Looking for new physics through $b \to s\nu\bar{\nu}$ decays

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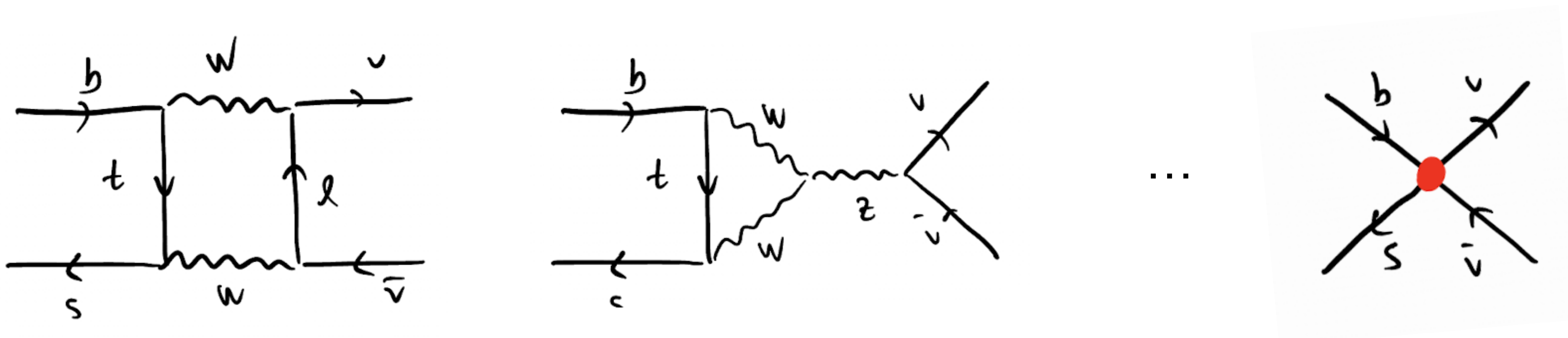
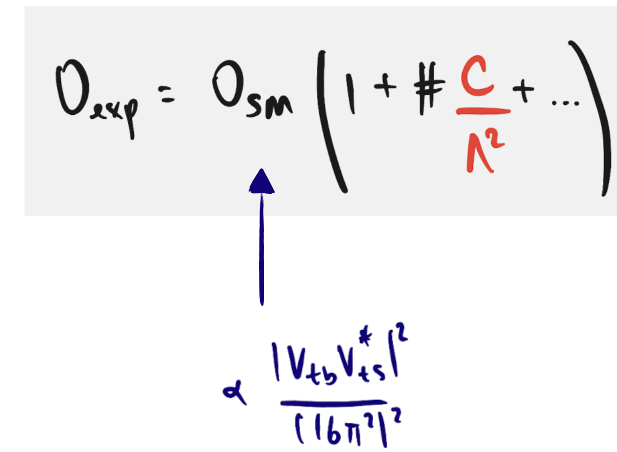
Based on [2301.06990, 2309.02246],
in collaboration with L. Allwicher, D. Becirevic, G. Piazza and S. Rosauro-Alcaraz

Moriond EW, 27 March, 2024

Motivation

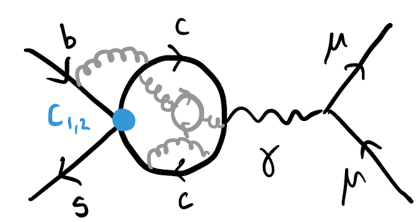
- **Flavor Changing Neutral Current (FCNC)** processes are powerful indirect probes of **New Physics (NP)** effects since they are **loop-** and **CKM suppressed**.





- The **main obstacle** to probe NP at **low energies** is the careful assessment of **hadronic uncertainties**:

  ⇒ Decays based on the $b \to s\nu\bar{\nu}$ transition are **theoretically cleaner** than those based on $b \to s\ell\ell$, since they are **not affected** by **problematic** long-distance contributions from $c\bar{c}$ **loops**.



- **Motivation** to study these decays:

  ⇒ **Progress** in the **lattice QCD** determinations of the $B \to K$ **form-factor** [HPQCD, 2207.12468].

  ⇒ **First observation** of $B \to K\nu\bar{\nu}$ by **Belle-II** [Belle-II, 2311.1467].

This talk:

i. Revisit the SM predictions for $B \to K^{(*)}\nu\bar{\nu}$.

ii. What can we learn from these measurements (in the SM and beyond)?

$B \to K^{(*)}\nu\bar{\nu}$ in the SM

$B \to K\nu\bar{\nu}$ in the SM

- **Effective Hamiltonian** in the SM:

see e.g. [Buras et al. '14]

$$\mathcal{L}_{\mathrm{eff}}^{\mathrm{b}\to\mathrm{s}\nu\nu} = \frac{4G_F \lambda_t}{\sqrt{2}} \frac{\alpha_{\mathrm{em}}}{2\pi} \sum_i C_L^{\mathrm{SM}} (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu \nu_{Li}) + \mathrm{h.c.}\,,$$

$\lambda_t = V_{tb}V_{ts}^*$

- **Short-distance** contributions known to **good precision**:

$$C_L^{\mathrm{SM}} = -X_t / \sin^2\theta_W$$
$$= -6.32(7)$$

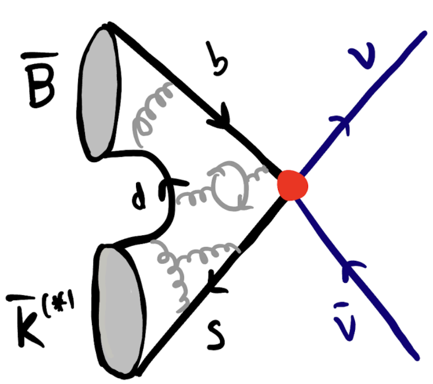
Including NLO QCD and two-loop EW contributions:

$$X_t = 1.462(17)(2)$$

[Buchala et al. '93, '99], [Misiak et al. '99], [Brod et al. '10]

Two main sources of uncertainties:

i) Hadronic matrix-element:



Known Lorentz factors

$$\langle K^{(*)} | \bar{s}_L \gamma^\mu b_L | B \rangle = \sum_a K_a^\mu \, \mathcal{F}_a(q^2)$$

Form-factors (e.g., LQCD)

ii) CKM matrix:

From CKM unitarity:

$$|V_{tb}V_{ts}^*| = |V_{cb}| \, (1 + \mathcal{O}(\lambda^2))$$

Which value to take (incl. vs. excl.)?

I. Form-factors: $B \to K\nu\bar{\nu}$

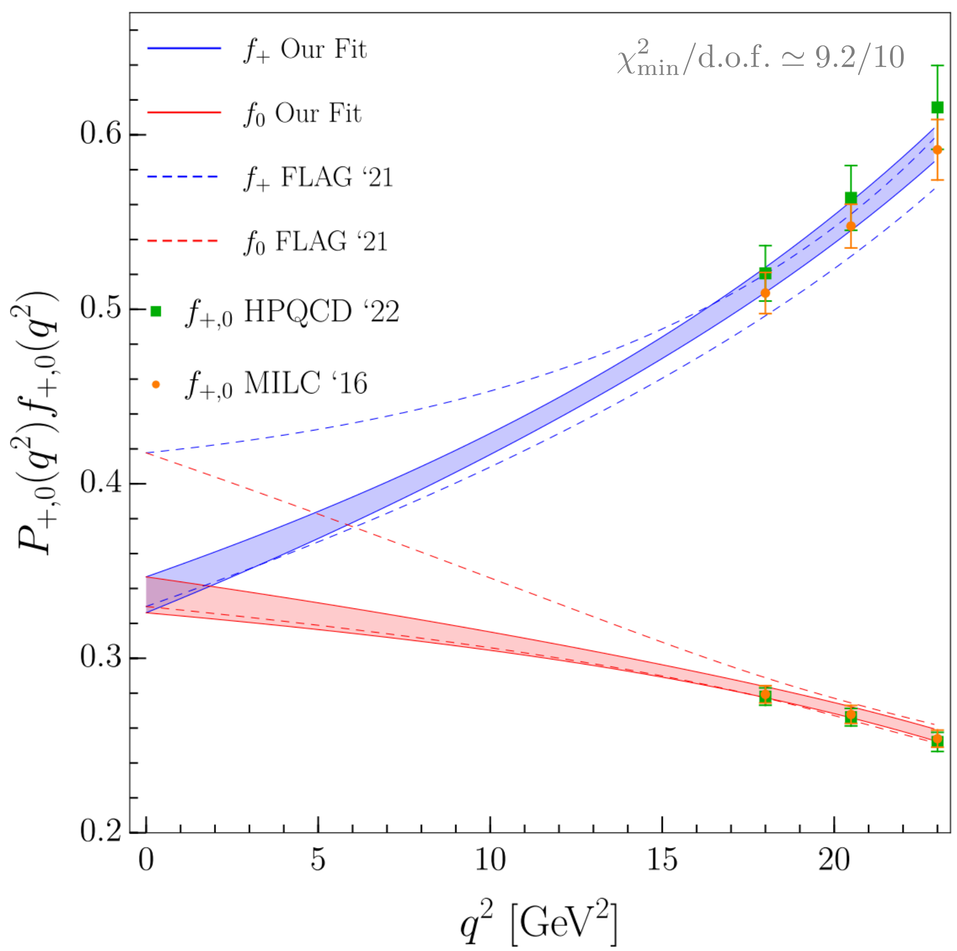
- **Lattice QCD** data available at **nonzero recoil** ($q^2 \neq q^2_{\max}$) for all form-factors:

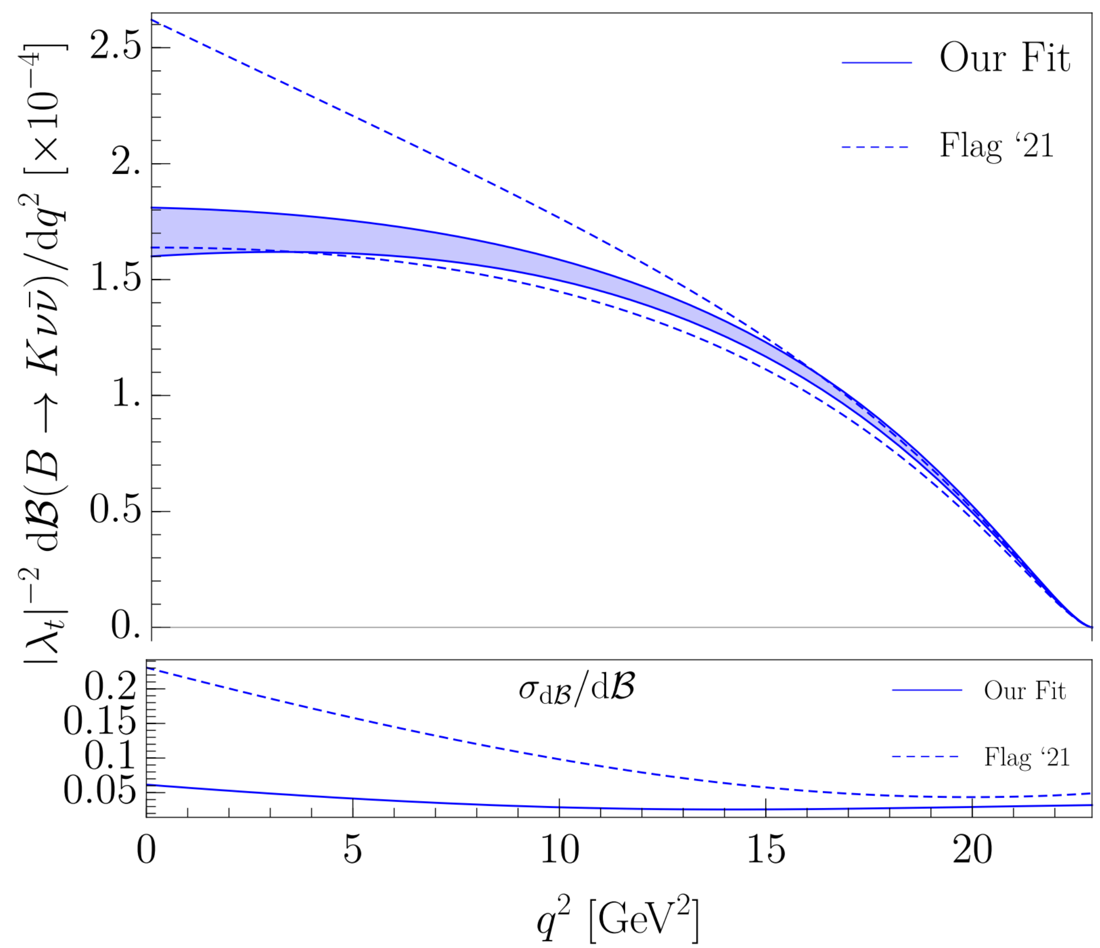
$$\langle K(k)|\bar{s}_L\gamma^\mu b_L|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu\right] f_+(q^2) + q^\mu \frac{m_B^2 - m_K^2}{q^2} f_0(q^2)$$

with $f_+(0) = f_0(0)$.

Only form-factor needed for $B \to K\nu\bar{\nu}$!

