Theoretical Aspects of Flavour and CP violation in the Lepton Sector

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Motivations

1 CLFV expected at some level

neutrino masses and $U_{PMNS} \neq 1$ ➡ L_i violated ($i=e,\mu,\tau$)

evidence for lepton flavor conversion

$\nu_e \to \nu_\mu, \nu_\tau$ sol, LBL exp

$\nu_\mu \to \nu_\tau$ atm, LBL exp

should show up in processes with charged leptons

2 CP violation in lepton sector [CPL]

-- expected once flavour is violated within three generations
-- welcome, since CP violation from quarks is insufficient to generate the Baryon Asymmetry of the Universe

in SM with 3 right-handed neutrinos there are 6 CP-violating phases
-> Leptogenesis

3 CLFV and CPL probe New Physics Beyond the νSM

CLFV

$$BR(\mu \to e\gamma) \approx \frac{3\alpha}{32\pi}\left|U^*_{\mu i}U_{ei}\frac{m_i^2}{m_W^2}\right|^2 \approx 10^{-53}$$

in the SM, minimally extended to accommodate e.g. Dirac neutrinos

[unobservable also within type I see-saw] $m_i \approx 0.05\, eV \quad U_{fi} \approx O(1)$

GIM mechanism
(mixing angle large,
neutrino masses tiny)

<->

GIM suppression
for quarks:
small mixing angles
large top mass

completely
out of reach
by many orders
of magnitude

Electron EDM

Estimate in SM 4 loops (massless neutrinos)

$$\frac{d_e}{e} \approx \frac{G_F m_e}{\pi^2}\left(\frac{\alpha}{2\pi}\right)^3 J \approx 6\times 10^{-37}\ cm$$

$J = (2.96^{+0.20}_{-0.16})\times 10^{-5}$

with Dirac (Majorana) neutrinos $d_e \neq 0$ at 3(2) loops, but negligibly small

[Archambault, Czarnecki and Pospelov hep-ph/0406089]

Questions

- what are the links to neutrino properties?
- which scales Λ_{NP} are we testing in current/future experiments?

↕

Λ_{NP} >> ew scale

↕

- if Λ_{NP} = 1 TeV, why we have not seen CLFV and CPL so far?
- theory mechanisms to suppress CLFV and CPL

experimental status of CLFV searches

tau: a richer flavour structure

$O(10^{-8})$

Channel	Best 90% C.L. Limit [x 10^{-8}]	Other 90% C.L. Limits [x 10^{-8}]
$\tau^+ \to e^+ \gamma$	**3.3 (BaBar)** PRL 104, 021802 (2010)	12 (Belle) PLB 666, 16 (2008)
$\tau^+ \to \mu^+ \gamma$	**4.4 (BaBar)** PRL 104, 021802 (2010)	4.5 (Belle) PLB 666, 16 (2008)
$\tau^+ \to e^+ e^+ e^-$	**2.7 (Belle)** PLB 687, 139 (2010)	3.4 (BaBar) PRD 81, 111101 (2010)
$\tau^+ \to e^+ \mu^+ \mu^-$	**2.7 (Belle)** ibidem	4.6 (BaBar) ibidem
$\tau^+ \to e^- \mu^+ \mu^+$	**1.7 (Belle)** ibidem	2.8 (BaBar) ibidem
$\tau^+ \to \mu^+ e^+ e^-$	**1.8 (Belle)** ibidem	3.7 (BaBar) ibidem
$\tau^+ \to \mu^- e^+ e^+$	**1.5 (Belle)** ibidem	2.2 (BaBar) ibidem
$\tau^+ \to \mu^+ \mu^+ \mu^-$	**2.1 (Belle)** ibidem	4.0 (BaBar) ibidem

similar sensitivity on semileptonic decays

future expected sensitivity should go down to the 10^{-9} level for most of these channels, from B factories and LHCb

$O(10^{-9})$

muon, the major player

	present upper bound		future sensitivity	
$BR(\mu^+ \to e^+\gamma)$	5.7×10^{-13}	[MEG]	6×10^{-14}	[MEG ~2018]
$BR(\mu^+ \to e^+e^+e^-)$	1.0×10^{-12}	[SINDRUM]	$\approx10^{-16}$	[Mu3e>2019]
$CR(\mu^- Ti \to e^- Ti)$	4.3×10^{-12}	[SINDRUM II]		
$CR(\mu^- Au \to e^- Au)$	7.0×10^{-13}	[SINDRUM II]		
$CR(\mu^- Al \to e^- Al)$			$(2\div6)\times10^{-17}$	[Mu2e>2018]
$CR(\mu^- Al \to e^- Al)$			$\approx3\times10^{-17}$	[COMET>2019]

great improvements expected within this decade
4-5 orders of magnitude: a golden age for CLFV searches

more ambicious project under Study both at FNAL and at J-PARC aiming at 10^{-18}

l	$d_l(e\ cm)$
e	$<8.7\times10^{-29}$
μ	$<1.8\times10^{-19}$
τ	$<10^{-16}$

l	$\Delta a_l = a_l^{EXP} - a_l^{SM}$
e	$(-10.5\pm8.1)\times10^{-13}$
μ	$(29\pm9)\times10^{-10}$
τ	$-0.007 < \Delta a_\tau < 0.005$

[more on this later on]

3.2 σ

soon checked by Muon g-2 at Fermilab > 2017 improving accuracy from 0.5 ppm to 0.2 ppm

What scales are we testing ?

at energies $m_W < E < \Lambda$ gauge invariance restricts the form of the most general FV and CPV Lagrangian [here leptons only]

