Understanding the first observation of $B \to K\nu\bar{\nu}$ by Belle-II

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IJCLab (Orsay)

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

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Outline

Flavor physics

- Gauge sector of the SM entirely **fixed by symmetry:**

  $\Rightarrow$ Only a handful of parameters.

  $\Rightarrow$ Theory renormalizable and verified at the loop level.

- Flavor sector **loose**:

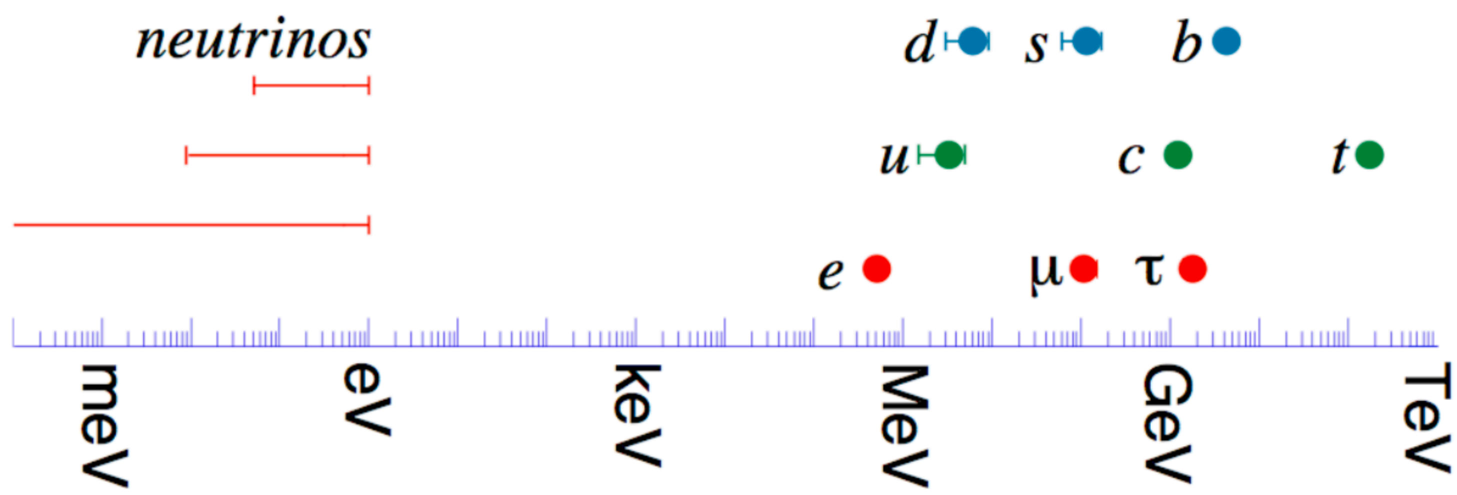
  $\Rightarrow$ 13 free parameters (masses and quark mixing) — *fixed by data.*

$$\mathcal{L}_{\rm Yuk} = -Y_d^{ij}\,\overline{Q}_i d_{Rj}\, H - Y_u^{ij}\,\overline{Q}_i u_{Rj}\, \widetilde{H} - Y_\ell^{ij}\,\overline{L}_i e_{Rj}\, H + \text{h.c.}$$

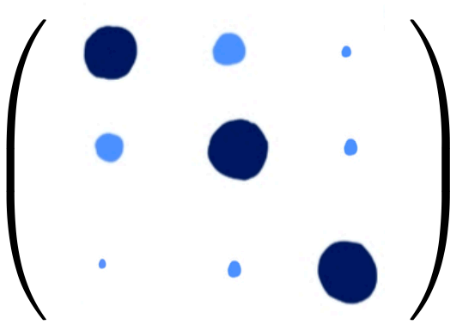
  $\Rightarrow$ These (many) parameters exhibit a hierarchical structure which we do not understand.

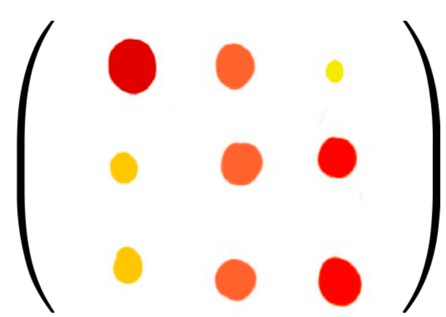
What is the origin of flavor?

- **Striking hierarchy** of fermion masses *[does not look accidental...]*



- Why **three families**? Why do **quarks** and **leptons** mix in **different ways**?

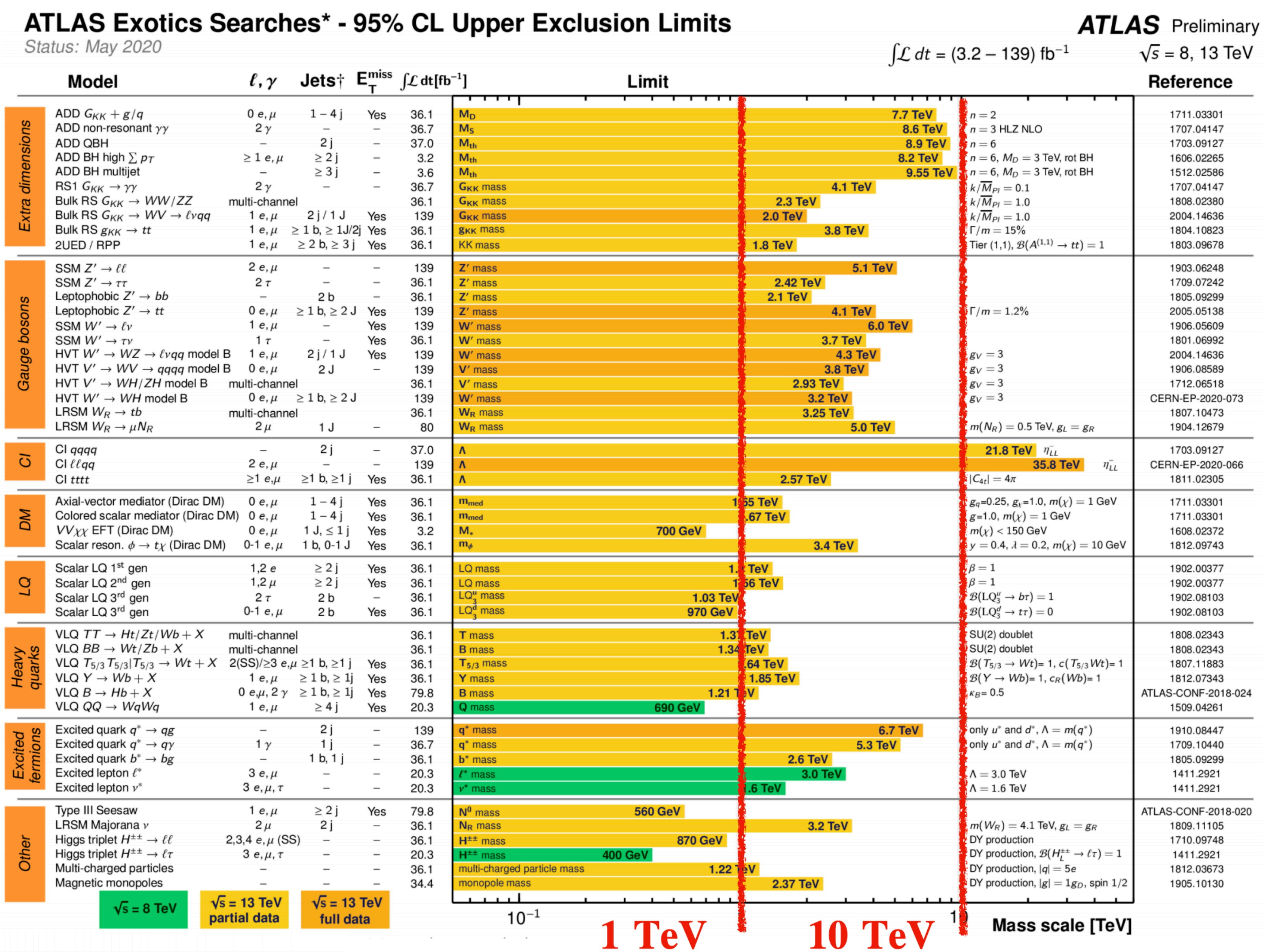
$V_{\mathrm{CKM}} =$ 

$V_{\mathrm{PMNS}} =$ 

One of the roles of **flavor physics** is to **unveil symmetries** beyond those present in the SM.

What is experiment telling us?

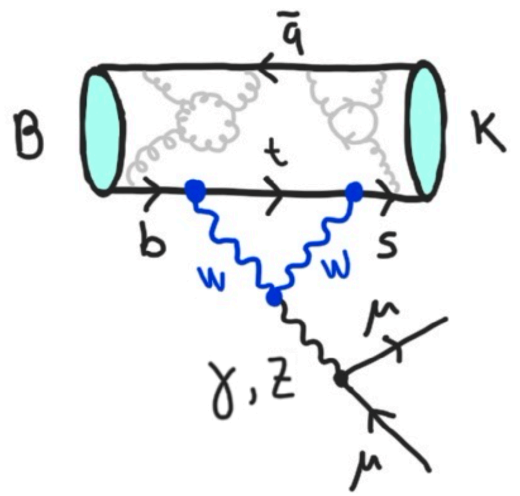
No **direct evidence** for New Physics in LHC data (presence of a mass gap?).

