Flavour Physics as a Probe of Physics Beyond the Standard Model

Nazila Mahmoudi (IP2I Lyon)

Rencontres de Physique des Particules 2026

Montpellier, 11-13 March 2026

- More than a decade of LHC data
- Both clearer and more puzzling picture of fundamental interactions
- The Standard Model has passed an extraordinary number of tests
- No clear evidence of new particles at the TeV scale

The key facts characterising the present situation:

- The SM has been confirmed
  Higgs discovery, and measurement of its properties (mass,...)

- No new particles have been seen so far
  "Probably" a mass gap above the SM spectrum
  with no clear signal of new states below roughly the TeV scale

- More than a decade of LHC data
- Both clearer and more puzzling picture of fundamental interactions
- The Standard Model has passed an extraordinary number of tests
- No clear evidence of new particles at the TeV scale

The key facts characterising the present situation:

- The SM has been confirmed
  Higgs discovery, and measurement of its properties (mass,...)

- No new particles have been seen so far
  "Probably" a mass gap above the SM spectrum
  with no clear signal of new states below roughly the TeV scale

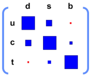
Open Questions in the Standard Model

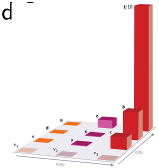
Despite its success, the SM leaves many questions unanswered, in particular:

- Dark matter and cosmological problems
- Theoretical questions regarding the inner structure of the SM

  $\rightarrow$ Flavour problems

  - Why do fermion masses span five orders of magnitud
  - Why are quark mixings hierarchical?





  - Why is the top Yukawa of order unity while others are tiny?

The SM **describes** flavour extremely well, but **does not explain** it

$\rightarrow$ flavour physics has become a central component of the broader program of indirect searches for new physics.

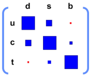
Open Questions in the Standard Model

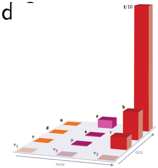
Despite its success, the SM leaves many questions unanswered, in particular:

- Dark matter and cosmological problems
- Theoretical questions regarding the inner structure of the SM

$\rightarrow$ Flavour problems

- Why do fermion masses span five orders of magnitud
- Why are quark mixings hierarchical?





- Why is the top Yukawa of order unity while others are tiny?

The SM **describes** flavour extremely well, but **does not explain** it

$\rightarrow$ flavour physics has become a central component
of the broader program of indirect searches for new physics.

The absence of direct discoveries does not imply the absence of new physics

Instead it motivates a complementary strategy:

precision measurements and indirect probes

The absence of direct discoveries does not imply the absence of new physics

Instead it motivates a complementary strategy:

precision measurements and indirect probes

Key point: flavour observables probe virtual effects of heavy particles.

If new states exist at some scale Λ, they modify low-energy amplitudes through higher-dimension operators:

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i$$

Even when Λ is well above the energy reachable at colliders, the corresponding operators can generate measurable deviations in:

- rare decays
- CP-violating observables
- flavour-changing neutral currents

1. Suppression in the SM

Many flavour transitions occur only through:

- loop processes
- CKM suppression
- helicity suppression

This makes them extremely sensitive to small BSM contributions.

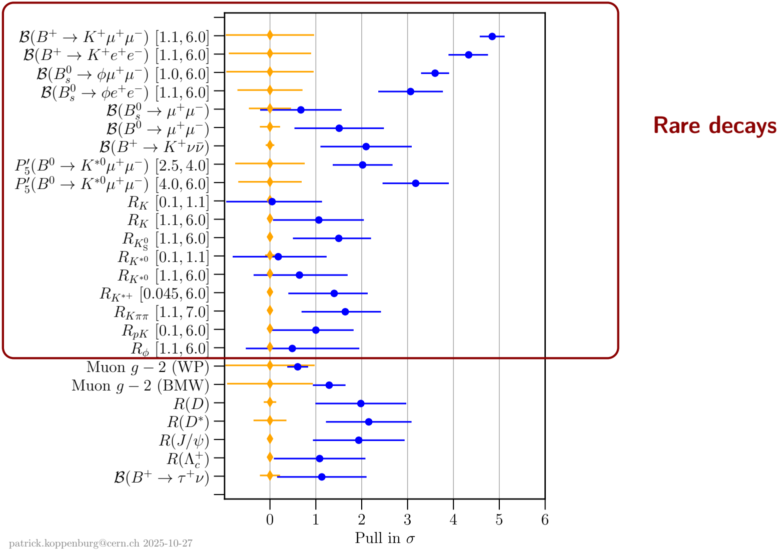
2. Theoretical control

For a number of observables (for example certain leptonic or semileptonic decays), theoretical uncertainties are sufficiently small to allow percent-level tests of the SM.

3. Experimental perspective

Several experiments and many measurements.

Experimental situation



Effective field theory

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big(\sum_{i=1\cdots10,S,P} \big(C_i(\mu) \mathcal{O}_i(\mu) + C'_i(\mu) \mathcal{O}'_i(\mu) \big) \Big)$$

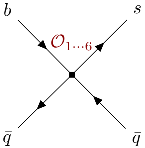
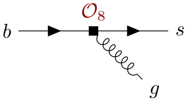
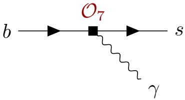
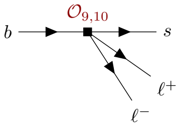
Separation between short distance (Wilson coefficients) and long distance (local operators) effects

Effective field theory

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1\cdots 10,S,P} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu) \right) \right)$$

Separation between short distance (Wilson coefficients) and long distance (local operators) effects

Operator set for $b \to s$ transitions:

4-quark operators	chromomagnetic dipole operator	electromagnetic dipole operator	semileptonic operators
			
$\mathcal{O}_{1,2} \propto (\bar{s}\Gamma_\mu c)(\bar{c}\Gamma^\mu b)$ $\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$	$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R) G^a_{\mu\nu}$	$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} P_R) F^a_{\mu\nu}$	$\mathcal{O}_9^\ell \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$ $\mathcal{O}_{10}^\ell \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$

+ the chirality flipped counter-parts of the above operators, $\mathcal{O}_i'$

The Wilson coefficients are calculated perturbatively and are process independent

Two main steps:

- matching between the effective and full theories $\rightarrow$ extraction of the $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$

$$C_i^{eff}(\mu) = C_i^{(0)eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)eff}(\mu) + \cdots$$

- Evolving the $C_i^{eff}(\mu)$ to the scale relevant for B decays, $\mu \sim m_b$ using the RGE runnings.

SM contributions known to NNLL **(Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06,...)**

$$C_7 = -0.294 \qquad C_9 = 4.20 \qquad C_{10} = -4.16$$

To compute the amplitudes:

$$\mathcal{A}(A \to B) = \langle B|\mathcal{H}_{\rm eff}|A\rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle B|\mathcal{O}_i|A\rangle(\mu)$$

$\langle B|\mathcal{O}_i|A\rangle$: hadronic matrix element

How to compute matrix elements?

$\to$ Model building, Lattice simulations, Light flavour symmetries, Heavy flavour symmetries, ...

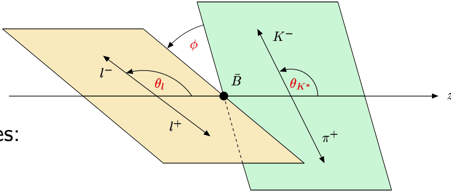
$\to$ Describe hadronic matrix elements in terms of **hadronic quantities**

Two types of hadronic quantities:

- **Decay constants**: Probability amplitude of hadronising quark pair into a given hadron
- **Form factors**: Transition from a meson to another through flavour change

Once the Wilson coefficients and hadronic quantities calculated, the physical observables (branching fractions,...) can be calculated.

Angular distributions



The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ ($\bar{K}^{*0} \to K^-\pi^+$) is completely described by four independent kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ

Differential decay distribution:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2)\, f_i(\theta_\ell, \theta_{K^*}, \phi)$

↘ angular coefficients J_{1-9}

↘ functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

Spin amplitudes: functions of Wilson coefficients and form factors

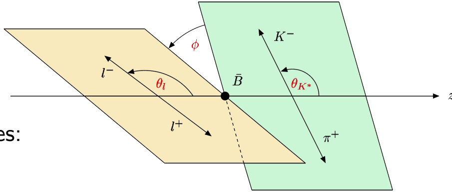
Main operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell), \qquad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5\ell)$$

Angular distributions

The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ ($\bar{K}^{*0} \to K^-\pi^+$) is completely described by four independent kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ



Differential decay distribution:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2)\, f_i(\theta_\ell, \theta_{K^*}, \phi)$

↘ angular coefficients J_{1-9}

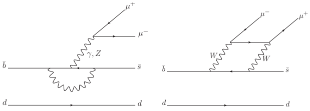
↘ functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)$$



Optimised observables: form factor uncertainties cancel at leading order

$$\langle P_1 \rangle_{\rm bin} = \frac{1}{2} \frac{\int_{\rm bin} dq^2 [J_3 + \bar{J}_3]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_2 \rangle_{\rm bin} = \frac{1}{8} \frac{\int_{\rm bin} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]}$$

$$\langle P_4' \rangle_{\rm bin} = \frac{1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_4 + \bar{J}_4] \qquad \langle P_5' \rangle_{\rm bin} = \frac{1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_5 + \bar{J}_5]$$

$$\langle P_6' \rangle_{\rm bin} = \frac{-1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_7 + \bar{J}_7] \qquad \langle P_8' \rangle_{\rm bin} = \frac{-1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_8 + \bar{J}_8]$$

with

$$\mathcal{N}'_{\rm bin} = \sqrt{- \int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}] \int_{\rm bin} dq^2 [J_{2c} + \bar{J}_{2c}]}$$