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

New Physics scale Λ

DIMENSION 6

$D \equiv \bar{L}\varphi\sigma_{\mu\nu}F^{\mu\nu}L$		$V \equiv i\varphi^+\overleftrightarrow{D}_\mu\varphi\bar{L}\gamma^\mu L$		$S \equiv \varphi^+\varphi\bar{L}\varphi L$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$		
		$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$		

[Buchmuller, Wyler 1986; Grzadkowsi,Iskzynski, Misiak,Rosiek 1008.4884

$C \equiv \bar{L}\gamma_\mu L\bar{L}\gamma^\mu L$					
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$

[+10 independent qqll operators, up to flavor combinations]

Bounds

[Pruna, Signer 1408.3565 Crivellin, S. Najjari, and J. Rosiek, 1312.0634]

assumption: one operator dominance

		$\lvert C_k \rvert (\Lambda = 1$ TeV$)$	Λ(TeV) $(\lvert C_k \rvert = 1)$	
D	$C_{D\gamma}^{12,21}$ γ	2.5×10^{-10}	6.4×10^{4}	$\mu \to e\gamma$
	$C_{D\gamma}^{13,31}$ γ	2.4×10^{-6}	6.5×10^{2}	$\tau \to e\gamma$
	$C_{D\gamma}^{23,32}$ γ	2.7×10^{-6}	6.1×10^{2}	$\tau \to \mu\gamma$
D	$C_{DZ}^{12,21}$ Z	1.4×10^{-7}	2.7×10^{3}	$\mu \to e\gamma$
	$C_{DZ}^{13,23,31,32}$ Z	$\approx 10^{-3}$	≈ 30	$\tau \to e\gamma, \tau \to \mu\gamma$
V,C	C_V^{12}, C_C^{1211}	3×10^{-5}	170	$\mu \to 3e$
	$C_V^{13,23}, C_C^{1311,2322}$	$\approx 10^{-2}$	≈ 9	$\tau \to 3e, \tau \to 3\mu$
S	C_S^{12}	3×10^{-2}	6	$\mu \to e\gamma$
	$C_S^{13,23}$	$O(1)$	$O(1)$	$\tau \to e\gamma, \tau \to \mu\gamma$

enter at 1 loop (D, Z rows)

enter at 1 loop (S rows)

	$\lvert \mathrm{Im}(C_k) \rvert (\Lambda = 1$ TeV$)$	Λ(TeV) $(\lvert \mathrm{Im}(C_k) \rvert = 1)$	
$C_{D\gamma}^{11}$	4.2×10^{-11}	1.5×10^{5}	d_e
$C_{D\gamma}^{22}$	9×10^{-2}	3.4	d_μ

[Blankenburg, Ellis and Isidori 1202.5704] Harnik, Kopp and Zupan, 1209.1397

scaling $\sqrt{BR}$ $1/(BR)^{1/4}$

a closer look to the em dipole

$$\frac{C_{D\gamma}^{ij}}{\Lambda^2} \bar{L}_i \varphi \sigma_{\mu\nu} F^{\mu\nu} E_j$$

redefine

$$\left(C_{D\gamma}^{ji}\right)^* \equiv e A_{ij} \frac{m_{[ij]}}{\sqrt{2}v}$$

[ij]=Max(ij)

-- em coupling
-- should vanish in the chiral limit

$i = j$

$$\Delta a_i = 2 \frac{m_i^2}{\Lambda^2} \mathrm{Re}\left(A_{ii}\right)$$

$$\frac{d_i}{e} = \frac{m_i}{\Lambda^2} \mathrm{Im}\left(A_{ii}\right)$$

$\Delta a_\mu = 30 \times 10^{-10}$

$\Lambda = 2.7$ TeV $(A = 1)$

$$\frac{d_i}{e} = \frac{\Delta a_i}{2 m_i} \tan \varphi_i \qquad \varphi_i \equiv \arg\left(A_{ii}\right)$$

model independent relation

$$\frac{d_\mu}{e} \approx 3 \times 10^{-22} \left(\frac{\Delta a_\mu}{30 \times 10^{-10}}\right) \tan \varphi_\mu \; cm$$

much smaller than the current bound if the phase is O(1) if $A_{ii} = A$ → $\frac{\Delta a_i}{\Delta a_j} = \frac{m_i^2}{m_j^2}$ $\frac{d_i}{d_j} = \frac{m_i}{m_j}$ naïve scaling = NS

[can be violated by NP particles with non universal masses and/or non-universal couplings to leptons]

- $$\Delta a_e = \frac{m_e^2}{m_\mu^2}\Delta a_\mu \approx 7\times 10^{-14}\left(\frac{\Delta a_\mu}{30\times 10^{-10}}\right)$$

$$\Delta a_e \equiv a_e^{EXP} - a_e^{SM} = (-10.5 \pm 8.1)\times 10^{-13}$$

not far from the 10^{-13} accuracy

[Giudice, Paradisi and Passera, 1208.6583]

using as input $\alpha(^{87}Rb)$ extracted from Rydberg constant measuring h/M_{Rb} by atom interferometry

error dominated by $\delta\alpha(^{87}Rb)$ and δa_e^{EXP}: $8.1^2=7.6^2+2.8^2$

- $$\frac{d_e}{e} = \frac{1}{2m_e}\frac{m_e^2}{m_\mu^2}\Delta a_\mu \tan\varphi \approx 1.4\times 10^{-24}\left(\frac{\Delta a_\mu}{30\times 10^{-10}}\right)\tan\varphi \quad cm$$

