2018 WPI-next Mini-workshop
"Hints for New Physics in Heavy Flavors"

Charged Lepton Flavour Violation

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Introduction to CLFV

Lepton flavour (non)universality and CLFV

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Introduction to CLFV

for a pedagogical review cf. : LC, G. Signorelli, arXiv:1709.00294 [hep-ph].

Lepton flavour (non)universality and CLFV

Why no CLFV in the Standard Model?

In the SM fermion masses, thus the *flavour sector*, stems from the Yukawa interactions:

$$-\mathcal{L}_Y = (Y_u)_{ij}\,\overline{Q}_{L\,i}\,u_{R\,j}\,\widetilde{\Phi} + (Y_d)_{ij}\,\overline{Q}_{L\,i}\,d_{R\,j}\,\Phi + (Y_e)_{ij}\,\overline{L}_{L\,i}\,e_{R\,j}\,\Phi + h.c.$$

Rotations to the fermion mass basis: $Y_f = V_f \hat{Y}_f W_f^\dagger, \qquad f = u, d, e$

Unitary rotation matrices, couplings to photon and Z remain flavour-diagonal:

$$e\ \bar{f}\gamma_\mu f A^\mu \qquad\qquad (g_L\ \bar{f}_L\gamma_\mu f_L + g_R\ \bar{f}_R\gamma_\mu f_R) Z^\mu$$

Couplings to the Higgs are also flavour-conserving (aligned to the mass matrix):

$$\frac{m_f}{v}\,\bar{f}_L f_R\, h$$

No (tree-level) flavour-changing neutral currents

Why no CLFV in the Standard Model?

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Rotations to the fermion mass basis: $Y_f = V_f \hat{Y}_f W_f^\dagger, \qquad f = u, d, e$

Flavour violation occurs in charged currents only:

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}}\left(\overline{u}_L\gamma^\mu(V_u^\dagger V_d)d_L + \overline{\nu}_L\gamma^\mu(V_\nu^\dagger V_e)e_L\right)W_\mu^+ + h.c.$$

$$V_{\rm CKM} \equiv V_u^\dagger V_d \qquad\qquad U_{\rm PMNS} \equiv V_\nu^\dagger V_e$$

However, if neutrinos are massless, we can choose:

$$V_\nu = V_e$$

No LFV (Y_e only ‘direction’ in the leptonic flavour space)

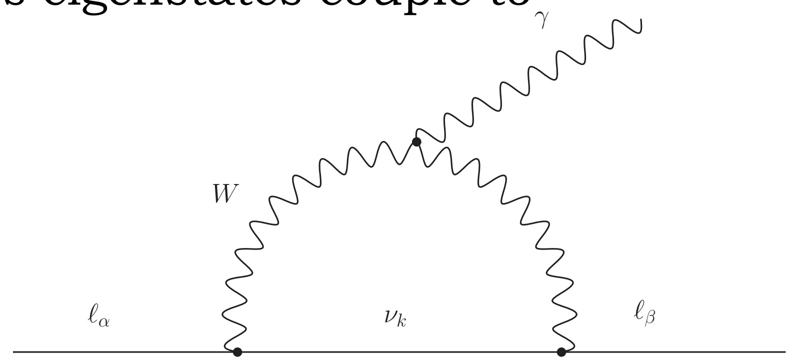
So why are we searching for CLFV?

- Neutrinos oscillate → Lepton family numbers are not conserved!

- PMNS becomes 'physical': neutrino mass eigenstates couple to charged leptons of different flavours

- In the SM + massive neutrinos:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$



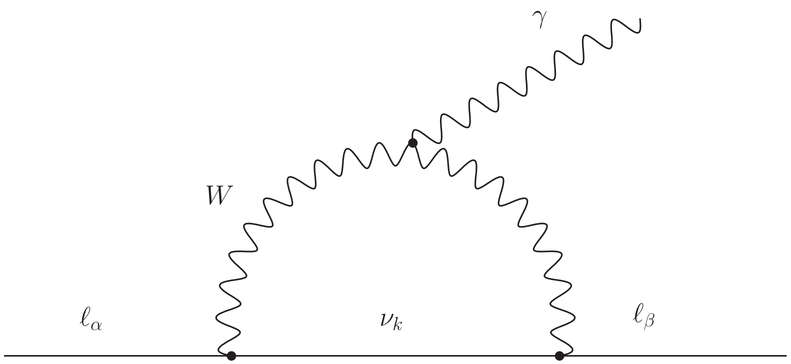
Cheng Li '77, '80; Petcov '77

⇨ $\text{BR}(\mu \to e\gamma) \approx \text{BR}(\tau \to e\gamma) \approx \text{BR}(\tau \to \mu\gamma) = 10^{-55} \div 10^{-54}$

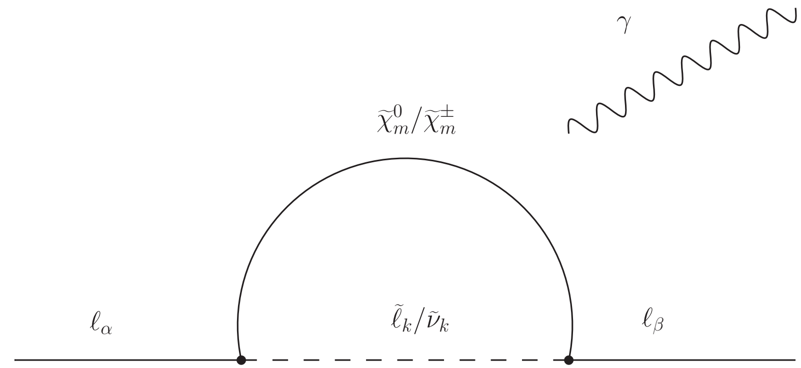
Large mixing, but huge suppression due to small neutrino masses

⇨ In presence of NP at the TeV we can expect large effects!

So why are we searching for CLFV?



e.g. SUSY



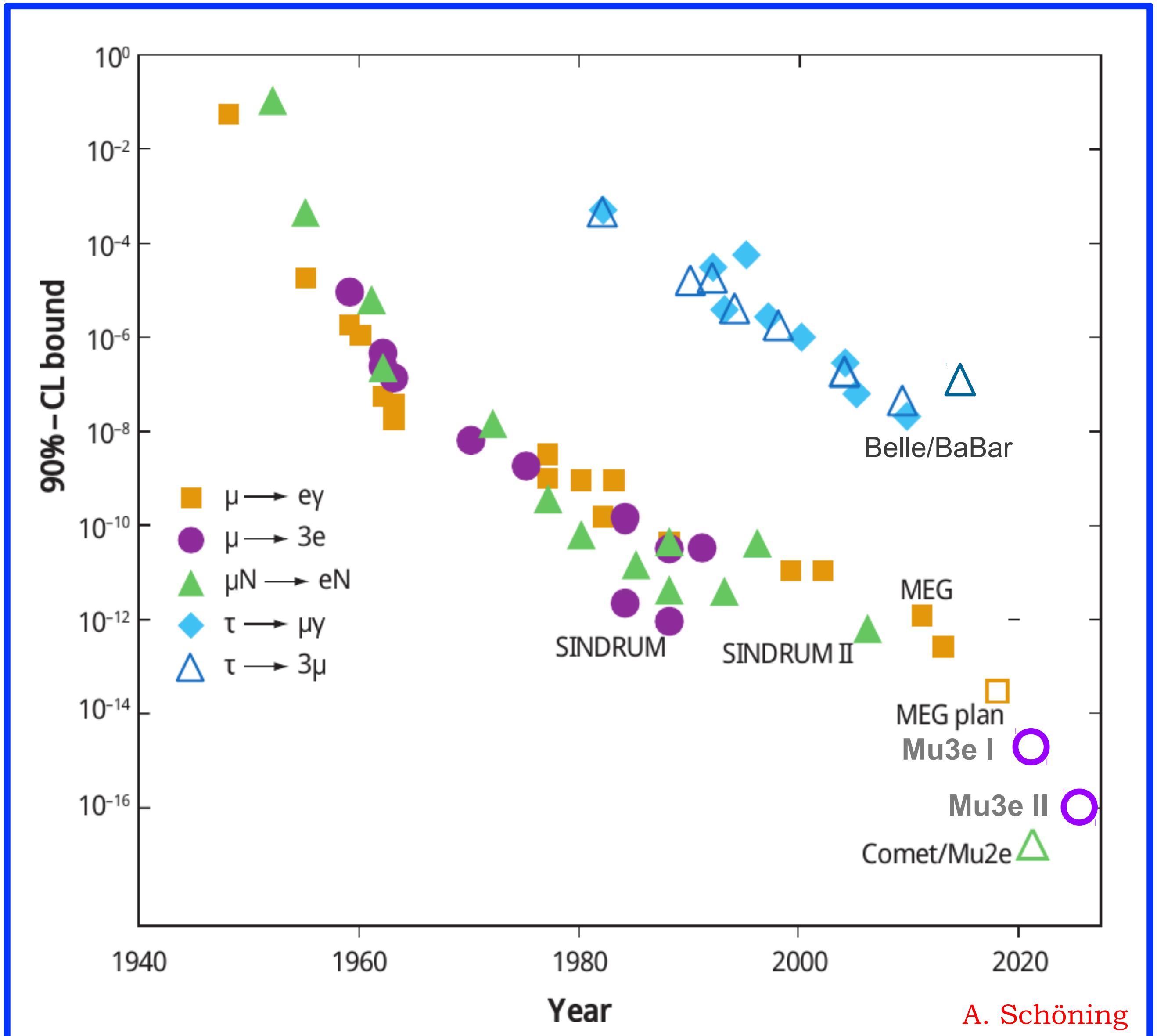
Borzumati Masiero '86;
Hisano et al. '95

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} \sim \frac{1}{G_F^2\, m^4_{\mathrm{SUSY}}}$$

- Unambiguous signal of New Physics
- Stringent test of NP models
- It probes scales far beyond the LHC reach

CLFV has been sought for more than 70 years...



Plenty of stringent limits

Reaction	Present limit	C.L.	Experiment	Year
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ †	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ †	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ †	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ †	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011

Plenty of stringent limits

Reaction	Present limit	C.L.	Experiment	Year
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998
$K_L^0 \to \pi^0 \mu^+ e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008
$K^+ \to \pi^+ \mu^+ e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004
$J/\psi \to \tau \mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004
$B^0 \to \mu e$	$< 1.0 \times 10^{-9}$	90%	LHCb	2017
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008
$B^0 \to \tau \mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008
$B \to K \mu e$ ‡	$< 3.8 \times 10^{-8}$	90%	BaBar	2006
$B^0 \to K^{*0} \mu e$	$< 1.8 \times 10^{-7}$	90%	Belle	2018
$B^+ \to K^+ \tau \mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012
$B^+ \to K^+ \tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012
$B_s^0 \to \mu e$	$< 5.4 \times 10^{-9}$	90%	LHCb	2017
$\Upsilon(1s) \to \tau \mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008

Plenty of stringent limits

Reaction	Present limit	C.L.	Experiment	Year
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017

Dimension-6 effective operators that can induce CLFV

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

Grzadkowski et al. '10

4-leptons operators		Dipole operators	
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
2-lepton 2-quark operators			
$Q_{\ell q}^{(1)}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q_{\ell q}^{(3)}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}_L^a e_R)(\bar{d}_R Q_L^a)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q_{\ell equ}^{(1)}$	$(\bar{L}_L^a e_R)\epsilon_{ab}(\bar{Q}_L^b u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q_{\ell equ}^{(3)}$	$(\bar{L}_i^a\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}_L^b\sigma^{\mu\nu}u_R)$
Lepton-Higgs operators			
$Q_{\Phi\ell}^{(1)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q_{\Phi\ell}^{(3)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

