Université Claude Bernard Lyon 1

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Data-driven analyses and model-independent fits for present $b \to s\ell\ell$ results

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Based on arXiv: 2508.09986

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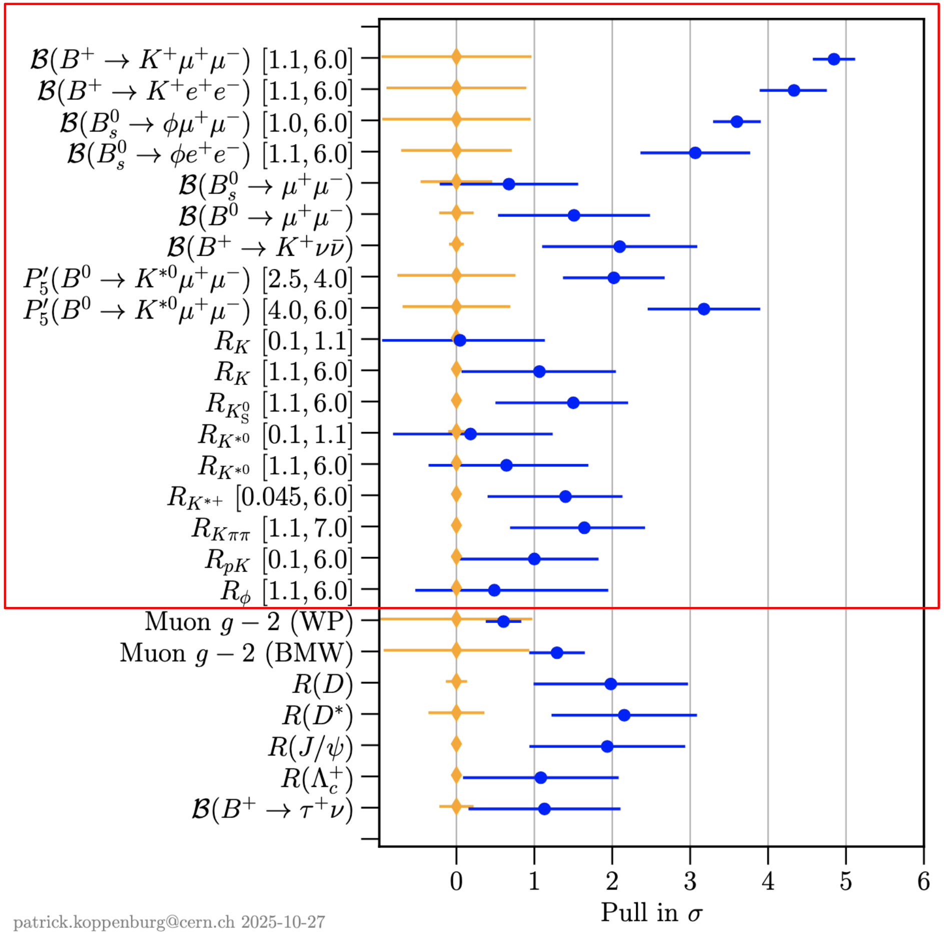
IRN Terascale @ Montpellier

24-26 November 2025

Introduction

- Rare decays of B mesons involving $b \to s\,\ell\ell$ transitions provide a powerful probe of new physics
- Loop- and CKM-suppressed in the Standard Model
  $\Rightarrow$ sensitive to BSM
- Persistent tension in measurement of branching fractions and angular distributions in $b \to s\,\ell\ell$ decays



Local and Non-local Matrix Elements

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum C_i O_i$$

1) Local contributions $\langle K^* \ell\ell | O_{7,9,10} | B \rangle \to$ form factors V_λ, T_λ, S

Calculations from Lattice QCD (high-q^2) and LCSR (low-q^2), with combined results over the full q^2 region

$$H_V(\lambda) = -iN' \Big\{ (C_9 - C_9') \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2} \Big[\frac{2\hat{m}_b}{m_B} (C_7^{\text{eff}} - C_7') \tilde{T}_\lambda(q^2) \Big] \Big\}$$

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

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

Local and Non-local Matrix Elements

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum C_i O_i$$

1) Local contributions $\langle K^* \ell\ell | O_{7,9,10} | B \rangle \rightarrow$ form factors V_λ, T_λ, S

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2) Non-local contributions ➝ in general "naïve" factorisation not applicable

Calculated at LO in QCDf [Beneke et al. '01 & '04], but higher powers unknown ("*guesstimated*")

↪ recent progress [van Dyk et al. '17 & '20]

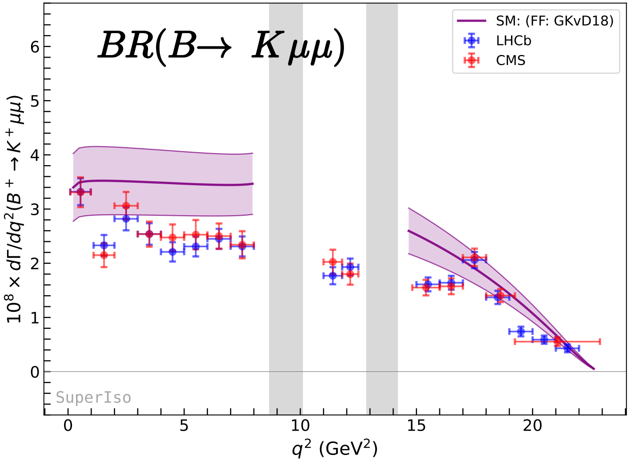
$$H_V(\lambda) = -iN' \Big\{ (C_9^{\text{eff}} - C_9') \tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2} \Big[\frac{2\hat{m}_b}{m_B} (C_7^{\text{eff}} - C_7') \tilde{T}_\lambda(q^2) - 16\pi^2 \mathcal{N}_\lambda(q^2) \Big] \Big\}$$

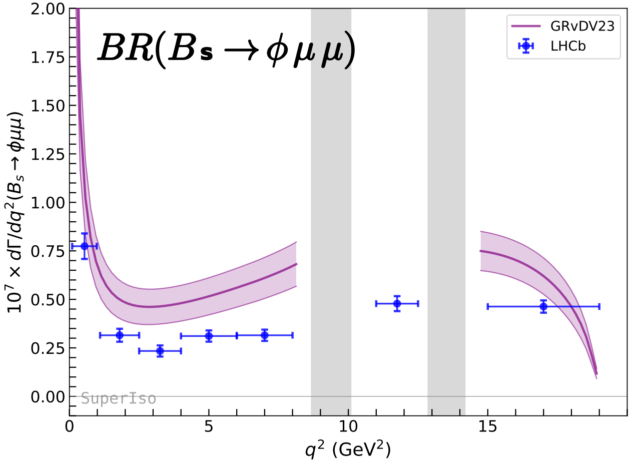
$$H_A(\lambda) = -iN' (C_{10} - C_{10}') \tilde{V}_\lambda(q^2)$$

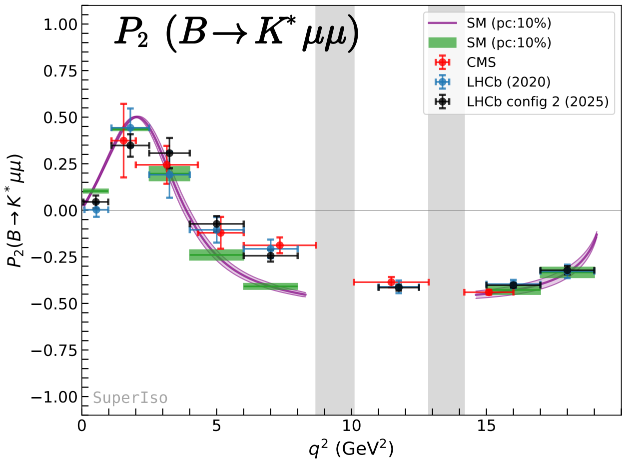
$$\mathcal{N}_\lambda(q^2) = \text{leading nonfact. QCDf } + h_\lambda$$

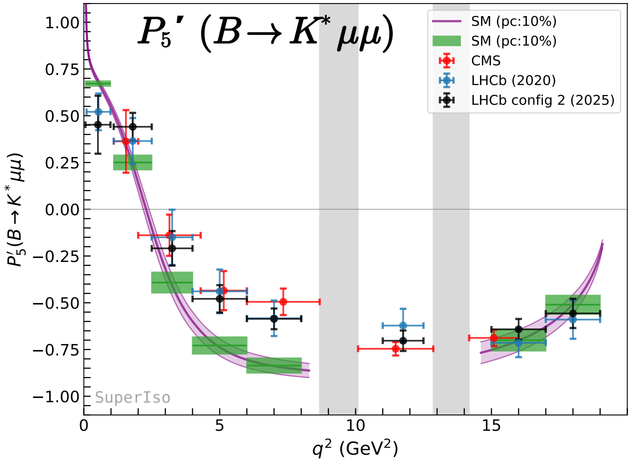
$$H_P = iN' \Big\{ \frac{2m_\ell \hat{m}_b}{q^2} (C_{10} - C_{10}') \Big(1 + \frac{m_s}{m_b} \Big) \tilde{S}(q^2) \Big\}$$

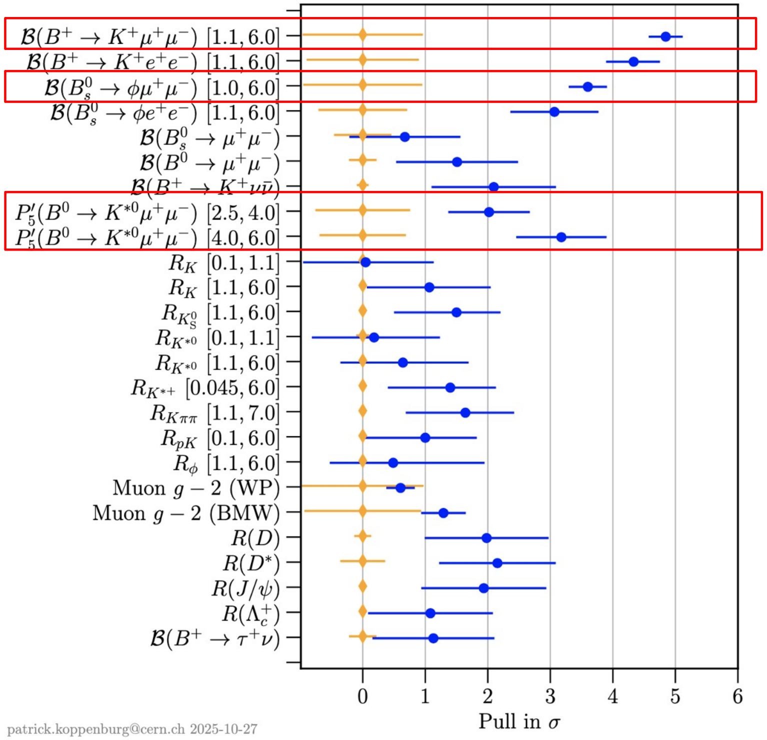
$b \to s\ell\ell$ anomalies











$b \to s$ observables

263 observables relevant for radiative, leptonic and semileptonic decays:

- $\mathrm{BR}(B \to X_s \gamma)$
- $\mathrm{BR}(B \to K^* \gamma)$
- $\Delta_0(B \to K^* \gamma)$
- $\mathrm{BR}^{\mathrm{low}}(B \to X_s \mu\mu)$
- $\mathrm{BR}^{\mathrm{high}}(B \to X_s \mu\mu)$
- $\mathrm{BR}^{\mathrm{low}}(B \to X_s ee)$
- $\mathrm{BR}^{\mathrm{high}}(B \to X_s ee)$
- $\mathrm{BR}(B_s \to \mu\mu)$
- $\mathrm{BR}(B_s \to ee)$
- 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
- $\mathrm{BR}(B \to K^0 \mu\mu)$

- $B \to K^+ \mu\mu$: BR, F_H in low and high q^2 bins (LHCb config. 2)
- $B \to K^* ee$: BR, $F_L, P_{1,2,3}, P'_{4,5,6,8}$ in [1.1, 6] bin (LHCb) and $F_L, A_T^{(2)}, A_T^{\mathrm{Re}}$ 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 and high q^2 bins
- $B \to K^{*+} \mu\mu$: BR, $F_L, A_{FB}, S_{3,4,5,7,8,9}$ in low and high q^2 bins
- $B_s \to \phi\mu\mu$: BR, $F_L, S_{3,4,7}$ in low and high q^2 bins
- $B_s \to \phi ee$: BR in low and high q^2bins and $F_L, A_T^{(2)}$ in [0.0009, 0.2615] bin
- $\Lambda_b \to \Lambda\mu\mu$: BR, $A_{FB}^{\ell}, A_{FB}^{h}, A_{FB}^{\ell h}$ in high q^2bins

Global Fit

Many observables interconnected via Wilson coefficients $\Rightarrow$ Global fit

Minimisation of χ^2, scanning over the values of δC_i

$$\chi^2 = \sum_{i,j=1}^{N} \left[O_i^{\rm th}(\delta C_i) - O_i^{\rm exp}\right] \; C_{ij}^{-1} \; \left[O_j^{\rm th}(\delta C_i) - O_j^{\rm exp}\right]$$

C: covariance matrix

$$C_{i,j} = {\rm Cov}_{\rm th}(O_i, O_j) + {\rm Cov}_{\rm exp}(O_i, O_j)$$

Theoretical uncertainties and correlations

- Evaluation of C, varying the input parameters: masses, scales, CKM, decay constant, form factors
- Parameterization of uncertainties due to power corrections:

$$\begin{array}{c}\text{Leading Order QCDf}\\ \text{of non-factorisable piece}\end{array} \times \left(1 + a_k \exp(i\phi_k) + b_k \frac{q^2}{6\,{\rm GeV}^2} \exp(i\theta_k)\right), \quad a_k = 10\%, \; b_k = \; 2.5 a_k$$

Computations performed using SuperIso public program

Fit to $B \to K^* \mu\mu$ angular observables

Comparison of CMS and LHCb results

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

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Angular observables $P_i^{(\prime)}$ by LHCb 2020 ($\chi^2_{\rm SM} = 64.3$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
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

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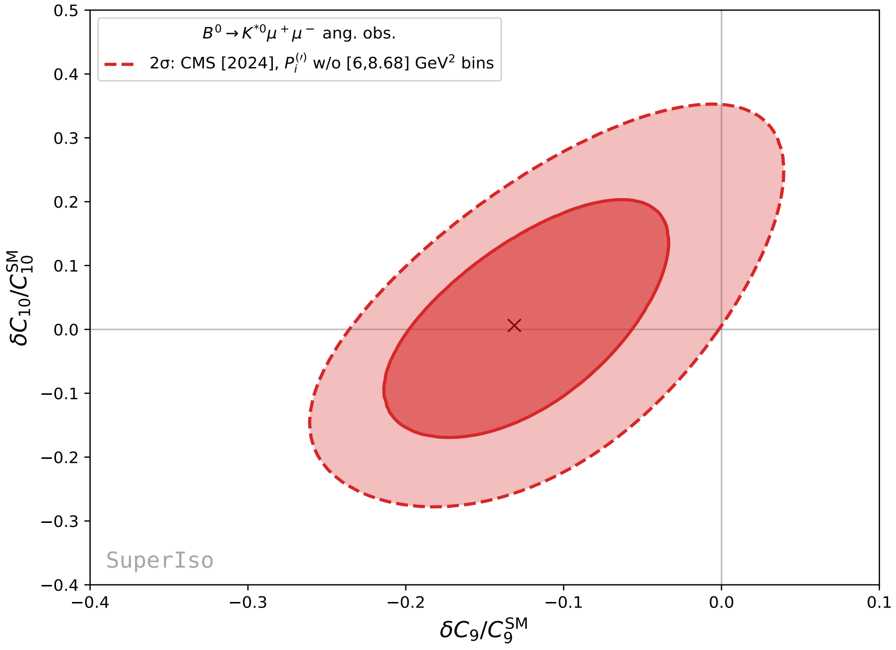
Angular observables $P_i^{(\prime)}$ by LHCb 2025 ($\chi^2_{\rm SM} = 97.2$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-0.89 ± 0.14	74.2	5.4σ
δC_{10}	-1.02 ± 0.30	91.5	3.4σ
$\{\delta C_9,\, \delta C_{10}\}$	$\delta C_9 = -0.84 \pm 0.17$ $\delta C_{10} = -0.17 \pm 0.30$	73.9	5.1σ

Significant impact from the new LHCb results!

Fit to $B \to K^* \mu\mu$ angular observables

1 and 2σ C.L. of the $\{C_9, C_{10}\}$ fit, excluding [6, 8] and [6, 8.68] GeV^2

Using measurments from CMS and LHCb separately



Red: CMS $(\mathrm{pull}_{\mathrm{SM}}\!: 2\sigma)$

Fit to $B \to K^* \mu\mu$ angular observables

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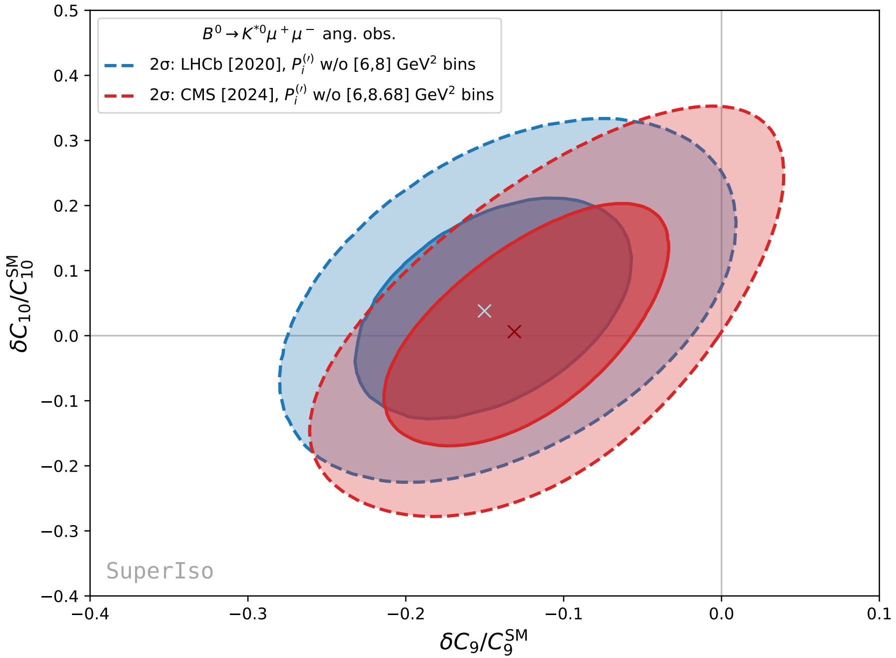


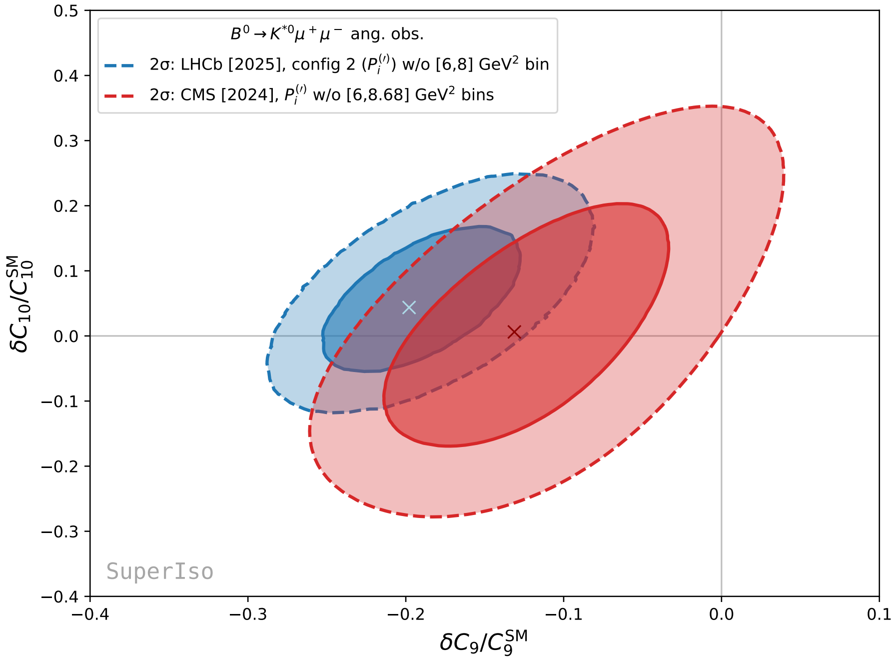
Red: CMS $(\mathrm{pull}_{\rm SM}\!: 2\sigma)$

Blue: LHCb 2020 $(\mathrm{pull}_{\rm SM}\!: 2.3\sigma)$

Fit to $B \to K^* \mu\mu$ angular observables

1 and 2σ C.L. of the $\{C_9, C_{10}\}$ fit, excluding [6, 8] and [6, 8.68] GeV^2

Using measurments from CMS and LHCb separately



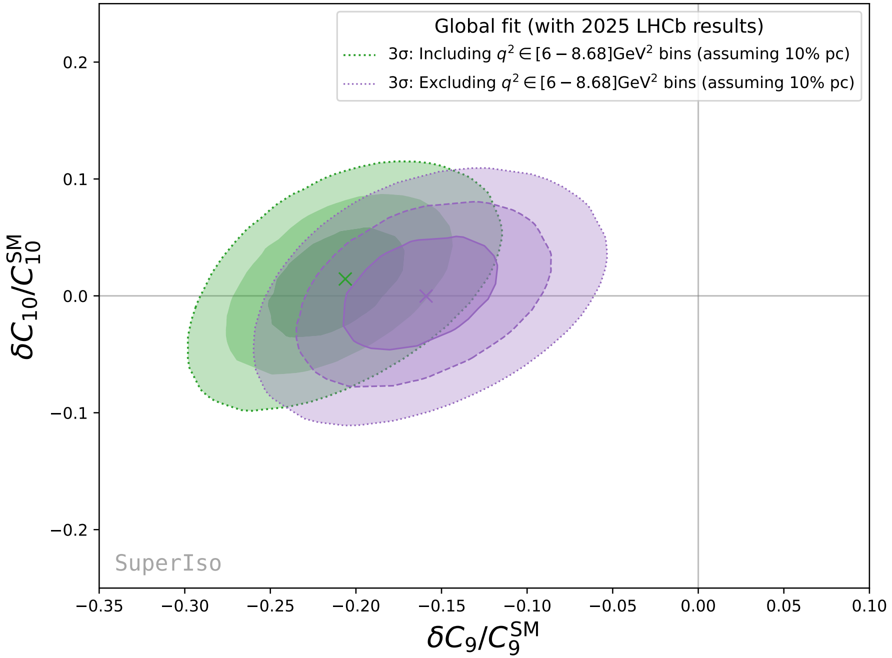
Red: CMS $(\mathrm{pull}_{\mathrm{SM}}\colon 2\sigma)$

Blue: LHCb 2025 $(\mathrm{pull}_{\mathrm{SM}}\colon 5\sigma)$

Global fit

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

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



Purple: Excluding $q^2 \in [6, 8.68]\ \ \mathrm{GeV}^2\ \ \mathrm{bins}$

Green: Including $q^2 \in [6, 8.68]\ \ \mathrm{GeV}^2\ \ \mathrm{bins}$

Global fit – role of power corrections

How will larger assumption for the size of the power corrections impact the fits?