NS and Δa_μ → $|\varphi| < 6\times 10^{-5}$ flavor blind phases should be tiny

some mechanisms to suppress CLFV and EDM

1 Tuning of scales [e.g. MFV]

the only sources of FV from New Physics at the scale Λ are the Yukawa couplings, formally treated as non-dynamical fields with appropriate transformation properties

$$L_Y = -\bar{L}\varphi\,\hat{y}_e\,E - \frac{1}{2\Lambda_L}\bar{L}\varphi\,w\,\bar{L}\varphi + ... + h.c.$$

possible additional terms depending on the type of neutrino masses

MFV unambiguous in the quark sector, not precisely defined in the lepton one

simple rules to estimate $C^{ij}_{D,V,S,C}$

dipole operator $C^{ij}_{D\gamma}$

$$\frac{1}{\Lambda^2}\bar{L}_i\varphi\left[\left(c_1 1 + c_2\,\hat{y}_e\hat{y}_e^+ + c_3\,w\,w^+ + ...\right)\hat{y}_e\right]_{ij}(\sigma_{\mu\nu}F^{\mu\nu})E_j$$

the only flavor-violating combination

as in the SM, CLFV vanishes in the limit of massless neutrinos

$$\frac{e}{2}A_{ii} \approx c_1 1 + \ldots$$

approximate
Naïve Scaling

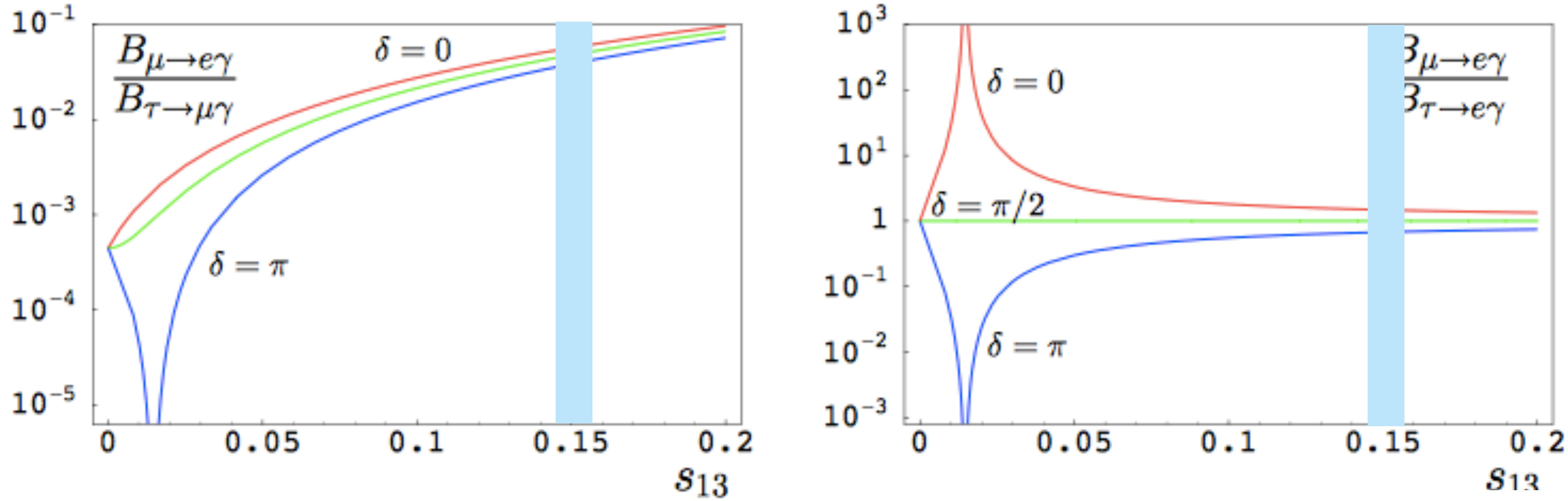
$$\frac{e}{2}A_{\mu e} >> \frac{e}{2}A_{e\mu}$$

$$w\,w^{+}\hat{y}_e = \frac{4\sqrt{2}}{v}\frac{\Lambda_L^2}{v^4}\left(U_{PMNS}\hat{m}_\nu^2 U_{PMNS}^{+}\right)\hat{m}_e$$

experimental bounds satisfied by $(\Lambda_L/\Lambda) < 10^9$

μ -> e γ observable if $\Lambda_L >> \Lambda$

[qualitatively similar conclusion when MFV extended to the type I see-saw case]



[Cirigliano, Grinstein, Isidori and Wise, 0507001]

from present bound on μ -> e γ

$$R_{\tau\mu} < (1.0 \div 1.6) \times 10^{-11}$$

2 Flavor Models/Symmetries [e.g. PC]

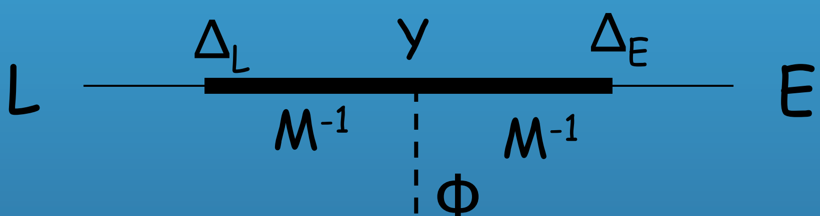
tailored to explain the hierarchies among fermion masses/mixing angles

a toy model

$$L_Y = -\bar{S}_L \Delta_E E - \bar{L}\,\Delta_L D_R$$
$$- \bar{S}_L\, M\, S_R - \bar{D}_L M\, D_R$$
$$- (\bar{D}_L \Phi) Y\, S_R - \bar{S}_L \tilde{Y} (\Phi^+ D_R) + h.c.$$

