CORFU 2018 – Workshop on the Standard Model and Beyond, Corfu, 03 September 2018

Flavour anomalies and (fundamental) partial compositeness

Presented by Peter Stangl

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Outline

1. Motivation: Flavour anomalies — see also talks by Paride Paradisi and Roger Forty
2. Violation of lepton flavour universality in composite Higgs models
3. Flavour analysis of minimal fundamental partial compositeness
4. Summary

Based on:

Wolfgang Altmannshofer, Christoph Niehoff, PS, David M. Straub [arXiv:1703.09189]
Wolfgang Altmannshofer, PS, David M. Straub [arXiv:1704.05435]
Christoph Niehoff, PS, David M. Straub [arXiv:1503.03865]
Francesco Sannino, PS, David M. Straub, Anders E. Thomsen [arXiv:1712.07646]

Outline

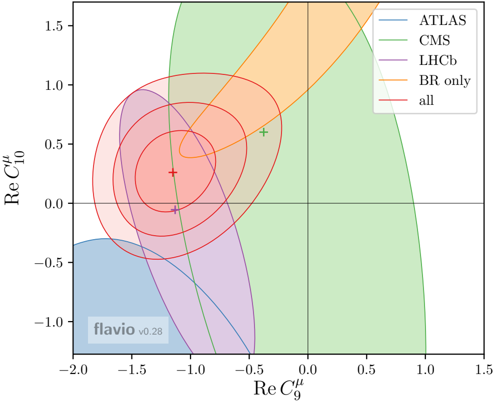
$b \to s\,\mu^+\mu^-$ anomaly

Several LHCb measurements deviate from Standard model (SM) predictions by 2-3σ:

- Angular observable P_5' in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:1512.04442
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$.

LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



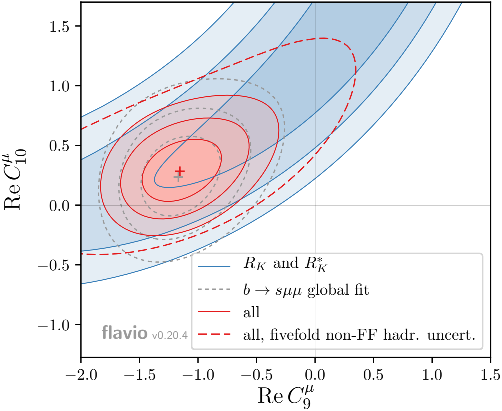
see also fits by other groups:
Capdevila et al., arXiv:1704.05340
D'Amico et al., arXiv:1704.05438
Geng et al., arXiv:1704.05446
Ciuchini et al., arXiv:1704.05447
Mahmoudi et al., arXiv:1611.05060

Altmannshofer, Niehoff, PS, Straub, arXiv:1703.09189

Hints for LFU violation in neutral current decays

Measurements of lepton flavour universality (LFU) ratios $R_K^{[1,6]}$, $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ show deviations from SM by about 2.5σ each. LHCb, arXiv:1406.6482, arXiv:1705.05802

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



Altmannshofer, PS, Straub, arXiv:1704.05435

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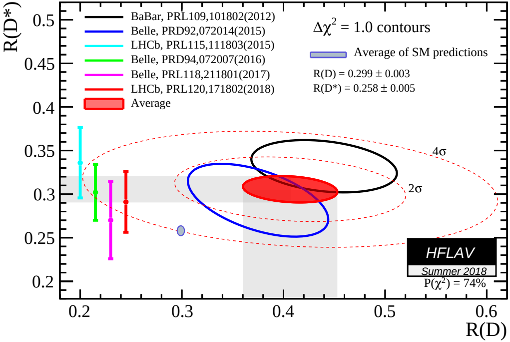
Hints for LFU violation in charged current decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by 3.6-3.8σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529

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

$$\ell \in \{e, \mu\}$$



HFLAV, arXiv:1612.07233

Explaining the anomalies

see also talks by Nejc Košnik,
Kenji Nishiwaki, German Valencia

Construct model to address flavour anomalies

- Plethora of models constructed to specifically address flavour anomalies.

