The quest for New Physics at the Intensity Frontier

Paride Paradisi

University of Padua

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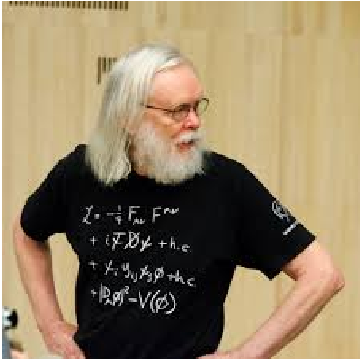
Plan of the talk

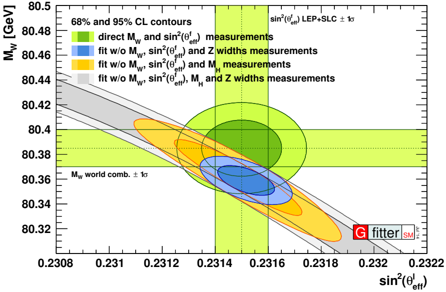
1. **Current status of the Standard(issimo) Model**
2. **Strategies to look for New Physics at high-energy (HL-LHC)**
3. **Strategies to look for New Physics at low-energy**
4. **Current low-energy anomalies and their interpretations**
5. **Conclusions and future prospects**

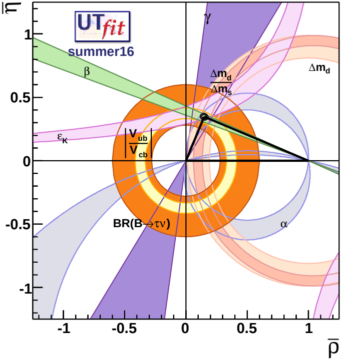
$$\begin{aligned}\mathbf{L_{SM}} &= -\frac{1}{4}\mathbf{F}^a_{\mu\nu}\mathbf{F}^{a\mu\nu} \\ &+ i\bar{\psi}\not{D}\psi + h.c. \\ &+ \psi_i y_{ij}\psi_j\phi + h.c. \\ &+ |D_\mu\phi|^2 - V(\phi)\end{aligned}$$

"This is short enough to write on a T-shirt!"

[J.Ellis]







The LEP legacy

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

The B-factories legacy

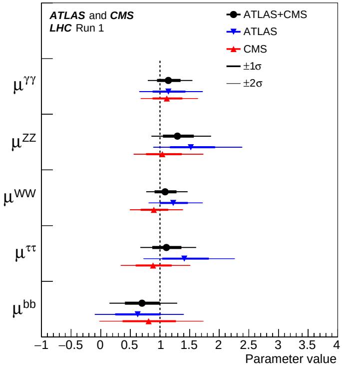
- Confirmation of the CKM mechanism
- Important constraints on many BSM

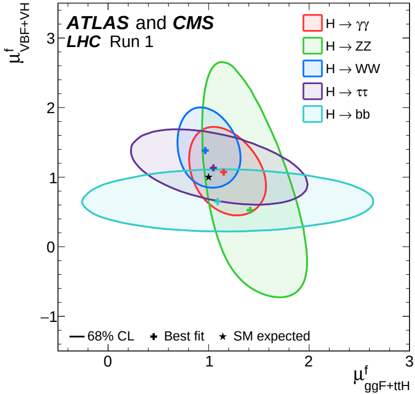
The LHC legacy

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

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

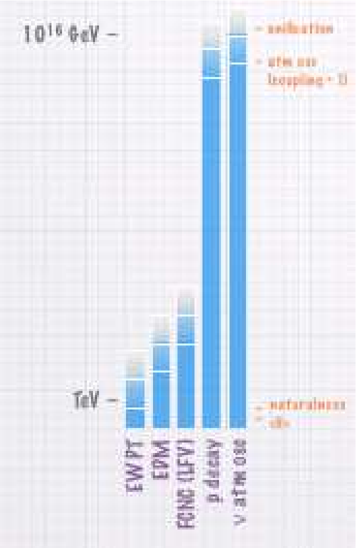
- **Higgs Boson couplings**: $\mu_i^f = \frac{\sigma_i Br^f}{(\sigma_i)_{SM}(Br^f)_{SM}}$ ($\mu_i^f \equiv$ signal strengths)





