GDR-InF annual workshop, Arles, 06 November 2018

Flavour anomalies and (fundamental) partial compositeness

Presented by Peter Stangl

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de Physique Théorique

Outline

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

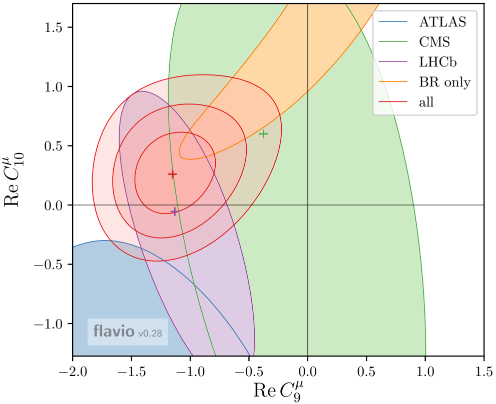
$b \to s\,\mu^+\mu^-$ anomaly

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

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



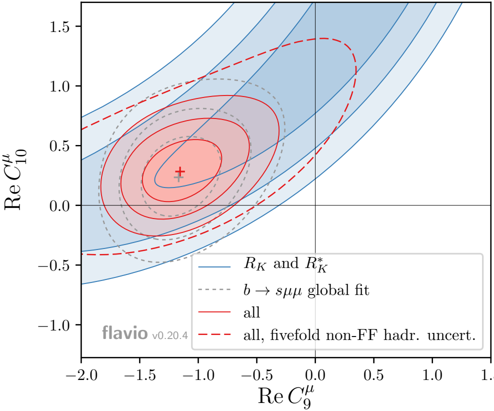
Altmannshofer, Niehoff, PS, Straub, arXiv:1703.09189

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

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

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



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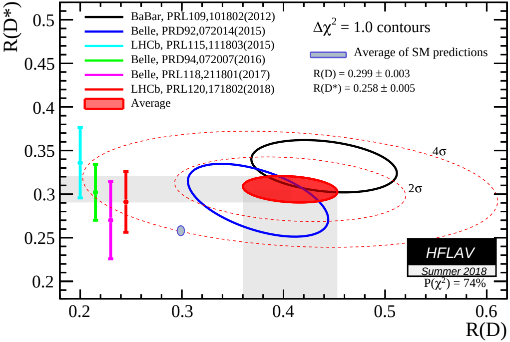
Hints for LFU violation in charged current decays

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 talk by Méril Reboud

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

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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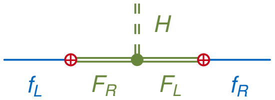
Dugan, Georgi, Kaplan, Nucl.Phys. B254 (1985) 299

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

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

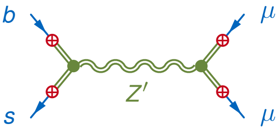
Niehoff, PS, Straub, arXiv:1503.03865

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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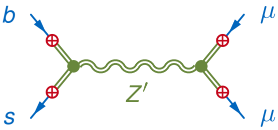

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- $C_9^\mu < 0$: sizable left- and right-handed degrees of compositeness s_{μ_L} and s_{μ_R}.
  $s_{\mu_L} \cdot s_{\mu_R}$ enters μ mass; has to be small!
- $C_9^\mu = -C_{10}^\mu < 0$: only sizable s_{μ_L}.

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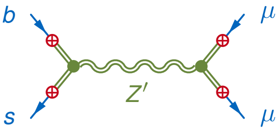

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  $s_{\mu_L} \cdot s_{\mu_R}$ enters μ mass; has to be small!
- $C_9^\mu = -C_{10}^\mu < 0$: only sizable s_{μ_L}. Seems possible!