This talk: analyze potential of existing models to explain anomalies

Consider models originally constructed to address **naturalness problem** of SM:

- **Composite Higgs model** (CHM) with **partial compositeness**.
- UV completion of CMH: **Minimal Fundamental Partial Compositeness**.

Outline

Composite Higgs models

see also talk by Gautam Bhattacharyya

Solving the naturalness problem

- Higgs not elementary but bound state of new strong interaction.
- Lightness of Higgs compared to new physics scale: **Higgs as pseudo-Nambu-Goldstone boson** (pNGB) of spontaneously broken global symmetry.

Kaplan, Georgi, Phys.Lett. B136 (1984) 183
Dugan, Georgi, Kaplan, Nucl.Phys. B254 (1985) 299

$$\mathcal{L} = \mathcal{L}_{elemenary} + \mathcal{L}_{composite}$$

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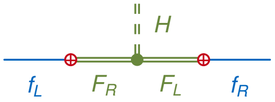
Kaplan, Georgi,
Phys.Lett. B136 (1984) 183
Dugan, Georgi, Kaplan,
Nucl.Phys. B254 (1985) 299

$$\mathcal{L} = \mathcal{L}_{elemenary} + \mathcal{L}_{composite} + \mathcal{L}_{mixing}$$

Avoiding flavour constraints

- Elementary fermions couple linearly to composite fermions.
- Mass eigenstates are mixture of both: **partial compositeness**.

Kaplan, Nucl. Phys. B365 (1991) 259–278



Violation of LFU in composite Higgs models

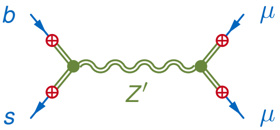
Niehoff, PS, Straub, arXiv:1503.03865

Considering only anomalies in rare B decays

$b \to s\mu\mu$ anomaly and hints for violation of LFU in R_K, R_{K^*} measurements.

LFU violating $b \to s\,\mu\mu$ transition

Only one possibility to violate LFU in $b \to s\,\mu\mu$ at tree-level:



Experimental data suggests

- $C_9^\mu < 0$: sizable left- and right-handed degrees of compositeness s_{μ_L} and s_{μ_R}.
- $C_9^\mu = -C_{10}^\mu < 0$: only sizable s_{μ_L}.

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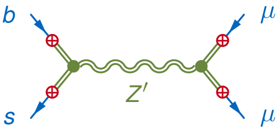

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- $C_9^\mu < 0$: sizable left- and right-handed degrees of compositeness s_{μ_L} and s_{μ_R}.
  $s_{\mu_L} \cdot s_{\mu_R}$ enters μ mass; has to be small!
- $C_9^\mu = -C_{10}^\mu < 0$: only sizable s_{μ_L}.

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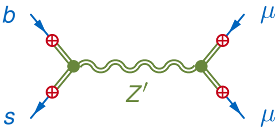

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- $C_9^\mu < 0$: sizable left- and right-handed degrees of compositeness s_{μ_L} and s_{μ_R}.
  $s_{\mu_L} \cdot s_{\mu_R}$ enters μ mass; has to be small!
- $C_9^\mu = -C_{10}^\mu < 0$: only sizable s_{μ_L}. Seems possible!

Constraints

Constraints from B_s-$\bar{B}_s$ mixing

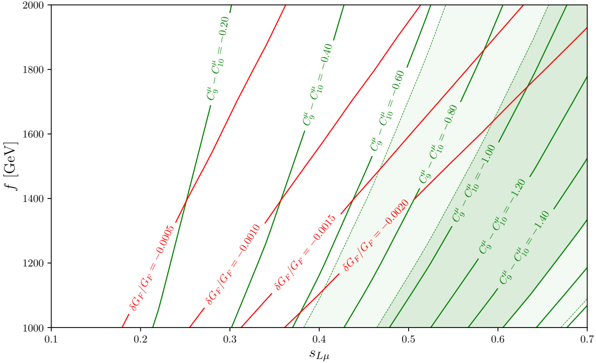
- $Z'bs$ coupling implies contribution to B_s-$\bar{B}_s$ mixing.
- Upper bound on $Z'bs$ coupling leads to **lower bound on s_{μ_L}**.