The NP "scale"

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

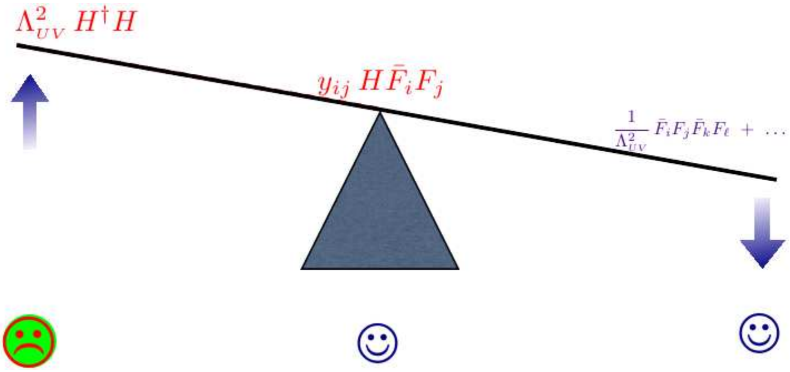


SM = effective theory at the EW scale

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

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

Hierarchy see-saw



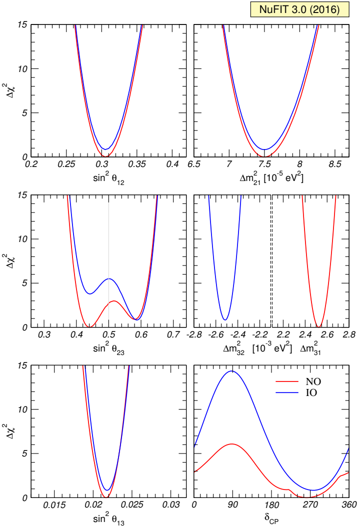
[Rattazzi @ ppLHCb2013, Genova]

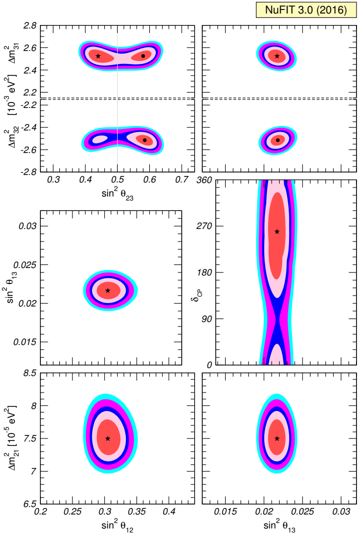
- **Hierarchy problem**: $\Lambda_{NP} \lesssim \mathrm{TeV}$
- **SM Yukawas**: $M_W \lesssim \Lambda_{NP} \lesssim M_P$
- **Flavor problem**: $\Lambda_{NP} \gg \mathrm{TeV}$

The evidence of neutrino oscillations has firmly established they have masses

1. **Are neutrinos Dirac or Majorana particles?**
2. **Which is the absolute neutrino mass scale?**
3. **Which is the neutrino mass ordering (NO or IO)?**
4. **Is there CPV in the neutrino sector?**
5. **Pattern of neutrino mixing angles: anarchy, TB, BM, ... ?**

3ν Flavour Parameters: Global Fit

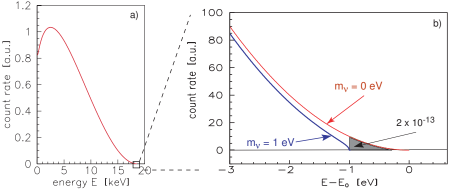




1. Mild preference for NO w.r.t. IO?
2. Preference for $\delta_{\rm CP} \in (\pi, 2\pi)$?
3. $\theta_{23} \neq 45^\circ$, preference for $\theta_{23} < 45^\circ$?

