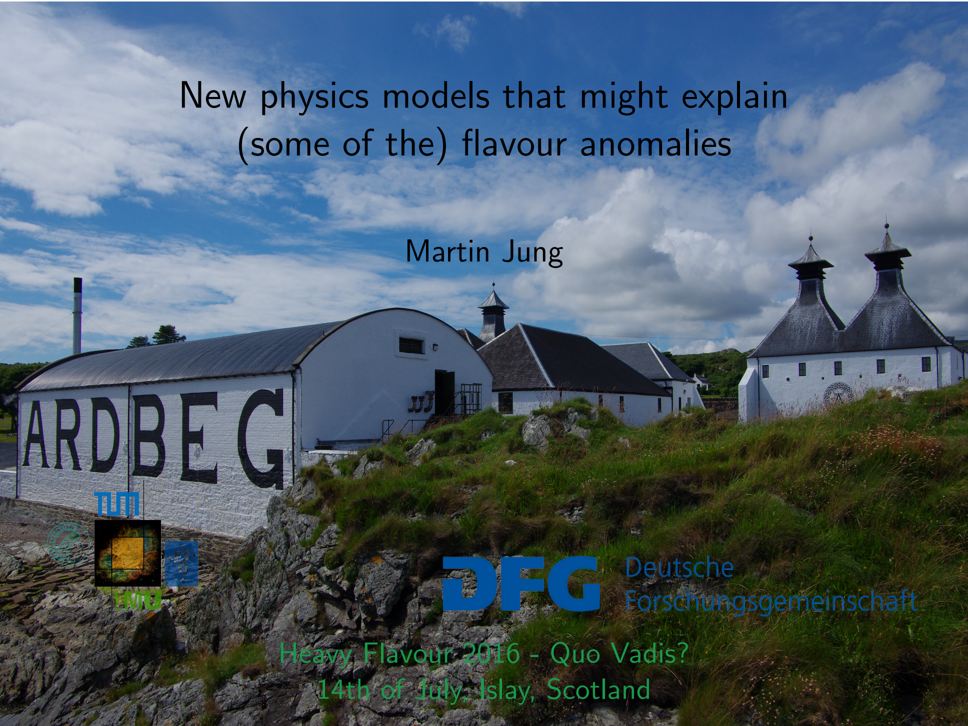
New physics models that might explain (some of the) flavour anomalies

Martin Jung



Deutsche Forschungsgemeinschaft

Heavy Flavour 2016 - Quo Vadis?
14th of July, Islay, Scotland

Anomalies in B decays

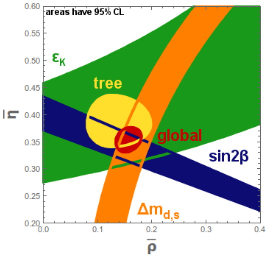
$b \to c\tau\nu$ [$R(D^{(*)})$] & $b \to s\ell\ell$ [$B \to K^*\ell\ell, R_K, \ldots$] both at $\gtrsim 4\sigma$!

Tensions not discussed here:

- $V_{ub,cb}$ inclusive vs. exclusive [see Thomas' talk]
- $g-2$ (but addressed by some of the models)
- ϵ'/ϵ (?)

Things I do not consider anomalous:

- Diphoton resonance @ 750 GeV
  [but see Dario's talk]
- $h \to \mu\tau$
- $B_{d,s} \to \mu^+\mu^-$, $\Delta m_{d,s}$

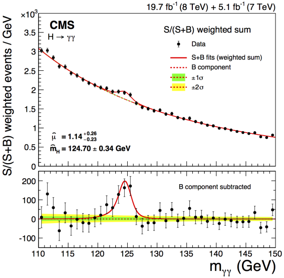


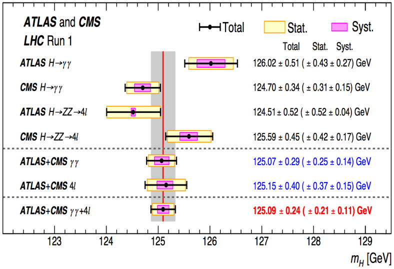
Generic models (templates) discussed here:

- Additional scalars ($\to$ 2HDMs)
- Additional gauge bosons ($\to U(1')$ models)
- Leptoquarks ($\to$ unified models)

A hierarchy of scales

A long-sought new particle. . .





A hierarchy of scales

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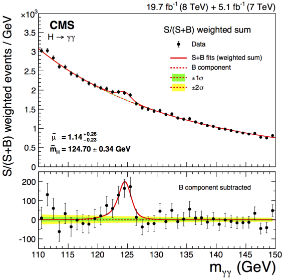
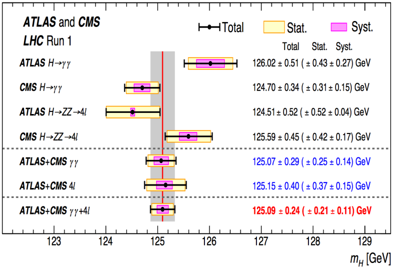
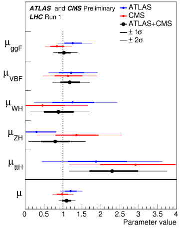
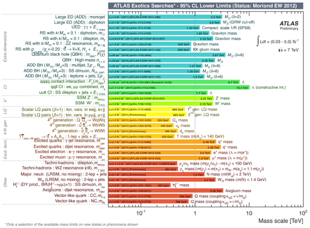
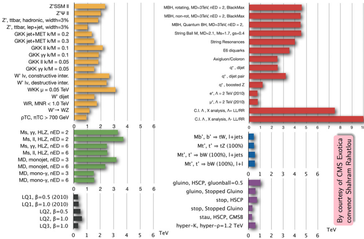




. . . but again everything looks like the Standard Model!



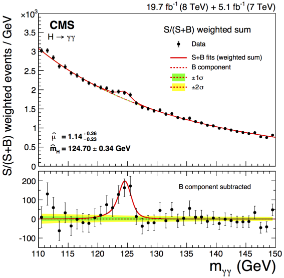


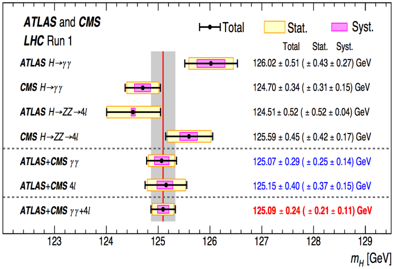


➜ Apparently hierarchy between the electroweak and NP scales!

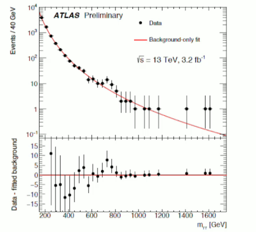
A hierarchy of scales

A long-sought new particle...





