Theory Keynote*

Gudrun Hiller, TU Dortmund * with a bias on FCNC BSM searches

Supported by great collaborators and the Federal Ministry for Education and Research (BMBF)

Contents

1. Implications appraisal
2. progress report (very selected)
3. evolution
4. coffee

Thank you (LHCb, organizers, participants) to continue triggering and exploiting synergies between TH and EXP

Previous Editions:

10-11 Nov. 2011, 16-18 April 2012, 14-16 Oct. 2013, 15-17 Oct. 2014, 3-5 Nov. 2015, 12-14 Oct. 2016, 8-10 Nov. 2017, 17-19 Oct 2018, 16-18 Oct 2019, 19-21 Oct 2020, 19-22 Oct 2021, 19-21 Oct 2022 and 25-27 Oct 2023

5 streams (Mixing & CP violation, FCNCs, FCCCs, QCD spectros. & exotics, EW and new particles)

Implications are great!

informal, informative and inspiring

Sensitivity to New Physics

charm FCNC:

SM coefficients

$|\mathcal{C}_9^{\text{eff}}(q^2)| \lesssim \mathcal{O}(0.1)(\lesssim\ 0.01)\ , \quad |\mathcal{C}_7^{\text{eff}}(q^2)| \lesssim\ 0.01(\simeq \mathcal{O}(0.001))$

values in parentheses for high $q^2 > 1$ GeV^2.

vanish by GIM: $C_{10}^{\text{SM}} = 0\,, C_\nu^{\text{SM}} = 0,\ C'^{\text{SM}}, C_{S,P,T,T5}^{\text{SM}} = 0$.

operator names as in $b \to s\mu\mu$

$$O_7 = \frac{m_c}{e}(\bar{u}_L\sigma_{\mu\nu}c_R)F^{\mu\nu}\,, O_9 = (\bar{u}_L\gamma_\mu c_L)(\bar{\ell}\gamma^\mu\ell)\,,$$
$$O_{10} = (\bar{u}_L\gamma_\mu c_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,, O_S = (\bar{u}_L c_R)(\bar{\ell}\ell)\,,$$
$$O_P = (\bar{u}_L c_R)(\bar{\ell}\gamma_5\ell)\,, O_T = \frac{1}{2}(\bar{u}\sigma_{\mu\nu}c)(\bar{\ell}\sigma^{\mu\nu}\ell)\,,$$
$$O_{T5} = \frac{1}{2}(\bar{u}\sigma_{\mu\nu}c)(\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell)\,.$$

2. progress

2018: $c \to u\mu\mu$: $|C_{9,10}^{(\prime)}| \lesssim 1, \; |C_{T,T5}| \lesssim 1, \; |C_{S,P}^{(\prime)}| \lesssim 0.1, \; |C_7^{(\prime)}| \lesssim 0.3$.

2024: $B(D \to \mu\mu) < 2.2 \cdot 10^{-9}$ (CMS24): $|C_{10} - C'_{10}| \lesssim 0.52$

$B(D^+ \to \pi^+ \mu\mu)$ (LHCb21) : $|C_{10} + C'_{10}| \lesssim 0.85 \to |C_{10}|, |C'_{10}| \lesssim 0.7$