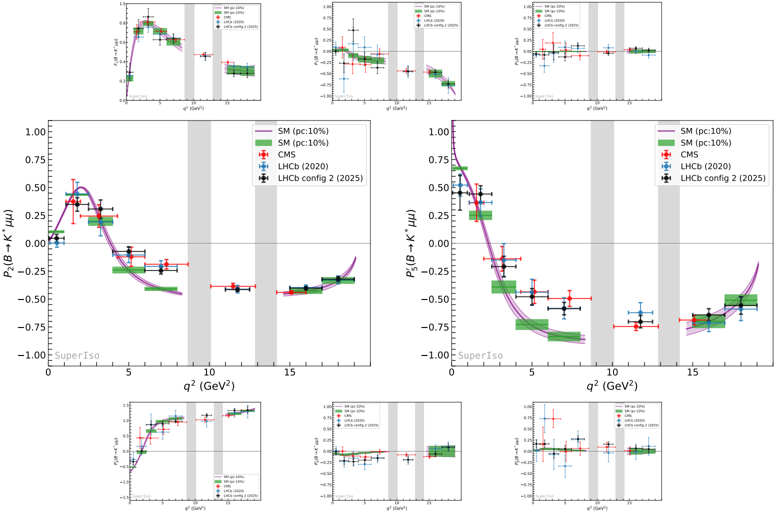
$+$ CP violating clean observables and other combinations

U. Egede et al., JHEP 0811 (2008) 032, JHEP 1010 (2010) 056
J. Matias et al., JHEP 1204 (2012) 104
S. Descotes-Genon et al., JHEP 1305 (2013) 137

Or alternatively:

$$S_i = \frac{J_{i(s,c)} + \bar{J}_{i(s,c)}}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}} \, , \qquad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

LHCb with 8.4 fb^{-1} (configuration 2), Nov. 2025



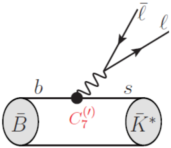
LHCb, arXiv:2512.18053

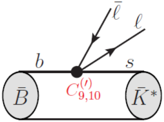
Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

Matrix elements of $B \to K^*\ell^+\ell^-$ decay:

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=7,9,10} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu)\Big]$$

$\langle \bar{K}^*\ell^+\ell^-|H_{\rm eff}^{\rm sl}|\bar{B}\rangle$:





⇨ $B \to K^*$ form factors $V, A_{0,1,2}, T_{1,2,3}$ or alternatively $\tilde{V}_\lambda, \tilde{T}_\lambda, \tilde{S}$ (λ = helicity of K^*)

Helicity amplitudes:

$$H_V(\lambda) \approx -i\,N'\Big\{(C_9 - C_9')\tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2}\Big[\frac{2\,\hat{m}_b}{m_B}(C_7^{\rm eff} - C_7')\tilde{T}_\lambda(q^2)\Big]\Big\}$$

$$H_A(\lambda) = -i\,N'(C_{10} - C_{10}')\tilde{V}_\lambda(q^2)$$

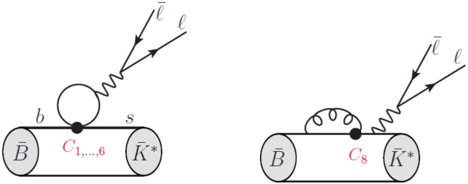
$$H_P = i\,N'\Big\{\frac{2\,m_\ell \hat{m}_b}{q^2}(C_{10} - C_{10}')\Big(1 + \frac{m_s}{m_b}\Big)\tilde{S}(q^2)\Big\}$$

Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

Matrix elements of $B \to K^*\ell^+\ell^-$ decay:

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=1\dots6} C_i(\mu) O_i(\mu) + C_8(\mu) O_8(\mu) \Big]$$

$\langle \bar{K}^* \ell^+ \ell^- | H_{\rm eff}^{\rm had} | \bar{B} \rangle$:



$H_{\rm eff}^{\rm had}$ contributes to $b \to s\bar\ell\ell$ through virtual photon exchange $\Rightarrow$ affect only the $H_V(\lambda)$

Helicity amplitudes:

$$H_V(\lambda) \approx -i\, N' \Big\{ (C_9 - C_9') \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2} \Big[\frac{2\,\hat{m}_b}{m_B} (C_7^{\rm eff} - C_7') \tilde{T}_\lambda(q^2) \Big] \Big\}$$

$$H_A(\lambda) = -i\, N' (C_{10} - C_{10}') \tilde{V}_\lambda(q^2)$$

$$H_P = i\, N' \Big\{ \frac{2\, m_\ell \hat{m}_b}{q^2} (C_{10} - C_{10}') \Big(1 + \frac{m_s}{m_b} \Big) \tilde{S}(q^2) \Big\}$$

Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

Matrix elements of $B \to K^*\ell^+\ell^-$ decay:

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=1...6} C_i(\mu)O_i(\mu) + C_8(\mu)O_8(\mu) \Big]$$

$$\langle \bar{K}^*\ell^+\ell^- | H_{\rm eff}^{\rm had} | \bar{B}\rangle: \; \mathcal{A}_\lambda^{\rm (had)} = -i\frac{e^2}{q^2} \int d^4x e^{-iq\cdot x} \langle \ell^+\ell^- | j_\mu^{\rm em,lept}(x)|0\rangle \times \int d^4y\, e^{iq\cdot y} \langle \bar{K}_\lambda^* | T\{j^{\rm em,had,\mu}(y)\mathcal{H}_{\rm eff}^{\rm had}(0)\}|\bar{B}\rangle$$

In general "naïve" factorization not applicable

Helicity amplitudes:

$$H_V(\lambda) \approx -i\,N' \Big\{ (C_9 - C_9')\tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2}\Big[\frac{2\,\hat{m}_b}{m_B}(C_7^{\rm eff} - C_7')\tilde{T}_\lambda(q^2)\Big]\Big\}$$

$$H_A(\lambda) = -i\,N'(C_{10} - C_{10}')\tilde{V}_\lambda(q^2)$$

$$H_P = i\,N' \Big\{ \frac{2\,m_\ell \hat{m}_b}{q^2}(C_{10} - C_{10}')\Big(1 + \frac{m_s}{m_b}\Big)\tilde{S}(q^2)\Big\}$$

Issue of hadronic contributions in a nutshell

Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

Matrix elements of $B \to K^*\ell^+\ell^-$ decay:

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=1...6} C_i(\mu)O_i(\mu) + C_8(\mu)O_8(\mu) \Big]$$

$$\langle \bar{K}^*\ell^+\ell^- | H_{\rm eff}^{\rm had} | \bar{B}\rangle:\ \mathcal{A}_\lambda^{\rm (had)} = -i\frac{e^2}{q^2}\int d^4x e^{-iq\cdot x}\langle \ell^+\ell^-|j_\mu^{\rm em,lept}(x)|0\rangle \times \int d^4y\, e^{iq\cdot y}\langle \bar{K}_\lambda^*|T\{j^{\rm em,had,\mu}(y)\mathcal{H}_{\rm eff}^{\rm had}(0)\}|\bar{B}\rangle$$

$$\longrightarrow \frac{e^2}{q^2}\epsilon_\mu L_V^\mu \Big[\underbrace{Y(q^2)\tilde{V}_\lambda}_{\text{fact., perturbative}} + \underbrace{\text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}})}_{\text{non-fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections, unknown}} \Big]$$

Helicity amplitudes:

$$H_V(\lambda) \approx -i\,N'\Big\{(C_9 - C_9')\tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2}\Big[\frac{2\,\hat{m}_b}{m_B}(C_7^{\rm eff} - C_7')\tilde{T}_\lambda(q^2)\Big]\Big\}$$

$$H_A(\lambda) = -i\,N'(C_{10} - C_{10}')\tilde{V}_\lambda(q^2)$$

$$H_P = i\,N'\Big\{\frac{2\,m_\ell \hat{m}_b}{q^2}(C_{10} - C_{10}')\Big(1 + \frac{m_s}{m_b}\Big)\tilde{S}(q^2)\Big\}$$

Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

Matrix elements of $B \to K^*\ell^+\ell^-$ decay:

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=1\dots6} C_i(\mu)O_i(\mu) + C_8(\mu)O_8(\mu)\Big]$$

$\langle \bar{K}^*\ell^+\ell^- | H_{\rm eff}^{\rm had} | \bar{B}\rangle$: $$\mathcal{A}_\lambda^{\rm (had)} = -i\frac{e^2}{q^2}\int d^4x e^{-iq\cdot x}\langle \ell^+\ell^- | j_\mu^{\rm em,lept}(x)|0\rangle \times \int d^4y\, e^{iq\cdot y}\langle \bar{K}_\lambda^* | T\{j^{\rm em,had,\mu}(y)\mathcal{H}_{\rm eff}^{\rm had}(0)\}|\bar{B}\rangle$$

$$\longrightarrow \frac{e^2}{q^2}\epsilon_\mu L_V^\mu \Big[\underbrace{Y(q^2)\tilde{V}_\lambda}_{\text{fact., perturbative}} + \underbrace{\text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}})}_{\text{non-fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections, unknown}} \Big]$$

