SUSY17

TIFR, Mumbai

Testing New Physics with flavour violation

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Why are we interested in Flavour Physics?

SM flavour puzzle

We need to find the scale of New Physics!

- Why three families?
- Why the hierarchies?

$(m_t / m_e = 3.4 \times 10^5)$

- LHC found a SM-like Higgs
- No sign of new phenomena
- We know there is new physics somewhere but we don't know the scale…

Why do we need New Physics?

- Hierarchy Problem (?)
- Dark Matter/Dark Energy
- Inflation
- Neutrino masses
- Baryon asymmetry
- Origin of flavour hierarchies

...

Why do we need New Physics?

- Hierarchy Problem (?) → TeV-scale New Physics?
- Dark Matter/Dark Energy
- Inflation
- Neutrino masses → See-saw?
- Baryon asymmetry → Leptogenesis?
- Origin of flavour hierarchies → Symmetries of flavour?

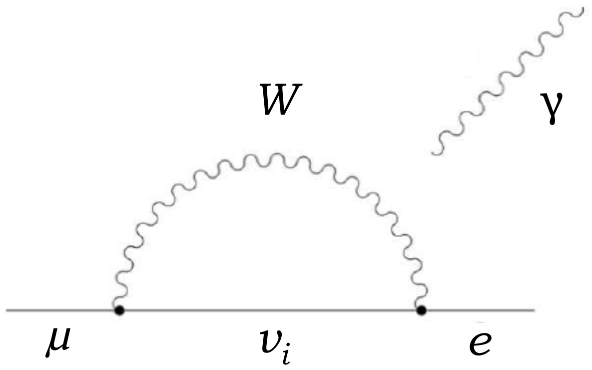
...

Testable through Hadronic/Leptonic Flavour/CP Violation?

- Neutrinos oscillate → Lepton family numbers are not conserved!
- Can we observe LFV in charged leptons decays?
- In the SM + massive neutrinos:

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\mathrm{em}}}{32\pi}\left|\sum_i U_{\mu i}U_{ei}\frac{m_{\nu_i}^2}{M_W^2}\right|^2$$

⇒ $\mathrm{BR}(\mu \to e\gamma) = 10^{-55} \div 10^{-54}$

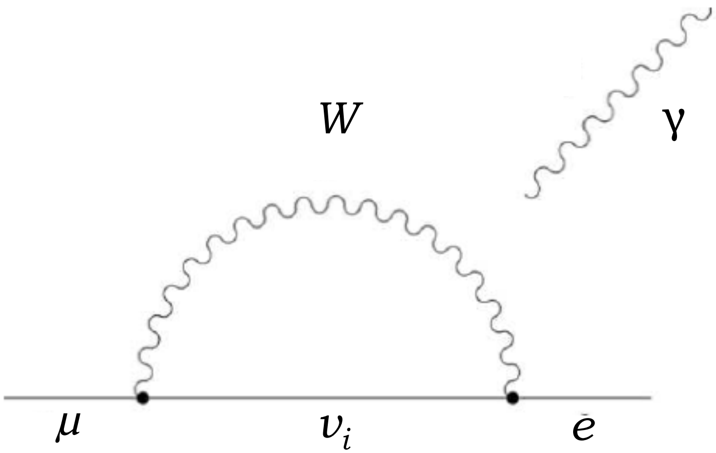


Suppression due to small neutrino masses

Cheng Li '77, '80; Petcov '77

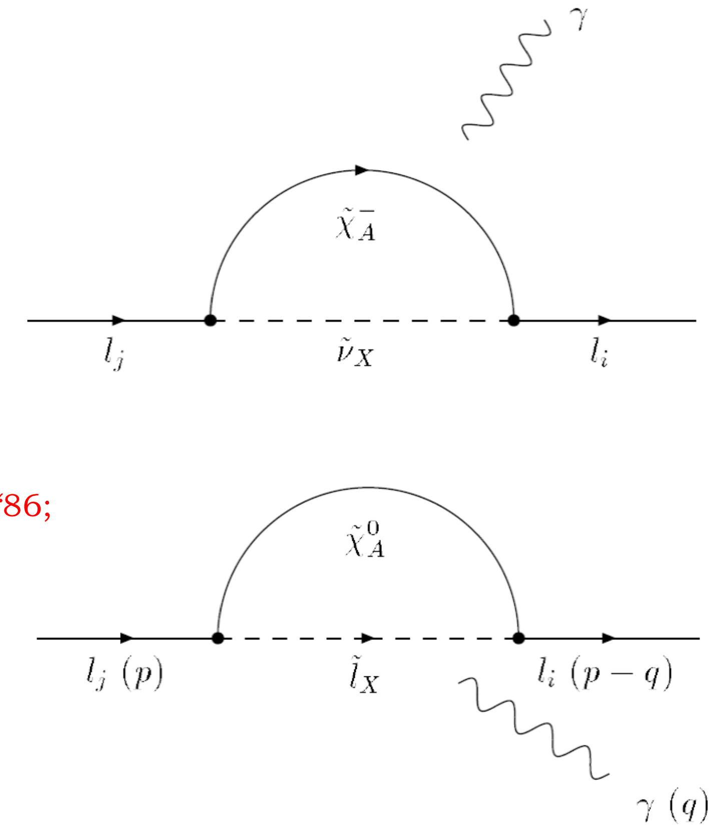
⇒ In presence of NP at the TeV we can expect large effects!

Clean example: charged Lepton Flavour Violation



SUSY

Borzumati Masiero '86;
Hisano et al. '95



$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{\rm em}}{32\pi}\left|\sum_i U_{\mu i}U_{ei}\frac{m^2_{\nu_i}}{M^2_W}\right|^2$$

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

Plenty of stringent limits

Reaction	Present limit	C.L.	Experiment	Year	Reference
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016	[49]
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988	[50]
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ †	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998	[51]
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ †	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996	[52]
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ †	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006	[54]
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ †	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998	[53]
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999	[55]
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007	[58]
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007	[59]
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011	[60]
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011	[60]

Plenty of stringent limits

Reaction	Present limit	C.L.	Experiment	Year	Reference
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008	[61]
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998	[62]
$K_L^0 \to \pi^0 \mu^+ e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008	[61]
$K^+ \to \pi^+ \mu^+ e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005	[63]
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013	[64]
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004	[65]
$J/\psi \to \tau \mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004	[65]
$B^0 \to \mu e$	$< 2.8 \times 10^{-9}$	90%	LHCb	2013	[68]
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008	[69]
$B^0 \to \tau \mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008	[69]
$B \to K \mu e$ ‡	$< 3.8 \times 10^{-8}$	90%	BaBar	2006	[66]
$B \to K^* \mu e$ ‡	$< 5.1 \times 10^{-7}$	90%	BaBar	2006	[66]
$B^+ \to K^+ \tau \mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012	[67]
$B^+ \to K^+ \tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012	[67]
$B_s^0 \to \mu e$	$< 1.1 \times 10^{-8}$	90%	LHCb	2013	[68]
$\Upsilon(1s) \to \tau \mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008	[70]

Plenty of stringent limits

Reaction	Present limit	C.L.	Experiment	Year	Reference
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014	[71]
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995	[72]
$Z \to \tau \mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997	[73]
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016	[74]
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017	[75]
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017	[75]

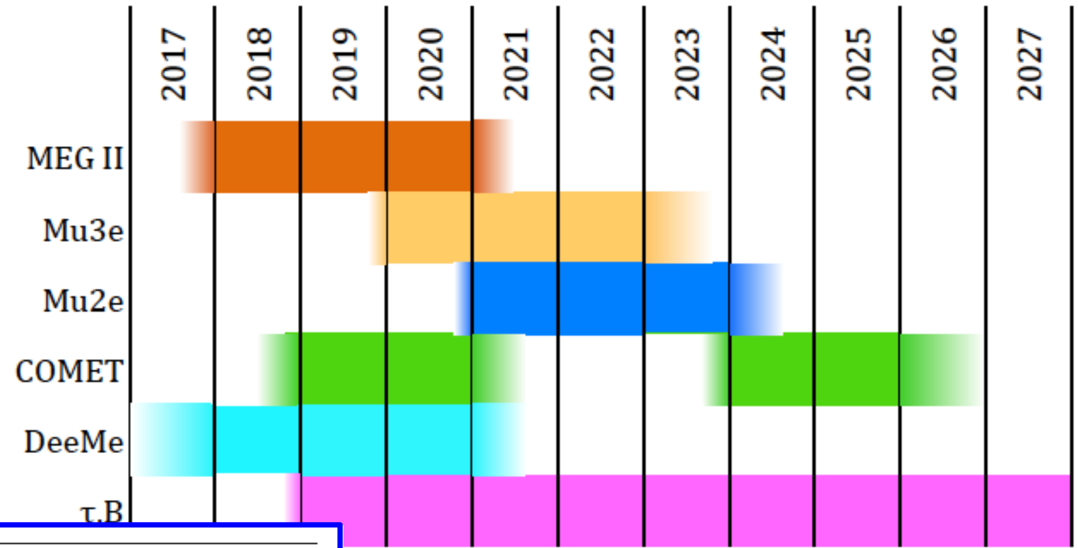
Probing high energy scales

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

	$\lvert C_a\rvert$ $[\Lambda = 1$ 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}	$\mu^-\text{Au}\to e^-\text{Au}$
$C_{\ell q,\ell d,ed}^{e\mu}$	1.8×10^{-6}	745	$\mu^-\text{Au}\to e^-\text{Au}$
$C_{eq}^{e\mu}$	9.2×10^{-7}	1.0×10^{3}	$\mu^-\text{Au}\to e^-\text{Au}$
$C_{\ell u,eu}^{e\mu}$	2.0×10^{-6}	707	$\mu^-\text{Au}\to e^-\text{Au}$
$C_{e\gamma}^{\tau\mu}$	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!

cf. e.g. LC and Signorelli, ‘17



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
$\mu^-\mathrm{Al} \to e^-\mathrm{Al}$ †	$< 6.1 \times 10^{-13}$	10^{-17}	[321, 324]	Mu2e, COMET
$\mu^-\mathrm{Si/C} \to e^-\mathrm{Si/C}$ †	–	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	$< 1.8 \times 10^{-8}$ ‡	3×10^{-10}	[339]	”
$\tau \to \mu$ had	$< 1.2 \times 10^{-8}$ ‡	3×10^{-10}	[339]	”
had $\to \mu e$	$< 4.7 \times 10^{-12}$ §	10^{-12}	[340]	NA62
$h \to e\mu$	$< 3.5 \times 10^{-4}$	3×10^{-5} ¶	[341]	HL-LHC
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	3×10^{-4} ¶	[341]	”
$h \to \tau e$	$< 6.1 \times 10^{-3}$	3×10^{-4} ¶	[341]	”

- Anomalies in semi-leptonic B-meson decays

- Charged Lepton Flavour Violation in SUSY

Hot topic! Hundreds of papers…

I am not even attempting a comprehensive review

Nice discussions in the Flavour parallel session

Experimental status and prospects:

talks by Caria, Dash, Lancierini, Nayak, Sahoo, Sandilya, Tolk and next plenary by Urquijo

Theoretical interpretations:

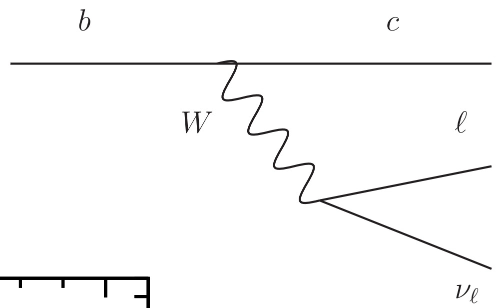
talks by Bardhan, Deshpande, Dev, Giri, Kumar, Mandal

Two classes of anomalies:

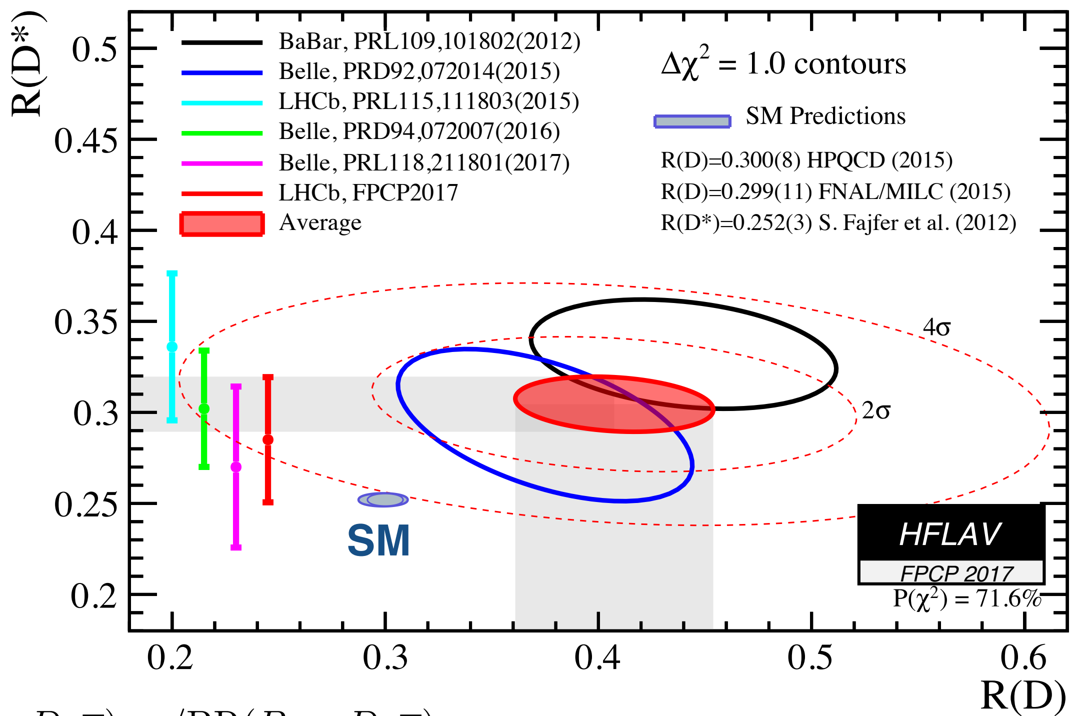
I. In charged-current processes of the type $b \to c\ell\nu$

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

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



test of Lepton Flavour Universality (LFU)



$\approx 4\sigma$
from the SM

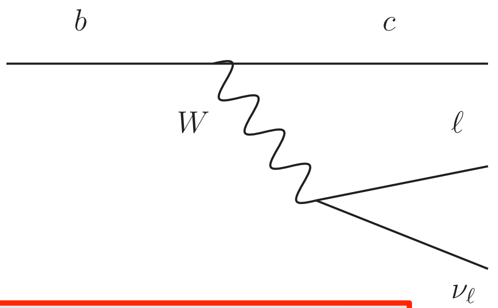
$$\frac{\mathrm{BR}(B \to D\tau\bar{\nu})_{\mathrm{exp}}/\mathrm{BR}(B \to D\tau\bar{\nu})_{\mathrm{SM}}}{\mathrm{BR}(B \to D\ell\bar{\nu})_{\mathrm{exp}}/\mathrm{BR}(B \to D\ell\bar{\nu})_{\mathrm{SM}}} = 1.34 \pm 0.17\ ,$$

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

it would point to a 20-30% enhancement wrt the SM

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

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



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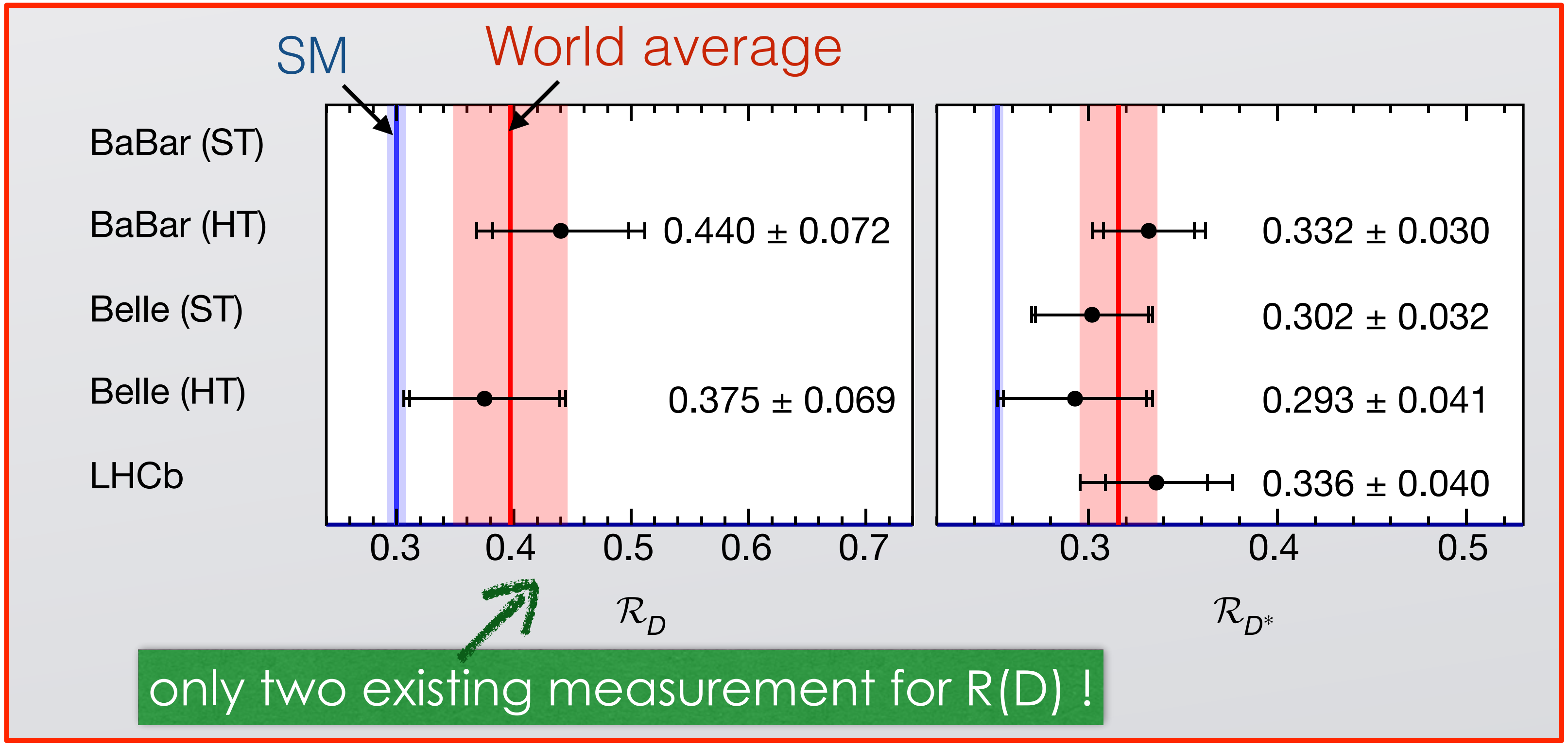
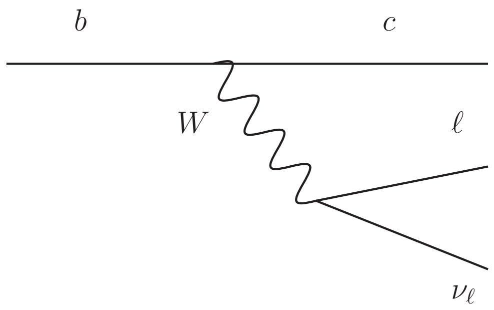


From G. Caria talk in Monday's FP

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

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

another LFU observable



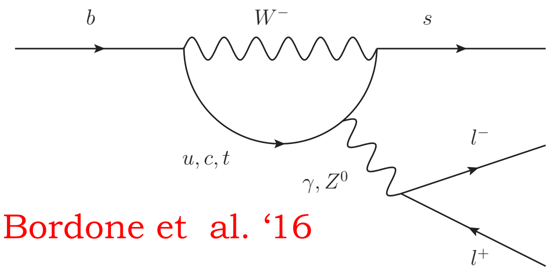
$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.71 \pm 0.17\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst}).$$

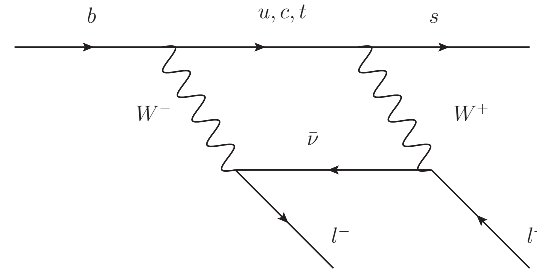
LHCb, arXiv:1711.05623

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

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

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



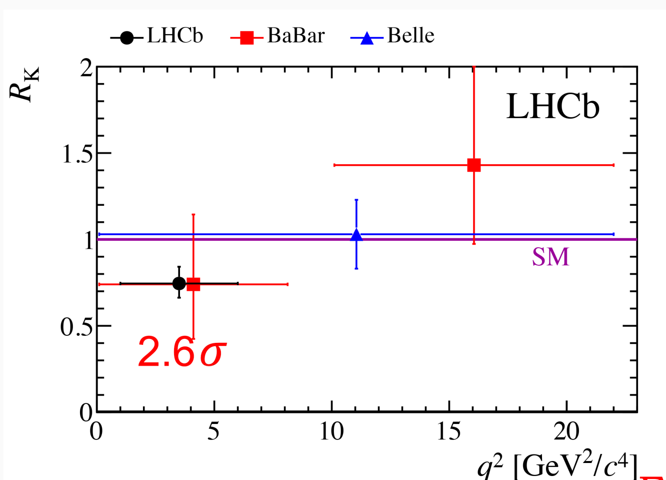


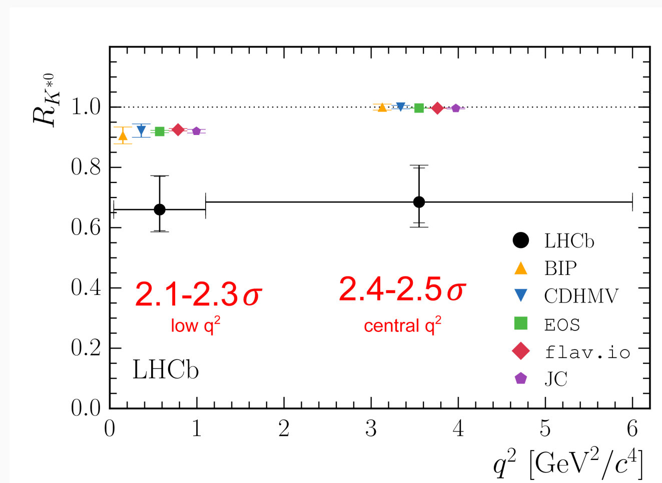
=1+-0.01 in the SM (q^2>1 GeV^2) Bordone et al. '16

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

$$R_K = 0.745^{+0.090}_{-0.074}\ (\mathrm{stat}) \pm 0.036\ (\mathrm{syst}) \qquad R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})\ [0.045 - 1.1]\ \mathrm{GeV}^2 \\ 0.69^{+0.11}_{-0.05}\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})\ [1.1 - 6.0]\ \mathrm{GeV}^2 \end{cases}$$

