Family non-universal Z' models with protected flavour-changing interactions

Martin Jung

in collaboration with A. Celis, J. Fuentes-Martín and H. Serôdio

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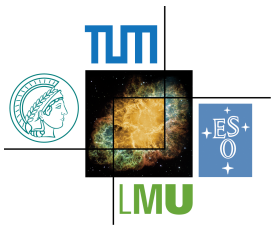


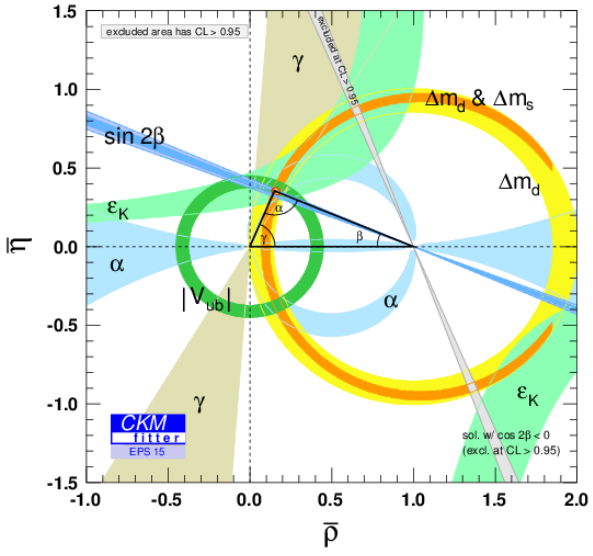
Workshop on
"Novel aspects of $b \to s$ transitions:
Investigating new channels"
Marseille, France
6th of October 2015

Motivation

Flavour and CP violation in the SM:

- CKM describes flavour and CP violation
- Extremely constraining, one phase
- Especially, K and B physics agree
- Only tensions so far(?)

➥ Works well!



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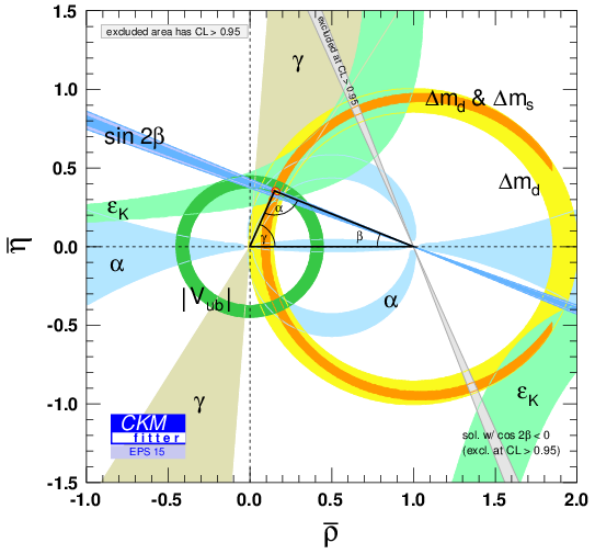
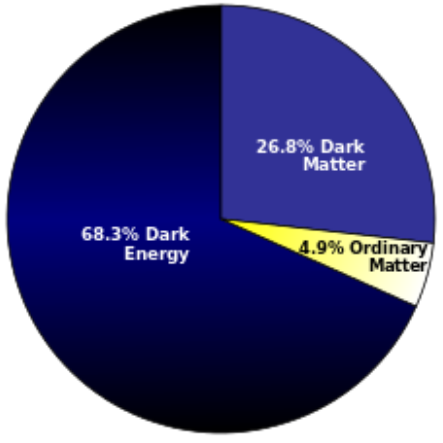


We expect new physics (ideally at the (few-)TeV scale):

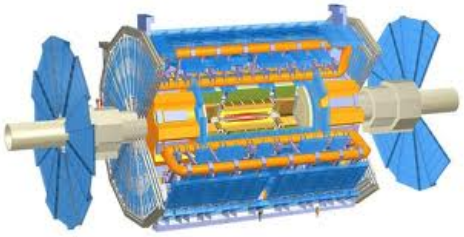
- Baryon asymmetry of the universe
- Hierarchy problem
- Dark matter and energy
- ...



↳ So where is it?