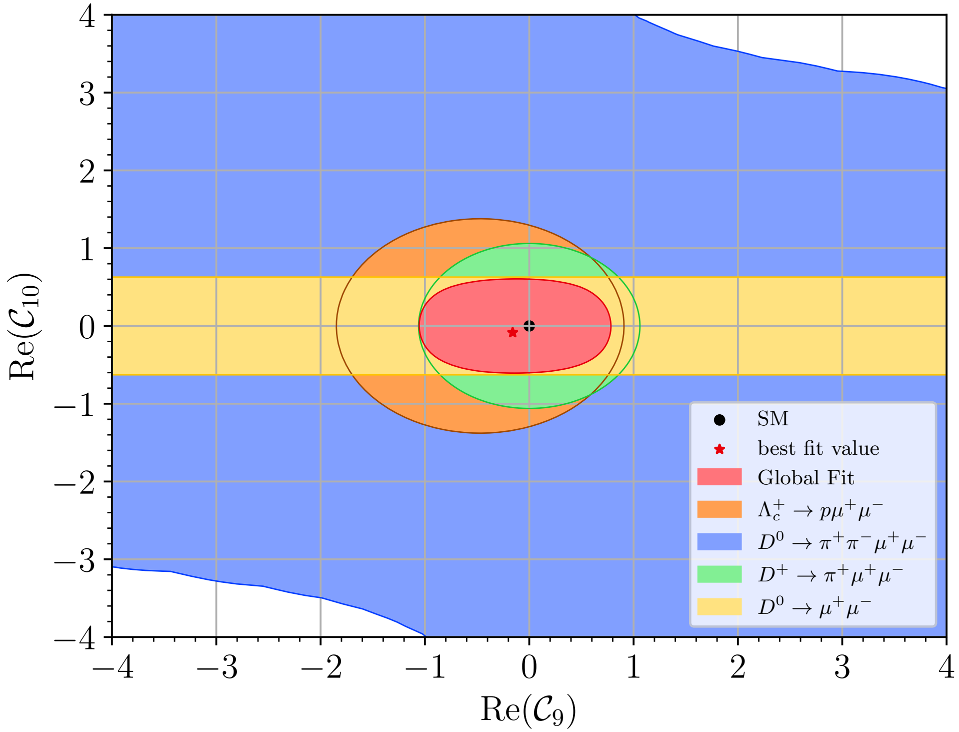
$B(D \to \mu\mu)$: $(|C_S - C'_S|^2 + C_P - C'_P|^2)^{1/2} \lesssim 0.04$

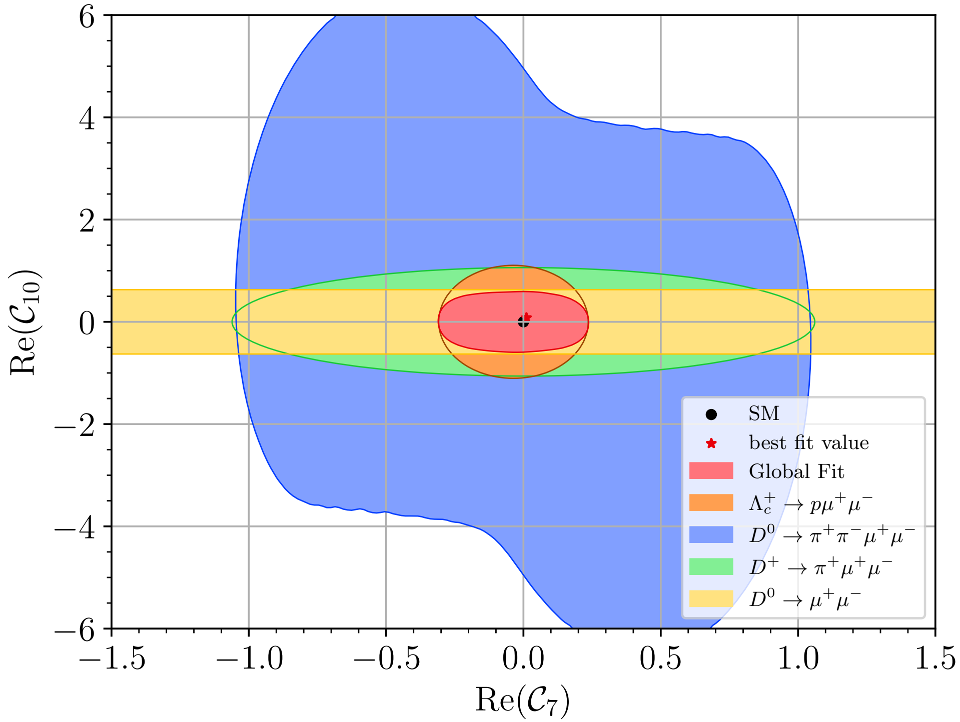
$B(\Lambda_c \to p\mu\mu)_{loq^2}$ (LHCb24) : $|C_7|, |C'_7| \lesssim 0.2$ (a bit stronger than $D \to \rho\gamma$)

... of course, combine more systematically...

First global $|\Delta c| = |\Delta u| = 1$ fit

Global analysis, using $D \to \mu\mu$, $D \to \pi\mu\mu$, $\Lambda_c \to p\mu\mu$, and $D \to \pi\pi\mu\mu$





2410.00115

$A_{FB}(\Lambda_c \to p\mu\mu)$, and $S_{5,6,7}, A_{5,6,7}$ of $D \to \pi\pi\mu\mu$ clean null tests due to GIM-protection ($\propto C_{10}$).

