Global analyses of rare $b \to d$ and $b \to s$ decays

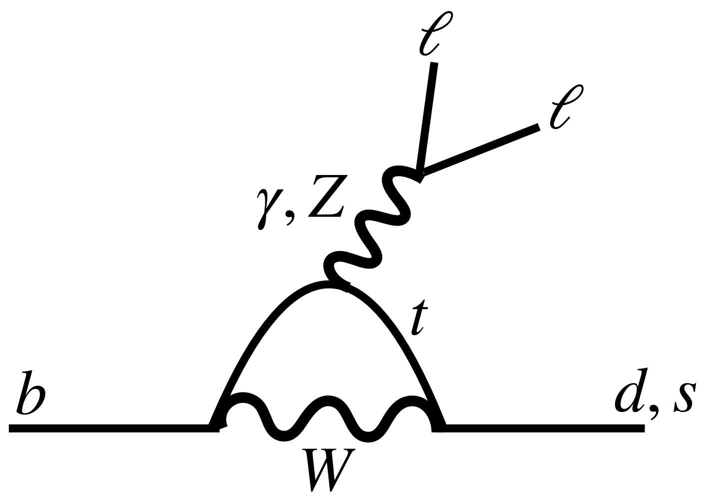
Aleks Smolkovic

University of Basel

Rare b decays

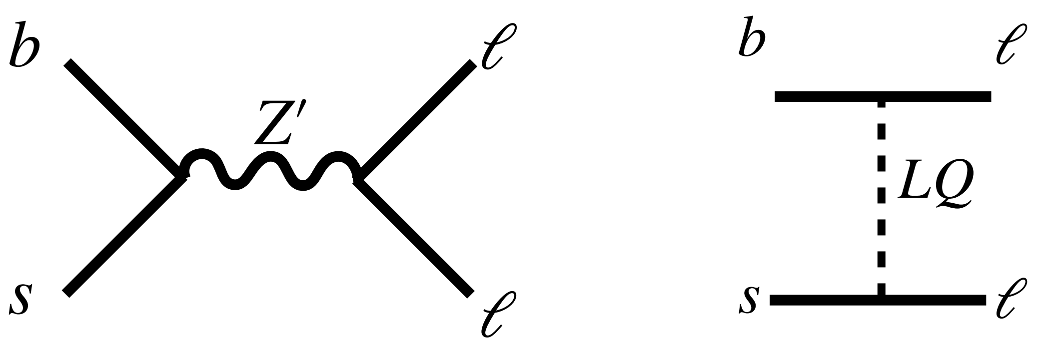
SM:

FCNCs: loop and CKM suppressed, breakdown of GIM due to t



NP:

Could enter already at tree-level, highly sensitive to short-distance NP



precision tests of both SM and BSM physics

Rare *b* decays

Weak effective Hamiltonian:

$$\mathscr{H}_{\text{eff}} = \mathscr{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\sum_q \sum_\ell \sum_i V_{tb}V_{tq}^* C_i^{bq\ell\ell} O_i^{bq\ell\ell} + \text{h.c.}$$

Rare b decays

Weak effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \sum_{q} \sum_{\ell} \sum_{i} V_{tb} V_{tq}^{*} C_i^{bq\ell\ell} O_i^{bq\ell\ell} + \text{h.c.}$$

Focus on semileptonic operators:

$$O_9^{(\prime)bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad O_{10}^{(\prime)bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_S^{(\prime)bq\ell\ell} = m_b(\bar{q} P_{R(L)} b)(\bar{\ell}\ell) \qquad O_P^{(\prime)bq\ell\ell} = m_b(\bar{q} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

Rare b decays

Weak effective Hamiltonian:

$$\mathscr{H}_{\text{eff}} = \mathscr{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\sum_q \sum_\ell \sum_i V_{tb}V_{tq}^* C_i^{bq\ell\ell} O_i^{bq\ell\ell} + \text{h.c.}$$

Focus on semileptonic operators:

$$O_9^{(\prime)bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad O_{10}^{(\prime)bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_S^{(\prime)bq\ell\ell} = m_b(\bar{q} P_{R(L)} b)(\bar{\ell}\ell) \qquad O_P^{(\prime)bq\ell\ell} = m_b(\bar{q} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

C_i encode short-distance physics: computed perturbatively

$\langle O \rangle$ encode long-distance physics: computed using non-perturbative techniques

$$\text{observables} \sim \left| \langle \mathscr{H}_{\text{eff}} \rangle \right|^2 = f(V_{\text{ckm}}, C, \langle O \rangle, \ldots)$$

- NP could shift the values of WCs from C_i^{SM}
- This assumes other quantities entering are under control: CKM values, matrix elements, …

[2104.09521, 2112.03437…]

Global analyses of $b \to d\ell\ell$

Rare $b \to d\ell\ell$

- Differential branching ratio (and CPA) of $B \to \pi\mu\mu$ [LHCb 2015]
  Upper limit on $B \to \pi ee$ [Belle 2008]
- Evidence of $B_s \to K^*\mu\mu$ [LHCb 2018]

Semileptonic $C_9^{(\prime)}, C_{10}^{(\prime)}$

- Upper limit on $B^0 \to \mu\mu$ [ATLAS 2018, LHCb 2021, CMS 2022]
  Upper limit on $B^0 \to ee$ [LHCb 2020]

Fully leptonic $C_{10}^{(\prime)}, C_S^{(\prime)}, C_P^{(\prime)}$

Matrix elements: LCSR, LQCD
[1501.00367, 1501.05373, 1503.05534, 1507.01618, 1712.09262, 1811.00983, 2102.07233, 2111.09849, 2310.06734]
[see also talk by A. M. Marshall]

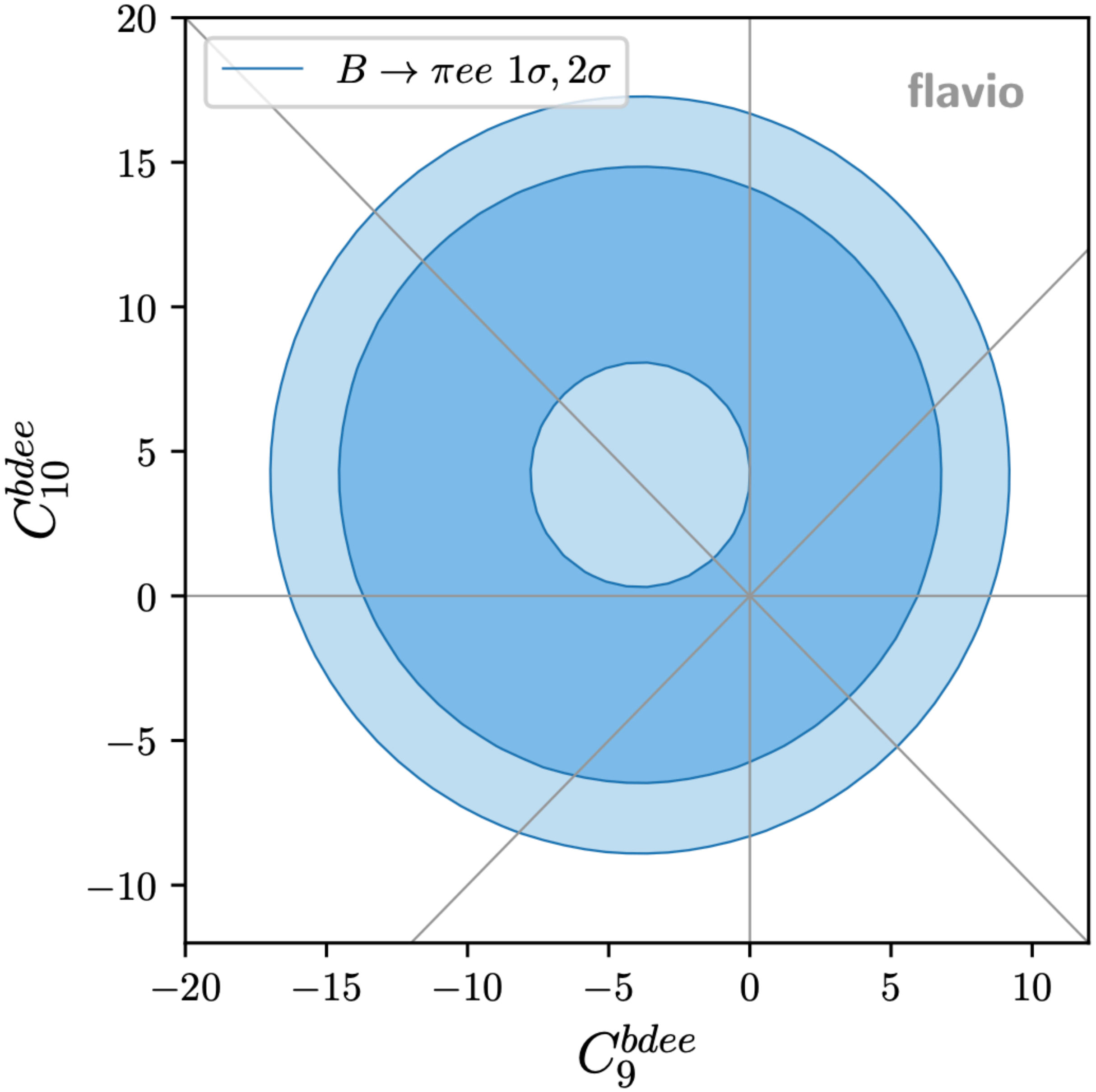
With this knowledge, we can start constraining heavy NP

R. Bause, H. Gisbert, M. Golz, G. Hiller, 2209.04457

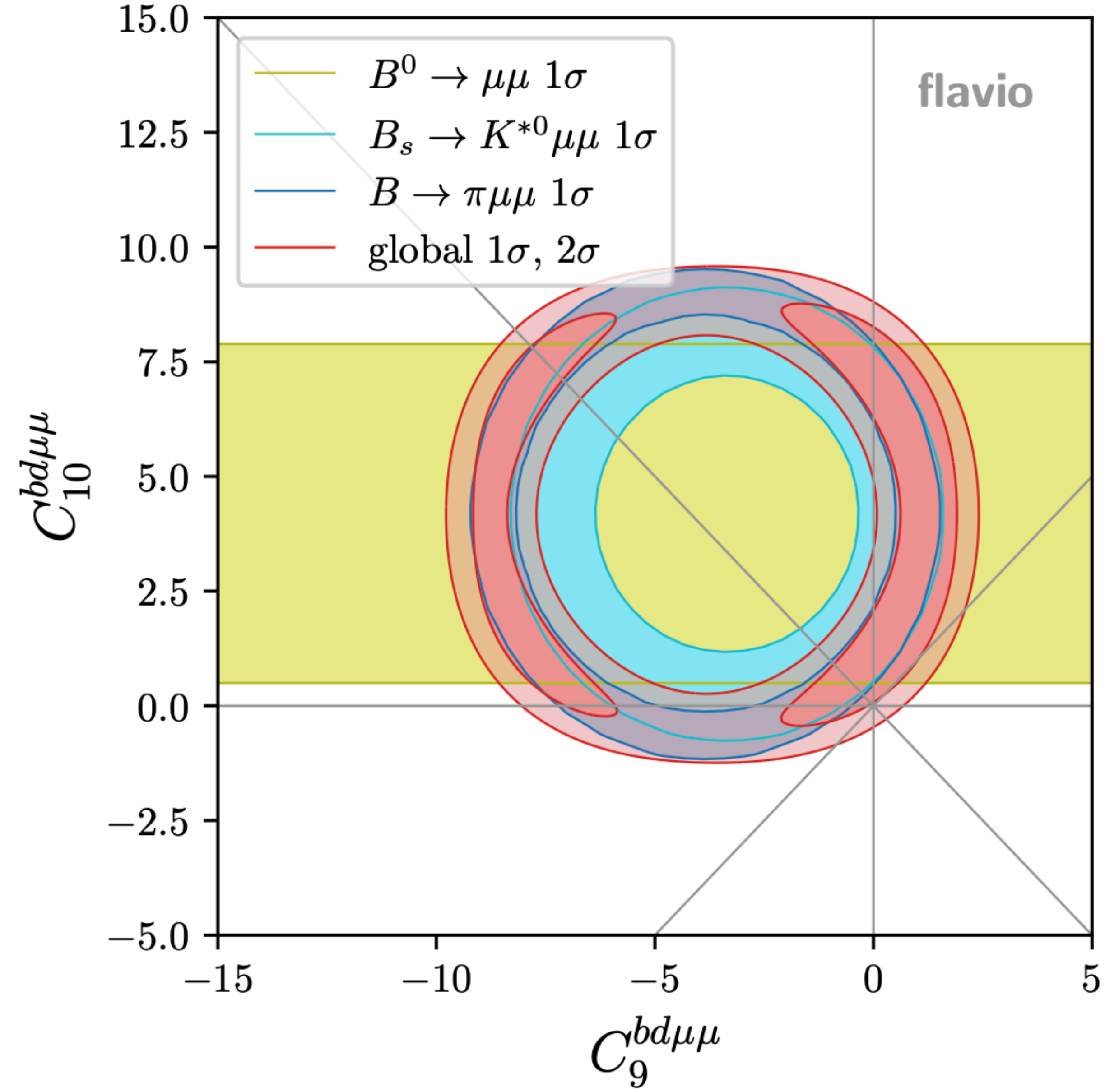
A. Greljo, J. Salko, AS, P. Stangl, 2212.10497

