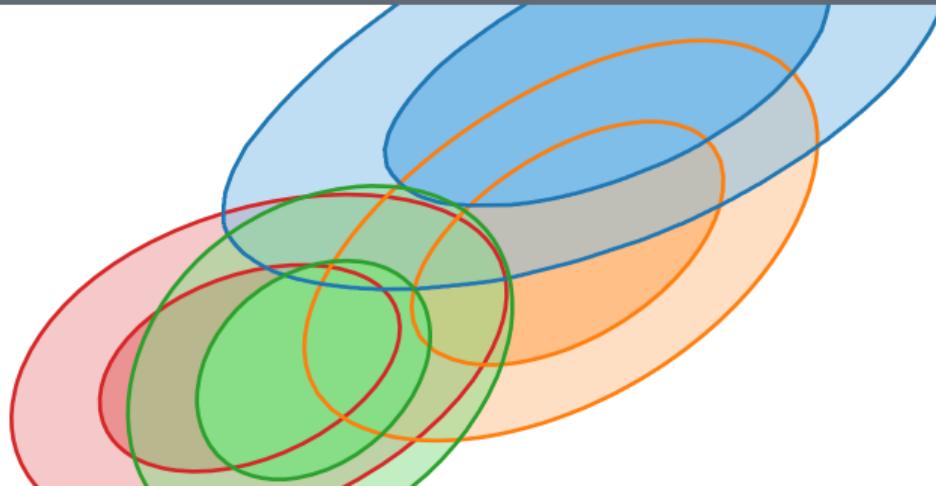


Status of global fits to data

B. Capdevila, M. Fedele, N. Mahmoudi University of Cambridge, DAMTP & Uni. Autònoma Barcelona



The $b \rightarrow s\ell\ell$ anomalies

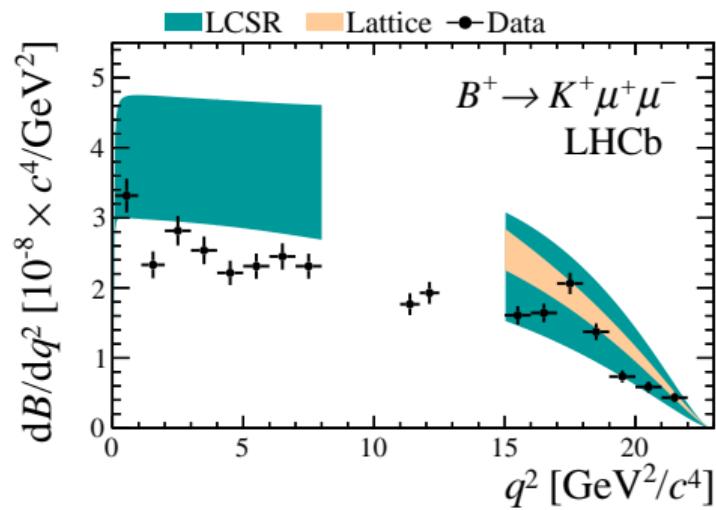
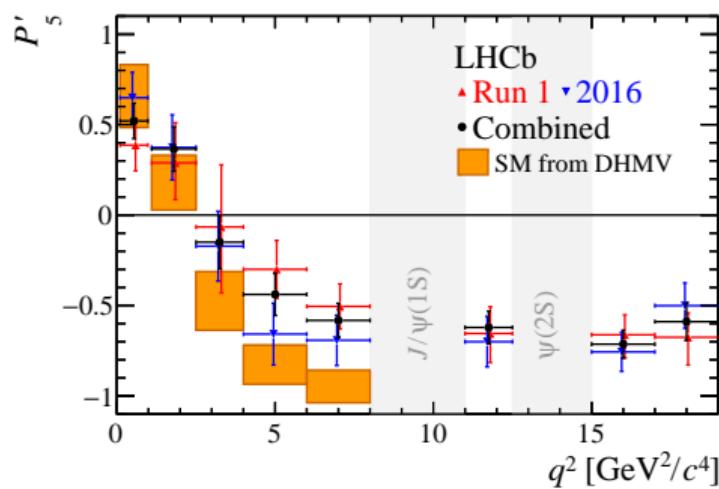
$b \rightarrow s \mu^+ \mu^-$ anomaly

Several LHCb measurements deviate from Standard model (SM) predictions* by $2\text{-}3\sigma$:

- Angular observables in $B^{(0,+)} \rightarrow K^{*(0,+)} \mu^+ \mu^-$
- Branching ratios of $B \rightarrow K \mu^+ \mu^-$, $B \rightarrow K^* \mu^+ \mu^-$, and $B_s \rightarrow \phi \mu^+ \mu^-$

LHCb, arXiv:2003.04831, arXiv:2012.13241

LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731, arXiv:2105.14007



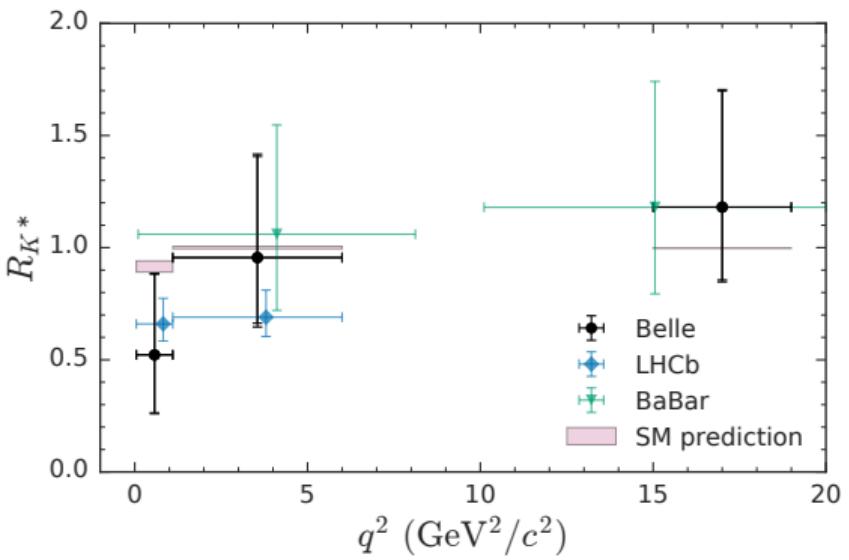
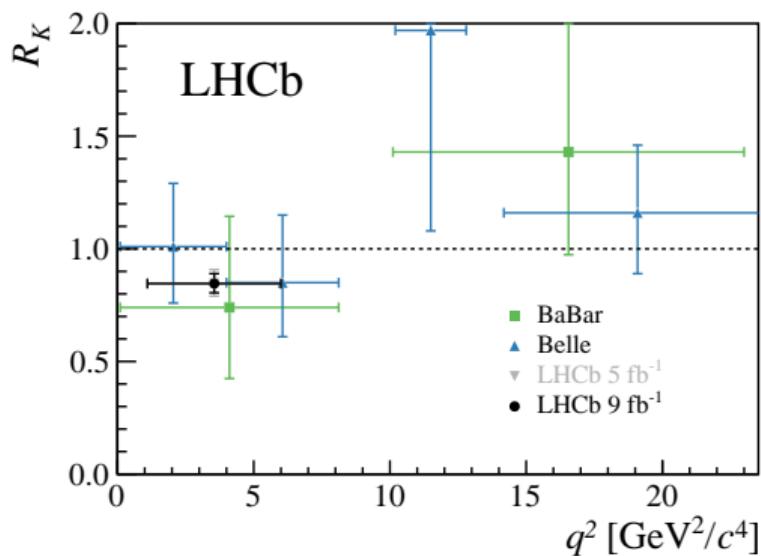
*: based on hadronic assumptions on which there is no theory consensus yet

LFU violation in $b \rightarrow s \ell^+ \ell^-$ decays (up to Dec. 2022)

Measurements of LFU ratios $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$, $R_K^{[1,6]}$ showed 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

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

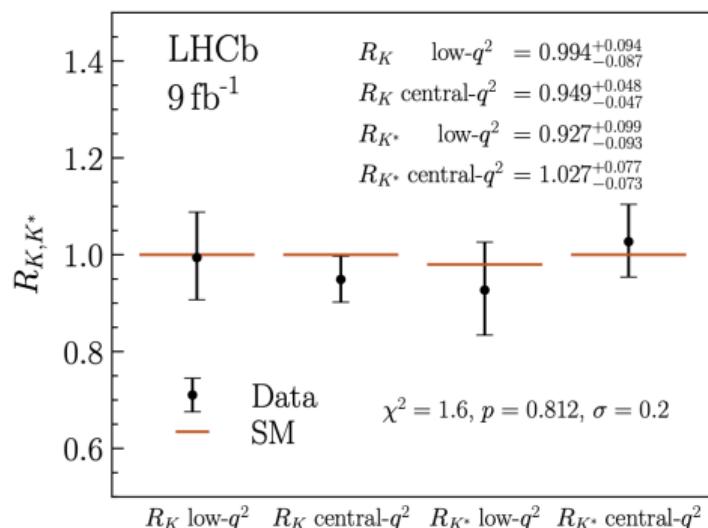


LFU violation in $b \rightarrow s \ell^+ \ell^-$ decays

New LHCb measurement of the LFU ratios $R_K^{[0.1,1.1]}$, $R_K^{[1.1,6]}$, $R_{K^*}^{[0.1,1.1]}$, $R_{K^*}^{[1.1,6]}$

LHCb, arXiv:2212.09152, arXiv:2212.09153.