- **[NEW]** We update the FLAG average by combining [HPQCD '22] results with [FNAL/MILC '16]:





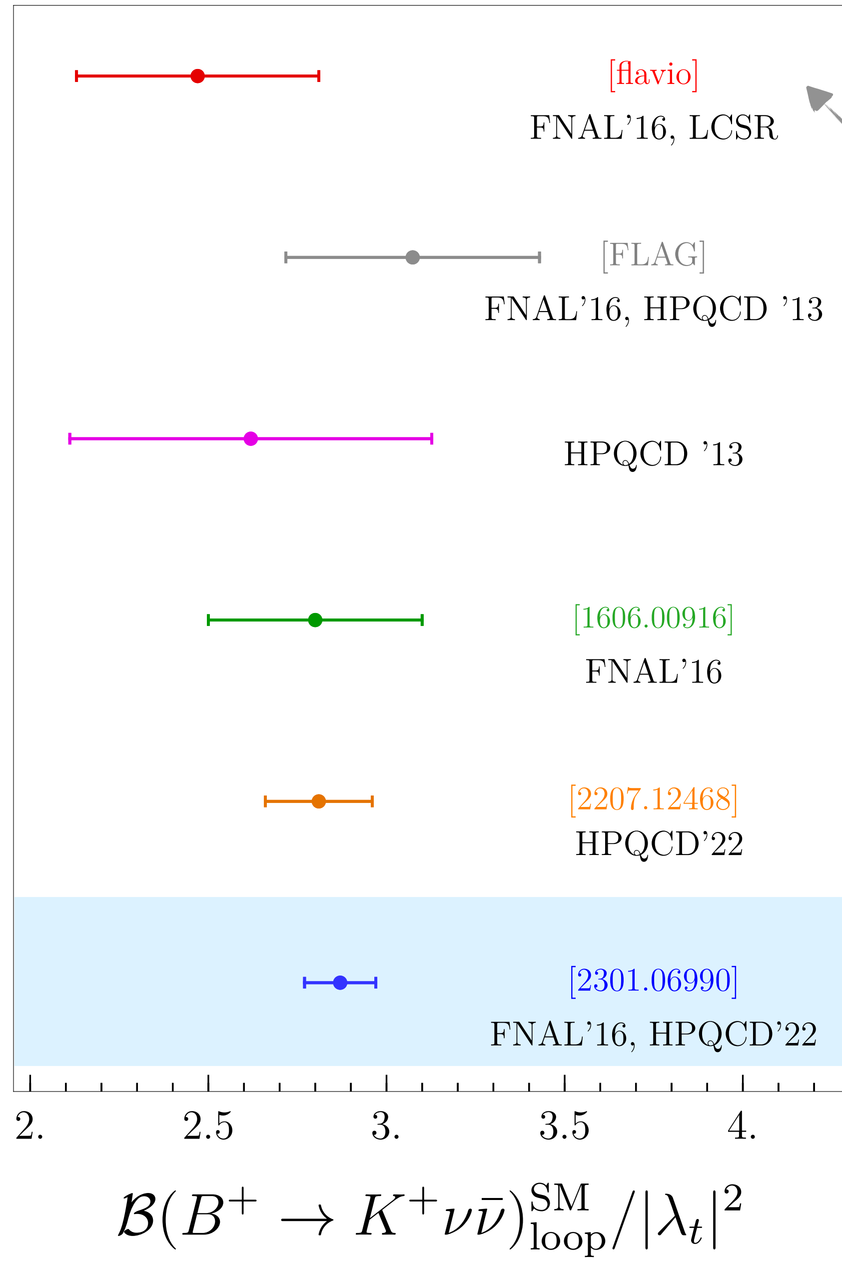
Pole factor:
$P_i(q^2) = 1 - q^2/M_i^2$

[Becirevic, Piazza, **OS**. 2301.06990]

I. Form-factors: $B \to K\nu\bar{\nu}$

**Annihilation contributions not included below (see back-up)*

- **Our final predictions**:



Form-factors based on Light-Cone Sum Rules (LCSR) lead to smaller branching fractions.

[Bharucha et al. '15, Gubernari et al. '18]

$$\mathcal{B}(B \to K\nu\bar{\nu})^{\rm SM}/|\lambda_t|^2 = \begin{cases} (1.33 \pm 0.04)_{K_S} \times 10^{-3} \\ (2.87 \pm 0.10)_{K^+} \times 10^{-3} \end{cases}$$

[$\approx 3\,\%$ uncertainty]

[Becirevic, Piazza, **OS**. 2301.06990]

[Intermezzo]: Cross-check of $f_+^{B\to K}(q^2)$

- SM predictions depend on the **extrapolation** of the LQCD **form factors to low q^2** values — **parameterisation dependent?**

  ⇒ How can we **test the shape** of the **extrapolated** LQCD **form-factors**?

- We propose to measure:

[Becirevic, Piazza, **OS**. 2301.06990]

$$r_{\mathrm{low/high}} = \frac{\mathcal{B}(B\to K\nu\bar{\nu})_{\mathrm{low}-q^2}}{\mathcal{B}(B\to K\nu\bar{\nu})_{\mathrm{high}-q^2}}$$

⇒ *Independent of λ_t and the form-factor normalisation, as well as of NP contributions.*

NB. w/o ν_R

- Using the bins $(0, q^2_{\mathrm{max}}/2)$ *vs.* $(q^2_{\mathrm{max}}/2, q^2_{\mathrm{max}})$:

e.g, using (old) FLAG average:

$$r_{\mathrm{low/high}} = 2.15 \pm 0.26$$

$$r_{\mathrm{low/high}} = 1.91 \pm 0.06$$

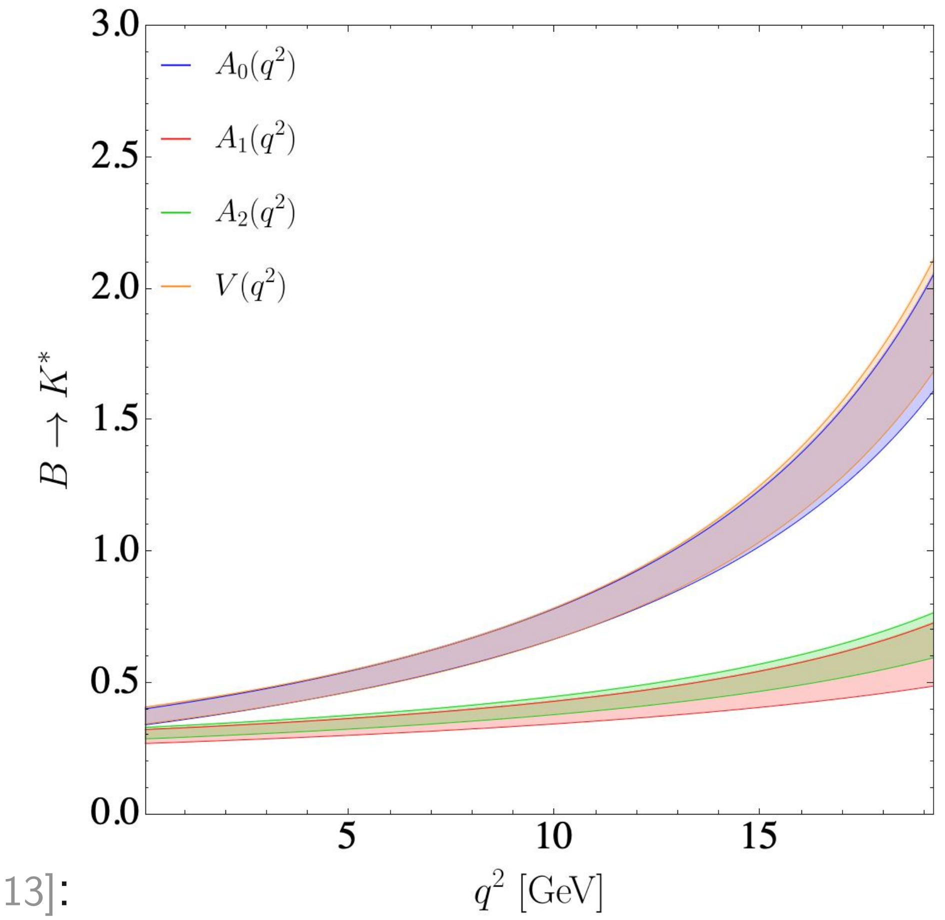
Binned measurements at Belle-II would be a **useful cross-check** of the **consistency** of the q^2**-shape** of **SM predictions**.

I. Form-factors: $B \to K^* \nu\bar{\nu}$

See talk by Gubernari

- $B \to K^* \nu\bar{\nu}$ decays are **more challenging** for several reasons:

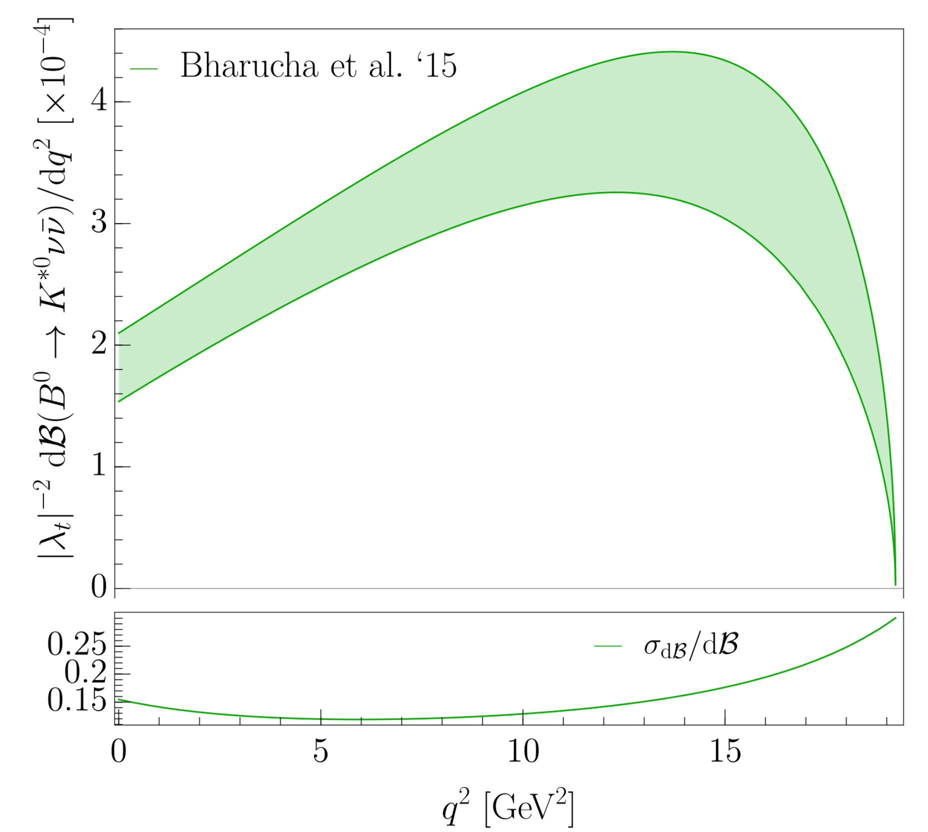
$$\langle \bar{K}^*(k)|\bar{s}\gamma_\mu(1-\gamma_5)b|\bar{B}(p)\rangle = \varepsilon_{\mu\nu\rho\sigma}\varepsilon^{*\nu}p^\rho k^\sigma \frac{2V(q^2)}{m_B+m_{K^*}} - i\varepsilon^*_\mu(m_B+m_{K^*})A_1(q^2) + i(p+k)_\mu(\varepsilon^*\cdot q)\frac{A_2(q^2)}{m_B+m_{K^*}} + iq_\mu(\varepsilon^*\cdot q)\frac{2m_{K^*}}{q^2}\left[A_3(q^2)-A_0(q^2)\right],$$



- We use LCSR (+LQCD) results from [Bharucha et al. '15, Horgan et al. '13]:

$$\mathcal{B}(B\to K^*\nu\bar{\nu})^{\rm SM}/|\lambda_t|^2 = \begin{cases}(5.9\pm0.8)_{K^{*0}}\times 10^{-3}\\(6.4\pm0.9)_{K^{*+}}\times 10^{-3}\end{cases}$$

[$\approx 15\,\%$ uncertainty]



⇒ Relatively small uncertainties, **but are they accurate**?

II. Which CKM value?

$$\lambda_t = V_{tb} V_{ts}^*$$

- Using available $b \to c\ell\bar{\nu}$ data:

$$|\lambda_t| \times 10^3 = \begin{cases} 41.4 \pm 0.8\,, & (B \to X_c l\bar{\nu}) \\ 39.3 \pm 1.0\,, & (B \to D l\bar{\nu}) \\ 37.8 \pm 0.7\,, & (B \to D^* l\bar{\nu}) \end{cases}$$

[HFLAV, '22]
[FLAG, '21]
[HFLAV, '22]

... to be compared to CKM global fits:

cf. also [Martinelli et al. '21]
See talk by Fedele

$$|\lambda_t|_{\mathrm{UTfit}} = (41.4 \pm 0.5) \times 10^{-2}$$

$$|\lambda_t|_{\mathrm{CKMfitter}} = (40.5 \pm 0.3) \times 10^{-2}$$

- Alternative strategy: to use $\Delta m_{B_s} \propto f_{B_s}^2 \hat{B}_{B_s} |\lambda_t|^2$ [Buras, Venturini. '21, '22]

$$|\lambda_t| \times 10^3 = \begin{cases} 41.9 \pm 1.0\,, & (N_f = 2+1+1) \\ 39.2 \pm 1.1\,, & (N_f = 2+1) \end{cases}$$

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 256 \pm 6~\mathrm{MeV} \qquad (N_f = 2+1+1)$$

[HPQCD '19]

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 274 \pm 8~\mathrm{MeV} \qquad (N_f = 2+1)$$

[FLAG '21]

There is **not a clear answer** to this **ambiguity** so far.