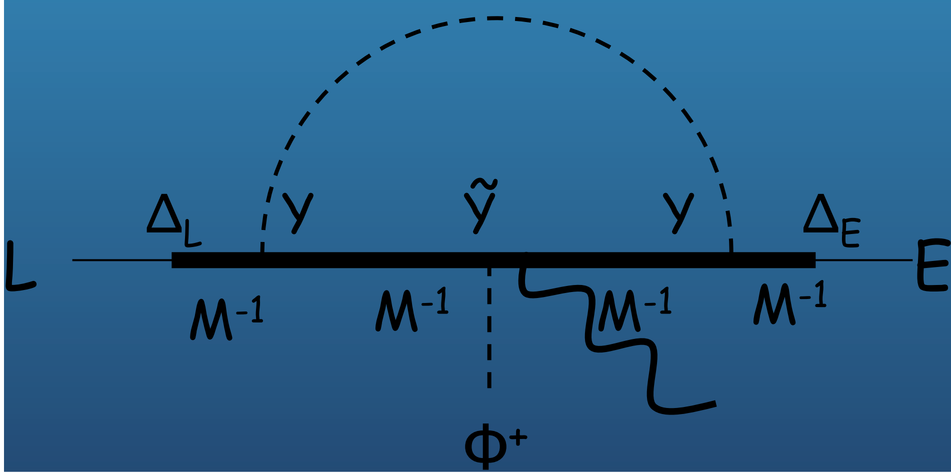
- elementary-composite mixing
- Dirac masses for composite fermions
- Yukawa coupling of composite fermions

here: massless neutrino limit $1 \le Y \le 4\pi$



$$y_e = \frac{\Delta_L}{M} Y \frac{\Delta_E}{M} + \dots$$

higher-orders in (v/M)



$$\frac{C^{ij}_{D\gamma}}{\Lambda^2} \approx \frac{1}{16\pi^2 M^2}\left[\frac{\Delta_L}{M} Y \tilde{Y} Y \frac{\Delta_E}{M}\right]_{ij} + \dots$$

$Y, \quad \tilde{Y}$

anarchical 3x3 matrices

→ $C_{D\gamma}^{ij}$, y_e

not diagonal in the same basis

LFV not suppressed by neutrino masses and unrelated to (B-L) breaking scale

$BR(\mu \to e\gamma)$, d_e

$\Delta_E \approx \Delta_L \qquad \frac{\Delta_f}{M} \approx \sqrt{\frac{m_f}{\langle Y \rangle v}}$ → $\frac{M}{\langle Y \rangle} > 10$ TeV

[Agashe, Blechman, Petriello 0606021
Csaki, Grossman, Tanedo, Tsai 1004.2037]

contact terms can be generated at tree-level

$$\frac{C_C^{ijkk}}{\Lambda^2} \approx \frac{1}{M^2}\left[\frac{\Delta_L}{M}\frac{\Delta_L^+}{M}\right]_{ij} + \ldots$$

$\mu \to 3e$ → $\sqrt{\langle Y \rangle} M > 1$ TeV

confirmed by explicit computation in Randall-Sundrum setup

- -- help from neutrinos? [large lepton mixing] $\frac{\Delta_L}{M} \propto 1$ → not sufficient to align dipole and mass operator

- -- set $\tilde{Y} = 0$? many other contributions possible

$$\frac{C_{D\gamma}^{ij}}{\Lambda^2} \approx \frac{1}{16\pi^2 M^2}\left[\frac{\Delta_L}{M}\left(c_1 Y Y^+ + c_2 \frac{\Delta_L^+}{M}\frac{\Delta_L}{M} + \ldots\right) Y \frac{\Delta_E}{M}\right]_{ij} + \ldots$$

[F. Paradisi, Pattori, in prep.]

way out: SYMMETRY
assume SU(3) invariance of all matrices except Δ_E

$$y_e = \left(\frac{\Delta_L Y}{M^2}\right)\Delta_E$$

we go back to MFV: CLFV only when neutrino masses are turned on

$$M, Y, \tilde{Y}, \Delta_L \propto 1$$

[Redi, 1306.1525]

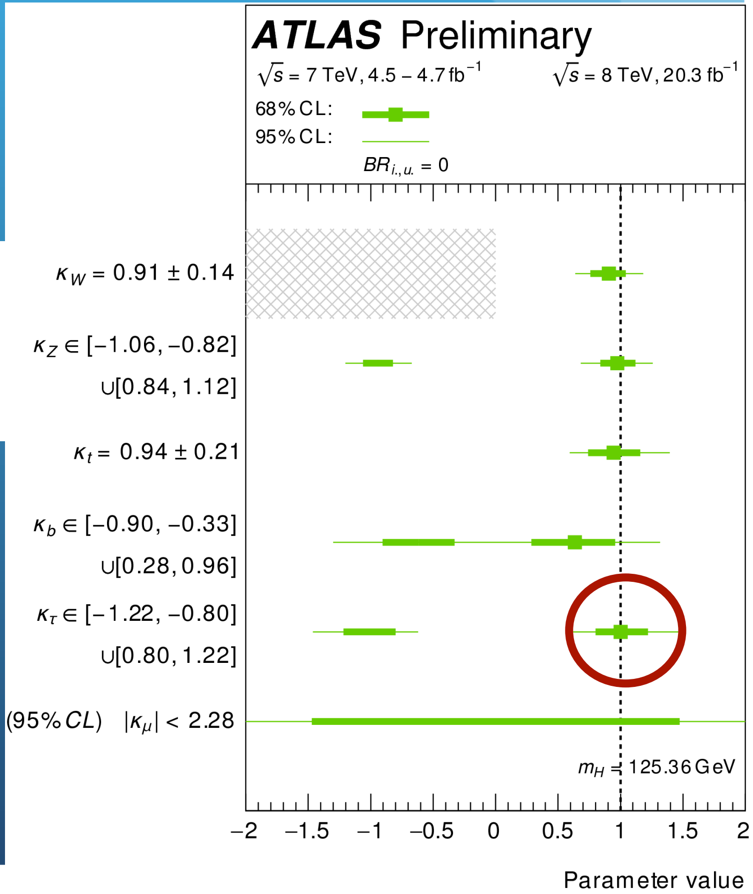
similar alignment invoked in [M.C. Chen and Yu, 08042503 Perez, Randall 0805.4652]