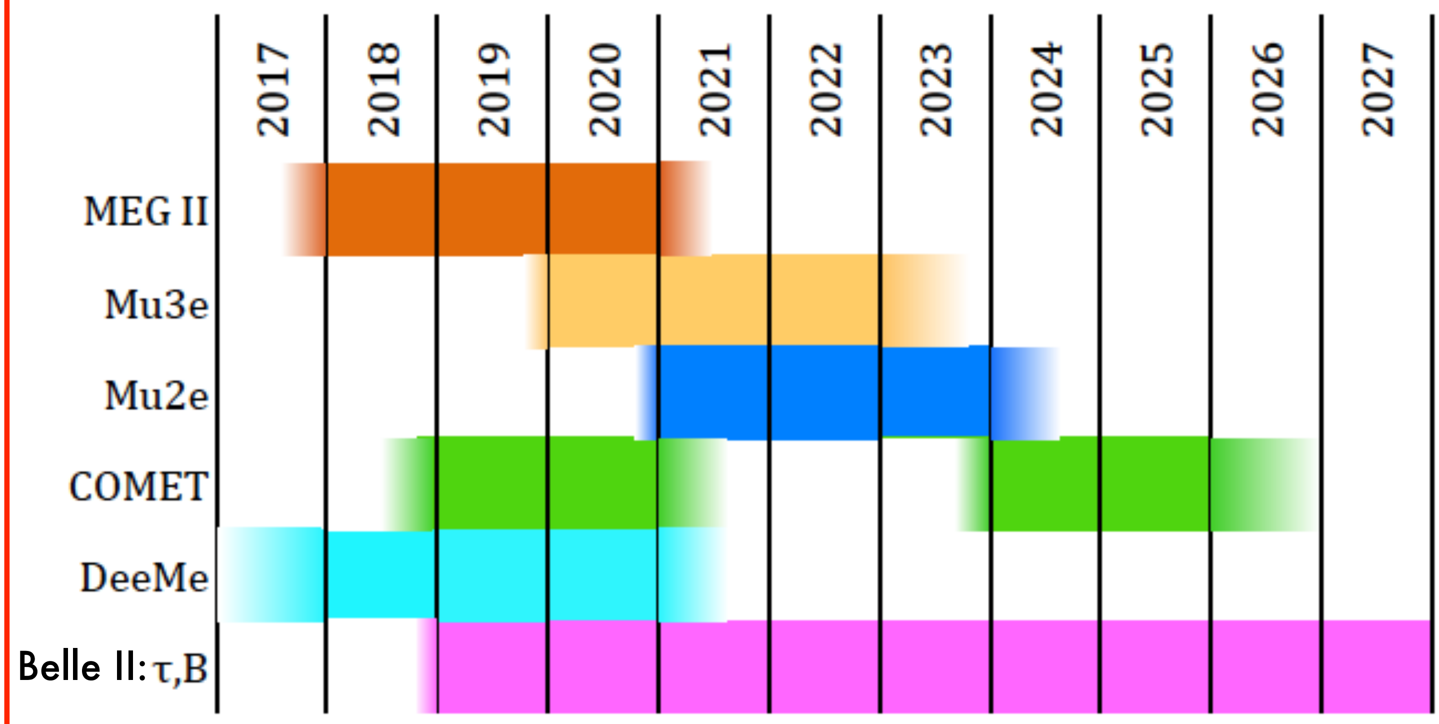
Crivellin Najjari Rosiek '13

Probing high energy scales

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \ldots$$

	$\lvert C_a\rvert$ [$\Lambda = 1$ TeV]	Λ (TeV) [$\lvert C_a\rvert = 1$]	CLFV Process
$C_{e\gamma}^{\mu e}$	2.1×10^{-10}	6.8×10^4	$\mu \to e\gamma$
$C_{\ell e}^{\mu\mu\mu e, e\mu\mu\mu}$	1.8×10^{-4}	75	$\mu \to e\gamma$ [1-loop]
$C_{\ell e}^{\mu\tau\tau e, e\tau\tau\mu}$	1.0×10^{-5}	312	$\mu \to e\gamma$ [1-loop]
$C_{e\gamma}^{\mu e}$	4.0×10^{-9}	1.6×10^4	$\mu \to eee$
$C_{\ell\ell, ee}^{\mu eee}$	2.3×10^{-5}	207	$\mu \to eee$
$C_{\ell e}^{\mu eee, ee\mu e}$	3.3×10^{-5}	174	$\mu \to eee$
$C_{e\gamma}^{\mu e}$	5.2×10^{-9}	1.4×10^4	$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$
$C_{\ell q, \ell d, ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$
$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^3	$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$
$C_{\ell u, eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$
$C_{e\gamma}^{\tau\mu}$	2.7×10^{-6}	610	$\tau \to \mu\gamma$
$C_{e\gamma}^{\tau e}$	2.4×10^{-6}	650	$\tau \to e\gamma$
$C_{\ell\ell, ee}^{\mu\tau\mu\mu}$	7.8×10^{-3}	11.3	$\tau \to \mu\mu\mu$
$C_{\ell e}^{\mu\tau\mu\mu, \mu\mu\mu\tau}$	1.1×10^{-2}	9.5	$\tau \to \mu\mu\mu$
$C_{\ell\ell, ee}^{e\tau ee}$	9.2×10^{-3}	10.4	$\tau \to eee$
$C_{\ell e}^{e\tau ee, eee\tau}$	1.3×10^{-2}	8.8	$\tau \to eee$

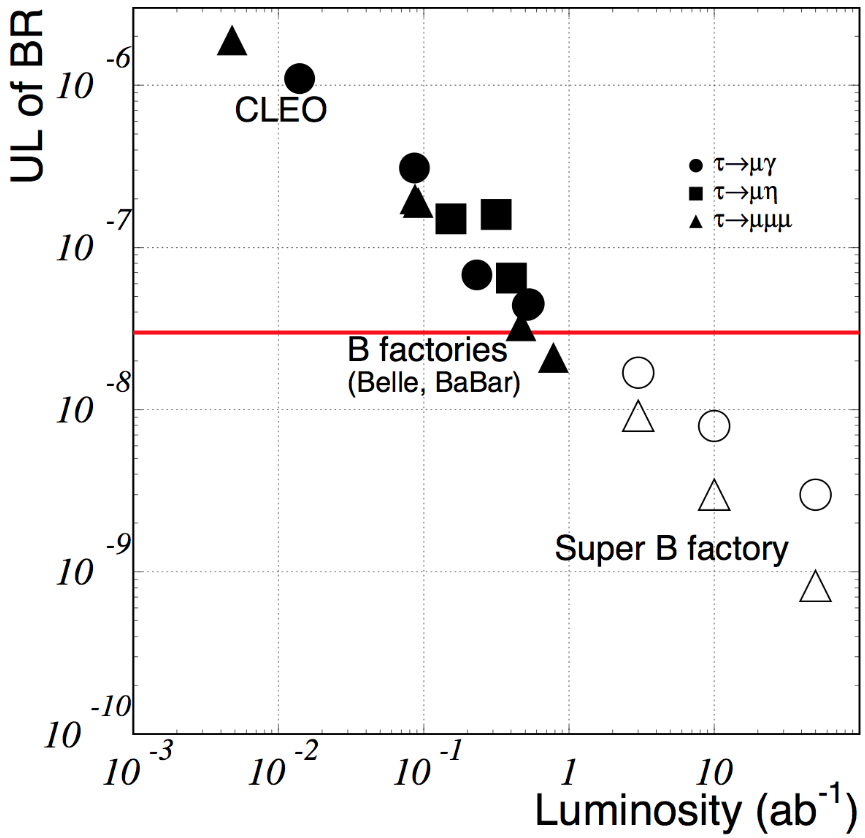
… and we have experiments!



… and we have experiments!

Reaction	Present limit	Expected Limit	Reference	Experiment
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	5×10^{-14}	[316]	MEG II
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	10^{-16}	[46]	Mu3e
$\mu^-\mathrm{Al} \to e^-\mathrm{Al}^{\dagger}$	$< 6.1 \times 10^{-13}$	10^{-17}	[321, 324]	Mu2e, COMET
$\mu^-\mathrm{Si/C} \to e^-\mathrm{Si/C}^{\dagger}$	–	5×10^{-14}	[282]	DeeMe
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	5×10^{-9}	[339]	Belle II
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	10^{-9}	[339]	”
$\tau \to eee$	$< 2.7 \times 10^{-8}$	5×10^{-10}	[339]	”
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	5×10^{-10}	[339]	”
$\tau \to e$ had	$< 1.8 \times 10^{-8\,\ddagger}$	3×10^{-10}	[339]	”
$\tau \to \mu$ had	$< 1.2 \times 10^{-8\,\ddagger}$	3×10^{-10}	[339]	”
had $\to \mu e$	$< 4.7 \times 10^{-12\,\S}$	10^{-12}	[340]	NA62
$h \to e\mu$	$< 3.5 \times 10^{-4}$	$3 \times 10^{-5\,\P}$	[341]	HL-LHC
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	$3 \times 10^{-4\,\P}$	[341]	”
$h \to \tau e$	$< 6.1 \times 10^{-3}$	$3 \times 10^{-4\,\P}$	[341]	”

… and we have experiments!



Aushev et al. '10

Also colliders: LFV Higgs decays

In the SM only one lepton Yukawa → flavour conserving

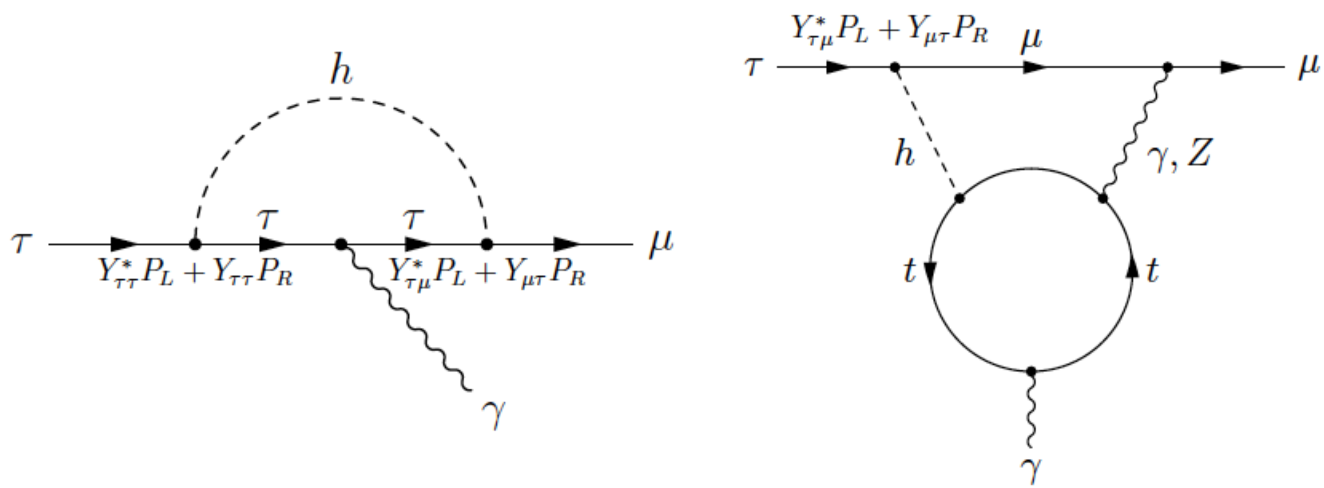
$$(m_f)_{ij} = \frac{v}{\sqrt{2}}(Y_f)_{ij}, \qquad -\mathcal{L}_{h\bar{f}f} = \frac{m_f}{v}\,\bar{f}_L f_R\, h + \text{h.c.}$$

This is not the case if there is 2nd Higgs doublet or ops like $\overline{L}_L e_R \Phi(\Phi^\dagger \Phi)$

Useful parameterisation: $-\mathcal{L} \supset (m_e)_i \bar{e}_{L\,i}\, e_{R\,i} + (Y_e^h)_{ij}\, \bar{e}_{L\,i}\, e_{R\,j}\, h + \text{h.c.}$

Harnik Kopp Zupan ‘12

These couplings induce both LFV Higgs decays and low-energy processes:



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Useful parameterisation: $-\mathcal{L} \supset (m_e)_i \bar{e}_{L\,i}\, e_{R\,i} + (Y_e^h)_{ij}\, \bar{e}_{L\,i}\, e_{R\,j}\, h + \text{h.c.}$

Process	Coupling	Bound
$h \to \mu e$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	$< 5.4 \times 10^{-4}$
$\mu \to e\gamma$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	$< 2.1 \times 10^{-6}$
$\mu \to eee$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
$\mu\,\text{Ti} \to e\,\text{Ti}$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	$< 1.2 \times 10^{-5}$
$h \to \tau e$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	$< 2.3 \times 10^{-3}$
$\tau \to e\gamma$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	< 0.014
$\tau \to eee$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	$\lesssim 0.12$
$h \to \tau\mu$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	$< 1.4 \times 10^{-3}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	< 0.016
$\tau \to \mu\mu\mu$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	$\lesssim 0.25$

$$(Y^h_{ee},\ Y^h_{\mu\mu}, Y^h_{\tau\tau}) \approx (10^{-6},\ 10^{-4},\ 10^{-2})$$

Harnik Kopp Zupan ’12
CMS ‘17

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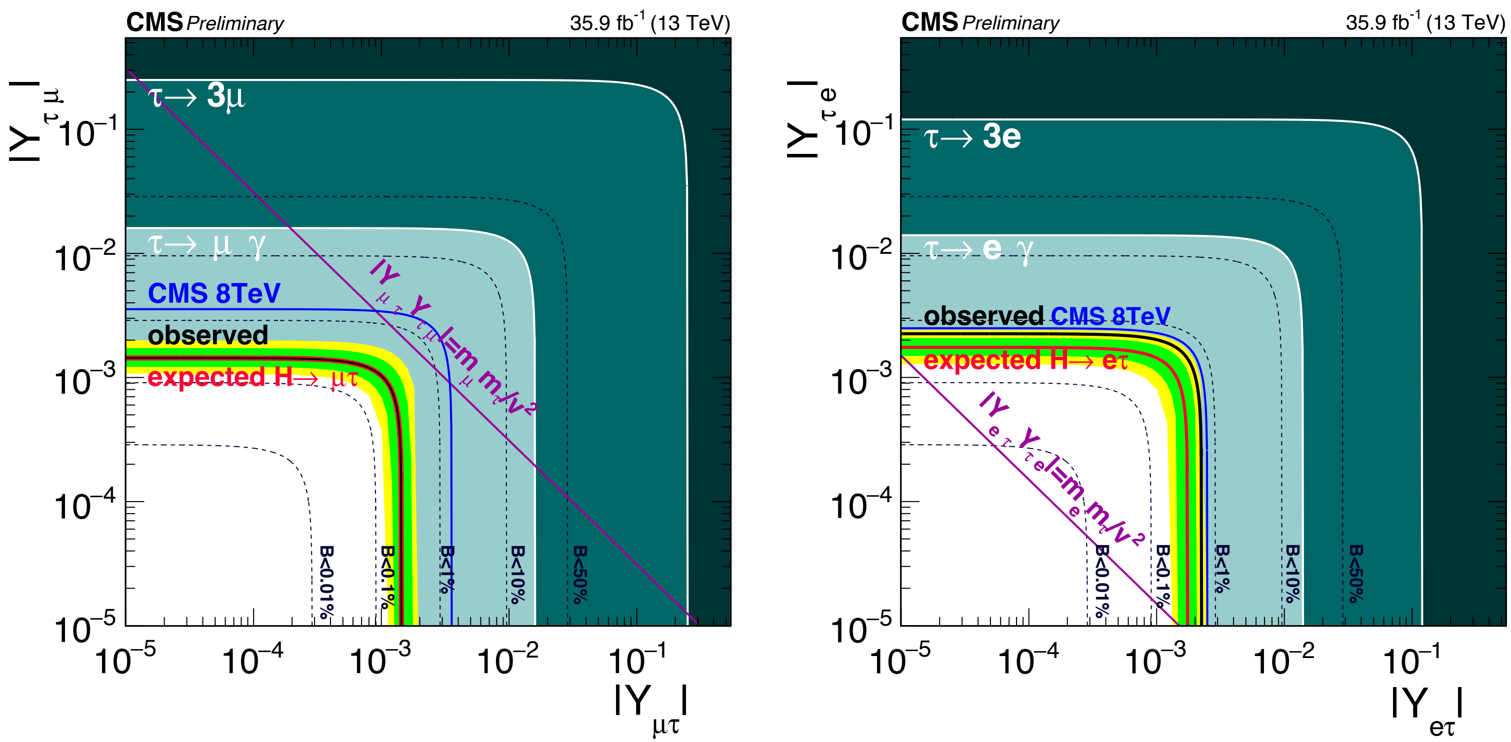
In the SM only one lepton Yukawa → flavour conserving

$$(m_f)_{ij} = \frac{v}{\sqrt{2}}(Y_f)_{ij}, \qquad -\mathcal{L}_{h\bar{f}f} = \frac{m_f}{v}\,\bar{f}_L f_R\, h + \text{h.c.}$$

