Status and prospects of semileptonic $b \to s$ decays:
A path to distinguish NP from hadronic uncertainties

Martín Novoa-Brunet

Based on works in collaboration with: Marcel Algueró, Aritra Biswas, Bernat Capdevila, Sébastien Descotes-Genon, Joaquim Matias, Keri K. Vos

arXiv:2005.03734, 2008.08000, 2104.08921, 2304.xxxxx

INFN Sezione di Bari, Italy

March 28, 2023

Motivation

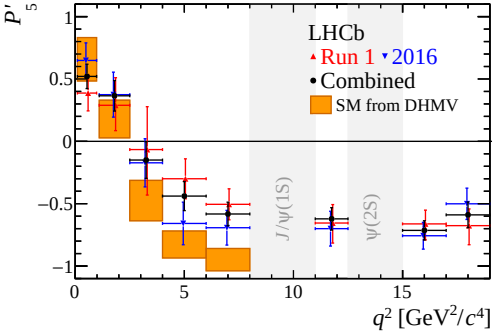
- Hints of NP in $b \to s\ell\ell$
- FCNC processes, which are loop supressed in the SM (potential sensitivity to NP)
- NP indications could be mimicked by hadronic contributions
- How to separate hadronic from NP?

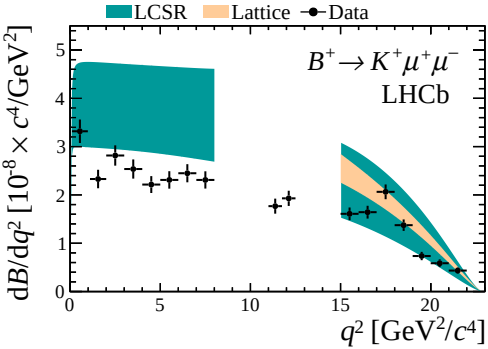
$b \to s\,\mu^+\mu^-$ anomaly

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

- Angular observables in $B^{(0,+)} \to K^{*(0,+)}\mu^+\mu^-$ LHCb, arXiv:2003.04831, arXiv:2012.13241
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$

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





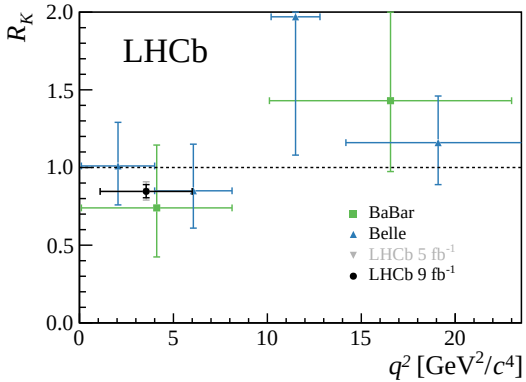
*: based on hadronic assumptions on which there is no theory consensus yet

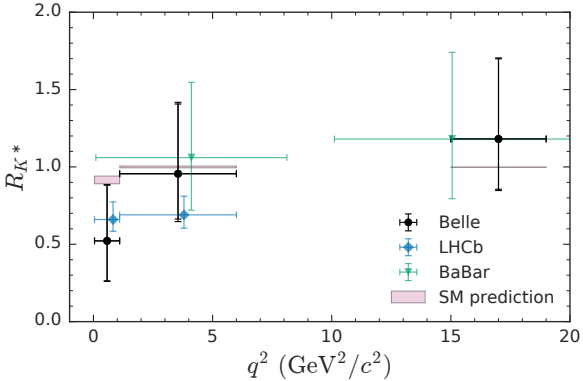
LFU violation in $b \to s\,\ell^+\ell^-$ decays (up to Dec. 2022)

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

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



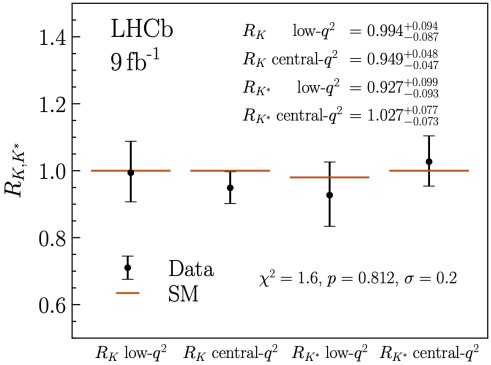


LFU violation in $b \to s\,\ell^+\ell^-$ decays

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.

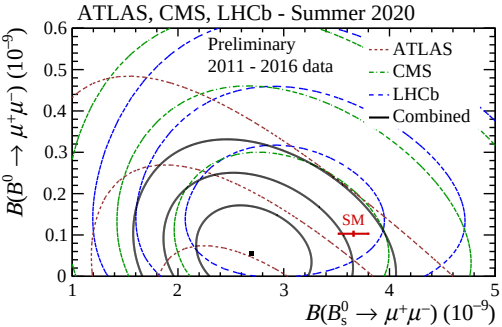
- sample of B meson decays in pp collisions collected between 2011 and 2018 (integrated luminosity of 9 fb^{-1})
- new modelling of residual backgrounds due to misidentified hadronic decays
- deviations from SM by ~ -0.0, $+1.1$, $+0.5$ and -0.4σ

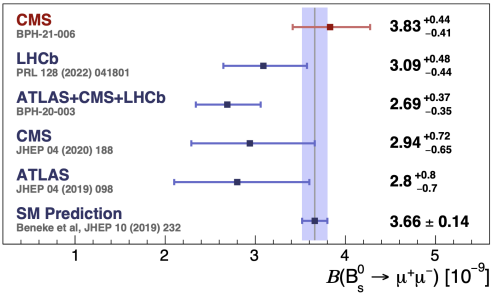


Leptonic modes $B_{s,d} \to \mu^+\mu^-$

Measurements of $\mathcal{B}(B_{s,d} \to \mu^+\mu^-)$ 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