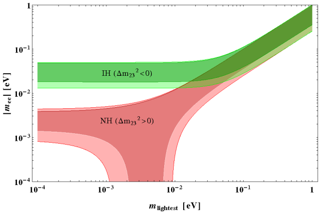
Neutrino Mass Scale

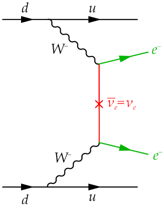
β decay



- m_{ν_e} modifies spectrum endpoint.
- $m^2_{\nu_e} = \sum |U_{ej}|^2 m_j^2 \leq 2.2$ eV
- Katrin sensitivity to $m_{\nu_e} \sim 0.2$ eV

$0\nu\beta\beta$ decay



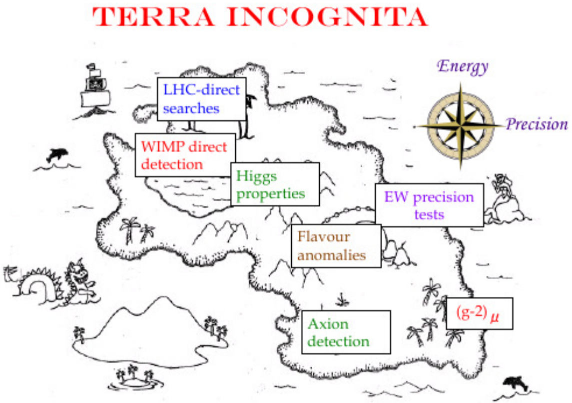


- $0\nu\beta\beta \iff$ Majorana ν's
- $m_{ee} = |\sum U_{ej}^2 m_j|$
- Present bound $m_{ee} \lesssim 0.8$ eV

Cosmology

- m_ν affect growth of structures
- Present bound $\sum m_i \lesssim 0.6$ eV

(Desperately) Looking for NP

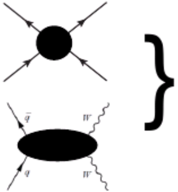


[Casas @ Moriond 2017]

- 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, ... ?

- **What kind of precision tests can we obtain at the end of the LHC?**
  - Being the LHC a hadron machine, it's difficult to go in accuracy beyond few percent
  - Still very relevant information, as the properties of the Higgs were not tested before

- **We can obtain precision tests of the SM at the LHC if we take profit of its energy, and look for deviations of the SM that grow at high-energy**



$$\frac{\delta \mathcal{A}}{\mathcal{A}_{\rm SM}} \sim \frac{g_*^2}{g^2}\frac{E^2}{\Lambda^2}$$

g_* = coupling to the BSM

can be larger than one for strongly-coupled theories: $g_* \gg 1$

- **Magnifying the effect:**

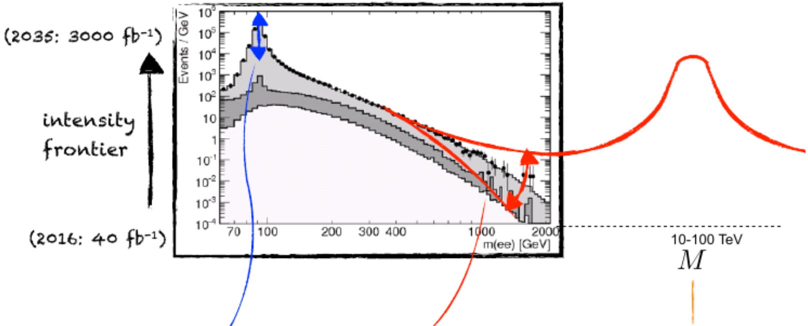
$$\mathbf{10\%} \times \left(\frac{\mathbf{TeV}}{\mathbf{m_W}}\right)^{\mathbf{2}} \sim \mathbf{0.1\%}$$

  - **A 10% accuracy can allow a per-mille test of the SM, competitive with LEP!**

[Pomarol @ Aspen 2017 Winter Conference]