This is not the case if there is 2nd Higgs doublet or ops like $\overline{L}_L e_R \Phi(\Phi^\dagger\Phi)$

Useful parameterisation: $-\mathcal{L} \supset (m_e)_i \bar{e}_{L\,i}\, e_{R\,i} + (Y_e^h)_{ij}\, \bar{e}_{L\,i}\, e_{R\,j}\, h + \text{h.c.}$



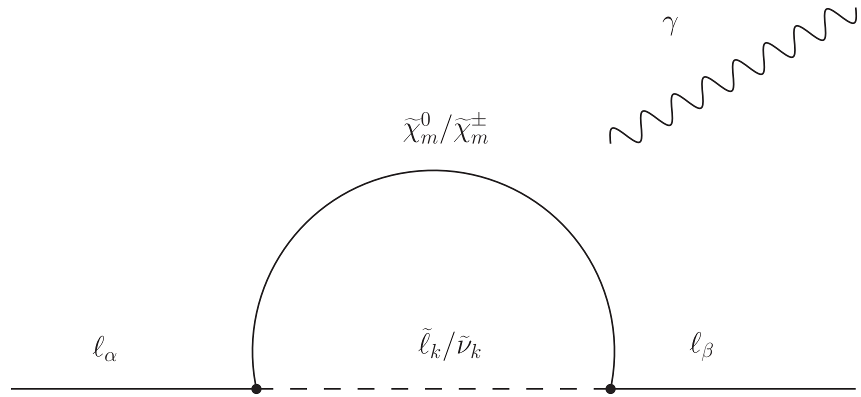
$$(Y^h_{ee},\; Y^h_{\mu\mu}, Y^h_{\tau\tau}) \approx (10^{-6},\, 10^{-4},\, 10^{-2})$$

Harnik Kopp Zupan ’12
CMS ‘17

Charged Lepton Flavour Violation in SUSY

Slepton mass matrix:

$$m^2_{\tilde{\ell}} = \begin{pmatrix} (\tilde{m}^2_L)_{ij} + (m^2_\ell)_{ij} - m^2_Z(\frac{1}{2} - \sin^2\theta_W)\delta_{ij} & A^{\ell *}_{ji} v_d - (m_\ell)_{ji}\mu \tan\beta \\ A^\ell_{ij} v_d - (m_\ell)_{ij}\mu^* \tan\beta & (\tilde{m}^2_E)_{ij} + (m^2_\ell)_{ij} - m^2_Z \sin^2\theta_W \delta_{ij} \end{pmatrix}$$



Flavour-conserving counterparts:

g-2, EDMs

$$\Rightarrow \quad BR(\ell_i \to \ell_j \gamma) = \frac{48\pi^3 \alpha_{\rm em}}{G_F^2}\left(|C_L^{ij}|^2 + |C_R^{ij}|^2\right) BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)$$

Hisano et al. '95

$$C_L^{ij} \sim \frac{g^2}{16\pi^2}\frac{(\tilde{m}^2_L)_{ij}}{\tilde{m}^4}\tan\beta$$

LC Galon Masiero Shadmi Paradisi ‘15
LC Signorelli ‘17

What is the impact of direct searches for SUSY particles at the LHC on the discovery prospects of LFV processes at low-energy experiments?

We can study LFV/LHC complementarity within the simplified models used by the collaborations for the interpretation of the searches

Examples that can address the muon g-2 anomaly:

$\widetilde{e}_L,\ \widetilde{\mu}_L,\ \widetilde{\tau}_L$

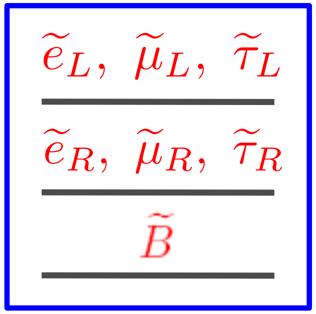
$\widetilde{e}_R,\ \widetilde{\mu}_R,\ \widetilde{\tau}_R$

$\widetilde{B}$

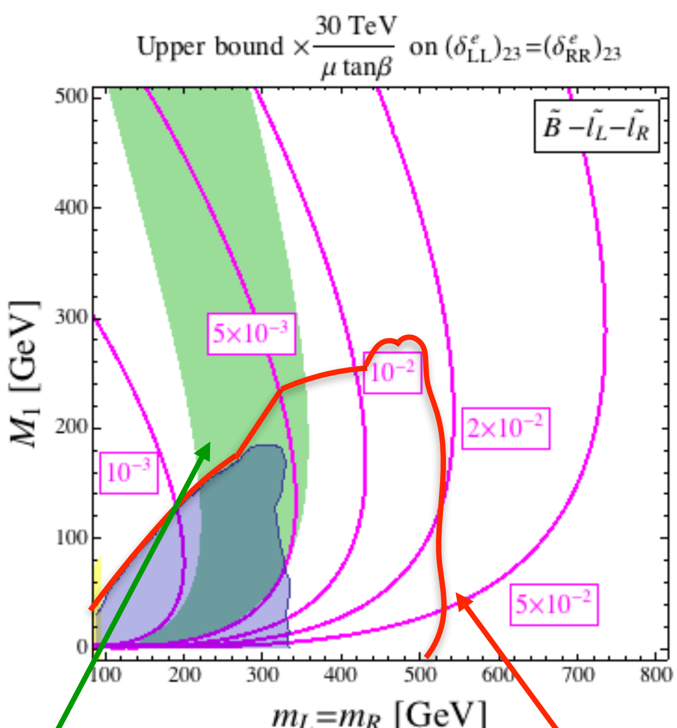
$\widetilde{e}_L,\ \widetilde{\mu}_L,\ \widetilde{\tau}_L$

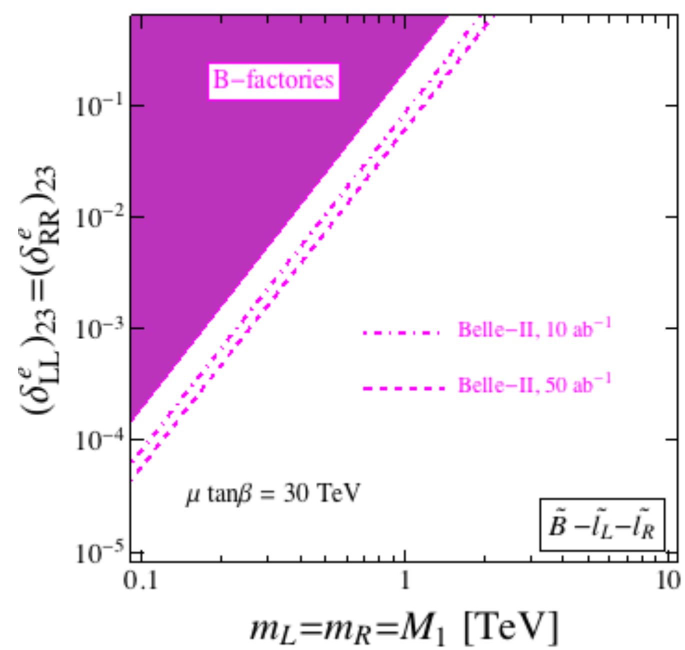
$\widetilde{W}\quad \widetilde{H}$

LFV vs LHC bounds within simplified models



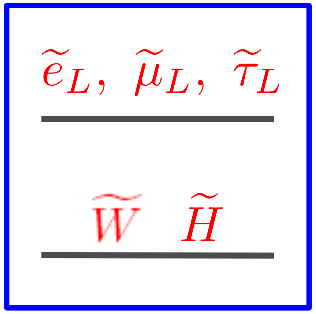
Bounds from $\tau \to \mu\gamma$



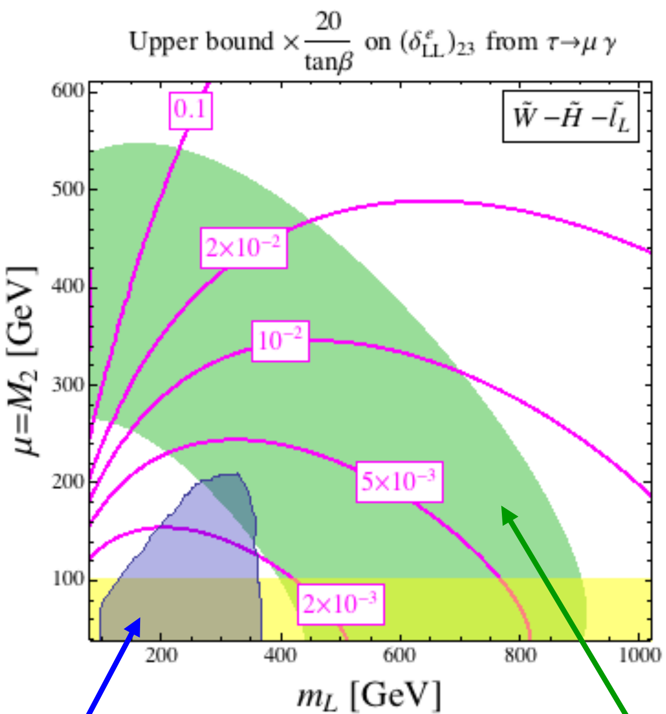


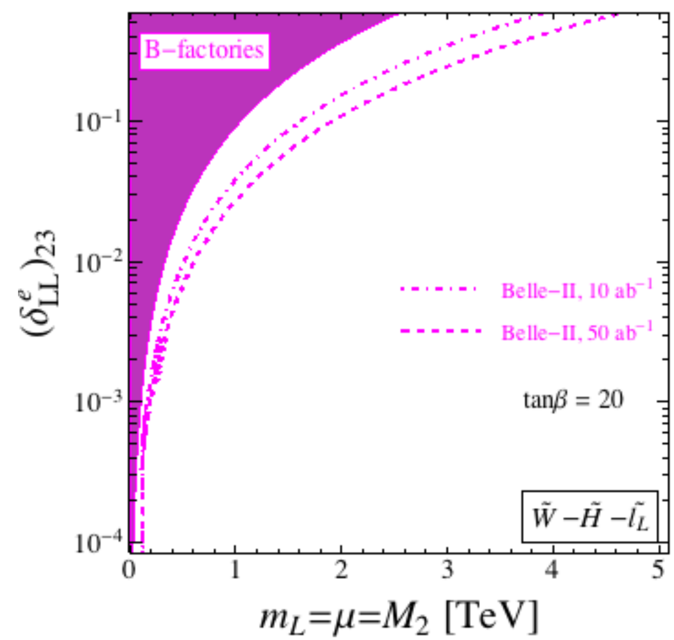
$\Delta a_\mu \equiv \left| a_\mu^{\mathrm{TH}} - a_\mu^{\mathrm{EXP}} \right| \lesssim 2\sigma$

ATLAS-CONF-2017-039



Bounds from $\tau \to \mu\gamma$





Eckel et al. arXiv:1408.2841

$$\boxed{\Delta a_\mu \equiv \left| a_\mu^{\rm TH} - a_\mu^{\rm EXP} \right| \lesssim 2\sigma}$$

Introduction to CLFV

Lepton flavour (non)universality and CLFV

Two classes of anomalies:

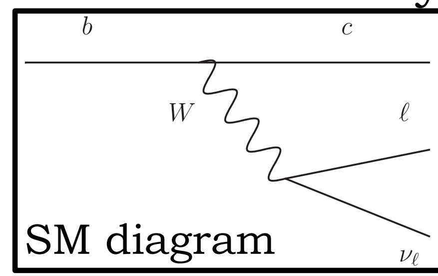
I. In charged-current processes of the type $b \to c\ell\nu$

II. In neutral-current $b \to s\ell^+\ell^-$ transitions

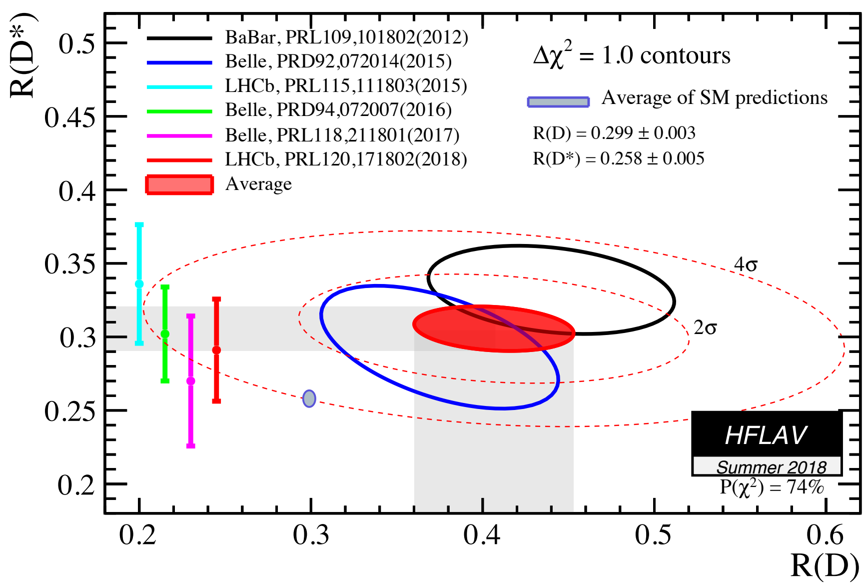
Class I.