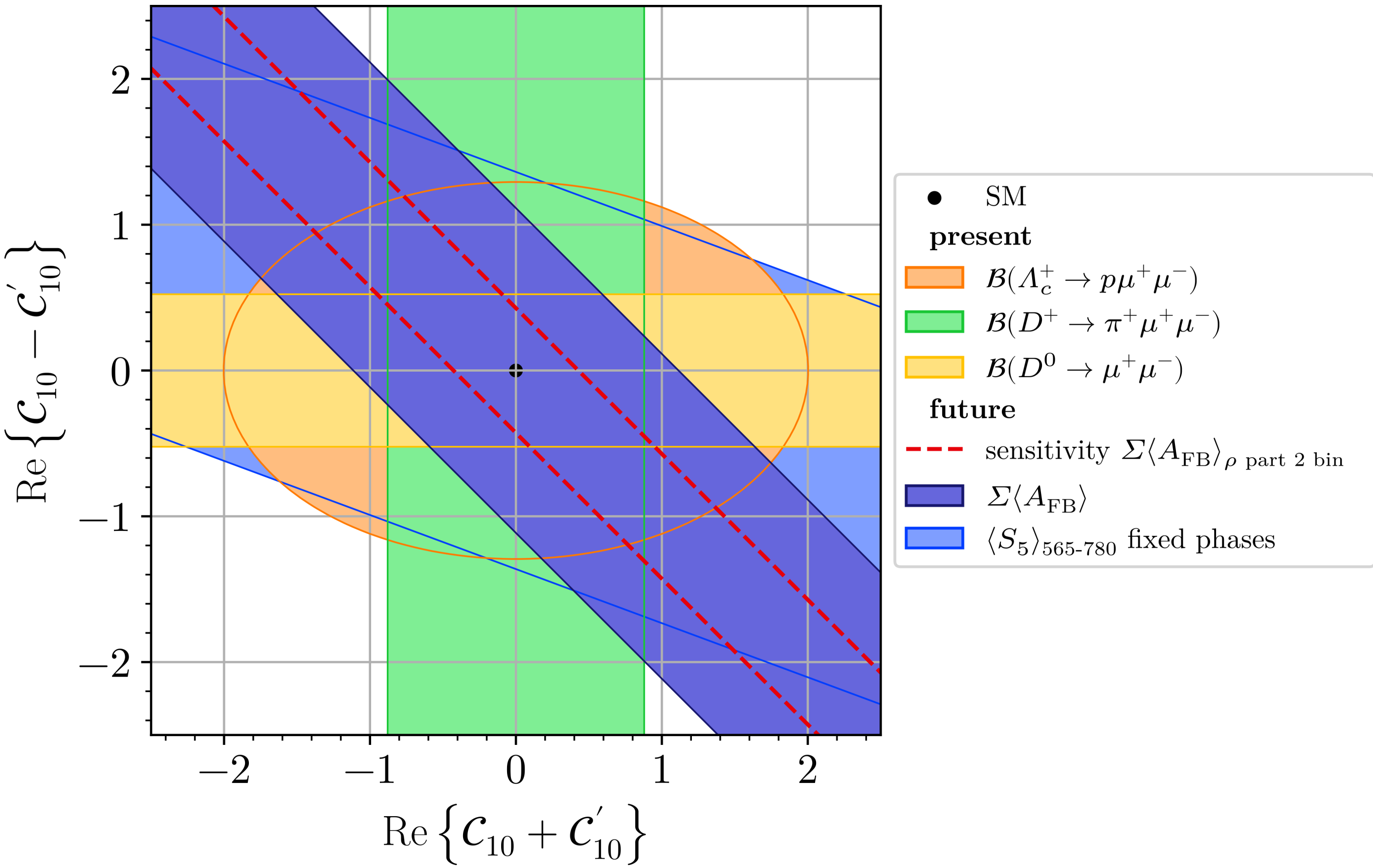


Figure 1: Complementarity of constraints in $\mathrm{Re}\,\{\mathcal{C}_{10} \pm \mathcal{C}'_{10}\}$ from current branching ratio data on $D \to \mu^+\mu^-$ (yellow), $D^+ \to \pi^+\mu^+\mu^-$ (green) and $\Lambda_c \to p\mu^+\mu^-$ (orange), together with hypothetical future measurements of $\Sigma\langle A_{\mathrm{FB}}\rangle$ at 7% level (dark blue) and $\langle S_5\rangle$ at 0.7% (light blue), see 2410.00115