- Using all $b \to s$ observables excluding q² ∈ [6, 8.68] GeV² bins
- Employing GvDV23 form factors for $B \to K^*, B_s \to \phi$ and GKvD18 for $B \to K$
- Considering 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% power correction would not be sufficient to explain the anomalies!

Data-driven analyses

New physics or underestimated hadronic power corrections?

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Instead of making assumptions on the size of the power corrections (h_λ) they can be parameterized by a general ansatz (compatible with the analycity structure):

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

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Fit to $B \to K^* \gamma/\ell\ell$ observables for low-q² bins

$B \to K^* \gamma/\ell\ell$ observables - $q^2 \leqslant 6$ GeV² 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 - $q^2 \leqslant 8.68$ GeV² 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 is still inconsistent with zero
- Still rather large uncertainty, we therefore expect that such a hadronic fit will improve further in the future

Data-driven analyses

New physics or underestimated hadronic power corrections?

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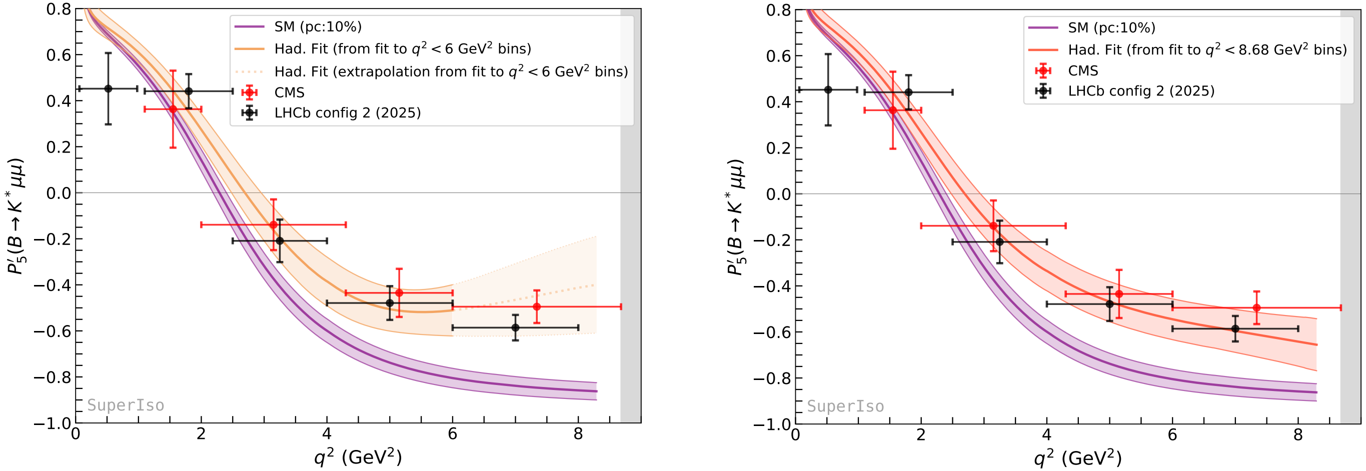
$$h_\pm(q^2) = h_\pm^{(0)} + \frac{q^2}{1\ \text{GeV}^2} h_\pm^{(1)} + \frac{q^4}{1\ \text{GeV}^4} h_\pm^{(2)}, \quad h_0(q^2) = \sqrt{q^2} \times h_0^{(0)} + \frac{q^2}{1\ \text{GeV}^2} h_0^{(1)} + \frac{q^4}{1\ \text{GeV}^4} h_0^{(2)}$$

Fit to $B \to K^* \gamma/\ell\ell$ observables for low-q² bins



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Data-driven analyses

Improvement of fits to $B \to K^* \gamma/\ell\ell$ observables for low-q² bins, for hadronic and NP scenarios compared 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 $h_{+,-,0}^{(0,1)}$)	9 (Real $h_{+,-,0}^{(0,1,2)}$)	12 (Comp. $h_{+,-,0}^{(0,1)}$)	18 (Comp. $h_{+,-,0}^{(0,1,2)}$)
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 $h_{+,-,0}^{(0,1)}$)	—	—	—	—	—	—	—	1.2	2.3	2.0
9 (Real $h_{+,-,0}^{(0,1,2)}$)	—	—	—	—	—	—	—	—	—	2.0
12 (Comp. $h_{+,-,0}^{(0,1)}$)	—	—	—	—	—	—	—	—	—	1.0

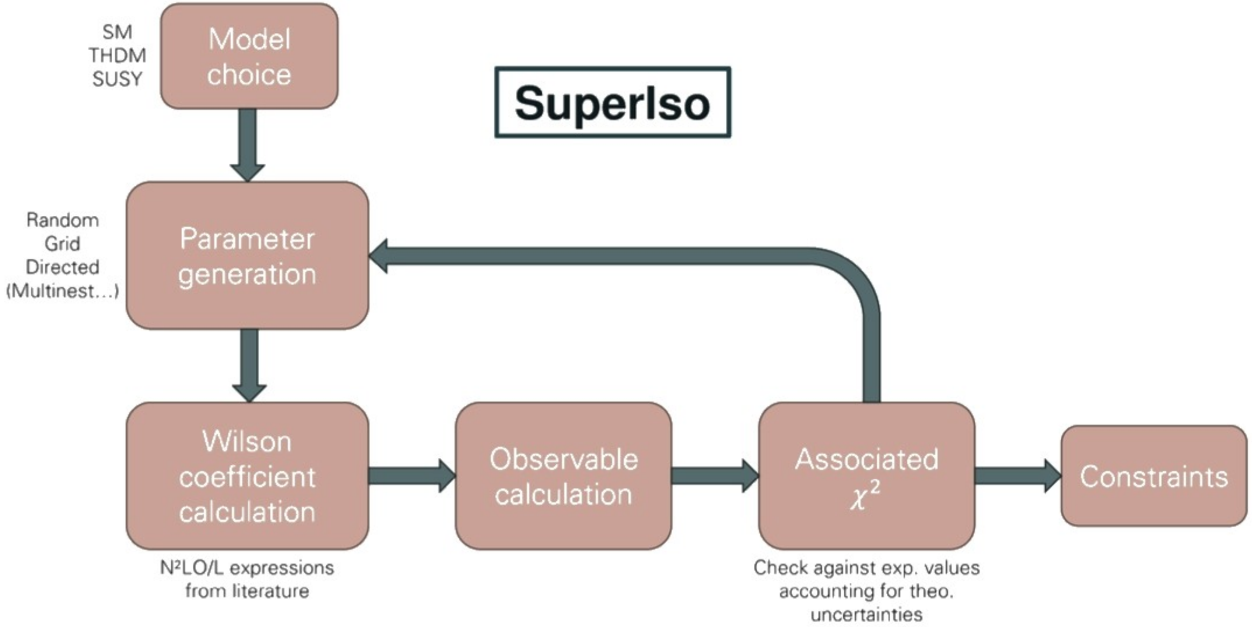
Adding hadronic parameters does not improve the fits significantly

The situation is still inconclusive!

SuperIso

- public C program
- dedicated to the flavour physics observable calculations
- user manual available (~200 pages)
- Key features: precision and simplicity of use

http://superiso.in2p3.fr



[F. Mahmoudi, Comput. Phys. Commun. 178 (2008) 745 – 180 (2009) 1579 – 180 (2009) 1718; F. Mahmoudi and SN PoS TOOLS2020 (2021) 036]

SuperIso

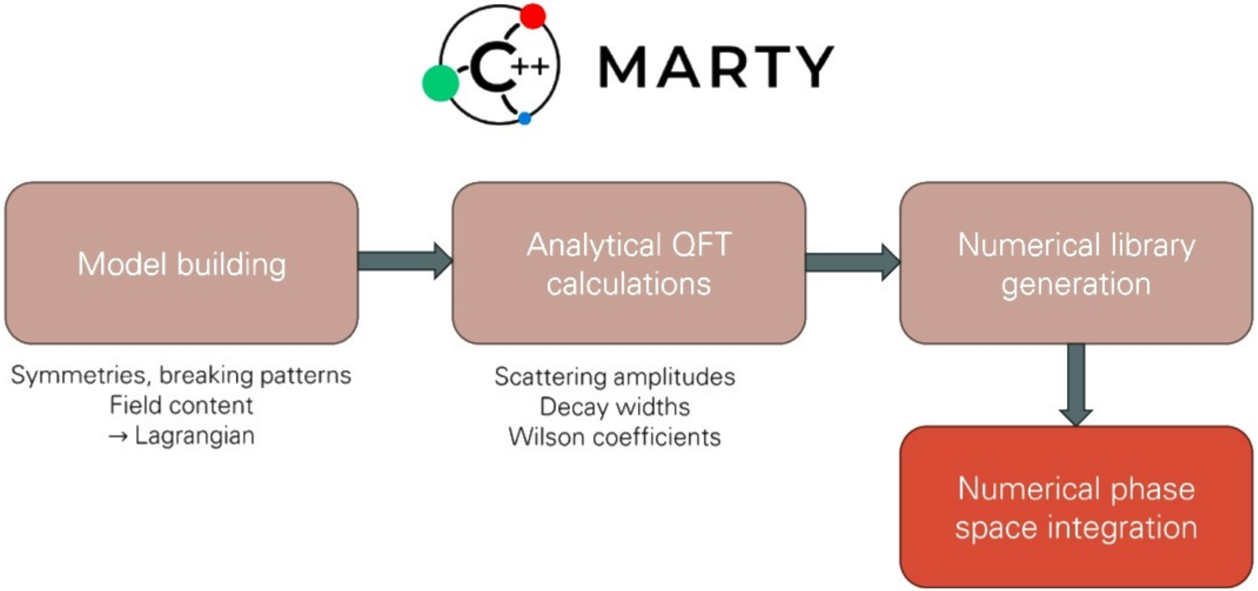
New release: `SuperIso_v5.0` http://superiso.in2p3.fr

- Comprehensive Physics Updates
  - Updated CKM parameters, form factors, masses, ...
  - Added new angular observables for $B \to K^* \ell\ell$ and $B_s \to \phi\ell\ell$, including CP-asymmetries
- Expanded Decay Channels
  - Addition of $K_L \to \pi^0 \ell\ell$ decay observables
  - Inclusion of lepton flavor choice for $K_L \to \ell\ell$
- Flexible Form Factor Options
  - Multiple new form factor sets for $B \to K^*, B_s \to \phi$ and $B \to K$ decays:
- New Routines to Facilitate Calculations
  - `predict.c`: generate SM or NP predictions with uncertainties interactively
  - `scan_coeffs.c`: scanning over Wilson coefficients