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}, \;\; \ell = e,\, \mu$$

Test of the Lepton Flavour Universality of SM couplings →



$\approx 4\sigma$ from the SM



it needs a 20-30% enhancement wrt the SM

Two classes of anomalies:

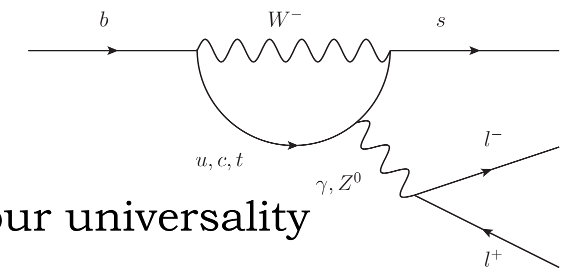
I. In charged-current processes of the type $b \to c\ell\nu$

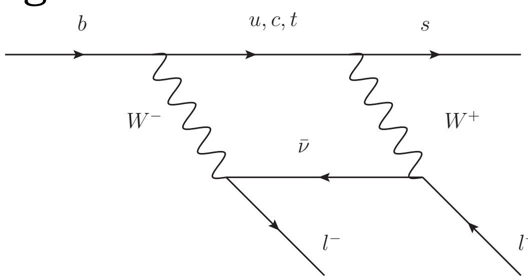
II. In neutral-current $b \to s\ell^+\ell^-$ transitions

Class II.

SM diagrams:

$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$





=1+-0.01 in the SM: lepton flavour universality

Bordone et al. ‘16

LHCb measurements:

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036 \qquad R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047 \qquad \approx 2.5\sigma \text{ off}$$

Few sigma discrepancies in other obs with larger hadronic uncertainties:

Angular observables in $B \to K^*\mu^+\mu^-$	Some $b \to s\mu^+\mu^-$ BRs

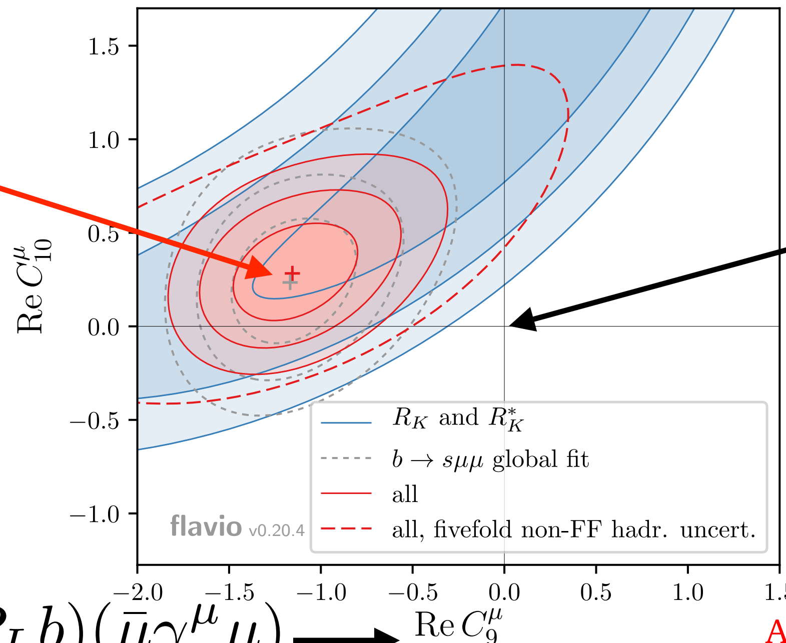
Global fits to $b \to s\ell^+\ell^-$ observables

It seems that we have to fit a deficit of muon events

$$\mathcal{O}_9^{\ell(\prime)} \sim (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{\ell(\prime)} \sim (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Best fit

New physics contribution to $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$



SM point

New physics contribution to (negative) $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\mu)$

Altmannshofer Stang Straub ’17

Fits to the data: non-standard contributions preferred at the 4-5σ level

Capdevilla et al . ’17, Altmannshofer et al. ’17, D’Amico et al. ’17, Geng et al. ’17,
Ciuchini et al. ’17, Neshatpour et al. ’17 + many older refs.

SU(2)-invariant operators:

Differ by SU(2) contractions:

$$(Q_{\ell q}^{(1)})_{\mu\mu bs} = (\bar{L}^a_{L\,2}\,\gamma^\mu\,L^a_{L\,2})(\bar{Q}^b_{L\,2}\,\gamma_\mu\,Q^b_{L\,3})$$ "singlet-singlet"

$$(Q_{\ell q}^{(3)})_{\mu\mu bs} = \sum_{I=1,3}(\bar{L}^a_{L\,2}\,\gamma^\mu(\tau_I)_{ab}\,L^b_{L\,2})(\bar{Q}^c_{L\,2}\,\gamma_\mu(\tau_I)_{cd}\,Q^d_{L\,3})$$ "triplet-triplet"

They both give C_9=-C_{10}

it gives also rise to charged-current, it can address the 1st class anomalies

One can attempt to explain class 1 and 2 anomalies simultaneously

Relevant constraints from $B \to K^{(*)}\nu\bar{\nu}$ which can be however relaxed if C_S=C_T

Alonso Grinstein Camalich '15
LC Crivellin Ota '15

Where do O_9 and O_{10} come from?

SU(2)-invariant operators:

Differ by SU(2) contractions:

$$(Q^{(1)}_{\ell q})_{\mu\mu bs} = (\bar{L}^a_{L\,2}\,\gamma^\mu\, L^a_{L\,2})(\bar{Q}^b_{L\,2}\,\gamma_\mu\, Q^b_{L\,3})$$ "singlet-singlet"

$$(Q^{(3)}_{\ell q})_{\mu\mu bs} = \sum_{I=1,3} (\bar{L}^a_{L\,2}\,\gamma^\mu(\tau_I)_{ab}\, L^b_{L\,2})(\bar{Q}^c_{L\,2}\,\gamma_\mu(\tau_I)_{cd}\, Q^d_{L\,3})$$ "triplet-triplet"

$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda^2}[(C_1+C_3)\,\lambda^d_{ij}\lambda^e_{kl}\,(\bar{d}_{Li}\gamma^\mu d_{Lj})(\bar{e}_{Lk}\gamma_\mu e_{Ll}) \;+$$ $B \to K^{(*)}\ell\ell'$

$$(C_1-C_3)\,\lambda^d_{ij}\lambda^e_{kl}\,(\bar{d}_{Li}\gamma^\mu d_{Lj})(\bar{\nu}_{Lk}\gamma_\mu \nu_{Ll})] \;+$$ $B \to K^{(*)}\nu\nu$

$$2C_3(V\lambda^d)_{ij}\lambda^e_{kl}\,(\bar{u}_{Li}\gamma^\mu d_{Lj})(\bar{e}_{Lk}\gamma_\mu \nu_{Ll})+h.c.]$$ $B \to D^{(*)}\ell\nu$

[Calibbi, Crivellin, Ota, '15]

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

P. Paradisi

Effective field theory approach

Ops with only 3rd family: $Q_{\ell q}^{(1)} = (\bar{L}_3 \gamma^\mu L_3)(\bar{Q}_3 \gamma_\mu Q_3)$, $Q_{\ell q}^{(3)} = (\bar{L}_3 \gamma^\mu \tau_I L_3)(\bar{Q}_3 \gamma_\mu \tau^I Q_3)$

(in the interaction basis)

Flavour structure justified by:

- Theoretical considerations (SM hierarchies, MFV paradigm, ...)
- Observed anomalies (3rd generation affected more than 2nd generation, 2nd generation more than 1st generation)

Glashow Guadagnoli Lane '14, Bhattacharya et al. '14, LC Crivellin Ota '15, Feruglio Paradisi Pattori '16,'17 ...

Operators involving 2nd generations generated by rotations to the mass basis:

$$Y^f = V^{f\dagger} \hat{Y}^f W^f, \qquad f = u, d, e$$

Giving e.g. :

$$C_S (\bar{L}_3 \gamma^\mu L_3)(\bar{Q}_3 \gamma_\mu Q_3) \longrightarrow C_S V_{23}^d V_{33}^{d\,*} |V_{23}^e|^2 \, (\bar{L}_2 \gamma^\mu L_2)(\bar{Q}_2 \gamma_\mu Q_3)$$

$\Rightarrow$ $b \to s\mu\mu$ $\qquad \sim V_{cb} \times V_{tb}$

Effective field theory approach

Ops with only 3$^{\mathrm{rd}}$ family: $Q_{\ell q}^{(1)} = (\bar{L}_3\gamma^\mu L_3)(\bar{Q}_3\gamma_\mu Q_3)$, $Q_{\ell q}^{(3)} = (\bar{L}_3\gamma^\mu \tau_I L_3)(\bar{Q}_3\gamma_\mu \tau^I Q_3)$

(in the interaction basis)

Flavour structure justified by:

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Operators involving 2nd generations generated by rotations to the mass basis:

$$Y^f = V^{f\dagger}\hat{Y}^f W^f, \qquad f = u, d, e$$

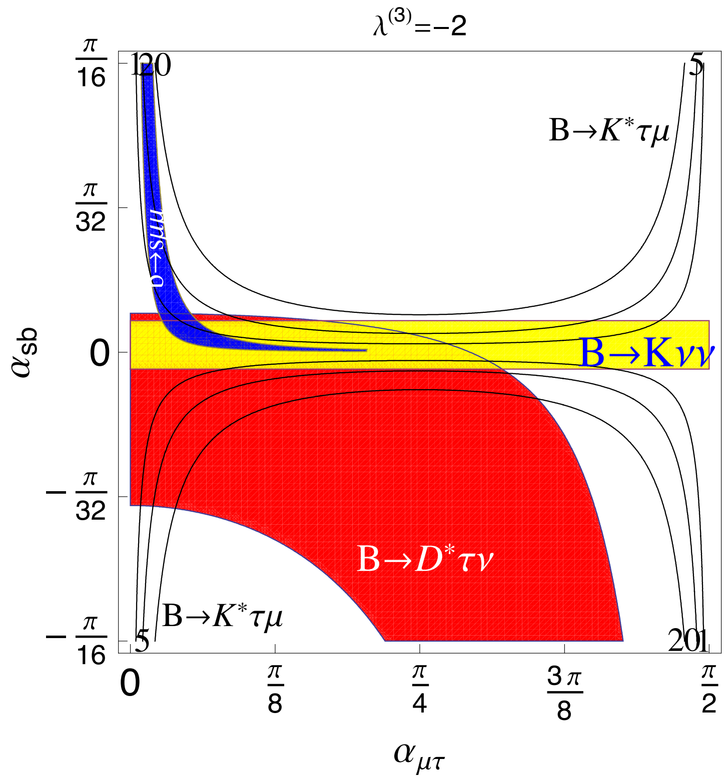
Correlated LFV operators are generated too:

$$C_S(\bar{L}_3\gamma^\mu L_3)(\bar{Q}_3\gamma_\mu Q_3) \longrightarrow C_S V^d_{23}V^{d\,*}_{33}V^e_{23}V^{e\,*}_{33}\,(\bar{L}_2\gamma^\mu L_3)(\bar{Q}_2\gamma_\mu Q_3)$$

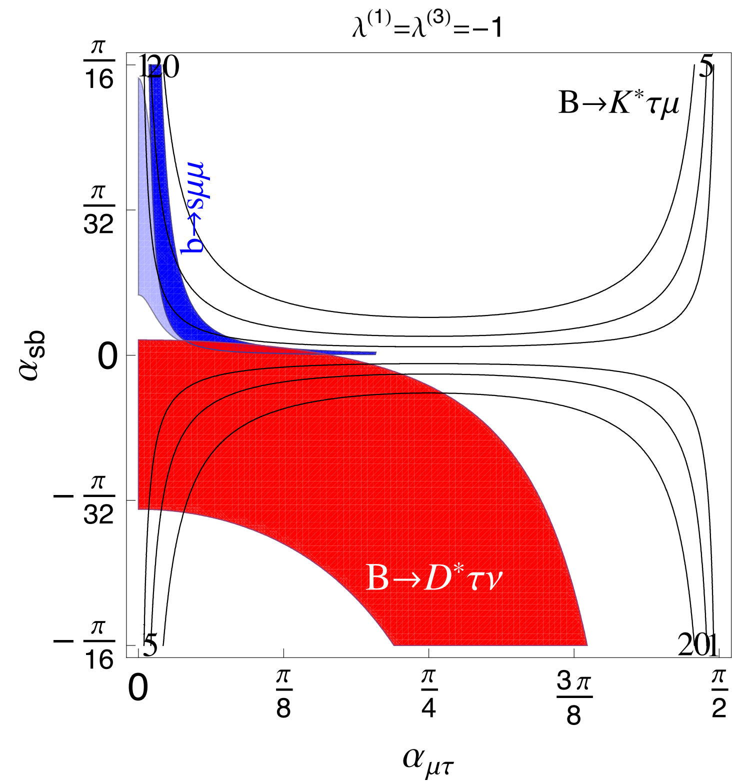
$\Rightarrow$ $b \to s\tau\mu$

Ops with only 3rd family: $Q_{\ell q}^{(1)} = (\bar{L}_3\gamma^\mu L_3)(\bar{Q}_3\gamma_\mu Q_3)$, $Q_{\ell q}^{(3)} = (\bar{L}_3\gamma^\mu \tau_I L_3)(\bar{Q}_3\gamma_\mu \tau^I Q_3)$

$C_T = -2, \quad C_S = 0 \quad (\Lambda = 1 \text{ TeV})$



$C_T = C_S = -1$



$$\text{BR}(B \to K^*\tau\mu) \approx 2 \times \text{BR}(B \to K\tau\mu) \approx 2 \times \text{BR}(B_s \to \tau\mu) \lesssim 10^{-6}$$

Considerably below current limit O(10^{-5})

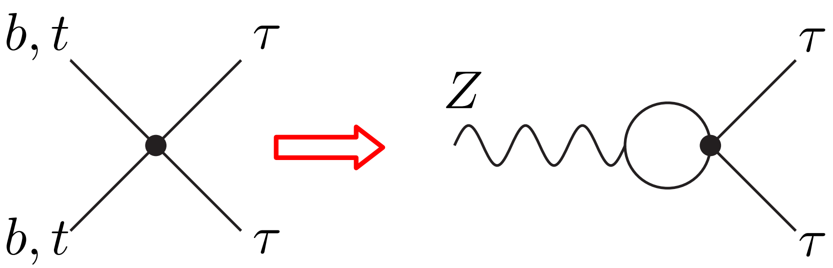
LC, Crivellin, Ota '15

Radiatively generated LFV and LFUV effects

Ops with only 3rd family: $Q_{\ell q}^{(1)} = (\bar{L}_3 \gamma^\mu L_3)(\bar{Q}_3 \gamma_\mu Q_3)$, $Q_{\ell q}^{(3)} = (\bar{L}_3 \gamma^\mu \tau_I L_3)(\bar{Q}_3 \gamma_\mu \tau^I Q_3)$