...but again everything looks like the Standard Model! (almost)

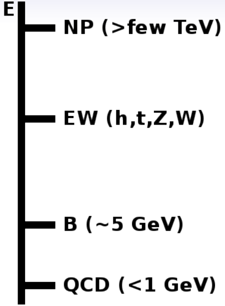


➥ Apparently hierarchy between the electroweak and NP scales!

Higgs EFT(s)

EFT approach at the electroweak scale:

- ✓ SM particle content
- ✓ SM gauge group
- ? Embedding of h
- ? Power-counting
- ➥ Formulate NLO



Linear embedding of h:

- h part of doublet H
- Appropriate for weakly-coupled NP
- Power-counting: dimensions
  ➥ Finite powers of fields

Non-linear embedding of h:

- h singlet, U Goldstones
- Appropriate for strongly-coupled NP
- Power-counting: loops ($\sim\chi$PT)
  ➥ Arbitrary powers of $h/v, \phi$

Non-linear EFT generalizes linear EFT, LO κ framework

Flavour EFTs for semi-leptonic decays

At scales $\mu \ll v, M_W$:
Construct EFT from $\psi_f, F_{\mu\nu}, G_{\mu\nu}$,
gauge group $SU(3)_C \times U(1)_{\rm em}$

Generically:

1. All coefficients independent
2. Coefficients for other processes unrelated (e.g. $\tau \leftrightarrow e, \mu$)

Implications of HEFT for the flavour-EFTs? [Cata/MJ'15]
Differences between linear and non-linear realization?
➥ Separate operators specific for non-linear HEFT

Previous work (linear EFT) e.g. [D'Ambrosio+'02,Cirigliano+'09,Alsonso+'14]

A word of caution: flavour hierarchies have to be considered!
➥ Mostly relevant when SM is highly suppressed, *e.g.* for EDMs

Implications of the Higgs EFT for flavour [Cata/MJ'15]

$\mathbf{q \to q'\ell\ell}$:

- Tensor operators absent in linear EFT for $d \to d'\ell\ell$ [Alonso+'14]
  - ➥ Present in general! (already in linear EFT for $u \to u'\ell\ell$)
- Scalar operators: linear EFT $C_S^{(d)} = -C_P^{(d)}$, $C_S'^{(d)} = C_P'^{(d)}$ [Alonso+'14]
  - ➥ Analogous for $u \to u'\ell\ell$, but no relations in general!

$\mathbf{q \to q'\ell\nu}$:

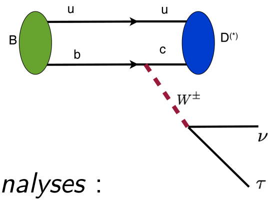
- All operators are independently present already in the linear EFT
- However: Relations between different transitions:
  C_{V_R} is lepton-flavour universal [see also Cirigliano+'09]
  Relations between charged- and neutral-current processes, *e.g.*
  $\sum_{U=u,c,t} \lambda_{Us} C_{S_R}^{(U)} = -\frac{e^2}{8\pi^2}\lambda_{ts} C_S^{(d)}$ [see also Cirigliano+'12,Alonso+'15]
- These relations are again absent in the non-linear EFT

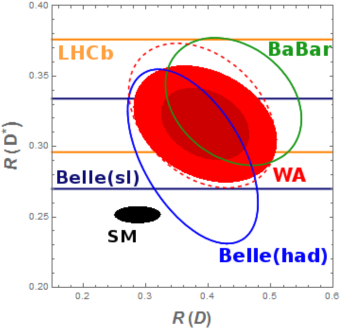
Flavour physics sensitive to Higgs embedding!
➥ Surprising, since no Higgs is involved
➥ Difficult differently [e.g. Barr+, Azatov+'15]

Experimental Situation for $b \to c\tau\nu$ 2016

Importance of semi-leptonic decays:

- SM: Determination of $|V_{ij}|$ (7/9)
  - ➡ Minimal hadronic input, improvable!
- NP: Relative to tree, τ least constrained





3 recent $R(D^{(*)})$*analyses* :

- $R(D^*)$ from LHCb [1506.08614]
- Belle update + new measurement (had./sl tag) [1507.03233,1603.06711]
- ➡ 4.0σ tension [HFAG]

Further $b \to c\tau\nu$ inputs:

- Differential rates from Belle, BaBar
- Total width of B_c
- $b \to X_c\tau\nu$ by LEP

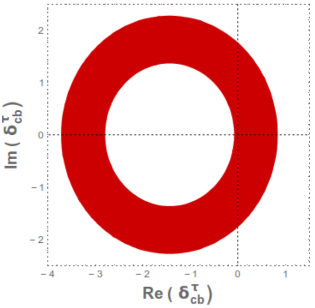
Tension $R(D^*)$ vs. $R(X_c)$: no space for $B \to D^{**}\tau\nu$ [Ligeti+'15]

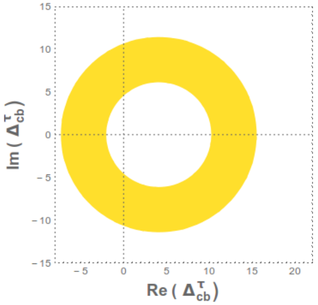
Charged scalars in $b \to c\tau\nu$

A charged scalar generally results in ($g_{L,R}^{q_u q_d l}$ complex)

$$\mathcal{L}_H^{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{q_u q_d} \left[\bar{q}_u \left(g_L^{q_u q_d l} \mathcal{P}_L + g_R^{q_u q_d l} \mathcal{P}_R \right) q_d \right] [l \mathcal{P}_L \nu_l]$$

- Model-independent subclass as long as $g_{L,R}^{q_u q_d l}$ general

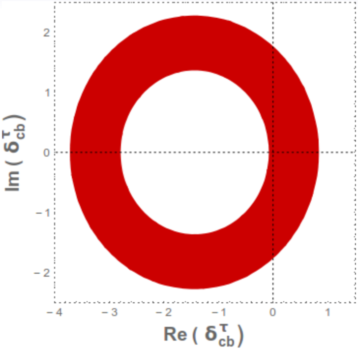


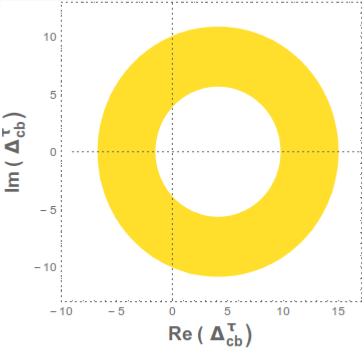


$$\delta^{cbl} \equiv \frac{(g_L^{cbl}+g_R^{cbl})(m_B-m_D)^2}{m_l(\bar{m}_b-\bar{m}_c)} \qquad \Delta^{cbl} \equiv \frac{(g_L^{cbl}-g_R^{cbl})m_B^2}{m_l(\bar{m}_b+\bar{m}_c)}$$

Can trivially explain $R(D^{(*)})$! Exclusion possible with specific flavour structure or more $b \to c\tau\nu$ observables!