$\left(C_9^{\rm eff} \equiv C_9 + Y(q^2)\right)$

Helicity amplitudes:

$$H_V(\lambda) = -i\,N'\Big\{(C_9^{\rm eff} - C_9')\tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2}\Big[\frac{2\,\hat{m}_b}{m_B}(C_7^{\rm eff} - C_7')\tilde{T}_\lambda(q^2) - 16\pi^2\mathcal{N}_\lambda(q^2)\Big]\Big\}$$

$$H_A(\lambda) = -i\,N'(C_{10} - C_{10}')\tilde{V}_\lambda(q^2)$$

$$H_P = i\,N'\Big\{\frac{2\,m_\ell\hat{m}_b}{q^2}(C_{10} - C_{10}')\Big(1 + \frac{m_s}{m_b}\Big)\tilde{S}(q^2)\Big\}$$

Local contributions

Local contributions arise from local operators in the weak effective Hamiltonian

The dominant ones for $b \to s\ell^+\ell^-$ are the semileptonic operators O_9, O_{10}, and the dipole operator O_7

The hadronic matrix elements can be written in terms of form factors

The hadronic uncertainty is entirely in the form factors, which can be computed on the lattice or evaluated with QCD sum rules.

Non-local contributions

Non-local contributions come from insertions of four-quark operators into the amplitude, with a photon emitted and then converting into the $\ell^+\ell^-$ pair

This generates long-distance effects, especially in the regions of dilepton invariant mass squared near the charmonium resonances (J/Ψ, $J/\Psi(2S)$, ...)

They are very hard to calculate from first principles; one often models them (using dispersion relations, quark-hadron duality approximations, or experimental input)

They are a key source of theoretical uncertainty in angular observables like P_5'

Local contributions

Local contributions arise from local operators in the weak effective Hamiltonian

The dominant ones for $b \to s\ell^+\ell^-$ are the semileptonic operators O_9, O_{10}, and the dipole operator O_7

The hadronic matrix elements can be written in terms of form factors

The hadronic uncertainty is entirely in the form factors, which can be computed on the lattice or evaluated with QCD sum rules.

Non-local contributions

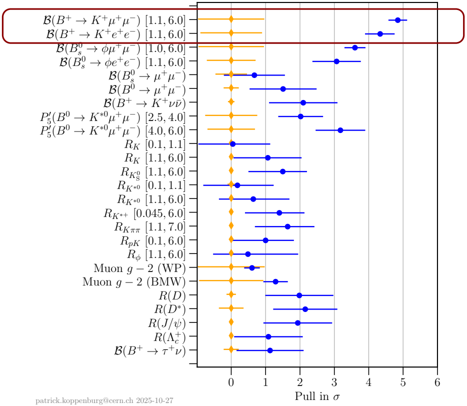
Non-local contributions come from insertions of four-quark operators into the amplitude, with a photon emitted and then converting into the $\ell^+\ell^-$ pair

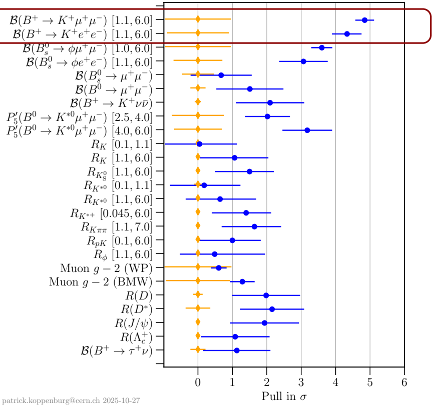
This generates long-distance effects, especially in the regions of dilepton invariant mass squared near the charmonium resonances (J/Ψ, $J/\Psi(2S)$, ...)

They are very hard to calculate from first principles; one often models them (using dispersion relations, quark-hadron duality approximations, or experimental input)

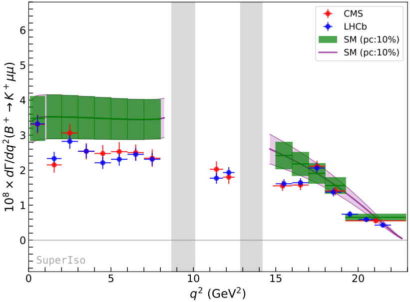
They are a key source of theoretical uncertainty in angular observables like P_5'

B "Anomalies": $B \to K\ell^+\ell^-$



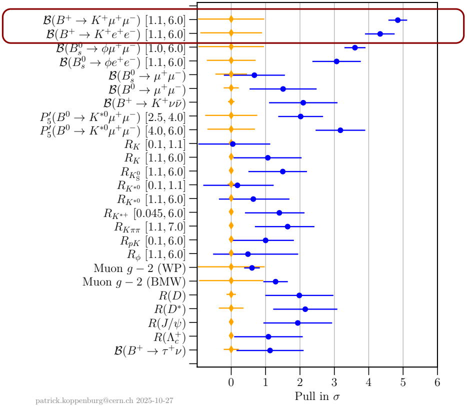


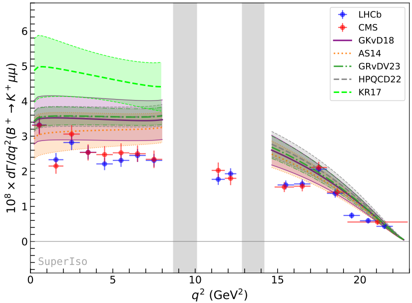
$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ [1.1, 6.0]
$\mathcal{B}(B^+ \to K^+e^+e^-)$ [1.1, 6.0]
$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$ [1.0, 6.0]
$\mathcal{B}(B_s^0 \to \phi e^+e^-)$ [1.1, 6.0]
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
$\mathcal{B}(B^0 \to \mu^+\mu^-)$
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$
$P_5'(B^0 \to K^{*0}\mu^+\mu^-)$ [2.5, 4.0]
$P_5'(B^0 \to K^{*0}\mu^+\mu^-)$ [4.0, 6.0]
R_K [0.1, 1.1]
R_K [1.1, 6.0]
$R_{K_S^0}$ [1.1, 6.0]
$R_{K^{*0}}$ [0.1, 1.1]
$R_{K^{*0}}$ [1.1, 6.0]
$R_{K^{*+}}$ [0.045, 6.0]
$R_{K\pi\pi}$ [1.1, 7.0]
R_{pK} [0.1, 6.0]
R_ϕ [1.1, 6.0]
Muon $g-2$ (WP)
Muon $g-2$ (BMW)
$R(D)$
$R(D^*)$
$R(J/\psi)$
$R(\Lambda_c^+)$
$\mathcal{B}(B^+ \to \tau^+\nu)$
0 1 2 3 4 5 6
Pull in σ
patrick.koppenburg@cern.ch 2025-10-27



CMS
LHCb
SM (pc:10%)
SM (pc:10%)
$10^8 \times d\Gamma/dq^2(B^+ \to K^+\mu\mu)$
q^2 (GeV^2)
SuperIso

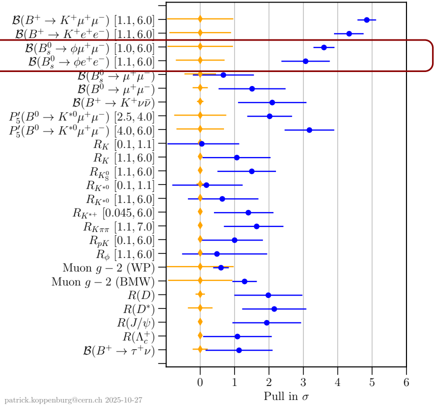
B “Anomalies”: $B \to K\ell^+\ell^-$



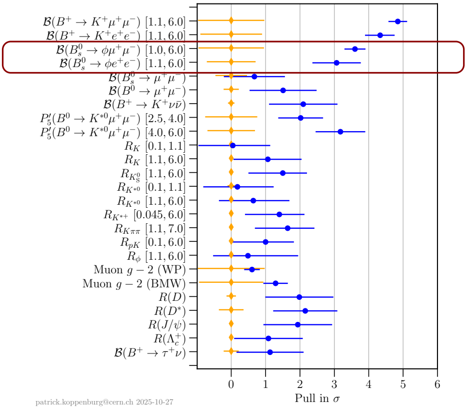


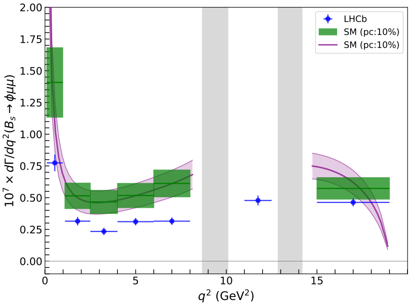
- **GKvD18**: **The combined LCSR (based on B-meson distribution amplitudes) and lattice QCD result from Gubernari et al. 2018, using lattice input from Bouchard et al. 2013.**
- **GRvDV23: The combined fit of Gubernari et al. 2023, based on LCSR calculations from Gubernari et al. 2018wyi and lattice QCD results from Bouchard et al. 2013, Bailey et al. 2015 and Parrott et al. 2022.**
- **HPQCD22: The lattice QCD result from Parrott et al. 2022, valid across the entire physical q^2 range.**
- **KR17: The results of Khodjamirian et al. 2017 calculated via LCSR with kaon distribution amplitude, applicable only for the low-q^2 region.**
- **AS14: The combination of LCSR results of Ball et al. 2004, Bartsch et al. 2009 and lattice input of Bouchard et al. 2013 used in Altmannshofer et al. 2014.**