Constraints from electroweak precision tests

$Z'\mu_L\mu_L$ coupling generically implies corrections to $Z\mu\mu$, $W\mu\nu_\mu$, and $Z\nu_\mu\nu_\mu$ couplings.

- $Z\mu\mu$ coupling can be protected by discrete symmetry. Agashe et al., arXiv:hep-ph/0605341; Agashe, arXiv:0902.2400
- Modification of $W\mu\nu_\mu$ coupling leads to correction of Fermi constant. Yields **upper bound on s_{μ_L}**.
- Modified $Z\nu_\mu\nu_\mu$ coupling can explain LEP 2σ deficit in invisible Z width. *Improves* agreement with data!

Results



$$C_9^\mu - C_{10}^\mu \approx \pm 0.92 \left[\frac{1.7\,\text{TeV}}{f}\right] \left[\frac{s_{\mu_L}}{0.6}\right]^2 \left[\frac{|\Delta M_s - \Delta M_s^{\text{SM}}|}{0.1\,\Delta M_s^{\text{SM}}}\right]^{1/2}$$

Outline

Fundamental partial compositeness

Sannino, Strumia, Tesi, Vigiani, arXiv:1607.01659

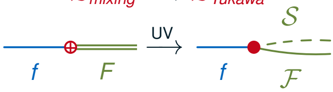
- New strong interaction: "Technicolor" (TC).
- SM fermions and vector bosons + "technifermions" $\mathcal{F}$ + "techniscalars" $\mathcal{S}$.
- Higgs: $(\mathcal{F}\mathcal{F})$ bound state.
- Composite fermions: $(\mathcal{F}\mathcal{S})$ bound states.
- SM fermions f and TC fields $\mathcal{F}$, $\mathcal{S}$ coupled by fundamental Yukawa couplings y_f.

Comparison with effective composite Higgs models

$$\mathcal{L}_{elemenary} \xrightarrow{\text{UV}} \mathcal{L}_{elemenary}$$

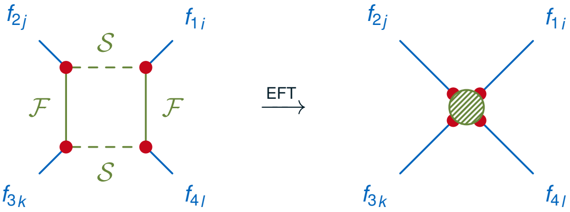
$$\mathcal{L}_{composite} \xrightarrow{\text{UV}} \mathcal{L}_{TC}$$

$$\mathcal{L}_{mixing} \xrightarrow{\text{UV}} \mathcal{L}_{Yukawa}$$



Effective field theory at electroweak scale

- Consider effective field theory (EFT) of Minimal Fundamental Partial Compositeness (MFPC): **MFPC-EFT**. Cacciapaglia, Gertov, Sannino, Thomsen, arXiv:1704.07845



$$\propto \left(y_{f_1}^T\, y_{f_2}\right)_{ij} \left(y_{f_3}^T\, y_{f_4}\right)_{kl}$$

- **Flavour structure** from fundamental Yukawa couplings.

Flavour analysis of MFPC

Sannino, PS, Straub, Thomsen, arXiv:1712.07646

- Consider parameters of MFPC-EFT relevant for flavour observables.
- Constrain parameter space by
  - SM fermion masses and CKM elements,
  - Electroweak scale observables,
  - Low-energy flavour observables.
- Make predictions for LFU observables $R_{K^{(*)}}$ and $R_{D^{(*)}}$.