- ▶ sample of B meson decays in pp collisions collected between 2011 and 2018 (integrated luminosity of 9 fb^{-1})
- ▶ new modelling of residual backgrounds due to misidentified hadronic decays
- ▶ deviations from SM by ~ -0.0 , $+1.1$, $+0.5$ and -0.4σ



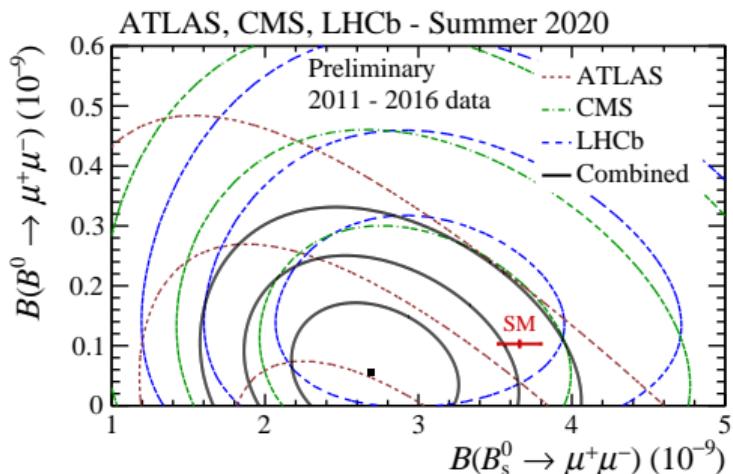
Leptonic modes $B_{s,d} \rightarrow \mu^+ \mu^-$

Measurements of $\mathcal{B}(B_{s,d} \rightarrow \mu^+ \mu^-)$ by LHCb, CMS, and ATLAS show deviations of only about $\sim 1\sigma$ with respect to SM predictions*

ATLAS, arXiv:1812.03017

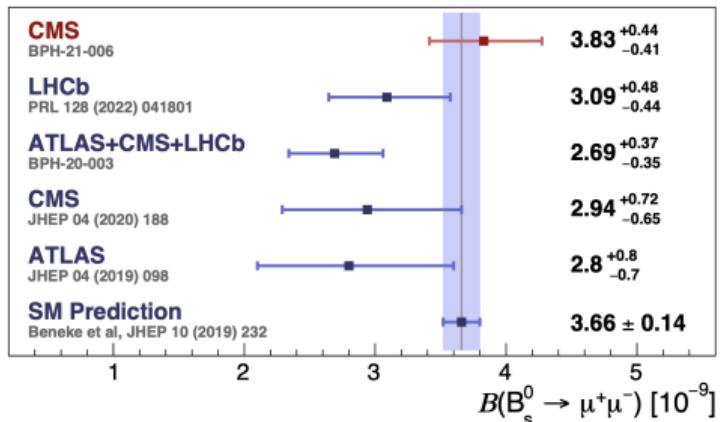
CMS, arXiv:1910.12127, 2212.10311

LHCb, arXiv:1703.05747, 2108.09283



ATLAS update missing \Rightarrow full Run 1 + Run 2 LHC combination

*: depends on parameters like V_{cb}



Bobeth, Buras, arXiv:2104.09521

Theoretical Framework

$b \rightarrow s\ell\ell$ 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:** ($\mathcal{N} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \approx (34 \text{ TeV})^{-2}$)

$$\mathcal{H}_{\text{eff, sl}} = -\mathcal{N} \left(\mathcal{C}_7 O_7 + \mathcal{C}'_7 O'_7 + \sum_{\ell} \sum_{i=9,10,P,S} \left(\mathcal{C}_i^\ell O_i^\ell + \mathcal{C}'_i^\ell O'_i^\ell \right) \right) + \text{h.c.}$$

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

$$\mathcal{C}_7^{\text{SM}} \simeq -0.3, \quad \mathcal{C}_9^{\text{SM}} \simeq 4, \quad \mathcal{C}_{10}^{\text{SM}} \simeq -4.$$

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:**

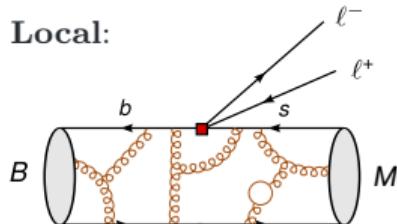
$$\mathcal{H}_{\text{eff, had}} = -\mathcal{N} \frac{16\pi^2}{e^2} \left(\mathcal{C}_8 O_8 + \mathcal{C}'_8 O'_8 + \sum_{i=1,\dots,6} \mathcal{C}_i O_i \right) + \text{h.c.}$$

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

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

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

Local:

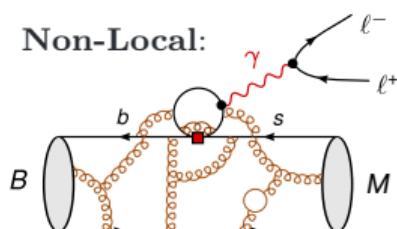


$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2} \mathcal{C}_7 \langle M | \bar{s} \sigma^{\mu\nu} q_\nu P_R b | B \rangle + \mathcal{C}_9 \langle M | \bar{s} \gamma^\mu P_L b | B \rangle + (P_L \leftrightarrow P_R, \mathcal{C}_i \rightarrow \mathcal{C}'_i)$$

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

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

Non-Local:



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

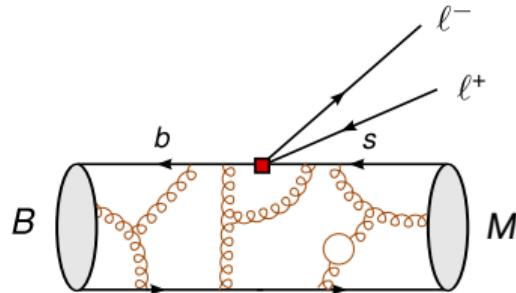
► **Wilson coefficients** $\mathcal{C}_i = \mathcal{C}_i^{\text{SM}} + \mathcal{C}_i^{\text{NP}}$:

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



$$\begin{aligned} \mathcal{A}_V^\mu &= -\frac{2im_b}{q^2} \mathcal{C}_7 \langle M | \bar{s} \sigma^{\mu\nu} q_\nu P_R b | B \rangle + \mathcal{C}_9 \langle M | \bar{s} \gamma^\mu P_L b | B \rangle + (P_L \leftrightarrow P_R, \mathcal{C}_i \rightarrow \mathcal{C}'_i) \\ \mathcal{A}_A^\mu &= \mathcal{C}_{10} \langle M | \bar{s} \gamma^\mu P_L b | B \rangle + (P_L \leftrightarrow P_R, \mathcal{C}_i \rightarrow \mathcal{C}'_i) \\ \mathcal{A}_{S,P} &= \mathcal{C}_{S,P} \langle M | \bar{s} P_R b | B \rangle + (P_L \leftrightarrow P_R, \mathcal{C}_i \rightarrow \mathcal{C}'_i) \end{aligned}$$

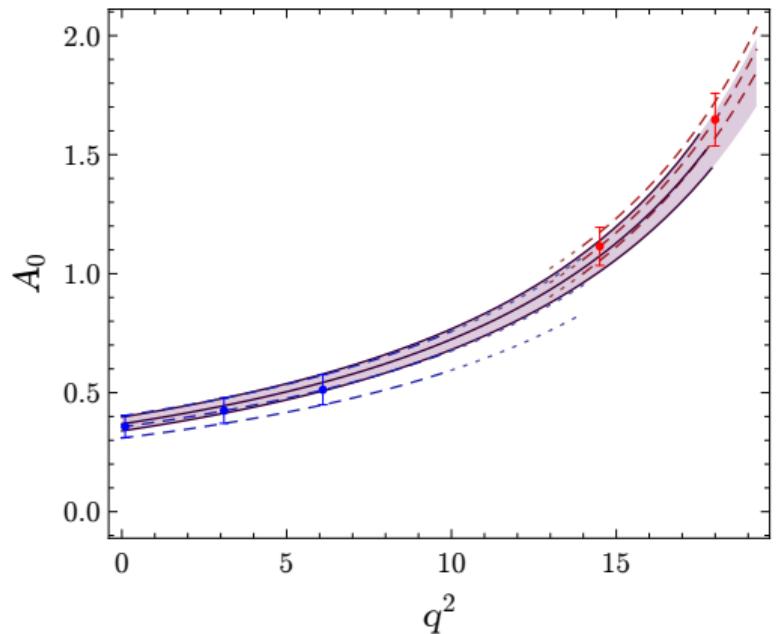
- ▶ $\langle M | \bar{s} \Gamma_i b | B \rangle$ matrix elements are parameterised by:
 - ▶ **3 form factors** for each **spin zero** final state $M = K$
 - ▶ **7 form factors** for each **spin one** final state $M = K^*, \phi$
- ▶ Determination of form factors
 - ▶ high q^2 : **Lattice QCD**
 - ▶ low q^2 : **Continuum methods**
e.g. Light-cone sum rules (LCSR)
 - ▶ low + high q^2 : Combined fit to **continuum methods + lattice / lattice**

HPQCD, arXiv:1306.2384, 2207.12468
 Fermilab, MILC, arXiv:1509.06235
 Horgan, Liu, Meinel, Wingate, arXiv:1310.3722, arXiv:1501.00367

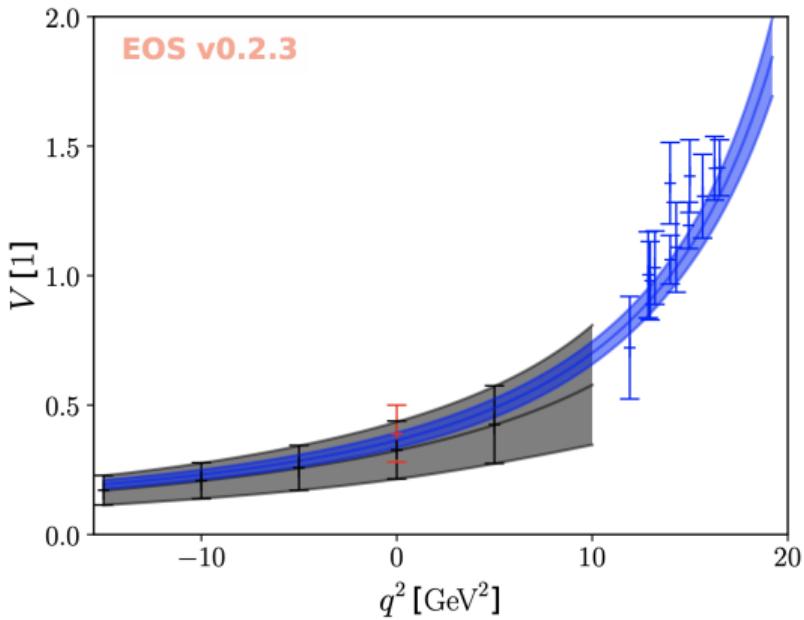
Ball, Zwicky, arXiv:hep-ph/0406232
 Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
 Bharucha, Straub, Zwicky, arXiv:1503.05534
 Gubernari, Kokulu, van Dyk, arXiv:1811.00983