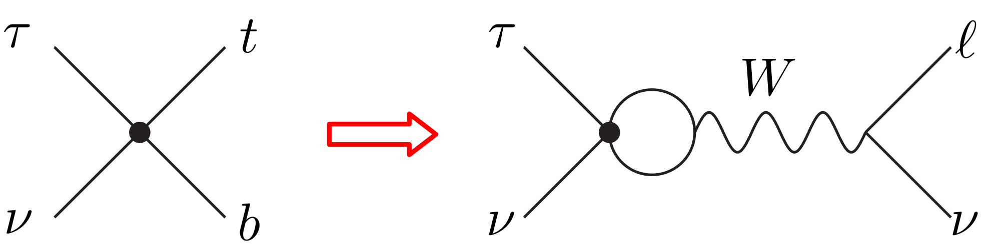
Important radiative effects:

Feruglio Paradisi Pattori ’16 & ’17



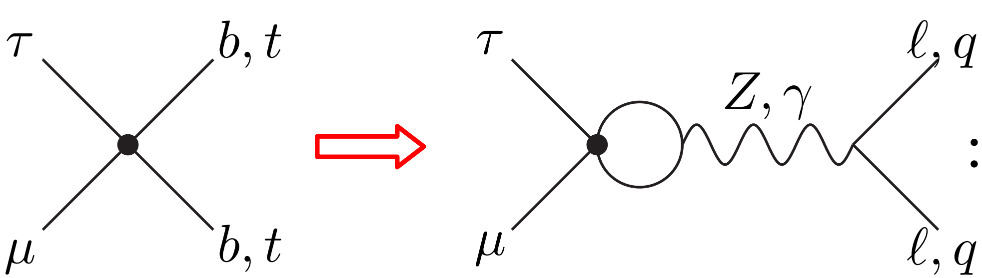
: $\dfrac{\mathrm{BR}(Z \to \tau\tau)}{\mathrm{BR}(Z \to ee)}$

(LFU in Z couplings tested at the permil level)



: $\dfrac{\mathrm{BR}(\tau \to \ell\nu\bar{\nu})}{\mathrm{BR}(\mu \to e\nu\bar{\nu})}$

(LFU in tau decays tested below the percent level)

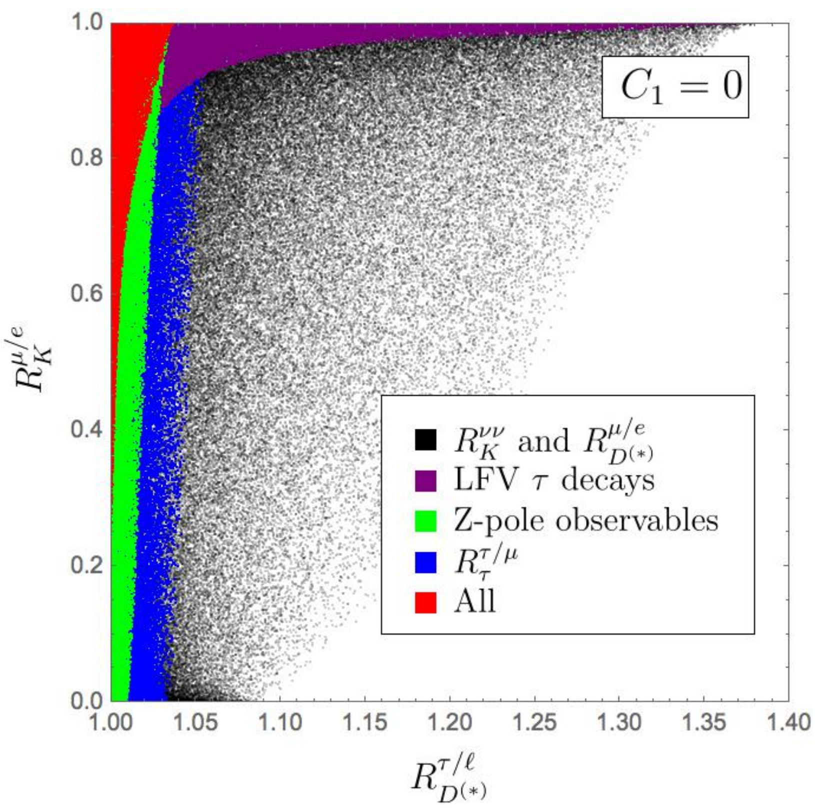


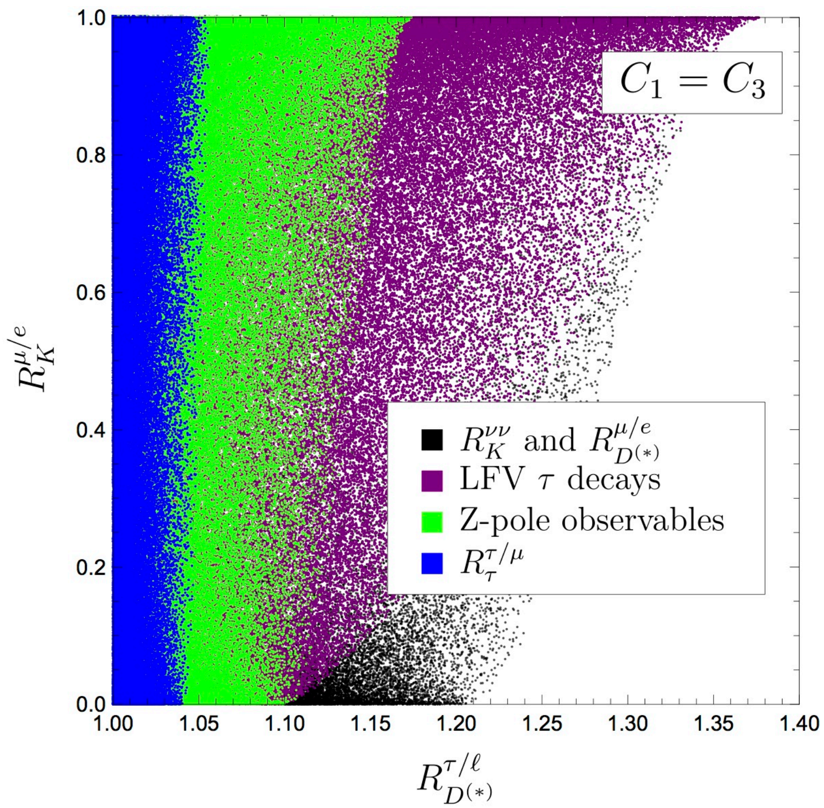
: $\tau \to \mu\ell\ell \quad \tau \to \mu\pi \quad \tau \to \mu\rho$

Tau CLFV!

Radiatively generated LFV and LFUV effects

Ops with only 3rd family: $Q_{\ell q}^{(1)} = (\bar{L}_3 \gamma^\mu L_3)(\bar{Q}_3 \gamma_\mu Q_3)$, $Q_{\ell q}^{(3)} = (\bar{L}_3 \gamma^\mu \tau_I L_3)(\bar{Q}_3 \gamma_\mu \tau^I Q_3)$



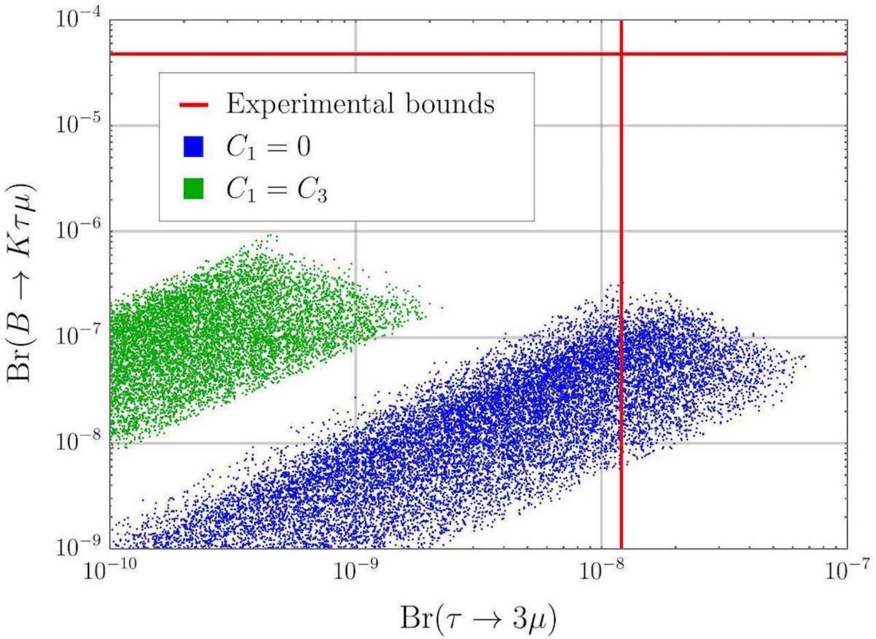


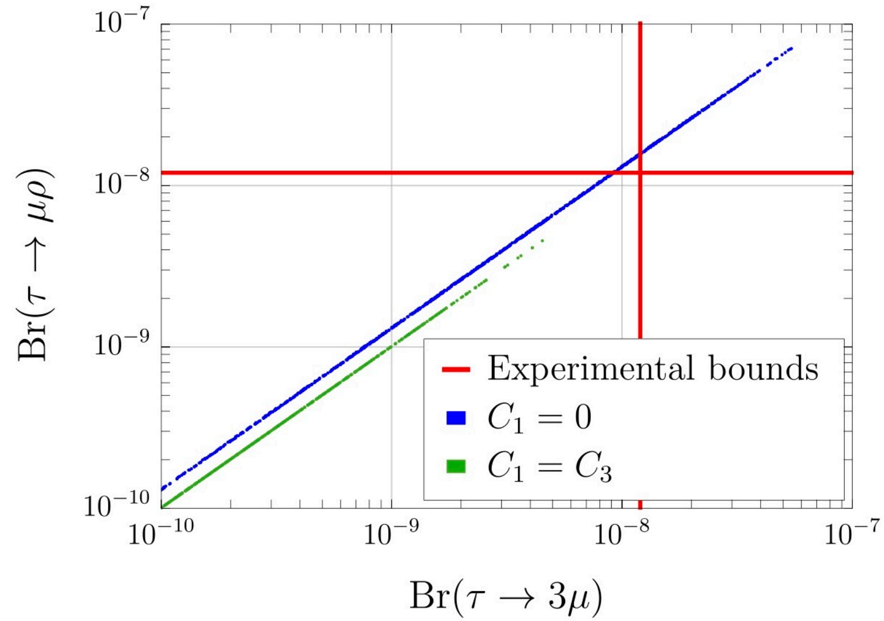
Feruglio Paradisi Pattori ’16 & ’17

LFV tests of the B anomalies

Ops with only 3rd family: $Q_{\ell q}^{(1)} = (\bar{L}_3\gamma^\mu L_3)(\bar{Q}_3\gamma_\mu Q_3)$, $Q_{\ell q}^{(3)} = (\bar{L}_3\gamma^\mu \tau_I L_3)(\bar{Q}_3\gamma_\mu \tau^I Q_3)$

All constraints imposed but $R_{D^{(*)}}$





$$\mathscr{B}(\tau \to 3\mu) \approx 5\times 10^{-8}\,\frac{(C_1-C_3)^2}{\Lambda^4(\mathrm{TeV}^4)}\left(\frac{\lambda^e_{23}}{0.3}\right)^2 \qquad \mathscr{B}(\tau \to \mu\rho) \approx 5\times 10^{-8}\,\frac{(C_1-1.3C_3)^2}{\Lambda^4(\mathrm{TeV}^4)}\left(\frac{\lambda^e_{23}}{0.3}\right)^2$$

Feruglio Paradisi Pattori '16 & '17

Combined explanations to class I and II anomalies

- LFV and LFUV observables limit the possibility of addressing *both* class of anomalies *simultaneously*

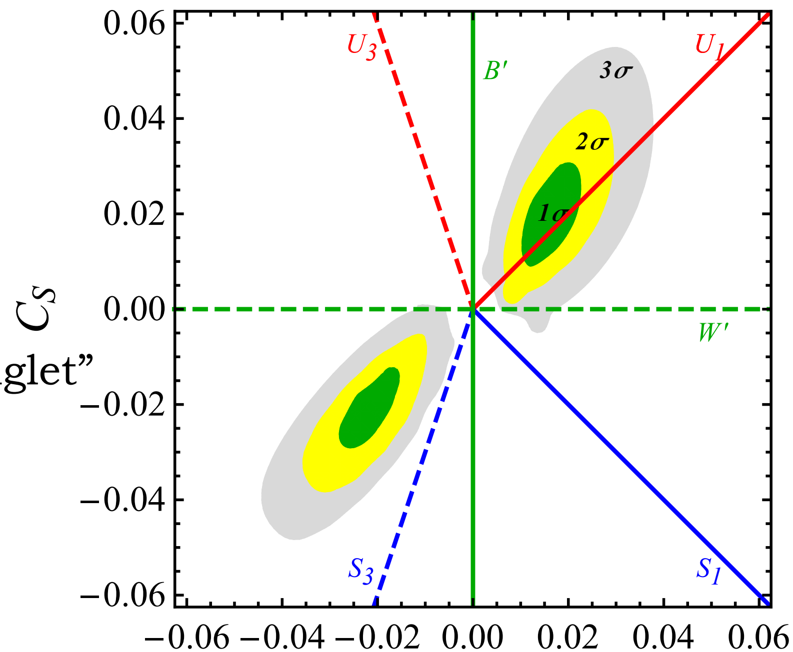
- On the other hand, these observables (in particular tau LFV decays) are expected to be in the reach of Belle II if there is NP behind the B anomalies

- A more general flavour structure (ops directly involving 2nd generations, 2-3 LH quark rotations > V_{ub} etc.) can still allow a combined explanation, although at the price of some tuning, see e.g. Buttazzo, Greljo, Isidori, Marzocca ‘17

- LFV processes are still a prediction/test of such construction!