(C_9, C_{10}) for $b \to dee$ and $b \to d\mu\mu$

$$O_9^{(')bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10}^{(')bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



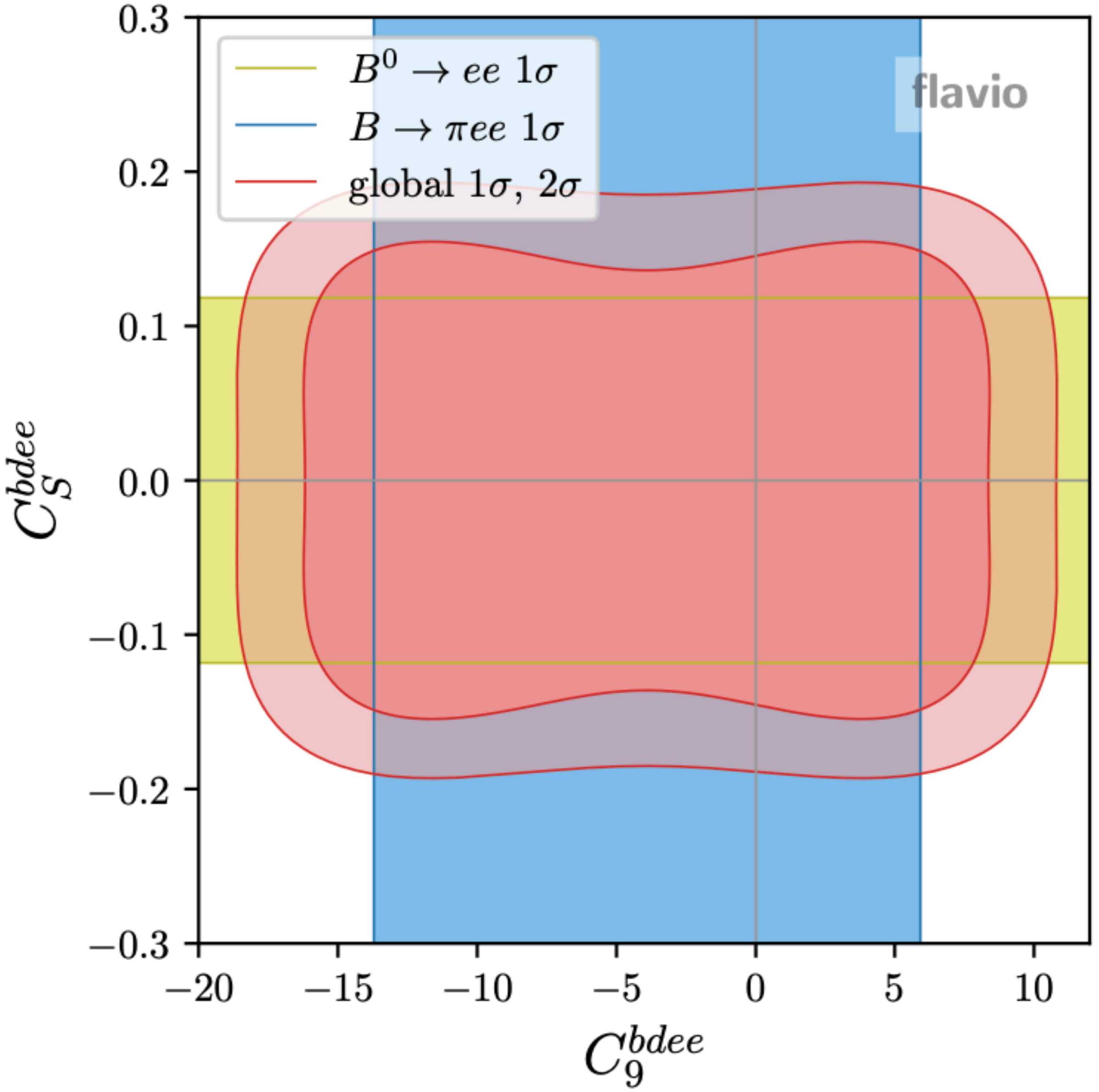
Sizeable room for NP!



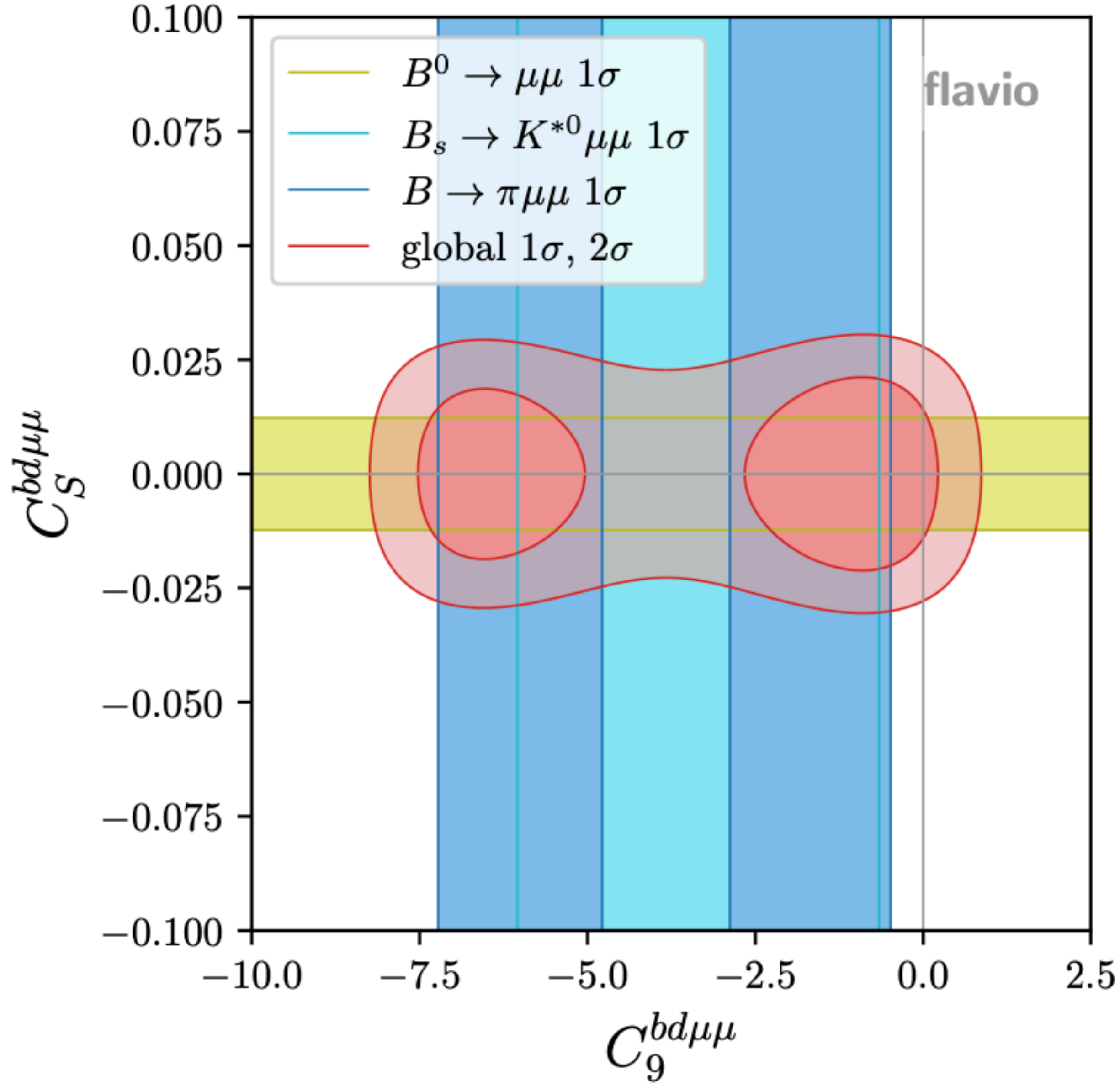
Slight preference for negative $C_9(=-C_{10})$

Purely leptonic decays importantly constrain (pseudo) scalar operators

$$O_9^{(\prime)bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_S^{(\prime)bq\ell\ell} = m_b(\bar{q}P_{R(L)} b)(\bar{\ell}\ell)$$



Sizeable room for NP!

