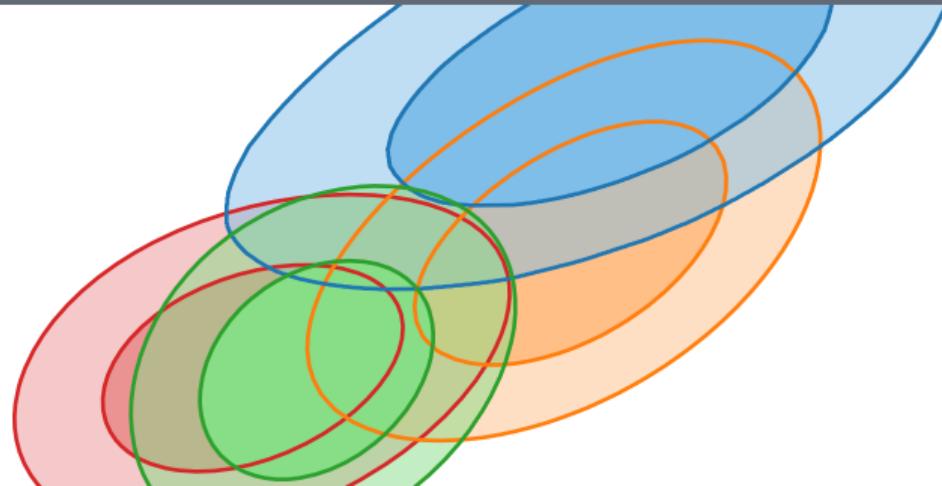
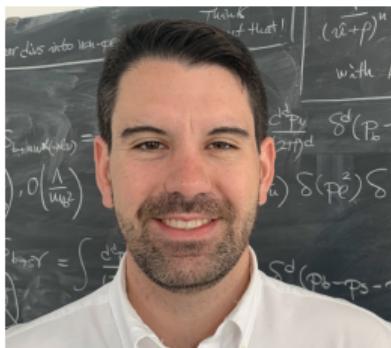


$b \rightarrow s\ell\ell$ fits overview

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





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A huge thanks goes to Danny Van Dyk and Niels Tuning for setting up this project!

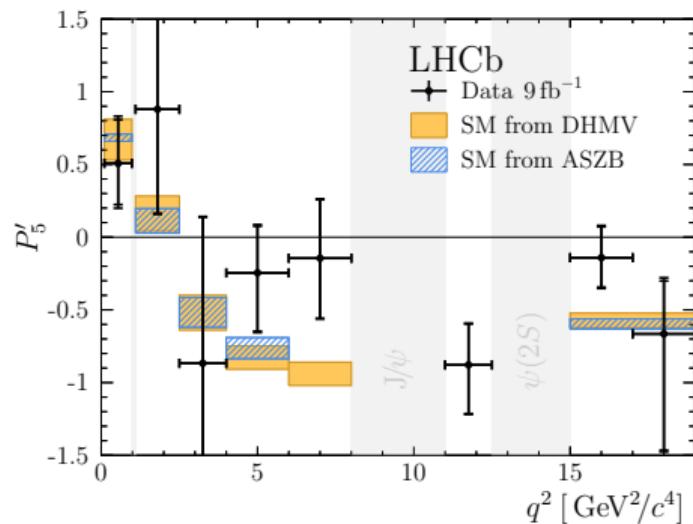
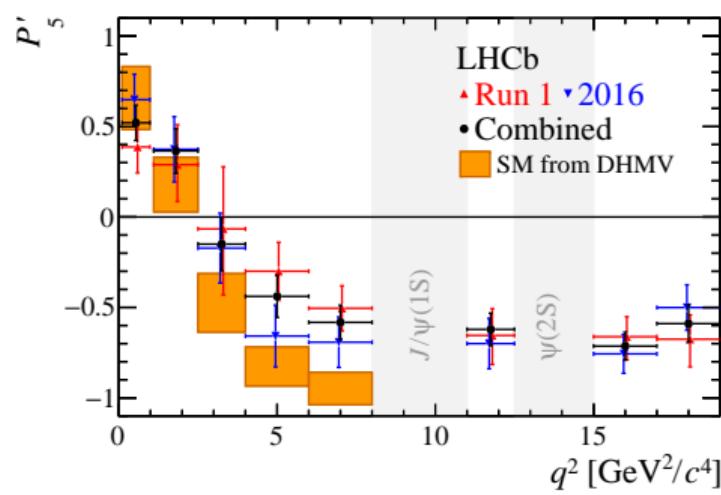
The $b \rightarrow s\ell\ell$ anomalies

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

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

- Angular observables in $B^{(0,+)} \rightarrow K^{*(0,+)} \mu^+ \mu^-$

LHCb, arXiv:2003.04831, arXiv:2012.13241



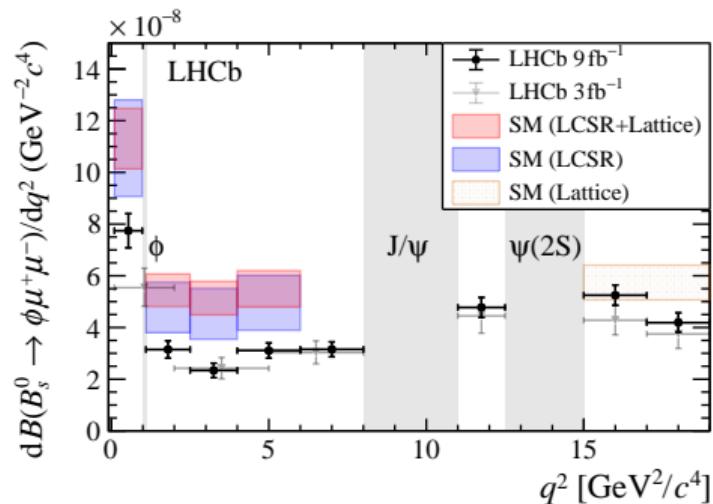
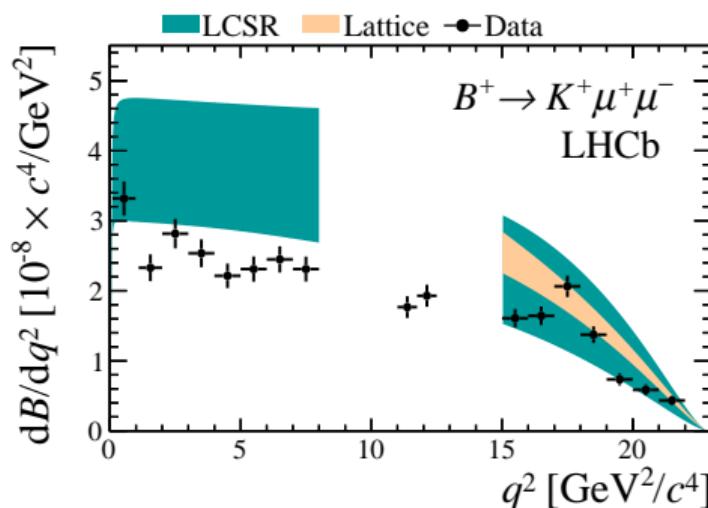
*: based on hadronic assumptions on which there is no theory consensus yet

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

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

- Branching ratios of $B \rightarrow K\mu^+\mu^-$, $B \rightarrow K^*\mu^+\mu^-$, and $B_s \rightarrow \phi\mu^+\mu^-$