LHC Exploration
(now -> 2030's)

Focus: Standard Model Precision Tests

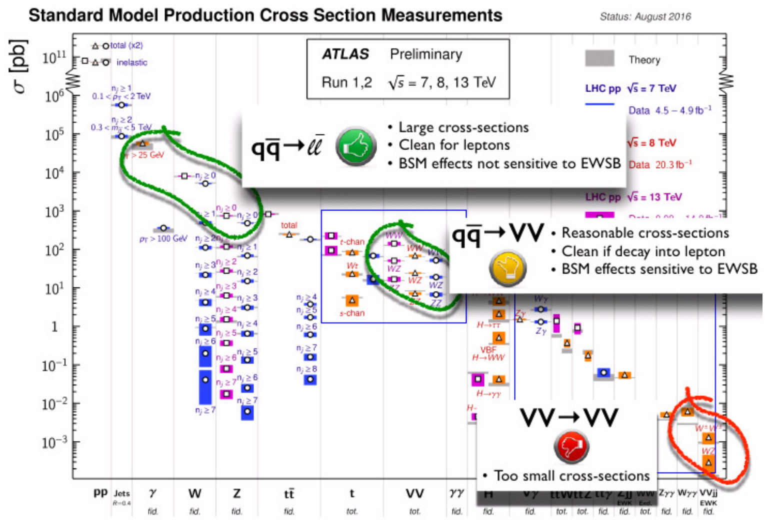


Effective Field Theory

$$\sigma \propto \sum |Amp|^2 \simeq SM^2\left(1 + c_i \frac{E^2}{M^2} + c_i^2 \frac{E^4}{M^4}\right) \leftarrow \mathcal{L}_{eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{M^2} \mathcal{O}_i^{(6)} + \cdots$$

[Rival @ Aspen 2017 Winter Conference]

SM tests @ HL-LHC



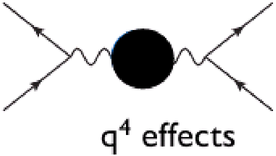
[Pomarol @ Aspen 2017 Winter Conference]

We have to look for SM deformations in those processes where

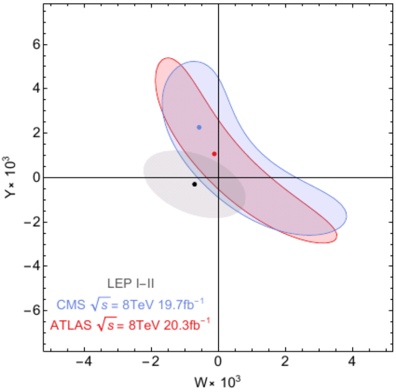
$$\delta A / A_{SM} \propto E^2/\Lambda^2$$

$q\,\overline{q} \to \ell\bar{\ell}, \ell\bar{\nu}$

- Can be sensitive to oblique corrections
- 8 TeV LHC already competitive with LEP



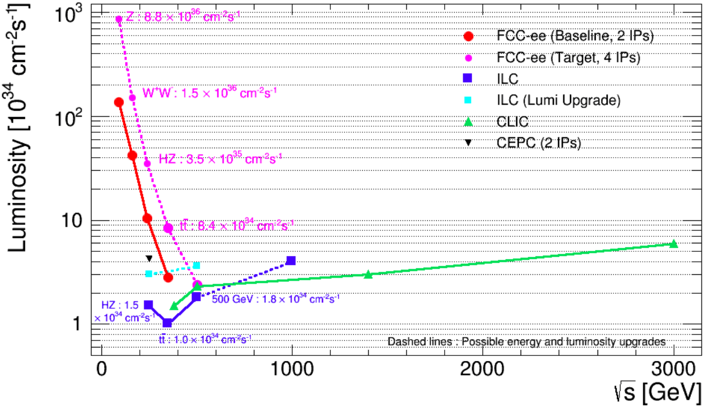
$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$



[M.Farina,G.Panico,D.Pappadopulo, J.T.Ruderman,R.Torre,A.Wulzer, '16]

Future e^+e^- colliders

[TLEP Design Study Working Group Collaboration]



- **ILC and CLIC high energies, CEPC and FCC-ee higher luminosities.**
  - CLIC if LHC will find new particles with masses $\lesssim$ 1 TeV
  - FCC-ee if high-precision Higgs and Z measurements are to be prioritized.