$b \to c\tau\nu$ data and scalar NP

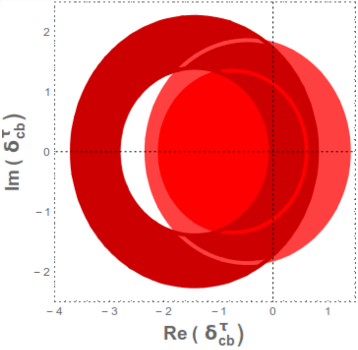


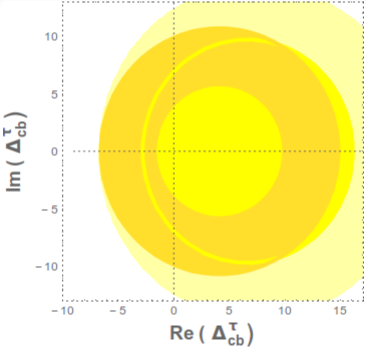


$R(D), R(D^*)$:

- $R(D)$ compatible with SM at $\sim 2\sigma$
- Preferred scalar couplings from $R(D^*)$ huge

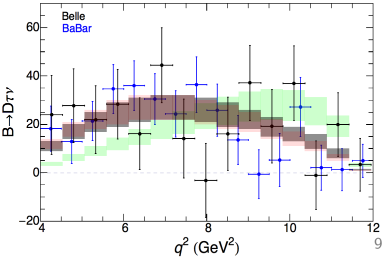
$b \to c\tau\nu$ data and scalar NP



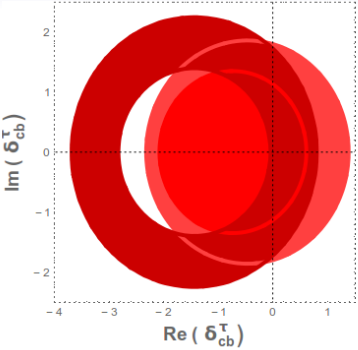


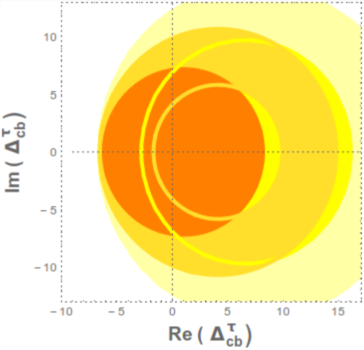
Differential rates:

- compatible with SM and NP
- already now constraining, especially in $B \to D\tau\nu$
- exclude 2nd real solution in δ^{τ}_{cb}



$b \to c\tau\nu$ data and scalar NP





Total width of B_c:

- $B_c \to \tau\nu$ is an obvious $b \to c\tau\nu$ transition
  - not measurerable in foreseeable future
  - can oversaturate total width of B_c! [X.Li+'16]
- Excludes second real solution in Δ^{τ}_{cb} plane

Consistent explanation in 2HDMs possible, flavour structure?

Generic features and issues in 2HDMs

Charged Higgs possible as explanation of $b \to c\tau\nu$ data...
However, generically $\Delta R(D^*) < \Delta R(D)$

Generic feature: Relative influence larger in leptonic decays!

- No problem in $b \to c\tau\nu$ since $B_c \to \tau\nu$ won't be measured
- Large charm coupling required for $R(D^*)$
- ➥ Embedding $b \to c\tau\nu$ into a viable model complicated!
- ➥ $D_{d,s} \to \tau, \mu\nu$ kill typical flavour structures with $g \sim m$
- ➥ Only fine-tuned models survive all (semi-)leptonic constraints

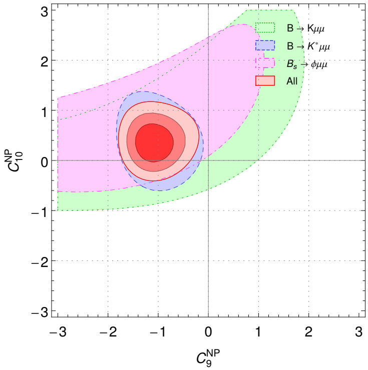
$b \to s\ell\ell$ very complicated to explain with scalar NP:

- Potential FCNC neutral Higgs coupling doesn't give C_9
- Large muon coupling very difficult to do
- ➥ 2HDM alone tends to predict $b \to s\ell\ell$ to be QCD-related

$B \to K^*\ell^+\ell^-$ and related modes [see talks by Quim & Costas]

Anomaly in $b \to s\ell^+\ell^-$ modes of $\sim 4.5\sigma$!

[Descotes-Genon+'15]



- Global fits necessary!
  [Descotes-Genon+,Beaujean+,Ghosh+, Altmannshofer+,Hurth+,Sinha+,Ciuchini+]
  ➥ different decays + observables
- QCD under control? [Camalich/ Jäger'15,Lyon/Zwicky'14,Ciuchini+'15]
  ➥ not the issue for R_K
- Agreed: $C_9^{\mu} \sim -1$ improves fits
  ➥ leptonic vector current

➥ not expected, but many models now! [e.g. Altmannshofer+,Buras+,Crivellin+] [Gauld+,Descotes-Genon+,Sierra+,Becirevic+, Bhattacharya+,Gripaios+,Hiller+,Niehoff+]

- Z' models: $b \to s\ell\ell$ ✓, $R(D, D^*)$ ✗, additional bounds ✓
- LQ models: $b \to s\ell\ell$ (✓), $R(D, D^*)$ ✓, additional bounds ?

$U(1)'$ models: some model building

We require:

1. Sizable contributions to $b \to s\ell^+\ell^-$
   ➥ specifically to C_9, i.e. vector coupling
2. Lepton non-universal couplings
3. Limited contributions to established constraints:
   - EW precision constaints
   - Unitarity triangle constraints
   - ...