even for this MFV case, deviations are expected in the Higgs couplings

[Falkowski, Straub and Vicente 1312.5329]

$$\frac{\delta y_f}{y_f} \approx Y\tilde{Y}\frac{v^2}{M^2} \approx 0.2 \times \left(\frac{Y\tilde{Y}}{3.3}\right) \times \frac{1}{[M(TeV)]^2}$$

not far from the present LHC sensitivity [ATLAS 1501.04943, CMS 1401.5041]



Conclusion

- major experimental advances expected within next few years

  Δa_μ, closely related to CLFV and EDM, hopefully clarified

- observation of CLFV and/or EDM would be evidence for physics beyond νSM at energy scales potentially very large

- if there is NP at the electroweak scale, there are reasons to believe that CLFV is well within the reach of next generation experiments

- NP at the TeV scale with generic flavor structure induces deviations from the SM that are ruled out by many orders of magnitudes

- there are mechanisms to suppress CLFV and EDM but, on general grounds, we can expect any size of deviation below the current bounds

Back-up slides

Low Energy SUSY

EM dipole operator, terms enhanced by both α_2 and $\tan\beta$

degenerate limit $|M_1| = |M_2| = |\mu| = \tilde{m}_i \equiv m_S$

a measure of the misalignement between lepton and sleptons

$$R_{ij} = \frac{BR(l_i \to l_j \gamma)}{BR(l_i \to l_j \nu_i \bar{\nu}_j)} = \frac{48\pi^3 \alpha}{G_F^2 m_S^4} \left(\frac{\alpha_2}{4\pi} \frac{\tan\beta}{15} \right)^2 \left| \delta_{LL}^{ji} \right|^2 + \ldots$$

$$\delta_{XY}^{ij} \equiv \frac{\left(\tilde{m}_{ij}\right)_{XY}}{m_S} \qquad X, Y = L, R$$

$$\Delta a_i \approx \frac{5}{12} \frac{\alpha_2}{4\pi} \frac{m_i^2}{m_S^2} \tan\beta \cos\varphi + \ldots$$

$$\Delta a_\mu \approx 30 \times 10^{-10} \left(\frac{200\ GeV}{m_S} \right)^2 \frac{\tan\beta}{10}$$

$$\varphi \equiv \arg(M_2 \mu) = 0$$

Naïve Scaling can be violated
if sleptons are non-degenerate

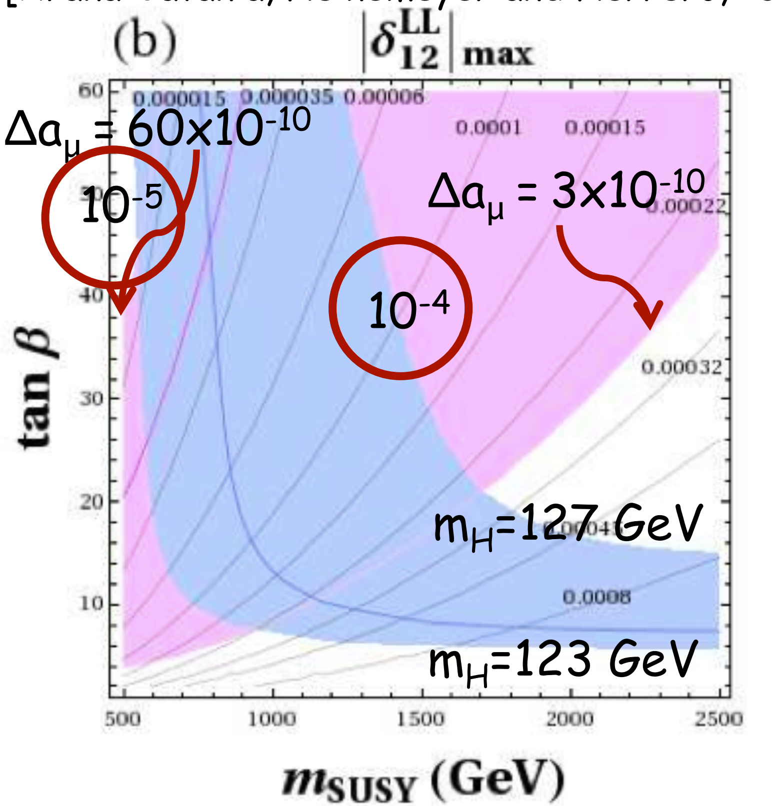
in the degenerate limit $R_{e\mu}$ and Δa_μ are fully correlated

$$R_{\mu e} \approx 5.7 \times 10^{-13} \left(\frac{\Delta a_\mu}{30 \times 10^{-10}} \right)^2 \left(\frac{\delta_{LL}^{12}}{6 \times 10^{-5}} \right)^2$$

tiny

with more realistic input parameters

[Arana-Catania, Heinemeyer and Herrero, 1304.2783].