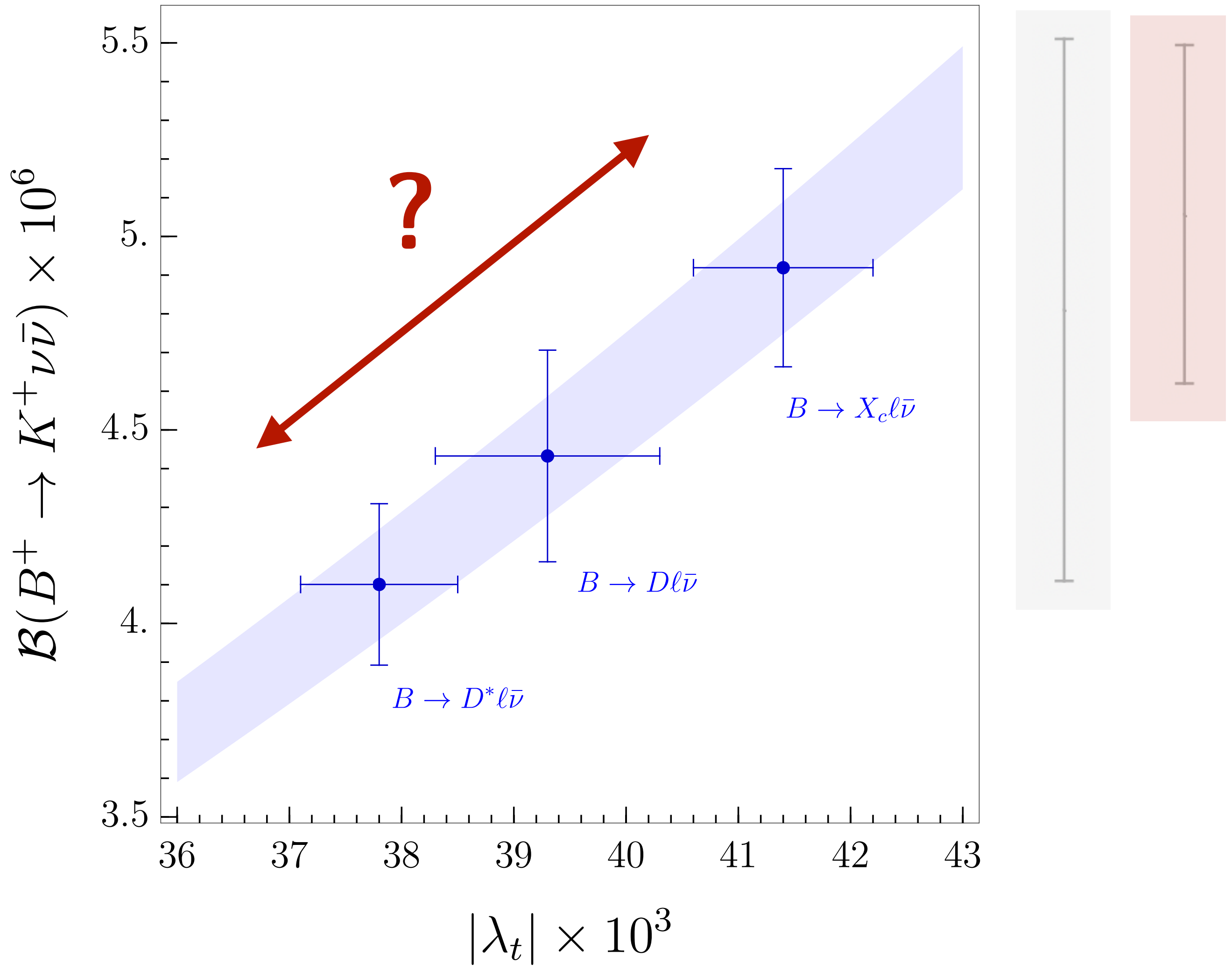
Summary

[Becirevic, Piazza, **OS**. 2301.06990]

*Using V_{cb} from $B \to D\ell\bar{\nu}$ for illustration

Decay	Branching ratio
$B^+ \to K^+\nu\bar{\nu}$	$(4.44 \pm 0.14 \pm 0.27) \times 10^{-6}$
$B^0 \to K_S\nu\bar{\nu}$	$(2.05 \pm 0.07 \pm 0.12) \times 10^{-6}$
$B^+ \to K^{*+}\nu\bar{\nu}$	$(9.79 \pm 1.30 \pm 0.60) \times 10^{-6}$
$B^0 \to K^{*0}\nu\bar{\nu}$	$(9.05 \pm 1.25 \pm 0.55) \times 10^{-6}$

FF CKM



Current Belle-II uncertainty: 0.7×10^{-6}

Projected sensitivity/SM ($50\ \mathrm{ab}^{-1}$)*:* $\approx 10\,\%$

Take-home:

- To remain **cautious** about **hadronic uncertainties** associated with the **form-factors** and the **CKM** values extracted from data — *non-negligible given the projected Belle-II sensitivity.*
- **Binned measurements** at Belle-II would be **valuable** for **testing** the $B \to K$ **form factors**.

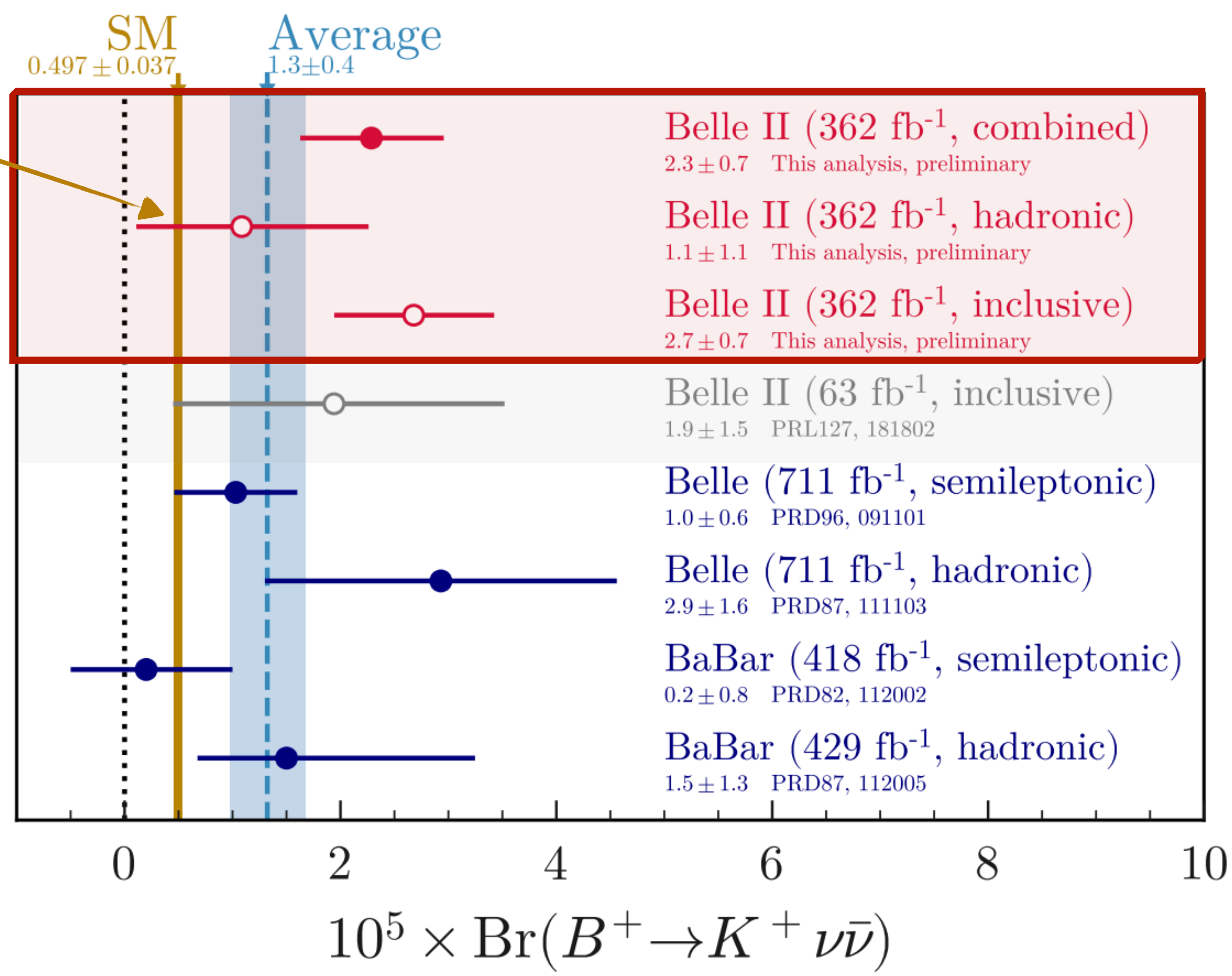
Understanding the first observation of $B \to K\nu\nu$ at Belle-II

[NEW] Belle-II results

See talks by Moneta and Goldenzweig

[Belle-II, 2311.14647]

Theory uncertainty sub-dominant (thus far!)



New Belle-II results

First Belle-II result

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{\text{exp}} = \left[2.3 \pm 0.5\,(\text{stat})^{+0.5}_{-0.4}\,(\text{syst})\right] \times 10^{-5}$$

$\approx 3\sigma$ above the SM prediction

⇒ **More data is needed! Many possible cross-checks** *(e.g., $B^0 \to K_S \nu\bar{\nu}$, semilep. tagging...)*

⇒ **Can these results be accommodated by new physics?**

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

- Low-energy EFT:

see e.g. [Buras et al. '14]

$$\mathcal{L}_{\mathrm{eff}}^{\mathrm{b}\to\mathrm{s}\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha_{\mathrm{em}}}{2\pi}\sum_{ij}\Big[C_L^{\nu_i\nu_j}\,(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj}) + C_R^{\nu_i\nu_j}\,(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})\Big] + \mathrm{h.c.}\,,$$

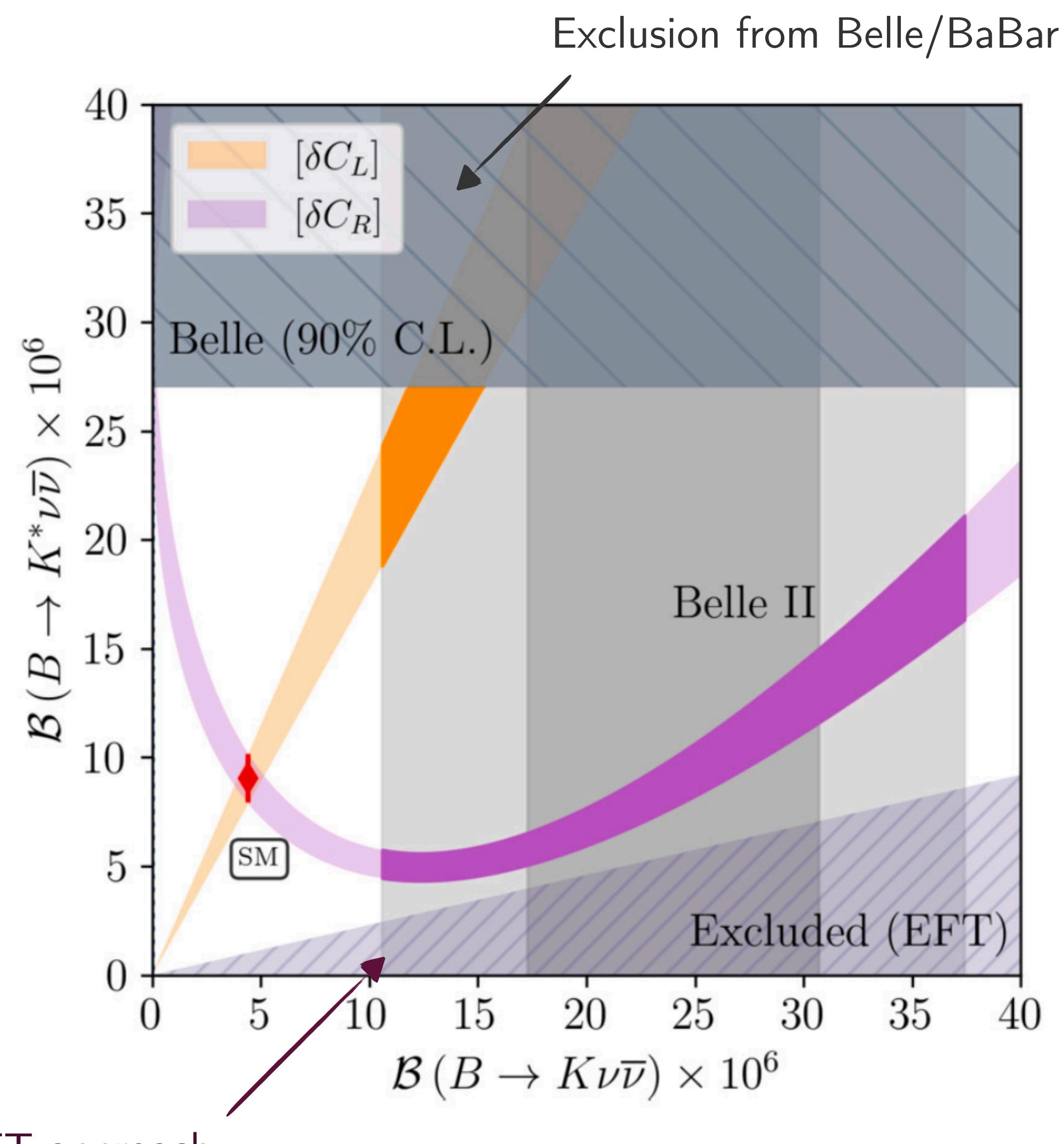
- Complementarity of $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$:

$$\frac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})^{\mathrm{SM}}} = 1 + \sum_i \frac{2\mathrm{Re}[C_L^{\mathrm{SM}}\,(\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3|C_L^{\mathrm{SM}}|^2} + \sum_{i,j}\frac{|\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j}|^2}{3|C_L^{\mathrm{SM}}|^2} - \eta_{K^{(*)}}\sum_{i,j}\frac{\mathrm{Re}[\delta C_R^{\nu_i\nu_j}(C_L^{\mathrm{SM}}\delta_{ij} + \delta C_L^{\nu_i\nu_j})]}{3|C_L^{\mathrm{SM}}|^2}\,,$$