Combined explanations to class I and II anomalies

Buttazzo, Greljo, Isidori, Marzocca '17



$U(2)_q$ x $U(2)_l$
flavour structure

"singlet-singlet"

C_T "triplet-triplet"

Simplified UV completions:

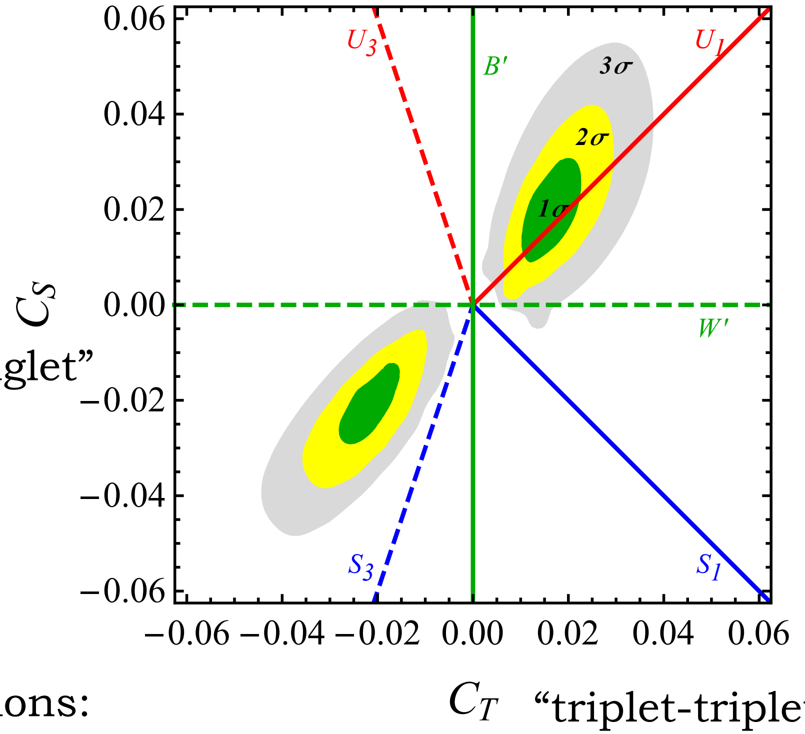
- Colorless vectors: B (1,1,0) W (1,3,0)
- Scalar Leptoquarks: S_1 (3,1,1/3) S_3 (3,3,1/3)
- Vector Leptoquarks: U_1 (3,1,2/3) U_3 (3,3,2/3)

A single vector LQ U_1 can do the job

Alonso Grinstein Camalich '15
LC Crivellin Ota '15

Combined explanations to class I and II anomalies

Buttazzo, Greljo, Isidori, Marzocca '17



"singlet-singlet"

"triplet-triplet"

$U(2)_q \times U(2)_l$ flavour structure

Simplified UV completions:

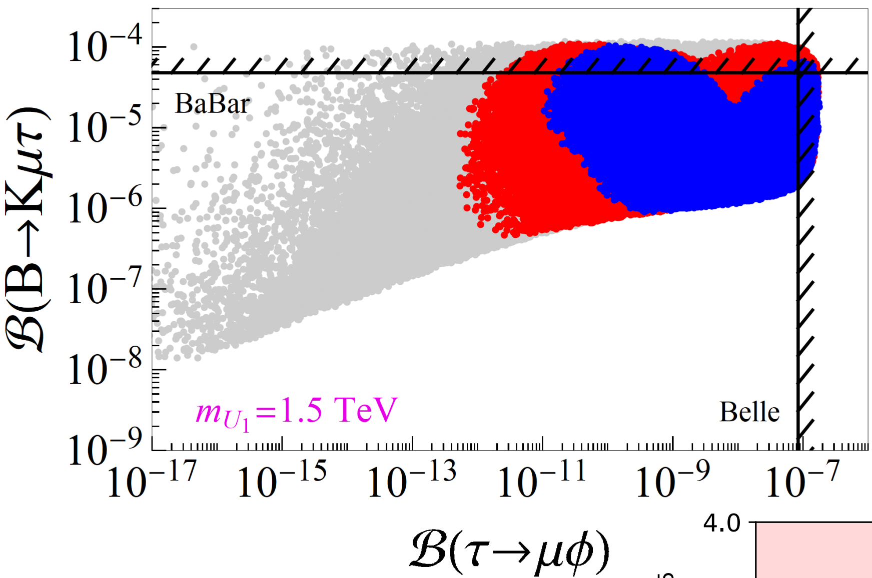
- Colorless vectors: B (1,1,0) W (1,3,0)
- Scalar Leptoquarks: S_1 (3,1,1/3) S_3 (3,3,1/3)
- Vector Leptoquarks: U_1 (3,1,2/3) U_3 (3,3,2/3)

U_1 has the quantum numbers of a SU(4) gauge boson!
Recent attempts to build Pati-Salam-like models

Di Luzio Greljo Nardecchia '17
LC Crivellin Li '17
Bordone Cornelia Fuentes Isidori '17

Combined explanations to class I and II anomalies

LFV processes are still a prediction/test of such construction! Examples:

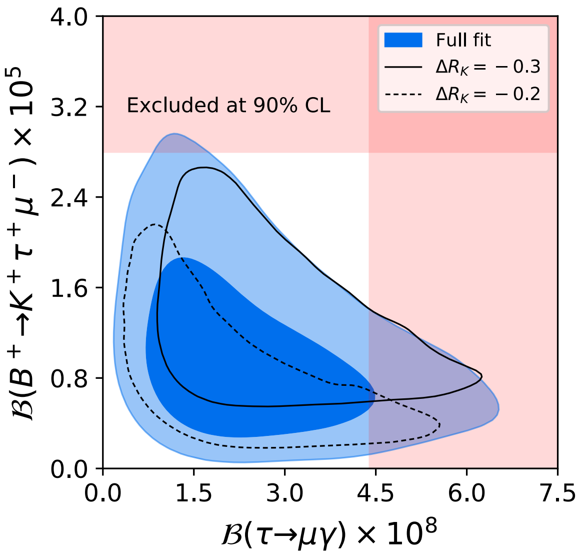


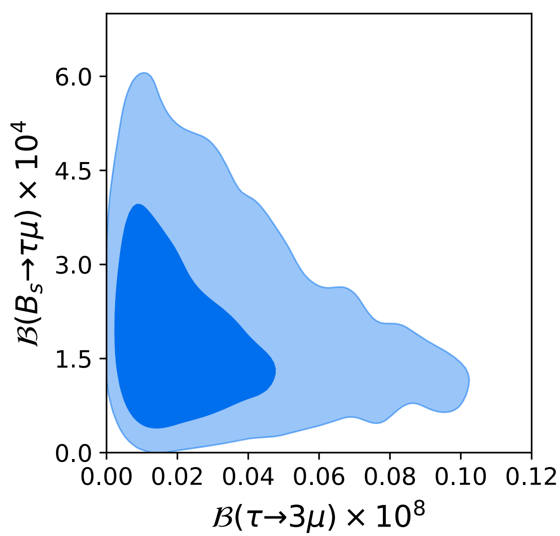
Generic vector LQ

Angelescu et al. ‘18

UV-complete vector LQ model based on $(SU(4)\mathrm{x}SU(2)_L\mathrm{x}SU(2)_R)^3$

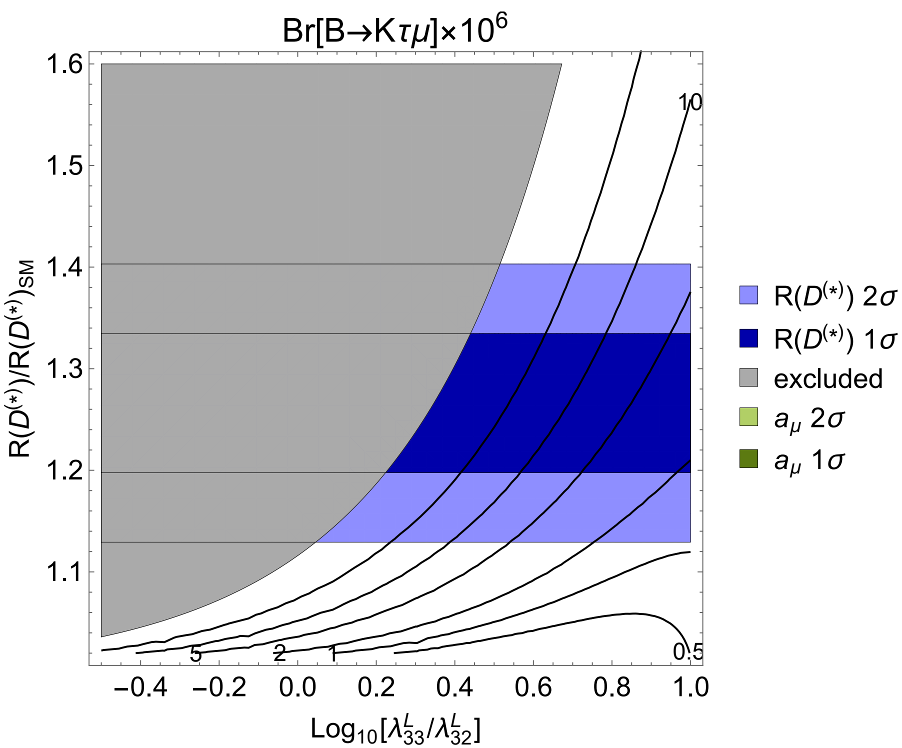
Bordone et al. ‘18

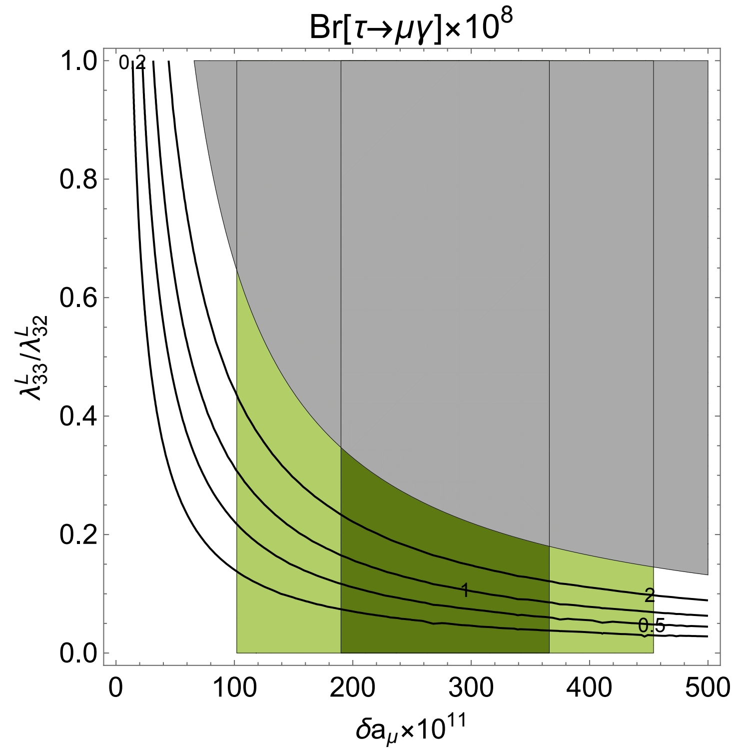




LFV processes are still a prediction/test of such construction! Examples:

Scalar LQs Crivellin Muller Ota ‘17





Concluding remarks

CLFV observables among the cleanest and most stringent test of physics beyond the Standard Model

CLFV in the tau sector nicely complementary to muon observables as a model discriminator (e.g. SUSY seesaw typically predicts tau LFV rates below the reach of Belle II)

B anomalies favours new physics more strongly coupled to 3rd generation fermions

LFUV and LFV involving taus are key observables to test the models addressing the anomalies (the latter typically predicted within the future Belle II/LHCb sensitivity)

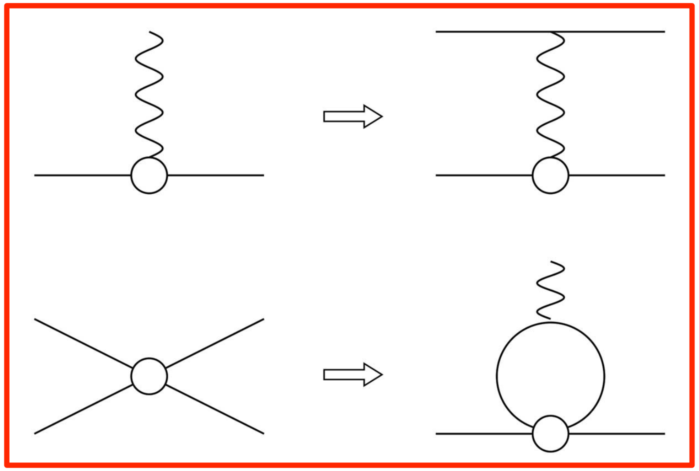
Additional Slides

Dimension-6 effective operators that can induce CLFV

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \ldots$$

Example, dipole operators:

$$\mathcal{L} \supset \frac{C_{e\gamma}^{e\mu}}{\Lambda^2}\frac{v}{\sqrt{2}}\,\bar{e}\,\sigma_{\mu\nu}P_R\,\mu\,F^{\mu\nu} + \frac{C_{e\gamma}^{\mu e}}{\Lambda^2}\frac{v}{\sqrt{2}}\,\bar{\mu}\,\sigma_{\mu\nu}P_R\,e\,F^{\mu\nu} + \text{h.c.},$$



Dimension-6 effective operators that can induce CLFV

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \ldots$$

Example, dipole operators:

$$\mathcal{L} \supset \frac{C_{e\gamma}^{e\mu}}{\Lambda^2}\frac{v}{\sqrt{2}}\,\bar{e}\,\sigma_{\mu\nu}P_R\,\mu\,F^{\mu\nu} + \frac{C_{e\gamma}^{\mu e}}{\Lambda^2}\frac{v}{\sqrt{2}}\,\bar{\mu}\,\sigma_{\mu\nu}P_R\,e\,F^{\mu\nu} + \text{h.c.},$$

$$\Gamma(\mu\to e\gamma) = \frac{m_\mu^3 v^2}{8\pi\Lambda^4}\left(|C_{e\gamma}^{e\mu}|^2 + |C_{e\gamma}^{\mu e}|^2\right)$$

$$\text{BR}(\mu\to eee) \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - 3\right)\times \text{BR}(\mu\to e\gamma),$$

$$\text{CR}(\mu\,\text{N}\to e\,\text{N}) \simeq \alpha\times\text{BR}(\mu\to e\gamma).$$