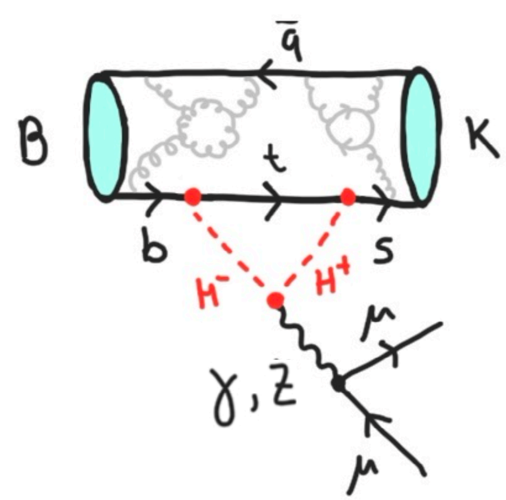


Indirect searches of New Physics

Search deviations w.r.t. SM predictions:

e.g.,





$$\mathcal{O}_{\rm exp} = \mathcal{O}_{\rm SM}\,(1 + \delta_{\rm NP})$$

Both **exp.** and **theory** must be **precise**!

⇒ **Complementary** to the effort in the **high-energy frontier!**

Look for observables:

- (Highly) sensitive to contributions from New Physics
- Mildly sensitive to hadronic uncertainties
- Accessible in current and/or (near) future experiments.

NB. *Processes forbidden by accidental symmetries are very clean:*

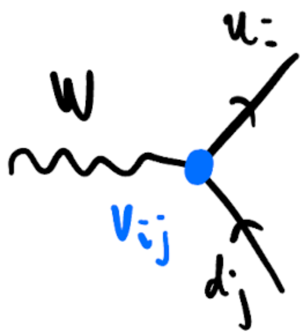
⇒ BNV, LNV and LFV

⇒ **Rare B-meson decays** are a **good example!**

Flavor Changing Neutral Currents (FCNCs)

- **FCNCs** are **absent** at **tree-level** in the SM — *i.e., couplings of neutral SM bosons to fermions are flavor diagonal.*

- The only source of **flavor violation** in the SM is the **CKM matrix**:



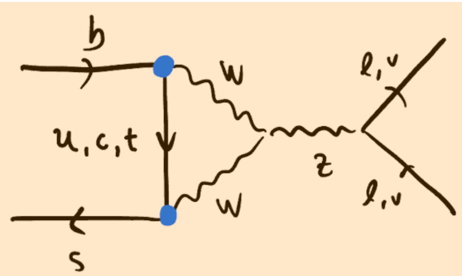
$$\mathcal{L}_{\text{c.c.}} \supset \frac{g}{\sqrt{2}} (V_{\text{CKM}})_{ij} (\bar{u}_{Li} \gamma^\mu d_{L_j}) W^+_\mu + \text{h.c.}$$

$$V_{\text{CKM}} = U^\dagger_{u_L} U_{d_L}$$

$V_{\text{CKM}} =$ 

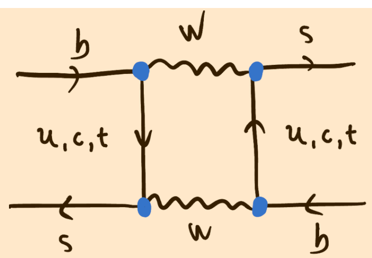
- **FCNC** processes are **loop-** and **CKM-suppressed**:

- $\Delta F = 1$:



$B \to K^{(*)} \nu\bar{\nu}$
$B \to K^{(*)} \ell\ell$
$\ldots$

- $\Delta F = 2$:



$\Delta m_{B_s} \neq 0$
$\ldots$

⇒ **Rare processes**

⇒ **Sensitive new physics probes!**

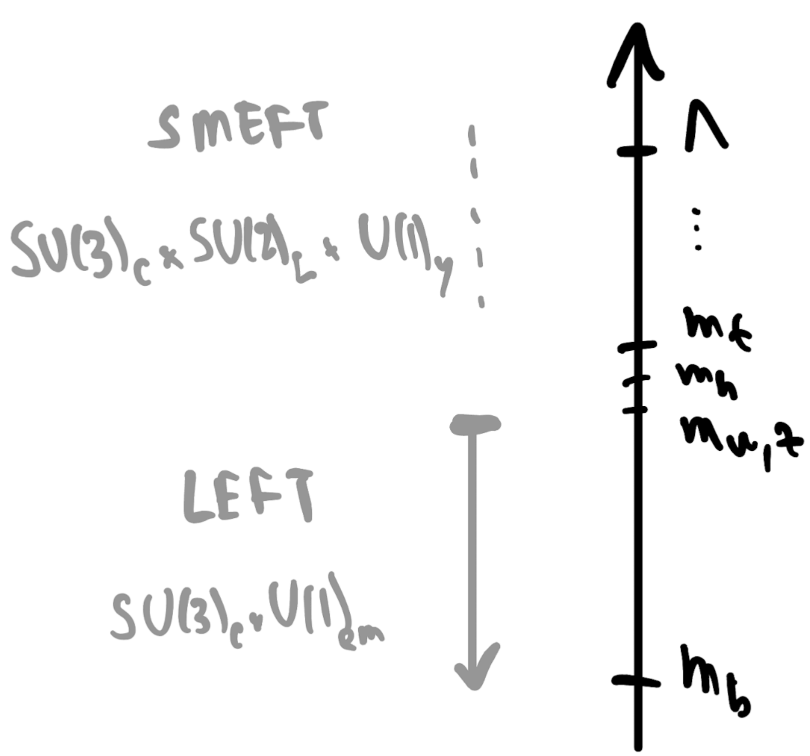
- **Reminder**: GIM mechanism

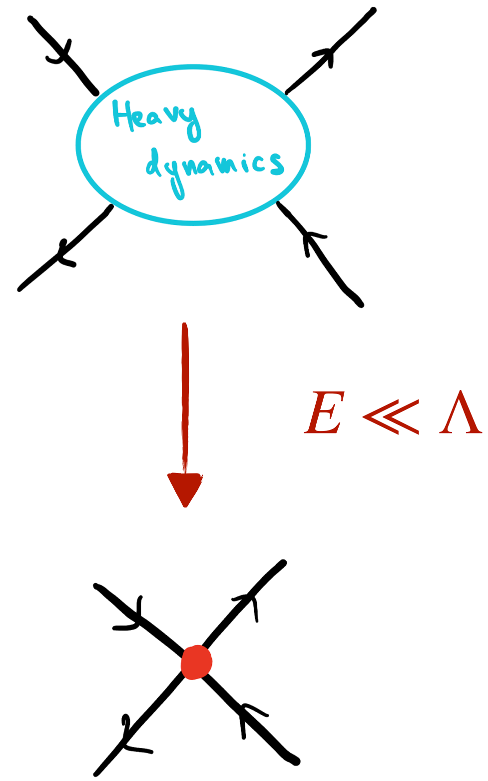
$$\mathcal{M}(b \to s\ell\ell) \propto \sum_{k=u,c,t} V^*_{ks} V_{kb}\, \underbrace{\varphi\left(\frac{m_k^2}{m_W^2}\right)}_{\varphi(x) = \text{cte} + x + \mathcal{O}(x^2)} \approx \sum_{k=u,c,t} V^*_{ks} V_{kb} \frac{m_k^2}{m_W^2}$$

⟶ **Top-quark dominates!**

EFT description

- B-**physics** depends on many **different scales** $\Rightarrow$ EFT approach!

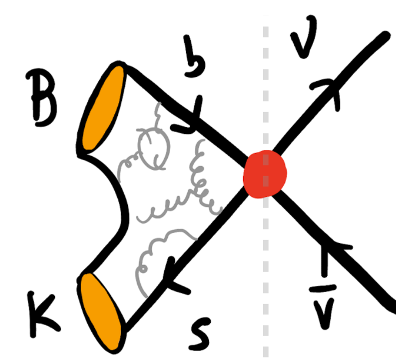




The EFT expansion can be truncated to a given order in E/Λ.

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{d=4} + \sum_{d>4} \sum_i \frac{\mathcal{C}_i^{(d)}}{\Lambda^{d-4}} \, \underbrace{\mathcal{O}_i^{(d)}(A, \psi, \phi)}_{\text{light d.o.f}}$$

- **Short-** and **long-distance** contributions are factorized:



$\mathcal{O}_i = L_i^\mu \, \mathcal{H}_\mu^i$

e.g., $\mathcal{M}(B \to K^{(*)} \nu \bar{\nu}) \propto \sum_i \mathcal{C}_i(\mu) \, L_i^\mu \, \langle K^{(*)} | \mathcal{H}_\mu^i | B \rangle$

short-distance contribution (perturbative) — leptonic tensor — long-distance cont. (to be computed non-pert.)

- **Low-energy coefficients** can be **precisely computed** through **matching + RGEs**.