Electroweak scale observables

- Use MFPC-EFT at electroweak (EW) scale.
- Most important constraints: ratios of ***Z* partial widths** (measured at LEP),

$$R_e = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to e\bar{e})}, \qquad R_\mu = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu\bar{\mu})}, \qquad R_\tau = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \tau\bar{\tau})},$$

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})}, \qquad R_c = \frac{\Gamma(Z \to c\bar{c})}{\Gamma(Z \to q\bar{q})}.$$

Low-energy flavour observables

- Match MFPC-EFT to weak effective Hamiltonian (WEH).
- **Meson-antimeson mixing**
  - Indirect *CP* violation in kaon mixing: $\boldsymbol{\epsilon_K}$.
  - Mixing-induced *CP* asymmetries in B_d and B_s systems: $\boldsymbol{S_{\psi K_S}}$ and $\boldsymbol{S_{\psi\phi}}$.
  - Mass differences in B_d and B_s systems: $\boldsymbol{\Delta M_d}$ and $\boldsymbol{\Delta M_s}$.
- **Charged-current semi-leptonic decays** (CKM elements and e-μ universality)
  - $\mathbf{BR}(\pi^+ \to e\nu)$, based on $d \to ue\nu$.
  - $\mathbf{BR}(K^+ \to \mu\nu)$, $\mathbf{BR}(K^+ \to e\nu)/\mathbf{BR}(K^+ \to \mu\nu)$, based on $s \to ue\nu$, $s \to u\mu\nu$.
  - $\mathbf{BR}(B \to De\nu)$, $\mathbf{BR}(B \to D\mu\nu)$, based on $b \to ce\nu$, $b \to c\mu\nu$.
  - **Predictions** for LFU observables $\boldsymbol{R_D}$ and $\boldsymbol{R_{D^*}}$.
- **Neutral-current semi-leptonic decays**
  - **Predictions** for LFU observables $\boldsymbol{R_K}$ and $\boldsymbol{R_{K^*}}$.

Numerical method

Parameter scan challenging

37 parameters (1 for strong coupling scale, 22 for fundamental Yukawa couplings, 14 for Wilson coefficients of MFPC-EFT)

Strategy

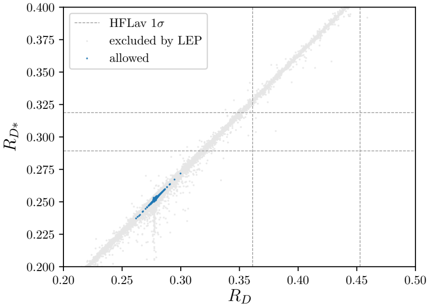
To find **viable parameter points** satisfying all constraints:

- Step 1
  - Construct $\chi^2_{\mathrm{mass},CKM}$ function for quark masses and CKM elements depending only on 19 parameters.
  - Numerically minimize $\chi^2_{\mathrm{mass},CKM}$ for 100 k random starting points.
  - Sample regions around local minima using Markov Chains from `pypmc` package to yield 1000 points for each minimum.

  Yields 100 M points predicting correct quark masses and CKM elements.
- Step 2
  - Randomly choose remaining 18 parameters for each point.
  - Calculate EW scale and flavour observables using `flavio` code.

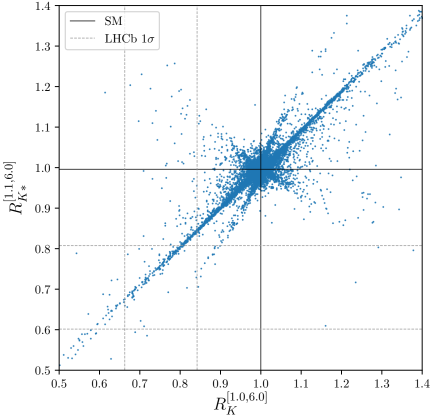
Results

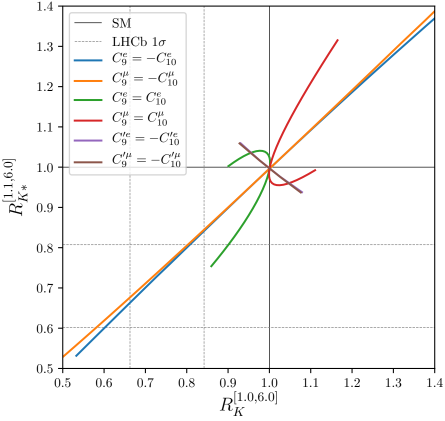
- ϵ_K provides very strong constraint, but can be satisfied by large number of parameter points.
- Tests of e-μ universality in charged-current decays are important constraints due to generic LFU violation from partial compositeness.
- Large deviation of $R_{D^{(*)}}$ from SM value is in conflict with Z partial widths (modified $Z\tau\tau$ coupling).