$\eta_K = 0$

$\eta_{K^*} = 3.5(1)$

[Becirevic, Piazza, **OS**. '22]



[Bause et al. '23]

[Allwicher et al (**OS**). '23]

Predictions

[Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

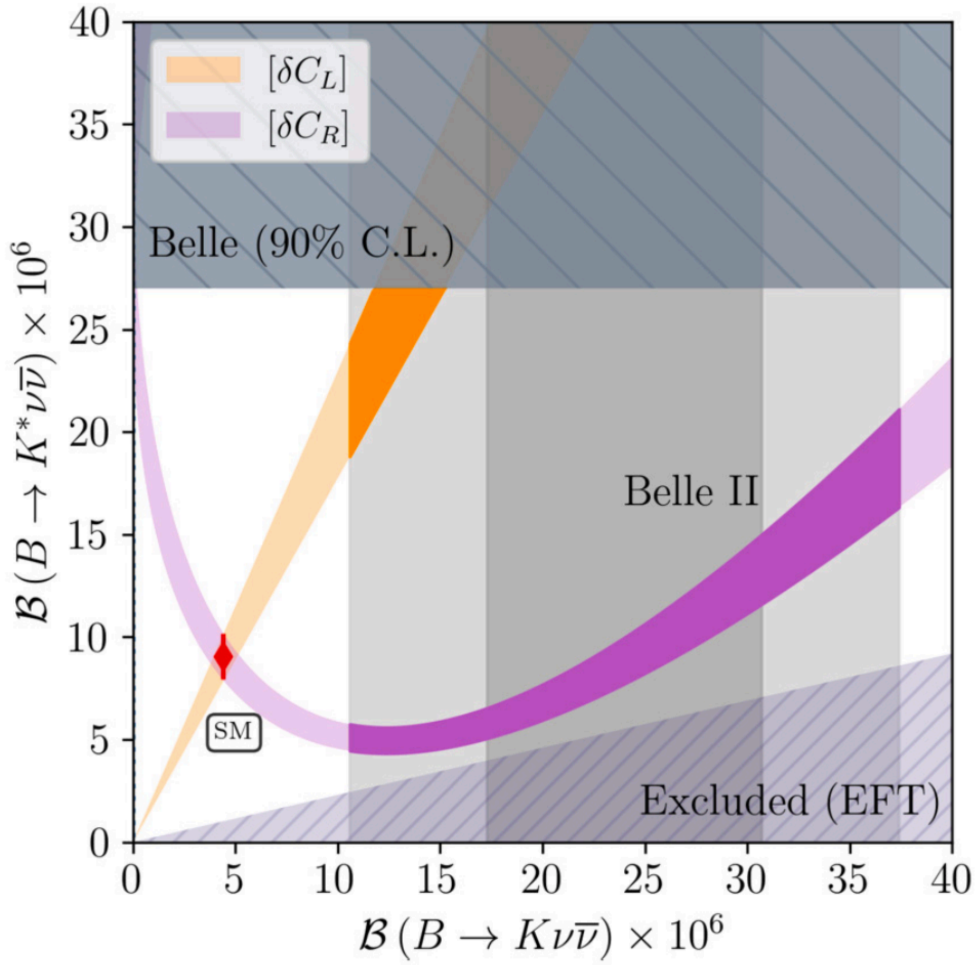
- Another observable to measure is the K^* longitudinal-polarisation asymmetry:

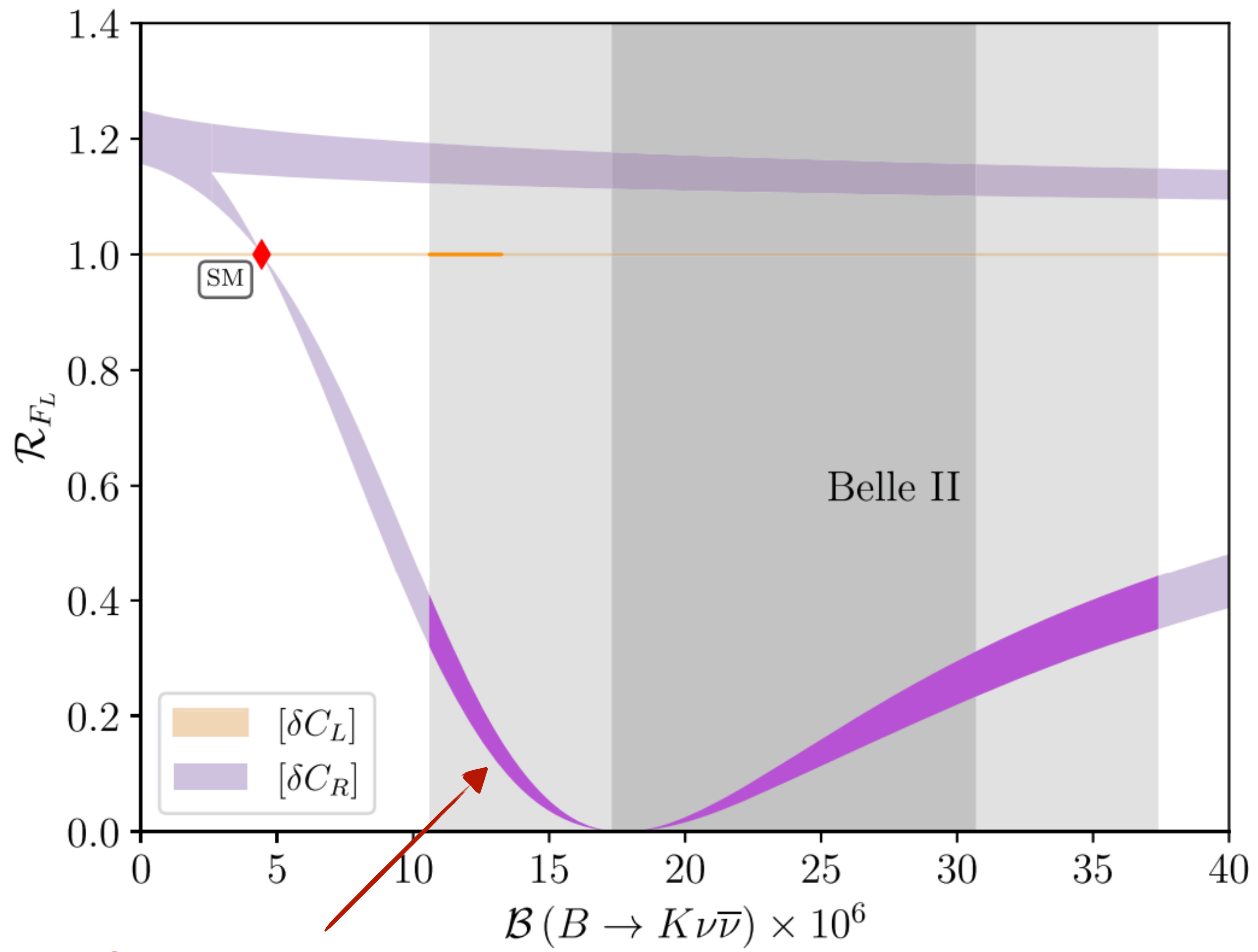
$$F_L \equiv \frac{\Gamma_L(B \to K^*\nu\bar{\nu})}{\Gamma(B \to K^*\nu\bar{\nu})}$$

$$F_L(B \to K^*\nu\bar{\nu})^{\rm SM} = 0.49(7)$$

$$\mathcal{R}_{F_L} \equiv \frac{F_L}{F_L^{\rm SM}}$$

[Altmannshofer et al. '09, Buras et al'. '14, Das et al. '17]





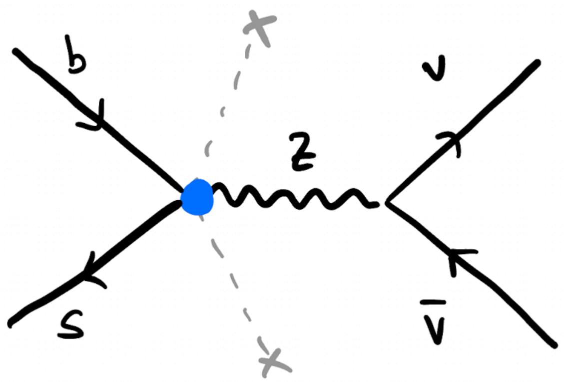
Depletion of SM prediction!

The measurement of $\mathscr{B}(B \to K^*\nu\bar{\nu})$ and $F_L(B \to K^*\nu\bar{\nu})$ would be **model-independent tests** of Belle-II results.

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

- **SMEFT** is formulated for $\Lambda \gg v_{\rm ew}$ with $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant operators.
- Gauge invariance **correlates** $b \to s\nu\bar{\nu}$ with $b \to s\ell\ell$ since $L_i = (\nu_{Li}, \ell_{Li})^T$.
- Two types of $d = 6$ **contributions** at tree-level: [Buchmuller & Wyler. '85, Gradkowski et al. '10]

i) $\psi^2 H^2 D$:

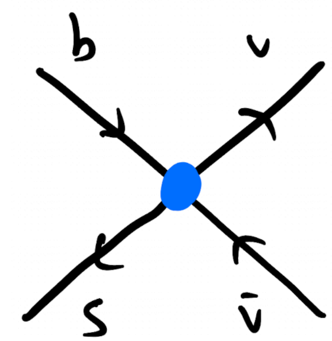


e.g.,

$$\mathcal{O}_{Hd} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{s}_R\gamma^\mu b_R)$$

Lepton flavor universal!

ii) ψ^4 :



e.g.,

$$\mathcal{O}_{ld} = \big(\bar{L}\gamma^\mu L\big)\big(\bar{s}_R\gamma_\mu b_R\big)$$

[Bause et al. '23] [Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

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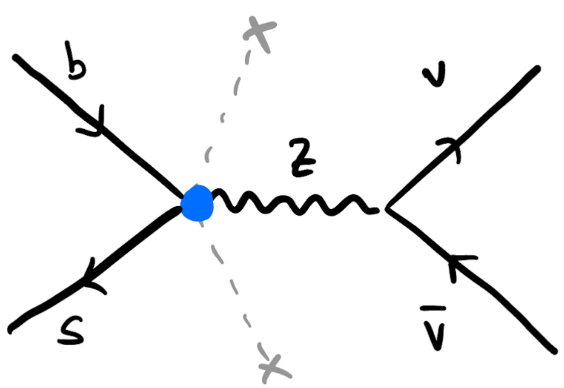
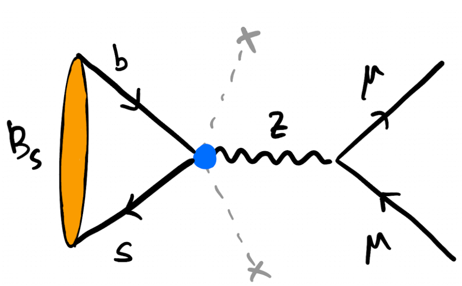


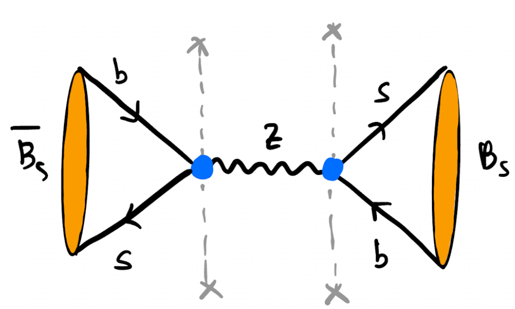
e.g.,

$\mathcal{O}_{Hd} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{s}_R \gamma^\mu b_R)$

Lepton flavor universal!

$\Rightarrow$ Severely constrained by $\mathcal{B}(B_s \to \mu\mu)$ and Δm_{B_s} :





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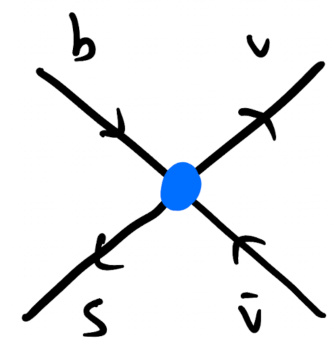

e.g.,

$\mathcal{O}_{ld} = (\bar{L}\gamma^\mu L)(\bar{s}_R \gamma_\mu b_R)$

$\Rightarrow$ Only viable option!

$$\frac{\mathcal{C}}{\Lambda^2} \simeq (5\ \text{TeV})^{-2}$$

[Bause et al. '23] [Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

- ψ^4 operators invariant under $SU(2) \times U(1)_Y$:

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

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{Q}_k\gamma_\mu Q_l)$$
$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i\gamma^\mu \tau^I L_j)(\overline{Q}_k\tau^I\gamma_\mu Q_l)$$
$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{d}_k\gamma_\mu d_l)$$
$$[\mathcal{O}_{eq}]_{ijkl} = (\overline{e}_i\gamma^\mu e_j)(\overline{Q}_k\gamma_\mu Q_l)$$
$$[\mathcal{O}_{ed}]_{ijkl} = (\overline{e}_i\gamma^\mu e_j)(\overline{d}_k\gamma_\mu d_l)$$

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{Q}_k\gamma_\mu Q_l) = (\overline{\ell}_{Li}\gamma^\mu \ell_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) + (\overline{\nu}_{Li}\gamma^\mu \nu_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) + \dots$$

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i\gamma^\mu \tau^I L_j)(\overline{Q}_k\gamma_\mu \tau^I Q_l) = (\overline{\ell}_{Li}\gamma^\mu \ell_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) - (\overline{\nu}_{Li}\gamma^\mu \nu_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) + \dots$$

$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{d}_k\gamma_\mu d_l) = (\overline{\ell}_{Li}\gamma^\mu \ell_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl}) + (\overline{\nu}_{Li}\gamma^\mu \nu_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl})$$

Which flavor?

