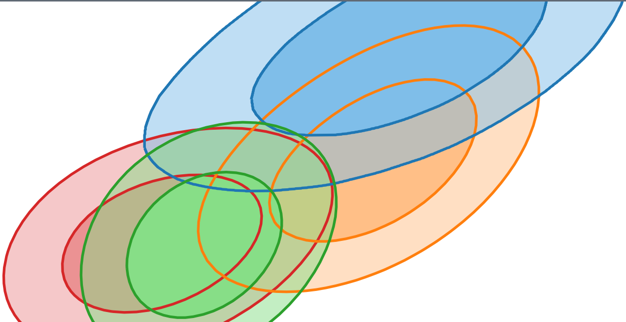
Beyond the Flavour Anomalies III, 26 Apr. 2022

Status of global fits to data

B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl



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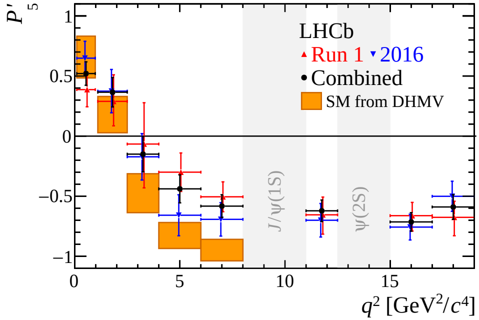
The $b \to s\ell\ell$ anomalies

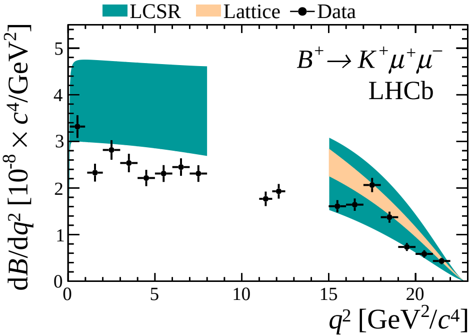
$b \to s\,\mu^+\mu^-$ anomaly

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

- Angular observables in $B^{(0,+)} \to K^{*(0,+)}\mu^+\mu^-$ LHCb, arXiv:2003.04831, arXiv:2012.13241
- 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, arXiv:2105.14007





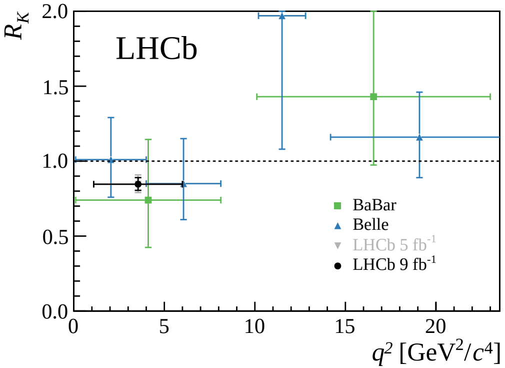
*: based on hadronic assumptions on which there is no theory consensus yet

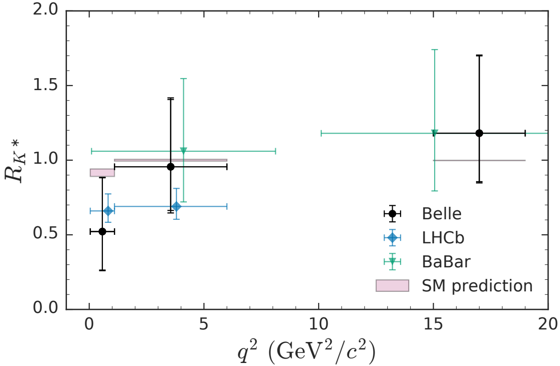
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurements of lepton flavor universality (LFU) ratios $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$, $R_K^{[1,6]}$ show deviations from SM by 2.3, 2.5, and 3.1σ

LHCb, arXiv:1705.05802, arXiv:2103.11769
Belle, arXiv:1904.02440, arXiv:1908.01848

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

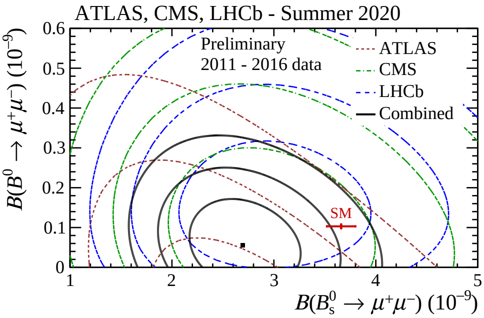


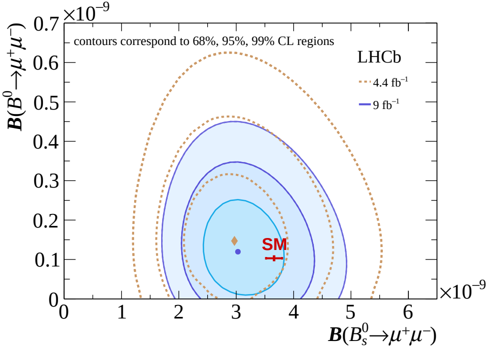


Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

Measurements of $\mathcal{B}(B_{s,d} \to \mu^+\mu^-)$ by LHCb, CMS, and ATLAS show combined deviation from SM predictions* by about 2σ

ATLAS, arXiv:1812.03017
CMS, arXiv:1910.12127
LHCb, arXiv:1703.05747,2108.09283





Waiting for CMS and ATLAS updates and consequent Run 1 + Run 2 LHC combination

*: depends on parameters like V_{cb} but tension persists in V_{cb}-free ratio $\mathcal{B}(B_s \to \mu^+\mu^-)/\Delta M_s$ — Bobeth, Buras, arXiv:2104.09521

Theoretical Framework

$b \to s\ell\ell$ in the weak effective theory

- Effective Hamiltonian at scale m_b: $\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff, sl}} + \mathcal{H}_{\text{eff, had}}$
- **Semileptonic operators**: $(\mathcal{N} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \approx (34\ \text{TeV})^{-2})$

$$\mathcal{H}_{\text{eff, sl}} = -\mathcal{N}\left(C_7 O_7 + C_7' O_7' + \sum_\ell \sum_{i=9,10,P,S} \left(C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell\right)\right) + \text{h.c.}$$

$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)\,F^{\mu\nu}\,, \quad O_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell)\,, \quad O_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,.$$

$$C_7^{\text{SM}} \simeq -0.3\,, \qquad C_9^{\text{SM}} \simeq 4\,, \qquad C_{10}^{\text{SM}} \simeq -4\,.$$

Not considered here: (pseudo)scalar $O_{P,S}$ vanish in SM, could appear at dim. 6 in SMEFT (and tensor O_T only at dim. 8 in SMEFT)

- **Hadronic operators**:

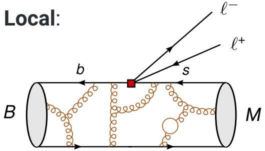
$$\mathcal{H}_{\text{eff, had}} = -\mathcal{N}\frac{16\pi^2}{e^2}\left(C_8 O_8 + C_8' O_8' + \sum_{i=1,\dots,6} C_i O_i\right) + \text{h.c.}$$

$$\text{e.g.} \quad O_1 = (\bar{s}\gamma_\mu P_L T^a c)(\bar{c}\gamma^\mu P_L T^a b)\,, \quad O_2 = (\bar{s}\gamma_\mu P_L c)(\bar{c}\gamma^\mu P_L b)\,.$$

Theory of $B \to M\ell\ell$ decays ($M = K, K^*, \phi$)

$$\mathcal{M}(B \to M\ell\ell) = \langle M\ell\ell|\mathcal{H}_{\text{eff}}|B\rangle = \mathcal{N}\left[(\mathcal{A}_V^\mu + \mathcal{H}^\mu)\, \bar{u}_\ell \gamma_\mu v_\ell + \mathcal{A}_A^\mu\, \bar{u}_\ell \gamma_\mu \gamma_5 v_\ell + \mathcal{A}_S\, \bar{u}_\ell v_\ell + \mathcal{A}_P\, \bar{u}_\ell \gamma_5 v_\ell \right]$$

Local:

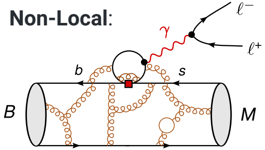


$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2} C_7 \langle M|\bar{s}\,\sigma^{\mu\nu} q_\nu\, P_R\, b|B\rangle + C_9 \langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

$$\mathcal{A}_A^\mu = C_{10} \langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

$$\mathcal{A}_{S,P} = C_{S,P} \langle M|\bar{s}\, P_R\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