TH predictions and PH interpretation

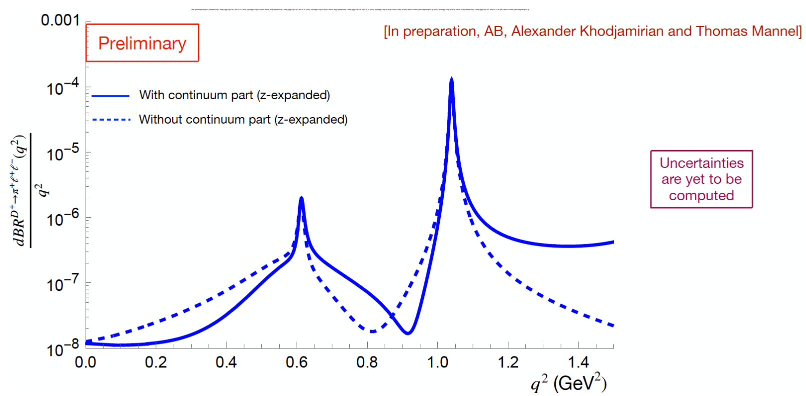
Null test observables can cleanly signal new physics – but how to extract new physics coefficients once there is a signal? Answer A: this is a fantastic dream-type scenario and luxury problem. Answer B: Same hadronic background hits as for other observables.

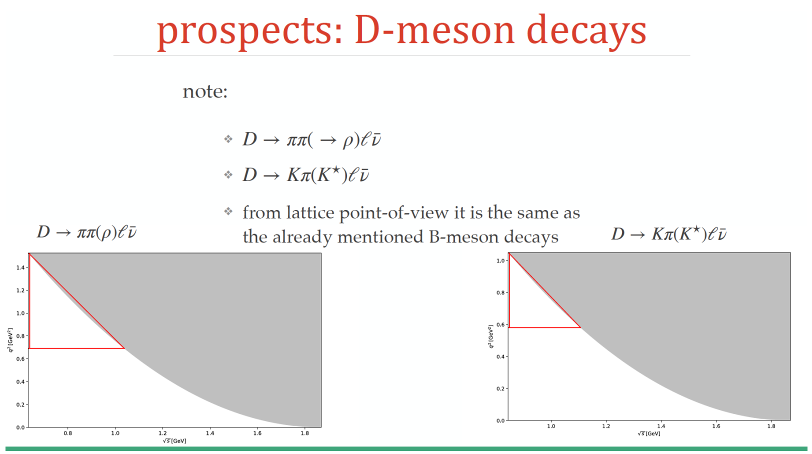
Progress in SM description from lattice, sum rules, modelling and data-driven methods by tuning params to NP-insensitive observables (resonance-dominated BRs, Cabibbo-favored decays, plus $SU(3)$, U-spin symmetrie). This requires effort and TH+EXP synergies.

This is very relevant for charm; we learned techniques from beauty, and here improvement in the BSM-reach is thanks to two decades of dedicated effort much harder to achieve in 2024+.

TH predictions and PH interpretation

Charming progress at this meeting by Anshika Bansal (Weak annihilation in $D \to \pi\ell\ell$), lattice (Felix Erben, Luca Leskovec $D \to \pi\pi$)





Charming ppportunity for matter effects in D-mixing presented by Alexej Petrov.

First LFU tests in $c \to u$

branching ratio	$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$D^0 \to K^+K^-\mu^+\mu^-$	$D^0 \to \pi^+\pi^-e^+e^-$	$D^0 \to K^+K^-e^+e^-$
LHCb 17 NEW24	$(9.64 \pm 1.20) \times 10^{-7}$	$(1.54 \pm 0.33) \times 10^{-7}$	$(13.3 \pm 3.0) \times 10^{-7}$	n.a.
BESIII 18	–	–	$< 0.7 \times 10^{-5}$	$< 1.1 \times 10^{-5}$
resonant	$\sim 1 \times 10^{-6}$	$\sim 1 \times 10^{-7}$	$\sim 10^{-6}$	$\sim 10^{-7}$
non-resonant	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$

$$R^D_{P_1P_2} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D \to P_1P_2\mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D \to P_1P_2e^+e^-)}$$ with same cuts $q^2_{\rm min} \geq 4m^2_\mu$