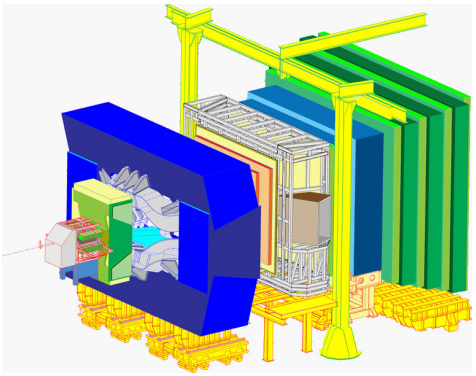
The Quest for New Physics

Three of the main strategies (missing are e.g. ν, DM, astro,...):



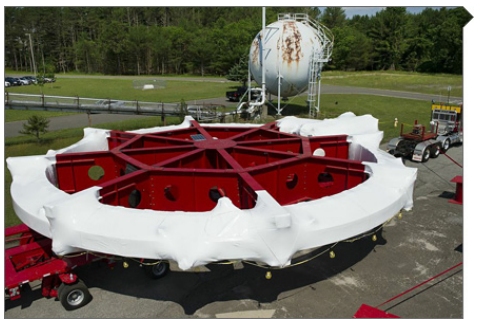
Direct search:

- Tevatron, LHC (Run 2 is here!)
- Maximal energy fixed



Indirect search, flavour violating:

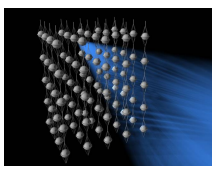
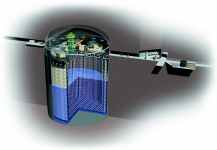
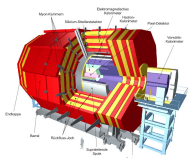
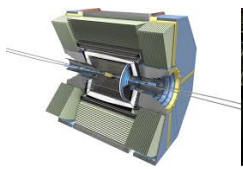
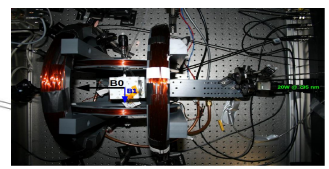
- LHCb, Belle II, BES III, NA62, MEG, ...
- Maximal reach flexible



Indirect search, flavour diagonal:

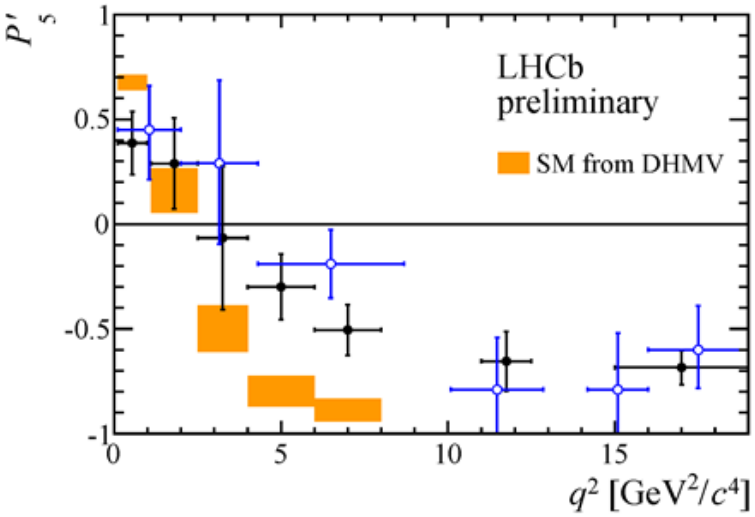
- EDM experiments, g-2, APV,...
- Maximal reach flexible, complementary to flavour-violating searches

A new era in particle physics!

Have we seen NP in $b \to s\ell\ell$?