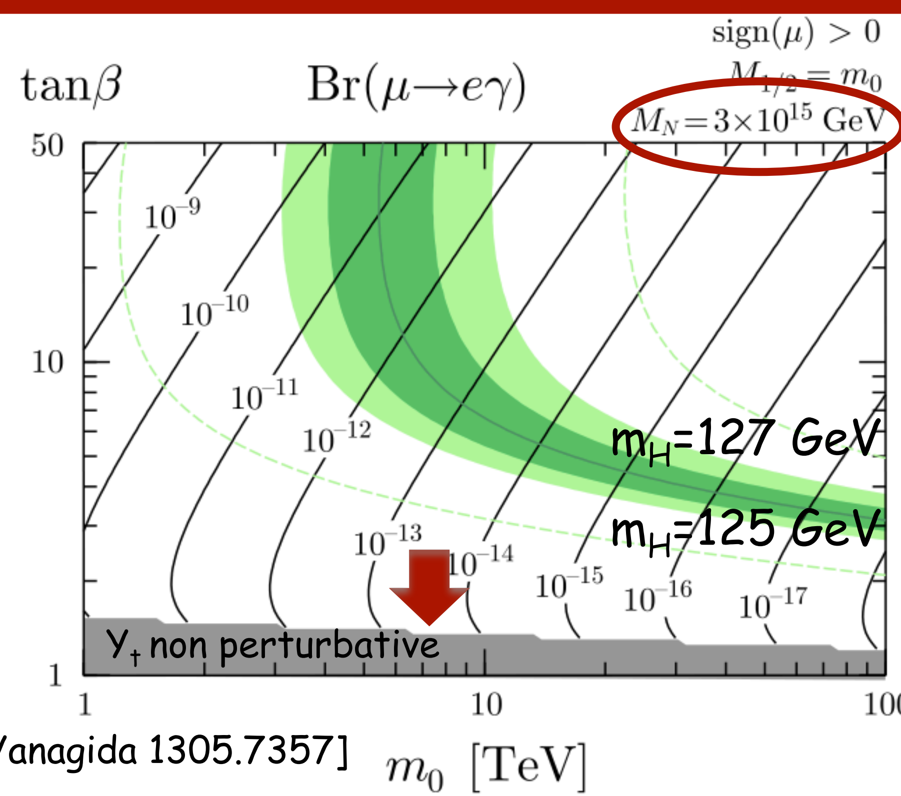
$$
\begin{aligned}
m_{\tilde L} &= m_{\tilde E} = m_{SUSY-EW} \\
M_2 &= m_{SUSY-EW}/5 \\
m_{\tilde Q} &= m_{\tilde U} = m_{\tilde D} = m_{SUSY-QCD} \\
A_t &= m_{SUSY-QCD} \\
m_{SUSY-QCD} &= 2\, m_{SUSY-EW}
\end{aligned}
$$

typical bounds

$$5\times10^{-5} < |\delta^{12}_{LL}| < 4\times10^{-4}$$
$$2\times10^{-6} < |\delta^{12}_{LR}| < 1\times10^{-5}$$
$$1\times10^{-3} < |\delta^{12}_{RR}| < 5\times10^{-3}$$

even setting δ_{ij} to zero, they can be generated by quantum corrections e.g. from RGE in a high-scale seesaw

$$m^2_{\tilde l,ij} \simeq m_0^2 \left[\delta_{ij} - \frac{(y_\nu^\dagger y_\nu)_{ij}}{16\pi^2}(6+2a_0^2)\ln\frac{M_{GUT}}{M_N}\right]$$



[Moroi, Nagai and Yanagida 1305.7357]

Lepton EDM in SUSY

$$\frac{d_i}{e} = FC_i + FV_i \qquad FC_i = FC_i^{(1)} + FC_i^{(2)} + \ldots$$

degenerate limit $\left|M_1\right| = \left|M_2\right| = \left|\mu\right| = \tilde{m}_i \equiv m_S$

$$FC_i^{(1)} \approx \frac{m_i}{m_S^2}\left[\left(\frac{1}{24}\frac{\alpha_1}{4\pi}\frac{\mathrm{Im}(M_1\mu)}{m_S^2} + \frac{5}{24}\frac{\alpha_2}{4\pi}\frac{\mathrm{Im}(M_2\mu)}{m_S^2}\right)\tan\beta - \frac{1}{12}\frac{\alpha_1}{4\pi}\frac{\mathrm{Im}(M_1 A_i^*)}{m_S^2}\right] + \ldots$$ 1-loop

$$FC_i^{(2)} \approx -\frac{m_i}{m_S^2}\frac{\alpha_1}{4\pi}\frac{y_t^2}{36\pi^2}\log\frac{m_S^2}{m_A^2}\frac{\mathrm{Im}(\mu A_i)}{m_S^2}\tan\beta + \ldots$$ 2-loop

strong bounds on phases if $m_S \approx 1$ TeV ➡ set $\arg(M_i)=\arg(A_i)=\arg(\mu)=0$

$$FV_i \approx \frac{\alpha_1}{4\pi}\sum_{k\neq i}\frac{m_k}{m_S^2}\mathrm{Im}\left(\delta_{LL}^{ik}\delta_{RR}^{ki}\right)\tan\beta + \ldots$$

Naïve Scaling is violated

if tau mass contribution dominates

$$\frac{d_i}{e} \approx 2.7\times 10^{-28}\,\mathrm{Im}\left(\frac{\delta_{LL}^{i3}\delta_{RR}^{3i}}{10^{-6}}\right)\frac{1}{\left[m_S(TeV)\right]^2}\frac{\tan\beta}{10}$$

$$\frac{d_e}{d_\mu} \approx \frac{\mathrm{Im}\left(\delta_{LL}^{13}\delta_{RR}^{31}\right)}{\mathrm{Im}\left(\delta_{LL}^{23}\delta_{RR}^{32}\right)} \neq \frac{m_e}{m_\mu}$$