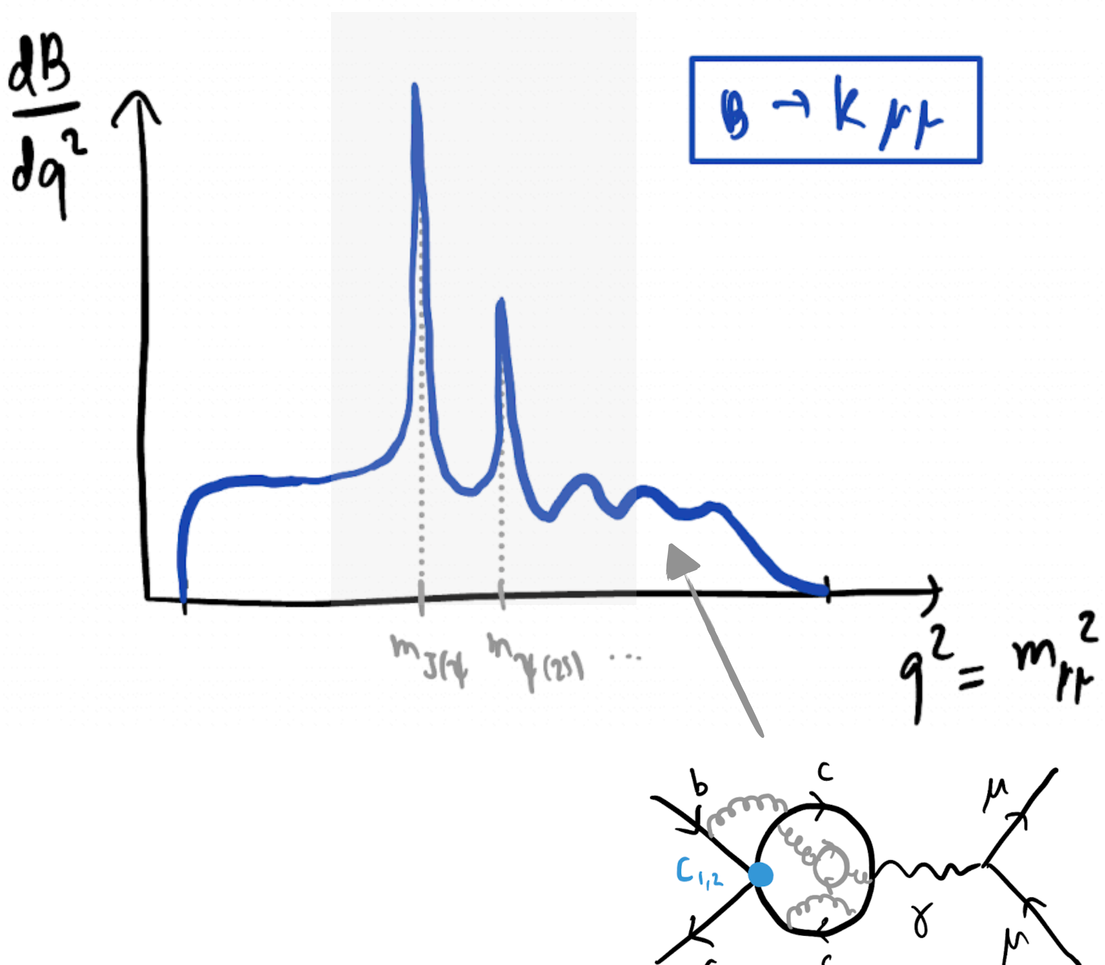
FCNC B-meson decays

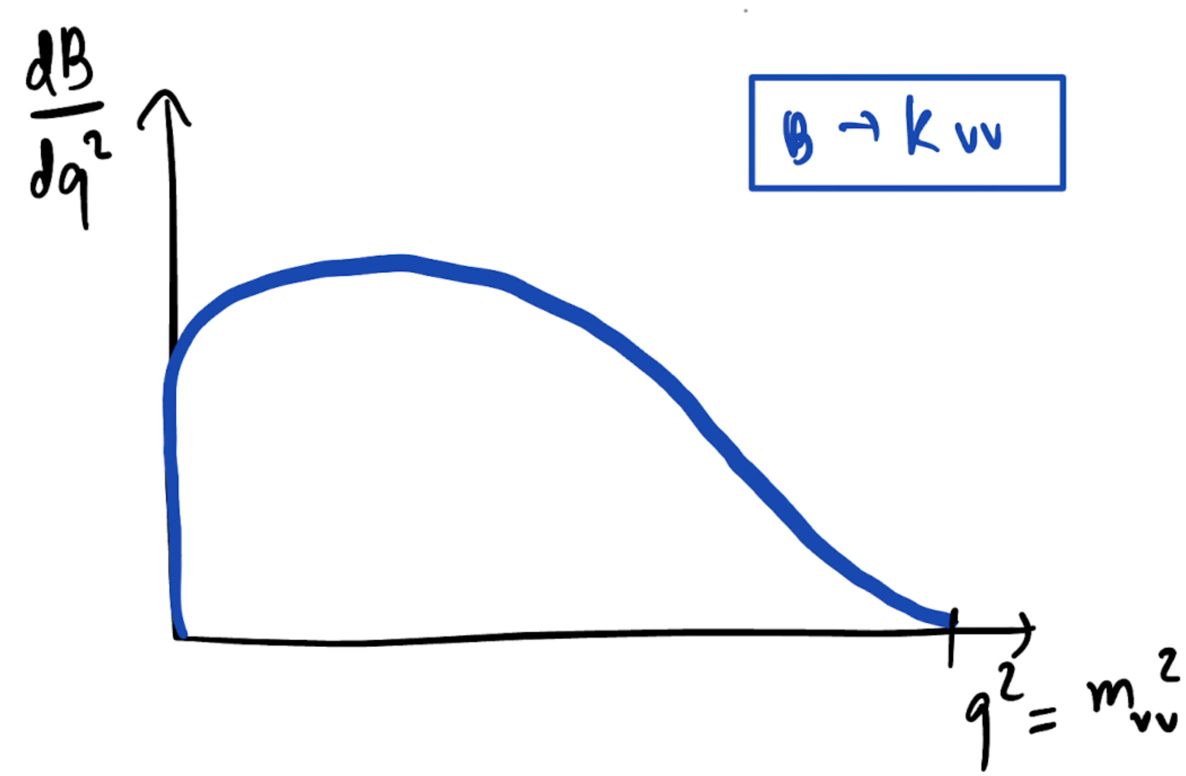
- $B \to K^{(*)}\ell\ell$:

  - *Sensitive to new physics effects.* ✓
  - *Experimentally clean (especially for $\ell = \mu$).* ✓
  - *Many observables (angular distribution).* ✓
  - *Theoretically challenging (non-factorizable contributions...)* ✗

- $B \to K^{(*)}\nu\bar{\nu}$:

  - *Sensitive to new physics effects.* ✓
  - *Exp. more challenging (missing energy).* ✓
  - *Fewer observables.* ✓
  - *Theoretically cleaner!* ✓
  - *Sensitive to operators with τ-leptons.* ✓





SM description

SM description

- **Effective Hamiltonian** within the SM:

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

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

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

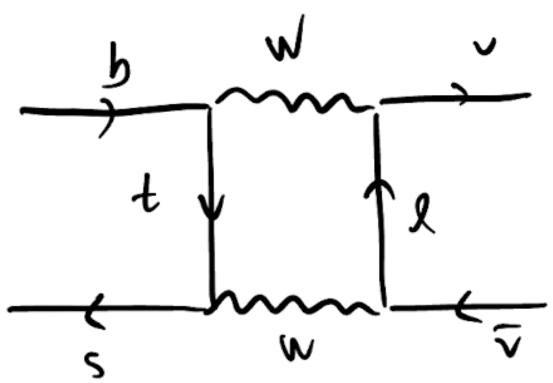
- **Short-distance** contributions known to **good precision**:

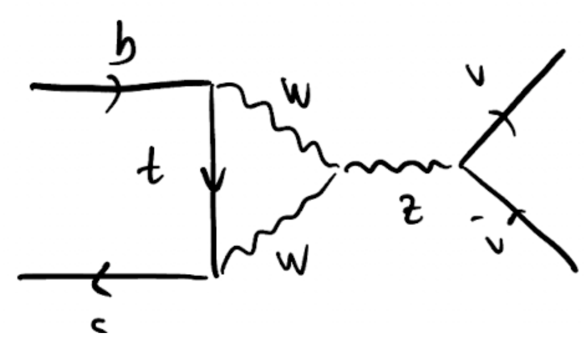
$$C_L^{\text{SM}} = -X_t / \sin^2\theta_W = -6.32(7)$$

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]





...