MARTY

- public C++ program, Mathematica-independent
- Designed for general BSM phenomenology
- Provides high-level Model Building utilities
- Tree-level and one-loop calculations for Amplitudes, Squared amplitudes and Wilson coefficients

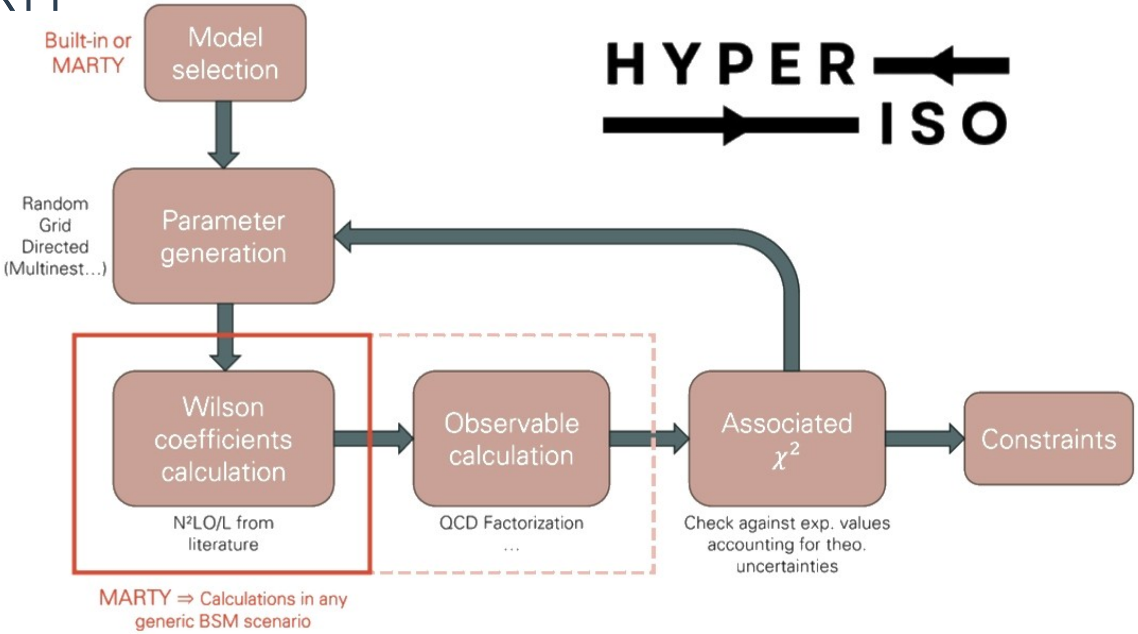
http://marty.in2p3.fr



[G. Uhlrich, F. Mahmoudi, A. Arbey, Comput. Phys. Commun. 264 (2021) 107928]

HyperIso

- C++ overhaul of SuperIso. Workflow diagram unchanged
- Various optimizations
- Reproduces SuperIso's results for the Wilson Coefficients (in SM, THDM and SUSY) and observables
- Greater flexibility and model-independence
- Seamless connection to MARTY



[N. Fardeau, FM, T. Reymermier, to be released soon]

Summary

- Several persisting deviations from the theoretical predictions in b → sll transitions since 2013
- Independent measurements indicate tension with "*theory*" prediction
- If deviations due to new physics, C_9 continues to be the Wilson coefficient which can best explain the deviations

New Physics or Not New Physics?

- ▸ More theoretical work is needed to assess the hadronic uncertainties!
- ▸ And of course more data!

Thank you

Data-driven analyses

Improvement of fits to $B \to K^* \gamma/\ell\ell$ observables for low-q² bins, for hadronic and NP scenarios compared 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 $h_{+,-,0}^{(0,1)}$)	9 (Real $h_{+,-,0}^{(0,1,2)}$)	12 (Comp. $h_{+,-,0}^{(0,1)}$)	18 (Comp. $h_{+,-,0}^{(0,1,2)}$)
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 $h_{+,-,0}^{(0,1)}$)	—	—	—	—	—	—	—	1.2	2.3	2.0
9 (Real $h_{+,-,0}^{(0,1,2)}$)	—	—	—	—	—	—	—	—	—	2.0
12 (Comp. $h_{+,-,0}^{(0,1)}$)	—	—	—	—	—	—	—	—	—	1.0

- with $q^2 < 6\ \mathrm{GeV}^2$ data: adding 17 more parameters for the hadronic fit compared to NP in C9 improves by 2.5σ

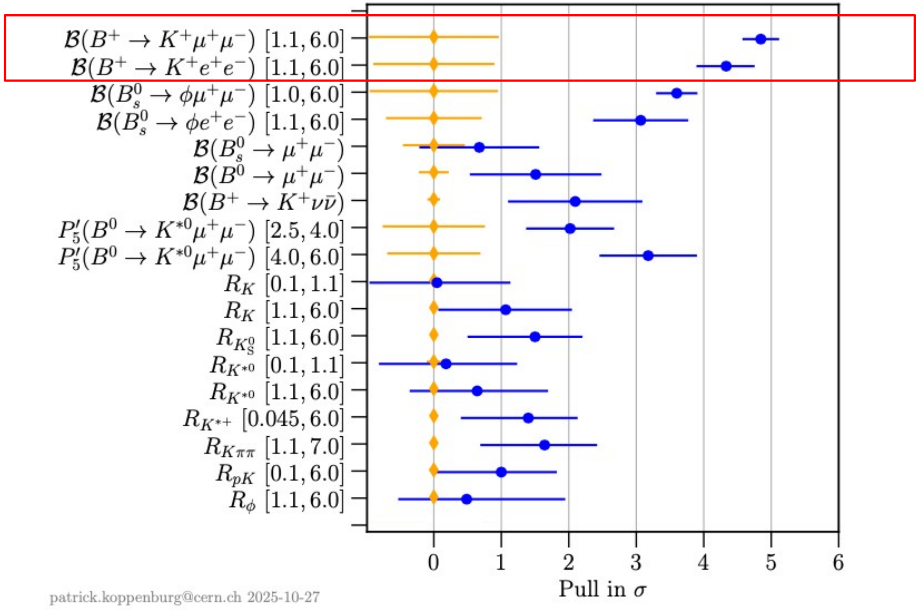
Data-driven analyses

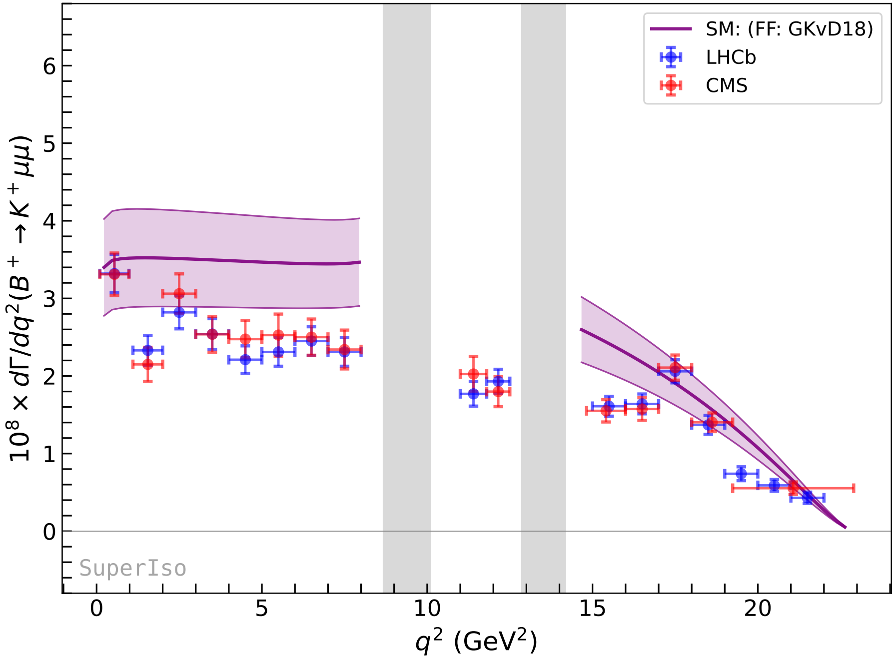
Improvement of fits to $B \to K^* \gamma/\ell\ell$ observables for low-q² bins, for hadronic and NP scenarios compared the plain QCDf hypothesis and compared to each other:

$B \to K^* \gamma/\ell\ell$ observables - $q^2 \leqslant 8.68$ 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 $h_{+,-,0}^{(0,1)}$)	9 (Real $h_{+,-,0}^{(0,1,2)}$)	12 (Comp. $h_{+,-,0}^{(0,1)}$)	18 (Comp. $h_{+,-,0}^{(0,1,2)}$)
0 (plain QCDf)	8.8	8.6	9.3	9.7	8.6	9.5	8.8	9.0	9.1	9.2
1 (Real δC_9)	—	1.4	3.9	4.8	1.9	4.6	3.1	3.9	4.3	4.8
2 (Real $\delta C_7, \delta C_9$)	—	—	—	4.9	—	—	3.1	3.9	4.3	4.8
2 (Comp. δC_9)	—	—	—	3.4	—	3.2	—	—	3.0	3.7
4 (Comp. $\delta C_7, \delta C_9$)	—	—	—	—	—	—	—	—	—	2.7
3 (Real $\Delta C_9^{\lambda,\mathrm{PC}}$)	—	—	—	—	—	4.6	2.9	3.7	4.1	4.7
6 (Comp. $\Delta C_9^{\lambda,\mathrm{PC}}$)	—	—	—	—	—	—	—	—	1.3	2.6
6 (Real $h_{+,-,0}^{(0,1)}$)	—	—	—	—	—	—	—	2.8	3.3	4.0
9 (Real $h_{+,-,0}^{(0,1,2)}$)	—	—	—	—	—	—	—	—	—	3.3
12 (Comp. $h_{+,-,0}^{(0,1)}$)	—	—	—	—	—	—	—	—	—	2.7

- with $q^2 < 6\ \mathrm{GeV}^2$ data: adding 17 more parameters for the hadronic fit compared to NP in C9 improves by 2.5σ
- with $q^2 < 8.68\ \mathrm{GeV}^2$ data: adding 17 more parameters for the hadronic fit compared to NP in C9 improves by 4.8σ