Dimension-6 effective operators that can induce CLFV

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

Model discrimination through the different muon modes:

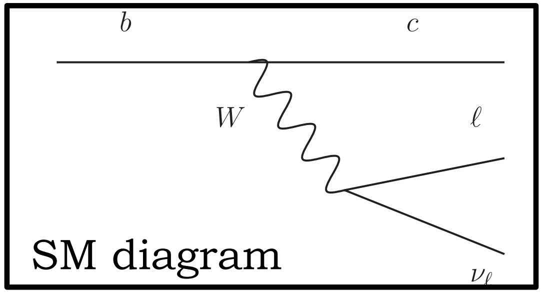
Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6\times10^{-3}$	$10^{-3}-10^{-2}$
Type-I seesaw	Loop*	Loop*	$3\times10^{-3}-0.3$	$0.1-10$
Type-II seesaw	Tree	Loop	$(0.1-3)\times10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop$^{*\,\dagger}$	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05-0.5$	$2-20$

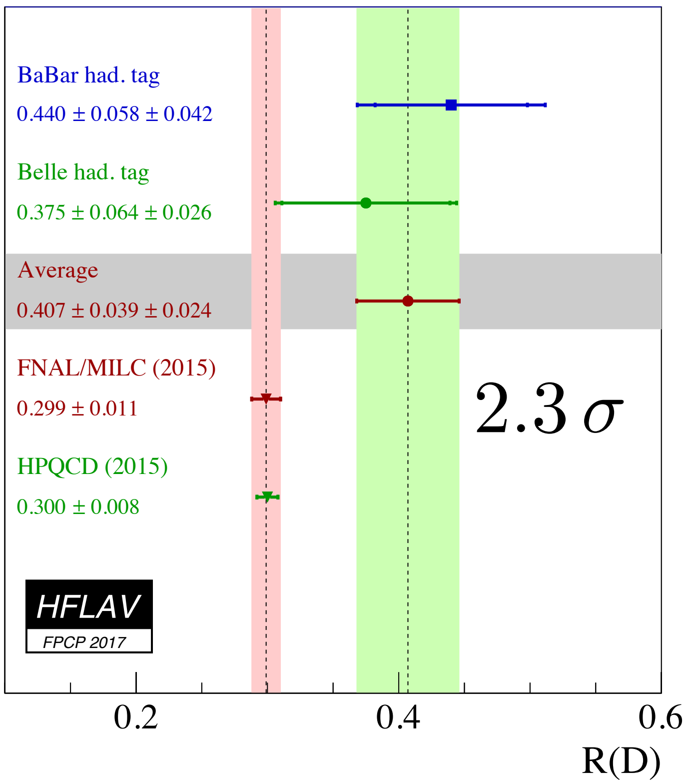
TABLE VII. – *Pattern of the relative predictions for the $\mu \to e$ processes as predicted in several models (see the text for details). It is indicated whether the dominant contributions to $\mu \to eee$ and $\mu \to e$ conversion are at the tree or at the loop level; Loop* indicates that there are contributions that dominate over the dipole one, typically giving an enhancement compared to Eq. (38, 39). † A tree-level contribution to this process exists but it is subdominant.*

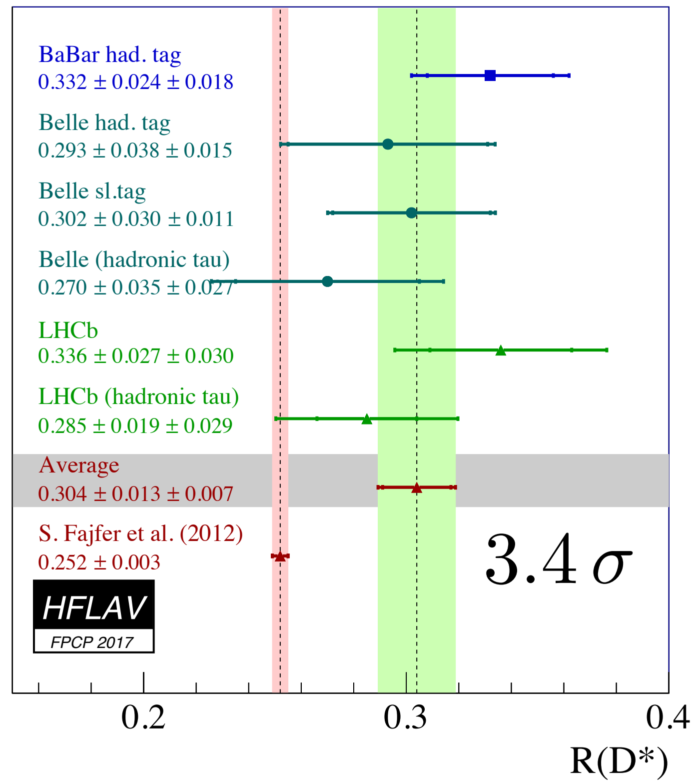
First class: charged-current $b \to c\ell\nu$

$$\boxed{R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)},\ \ell = e,\ \mu}$$

test of Lepton Flavour Universality (LFU)





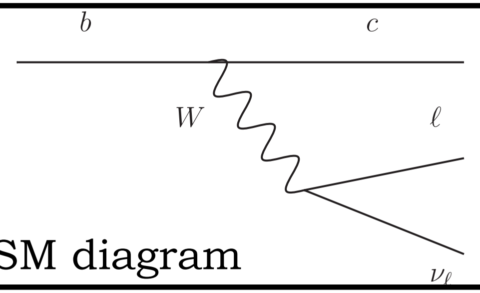


Only two measurements available for R(D)

First class: charged-current $b \to c\ell\nu$

$$R_{J/\psi} \equiv \frac{\mathrm{BR}(B_c^+ \to J/\psi\,\tau^+\,\nu_\tau)}{\mathrm{BR}(B_c^+ \to J/\psi\,\mu^+\,\nu_\mu)}$$

another LFU observable



SM diagram

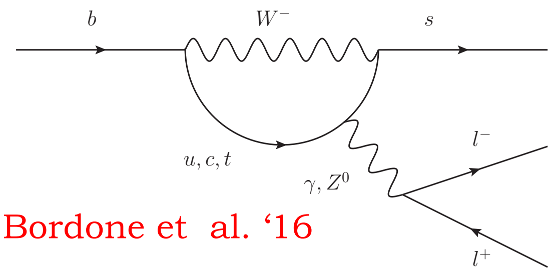
$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.71 \pm 0.17\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst}).$$

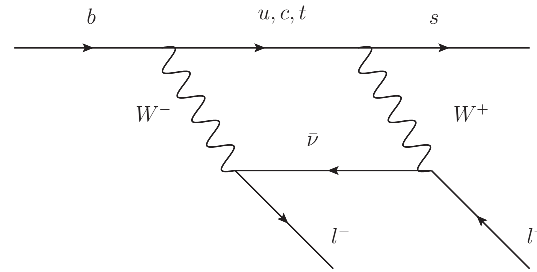
LHCb, arXiv:1711.05623

~2σ above the range predicted by the SM: 0.25-0.28

Second class: neutral-current $b \to s\ell^+\ell^-$

$$\boxed{R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}}$$





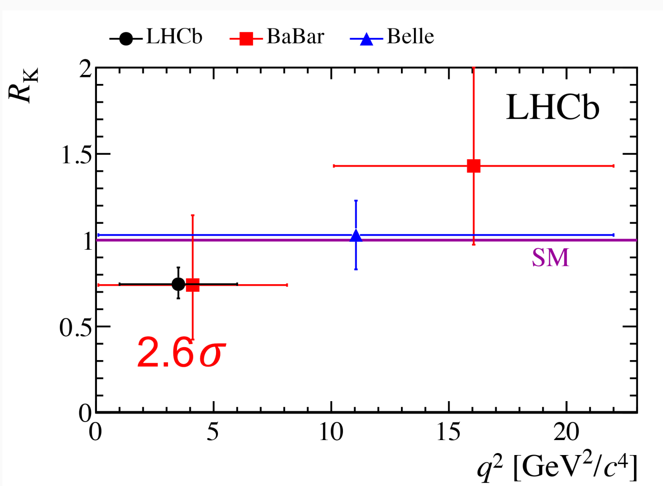
=1+-0.01 in the SM (q^2>1 GeV^2) Bordone et al. ‘16

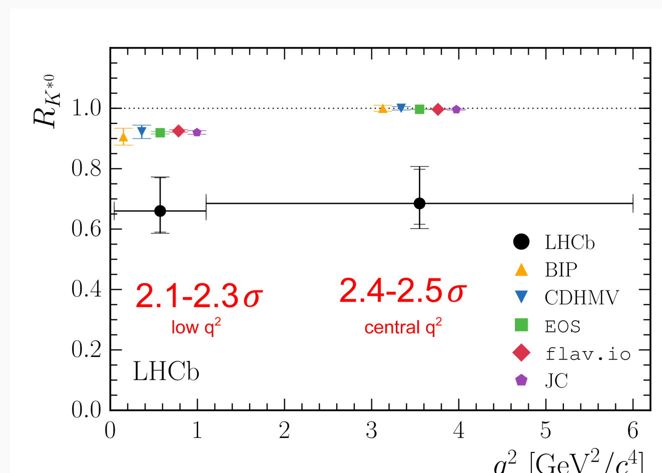
Most precise measurements up to date, integrated luminosity of $3fb^{-1}$

$$\mathrm{R}_K = 0.745^{+0.090}_{-0.074}\ (\mathrm{stat}) \pm 0.036\ (\mathrm{syst})$$

$$\mathrm{R}_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})\ [0.045 - 1.1]\ \mathrm{GeV}^2 \\ 0.69^{+0.11}_{-0.05}\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})\ [1.1 - 6.0]\ \mathrm{GeV}^2 \end{cases}$$