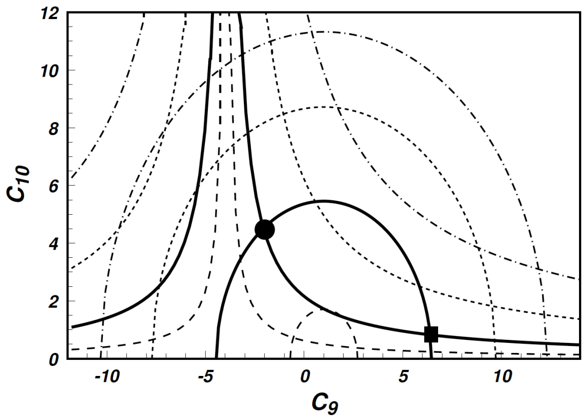
full q^2	SM	BSM	LQ	naive-exp24	hi q^2 SM	LQs	lo q^2 SM	BSM
$R^D_{\pi\pi}$	$1.00 \pm \mathcal{O}(\%)$	0.85 ...0.99	SM-like	$\sim 0.72 \pm 0.19$	$1.00 \pm \mathcal{O}(\%)$	0.7 ...4.4		
R^D_{KK}	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	na	NA	NA	$0.83 \pm \mathcal{O}(\%)$	0.60..0.87

O(1)BSM effects in $R^D_{\pi\pi}$ above Φ; small BSM effects in R^D_{KK} below η.

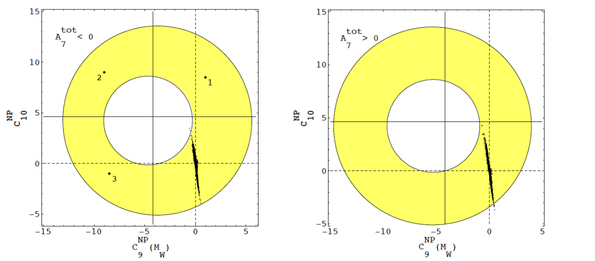
New LHCb result for $D \to h^+h^-e^+e^-$ reported by A. Scarabotto

Complements LFU tests in other sectors

doing global fits in WET since 94 (Ali, Giudice, Mannel), Greub, Lunghi, GH,vanDyk, Bobeth



'igure 1: Contour plots of $\mathcal{B}(\Delta s)$ and $\mathcal{A}(\Delta s)$ in the C_9-C_{10} plane for the low-invariant-
1ass region $4m_\ell^2 < s < m_{J/\psi}^2$ and $C_7 = 0.3$. The circles correspond to fixed values of $\mathcal{B}$:



10: **NNLO Case.** *Superposition of all the constraints. The plots correspond to the*

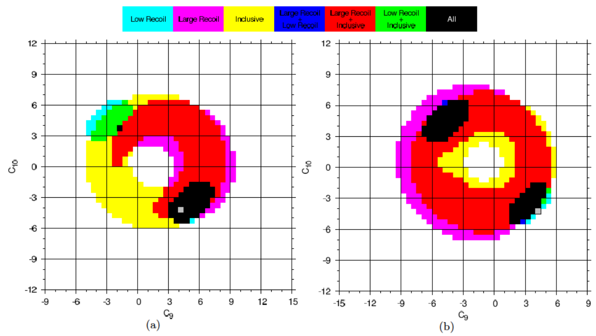
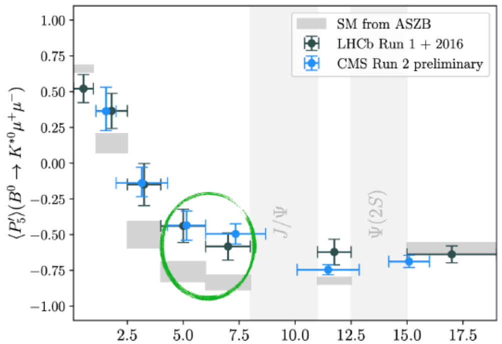


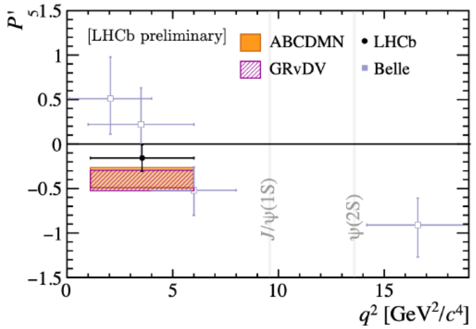
FIG. 7: The individual 68% CL constraints on $\mathcal{C}_9$ and $\mathcal{C}_{10}$ from $B \to K^* l^+ l^-$ at large and low recoil and

then EOS, flavio came and the first angular mesurements with P_5' by LHCb at EPS13 started a wave