The LHCb anomalies [see also talks by Martin, Mitesh, Nejc, Javier]



$$R_K = \frac{\mathrm{BR}(B \to K \mu^+ \mu^-)}{\mathrm{BR}(B \to K\, e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \overset{?}{\neq} 1 + \mathcal{O}(m_\mu^2/m_b^2)$$

[LHCb'14,'15]

- Global fits necessary [Descotes-Genon+,Camalich+,Beaujean+,Ghosh+, Altmannshofer+,Hurth+,Sinha+]
- QCD under control? [Camalich/Jäger'15,Lyon/Zwicky'14]
- Agreed: $C_9^\mu \sim -1$ improves fit
- QCD effects tiny [Hiller/Krüger,Bobeth+]
- Influence from cuts? [e.g. Gorbahn]

Here: take data at face value

Some model building

We require:

1. Sizable contributions to $b \to s\ell^+\ell^-$
2. Lepton non-universal couplings

Wish list:

- Minimal particle content (no new fermions)
- Predictivity for up-, down-, lepton-FCNCs

- 1.(+2.): $U(1)'$ good candidate
  [e.g. Altmannshofer+,Buras+,Crivellin+,Gauld+,Descotes-Genon+,Sierra+]
  Alternatives: [e.g. Becirevic+,Bhattacharya+,Gripaios+,Hiller+,Niehoff+]
- Particle content $U(1)'$:
  SM $\Rightarrow$ only $L_{\alpha-\beta}$ $\Rightarrow$ no $b \to s$
  $L_{\alpha-\beta}$ + vector-like quarks $\Rightarrow$ effective $b \to s$ [Altmannshofer+'14]
  Include quarks directly $\Rightarrow$ extended scalar sector [Leurer+'92]
  2HDMs: $L_{\alpha-\beta}$ + non-trivial quark sector possible [Crivellin+'15]

Flavour violation in 2HDMs

Generic 2HDMs: huge flavour violation

- solution to this a main characteristic
  - Avoid FCNCs at tree level
    - NFC, MFV, Alignment, ...
  - Allow for controlled FCNCs
    - Cheng-Sher ansatz/Type III $\Rightarrow$ little predictivity
    - Branco-Grimus-Lavoura (BGL) models

BGL models:

- Use flavour symmetry to relate all flavour-change to CKM
  - Unique pattern in 2HDMs! [Ferreira/Silva'11,Serôdio'13]
- Choice: FCNCs in down-quark sector, up-sector diagonal

$$\text{Up Yukawas:} \quad \Delta_1^{\mathrm{BGL}} = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \Delta_2^{\mathrm{BGL}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\text{Down Yukawas:} \quad \Gamma_1^{\mathrm{BGL}} = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} \quad \Gamma_2^{\mathrm{BGL}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

Gauging BGL models - quark sector

- BGL via discrete symmetries yields accidental $U(1)$
- Scalars disfavoured as solution for $b \to s$ anomalies
- Idea: Gauge BGL models! [Celis/Fuentes-Martín/MJ/Serôdio]

Gauging BGL models - quark sector

- BGL via discrete symmetries yields accidental $U(1)$
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➥ Idea: Gauge BGL models! [Celis/Fuentes-Martín/MJ/Serôdio]

Implementation of BGL patterns: $\psi \to e^{i\mathcal{X}^\psi}\psi$, 3 free charges

$$\mathcal{X}_R^u = \text{diag}\,(X_{uR}, X_{uR}, X_{tR}) \qquad \mathcal{X}_R^d = X_{dR}\,\mathbb{1}$$

$$\mathcal{X}_L^q = \frac{1}{2}\left[\text{diag}\,(X_{uR}, X_{uR}, X_{tR}) + X_{dR}\,\mathbb{1}\right]$$

$$\mathcal{X}^\Phi = \frac{1}{2}\text{diag}\,(X_{uR} - X_{dR}, X_{tR} - X_{dR})$$

Require $U(1)_{\rm BGL}$ to be anomaly-free:

- Automatic in the $SU(3)_C$ sector [Celis+'14]
- Not possible using only the SM quark sector

➥ Include lepton sector

Gauging BGL models - including leptons

Most general charges: arbitrary $X_{\ell L,R}$ with $\ell = e, \mu, \tau$
Anomaly conditions from 5 combinations:

- Linear: $U(1)'[SU(2)_L]^2$, $U(1)'[U(1)_Y]^2$, $U(1)'[(\mathrm{gravity})]^2$
- Quadratic: $[U(1)']^2 U(1)_Y$
- Cubic: $[U(1)']^3$

➥ Highly non-trivial system to solve, only one class of solutions!