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

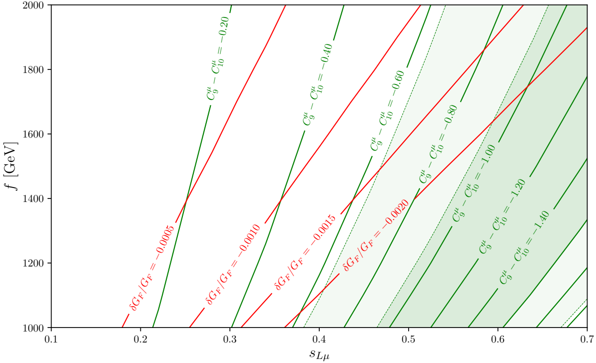
$Z'\mu_L\mu_L$ coupling generically implies corrections to $Z\mu\mu$, $W\mu\nu_\mu$, and $Z\nu_\mu\nu_\mu$ couplings.

- $Z\mu\mu$ 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

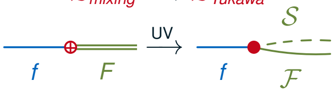
- New strong interaction: “Technicolor” (TC).
- SM fermions and vector bosons + “technifermions” $\mathcal{F}$ + “techniscalars” $\mathcal{S}$.
- Higgs: $(\mathcal{F}\mathcal{F})$ bound state.
- Composite fermions: $(\mathcal{F}\mathcal{S})$ bound states.
- SM fermions f and TC fields $\mathcal{F}$,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

Comparison with effective composite Higgs models

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

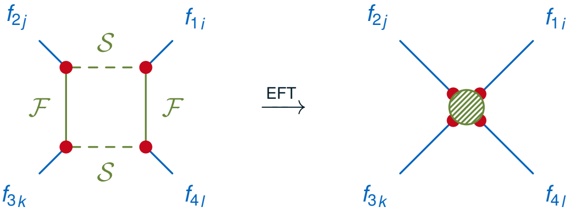
$$\mathcal{L}_{composite} \xrightarrow{\text{UV}} \mathcal{L}_{TC}$$

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



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

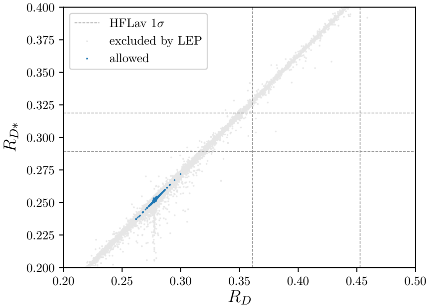
To find **viable parameter points** satisfying all constraints:

- 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.

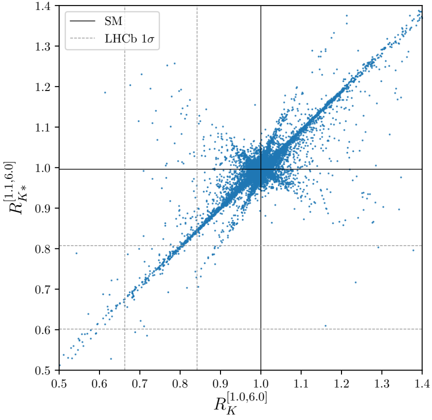
Results

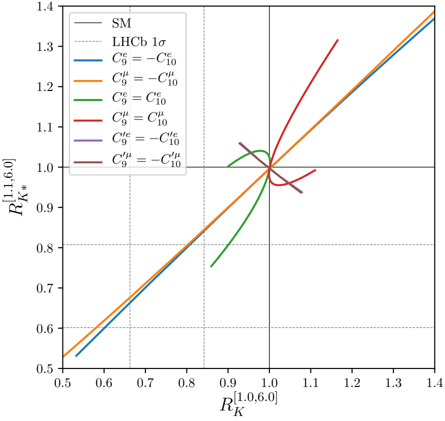
- ϵ_K provides very strong constraint, but can be satisfied by large number of parameter points.
- Tests of e-μ universality in charged-current decays are important constraints due to generic LFU violation from partial compositeness.
- Large deviation of $R_{D^{(*)}}$ from SM value is in conflict with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