$b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$ Effective Hamiltonians

Local operator effective theory at scales below the electroweak scale

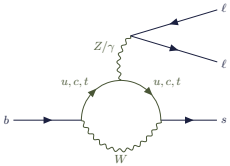
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \, \mathcal{O}_i$$

Short distance dynamics

Long distance structure

$$\mathcal{C}_i = \mathcal{C}_i^{NP} + \mathcal{C}_i^{SM}$$

Operators relevant for this transition



$b \to s\ell\ell$

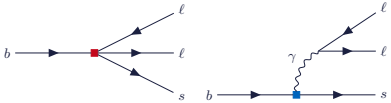
$$\mathcal{O}_{9^{(\prime)}} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10^{(\prime)}} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_{7^{(\prime)}} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

$b \to s\nu\bar{\nu}$

$$\mathcal{O}^{\nu}_{L(R)} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\nu}\gamma^\mu (1-\gamma_5)\nu)$$



Hadronic

Contribute to $b \to s\ell\ell$ through loops:

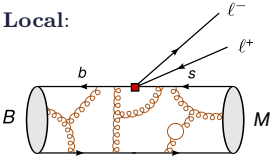
$$\mathcal{O}_1 = (\bar{s}\gamma_\mu P_L T^a c)(\bar{c}\gamma^\mu P_L T^a b)\,, \quad \mathcal{O}_2 = (\bar{s}\gamma_\mu P_L c)(\bar{c}\gamma^\mu P_L b)\,, \quad \cdots$$

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

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

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

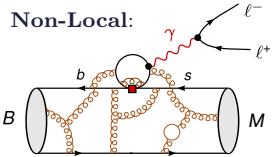
Local:



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

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

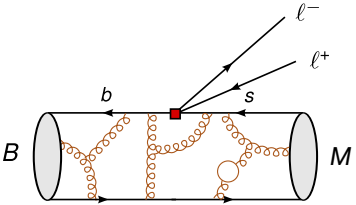
Non-Local:



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

- **Wilson coefficients** $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$:
  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), depends on external states, **main source of uncertainty**

Local matrix elements



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

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

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

- $\langle M|\bar{s}\,\Gamma_i\,b|B\rangle$ matrix elements are parameterised by:
  - **3 form factors** for each **spin zero** final state $M = \boldsymbol{K}$
  - **7 form factors** for each **spin one** final state $M = \boldsymbol{K^*}, \boldsymbol{\phi}$
- Determination of form factors
  - high q^2: **Lattice QCD**

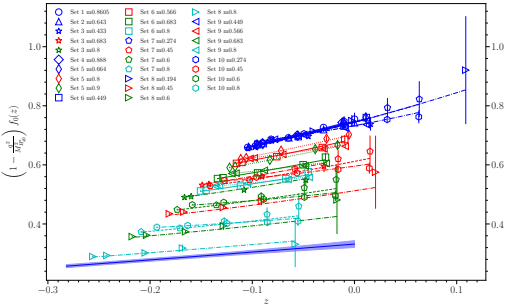
    HPQCD, arXiv:1306.2384,**2207.12468**
    Fermilab, MILC, arXiv:1509.06235
    Horgan, Liu, Meinel, Wingate, arXiv:1310.3722, arXiv:1501.00367
  - low q^2: **Continuum methods**
    e.g. Light-cone sum rules (LCSR)

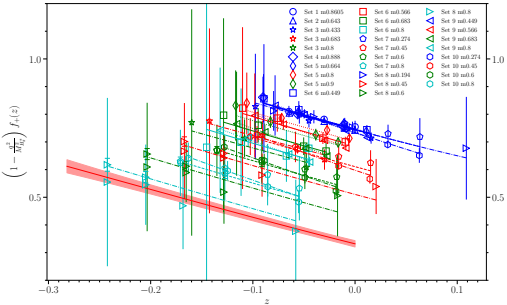
    Ball, Zwicky, arXiv:hep-ph/0406232
    Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
    Bharucha, Straub, Zwicky, arXiv:1503.05534
    Gubernari, Kokulu, van Dyk, arXiv:1811.00983
  - low + high q^2: Combined fit to **continuum methods + lattice**

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

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

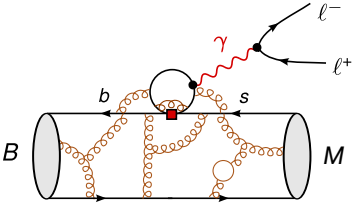
- Lattice QCD calculation of the $B \to K$ form factors **across the full physical** q^2 range
  - ⇒ highly improved staggered quark (HISQ) formalism (valence quarks)
  - ⇒ gluon field configurations by MILC
  - ⇒ first fully relativistic calculation, using the heavy-HISQ method





HPQCD, arXiv:2207.12468

Non-local matrix elements



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

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

- Contributions at low q^2 from QCD factorization (QCDF) — Beneke, Feldmann, Seidel, arXiv:hep-ph/0106067
- **Beyond-QCDF** contributions **the main source of uncertainty**
- Non-local contributions can mimic New Physics in $\mathcal{C}_9$
- 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 $b \to sc\bar{c}$ — Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305; Gubernari, van Dyk, Virto, arXiv:2011.09813

"cleanliness" of $b \to s$ observables in the SM

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

Theory setup

Improved QCDF (Local)

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

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

  $\Rightarrow$ **Dominant correlations** automatically taken into account (important for a maximal cancellation of errors)

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

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

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

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

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

  corrections

  Jäger, Camalich; arXiv:1212.22
  Descotes-Genon, Hofer, Matias, Virto; arXiv:1407.85