B "Anomalies": $B_s \to \phi \ell^+ \ell^-$

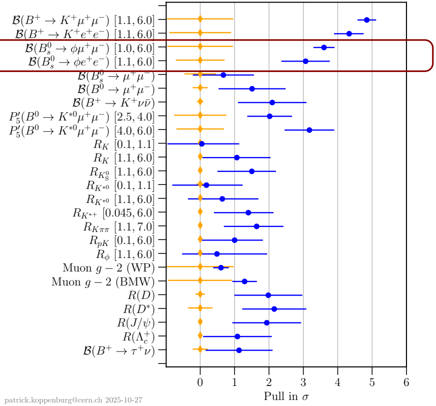


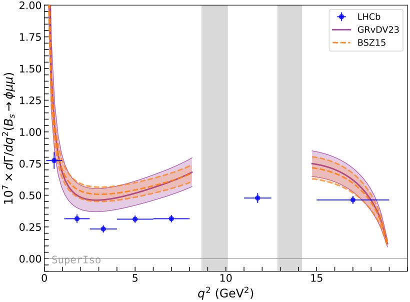
B "Anomalies": $B_s \to \phi\ell^+\ell^-$





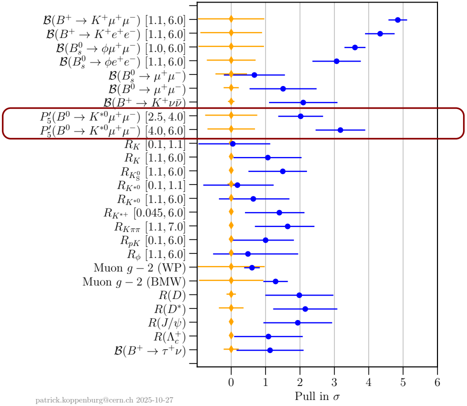
B “Anomalies”: $B_s \to \phi \ell^+ \ell^-$



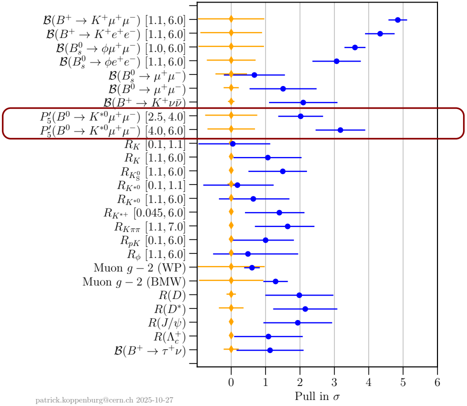


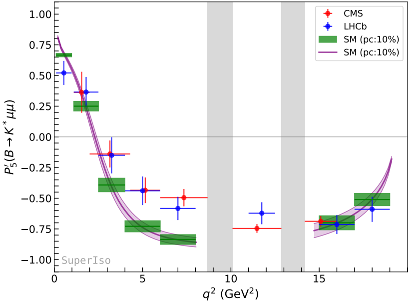
- **GRvDV23: The combined fit to lattice QCD data of Horgan et al. 2013, Horgan et al. 2015 and light-cone sum rule (LCSR) calculations of Gubernari et al. 2018 and Gubernari et al. 2020 with B-meson distribution amplitudes**
- **BSZ15: Based on a combined fit to the same lattice results and LCSR calculation with K^*-meson distribution amplitudes from Bharucha et al. 2015**

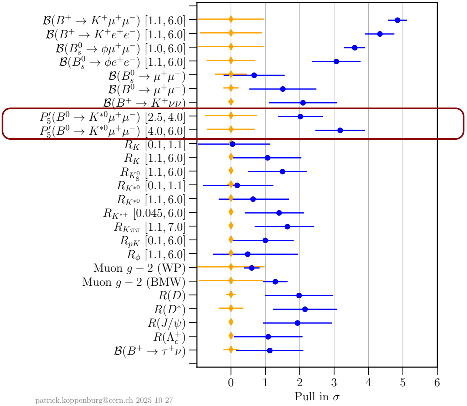
B "Anomalies": $B \to K^*\mu^+\mu^-$

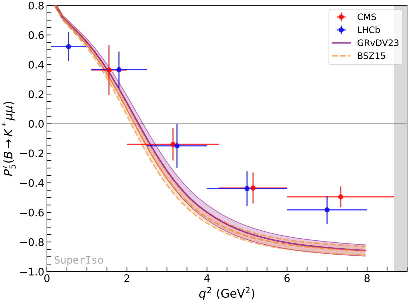


B “Anomalies”: $B \to K^* \mu^+ \mu^-$



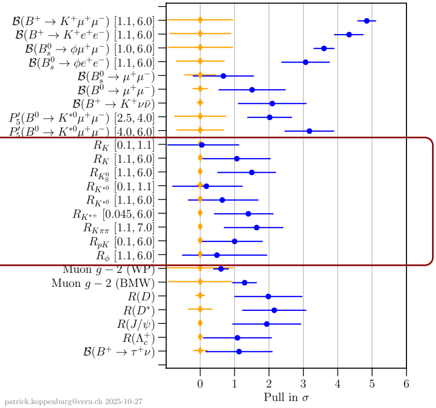


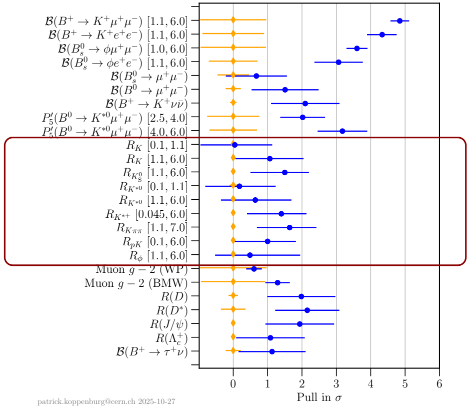




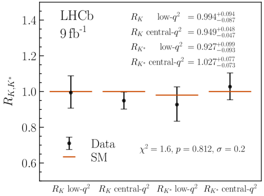
- **GRvDV23: The combined fit to lattice QCD data of Horgan et al. 2013, Horgan et al. 2015 and light-cone sum rule (LCSR) calculations of Gubernari et al. 2018 and Gubernari et al. 2020 with B-meson distribution amplitudes**
- **BSZ15: Based on a combined fit to the same lattice results and LCSR calculation with K^*-meson distribution amplitudes from Bharucha et al. 2015**

B "Anomalies": Lepton flavour universality ratios

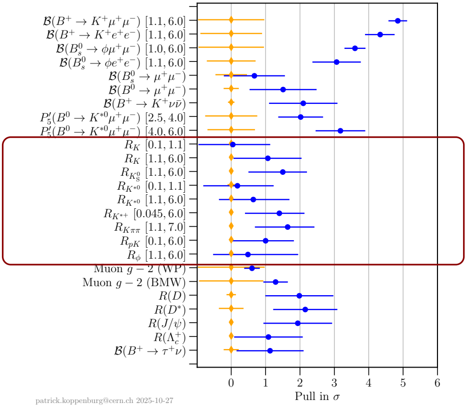




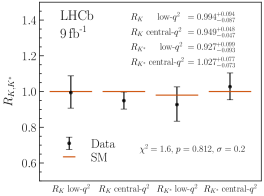
$$R_X = \frac{BR(B \to X\mu^+\mu^-)}{BR(B \to Xe^+e^-)}$$



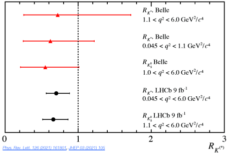
LHCb, PRL 131 (2023) 5, 051803

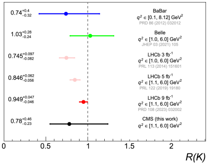


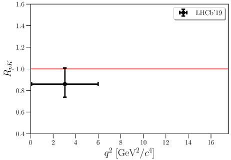
$$R_X = \frac{BR(B \to X\mu^+\mu^-)}{BR(B \to Xe^+e^-)}$$

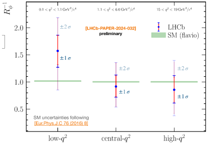


LHCb, PRL 131 (2023) 5, 051803









Rep. Prog. Phys. 87 (2024) 077802 JHEP 2020, 40 (2020) arXiv:2410.13748

Possible approaches:

- Work out a model-independent analysis of all $b \to s$ observables
  - Using a guesstimate of 10%, 50% or 100% for the uncertainty due to the non-factorisable power corrections
  - This serves as a placeholder for a robust estimate of these contributions
- Use data-driven approaches to get indications about the nature of the tensions

  $\to$ Make a fit to the data for these power corrections
- Comparison between NP fits and general hadronic fits to the low-q^2 region

Global fits of the observables obtained by minimisation of

$$\chi^2 = \left(\vec{O}^{\rm th} - \vec{O}^{\rm exp}\right) \cdot (\Sigma_{\rm th} + \Sigma_{\rm exp})^{-1} \cdot \left(\vec{O}^{\rm th} - \vec{O}^{\rm exp}\right)$$

$(\Sigma_{\rm th} + \Sigma_{\rm exp})^{-1}$ is the inverse covariance matrix.