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



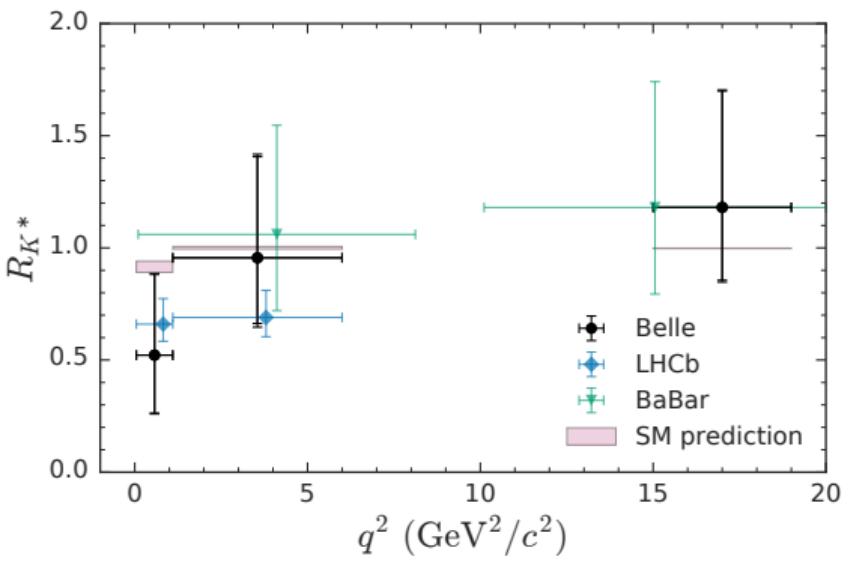
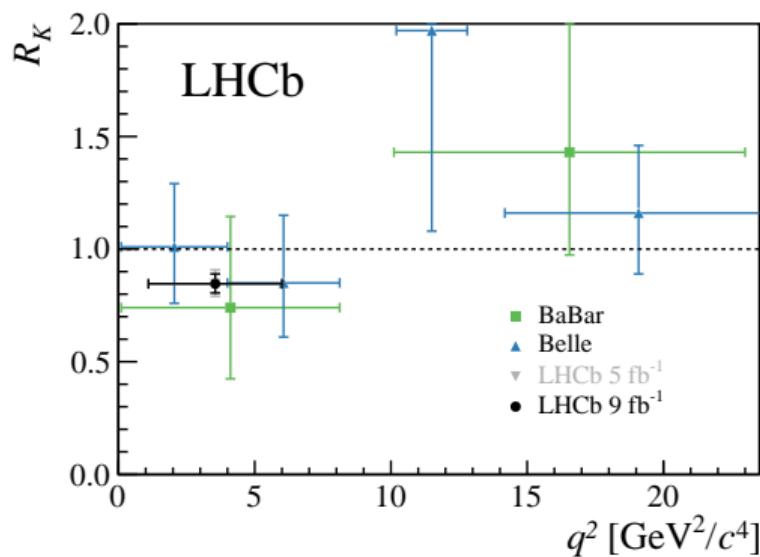
*: based on hadronic assumptions on which there is no theory consensus yet

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

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



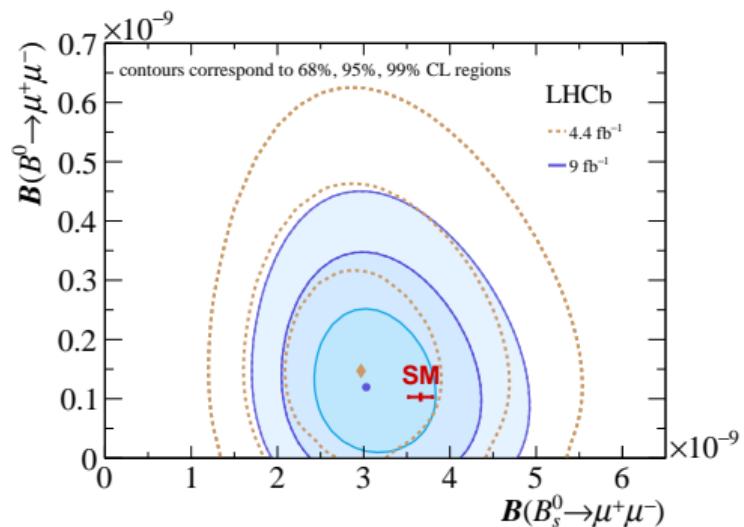
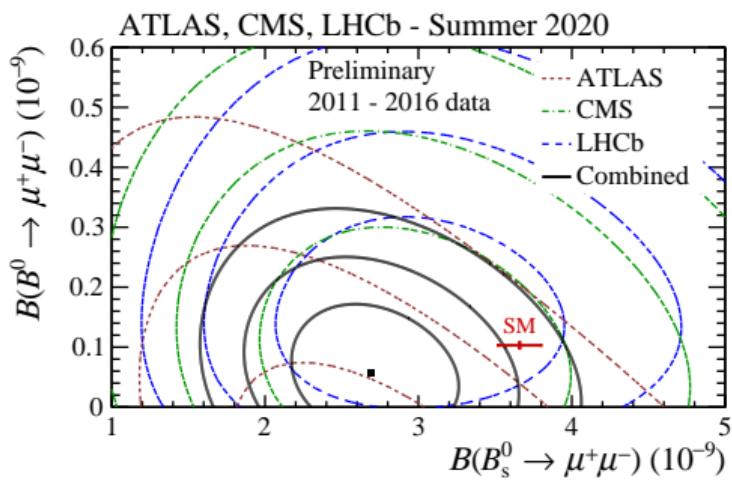
Combination of $B_{s,d} \rightarrow \mu^+ \mu^-$ measurements

Measurements of $\mathcal{B}(B_{s,d} \rightarrow \mu^+ \mu^-)$ 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 $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)/\Delta M_s$

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

$$\mathcal{H}_{\text{eff, sl}} = -\mathcal{N} \left(C_7 O_7 + C'_7 O'_7 + \sum_{\ell} \sum_{i=9,10,P,S} \left(C_i^\ell O_i^\ell + C'_i O'_i \right) \right) + \text{h.c.}$$

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

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

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:**

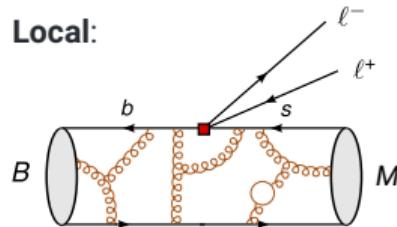
$$\mathcal{H}_{\text{eff, had}} = -\mathcal{N} \frac{16\pi^2}{e^2} \left(C_8 O_8 + C'_8 O'_8 + \sum_{i=1,\dots,6} C_i O_i \right) + \text{h.c.}$$

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 ($M = K, K^*, \phi$)

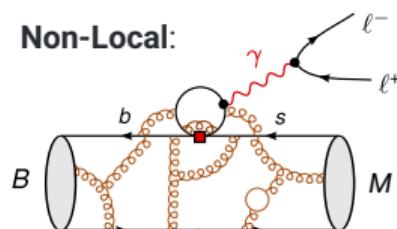
$$\mathcal{M}(B \rightarrow M\ell\ell) = \langle M\ell\ell | \mathcal{H}_{\text{eff}} | B \rangle = \mathcal{N} \left[(\mathcal{A}_V^\mu + \mathcal{H}^\mu) \bar{u}_\ell \gamma_\mu v_\ell + \mathcal{A}_A^\mu \bar{u}_\ell \gamma_\mu \gamma_5 v_\ell + \mathcal{A}_S \bar{u}_\ell v_\ell + \mathcal{A}_P \bar{u}_\ell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

Local:



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

Non-Local:



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

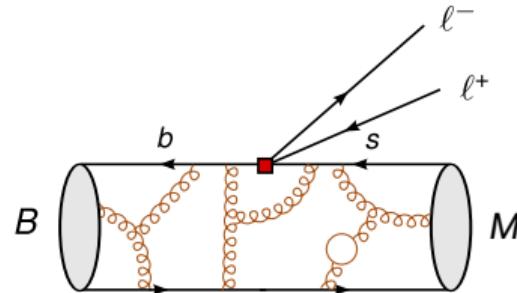
► **Wilson coefficients** $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$:

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



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

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

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

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

HPQCD, arXiv:1306.2384

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

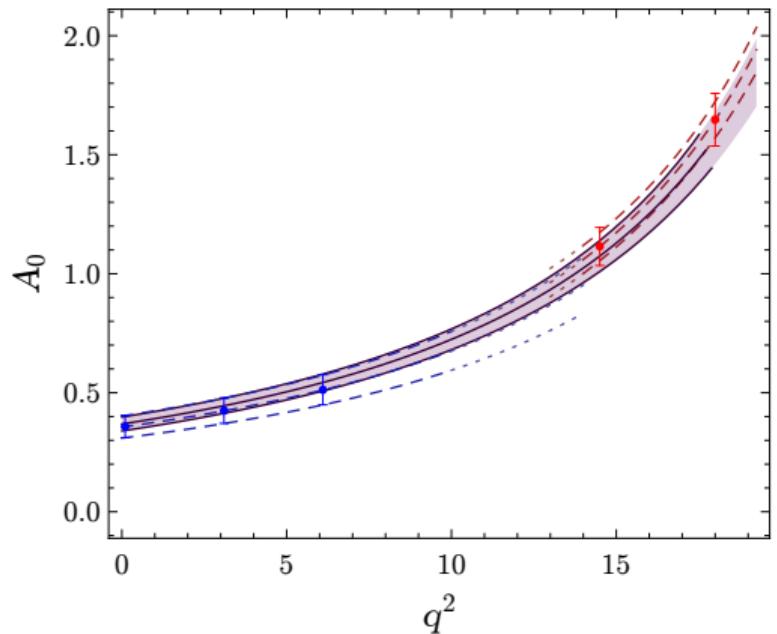
Gubernari, Kokulu, van Dyk, arXiv:1811.00983

Altmannshofer, Straub, arXiv:1411.3161

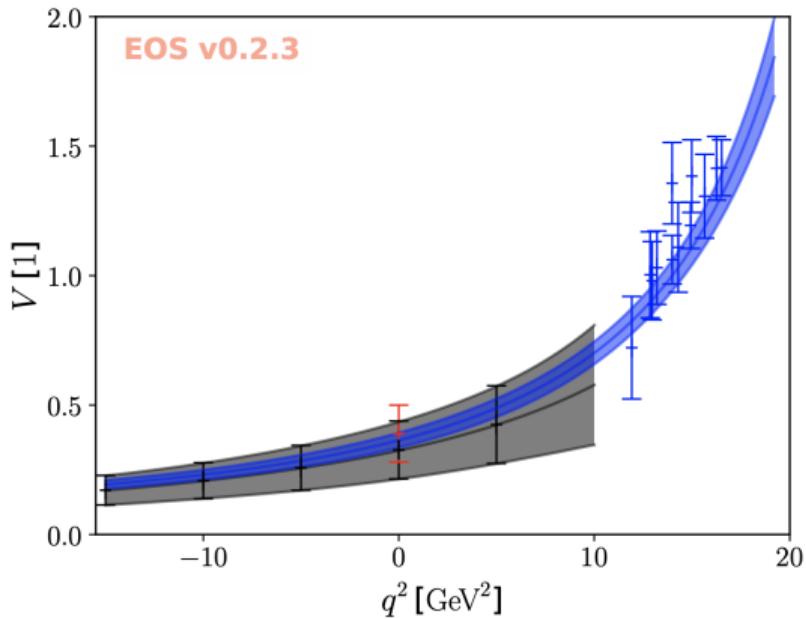
Bharucha, Straub, Zwicky, arXiv:1503.05534

Gubernari, Kokulu, van Dyk, arXiv:1811.00983

Form factors

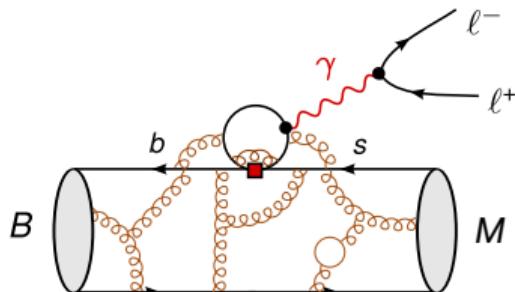


Bharucha, Straub, Zwicky, arXiv:1503.05534



Gubernari, Kokulu, van Dyk, arXiv:1811.00983

Non-local matrix elements



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

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

- ▶ Contributions at low q^2 from QCDF
- ▶ **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
 - ▶ direct fit to angular data
 - ▶ Light-Cone Sum Rules estimates
 - ▶ analyticity + experimental data on $b \rightarrow s c \bar{c}$

Beneke, Feldmann, Seidel, arXiv:hep-ph/0106067

Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921

Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli, arXiv:1512.07157

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

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:

- ▶ **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:2110.10126
- ▶ **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:

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
 - ▶ $B \rightarrow K^* \gamma (\mathcal{B}, S_{K^* \gamma}, A_I)$
 - ▶ $B^{(0,+)} \rightarrow K^{(0,+)} \ell^+ \ell^- (\mathcal{B}_\mu, R_K, \text{angular observables})$
 - ▶ $B^{(0,+)} \rightarrow K^{*(0,+)} \ell^+ \ell^- (\mathcal{B}_\mu, R_{K^{*0}}, \text{angular observables})$
 - ▶ $B_s \rightarrow \phi \mu^+ \mu^- (\mathcal{B}, \text{angular observables})$
 - ▶ $\Lambda_b \rightarrow \Lambda \mu^+ \mu^- (\mathcal{B}, \text{angular observables})$
- ▶ Fits might include $150 \sim 250$ observables ⇒ **global** $b \rightarrow s\ell\ell$ analyses

Comparison between the groups

- ▶ 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 $q^2 \leq 1 \text{ GeV}^2$ while allowing them to freely grow for larger q^2 (**CFFPSV**)
- ▶ Different experimental inputs, e.g.
 - ▶ $q^2 \in [6, 8] \text{ GeV}^2$ data (**ACDMN**, **CFFPSV**, **HMMN**)
 - ▶ High- q^2 data (**AS**, **ACDMN**, **HMMN**)
 - ▶ Radiative decays (**ACDMN**, **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 (**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 statistical frameworks

New physics interpretation

p-value SM fit

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

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

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**

Global fit : $n_{dof} = 246 \Rightarrow p\text{-value} = 1.1\%$

*LFU fit** : $n_{dof} = 22 \Rightarrow p\text{-value} = 1.4\%$

► **AS**

Global fit : $n_{dof} = 191 \Rightarrow p\text{-value} = 1.2\%$

*LFU fit** : $n_{dof} = 21 \Rightarrow p\text{-value} = 0.5\%$

► **HMMN**

Global fit : $n_{dof} = 173 \Rightarrow p\text{-value} = 0.4\%$

*LFU fit** : $n_{dof} = 7 \Rightarrow p\text{-value} = 0.02\%$

*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)

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 $B_s \rightarrow \mu\mu$, LFU observables

Wilson coefficients not considered in the following:

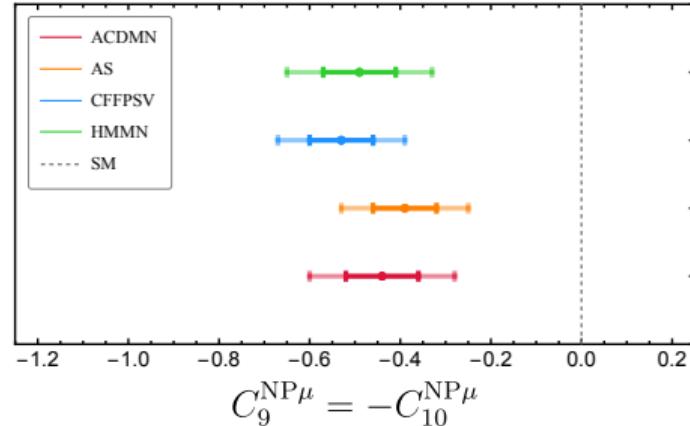
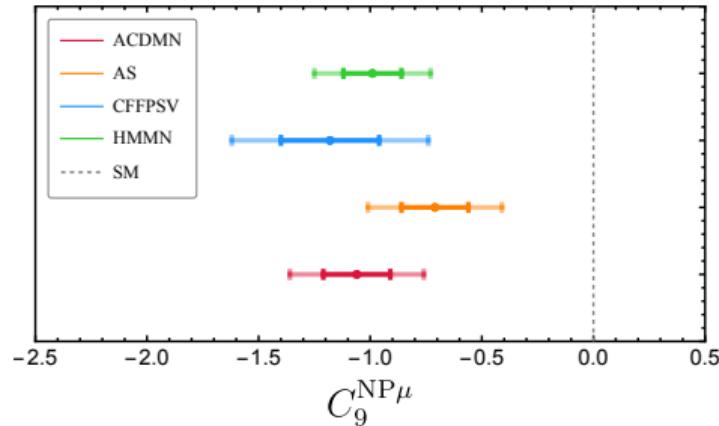
- ▶ $C_7^{(\prime)}$: strongly constrained by radiative decays and very low- q^2 bin of $B \rightarrow K^* e^+ e^-$
- ▶ C_i^e : current data does not indicate NP in electron coefficients, but not enough data to be conclusive
- ▶ $C'_{9,10}$: dominant contribution from coefficients with right-handed quarks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