Estimating beyond QCDF contribution at low-q^2 (Non-local)

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

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

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

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

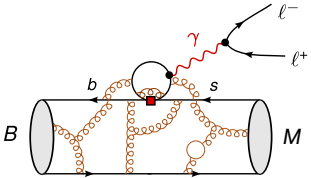
  ⇒ Calculations based on continuum methods

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

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

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

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



Estimating beyond QCDF contribution at low-q^2 (Non-local)

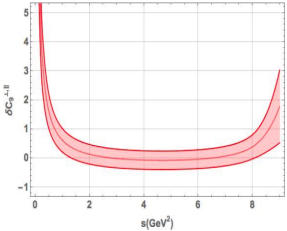
- Parameterisation for the long-distance contribution

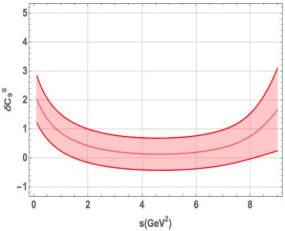
$$\delta\mathcal{C}_9^{\mathrm{LD},\perp}(q^2) = \frac{a^\perp + b^\perp q^2(c^\perp - q^2)}{q^2(c^\perp - q^2)} \qquad \delta\mathcal{C}_9^{\mathrm{LD},\parallel}(q^2) = \frac{a^{||} + b^{||} q^2(c^{||} - q^2)}{q^2(c^{||} - q^2)}$$

$$\delta\mathcal{C}_9^{\mathrm{LD},0}(q^2) = \frac{a^0 + b^0(q^2 + s_0)(c^0 - q^2)}{(q^2 + s_0)(c^0 - q^2)}$$

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

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





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

Summary theory framework (Now and then)

Theory status up to Dec. 2022

- Pseudoscalar channels: $B \to K\ell\ell$
  - ⇒ Local form factors: improved QCDf with KMPW LCSRs (low-q^2), Lattice QCD (high-q^2)
  - ⇒ Non-local form factors: parametrisation based on KMPW LCSRs
- Vector channels: $B \to \{K^*, \phi\}\,\ell\ell$
  - ⇒ Local form factors: improved QCDf with KMPW LCSRs (low-q^2), Lattice QCD (high-q^2)
  - ⇒ Non-local form factors: parametrisation based on KMPW LCSRs

Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239
Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921

Updated theory status

- Pseudoscalar channels: $B \to K\ell\ell$
  - ⇒ Local form factors: Lattice QCD (all-q^2)
  - ⇒ Non-local form factors: parametrisation based on KMPW LCSRs
- Vector channels: $B \to \{K^*, \phi\}\,\ell\ell$
  - ⇒ Local form factors: improved QCDf based on GKvD LCSRs (low-q^2), Lattice QCD (high-q^2)
  - ⇒ Non-local form factors: parametrisation based on KMPW LCSRs

Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; In Preparation

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

Predictions with HPQCD'22 Form Factors			
$10^7 \times \mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[0.1, 0.98]$	0.325 ± 0.025	0.29 ± 0.02	$+1.0$
$[1.1, 2]$	0.334 ± 0.025	0.21 ± 0.02	$+4.0$
$[2, 3]$	0.371 ± 0.028	0.28 ± 0.02	$+2.5$
$[3, 4]$	0.371 ± 0.028	0.25 ± 0.02	$+3.4$
$[4, 5]$	0.371 ± 0.028	0.22 ± 0.02	$+4.5$
$[5, 6]$	0.371 ± 0.030	0.23 ± 0.02	$+4.0$
$[6, 7]$	0.372 ± 0.033	0.25 ± 0.02	$+3.3$
$[7, 8]$	0.376 ± 0.043	0.23 ± 0.02	$+3.1$
$[15, 22]$	1.150 ± 0.161	0.85 ± 0.05	$+1.8$

HPQCD, arXiv:2207.12468
LHCb, arXiv:1403.8044

Fit setup

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

- Inclusive decays
  - $B \to X_s\gamma$ ($\mathcal{B}$)
  - $B \to X_s\ell^+\ell^-$ ($\mathcal{B}$)
- Exclusive leptonic decays
  - $B_s \to \mu^+\mu^-$ ($\mathcal{B}$)
- Exclusive radiative/semileptonic decays
  - $B \to K^*\gamma$ ($\mathcal{B}$, $S_{K^*\gamma}$, A_I)
  - $B^{(0,+)} \to K^{(0,+)}\ell^+\ell^-$ ($\mathcal{B}_\mu$, R_K, R_{K_S}, angular observables)
  - $B^{(0,+)} \to K^{*(0,+)}\ell^+\ell^-$ ($\mathcal{B}_\mu$, $R_{K^{*0}}$, $R_{K^{*+}}$, angular observables)
  - $B_s \to \phi\mu^+\mu^-$ ($\mathcal{B}$, angular observables)
  - $\Lambda_b \to \Lambda\mu^+\mu^-$ ($\mathcal{B}$, angular observables) (not included)
- Fits might include ~ 250 observables $\Rightarrow$ **global** $b \to s\ell\ell$ analyses

Statistical framework

We parametrise the Wilson coefficients as,

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

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

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

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

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

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 $B_s \to \mu\mu$, LFU observables

"Uninteresting" NP scenarios:

- $\mathcal{C}_{7^{(\prime)}}$: strongly constrained by radiative decays and very low-q^2 bin of $B \to K^* e^+ e^-$
- $\mathcal{C}_{ie}$: 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: $\mathcal{C}_{9\mu}^{\rm NP}$ or $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$
- 2D scenario: $\mathcal{C}_{9\mu}^{\rm NP}$ and $\mathcal{C}_{10\mu}^{\rm NP}$