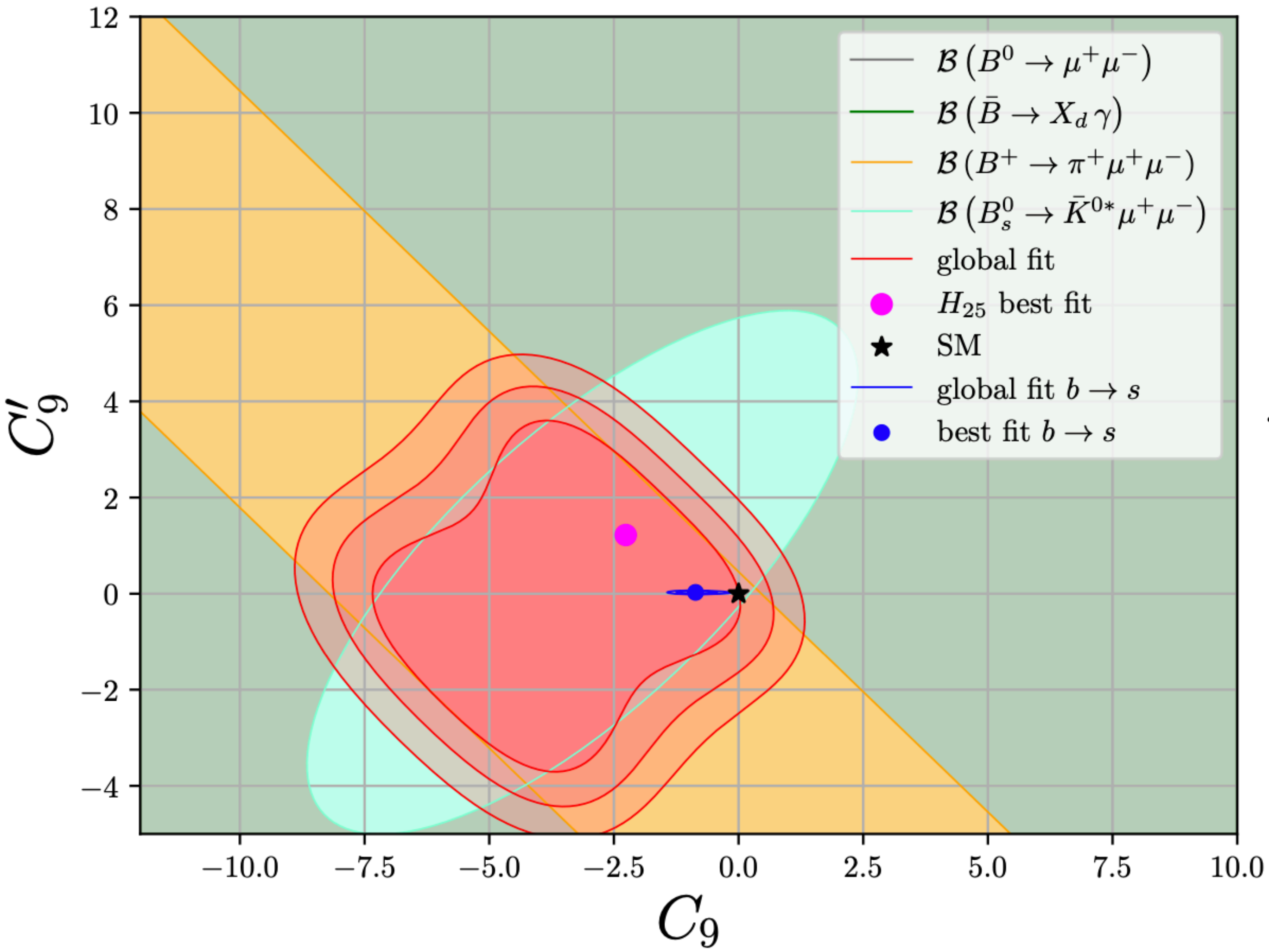


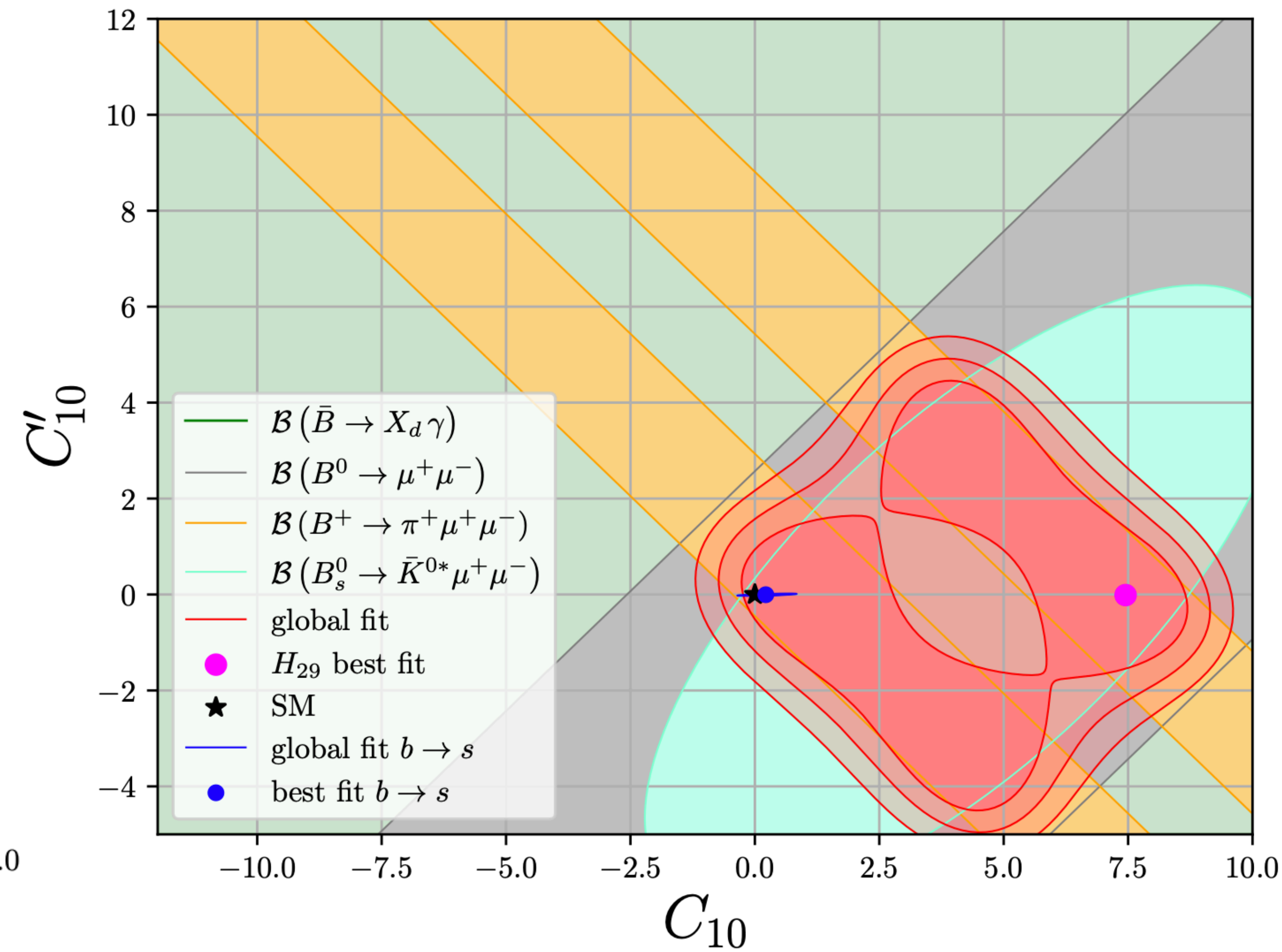
Slight preference for negative $C_9(=-C_{10})$

R. Bause, H. Gisbert, M. Golz, G. Hiller, 2209.04457

Regarding helicity-flipped operators:

$$O_9^{(')bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10}^{(')bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$





Nice complementarity between different modes

Global analyses of $b \to s\ell\ell$

Rare $b \to s\ell\ell$

[see talk by D. Moise]

$b \to s\mu\mu$ infamously well explored

Various branching ratios, angular observables, CP asymmetries, measured in many modes:

$B \to K^{(*)}\mu\mu$, $B_s \to \phi\mu\mu$, $B_s \to \mu\mu$, $\Lambda_b \to \Lambda\mu\mu$

anomalous!

$b \to see$ so-far under-represented

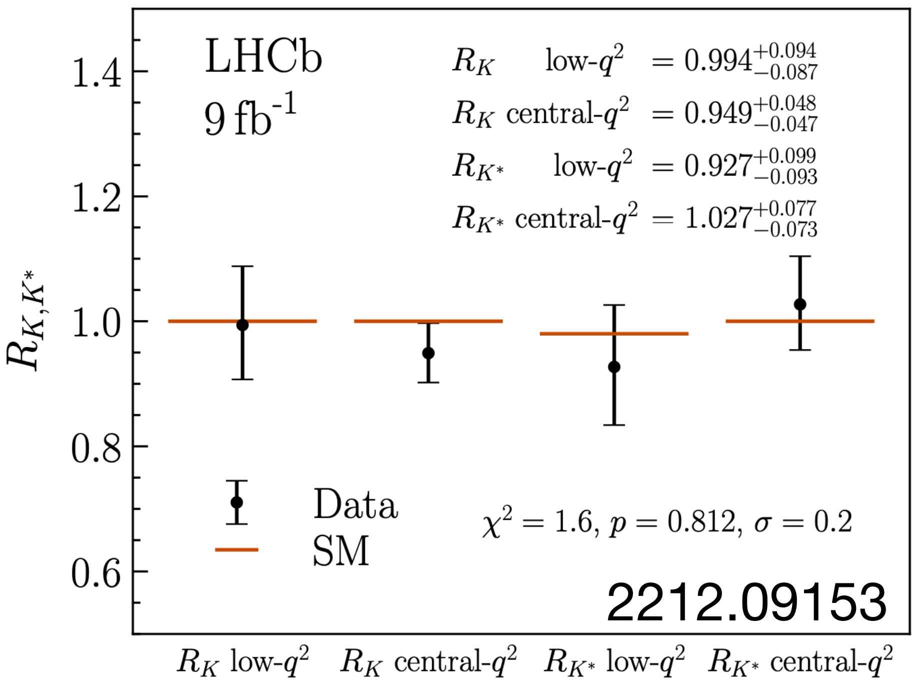
Upper limit on $B_s \to ee$ [LHCb 2020]

Inclusive $B \to X_s ee$ [BaBar 2013]

$B \to K^*ee$ at very low q^2 - [LHCb 2020]

anomalous?

LFU ratios



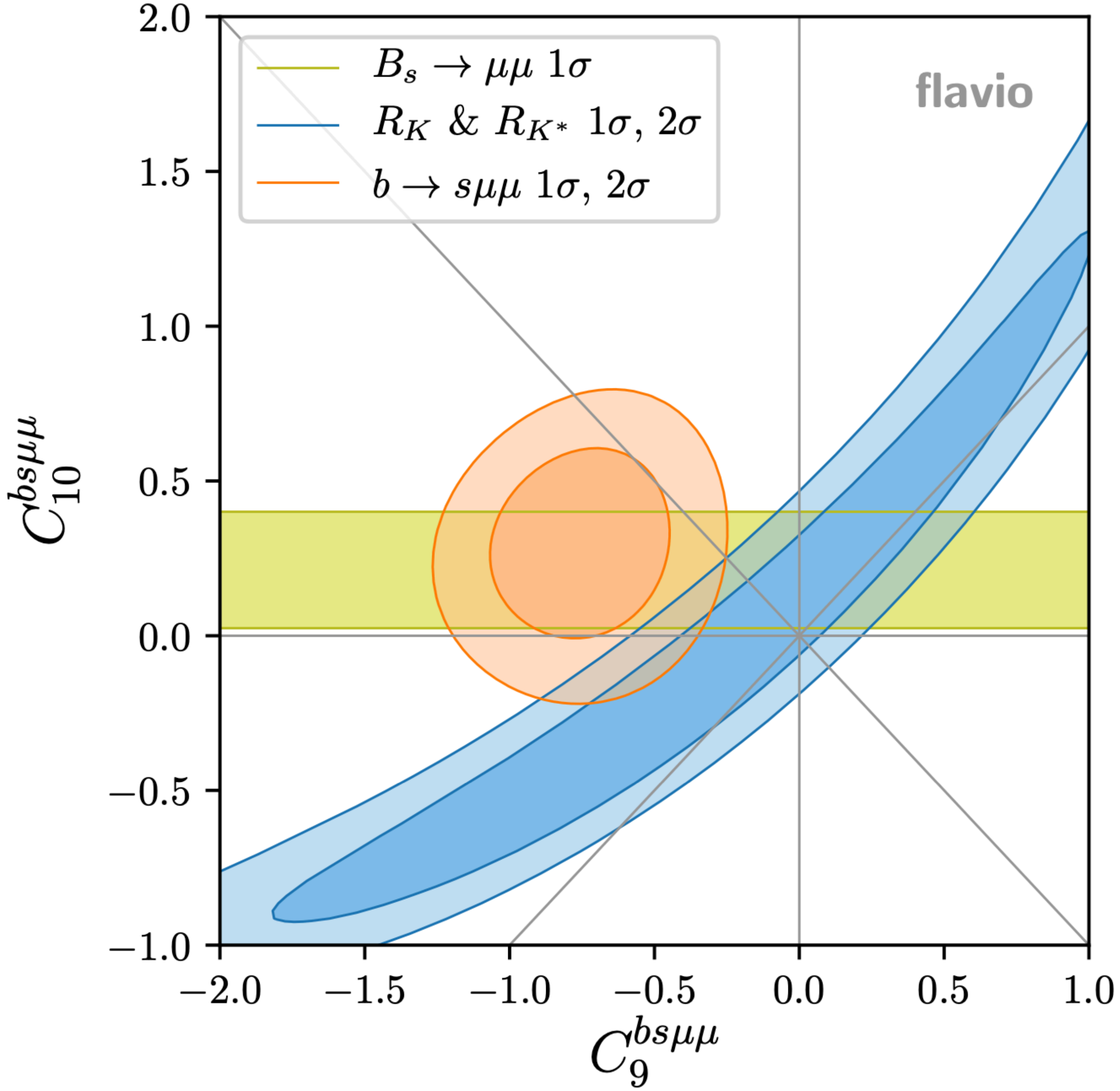
!anomalous

Excellent progress in understanding local and non-local matrix elements [1501.00367, 1503.05534, 1509.06235, 1707.07305, 1811.00983, 2011.09813, 2206.03797, 2207.12468, 2305.06301, …]

What's the situation with muonic (C_9, C_{10})?

$$O_9^{(\prime)bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10}^{(\prime)bq\ell\ell} = (\bar{q}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

A. Greljo, J. Salko, AS, P. Stangl, 2212.10497



Main updates:

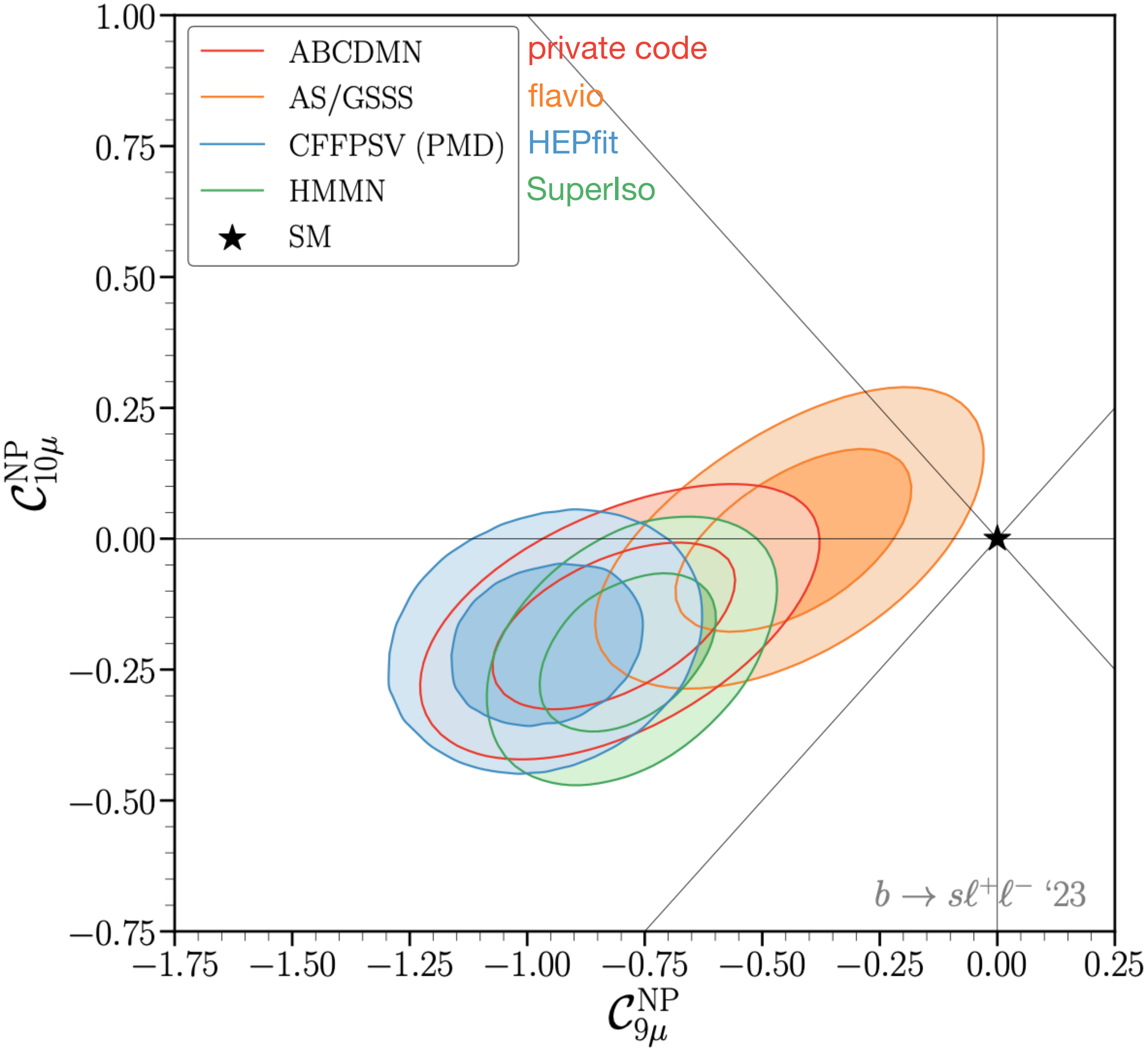
- $B_s \to \mu\mu$ now more compatible with SM
  [ATLAS 2018, LHCb 2021, CMS 2022]
- R_K, R_{K^*} now SM-like
  [LHCb 2022]

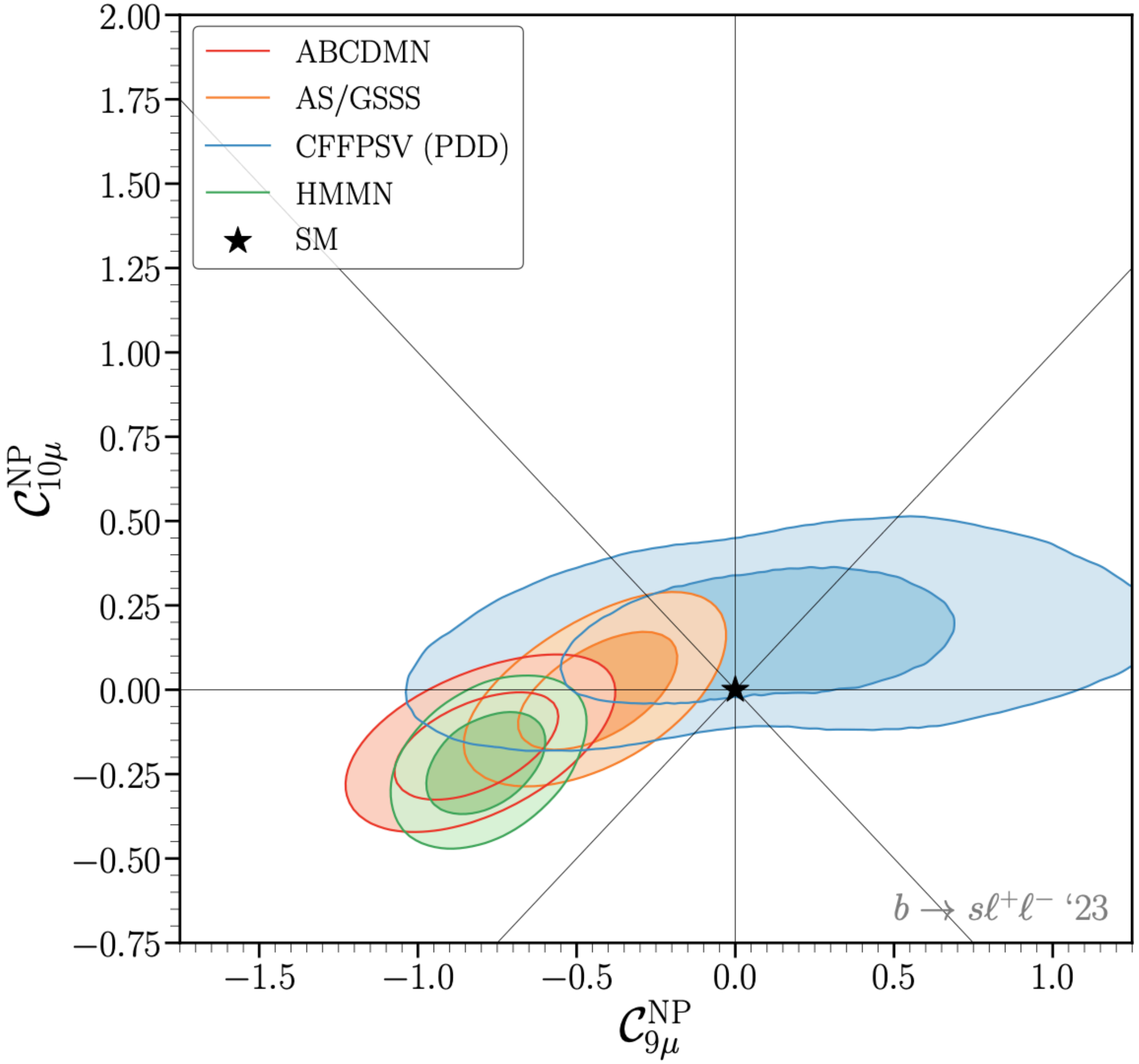
Upshot:

- $b \to s\mu\mu$ still pulling $C_9^{bs\mu\mu}$
- this is now in (slight) tension with $R_{K^{(*)}}$
- $C_9^{\text{univ.}}$ alleviates this tension

Many fits produced in the literature,
recently nicely reviewed in [B. Capdevila, A. Crivellin, J. Matias, 2309.01311]

2304.07330, 2212.10497, 2212.10516, 2310.05585, also 2306.15017, 2308.13426, …





Good agreement between fits even with different statistical frameworks, observable sets, parameterisations and parameters used

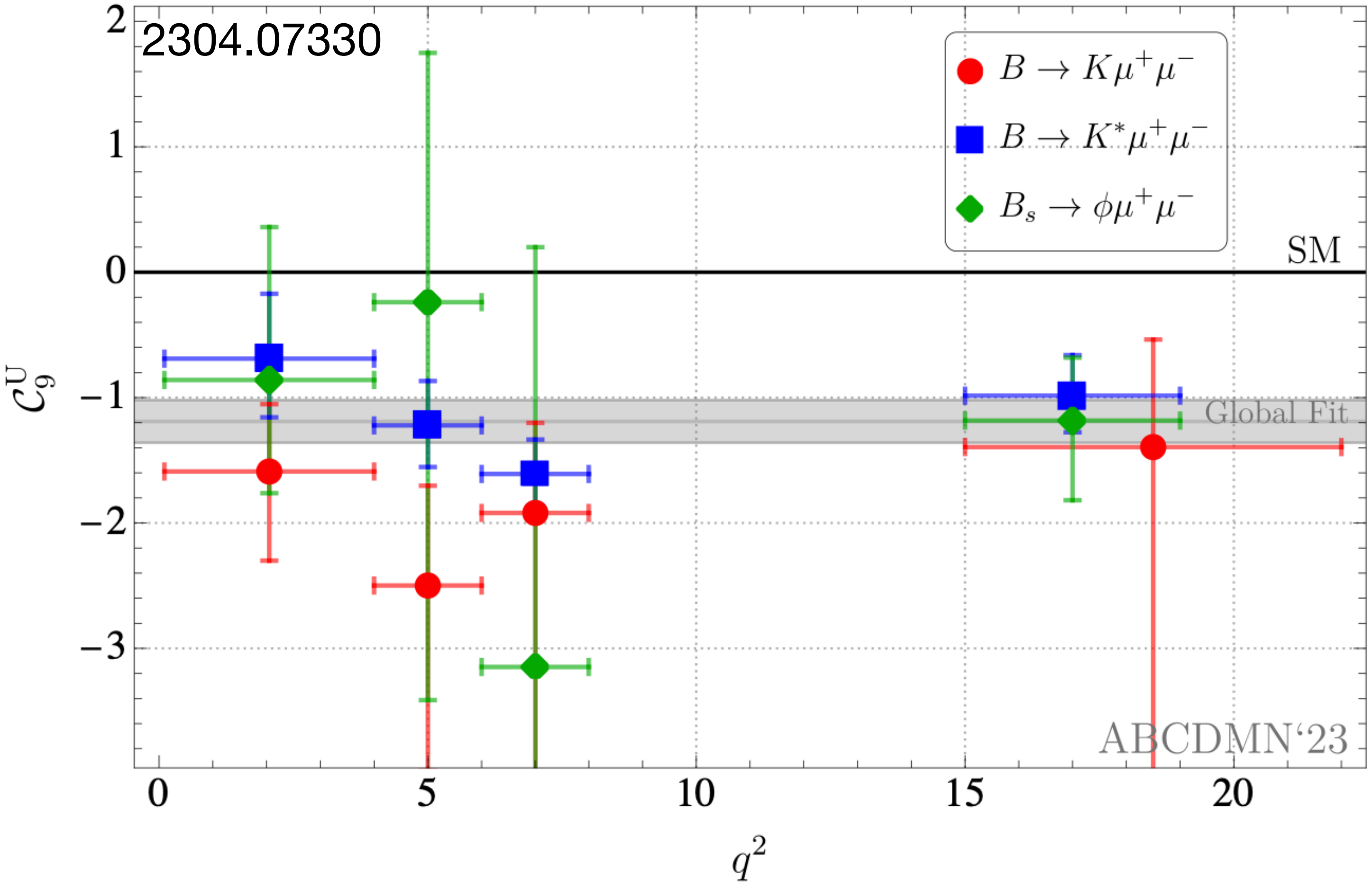
Non-local, non-perturbative effects under control?