➥ $U(1)'$ models good candidates (leptoquarks later)

[e.g. Altmannshofer+,Buras+,Crivellin+,Gauld+,Descotes-Genon+,Sierra+]

Wish list:

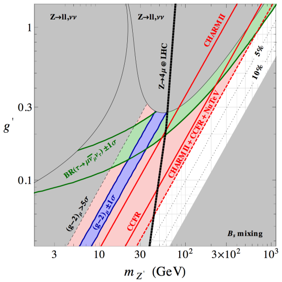
- Minimal particle content (no new fermions)
- Predictivity for up-, down-, lepton-FCNCs

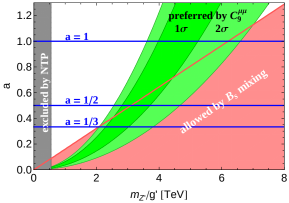
Incarnations of $U(1)'$

Z' models have been popular for a long time [review e.g. Langacker'08]

Starting a new construction:

1. SM particle content: $L_\alpha - L_\beta$ only option [2×He+'91]
   - No coupling to quarks, mostly used in ν sector $\to L_\mu - L_\tau$
2. Adding vector-like quarks (+scalars) $\to$ effective $Z'\bar{q}q'$-coupling [Altmannshofer+'14]
   - LHCb anomalies ✔, independent $C_9^{\mu(\prime)}$
   - no $Z'ee$-coupling $\to$ avoid LEP bounds
   - $\Delta m_s \to u, d$ couplings small
3. Gauging $L_\mu - L_\tau - a(B_1 + B_2 - 2B_3)$ $\to$ new scalars suffice [Crivellin+'15]
   - LHCb anomalies ✔, $|C_9^\mu| \gg |C_9^{\mu\prime}|$
   - L and B separately anomaly-free
   - down-FCNCs approximately $\sim V_{ti}V_{tj}^*$
   - arbitrary up-FCNCs



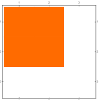
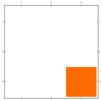


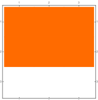
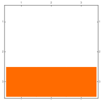
Flavour violation in 2HDMs

Generic 2HDMs: huge flavour violation
➥ solution to this a main characteristic

Option 1: Avoid tree-level FCNCs $\longrightarrow$ NFC, MFV, Alignment, ...
Option 2: Allow for controlled FCNCs

- Cheng-Sher ansatz/Type III $\longrightarrow$ little predictivity
- Branco-Grimus-Lavoura (BGL) models [BGL'96]
  - Use flavour symmetry to relate all flavour-change to CKM
    ➥ Unique pattern in 2HDMs! [Ferreira/Silva'11,Serôdio'13]
  - Choice: top quark only couples to ϕ_2 $\to$ FCNCs in down-sector

Up Yukawas: $\Delta_1^{\rm BGL} =$  $\Delta_2^{\rm BGL} =$ 

Down Yukawas: $\Gamma_1^{\rm BGL} =$  $\Gamma_2^{\rm BGL} =$ 

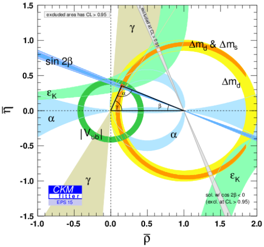
$U(1)'_{\mathrm{BGL}}$ – Overview

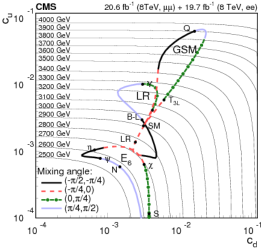
ATTENTION: ADVERTISEMENT

Gauging the BGL symmetry yields $U(1)'_{\mathrm{BGL}}$ model:

- Controlled tree-level down-FCNCs, determined by CKM
  - ➥ left-handed, $C_{9,10}^{e,\mu}$, $|C_{10}^{\ell}| < (\ll)|C_9^{\ell}|$
- No FCNCs in the up-quark sector
- Symmetry yields lepton-flavour non-universality without lepton-flavour violation
- Higgs sector phenomenologically viable, no large effects
- Z' extremely predictive: 2 parameters (plus one charge)

➥ Let's check the available constraints...



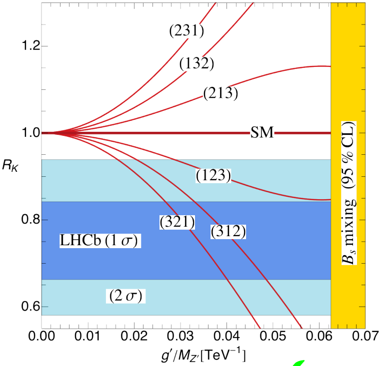


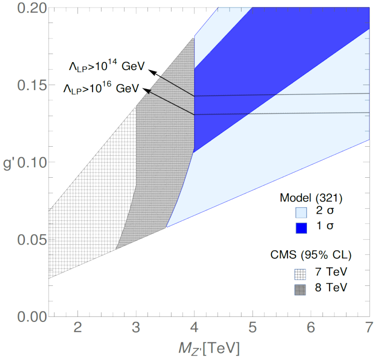
Phenomenological consequences

Most observables are unaffected! $(M_W^2/M_{Z'}^2 \lesssim 0.1\%!)$

➡ Effects only for SM suppression *in addition to* G_F+CKM

EW penguin decays, mixing, CP violation, leptonic decays, ...





Fits $B \to K^*\mu^+\mu^-$ ✓

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

➡ "Easily" verifiable

Direct bound from $pp \to Z'(\to f\bar{f})X$

Differentiability from LFNU vs. FCNC

$+\mu_{ff'} = \sigma(Z' \to f\bar{f})/\sigma(Z' \to f'\bar{f}')$

Phenomenological consequences

Most observables are unaffected! $(M_W^2/M_{Z'}^2 \lesssim 0.1\%!)$

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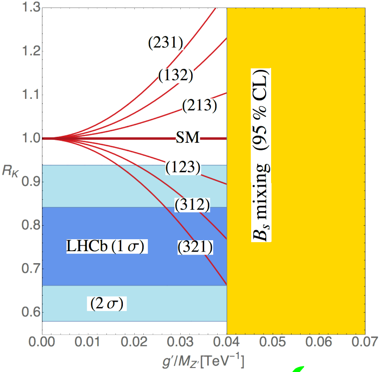
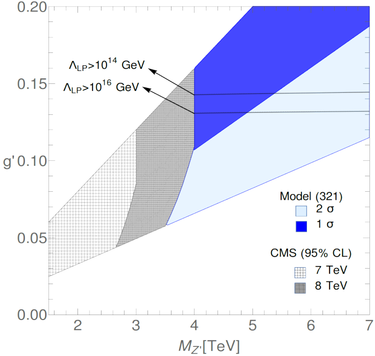
New B-mixing matrix elements [Aida's talk]





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Leptoquark models

$\mathcal{O}_9$ also generated from coloured exchange particles ⇒ leptoquarks

➥ e.g. [Barbieri+,Bauer+,Becirevic+,Fajfer+,Freytsis+,Gripaios+,Hiller+,Sahoo+]

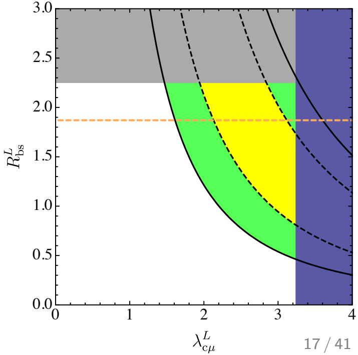
Some models can explain $b \to s\ell\ell$ and $b \to c\tau\nu$ data!

➥ correlated with $b \to s\bar{\nu}\nu$!