$i \neq j$

$$R_{ij} = \frac{BR(l_i \to l_j \gamma)}{BR(l_i \to l_j \nu_i \bar{\nu}_j)} = \frac{48\pi^3 \alpha}{G_F^2 \Lambda^4}\left(|A_{ij}|^2 + |A_{ji}|^2\right) \quad i > j$$

$\Lambda > 730$ GeV

$(A_{\mu e} = A_{e\mu} = 1)$

$$R_{\mu e} \approx 5.7 \times 10^{-13}\left(\frac{\Delta a_\mu}{30 \times 10^{-10}}\right)^2 \left(\frac{\vartheta_{\mu e}}{1.4 \times 10^{-5}}\right)^2$$

$$A_{\mu e} = A_{e\mu} = A\,\vartheta_{\mu e}$$

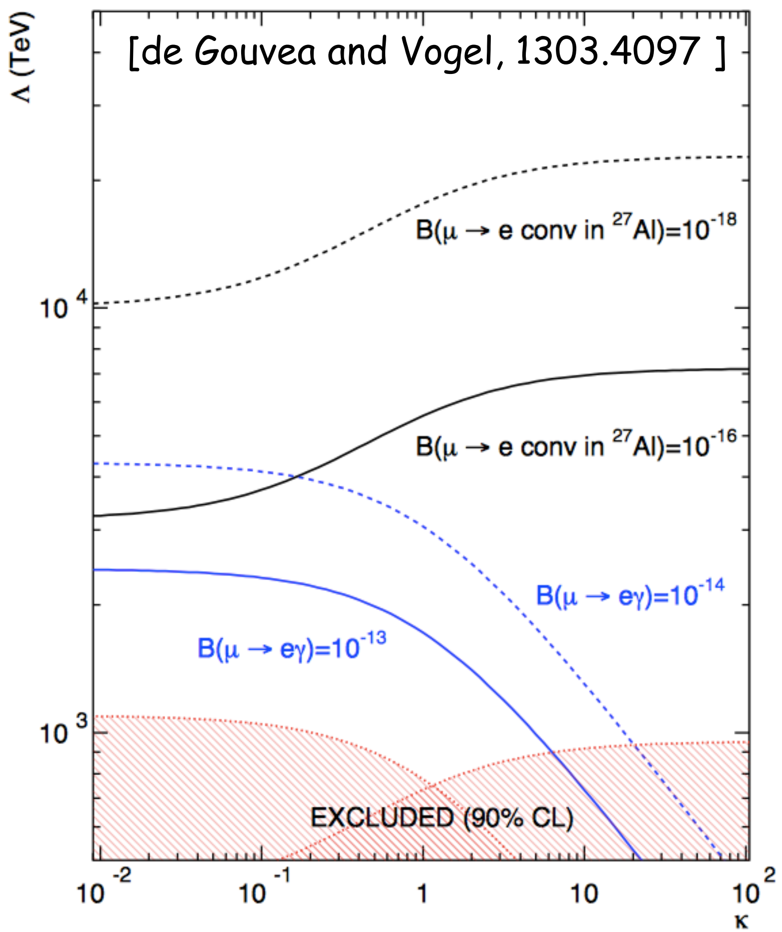
if the em dipole operator dominates

$$\frac{BR(l_i \to l_j l_k l_k)}{BR(l_i \to l_j \gamma)} \approx \frac{\alpha}{3\pi}\log\left(\frac{m_i^2}{m_j^2} - 3\right)$$

$$CR(\mu \to eN) \approx \alpha\, BR(\mu \to e\gamma)$$

otherwise...

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + h.c.$$
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L\right) + h.c.\,.$$



EDM and (g-2)/2

[2014] →

l	$d_l (e\ cm)$
e	$< 8.7 \times 10^{-29}$
μ	$< 1.8 \times 10^{-19}$
τ	$< 10^{-16}$

-> 10^{-29}

-> 10^{-21} [FNAL]

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration*, J. Baron[1], W. C. Campbell[2], D. DeMille[3,†], J. M. Doyle[1,†], G. Gabrielse[1,†], Y. V. Gurevich[1,‡], P. W. Hess[1], N. R. Hutzler[1], E. Kirilov[3,§], I. Kozyryev[3,||], B. R. O'Leary[3], C. D. Panda[1], M. F. Parsons[1], E. S. Petrik[1], B. Spaun[1], A. C. Vutha[4], A. D. West[3]

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μ	$(29 \pm 9) \times 10^{-10}$
τ	$-0.007 < \Delta a_\tau < 0.005$

[more on this later on]

3.2 σ

soon checked by Muon g-2
at Fermilab > 2017 improving
accuracy from 0.5 ppm to 0.2 ppm

$\|\delta_{13}^{LL}\|_{\max}$	5×10^{-2}	5×10^{-2}	3×10^{-2}	3×10^{-2}	23×10^{-2}	5×10^{-2}
$\|\delta_{13}^{LR}\|_{\max}$	2×10^{-2}	3×10^{-2}	4×10^{-2}	2.5×10^{-2}	2×10^{-2}	11×10^{-2}
$\|\delta_{13}^{RR}\|_{\max}$	5.4×10^{-1}	5×10^{-1}	4.8×10^{-1}	5.3×10^{-1}	7.7×10^{-1}	7.7×10^{-1}
$\|\delta_{23}^{LL}\|_{\max}$	6×10^{-2}	6×10^{-2}	4×10^{-2}	4×10^{-2}	27×10^{-2}	6×10^{-2}
$\|\delta_{23}^{LR}\|_{\max}$	2×10^{-2}	3×10^{-2}	4×10^{-2}	3×10^{-2}	2×10^{-2}	12×10^{-2}
$\|\delta_{23}^{RR}\|_{\max}$	5.7×10^{-1}	5.2×10^{-1}	5×10^{-1}	5.6×10^{-1}	8.3×10^{-1}	8×10^{-1}