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 $B_s \to \mu\mu$, LFU observables

"Uninteresting" NP scenarios:

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

Interesting NP scenarios:

- 1D scenarios: $\mathcal{C}_9^{\rm U}$, $\mathcal{C}_{9\mu}^{\rm NP}$ or $\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$ (though much less competitive because of $B_s \to \mu^+\mu^-$)
- 2D scenario: $\mathcal{C}_{9\mu}^{\rm NP}$ and $\mathcal{C}_{9e}^{\rm NP}$ (since $R_K \approx R_{K^*} \approx 1$)

1D NP fits

	Global (before exp. updates 2022)			
1D Hyp.	bfp	1σ	Pull_{SM}	p-value (%)
$\mathcal{C}_{9\mu}^{\text{NP}}$	-0.67 (-1.01)	[-0.83,-0.52] $([-1.15, -0.87])$	4.5 (7.0)	19.6 (24.0)
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.19 (-0.45)	[-0.25, -0.12] $([-0.52, -0.37])$	3.0 (6.5)	9.5 (16.9)
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9\mu}'$	-0.49 (-0.92)	[-0.67, -0.32] $([-1.07, -0.75])$	3.1 (5.7)	10.0 (8.2)
	LFUV			
1D Hyp.	bfp	1σ	Pull_{SM}	p-value (%)
$\mathcal{C}_{9\mu}^{\text{NP}}$	-0.21 (-0.87)	$[-0.39, -0.04]$ $([-1.11, -0.65])$	1.2 (4.4)	92.4 (40.7)
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.08 (-0.39)	$[-0.15, -0.01]$ $([-0.48, -0.31])$	1.1 (5.0)	91.5 (73.5)
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9\mu}'$	-0.04 (-1.60)	$[-0.26, 0.15]$ $([-2.10, -0.98])$	0.2 (3.2)	87.5 (8.4)

⇒ Substantial drop in significances

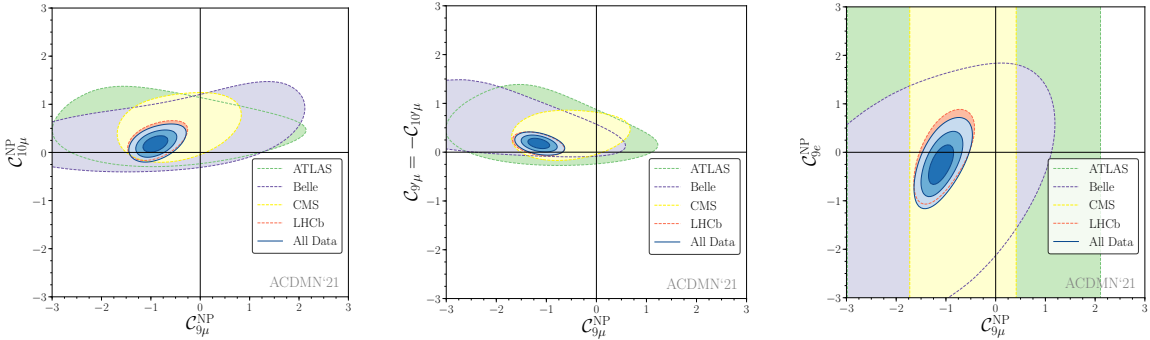
⇒ $\mathcal{C}_{9\mu}^{\text{NP}}$ is the strongest signal for the Global fit

⇒ p-value for $\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$ reduces significantly (less fit coherence: ang. obs. vs LFU 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:2303.xxxxx

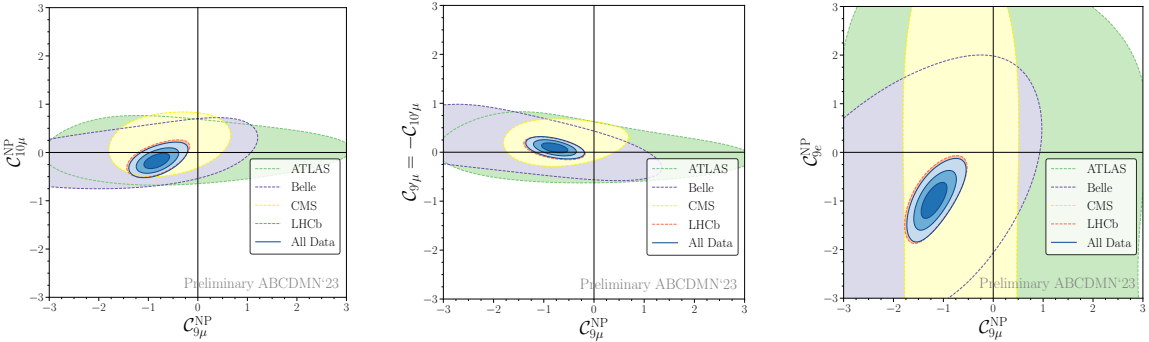
2D NP fits (before exp. updates 2022)



- 3σ regions experiment by experiment
- Pulls$_{\rm SM}$ (p-values): 6.8σ (25.6%), 7.1σ (31.8%) & 6.7σ (23.8%) (respectively)
- High significances for NP solutions with right-handed currents (RHC)
- $\mathcal{C}_{9e}^{\rm NP}$ compatible with SM