Example 1: [Bauer+'15]

Scalar LQ ϕ with quantum numbers $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

- $\mathcal{L} \supset \bar{Q}_L^C \phi L,\ \bar{u}_R^C \phi^* d_R$
- Explains $b \to c\tau\nu$ on tree-level, $b \to s\ell\ell$ on loop-level
  - ➥ natural hierarchies, also $g-2$
- Grey: $B \to K^{(*)}\bar{\nu}\nu$, Blue: $Z \to \mu^+\mu^-$
  - ➥ Specific assumptions on flavour structure nevertheless necessary

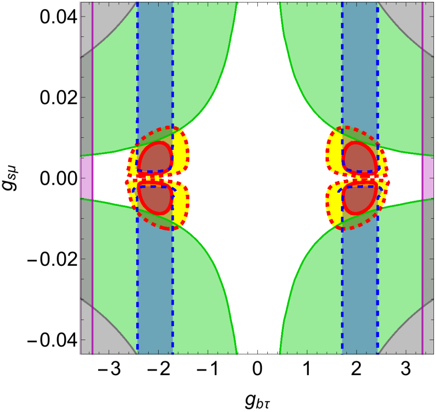


Leptoquark models II

Example 2: [Fajfer/Kosnik'16]

Vector LQ V with quantum numbers $U_1 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

- $b \to s\ell\ell$ and $b \to c\tau\nu$ both on tree-level
  - ➡ Hierarchy in couplings necessary
- Proton decay not problematic
- $B \to K\bar{\nu}\nu$ main constraint (green excluded)



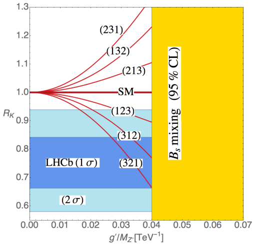
Further general features and issues [see also talk by Gudrun]

LFV possibly related to LFNU ⇒ NP typically *not* in mass basis
➥ Rotation to mass basis induces LFV [Glashow+,Bhattacharya+'14,...]

- LFV B decays additionally motivated!
- Strong constraints from LFV processes

However...

- "typically" does not mean "necessarily"
  ➥ diagnonal mass matrix possible
- Examples: [Altmannshofer+'14,Celis+'15⇒]



LQ models ok as templates, but UV-embedding complicated ($p \to X$)
➥ light LQ very complicated with simple groups [e.g. Doršner+'16]
➥ more complicated groups can work, but many more d.o.f.!

Models with $(\bar{Q}\gamma^\mu t^A Q)(\bar{L}\gamma^\mu t^A L)$ create $\tau \to \mu\bar{\nu}\nu$ on 1-loop!
➥ violates generically $\Gamma(\tau \to \mu\bar{\nu}\nu)/\Gamma(\mu \to e\bar{\nu}\nu)$-bound! [Feruglio+'16]
➥ Issue for LQ models, models with a W' [e.g. Isidori+'15]

Conclusions

Exciting anomalies in $b \to s\ell\ell$ and $b \to c\tau\nu$ at $\gtrsim 4\sigma$:

- intriguing + unexpected results, but not beyond doubt
- imply testable deviations in other modes

Scale-hierarchies allow for model-independent EFT analyses:

- SMEFT yields relations between flavour-coefficients
  ➥ allows to distinguish between Higgs-realizations!

2HDMs (scalar NP):

- can explain $b \to c\tau\nu$ data, $b \to s\ell\ell$ very difficult
- model difficult, (semi-)leptonic data implies fine-tuning

$U(1)'$ models:

- explain elegantly $b \to s\ell\ell$ + absence of other signals
- LFNU possible without LFV!
- testable e.g. directly, in $\hat{R}_{\phi,K^*,\ldots}$ & B mixing

Leptoquark models:

- can explain $b \to s\ell\ell$ and $b \to c\tau\nu$
- are difficult to embed into e.g. a unified model
- potentially violate $\tau \to \mu\nu\nu/\mu \to e\nu\nu$ bound

Thank you!

Implications of the Higgs EFT for Flavour: $q \to q'\ell\ell$

$$\mathcal{L}_{\rm eff}^{b\to s\ell\ell} = \frac{4G_F}{\sqrt{2}}\lambda_{ts}\frac{e^2}{(4\pi)^2}\sum_i^{12} C_i^{(d)}\mathcal{O}_i^{(d)}\,, \quad \lambda_{ts} = V_{tb}V_{ts}^*, \quad \text{with}$$

$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma^{\mu\nu}P_{R(L)}b)F_{\mu\nu}\,,$$

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

$$\mathcal{O}_S^{(\prime)} = (\bar{s}P_{R(L)}b)\,\bar{l}l\,, \qquad \mathcal{O}_P^{(\prime)} = (\bar{s}P_{R(L)}b)\,\bar{l}\gamma_5 l\,,$$

$$\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu}b)\,\bar{l}\sigma^{\mu\nu}l\,, \qquad \mathcal{O}_{T5} = (\bar{s}\sigma_{\mu\nu}b)\,\bar{l}\sigma^{\mu\nu}\gamma_5 l\,.$$

Generalized matching from HEFT yields:

- No changes for photon penguin, insensitive to EWSB
- Additional contributions in $C_{9,10}^{(\prime)}$ (but linear EFT already general)
- Tensor operators absent in linear EFT for $d \to d'\ell\ell$ [Alonso+'14]
  - ➡ Present in general! (already in linear EFT for $u \to u'\ell\ell$)
- Scalar operators: linear EFT $C_S^{(d)} = -C_P^{(d)}$, $C_S^{\prime(d)} = C_P^{\prime(d)}$ [Alonso+'14]
  - ➡ Analogous for $u \to u'\ell\ell$, but no relations in general!

Implications of the Higgs EFT for Flavour: $q \to q'\ell\nu$

$b \to c\tau\nu$ transitions (SM: $C_{V_L} = 1, C_{i\neq V_L} = 0$):

$$\mathcal{L}_{\text{eff}}^{b\to c\tau\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_j^5 C_j \mathcal{O}_j \,, \qquad \text{with}$$

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)\bar{\tau}\gamma_\mu\nu \,, \qquad \mathcal{O}_{S_{L,R}} = (\bar{c}P_{L,R}b)\bar{\tau}\nu \,,$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu}P_L b)\bar{\tau}\sigma_{\mu\nu}\nu \,.$$

- All operators are independently present already in the linear EFT
- However: Relations between different transitions:
  C_{V_R} is lepton-flavour universal [see also Cirigliano+'09]
  Relations between charged- and neutral-current processes, *e.g.* $\sum_{U=u,c,t} \lambda_{Us} C_{S_R}^{(U)} = -\frac{e^2}{8\pi^2}\lambda_{ts} C_S^{(d)}$ [see also Cirigliano+'12,Alonso+'15]
- These relations are again absent in the non-linear EFT

Interpretation

Lessons:

- When assuming a linear EFT:
  Simplifications of model-indepent analyses
- However: Relations do *not* hold model-independently
  ➥ $SU(2)_L \times U(1)_Y$ together with linear embedding