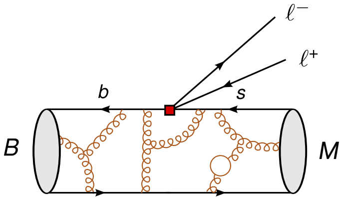
Non-Local:



$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2} \sum_{i=1,\dots,6,8} C_i \int dx^4 e^{iq\cdot x} \langle M|T\{j^\mu_{\text{em}}(x), O_i(0)\}|B\rangle\,, \qquad j^\mu_{\text{em}} = \sum_q Q_q\, \bar{q}\gamma^\mu q$$

- **Wilson coefficients** $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$:
  perturbative, short-distance physics (q^2 independent), well-known in SM, parameterise heavy NP
- **local** and **non-local** **hadronic matrix elements**:
  non-perturbative, long-distance physics (q^2 dependent), **main source of uncertainty**

Local matrix elements



$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2} C_7 \langle M|\bar{s}\,\sigma^{\mu\nu}q_\nu\, P_R\, b|B\rangle + C_9 \langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

$$\mathcal{A}_A^\mu = C_{10} \langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

$$\mathcal{A}_{S,P} = C_{S,P} \langle M|\bar{s}\, P_R\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

- $\langle M|\bar{s}\,\Gamma_i\, b|B\rangle$ matrix elements are parameterised by:
  - **3 form factors** for each **spin zero** final state $M = \boldsymbol{K}$
  - **7 form factors** for each **spin one** final state $M = \boldsymbol{K^*}, \phi$

- Determination of form factors
  - high q^2: **Lattice QCD**

    HPQCD, arXiv:1306.2384
    Fermilab, MILC, arXiv:1509.06235
    Horgan, Liu, Meinel, Wingate, arXiv:1310.3722, arXiv:1501.00367

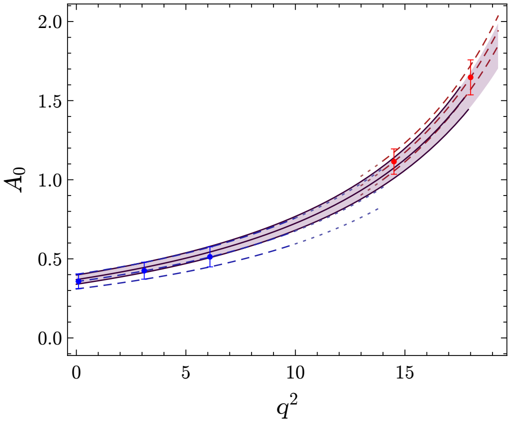
  - low q^2: **Continuum methods**
    e.g. Light-cone sum rules (LCSR)

    Ball, Zwicky, arXiv:hep-ph/0406232
    Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
    Bharucha, Straub, Zwicky, arXiv:1503.05534
    Gubernari, Kokulu, van Dyk, arXiv:1811.00983

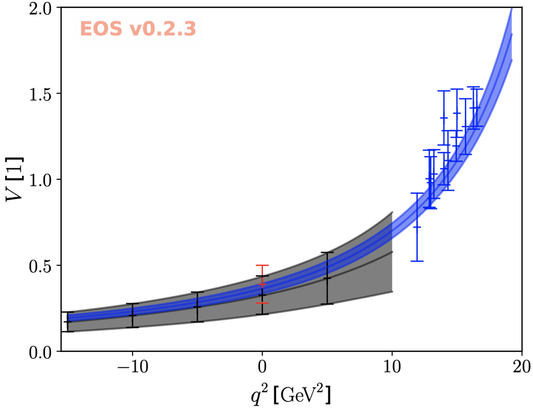
  - low + high q^2: Combined fit to **continuum methods + lattice**

    Altmannshofer, Straub, arXiv:1411.3161
    Bharucha, Straub, Zwicky, arXiv:1503.05534
    Gubernari, Kokulu, van Dyk, arXiv:1811.00983

Form factors

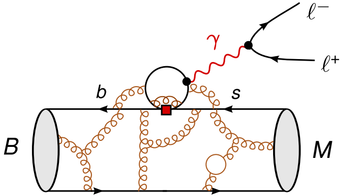


Bharucha, Straub, Zwicky, arXiv:1503.05534



Gubernari, Kokulu, van Dyk, arXiv:1811.00983

Non-local matrix elements



$$\mathcal{H}^\mu = \frac{-16 i \pi^2}{q^2} \sum_{i=1..6,8} C_i \int dx^4 e^{iq\cdot x} \langle M | T\{ j^\mu_{\rm em}(x), O_i(0)\} | B\rangle$$

$$j^\mu_{\rm em} = \sum_q Q_q \, \bar{q} \gamma^\mu q$$

- Contributions at low q^2 from QCD factorization (QCDF) — Beneke, Feldmann, Seidel, arXiv:hep-ph/0106067
- **Beyond-QCDF** contributions **the main source of uncertainty**
- Non-local contributions can mimic New Physics in C_9
- Several approaches to estimate beyond-QCDF contributions at low q^2
  - fit of sum of resonances to data — Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921
  - direct fit to angular data — Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli, arXiv:1512.07157
  - Light-Cone Sum Rules estimates — Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945; Gubernari, van Dyk, Virto, arXiv:2011.09813
  - analyticity + experimental data on $b \to s c\bar{c}$ — Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305; Gubernari, van Dyk, Virto, arXiv:2011.09813

“cleanliness” of $b \to s$ observables in the SM

	parametric uncertainties	form factors	non-local matrix elements
$\mathcal{B}(B \to M\ell\ell)$	✗	✗	✗
angular observables	✓	✗	✗
$\overline{\mathcal{B}}(B_s \to \ell\ell)$	✗	✓	✓ (N/A)
LFU observables	✓	✓	✓

Fit setup

$b \to s\ell\ell$ global analyses

Results presented here by:

- ACDMN (M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code — arXiv:2104.08921
- AS (W. Altmannshofer, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio` — arXiv:2103.13370
- CFFPSV (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
  Statistical framework: Bayesian MCMC fit, based on public code `HEPfit` — arXiv:2011.01212
- HMMN (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
  Statistical framework: χ^2-fit, based on public code `SuperIso` — arXiv:2104.10058

See also similar fits by other groups:

- N. Gubernari, M. Reboud, D. van Dyk, J. Virto
  Statistical framework: Bayesian fit with improved parameterisation of non-local matrix elements, based on public code EOS (in preparation, see Meril Reboud talk)

Geng et al., arXiv:2103.12738, Alok et al., arXiv:1903.09617, Datta et al., arXiv:1903.10086, Kowalska et al., arXiv:1903.10932, D'Amico et al., arXiv:1704.05438, Hiller et al., arXiv:1704.05444, …

Observables in $b \to s\ell\ell$ global analyses

- Inclusive decays
  - $B \to X_s\gamma$ ($\mathcal{B}$)
  - $B \to X_s\ell^+\ell^-$ ($\mathcal{B}$)
- Exclusive leptonic decays
  - $B_{s,d} \to \ell^+\ell^-$ ($\mathcal{B}$)
- Exclusive radiative/semileptonic decays
  - $B \to K^*\gamma$ ($\mathcal{B}, S_{K^*\gamma}, A_I$)
  - $B^{(0,+)} \to K^{(0,+)}\ell^+\ell^-$ ($\mathcal{B}_\mu$, R_K, angular observables)
  - $B^{(0,+)} \to K^{*(0,+)}\ell^+\ell^-$ ($\mathcal{B}_\mu$, $R_{K^{*0}}$, angular observables)
  - $B_s \to \phi\mu^+\mu^-$ ($\mathcal{B}$, angular observables)
  - $\Lambda_b \to \Lambda\mu^+\mu^-$ ($\mathcal{B}$, angular observables)
- Fits might include $150 \sim 250$ observables $\Rightarrow$ **global** $b \to s\ell\ell$ analyses

Comparison between the groups

- Different experimental inputs, e.g.
  - $q^2 \in [6, 8]$ GeV^2 data (ACDMN, CFFPSV, HMMN)
  - High-q^2 data (AS, ACDMN, HMMN)
  - Radiative decays (ACDMN, CFFPSV, HMMN)
  - $\Lambda_b \to \Lambda\mu^+\mu^-$ (AS, HMMN)
- Different form factor inputs
  - Low-q^2: form factors from LCSR, reduced with heavy-quark & large-energy symmetries + (uncorrelated) power corrections. High-q^2: lattice form factors (ACDMN)
  - Full q^2 region: form factors from combined LCSR + lattice fit, with full correlations (AS, HMMN)
  - Low q^2 region: form factors from combined LCSR + lattice fit, with full correlations (CFFPSV)
- Different assumptions about non-local matrix elements
  - Order of magnitude estimates based on theory calculations from continuum methods, with different parameterisations (ACDMN, AS, HMMN)
  - Direct fit to data in each scenario, relying on continuum methods only for $q^2 \leq 1$ GeV^2 while allowing them to freely grow for larger q^2 (CFFPSV)
- Different statistical frameworks