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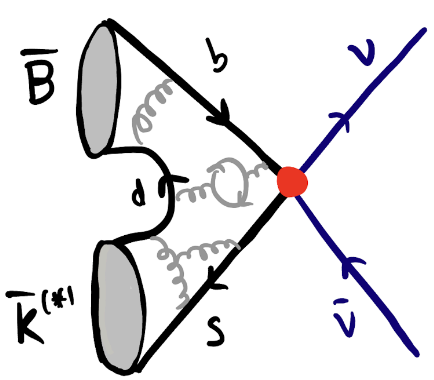
Two main sources of uncertainties:

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: $B \to K\nu\bar{\nu}$

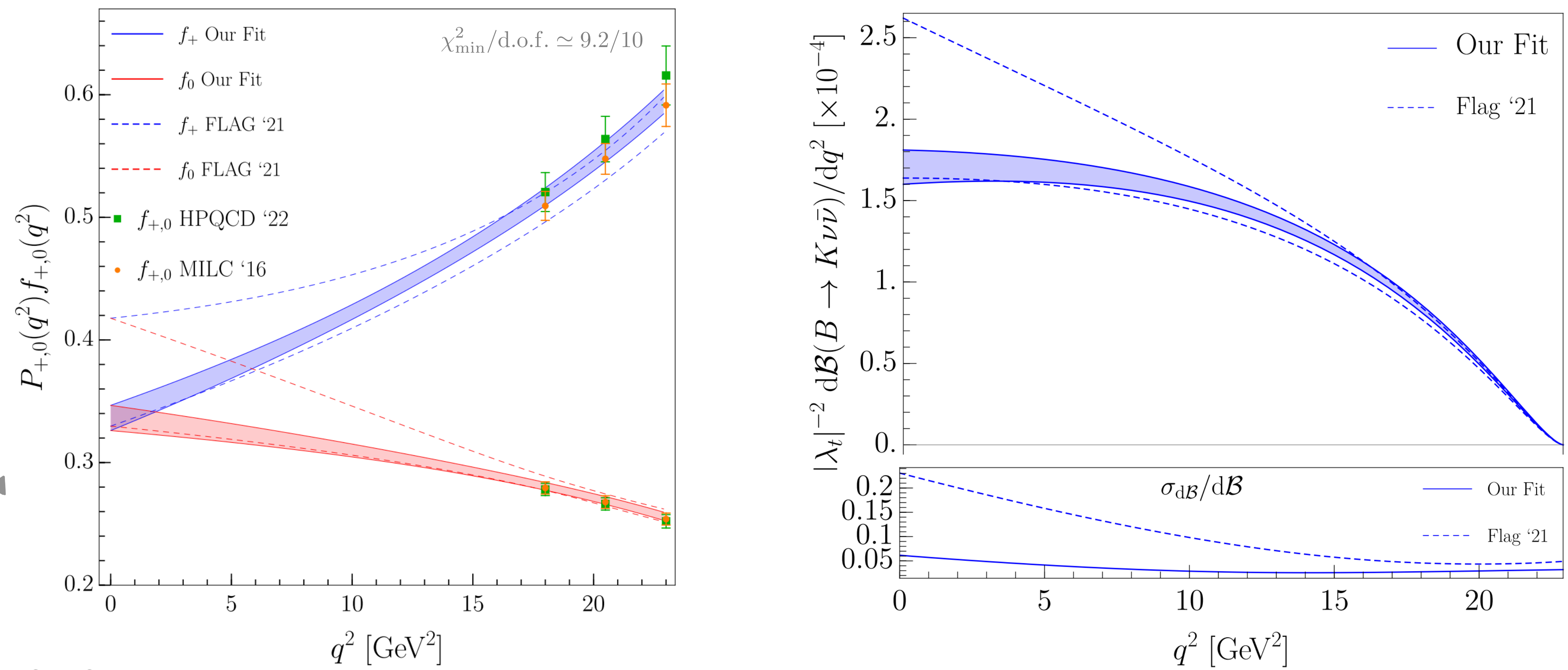
- **Lattice QCD** data available at **nonzero recoil** $(q^2 \neq q^2_{\text{max}})$ for all form-factors:

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

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]:



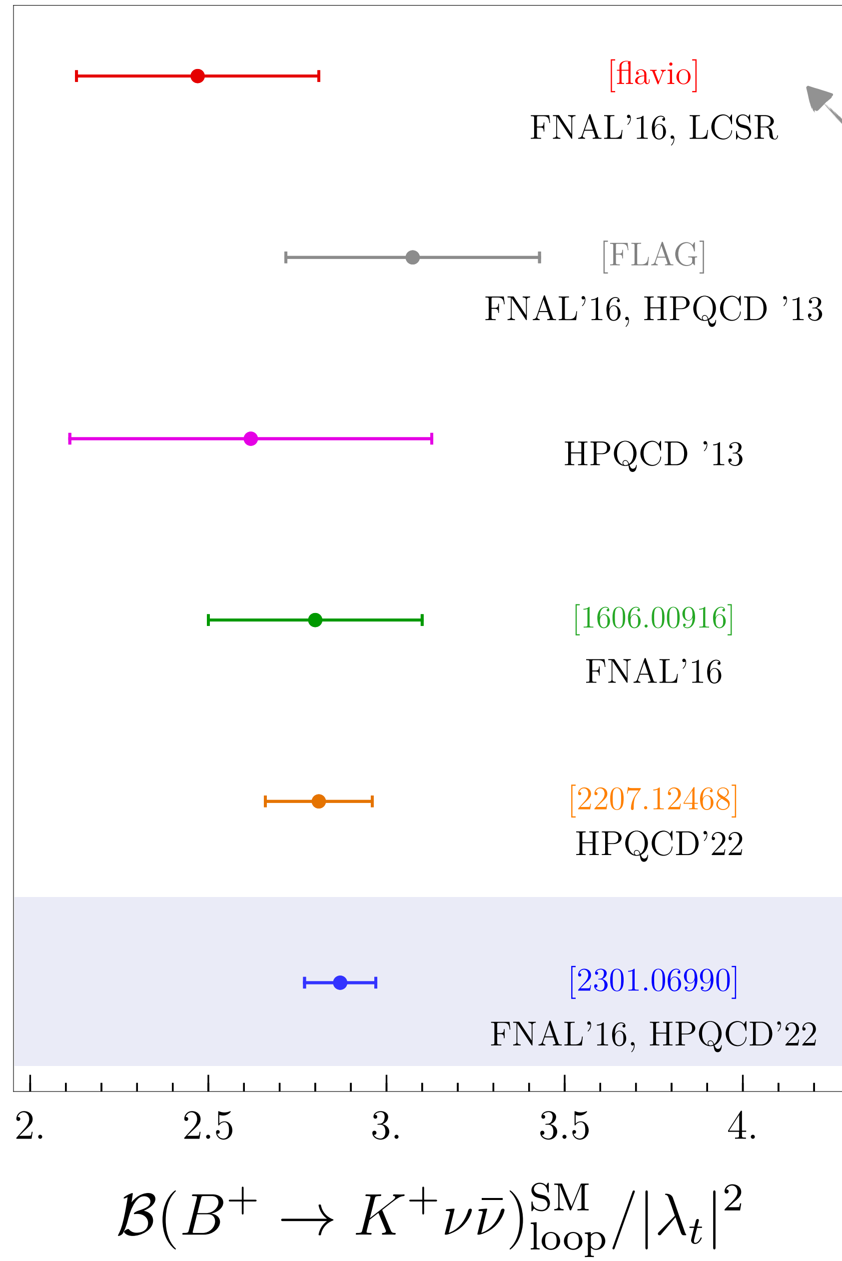
Pole factor:

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

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

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

**Annihilation contributions not included below (see next slides)!*



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

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

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

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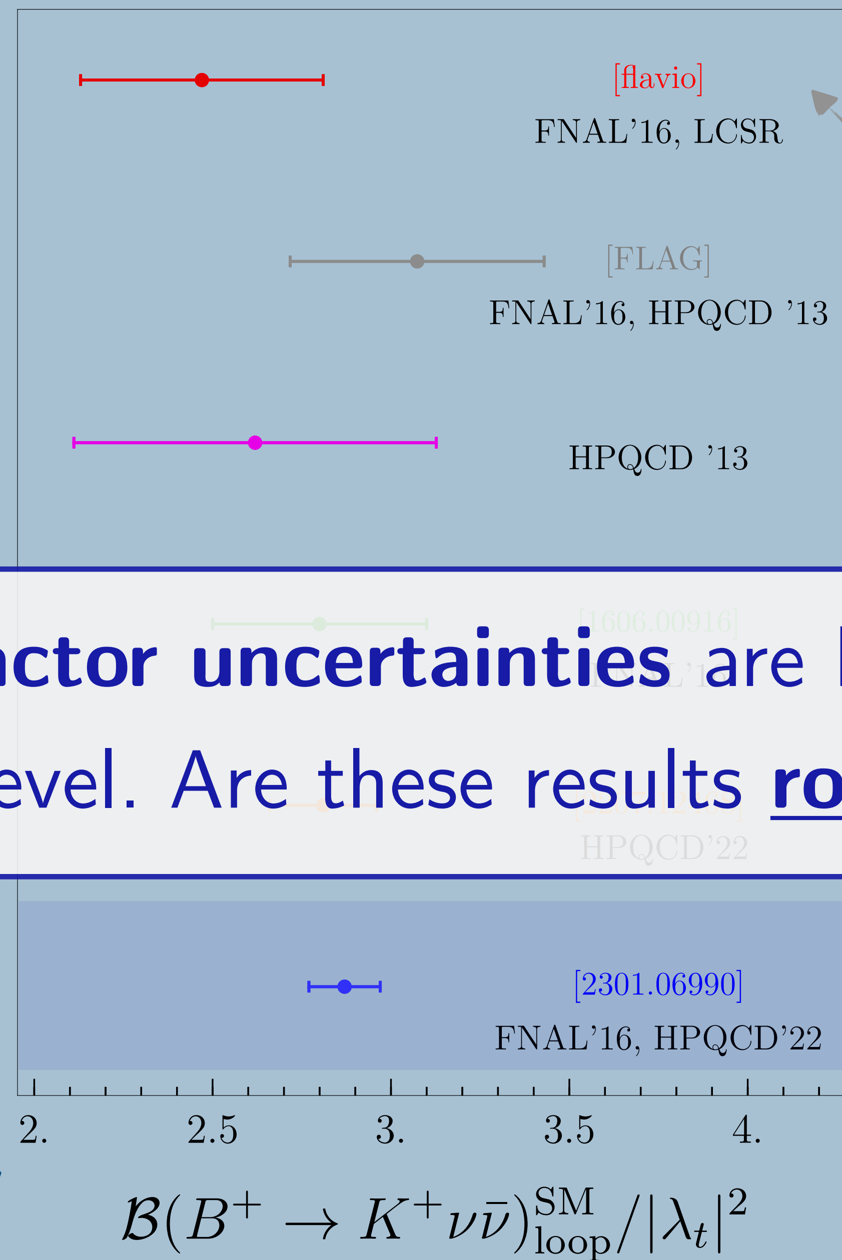

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Form-factor uncertainties are known to $\mathcal{O}(1\%)$ level. Are these results **robust**?

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

[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?**

  $\Rightarrow$ How can we **test the shape** of the **extrapolated** LQCD **form-factors**?

- We propose to measure: [Becirevic, Piazza, **OS**. 2301.06990]

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

$\Rightarrow$ *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. $(q^2_{\mathrm{max}}/2,\, q^2_{\mathrm{max}})$:

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

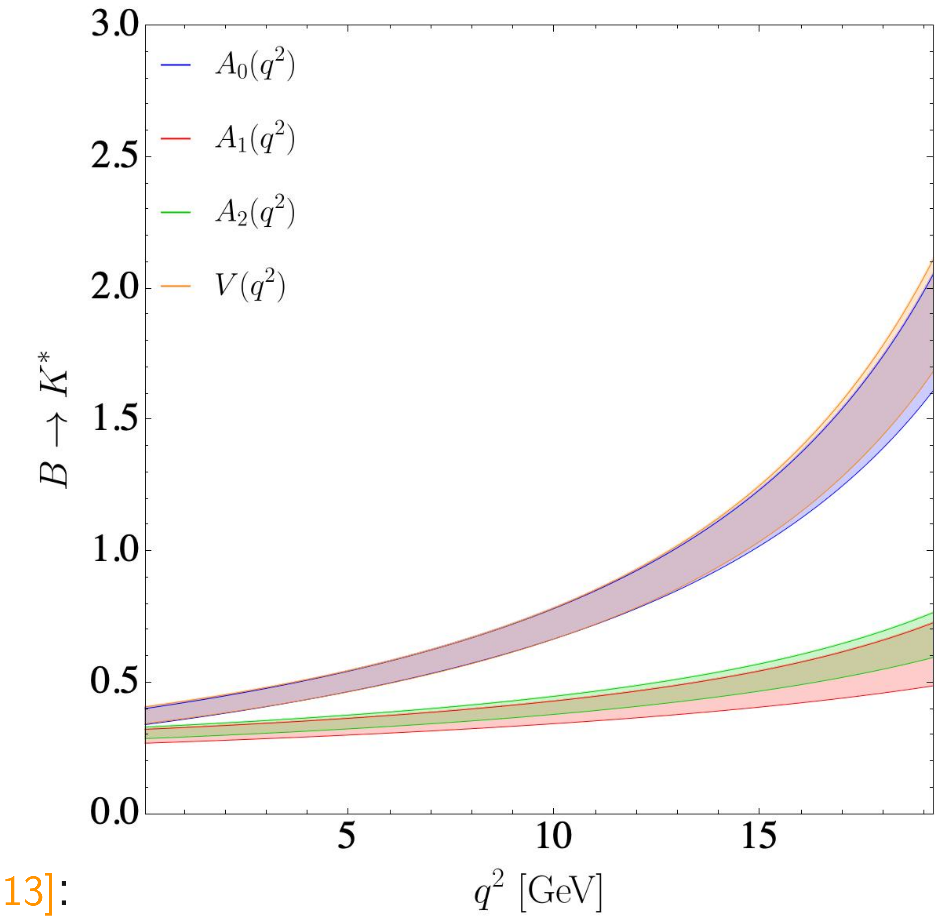
e.g, using (old) FLAG average:

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

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

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

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

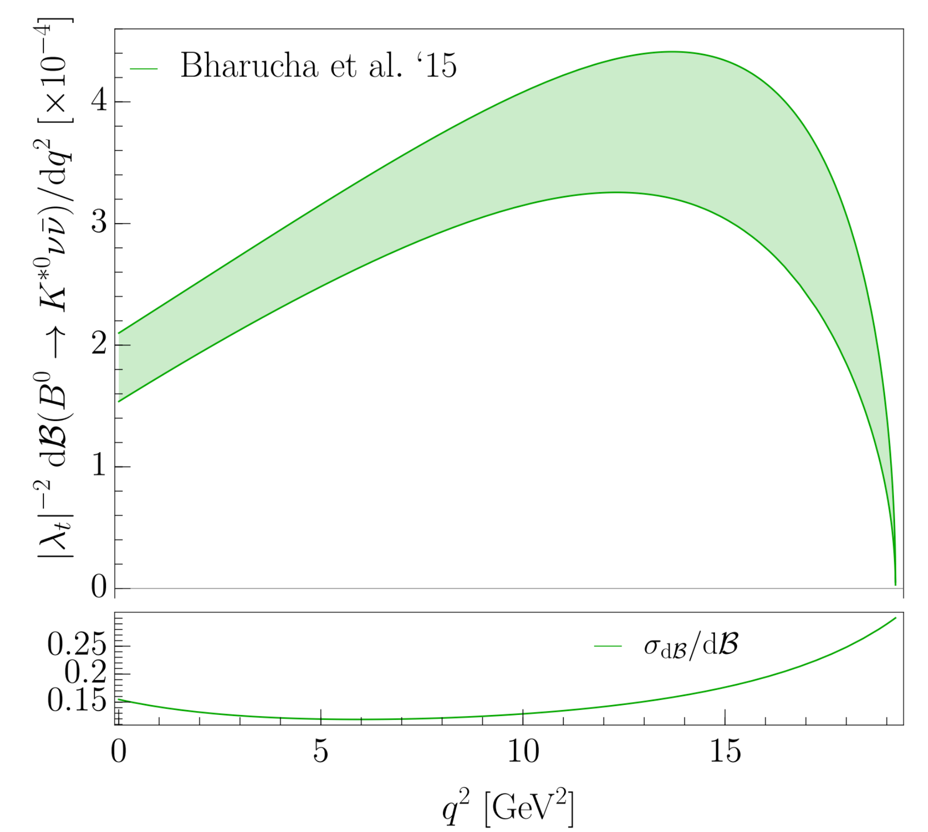


- We use LCSR (+LQCD) results from [Bharucha et al. '15, Horgan et al. '13]:

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

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

$\Rightarrow$ Relatively small uncertainties, **but are they accurate**?



II. Which CKM value?

Se talk by K. Vos

- 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]

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

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

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

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

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

[HPQCD '19]

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

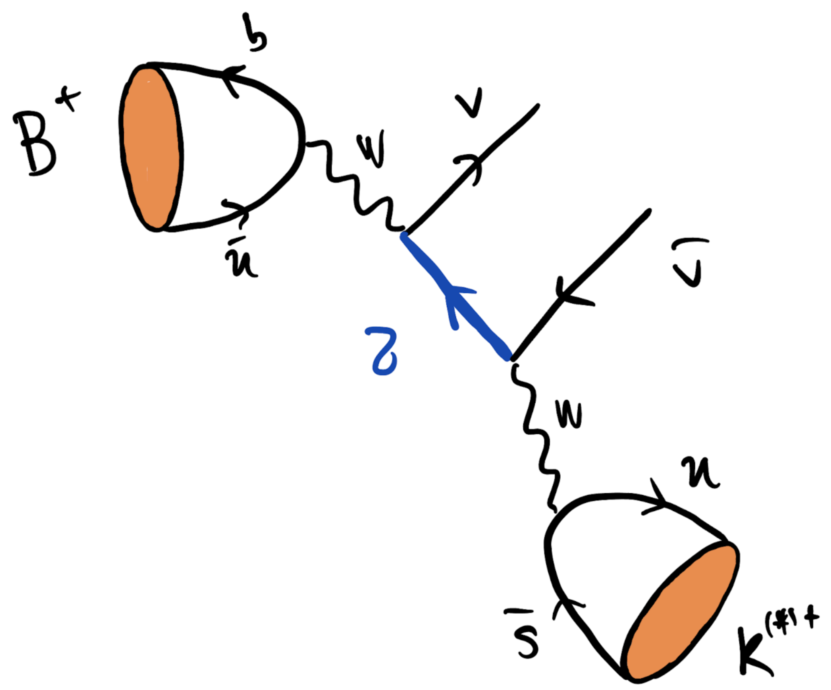
[FLAG '21]

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

Weak-annihilation contributions

[Kamenik, Smith. '09]

- **To keep in mind**: decay modes with **charged mesons** are affected by **tree-level** weak **annihilation contributions**.



$$m_{K^{(*)+}} \leq m_\tau \leq m_B$$

- Using *narrow-width* approximation:

$$\mathcal{B}(B^+ \to K^{(*)+}\nu\bar{\nu}) \simeq \mathcal{B}(B^+ \to \tau^+\bar{\nu})\,\mathcal{B}(\tau^+ \to K^{(*)+}\nu)$$

- *Non-negligible* contributions:

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{tree}}}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu}))_{\mathrm{loop}}} \simeq 14\ \%$$

$$\frac{\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})_{\mathrm{tree}}}{\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu}))_{\mathrm{loop}}} \simeq 11\ \%$$

⇒ They *cannot be removed* by a *simple kinematical cut*...