Where to look for New Physics at low-energy?

- **Processes very suppressed or even forbidden in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\mu \to e$ in N, $\tau \to \mu\gamma$, $\tau \to 3\mu$, $B \to K\tau\mu$, $\cdots$)
  - 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 $(g-2)_\mu$: $a_\mu^{exp} - a_\mu^{SM} \approx (3 \pm 1) \times 10^{-9}$, a discrepancy at 3σ!
  - 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
$\mu \to e\gamma$	5.7×10^{-13}	MEG	$\approx 6 \times 10^{-14}$	MEG
$\mu \to 3e$	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.

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

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

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

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

- the dipole-operator leads to $\ell \to \ell' \gamma$ while 4-fermion operators generate processes like $\ell_i \to \ell_j \bar{\ell}_k \ell_k$ and $\mu \to e$ conversion in Nuclei.
- When the dipole-operator is dominant:

$$\frac{\mathrm{BR}(\ell_i \to \ell_j \ell_k \bar{\ell}_k)}{\mathrm{BR}(\ell_i \to \ell_j \bar{\nu}_j \nu_i)} \simeq \frac{\alpha_{el}}{3\pi}\left(\log \frac{m^2_{\ell_i}}{m^2_{\ell_k}} - 3\right) \frac{\mathrm{BR}(\ell_i \to \ell_j \gamma)}{\mathrm{BR}(\ell_i \to \ell_j \bar{\nu}_j \nu_i)}\,,$$

$$\mathrm{CR}(\mu \to e \text{ in N}) \simeq \alpha_{\rm em} \times \mathrm{BR}(\mu \to e\gamma)\,.$$

- $\mathrm{BR}(\mu \to \mathbf{e}\gamma) \sim \mathbf{5} \times \mathbf{10}^{-\mathbf{13}}$ implies

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

- $\mu + N \to e + N$ on different N discriminates the operator at work [Okada et al. 2004].
- An angular analysis for $\mu \to eee$ can test operator which is at work.

Pattern of LFV in NP models

- **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**

ratio	LHT	MSSM	SM4
$\frac{Br(\mu\to eee)}{Br(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\cdot 10^{-2}$	$0.07\ldots 2.2$
$\frac{Br(\tau\to \mu\mu\mu)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{Br(\tau\to e\mu\mu)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\cdot 10^{-3}$	$0.03\ldots 1.3$
$\frac{Br(\tau\to \mu ee)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\cdot 10^{-2}$	$0.04\ldots 1.4$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\mu\mu)}$	$0.8\ldots 2$	~ 5	$1.5\ldots 2.3$
$\frac{Br(\tau\to \mu\mu\mu)}{Br(\tau\to \mu ee)}$	$0.7\ldots 1.6$	~ 0.2	$1.4\ldots 1.7$
$\frac{\mathrm{R}(\mu \mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$10^{-12}\ldots 26$

[Buras et al., '07, '10]

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

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

$$A_{\ell\ell'} = \frac{1}{(4\pi\,\Lambda_{\rm NP})^2}\left[\left(g^L_{\ell k}\,g^{L*}_{\ell' k} + g^R_{\ell k}\,g^{R*}_{\ell' k}\right)f_1(x_k) + \frac{v}{m_\ell}\left(g^L_{\ell k}\,g^{R*}_{\ell' k}\right)f_2(x_k)\right]\,,$$

  - **Δa_ℓ and leptonic EDMs are given by**

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

  - **The branching ratios of $\ell \to \ell'\gamma$ are given by**

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

- **"Naive scaling":**

$$\Delta a_{\ell_i}/\Delta a_{\ell_j} = m^2_{\ell_i}/m^2_{\ell_j}, \qquad d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}\,.$$

(for instance, if the new particles have an underlying SU(3) flavor symmetry in their mass spectrum and in their couplings to leptons, which is the case for gauge interactions).