Results

- Anomalies in rare B decays can be explained!





Outline

Summary

CHM with sizable degree of compositeness of left-handed muons can explain anomalies in rare B decays.

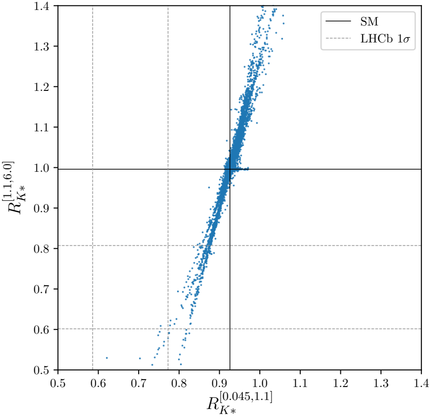
- Corresponds to new physics contriution to $C_9^\mu = -C_{10}^\mu < 0$.
- Predicts deviation in B_s-$\bar{B}_s$ mixing.
- Correction to Fermi constant yields strongest constraint from EWPT if tree level Z couplings are protected by discrete symmetry.

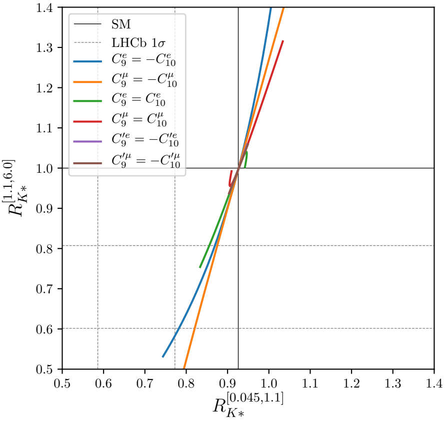
Performed comprehensive numerical analysis of flavour and EW scale effects of MFPC model.

- Numerical method allows for scan of high dimensional parameter space.
- Strongest constraints from ϵ_K, but satisfied by large number of parameter points.
- Large deviation of $R_{D^{(*)}}$ from SM value is in conflict with Z partial widths.
- Anomalies in rare B decays can be explained.

Backup slides

R_{K*} predictions





ϵ_K

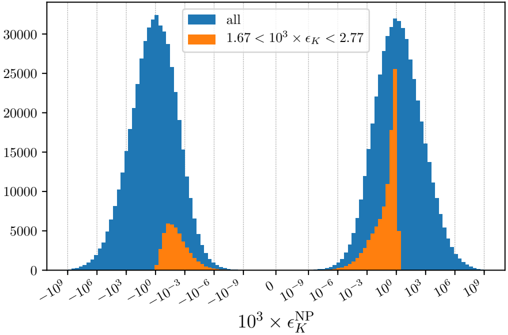
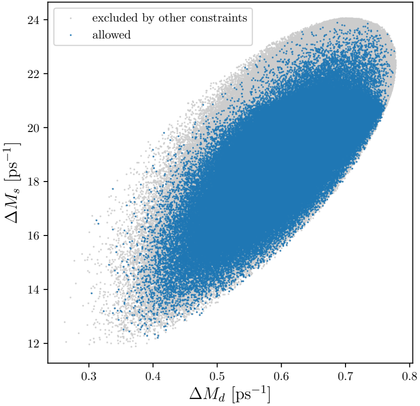


Figure: Histogram showing the NP contribution to ϵ_K for a representative subset of all points that feature the right masses and CKM elements, compared to the points among those that pass the experimental constraint. A positive NP contribution corresponds to constructive interference with the SM.