Belle-II: These contributions are treated as a **background** thanks to the τ **lifetime**

Summary (circa '22)

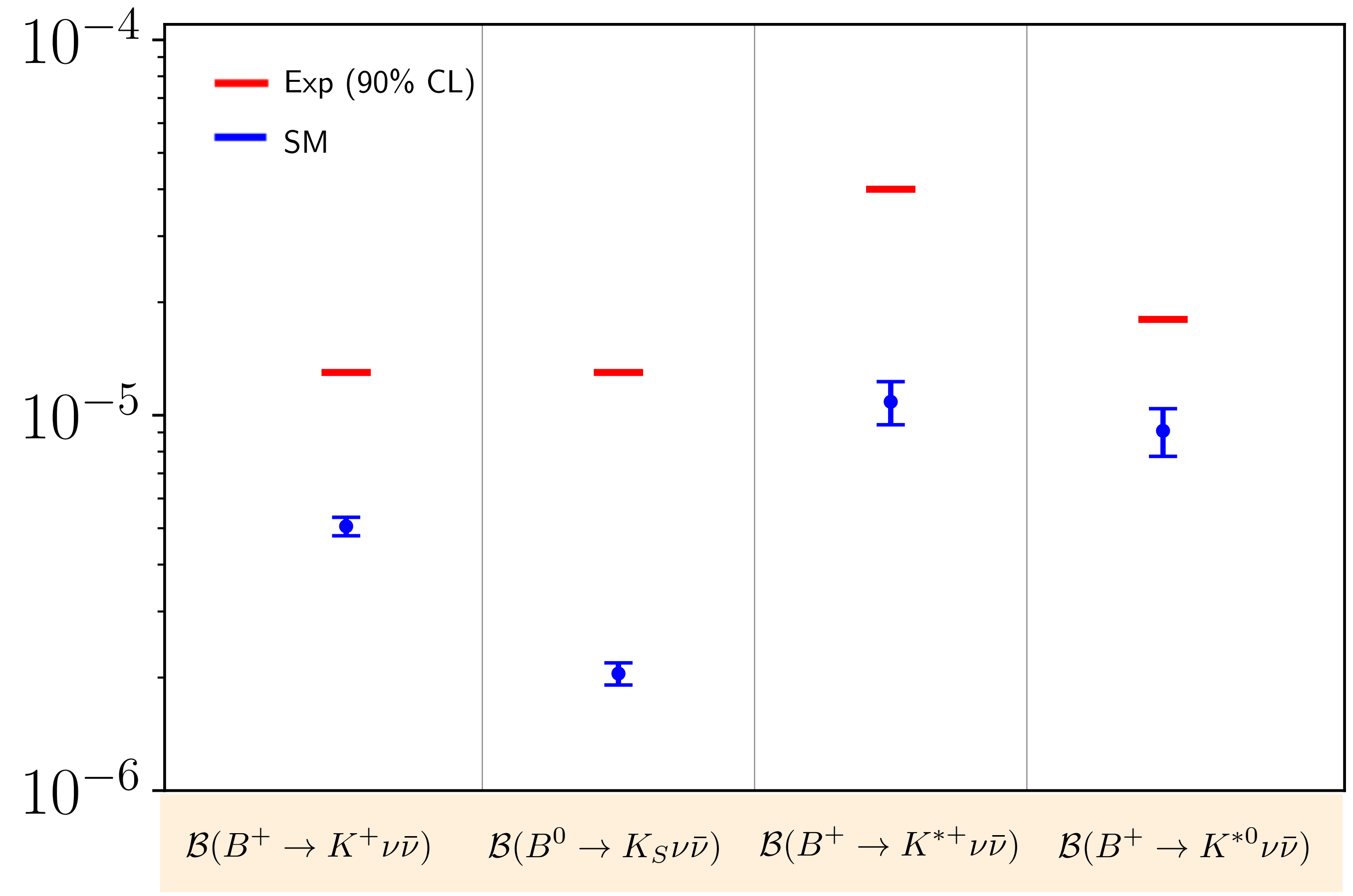
[Belle 1303.3719, 1702.03224]

[BaBar 1009.1529, 1303.7465]

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

Decay	Branching ratio
$B^+ \to K^+\nu\bar{\nu}$	$(5.06 \pm 0.14 \pm 0.25) \times 10^{-6}$
$B^0 \to K_S\nu\bar{\nu}$	$(2.05 \pm 0.07 \pm 0.12) \times 10^{-6}$
$B^+ \to K^{*+}\nu\bar{\nu}$	$(10.86 \pm 1.30 \pm 0.59) \times 10^{-6}$
$B^0 \to K^{*0}\nu\bar{\nu}$	$(9.09 \pm 1.20 \pm 0.55) \times 10^{-6}$

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



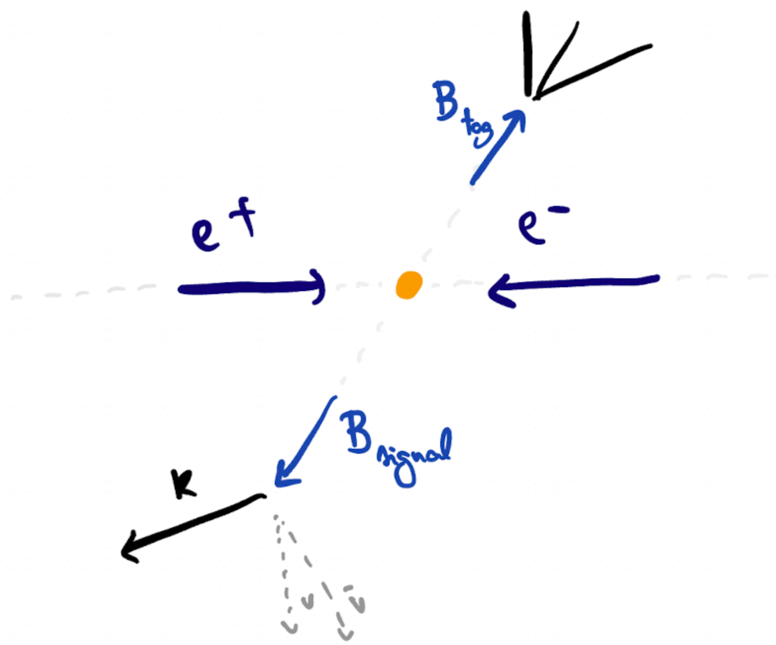
Take-home:

- To remain **cautions** about **hadronic uncertainties** associated to the **form-factors** and the extraction of **CKM** matrix-elements — *non-negligible given the projected Belle-II sensitivity.*
- **Binned measurements** at Belle-II would be a **valuable piece of information** to **test the consistency the SM predictions**.

Belle-II results

Belle-II strategy

- **Belle-II** (SuperKEKB) is an asymmetric e^+e^- collider operating at $\sqrt{s} \simeq m_{\Upsilon(4S)}$:



$$e^+e^- \to \Upsilon(4S) \to \underbrace{B\bar{B}}_{B_{\text{tag}}\bar{B}_{\text{signal}}}$$