Compatible with SM at

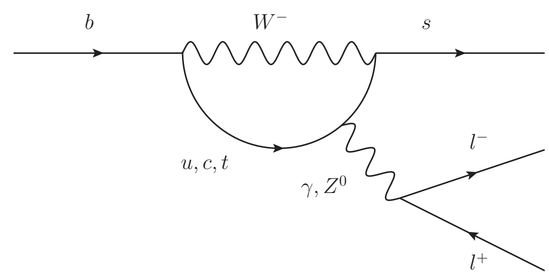


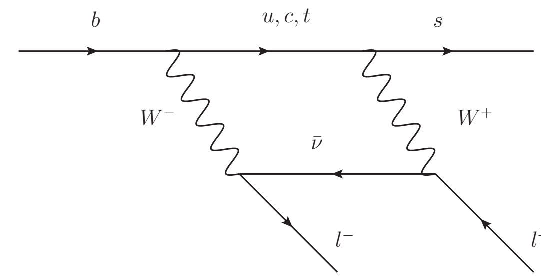


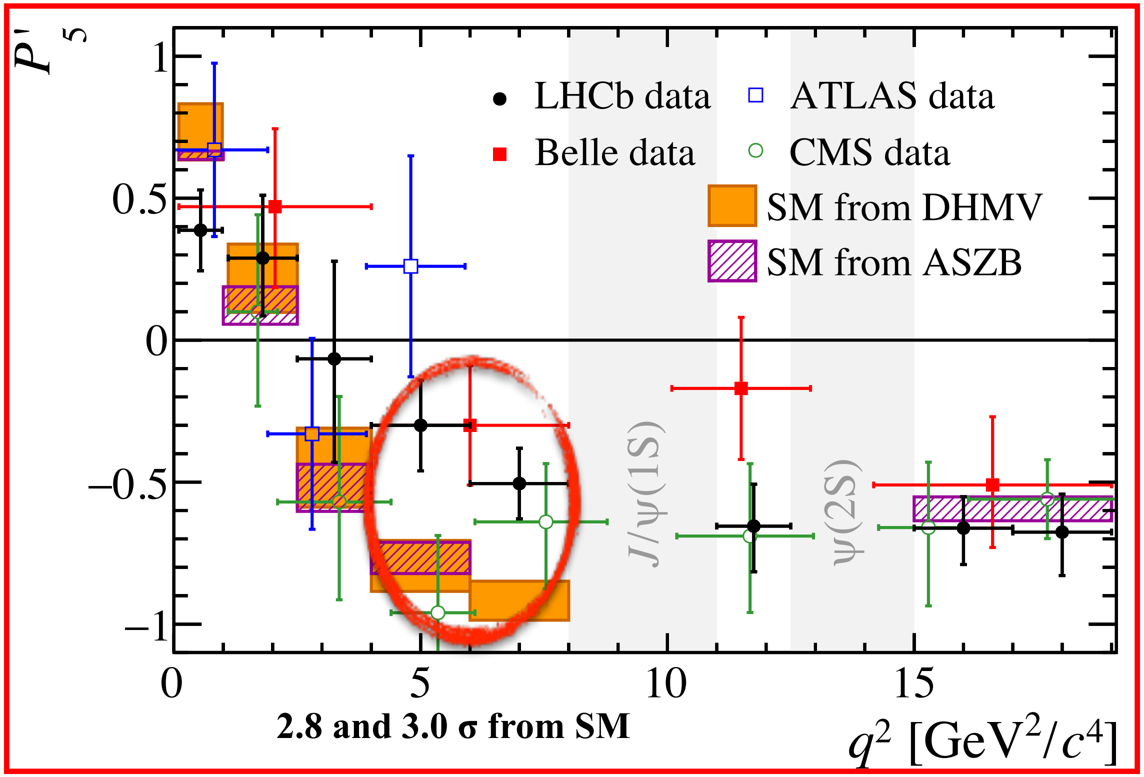
From D. Lancierini talk in Monday's FP

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

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



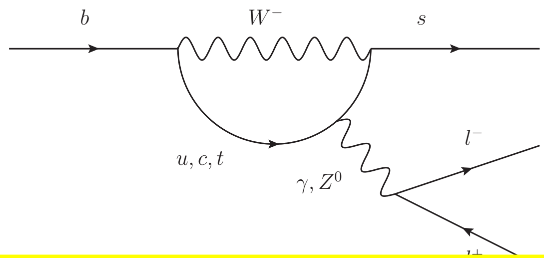


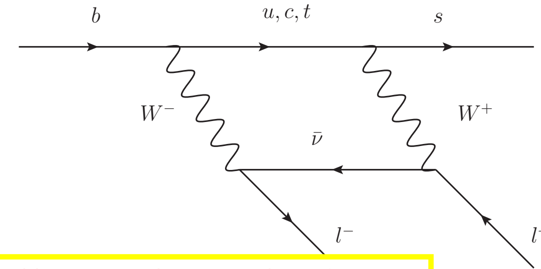


… but are hadronic uncertainties fully under control?

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

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

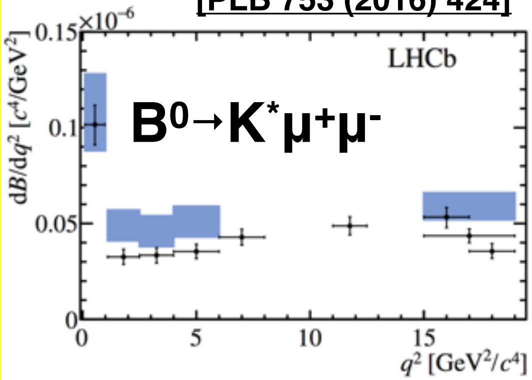




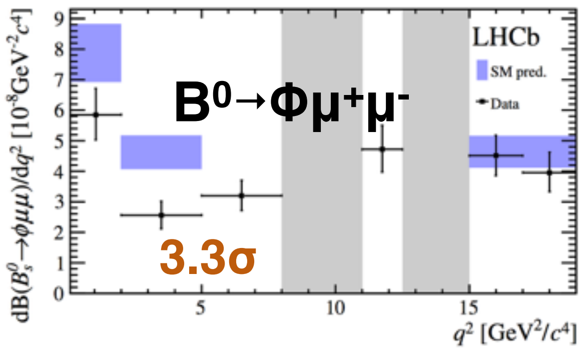
From S. Tolk talk in Thursday's FP

[JHEP 04 (2017) 142]

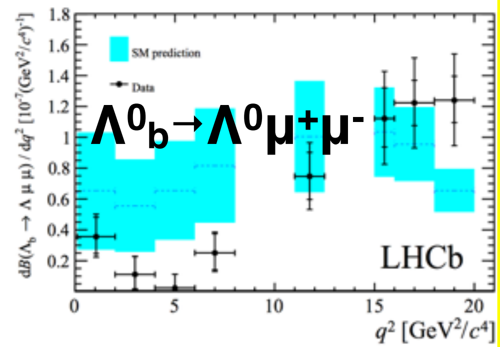
[PLB 753 (2016) 424]



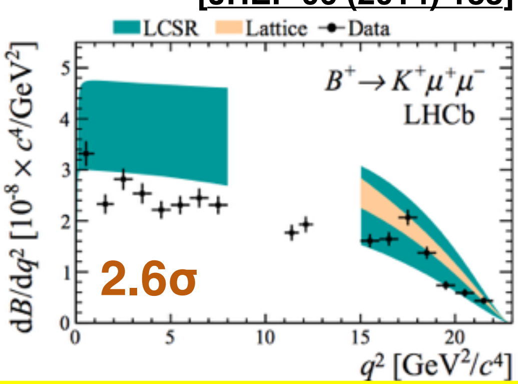
[JHEP 09 (2015) 179]



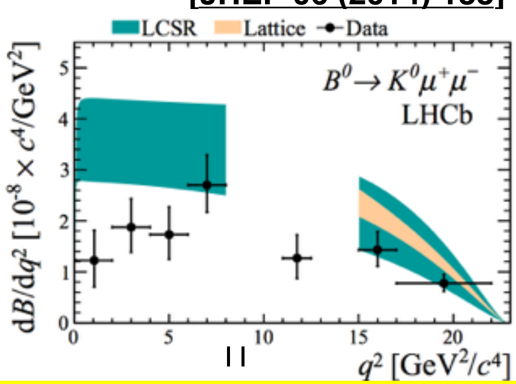
[JHEP 06 (2015) 115]



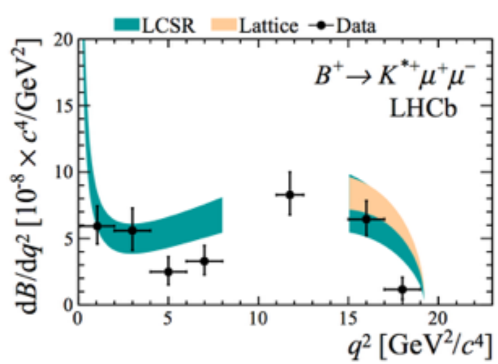
[JHEP 06 (2014) 133]



[JHEP 06 (2014) 133]



[JHEP 06 (2014) 133]

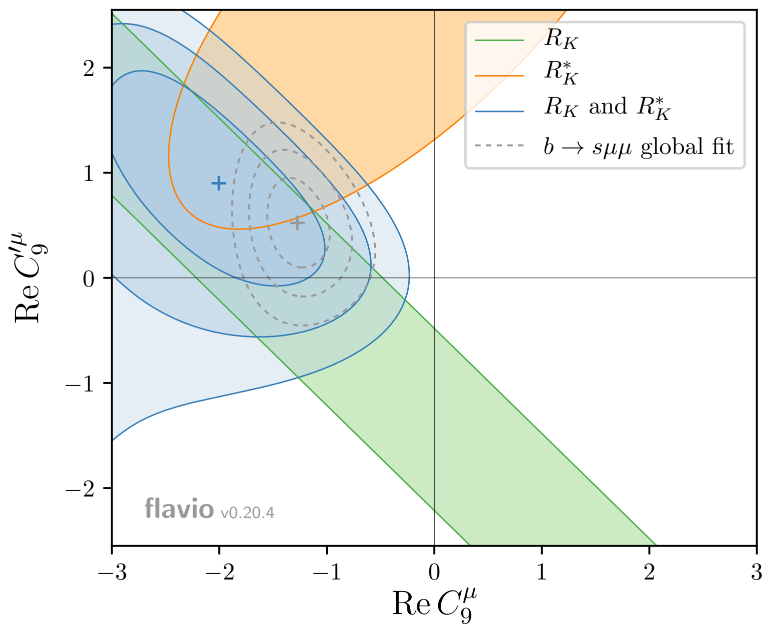


… but are hadronic uncertainties fully under control?

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

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

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



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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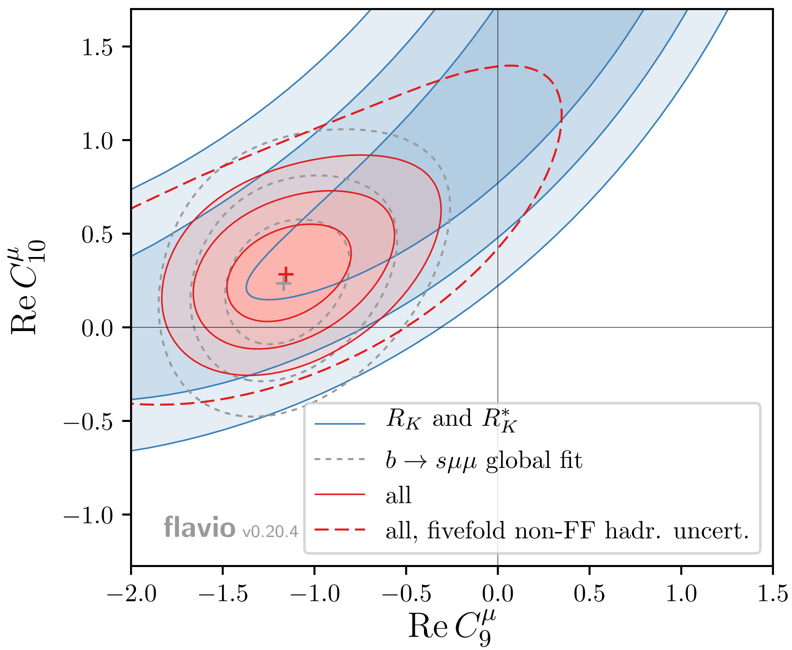