Flavour physics can help to distinguish between embeddings!
➥ Surprising, since no Higgs is involved
➥ Difficult differently [e.g. Barr+, Azatov+'15]

- Key operators $\mathcal{O}_{Y_i}$: 4f-operators with Goldstone fields
  ➥ Hypercharges of fermions alone do not sum to 0
  ➥ Appear in linear EFT at dimension 8

Operator basis

$\hat{\tau}_3 = U\tau_3 U^\dagger$, $\hat{\tau}_\pm = U\frac{1}{2}(\tau_1 \pm i\tau_2)U^\dagger$, $L_\mu \equiv iUD_\mu U^\dagger$.

$$\mathcal{O}_{X1,2} = g'\bar{q}\sigma^{\mu\nu}UP_\pm r B_{\mu\nu}, \quad \mathcal{O}_{X3,4} = g\bar{q}\sigma^{\mu\nu}UP_\pm r\langle\hat{\tau}_3 W_{\mu\nu}\rangle,$$
$$\mathcal{O}'_{X1,2} = g'\bar{r}P_\pm U^\dagger\sigma^{\mu\nu}qB_{\mu\nu}, \quad \mathcal{O}'_{X3,4} = g\bar{r}P_\pm U^\dagger\sigma^{\mu\nu}q\langle\hat{\tau}_3 W_{\mu\nu}\rangle,$$

$$\mathcal{O}_{V1} = \bar{q}\gamma^\mu q\langle\hat{\tau}_3 L_\mu\rangle\,, \qquad \mathcal{O}_{V2} = \bar{q}\gamma^\mu\hat{\tau}_3 q\langle\hat{\tau}_3 L_\mu\rangle\,,$$
$$\mathcal{O}_{V3} = \bar{u}\gamma^\mu u\langle\hat{\tau}_3 L_\mu\rangle\,, \qquad \mathcal{O}_{V4} = \bar{d}\gamma^\mu d\langle\hat{\tau}_3 L_\mu\rangle\,,$$
$$\mathcal{O}_{V5} = \bar{q}\gamma^\mu\hat{\tau}_+ q\langle\hat{\tau}_- L_\mu\rangle\,, \qquad \mathcal{O}_{V6} = \bar{u}\gamma^\mu d\langle\hat{\tau}_- L_\mu\rangle\,,$$
$$\mathcal{O}_{V7} = \bar{l}\gamma^\mu\hat{\tau}_- l\langle\hat{\tau}_+ L_\mu\rangle\,,$$

$$\mathcal{O}_{LL1} = \bar{q}\gamma^\mu q\;\bar{l}\gamma_\mu l\,, \qquad \mathcal{O}_{LL2} = \bar{q}\gamma^\mu\tau^j q\;\bar{l}\gamma_\mu\tau^j l\,,$$
$$\hat{\mathcal{O}}_{LL3} = \bar{q}\gamma^\mu\hat{\tau}_3 q\;\bar{l}\gamma_\mu l\,, \qquad \hat{\mathcal{O}}_{LL4} = \bar{q}\gamma^\mu q\;\bar{l}\gamma_\mu\hat{\tau}_3 l\,,$$
$$\hat{\mathcal{O}}_{LL5} = \bar{q}\gamma^\mu\hat{\tau}_3 q\;\bar{l}\gamma_\mu\hat{\tau}_3 l\,, \qquad \hat{\mathcal{O}}_{LL6} = \bar{q}\gamma^\mu\hat{\tau}_3 l\;\bar{l}\gamma_\mu\hat{\tau}_3 q\,,$$
$$\hat{\mathcal{O}}_{LL7} = \bar{q}\gamma^\mu\hat{\tau}_3 l\;\bar{l}\gamma_\mu q\,,$$

Operator basis II

$$\mathcal{O}_{LR1} = \bar{q}\gamma^{\mu}q\ \bar{e}\gamma_{\mu}e\,, \qquad \mathcal{O}_{LR2} = \bar{u}\gamma^{\mu}u\ \bar{l}\gamma_{\mu}l\,,$$
$$\mathcal{O}_{LR3} = \bar{d}\gamma^{\mu}d\ \bar{l}\gamma_{\mu}l\,, \qquad \hat{\mathcal{O}}_{LR5} = \bar{q}\gamma^{\mu}\hat{\tau}_3 q\ \bar{e}\gamma_{\mu}e\,,$$
$$\hat{\mathcal{O}}_{LR6} = \bar{u}\gamma^{\mu}u\ \bar{l}\gamma_{\mu}\hat{\tau}_3 l\,, \qquad \hat{\mathcal{O}}_{LR7} = \bar{d}\gamma^{\mu}d\ \bar{l}\gamma_{\mu}\hat{\tau}_3 l\,,$$
$$\mathcal{O}_{RR1} = \bar{u}\gamma^{\mu}u\bar{e}\gamma_{\mu}e\,, \qquad \mathcal{O}_{RR2} = \bar{d}\gamma^{\mu}d\ \bar{e}\gamma_{\mu}e\,.$$

$$\mathcal{O}_{LR4} = \bar{q}\gamma^{\mu}l\ \bar{e}\gamma_{\mu}d\,, \qquad \hat{\mathcal{O}}_{LR8} = \bar{q}\gamma^{\mu}\hat{\tau}_3 l\ \bar{e}\gamma_{\mu}d\,,$$

$$\mathcal{O}_{S1} = \epsilon_{ij}\bar{l}^i e\bar{q}^j u\,, \qquad \mathcal{O}_{S2} = \epsilon_{ij}\bar{l}^i\sigma^{\mu\nu}e\bar{q}^j\sigma_{\mu\nu}u\,,$$
$$\hat{\mathcal{O}}_{S3} = \bar{q}UP_+ r\bar{l}UP_-\eta\,, \qquad \hat{\mathcal{O}}_{S4} = \bar{q}\sigma_{\mu\nu}UP_+ r\bar{l}\sigma^{\mu\nu}UP_-\eta\,,$$
$$\hat{\mathcal{O}}_{S5} = \bar{q}\hat{\tau}_- Ur\bar{l}\hat{\tau}_+ U\eta\,, \qquad \hat{\mathcal{O}}_{S6} = \bar{q}\sigma_{\mu\nu}\hat{\tau}_- Ur\bar{l}\sigma^{\mu\nu}\hat{\tau}_+ U\eta\,,$$

$$\hat{\mathcal{O}}_{Y1} = \bar{q}UP_- r\bar{l}UP_-\eta\,, \qquad \hat{\mathcal{O}}_{Y2} = \bar{q}\sigma_{\mu\nu}UP_- r\bar{l}\sigma^{\mu\nu}UP_-\eta\,,$$
$$\hat{\mathcal{O}}_{Y3} = \bar{l}UP_-\eta\bar{r}P_+U^{\dagger}q\,, \qquad \hat{\mathcal{O}}_{Y4} = \bar{l}UP_- r\bar{r}P_+U^{\dagger}l\,.$$

Flavor family indices have been omitted.