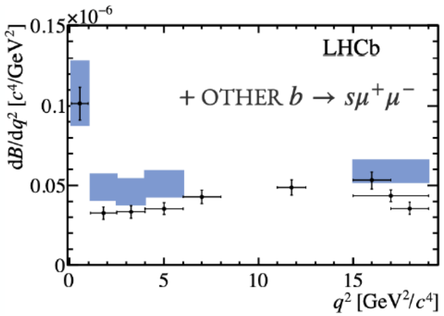


CMS-PAS-BPH-21-002 PRL. 125 (2020) 011802

[Plot by M. Andersson]



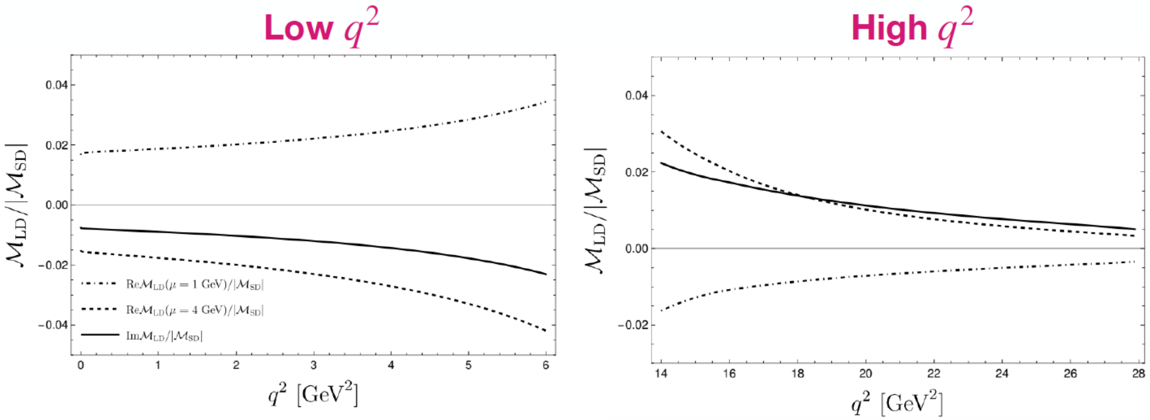
[LHCb-PAPER-2024-022, angular analysis of $B \to K^*\bar{e}e$]



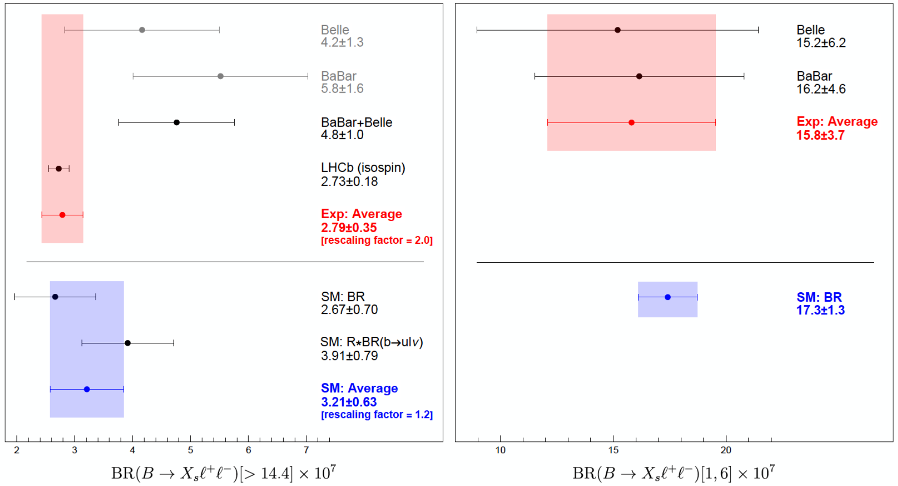
[LHCb, JHEP 11 (2016) 047]