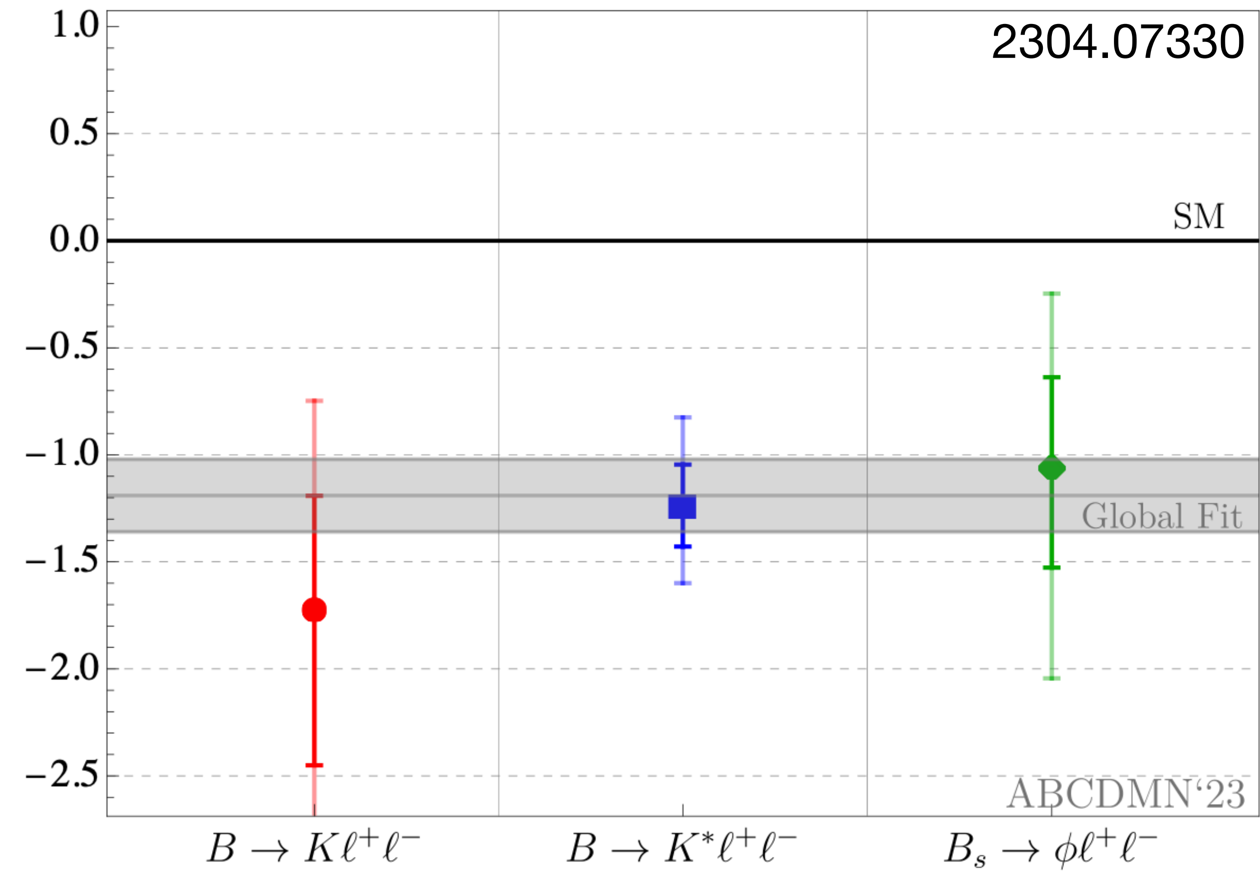
[see talk by M. Reboud]

Important check:

NP effects from local operators: mode and q^2 independence

C_9^U: universal for electrons and muons

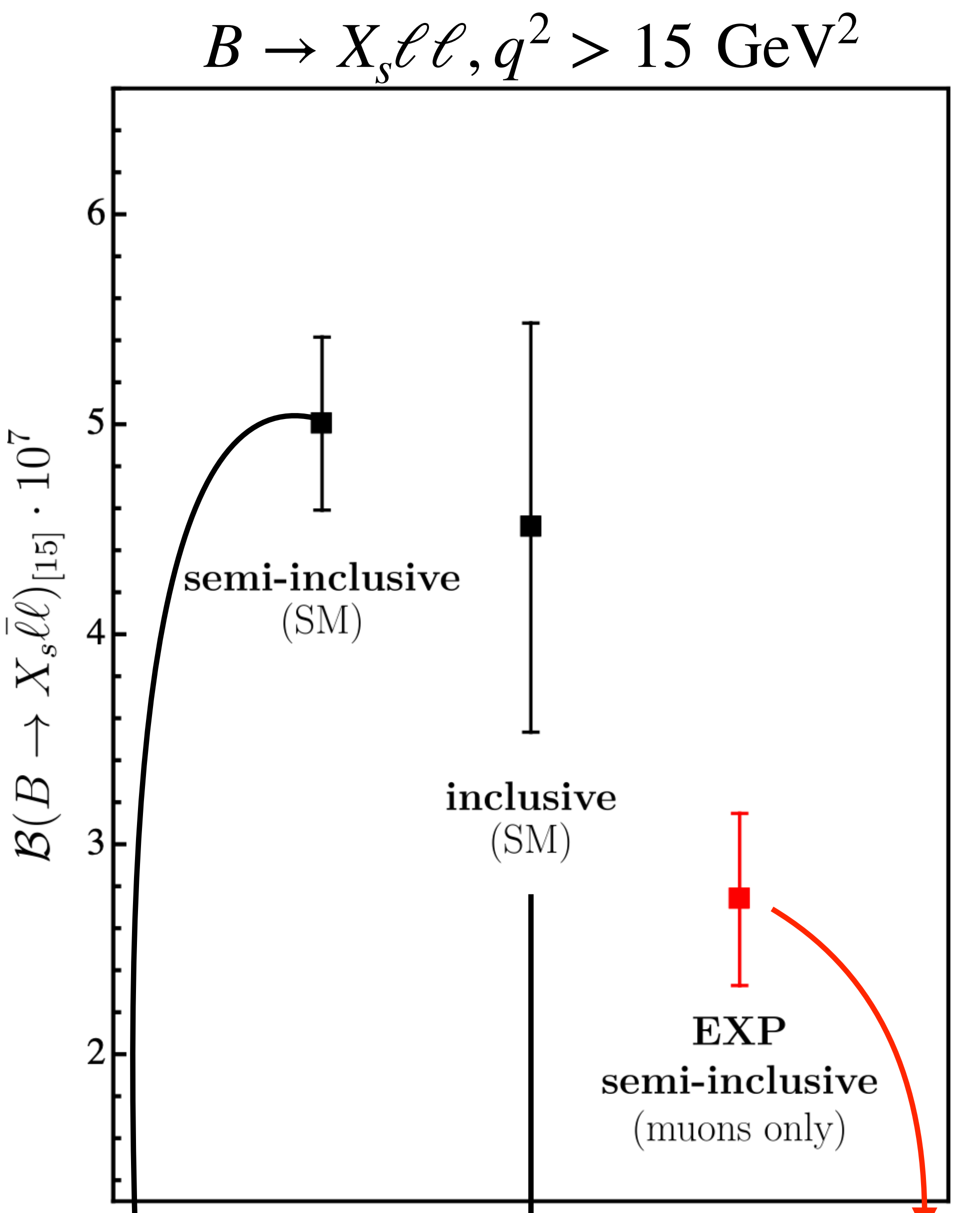




Data supports short-distance source of C_9, improvable with more statistics

Tension not exclusive to exclusive

G. Isidori, Z. Polonsky, A. Tinari, 2305.03076



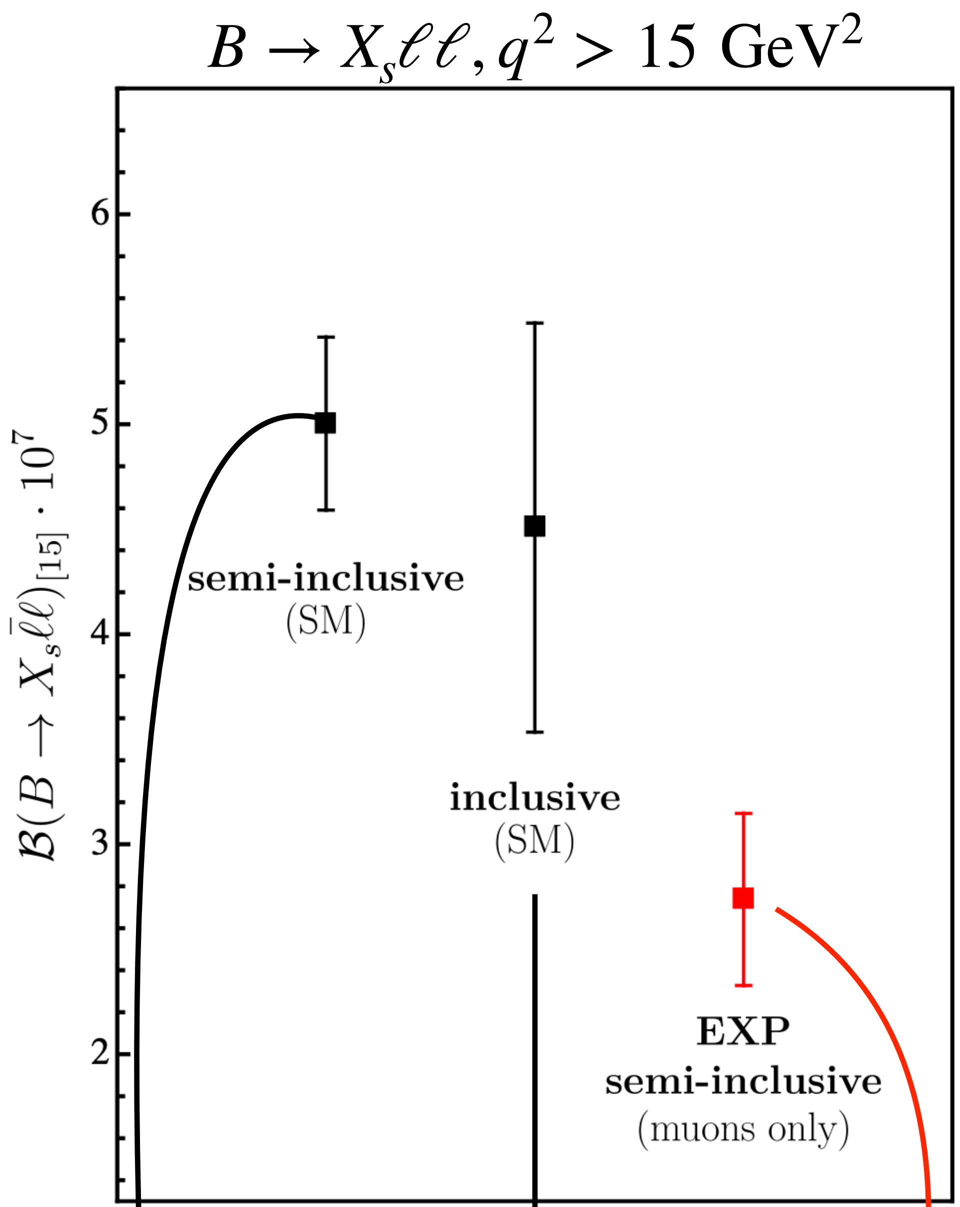
Prediction, leading 1- and 2-body modes

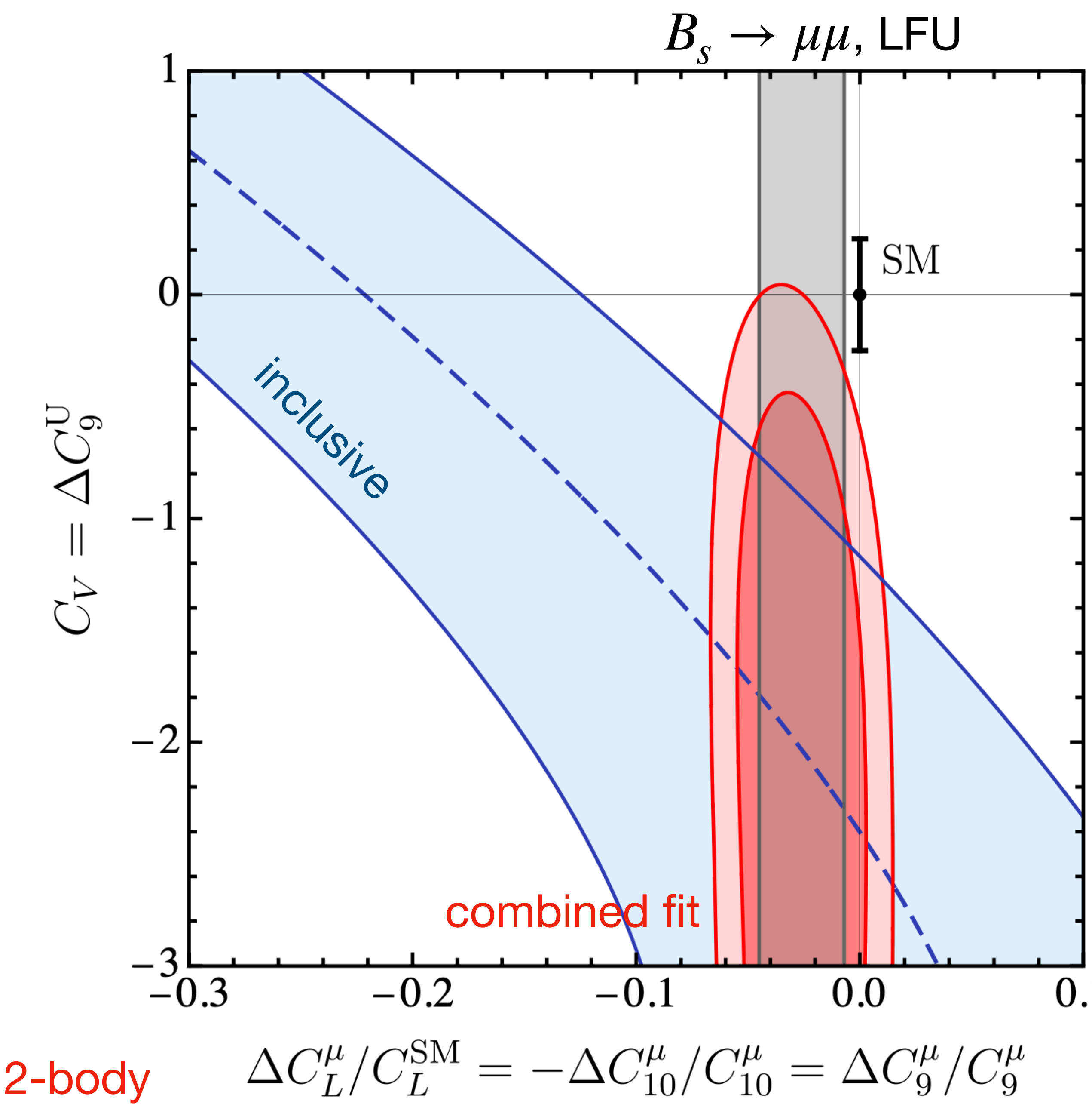
Exp., leading 1- and 2-body modes, LHCb

Prediction, through ratio with inclusive $B \to X_u \ell \nu$ [Belle 2021]
Significant cancellation of non-perturbative uncertainties [0707.1694]

