IFAE 2014

GSSI & LNGS, April 11th 2014

Testing New Physics with flavour violating processes

Lorenzo Calibbi
ULB

UNIVERSITÉ
LIBRE
DE BRUXELLES

Why is Flavour Physics important?

Introduction

Why is Flavour Physics important?

SM flavour puzzle

- Why three families?
- Why the hierarchies?

  $(m_t/m_e = 3.4 \text{ x } 10^5)$

Introduction

Hierarchy of SM fermion masses and mixing

Up quarks

$$\frac{m_c}{m_t} \approx \epsilon^4, \quad \frac{m_u}{m_t} \approx \epsilon^8$$

Down quarks

$$\frac{m_s}{m_b} \approx \epsilon^3, \quad \frac{m_d}{m_b} \approx \epsilon^5$$

CKM matrix

$$V_{CKM} \approx \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

$$\boxed{\epsilon \approx 0.23}$$

Hints for an organizing principle: is there a dynamical explanation?

Introduction

Why is Flavour Physics important?

SM flavour puzzle

- Why three families?
- Why the hierarchies?

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

We need to find the scale of New Physics!

- LHC found a SM-like Higgs
- No sign of new phenomena
- Do we need to go beyond SM at all?

Introduction

Do we really need New Physics?

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

...

Introduction

Do we really need New Physics?

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

...

Testable through Hadronic/Leptonic Flavor/CP Violation?

Clean example: charged Lepton Flavour Violation

- Neutrinos oscillate → Lepton family numbers are not conserved!

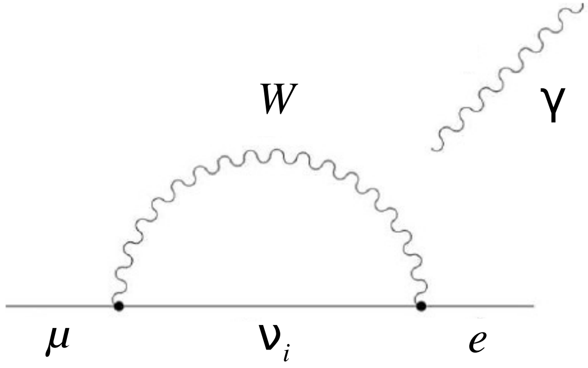
- Can we observe LFV in charged leptons decays?

- In the SM + massive neutrinos:

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

$$\Rightarrow \quad \mathrm{BR}(\mu \to e\gamma) \lesssim \mathcal{O}(10^{-50})$$

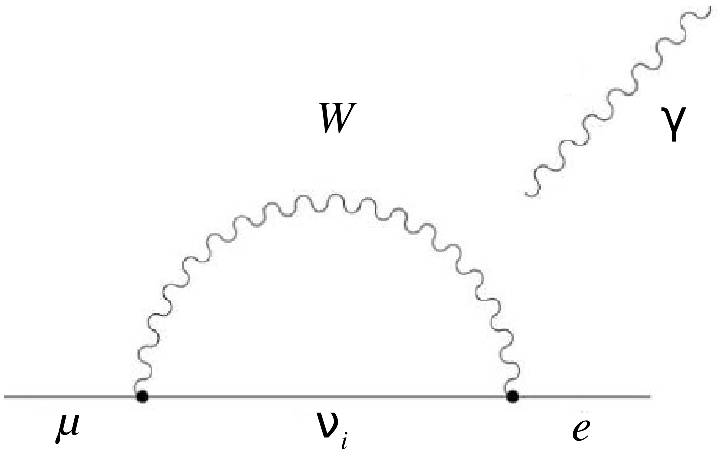
Suppression due to small neutrino masses



Cheng Li ’77, ’80; Petcov ‘77

$\Rightarrow$ In presence of NP at the TeV we can expect large effects!

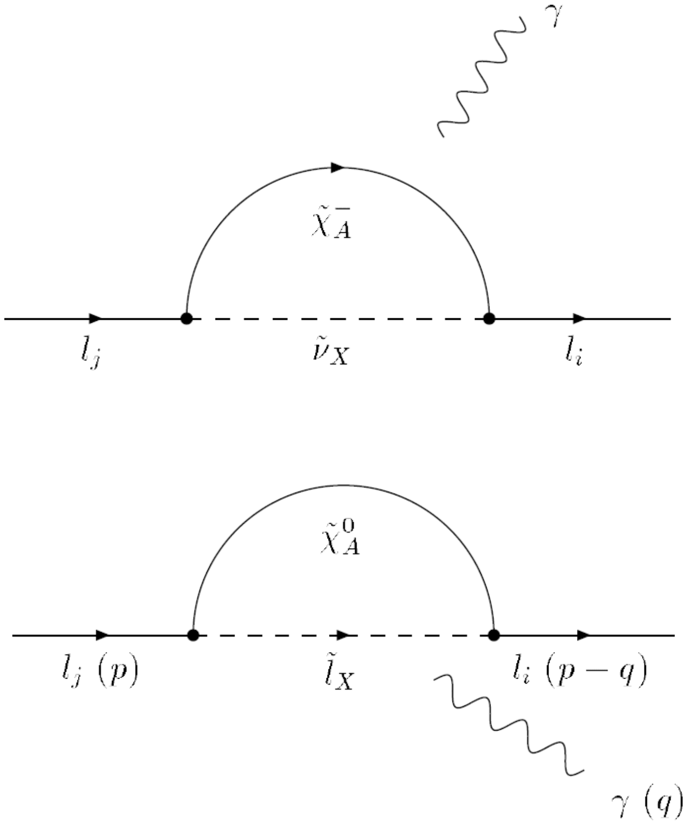
Clean example: charged Lepton Flavour Violation



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

SUSY

Borzumati Masiero '86;
Hisano et al. '95



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

Probing high-energy scales

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

$\mathrm{BR}(\mu \to e\gamma) < 5 \times 10^{-14}$

Process	Relevant operators	Present Bound on Λ (TeV)		Future Bound on Λ (TeV)	
		$C = 1/16\pi^2$	$C = 1$	$C = 1/16\pi^2$	$C = 1$
$\mu \to e\gamma$	$\frac{C}{\Lambda^2}\frac{m_\mu}{16\pi^2}\overline{\mu}_L\sigma^{\mu\nu}e_R F_{\mu\nu}$	50	—	90	—
$\mu \to eee$	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{e}_L\gamma^\mu e_L)$	17	210	170	2100
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{e}_R e_L)$	10	120	100	1200
$\mu \to e$ in Ti	$\frac{C}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{d}_L\gamma^\mu d_L)$	30	420	580	7300
	$\frac{C}{\Lambda^2}(\overline{\mu}_L e_R)(\overline{d}_R d_L)$	60	750	1000	13000

updated from LC Lalak Pokorski Ziegler ‘12

$\mathrm{BR}(\mu \to eee) < 10^{-16}$

$\mathrm{CR}(\mu \to e \text{ in Ti}) < 5 \times 10^{-17}$

Probing high-energy scales

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

Hadronic FCNC and CPV:

Isidori Nir Perez ‘10

Operator	Bounds on Λ in TeV $(c_{ij}=1)$		Bounds on c_{ij} $(\Lambda = 1$ TeV$)$		Observables
	Re	Im	Re	Im	
$(\bar s_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar s_R\, d_L)(\bar s_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar c_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar c_R\, u_L)(\bar c_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar b_R\, d_L)(\bar b_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar b_R\, s_L)(\bar b_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

Update for D-$\overline{\rm D}$: Carrasco et al. '14

An example: low-energy flavour models

- SM fermions charged under a new horizontal symmetry G_F
- G_F forbids Yukawa couplings at the renormalisable level
- G_F spontanously broken by “flavons” vevs $\langle\phi_I\rangle$
- Yukawas arise as higher dimensional operators

Froggatt Nielsen ‘79

Leurer Seiberg Nir ’92, ’93

$$W_{yuk} = y^U_{ij} q_i u^c_j h_u + y^D_{ij} q_i d^c_j h_d$$

$$\boxed{y^{U,D}_{ij} \sim \prod_I \left(\frac{\langle\phi_I\rangle}{M}\right)^{n^{U,D}_{I,ij}}}$$

$\phi_I < M \quad \Rightarrow \quad \epsilon_I \equiv \langle\phi_I\rangle/M \qquad n^{U,D}_{I,ij}$ dictated by the symmetry

What is G_F ?

An example: low-energy flavour models

G_F abelian or non-abelian, continuous or discrete

U(1), U(1)xU(1), SU(2), SU(3), SO(3), A_4...

Froggatt Nielsen '79; Leurer Seiberg Nir '92, '93; Ibanez Ross '94; Dudas Pokorski Savoy '95; Binetruy Lavignac Ramond '96; Barbieri Dvali Hall '95; Pomarol Tommasini '95; Berezhiani Rossi '98; King Ross '01; Altarelli Feruglio '05...

U(1) example

Chankowski et al. '05

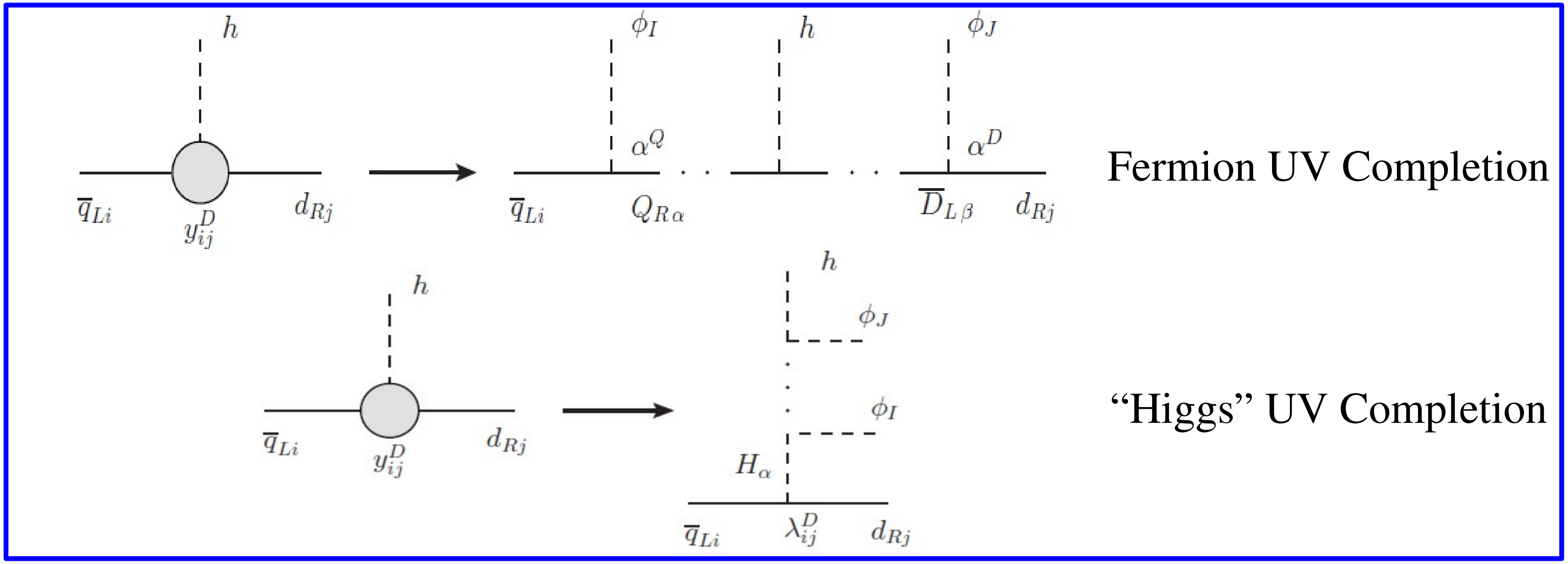
$$\begin{array}{lcl} q_{1,2,3} & : & (3,2,0) \\ u^c_{1,2,3} & : & (3,2,0) \\ d^c_{1,2,3} & : & (2,1,1) \end{array} \qquad \phi \;:\; -1 \qquad \Longrightarrow \qquad \begin{array}{l} y^U_{ij} \sim \epsilon^{q_i+u_j} \\ y^D_{ij} \sim \epsilon^{q_i+d_j} \end{array} \qquad \epsilon = \phi/M \approx 0.23$$

$$Y_u \sim \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \qquad\qquad Y_d \sim \begin{pmatrix} \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^2 & \epsilon & \epsilon \end{pmatrix}$$

What is *M* ?

An example: low-energy flavour models

- If smaller than M_{Pl}, M can be interpreted as the mass scale of new degrees of freedom: the “flavour messengers”
- New fields in vector-like representations of the SM group and G_F-charged
- Effective Yukawa couplings generated by integrating out the messengers.
- Two possibilities: heavy fermions or heavy scalars:



Fermion UV Completion

“Higgs” UV Completion

⇒ messengers mix with SM fermions or scalar fields and induce FCNC

An example: low-energy flavour models

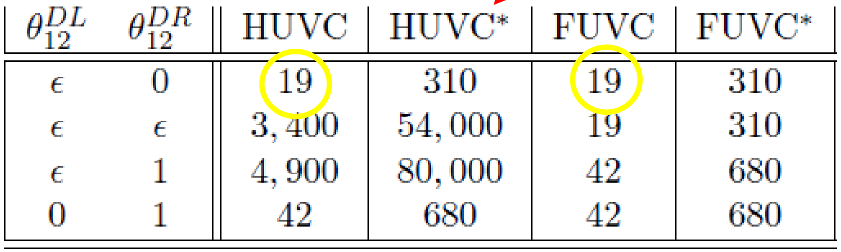
How light can the messenger sector be?

Bounds on M (in TeV):

CPC

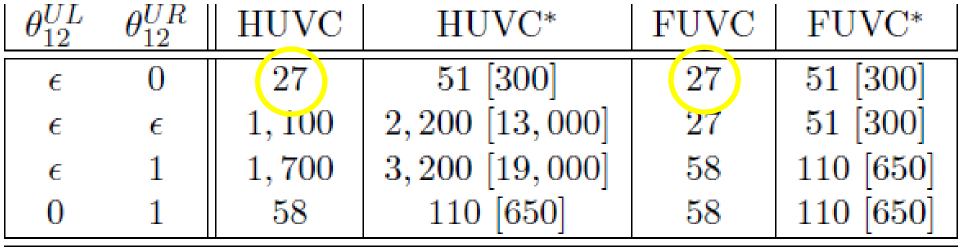
CPV

$K-\overline{K}$



θ_{12}^{DL}	θ_{12}^{DR}	HUVC	HUVC*	FUVC	FUVC*
ϵ	0	19	310	19	310
ϵ	ϵ	3, 400	54, 000	19	310
ϵ	1	4, 900	80, 000	42	680
0	1	42	680	42	680

$D-\overline{D}$



θ_{12}^{UL}	θ_{12}^{UR}	HUVC	HUVC*	FUVC	FUVC*
ϵ	0	27	51 [300]	27	51 [300]
ϵ	ϵ	1, 100	2, 200 [13, 000]	27	51 [300]
ϵ	1	1, 700	3, 200 [19, 000]	58	110 [650]
0	1	58	110 [650]	58	110 [650]

⇨ $M \gtrsim 20 \text{ TeV}$

$M \gtrsim O(1)$ TeV for non-abelian symmetries

Still possible: large effects in LFV decays, $B_{d,s}$ mixing and decays, etc.

LC Lalak Pokorski Ziegler '12

An example: low-energy flavour models

How light can the messenger sector be?

Bounds on *M* (in TeV):

CPC

CPV

$K-\overline{K}$

θ_{12}^{DL}	θ_{12}^{DR}	HUVC	HUVC*	FUVC	FUVC*
ϵ	0	19	310	19	310
ϵ	ϵ	3,400	54,000	19	310
ϵ	1	4,900	80,000	42	680
0	1	42	680	42	680

$D-\overline{D}$

θ_{12}^{UL}	θ_{12}^{UR}	HUVC	HUVC*	FUVC	FUVC*
ϵ	0	27	51 [300]	27	51 [300]
ϵ	ϵ	1,100	2,200 [13,000]	27	51 [300]
ϵ	1	1,700	3,200 [19,000]	58	110 [650]
0	1	58	110 [650]	58	110 [650]

LFV:

$$\mathrm{BR}(\mu\to e\gamma)\simeq 5.3\times10^{-12}\left(\frac{19\ \mathrm{TeV}}{M}\right)^4\left(\frac{\max(\theta_{12}^{EL},\theta_{12}^{ER})}{\epsilon}\right)^2,$$

$$\mathrm{BR}(\mu\to eee)\simeq 2.9\times10^{-13}\left(\frac{19\ \mathrm{TeV}}{M}\right)^4\left(\frac{\max(\theta_{12}^{EL},\theta_{12}^{ER})}{\epsilon}\right)^2\left(\frac{\theta_{12}^{EL}}{\epsilon}\right)^2\left(\frac{\theta_{12}^{ER}}{\epsilon}\right)^2$$

LC Lalak Pokorski Ziegler '12

Selected observables

- $B_{s,d} \to \mu^+\mu^-$
- $B \to K^* \mu^+\mu^-$
- Charm CPV
- Charged LFV

For the experimental situation see talks by Baldini, Sarra, Di Canto, Galanti, Lanfranchi

$B_{s,d} \to \mu^+\mu^-$

Predicted to be very rare in the SM:

the amplitude is loop, CKM and helicity suppressed

For long time considered “golden channels” for

discovery of New Physics

Discovered by LHCb in 2012:

the rate agrees with the SM expectaction

$B_{s,d} \to \mu^+\mu^-$

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\overline{\mathcal{B}}(B_d \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

LHCb (3/fb) + CMS (25/fb)

[LHCb arXiv:1307.5024]
[CMS arXiv:1307.5025]

New SM calculation:

Standard Model predictions @ (NLO EW + NNLO QCD)

in OS-2 Scheme

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$\overline{\mathcal{B}}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

$$\overline{\mathcal{B}}(B_s \to e^+e^-) = (8.54 \pm 0.55) \times 10^{-14}, \quad \overline{\mathcal{B}}(B_s \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7},$$

$$\overline{\mathcal{B}}(B_d \to e^+e^-) = (2.48 \pm 0.21) \times 10^{-15}, \quad \overline{\mathcal{B}}(B_d \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

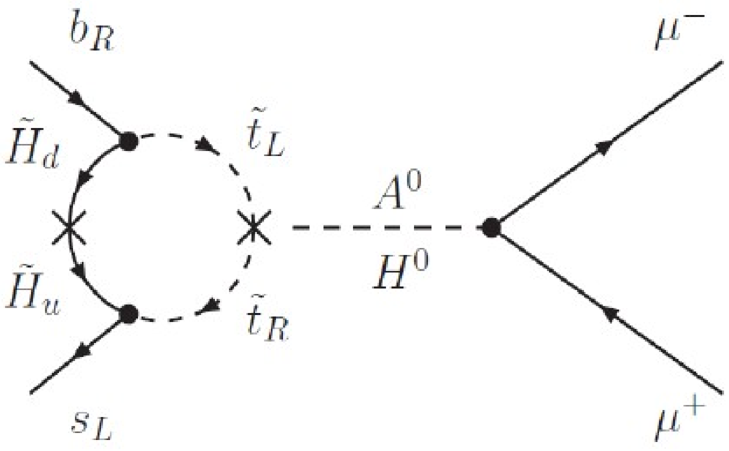
[CB/Gorbahn/Hermann/Misiak/Stamou/Steinhauser arXiv:1311.0903]

Error budget	f_{B_q}	CKM	τ_H^q	M_t	α_s	non-param.	other param.	$\sum$
$\overline{\mathcal{B}}_{s\mu}$	4.0%	4.3%	1.3%	1.6%	0.1%	1.5%	< 0.1%	6.4%
$\overline{\mathcal{B}}_{d\mu}$	4.5%	6.9%	0.5%	1.6%	0.1%	1.5%	< 0.1%	8.5%

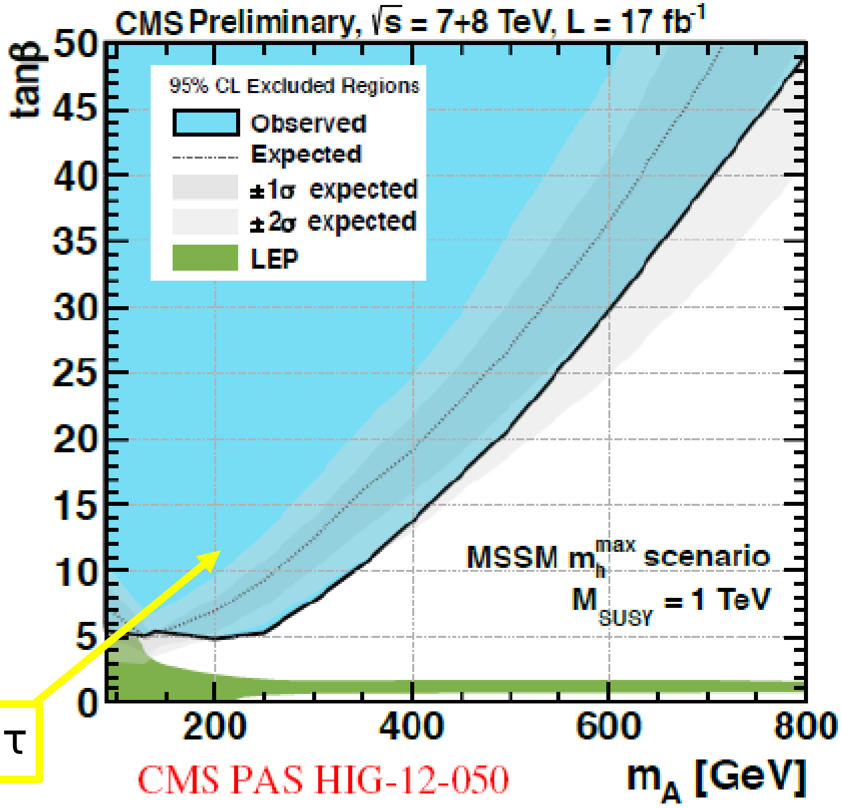
from C. Bobeth's talk at Moriond EW 2014

$B_{s,d} \to \mu^+\mu^-$

Does this result kill SUSY?



$$\propto \frac{\tan^3\beta}{M_A^2}$$

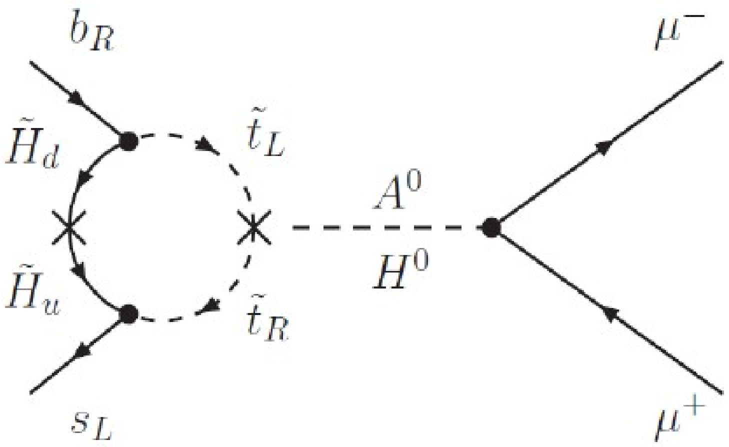


CMS PAS HIG-12-050

pp → h,H,A→ττ

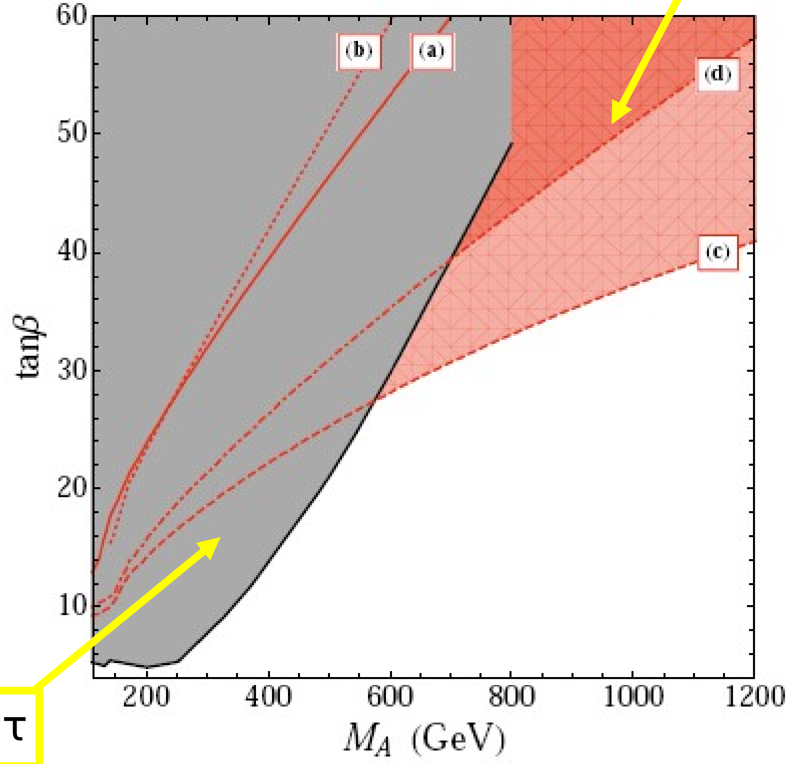
$B_{s,d} \to \mu^+\mu^-$

Does this result kill SUSY?



$$\propto \frac{\tan^3\beta}{M_A^2}$$

$B_s \longrightarrow \mu\mu$



pp → h,H,A→ττ

Altmannshofer et al. ‘12

Well... no more than direct searches at the LHC!

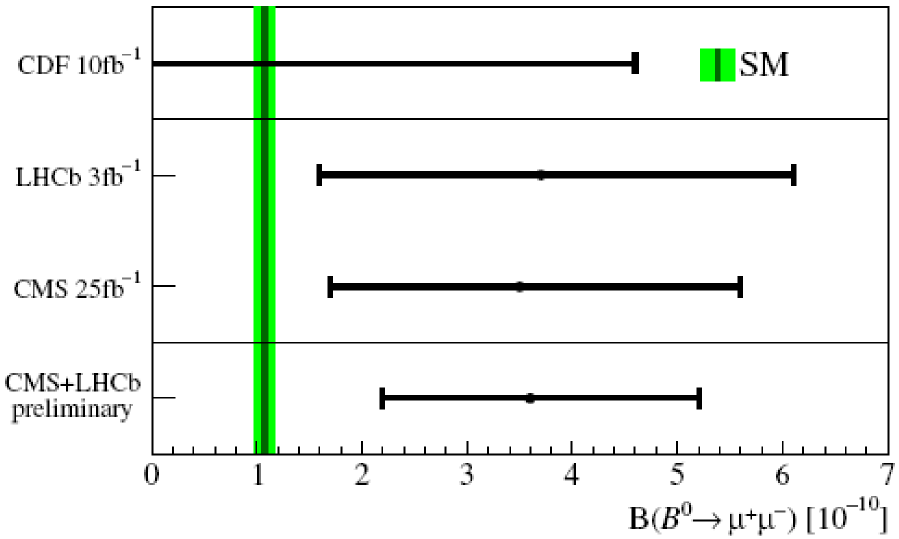
$B_{s,d} \to \mu^+\mu^-$

In the SM, but also in MFV New Physics:

$$\frac{\mathrm{Br}(B_d \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)} \simeq \frac{f_{B_d}^2}{f_{B_s}^2}\frac{\tau_{B_d}}{\tau_{B_s}}\frac{|V_{td}|^2}{|V_{ts}|^2} \simeq 0.03$$

Hurth Isidori Kamenik Mescia ‘08

$B_d \to \mu^+\mu^-$



$$\frac{\mathrm{Br}(B_d \to \mu^+\mu^-)_{\mathrm{exp}}}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{exp}}} \simeq 0.14 \pm 0.06$$

We will test soon SM and MFV in general!

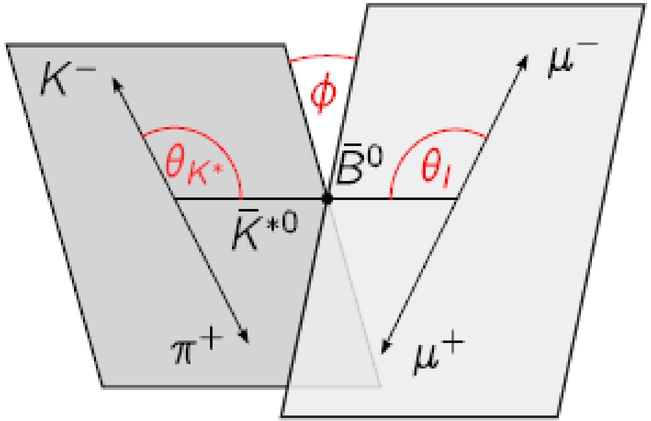
$B \to K^* \mu^+\mu^-$

Loop and CKM suppressed in the SM

It can probe $\Lambda_{\rm NP} \sim \frac{M_W}{g^2}\sqrt{\frac{16\pi^2}{|V_{ts}^* V_{tb}|}} \sim 10$ TeV

K* vector (3 helicities), 4 body decay: plenty of info from angular distribution!

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \frac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

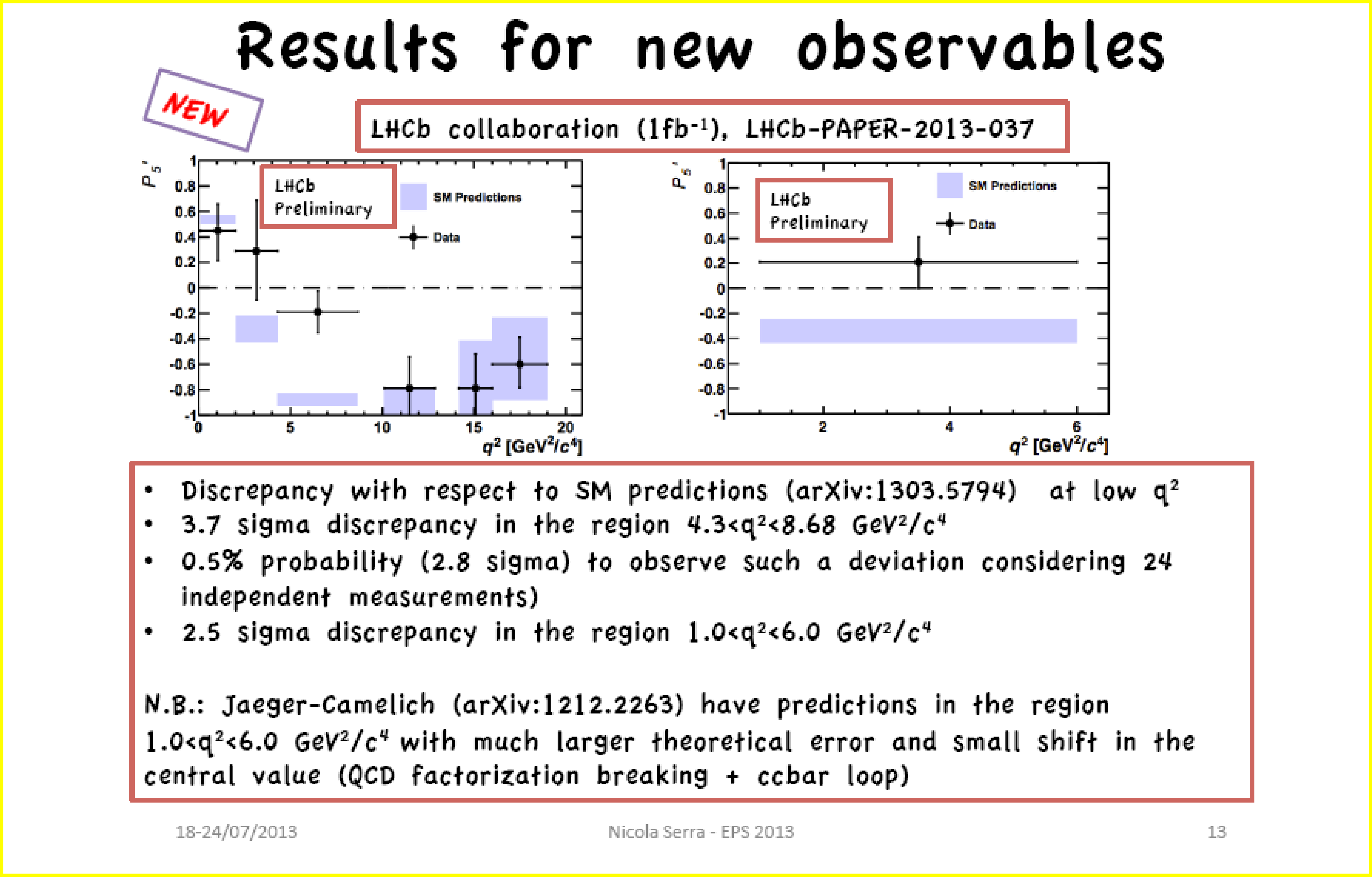


Clean observables (little dependence on hadronic form factors):

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}.$$

Becirev Schneider '11, Matias Mescia Ramon Virto '12, Descotes-Guenon Hurth Matias Virto '13

$B \to K^* \mu^+\mu^-$



Results for new observables

NEW

LHCb collaboration ($1 fb^{-1}$), LHCb-PAPER-2013-037

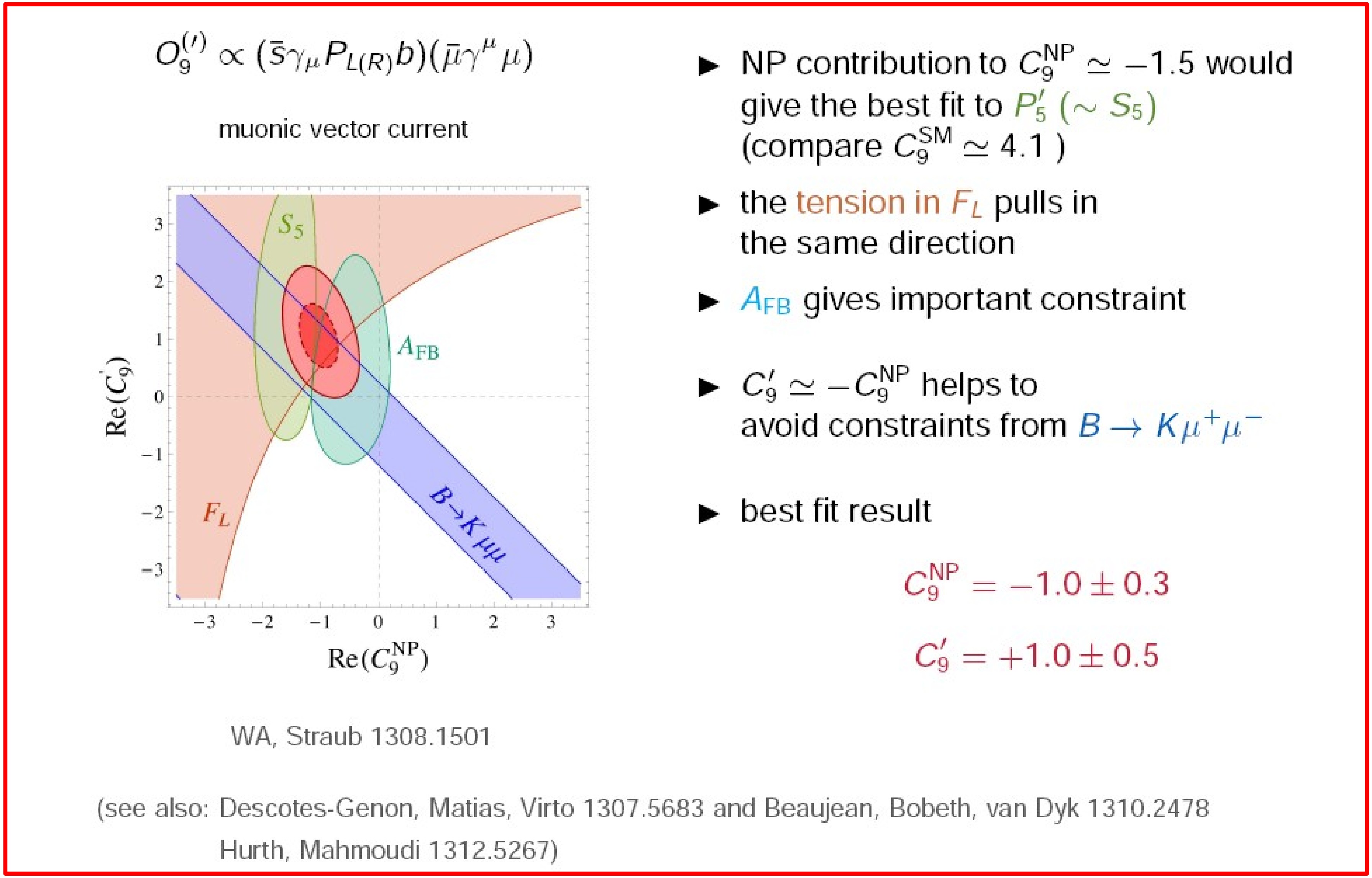
- Discrepancy with respect to SM predictions (arXiv:1303.5794) at low q^2
- 3.7 sigma discrepancy in the region $4.3<q^2<8.68$ GeV^2/c^4
- 0.5% probability (2.8 sigma) to observe such a deviation considering 24 independent measurements)
- 2.5 sigma discrepancy in the region $1.0<q^2<6.0$ GeV^2/c^4

N.B.: Jaeger-Camelich (arXiv:1212.2263) have predictions in the region $1.0<q^2<6.0$ GeV^2/c^4 with much larger theoretical error and small shift in the central value (QCD factorization breaking + ccbar loop)

18-24/07/2013 Nicola Serra - EPS 2013 13

from N. Serra's talk at EPS 2013

B → K* $\mu^+\mu^-$



$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$

muonic vector current

WA, Straub 1308.1501

- NP contribution to $C_9^{\rm NP} \simeq -1.5$ would give the best fit to P_5' ($\sim S_5$) (compare $C_9^{\rm SM} \simeq 4.1$)
- the tension in F_L pulls in the same direction
- $A_{\rm FB}$ gives important constraint
- $C_9' \simeq -C_9^{\rm NP}$ helps to avoid constraints from $B \to K\mu^+\mu^-$
- best fit result

$$C_9^{\rm NP} = -1.0 \pm 0.3$$

$$C_9' = +1.0 \pm 0.5$$

(see also: Descotes-Genon, Matias, Virto 1307.5683 and Beaujean, Bobeth, van Dyk 1310.2478
Hurth, Mahmoudi 1312.5267)

from W. Altmannshofer's talk at Moriond EW '14

$B \to K^* \mu^+\mu^-$

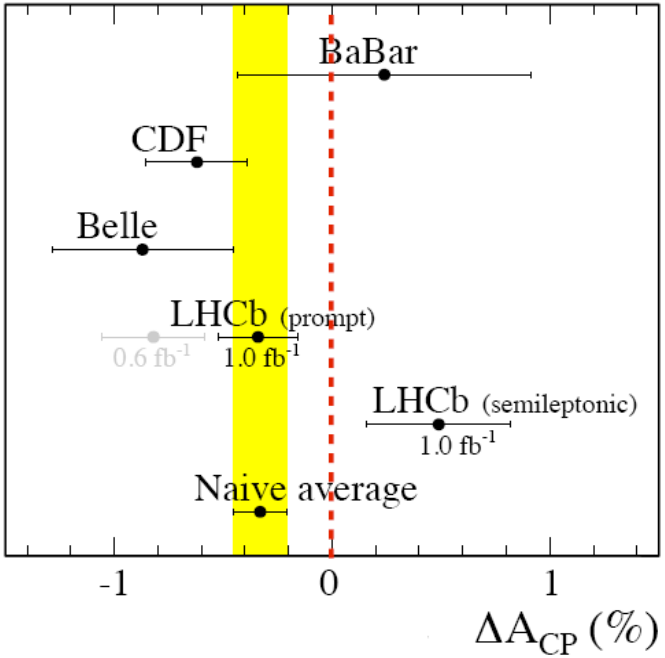
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35$ TeV
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2} V_{tb} V_{ts}^* (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7$ TeV
generic loop	$\frac{1}{\Lambda_{\rm NP}^2} \frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3$ TeV
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2} \frac{1}{16\pi^2} V_{tb} V_{ts}^* (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6$ TeV

from W. Altmannshofer's talk at Moriond EW '14

Sizeable C9 cannot be induced by SUSY evading LHC searches

The only known option given by Z' models with m~O(1-100) TeV

Direct charm CPV



$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}, \quad f = K^+K^-, \pi^+\pi^-.$$

$$\Delta \mathrm{A_{CP}} = \mathrm{A_{CP}}(K^+K^-) - \mathrm{A_{CP}}(\pi^+\pi^-)$$

Theoretical estimate:

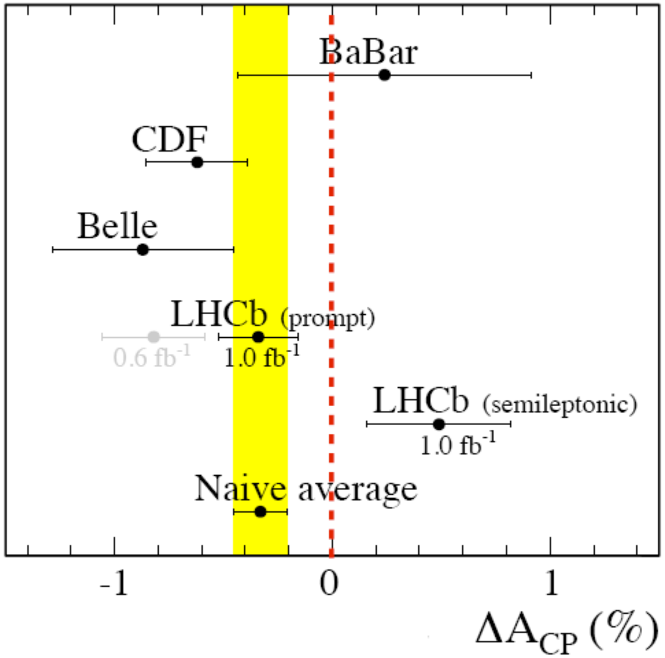
$$\begin{aligned} \Delta a_{CP} &\approx \frac{-2}{\sin\theta_c}\left[\mathrm{Im}(V_{cb}^* V_{ub})\mathrm{Im}(\Delta R^{\mathrm{SM}}) + \sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R^{\mathrm{NP}_i})\right] \\ &= -(0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}}) - 9\sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R^{\mathrm{NP}_i}), \end{aligned}$$

Naïve SM expectation:

Isidori et al. '11, Giudice Isidori Paradisi '12

$$\Delta R^{\mathrm{SM}} \approx \alpha_s(m_c)/\pi \approx 0.1,$$

Direct charm CPV



$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}, \quad f = K^+K^-, \pi^+\pi^-.$$

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

New Physics contribution:

$$|\Delta a_{CP}| \approx \frac{4}{\sin\theta_c} \frac{\alpha_s(m_c)}{\pi} \left| \mathrm{Im}\left(C_8(m_c) + C_8'(m_c)\right) \right|$$

$$Q_7 = \frac{m_c}{4\pi^2} \, \bar{u}_L \sigma_{\mu\nu} e F^{\mu\nu} c_R \,,$$
$$Q_8 = \frac{m_c}{4\pi^2} \, \bar{u}_L \sigma_{\mu\nu} g_s G^{\mu\nu} c_R \,.$$

In SUSY (misaligned A-terms):

$$C_{7,8}^{(\tilde{g})} = -\frac{\sqrt{2}\pi\alpha_s \tilde{m}_g}{G_F m_c} \frac{(\delta^u_{12})_{LR}}{\tilde{m}_q^2} \, g_{7,8}(x_{gq}) \qquad |\Delta a_{CP}^{SUSY}| \approx 0.6\% \left(\frac{\left|\mathrm{Im}\,(\delta^u_{12})_{LR} + \mathrm{Im}\,(\delta^u_{12})_{RL}\right|}{10^{-3}} \right) \left(\frac{\mathrm{TeV}}{\tilde{m}} \right)$$

Giudice Isidori Paradisi '12

Direct charm CPV

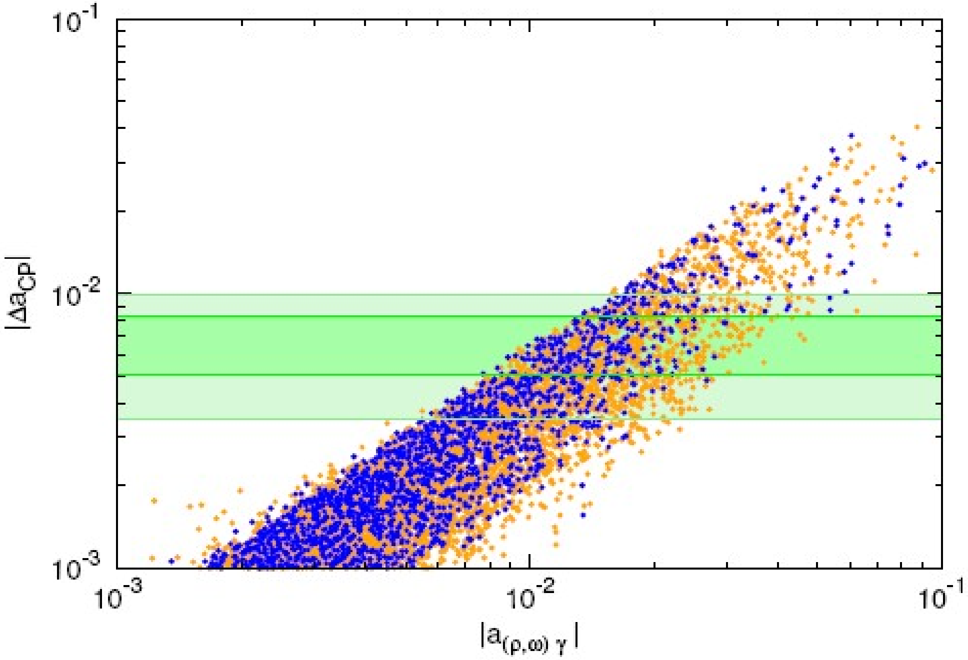
Correlated observable, CP asymmetry in $D \to V\gamma$:

Isidori Kamenik '12

$$|a_{(\rho,\omega)\gamma}| = 0.04(1) \left|\frac{\mathrm{Im}[C_7(m_c)]}{0.4 \times 10^{-2}}\right| \left[\frac{10^{-5}}{\mathcal{B}(D \to (\rho,\omega)\gamma)}\right]^{1/2}$$

$$Q_7 = \frac{m_c}{4\pi^2}\,\bar{u}_L \sigma_{\mu\nu} e F^{\mu\nu} c_R\,,$$
$$Q_8 = \frac{m_c}{4\pi^2}\,\bar{u}_L \sigma_{\mu\nu} g_s G^{\mu\nu} c_R\,.$$

Example in an explicit scenario of gauge medited SUSY breaking:

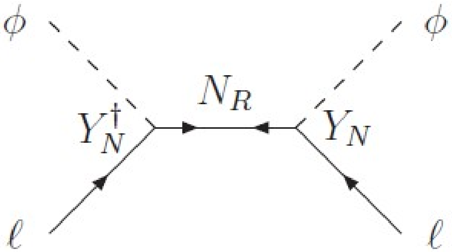


LC Paradisi Ziegler '13

LFV in SUSY seesaw

Tree level generation of the neutrino mass operator

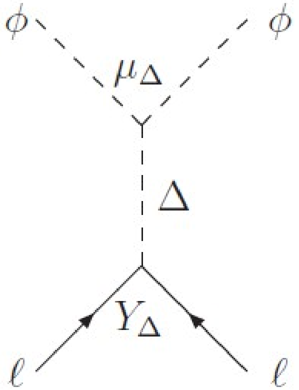
$$\boxed{\frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_{L\alpha}}\, \tilde{\phi}^*\right) \left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right)}$$



Type I

Heavy fermionic singlets (RH neutrinos)

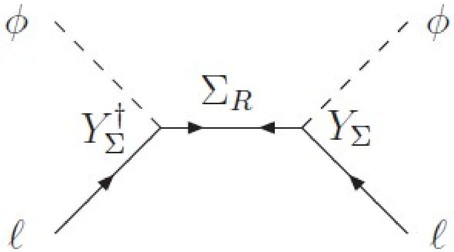
Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, …



Type II

Heavy scalar triplet

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle, …



Type III

Heavy fermionic triplets

Foot, Lew, He, Joshi, Ma, Roy, Hambye et al., Bajc et al., Dorsner, Fileviez-Perez, ...

In SUSY, new fields interacting with the MSSM fields enter the radiative corrections of the sfermion masses

Hall Kostelecky Raby '86

⇨ This applies to the new seesaw interactions: generically induce LFV in the slepton mass matrix!

Borzumati Masiero '86

Experimental News

SM-like Higgs!

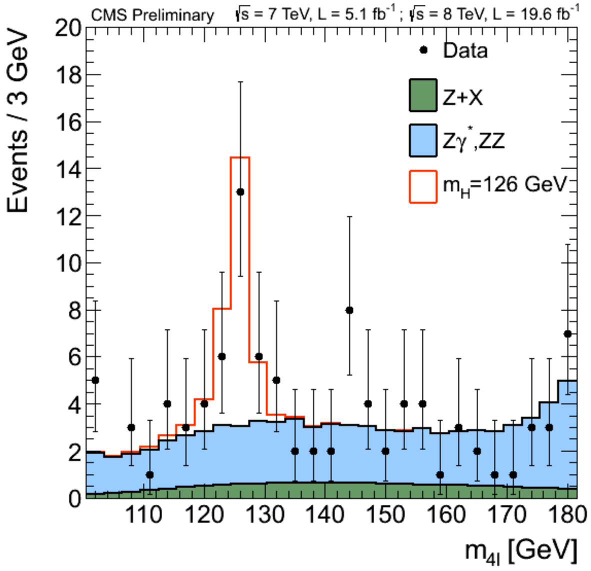
$$m_h \approx 126\,\mathrm{GeV}$$

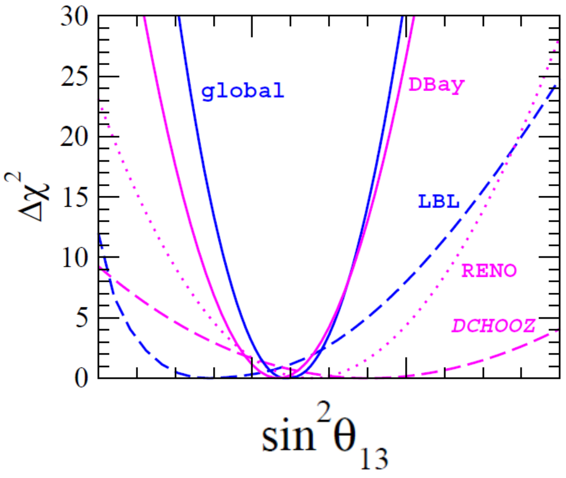
PMNS reactor angle:

$$\theta_{13} \approx 9^{\circ}$$

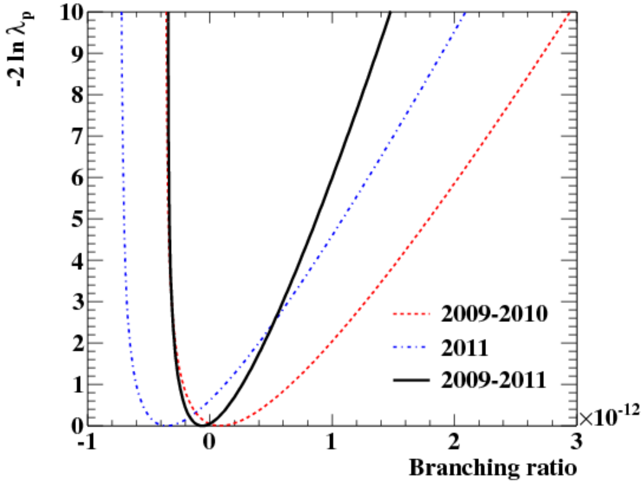
MEG limit:

$$\mathrm{BR}(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13}$$



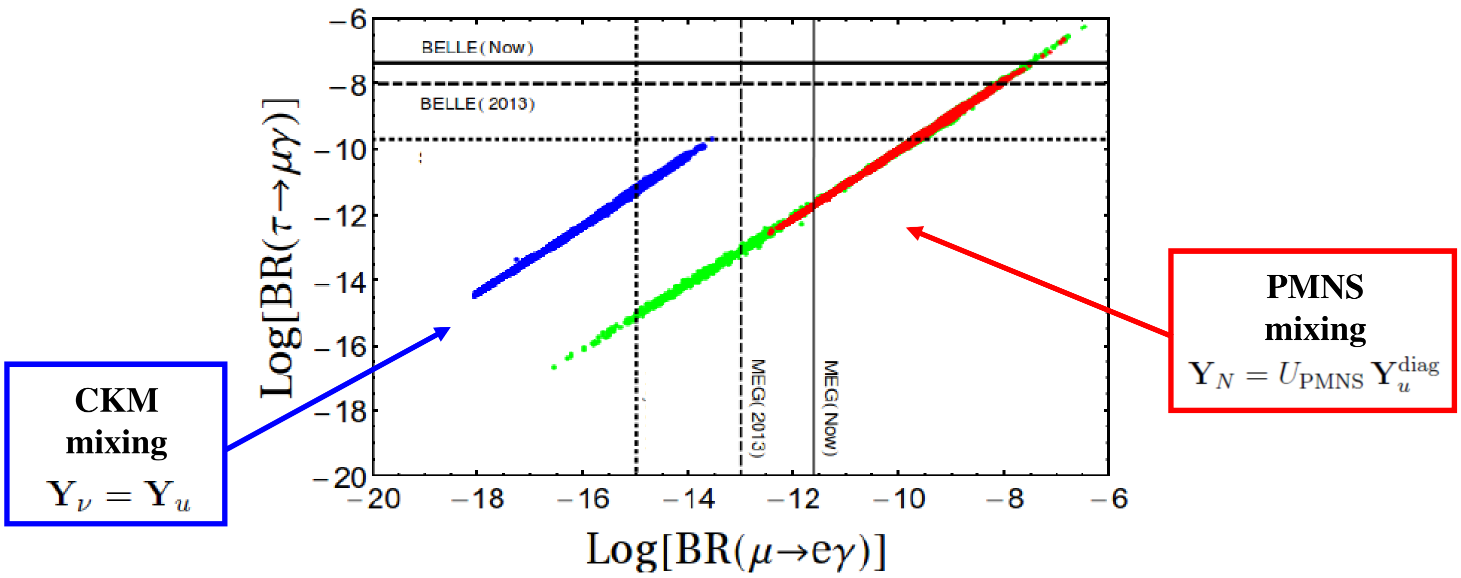


Forero et al. ‘12



MEG ‘13

τ-μ vs. μ-e transitions



Scenarios that could 'naturally' suppress $\mu \to e$ transitions relative to $\tau \to \mu$ cannot be realized with $\theta_{13} \sim O(0.1)$

Random variation of matrix R and neutrino parameters:

$$\frac{\mathrm{BR}(\tau \to \mu\gamma)}{\mathrm{BR}(\mu \to e\gamma)} \lesssim \mathcal{O}(1000) \Longrightarrow \mathrm{BR}(\tau \to \mu\gamma) \lesssim \mathcal{O}(10^{-9})$$

θ_{13} measurements imply that SUSY seesaw(s) can be preferably tested through $\mu \to e$ transitions

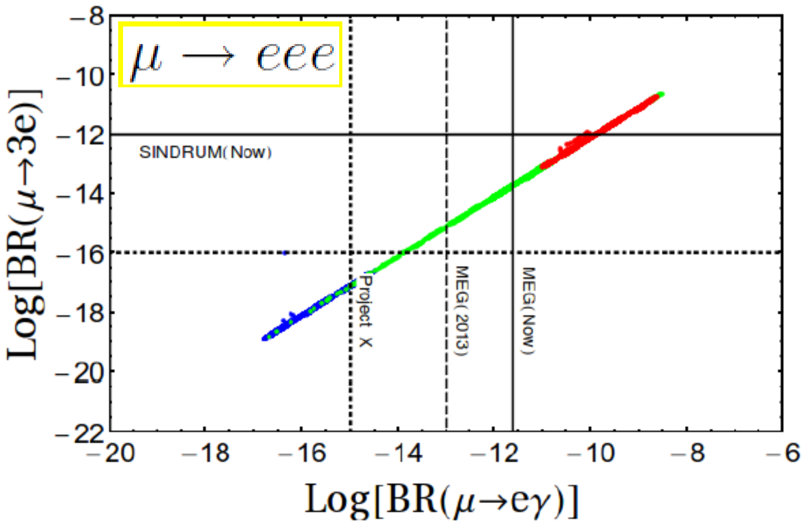
Correlations in the μ-e sector

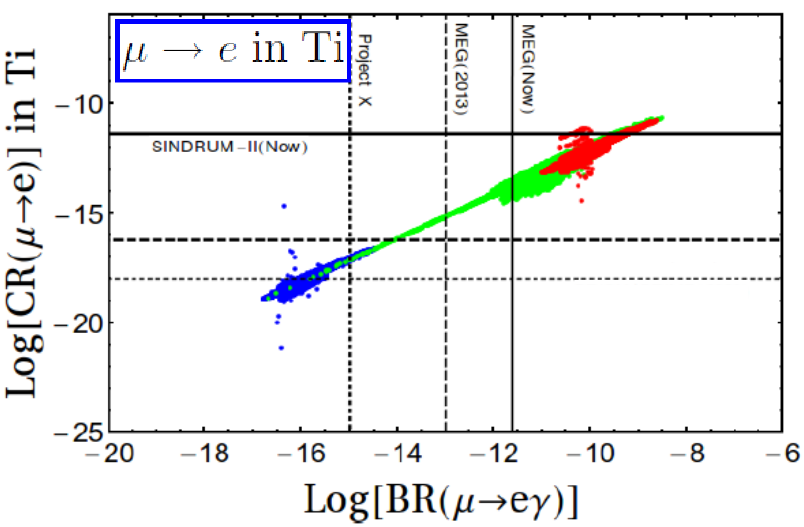
In SUSY (with R_P) $\mu \to eee$ and $\mu \to e$ conversion dominated by the dipole $\mu \to e\gamma^*$ Strong correlations:

not only seesaw models!

$$\boxed{\begin{aligned} \mathrm{BR}(\mu \to eee) &\sim \alpha_{\mathrm{em}} \times \mathrm{BR}(\mu \to e\gamma) \\ \mathrm{CR}(\mu \to \text{ in N}) &\sim \alpha_{\mathrm{em}} \times \mathrm{BR}(\mu \to e\gamma) \end{aligned}}$$

- Sensitivities < 10^{-15} would go beyond MEG
- Crucial model discriminators





LC Chowdhury Masiero Patel Vempati '12

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 convincing deviation from SM expectations yet
but many experiments are at work or in preparation:
they could give us surprises soon!