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

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"** $d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-24} \ \tan\phi_e \ \ e\,\mathrm{cm}\,,$$

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

$$d_\tau \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 4 \times 10^{-21} \ \tan\phi_\tau \ \ e\,\mathrm{cm}\,,$$

- $(g-2)_\ell$ **assuming "Naive scaling"** $\Delta a_{\ell_i}/\Delta a_{\ell_j} = m^2_{\ell_i}/m^2_{\ell_j}$

$$\Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}\,, \qquad \Delta a_\tau = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.8 \times 10^{-6}.$$

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

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

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 2.90(90)\times 10^{-9}\,, \qquad \textbf{3.5}\sigma\ \textbf{discrepancy}$$

- **NP effects are expected to be of order $a_\ell^{\rm NP} \sim a_\ell^{\rm EW}$**

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

- **Main question: how could we check if the a_μ discrepancy is due to NP?**
- **Answer: testing new-physics effects in a_e** [Giudice, P.P, & Passera, '12]
- **"Naive scaling":** $\Delta a_{\ell_i}/\Delta a_{\ell_j} = m_{\ell_i}^2/m_{\ell_j}^2$

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

  - a_e has never played a role in testing beyond SM 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 progresses both on the th. and exp. sides.

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

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

$$\Delta a_e = a_e^{\mathrm{EXP}} - a_e^{\mathrm{SM}} = -10.6\,(8.1) \times 10^{-13},$$

  - 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**

$$\underbrace{(0.6)_{\mathrm{QED4}},\ \ (0.4)_{\mathrm{QED5}},\ \ \ (0.2)_{\mathrm{HAD}}}_{(0.7)_{\mathrm{TH}}},\ \ (7.6)_{\delta\alpha},\ \ (2.8)_{\delta a_e^{\mathrm{EXP}}}.$$

  - The first error, 0.6×10^{-13}, stems from numerical uncertainties in the four-loop QED. It can be reduced to 0.1×10^{-13} with a large scale numerical recalculation [Kinoshita]
  - The second error, from five-loop QED term may soon drop to 0.1×10^{-13}.
  - Experimental uncertainties 2.8×10^{-13} ($\delta a_e^{\mathrm{EXP}}$) and 7.6×10^{-13} ($\delta\alpha$) dominate. We expect a reduction of the former error to a part in 10^{-13} (or better) [Gabrielse]. Work is also in progress for a significant reduction of the latter error [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.**

- **Experimental data in B physics hints at non-standard LFU violations both in charged-current as well as neutral-current transitions:**

  - An overall 3.9σ violation from τ/ℓ universality ($\ell = \mu, e$) in the charged-current $b \to c$ decays [BaBar '13, Belle '15, LHCb '15, Fajfer, Kamenik and Nisandzic '12]

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

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

  - A 2.6σ deviation from μ/e universality in the neutral-current $b \to s$ transition

$$R^{\mu/e}_{K} = \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{\rm exp}}{\mathcal{B}(B \to Ke^+e^-)_{\rm exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