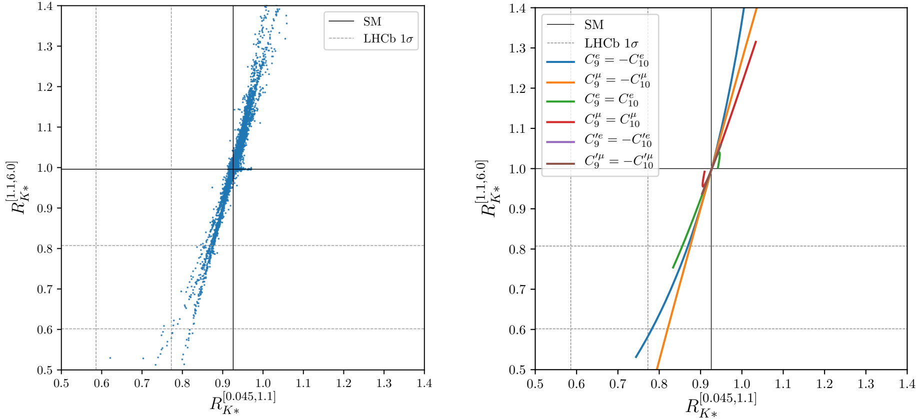
- Corresponds to new physics contriution to $C_9^\mu = -C_{10}^\mu < 0$.
- Predicts deviation in B_s-$\bar{B}_s$ mixing.
- Correction to Fermi constant yields strongest constraint from EWPT if tree level Z couplings are protected by discrete symmetry.

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

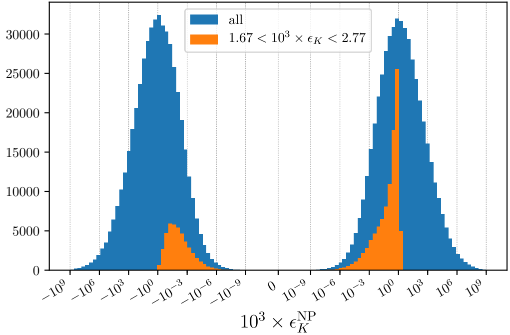
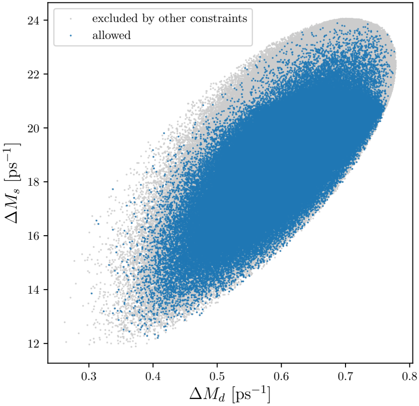


Figure: Histogram showing the NP contribution to ϵ_K for a representative subset of all points that feature the right masses and CKM elements, compared to the points among those that pass the experimental constraint. A positive NP contribution corresponds to constructive interference with the SM.

ΔM_d and ΔM_s



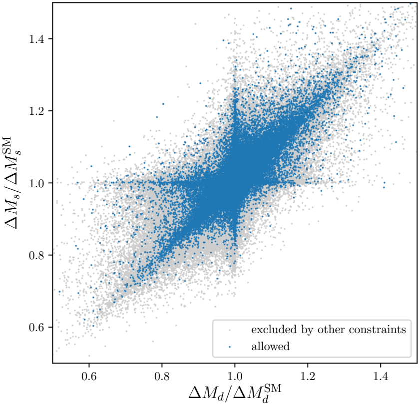


Figure: Predictions for ΔM_d and ΔM_s. Gray points are excluded by constraints other than $\Delta F = 2$. Blue points are allowed by all constraints.