$$m_{\Upsilon(4S)} \simeq 10.579 \text{ GeV}$$

$$m_{B^+} \simeq m_{B^0} \simeq 5.279 \text{ GeV}$$

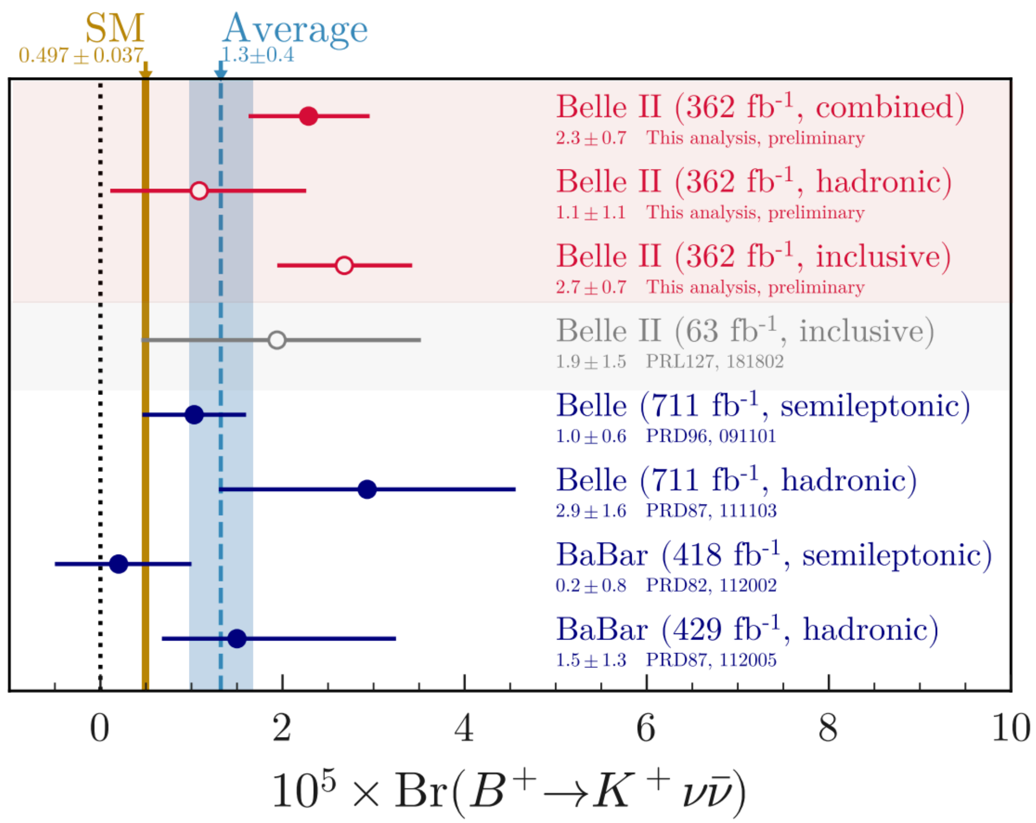
- **Different tagging methods:**

	Hadronic Fully reconstructed hadronic decay	**Semileptonic** $B_{\text{tag}} \to D^{(*)}\ell\nu$	**Inclusive** Several channels
Efficiency	≈ 0.5 %	≈ 2 %	≈ 8 %
Background	Small	Large	Large

NB. The inclusive-tagging method was not applied to BaBar and Belle data (yet)!

[NEW] Belle-II results

[Belle-II, 2311.14647]



Belle-II results

First Belle-II result

$\approx 3\sigma$ above the SM prediction

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{\rm exp} = \left[2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right] \times 10^{-5}$$

- Only the **incl. method** shows an excess **above background** (and w.r.t. the SM predictions).
- The **had. method** is **compatible** with the **SM** (and with no observed signal).
- **Semileptonic tagging** (i.e., $B_{\rm tag} \to X\ell\nu$) could be a **useful cross-check**, as well as the measurement of $B^0 \to K_S \nu\bar{\nu}$ decays.

⇒ More data is needed! Many possible cross-checks.

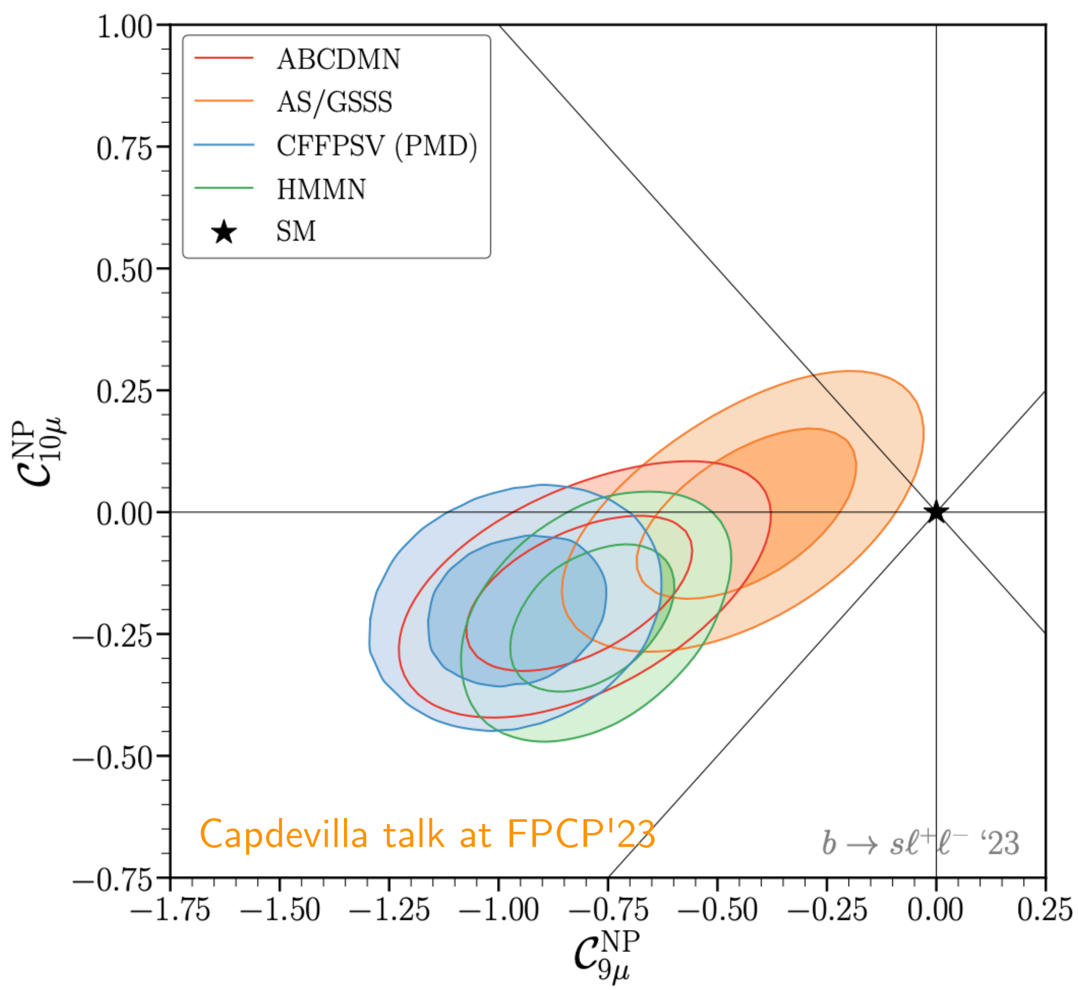
What can we learn from $B \to K^{(*)}\nu\bar{\nu}$?

- Remarks on $B \to K^{(*)}\nu\bar{\nu} / B \to K^{(*)}\mu\mu$
- Implications beyond the SM
- Hidden sectors?

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

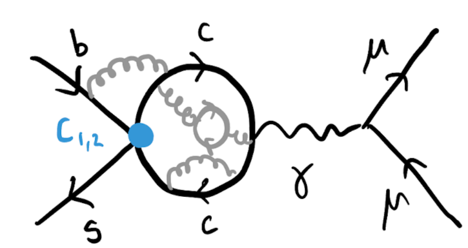
$$\mathcal{L}_{\text{eff}}^{b\to s\ell\ell} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_\ell \left[C_9^{\ell\ell}\,(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell) + C_{10}^{\ell\ell}\,(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5 \ell) + \dots \right] + \text{h.c.}$$