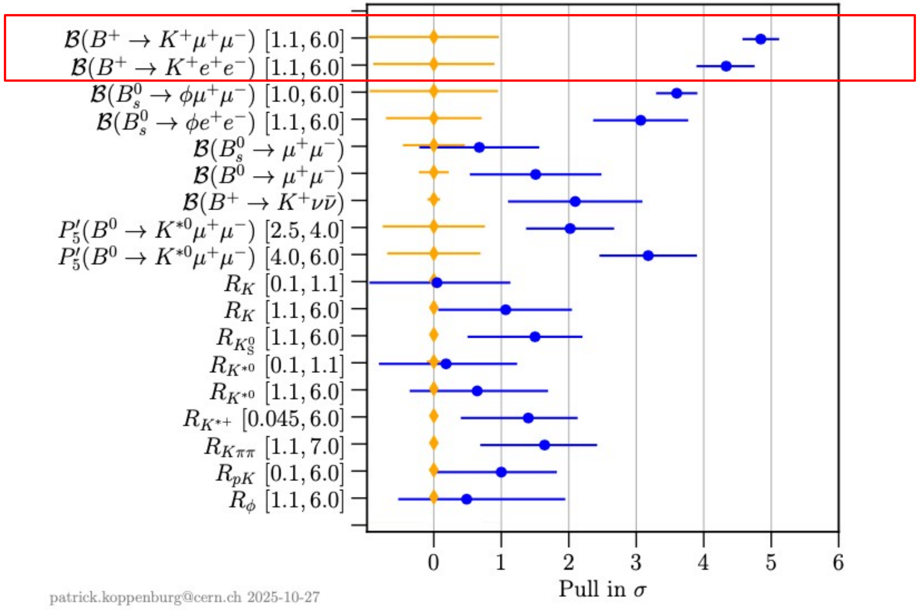
BR($B \to K\mu\mu$)

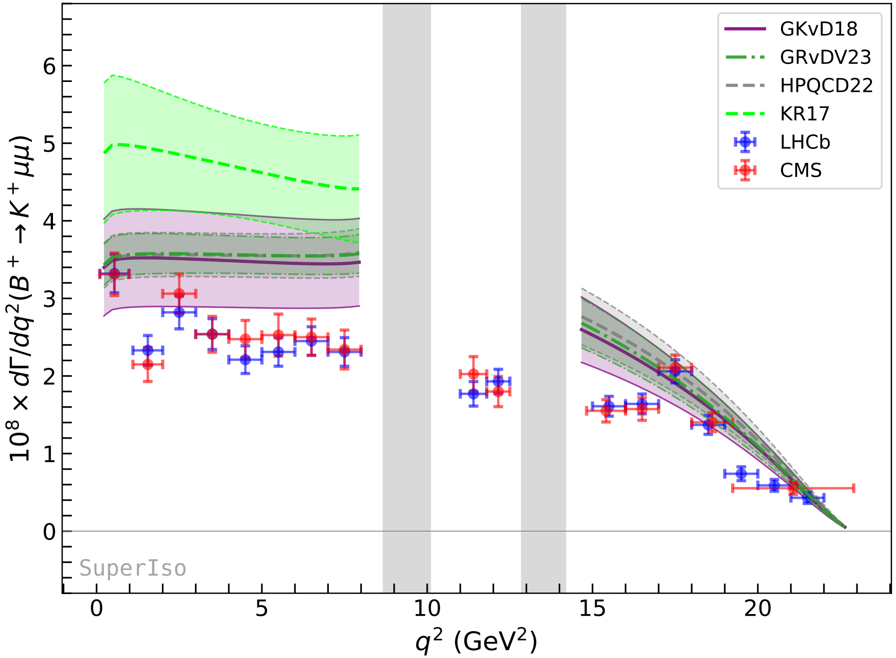




GKvD18 (default) [Gubernari et al '18]: Combined fit to LCSR results (with B-meson distribution amplitude) [Gubernari et al. '18] & lattice QCD results [Bouchard et al. '13].

BR($B \to K\mu\mu$)





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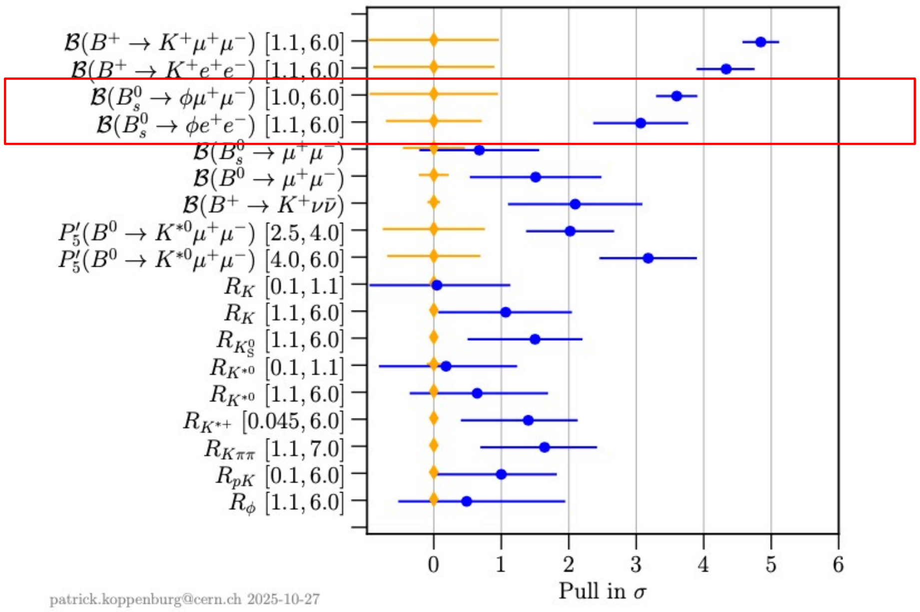
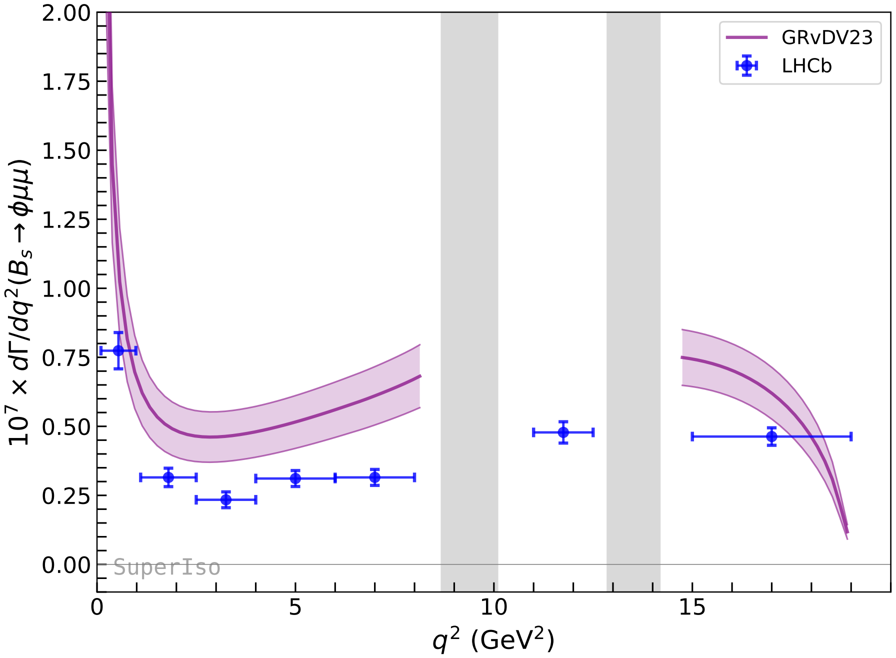
GRvDV23 [Gubernari et al '18]: Combined fit to LCSR results (with B-meson distribution amplitude) [Gubernari et al. '18] & lattice QCD results [Bouchard et al. '13, Bailey et al. '15, Parrott et al. '22]

HPQCD22 [Parrott et al. '22]: Lattice QCD result, valid across the entire physical q2 range.

KR17 [Khodjamirian et al. '17]: LCSR results (with kaon distribution amplitude) [Khodjamirian et al. '17], applicable only in the low-q2 region

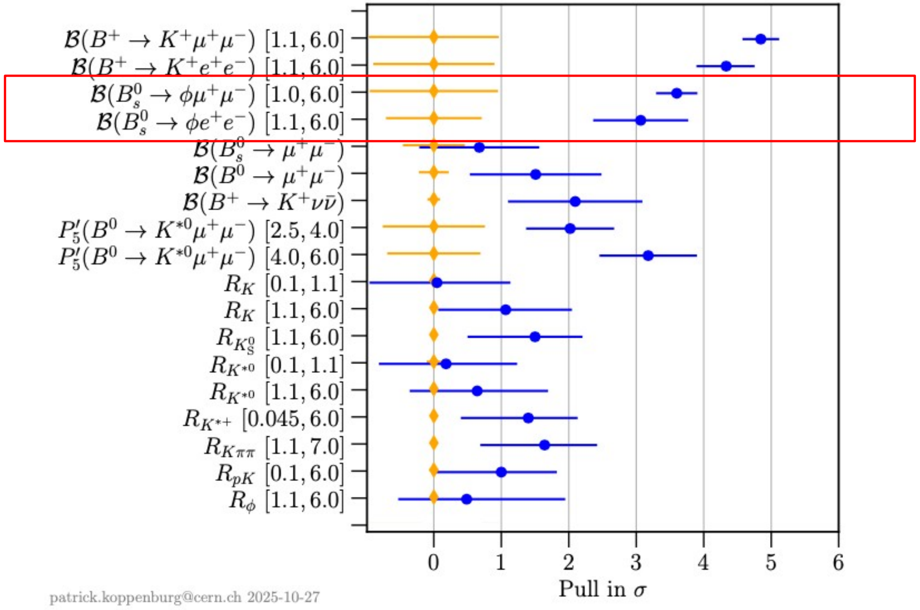
$\mathbf{BR}(B_s \to \phi\,\mu\,\mu)$

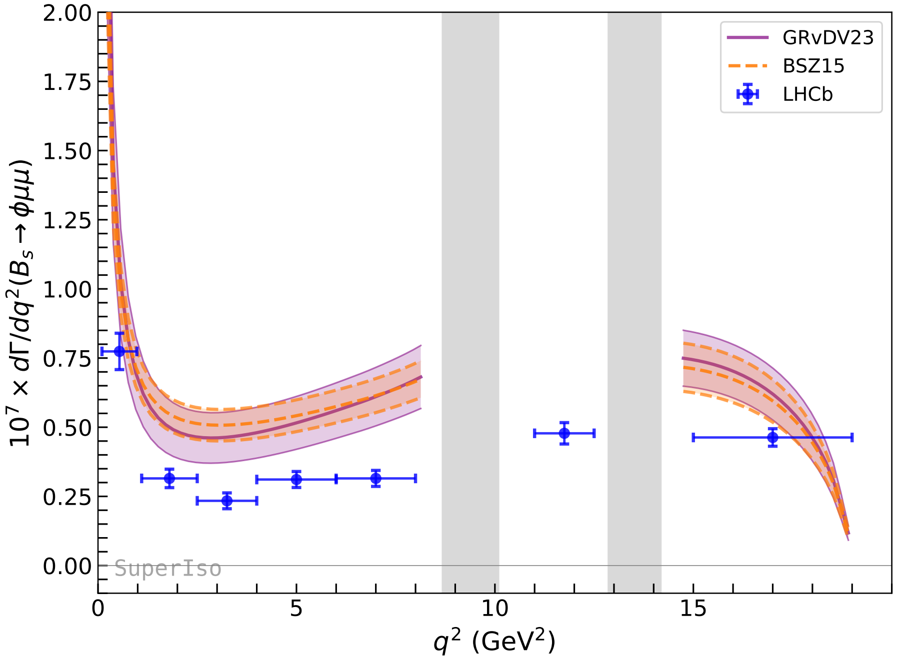




GRvDV23 (default) [Gubernari et al. '23]: Combined fit to LCSR reults (with B-meson distribution amplitudes) [Gubernari et al. '18, '20] & lattice QCD results [Horgan et al. '15].