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

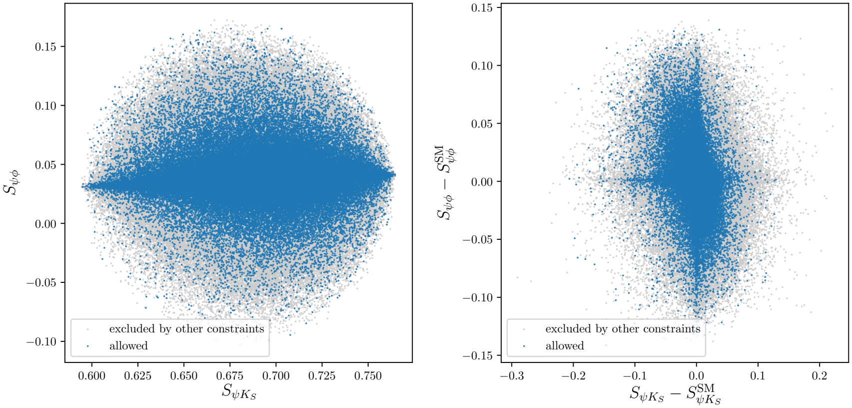


Figure: Predictions for the mixing induced CP asymmetries in $B^0 \to J/\psi K_S$ and $B_s \to J/\psi\phi$, sensitive to the B^0 and B_s mixing phases. Gray points are excluded by constraints other than $\Delta F = 2$. Blue points are allowed by all constraints.

e-μ universality

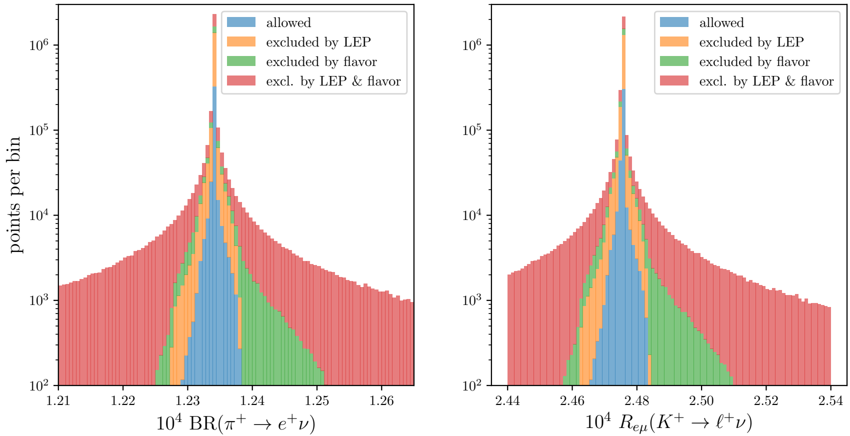


Figure: Histogram showing distribution of predictions for two observables probing e-μ universality violation in Z couplings for all points passing $\Delta F = 2$ constraints. "excluded by flavour" is excluded by charged-current decays imposed as constraints.

MFPC particle content

	Q	$\bar{u}$	$\bar{d}$	L	$\bar{\nu}$	$\bar{e}$	$\mathcal{F}_{\updownarrow}$	$\bar{\mathcal{F}}_{\uparrow}$	$\bar{\mathcal{F}}_{\downarrow}$	$\mathcal{S}_q$	$\mathcal{S}_l$
$\mathrm{Sp}(N)_{\mathrm{TC}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{N}$	$\mathbf{N}$	$\mathbf{N}$	$\mathbf{N}$	$\mathbf{N}$
$\mathrm{SU}(3)_{\mathrm{C}}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$
$\mathrm{SU}(2)_{\mathrm{L}}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U}(1)_{\mathrm{Y}}$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	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]
- $\mathcal{B}(B^{0,\pm} \to K^{0,\pm}\mu^+\mu^-)$
  LHCb [arXiv:1403.8044], CDF [public note 10894]
- $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$
  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	$\boldsymbol{5.2\sigma}$	-1.13	$\boldsymbol{4.0\sigma}$	-1.30	$\boldsymbol{4.4\sigma}$
C_{10}^{NP}	$+0.79$	$\boldsymbol{3.4\sigma}$	$+0.57$	1.9σ	$+0.74$	$\boldsymbol{2.9\sigma}$
$C_9^{NP} = -C_{10}^{NP}$	-0.67	$\boldsymbol{4.8\sigma}$	-0.64	$\boldsymbol{3.4\sigma}$	-0.64	$\boldsymbol{4.0\sigma}$
$C_9^{NP} = C_{10}^{NP}$	-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