[Bause et al. '23] [Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

i. *Couplings to muons* are *tightly constrained* by $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$. ✗

ii. The **only viable option** is coupling to τ's *(due to weak exp. limits on $b \to s\tau\tau$).* ✓

⇒ **Predictions:**

$$\frac{\mathcal{B}(B_s \to \tau\tau)}{\mathcal{B}(B_s \to \tau\tau)^{\rm SM}} \simeq \frac{\mathcal{B}(B \to K^{(*)}\tau\tau)}{\mathcal{B}(B \to K^{(*)}\tau\tau)^{\rm SM}} \simeq 10$$

However, **experimentally challenging**... $\qquad$ see e.g. Capdevilla et al. '17

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

- ψ^4 operators invariant under $SU(2) \times U(1)_Y$:

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i \gamma^\mu L_j)(\overline{Q}_k \gamma_\mu Q_l)$$
$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i \gamma^\mu \tau^I L_j)(\overline{Q}_k \tau^I \gamma_\mu Q_l)$$
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$$[\mathcal{O}_{ed}]_{ijkl} = (\overline{e}_i \gamma^\mu e_j)(\overline{d}_k \gamma_\mu d_l)$$

- Correlations for concrete mediators:

-	$Z' \sim (\mathbf{1},\mathbf{1},0)$:	$\mathcal{C}_{lq}^{(1)}$, $\mathcal{C}_{ld}$
-	$V \sim (\mathbf{1},\,\mathbf{3},\,0)$:	$\mathcal{C}_{lq}^{(3)}$
-	$U_1 \sim (\mathbf{3},\mathbf{1},2/3)$:	$\mathcal{C}_{lq}^{(1)} = \mathcal{C}_{lq}^{(3)}$
-	$S_3 \sim (\overline{\mathbf{3}},\mathbf{3},1/3)$:	$\mathcal{C}_{lq}^{(1)} = 3\,\mathcal{C}_{lq}^{(3)}$
-	$\widetilde{R}_2 = (\mathbf{3},\mathbf{2},1/6)$:	$\mathcal{C}_{ld}$

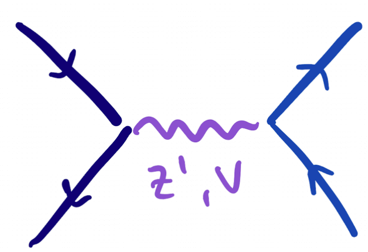
...

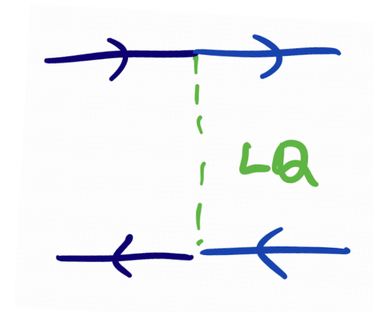
$(SU(3)_c,\, SU(2)_L,\, U(1)_Y)$

- $B_s - \overline{B}_s$ **mixing** imposes **strict bounds**! See back-up!

  $\Rightarrow$ Scenarios with a Z' would be in tension with Δm_{B_s} .

  $\Rightarrow$ There are LQ models that could explain the excess for $m_{\mathrm{LQ}} \lesssim 3$ TeV.





- **Many more correlations** with **low-energy observables** can appear in complete scenarios:

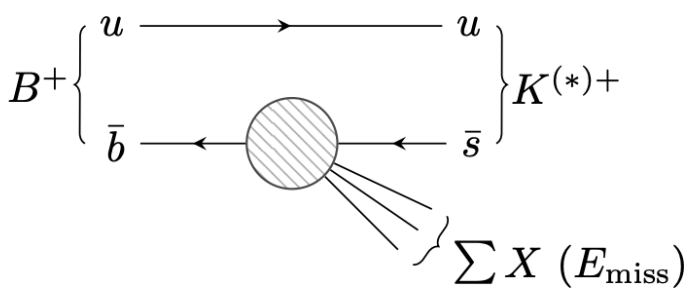
  $K^+ \to \pi^+ \nu\bar{\nu}$ (NA62), $B \to D^{(*)}\tau\nu$ (LHCb, Belle-II) and Drell-Yan (CMS, ATLAS)

Other directions?

Hidden sectors?

see e.g. [Izaguirre et al. '17, Gavela et al.'19, Felk et al'. 23, Altmannshofer et al. '23]
[Bauer et al. '21, Alonso-Alvarez et al. '23, He et al. '23]...

- $B \to K + \text{inv}$ is also a probe of light/invisibles particles — different EFT description needed:

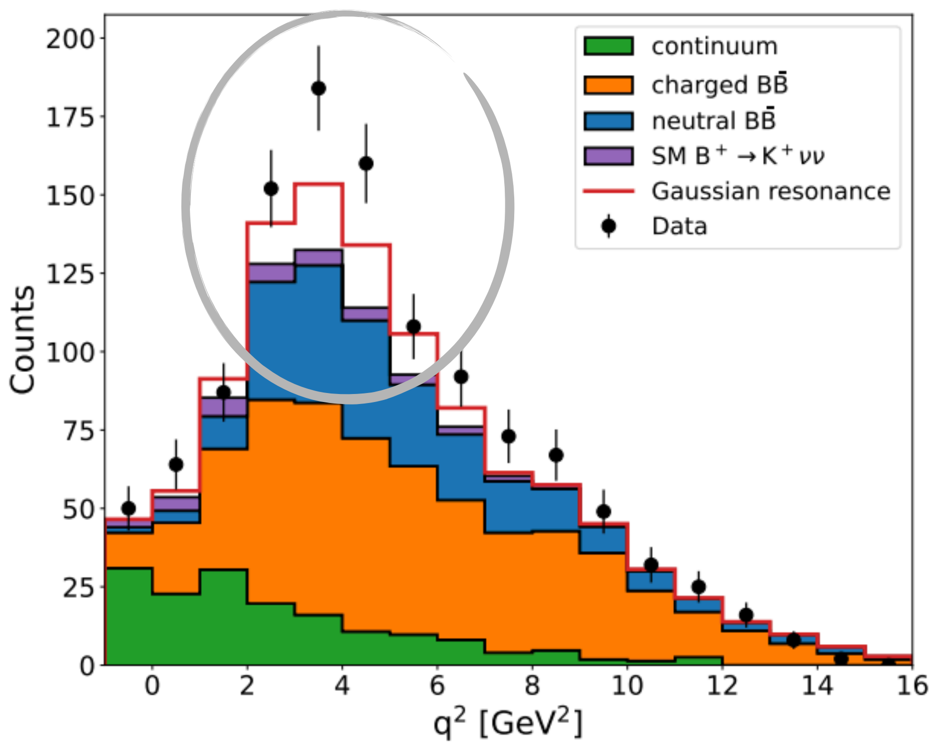


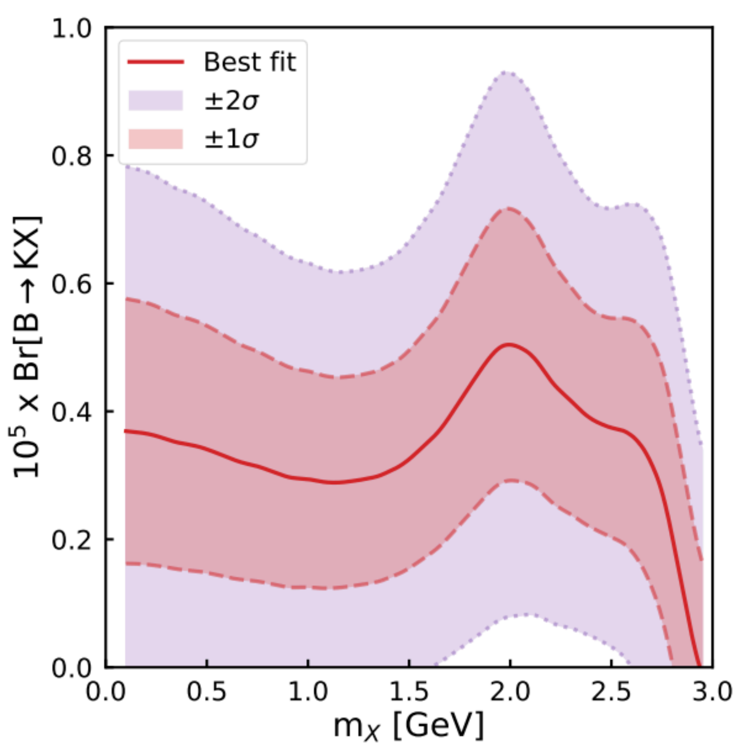
$B \to KX$ $B \to K\nu_L\nu_R$ $B \to K\chi\chi$ $B \to K\phi\phi$ ...

[Kamenik et al. '11, Bolton et al. '24]

- If the excess is due to $B \to KX(\to \text{inv})$, where $X \sim (\mathbf{1},\mathbf{1},0)$ is a mediator produced on-shell *(i.e., with $m_X < m_B$),* the main difference would be a **peak** at $q^2 \simeq m_X^2$.

- **Good fit** to Belle-II data too, since the excess is mostly localised (**within large uncertainties**):





Best fit (2.8σ): $m_X \approx 2$ GeV

$$\mathcal{B}(B \to KX) = (5.1 \pm 2.1) \times 10^{-6}$$

[Altmannshofer et al. '23]

⇒ To be checked by **dedicated searches**!

Summary & Outlook

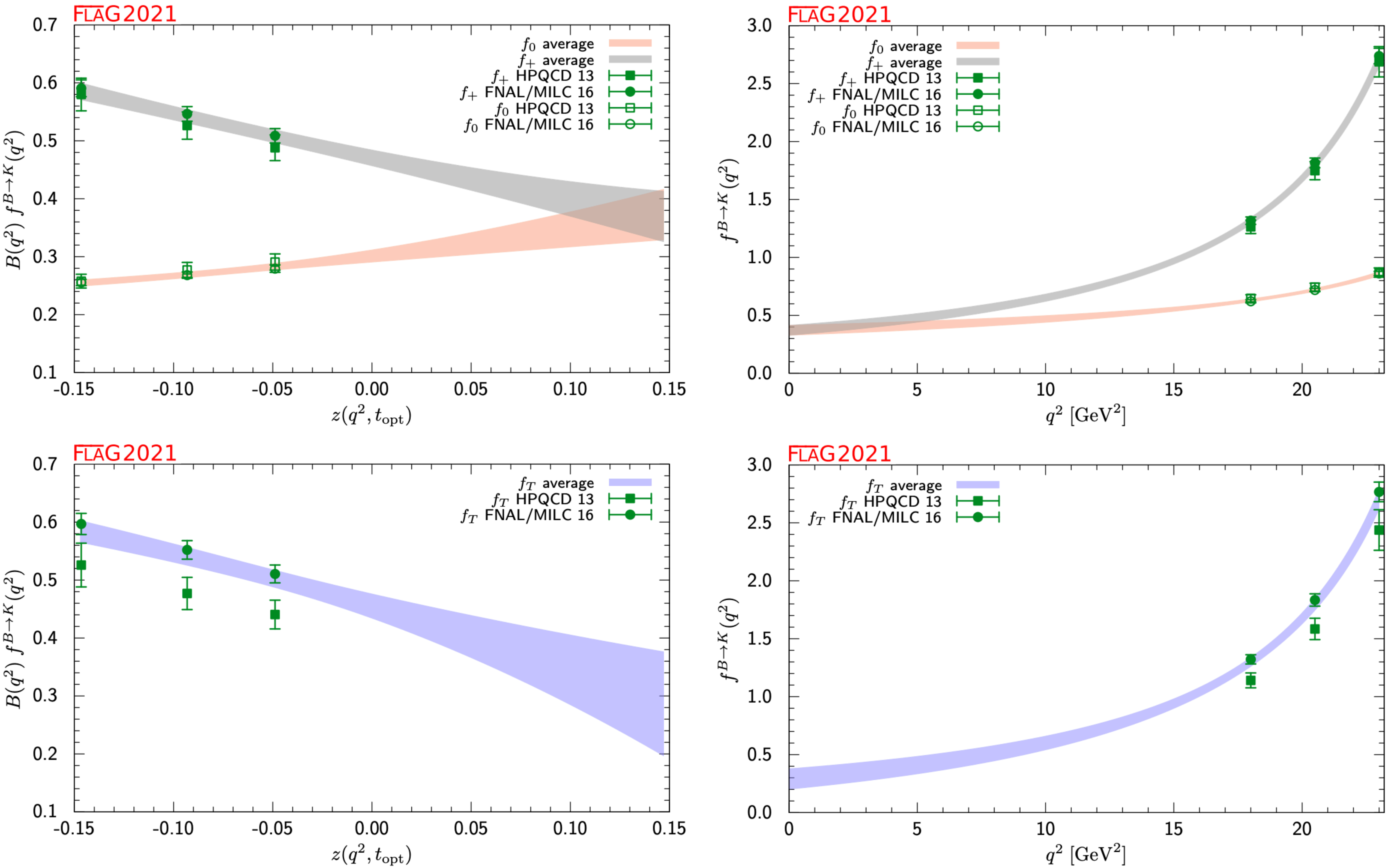
Summary & *Outlook*

- **Precision frontier:** fundamental to seek new physics particles that cannot be produced on-shell at the LHC — *complementary approach*!
- **Hadronic uncertainties:** QCD remains the main obstacle to using low-energy observables to probe new physics — *caution is advised*!
- V_{cb}**:** theory and exp. progress is needed to solve this issue — *needed to fix the parametric uncertainties of rare decays in the SM...* Belle-II data and new LQCD results will be essential.
- $B \to K\nu\nu$**:** Theoretically clean and very helpful to constrain (B)SM physics. More data and further cross-checks are needed to understand the first Belle-II results — *e.g.,* $B^0 \to K_S \nu\bar{\nu}$, $B \to K^* \nu\bar{\nu}$ *and* $F_L(B \to K^* \nu\bar{\nu})$.