ΔM_d and ΔM_s



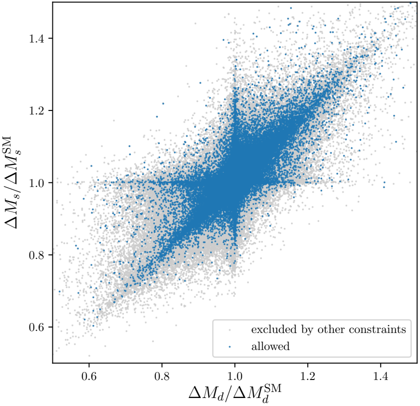


Figure: Predictions for ΔM_d and ΔM_s. Gray points are excluded by constraints other than $\Delta F = 2$. Blue points are allowed by all constraints.

$S_{\psi K_S}$ and $S_{\psi\phi}$

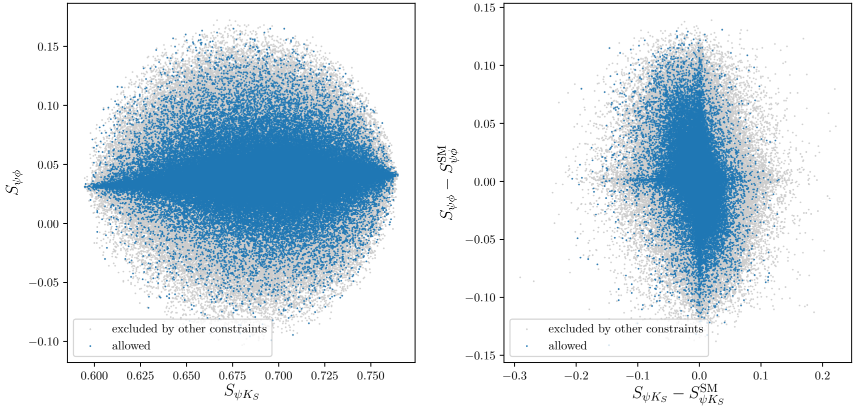


Figure: Predictions for the mixing induced CP asymmetries in $B^0 \to J/\psi K_S$ and $B_s \to J/\psi\phi$, sensitive to the B^0 and B_s mixing phases. Gray points are excluded by constraints other than $\Delta F = 2$. Blue points are allowed by all constraints.

e-μ universality

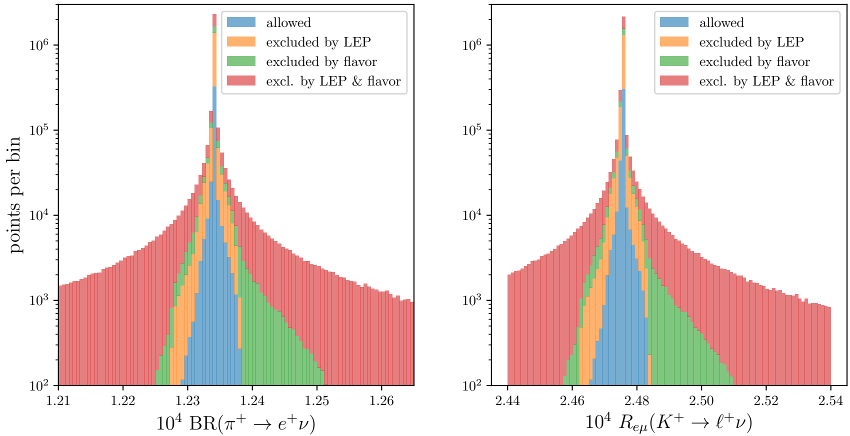


Figure: Histogram showing distribution of predictions for two observables probing e-μ universality violation in Z couplings for all points passing $\Delta F = 2$ constraints. "excluded by flavour" is excluded by charged-current decays imposed as constraints.