Tension not exclusive to exclusive

G. Isidori, Z. Polonsky, A. Tinari, 2305.03076





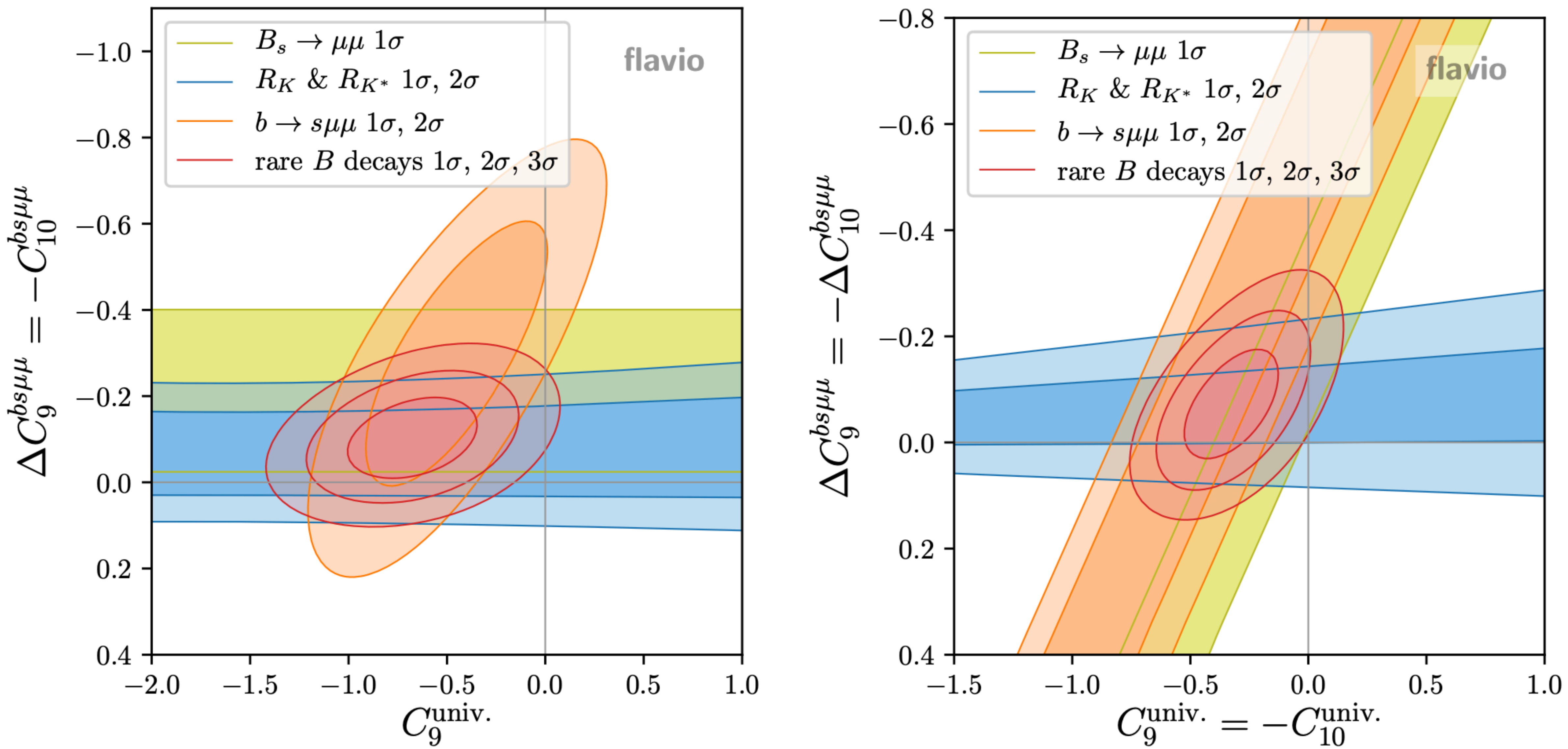
Prediction, leading 1- and 2-body modes

Exp., leading 1- and 2-body modes, LHCb

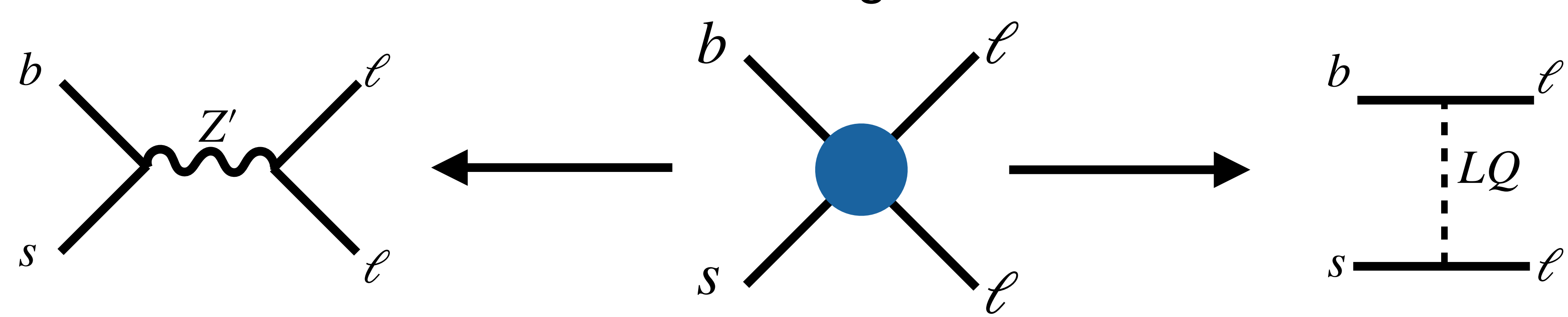
Prediction, through ratio with inclusive $B \to X_u \ell \nu$ [Belle 2021]
Significant cancellation of non-perturbative uncertainties [0707.1694]

- Tension even with inclusive prediction, improvable with $B \to X_u \ell \nu$ data
- Independent of hadronic form factors

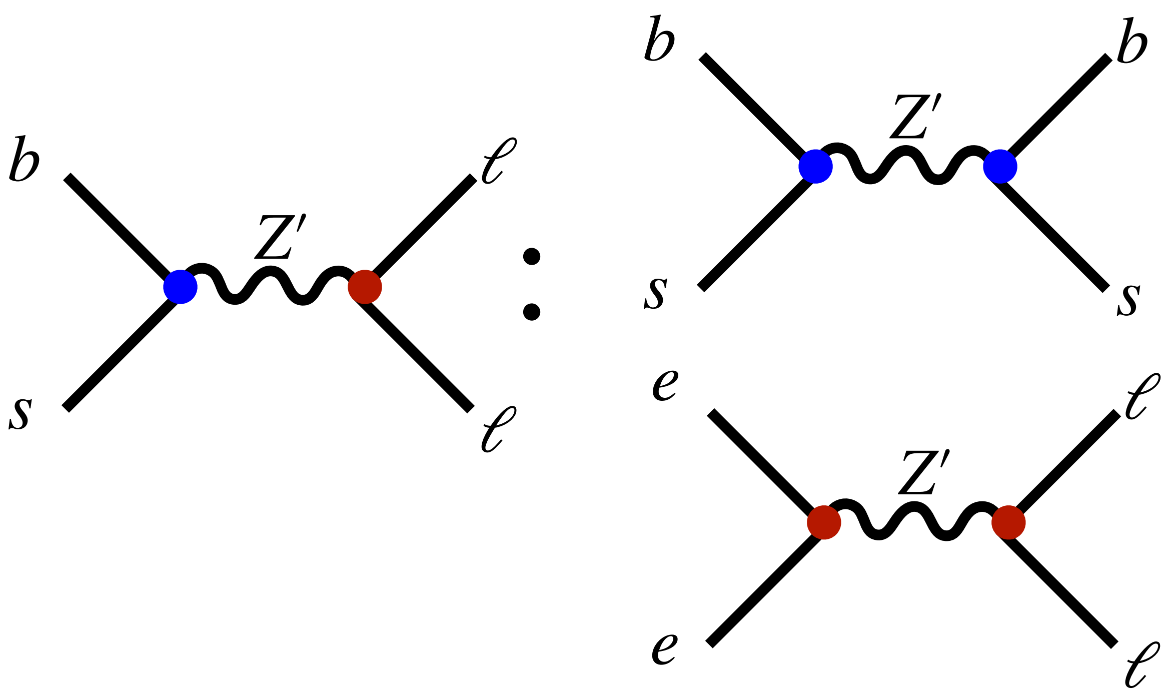
R_K & R_{K*} now prefer universal NP → implications for models



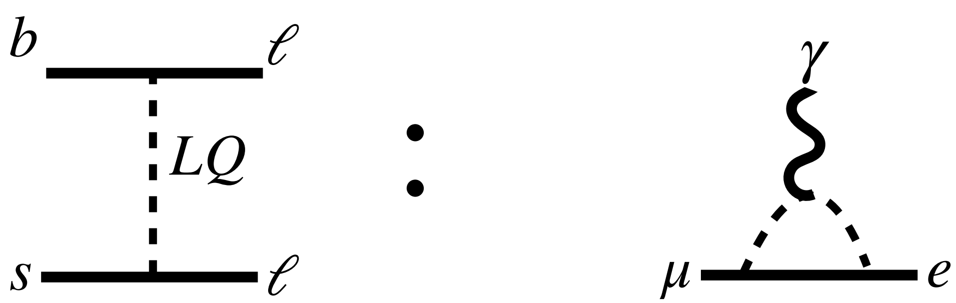
e.g.



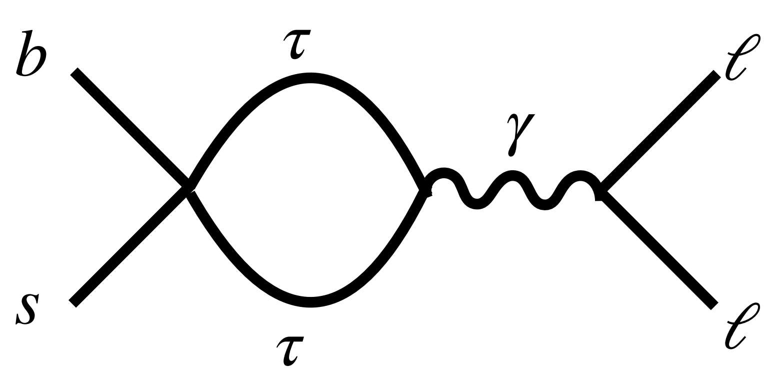
Implications for (simplified) models in a nutshell



Can easily be LFU (e.g. $U(1)_{B-L}$), stringent complementary constraints (there is wiggle room)
[2211.11766, 2212.10497, 2306.08669, …]



Not that easily LFU because of stringent cLFV constraints, can be done if LQ e.g. lepton-flavored
[1503.01084,1706.08511, 2212.10497, 2307.15117, …]



RG effect, connection with $R_{D^{(*)}}$ with τ, also possible through 4q operator
[1109.1826, 1701.09183, 1712.01919, 1807.02068, 1809.08447,1903.09578, 1910.12924, 2210.13422, 2304.07330, 2308.00034, 2309.01311, 2309.07205, …]