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

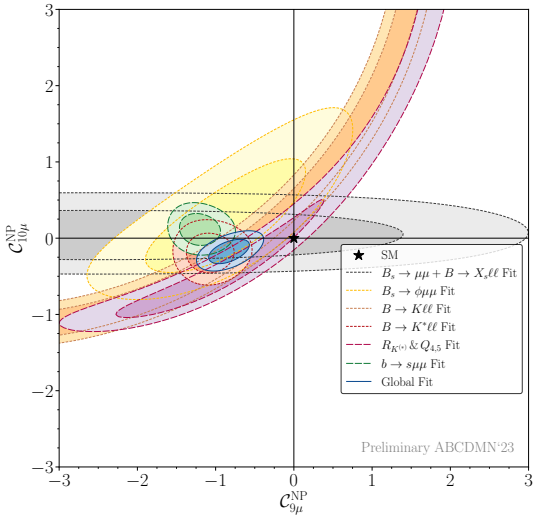
Updated 2D NP fits

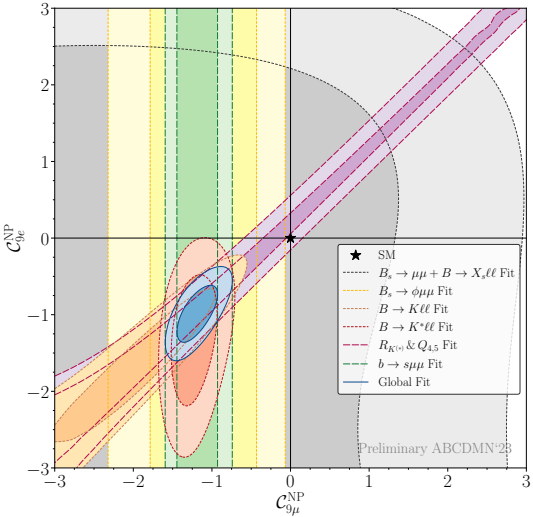


- 3σ regions experiment by experiment
- $\text{Pulls}_{\rm SM}$ (p-values): 4.4σ (21.6%), 4.3σ (20.5%) & 5.6σ (40.4%) (respectively)
- Drop in significance for NP solutions with RHC (compatible with SM)
- Increased NP contribution to $\mathcal{C}_{9e}$, compatible with LFU NP

Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2303.xxxxx

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

Are we overlooking LFU NP?

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

$$\mathcal{C}_{i\ell}^{\rm NP} = \mathcal{C}_{i\ell}^{\rm V} + \mathcal{C}_i^{\rm U} \quad (\mathcal{C}_i^{\rm U} \text{ the same } \forall \ell)$$

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

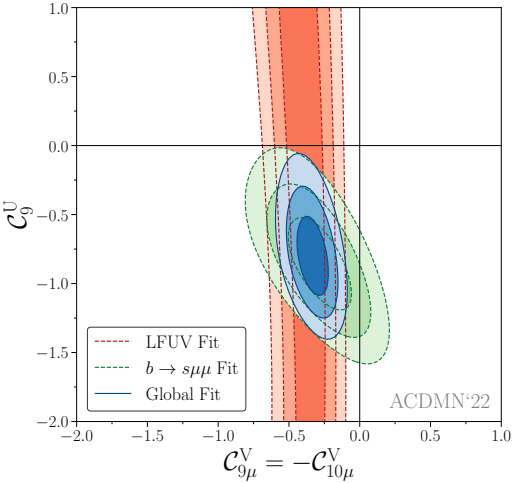
⇒ The NP parameter space can be equally described with $\{\mathcal{C}_{i\mu}^{\rm NP}, \mathcal{C}_{ie}^{\rm NP}\}$ or $\{\mathcal{C}_{i\mu}^{\rm V}, \mathcal{C}_i^{\rm U}\}$ ($\mathcal{C}_{ie}^{\rm V} = 0$)

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

$$\left\{ \begin{array}{l} \mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V} \\ \mathcal{C}_9^{\rm U} \end{array} \right. \Rightarrow \left\{ \begin{array}{l} \mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP} + \mathcal{C}_{9e}^{\rm NP} \\ \mathcal{C}_{9e}^{\rm NP} \end{array} \right.$$

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

NP fits with LFU contributions (before exp. updates 2022)

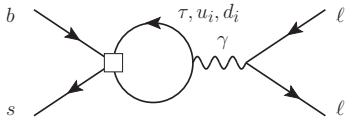


WET at 4.8 GeV

- Two-parameter fit in space of $\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$ and $\mathcal{C}_9^{\rm U}$

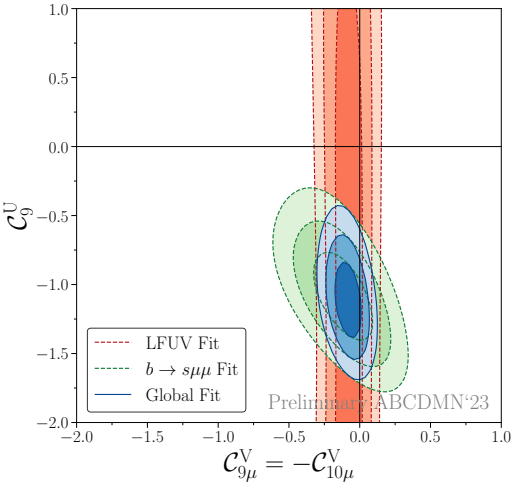
  scenario first considered in Algueró et al., arXiv:1809.08447

- Significant preference for **non-zero** $\mathcal{C}_9^{\rm U}$
- This scenario is one of the most successful NP solutions to solve the $b \to s\ell\ell$ anomalies
  - ⇒ $\text{Pull}_{\rm SM} = 7.2\sigma$
  - ⇒ It successfully describes, with optimal internal consistency, $b \to s\mu\mu$ 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

NP fits with LFU contributions

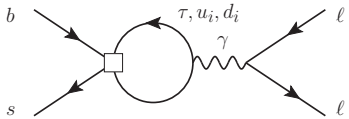


WET at 4.8 GeV

- Two-parameter fit in space of $\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$ and $\mathcal{C}_9^{\mathrm{U}}$