BR($B_s \to \phi\,\mu\,\mu$)





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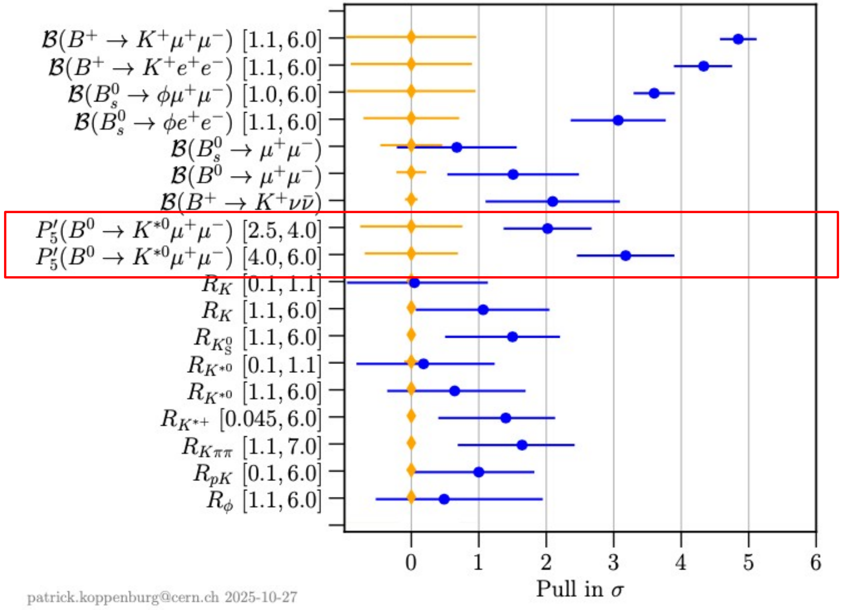
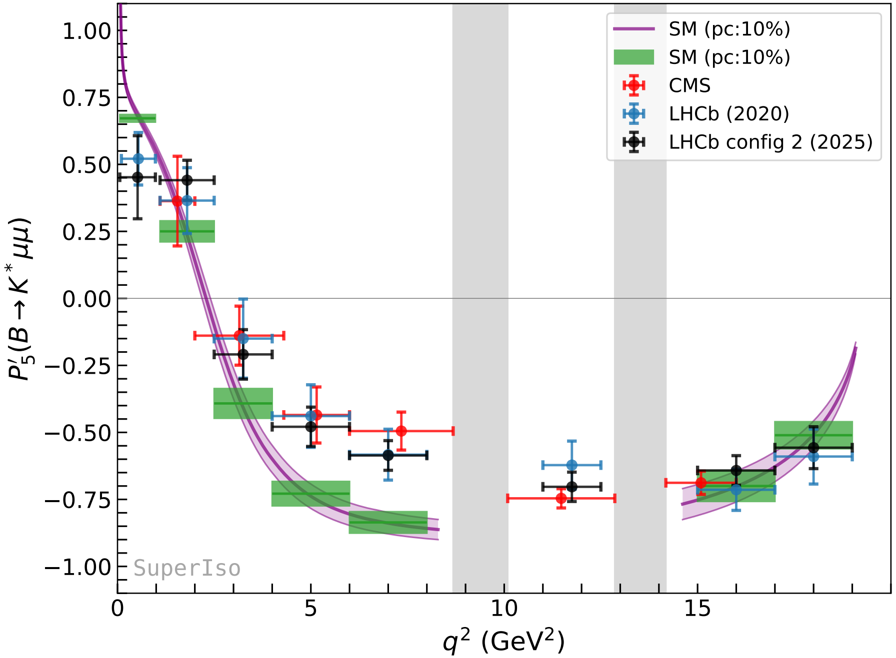
BSZ15 [Bharucha et al. ‘15]: Combined fit to LCSR results (with K*-meson distribution amplitude) [Bharucha et al. ‘15] & lattice QCD results [Horgan et al. ‘15]

P_5' $(B \to K^* \mu\mu)$





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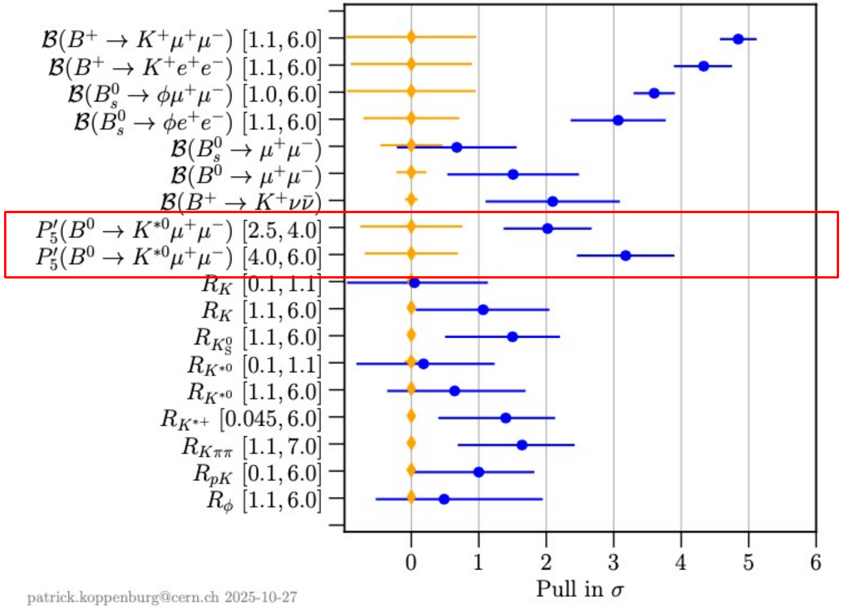
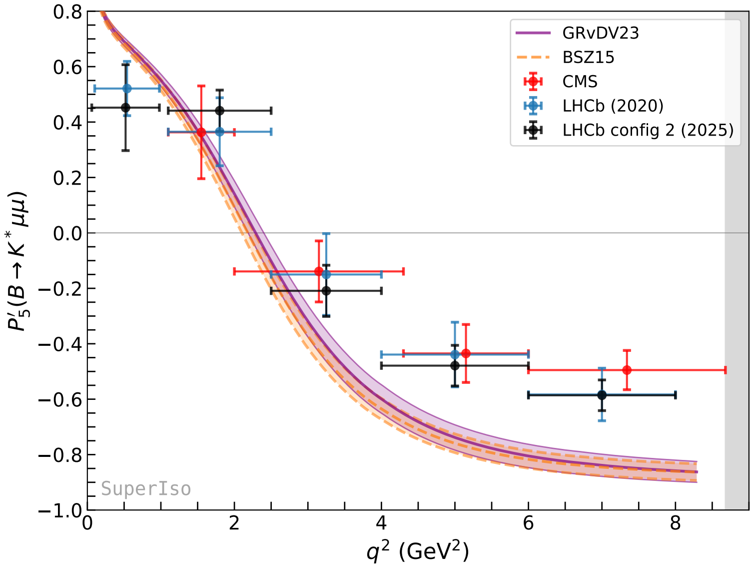
P_5' $(B \to K^* \mu\mu)$





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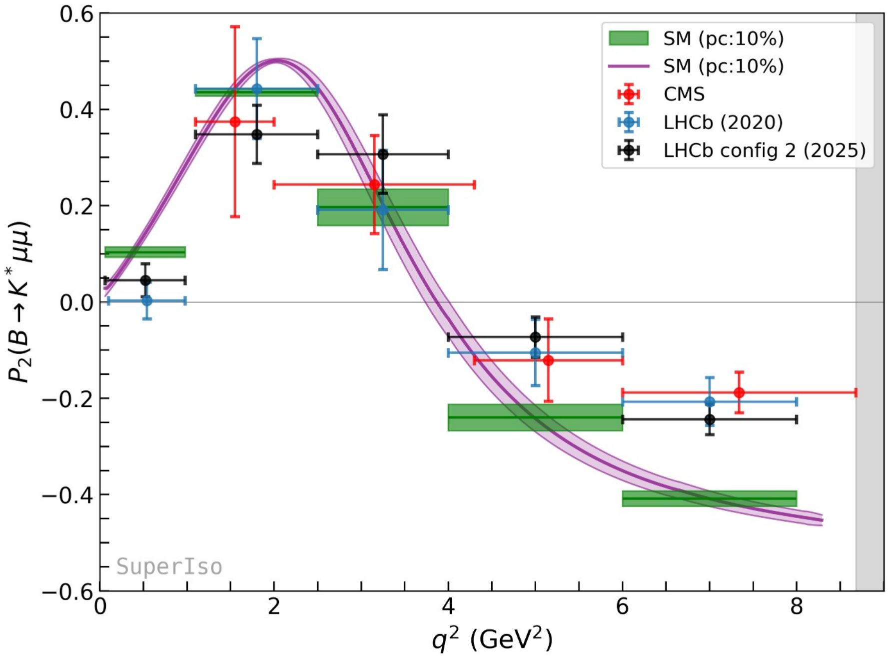
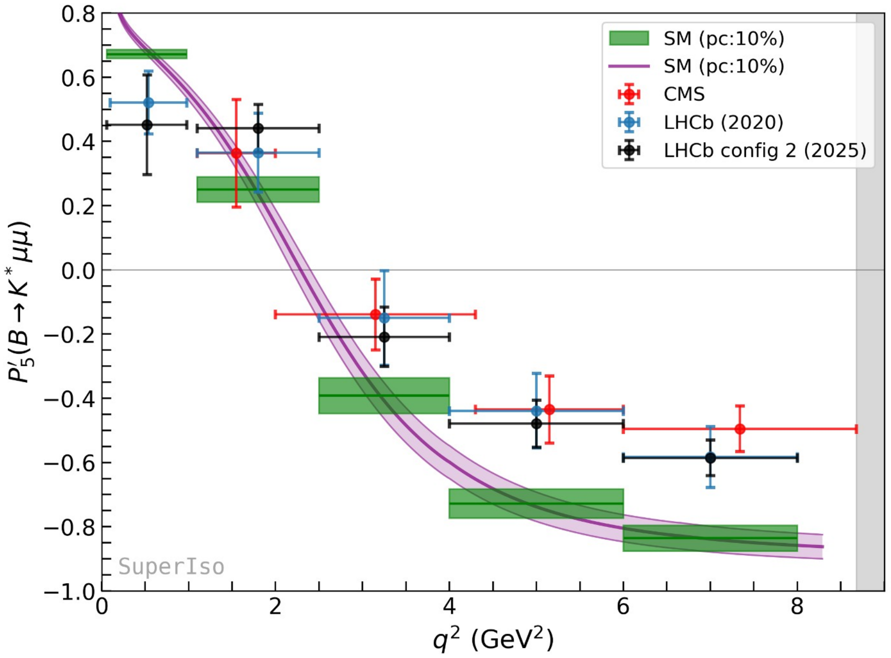
$P_{2,} P_5{}' \; (B \to K^* \mu\mu)$ – power corrections