263 observables relevant for radiative, leptonic and semileptonic decays:

- BR$(B \to X_s\gamma)$
- BR$(B \to K^*\gamma)$
- $\Delta_0(B \to K^*\gamma)$
- BR$^{\rm low}(B \to X_s\mu^+\mu^-)$
- BR$^{\rm high}(B \to X_s\mu^+\mu^-)$
- BR$^{\rm low}(B \to X_s e^+e^-)$
- BR$^{\rm high}(B \to X_s e^+e^-)$
- BR$(B_s \to \mu^+\mu^-)$
- BR$(B_s \to e^+e^-)$
- R_K in the low q^2 bin
- R_{K^*} in 2 low q^2 bins
- R_ϕ in low and high q^2 bins
- BR$(B \to K^0\mu^+\mu^-)$

- $B \to K^+\mu^+\mu^-$: BR, F_H
- $B \to K^*e^+e^-$: BR, F_L, $P_{1,2,3}$, $P'_{4,5,6,8}$ in [1.1, 6] bin (LHCb) and F_L, $A_T^{(2)}$, A_T^{Re} in [0.0008, 0.257] bin (LHCb) and $A_T^{(2)}$ in [0.008, 1.12] bin (Belle)
- $B \to K^{*0}\mu^+\mu^-$: BR, F_L, $P_{1,2,3}$, $P'_{4,5,6,8}$, S_1^c, S_2^s, S_6^c in low q^2 and high q^2 bins
- $B^+ \to K^{*+}\mu^+\mu^-$: BR, F_L, A_{FB}, S_3, S_4, S_5, S_7, S_8, S_9 in low q^2 and high q^2 bins
- $B_s \to \phi\mu^+\mu^-$: BR, F_L, S_3, S_4, S_7, $A_T^{(2)}$ in low q^2 and high q^2 bins
- $\Lambda_b \to \Lambda\mu^+\mu^-$: BR, A_{FB}^ℓ, A_{FB}^h, $A_{FB}^{\ell h}$, F_L in high q^2 bins
- $B_s \to \phi e^+e^-$: BR in low q^2 and high q^2 bin, and F_L, $A_T^{(2)}$ in [0.0009, 0.2615] bin

Computations performed using **SuperIso** public program

T. Hurth, FM, Y. Monceaux, S. Neshatpour, PRD 112 (2025) 11, 113003

Comparison of CMS and LHCb results

- Since the QCDf framework is only valid in the low-q^2 region below the charm threshold, $q^2 < 4m_c^2 \approx 7\,\mathrm{GeV}^2$, we don't consider the largest low-q^2 bins (i.e., $[6, 8]$ for LHCb and $[6, 8.68]$ for CMS)

- including a 10% guesstimate on the non-factorisable power corrections

T. Hurth, FM, Y. Monceaux, S. Neshatpour, PRD 112 (2025) 11, 113003

Comparison of CMS and LHCb results

- Since the QCDf framework is only valid in the low-q^2 region below the charm threshold, $q^2 < 4m_c^2 \approx 7\,\mathrm{GeV}^2$, we don't consider the largest low-q^2 bins (i.e., $[6, 8]$ for LHCb and $[6, 8.68]$ for CMS)

- including a 10% guesstimate on the non-factorisable power corrections

T. Hurth, FM, Y. Monceaux, S. Neshatpour, PRD 112 (2025) 11, 113003

Comparison of CMS and LHCb results

- Since the QCDf framework is only valid in the low-q^2 region below the charm threshold, $q^2 < 4m_c^2 \approx 7\,\mathrm{GeV}^2$, we don't consider the largest low-q^2 bins (i.e., $[6, 8]$ for LHCb and $[6, 8.68]$ for CMS)

- including a 10% guesstimate on the non-factorisable power corrections

Angular observables $P_i^{(\prime)}$ by CMS ($\chi^2_{\mathrm{SM}} = 39.0$)			
	b.f. value	χ^2_{min}	$\mathrm{Pull}_{\mathrm{SM}}$
δC_9	-0.56 ± 0.20	32.7	2.5σ
δC_{10}	-0.80 ± 0.50	36.6	1.6σ
$\{\delta C_9, \delta C_{10}\}$	$\delta C_9 = -0.55 \pm 0.25$ $\delta C_{10} = 0.00 \pm 0.50$	32.7	2.0σ

T. Hurth, FM, Y. Monceaux, S. Neshatpour, PRD 112 (2025) 11, 113003

Comparison of CMS and LHCb results

- Since the QCDf framework is only valid in the low-q^2 region below the charm threshold, $q^2 < 4m_c^2 \approx 7\,\mathrm{GeV}^2$, we don't consider the largest low-q^2 bins (i.e., $[6, 8]$ for LHCb and $[6, 8.68]$ for CMS)

- including a 10% guesstimate on the non-factorisable power corrections

Angular observables $P_i^{(\prime)}$ by CMS ($\chi^2_{\rm SM} = 39.0$)			
	b.f. value	$\chi^2_{\rm min}$	$\rm Pull_{SM}$
δC_9	-0.56 ± 0.20	32.7	2.5σ
δC_{10}	-0.80 ± 0.50	36.6	1.6σ
$\{\delta C_9, \delta C_{10}\}$	$\delta C_9 = -0.55 \pm 0.25$ $\delta C_{10} = 0.00 \pm 0.50$	32.7	2.0σ

Angular observables $P_i^{(\prime)}$ by LHCb 2020 ($\chi^2_{\rm SM} = 64.3$)			
	b.f. value	$\chi^2_{\rm min}$	$\rm Pull_{SM}$
δC_9	-0.66 ± 0.21	56.7	2.8σ
δC_{10}	-0.70 ± 0.50	62.1	1.5σ
$\{\delta C_9, \delta C_{10}\}$	$\delta C_9 = -0.63 \pm 0.24$ $\delta C_{10} = -0.10 \pm 0.50$	56.6	2.3σ

T. Hurth, FM, Y. Monceaux, S. Neshatpour, PRD 112 (2025) 11, 113003

Comparison of CMS and LHCb results

- Since the QCDf framework is only valid in the low-q^2 region below the charm threshold, $q^2 < 4m_c^2 \approx 7\,\mathrm{GeV}^2$, we don't consider the largest low-q^2 bins (i.e., [6, 8] for LHCb and [6, 8.68] for CMS)

- including a 10% guesstimate on the non-factorisable power corrections

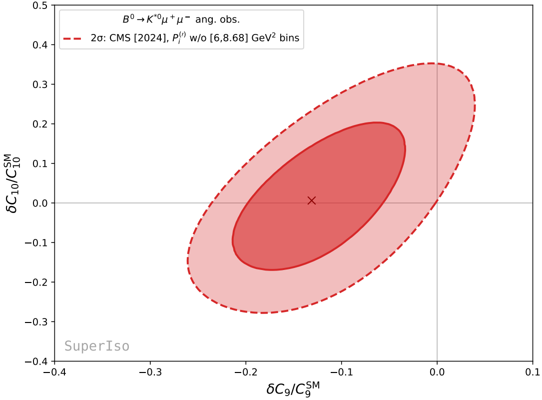
Angular observables $P_i^{(\prime)}$ by CMS ($\chi^2_{\rm SM} = 39.0$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-0.56 ± 0.20	32.7	2.5σ
δC_{10}	-0.80 ± 0.50	36.6	1.6σ
$\{\delta C_9,\, \delta C_{10}\}$	$\delta C_9 = -0.55 \pm 0.25$ $\delta C_{10} = 0.00 \pm 0.50$	32.7	2.0σ

Angular observables $P_i^{(\prime)}$ by LHCb 2025 ($\chi^2_{\rm SM} = 97.2$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-0.89 ± 0.14	74.2	5.4σ
δC_{10}	-1.02 ± 0.30	91.5	3.4σ
$\{\delta C_9,\, \delta C_{10}\}$	$\delta C_9 = -0.84 \pm 0.17$ $\delta C_{10} = -0.17 \pm 0.30$	73.9	5.1σ

Significant impact from the new LHCb results!