New physics interpretation

General remarks about global fits

Most important Wilson coefficients:

- C_9^μ: dominant contributions to angular observables, LFU observables
- C_{10}^μ: dominant contributions to $B_s \to \mu\mu$, LFU observables

Wilson coefficients not considered in the following:

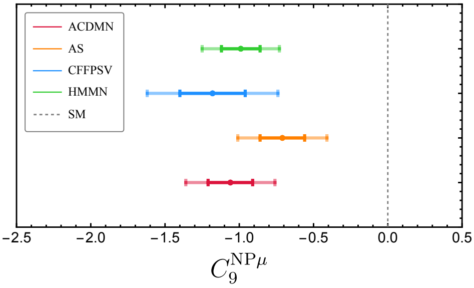
- $C_7^{(\prime)}$: strongly constrained by radiative decays and very low-q^2 bin of $B \to K^* e^+ e^-$
- C_i^e: current data does not indicate NP in electron coefficients, but not enough data to be conclusive
- $C'_{9,10}$: dominant contribution from coefficients with right-handed quarks disfavoured by $R_K \approx R_{K^*}$

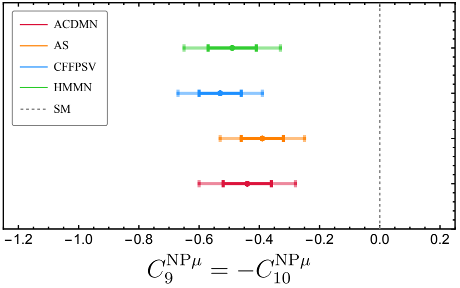
Interesting NP scenarios:

- 1D scenarios: $C_9^{\text{NP}\mu}$ or $C_9^{\text{NP}\mu} = -C_{10}^{\text{NP}\mu}$
- 2D scenario: $C_9^{\text{NP}\mu}$ and $C_{10}^{\text{NP}\mu}$

See backup slides for highly preferred NP scenarios for each group

1-dimensional global fits

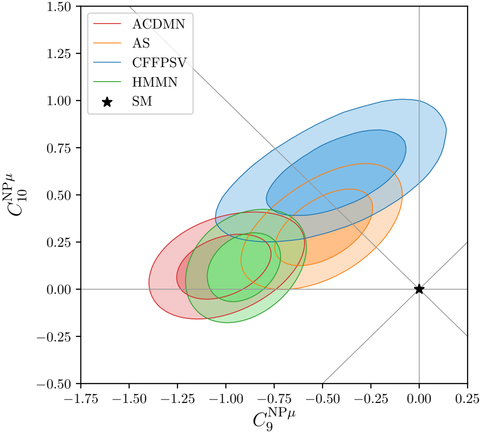




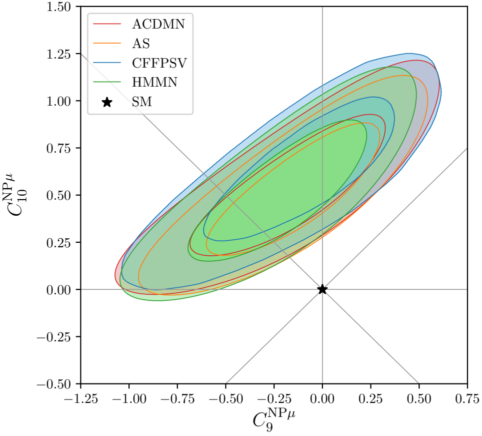
- NP scenarios preferred over SM with $\mathrm{Pull}_{\mathrm{SM}}{}^{*} > 5\sigma$
- Different results due to different assumptions about non-local matrix elements, different choices of form factors and observables, etc.
- Remarkable agreement between fits of different groups despite different approaches
  $\Rightarrow$ **$b \to s\ell\ell$ global analyses are robust**

*: $\mathrm{Pull}_{\mathrm{SM}} \neq$ global significance; conservative global significance $\simeq 4.3\sigma$ determined in Isidori, Lancierini, Owen, Serra, arXiv:2104.05631

2-dimensional fits



global fit



fit to LFU observables + $B_s \to \mu\mu$

Conclusions

- Discrepancies in numerous $b \to s\ell\ell$ observables can be **consistently explained by NP**
- Fits show preference for NP contributions to $\boldsymbol{C_9^\mu}$ and/or $\boldsymbol{C_{10}^\mu}$
- Different fits with different setups, inputs and statistical frameworks show **remarkable agreement**
- Main source of theory uncertainty in global fit due to **non-local hadronic contributions**
- SM predictions of **LFU observables** very well under control
  $\Rightarrow$ experimental observation of discrepancy in these observables would be **clear sign of NP**

Wishlist

- Explicit numerical experimental likelihoods, e.g. to avoid digitisation of $B_{s,d} \to \mu\mu$ contour plots
- Measurements of other LFU observables, like e.g. R_ϕ or $Q_{4,5}/D_{P'_{4,5}}$
- $B \to K^* e^+ e^-$ angular analysis
- CP asymmetries to constrain imaginary parts of Wilson coefficients
- **Experimental updates** and **new measurements**, not only from **LHCb** but also from **ATLAS** and **CMS**, and eventually from **Belle II**

Backup slides

p-value SM fit

For the frequentist fits, the p-value of goodness-of-fit can be computed from Wilks' theorem

$$p - value_{SM} = 1 - F(\chi^2_{SM}; n_{obs})$$

with $F(\chi^2; n_{obs})$ the χ^2 CDF and n_{obs} the number of independent observables in the fit (measurements of a given observable by different experiments are counted as different observables).

- ACDMN

$$\begin{aligned} \text{Global fit}: \; n_{\rm dof} &= 246 \quad \Rightarrow \quad p - value = 1.1\% \\ \text{LFU fit}^*: \; n_{\rm dof} &= 22 \quad \Rightarrow \quad p - value = 1.4\% \end{aligned}$$

- AS

$$\begin{aligned} \text{Global fit}: \; n_{\rm dof} &= 191 \quad \Rightarrow \quad p - value = 1.2\% \\ \text{LFU fit}^*: \; n_{\rm dof} &= 21 \quad \Rightarrow \quad p - value = 0.5\% \end{aligned}$$

- HMMN

$$\begin{aligned} \text{Global fit}: \; n_{\rm dof} &= 173 \quad \Rightarrow \quad p - value = 0.4\% \\ \text{LFU fit}^*: \; n_{\rm dof} &= 7 \quad \Rightarrow \quad p - value = 0.02\% \end{aligned}$$

* LFU fit: all the measured LFU observables + $\mathcal{B}(B_s \to \mu^+\mu^-)$ (all groups)
+ effective $B_s \to \mu\mu$ lifetime + radiative decays + $\mathcal{B}(B_s \to X_s\mu^+\mu^-)$ (depending on the group)

ACDMN: Improved QCDF

Improved QCDF (iQCDF) approach: $m_b \to \infty$ and $E_{V,P} \to \infty$ ($V = K^*, \phi, P = K$) decomposition of full form factors (FF)

$$F^{\text{Full}}(q^2) = F^{\infty}(\xi_\perp(q^2), \xi_\|(q^2)) + \Delta F^{\alpha_s}(q^2) + \Delta F^{\Lambda}(q^2)$$

where F stands for any FF (either helicity or transversity basis)

Charles et al; hep-ph/9901378
Beneke, Feldman; hep-ph/0008255
Descotes-Genon, Hofer, Matias, Virto; arXiv:1407.8526

- $m_b \to \infty$ and $E_{V,P} \to \infty$ symmetries: low-q^2 and LO in α_s and Λ/m_b
  $\Rightarrow$ **Dominant correlations** automatically taken into account
  (important for a maximal cancellation of errors)

Capdevila, Descotes-Genon, Hofer, Matias; arXiv:1701.08672

- $\mathcal{O}(\alpha_s)$ corrections $\Rightarrow$ QCDF

$$\langle \ell^+\ell^- \bar{K}_i^* | \mathcal{H}_{\text{eff}} | \bar{B} \rangle = \sum_{a,\pm} C_{i,a}\xi_a + \Phi_{B,\pm} \otimes T_{i,a,\pm} \otimes \Phi_{K^*,a} \quad (i = \perp, \|, 0)$$

Beneke, Feldman; hep-ph/0008255
Beneke, Feldman, Seidel; hep-ph/0106067

- $\mathcal{O}(\Lambda/m_b)$ corrections $\Rightarrow \Delta F^{\Lambda}(q^2) = a_F + b_F \dfrac{q^2}{m_B^2} + c_F \dfrac{q^4}{m_B^4}$

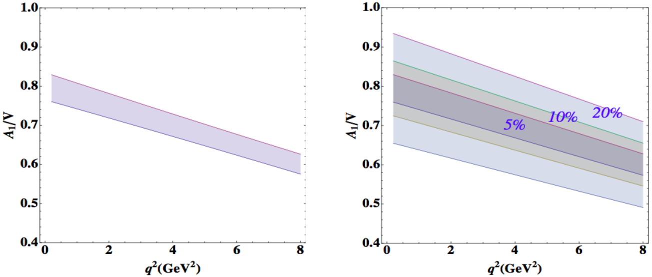
Jäger, Camalich; arXiv:1212.2263
Descotes-Genon, Hofer, Matias, Virto; arXiv:1407.8526

ACDMN: Improved QCDF (vs full FF approach)

- How to estimate ΔF^{Λ}?
  - $\Rightarrow$ Central values for a_F, b_F, c_F from **fit to full FF** (continuum calculation)
  - $\Rightarrow$ Error estimate: assign **uncorrelated** errors to $\Delta a_F, \Delta b_F, \Delta c_F = \mathcal{O}(\Lambda/m_b) \times F$

Descotes-Genon, Hofer, Matias, Virto; arXiv:1407.8526

- Is this a conservative estimation of errors?



$\Rightarrow$ iQCDF with a 5% power corrections (right) reproduces the full FF (BSZ param.) approach errors (left)

Capdevila, Descotes-Genon, Hofer, Matias; arXiv:1701.08672

ACDMN: Estimating beyond QCDF contribution at low-q^2

- LO (factorisable) charm-loop contribution accounted for in the $Y(q^2)$ (perturbative) function,

$$C_9^{\text{eff}}(q^2) = C_9^{\text{SM}} + Y(q^2)$$

Buras, Münz; hep-ph/9501281
Krüger, Lunghi; hep-ph/0008210

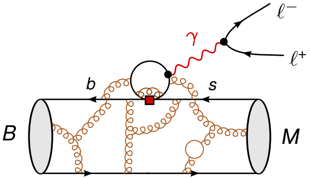
- Estimate of the soft-gluon emission contribution at low q^2:
  - ⇒ Calculations based on continuum methods

Khodjamirian, Mannel, Pivovarov, Wang; arxiv:1006.4945
Gubernari, van Dyk, Virto; arxiv:2011.09813

  - ⇒ Shift in C_9^{eff}. Order of magnitude for the shift estimated from theory calculations

$$C_{9\,i}^{\text{eff}}(q^2) = C_9^{\text{eff}}(q^2) + C_9^{\text{NP}} + s_i \delta C_9^{\text{LD},i}(q^2) \quad (i = \perp, \parallel, 0)$$

Descotes-Genon, Hofer, Matias, Virto; arxiv:1407.8526
Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239



ACDMN: Estimating beyond QCDF contribution at low-q^2

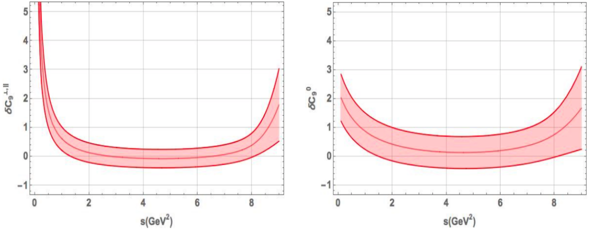
- Parameterisation for the long-distance contribution

$$\delta C_9^{\mathrm{LD},\perp}(q^2) = \frac{a^\perp + b^\perp q^2(c^\perp - q^2)}{q^2(c^\perp - q^2)} \qquad \delta C_9^{\mathrm{LD},\|}(q^2) = \frac{a^{||} + b^{||} q^2(c^{||} - q^2)}{q^2(c^{||} - q^2)}$$

$$\delta C_9^{\mathrm{LD},0}(q^2) = \frac{a^0 + b^0(q^2 + s_0)(c^0 - q^2)}{(q^2 + s_0)(c^0 - q^2)}$$

$\Rightarrow$ We vary s_i in the range $[-1, 1]$

$\Rightarrow$ a^i, b^i, c^i parameters floated according to KMPW calculation

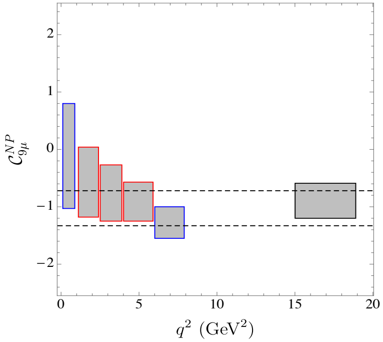


Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
Descotes-Genon, Hofer, Matias, Virto; arxiv:1407.8526
Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239

ACDMN: Consistency over q^2

Testing the q^2 dependence of $C_9^{\rm NP}$ by means of data:

- Fit to $B \to K^* \mu^+ \mu^-$ ($\mathcal{B}$'s + Ang. obs) + $B_s \to \mu^+ \mu^-$ + $B \to X_s \mu^+ \mu^-$ + $b \to s\gamma$
- $C_9^{\rm NP}$ bin-by-bin fit (assuming KMPW-like $\delta C_9^{{\rm LD},i}(q^2)$)
- Good agreement with global fit (2σ range)
- No indication of a strong q^2 dependence
- Consistency large and low recoil (different theo. treatments)



ACDMN: Statistical framework

We parametrise the Wilson coefficients as,

$$C_i = C_i^{\rm SM} + C_i^{\rm NP} \quad (i = 7_\mu^{(\prime)}, 9_\mu^{(\prime)}, 10_\mu^{(\prime)}, C_i^{\rm NP} \in \mathbb{R} \Rightarrow \text{no CPV})$$

Standard frequentist fit to the NP contributions to the Wilson coefficients,

$$\chi^2(C_i^{\rm NP}) = \left(\mathcal{O}^{\rm th}(C_i^{\rm NP}) - \mathcal{O}^{\rm exp}\right)_i Cov_{ij}^{-1} \left(\mathcal{O}^{\rm th}(C_i^{\rm NP}) - \mathcal{O}^{\rm exp}\right)_j$$

- Both **theory and experiment** contribute to the covariance matrix
  $\Rightarrow$ $Cov = Cov^{\rm th} + Cov^{\rm exp}$
- Experimental covariance
  $\Rightarrow$ **Experimental correlations** between observables (if not provided, assumed uncorrelated). Assume gaussian errors (symmetrize if needed)
- Theoretical covariance
  $\Rightarrow$ Compute the **theoretical correlations** by performing a multivariate gaussian scan over all nuisance parameters
- $Cov = Cov(C_i)$
  $\Rightarrow$ **Mild** dependency $\Rightarrow Cov = Cov_{\rm SM} \equiv Cov(C_i = 0)$.

Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239
Capdevila, Crivellin, Descotes-Genon, Matias, Virto; arxiv:1704.05340

ACDMN: Statistical framework

- Fit procedure:
  - $\Rightarrow$ **Best fit points** (bfp): $\chi^2(C_i^{\rm NP}) \to \chi^2_{\rm min} = \chi^2(C_{i{\rm NP}}^{})$
  - $\Rightarrow$ **Confidence intervals**: $\chi^2(C_i^{\rm NP}) - \chi^2_{\rm min} \le Q^2$
    $(1\sigma \to Q^2 = 1, 2\sigma \to Q^2 = 4, ...)$
  - $\Rightarrow$ Compute **pulls** (σ): $\text{Pull}_{\rm SM} = \sqrt{\chi^2_{\rm SM} - \chi^2_{\rm min,Sc}}$
- Two types of fits
  - $\Rightarrow$ *Canonical* (or *All*) fit: fit to **all data** (246 data points)
  - $\Rightarrow$ LFUV fit: R_K, R_{K^*}, $P'^{e\mu}_{4,5}(B \to K^* \ell\ell)$ and $b \to s\gamma$ (22 data points)
- Testing different **hypotheses**
  - $\Rightarrow$ Hypotheses with NP only in one Wilson coefficient (**1D fits**)
  - $\Rightarrow$ Hypotheses with NP in two Wilson coefficients (**2D fits**)
  - $\Rightarrow$ Hypotheses with NP in the six Wilson coefficients (**6D fits**)

Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239
Capdevila, Crivellin, Descotes-Genon, Matias, Virto; arxiv:1704.05340

ACDMN: 1D NP fits

1D Hyp.	bfp	1σ	Pull_{SM}	p-value (%)
Global				
$C_{9\mu}^{\text{NP}}$	-1.06	$[-1.20, -0.91]$	7.0	39.5
$C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$	-0.44	$[-0.52, -0.37]$	6.2	22.8
$C_{9\mu}^{\text{NP}} = -C_{9\mu}'$	-1.11	$[-1.25, -0.96]$	6.5	28.0
$C_{9\mu}^{\text{NP}} = -3C_{9e}^{\text{NP}}$	-0.89	$[-1.03, -0.75]$	6.7	32.2
LFUV				
$C_{9\mu}^{\text{NP}}$	-0.82	$[-1.06, -0.60]$	4.0	36.0
$C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$	-0.37	$[-0.46, -0.29]$	4.6	68.0
$C_{9\mu}^{\text{NP}} = -C_{9\mu}'$	-1.61	$[-2.13, -0.96]$	3.0	9.3
$C_{9\mu}^{\text{NP}} = -3C_{9e}^{\text{NP}}$	-0.61	$[-0.78, -0.44]$	4.0	36.0

$\Rightarrow$ $C_{9\mu}^{\text{NP}}$ is the strongest signal for the Global fit. $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$ dominates the "LFUV fit".

$\Rightarrow$ $C_{10\mu}^{\text{NP}}$ solution with a significance of $\sim 4\sigma$.

Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921

ACDMN: 2D NP fits

	Global		LFUV	
2D Hyp.	Best fit	Pull_{SM}	Best fit	Pull_{SM}
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	$(-1.00, +0.11)$	6.8	$(-0.12, +0.54)$	4.3
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{7'})$	$(-1.06, +0.00)$	6.7	$(-0.82, -0.03)$	3.7
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	$(-1.22, +0.56)$	7.2	$(-1.80, +1.12)$	4.1
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu})$	$(-1.26, -0.35)$	7.4	$(-1.82, -0.59)$	4.7
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9e}^{\text{NP}})$	$(-1.20, -0.41)$	6.9	$(-0.73, +0.08)$	3.6
Hyp. 1	$(-1.21, +0.28)$	7.2	$(-1.62, +0.30)$	4.1
Hyp. 2	$(-1.11, +0.09)$	6.3	$(-1.95, +0.25)$	3.4
Hyp. 3	$(-0.44, +0.03)$	5.9	$(-0.37, -0.15)$	4.3
Hyp. 4	$(-0.48, +0.11)$	6.0	$(-0.46, +0.15)$	4.5
Hyp. 5	$(-1.26, +0.25)$	7.4	$(-2.08, +0.51)$	4.7

$\Rightarrow$ Hyp. 1: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = \mathcal{C}_{10'\mu})$, Hyp. 2: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = -\mathcal{C}_{10'\mu})$, Hyp. 3: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = \mathcal{C}_{10'\mu})$, Hyp. 4: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$ and Hyp. 5: $(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$

$\Rightarrow$ High significances for NP solutions with $\mathcal{C}_{9\mu}^{\text{NP}}$ or $\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$ + RHC

Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921

ACDMN: Are we overlooking LFU NP?

⇒ Rotation of the basis of operators with a **LFU-LFUV alignment** (instead of flavour)

$$C_{i\ell}^{\text{NP}} = C_{i\ell}^{\text{V}} + C_i^{\text{U}} \quad (C_i^{\text{U}} \text{ the same } \forall \ell)$$

where $i = 9, 10, 9', 10'$ and $\ell = e, \mu$ (trivial extension to $\ell = \tau$)

⇒ The NP parameter space can be equally described with $\{C_{i\mu}^{\text{NP}}, C_{ie}^{\text{NP}}\}$ or $\{C_{i\mu}^{\text{V}}, C_i^{\text{U}}\}$ $(C_{ie}^{\text{V}} = 0)$

⇒ The LFU vs LFUV language generates non-obvious NP directions in the μ vs e language

$$\left\{ \begin{array}{l} C_{9\mu}^{\text{V}} = -C_{10\mu}^{\text{V}} \\ C_9^{\text{U}} \end{array} \right. \Rightarrow \left\{ \begin{array}{l} C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}} + C_{9e}^{\text{NP}} \\ C_{9e}^{\text{NP}} \end{array} \right.$$

Algueró, BC, Descotes-Genon, Masjuan, Matias; arxiv:1809.08447

ACDMN: LFU NP Fits

Scenario	Best-fit point	$1\,\sigma$	Pull_{SM}
$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$ $\mathcal{C}_{9}^{\rm U} = \mathcal{C}_{10}^{\rm U}$	-0.52 -0.41	$[-0.60, -0.44]$ $[-0.54, -0.28]$	6.8
$\mathcal{C}_{9\mu}^{\rm V}$ $\mathcal{C}_{9}^{\rm U}$	-0.76 -0.39	$[-1.00, -0.52]$ $[-0.68, -0.09]$	6.9
$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$ $\mathcal{C}_{9}^{\rm U}$	-0.30 -0.92	$[-0.39, -0.21]$ $[-1.10, -0.72]$	7.3
$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$ $\mathcal{C}_{10}^{\rm U}$	-0.51 -0.27	$[-0.64, -0.39]$ $[-0.49, -0.05]$	6.0
$\mathcal{C}_{9\mu}^{\rm V}$ $\mathcal{C}_{10}^{\rm U}$	-1.02 $+0.27$	$[-1.18, -0.85]$ $[+0.11, +0.44]$	6.9
$\mathcal{C}_{9\mu}^{\rm V}$ $\mathcal{C}_{10'}^{\rm U}$	-1.12 -0.31	$[-1.28, -0.95]$ $[-0.46, -0.15]$	7.1

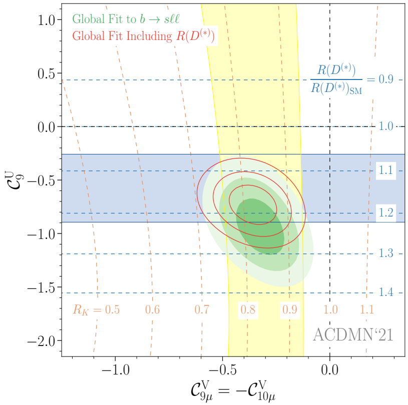
$\Rightarrow$ Left-handed structure $C_{9\mu}^{\rm V} = -C_{10\mu}^{\rm V}$ preferred over the vector structure $C_{9\mu}^{\rm V}$, in the presence of LFU NP in $C_9^{\rm U}$

Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921

ACDMN: Model independent connection $b \to s\mu\mu$ & $b \to c\ell\nu$ (with LFU-NP)

- NP scenario ($\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}, \mathcal{C}^{\rm U}_9$) allows for connections between $b \to s\ell\ell$ and $b \to c\tau\nu$ ($R_{D^{(*)}}$)
- SMEFT condition: $\mathcal{C}^{(1)} = \mathcal{C}^{(3)}$
- $\mathcal{O}_{2322} \Rightarrow$ LFUV NP $\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}$ & $\mathcal{O}_{2333} \Rightarrow$ LFU NP $\mathcal{C}^{\rm U}_9$

Crivellin, Greub, Muller, Saturnino; arxiv:1807.02068



$\Rightarrow$ Pull$_{\rm SM} = 8.1\sigma$.

Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921

AS: Setup

- Quantify agreement between theory and experiment by χ^2 function

$$\chi^2(\vec{C}) = \left(\vec{O}_{\rm exp} - \vec{O}_{\rm th}(\vec{C})\right)^{\rm T} \left(C_{\rm exp} + C_{\rm th}(\vec{C})\right)^{-1} \left(\vec{O}_{\rm exp} - \vec{O}_{\rm th}(\vec{C})\right) .$$

- **theory errors** and **correlations** in covariance matrix $\boldsymbol{C}_{\rm th}$
- **experimental errors** and available **correlations** in covariance matrix $\boldsymbol{C}_{\rm exp}$
- Theory errors depend on new physics Wilson coefficients $\boldsymbol{C}_{\rm th}(\vec{\boldsymbol{C}})$ *NEW*
- $\Delta\chi^2$ and pull

Altmannshofer, PS, arXiv:2103.13370

$$\text{pull}_{\rm 1D} = 1\sigma \cdot \sqrt{\Delta\chi^2} , \qquad \text{where } \Delta\chi^2 = \chi^2(\vec{0}) - \chi^2(\vec{C}_{\text{best fit}}) .$$

$$\text{pull}_{\rm 2D} = 1\sigma, 2\sigma, 3\sigma, \ldots \quad \text{for} \quad \Delta\chi^2 \approx 2.3, 6.2, 11.8, \ldots$$

- New physics scenarios in **Weak Effective Theory (WET)** at scale 4.8 GeV

AS: Scenarios with a single Wilson coefficients

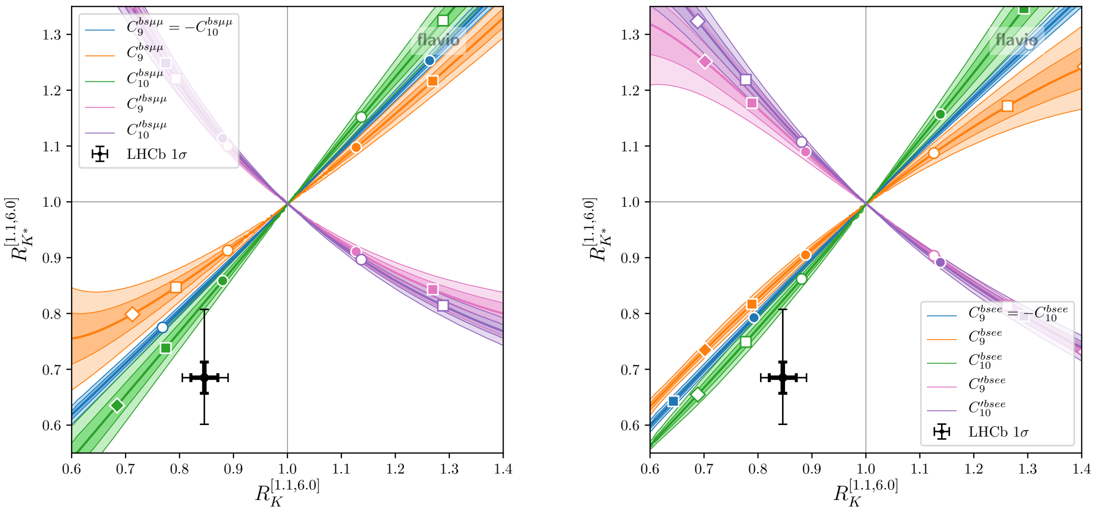
Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	$\mathbf{3.3\sigma}$	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	$\mathbf{5.1\sigma}$
$C_{10}^{bs\mu\mu}$	$+0.45^{+0.22}_{-0.23}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	$\mathbf{4.7\sigma}$	$+0.54^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$+0.15^{+0.24}_{-0.24}$	0.6σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.19^{+0.13}_{-0.13}$	1.5σ
$C_{10}^{\prime bs\mu\mu}$	$-0.09^{+0.15}_{-0.15}$	0.6σ	$+0.07^{+0.11}_{-0.13}$	0.5σ	$+0.04^{+0.10}_{-0.09}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.16^{+0.14}_{-0.14}$	1.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$+0.05^{+0.11}_{-0.11}$	0.5σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.55^{+0.13}_{-0.13}$	$\mathbf{3.8\sigma}$	$-0.35^{+0.08}_{-0.08}$	$\mathbf{4.6\sigma}$	$-0.39^{+0.07}_{-0.07}$	$\mathbf{5.6\sigma}$
C_9^{bsee}			$+0.74^{+0.20}_{-0.19}$	4.1σ	$+0.75^{+0.20}_{-0.19}$	4.1σ
C_{10}^{bsee}			$-0.67^{+0.17}_{-0.18}$	4.2σ	$-0.66^{+0.17}_{-0.18}$	4.3σ
$C_9^{\prime bsee}$			$+0.36^{+0.18}_{-0.17}$	2.1σ	$+0.40^{+0.19}_{-0.18}$	2.3σ
$C_{10}^{\prime bsee}$			$-0.32^{+0.16}_{-0.16}$	2.1σ	$-0.31^{+0.15}_{-0.16}$	2.1σ
$C_9^{bsee} = C_{10}^{bsee}$			$-1.39^{+0.26}_{-0.26}$	4.0σ	$-1.28^{+0.24}_{-0.23}$	4.1σ
$C_9^{bsee} = -C_{10}^{bsee}$			$+0.37^{+0.10}_{-0.10}$	4.2σ	$+0.37^{+0.10}_{-0.10}$	4.3σ

AS: Scenarios with a single Wilson coefficients

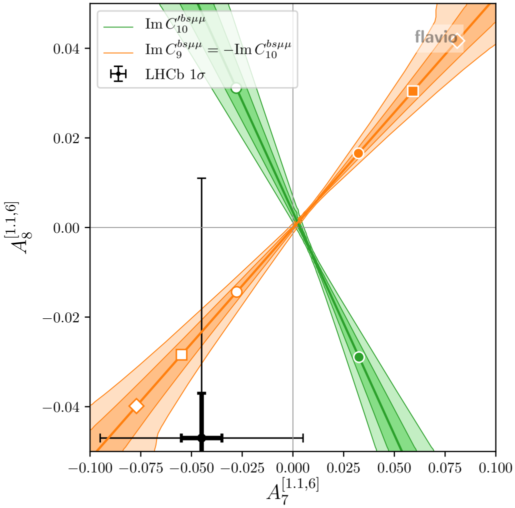
	Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
NP err.	$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	**3.3σ**	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	**5.1σ**
	$C_{10}^{bs\mu\mu}$	$+0.45^{+0.22}_{-0.23}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	**4.7σ**	$+0.54^{+0.12}_{-0.12}$	4.8σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.55^{+0.13}_{-0.13}$	**3.8σ**	$-0.35^{+0.08}_{-0.08}$	**4.6σ**	$-0.39^{+0.07}_{-0.07}$	**5.6σ**
SM err.	$C_9^{bs\mu\mu}$	$-0.83^{+0.22}_{-0.20}$	**3.6σ**	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.77^{+0.15}_{-0.15}$	**5.3σ**
	$C_{10}^{bs\mu\mu}$	$+0.45^{+0.21}_{-0.20}$	2.3σ	$+0.60^{+0.14}_{-0.14}$	**4.7σ**	$+0.54^{+0.12}_{-0.12}$	4.9σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.17}_{-0.18}$	**3.8σ**	$-0.35^{+0.08}_{-0.08}$	**4.6σ**	$-0.39^{+0.07}_{-0.07}$	**5.6σ**

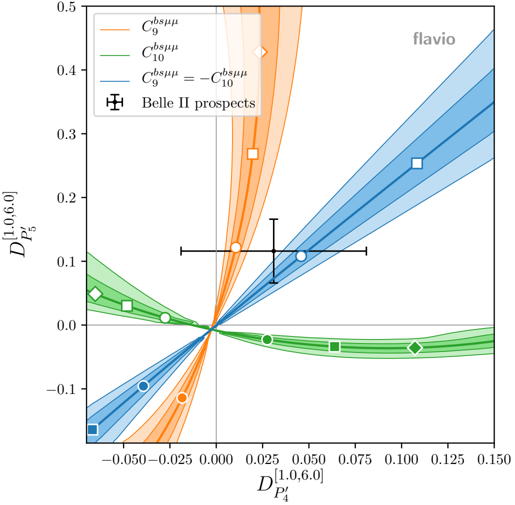
Visible effect of theory errors depending on new physics, in particular for $C_9^{bs\mu\mu}$

AS: Theory uncertainties in presence of NP



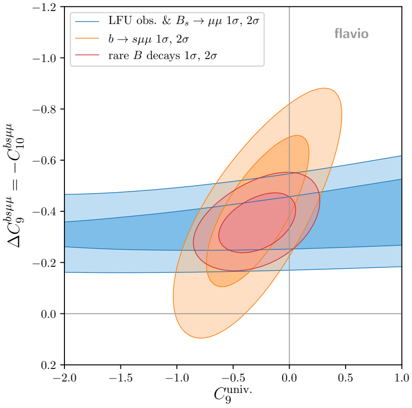
AS: Theory uncertainties in presence of NP





AS: Scenario with two Wilson coefficients

- **New 2021 data**:
  smaller uncertainty, better agreement between R_K & R_{K^*} and $B_s \to \mu\mu$, smaller best-fit value of $C_9^{\text{univ.}}$



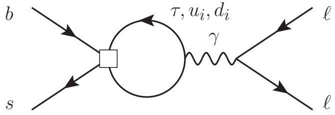
WET at 4.8 GeV

- Perform two-parameter fit in space of $C_9^{\text{univ.}}$ and $\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$:

$$C_9^{bsee} = C_9^{bs\tau\tau} = C_9^{\text{univ.}}$$
$$C_9^{bs\mu\mu} = C_9^{\text{univ.}} + \Delta C_9^{bs\mu\mu}$$
$$C_{10}^{bsee} = C_{10}^{bs\tau\tau} = 0$$
$$C_{10}^{bs\mu\mu} = -\Delta C_9^{bs\mu\mu}$$

scenario first considered in
Algueró et al., arXiv:1809.08447

- Slight preference for **non-zero $C_9^{\text{univ.}}$**
  - could be mimicked by hadronic effects
  - can arise from RG effects:



Bobeth, Haisch, arXiv:1109.1826
Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068

AS: Parameterisation of beyond-QCDF contributions for $B \to K$

$$C_9^{\text{eff}}(q^2) \to C_9^{\text{eff}}(q^2) + a_K + b_K(q^2/\,\text{GeV}^2) \quad \text{at low } q^2\,,$$

$$C_9^{\text{eff}}(q^2) \to C_9^{\text{eff}}(q^2) + c_K \quad \text{at high } q^2\,,$$

$$\text{Re}(a_K) = 0.0 \pm 0.08\,, \qquad \text{Re}(b_K) = 0.0 \pm 0.03\,, \qquad \text{Re}(c_K) = 0.0 \pm 0.2\,,$$
$$\text{Im}(a_K) = 0.0 \pm 0.08\,, \qquad \text{Im}(b_K) = 0.0 \pm 0.03\,, \qquad \text{Im}(c_K) = 0.0 \pm 0.2\,.$$

1σ uncertainties enclose the effects considered in Khodjamirian et al. arXiv:1006.4945, Beylich et al. arXiv:1101.5118, Khodjamirian et al. arXiv:1211.0234

AS: Parameterisation of beyond-QCDF contributions for $B \to K^*$ and $B_s \to \phi$

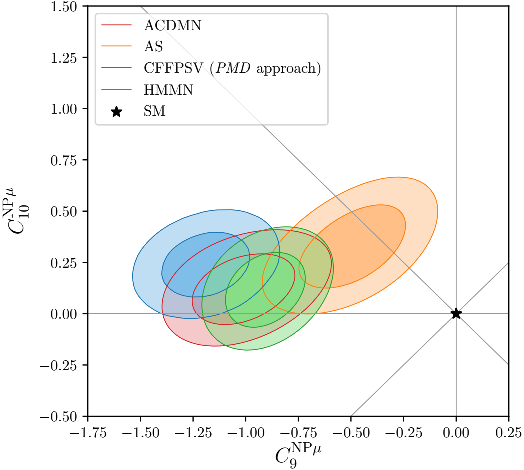
$$\begin{aligned} C_7^{\text{eff}}(q^2) &\to C_7^{\text{eff}}(q^2) + a_{0,-} + b_{0,-}(q^2/\,\text{GeV}^2) \\ C_7' &\to C_7' + a_+ + b_+(q^2/\,\text{GeV}^2) \end{aligned} \qquad \text{at low } q^2\,,$$

$$C_9^{\text{eff}}(q^2) \to C_9^{\text{eff}}(q^2) + c_\lambda \qquad \text{at high } q^2\,,$$

$$\begin{aligned} \text{Re}(a_+) &= 0.0 \pm 0.004\,, & \text{Re}(b_+) &= 0.0 \pm 0.005\,, & \text{Re}(c_+) &= 0.0 \pm 0.3\,, \\ \text{Im}(a_+) &= 0.0 \pm 0.004\,, & \text{Im}(b_+) &= 0.0 \pm 0.005\,, & \text{Im}(c_+) &= 0.0 \pm 0.3\,, \\ \text{Re}(a_-) &= 0.0 \pm 0.015\,, & \text{Re}(b_-) &= 0.0 \pm 0.01\,, & \text{Re}(c_-) &= 0.0 \pm 0.3\,, \\ \text{Im}(a_-) &= 0.0 \pm 0.015\,, & \text{Im}(b_-) &= 0.0 \pm 0.01\,, & \text{Im}(c_-) &= 0.0 \pm 0.3\,, \\ \text{Re}(a_0) &= 0.0 \pm 0.12\,, & \text{Re}(b_0) &= 0.0 \pm 0.05\,, & \text{Re}(c_0) &= 0.0 \pm 0.3\,, \\ \text{Im}(a_0) &= 0.0 \pm 0.12\,, & \text{Im}(b_0) &= 0.0 \pm 0.05\,, & \text{Im}(c_0) &= 0.0 \pm 0.3\,. \end{aligned}$$

1σ uncertainties enclose the effects considered in Khodjamirian et al. arXiv:1006.4945, Beylich et al. arXiv:1101.5118

CFFPSV: 2-dimensional global fit w/out large hadronic effects



Result of the global fit when order of magnitude estimate based on theory calculations from continuum methods is employed

CFFPSV: Parameterisation of non-local hadronic matrix elements

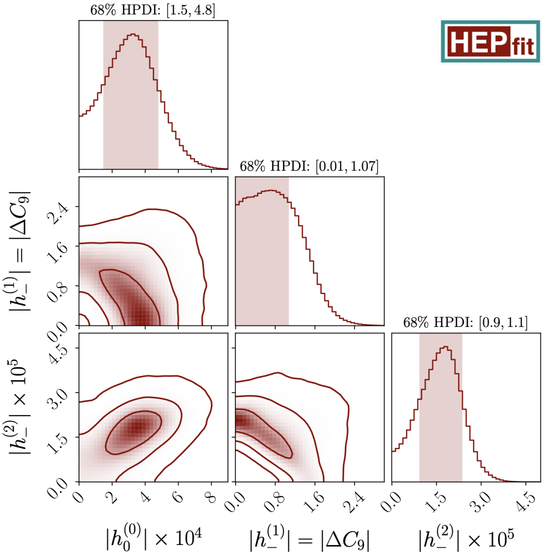
$$H_V^- \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right) \widetilde{V}_{L-} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(C_7^{\rm SM} + h_-^{(0)}\right) \widetilde{T}_{L-} - 16\pi^2 h_-^{(2)}\, q^4 \right] \right\}$$

$$H_V^+ \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right) \widetilde{V}_{L+} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(C_7^{\rm SM} + h_-^{(0)}\right) \widetilde{T}_{L+} - 16\pi^2 \left(h_+^{(0)} + h_+^{(1)}\, q^2 + h_+^{(2)}\, q^4\right) \right] \right\}$$

$$H_V^0 \propto \left\{ \left(C_9^{\rm SM} + h_-^{(1)}\right) \widetilde{V}_{L0} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(C_7^{\rm SM} + h_-^{(0)}\right) \widetilde{T}_{L0} - 16\pi^2 \sqrt{q^2} \left(h_0^{(0)} + h_0^{(1)}\, q^2\right) \right] \right\}$$

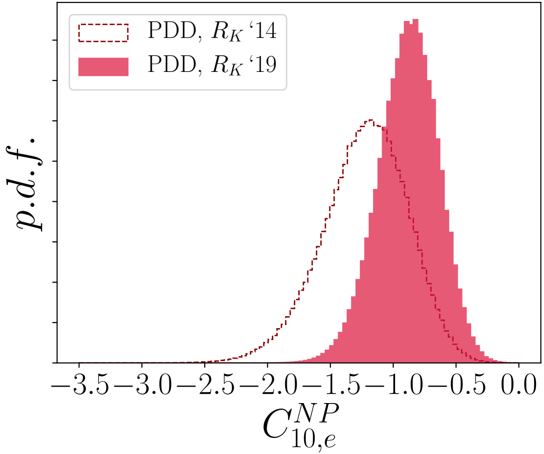
- $h_-^{(0)}$ and $h_-^{(1)}$ can be considered as constant shifts to the WCs $C_{7,9}^{\rm SM}$, hence indistinguishable from universal NP contributions to $O_{7,9}$
- remaining parameters describing purely hadronic contributions

CFFPSV: Inference of non-local hadronic parameters



- obtained by a SM fit to $b \to s\mu\mu$ data
- rising evidence for purely hadronic parameters
- Strong correlations among $h_-^{(1)}$ (indistinguishable from NP contribution to C_9) and purely hadronic parameters $h_0^{(0)}$ and $h_-^{(2)}$
- $C_9^{\rm NP}$ solution recovered for vanishing $h_0^{(0)}$ and $h_-^{(2)}$