Many **opportunities** to **explore** physics **(B)SM** in flavor experiments!

Thank you!

Back-up

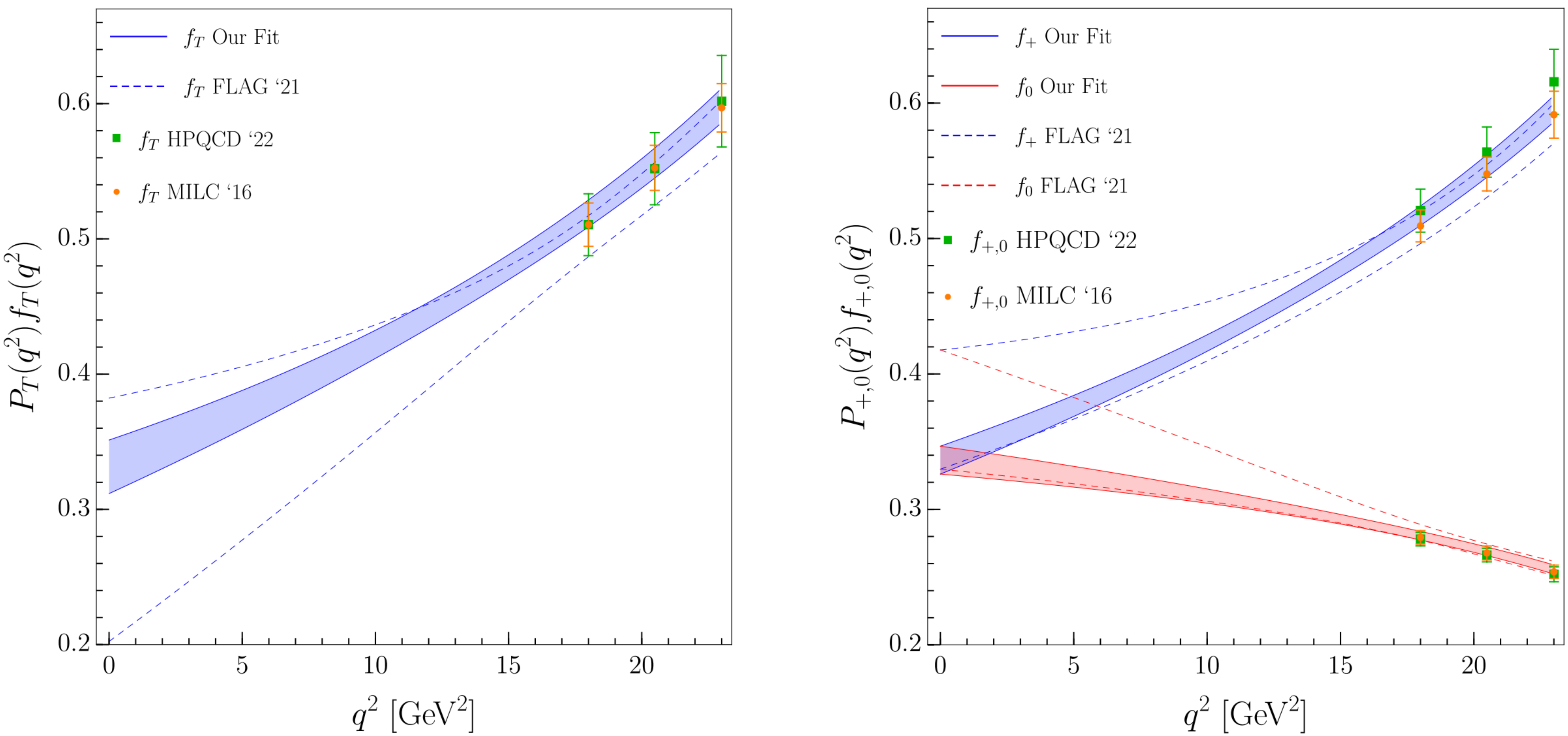

FLAG2021
f_0 average
f_+ average
f_+ HPQCD 13
f_+ FNAL/MILC 16
f_0 HPQCD 13
f_0 FNAL/MILC 16
$B(q^2)\ f^{B\to K}(q^2)$
$z(q^2, t_{\rm opt})$
$f^{B\to K}(q^2)$
q^2 [GeV^2]
FLAG2021
f_T average
f_T HPQCD 13
f_T FNAL/MILC 16
$B(q^2)\ f^{B\to K}(q^2)$
$z(q^2, t_{\rm opt})$
$f^{B\to K}(q^2)$
q^2 [GeV^2]

$$f_+(q^2) = \frac{1}{P_+(q^2)} \sum_{n=0}^{N-1} a_n^+ \left[z^n - (-1)^{n-N} \frac{n}{N} z^N \right]$$

$$f_T(q^2) = \frac{1}{P_T(q^2)} \sum_{n=0}^{N-1} a_n^T \left[z^n - (-1)^{n-N} \frac{n}{N} z^N \right]$$

$$f_0(q^2) = \frac{1}{P_0(q^2)} \sum_{n=0}^{N-1} a_n^0 \, z^n \,,$$

$$P_i(q^2) = 1 - q^2/M_i^2 \,,$$



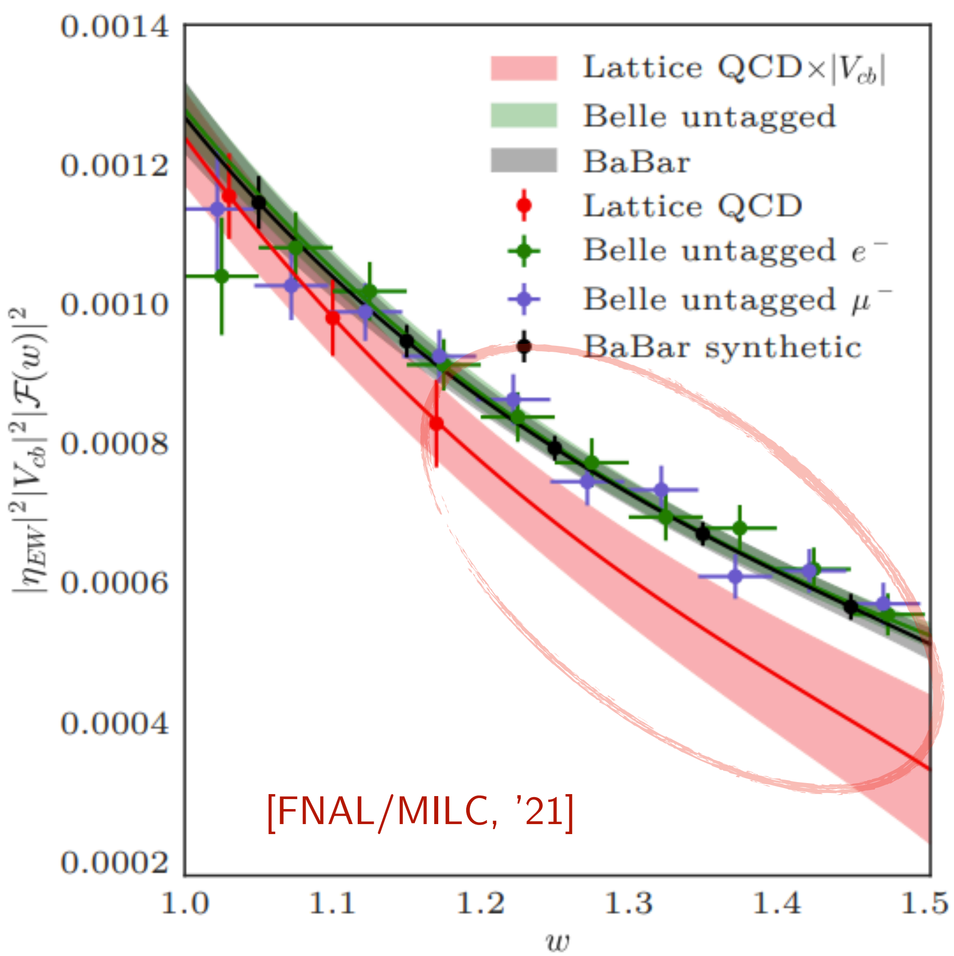
[Belle-II, SnowMass - 2207.06307]

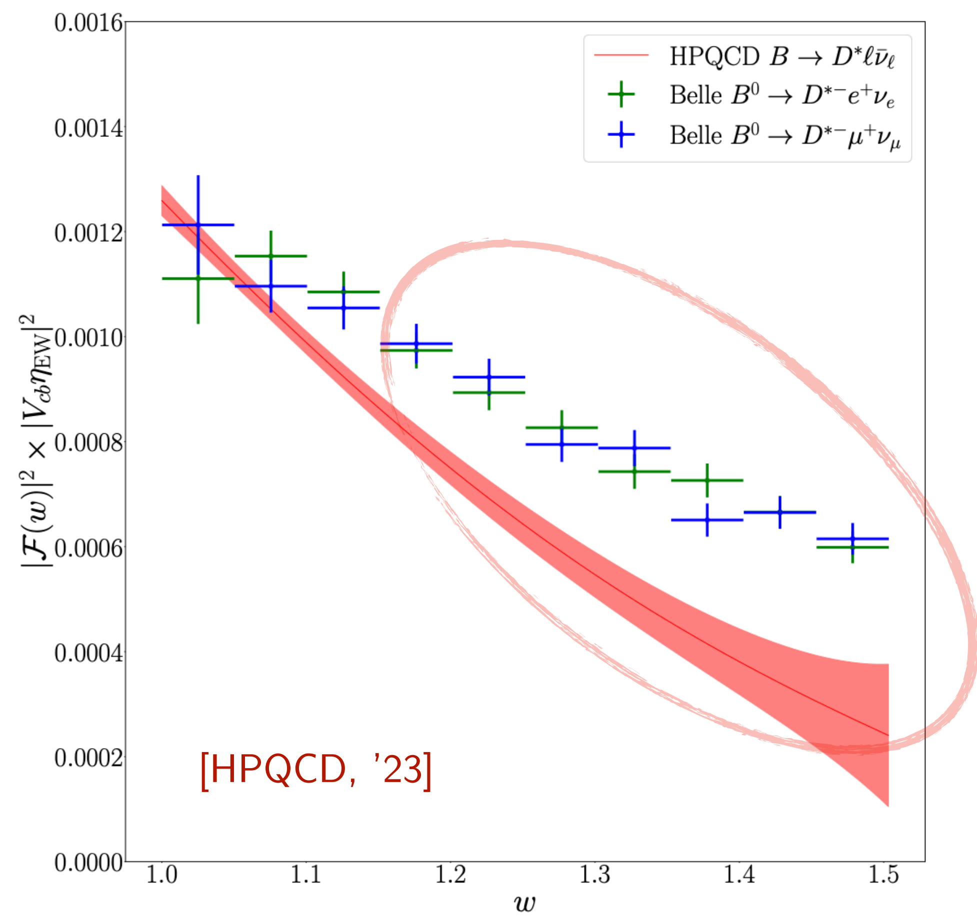
Table 3: Baseline (improved) expectations for the uncertainties on the signal strength μ (relative to the SM strength) for the four decay modes as functions of data set size.

Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

[NEW] Warning!

$$\frac{d\mathcal{B}}{dq^2}(B \to D^* \ell \nu) \propto |V_{cb}|^2 \, |\mathcal{F}(w)|^2 \qquad \left[w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}} \right]$$

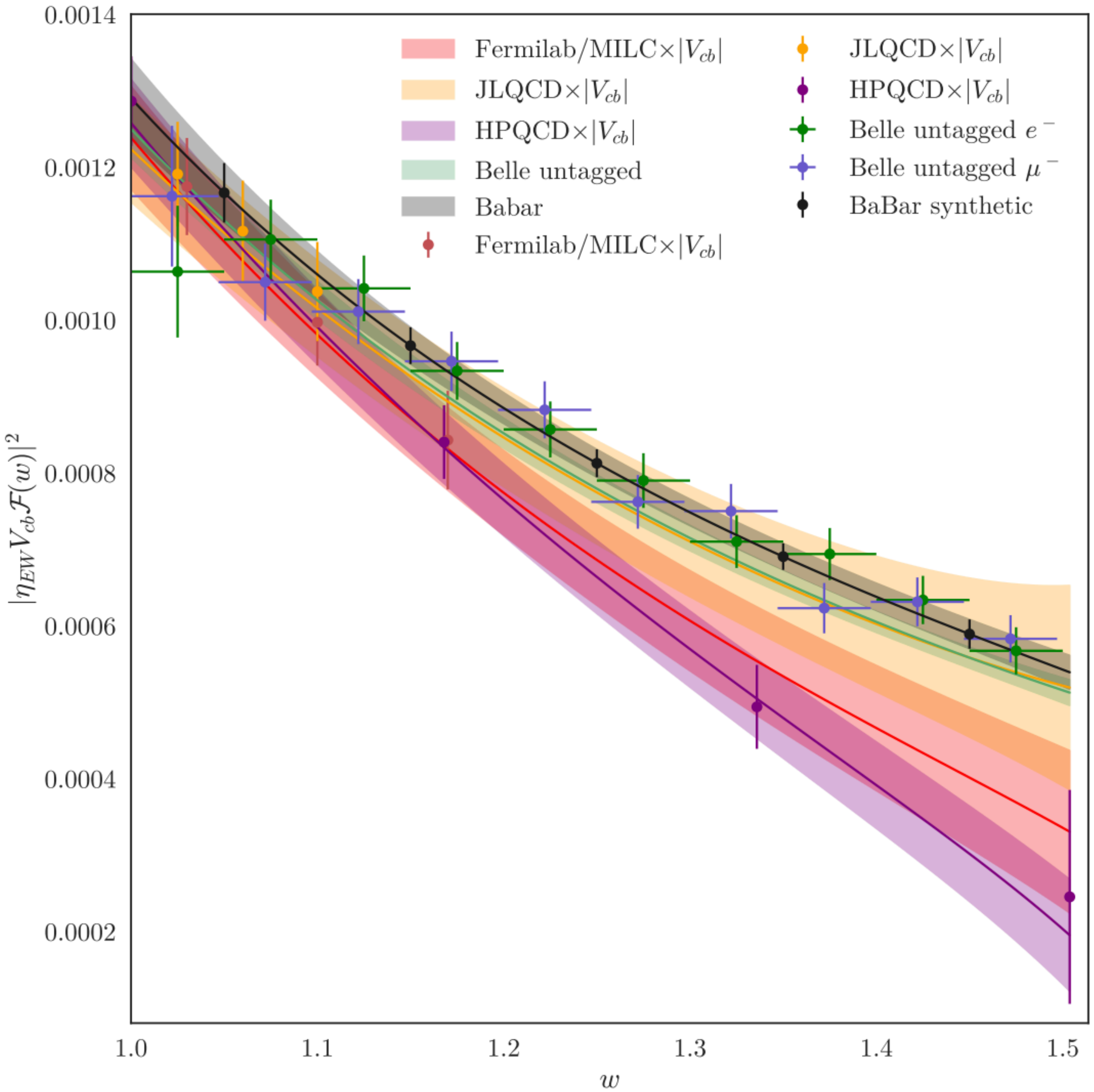


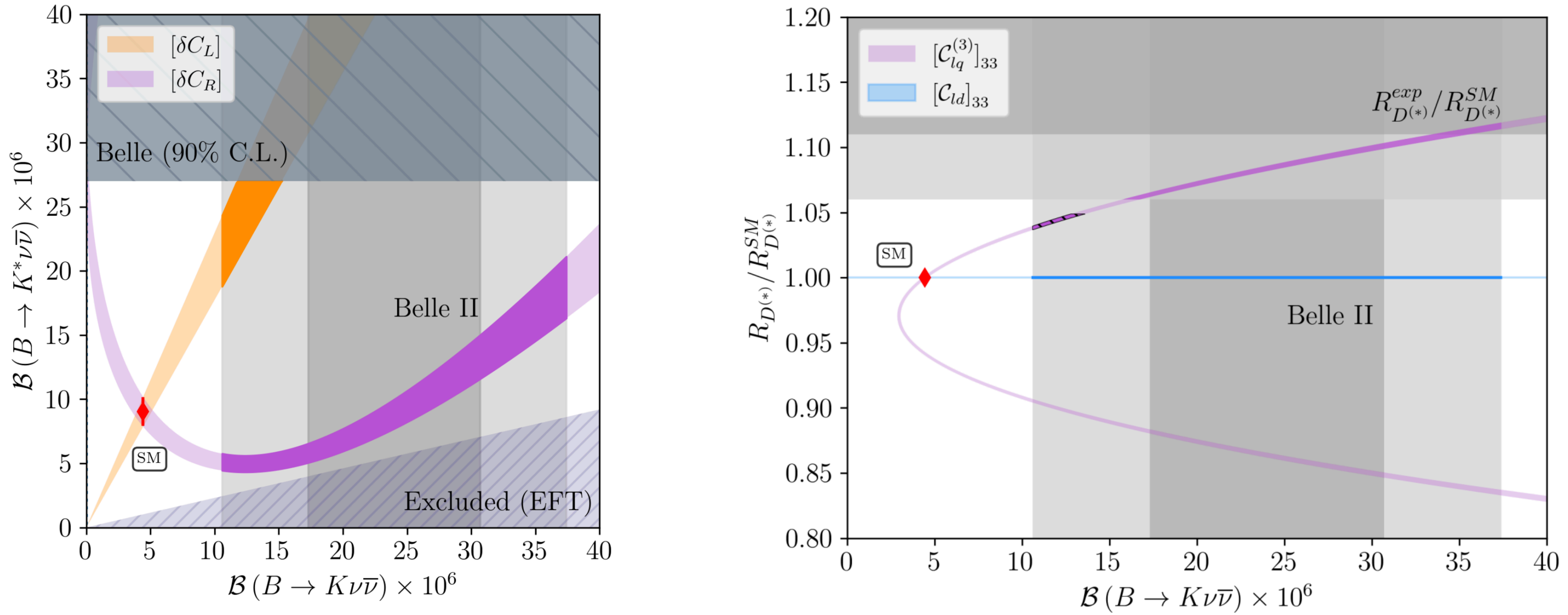


$\Rightarrow$ **Needs clarification** to reliably **extract** $|V_{cb}|$ from $B \to D^* \ell \bar{\nu}$...

NB. Recent JLQCD agrees well with exp. data!

Comparison from A. Lytle talk





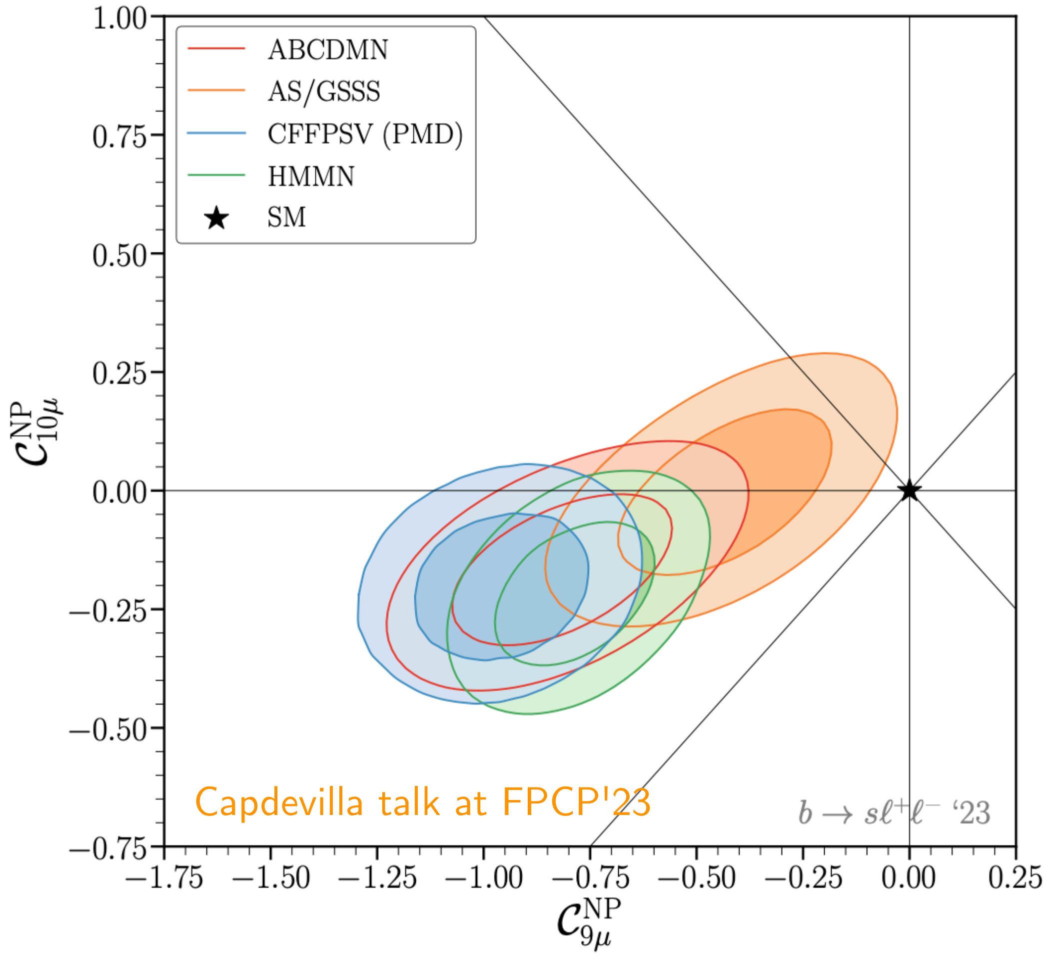
$$
\begin{aligned}
\mathcal{L}^{(6)}_{\rm SMEFT} \supset \frac{1}{\Lambda^2}\Big\{ & \left(\mathcal{C}^{(1)}_{lq} + \mathcal{C}^{(3)}_{lq}\right)_{ij} (\bar{s}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu e_{Lj}) \\
& + \left(\mathcal{C}^{(1)}_{lq} - \mathcal{C}^{(3)}_{lq}\right)_{ij} (\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj}) \\
& + 2\, V_{cs} \left[\mathcal{C}^{(3)}_{lq}\right]_{ij} (\bar{c}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu \nu_{Lj}) \\
& + [\mathcal{C}_{ld}]_{ij} (\bar{s}_R\gamma^\mu b_R)\left[(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj}) + (\bar{e}_{Li}\gamma_\mu e_{Lj})\right] + \text{h.c.}\Big\},
\end{aligned}
$$

[Intermezzo] Anomalies in $B \to K^{(*)}\mu\mu$ decays?

$$\mathcal{L}_{\text{eff}}^{b\to s\ell\ell} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_\ell \Big[C_9^{\ell\ell}\,(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell) + C_{10}^{\ell\ell}\,(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5 \ell) + \dots \Big] + \text{h.c.}$$

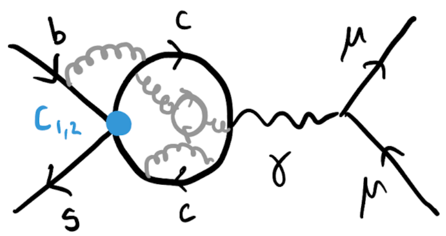
- Angular $B \to K^{(*)}\mu\mu$ observables show a preference for $\delta C_9^{\mu\mu} < 0$:

[Algueró et al. '21, Altmannshofer et al. '21, Hurth et al. '21]



New physics effects or **underestimated hadronic uncertainties**?