Subsequent slides about highly preferred NP scenarios for each group, "not combined"

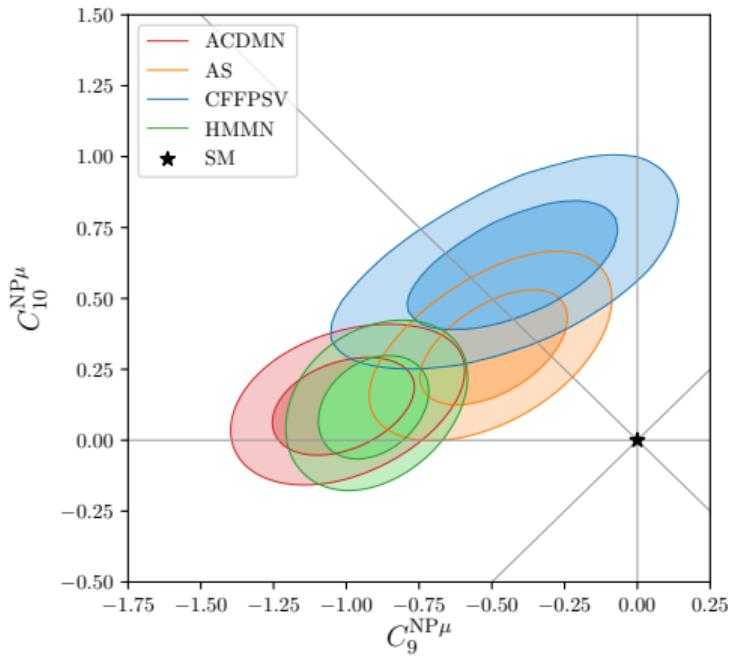
1-dimensional global fits



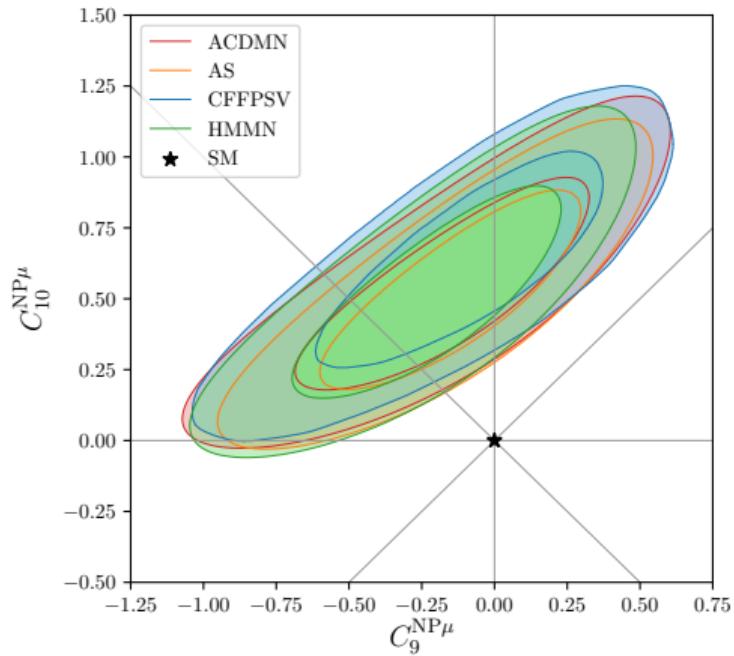
- ▶ NP scenarios preferred over SM with $\text{Pull}_{\text{SM}}^* > 5\sigma$
- ▶ Different results due to different assumptions about non-local matrix elements, different choices of form factors and observables, etc.
- ▶ Remarkable agreement between fits of different groups despite different approaches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

*: $\text{Pull}_{\text{SM}} \neq$ 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 + $B_s \rightarrow \mu\mu$

ACDMN: 1D NP fits

1D Hyp.	Global			
	bfp	1σ	Pull _{SM}	p-value (%)
$C_{9\mu}^{\text{NP}}$	-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				
1D Hyp.	bfp	1σ	Pull _{SM}	p-value (%)
$C_{9\mu}^{\text{NP}}$	-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

- ⇒ $C_{9\mu}^{\text{NP}}$ is the strongest signal for the Global fit. $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$ dominates the "LFUV fit".
- ⇒ $C_{10\mu}^{\text{NP}}$ solution with a significance of $\sim 4\sigma$.

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

ACDMN: 2D NP fits

2D Hyp.	Global		LFUV	
	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
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{7'}^{\text{NP}})$	(-1.06, +0.00)	6.7	(-0.82, -0.03)	3.7
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu}^{\text{NP}})$	(-1.22, +0.56)	7.2	(-1.80, +1.12)	4.1
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu}^{\text{NP}})$	(-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

- ⇒ Hyp. 1: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}} = \mathcal{C}_{10'\mu}^{\text{NP}})$, Hyp. 2: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}} = -\mathcal{C}_{10'\mu}^{\text{NP}})$, Hyp. 3: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu}^{\text{NP}} = \mathcal{C}_{10'\mu}^{\text{NP}})$, Hyp. 4: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu}^{\text{NP}} = -\mathcal{C}_{10'\mu}^{\text{NP}})$ and Hyp. 5: $(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu}^{\text{NP}} = -\mathcal{C}_{10'\mu}^{\text{NP}})$
- ⇒ High significances for NP solutions with $\mathcal{C}_{9\mu}^{\text{NP}}$ or $\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}} + \text{RHC}$

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

ACDMN: LFU NP Fits

Scenario	Best-fit point	1σ	Pull _{SM}
$\mathcal{C}_{9\mu}^V = -\mathcal{C}_{10\mu}^V$ $\mathcal{C}_9^U = \mathcal{C}_{10}^U$	-0.52 -0.41	[-0.60, -0.44] [-0.54, -0.28]	6.8
$\mathcal{C}_{9\mu}^V$ \mathcal{C}_9^U	-0.76 -0.39	[-1.00, -0.52] [-0.68, -0.09]	6.9
$\mathcal{C}_{9\mu}^V = -\mathcal{C}_{10\mu}^V$ \mathcal{C}_9^U	-0.30 -0.92	[-0.39, -0.21] [-1.10, -0.72]	7.3
$\mathcal{C}_{9\mu}^V = -\mathcal{C}_{10\mu}^V$ \mathcal{C}_{10}^U	-0.51 -0.27	[-0.64, -0.39] [-0.49, -0.05]	6.0
$\mathcal{C}_{9\mu}^V$ \mathcal{C}_{10}^U	-1.02 +0.27	[-1.18, -0.85] [+0.11, +0.44]	6.9
$\mathcal{C}_{9\mu}^V$ $\mathcal{C}_{10'}^U$	-1.12 -0.31	[-1.28, -0.95] [-0.46, -0.15]	7.1

→ Left-handed structure $\mathcal{C}_{9\mu}^V = -\mathcal{C}_{10\mu}^V$ preferred over the vector structure $\mathcal{C}_{9\mu}^V$, in the presence of LFU NP in \mathcal{C}_9^U