The 1 and 2σ C.L. of the $\{C_9, C_{10}\}$, **without** $[6, 8]$ and $[6., 8.68]$ GeV^2 bins

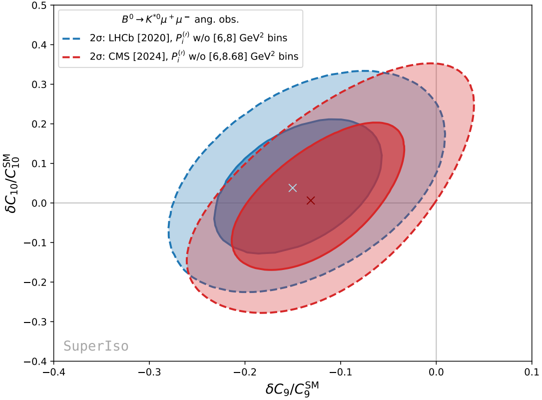
Using the measurements from LHCb and CMS separately



Red: CMS (pull$_{SM}$: 2σ)

The 1 and 2σ C.L. of the $\{C_9, C_{10}\}$, **without** $[6, 8]$ and $[6., 8.68]$ GeV^2 bins

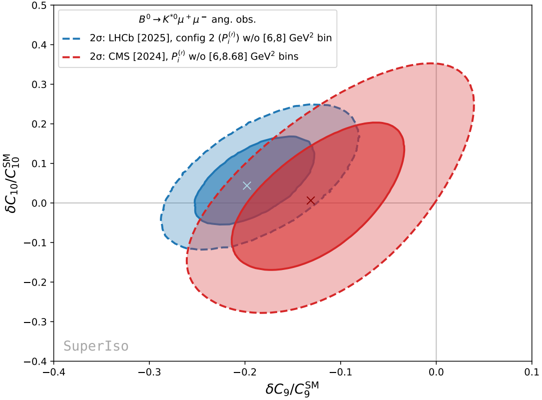
Using the measurements from LHCb and CMS separately



Red: CMS (pull$_{\rm SM}$: 2σ)
Blue: LHCb 2020 (pull$_{\rm SM}$: 2.3σ)

The 1 and 2σ C.L. of the $\{C_9, C_{10}\}$, **without** $[6, 8]$ and $[6., 8.68]$ GeV^2 bins

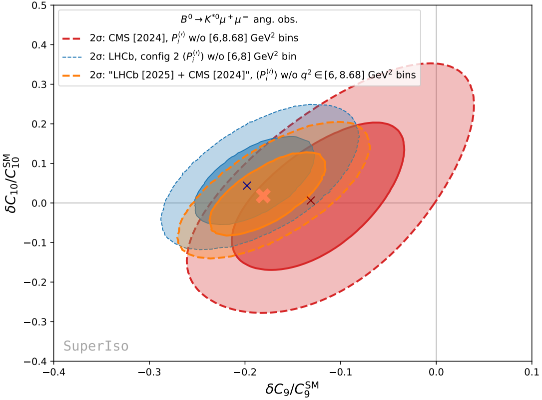
Using the measurements from LHCb and CMS separately



Red: CMS (pull$_{\rm SM}$: 2σ)
Blue: LHCb 2025 (pull$_{\rm SM}$: 5σ)

The 1 and 2σ C.L. of the $\{C_9, C_{10}\}$, **without** $[6, 8]$ and $[6., 8.68]$ GeV^2 bins

Combining LHCb and CMS results

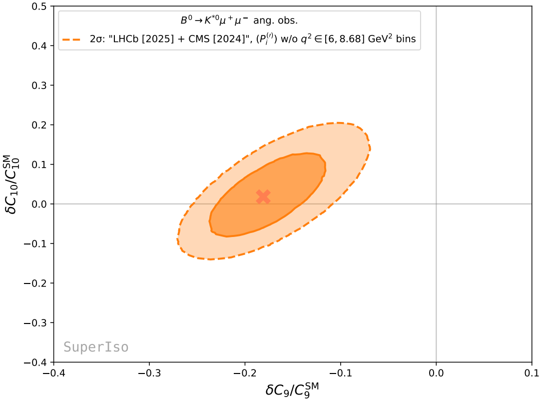


Blue: LHCb 2025 (pull$_{SM}$: 5σ)

Orange: LHCb+CMS (pull$_{SM}$: 4.9σ)

The 1 and 2σ C.L. of the $\{C_9, C_{10}\}$, **without** $[6, 8]$ and $[6., 8.68]$ GeV^2 bins

Combined LHCb and CMS results, impact of the choice of the form factors

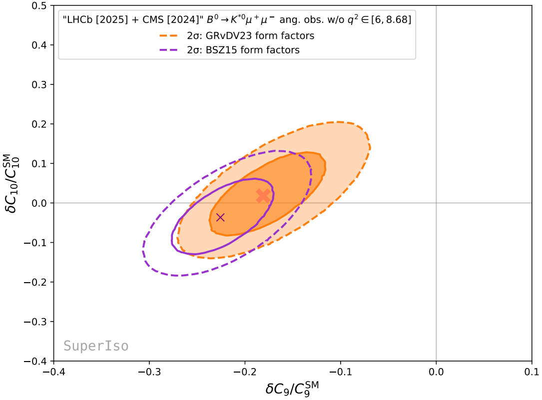


Orange: GRvDV23-FF (pull$_{\rm SM}$: 4.9σ)

The combined fit to lattice QCD data of Horgan et al. 2013, Horgan et al. 2015 and light-cone sum rule (LCSR) calculations of Gubernari et al. 2018 and Gubernari et al. 2020 with B-meson distribution amplitudes

The 1 and 2σ C.L. of the $\{C_9, C_{10}\}$, **without** $[6, 8]$ and $[6., 8.68]$ GeV^2 bins

Combined LHCb and CMS results, impact of the choice of the form factors

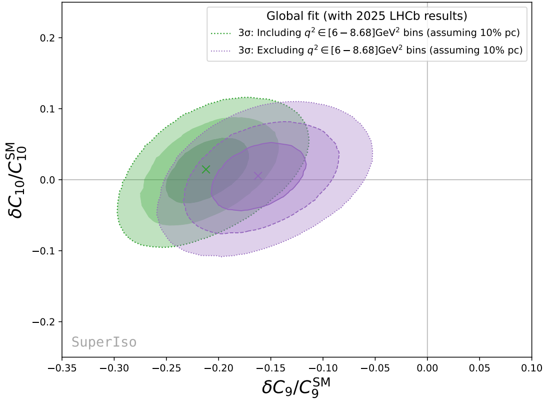


Purple contours : BSZ15-FF (pull$_{SM}$: 6σ)

Based on a combined fit to the same lattice results and LCSR calculation with K^*-meson distribution amplitudes from Bharucha et al. 2015

Two-dimensional fit of $\{C_9, C_{10}\}$ to **all** observables

Assuming a 10% uncertainty to the leading-order non-factorisable QCDf amplitude



Purple : Without $q^2 \in [6, 8.68]$ GeV^2 bins
Green : With $q^2 \in [6, 8.68]$ GeV^2 bins

How large the guesstimate of the non-local power corrections should be in order to accommodate the tensions?

$\rightarrow$ NP fits to all $b \rightarrow s\ell\ell$ observables excluding $q^2 \in [6, 8.68]$ GeV^2 bins

$\rightarrow$ Using GRvDV23 form factors for $B \rightarrow K^*, B_s \rightarrow \phi$ and GKvD18 for $B \rightarrow K$

$\rightarrow$ Assuming 10%, 50% and 100% power corrections from left to right

How large the guesstimate of the non-local power corrections should be in order to accommodate the tensions?

→ NP fits to all $b \to s\ell\ell$ observables excluding $q^2 \in [6, 8.68]$ GeV^2 bins
→ Using GRvDV23 form factors for $B \to K^*, B_s \to \phi$ and GKvD18 for $B \to K$
→ Assuming 10%, 50% and 100% power corrections from left to right

All observables except $q^2 \in$ [6-8.68] GeV^2 bins **10% pc** ($\chi^2_{\rm SM} = 329.3$)			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-0.69 ± 0.12	302.6	5.2σ
δC_{10}	-0.19 ± 0.12	326.9	1.5σ
$\{\delta C_9,\ \delta C_{10}\}$	$\delta C_9 = -0.69 \pm 0.12$ $\delta C_{10} = -0.01 \pm 0.13$	302.6	4.8σ

How large the guesstimate of the non-local power corrections should be in order to accommodate the tensions?

$\rightarrow$ NP fits to all $b \rightarrow s\ell\ell$ observables excluding $q^2 \in [6, 8.68]$ GeV^2 bins

$\rightarrow$ Using GRvDV23 form factors for $B \rightarrow K^*, B_s \rightarrow \phi$ and GKvD18 for $B \rightarrow K$

$\rightarrow$ Assuming 10%, 50% and 100% power corrections from left to right

All observables except $q^2 \in$ [6-8.68] GeV^2 bins **10% pc** ($\chi^2_{\rm SM} = 329.3$)			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-0.69 ± 0.12	302.6	5.2σ
δC_{10}	-0.19 ± 0.12	326.9	1.5σ
$\{\delta C_9, \delta C_{10}\}$	$\delta C_9 = -0.69 \pm 0.12$ $\delta C_{10} = -0.01 \pm 0.13$	302.6	4.8σ

All observables except $q^2 \in$ [6-8.68] GeV^2 bins **50% pc** ($\chi^2_{\rm SM} = 304.0$)			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-0.64 ± 0.17	293.8	3.2σ
δC_{10}	-0.03 ± 0.14	304.0	0.0σ
$\{\delta C_9, \delta C_{10}\}$	$\delta C_9 = -0.65 \pm 0.17$ $\delta C_{10} = 0.01 \pm 0.14$	293.8	2.7σ

Can power corrections explain the anomalies?

How large the guesstimate of the non-local power corrections should be in order to accommodate the tensions?