Compatible with SM at

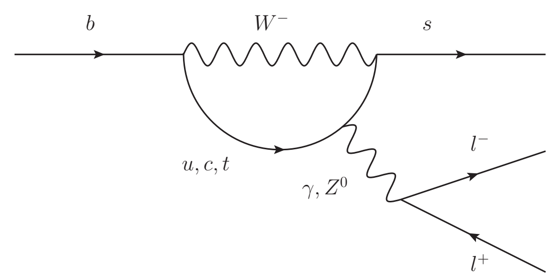


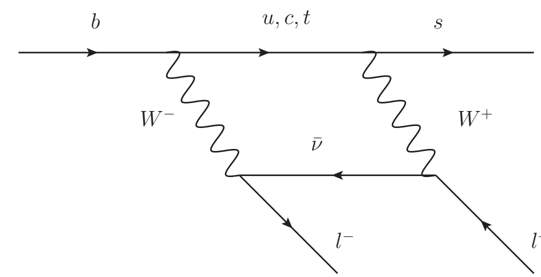


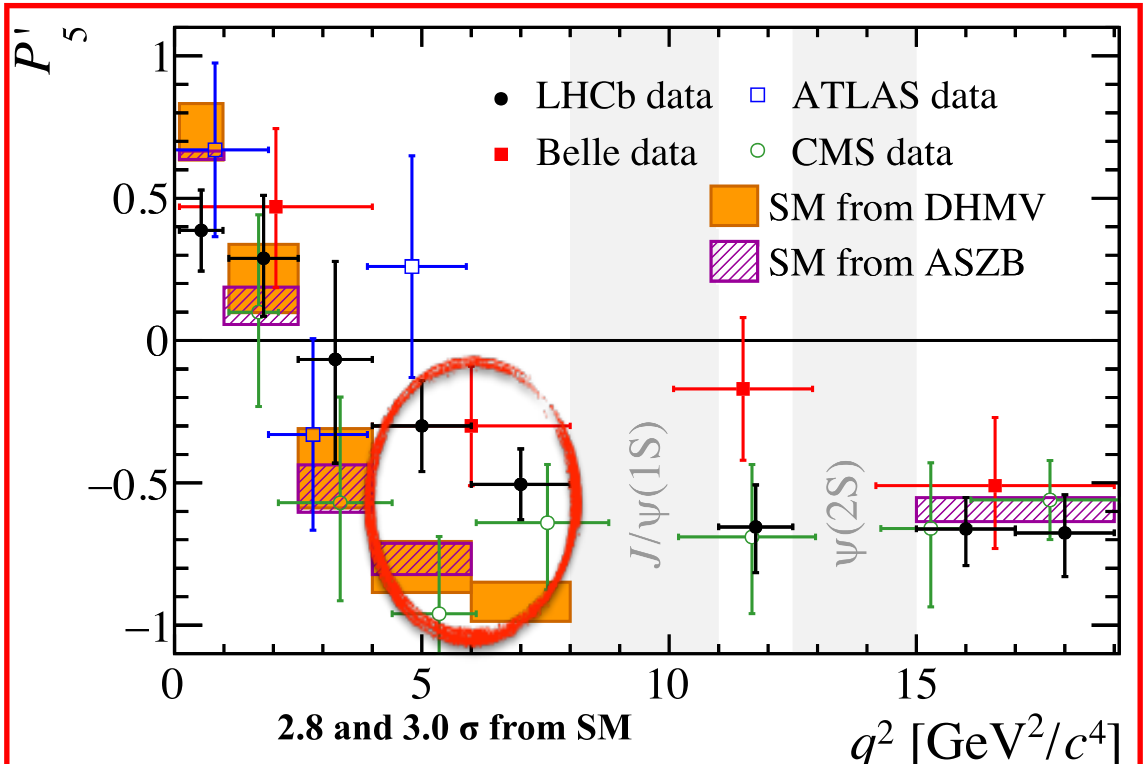
From D. Lancierini talk at SUSY17

Second class: neutral-current $b \to s\ell^+\ell^-$

Angular observables in
$B \to K^*\mu^+\mu^-$



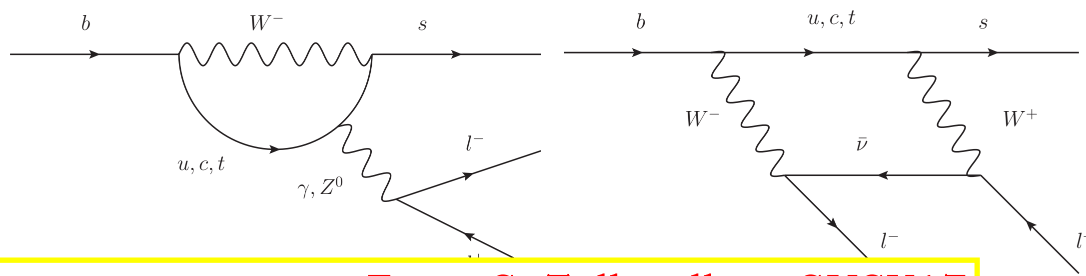


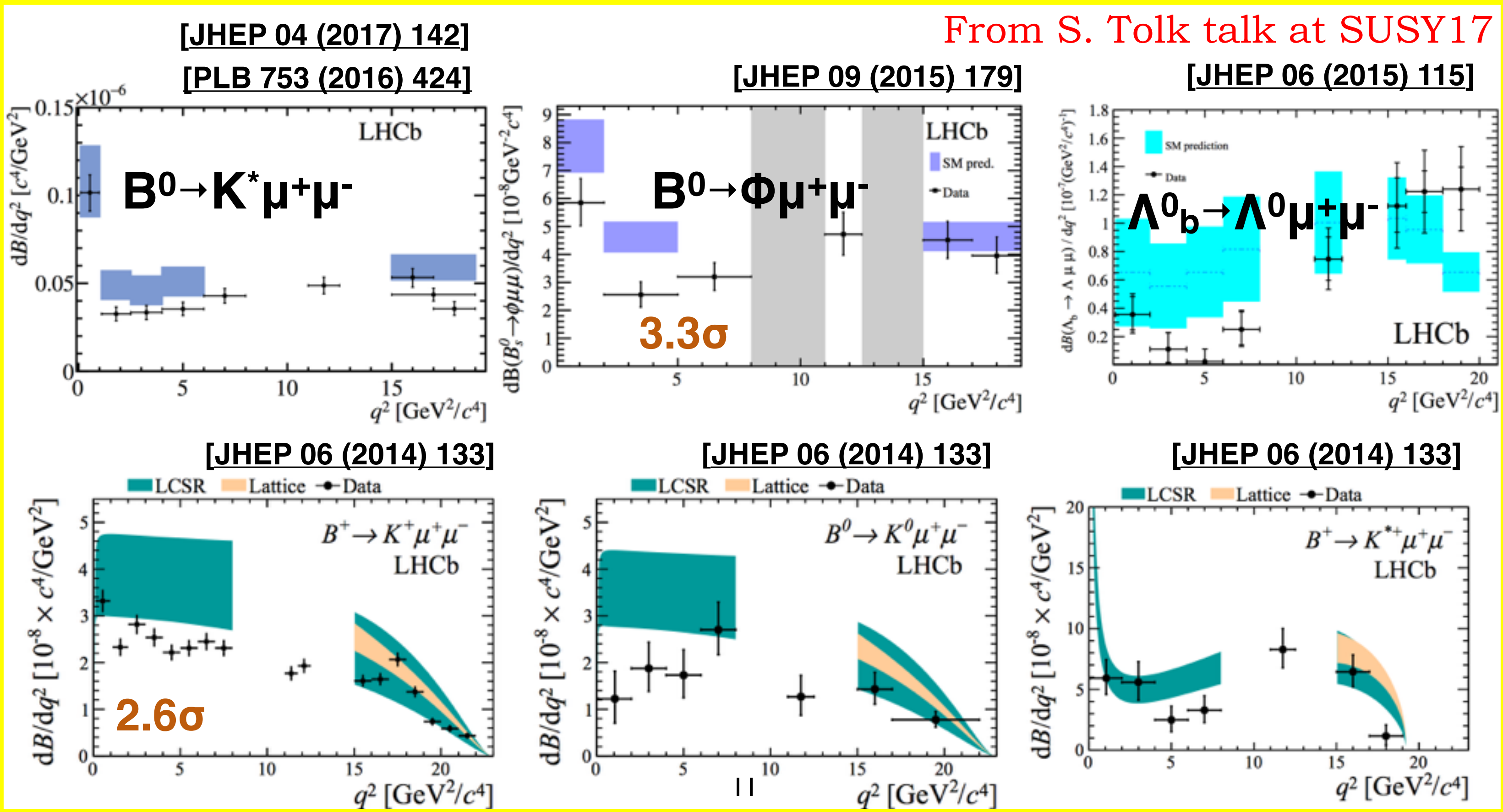


... but are hadronic uncertainties fully under control?

Second class: neutral-current $b \to s\ell^+\ell^-$

Some $b \to s\mu^+\mu^-$ BRs





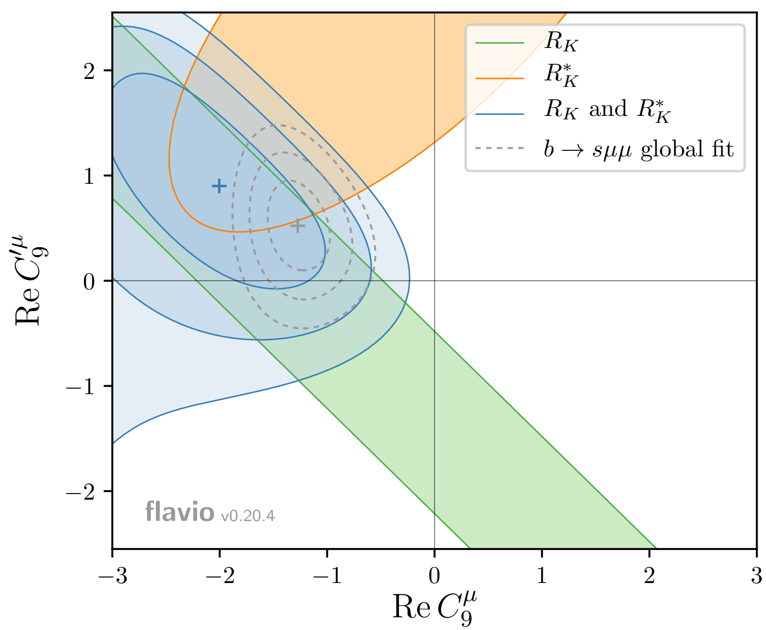
… but are hadronic uncertainties fully under control?

Global fits to $b \to s\ell^+\ell^-$ observables

It seems that we have to fit a deficit of muon events

$$\mathcal{O}_9^{\ell(\prime)} \sim (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{\ell(\prime)} \sim (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

RH currents not favored



Altmannshofer Stang Straub '17

Fits to the data: non-standard contributions preferred at the 4-5σ level

Capdevilla et al . '17, Altmannshofer et al. '17, D'Amico et al. '17, Geng et al. '17, Ciuchini et al. '17, Neshatpour et al. '17 + many older refs.

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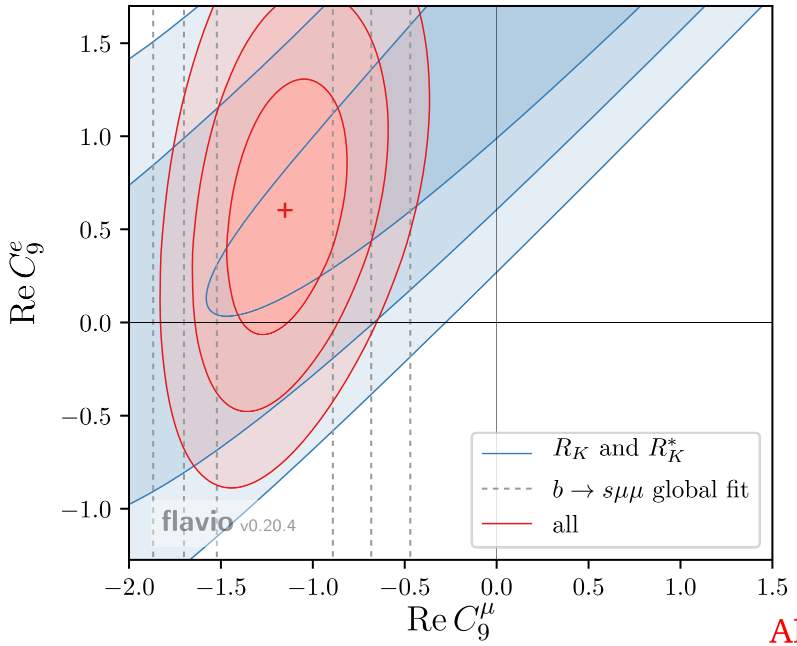
No need of electron ops



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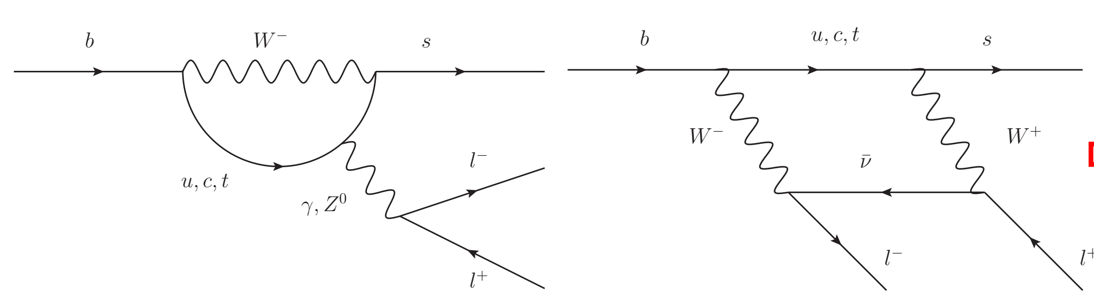
	All					LFUV				
1D Hyp.	Best fit	1 σ	2 σ	$\mathrm{Pull_{SM}}$	p-value	Best fit	1 σ	2 σ	$\mathrm{Pull_{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.10	$[-1.27,-0.92]$	$[-1.43,-0.74]$	5.7	72	-1.76	$[-2.36,-1.23]$	$[-3.04,-0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.61	$[-0.73,-0.48]$	$[-0.87,-0.36]$	5.2	61	-0.66	$[-0.84,-0.48]$	$[-1.04,-0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9\mu}'$	-1.01	$[-1.18,-0.84]$	$[-1.33,-0.65]$	5.4	66	-1.64	$[-2.12,-1.05]$	$[-2.52,-0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-1.06	[-1.23,-0.89]	[-1.39,-0.71]	5.8	74	-1.35	$[-1.82,-0.95]$	$[-2.38,-0.59]$	4.0	71

Capdevilla et al. '17

"Clean" observables only!

Sizeable NP contribution would be required, O(10)% of the SM one:



$$C_9^{\rm SM} \simeq -C_{10}^{\rm SM} \simeq 4.1$$

Vector Leptoquarks for the B-physics anomalies

LC Crivellin Li '17

Both classes of anomalies can be explained by adding a single new field:
a spin-1 leptoquark with $SU(3)_c \times SU(2)_L \times U(1)_Y$ quantum numbers as
(3, 1, 2/3)

LC Crivellin Ota '15

Where does such an exotic field come from?
Interestingly, it has the quantum numbers of a $SU(4)$ vector boson

We built a Pati-Salam - $SU(4) \times SU(2)_L \times SU(2)_R$ - model
to accommodate this vector leptoquark

We have to introduce extra vectorlike fermions embedded in the same
PS representations containing the SM fermions, in order to generate
flavour non-universal couplings of the leptoquark

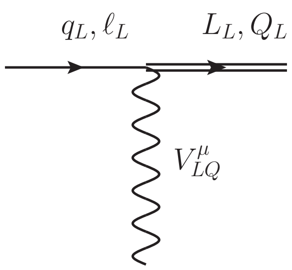
Field content:

	$SU(4)$	$SU(2)_L$	$SU(2)_R$	$U(1)_{PQ}$
X_i^L	4	2	1	0
Y_i^L	4	2	1	0
Y_i^R	4	2	1	1
X_i^R	4	1	2	0
Z_i^R	4	1	2	0
Z_i^L	4	1	2	1
Σ	$\bar{4} \otimes 4$	1	1	- 1

SU(4)-breaking scalar

Contain SM doublets and extra fermions: $Y_R = \begin{pmatrix} Q'_R \\ L'_R \end{pmatrix}_i, \quad Y_L = \begin{pmatrix} Q_L \\ \ell_L \end{pmatrix}_i, \quad X_L = \begin{pmatrix} q_L \\ L_L \end{pmatrix}_i$

Because of this embedding, the leptoquark couple light to heavy fields:



SM and vectorlike quarks and leptons mix upon *SU*(4) breaking:

$$\mathcal{L} \supset -v_\Sigma^{ab} \bar{X}_i^{aL} x_{ij} Y_j^{aR} - v_\Sigma^{ab} \bar{Y}_i^{aL} y_{ij} Y_j^{bR} + h.c. \quad \Rightarrow \quad \mathcal{L} \supset -\left(m_{ij}^Q \bar{q}_{iL} + M_{ij}^Q \bar{Q}_{iL}\right) Q'_{jR} - \left(M_{ij}^L \bar{L}_{iL} + m_{ij}^L \bar{\ell}_{iL}\right) L'_{jR}$$

SM/vectorlike fermion mixing generates flavour non-universal leptoquark couplings:

$$\mathcal{L} \supset \kappa_{ij}\, \bar{q}_i^L \gamma^\mu P_L \ell_j^L V_\mu + h.c. \quad \text{with} \quad \kappa_{ij} = \frac{-g_s}{\sqrt{2}} \begin{pmatrix} c_1^Q s_1^L + c_1^L s_1^Q & 0 & 0 \\ 0 & \left(c_2^Q s_2^L + c_2^L s_2^Q\right) c_{23}^{q\ell} & -s_{23}^{q\ell}\left(c_2^Q s_2^L + c_2^L s_2^Q\right) \\ 0 & \left(c_2^Q s_2^L + c_2^L s_2^Q\right) s_{12}^{q\ell} & c_{23}^{q\ell}\left(c_3^Q s_3^L + c_3^L s_3^Q\right) \end{pmatrix}_{ij}$$

Depending on the field rotations, both class I (in blue) and class II (in red) can be fitted: