Flavored surprises at the LHC

Avelino Vicente
IFIC Valencia & Université de Liège

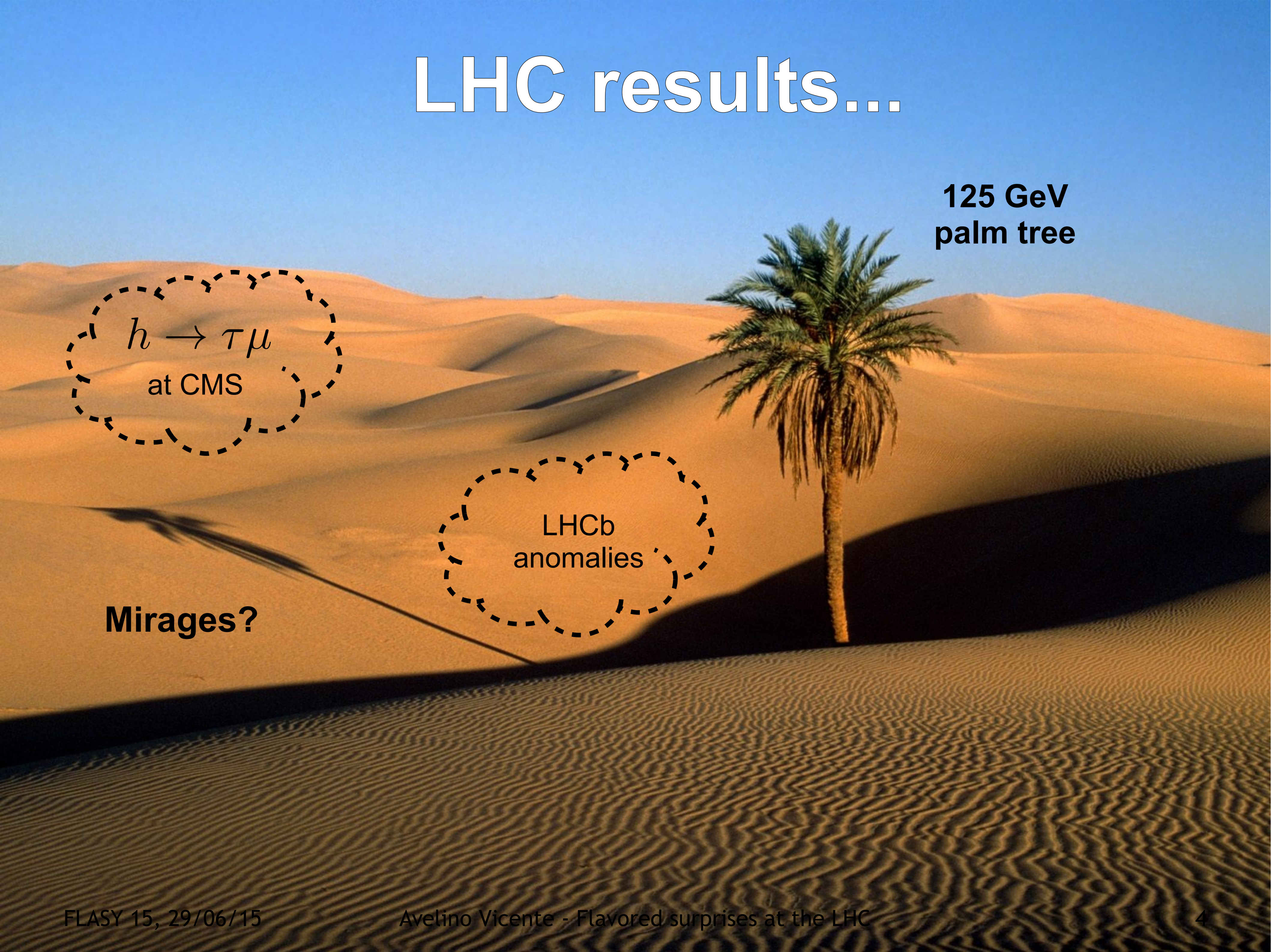
FLASY 15
Manzanillo (Mexico)

Introduction

Last year at FLASY 14...

LHC results...

LHC results...



Higgs LFV decays

Where lepton physicists meet collider physicists

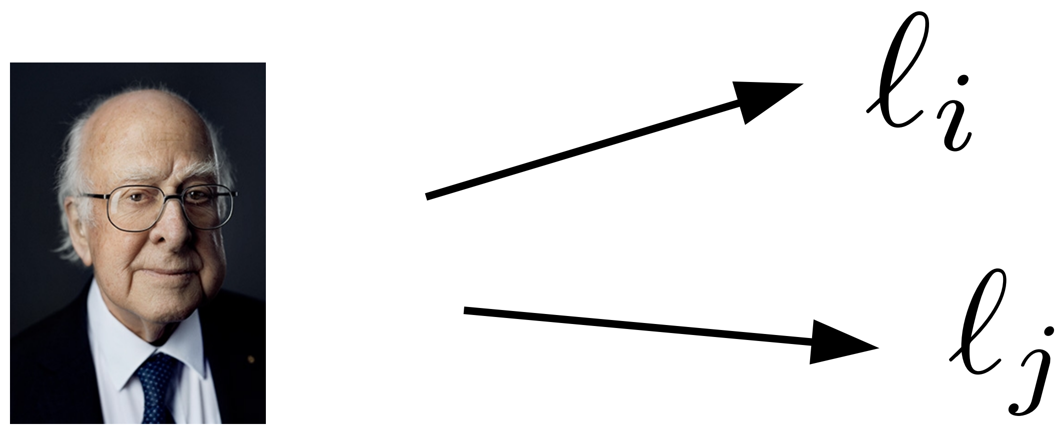
See talk by
Gomez Bock

Higgs LFV decays

Where lepton physicists meet collider physicists

Higgs LFV decays

We have discovered the Higgs
However, is there room for non-standard decays?



Higgs LFV decays

We have discovered the Higgs
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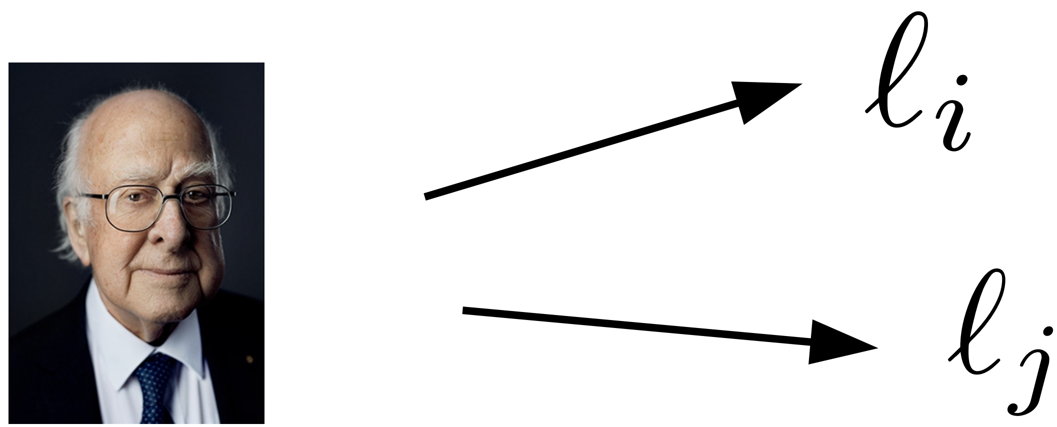


Popular BSM signature: [Blankenburg et al, 2013; Harnik et al, 2013]

LHC sensitivity: $\text{Br} \sim 10^{-3}$ [Davidson, Verdier, 2012]

$20 fb^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$

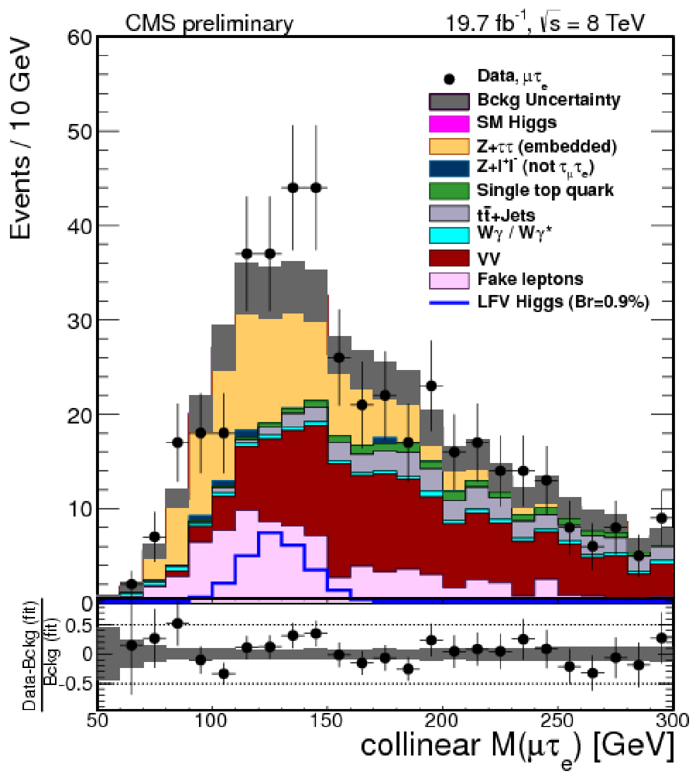
Early works: [Pilaftsis, 1992; Diaz-Cruz, Toscano, 2000]

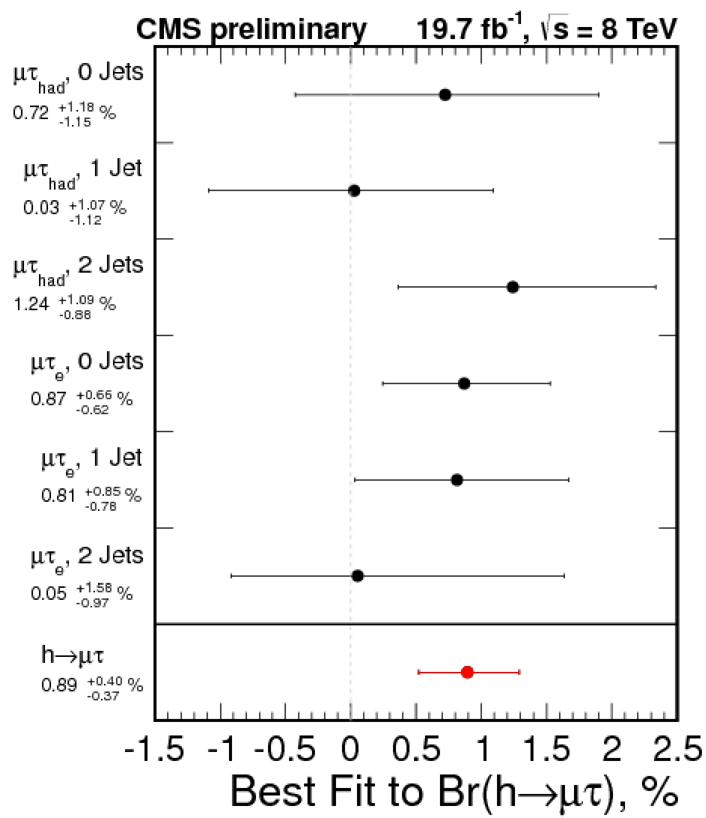
A hint from CMS?

A 2.5σ excess in $h \to \tau\mu$

See recent update [arXiv:1502.07400]

[CMS-PAS-HIG-14-005, July 2014]





$$\mathrm{BR}(h \to \tau\mu) = (0.89^{+0.40}_{-0.37})\%$$

A hint from CMS?

$$\boxed{\mathrm{BR}(h \to \tau\mu) = (0.89^{+0.40}_{-0.37})\%}$$

- Large LFV branching ratio

$$\mathrm{BR}(h \to \tau\bar{\tau})_{\mathrm{SM}} \sim 6\%$$

- Needs more statistics and confirmation from ATLAS
- If taken seriously, any model?

Any model?

DO OR DO
NOT
THERE
IS NO
TRY

Flavor constraints seem to preclude any explanation for the CMS excess...

MSSM [Arana-Catania et al, 2013] $\text{BR}(h \to \tau\mu) \lesssim 10^{-4}$

RPV Supersymmetry [Arhrib et al, 2013] $\text{BR}(h \to \tau\mu) \lesssim 10^{-5}$

Vector-like leptons [Falkowski et al, 2014] $\text{BR}(h \to \tau\mu) \lesssim 10^{-5}$

Inverse Seesaw [Arganda et al, 2014] $\text{BR}(h \to \tau\mu) \lesssim 10^{-5}$

No hope? 

Vector-like leptons

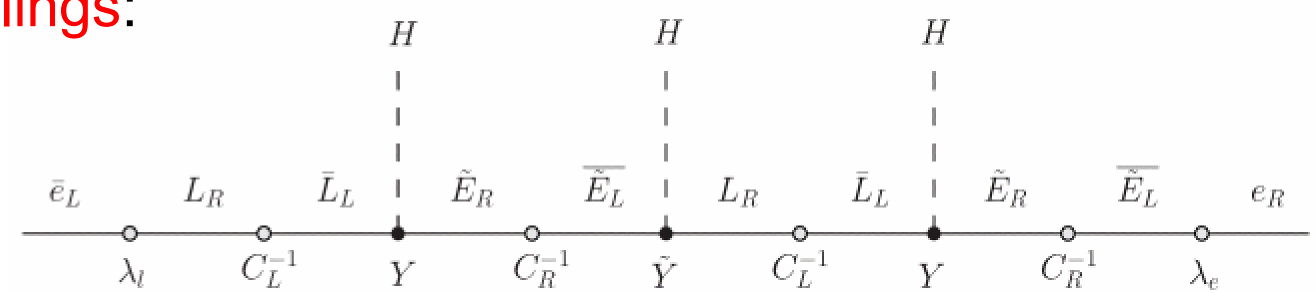
[Falkowski, Straub, AV, 2014]

Model with vector-like leptons
"Composite Higgs inspired"

$$\mathcal{L}_{F,c} = -M\left(\bar{L}C_L L + \tilde{E}C_R\tilde{E}\right) - \left(\bar{L}_L Y\tilde{E}_R H + \bar{L}_R\tilde{Y}\tilde{E}_L H + \text{h.c.}\right)$$

$$\mathcal{L}_{\text{mix}} = M\left(\bar{l}_L\lambda_l L_R + \tilde{E}_L\lambda_e e_R\right) + \text{h.c.}$$

Higgs LFV couplings:

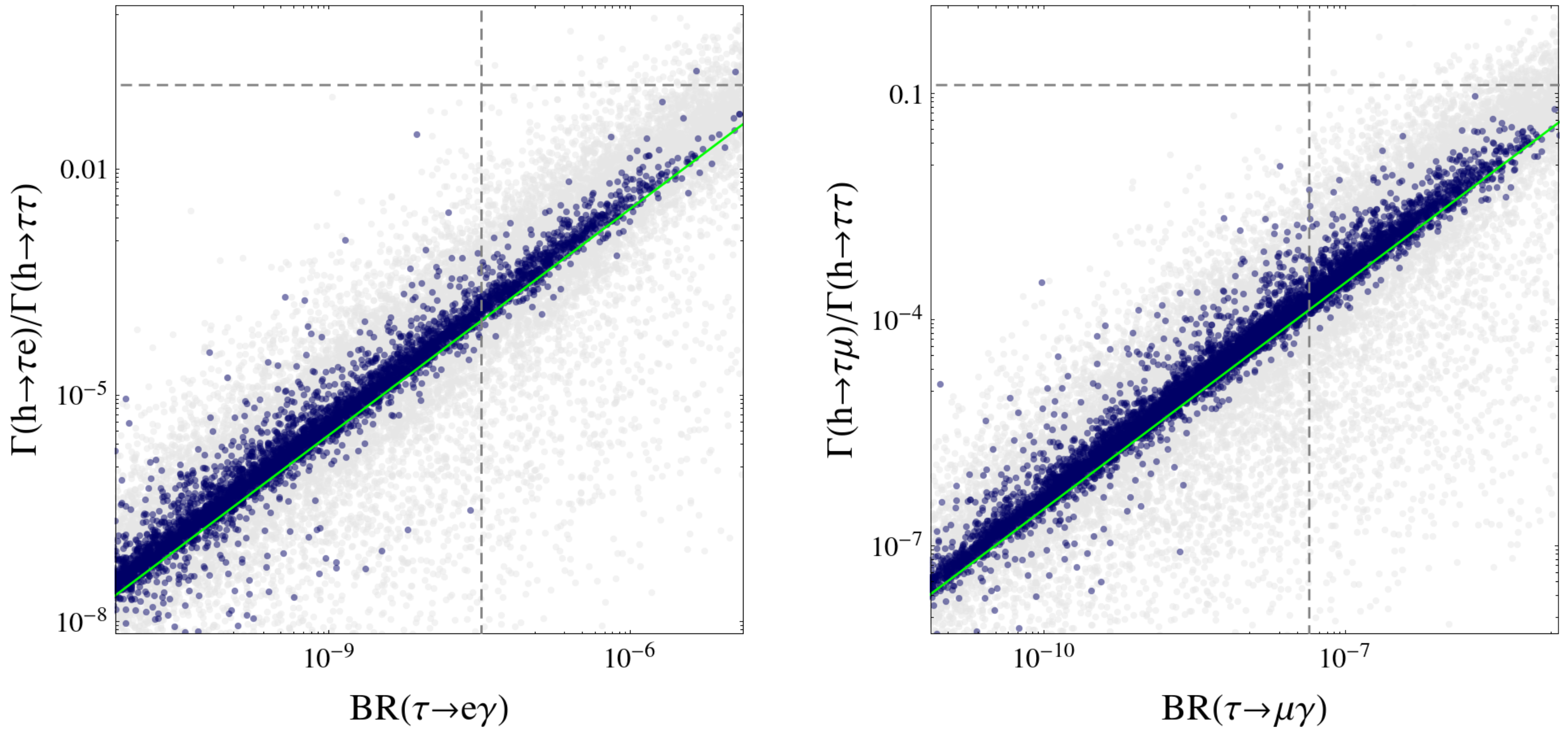


$$\mathcal{L}_{\text{eff}} = -\frac{h}{\sqrt{2}}\bar{e}_L c_{\text{eff}} e_R + \text{h.c.} \qquad c_{\text{eff}} = Y_{\text{eff}} + \frac{v^2}{M^2}\lambda_l C_L^{-1} Y C_R^{-1}\tilde{Y} C_L^{-1} Y C_R^{-1}\lambda_e$$

Vector-like leptons

[Falkowski, Straub, AV, 2014]

$\Rightarrow$ BR's $\lesssim 10^{-5}$



Unfortunately... unobservable at the LHC

A new hope: Type-III 2HDM

[Davidson, Grenier, 2010; Harnik et al, 2013; Kopp, Nardecchia, 2014]

A model! Type-III 2HDM

[Type-III = most general case]

$$\mathcal{L}_Y = m_i \bar{f}_L^i f_R^i - \rho_{ij} (\bar{f}_L^i f_R^j + \text{h.c.})\, h$$

General 3x3 matrix

In *principle*... it is possible to account for the CMS excess!

A new hope: Type-III 2HDM

[Davidson, Grenier, 2010; Harnik et al, 2013; Kopp, Nardecchia, 2014]

A model! Type-III 2HDM

[Type-III = most general case]

See talks by
Montes de Oca Yemha,
Solaguren-Beascoa Negre

In *principle*... it is possible to account for the CMS excess!

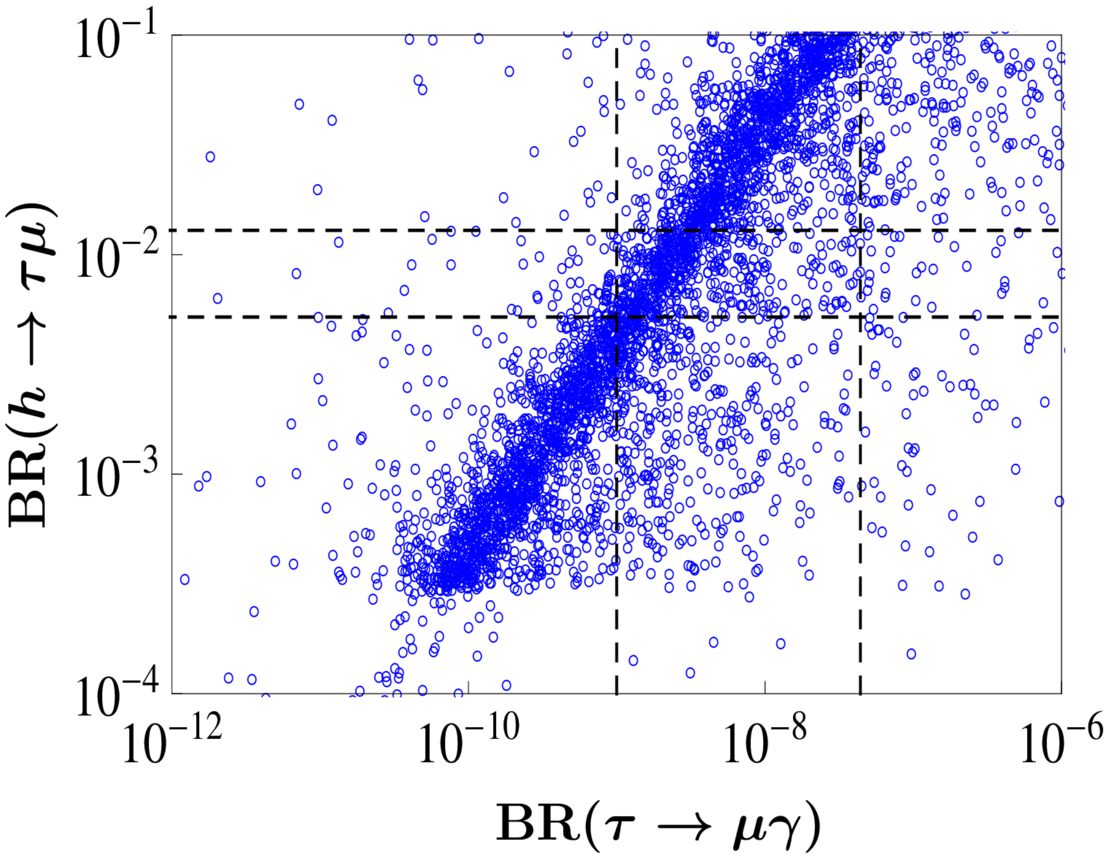
A new hope: Type-III 2HDM

[Aristizabal Sierra, AV, 2014]

Explicit *proof of validity* including the relevant constraints

- Direct searches
- Indirect constraints from flavor
- $\tau \to \mu\gamma$
- Higgs couplings to fermions
- T parameter
- Perturbativity and boundedness from below

A new hope: Type-III 2HDM



[Aristizabal Sierra, AV, 2014]

Explicit *proof of validity* including the relevant constraints

The signal is consistent with the Sher-Cheng ansatz

$$\rho_{\tau\mu} \simeq \frac{\sqrt{m_\tau m_\mu}}{\langle H \rangle}$$

A flavor symmetry at work?

In this model $\mathrm{BR}(\tau \to 3\,\mu) \simeq 2 \cdot 10^{-3}\,\mathrm{BR}(\tau \to \mu\gamma)$

The observation of $\tau \to 3\,\mu$ at LHCb would exclude this explanation!

Other models?

Other models?

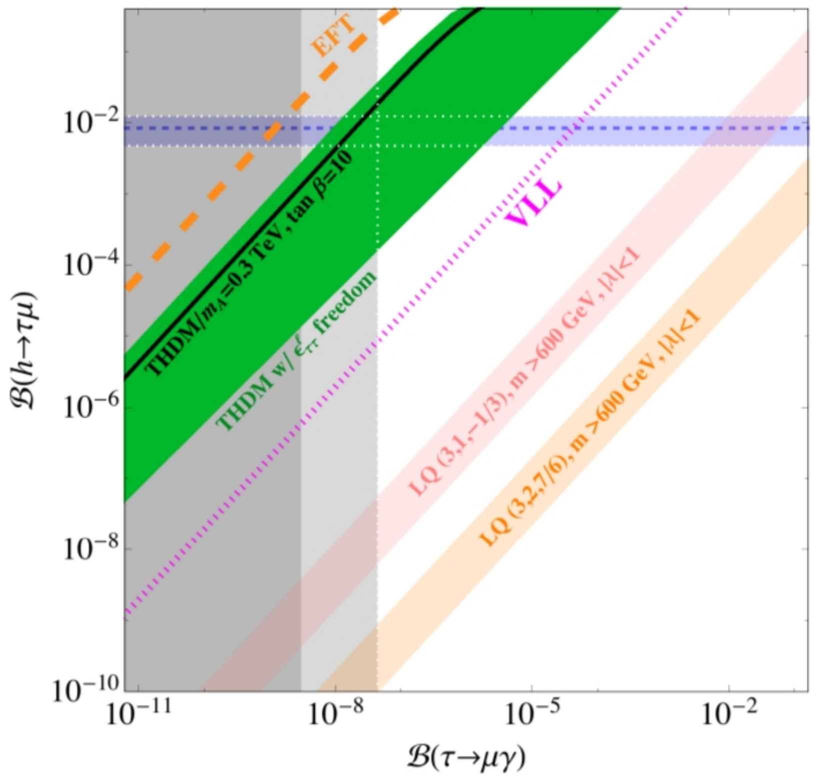
[Doršner et al, 2015]

$$\mathcal{O}_6 = \bar{L} H e \left(H^\dagger H \right)$$

$$\mathcal{O}_{\text{dipole}} = \bar{L} H \left(\sigma \cdot F \right) e$$

Same properties under flavor transformations

- Extended scalar sectors seem to be the only valid scenario
- No way with 1-loop induced Higgs LFV (unless huge fine-tuning!)



[Figure from Doršner et al, arXiv:1502.07784]

LFV in B meson decays

Where lepton physicists meet quark physicists

See talk by
Martin Camalich

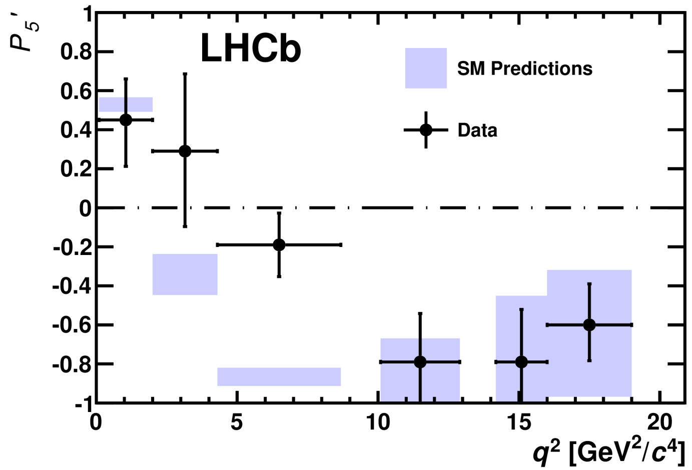
LFV in B meson decays

Where lepton physicists meet quark physicists

The $b \to s$ anomalies

Episode 1

2013 : First anomalies found by LHCb



Episode 2

2014 : Lepton universality violation

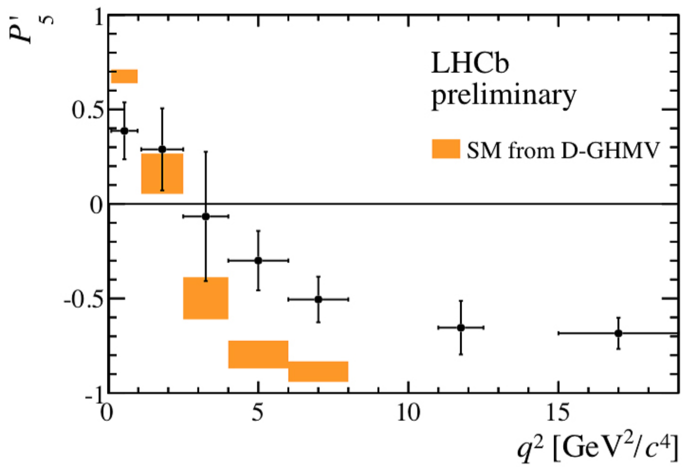
$$R_K = \frac{\mathrm{BR}(B \to K \mu^+ \mu^-)}{\mathrm{BR}(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$ [Hiller, Kruger, 2004]

2.6σ away from the SM

Episode 3

2015 : LHCb confirms first anomalies



Interpreting the anomalies

$$\boldsymbol{b \to s}$$

Effective hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + \text{h.c.}$$

C_i : Wilson coefficients

$\mathcal{O}_i$: Operators

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\ \left(\bar{\ell}\gamma^\mu \ell\right) \qquad \mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)\ \left(\bar{\ell}\gamma^\mu \ell\right)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\ \left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right) \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu P_R b)\ \left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right)$$

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

[analogous for primed operators]

...including also $b \to s\, e^+ e^-$

David Straub's talk Moriond 2015

Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\rm b.f.} - \chi^2_{\rm SM}}$	p [%]
$C_7^{\rm NP}$	-0.04	$[-0.07, -0.02]$	$[-0.10, 0.01]$	1.52	1.1
C_7'	0.00	$[-0.05, 0.06]$	$[-0.11, 0.11]$	0.05	0.8
$C_9^{\rm NP}$	-1.12	$[-1.34, -0.88]$	$[-1.55, -0.63]$	4.33	10.6
C_9'	-0.04	$[-0.26, 0.18]$	$[-0.49, 0.40]$	0.18	0.8
$C_{10}^{\rm NP}$	0.65	$[0.40, 0.91]$	$[0.17, 1.19]$	2.75	2.5
C_{10}'	-0.01	$[-0.19, 0.16]$	$[-0.36, 0.33]$	0.09	0.8
$C_9^{\rm NP} = C_{10}^{\rm NP}$	-0.20	$[-0.41, 0.05]$	$[-0.60, 0.33]$	0.82	0.8
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.57	$[-0.73, -0.41]$	$[-0.90, -0.27]$	3.88	6.8
$C_9' = C_{10}'$	-0.08	$[-0.33, 0.17]$	$[-0.58, 0.41]$	0.32	0.8
$C_9' = -C_{10}'$	-0.00	$[-0.11, 0.10]$	$[-0.22, 0.20]$	0.03	0.8

$\chi^2_{\rm SM}$ =125.8 for 91 measurements ($p = 0.92$ %)

The $b \to s$ anomalies

Composite Higgs

Buras, Girrbach-Noe, Niehoff, Stangl, Straub

Z' boson

Altmannshofer, Aristizabal Sierra, Buras, Celis, Crivellin, D' Ambrosio, Fuentes-Martín, Gauld, Girrbach-Noe, Goertz, Gori, Haisch, Heeck, Jung, Niehoff, Pospelov, Serôdio, Staub, Straub, Vicente, Yavin

Global fits

Alonso, Altmannshofer, Beaujean, Bobeth, Descotes-Genon, Egede, Ghosh, Grinstein, Hiller, Hurth, Mahmoudi, Martin Camalich, Matias, Nardecchia, Neshatpour, Patel, Petridis, Renner, Schmaltz, Straub, van Dyk, Virto

Other

Calibbi, Crivellin, Greljo, Isidori, Marzocca, Ota

Model building

$b \to s$ anomalies

Leptoquarks

Alonso, Becirevic, Biswas, Chowdhuri, de Medeiros Varzielas, Fajfer, Grinstein, Gripaios, Han, Hiller, Kosnik, Lee, Martin Camalich, Mohanta, Nardecchia, Renner, Sahoo, Schmaltz

Implications - LFV -

Bhattacharya, Boucenna, Civellin, Datta, de Medeiros Varzielas, Glashow, Gripaios, Guadagnoli, Hiller, Hofer, Kane, Lee, London, Matias, Mohanta, Nardecchia, Nierste, Pokorski, Renner, Rosiek, Sahoo, Shivashankara, Tandean, Valle, Vicente

SM uncertainties

Altmannshofer, Bharucha, Descotes-Genon, Ghosh, Hiller, Hofer, Horgan, Hurth, Jaeger, Liu, Lyon, Martin Camalich, Matias, Meinel, Straub, Virto, Wingate, Zwicky

The $b \to s$ anomalies

Beyond the **S**tandard Model

The $b \to s$ anomalies

Boring **S**izable corrections

What do we need?

Z' model building

Easiest (but not unique) solution

List of “ingredients”:

- A Z' boson that contributes to $\mathcal{O}_9$ (and optionally to $\mathcal{O}_{10}$)
- The Z' must have flavor violating couplings to quarks
- The Z' must have non-universal couplings to leptons
- Optional (but highly desirable!): interplay with some other physics

A model with a dark sector

[Aristizabal Sierra, Staub, AV, 2015]

Vector-like = “joker”
for model builders

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

Vector-like fermions

Link to SM fermions

$$Q = \left(\mathbf{3}, \mathbf{2}, \frac{1}{6}, 2\right) \qquad L = \left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2\right)$$

Scalars

$$\phi = (\mathbf{1}, \mathbf{1}, 0, 2) \qquad \chi = (\mathbf{1}, \mathbf{1}, 0, -1)$$

$U(1)_X$ breaking

Dark matter candidate

A model with a dark sector

[Aristizabal Sierra, Staub, AV, 2015]

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

Vector-like = “joker”
for model builders

$$\mathcal{L}_m = m_Q \overline{Q} Q + m_L \overline{L} L$$

Vector-like (Dirac) masses

$$\mathcal{L}_Y = \lambda_Q \overline{Q_R} \phi q_L + \lambda_L \overline{L_R} \phi \ell_L + \text{h.c.}$$

VL – SM mixing

Symmetry breaking and dark matter

[Aristizabal Sierra, Staub, AV, 2015]

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}} \qquad \langle \phi \rangle = \frac{v_\phi}{\sqrt{2}}$$

Massive Z' boson: $m_{Z'} = 2 g_X v_\phi$

DM candidate: χ

$$\begin{aligned} \mathcal{V}(\chi) &= m_\chi^2 |\chi|^2 + \frac{\lambda_\chi}{2} |\chi|^4 + \lambda_{H\chi} |H|^2 |\chi|^2 \\ &+ \lambda_{\phi\chi} |\phi|^2 |\chi|^2 + \left(\mu \, \phi \chi^2 + \text{h.c.} \right) \end{aligned}$$

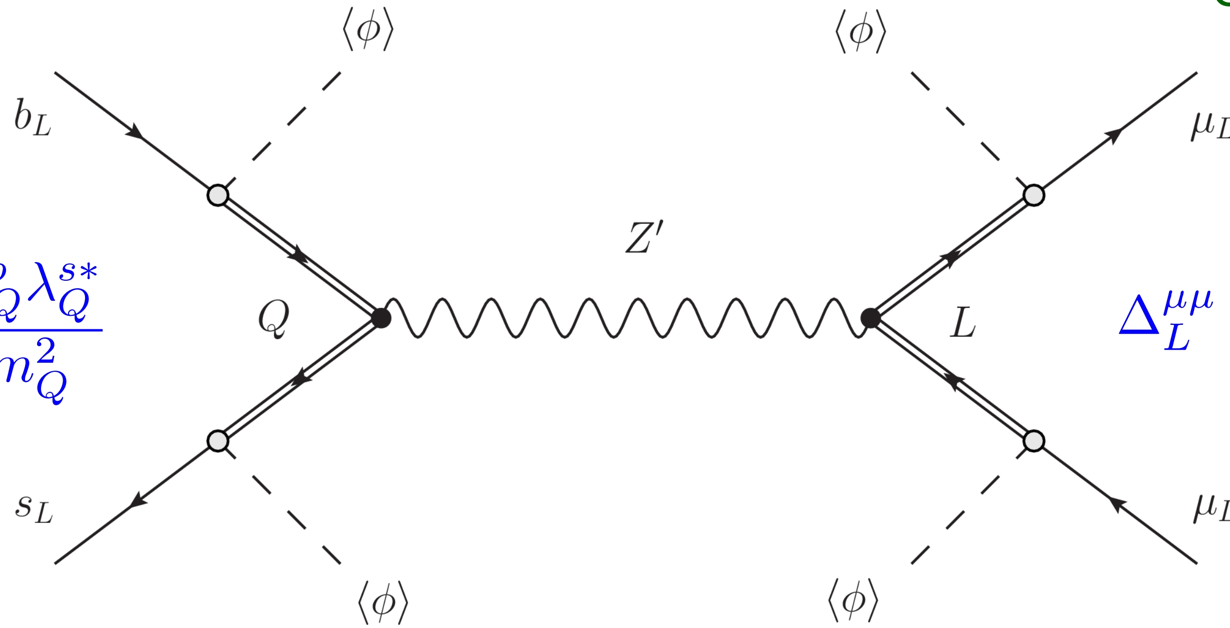
$$\boxed{U(1)_X \to \mathbb{Z}_2}$$

Automatic DM stability

Solving the LHCb anomalies

Similar to
Altmannshofer et al,
Crivellin et al, 2014

$$\Delta_L^{bs} \simeq g_X v_\phi^2 \, \frac{\lambda_Q^b \lambda_Q^{s*}}{m_Q^2}$$



$$\Delta_L^{\mu\mu} \simeq \frac{2\, g_X |\lambda_L^\mu|^2 v_\phi^2}{2m_L^2 + |\lambda_L^\mu|^2 v_\phi^2}$$

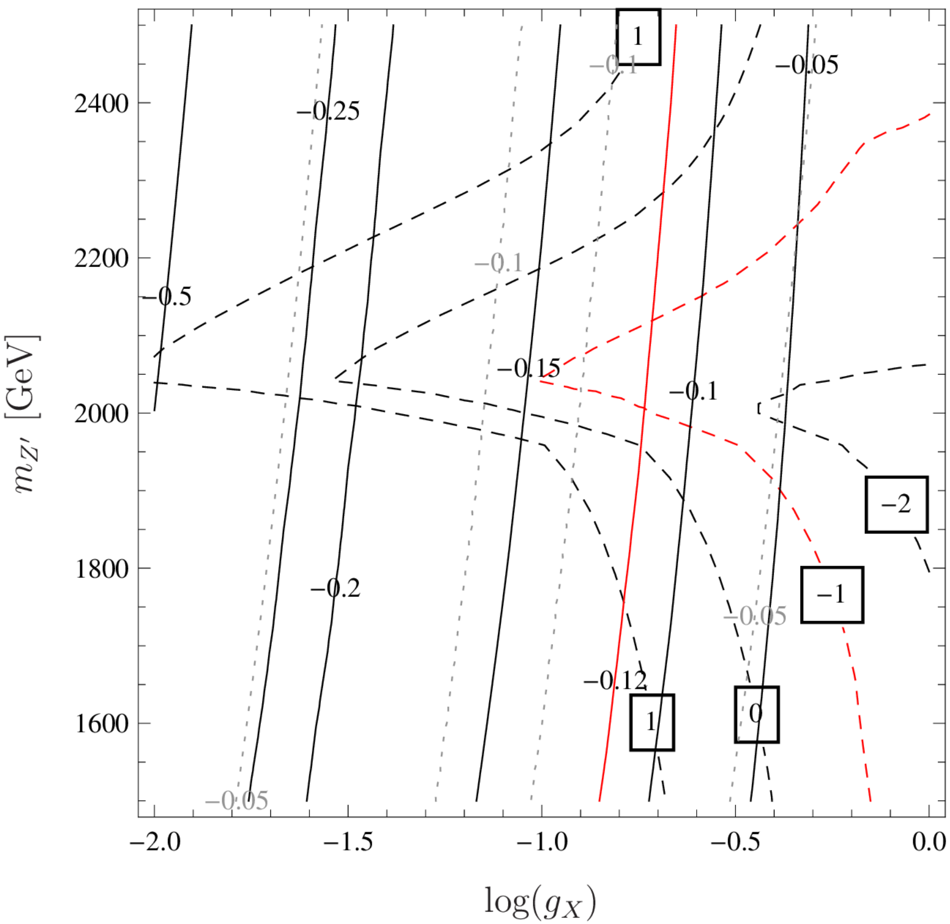
$$\mathcal{O} = (\bar{s}\gamma_\alpha P_L b)\ (\bar{\mu}\gamma^\alpha P_L \mu)$$

Contributions to $\mathcal{O}_{9,10}$

$$C_9^{\rm NP} = -C_{10}^{\rm NP}$$

Dark matter and LHCb anomalies

$C_9^{\rm NP}/C_9^{\rm SM}$ (full) $\log\left(\Omega_{\rm DM} h^2\right)$ (dashed) $C_9^{\rm NP}/C_9^{\rm SM}$ (tree) (dotted gray)



[DM RD Computed with **micrOMEGAs**]

Parameters:

$$\lambda_Q^b = \lambda_Q^s = 0.025$$

$$\lambda_L^\mu = 0.5$$

$$m_Q = m_L = 1 \text{ TeV}$$

$$m_\chi^2 = 1 \text{ TeV}^2$$

- Compatible with flavor constraints (small quark mixings)
- Resonance required to get the correct DM relic density
- Large loop effects for low g_X

LFV in B meson decays

What about LFV?

LFV in B meson decays

What about LFV?

[Glashow et al, 2014]

Lepton universality violation generically implies lepton flavor violation

Gauge basis

Mass basis

$$\mathcal{O} = \widetilde{C}^Q \, (\bar{q}' \gamma_\alpha P_L q') \, \widetilde{C}^L \, (\bar{\ell}' \gamma^\alpha P_L \ell') \longrightarrow \mathcal{O} = C^Q \, (\bar{q} \gamma_\alpha P_L q) \, C^L \, (\bar{\ell} \gamma^\alpha P_L \ell)$$

$$C^L = U_\ell^\dagger \, \widetilde{C}^L \, U_\ell$$

However: we must have a flavor theory in order to make predictions

Are the LHCb anomalies related to neutrino oscillations?

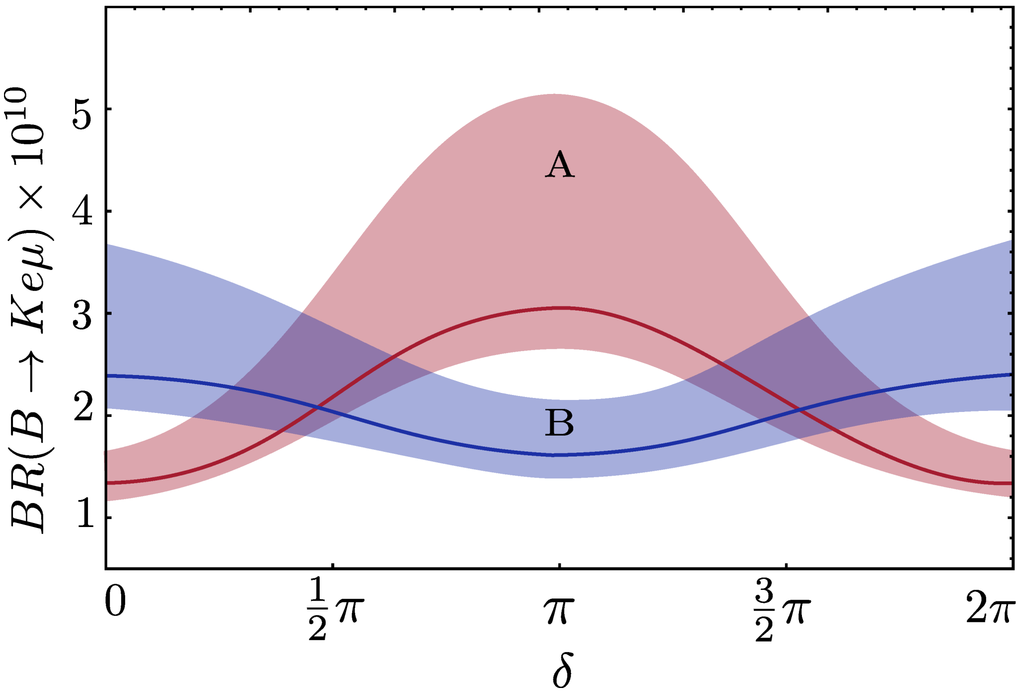
Working hypothesis: What if $U_\ell = K^\dagger$?

[Boucenna, Valle, AV, 2015]

Neutrino oscillations

Neutrinos ⟷ B-physics

LHCb sensitivity $\sim 10^{-10}$



Lines: BF
Bands: 1σ

LHCb anomalies and flavor symmetries

[de Medeiros Varzielas, Hiller, 2015]

Flavor symmetries!

symmetry	flavons	Δ assignment
$SU(3)_F \times U(1)_F$	$\langle \phi_{23} \rangle = (0, b, -b)$	$\{\Delta\} = -2$
$A_4 \times Z_3$	$\langle \phi_l \rangle = (u, 0, 0)$	$1, \{\Delta\} = 2$
$A_4 \times Z_3$	$\langle \phi_l \rangle = (u, 0, 0)$	1”, $\{\Delta\} = 2$
$1^x, \{\Delta\} = 0$		
$A_4 \times Z_4$	$\langle \phi_l \rangle = (0, u, 0), \xi''$	1’, $\{\Delta\} = 2$
$A_4 \times Z_4$	$\langle \phi_l \rangle = (0, u, 0), \xi''$	1”, $\{\Delta\} = 2$
$A_4 \times Z_4$	$\langle \phi_l \rangle = (0, u, 0)$	1’ , $\{\Delta\} = 2$

$$\lambda = \begin{pmatrix} 0 & \lambda_{d\mu} & 0 \\ 0 & \lambda_{s\mu} & 0 \\ 0 & \lambda_{b\mu} & 0 \end{pmatrix}$$

[Table from de Medeiros Varzielas, Hiller, arXiv:1503.01084]

The rates for the different channels are predicted by the symmetry!

Final remarks

Final remarks

LFV is going to live a golden age

Or perhaps it has already begun?

Whether is new physics or not, only time can tell

In the meantime: let's do some physics and try to learn as much as possible!

Thank you!

Backup slides

Experimental projects

Great experimental perspectives!

LFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	5.7×10^{-13}	6×10^{-14} (MEG)
$\tau \to e\gamma$	3.3×10^{-8}	$\sim 10^{-8} - 10^{-9}$ (B factories)
$\tau \to \mu\gamma$	4.4×10^{-8}	$\sim 10^{-8} - 10^{-9}$ (B factories)
$\mu \to 3e$	1.0×10^{-12}	$\sim 10^{-16}$ (Mu3e)
$\tau \to 3e$	2.7×10^{-8}	$\sim 10^{-9} - 10^{-10}$ (B factories)
$\tau \to 3\mu$	2.1×10^{-8}	$\sim 10^{-9} - 10^{-10}$ (B factories)
μ^-, Au $\to e^-$, Au	7.0×10^{-13}	—
μ^-, SiC $\to e^-$, SiC	—	2×10^{-14} (DeeMe)
μ^-, Al $\to e^-$, Al	—	$10^{-15} - 10^{-17}$ (COMET) $10^{-17} - 10^{-18}$ (Mu2e)
μ^-, Ti $\to e^-$, Ti	4.3×10^{-12}	$\sim 10^{-18}$ (PRISM/PRIME)

LFV : Where to look for?

$\ell_i \to \ell_j \gamma$

$\ell_i \to 3\,\ell_j$

$\ell_i \to \ell_j \ell_k \ell_k$

$\mu - e$

conversion in nuclei

BSM

LFV at colliders

This talk!

$M \to \ell_i \ell_j$

FlavorKit

[Porod, Staub, AV, 2014]

A computer tool that provides automatized analytical and numerical computation of flavor observables. It is based on SARAH, SPheno and FeynArts/FormCalc.

Lepton flavor	**Quark flavor**
$\ell_\alpha \to \ell_\beta \gamma$	$B^0_{s,d} \to \ell^+ \ell^-$
$\ell_\alpha \to 3\,\ell_\beta$	$\bar{B} \to X_s \gamma$
$\mu - e$ conversion in nuclei	$\bar{B} \to X_s \ell^+ \ell^-$
$\tau \to P\,\ell$	$\bar{B} \to X_{d,s} \nu \bar{\nu}$
$h \to \ell_\alpha \ell_\beta$	$B \to K \ell^+ \ell^-$
$Z \to \ell_\alpha \ell_\beta$	$K \to \pi \nu \bar{\nu}$
	$\Delta M_{B_{s,d}}$
	ΔM_K and ε_K
	$P \to \ell \nu$

Not limited to a single model: use it for the model of your choice

Easily extendable

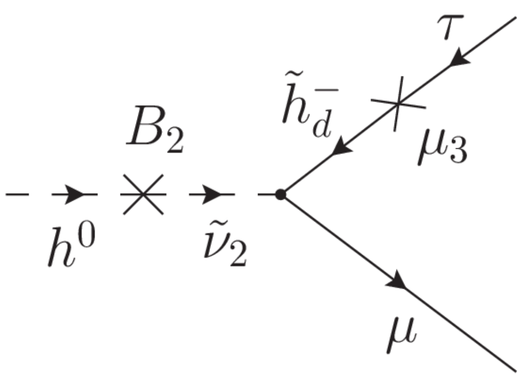
Many observables ready to be computed in your favourite model!

Manual: arXiv:1405.1434
Website: http://sarah.hepforge.org/FlavorKit.html

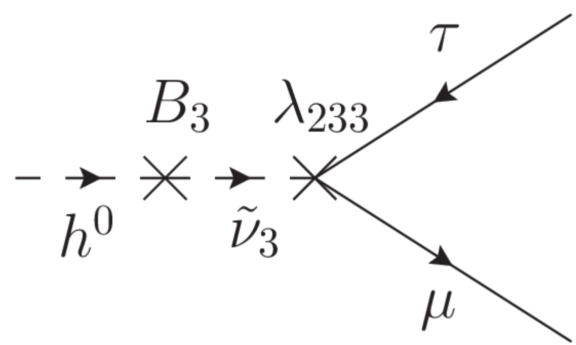
$H \to \mu\tau$ in RPV

[Arhrib, Cheng, Kong, 2013]

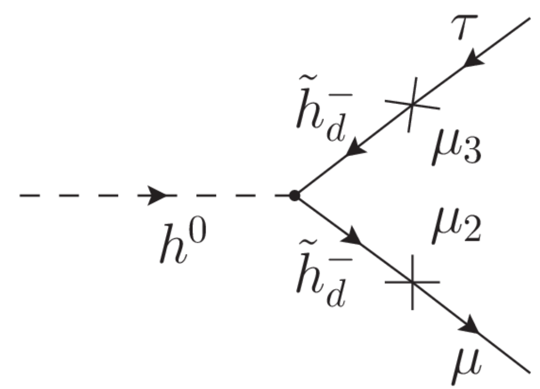
The particles-sparticles mixing induced by RPV lead to
tree-level LFV Higgs decays



$B\epsilon$ contribution



$B\lambda$ contribution

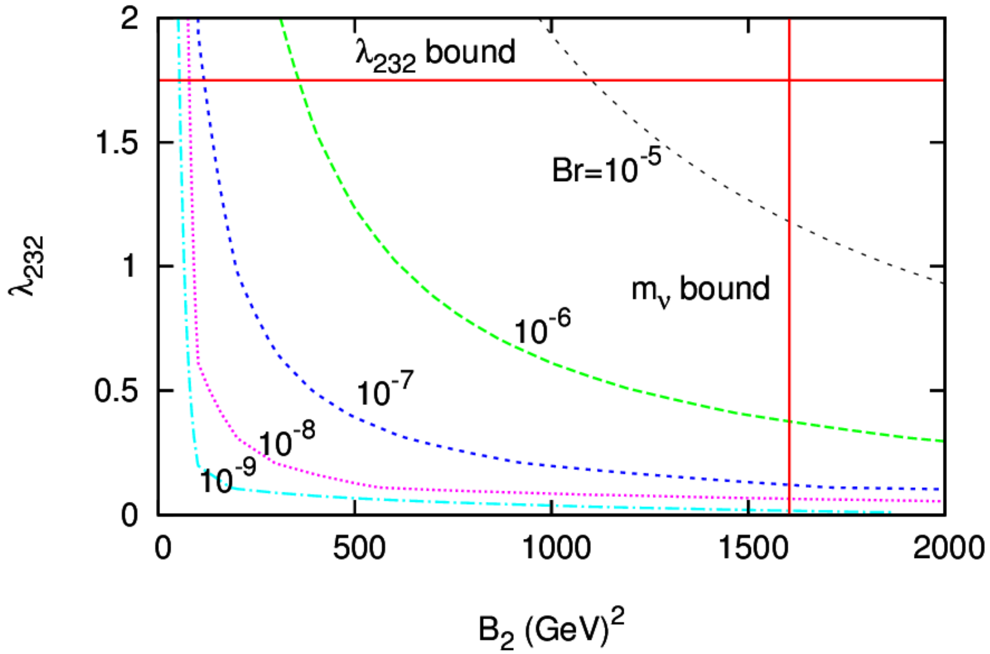


ϵ^2 contribution

Note: $\mathcal{L}_{soft} \supset B\tilde{L}H_u$

$H \to \mu\tau$ in RPV

[Arhrib, Cheng, Kong, 2013]

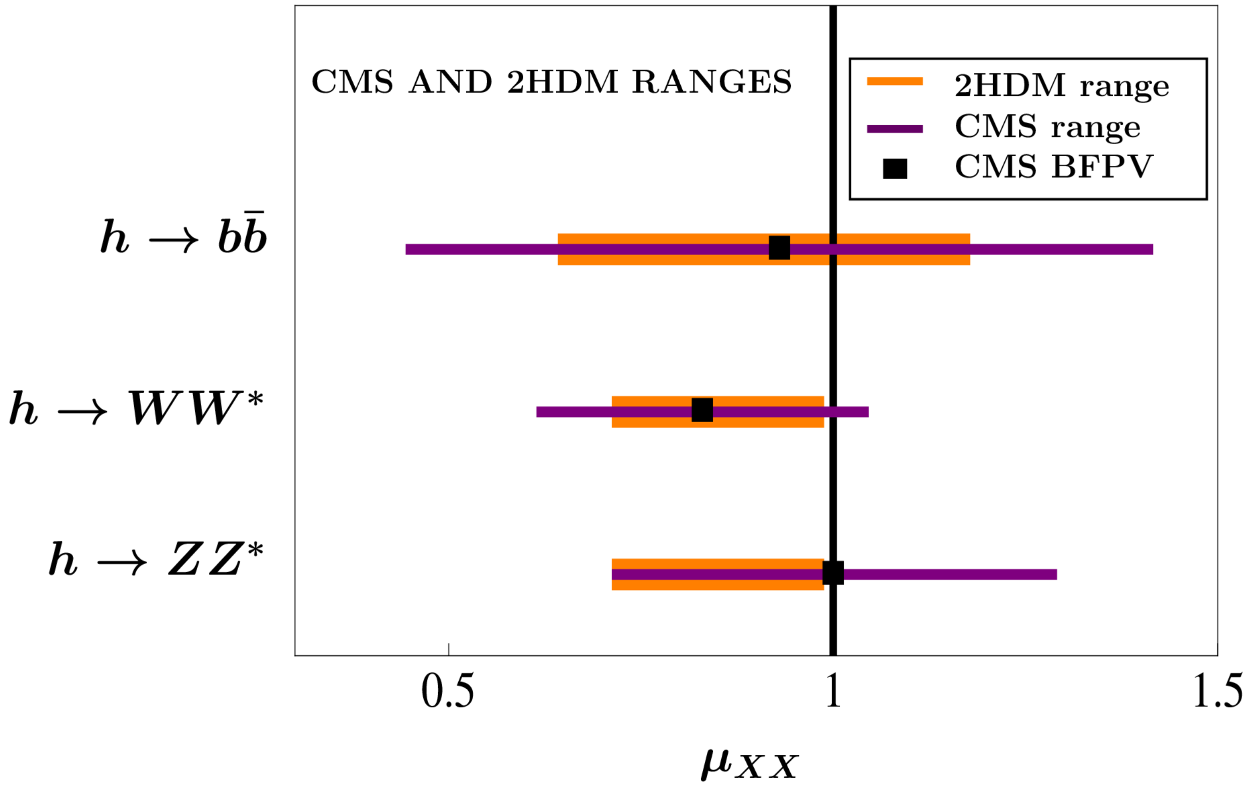


RPV Parameter Combinations	Br with Neutrino Mass $\lesssim 1$ eV Constraint
$B_2\,\mu_3$	1×10^{-15}
$B_3\,\mu_2$	1×10^{-13}
$B_1\,\lambda_{123}$	1×10^{-5}
$B_1\,\lambda_{132}$	3×10^{-5}
$B_2\,\lambda_{232}$	3×10^{-5}
$B_3\,\lambda_{233}$	3×10^{-5}
$\mu_2\,\mu_3$	2×10^{-18}
$B_1\,A^{\lambda}_{123}$	5×10^{-11}
$B_1\,A^{\lambda}_{132}$	5×10^{-11}
$B_2\,A^{\lambda}_{232}$	5×10^{-11}
$B_3\,A^{\lambda}_{233}$	5×10^{-11}

Again... unobservable at the LHC

A new hope: Type-III 2HDM

[Aristizabal Sierra, AV, 2014]



Signal strengths ranges in the 2HDM
Compatible with all constraints and the CMS signal for $h \to \tau\mu$

The $b \to s$ anomalies

[LHCb, 2013]
1305.2168, 1308.1707, 1403.8044

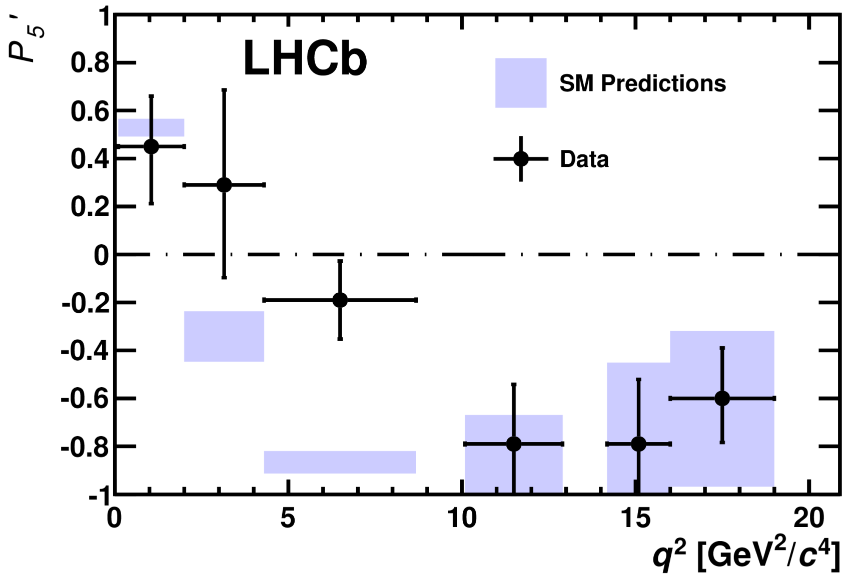
Episode 1

2013 : First anomalies found by LHCb

- Data collected: $1\ \mathrm{fb}^{-1}$ $(3\ \mathrm{fb}^{-1}$ in some observables$)$
- Decrease (w.r.t. the SM) in several branching ratios
- Several anomalies in angular observables

arXiv:1308.1707

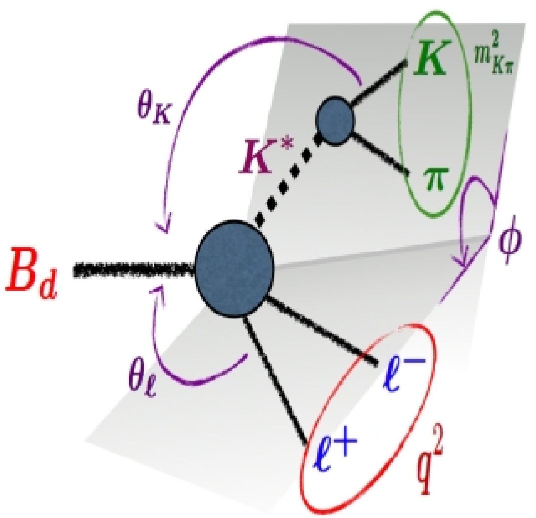
Popular example: P_5' in $B \to K^* \mu^+ \mu^-$



The $b \to s$ anomalies

$B \to K^* (\to K\pi)\, \mu^+\mu^-$ differential angular distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



[Figure borrowed from Javier Virto]

J_i : functions of q^2, C_i, FF

Optimized observables
[Descotes-Genon et al, 2012, 2013]

$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}}$$

The $b \to s$ anomalies

[LHCb, 2014]
arXiv:1406.6482

Episode 2

2014 : Lepton universality violation

Obtained with 3 fb^{-1}

$$R_K = \frac{\text{BR}(B \to K \mu^+ \mu^-)}{\text{BR}(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_K^{\text{SM}} = 1.0003 \pm 0.0001$$ [Hiller, Kruger, 2004]

2.6σ away from the SM

The $b \to s$ anomalies

[LHCb, 2015]
C. Langenbruch, Moriond 2015
March 20th

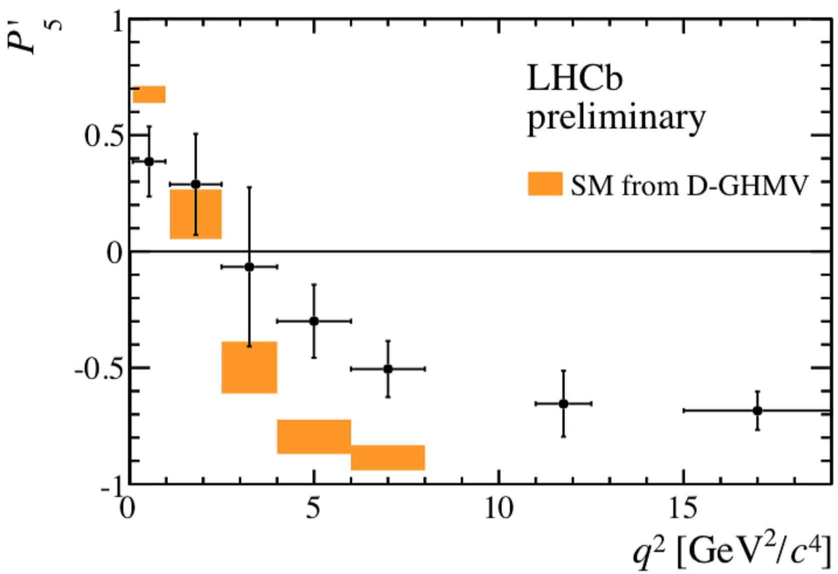
Episode 3

2015 : LHCb confirms first anomalies

All observables updated to 3 fb^{-1}

[Complete LHC Run I dataset]

Errors shrunk...
... anomalies persist



Fit result in the SM

David Straub's talk Moriond 2015

- $\chi^2_{SM} = 116.9$ for 88 measurements (p value 2.14 %)

Including also $b \to s e^+ e^-$ processes:

- $\chi^2_{SM} = 125.8$ for 91 measurements (p value 0.92 %)

Biggest tensions: (careful, these observables are not independent! E.g. only P_5' or S_5 in fit)

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	[2, 4.3]	0.81 ± 0.02	0.26 ± 0.19	ATLAS	+2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	[4, 6]	0.74 ± 0.04	0.61 ± 0.06	LHCb	+1.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	[4, 6]	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	−2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	[1.1, 6]	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	−2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	[4, 6]	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	−2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[4, 6]	0.54 ± 0.08	0.26 ± 0.10	LHCb	+2.1
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	[0.1, 2]	2.71 ± 0.50	1.26 ± 0.56	LHCb	+1.9
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	[16, 23]	0.93 ± 0.12	0.37 ± 0.22	CDF	+2.2
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[1, 6]	0.48 ± 0.06	0.23 ± 0.05	LHCb	+3.1

Some comments on DM

However:

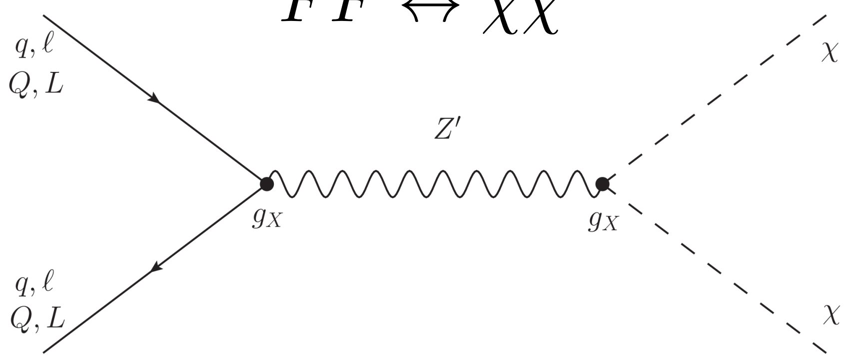
Higgs portal also possible

Assumption:

$\lambda_{H\chi} \ll 1$ → **Z' portal**

Interplay between flavor and DM

$\bar{F}F \leftrightarrow \chi\chi^*$



$$\sigma(s) \sim \left|\Delta^{f_i f_j}\right|^2 g_X^2 \frac{1}{s} \frac{m_{Z'}^4}{\left(m_{Z'}^2 - s\right)^2 - m_{Z'}^2 \Gamma_{Z'}^2} F_{\text{kin}}$$

Favorable conditions

$$m_\chi > m_{Q,L}$$

$$m_{Z'} > m_\chi$$

$$m_\chi \simeq \frac{m_{Z'}}{2}$$

(resonance)

Z-Z' mixing

Nothing prevents U(1) factors from mixing

$$\mathcal{L} \supset \varepsilon \, F^{Y}_{\mu\nu} F^{\mu\nu}_{X}$$

Problem: The Z' would have flavor violating couplings to all SM fermions

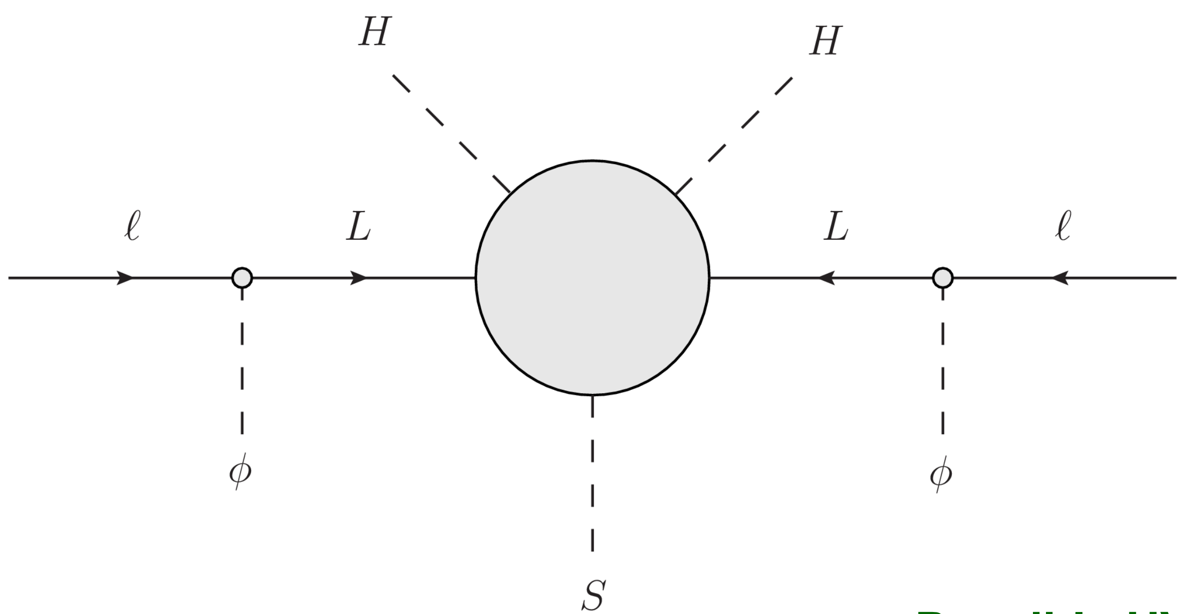
However, this is under control in this model:

- Not induced via renormalization group running if it is zero at some high-energy scale
- Suppressed for $m_Q \sim m_L$

$$\varepsilon_{\text{1-loop}} \propto \frac{g_1 g_X}{16\pi^2} \log\left(\frac{m_Q}{m_L}\right)$$

Neutrino masses

Non-trivial neutrino mass generation



$$S = (1, 1, 0, -4)$$

[preserves $\mathbb{Z}_2$]

$$\mathcal{O}_\nu = \frac{1}{\Lambda_\nu^5} \ell \ell H H \phi \phi S$$

Possible UV completion

Vector-like fermion $F = (1, 1, 0, 2)$

$$\mathcal{L} \supset \lambda_S S \overline{F^c} F + y \overline{L} H F$$

$\boldsymbol{B_s \to \mu^+\mu^-}$

$$\mathcal{O} = (\bar{s}\gamma_\alpha P_L b)\ (\bar{\mu}\gamma^\alpha P_L \mu) \qquad \Rightarrow \qquad \overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$$

Contributes to
$\mathcal{O}_9$ and $\mathcal{O}_{10}$

[CMS and LHCb, 2013]

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = (2.9 \pm 0.7) \times 10^{-9}$$

[Bobeth et al, 2013]

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

$$-0.25 < C_{10}^{\mu,\mathrm{NP}} / C_{10}^{\mu,\mathrm{SM}} < 0.03$$ (at 1σ)

The model is compatible at 2σ

$\boldsymbol{B_s - \bar{B}_s}$ mixing

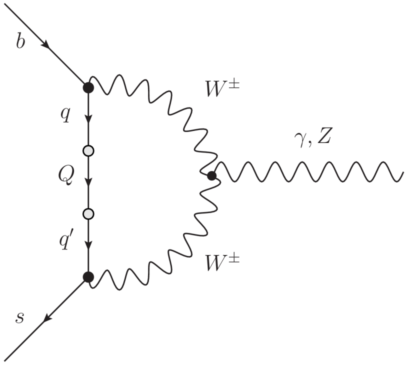
[Altmannshofer et al, 2014]

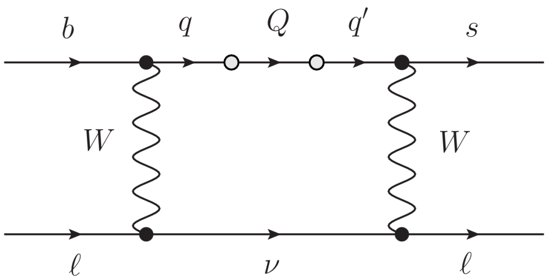
Allowing for a 10% deviation from the SM expectation in the mixing amplitude

$$\frac{m_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244\ \mathrm{TeV}$$

Loop corrections

At 1-loop, the vector-like quarks contribute to all operators





- Non-negligible corrections to C_9

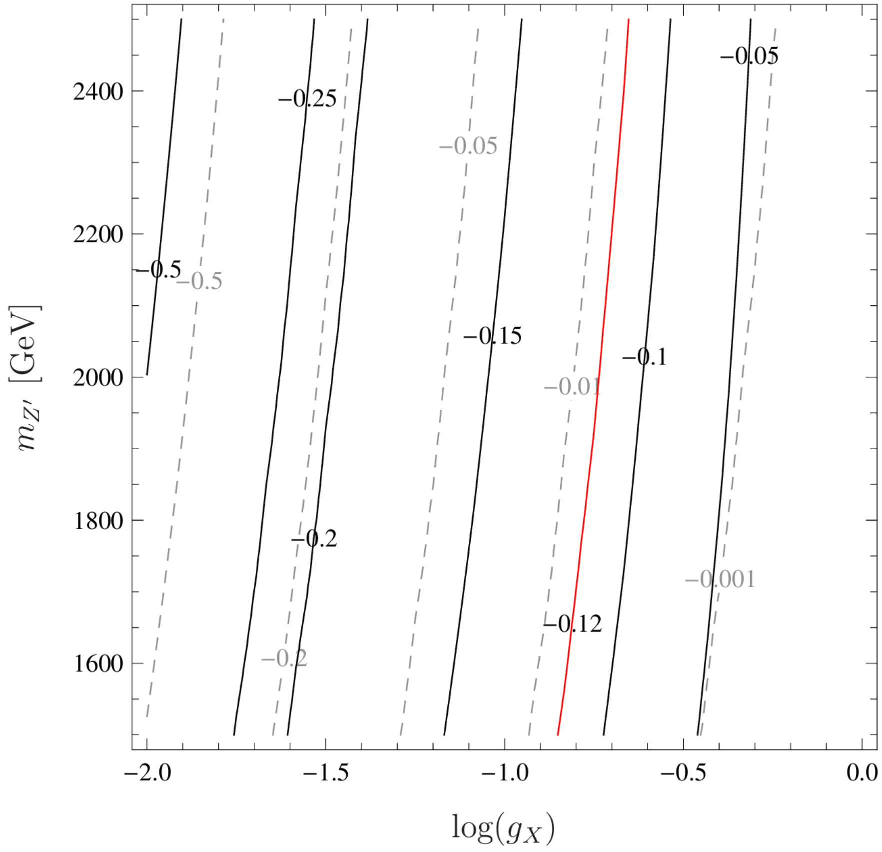
- Unwanted contributions to other Wilson coefficients

However: "Valid" region is safe

$$C_7^{\rm NP}/C_7^{\rm SM} < 1\%$$

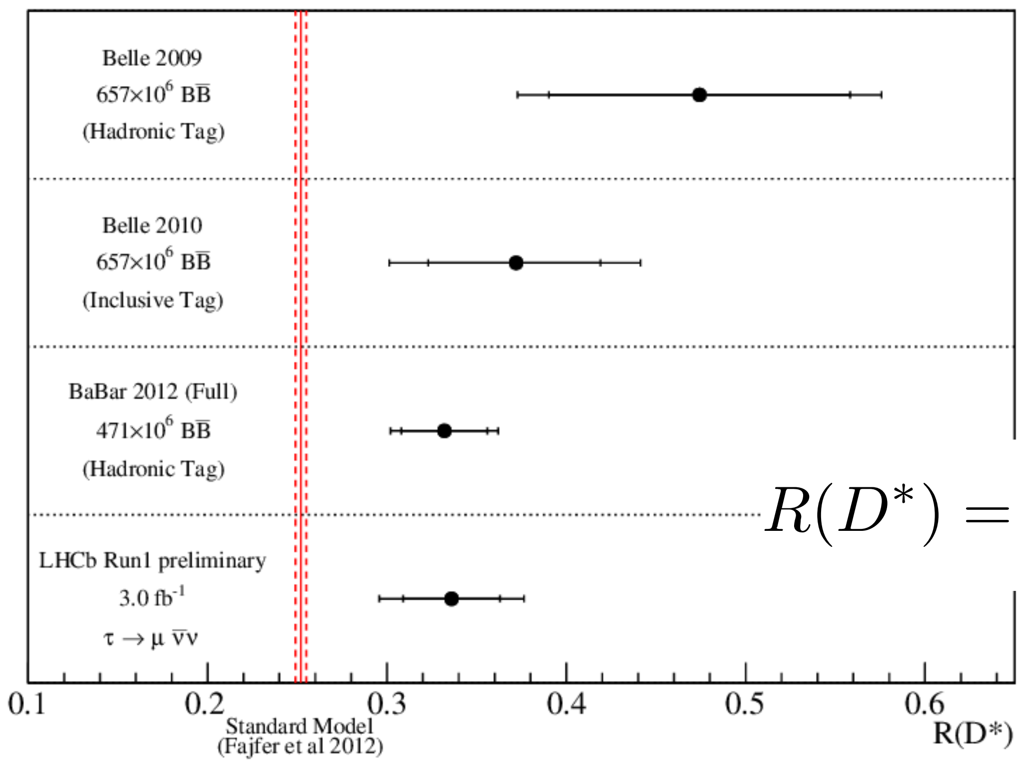
[Computed with **FlavorKit**]

$C_9^{\rm NP}/C_9^{\rm SM}$ (full) $C_7^{\rm NP}/C_7^{\rm SM}$ (dotted gray)



Result

More anomalies?
Greg Ciezarek's talk
FPCP 2015



$$R(D^*) = \frac{\mathrm{BR}(B \to D^* \tau\nu)}{\mathrm{BR}(B \to D^* \ell\nu)}$$

- We measure $\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$
  - In good agreement with past measurements
  - Agreement with SM at 2.1σ level
- Measurement will improve with more data: largest systematic uncertainties depend on control samples (or simulation size)
- Paper (LHCB-PAPER-2015-025) to come in a few weeks