Altmannshofer, Straub, arXiv:1411.6743
 Bharucha, Straub, Zwicky, arXiv:1503.05534
 Gubernari, Kokulu, van Dyk, arXiv:1811.00983

Form factors



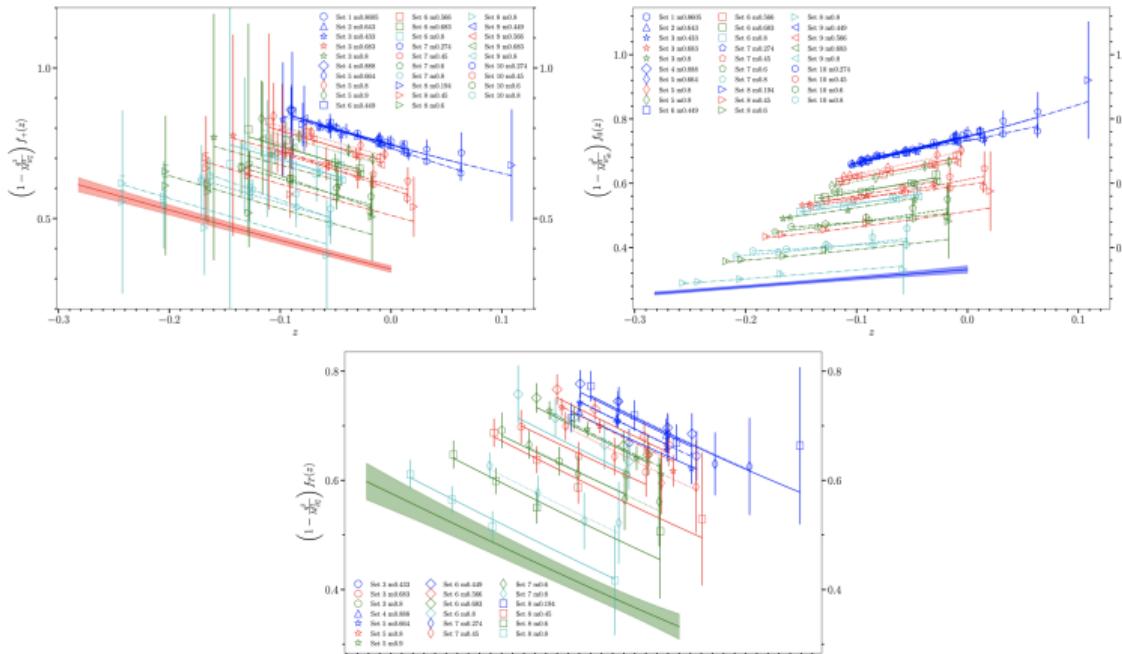
Bharucha, Straub, Zwicky, arXiv:1503.05534



Gubernari, Kokulu, van Dyk, arXiv:1811.00983

Theory Update: $B \rightarrow K$ lattice form factors at all q^2

- Lattice QCD calculation of the $B \rightarrow K$ form factors **across the full physical q^2 range**
 - ⇒ highly improved staggered quark (HISQ) formalism (valence quarks)
 - ⇒ gluon field configurations by MILC
 - ⇒ first fully relativistic calculation, using the heavy-HISQ method

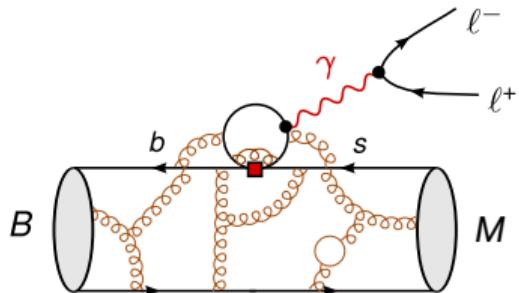


Non-negligible impact on $B \rightarrow K\ell\ell$ observables

Predictions with HPQCD'22 Form Factors			
$10^7 \times \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[0.1, 0.98]	0.320 ± 0.025	0.29 ± 0.02	+0.8
[1.1, 2]	0.329 ± 0.025	0.21 ± 0.02	+3.9
[2, 3]	0.365 ± 0.027	0.28 ± 0.02	+2.4
[3, 4]	0.366 ± 0.027	0.25 ± 0.02	+3.3
[4, 5]	0.366 ± 0.028	0.22 ± 0.02	+4.4
[5, 6]	0.366 ± 0.029	0.23 ± 0.02	+3.9
[6, 7]	0.367 ± 0.032	0.25 ± 0.02	+3.3
[7, 8]	0.371 ± 0.042	0.23 ± 0.02	+3.1
[15, 22]	1.150 ± 0.159	0.85 ± 0.05	+1.8

HPQCD, arXiv:2207.12468
 LHCb, arXiv:1403.8044

Non-local matrix elements



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

$$j_{\text{em}}^\mu = \sum_q Q_q \bar{q} \gamma^\mu q$$

- ▶ 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 \mathcal{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 $b \rightarrow s c\bar{c}$ Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305
Gubernari, van Dyk, Virto, arXiv:2011.09813

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

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

Fit setup

$b \rightarrow s\ell\ell$ global analyses

Results presented here by:

- ▶ **ABCDMN** (M. Algueró, A. Biswas, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
Statistical framework: χ^2 -fit, based on private code arXiv:2304.07330
- ▶ **AS / GSSS** (W. Altmannshofer, P. Stangl / A. Greljo, J. Salko, A. Smolkovic, P. Stangl)
Statistical framework: χ^2 -fit, based on public code `flavio` arXiv:2212.10497.
- ▶ **CFFPSV** (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
Statistical framework: Bayesian MCMC fit, based on public code `HEPfit` arXiv:2212.10516
- ▶ **HMMN** (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
Statistical framework: χ^2 -fit, based on public code `SuperIso` arXiv:23xx.xxxxx

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 (see Nico Gubernari & Javier Virto's talks) arXiv:2206.03797

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 $b \rightarrow s\ell\ell$ global analyses

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

Comparison between the groups

- ▶ Different experimental inputs, e.g.
 - ▶ $q^2 \in [6, 8]$ GeV 2 data (**ABCDMN**, **CFFPSV**, **HMMN**)
 - ▶ High- q^2 data (**AS**, **ABCDMN**, **HMMN**)
 - ▶ Radiative decays (**ABCDMN**, **CFFPSV**, **HMMN**)
 - ▶ $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ (**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 ($B \rightarrow V \ell \ell$ **ABCDMN**)
 - ▶ Full q^2 region: form factors from HPQCD lattice fit across all q^2 , with full correlations ($B \rightarrow P \ell \ell$ **ABCDMN**)
 - ▶ 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 (**ABCDMN**, **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 (before exp. updates 2022)

Most important Wilson coefficients:

- ▶ $\mathcal{C}_{9\mu}$: dominant contributions to angular observables, LFU observables
- ▶ $\mathcal{C}_{10\mu}$: dominant contributions to $B_s \rightarrow \mu\mu$, LFU observables

“Uninteresting” NP scenarios:

- ▶ $\mathcal{C}_{7(\prime)}$: strongly constrained by radiative decays and very low- q^2 bin of $B \rightarrow K^* e^+ e^-$
- ▶ \mathcal{C}_{ie} : current data does not indicate NP in electron coefficients, but not enough data to be conclusive
- ▶ $\mathcal{C}_{9'\ell, 10'\ell}$: dominant contribution from coefficients with right-handed quarks disfavoured by $R_K \approx R_{K^*}$

Interesting NP scenarios:

- ▶ 1D scenarios: $\mathcal{C}_{9\mu}^{\text{NP}}$ or $\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$
- ▶ 2D scenario: $(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$

Updated general remarks about global fits

Most important Wilson coefficients:

- ▶ $\mathcal{C}_{9\mu}$: dominant contributions to angular observables, LFU observables
- ▶ $\mathcal{C}_{10\mu}$: dominant contributions to $B_s \rightarrow \mu\mu$, LFU observables

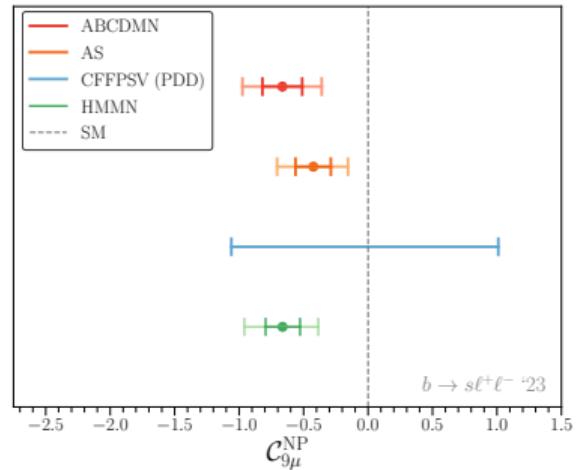
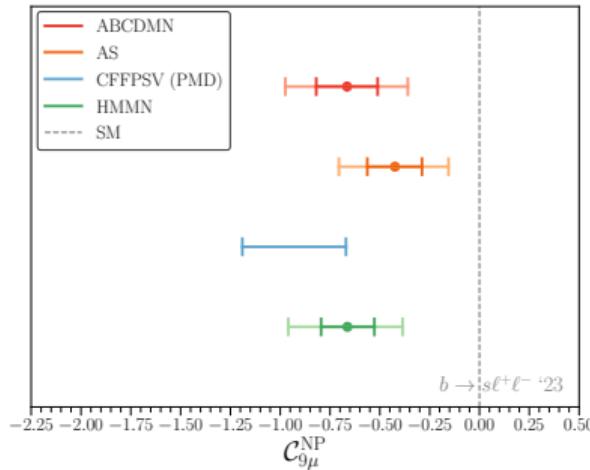
“Uninteresting” NP scenarios:

- ▶ $\mathcal{C}_{7(\prime)}$: strongly constrained by radiative decays and very low- q^2 bin of $B \rightarrow K^* e^+ e^-$
- ▶ $\textcolor{red}{\mathcal{C}_{10\mu}}$: new $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ combination greatly constraints $\mathcal{C}_{10\mu}^{\text{NP}} \approx 0$
- ▶ $\mathcal{C}_{9'\ell,10'\ell}$: dominant contribution from coefficients with right-handed quarks disfavoured by $R_K \approx R_{K^*}$

Interesting NP scenarios:

- ▶ 1D scenarios: $\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9\mu}^{\text{NP}} = \mathcal{C}_{9e}^{\text{NP}} = \mathcal{C}_9^U$
- ▶ 2D scenario: $(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}}), (\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9e}^{\text{NP}}), (\mathcal{C}_9^U, \mathcal{C}_{i=10(\mu),9'(\mu),10'(\mu)}^{V,U})$ (since $R_K \approx R_{K^*} \approx 1$)

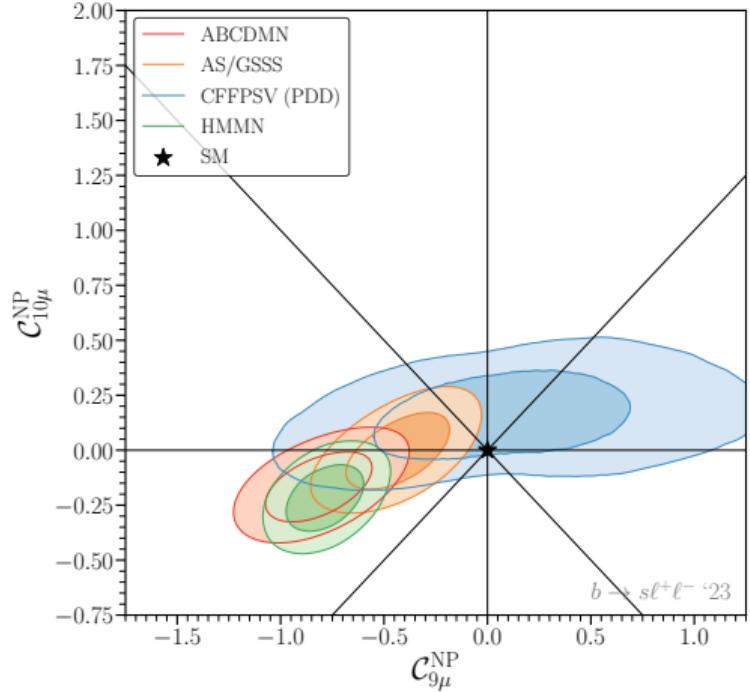
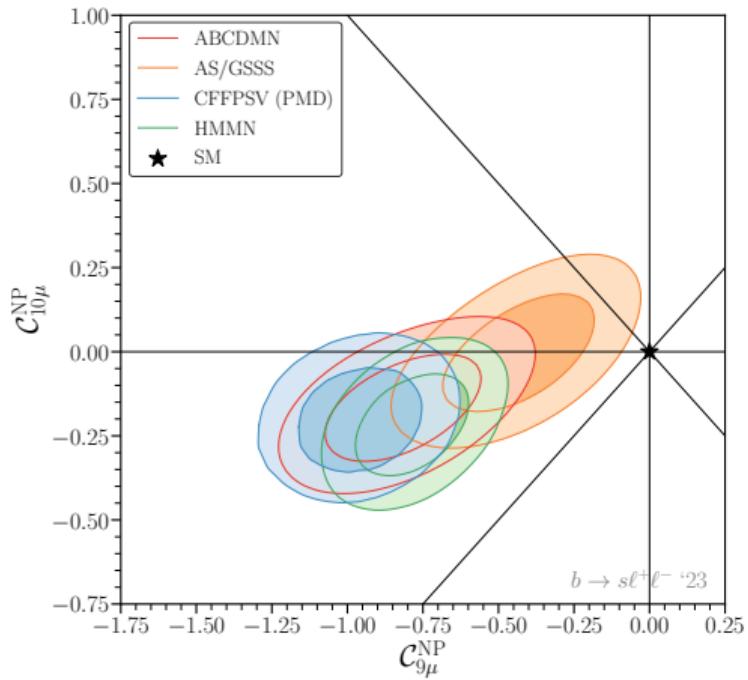
1-dimensional global fits



- ▶ NP scenarios preferred over SM with $\text{Pull}_{\text{SM}}^* \sim 4\sigma$
- ▶ 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
⇒ **$b \rightarrow s \ell \ell$ global analyses are robust**

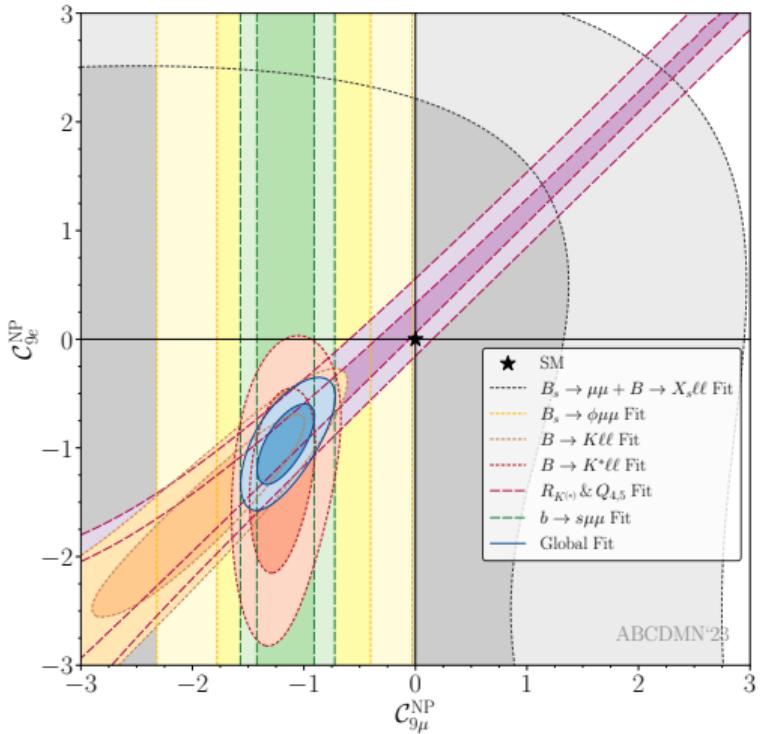
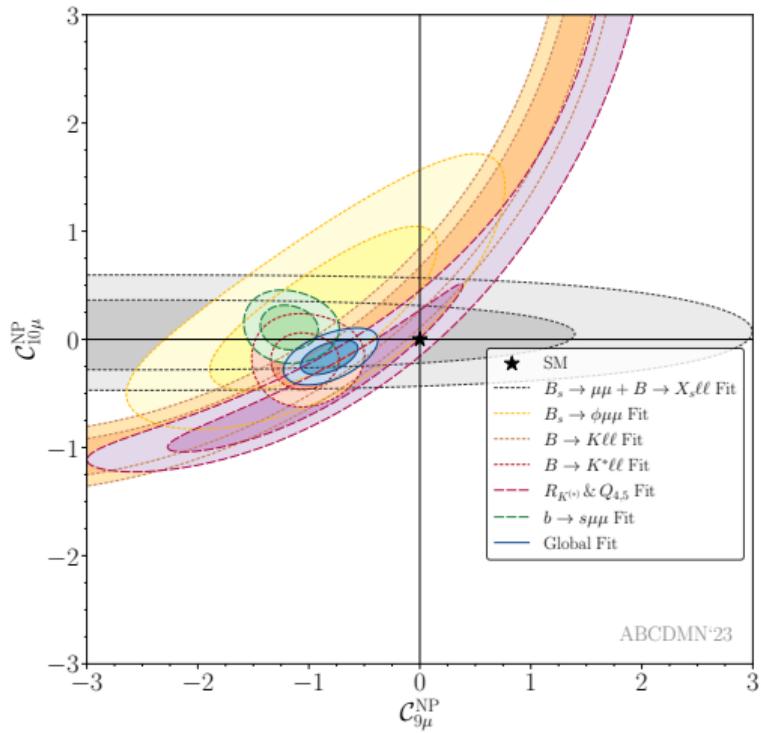
*: $\text{Pull}_{\text{SM}} \neq$ global significance; conservative global significance (2021) $\simeq 4.3\sigma$ determined in Isidori, Lancierini, Owen, Serra, arXiv:2104.05631

2-dimensional global fits



- ▶ Again, 2D NP scenarios preferred over SM with $\text{Pull}_{\text{SM}} \sim 4\sigma$
- ▶ Impressive agreement between fits of different groups despite different approaches (PMD vs PDD & bin [6., 8.])

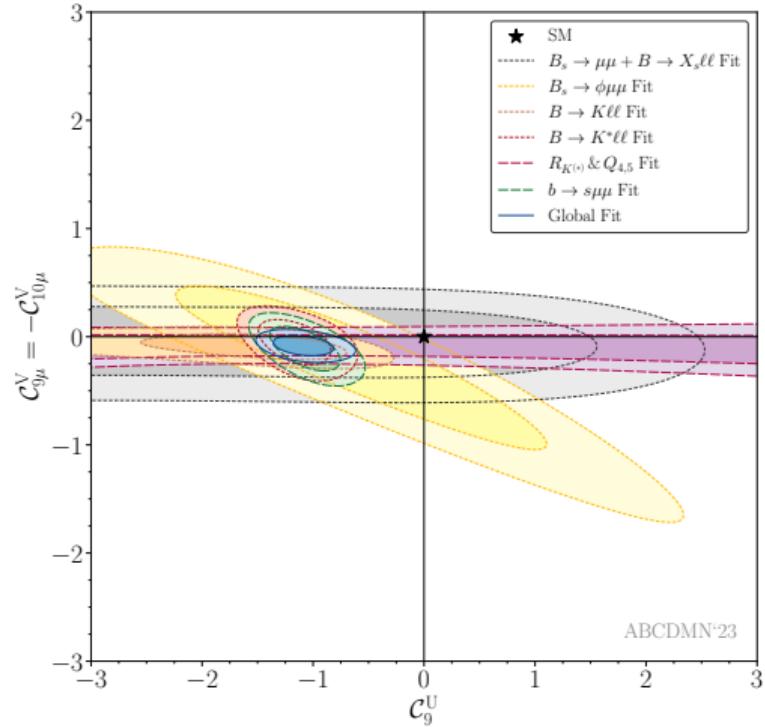
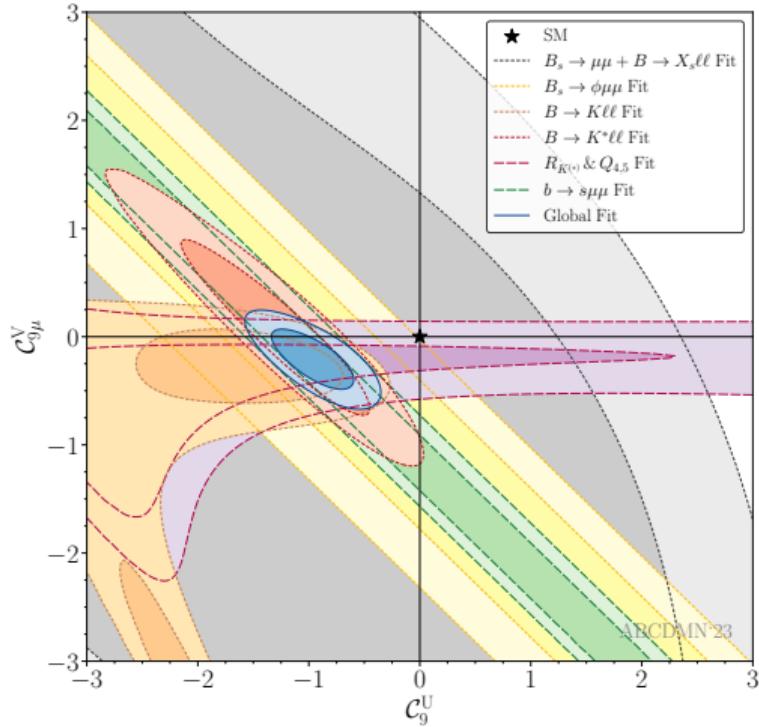
Structure of the multidimensional fits



- NP hypothesis that do not allow for LFU show important internal tensions among fit components
- NP hypothesis with LFU embedded are very competitive describing all data

Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2304.07330

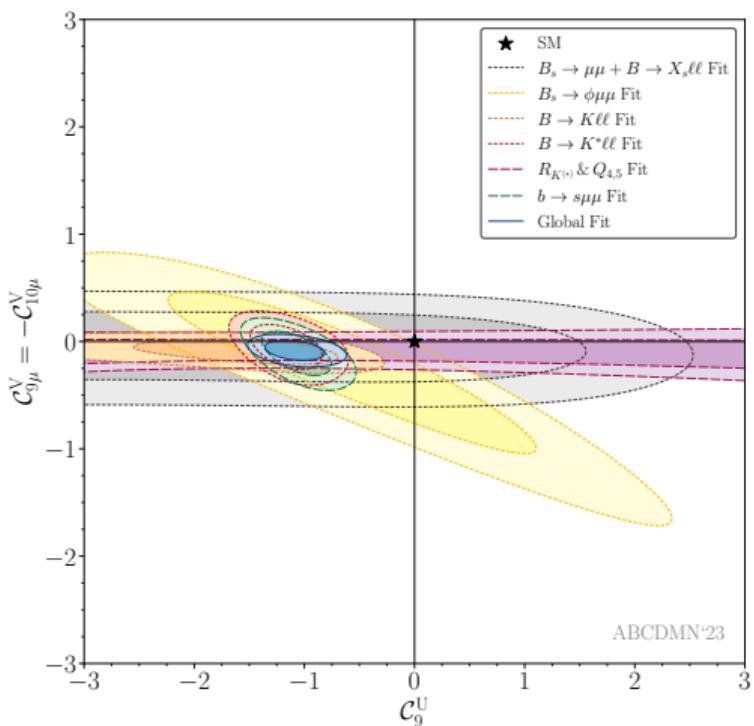
Internal coherence of fits including LFU NP to C_9



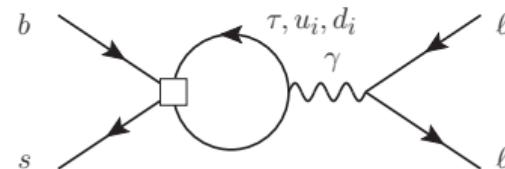
- NP hypothesis with C_9^U are very competitive in explaining the data (Pull_{SM} $\sim 5.5\sigma$)

Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2304.07330

NP fits with LFU contributions



- ▶ Two-parameter fit in space of $C_{9\mu}^V = -C_{10\mu}^V$ and C_9^U
scenario first considered in
[Algueró et al., arXiv:1809.08447](#)
- ▶ Large **non-zero** C_9^U but LFUV compatible with 0
- ▶ This scenario is one of the most successful NP solutions to solve the $b \rightarrow s\ell\ell$ anomalies
 - ⇒ $\text{Pull}_{\text{SM}} = 5.6\sigma$
 - ⇒ It successfully describes, with optimal internal consistency, $b \rightarrow s\mu\mu$ angular data + LFU ratios
 - ⇒ Could be mimicked by hadronic effects
 - ⇒ Can arise from RG effects:

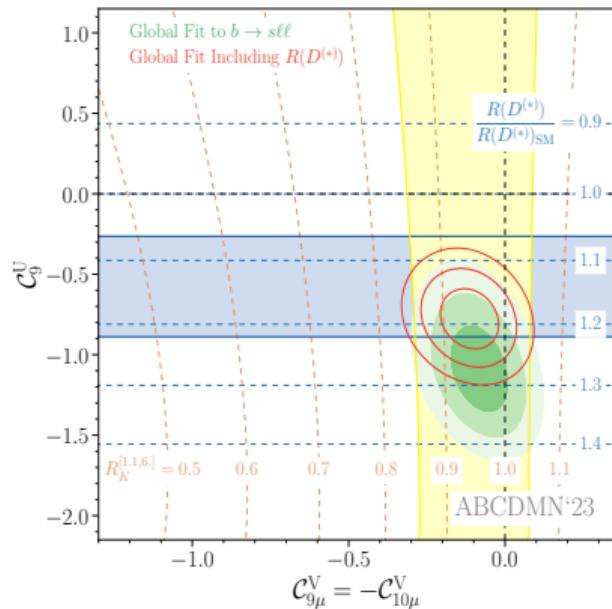


[Bobeth, Haisch, arXiv:1109.1826](#)
[Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068](#)

Model independent connection $b \rightarrow s\mu\mu$ & $b \rightarrow c\ell\nu$ (with LFU NP)

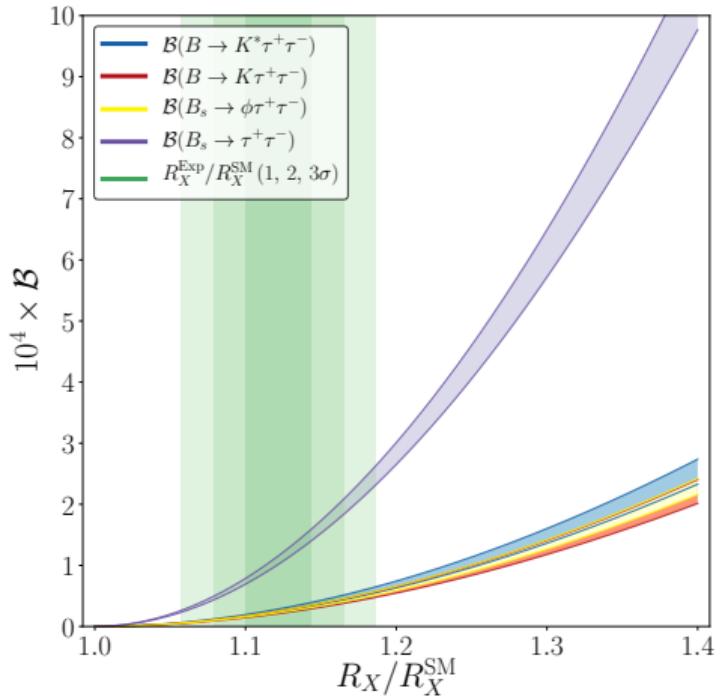
- NP scenario ($\mathcal{C}_9^U, \mathcal{C}_{9\mu}^V = -\mathcal{C}_{10\mu}^V$) allows for connections between $b \rightarrow s\ell\ell$ and $b \rightarrow c\tau\nu$ ($R_{D^{(*)}}$)
- SMEFT condition: $\mathcal{C}^{(1)} = \mathcal{C}^{(3)}$
- $\mathcal{O}_{2322} \Rightarrow$ LFUV NP $\mathcal{C}_{9\mu}^V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

Crivellin, Greub, Muller, Saturnino; arxiv:1807.02068



$\Rightarrow \text{Pull}_{\text{SM}} = 6.3\sigma$

Enhancement of $b \rightarrow s\tau\tau$



⇒ Typical **enhancement** by 10^2 - 10^3 compared to SM value.

Capdevila, Crivellin, Descotes-Genon, Hofer, Matias; arxiv:1712.01919

Conclusions

Conclusions

- ▶ Substantial reduction on the significance of the most preferred NP scenarios
 - ⇒ \mathcal{C}_9 continues to be the WC where most of the NP signal is encapsulated
 - ⇒ LFUV components are mostly suppressed
 - ⇒ High significances for scenarios with universal NP \mathcal{C}_9^U
- ▶ Important tensions in the inner structure of the fit:
 - ⇒ LFU ratios are SM-like
 - ⇒ $B \rightarrow K^{(*)}\mu\mu$ and branching ratios for $B \rightarrow K\mu\mu$ continue to deviate with high significance
- ▶ $R_{D^{(*)}}$ and $b \rightarrow s\tau^+\tau^-$ can be correlated from fairly general assumptions:
 - ⇒ $b \rightarrow s\tau^+\tau^-$ processes dominated by NP approximately three orders of magnitude larger than SM
- ▶ Exploit the correlations among $b \rightarrow s\ell\ell$ and $b \rightarrow c\ell\nu$ and $b \rightarrow s\tau\tau$ to test the nature of \mathcal{C}_9^U : either NP or hadronic effects (or a combination)

Wishlist

- ▶ Explicit numerical experimental likelihoods, e.g. to avoid digitisation of $B_{s,d} \rightarrow \mu\mu$ contour plots
- ▶ Measurements of other LFU observables, like e.g. R_ϕ or $Q_{4,5}/D_{P'_{4,5}}$
- ▶ $B \rightarrow K^* e^+ e^-$ 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**

Thank you!

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).

► ABCDMN

$$\begin{aligned} \textit{Global fit} : n_{\text{dof}} &= 256 &\Rightarrow p\text{-value} &= 5.13\% \\ \textit{LFU fit*} : n_{\text{dof}} &= 26 &\Rightarrow p\text{-value} &= 92.45\% \end{aligned}$$

► AS

$$\begin{aligned} \textit{Global fit} : n_{\text{dof}} &= ??? &\Rightarrow p\text{-value} &= ?.?.\% \\ \textit{LFU fit*} : n_{\text{dof}} &= ?? &\Rightarrow p\text{-value} &= ?.?.\% \end{aligned}$$

► HMMN

$$\begin{aligned} \textit{Global fit} : n_{\text{dof}} &= ??? &\Rightarrow p\text{-value} &= ?.?.\% \\ \textit{LFU fit*} : n_{\text{dof}} &= ?? &\Rightarrow p\text{-value} &= ?.?.\% \end{aligned}$$

*LFU fit: all the measured LFU observables + $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ (all groups)

+ effective $B_s \rightarrow \mu\mu$ lifetime + radiative decays + $\mathcal{B}(B_s \rightarrow X_s \mu^+ \mu^-)$ (depending on the group)

ABCDMN: Improved QCDF

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

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

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

- $m_b \rightarrow \infty$ and $E_{V,P} \rightarrow \infty$ symmetries: low- q^2 and LO in α_s and Λ/m_b

⇒ **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 ⇒ QCDF

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

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

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

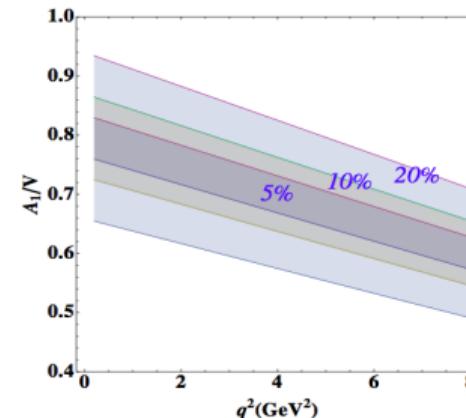
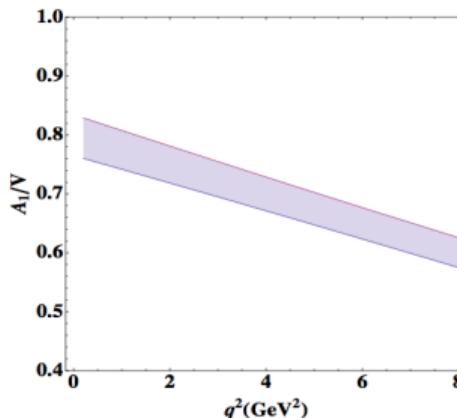
Jäger, Camalich; arXiv:1212.2263
Descotes-Genon, Hofer, Matias, Virto; arXiv:1407.8526

ABCDMN: Improved QCDF (vs full FF approach)

- ▶ How to estimate ΔF^Λ ?
 - ⇒ Central values for a_F , b_F , c_F from **fit to full FF** (continuum calculation)
 - ⇒ 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?



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

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

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

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

$$\mathcal{C}_9^{\text{eff}}(q^2) = \mathcal{C}_9^{\text{SM}} + Y(q^2)$$

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

- Estimate of the soft-gluon emission contribution at low q^2 :

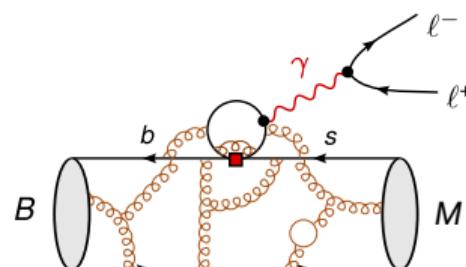
⇒ Calculations based on continuum methods

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

⇒ Shift in $\mathcal{C}_9^{\text{eff}}$. Order of magnitude for the shift estimated from theory calculations

$$\mathcal{C}_{9,i}^{\text{eff}}(q^2) = \mathcal{C}_9^{\text{eff}}(q^2) + \mathcal{C}_9^{\text{NP}} + s_i \delta \mathcal{C}_9^{\text{LD},i}(q^2) \quad (i = \perp, \parallel, 0)$$

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



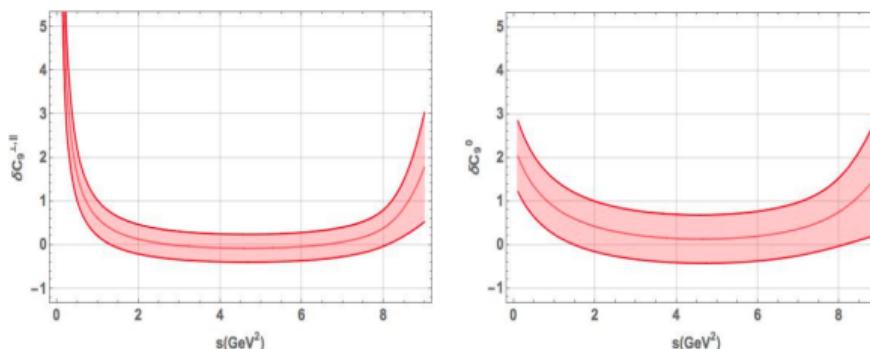
ABCDMN: Estimating beyond QCDF contribution at low- q^2

- Parameterisation for the long-distance contribution

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

⇒ We vary s_i in the range $[-1, 1]$

⇒ a^i, b^i, c^i parameters floated according to KMPW calculation

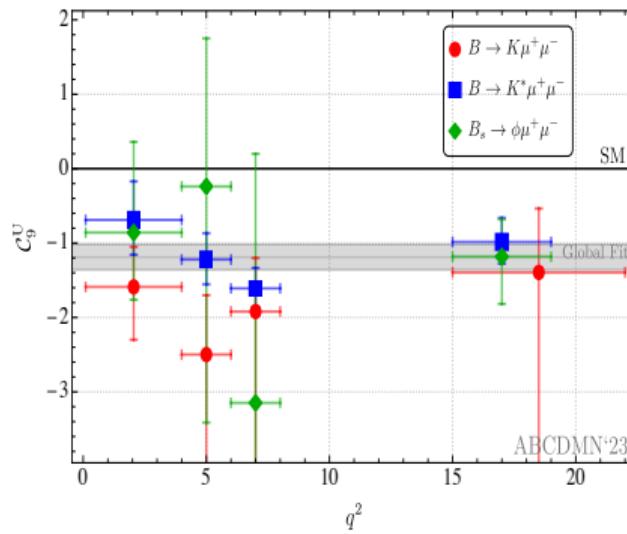


Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
Descotes-Genon, Hofer, Matias, Virto; arxiv:1407.8526
Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239

ABCDMN: Consistency over q^2

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

- ▶ Fit to $B \rightarrow K^* \mu^+ \mu^-$ (\mathcal{B} 's + Ang. obs) + $B_s \rightarrow \mu^+ \mu^-$ + $B \rightarrow X_s \mu^+ \mu^-$ + $b \rightarrow s\gamma$
- ▶ C_9^{NP} bin-by-bin fit (assuming KMPW-like $\delta C_9^{\text{LD},i}(q^2)$)
- ▶ Good agreement with global fit (1σ range)
- ▶ No indication of a strong q^2 dependence
- ▶ Consistency large and low recoil (different theo. treatments)



ABCDMN: Statistical framework

We parametrise the Wilson coefficients as,

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

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

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

- ▶ Both **theory and experiment** contribute to the covariance matrix
 - ⇒ $\text{Cov} = \text{Cov}^{\text{th}} + \text{Cov}^{\text{exp}}$
- ▶ Experimental covariance
 - ⇒ **Experimental correlations** between observables (if not provided, assumed uncorrelated).
- Assume
 - gaussian errors (symmetrize if needed)
- ▶ Theoretical covariance
 - ⇒ Compute the **theoretical correlations** by performing a multivariate gaussian scan over all nuisance parameters
- ▶ $\text{Cov} = \text{Cov}(C_i)$
 - ⇒ **Mild** dependency ⇒ $\text{Cov} = \text{Cov}_{\text{SM}} \equiv \text{Cov}(C_i = 0)$. Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239
Capdevila, Crivellin, Descotes-Genon, Matias, Virto; arxiv:1704.05340

ABCDMN: Statistical framework

► Fit procedure:

⇒ **Best fit points** (bfp): $\chi^2(C_i^{\text{NP}}) \rightarrow \chi_{\min}^2 = \chi^2(C_i^{\text{NP}})$

⇒ **Confidence intervals**: $\chi^2(C_i^{\text{NP}}) - \chi_{\min}^2 \leq Q^2$
 $(1\sigma \rightarrow Q^2 = 1, 2\sigma \rightarrow Q^2 = 4, \dots)$

⇒ Compute **pulls** (σ): $\text{Pull}_{\text{SM}} = \sqrt{\chi_{\text{SM}}^2 - \chi_{\min, \text{Sc}}^2}$

► Two types of fits

⇒ *Canonical* (or *All*) fit: fit to **all data** (246 data points)

⇒ LFUV fit: R_K , R_{K^*} , $P_{4,5}^{\prime\, e\mu}(B \rightarrow K^*\ell\ell)$ and $b \rightarrow s\gamma$ (22 data points)

► Testing different **hypotheses**

⇒ Hypotheses with NP only in one Wilson coefficient (**1D fits**)

⇒ Hypotheses with NP in two Wilson coefficients (**2D fits**)

⇒ 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

ABCDMN: 1D NP fits

1D Hyp.	Global (before exp. updates 2022)				p -value (%)
	bfp	1σ	Pull _{SM}		
$C_{9\mu}^{\text{NP}}$	-0.67 (-1.01)	[-0.82, -0.52] ([−1.15, −0.87])	4.5 (7.0)	20.2 (24.0)	
$C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$	-0.19 (-0.45)	[-0.25, -0.13] ([−0.52, −0.37])	3.1 (6.5)	9.9 (16.9)	
$C_{9\mu}^{\text{NP}} = -C'_{9\mu}$	-0.47 (-0.92)	[-0.66, -0.30] ([−1.07, −0.75])	3.0 (5.7)	9.5 (8.2)	
LFUV					
1D Hyp.	bfp	1σ	Pull _{SM}	p -value (%)	
	-0.21 (-0.87)	[-0.38, -0.04] ([−1.11, −0.65])	1.2 (4.4)	92.4 (40.7)	
$C_{9\mu}^{\text{NP}}$	-0.08 (-0.39)	[-0.15, -0.01] ([−0.48, −0.31])	1.1 (5.0)	91.6 (73.5)	
$C_{9\mu}^{\text{NP}} = -C'_{9\mu}$	-0.04 (-1.60)	[-0.26, 0.15] ([−2.10, −0.98])	0.2 (3.2)	87.5 (8.4)	

- ⇒ Substantial drop in significances
- ⇒ $C_{9\mu}^{\text{NP}}$ is the strongest signal for the Global fit
- ⇒ p -value for $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$ reduces significantly (less fit coherence: ang. obs. vs LFUV ratios)
- ⇒ NP contributions to the WC compatible with SM values for the LFUV fit

Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921
 Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2304.07330

ABCDMN: Are we overlooking LFU NP?

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

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

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 $\{C_{i\mu}^V, C_i^U\}$ ($C_{ie}^V = 0$)

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

$$\begin{cases} C_{9\mu}^V = -C_{10\mu}^V \\ C_9^U \end{cases} \Rightarrow \begin{cases} C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}} + C_{9e}^{\text{NP}} \\ C_{9e}^{\text{NP}} \end{cases}$$

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

AS: Setup

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

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

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

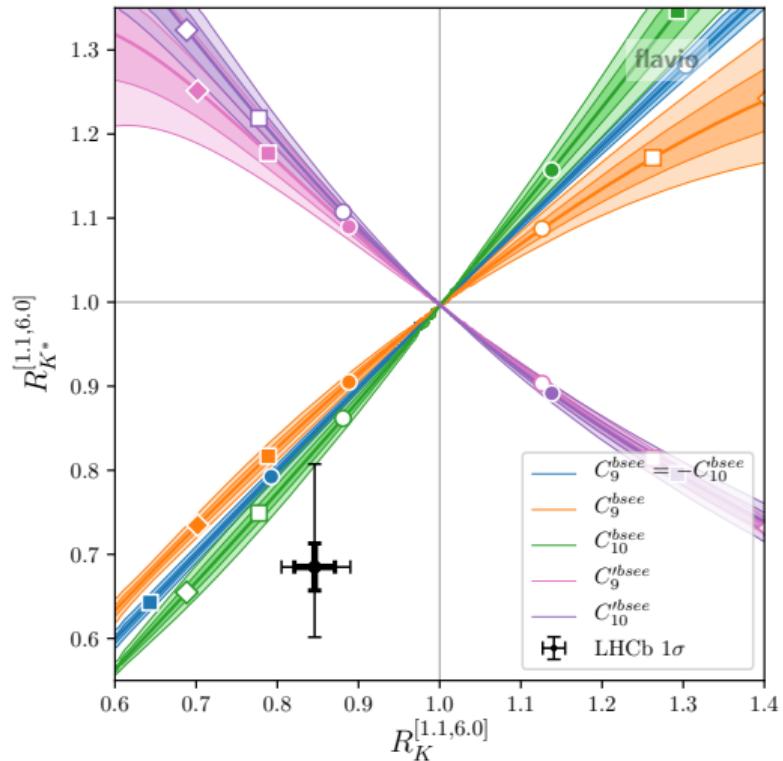
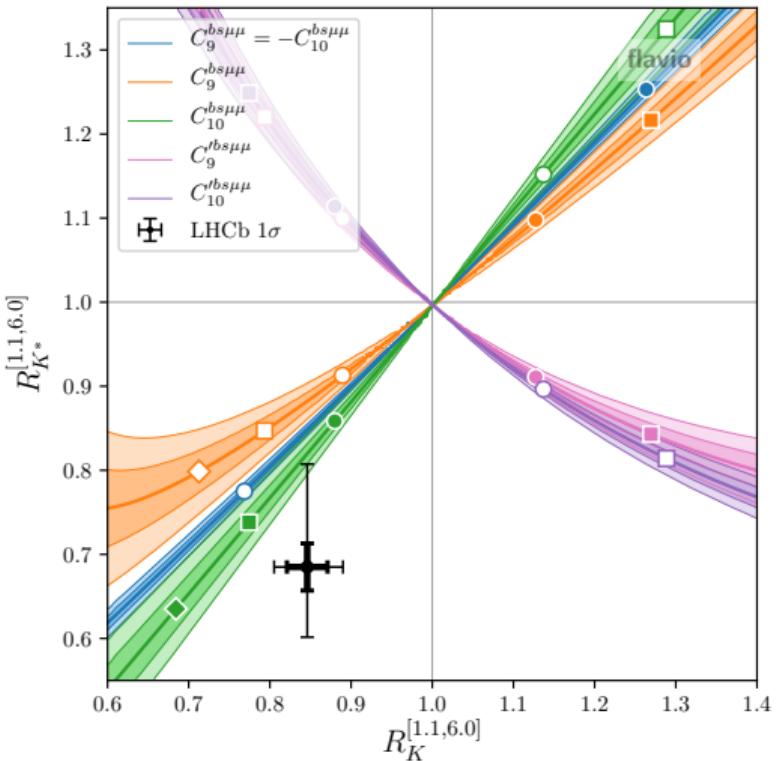
$$\text{pull}_{1\text{D}} = 1\sigma \cdot \sqrt{\Delta\chi^2}, \quad \text{where } \Delta\chi^2 = \chi^2(\vec{0}) - \chi^2(\vec{C}_{\text{best fit}}).$$

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

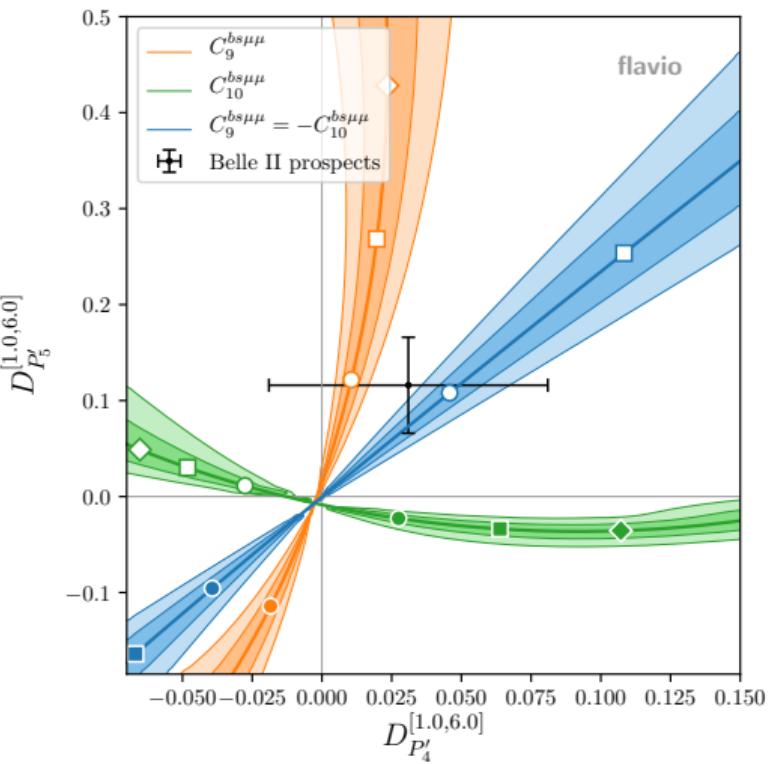
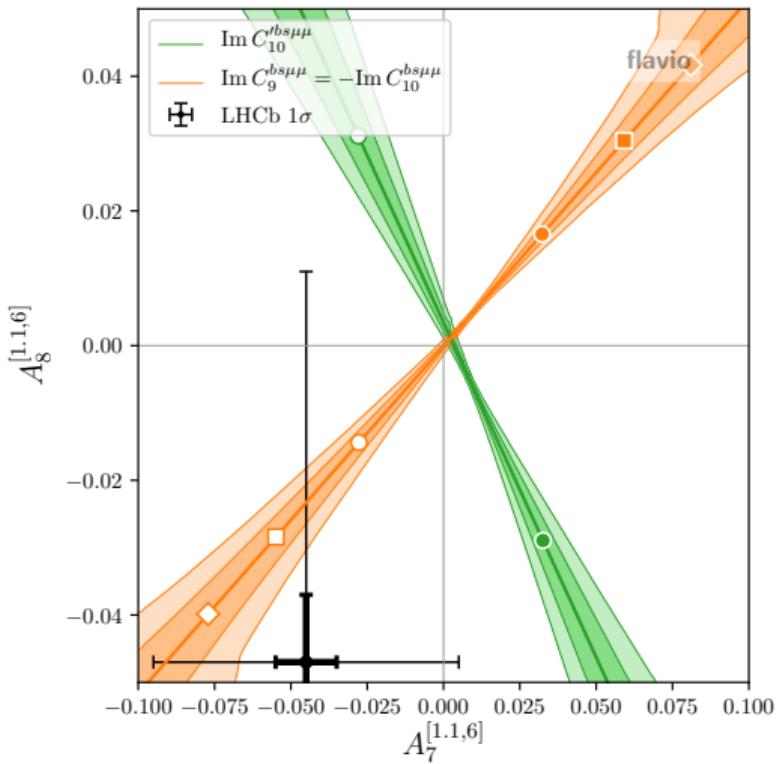
- ▶ New physics scenarios in **Weak Effective Theory (WET)** at scale 4.8 GeV

Altmannshofer, PS, arXiv:2103.13370

AS: Theory uncertainties in presence of NP



AS: Theory uncertainties in presence of NP



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

$$\mathcal{C}_9^{\text{eff}}(q^2) \rightarrow \mathcal{C}_9^{\text{eff}}(q^2) + a_K + b_K(q^2/\text{GeV}^2) \quad \text{at low } q^2,$$

$$\mathcal{C}_9^{\text{eff}}(q^2) \rightarrow \mathcal{C}_9^{\text{eff}}(q^2) + \mathcal{C}_K \quad \text{at high } q^2,$$

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

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 $B \rightarrow K^*$ and $B_s \rightarrow \phi$

$$\begin{aligned}\mathcal{C}_7^{\text{eff}}(q^2) &\rightarrow \mathcal{C}_7^{\text{eff}}(q^2) + a_{0,-} + b_{0,-}(q^2/\text{GeV}^2) && \text{at low } q^2, \\ \mathcal{C}'_7 &\rightarrow \mathcal{C}'_7 + a_+ + b_+(q^2/\text{GeV}^2)\end{aligned}$$

$$\mathcal{C}_9^{\text{eff}}(q^2) \rightarrow \mathcal{C}_9^{\text{eff}}(q^2) + c_\lambda \quad \text{at high } q^2,$$

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

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

CFFPSV: Parameterisation of non-local hadronic matrix elements

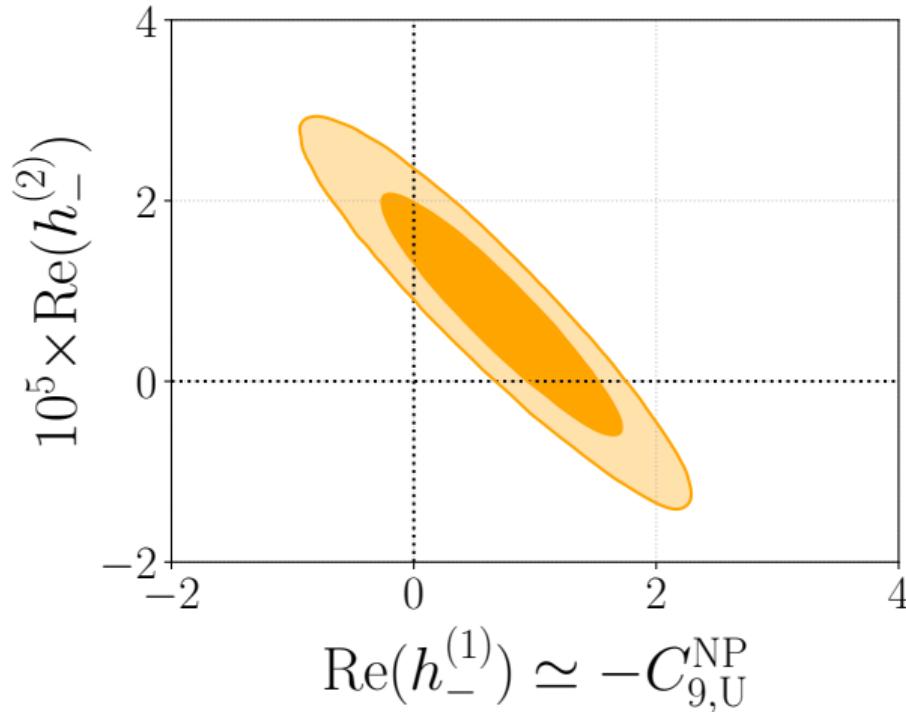
$$H_V^- \propto \left\{ \left(\mathcal{C}_9^{\text{SM}} + h_-^{(1)} \right) \tilde{V}_{L-} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(\mathcal{C}_7^{\text{SM}} + h_-^{(0)} \right) \tilde{T}_{L-} - 16\pi^2 h_-^{(2)} q^4 \right] \right\}$$

$$H_V^+ \propto \left\{ \left(\mathcal{C}_9^{\text{SM}} + h_-^{(1)} \right) \tilde{V}_{L+} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(\mathcal{C}_7^{\text{SM}} + h_-^{(0)} \right) \tilde{T}_{L+} - 16\pi^2 \left(h_+^{(0)} + h_+^{(1)} q^2 + h_+^{(2)} q^4 \right) \right] \right\}$$

$$H_V^0 \propto \left\{ \left(\mathcal{C}_9^{\text{SM}} + h_-^{(1)} \right) \tilde{V}_{L0} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(\mathcal{C}_7^{\text{SM}} + h_-^{(0)} \right) \tilde{T}_{L0} - 16\pi^2 \sqrt{q^2} \left(h_0^{(0)} + h_0^{(1)} q^2 \right) \right] \right\}$$

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

CFFPSV: Parameterisation of non-local hadronic matrix elements



HMMN: New Physics vs hadronic fit (Status 2021)

Non-local matrix element contributions can mimic $\mathcal{C}_9^{\text{NP}}$ since both appear in the vectorial helicity amplitude

$$H_V^\mu \propto \left\{ \mathcal{C}_9^{\text{eff}} \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \mathcal{C}_7^{\text{eff}} \tilde{T}_\lambda(q^2) - 16\pi^2 (\text{LO in QCDF} + h_\lambda(q^2)) \right] \right\}$$

Instead of *guesstimating* $h_\lambda(q^2)$, can be parameterised by a general ansatz: Jäger, Camalich, arXiv:1412.3183

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

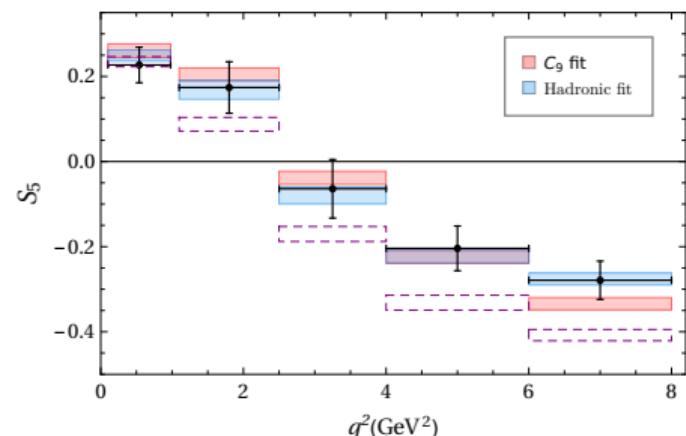
Ciuchini et al., arXiv:1512.07157
Bobanova, Hurth, Mahmoudi, Martinez-Santos, SN, arXiv:1702.02234

NP effect in \mathcal{C}_9 are embedded in the hadronic contributions
 ⇒ Wilks' test can be used to compare separate fits to:

- ▶ Hadronic quantities $h_{+,-,0}^{(0,1,2)}$ (18 parameters)
- ▶ Wilson coefficient $\mathcal{C}_9^{\text{NP}}$ (1 parameter)

$B \rightarrow K^* \gamma/\mu\mu$ observables		
	Real $\mathcal{C}_9^{\text{NP}}$ (1)	Hadronic fit h_λ (18)
Plain SM	6.0σ	4.7σ
Real $\mathcal{C}_9^{\text{NP}}$	–	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

HMMN: New Physics vs hadronic fit (minimal description, Status 2021)

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

A (minimal) description of hadronic contributions with fewer parameters

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

a different $\Delta C_9^{\lambda, \text{PC}}$ 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
$\Delta C_9^{+, \text{PC}}$	$(3.39 \pm 6.44) + i(-14.98 \pm 8.40)$
$\Delta C_9^{-, \text{PC}}$	$(-1.02 \pm 0.22) + i(-0.68 \pm 0.79)$
$\Delta C_9^{0, \text{PC}}$	$(-0.83 \pm 0.53) + i(-0.89 \pm 0.69)$

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

$B \rightarrow K^* \gamma/\mu\mu$ observables		
	Real C_9^{NP} (1)	Hadronic fit $\Delta C_9^{\lambda, \text{PC}}$ (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 (Status 2021)

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

A generic set of Wilson coefficients: $\mathcal{C}_7, \mathcal{C}_8, \mathcal{C}_9^\ell, \mathcal{C}_{10}^\ell, \mathcal{C}_S^\ell, \mathcal{C}_P^\ell + \text{primed coefficients}$

All observables with $\chi^2_{\text{SM}} = 225.8$ $\chi^2_{\text{min}} = 151.6; \text{ Pull}_{\text{SM}} = 5.5(5.6)\sigma$			
$\delta\mathcal{C}_7$ 0.05 ± 0.03		$\delta\mathcal{C}_8$ -0.70 ± 0.40	
$\delta\mathcal{C}'_7$ -0.01 ± 0.02		$\delta\mathcal{C}'_8$ 0.00 ± 0.80	
$\delta\mathcal{C}_9^\mu$ -1.16 ± 0.17	$\delta\mathcal{C}_9^e$ -6.70 ± 1.20	$\delta\mathcal{C}_{10}^\mu$ 0.20 ± 0.21	$\delta\mathcal{C}_{10}^e$ degenerate w/ \mathcal{C}_{10}^e
$\delta\mathcal{C}'_9^\mu$ 0.09 ± 0.34	$\delta\mathcal{C}'_9^e$ 1.90 ± 1.50	$\delta\mathcal{C}'_{10}^\mu$ -0.12 ± 0.20	$\delta\mathcal{C}'_{10}^e$ degenerate w/ \mathcal{C}_{10}^e
$\mathcal{C}_{Q_1}^\mu$ 0.04 ± 0.10	$\mathcal{C}_{Q_1}^e$ -1.50 ± 1.50	$\mathcal{C}_{Q_2}^\mu$ -0.09 ± 0.10	$\mathcal{C}_{Q_2}^e$ -4.10 ± 1.5
$\mathcal{C}'_{Q_1}^\mu$ 0.15 ± 0.10	$\mathcal{C}'_{Q_1}^e$ -1.70 ± 1.20	$\mathcal{C}'_{Q_2}^\mu$ -0.14 ± 0.11	$\mathcal{C}'_{Q_2}^e$ -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 weakly constrained at the moment
- ▶ Effective degree of freedom is (19)
- ▶ **Effective degrees of freedom:** degrees of freedom minus the spurious degrees of freedom from likelihood profiles, correlations and $\mathcal{C}_i^{\text{NP}}$ only weakly affecting the χ^2 such that $|\chi^2(\mathcal{C}_i^{\text{NP}} \neq 0) - \chi^2(\mathcal{C}_i^{\text{NP}} = 0)| \lesssim 1$

HMMN: Comparison of different multi-dimensional global fits (Status 2021)

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	-	-
\mathcal{C}_9^μ	1	168.6	7.6σ	7.6σ
$\mathcal{C}_9^\mu, \mathcal{C}_{10}^\mu$	2	167.5	7.3σ	1.0σ
$\mathcal{C}_7, \mathcal{C}_8, \mathcal{C}_9^{(e,\mu)}, \mathcal{C}_{10}^{(e,\mu)}$	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)

HMMN: Evolution in the $(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$ plane