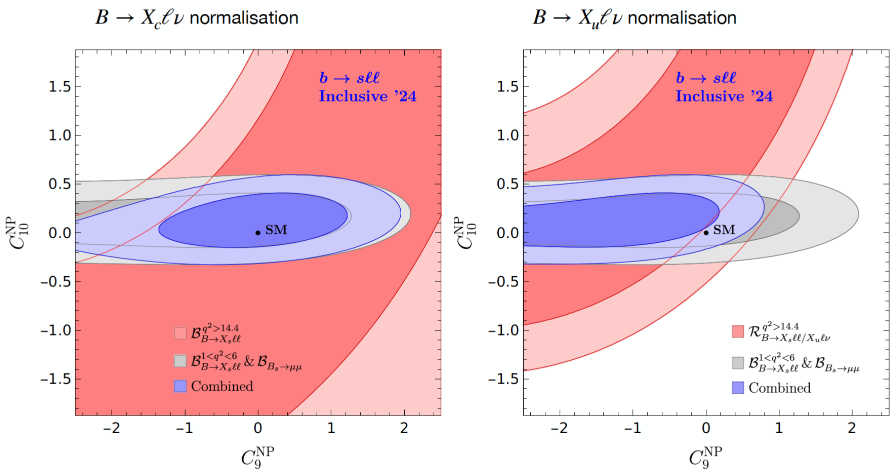
Thanks to LHCb's high precision what used to be an optimized observable in $B \to K^*(\to K\pi)\ell\ell$ is not clean enough anymore. The global fit cannot cleanly reveal NP due to non-perturbative SM-backgrounds.

TH efforts to understand non-local contributions (M.Hoferichter, A.Tinari) and the revival of inclusive $B \to X_s\ell\ell$ decays



conservatively 10 % shift in C_9, somewhat flat and the return of inclusive $B \to X_s \ell\ell$ decays J. Jenkins

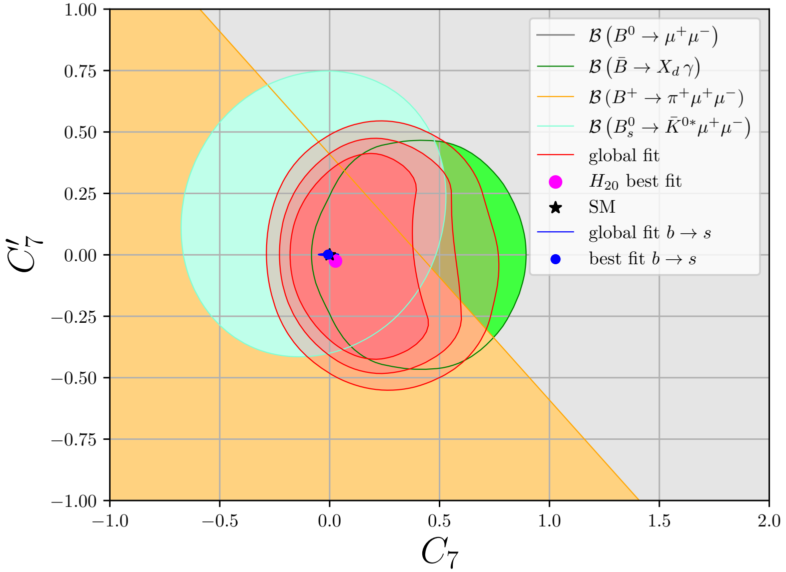


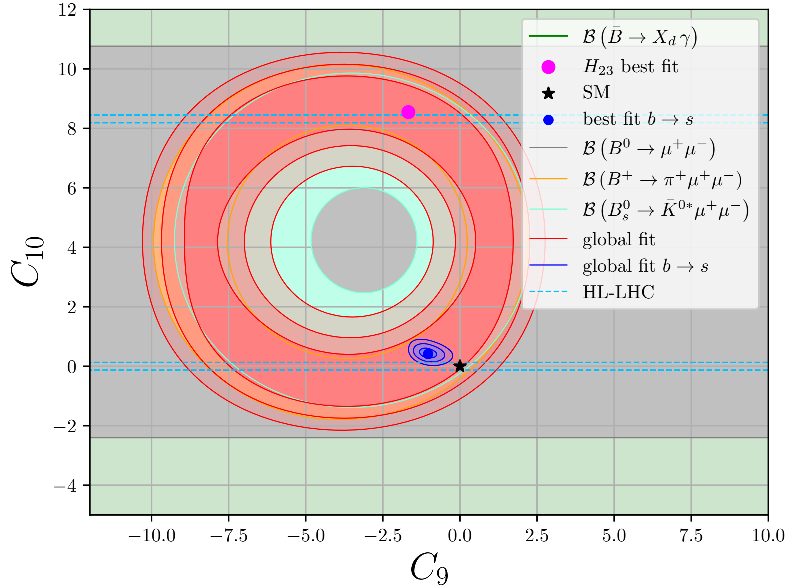


different systematics than exclusives;

depends on normalization, high and low q^2 (Krueger-Sehgal, $1/m_c$ Buchalla,Isidori), great for e^+e^--machines, LHCb?