Matching for $b \to s\ell\ell$ transitions

$\mathcal{N}_{\rm NC}^{(d)} = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}$

$$\delta C_{7(d)}^{(\prime)} = \frac{8\pi^2}{m_b\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c_{X2}^{(\prime)} + c_{X4}^{(\prime)}\right] ,$$

$$\delta C_{7(u)}^{(\prime)} = \frac{8\pi^2}{m_c\lambda_{bu}}\frac{v^2}{\Lambda^2}\left[c_{X1}^{(\prime)} + c_{X3}^{(\prime)}\right] ,$$

$$\delta C_{9,10}^{(q)} = \mathcal{N}_{\rm NC}^{(q)}\left[(C_{LR}^{(q)} \pm C_{LL}^{(q)}) \pm 4g_{V,A}\frac{\Lambda^2}{v^2}C_{VL}^{(q)}\right] ,$$

$$C_{9,10}^{\prime(q)} = \mathcal{N}_{\rm NC}^{(q)}\left[(C_{RR}^{(q)} \pm C_{RL}^{(q)}) \pm 4g_{V,A}\frac{\Lambda^2}{v^2}C_{VR}^{(q)}\right] .$$

$$C_{LL}^{(d)} = c_{LL1} + c_{LL2} - \hat{c}_{LL3} - \hat{c}_{LL4} + \hat{c}_{LL5} + \hat{c}_{LL6} - \hat{c}_{LL7} ,$$

$$C_{RR}^{(d)} = c_{RR2} ,\ C_{LR}^{(d)} = c_{LR1} - \hat{c}_{LR5} ,\ C_{RL}^{(d)} = c_{LR3} - \hat{c}_{LR7} ,$$

$$C_{VL}^{(d)} = c_{V1} - c_{V2} ,\ C_{VR}^{(d)} = c_{V4} .$$

$b \to s\ell\ell$ matching continued

$$C_{S,P}^{(d)} = \mathcal{N}_{\rm NC}^{(d)} \left[\pm c_S^{(d)} + \hat{c}_{Y1} \right] , \quad C_{S,P}^{\prime(d)} = \mathcal{N}_{\rm NC}^{(d)} \left[c_S^{\prime(d)} \pm \hat{c}_{Y1}^{\prime} \right] ,$$

$$C_T^{(d)} = \mathcal{N}_{\rm NC}^{(d)} \left[\hat{c}_{Y2} + \hat{c}_{Y2}^{\prime} \right] , \quad C_{T5}^{(d)} = \mathcal{N}_{\rm NC}^{(d)} \left[\hat{c}_{Y2} - \hat{c}_{Y2}^{\prime} \right] ,$$

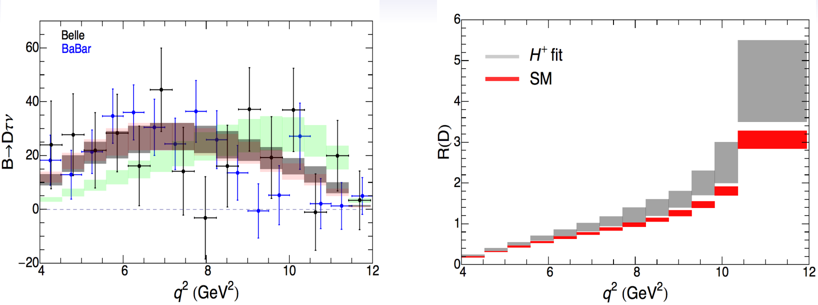
where $c_S^{(\prime)(d)} = 2(\hat{c}_{LR8}^{(\prime)} - c_{LR4}^{(\prime)})$.

Matching for $b \to c\ell\nu$ transitions

$$
\begin{aligned}
C_{V_L} &= -\mathcal{N}_{\rm CC}\left[C_L + \frac{2}{v^2}c_{V5} + \frac{2V_{cb}}{v^2}c_{V7}\right]\,,\\
C_{V_R} &= -\mathcal{N}_{\rm CC}\left[\hat{C}_R + \frac{2}{v^2}c_{V6}\right]\,,\\
C_{S_L} &= -\mathcal{N}_{\rm CC}\left(c'_{S1} + \hat{c}'_{S5}\right),\\
C_{S_R} &= 2\,\mathcal{N}_{\rm CC}\left(c_{LR4} + \hat{c}_{LR8}\right),\\
C_T &= -\mathcal{N}_{\rm CC}\left(c'_{S2} + \hat{c}'_{S6}\right),
\end{aligned}
$$

where $\mathcal{N}_{\rm CC} = \frac{1}{2V_{cb}}\frac{v^2}{\Lambda^2}$, $C_L = 2c_{LL2} - \hat{c}_{LL6} + \hat{c}_{LL7}$ and $\hat{C}_R = -\frac{1}{2}\hat{c}_{Y4}$.

The differential distributions $d\Gamma(B \to D^{(*)}\tau\nu)/dq^2$



- Data stat. uncertainties only, BaBar rescaled
- Bands 68% CL (bins highly correlated):
  Grey: NP fit including $R(D)$
  Red: SM fit (distributions only)
  Green: Allowed by $R(D)$, excluded by distribution
- Need better experimental precision, ideally $dR(D)/dq^2$
- Parts of NP parameter space clearly excluded

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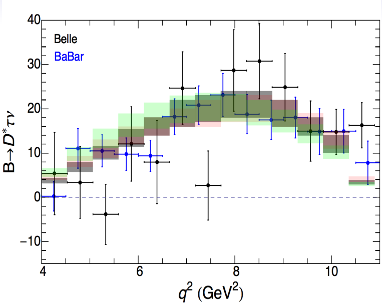

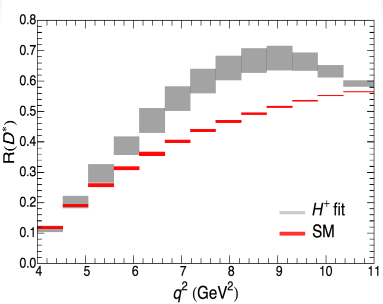

- Data stat. uncertainties only, BaBar rescaled
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  Grey: NP fit including $R(D^*)$
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  Green: Allowed by $R(D^*)$, excluded by distribution
- Need better experimental precision, ideally $dR(D^*)/dq^2$
- Not very restrictive at the moment

Gauging BGL models

- 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]

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Require $U(1)_{\mathrm{BGL}}$ to be anomaly-free: 5 non-linear conditions

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

➥ Include lepton sector

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- Not possible using only the SM quark sector

➥ Include lepton sector

Most general charges: arbitrary $X_{\ell L,R}$ with $\ell = e, \mu, \tau$

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

➥ 1 physical free charge $\to X_{\phi_2} \equiv 0$, 6 permutations

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

1. Lepton-flavour non-universality
2. Lepton-flavour conservation

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

Gauging BGL models - including leptons

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

- Linear: $U(1)'[SU(2)_L]^2$, $U(1)'[U(1)_Y]^2$, $U(1)'[(\text{gravity})]^2$
- 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 ($\tan\beta \gg 1$)

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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 $(e, \mu, \tau) = (i, j, k)$

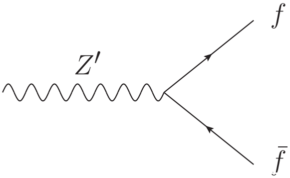
Z' couplings of the $U(1)'_{\rm BGL}$ model

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:

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

Controlled Z'-mediated FCNCs:



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

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 $\Delta m_{d,s}$, but $\Delta m_d/\Delta m_s = \Delta m_d/\Delta m_s|_{\rm SM}$)
- $\Delta m_d, \Delta m_s, \epsilon_K$ give similar bounds.