	S1	S2	S3	S4	S5	S6
$\lvert\delta^{LL}_{12}\rvert_{\max}$	10×10^{-5}	7.5×10^{-5}	5×10^{-5}	6×10^{-5}	42×10^{-5}	8×10^{-5}
$\lvert\delta^{LR}_{12}\rvert_{\max}$	2×10^{-6}	3×10^{-6}	4×10^{-6}	3×10^{-6}	2×10^{-6}	1.2×10^{-5}
$\lvert\delta^{RR}_{12}\rvert_{\max}$	1.5×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	1×10^{-3}	2×10^{-3}	5.2×10^{-3}

[Arana-Catania, Heinemeyer and Herrero, 1304.2783].

Table 2: Present upper bounds on the slepton mixing parameters $|\delta^{AB}_{ij}|$ for the selected S1-S6 MSSM points defined in Tab. 1. The bounds for $|\delta^{RL}_{ij}|$ are similar to those of $|\delta^{LR}_{ij}|$.

[Arana-Catania, Heinemeyer and Herrero, 1304.2783].

	S1	S2	S3	S4	S5	S6
$m_{\tilde{L}_{1,2}}$	500	750	1000	800	500	1500
$m_{\tilde{L}_3}$	500	750	1000	500	500	1500
M_2	500	500	500	500	750	300
A_τ	500	750	1000	500	0	1500
μ	400	400	400	400	800	300
$\tan\beta$	20	30	50	40	10	40
M_A	500	1000	1000	1000	1000	1500
$m_{\tilde{Q}_{1,2}}$	2000	2000	2000	2000	2500	1500
$m_{\tilde{Q}_3}$	2000	2000	2000	500	2500	1500
A_t	2300	2300	2300	1000	2500	1500
$m_{\tilde{l}_1} - m_{\tilde{l}_6}$	489-515	738-765	984-1018	474-802	488-516	1494-1507
$m_{\tilde{\nu}_1} - m_{\tilde{\nu}_3}$	496	747	998	496-797	496	1499
$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_2^\pm}$	375-531	376-530	377-530	377-530	710-844	247-363
$m_{\tilde{\chi}_1^0} - m_{\tilde{\chi}_4^0}$	244-531	245-531	245-530	245-530	373-844	145-363
M_h	126.6	127.0	127.3	123.1	123.8	125.1
M_H	500	1000	999	1001	1000	1499
M_A	500	1000	1000	1000	1000	1500
$M_{H^\pm}$	507	1003	1003	1005	1003	1502
$m_{\tilde{u}_1} - m_{\tilde{u}_6}$	1909-2100	1909-2100	1908-2100	336-2000	2423-2585	1423-1589
$m_{\tilde{d}_1} - m_{\tilde{d}_6}$	1997-2004	1994-2007	1990-2011	474-2001	2498-2503	1492-1509
$m_{\tilde{g}}$	2000	2000	2000	2000	3000	1200

Table 1: Selected points in the MSSM parameter space (upper part) and their corresponding spectra (lower part). All mass parameters and trilinear couplings are given in GeV.

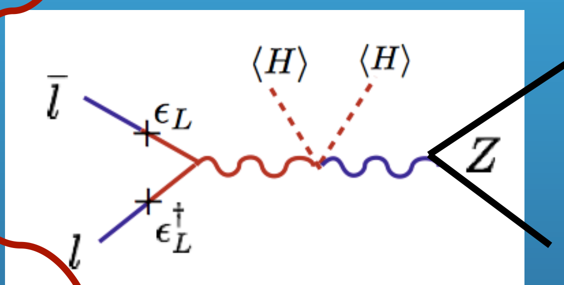
- $Y, \quad \tilde{Y}$ anarchical 3x3 matrices — $C^{ij}_{D\gamma}$ and y_e — Naïve Scaling violated by O(1) factors

- LFV not suppressed by neutrino masses and unrelated to (B-L) breaking scale

$$\frac{M}{\langle Y \rangle} > 10 \text{ TeV} \Leftarrow BR(\mu \to e\gamma)\ , \quad d_e$$

$$\Delta_E \approx \Delta_L \qquad \frac{\Delta_f}{M} \approx \sqrt{\frac{m_f}{\langle Y \rangle v}}$$

- contact terms can be generated at tree-level



$$\frac{C_C^{ijkk}}{\Lambda^2} \bar{L}_i \gamma_\mu L_j \, \bar{L}_k \gamma^\mu L_k$$

$$\frac{C_C^{ijkk}}{\Lambda^2} \approx \frac{1}{M^2} \left[\frac{\Delta_L}{M} \frac{\Delta_L^+}{M} \right]_{ij} + \ldots$$

$$\sqrt{\langle Y \rangle} M > 1 \text{ TeV} \Leftarrow \mu \to 3e$$

- way out:
  assume SU(3) invariance of all matrices except Δ_E

$$M, Y, \tilde{Y}, \Delta_L \propto 1$$

$$y_e = \left(\frac{\Delta_L Y}{M^2} \right) \Delta_E$$

we go back to MFV: CLFV only when neutrino masses are turned on