➥ Involves one free charge (physical choice) with 6 permutations

➥ Here: $X_{\phi_2} \equiv 0 \Rightarrow Z - Z'$ mixing suppressed ($\tan\beta \gg 1$)

Patterns in quark sector imply (independent of charge choice):

1. Lepton-flavour non-universality
2. Lepton-flavour conservation [cf. talks by Damir, Diego & Lars]

Scalar sector of the $U(1)'_{\mathrm{BGL}}$ model

Higgs sector has 2 doublets Φ_i and 1 complex singlet S:

- vev for S (v_S) yields $U(1)'$ breaking
  - ➥ $v_S/v \gg 1 \Rightarrow$ characterizes scalar sector
- Parameters: 10 dof $\Rightarrow$ 6 scalars, 4 massive Goldstone bosons
- Spectrum: $H_{1,2,3}, H^{\pm}, A$, $M_{H_1} \sim v$, $M_{H^{\pm},H_{2,3},A} \sim v_S$
- Potential CP-invariant because of $U(1)'$
- Spontaneous CP violation is also absent
- H_3 couplings additionally suppressed by v/v_S

Phenomenology:

- BGL structure in 2HDMs viable for $M \sim \mathrm{few} \times 100\ \mathrm{GeV}$
  [Botella+'14,Batthacharya+'14]
- Here scalars mostly decoupling $\Rightarrow$ Higgs measurements fine
- Basically one constraint from flavour: $B_{d,s} \to \mu^+\mu^-$
  - ➥ Uncorrelated to Z' constraints

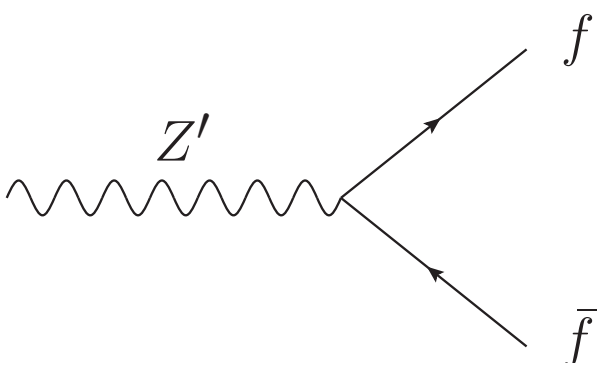
Z' couplings of the $U(1)'_{\rm BGL}$ model

Mass eigenbasis:

- Couplings to u_L, u_R, d_R: diagonal and 2-family universal (1,2)
- Couplings to ℓ_L, e_R: diagonal and family-non-universal
- Couplings to d_L:

$$\widetilde{\mathcal{X}}_L^d = -\frac{5}{4}\mathbb{1} + \frac{9}{4}\begin{pmatrix} |V_{td}|^2 & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & |V_{ts}|^2 & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & |V_{tb}|^2 \end{pmatrix}$$

Controlled Z'-mediated FCNCs:



$$= g'\gamma^\mu\left(\widetilde{\mathcal{X}}_L^f P_L + \widetilde{\mathcal{X}}_R^f P_R\right)$$

$U(1)'_{\mathrm{BGL}}$ – Overview

Features of the $U(1)'_{\mathrm{BGL}}$ model:

- No FCNCs in the up-quark sector
- Symmetry yields lepton-flavour non-universality without lepton-flavour violation
- Controlled tree-level FCNCs, determined by CKM
- Higgs sector phenomenologically viable, no large effects
- Z' extremely predictive: 2 parameters (plus one charge)

➥ Let's check the available constraints...

Phenomenological consequences - Generalities

What can we say without a detailed analysis?

- Strong direct limits $\Rightarrow$ potential Z' is very heavy
  $M_W^2/M_{Z'}^2 \lesssim 0.1\%$!
  - Most observables are unaffected!
  - Effects only for SM suppression *in addition to* G_F+*CKM*
    EW penguin decays, mixing, CP violation, leptonic decays, ...
- Z' gives the dominant NP effect almost everywhere

A bit more detail:

- UT analysis basically unaffected (exceptions ϵ_K and Δm_d, but $\Delta m_d/\Delta m_s = \Delta m_d/\Delta m_s|_{\mathrm{SM}}$)
- $\Delta m_d, \Delta m_s, \epsilon_K$ give similar bounds.