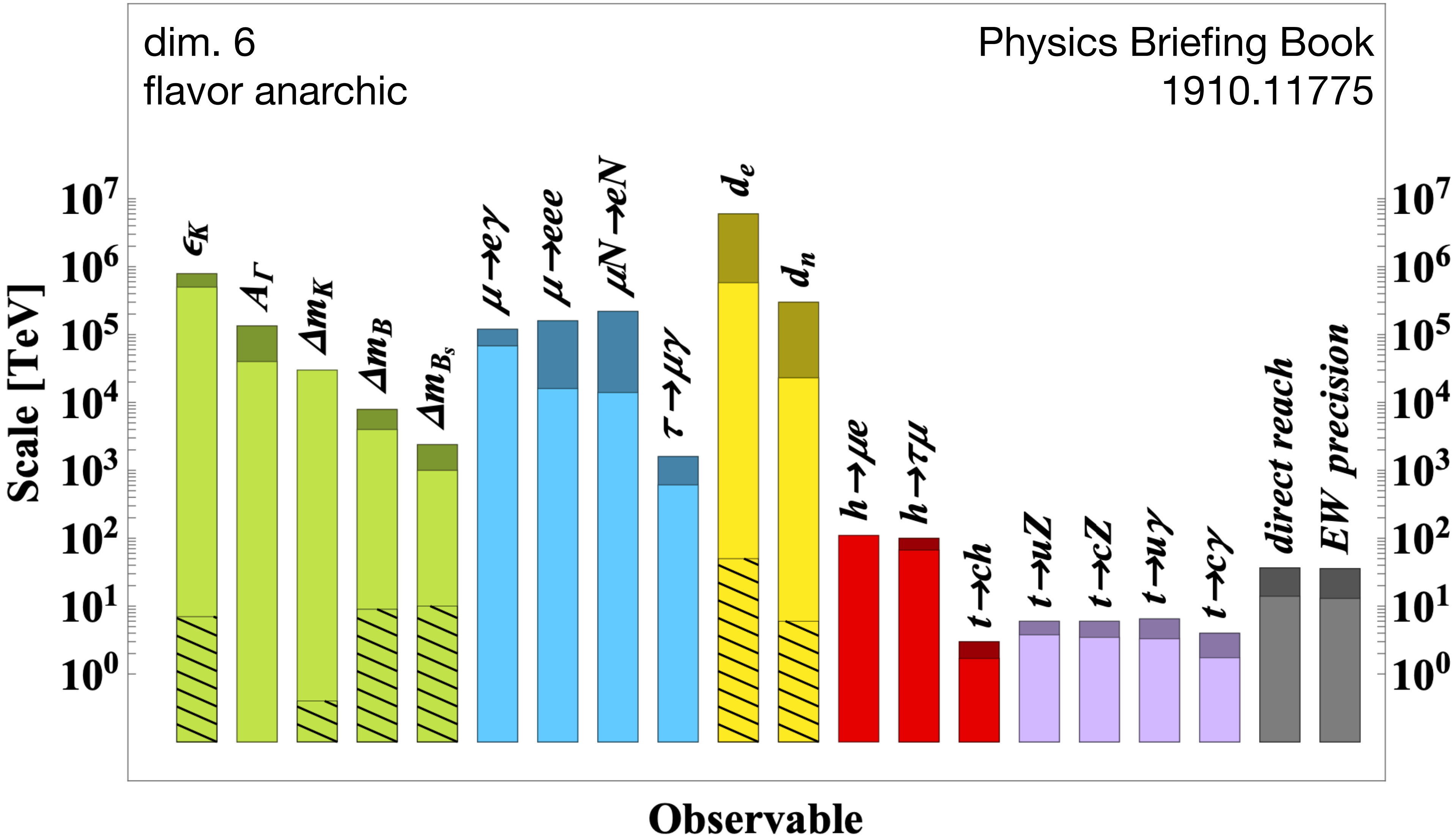
Flavorful connections in the SMEFT

Flavorful connections in the SMEFT

- SMEFT: $$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_Q \frac{C_Q}{\Lambda_Q^{[Q]-4}} Q$$

  implies correlations between various observable sectors (important to build a *global* SMEFT likelihood, e.g. *smelli*)
- NP is expected to have some kind of flavor protection, e.g. MFV

hep-ph/0207036, 2005.05366, 2203.09561



Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t)$$

Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t) \rightarrow [C_{lq}^{(1)}]_{st} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}$$

flavor conserving

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}$$

flavor conserving

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

flavor violating

$$\sim y_t^2 \begin{pmatrix} |V_{td}|^2 & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & |V_{ts}|^2 & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & |V_{tb}|^2 \end{pmatrix}$$

$b \to d\ell\ell$

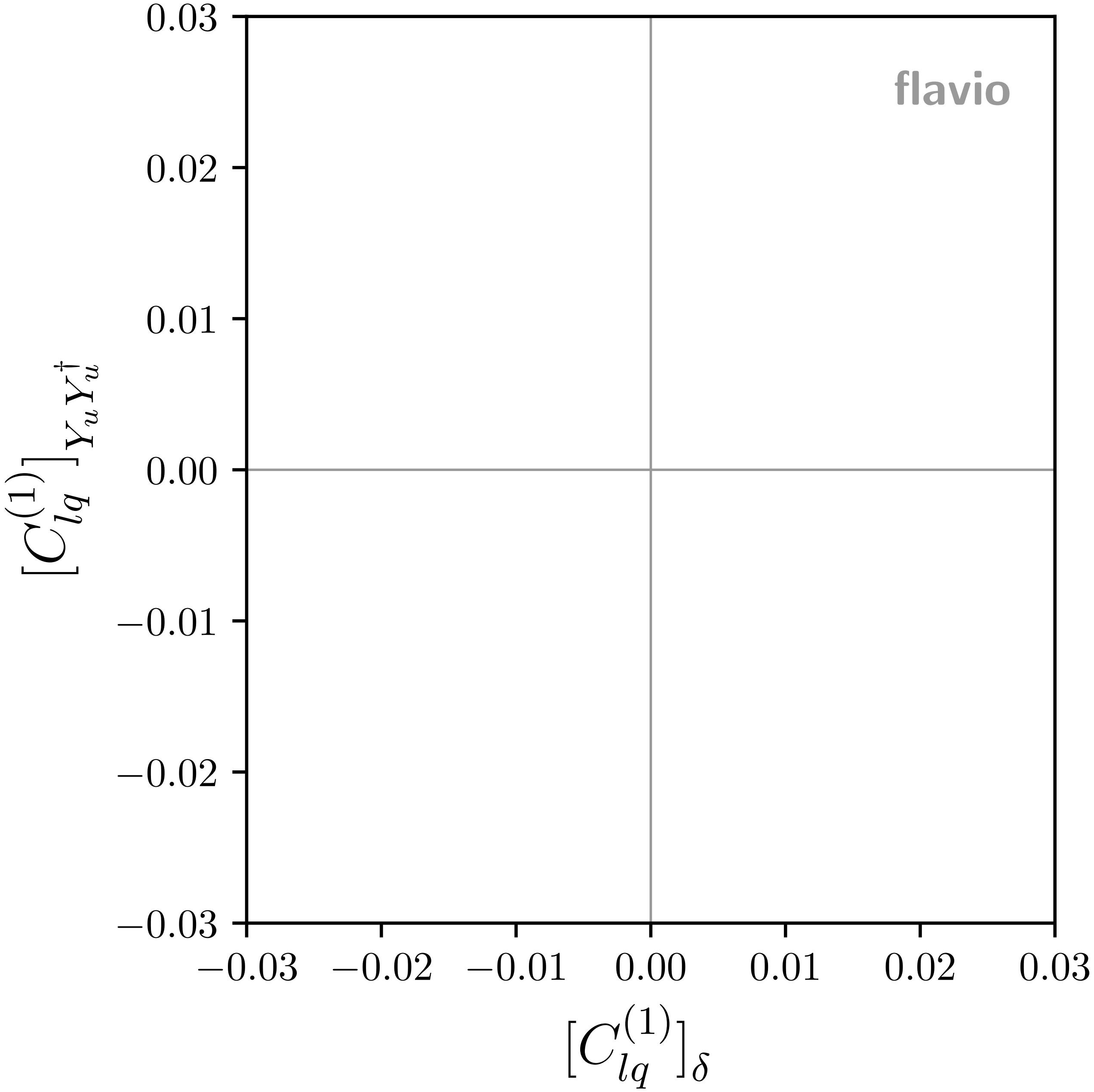
$b \to s\ell\ell$

Two UV parameters: $[C_{lq}^{(1)}]_\delta$ and $[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}$

Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

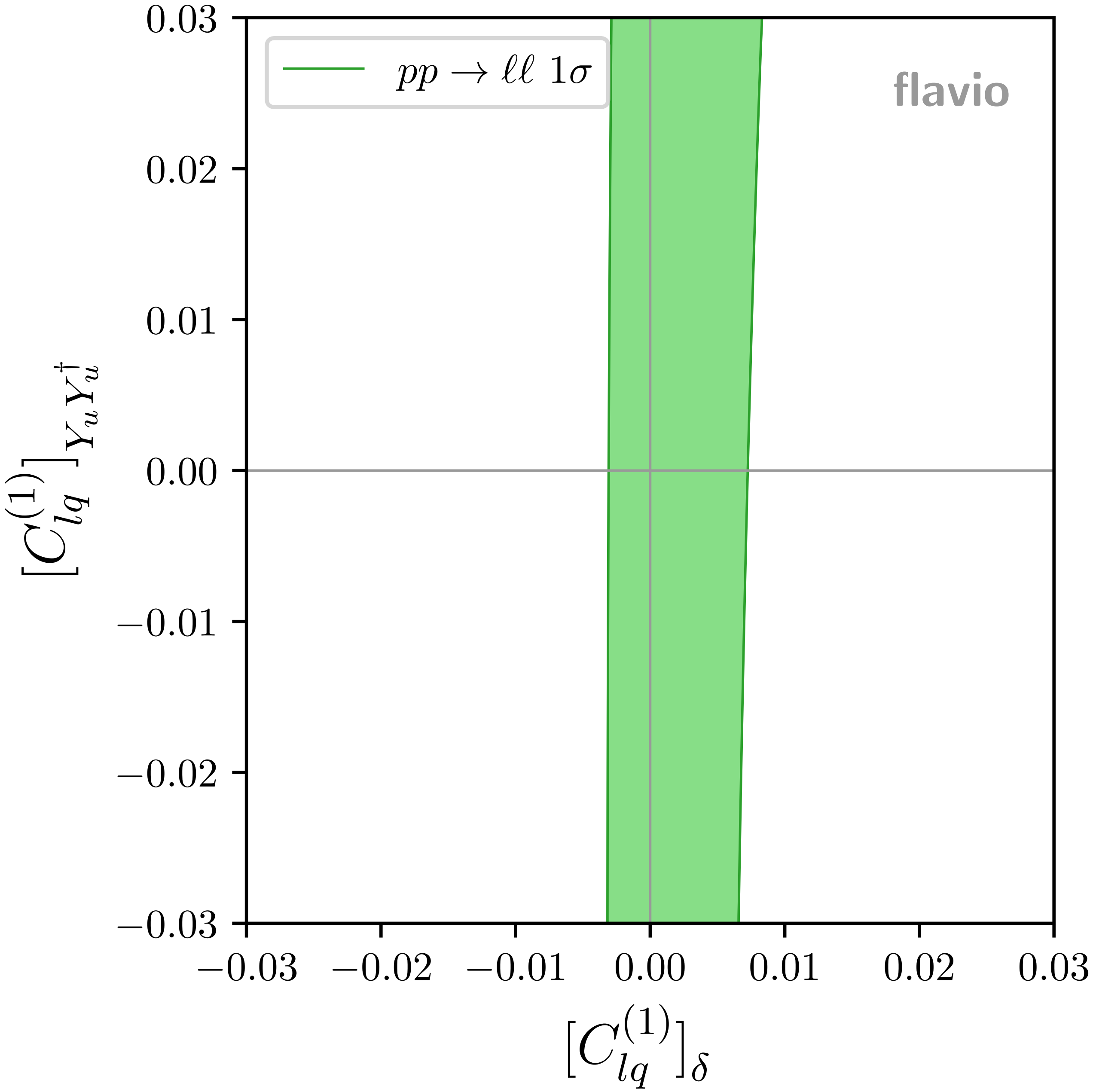
$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}$$



Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

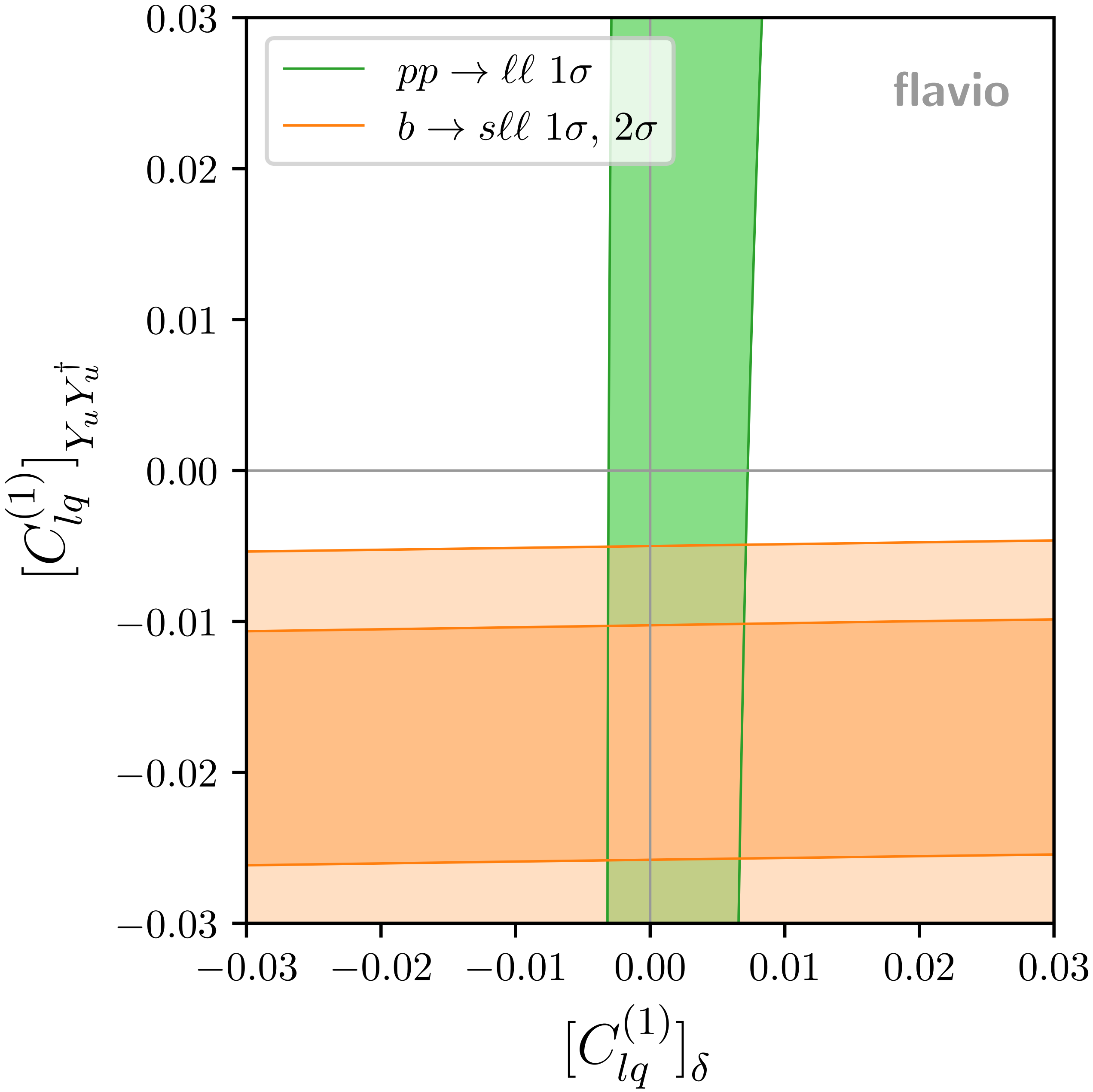
$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}$$



Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

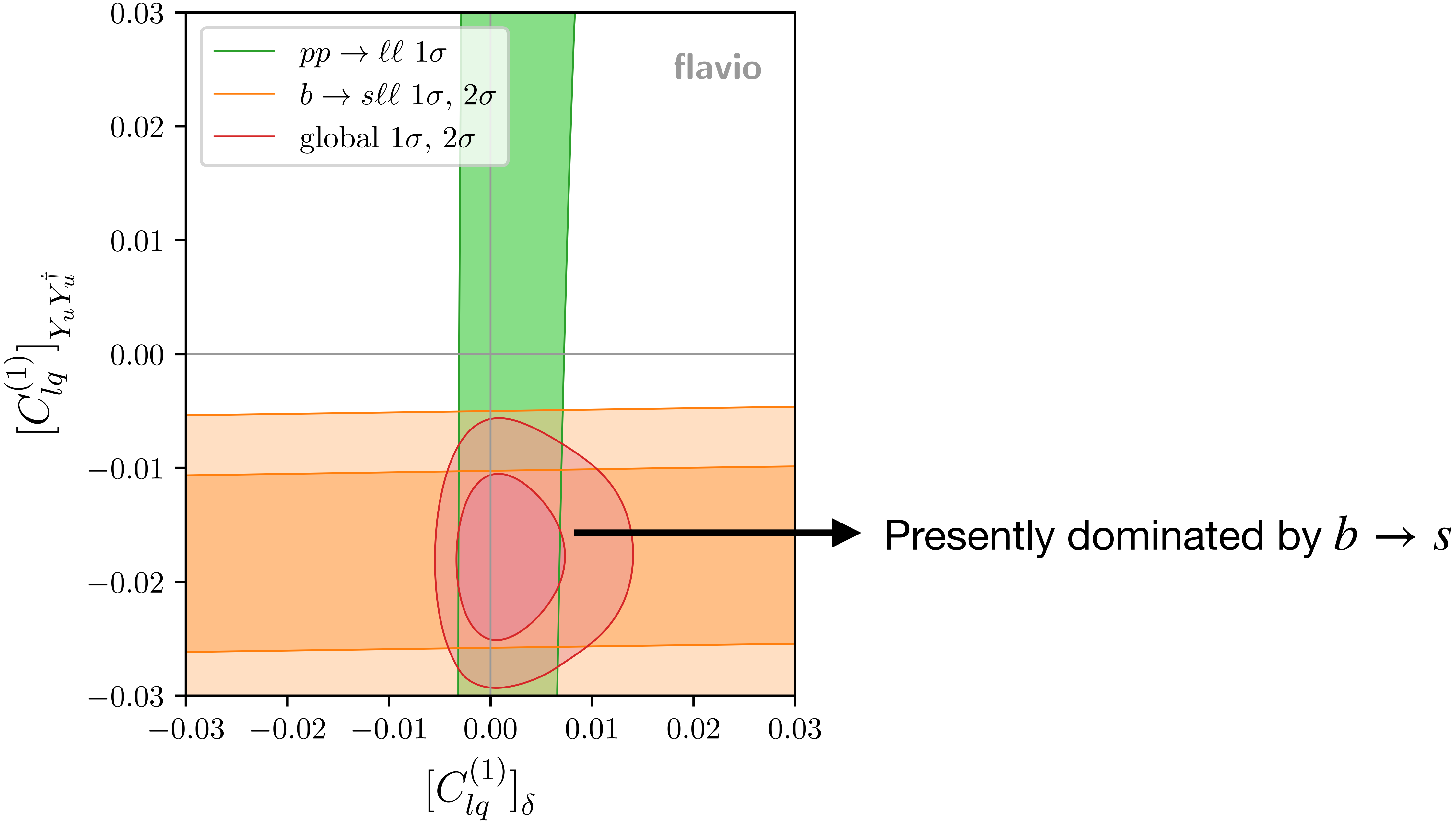
$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t) \rightarrow [C_{lq}^{(1)}]_{st} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}$$



Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

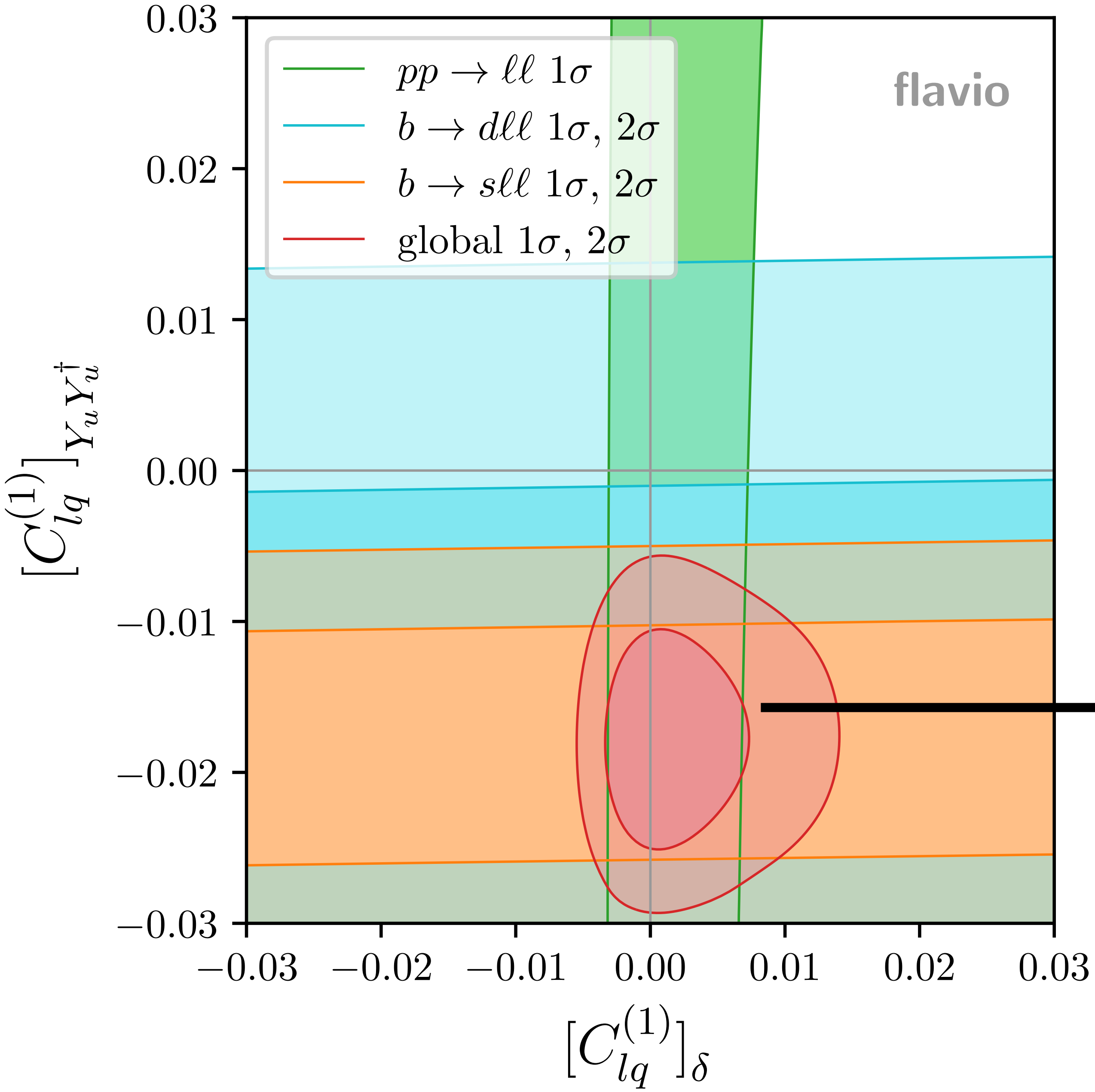
$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t) \rightarrow [C_{lq}^{(1)}]_{st} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}$$



Flavorful connections in the SMEFT

Consider the $Q_{lq}^{(1)}$ operator:

$$[C_{lq}^{(1)}]_{st}(\bar{l}\gamma_\mu l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st} = \delta_{st}[C_{lq}^{(1)}]_\delta + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}$$



Presently dominated by $b \to s$

Improvements in $b \to d$ will allow to test flavorful BSM hypotheses

A. Greljo, J. Salko, AS, P. Stangl, 2212.10497

[see also 2209.04457]

Future prospects

[see also talk by M. Vieites Díaz]

$b \to d$

- Excellent prospects at LHCb, Belle II, especially with higher luminosities
- Increased statistics should improve the already explored channels, clear candidate is $B_s \to K^* \mu\mu$ with differential BR in theory-friendly bins [see discussion in 2209.04457]
- Complementary observables: angular observables, baryonic modes, LFU ratios, …
- $b \to d$ to become the new $b \to s$, improvements will allow to test BSM flavor structure

$b \to s$

- LFU established in $R_{K^{(*)}}$, can we see the same pattern of deviations in electrons? What about taus?
- NP effects should be universal for all processes, helicities, independent of q^2 [e.g. 2304.07330]
- Plenty of complementary tests,
  e.g. semi-inclusive $b \to s\ell\ell$ and $B_s \to \mu\mu\gamma$ at high q^2, unbinned analyses…
  [e.g. 2008.08000, 2102.13390, 2305.03076, 2308.00034, …]
- NP could be CPV: updates and improved measurements of CPV observables anticipated
  [e.g. 2008.08000, 2008.09064, 2212.09575, 2308.00034, …]

Thank you