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

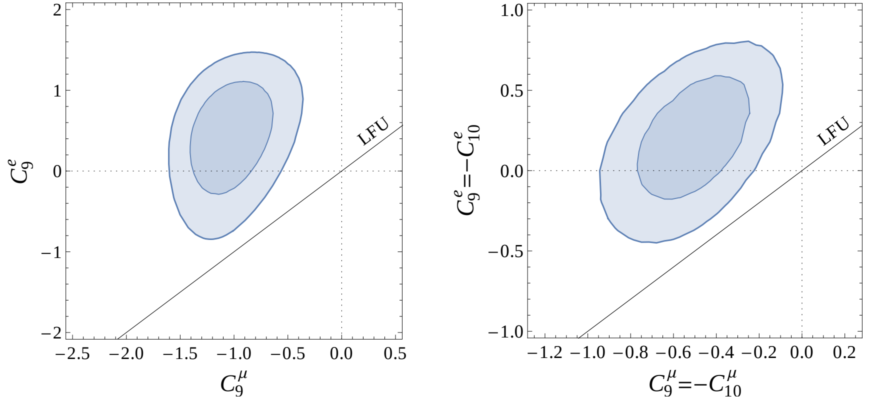


Figure: Best fit regions at 1 and 2σ in the plane C_9^μ vs. C_9^e (left) and $C_9^\mu = -C_{10}^\mu$ vs. $C_9^e = -C_{10}^e$ (right). The diagonal line corresponds to lepton flavour universality.

$$\mathcal{L}_{\rm eff}^{\rm NC} = \frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

[Altmannshofer & Straub, '15, see also Hiller et al., '14, Hurth et al., '14, Descotes-Genon et al., '15]

B anomalies

- The explanation of the $R_K^{\mu/e}$ anomaly favours an effective 4-fermion operator involving left-handed currents, $(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$ [Hiller et al., '14, Hurth et al.,'14, Altmannshofer and Straub '14, Descotes-Genon et al., '15, ...]

- This naturally suggests to account also for the charged-current anomaly through 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].

- 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 through small flavour mixing angles. LFU violation necessarily implies LFV [Glashow, Guadagnoli and Lane, '14] .

  - **Lepton Flavour Conserving case:** NP couples to different fermion generations proportionally to their mass squared [Alonso, '15]. The non-abelian leptonic flavour group is broken but $U(1)_e \times U(1)_\mu \times U(1)_\tau$ is preserved.

- 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 $SU(2)_L \otimes U(1)_Y$.

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

- After EWSB we move from the interaction to the mass basis through the unitary transformations ($V_u^\dagger V_d = V_{\rm CKM} \equiv V$)

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

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

$$\lambda^d_{ij} = V^*_{d3i} V_{d3j} \qquad \lambda^e_{ij} = U^*_{e3i} U_{e3j} \qquad \lambda^{ud}_{ij} = V^*_{u3i} V_{d3j}$$

Lesson: at tree-level Z, τ LFU & LFV processes are not generated!!

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:
  - In the first step, the RGEs in the unbroken phase of the $SU(2) \otimes U(1)$ theory are used to compute the coefficients in the effective lagrangian down to a scale $\mu \sim m_Z$.
  - In the second step, the coefficients are matched to those of an effective lagrangian for the theory in the broken symmetry phase of $SU(2) \otimes U(1)$, that is $U(1)_{el}$.
  - In the third step, the coefficients of this effective lagrangian are computed at $\mu \sim 1$ GeV using the RGEs for the theory with only $U(1)_{el}$ gauge group.
- Then we take matrix elements of the relevant operators, using perturbative QCD for heavy quarks and chiral perturbation theory for light quark loops.The scale dependence of the RGE contributions cancels with that of the matrix elements.

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

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

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

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

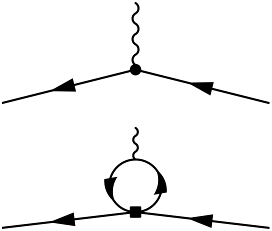


Figure: Upper: RGE induced coupling. Lower: one-loop matrix element.

- These expressions provide a good approximation of the **exact results** obtained adding to the **RGE** contributions from gauge and top yukawa interactions the **one-loop matrix element** with the Z four-momentum set on the mass-shell.

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

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

$$\mathcal{L}_{\rm eff}^{\rm NC} = -\frac{4G_F}{\sqrt{2}}\lambda_{ij}^e\left[(\bar{e}_{Li}\gamma_\mu e_{Lj})\sum_\psi \bar{\psi}\gamma^\mu\psi\,(2g_\psi^Z \mathbf{c_t^e} - Q_\psi \mathbf{c_\gamma^e}) + h.c.\right]$$

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

where $\psi = \{\nu_{Lk}, e_{Lk,Rk}, u_{L,R}, d_{L,R}, s_{L,R}\}$ and $g_\psi^Z = T_3(\psi) - Q_\psi \sin^2\theta_W$.