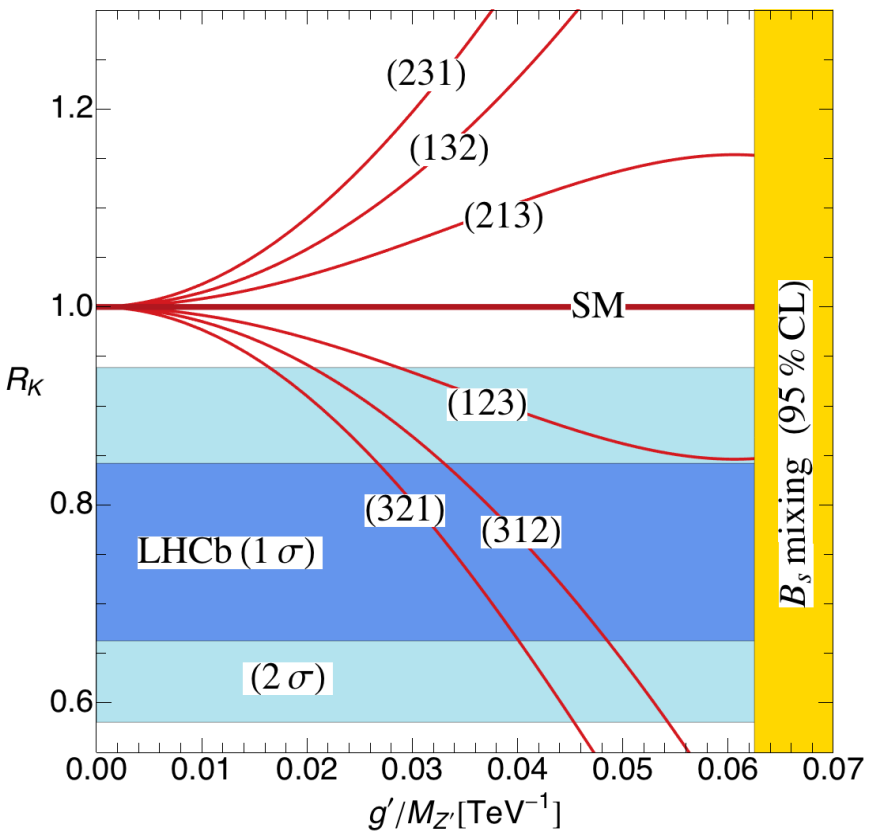
$$\text{From } \Delta m_s: \quad M_{Z'}/g' \geq 16 \text{ TeV } (95\% \text{ CL})$$

Improvement here just depends on LQCD!

R_K and its sisters

$$R_M^q \equiv \frac{\mathrm{Br}(B_q \to \bar{M}\mu^+\mu^-)}{\mathrm{Br}(B_q \to \bar{M}e^+e^-)} \qquad M \in \{K, K^*, X_s, \phi, \ldots\},\ q = u, d, s$$

Note: $R(X_s) = 0.42 \pm 0.25$ (Belle) 0.58 ± 0.19 (BaBar)
(but not a consistent picture [cf. Hiller/Schmaltz'15])



Model	$C_9^{\mathrm{NP}\mu}(1\sigma)$	$C_9^{\mathrm{NP}\mu}(2\sigma)$
(1,2,3)	–	$[-2.92, -0.61]$
(3,1,2)	$[-0.93, -0.43]$	$[-1.16, -0.17]$
(3,2,1)	$[-1.20, -0.53]$	$[-1.54, -0.20]$

Fits $B \to K^*\mu^+\mu^-$ ✓

Furthermore:

$$\widehat{R}_M \equiv \frac{R_M}{R_K} = 1$$

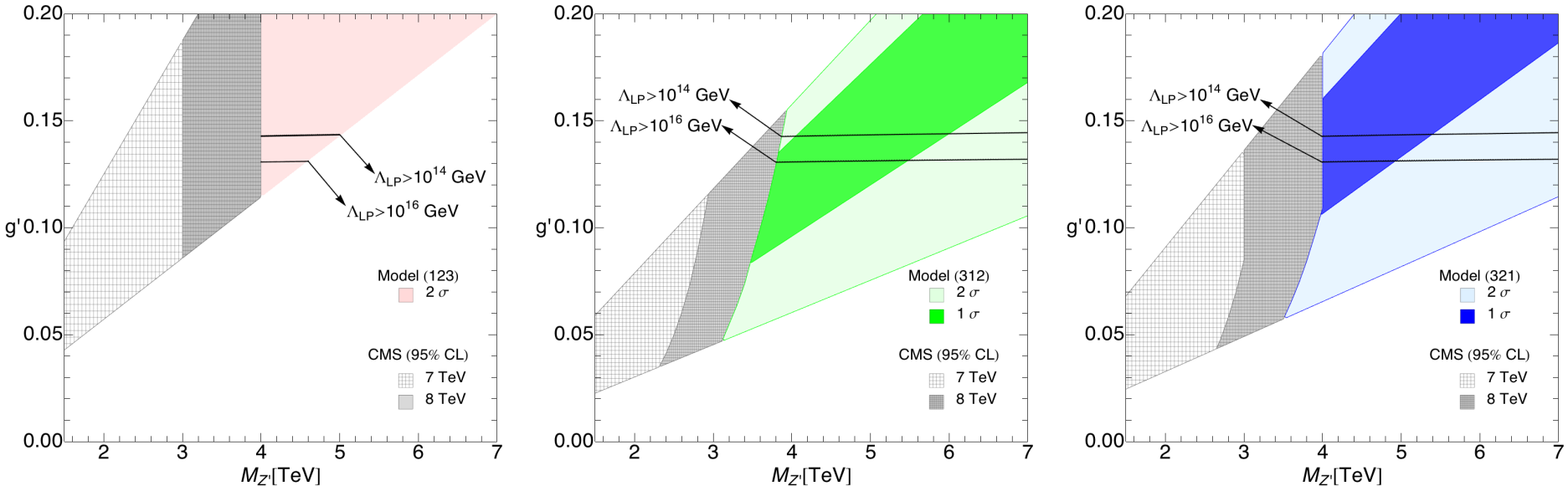
➥ "Easily" verifiable for any charge assignment

Combination with direct searches and perturbativity

Obvious way to search for Z': $\sigma(pp \to Z'(\to f\bar{f})X)$

Strong semi-model-independent limits from ATLAS and CMS:

[Carena+'04,Accomando+'11]



- 2.5 models survive all constraints, $M_{Z'} \geq 3 - 4$ TeV
- Strong upper bound on one model from perturbativity
- Differentiable from each other and different models:
  (i) Flavour (LNU vs. FCNC) (ii) $\mu_{ff'} = \sigma(Z' \to f\bar{f})/\sigma(Z' \to f'\bar{f}')$

Further constraints

We also considered the following observables:

- Neutrino trident production
- Atomic parity violation
- EDMs (cancellations in the Higgs sector [MJ/Pich'14])
- $g-2$

All of these are weaker than the ones discussed earlier

Bounds on contact interactions problematic (benchmarks don't fit)
Potentially strong for very heavy Z' (LHC)

Model predicts change in $B_{d,s} \to \mu\mu$ central values: [cf. Flavio's talk]

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)|_{\rm SM}} = \frac{\mathrm{BR}(B_d \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)|_{\rm SM}}$$

➥ wait for additional data, value uncorrelated with Z' observables

Conclusions

$U(1)'_{\mathrm{BGL}}$ viable, predictive model:

- Starting point: 2HDM solving FCNC problem
  - No FCNCs for up-quarks
  - Controlled FCNCs on tree-level for down-quarks
  - All flavour-changing interactions determined by CKM
- Gauging symmetry yields LNU, but no LFV for leptons
- Z' sector depends only on $g'/M_{Z'}$ and $M_{Z'}$
  - Will be further tested soon

Things to do:

- Investigate other model realizations
- Include neutrino masses
  - Possible without spoiling above features
- Global fit to $b \to s$ data
  - Volunteers from the fitting groups?

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Thank you!