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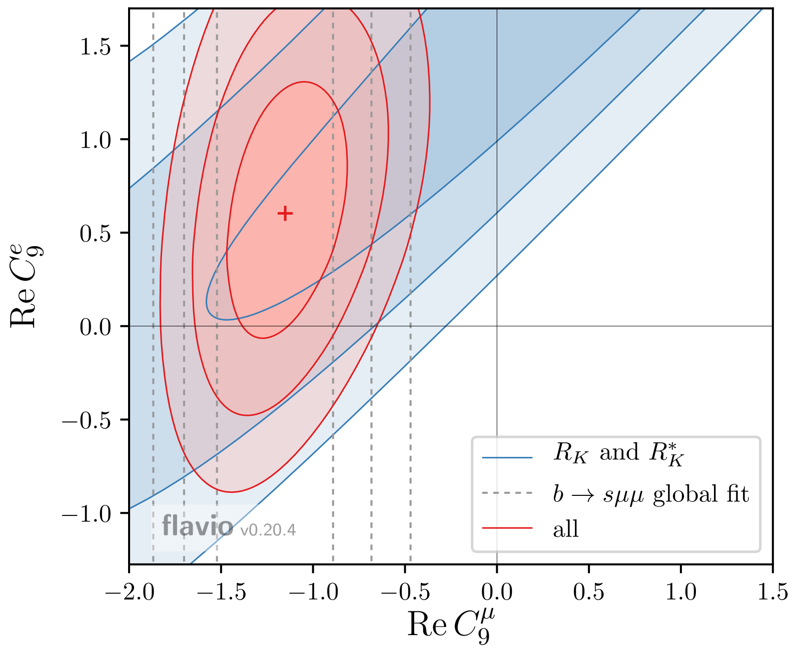

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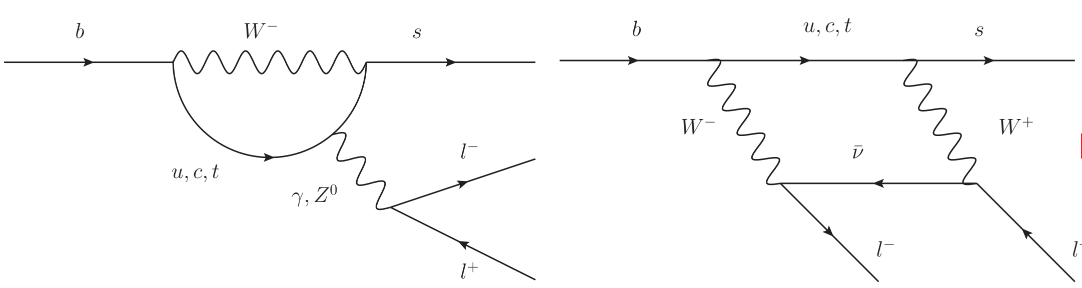
Global fits to $b \to s\ell^+\ell^-$ observables

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

	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

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



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

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"

They both give C_9=-C_{10}

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

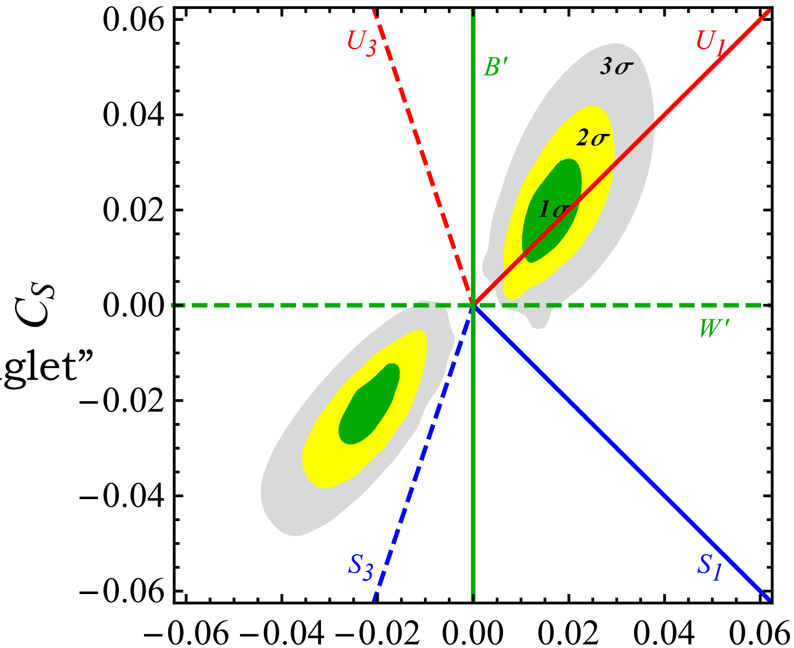
One can attempt to explain class 1 and 2 anomalies simultaneously

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

Combined explanations to class I and II anomalies

Buttazzo, Greljo, Isidori, Marzocca '17

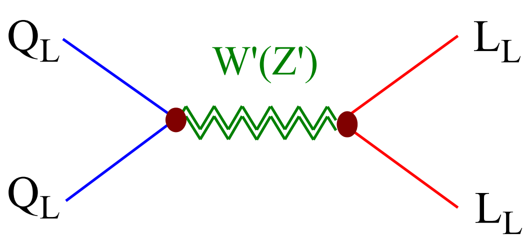


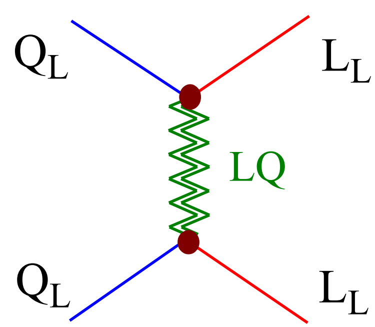
$U(2)_q \times U(2)_l$
flavour structure

"singlet-singlet"

C_T "triplet-triplet"

Simplified UV completions:





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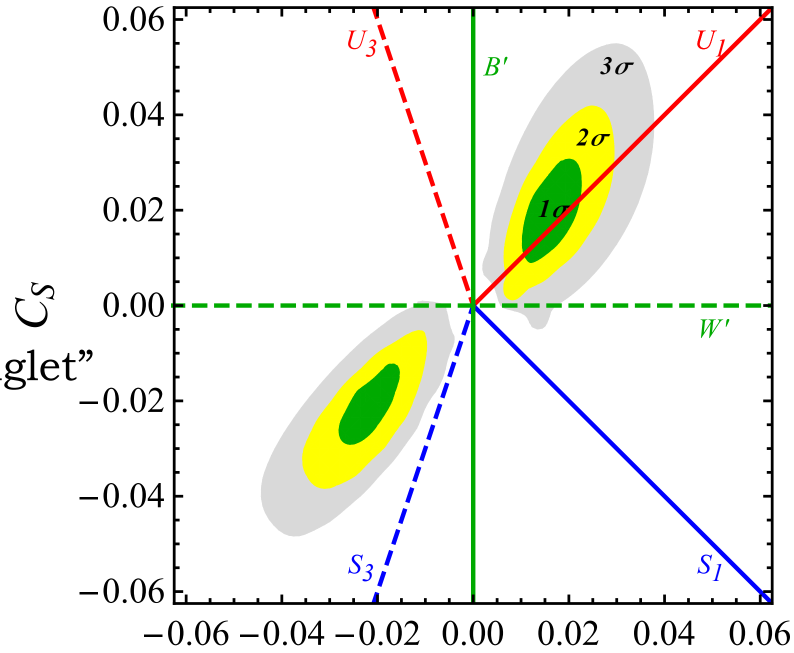


"singlet-singlet"

C_T "triplet-triplet"

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

Simplified UV completions:

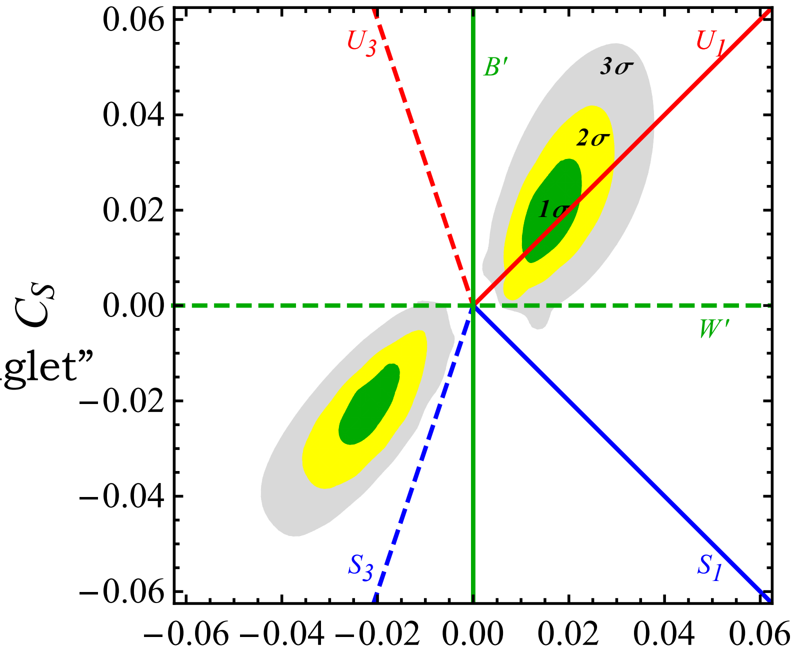
- Colorless vectors: B (1,1,0) W (1,3,0)
- Scalar Leptoquarks: S_1 (3,1,1/3) S_3 (3,3,1/3)
- Vector Leptoquarks: U_1 (3,1,2/3) U_3 (3,3,2/3)

A single vector LQ U_1 can do the job

see also LC Crivellin Ota '15
Bauer Neubert '15

Combined explanations to class I and II anomalies

Buttazzo, Greljo, Isidori, Marzocca '17



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

"singlet-singlet"

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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

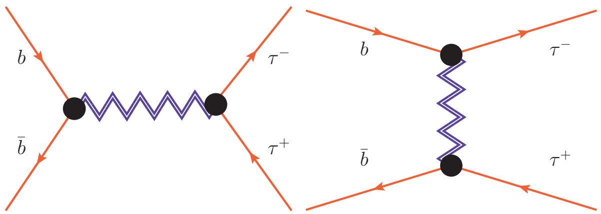
Scales and constraints

Class 1 anomalies (charged-current) require a NP scale at $O(1)$ TeV

Addressing only class 2 anomalies give much more freedom

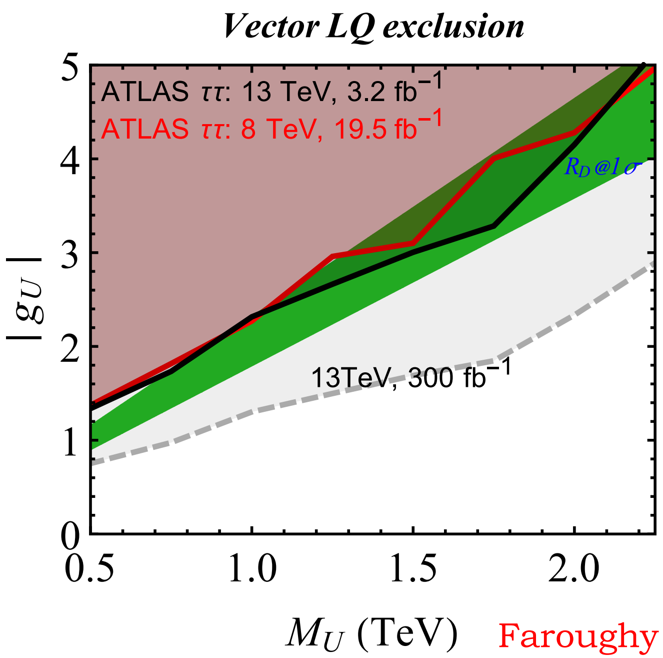
(plenty of beautiful Z' models, but dangerous tree-level contribution to $B_s - \bar{B}_s$)

with scales up to ~100 TeV, but it depends on the flavour structure…

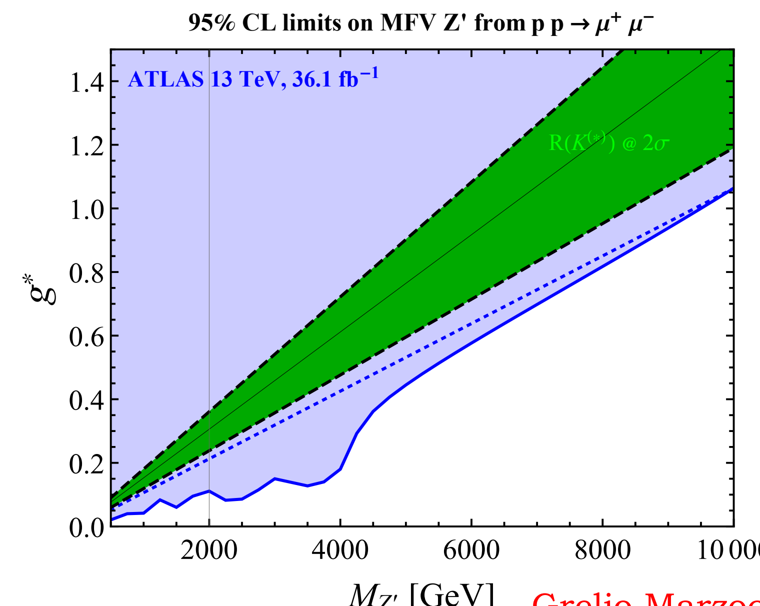


cf. Di Luzio Nardecchia '17

MFV Z':



Faroughy Greljo Kamenik '16



Greljo Marzocca '17

What I could not even mention...