→ NP fits to all $b \to s\ell\ell$ observables excluding $q^2 \in [6, 8.68]$ GeV^2 bins
→ Using GRvDV23 form factors for $B \to K^*, B_s \to \phi$ and GKvD18 for $B \to K$
→ Assuming 10%, 50% and 100% power corrections from left to right

All observables except $q^2 \in$ [6-8.68] GeV^2 bins **10% pc** ($\chi^2_{\rm SM} = 329.3$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-0.69 ± 0.12	302.6	5.2σ
δC_{10}	-0.19 ± 0.12	326.9	1.5σ
$\{\delta C_9, \delta C_{10}\}$	$\delta C_9 = -0.69 \pm 0.12$ $\delta C_{10} = -0.01 \pm 0.13$	302.6	4.8σ

All observables except $q^2 \in$ [6-8.68] GeV^2 bins **50% pc** ($\chi^2_{\rm SM} = 304.0$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-0.64 ± 0.17	293.8	3.2σ
δC_{10}	-0.03 ± 0.14	304.0	0.0σ
$\{\delta C_9, \delta C_{10}\}$	$\delta C_9 = -0.65 \pm 0.17$ $\delta C_{10} = 0.01 \pm 0.14$	293.8	2.7σ

All observables except $q^2 \in$ [6-8.68] GeV^2 bins **100% pc** ($\chi^2_{\rm SM} = 291.4$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-0.56 ± 0.20	286.0	2.3σ
δC_{10}	0.05 ± 0.16	291.3	0.3σ
$\{\delta C_9, \delta C_{10}\}$	$\delta C_9 = -0.57 \pm 0.21$ $\delta C_{10} = 0.03 \pm 0.15$	286.0	1.8σ

Even 100% correction would not be sufficient to explain the anomalies!

New physics or underestimated hadronic power corrections?

$\rightarrow$ Derive a general ansatz for the non-factorisable power corrections

$$H_V(\lambda) = -i\,N'\left\{C_9^{\rm eff}\,\tilde{V}_\lambda - C_9'\,\tilde{V}_{-\lambda} + \frac{m_B^2}{q^2}\left[\frac{2\,\hat{m}_b}{m_B}(C_7^{\rm eff}\,\tilde{T}_\lambda - C_7'\,\tilde{T}_{-\lambda}) - 16\pi^2\mathcal{N}_\lambda\right]\right\}$$

$\left(N' = -\frac{4G_F m_B}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\right)$,

$\mathcal{N}_\lambda(q^2) =$ leading nonfact. $+\, h_\lambda$

The general ansatz for the unknown h_λ terms respecting the analyticity of the amplitude (up to higher-order terms in q^2) is:

$$h_\pm(q^2) = h_\pm^{(0)} + \frac{q^2}{1\,\mathrm{GeV}^2}h_\pm^{(1)} + \frac{q^4}{1\,\mathrm{GeV}^4}h_\pm^{(2)}$$

$$h_0(q^2) = \sqrt{q^2}\times\left(h_0^{(0)} + \frac{q^2}{1\,\mathrm{GeV}^2}h_0^{(1)} + \frac{q^4}{1\,\mathrm{GeV}^4}h_0^{(2)}\right)$$

$\rightarrow$ fit to the data for these power corrections

Hadronic power correction fit to $B \to K^* \gamma/\ell\ell$ observables for low-q^2 bins, with complex power corrections up to q^4 terms with 18 free parameters in total:

$B \to K^* \gamma/\ell\ell$ observables - $q^2 \leqslant 6$ GeV^2 bins ($\chi^2_{\rm QCDf} = 158.8$ $\chi^2_{\rm min} = 94.9$; ${\rm Pull}_{\rm QCDf} = 5.0\sigma$)		
	Real	Imaginary
$h_+^{(0)}$	$(0.0 \pm 5.0) \times 10^{-5}$	$(1.1 \pm 0.8) \times 10^{-4}$
$h_+^{(1)}$	$(-2.0 \pm 8.0) \times 10^{-5}$	$(-7.0 \pm 12.0) \times 10^{-5}$
$h_+^{(2)}$	$(1.7 \pm 2.0) \times 10^{-5}$	$(0.0 \pm 2.6) \times 10^{-5}$
$h_-^{(0)}$	$(-1.0 \pm 0.6) \times 10^{-4}$	$(-2.5 \pm 1.4) \times 10^{-4}$
$h_-^{(1)}$	$(5.0 \pm 6.0) \times 10^{-5}$	$(3.7 \pm 1.4) \times 10^{-4}$
$h_-^{(2)}$	$(7.0 \pm 12.0) \times 10^{-6}$	$(-8.5 \pm 3.2) \times 10^{-5}$
$h_0^{(0)}$	$(6.0 \pm 12.0) \times 10^{-5}$	$(3.7 \pm 1.6) \times 10^{-4}$
$h_0^{(1)}$	$(8.0 \pm 10.0) \times 10^{-5}$	$(-1.1 \pm 1.5) \times 10^{-4}$
$h_0^{(2)}$	$(-4.0 \pm 17.0) \times 10^{-6}$	$(-1.3 \pm 2.5) \times 10^{-5}$

$B \to K^* \gamma/\ell\ell$ observables - $q^2 \leqslant 8.68$ GeV^2 bins ($\chi^2_{\rm QCDf} = 269.8$ $\chi^2_{\rm min} = 133.6$; ${\rm Pull}_{\rm QCDf} = 9.2\sigma$)		
	Real	Imaginary
$h_+^{(0)}$	$(-2.0 \pm 4.0) \times 10^{-5}$	$(6.0 \pm 7.0) \times 10^{-5}$
$h_+^{(1)}$	$(4.0 \pm 7.0) \times 10^{-5}$	$(1.0 \pm 8.0) \times 10^{-5}$
$h_+^{(2)}$	$(-6.0 \pm 13.0) \times 10^{-6}$	$(-1.3 \pm 1.6) \times 10^{-5}$
$h_-^{(0)}$	$(-7.0 \pm 5.0) \times 10^{-5}$	$(-7.0 \pm 13.0) \times 10^{-5}$
$h_-^{(1)}$	$(1.0 \pm 4.0) \times 10^{-5}$	$(9.0 \pm 12.0) \times 10^{-5}$
$h_-^{(2)}$	$(1.5 \pm 0.5) \times 10^{-5}$	$(-9.0 \pm 26.0) \times 10^{-6}$
$h_0^{(0)}$	$(9.0 \pm 10.0) \times 10^{-5}$	$(3.8 \pm 1.3) \times 10^{-4}$
$h_0^{(1)}$	$(8.0 \pm 6.0) \times 10^{-5}$	$(-1.6 \pm 0.9) \times 10^{-4}$
$h_0^{(2)}$	$(-9.0 \pm 7.0) \times 10^{-6}$	$(1.0 \pm 1.1) \times 10^{-5}$

- Half of the fitted parameters in such a fit are still consistent with zero

- This is a large change to our previous corresponding analysis (2020) where almost all parameters were compatible with zero within the 1σ range

- There are still rather large uncertainties, we therefore expect that such a hadronic fit will improve further in the future

Improvement of the fits to $B \to K^* \gamma/\ell\ell$ observables for low-q^2 bins for the hadronic fit and the scenarios with real and complex NP contributions to Wilson coefficients C_7 and C_9 compared to the plain QCDf hypothesis and compared to each other:

$B \to K^* \gamma/\ell\ell$ observables - $q^2 \leqslant 6$ GeV^2 bins										
nr. of free parameters	1 (Real δC_9)	2 (Real $\delta C_7, \delta C_9$)	2 (Comp. δC_9)	4 (Comp. $\delta C_7, \delta C_9$)	3 (Real $\Delta C_9^{\lambda,\mathrm{PC}}$)	6 (Comp. $\Delta C_9^{\lambda,\mathrm{PC}}$)	6 (Real $h^{(0,1)}_{+,-,0}$)	9 (Real $h^{(0,1,2)}_{+,-,0}$)	12 (Comp. $h^{(0,1)}_{+,-,0}$)	18 (Comp. $h^{(0,1,2)}_{+,-,0}$)
0 (plain QCDf)	5.6	5.4	5.7	5.9	5.0	5.8	5.2	5.0	5.4	5.0
1 (Real δC_9)	—	1.3	2.3	3.0	0.5	3.1	2.0	2.0	2.7	2.5
2 (Real $\delta C_7, \delta C_9$)	—	—	—	3.1	—	—	1.9	1.9	2.7	2.5
2 (Comp. δC_9)	—	—	—	2.6	—	2.6	—	—	2.3	2.1
4 (Comp. $\delta C_7, \delta C_9$)	—	—	—	—	—	—	—	—	—	1.3
3 (Real $\Delta C_9^{\lambda,\mathrm{PC}}$)	—	—	—	—	—	3.5	2.4	2.2	3.0	2.7
6 (Comp. $\Delta C_9^{\lambda,\mathrm{PC}}$)	—	—	—	—	—	—	—	—	1.0	1.0
6 (Real $h^{(0,1)}_{+,-,0}$)	—	—	—	—	—	—	—	1.2	2.3	2.0
9 (Real $h^{(0,1,2)}_{+,-,0}$)	—	—	—	—	—	—	—	—	—	2.0
12 (Comp. $h^{(0,1)}_{+,-,0}$)	—	—	—	—	—	—	—	—	—	1.0

Adding hadronic parameters does not improve the fits significantly

The situation is still inconclusive!

How to resolve the issue?

1) Calculate the missing hadronic contributions

- Problem: they are not calculable in QCD factorisation
- Alternative approaches exist, e.g. based on light cone sum rule techniques, analyticity or empirical approaches

2) Cross-check with other $R_{\mu/e}$ ratios

- R ratios are theoretically very clean
- R_K and R_{K^*} are now SM-like, but several other ratios can be measured to cross check the results

3) The measurement of the electron modes will be very important

- R ratios impose lepton flavour universality
- Still several measurements in muon modes with significant deviations
  $\rightarrow$ the corresponding electron modes must show the same deviations!

1) Calculate the missing hadronic contributions

- Problem: they are not calculable in QCD factorisation
- Alternative approaches exist, e.g. based on light cone sum rule techniques, analyticity or empirical approaches

2) Cross-check with other $R_{\mu/e}$ ratios

- R ratios are theoretically very clean
- R_K and R_{K^*} are now SM-like, but several other ratios can be measured to cross check the results

3) The measurement of the electron modes will be very important

- R ratios impose lepton flavour universality
- Still several measurements in muon modes with significant deviations
  $\rightarrow$ the corresponding electron modes must show the same deviations!

How to resolve the issue?

1) Calculate the missing hadronic contributions

- Problem: they are not calculable in QCD factorisation
- Alternative approaches exist, e.g. based on light cone sum rule techniques, analyticity or empirical approaches

2) Cross-check with other $R_{\mu/e}$ ratios

- R ratios are theoretically very clean
- R_K and R_{K^*} are now SM-like, but several other ratios can be measured to cross check the results

3) The measurement of the electron modes will be very important

- R ratios impose lepton flavour universality
- Still several measurements in muon modes with significant deviations
  $\rightarrow$ the corresponding electron modes must show the same deviations!

4) Belle II measurements

- Measuring the branching rations and angular observables in $B \to K^{(*)}\ell\ell$ decays will allow direct verification of the LHCb result!
- Measurements of the tau modes (e.g. $b \to s\tau\tau$) will provide an additional and valuable insight
- Measurement of the inclusive modes
- Measurement of decays with neutrino final states

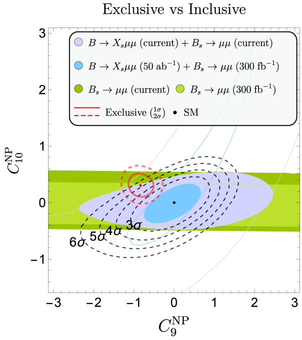
4) Belle II measurements

- Measuring the branching rations and angular observables in $B \to K^{(*)}\ell\ell$ decays will allow direct verification of the LHCb result!
- Measurements of the tau modes (e.g. $b \to s\tau\tau$) will provide an additional and valuable insight
- Measurement of the inclusive modes
- Measurement of decays with neutrino final states

Inclusive decays are theoretically cleaner!

→ Theoretical description of power corrections available
→ they can be calculated or estimated within the theoretical approach

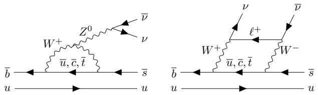
At Belle II, for inclusive $b \to s\ell\ell$:



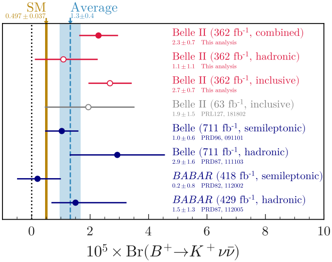
T. Hurth, FPCP 2023

→ Belle II will check the NP interpretation with theoretically clean modes

Branching ratio of $B^+ \to K^+ \nu\bar{\nu}$



2.7σ deviation with the SM



Belle II, Phys.Rev.D 109 (2024) 11, 112006

Theoretically very clean:

$$\frac{d\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})}{dq^2} = \tau_B \frac{G_F^2 \alpha^2 m_B^3}{256\pi^5} |V_{ts} V_{tb}|^2 \lambda_K^{3/2}(q^2)\, f_+^2(q^2)\, |C_L|^2$$

M. Bartsch, M. Beylich, G. Buchalla, D.-N. Gao, JHEP 11 (2009) 011

The ratio $\mathcal{B}(B \to K\mu^+\mu^-)/\mathcal{B}(B \to K\nu\bar{\nu})$ at low q^2 is very clean

$\rightarrow$ Can give access to the size of C_9^{eff}!

Flavour-Changing Neutral Current (FCNC): $s \to d\ell^+\ell^-$

$\to$ Sensitive to: CKM parameters, CP violation, New Physics

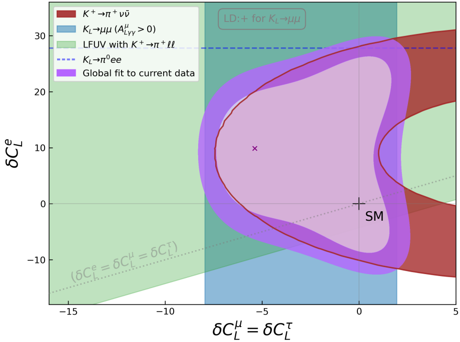
$\to$ Complementary to B physics

Different channels provide complementary information:

- $K^+ \to \pi^+\nu\nu$ and $K_L \to \pi^0\nu\nu$ are the golden channels, predicted in the SM with very high precision
- $K^+ \to \pi^+\ell^+\ell^-$: Forward-backward asymmetry offers a clean handle on scalar contributions; improved measurements will sharpen constraints
- $K_L \to \mu^+\mu^-$: Already imposes very strong limits; further progress requires reducing theoretical uncertainties
- $K_S \to \mu^+\mu^-$ and $K_L \to \pi^0\ell^+\ell^-$: Future measurements can significantly tighten bounds on scalar/pseudoscalar operators

Strong interplay between charged and neutral kaon modes (K^0, K^+) makes NA62, LHCb and KOTO-II highly complementary in probing possible new physics

Global fits

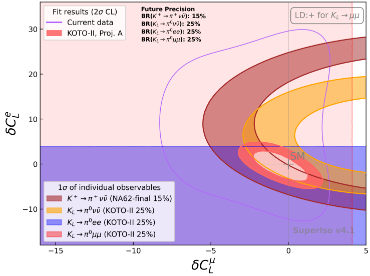


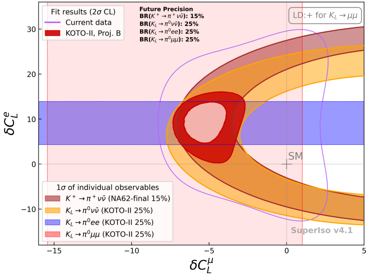
Lighter / darker purple region: 68% / 95% CL of global fit

Main constraining observables BR($K^+ \to \pi^+ \nu\nu$) followed by BR($K_L \to \mu\mu$)

G. D'Ambrosio, A.M. Iyer, FM, S. Neshatpour, JHEP 09 (2022) 148

Global fits - projections





Projection A:
Observables already measured are kept, others assumed at their SM values, all with target precision of KOTO-II

Projection B
All measurements give current best-fit point with target precision of KOTO-II

G. D'Ambrosio, A.M. Iyer, FM, S. Neshatpour, Phys.Rev.D 111 (2025) 1, L011701

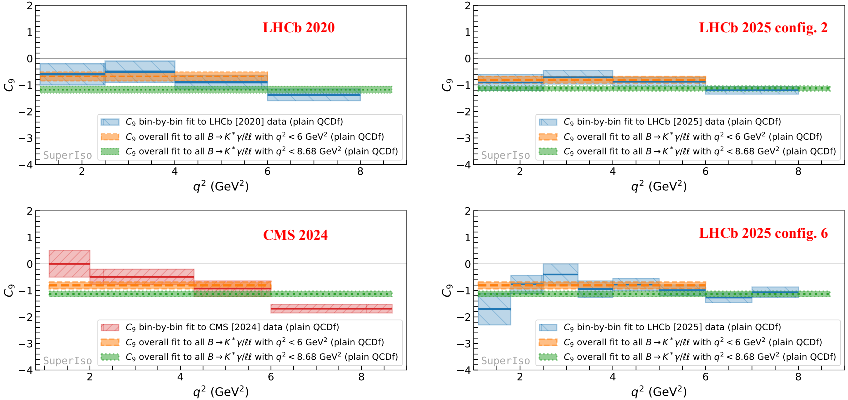
- Flavour physics remains a key probe of physics beyond the Standard Model
- Further progress requires improved theoretical control of hadronic quantities
- New and more precise experimental data will continue to sharpen these tests

Thank you!

Backup

q^2-independence of NP fit

Determination of the Wilson coefficients in a bin-by-bin fit



Not conclusive yet!

- Charged kaon modes are measured precisely (BR at $\sim 5\%$)
- Neutral kaon modes are much rarer: only upper limits (for K_L) or low-statistics signals (for K_S)

Results (NA48/2, NA62):

BR($K^+ \to \pi^+ e^+ e^-$) ~ 3×10^{-7}

BR($K^+ \to \pi^+ \mu^+ \mu^-$) ~ 1×10^{-7}

K_S (NA48/1)

B($K_S \to \pi^0 e^+ e^-$)=$(5.8^{+2.8}_{-2.3})\times10^{-9}$

B($K_S \to \pi^0 \mu^+ \mu^-$)=$(2.9^{+1.5}_{-1.2})\times10^{-9}$

Upper limits for K_L (KTeV)

BR($K_L \to \pi^0 e^+ e^-$) < 2.8×10^{-10} (90% CL)

BR($K_L \to \pi^0 \mu^+ \mu^-$) < 3.8×10^{-10} (90% CL)