Anomaly-free top-BGL implementation [Slide from J. Fuentes-Martín]

$$\psi^0 \to e^{i\mathcal{X}^\psi}\psi^0$$

Only one class of models (with X_{Φ_2} and X_{dR} free parameters)

$$\mathcal{X}_L^q = \mathrm{diag}\left(-\frac{5}{4}, -\frac{5}{4}, 1\right) \qquad \mathcal{X}_R^u = \mathrm{diag}\left(-\frac{7}{2}, -\frac{7}{2}, 1\right)$$

$$\mathcal{X}_R^d = \mathbb{1}$$

$$\mathcal{X}_L^\ell = \mathrm{diag}\left(\frac{9}{4}, \frac{21}{4}, -3\right) \qquad \mathcal{X}_R^e = \mathrm{diag}\left(\frac{9}{2}, \frac{15}{2}, -3\right)$$

$$\mathcal{X}^\Phi = \mathrm{diag}\left(-\frac{9}{4}, 0\right)$$

- $X_{dR} = 1$, unphysical normalization. But it also normalizes g'!
- $X_{\Phi_2} = 0$ to avoid large $Z - Z'$ mass mixing (for large t_β)
- Six possible model variations $(e, \mu, \tau) = (i, j, k)$

Details on direct searches

Approximation for NWA, negligible SM interference and flavour-universal quark couplings:

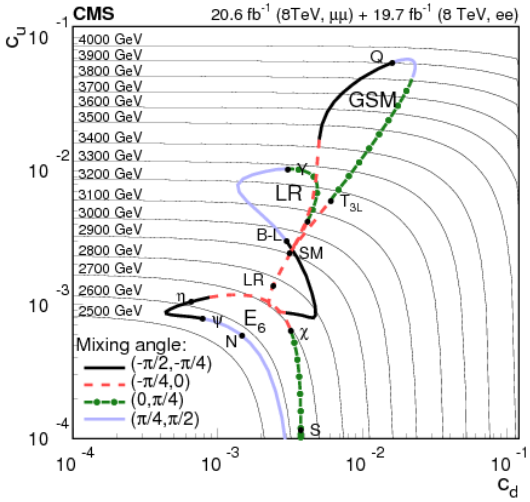
$$\sigma = \frac{\pi}{48s}\left[c_u^f w_u\left(s,\, M_{Z'}^2\right) + c_d^f w_d\left(s,\, M_{Z'}^2\right)\right]$$

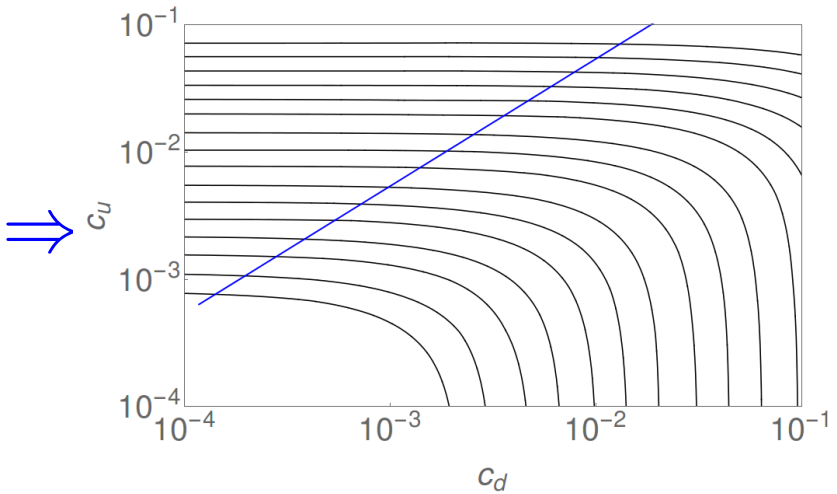
$$c_{u,d}^f \simeq g'^2\left(X_{qL}^2 + X_{(u,d)R}^2\right)\mathrm{Br}\left(Z' \to f\bar{f}\right)$$

Applicable for $g' \leq 0.2$!

- First two generations dominate and couple universally

CMS model-independent bounds: [CMS-EXO-12-061]





Correlations among the effective operators $\mathcal{O}^{\ell}_{9,10}$

Model	$C_{10}^{\mathrm{NP}\mu}/C_{9}^{\mathrm{NP}\mu}$	$C_{9}^{\mathrm{NP}e}/C_{9}^{\mathrm{NP}\mu}$	$C_{10}^{\mathrm{NP}e}/C_{9}^{\mathrm{NP}\mu}$
(1,2,3)	$3/17$	$9/17$	$3/17$
(1,3,2)	0	$-9/8$	$-3/8$
(2,1,3)	$1/3$	$17/9$	$1/3$
(2,3,1)	0	$-17/8$	$-3/8$
(3,1,2)	$1/3$	$-8/9$	0
(3,2,1)	$3/17$	$-8/17$	0