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

Improvement here just depends on LQCD!

Phenomenological consequences - Generalities

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- $\Delta m_d, \Delta m_s, \epsilon_K$ give similar bounds.

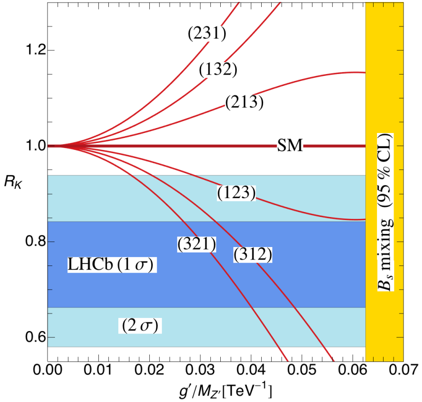
$$\text{From } \Delta m_s: \; M_{Z'}/g' \geq 25 \text{ TeV} \; (95\% \text{ CL})$$

Improvement here thanks to LQCD! [Bazazov+'16, see Aida's talk]

R_K and its sisters

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

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

R_K and its sisters

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

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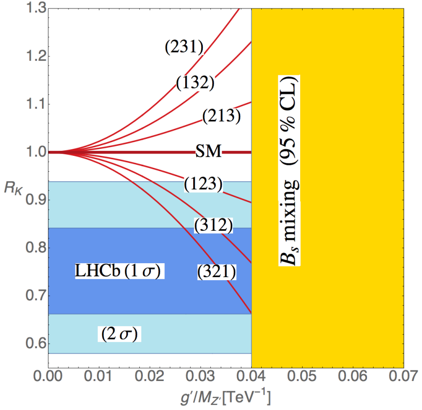


Model	$C_9^{NP\mu}(1\sigma)$	$C_9^{NP\mu}(2\sigma)$
(1,2,3)	–	[−1.20, −0.61]
(3,1,2)	[−0.63, −0.43]	[−0.63, −0.17]
(3,2,1)	[−1.20, −0.53]	[−1.20, −0.20]

Fits $B \to K^*\mu^+\mu^-$ ✓
Furthermore:

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

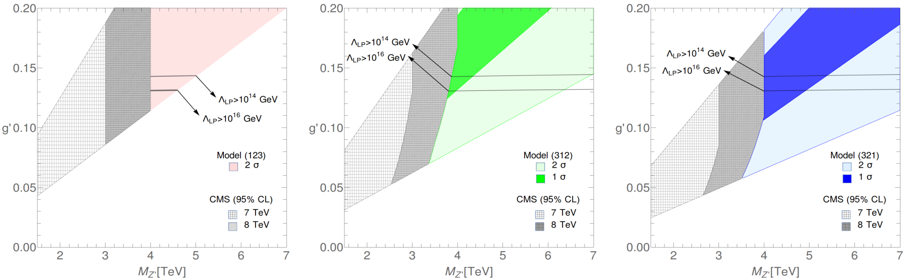
➥ "Easily" verifiable for any charge assignment

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,ATLAS'12,'14,CMS'12,'15]



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

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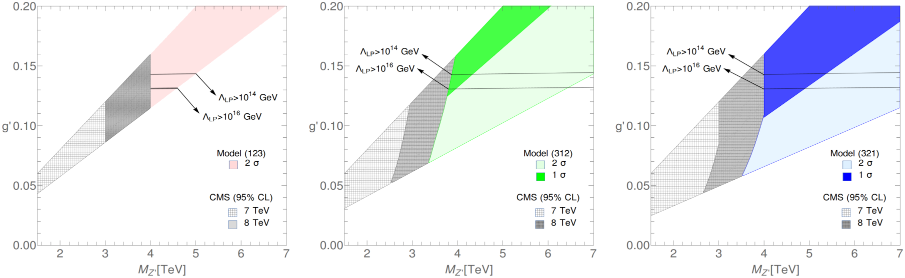

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Details on direct searches

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

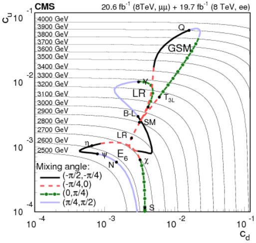
$$\sigma = \frac{\pi}{48s}\left[c_u^f w_u\left(s,\ M_{Z'}^2\right) + c_d^f w_d\left(s,\ M_{Z'}^2\right)\right]$$

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

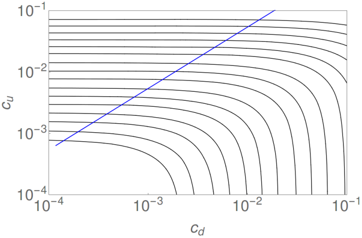
Applicable for $g' \leq 0.2$!

➡ First two generations dominate and couple universally

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



$\Rightarrow$



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

BR measurements and isospin violation

Isospin asymmetries test NP with $\Delta I = 1, 3/2$ (e.g. $b \to s\bar{u}u$)
Again: relevant due to high precision and small NP

Branching ratio measurements require normalization...

- B factories: depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
- LHCb: normalization mode, usually obtained from B factories

Assumptions entering this normalization:

- PDG: assumes $r_{+0} \equiv \Gamma(\Upsilon \to B^+B^-)/\Gamma(\Upsilon \to B^0\bar{B}^0) \equiv 1$
- LHCb: assumes $f_u \equiv f_d$, uses $r_{+0}^{\rm HFAG} = 1.058 \pm 0.024$

Both approaches problematic: [MJ'16 [1510.03423]]

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in $r_{+0}^{\rm HFAG}$ assume isospin in exclusive decays
  - ➥ This is one thing we want to test!
- ➥ Avoiding this assumption yields $r_{+0} = 1.027 \pm 0.037$
- ➥ Isospin asymmetry $B \to J/\psi K$: $A_I = -0.009 \pm 0.024$

Improvement necessary for high-precision BRs
➥ $B \to J/\Psi K$ can be used to determine f_u/f_d!