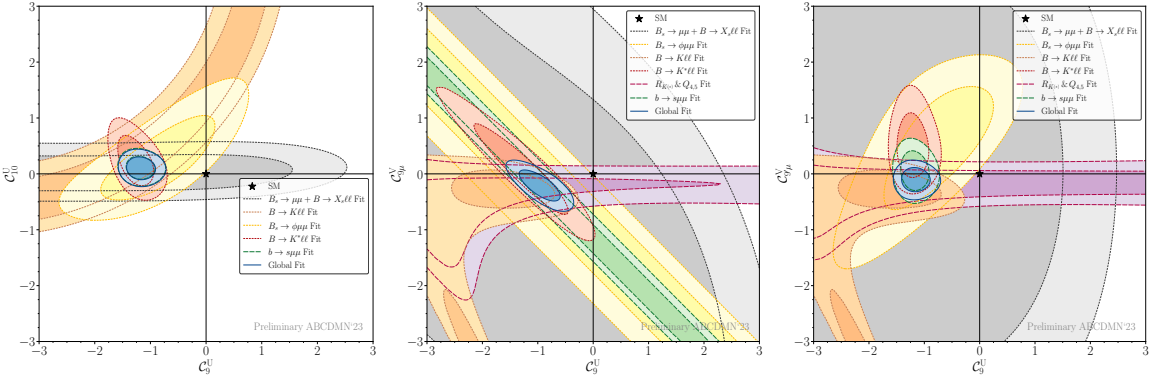
  scenario first considered in Algueró et al., arXiv:1809.08447

- Large **non-zero** $\mathcal{C}_9^{\mathrm{U}}$ but LFUV compatible with 0
- This scenario is one of the most successful NP solutions to solve the $b \to s\ell\ell$ anomalies
  - ⇒ $\mathrm{Pull}_{\mathrm{SM}} = 5.6\sigma$
  - ⇒ It successfully describes, with optimal internal consistency, $b \to s\mu\mu$ 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

Internal coherence of fits including LFU NP to $\mathcal{C}_9$

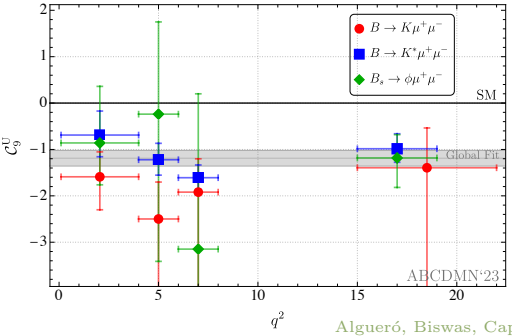


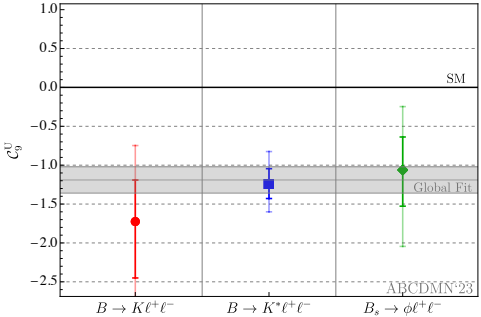
Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2303.xxxxx

Consistency over q^2 and over different modes

Testing the q^2 and mode dependence of $\mathcal{C}_9^{\rm U}$ by means of data:

- Fit to $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ ($\mathcal{B}$'s + Ang. obs) separetely by bin
- $\mathcal{C}_9^{\rm U}$ bin-by-bin fit (assuming KMPW-like $\delta\mathcal{C}_9^{{\rm LD},i}(q^2)$)
- Good agreement with global fit ($1-2\sigma$ range)
- Consistency over different modes and no indication of a strong q^2 dependence
- Consistency large and low recoil (different theo. treatments)





Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2303.xxxxx

Hadronic vs NP

How can we distinguish between a hadronic contribution and a NP contribution?
We propose three ways with different assumptions on the NP:

- Measure precisely the CP-odd phase of $\mathcal{C}_9^{\mathrm{U}}$ since the hadronic contributions are CP-even to a good degree of approximation CP-odd phase can only be constrained cleanly by looking at its interference with another phase.
  - Interference with time-evolution of B-meson.

    Descotes-Genon, Novoa-Brunet, Vos; arXiv:2008.08000
  - Interference with strong phases in resonance regions.

    Bečirević, Fajfer, Košnik, Smolkovič; arXiv:2008.09064
- SMEFT connection with $b \to s\nu\bar{\nu}$ and other neutrino modes.

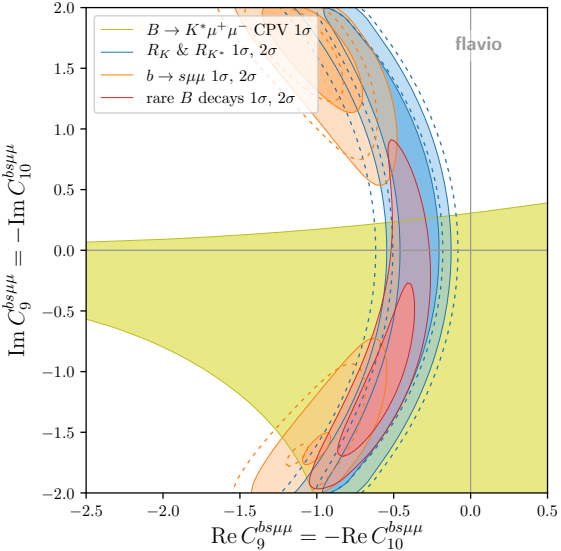
  Descotes-Genon, Fajfer, Kamenik, Novoa-Brunet; arXiv:2005.03734
- A big enhancement of $b \to s\tau\tau$ could generate $\mathcal{C}_9^{\mathrm{U}}$ through running and rescattering.

