [Crivellin, Muller and Ota, '17]
    - $\lambda^d_{23} \sim 1$, $\lambda^e_{22} \ll 10^{-2}$, $\Lambda \sim 5$ TeV $\Longrightarrow R^{\tau/\ell}_{D^{(*)}}$
    - $\lambda^d_{23} \sim 1$, $\lambda^e_{22} \sim 1$, $\Lambda \sim 30$ TeV $\Longrightarrow R^{\mu/e}_{K^{(*)}}$
    - $\lambda^d_{23} \sim 1$, $\lambda^e_{22} \sim 10^{-2}$, $\Lambda \sim 5$ TeV $\Longrightarrow R^{\tau/\ell}_{D^{(*)}}$ and $R^{\mu/e}_{K^{(*)}}$

  $\lambda^d_{23} \sim 1$ requires a large fine tuning to reproduce the CKM matrix

$$V_{\rm CKM} = V_u^\dagger V_d \qquad \lambda^q_{ij} = V^*_{q3i} V_{q3j} \qquad (q = u, d)$$

- **Answer: Yes but they require some amount of fine tunings.**

Testable predictions in models with $U(2)^n$ flavor symmetry

- $b \to c(u)\, l\nu$ — $BR(B\to D^*\tau\nu)/BR_{SM} = BR(B\to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c\tau\nu)/BR_{SM}$ $= BR(B \to \pi\, \tau\nu)/BR_{SM} = BR(\Lambda_b \to p\, \tau\nu)/BR_{SM} = BR(B_u \to \tau\nu)/BR_{SM}$

- $b \to s\, \mu\mu$ — $\Delta C_9^\mu = -\Delta C_{10}^\mu$ ($\to$ to be checked in several other modes...)
- $b \to s\, \tau\tau$ — $|NP| \sim |SM|$ $\to$ large enhancement (easily $10\times$SM)
- $b \to s\, \nu\nu$ — $\sim$ O(1) deviation from SM in the rate

---

- $K \to \pi\, \nu\nu$ — $\sim$ O(1) deviation from SM in the rate

---

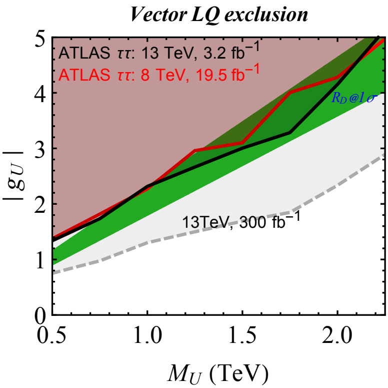
- Meson mixing — $\sim$ 10% deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays — $\tau \to 3\mu$ not far from present exp. Bound ($BR \sim 10^{-9}$)

[Isidori @ Planck 2017]

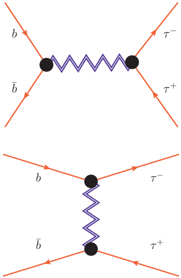
- **The $b \to c\tau\nu$ process is related to $b\bar{b} \to \tau^+\tau^-$**

$$\mathcal{L}_U^{\rm eff} \supset -\frac{|g_U|^2}{M_U^2}\left[(V_{cb}(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L) + h.c.) + (\bar{b}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\tau_L)\right]$$

- **The explanation of the $b \to c\tau\nu$ anomaly is constrained by LHC searches**



$b\bar{b} \to \tau^+\tau^-$ @ LHC



[Faroughy, Greljo, Kamenik, '16]

Conclusions and future prospects

- **Important questions in view of ongoing/future experiments are**:
  - What are the expected deviations from the SM predictions induced by TeV NP?
  - Which observables are not limited by theoretical uncertainties?
  - In which case we can expect a substantial improvement on the experimental side?
  - What will the measurements teach us if deviations from the SM are [not] seen?

- **(Personal) answers**:
  - We can expect any deviation from the SM expectations below the current bounds.
  - LFV processes, leptonic EDMs and LFUV observables do not suffer from theoretical limitations and there are still excellent prospects for experimental improvements.
  - The observed LFUV in $B \to D^{(*)}\ell\nu$, $B \to K\ell\ell'$ might be true NP signals. It's worth to look for LFUV in $B_{(c)} \to \ell\nu$, $B \to K\tau\tau$, $\Lambda_b \to \Lambda_c\tau\nu$ and $\tau \to \ell\nu\nu$, ...
  - If LFUV arise from LFV sources, the most sensitive LFV channels are typically not B-decays but τ decays such as $\tau \to \mu\ell\ell$ and $\tau \to \mu\rho$, ...
  - The longstanding $(g-2)_\mu$ anomaly will be checked soon by the experiments E989 at Fermilab and E34 at J-PARK. If confirmed it will imply NP at/below the TeV scale!

Message: an exciting Physics program is in progress at the Intensity Frontier!