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

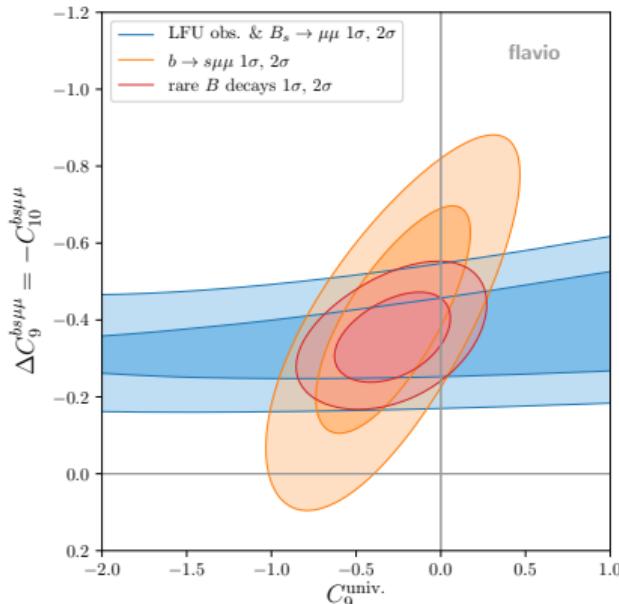
AS: Scenarios with a single Wilson coefficients

Wilson coefficient	$b \rightarrow s\mu\mu$		LFU, $B_s \rightarrow \mu\mu$		all rare B decays	
	best fit	pull	best fit	pull	best fit	pull
$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	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
$C_9'^{bs\mu\mu}$	$+0.15^{+0.24}_{-0.24}$	0.6σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.19^{+0.13}_{-0.13}$	1.5σ
$C_{10}'^{bs\mu\mu}$	$-0.09^{+0.15}_{-0.15}$	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
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.55^{+0.13}_{-0.13}$	3.8σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.39^{+0.07}_{-0.07}$	5.6σ
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
$C_9'^{bsee}$			$+0.36^{+0.18}_{-0.17}$	2.1σ	$+0.40^{+0.19}_{-0.18}$	2.3σ
$C_{10}'^{bsee}$			$-0.32^{+0.16}_{-0.16}$	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: Scenario with two Wilson coefficients

- **New 2021 data:**

smaller uncertainty, better agreement between R_K & R_{K^*} and $B_s \rightarrow \mu\mu$, 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 $\Delta C_9^{\text{bs}\mu\mu} = -C_{10}^{\text{bs}\mu\mu}$:

$$C_9^{\text{bsee}} = C_9^{\text{bs}\tau\tau} = C_9^{\text{univ.}}$$

$$C_9^{\text{bs}\mu\mu} = C_9^{\text{univ.}} + \Delta C_9^{\text{bs}\mu\mu}$$

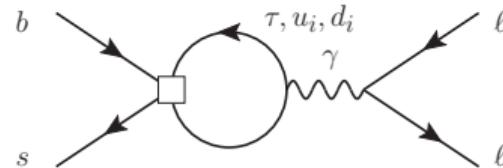
$$C_{10}^{\text{bsee}} = C_{10}^{\text{bs}\tau\tau} = 0$$

$$C_{10}^{\text{bs}\mu\mu} = -\Delta C_9^{\text{bs}\mu\mu}$$

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

CFFPSV: Collection of relevant global fit results

NP scenario	68.27% HPDI	ΔIC
A: C_9^{NP}	$[-1.44, -1.01]$	43
B: C_{2223}^{LQ}	$[0.67, 0.88]$	60
C: C_{10}^{NP}	$[0.66, 0.90]$	54
D: $\{C_{2223}^{LQ}, C_{2322}^{Qe}\}$	$\{[0.61, 0.86], [-0.37, 0.11]\}$	57
D: $\{C_9^{\text{NP}}, C_{10}^{\text{NP}}\}$	$\{[-0.67, -0.20], [0.47, 0.76]\}$	57
E: $\{C_{2223}^{LQ}, C_{2322}^{Qe}, C_{2223}^{Ld}, C_{2223}^{ed}\}$	$\{[0.83, 1.32], [-0.05, 0.76], [-0.59, -0.10], [-0.58, 0.27]\}$	54
E: $\{C_9^{\text{NP}}, C_{10}^{\text{NP}}, C_9^{\prime,\text{NP}}, C_{10}^{\prime,\text{NP}}\}$	$\{[-1.45, -0.59], [0.29, 0.70], [-0.06, 0.82], [-0.37, 0.08]\}$	54

- 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
- Scenarios above might be interpreted having a C_9^U component too, since one of the hadronic parameters employed has the same quantum numbers

HMMN: Multi-dimensional global fit

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

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

All observables with $\chi^2_{\text{SM}} = 225.8$			
$\chi^2_{\text{min}} = 151.6; \text{ Pull}_{\text{SM}} = 5.5(5.6)\sigma$			
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	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	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 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 C_i^{NP} only weakly affecting the χ^2 such that $|\chi^2(C_i^{\text{NP}} \neq 0) - \chi^2(C_i^{\text{NP}} = 0)| \lesssim 1$

Conclusions

- ▶ Discrepancies in numerous $b \rightarrow s\ell\ell$ observables can be **consistently explained by NP**
- ▶ Fits show preference for NP contributions to C_9^μ and/or C_{10}^μ
- ▶ 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
⇒ experimental observation of discrepancy in these observables would be **clear sign of NP**

Wishlist

- ▶ Global fit based on improved parameterisation of non-local matrix elements
Gubernari, Reboud, van Dyk, Virto, in preparation
- ▶ 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**

Backup slides

ACDMN: Improved QCDF

Improved QCDF (iQCDF) approach: $m_b \rightarrow \infty$ and $E_{V,P} \rightarrow \infty$ ($V = K^*, \phi, P = K$) 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

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

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

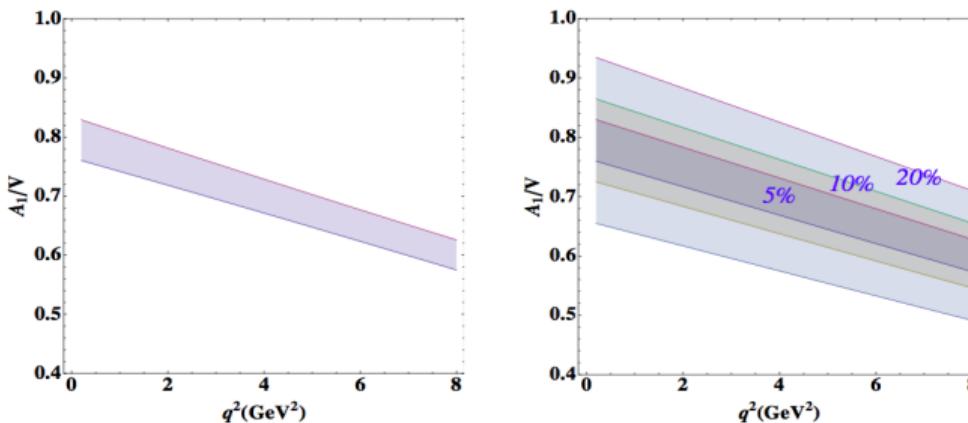
► $\mathcal{O}(\Lambda/m_b)$ corrections ⇒ $\Delta F^\Lambda(q^2) = a_F + b_F \frac{q^2}{m_B^2} + c_F \frac{q^4}{m_B^4}$

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

Λ CDMN: 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
 $\Delta a_F, \Delta b_F, \Delta c_F = \mathcal{O}(\Lambda/m_b) \times F$
- ▶ Is this a conservative estimation of errors?