  Capdevila, Crivellin, Descotes-Genon, Hofer, Matias; arxiv:1712.01919
  Crivellin, Greub, Muller, Saturnino; arxiv:1807.02068

Constraining CP-odd phases through time-evolution

Constrains on CP-odd phases in $b \to s\ell\ell$

- Weak phases of potential NP are poorly constrained
- Direct CP-asymmetries probe only the interplay of strong and weak phases
- Other observables have sensitivity to weak phases but are not clean.
- How to probe cleanly weak (CP-odd) phases in NP?



[Altmannshofer and Stangl '21]

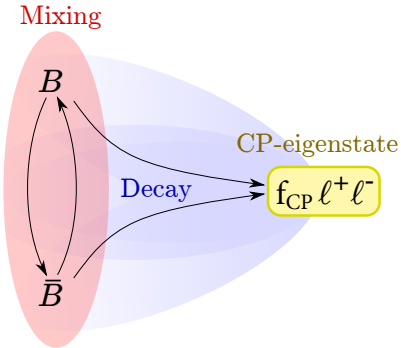
Constrain CP-odd phases through time-evolution

- To cleanly constrain CP-odd phases of NP we can look at the interaction of $B\bar{B}$ mixing and weak phases

$$B \to f_{\rm CP}\ \ell\bar{\ell} \qquad vs \qquad \bar{B} \to f_{\rm CP}\ \ell\bar{\ell}$$

- You can look at the following cases:
  - P vs V meson
  - Charged vs Neutral

$$f_{\rm CP} = K_S,\, K_S\pi^0,\, \phi \qquad\qquad \ell\bar{\ell} = \ell^+\ell^-,\, \nu\bar{\nu}$$



$B_d \to K_S\ell^+\ell^-$ $\qquad$ $B_d \to K_S\nu\bar{\nu}$

$B_d \to K^{*0}(\to K_S\pi^0)\ell^+\ell^-$ $\qquad$ $B_d \to K^{*0}(\to K_S\pi^0)\nu\bar{\nu}$

$B_s \to \phi\ell^+\ell^-$ $\qquad$ $B_s \to \phi\nu\bar{\nu}$

$B \to K\ell\ell$: Charged vs Neutral mode

$$\frac{d^2\Gamma(B^+ \to K^+\ell^+\ell^-)}{dq^2\, d\cos\theta_\ell} = G_0(q^2) + G_1(q^2)\cos\theta_\ell + G_2(q^2)\frac{1}{2}(3\cos^2\theta_\ell - 1)$$

$$G_2 = -\frac{4\beta_\ell^2}{3}\left(|h_V|^2 + |h_A|^2 - 2\,|h_T|^2 - 4\,|h_{T_t}|^2\right) \qquad h_A \propto (\mathcal{C}_{10} + \mathcal{C}_{10'})^* f_+(q^2)$$

$B^+ \to K^+\ell^+\ell^-$
h_X

$\longleftrightarrow$ CP $\longleftrightarrow$

$B^- \to K^-\ell^+\ell^-$
$\bar{h}_X$

$\updownarrow$ $\qquad$ $\tilde{h}_X = \bar{h}_X \eta_X$ $\qquad$ $\updownarrow$

$B_d \to K_S\ell^+\ell^-$
h_X

$\longleftrightarrow$ $B_d \leftrightarrow \bar{B}_d$ $\longleftrightarrow$

$\bar{B}_d \to K_S\ell^+\ell^-$
$\tilde{h}_X$

h_X: Transversity amplitudes $\quad \eta_X$: CP-parity associated to h_X

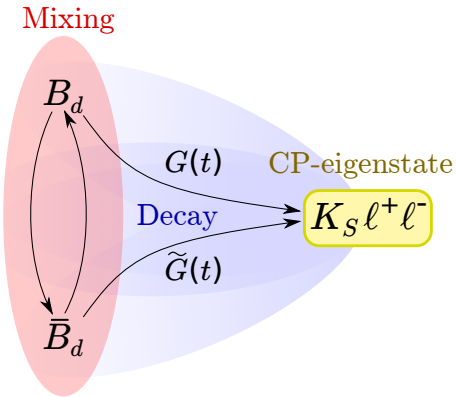
$$\boxed{\eta_{V,A,P,T_t} = -1 \quad \text{and} \quad \eta_{S,T} = 1 \quad \Longrightarrow \quad \tilde{h}_X^{\rm SM} = -\bar{h}_X^{\rm SM}}$$

Dunietz et al '01
Descotes-Genon et al '15

Time dependent analysis of $B_d \to K_S \ell\ell$ [2008.08000]

$$G_i(t) + \widetilde{G}_i(t) = e^{-\Gamma t}\left[(G_i + \widetilde{G}_i) \cosh\left(\frac{\Delta\Gamma t}{2}\right) - h_i \sinh\left(\frac{\Delta\Gamma t}{2}\right)\right]$$

$$G_i(t) - \widetilde{G}_i(t) = e^{-\Gamma t}\left[(G_i - \widetilde{G}_i) \cos(\Delta m t) - s_i \sin(\Delta m t)\right]$$



- 6 new observables

$$\sigma_i \equiv \frac{s_i}{\Gamma_\ell} \qquad \theta_i \equiv \frac{h_i}{\Gamma_\ell}$$

- $y = \Delta\Gamma_{B_d}/2\Gamma$ very small $\Rightarrow$ Only 3 observables (σ_i) accessible in $B_d \to K_S \ell^+ \ell^-$
- Interplay between mixing and decay $\Rightarrow$ Access weak phases!