MFPC particle content

	Q	$\bar{u}$	$\bar{d}$	L	$\bar{\nu}$	$\bar{e}$	$\mathcal{F}_{\updownarrow}$	$\bar{\mathcal{F}}_{\uparrow}$	$\bar{\mathcal{F}}_{\downarrow}$	$\mathcal{S}_q$	$\mathcal{S}_l$
$\mathrm{Sp}(N)_{\mathrm{TC}}$	**1**	**1**	**1**	**1**	**1**	**1**	**N**	**N**	**N**	**N**	**N**
$\mathrm{SU}(3)_{\mathrm{C}}$	**3**	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	**1**	**1**	**1**	**1**	**1**	**1**	$\bar{\mathbf{3}}$	**1**
$\mathrm{SU}(2)_{\mathrm{L}}$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**
$\mathrm{U}(1)_{\mathrm{Y}}$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	0	1	0	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{6}$	$\frac{1}{2}$
N_{g}	3	3	3	3	3	3	1	1	1	3	3

Table: Quantum numbers of SM fields, TC fermions, and TC scalars in MFPC. The last line gives the number of generations N_{g}. All fermion fields are left-handed Weyl spinors.

$b \to s\,\mu\mu$ analysis

Global fits to data using open source code `flavio`, including the following observables: Straub et al. [flav-io.github.io]

- $B^0 \to K^{*0}\mu^+\mu^-$ angular observables
  CDF [public note 10894], LHCb [arXiv:1512.04442], ATLAS [CONF-2017-023], CMS [arxiv:1507.08126, PAS-BPH-15-008]
- $B_s \to \phi\mu^+\mu^-$ angular observables
  LHCb [arXiv:1506.08777]
- $\mathcal{B}(B^{0,\pm} \to K^{*0,\pm}\mu^+\mu^-)$
  LHCb [arXiv:1403.8044, arXiv:1606.04731], CMS [arXiv:1507.08126], CDF [public note 10894]
- $\mathcal{B}(B^{0,\pm} \to K^{0,\pm}\mu^+\mu^-)$
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- $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$
  LHCb [arXiv:1506.08777], CDF [public note 10894]
- $\mathcal{B}(B \to X_s\mu^+\mu^-)$
  BaBar [arXiv:1312.5364]

$b \to s\,\mu\mu$ analysis

Not included:

- lepton-averaged observables:
  focus on new physics in $b \to s\,\mu^+\mu^-$
- $B \to K\mu^+\mu^-$ angular observables:
  only relevant in presence of scalar or tensor operators
  Beaujean, Bobeth, Jahn, [arXiv:1508.01526]
- $B \to K^*\mu^+\mu^-$ angular observables by Belle:
  unknown mixture of B^0 and $B^\pm$
  Belle [arXiv:1612.05014]
- $\Lambda_b \to \Lambda\mu^+\mu^-$ by LHCb: large experimental uncertainties,
  central values not compatible with viable short-distance hypothesis
  LHCb [arXiv:1503.07138], Meinel, van Dyk [arXiv:1603.02974]

$b \to s\,\mu\mu$ analysis

	standard uncert.		2×FF uncert.		2×non-FF uncert.	
Coeff.	best fit	pull	best fit	pull	best fit	pull
C_9^{NP}	-1.21	$\mathbf{5.2\sigma}$	-1.13	$\mathbf{4.0\sigma}$	-1.30	$\mathbf{4.4\sigma}$
C_{10}^{NP}	$+0.79$	$\mathbf{3.4\sigma}$	$+0.57$	1.9σ	$+0.74$	$\mathbf{2.9\sigma}$
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.67	$\mathbf{4.8\sigma}$	-0.64	$\mathbf{3.4\sigma}$	-0.64	$\mathbf{4.0\sigma}$
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.30	1.3σ	-0.46	1.8σ	-0.14	0.5σ
C_9'	$+0.19$	0.9σ	$+0.31$	1.0σ	$+0.36$	1.5σ
C_{10}'	-0.10	0.6σ	-0.10	0.4σ	-0.23	1.2σ
$C_9' = -C_{10}'$	$+0.08$	0.8σ	$+0.11$	0.8σ	$+0.17$	1.4σ
$C_9' = C_{10}'$	$+0.06$	0.3σ	$+0.11$	0.4σ	-0.03	0.1σ