see e.g. Ciuchini et al'. '21

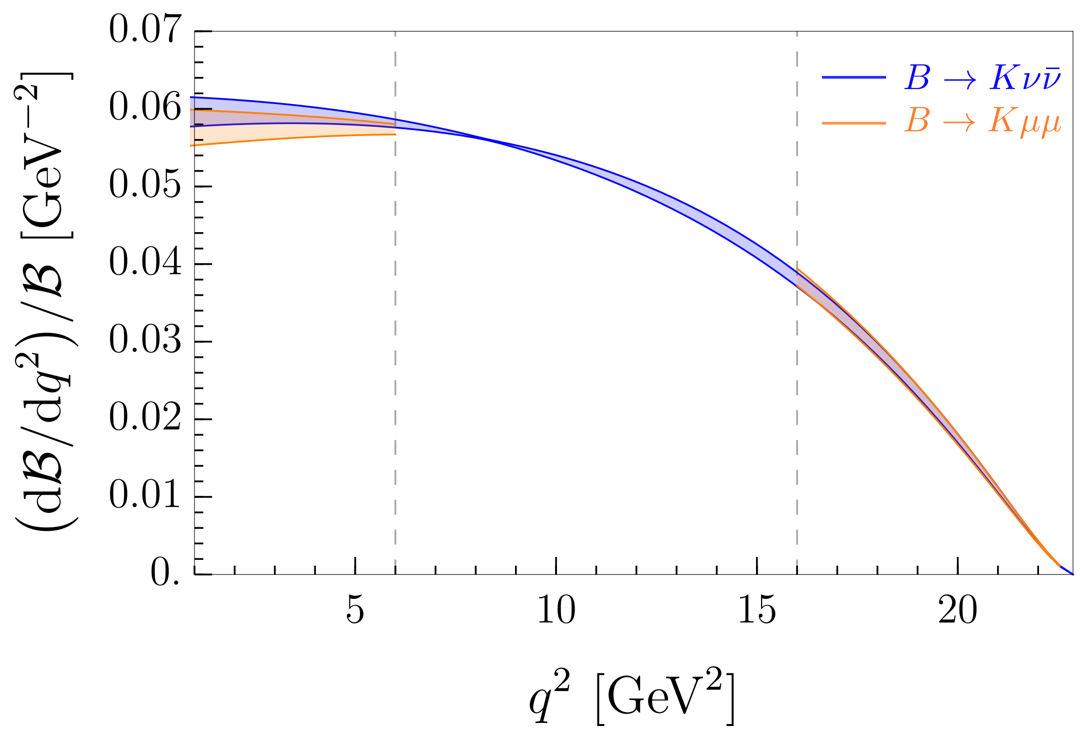


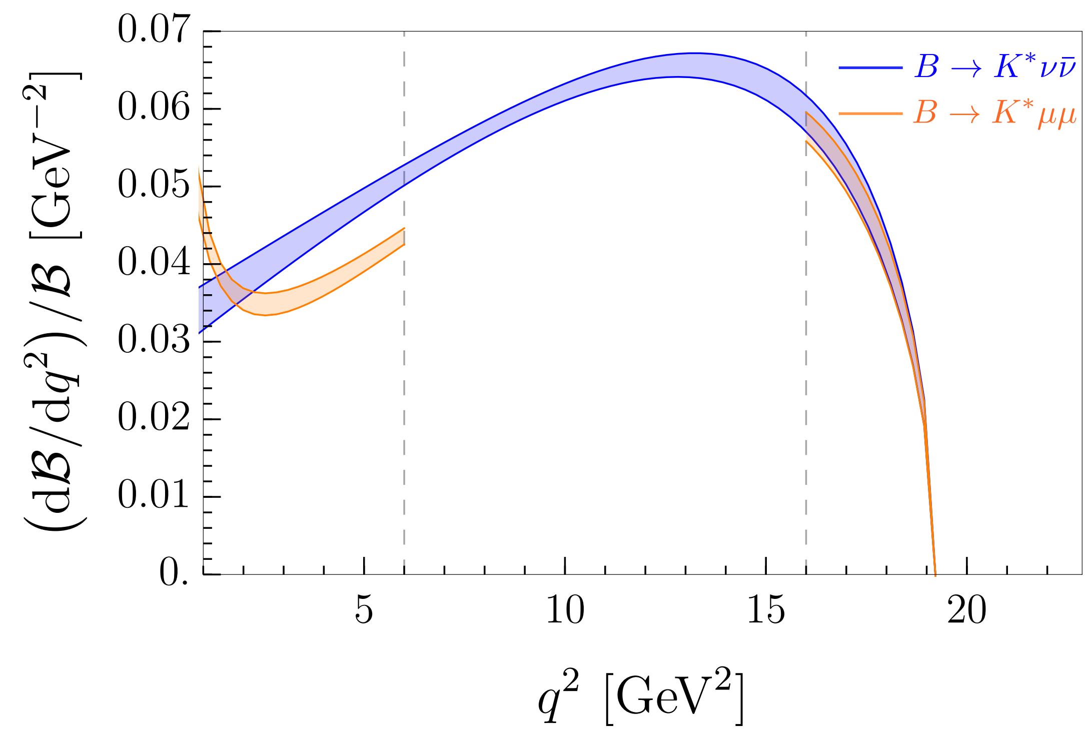
NB. LFU ratios $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee)$ do not depend on $C_9^{\ell\ell}$, but they are difficult to measure — cf. latest LHCb results, which now agree with the SM predictions.

Remarks on $B \to K^{(*)}\nu\nu$/ $B \to K^{(*)}\mu\mu$

- $B \to K^{(*)}\nu\nu$ and $B \to K^{(*)}\mu\mu$ have a similar decay spectrum away from the narrow $c\bar{c}$ resonances:

[Becirevic, Piazza, **OS**. 2301.06990] [Bartsch et al. '09]





*using 2-loop results for $c\bar{c}$ loops from [Asatryan et al. '09]

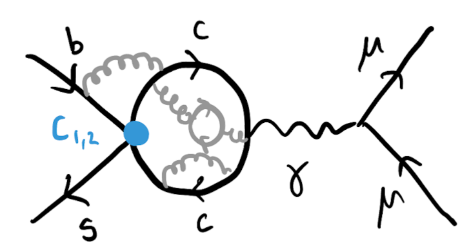
- We can defined the **CKM-free ratio**:

$$\mathcal{R}^{(\nu/l)}_{K^{(*)}}[q_0^2, q_1^2] \equiv \frac{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \to K^{(*)}ll)}\Bigg|_{[q_0^2,q_1^2]}$$

Ratio of partial branching fractions integrated in the same q^2-bin.

$\Rightarrow$ **Form-factor** uncertainties **cancel out** to a good extent for $q^2 \gg m_\ell^2$.

$\Rightarrow$ Neglecting NP contributions, this ratio can be used to **extract** $C_9^{\mu\mu}$!



See back-up!

- Predictions using perturbative calculation of $c\bar{c}$ loops: [Becirevic, Piazza, **OS**. 2301.06990]

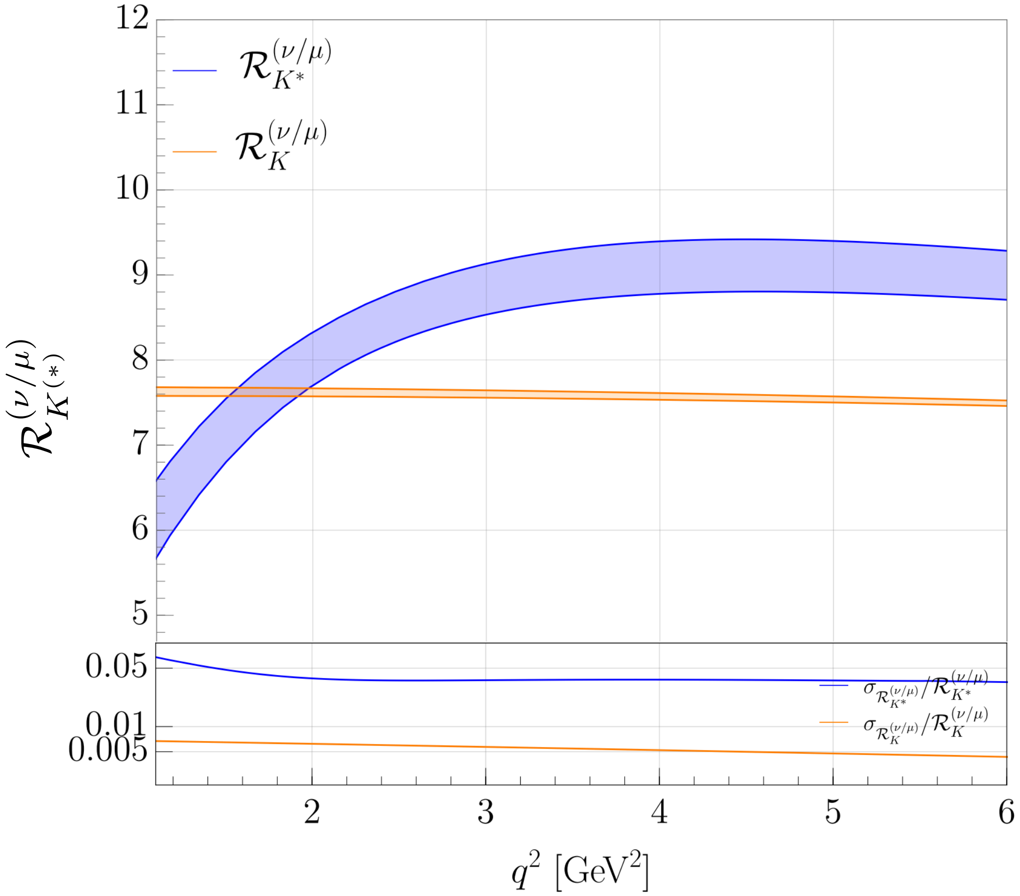
$$\mathcal{R}_K^{(\nu/l)}[1.1,6]\Big|_{\rm SM} = 7.58 \pm 0.04$$

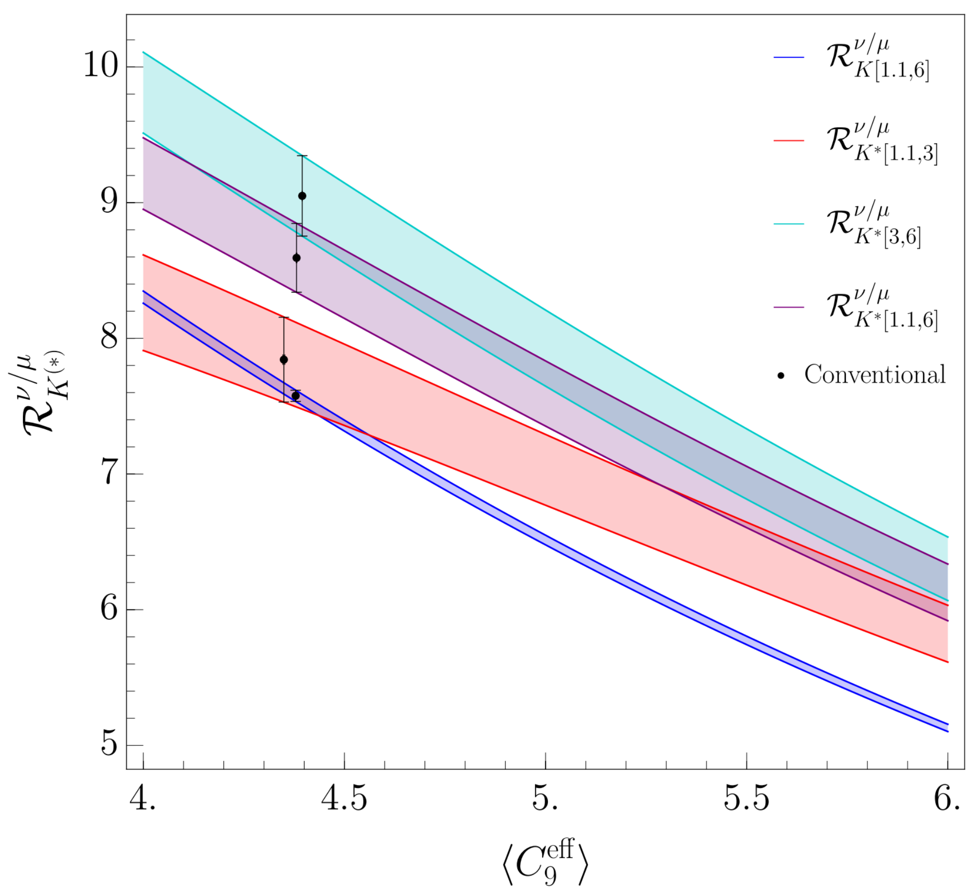
$$\mathcal{R}_{K^*}^{(\nu/l)}[1.1,6]\Big|_{\rm SM} = 8.6 \pm 0.3$$

with the following dependence on $C_9^{\rm eff}$: using [Asatryan et al. '09]

$$\frac{1}{\mathcal{R}_K^{(\nu/l)}[1.1,6]}\Big|_{\rm SM} \simeq \left[7.15 - 0.45 \cdot C_9^{\rm eff} + 0.42 \cdot \left(C_9^{\rm eff}\right)^2\right] \times 10^{-2}$$

$$\frac{1}{\mathcal{R}_{K^*}^{(\nu/l)}[1.1,6]}\Big|_{\rm SM} \simeq \left[9.98 - 1.45 \cdot C_9^{\rm eff} + 0.42 \cdot \left(C_9^{\rm eff}\right)^2\right] \times 10^{-2}$$





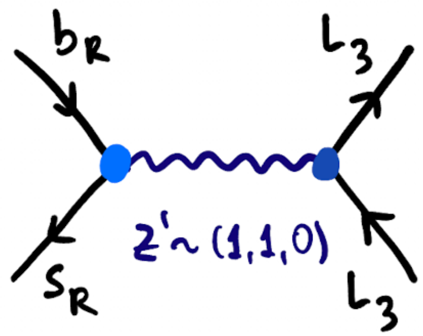
Precise measurements could help us to understand the various anomalies in $b \to s\mu\mu$ data.

Which concrete model?

[Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

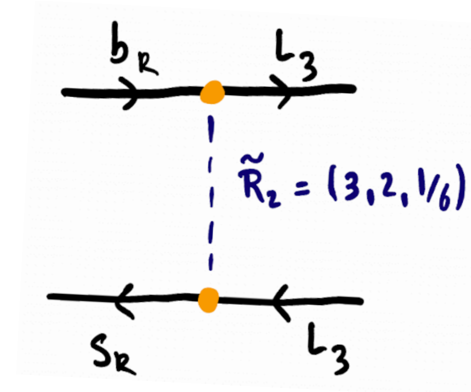
- More **correlations** between **observables** can arise in **concrete models**:

  - Z':



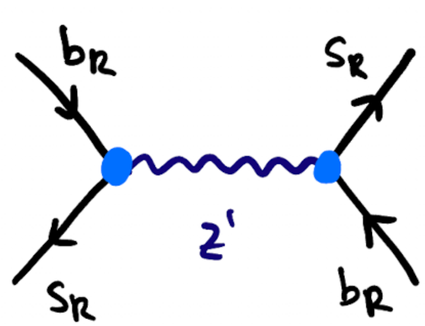
$$\mathcal{L}_{Z'} \supset g_{ij}^{\psi}\,(\bar{\psi}_i \gamma^\mu \psi_j) Z'_\mu$$

  - LQs:



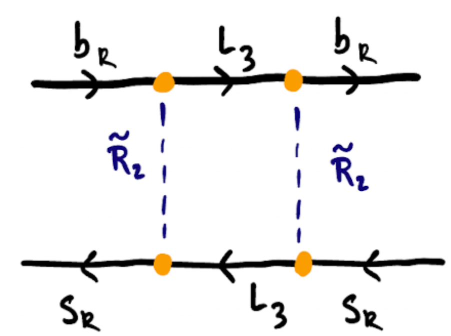
$$\mathcal{L}_{\widetilde{R}_2} \supset y_{ij}^{R}\,(\bar{d}_{Ri} \widetilde{R}_2 i\tau_2 L_j) + \text{h.c.}$$

- $\Delta F = 2$ imposes strict bounds :



⇒ Small coupling to quarks: $\dfrac{|g_{sb}^R|}{m_{Z'}} \lesssim 2 \times 10^{-3}\ \text{TeV}^{-1}$

⇒ *Impossible to fit data* with a *perturbative coupling* to τ's for a heavy Z'.



⇒ Upper bound on LQ mass:

$$m_{\text{LQ}} \lesssim 3\ \text{TeV}$$

Difficult to accommodate such a large excess, but possible in certain models.