Typically flavour structure rather ad hoc:
plenty of room for model building

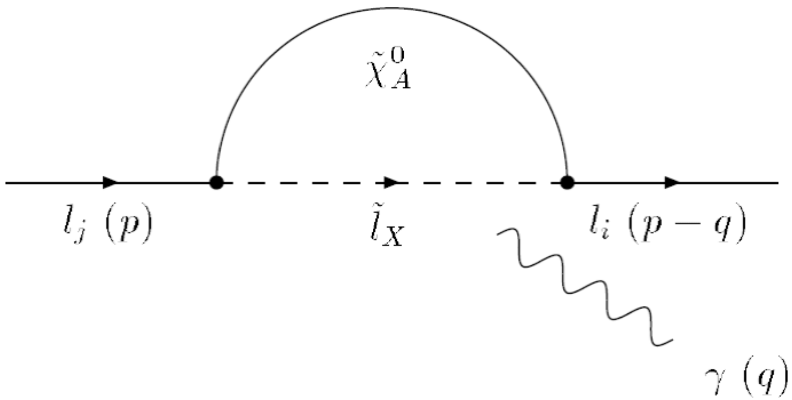
Explanations in R-conserving SUSY excluded by the LHC
(loop&coupling suppression would require a Wino
at the LEP limit and 200-300 GeV down squarks)

But RPV SUSY can!
See FP talks by Dev, Giri, Kumar

Correlated obs: other processes of the two classes
+ depending on the model $B \to K^{(*)}\tau\tau \;/\; \tau\mu, \;\; B_s \to \tau\tau \;/\; \tau\mu, \;\; \ldots$

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

$$T = m_{l_i}\epsilon^\lambda \overline{u}_j(p-q)[iq^\nu\sigma_{\lambda\nu}(A_L P_L + A_R P_R)]u_i(p)$$

⇨

$$\frac{BR(l_i \to l_j\gamma)}{BR(l_i \to l_j\nu_i\bar{\nu_j})} = \frac{48\pi^3\alpha}{G_F^2}(|A_L^{ij}|^2 + |A_R^{ij}|^2)$$

Hisano et al. ‘95

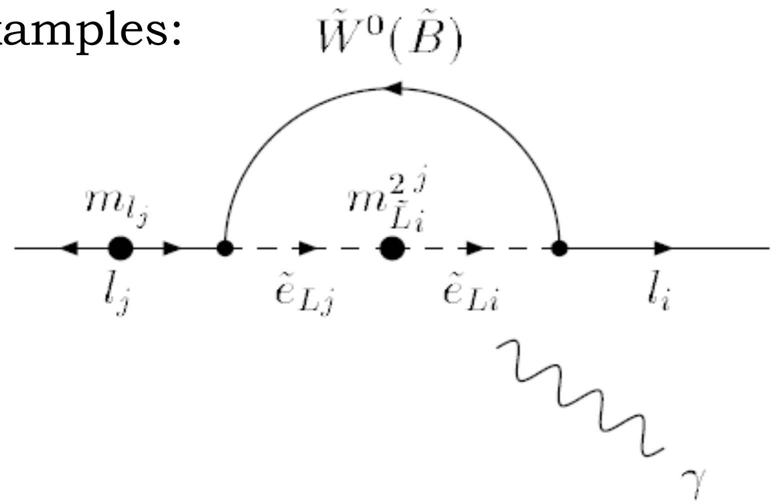
Mass Insertion Approximation

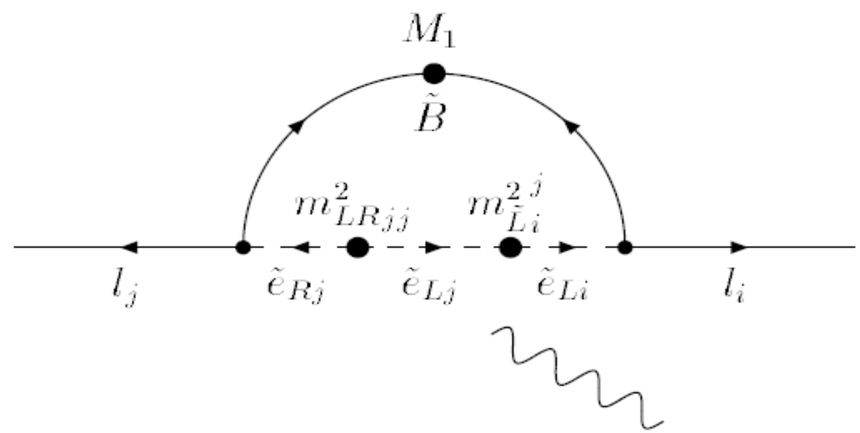
Hall Kostelecky Raby '86
Pokorski Rosiek Savoy '99

Slepton mass matrix:

$$(\tilde{l}_L^\dagger \tilde{l}_R^\dagger) \begin{pmatrix} m_L^2(1+\delta_{LL}) & (A-\mu\tan\beta)m_l + m_L m_R \delta_{LR} \\ (A-\mu\tan\beta)m_l + m_L m_R {\delta_{LR}}^\dagger & m_R^2(1+\delta_{RR}) \end{pmatrix} \begin{pmatrix} \tilde{l}_L \\ \tilde{l}_R \end{pmatrix}$$

Examples:





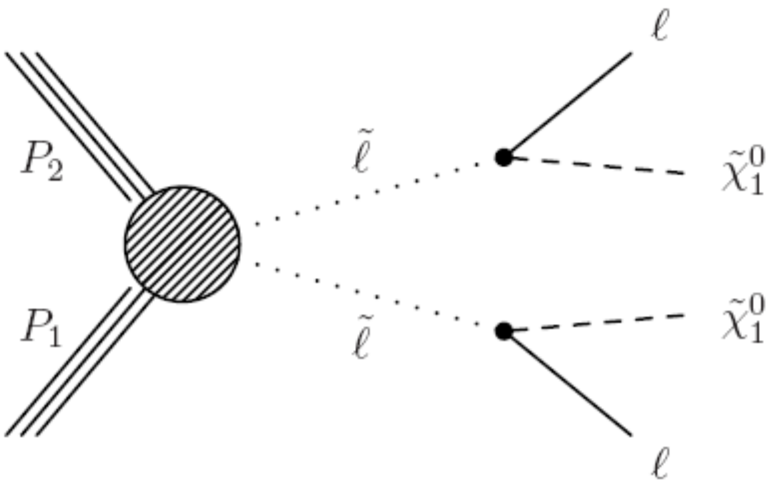
⇒

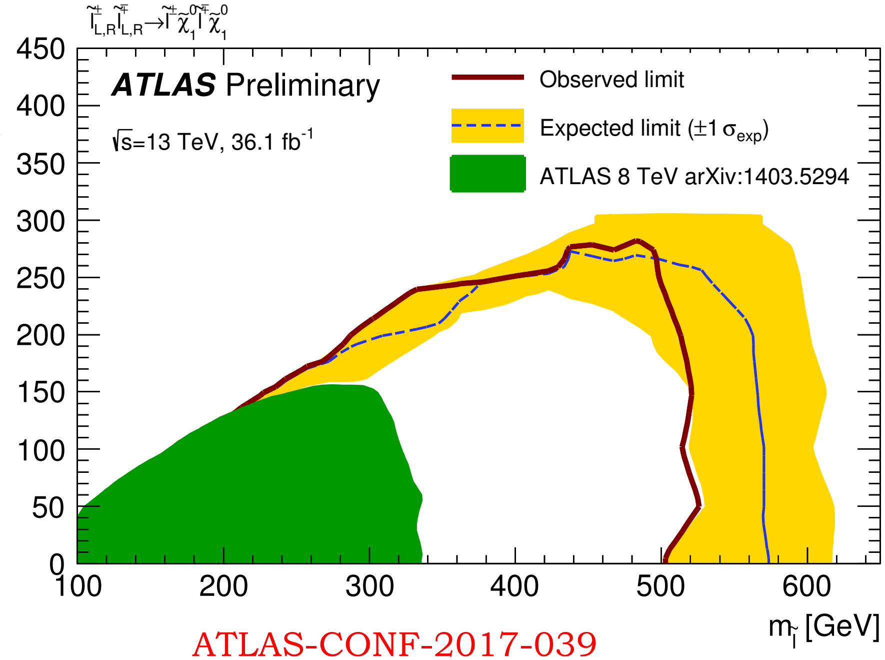
$$\frac{BR(l_i \to l_j \gamma)}{BR(l_i \to l_j \nu_i \bar{\nu_j})} \propto \frac{\delta_{ij}^2}{\tilde{m}^2}$$

⇒ Limits on δ's

Gabbiani Masiero '89
Gabbiani et al. '96
Masina Savoy '02
Paradisi '05 ...

Comparing LFV and LHC bounds

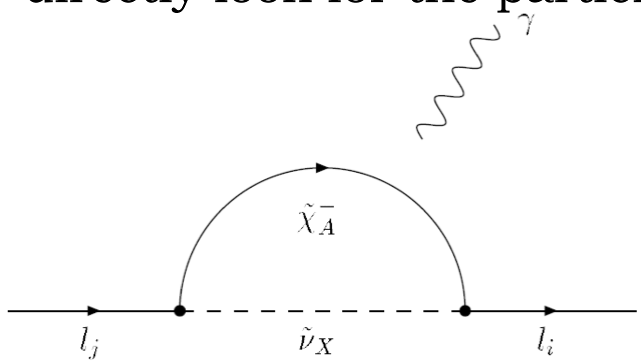


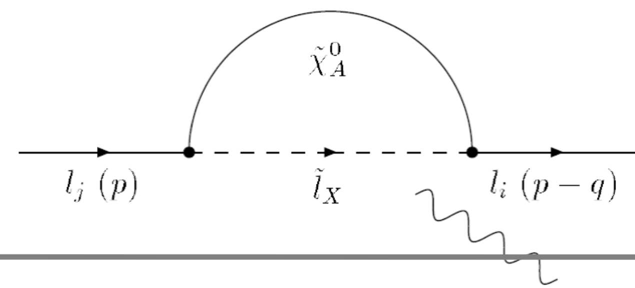


ATLAS-CONF-2017-039

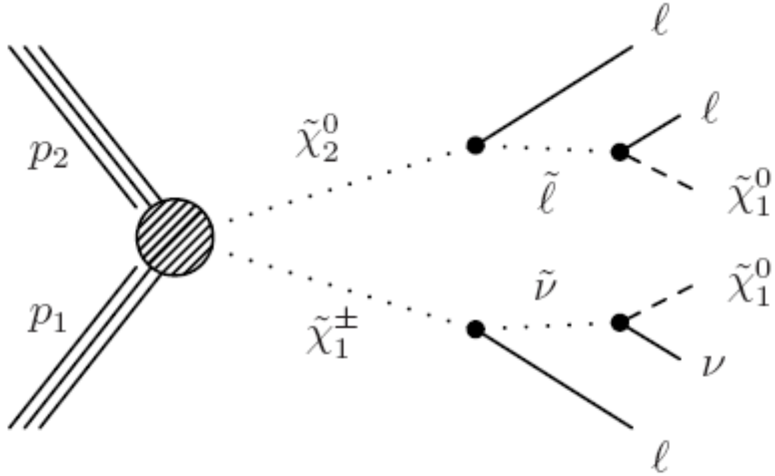
EW-searches at the LHC went far beyond the limits set by LEP