$b \to d$ much less explored than $b \to s$





2209.04457

lots of room for NP with or without MFV; angular info on $b \to d\mu\mu$ missing to break main ambiguity

$A_{FB} \propto C_9 C_{10} + ..$ in $B_s \to K^*\ell\ell$, or $B \to \rho\ell\ell$, or $\Xi_b \to \Sigma\,\ell^+\ell^-$, $\Omega_b^- \to \Xi^-\,\ell^+\ell^-$

Recent $SU(3)$-flavor fits in hadronic 2-body B-decays reveal that with current data the fit doesnt work. B. Bhattacharya

Combined $B \to PP$ data: the anomaly

- BB with others in arxiv:2311.18011: fit the entire set of $B \to PP$ data
- 30 observables, 26 parameters: fit gives $|T_s/T_d| = 12 \pm 4$
- SU(3) hypothesis: 30 observables, 13 parameters: fit gives $\chi^2_{\rm min}/{\rm dof} \sim 44/17$ (3.6σ)
- Fit with QCDf-inspired constraint $|C/T| = 0.2$
  - → $\Delta S = 1$ fit: $\chi^2_{\rm min}/{\rm dof} \sim 7/3$, $p \sim 0.1$
  - → $\Delta S = 0$ fit: $\chi^2_{\rm min}/{\rm dof} \sim 19/3$, $p \sim 3 \times 10^{-4}$ or 3.6σ away from SM SU(3)$_F$
  - → Combined fit: $\chi^2_{\rm min}/{\rm dof} \sim 56/18$, $p \sim 10^{-5}$ or 4.4σ away from SM SU(3)$_F$
- Both fits find deviations in $B^0_s \to K^+K^-$ observables
- Deviations also in $B^+ \to \pi^0 K^+, B^0 \to \pi^- K^+, \pi^0 K^0, K^0 \overline{K}^0$

B Bhattacharya (LTU) | Anomalies in Hadronic B-meson decays | October 23, 2024 | 14 / 17

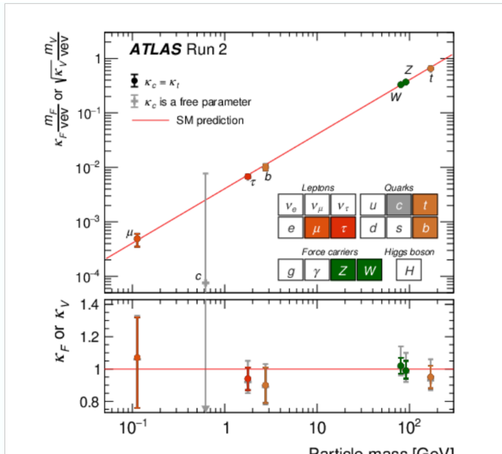
This adds to an existing list of unsatisfactory fits in hadronic 2-body decays. Needs further scrutiny (flavor-breaking, more modes included and measured, cross correlations)

– TH and joint TH+EXP efforts attack hadronic walls to further precision and sharpen interpretation in $b \to s$

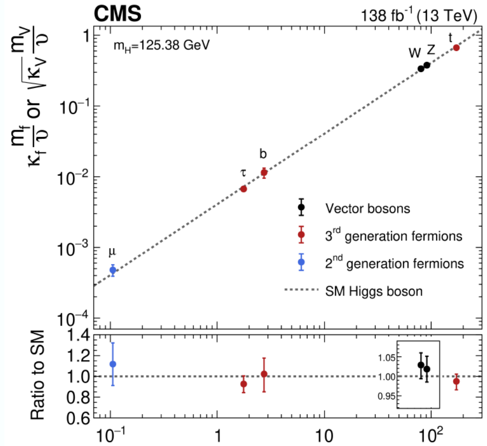
– further tests of SM and look for BSM in $c \to u, b \to d, s \to d$, light sectors

– improving precision in SM input (CKM, FFs..) improves NP reach

– the flavor puzzle is still out there!



Nature 607, 52–59 (2022)



Nature 607, 60-68 (2022)

origin of mass largely open for 1st generation u, d, e and strange