CFFPSV: Possible solution with NP in electron axial current



- Solution only viable with hadronic parameters allowed to freely grow approaching the $q^2 \simeq 4m_c^2$ threshold
- Anomalies in the $b \to s\mu\mu$ sector explained by purely hadronic contributions (see previous slide)
- Anomalies in the LFUV ratios addressed by NP in the electron axial current
- Goodness-of-fit comparable to the one obtained in the other presented scenarios

CFFPSV: Collection of relevan global fit results

NP scenario	68.27% HPDI	ΔIC
A: C_9^{NP}	$[-1.38, -0.94]$	37
B: C_{2223}^{LQ}	$[0.65, 0.86]$	53
C: $\{C_{2223}^{LQ}, C_{2322}^{Qe}\}$	$\{[0.59, 0.85], [-0.37, 0.10]\}$	51
C': $\{C_9^{\mathrm{NP}}, C_{10}^{\mathrm{NP}}\}$	$\{[-0.65, -0.18], [0.46, 0.75]\}$	51
D: $\{C_{2223}^{LQ}, C_{2322}^{Qe}, C_{2223}^{Ld}, C_{2223}^{ed}\}$	$\{[0.83, 1.36], [-0.03, 0.80], [-0.66, -0.13], [-0.66, 0.23]\}$	48
D': $\{C_9^{\mathrm{NP}}, C_{10}^{\mathrm{NP}}, C_9^{\prime,\mathrm{NP}}, C_{10}^{\prime,\mathrm{NP}}\}$	$\{[-1.51, -0.61], [0.28, 0.70], [-0.01, 0.94], [-0.38, 0.09]\}$	48

- ΔIC is a measurement of the goodness of the fit, which takes into account the number of model parameters as a penalty factor
- Scenarios better reproducing data are described by higher values for ΔIC

HMMN: New Physics vs hadronic fit

Non-local matrix element contributions can mimic $C_9^{\rm NP}$ since both appear in the vectorial helicity amplitude

$$H_V^\mu \propto \left\{ C_9^{\rm eff} \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B} C_7^{\rm eff} \tilde{T}_\lambda(q^2) - 16\pi^2 \left(\text{LO in QCDf} + h_\lambda(q^2)\right)\right]\right\}$$

Instead of *guesstimating* $h_\lambda(q^2)$, can be parameterised by a general ansatz:

Jäger, Camalich, arXiv:1412.3183
Ciuchini et al., arXiv:1512.07157
Chobanova, Hurth, Mahmoudi, Martinez-Santos, SN, arXiv:1702.02234

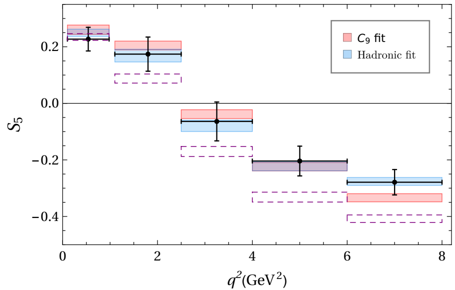
$$h_{\pm,[0]} = \left[\sqrt{q^2}\times\right]\left(h^{(0)}_{\pm,[0]} + q^2 h^{(1)}_{\pm,[0]} + q^4 h^{(2)}_{\pm,[0]}\right)$$

NP effect in C_9 are embedded in the hadronic contributions
⇒ Wilks' test can be used to compare separate fits to:

- Hadronic quantities $h^{(0,1,2)}_{+,-,0}$ (18 parameters)
- Wilson coefficient $C_9^{\rm NP}$ (1 parameter)

$B \to K^*\gamma/\mu\mu$ observables		
	Real $C_9^{\rm NP}$ (1)	Hadronic fit h_λ (18)
Plain SM	6.0σ	4.7σ
Real $C_9^{\rm NP}$	–	1.5σ

A. Arbey, T. Hurth, F. Mahmoudi, SN: 2006.04213



■ Hadronic fit describes the data well, however adding 17 more param. to NP doesn't significantly improve the fit (1.5σ)

HMMN: New Physics vs hadronic fit (minimal description)

18-parameter description of the hadronic contributions cannot get strongly constrained with current data

A (minimal) description of hadronic contributions with fewer parameters

$$h_\lambda(q^2) = -\frac{\tilde{V}_\lambda(q^2)}{16\pi^2}\frac{q^2}{m_B^2}\Delta C_9^{\lambda,\mathrm{PC}}$$

a different Δ_9^{PC} for each helicity $\lambda = +, -, 0$
$\rightarrow$ 3 (6) free parameters if assumed real (complex)

If NP in C_9 is the favoured scenario, the different fitted helicities should give the same value
$\Rightarrow$ Can work as a null test for NP

	best fit value
$\Delta C_9^{+,\mathrm{PC}}$	$(3.39 \pm 6.44) + i(-14.98 \pm 8.40)$
$\Delta C_9^{-,\mathrm{PC}}$	$(-1.02 \pm 0.22) + i(-0.68 \pm 0.79)$
$\Delta C_9^{0,\mathrm{PC}}$	$(-0.83 \pm 0.53) + i(-0.89 \pm 0.69)$

Fitted parameters not the same for different helicities but in agreement with each other within 1σ

$B \to K^*\gamma/\mu\mu$ observables		
	Real C_9^{NP} (1)	Hadronic fit $\Delta C_9^{\lambda,\mathrm{PC}}$ (6)
Plain SM	6.0σ	5.5σ
Real C_9^{NP}	–	1.8σ

- Adding the hadronic parameters improve the fit with less than 2σ significance

$\Rightarrow$ Strong indication that the NP interpretation is a valid option, although the situation remains inconclusive

HMMN: Multi-dimensional global fit

Considering only one or two Wilson coefficients may not give the full picture

A generic set of Wilson coefficients: $C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$ + primed coefficients

All observables with $\chi^2_{\rm SM} = 225.8$; $\chi^2_{\rm min} = 151.6$; $\rm Pull_{SM} = 5.5(5.6)\sigma$			
δC_7: 0.05 ± 0.03		δC_8: -0.70 ± 0.40	
$\delta C_7'$: -0.01 ± 0.02		$\delta C_8'$: 0.00 ± 0.80	
δC_9^μ: -1.16 ± 0.17	δC_9^e: -6.70 ± 1.20	δC_{10}^μ: 0.20 ± 0.21	δC_{10}^e: degenerate w/ $C_{10}'^e$
$\delta C_9'^\mu$: 0.09 ± 0.34	$\delta C_9'^e$: 1.90 ± 1.50	$\delta C_{10}'^\mu$: -0.12 ± 0.20	$\delta C_{10}'^e$: degenerate w/ C_{10}^e
$C_{Q_1}^\mu$: 0.04 ± 0.10	$C_{Q_1}^e$: -1.50 ± 1.50	$C_{Q_2}^\mu$: -0.09 ± 0.10	$C_{Q_2}^e$: -4.10 ± 1.5
$C_{Q_1}'^\mu$: 0.15 ± 0.10	$C_{Q_1}'^e$: -1.70 ± 1.20	$C_{Q_2}'^\mu$: -0.14 ± 0.11	$C_{Q_2}'^e$: -4.20 ± 1.2

- Considering most general NP description and eliminating insensitive params. and flat directions based on the fit and not based on data, look-elsewhere effect is avoided
- Many parameters are weekly constrained at the moment
- Effective degree of freedom is (19)
- **Effective degrees of freedom**: degrees of freedom minus the spurious degrees of as realised from likelihood profiles, correlations and $C_i^{\rm NP}$ only weakly affecting the χ^2 such that $|\chi^2(C_i^{\rm NP} \neq 0) - \chi^2(C_i^{\rm NP} = 0)| \lesssim 1$

HMMN: Comparison of different multi-dimensional global fits

Pull_{SM} of 1, 2, 6, 10 and 20 dimensional fit:

Set of WC	param.	χ^2_{min}	Pull_{SM}	Improvement
SM	0	225.8	-	-
C_9^μ	1	168.6	7.6σ	7.6σ
C_9^μ, C_{10}^μ	2	167.5	7.3σ	1.0σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$	6	158.0	7.1σ	2.0σ
All non-primed WC	10	157.2	6.5σ	0.1σ
All WC (incl. primed)	20 (19)	151.6	$5.5\,(5.6)\sigma$	$0.2\,(0.3)\sigma$

- In the last column the significance of improvement of the fit compared to the scenario of the previous row is given
- The "All non-primed WC" includes in addition to the previous row, the scalar and pseudoscalar Wilson coefficients
- The last row also includes the chirality-flipped counterparts of the Wilson coefficients
- The number in parentheses corresponds to the effective degrees of freedom (19)