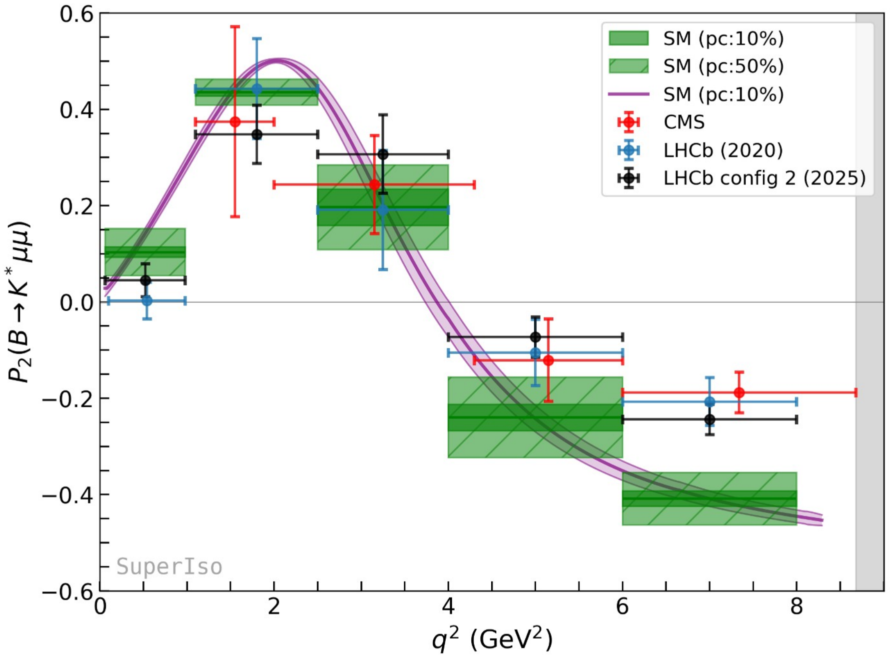


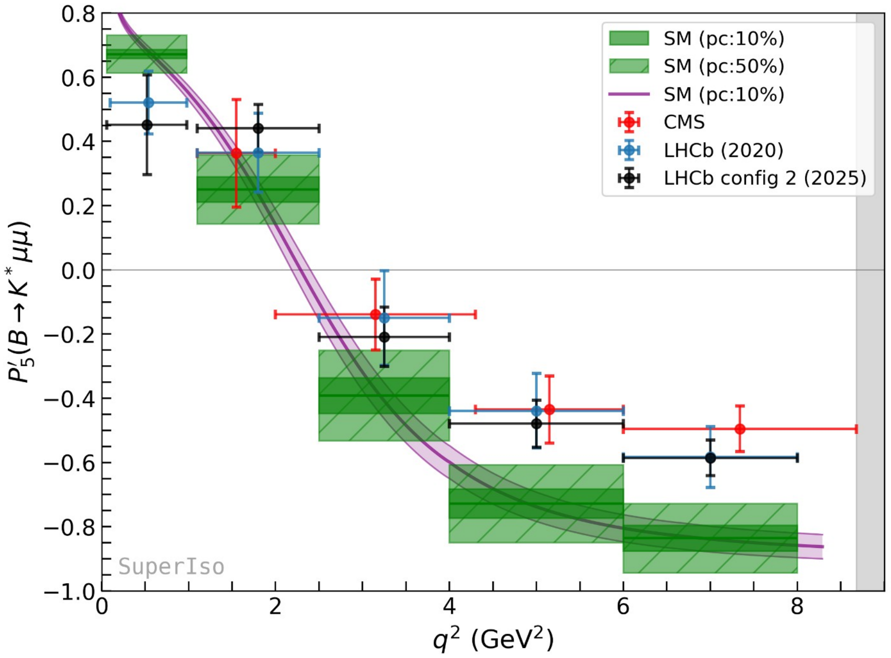


Different assumptions on power corrections:

- 10%

$P_{2,} P_5{}' \ (B \to K^* \mu\mu)$ – power corrections

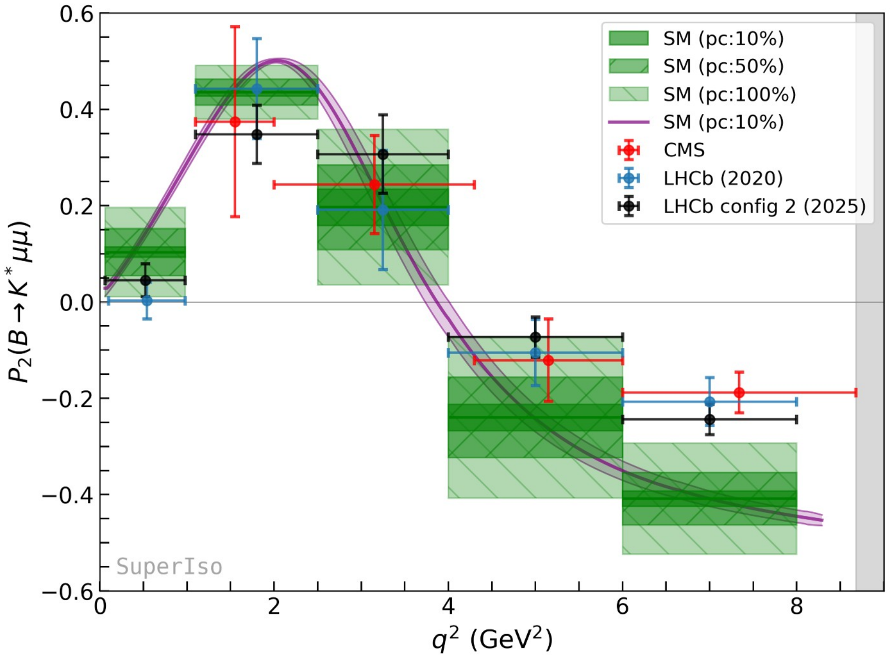


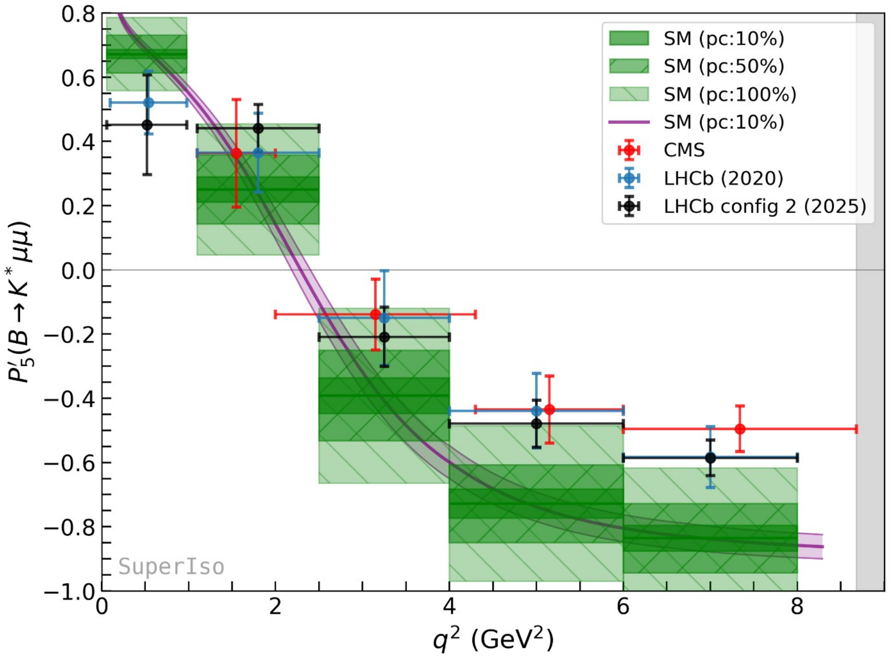


Different assumptions on power corrections:

- 10%
- 50%

$P_2, P_5{}'\ (B \to K^* \mu\mu)$ – power corrections

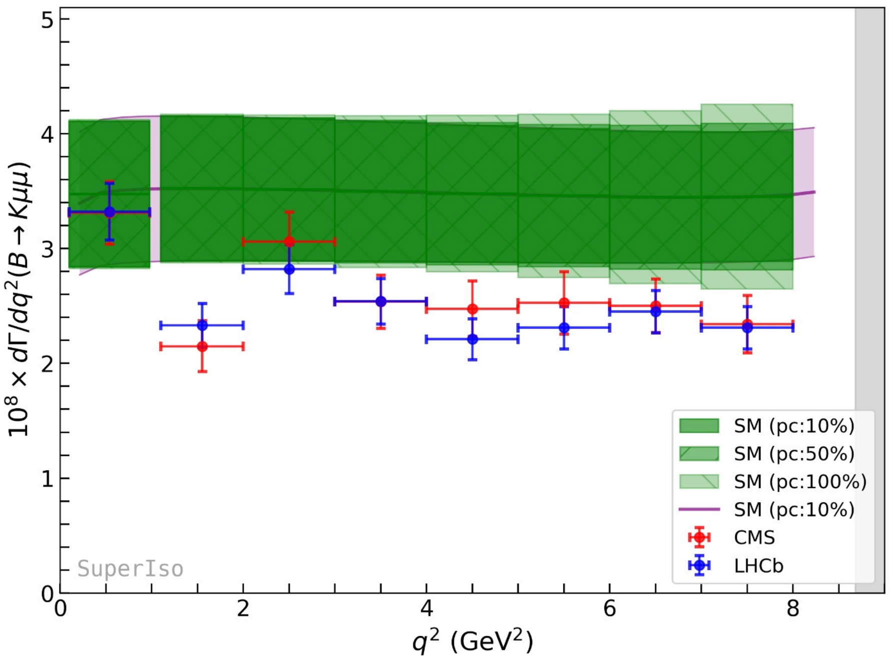




Different assumptions on power corrections:

- 10%
- 50%
- 100%

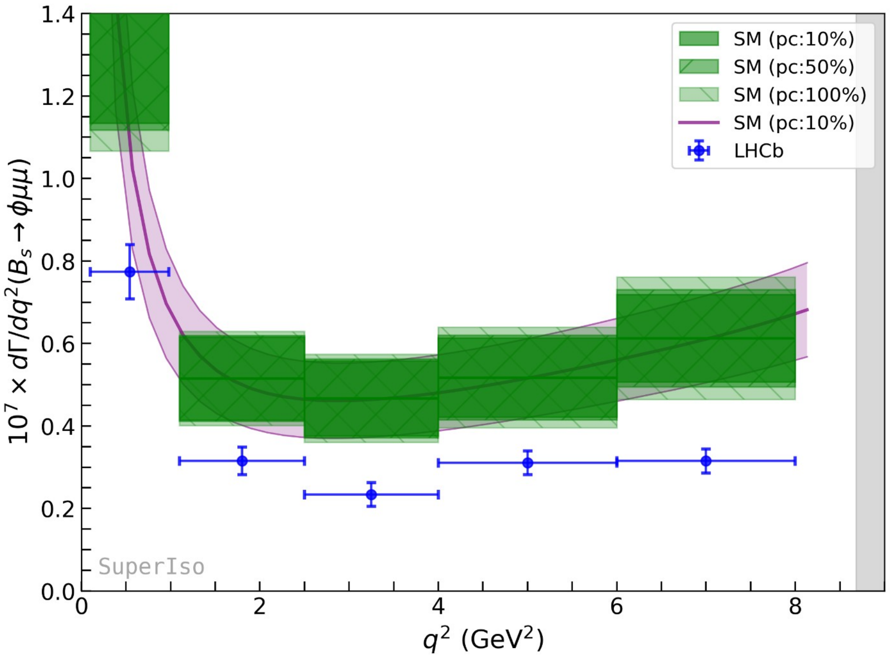
BR$(B\to K\mu\mu)$–power corrections



Different assumptions on power corrections:

- 10%
- 50%
- 100%

BR$(B_s \to \phi\mu\mu)$–power corrections



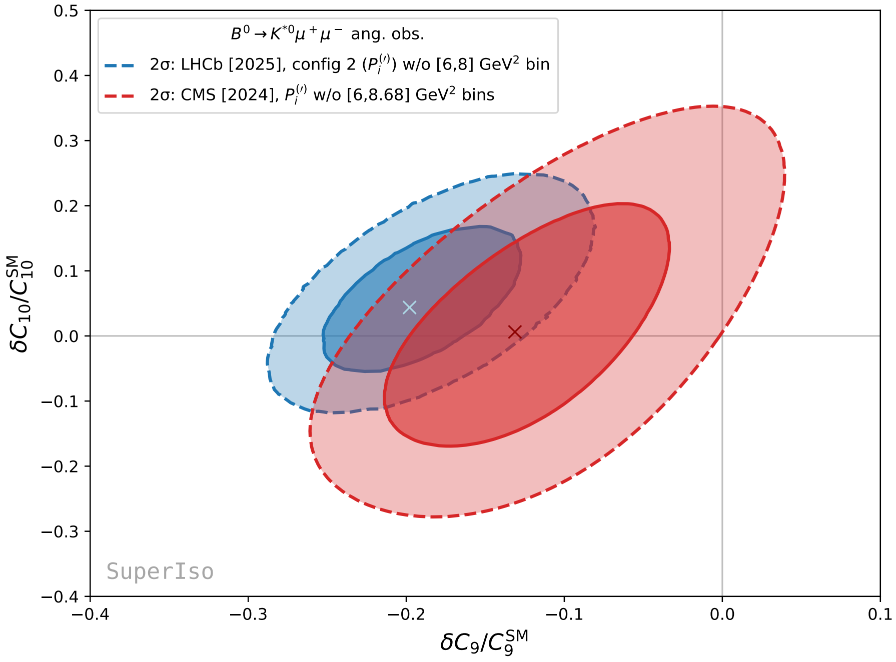
Different assumptions on power corrections:

- 10%
- 50%
- 100%

Fit to $B \to K^* \mu\mu$ angular observables

1 and 2σ C.L. of the $\{C_9, C_{10}\}$ fit, excluding [6, 8] and [6, 8.68] GeV^2

Using measurments from CMS and LHCb separetely



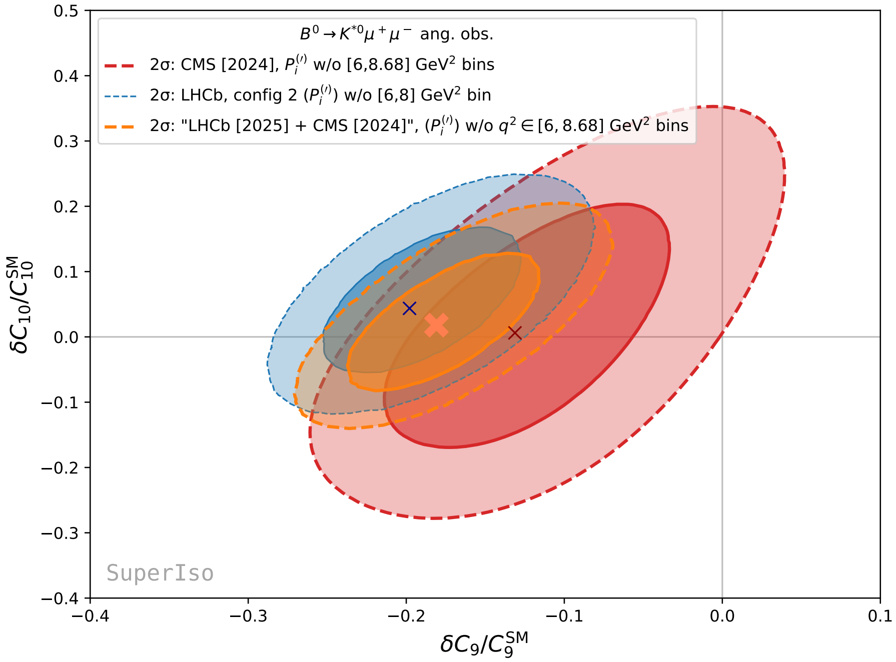
Red: CMS $(\mathrm{pull_{SM}}: 2\sigma)$

Blue: LHCb 2025 $(\mathrm{pull_{SM}}: 5\sigma)$

Fit to $B \to K^* \mu\mu$ angular observables

1 and 2σ C.L. of the $\{C_9, C_{10}\}$ fit, excluding [6, 8] and [6, 8.68] GeV^2

Using measurments from CMS and LHCb together



Red: CMS $(\mathrm{pull}_{\mathrm{SM}}: 2\sigma)$

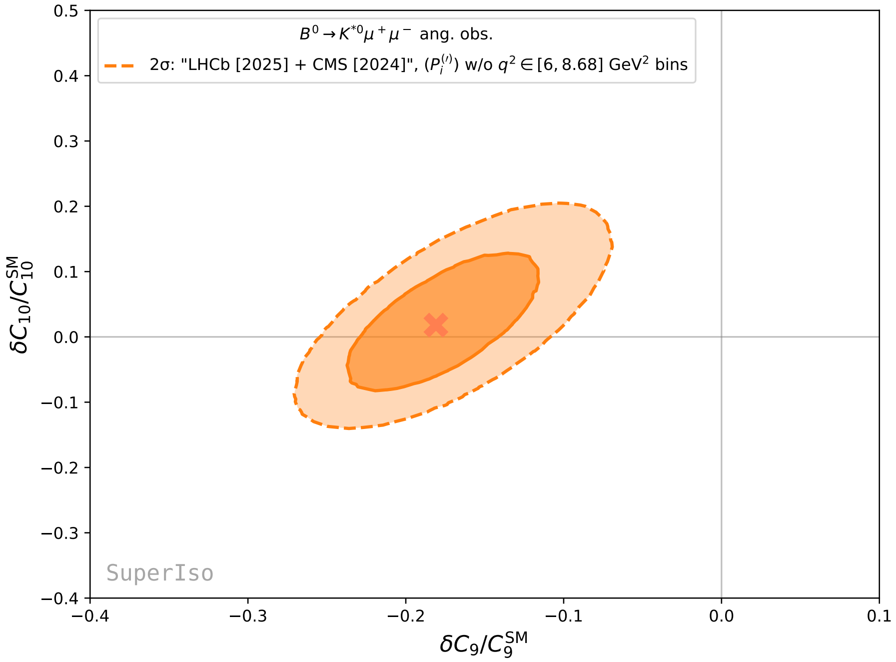
Blue: LHCb 2025 $(\mathrm{pull}_{\mathrm{SM}}: 5\sigma)$

Orange: CMS2024+LHCb 2025 [GvDRV23-FF] $(\mathrm{pull}_{\mathrm{SM}}: 4.9\sigma)$

Fit to $B \to K^* \mu\mu$ angular observables

1 and 2σ C.L. of the $\{C_9, C_{10}\}$ fit, excluding [6, 8] and [6, 8.68] GeV^2

Using measurments from CMS and LHCb together

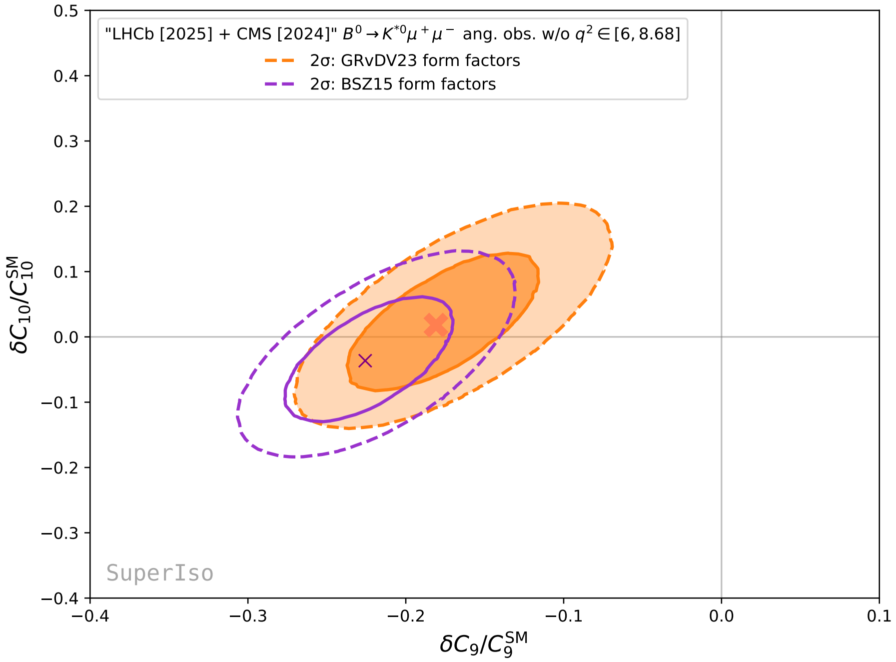


Orange: CMS2024+LHCb 2025 [GvDRV23-FF] $(\mathrm{pull_{SM}}: 4.9\sigma)$

Fit to $B \to K^* \mu\mu$ angular observables

1 and 2σ C.L. of the $\{C_9, C_{10}\}$ fit, excluding [6, 8] and [6, 8.68] GeV^2

Using measurments from CMS and LHCb together with different form factor choices



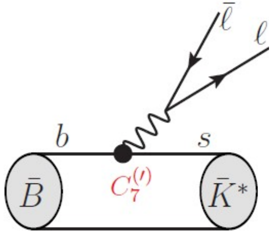
Orange: CMS2024+LHCb 2025 [GvDRV23-FF] $(\mathrm{pull}_{\mathrm{SM}}: 4.9\sigma)$

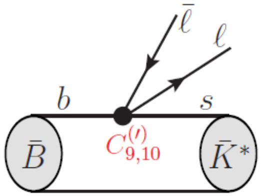
Purple: CMS2024+LHCb 2025 [BSZ15-FF] $(\mathrm{pull}_{\mathrm{SM}}: 6.1\sigma)$

Local and Non-local Matrix Elements

Effective Hamiltonian for transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

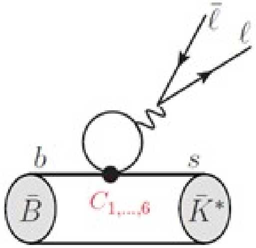
$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=7,9,10,Q_1,Q_2} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu)\Big]$$

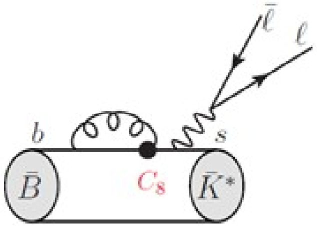




factorisable contributions:
7 independent form factors $\tilde V_\lambda, \tilde T_\lambda, \tilde S$

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





non-local effects: in general “naïve”
factorization not applicable

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

$$H_V(\lambda) = -i\,N'\Big\{(C_9^{\rm eff} - C_9')\tilde V_\lambda(q^2) + \frac{m_B^2}{q^2}\Big[\frac{2\,\hat m_b}{m_B}(C_7^{\rm eff} - C_7')\tilde T_\lambda(q^2) - 16\pi^2 \mathcal{N}_\lambda(q^2)\Big]\Big\}$$

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

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