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



⇒ 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 :

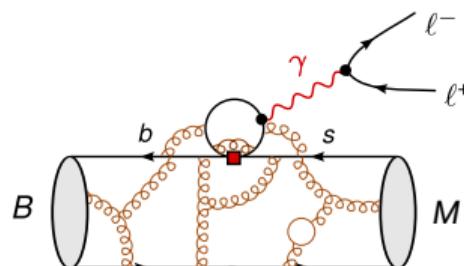
⇒ Calculations based on continuum methods

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

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

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



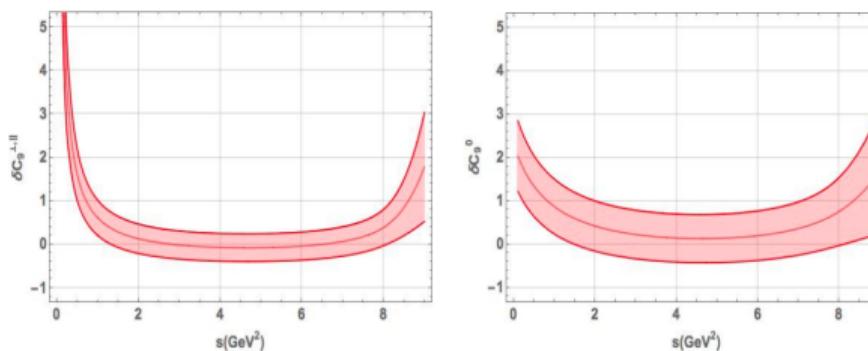
Λ CDMN: Estimating beyond QCDF contribution at low- q^2

- 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

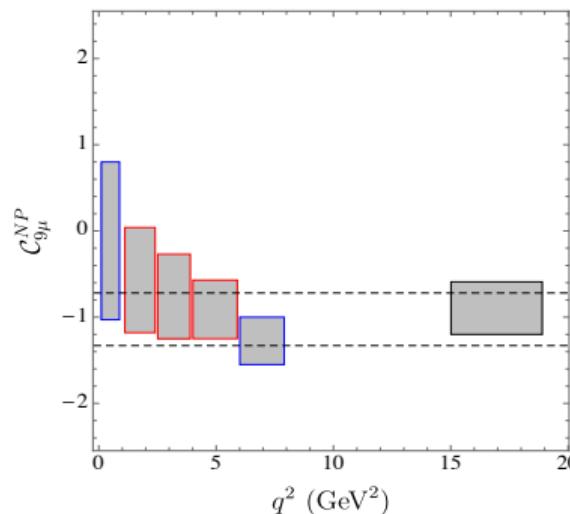


Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
Descotes-Genon, Hofer, Matias, Virto; arxiv:1407.8526
Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239

Λ CDMN: 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 (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,

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

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

ACDMN: Statistical framework

- ▶ Fit procedure:
 - ⇒ **Best fit points** (bfp): $\chi^2(C_i^{\text{NP}}) \rightarrow \chi_{\min}^2 = \chi^2(C_{\text{NP}})$
 - ⇒ **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: $R_K, R_{K^*}, P'_{4,5}^{e\mu}(B \rightarrow K^* \ell\ell)$ 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

ACDMN: Are we overlooking LFU NP?

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

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

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

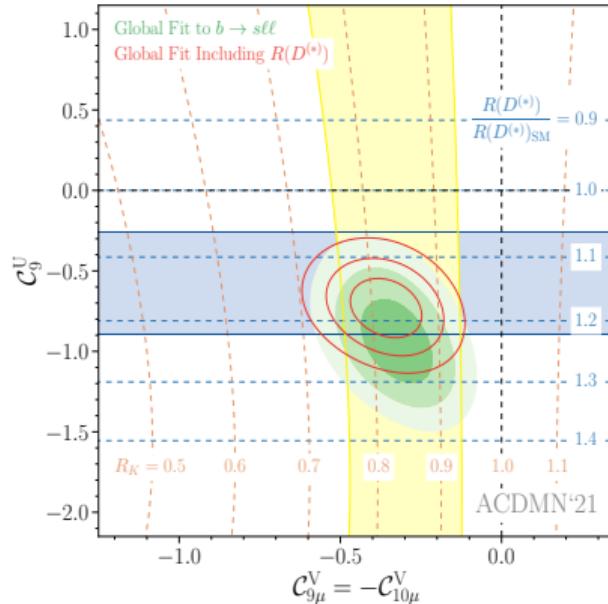
$$\begin{cases} C_{9\mu}^V = -C_{10\mu}^V \\ C_9^U \end{cases} \Rightarrow \begin{cases} C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}} + C_{9e}^{\text{NP}} \\ C_{9e}^{\text{NP}} \end{cases}$$

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

Λ CDMN: Model independent connection $b \rightarrow s\mu\mu$ & $b \rightarrow c\tau\nu$ (with LFU-NP)

- NP scenario ($\mathcal{C}_{9\mu}^V = -\mathcal{C}_{10\mu}^V, \mathcal{C}_9^U$) 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



⇒ Pull_{SM} = 8.1 σ .

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

AS: Setup

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

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

- ▶ **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

Altmannshofer, PS, arXiv:2103.13370

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

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

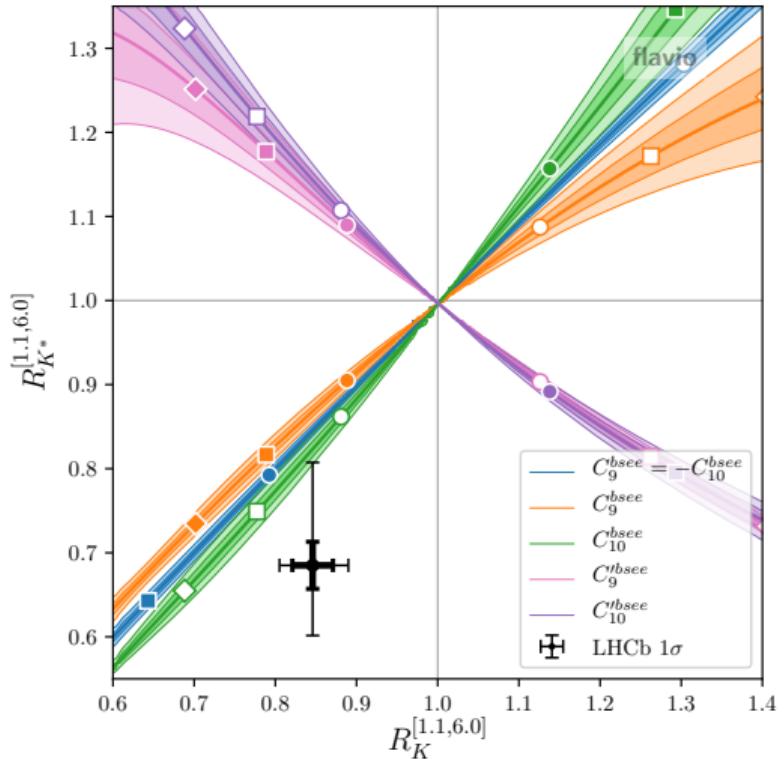
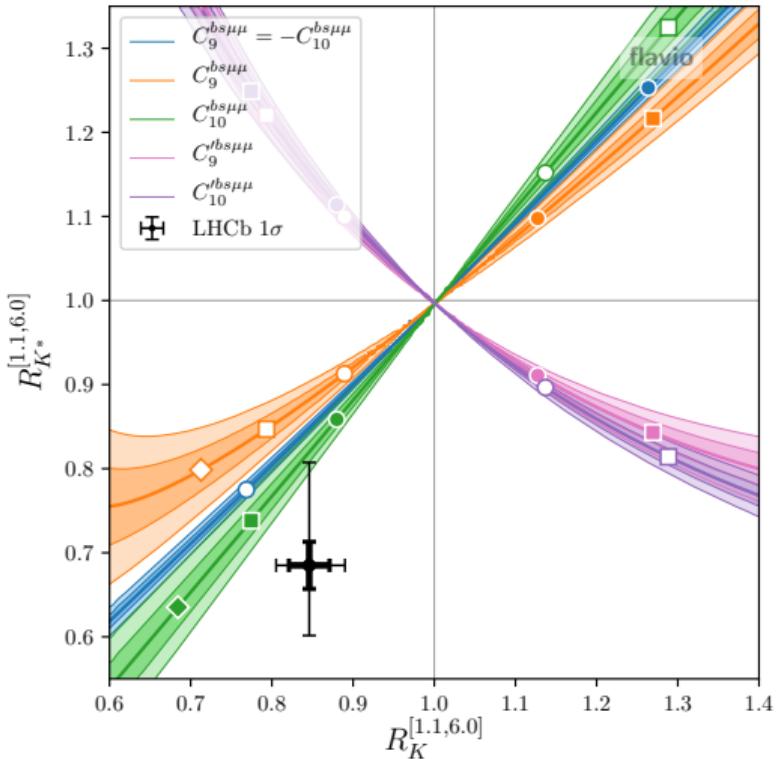
- ▶ New physics scenarios in **Weak Effective Theory (WET)** at scale 4.8 GeV

AS: Scenarios with a single Wilson coefficients

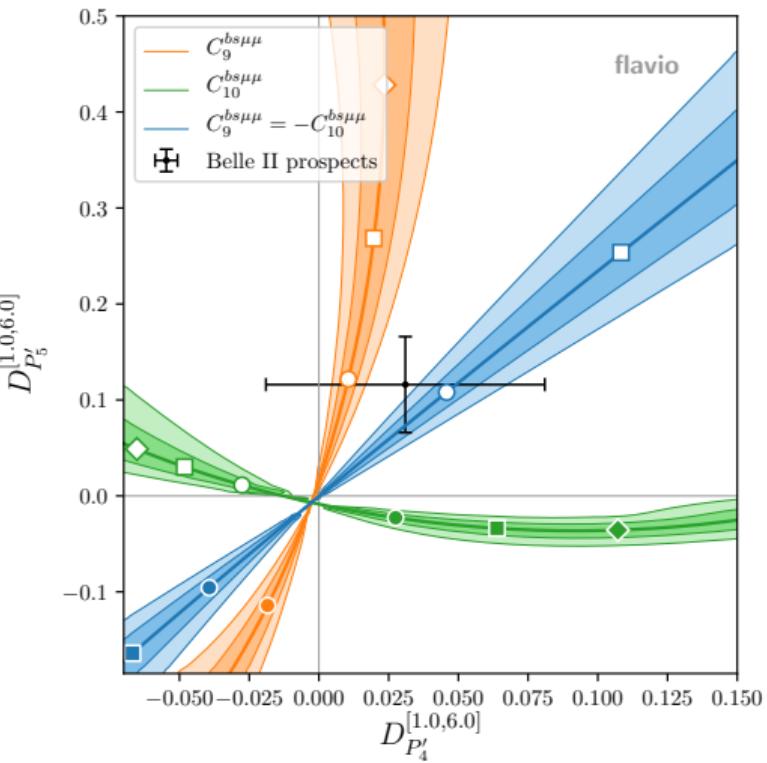
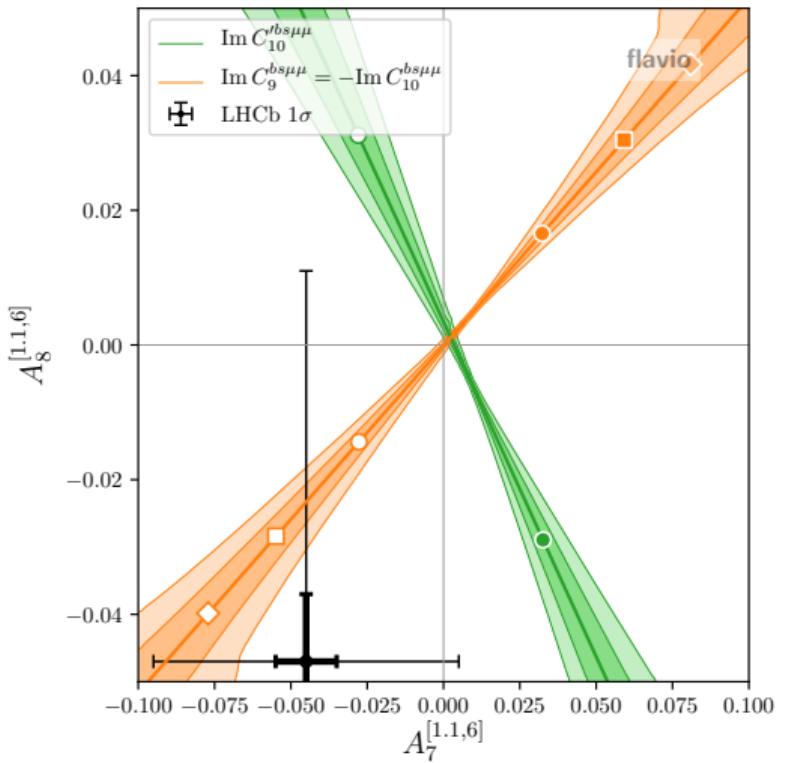
	Wilson coefficient	$b \rightarrow s\mu\mu$ best fit	pull	LFU, $B_s \rightarrow \mu\mu$ best fit	pull	all rare B decays best fit	pull
NP err.	$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	3.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	5.1σ
	$C_{10}^{bs\mu\mu}$	$+0.45^{+0.22}_{-0.23}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	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: Parameterisation of beyond-QCDF contributions for $B \rightarrow K$

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

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

$$\text{Re}(a_K) = 0.0 \pm 0.08,$$

$$\text{Im}(a_K) = 0.0 \pm 0.08,$$

$$\text{Re}(b_K) = 0.0 \pm 0.03,$$

$$\text{Im}(b_K) = 0.0 \pm 0.03,$$

$$\text{Re}(c_K) = 0.0 \pm 0.2,$$

$$\text{Im}(c_K) = 0.0 \pm 0.2.$$

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

$$\begin{aligned} C_7^{\text{eff}}(q^2) &\rightarrow C_7^{\text{eff}}(q^2) + a_{0,-} + b_{0,-}(q^2/\text{GeV}^2) && \text{at low } q^2, \\ C'_7 &\rightarrow C'_7 + a_+ + b_+(q^2/\text{GeV}^2) \end{aligned}$$

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

$$\text{Re}(a_+) = 0.0 \pm 0.004, \quad \text{Re}(b_+) = 0.0 \pm 0.005, \quad \text{Re}(c_+) = 0.0 \pm 0.3,$$

$$\text{Im}(a_+) = 0.0 \pm 0.004, \quad \text{Im}(b_+) = 0.0 \pm 0.005, \quad \text{Im}(c_+) = 0.0 \pm 0.3,$$

$$\text{Re}(a_-) = 0.0 \pm 0.015, \quad \text{Re}(b_-) = 0.0 \pm 0.01, \quad \text{Re}(c_-) = 0.0 \pm 0.3,$$

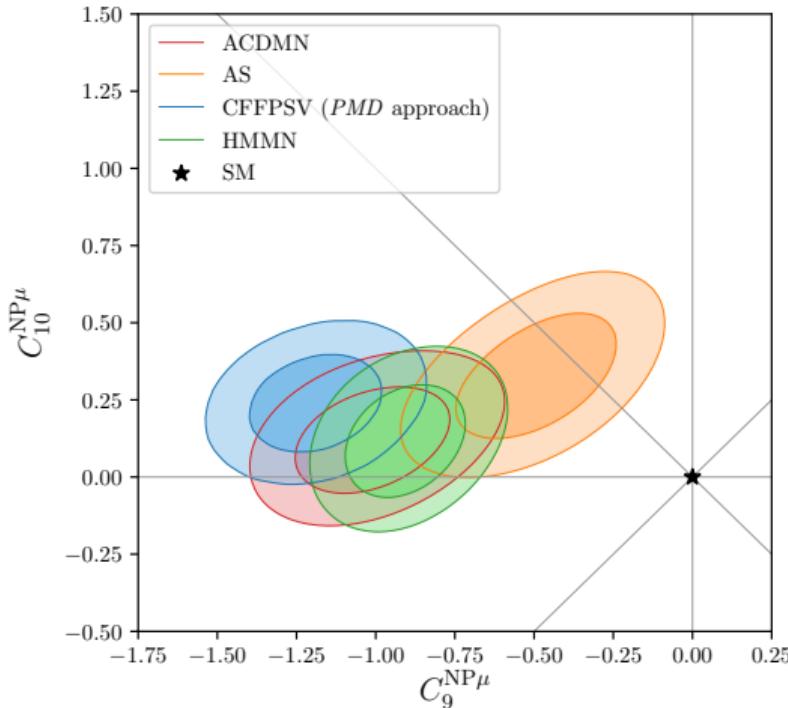
$$\text{Im}(a_-) = 0.0 \pm 0.015, \quad \text{Im}(b_-) = 0.0 \pm 0.01, \quad \text{Im}(c_-) = 0.0 \pm 0.3,$$

$$\text{Re}(a_0) = 0.0 \pm 0.12, \quad \text{Re}(b_0) = 0.0 \pm 0.05, \quad \text{Re}(c_0) = 0.0 \pm 0.3,$$

$$\text{Im}(a_0) = 0.0 \pm 0.12, \quad \text{Im}(b_0) = 0.0 \pm 0.05, \quad \text{Im}(c_0) = 0.0 \pm 0.3.$$

1 σ 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

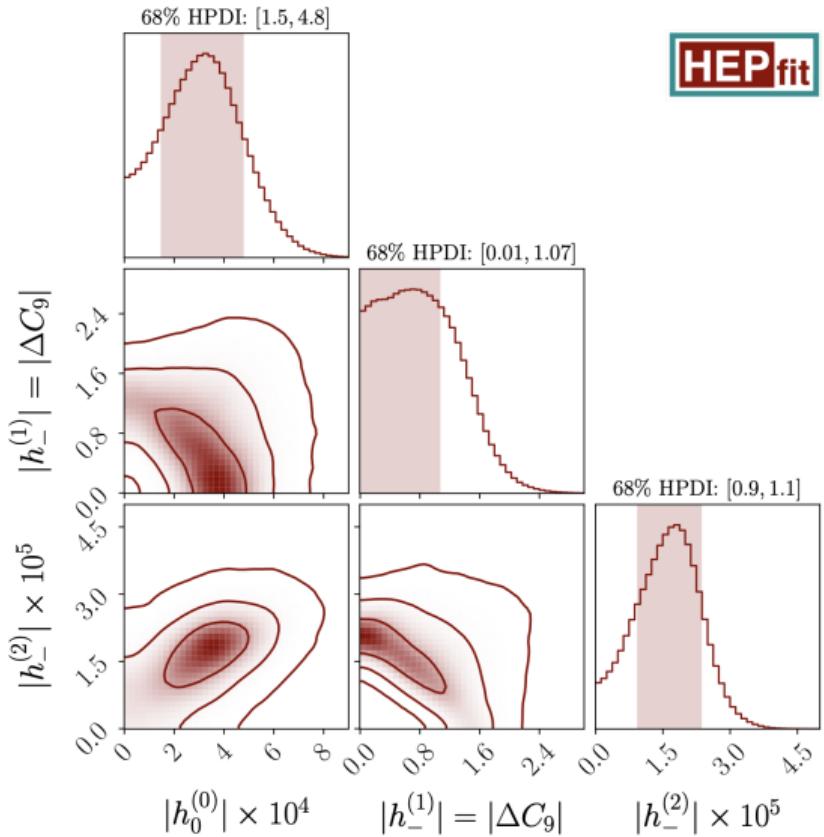
$$H_V^- \propto \left\{ \left(C_9^{\text{SM}} + h_-^{(1)} \right) \tilde{V}_{L-} + \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(C_7^{\text{SM}} + h_-^{(0)} \right) \tilde{T}_{L-} - 16\pi^2 h_-^{(2)} q^4 \right] \right\}$$

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

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

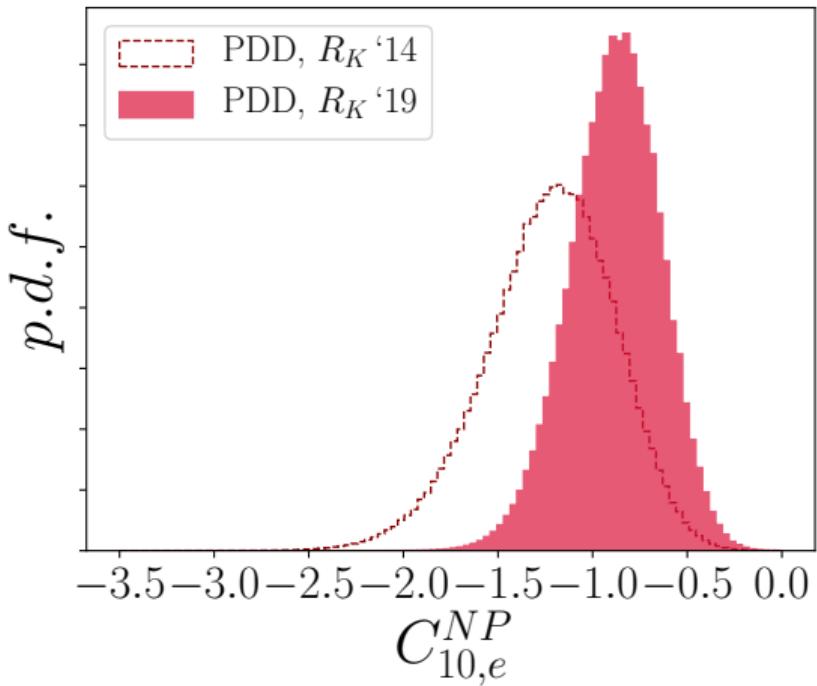
- ▶ $h_-^{(0)}$ and $h_-^{(1)}$ can be considered as constant shifts to the WCs $C_{7,9}^{\text{SM}}$, hence indistinguishable from universal NP contributions to $O_{7,9}$
- ▶ remaining parameters describing purely hadronic contributions

CFFPSV: Inference of non-local hadronic parameters



- obtained by a SM fit to $b \rightarrow s\mu\mu$ 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^{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 $b \rightarrow s\mu\mu$ 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

HMMN: New Physics vs hadronic fit

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

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

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

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

Jäger, Camalich, arXiv:1412.3183
Ciuchini et al., arXiv:1512.07157

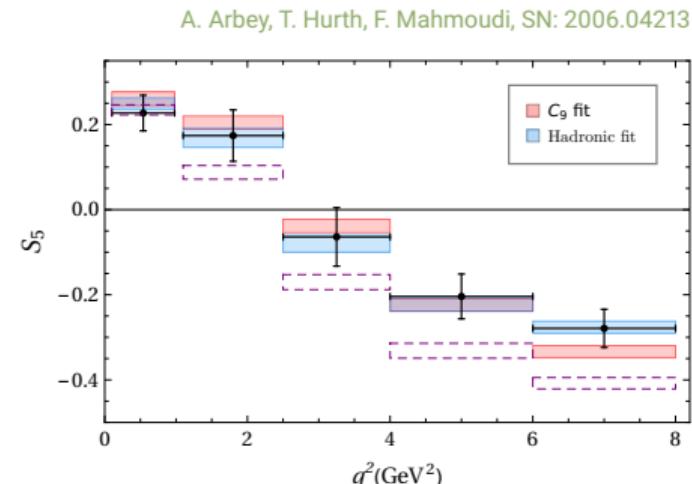
Chobanova, Hurth, Mahmoudi, Martinez-Santos, SN, arXiv:1702.02234

NP effect in C_9 are embedded in the hadronic contributions

⇒ Wilks' test can be used to compare separate fits to:

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

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



- 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

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

a different $\Delta C_9^{\lambda, \text{PC}}$ for each helicity $\lambda = +, -, 0$
→ 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
⇒ 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

⇒ Strong indication that the NP interpretation is a valid option, although the situation remains inconclusive

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)