$$s_2 = -\frac{8\beta_\ell^2}{3} \mathrm{Im}\left[e^{i\phi}\left[\tilde{h}_V h_V^* + \tilde{h}_A h_A^* - 2\tilde{h}_T h_T^* - 4\tilde{h}_{T_t} h_{T_t}^*\right]\right]$$

$$G_2 = -\frac{4\beta_\ell^2}{3}\left(|h_V|^2 + |h_A|^2 - 2|h_T|^2 - 4|h_{T_t}|^2\right)$$

Time dependent analysis of $B_d \to K_S \ell^+ \ell^-$ [2008.08000]

- **Accurately** computed in the SM (independent of form factors and $c\bar{c}$ contributions!)

$$\sigma_2 \approx \sigma_0 = -\frac{\sin\phi}{2}$$

- **Big sensitivity to CP-odd phases** and independent of real V,A NP

Observable	SM	$\mathcal{C}_{9\mu}^{\rm NP} = -1.12$	$\mathcal{C}_{9\mu}^{\rm NP} = -1.12 + i1.00$
σ_0	0.368(5)	0.368(5)	0.273(6)
σ_2	−0.359(5)	−0.359(5)	−0.266(6)

- Flavour tagging required (easier at B-factories)
- Two ways of measuring these observables:
  - Dedicated time-dependent analysis
  - Measuring time-integrated observables and time-asymmetries

Time-integrated observables: Coherent vs incoherent production

- Time integration different for hadronic machines (incoherent production) and B-factories (coherent production).
  - Incoherent: $t \in [0, \infty) \Rightarrow$ time since b-quarks have been produced

$$\langle G_i - \widetilde{G}_i \rangle_{\text{Hadronic}} = \frac{1}{\Gamma}\left[\frac{1}{1+x^2} \times (G_i - \widetilde{G}_i) - \frac{x}{1+x^2} \times s_i\right]$$

    Hadronic machines involve an additional term compared to the B-factories ($x = \delta m/\Gamma \Rightarrow$ mixing parameter).
  - Coherent: $t \in (-\infty, \infty) \Rightarrow$ time difference between B and $\bar{B}$ decay

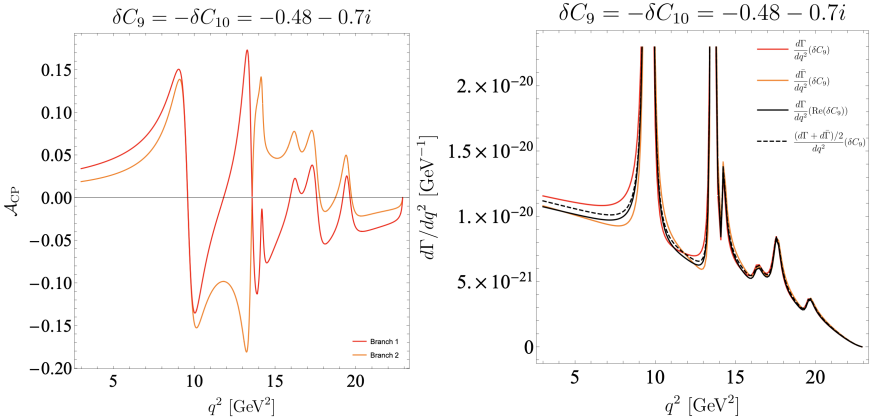
$$\langle G_i - \widetilde{G}_i \rangle_{\text{B-factory}} = \frac{2}{\Gamma}\frac{1}{1+x^2}[G_i - \widetilde{G}_i]$$

$$\langle (G_i - \widetilde{G}_i)\text{sgn}(t) \rangle_{\text{B-factory}} = -\frac{2}{\Gamma}\frac{x}{1+x^2}[s_i]$$

    B-factories can cleanly access this term through time asymmetries.

Enhanced CP-asymmetries through $c\bar{c}$ resonances

- Probe interference between strong phase and NP weak phase in Direct CP-asymmetries.
- Enhancement of CP-asymmetries near J/Ψ and $\Psi(2S)$ resonances.
- Model resonances with Breitt-Weigner + non resonant background .
- Fit parameters from data, and extract information on CP-odd phase from Direct asymmetry near resonance regions.



Bečirević, Fajfer, Košnik, Smolkovič; arXiv:2008.09064

Conclusions

- Strong hints of NP remain in the $b \to s\ell\ell$ after new results of LHCb
- Current data points towards a **large LFU contribution to** $\mathcal{C}_9$ which could be either explained by NP or a substantial underestimation of hadronic contributions.
- Two options to disentangle these effects
  - Probe the **CP-odd phases** of the NP:
    - Interference between mixing and decay allows to access a full new set of observables that are not affected by hadronic uncertainties and **highly sensitive to weak phases**
    - Time-integrated observables and time-asymmetries might be enough to extract these new observables
  - Looking at connections with **other modes**:
    - These LFU effects can come from RGE of a large non-standard effect in $b \to s\tau^+\tau^-$
    - NP effects should naturally show in $b \to s\nu\bar{\nu}$ and potentially $s \to d\nu\bar{\nu}$ unless there is an exact cancellation.

Status and prospects of semileptonic $b \to s$ decays:
A path to distinguish NP from hadronic uncertainties

Martín Novoa-Brunet

Based on works in collaboration with: Marcel Algueró, Aritra Biswas, Bernat Capdevila, Sébastien Descotes-Genon, Joaquim Matias, Keri K. Vos

arXiv:2005.03734, 2008.08000, 2104.08921, 2304.xxxxx

INFN Sezione di Bari, Italy

March 28, 2023