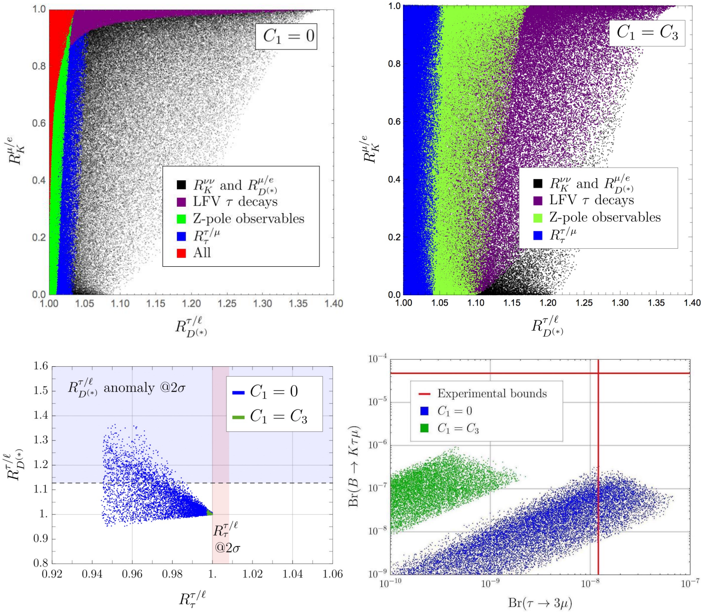
$$\mathbf{c_t^e} = \mathbf{y_t^2}\frac{3}{32\pi^2}\frac{v^2}{\Lambda^2}(C_1 - C_3)\lambda_{33}^u \log\frac{\Lambda^2}{m_t^2}$$

$$\mathbf{c_t^{cc}} = \mathbf{y_t^2}\frac{3}{16\pi^2}\frac{v^2}{\Lambda^2}C_3\,\lambda_{33}^u \log\frac{\Lambda^2}{m_t^2}$$

$$\mathbf{c_\gamma^e} = \frac{\mathbf{e^2}}{48\pi^2}\frac{v^2}{\Lambda^2}\left[(3C_3 - C_1)\log\frac{\Lambda^2}{\mu^2} - (C_1 + C_3)\lambda_{33}^d \log\frac{m_b^2}{\mu^2} + 2(C_1 - C_3)\left(\lambda_{33}^u \log\frac{m_t^2}{\mu^2} + \lambda_{22}^u \log\frac{m_c^2}{\mu^2}\right)\right]$$

- Top-quark yukawa interactions affect both neutral and charged currents.
- Gauge interactions are proportional to e^2 and to the e.m. current.
- The μ dependence is removed by the matrix elements in the low energy theory.

B anomalies

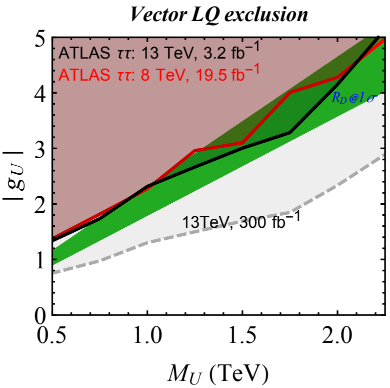


[Feruglio, P.P. & Pattori, PRL '16]

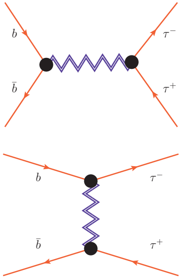
- **The** $b \to c\tau\nu$ **process is related to** $b\bar{b} \to \tau^+\tau^-$

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

- **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 $B_{(c)} \to \ell\nu$, $B \to K\tau\tau$ 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 below the TeV scale!