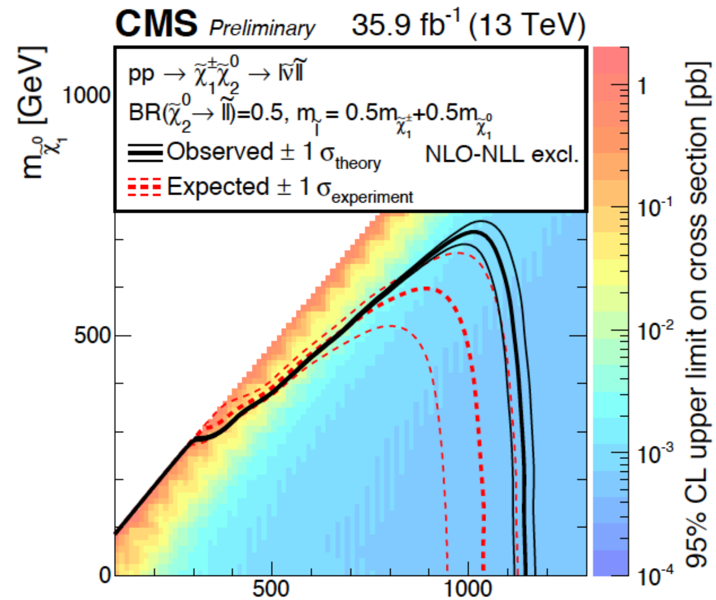
They directly look for the particles that can induce LFV transitions





Comparing LFV and LHC bounds





CMS-PAS-SUS-16-039

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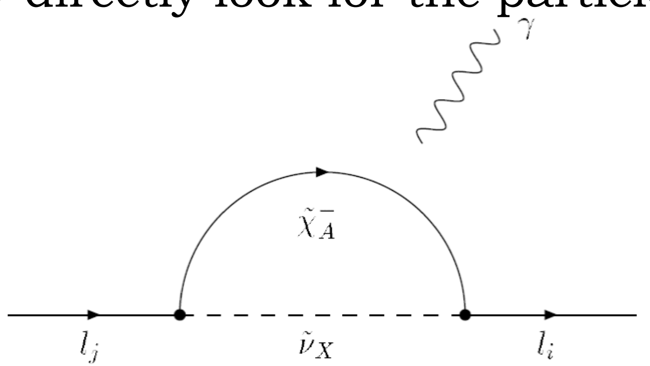
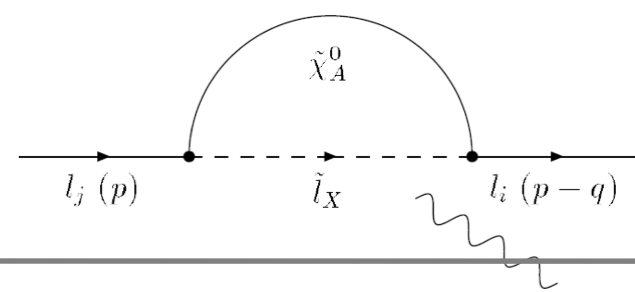


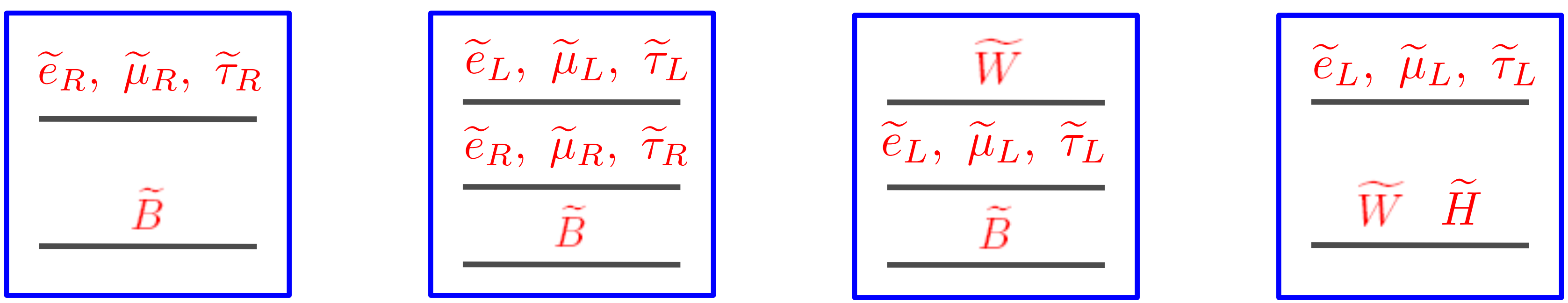


LC Galon Masiero Shadmi Paradisi ‘15
LC Signorelli ‘17

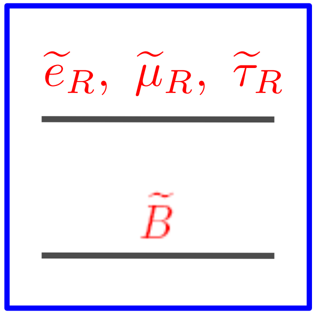
What is the impact of direct searches for SUSY particles at the LHC on the discovery prospects of LFV processes at low-energy experiments?

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

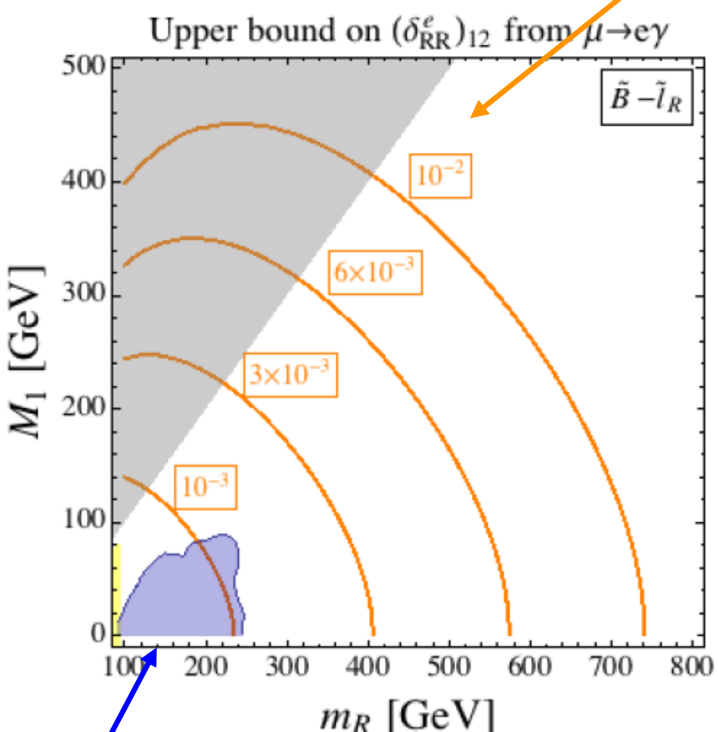
Examples:

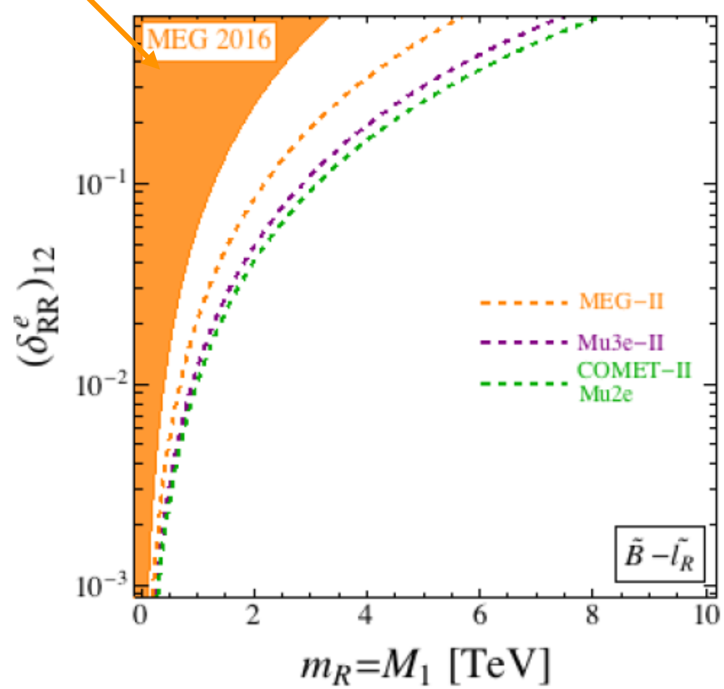


LFV vs LHC bounds within simplified models



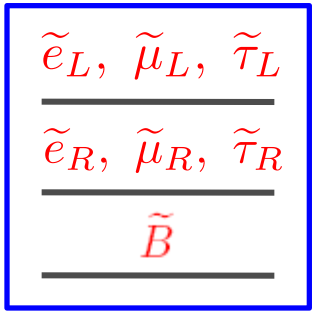
MEG ‘16
$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

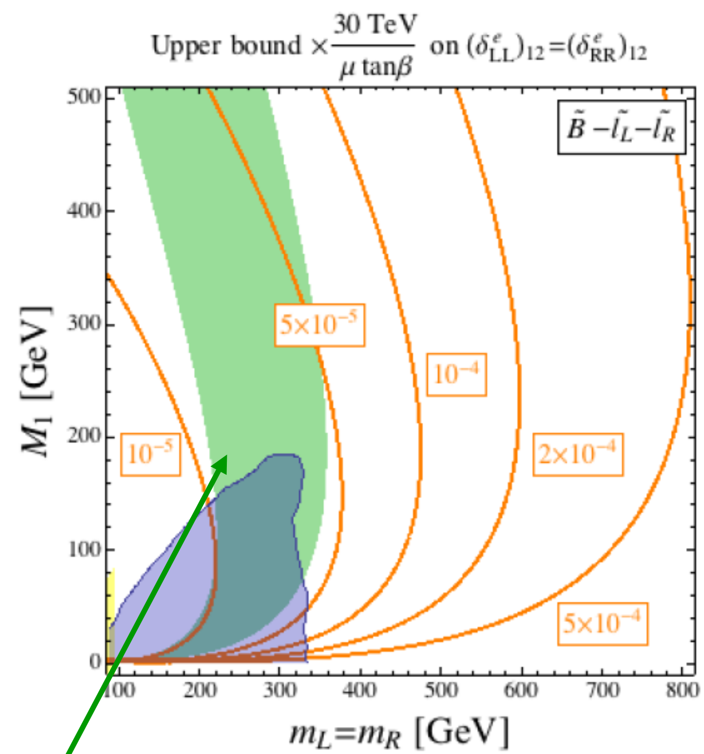


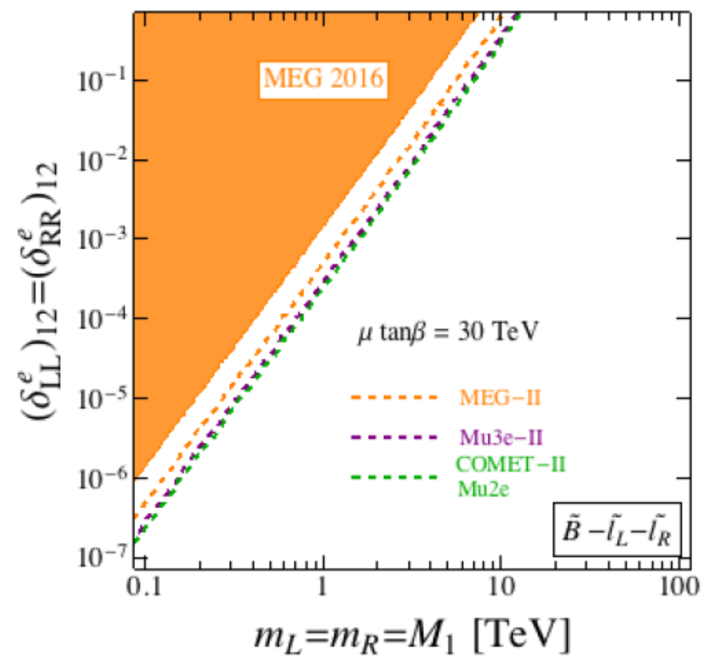


ATLAS arXiv:1403.5294

LFV vs LHC bounds within simplified models







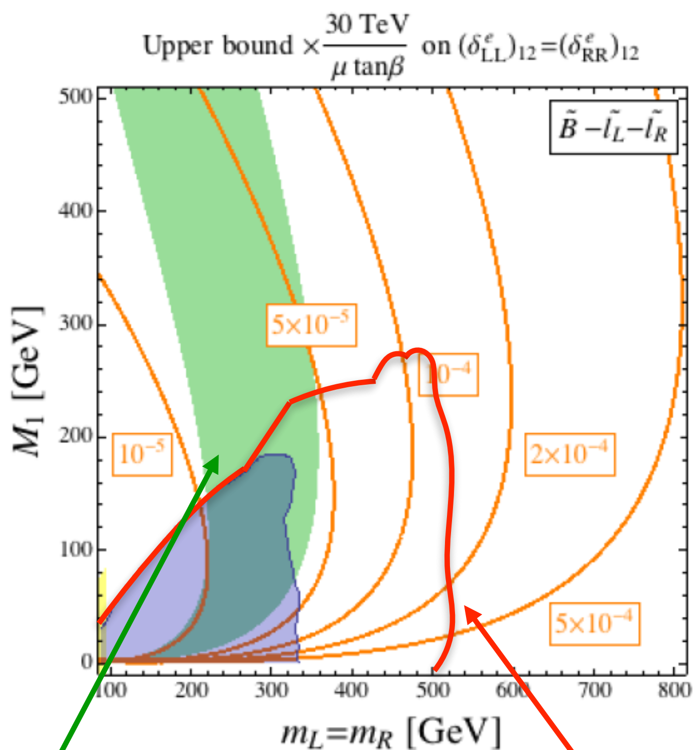
$$\Delta a_\mu \equiv \left|a_\mu^{\rm TH} - a_\mu^{\rm EXP}\right| \lesssim 2\sigma$$

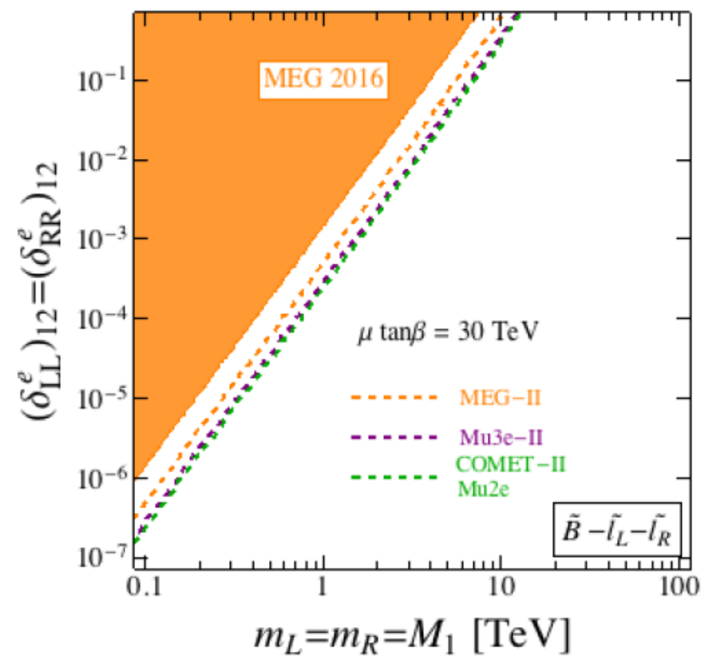
LFV vs LHC bounds within simplified models

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

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

$\widetilde{B}$





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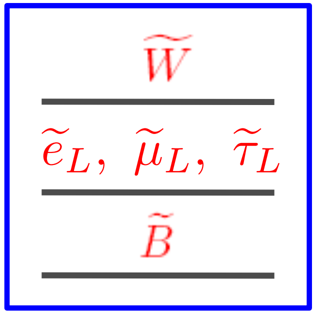
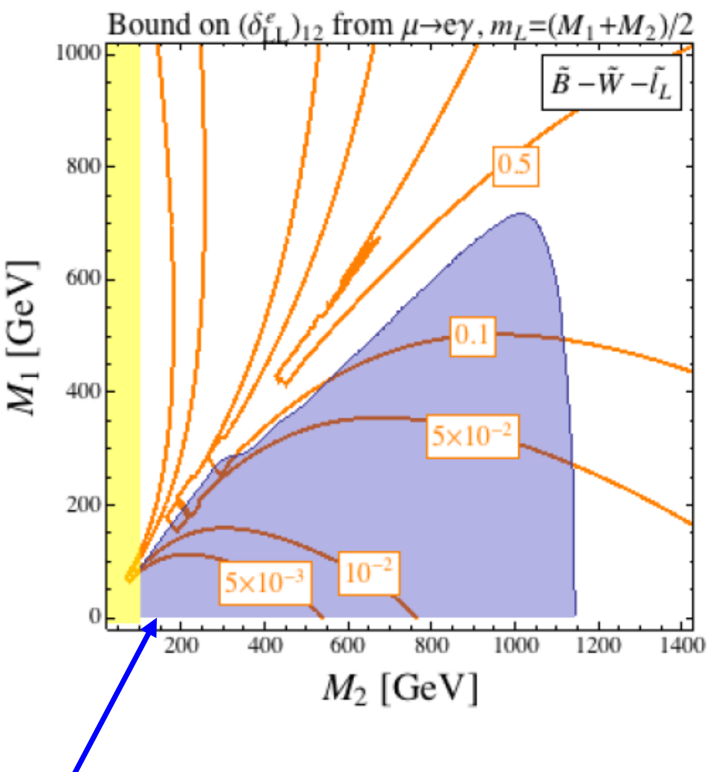
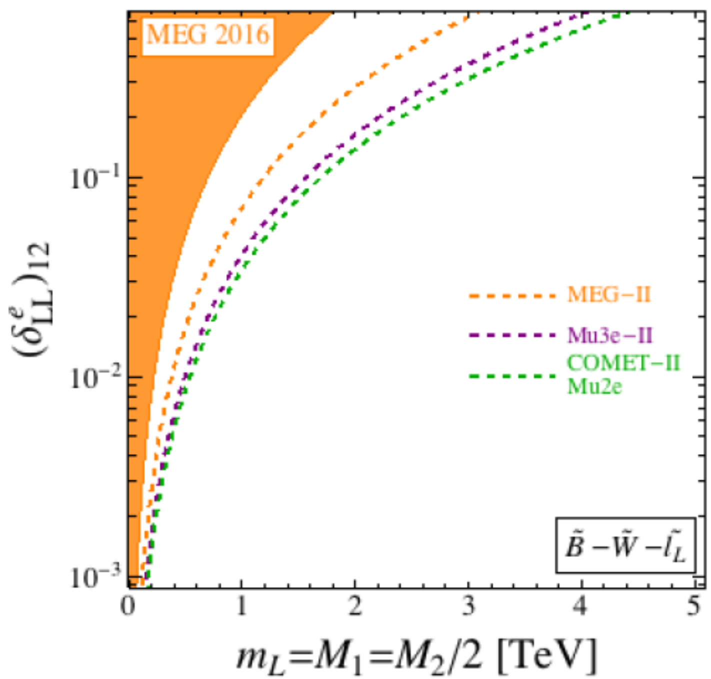
ATLAS-CONF-2017-039

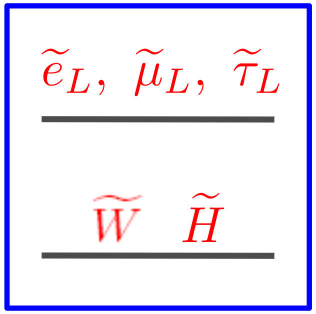
LFV vs LHC bounds within simplified models

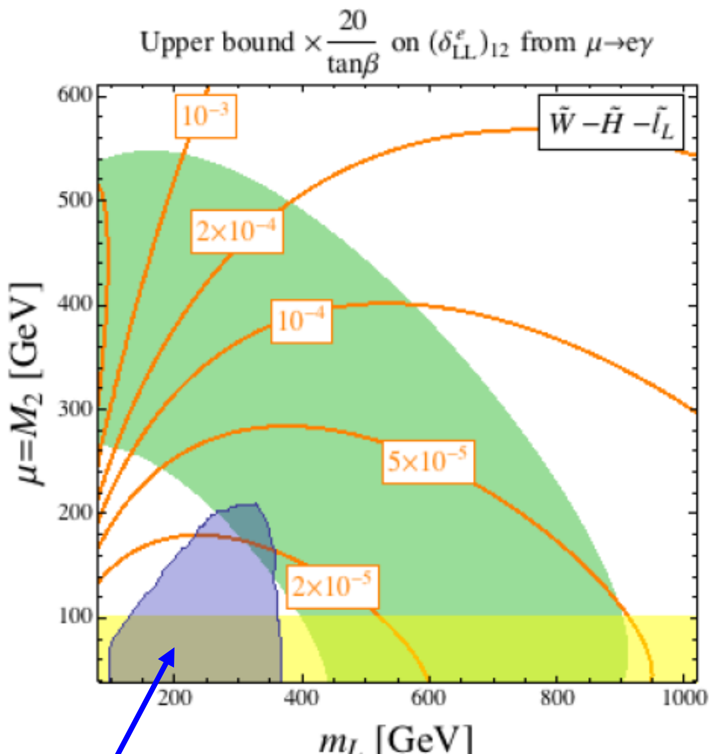


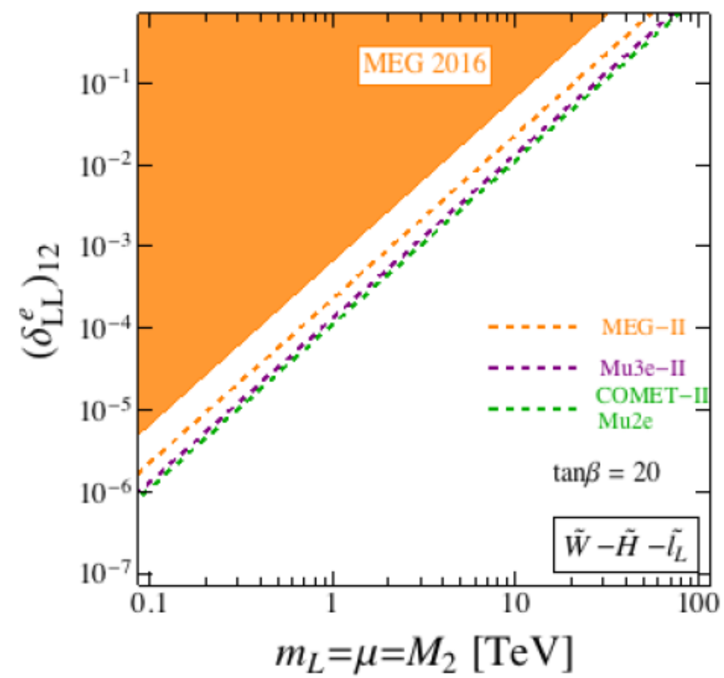




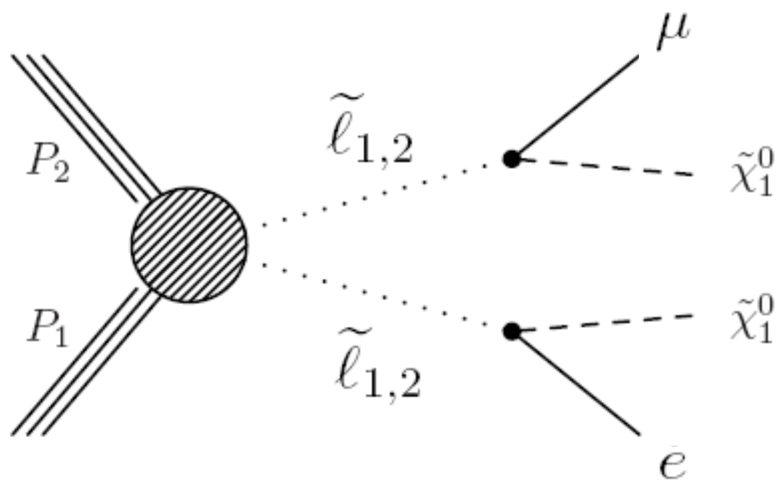
CMS-PAS-SUS-16-039







Eckel et al. arXiv:1408.2841



$$\tilde{\ell}_1 = \cos\theta_{\tilde{\ell}}\,\tilde{\mu} + \sin\theta_{\tilde{\ell}}\,\tilde{e}$$
$$\tilde{\ell}_2 = -\sin\theta_{\tilde{\ell}}\,\tilde{\mu} + \cos\theta_{\tilde{\ell}}\,\tilde{e}$$

Fraction of LFV events:

$$R_{e\mu} \equiv \frac{N(e^+\mu^-) + N(\mu^+e^-)}{N(e^+e^-) + N(\mu^+\mu^-)} = \frac{S_{e\mu}}{1 - S_{e\mu}} \qquad S_{e\mu} \equiv \frac{\sin^2 2\theta}{2}\,\frac{x^4 + 3x^2}{(1+x^2)^2}, \qquad x \equiv \frac{\Delta m_{\tilde{\ell}}}{\Gamma_{\tilde{\ell}}}$$

Arkani-Hamed et al. '96. '97

For maximal smuon-selectron mixing, one has $R_{e\mu} \approx 50\%$ if $\Delta m_{\tilde{\ell}} > \Gamma_{\tilde{\ell}}$!

(if $\Delta m_{\tilde{\ell}} < \Gamma_{\tilde{\ell}}$, decay is faster than oscillation) $\qquad \Gamma_{\tilde{\ell}_L} \approx 10^{-3} m_{\tilde{\ell}_L}$

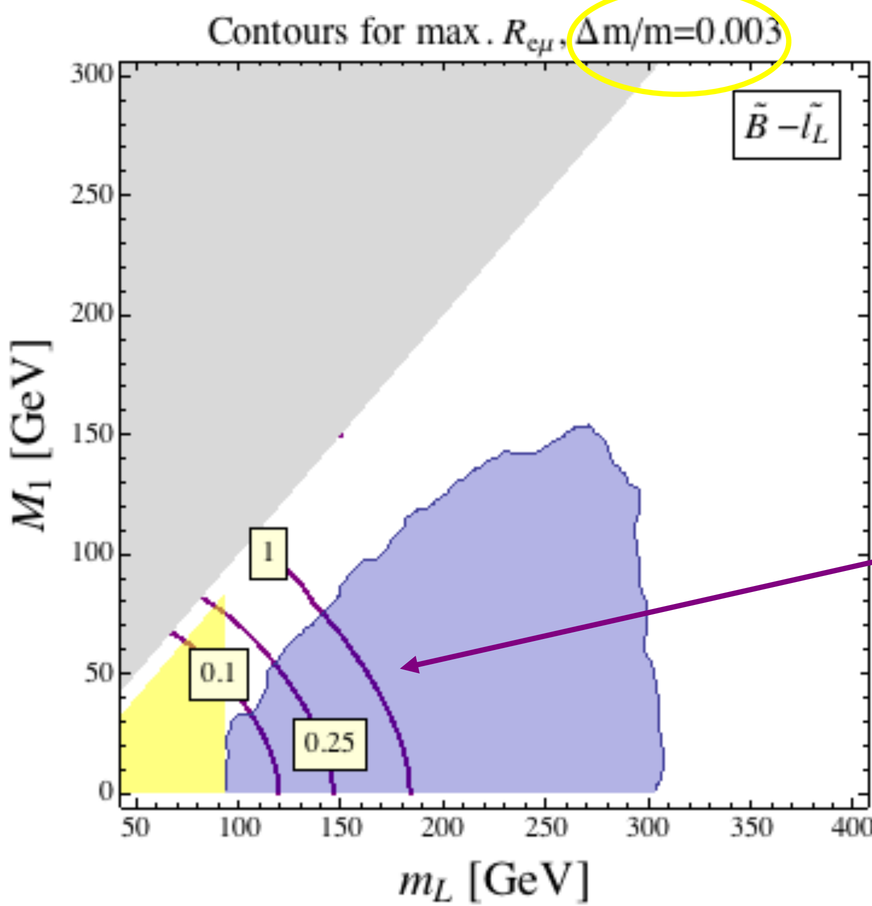
see also Guchait et al. '15

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

$\widetilde{B}$

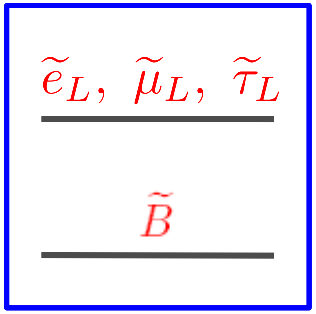
$$\delta \approx 2 \sin\theta_{\tilde{\ell}} \cos\theta_{\tilde{\ell}}\ \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}$$

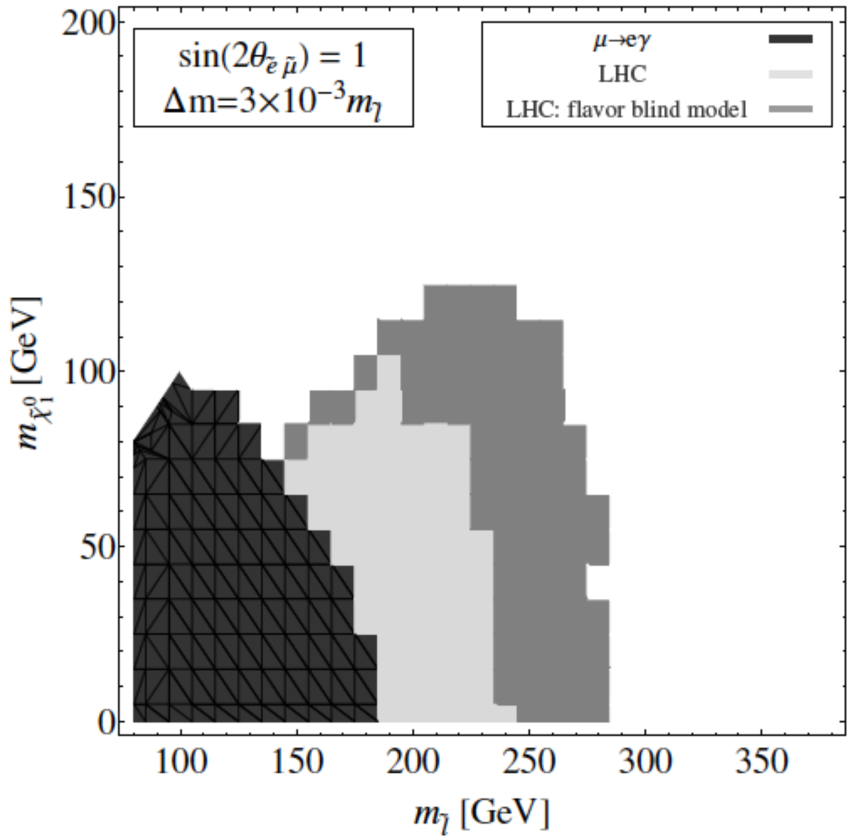
$$\Gamma_{\tilde{\ell}_L} \approx 10^{-3} m_{\tilde{\ell}_L}$$



50% of e-μ events still compatible with MEG!

LC Galon Masiero Shadmi Paradisi '15



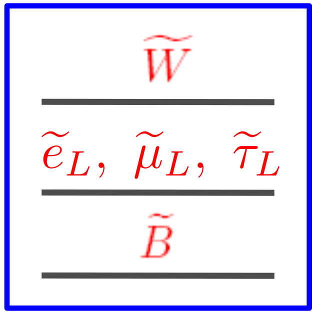


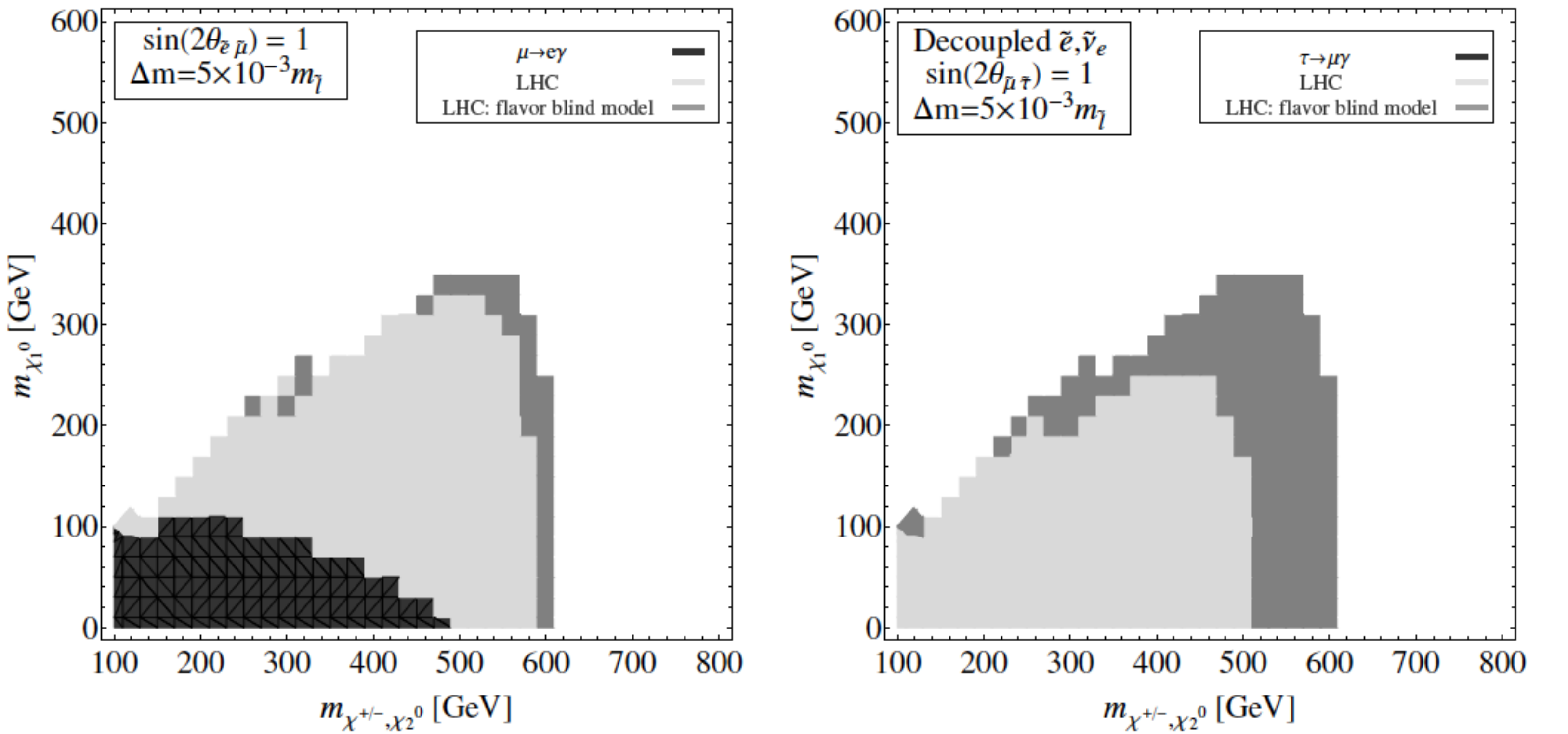
(c) $\frac{\Delta m}{m} = 3\times10^{-3},\ \sin 2\theta = 1$

⇨ LHC bound relaxed by about 50 GeV (with 50% of e-μ events) !

Impact on slepton searches at the LHC

LC Galon Masiero Shadmi Paradisi ‘15





(a) $\Delta m_{\tilde{e}\tilde{\mu}} = 5\times10^{-3} m,\ \sin 2\theta_{\tilde{e}\tilde{\mu}} = 1$ (b) $\Delta m_{\tilde{\mu}\tilde{\tau}} = 5\times10^{-3} m,\ \sin 2\theta_{\tilde{\mu}\tilde{\tau}} = 1$

As we have been knowing for long, there is indeed a SUSY flavour problem, especially in setups accounting for the muon g-2

However, peculiar spectra can alleviate it (and obviously the LHC limits do that too)

LFV can affect the interpretation of slepton/EWKinos searches at the LHC and mass limits can be relaxed

Concluding remarks

There is New Physics out there
but we don't know the scale!

If naturalness paradigm is incorrect,
the next fundamental scale might be >> M_{EW}

FCNC and CPV processes (hadronic and leptonic) are a unique laboratory to search for NP beyond the LHC reach

No established breakdown of the SM yet
but many experiments are at work or in preparation:
they could give us surprises soon!