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



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

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

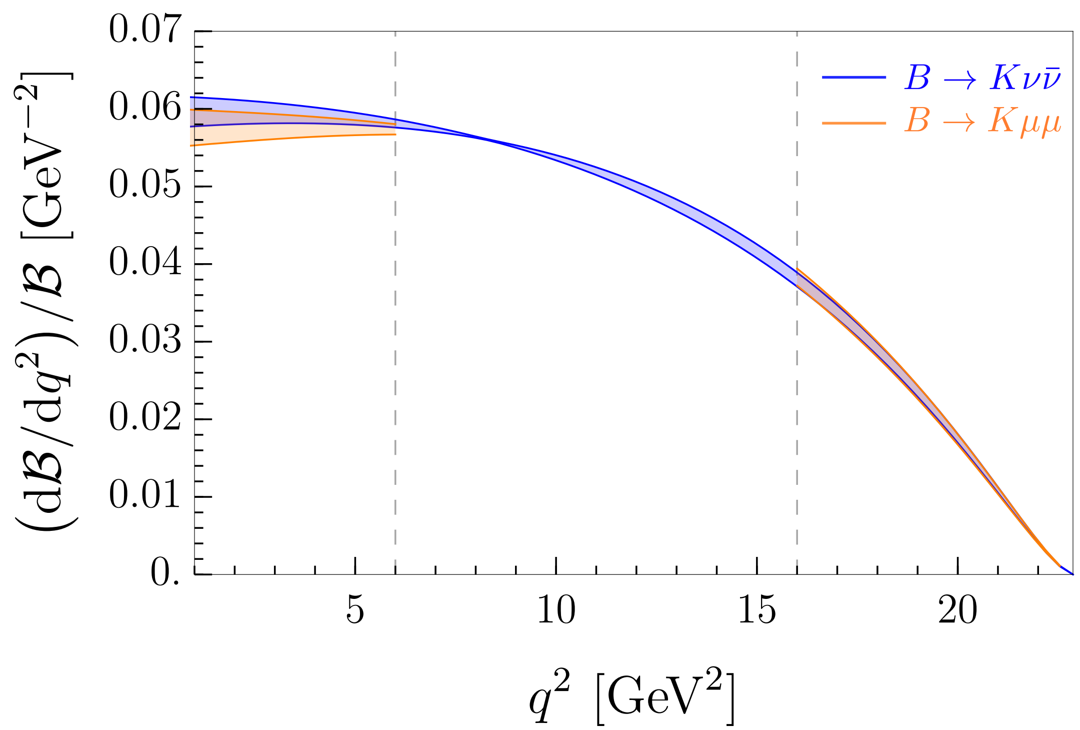


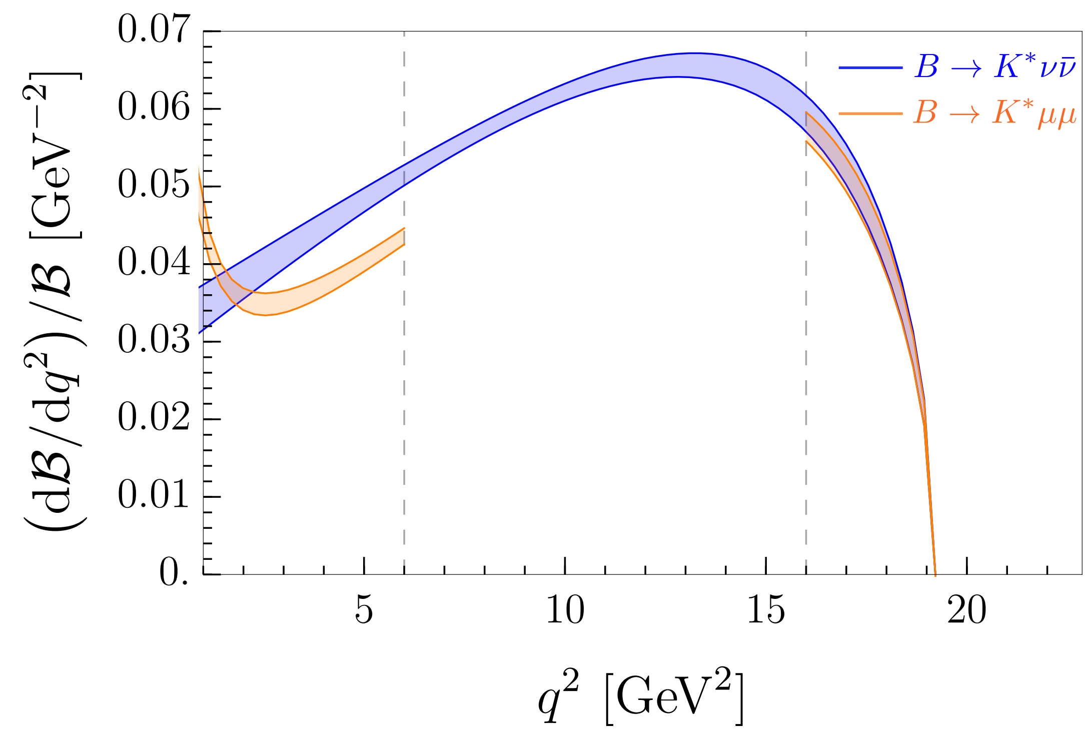
NB. LFU ratios $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee)$ do not depend on $C_9^{\ell\ell}$, but they are difficult to measure — cf. latest LHCb results, which now agree with the SM predictions.

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]

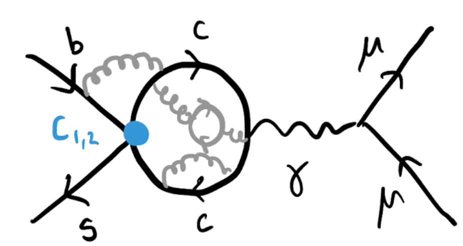
- We can defined the **CKM-free ratio**:

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

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

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

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



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

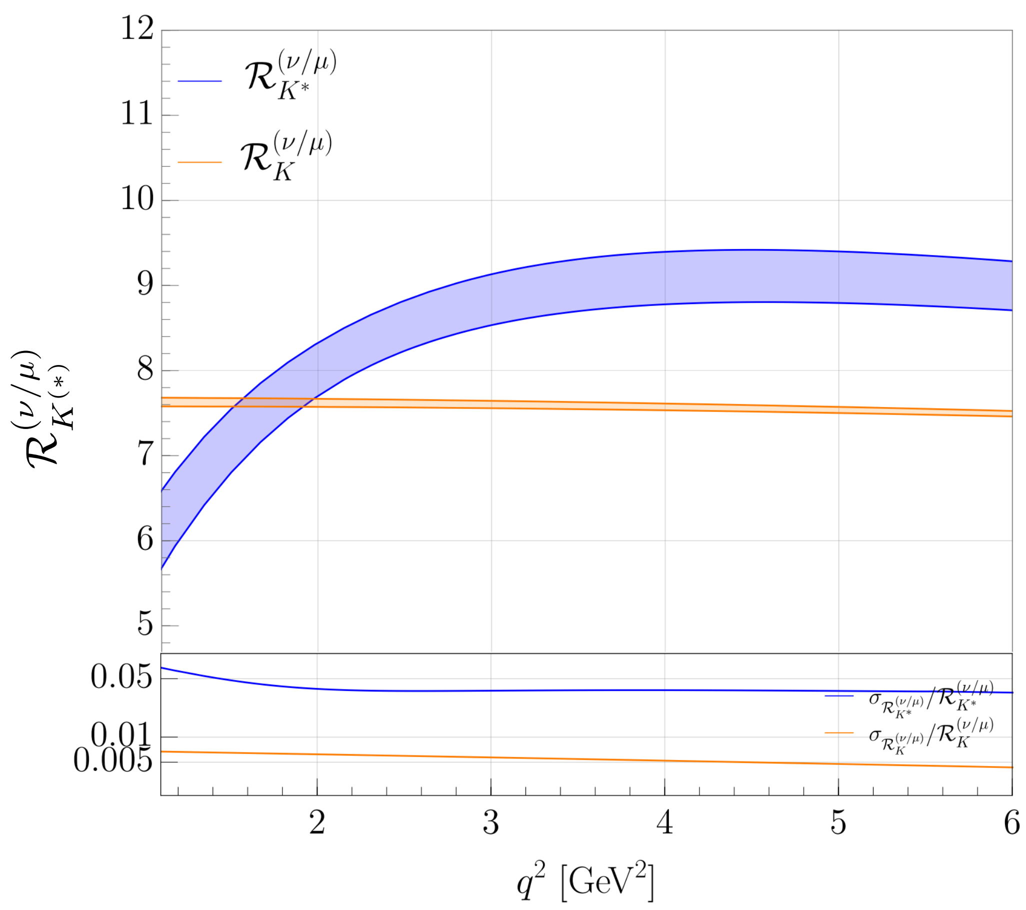
$$\mathcal{R}_K^{(\nu/l)}[1.1,6]\Big|_{\rm SM} = 7.58 \pm 0.04$$

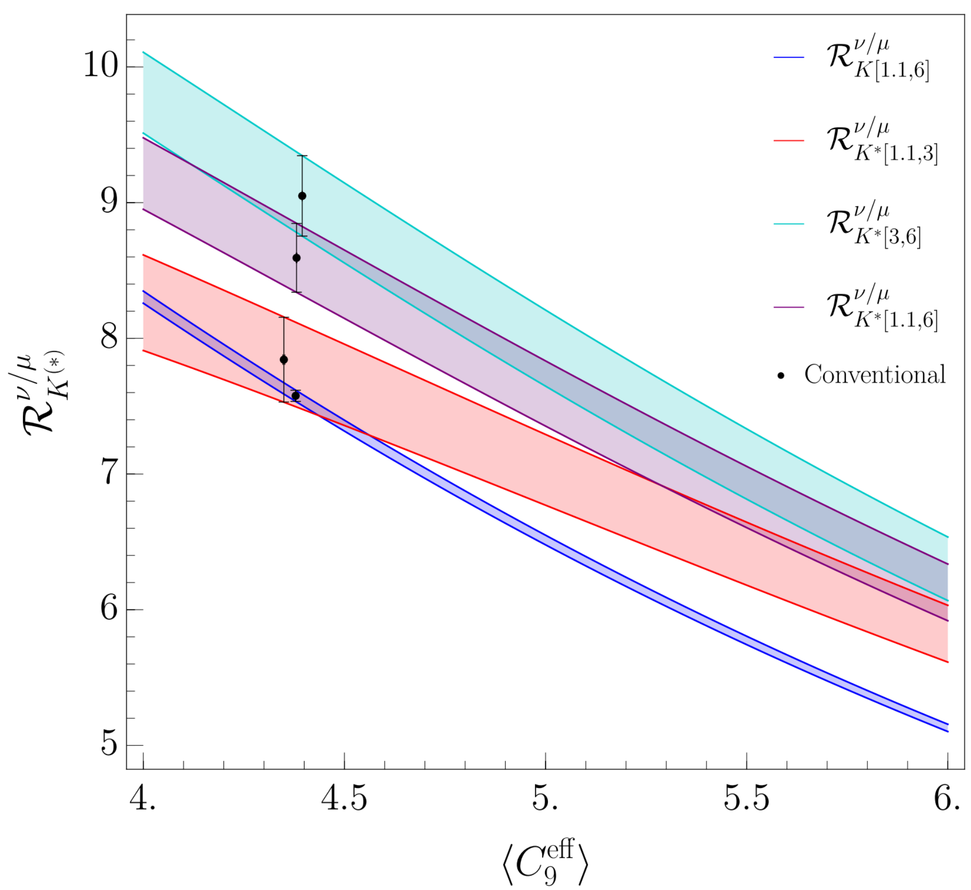
$$\mathcal{R}_{K^*}^{(\nu/l)}[1.1,6]\Big|_{\rm SM} = 8.6 \pm 0.3$$

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.

What can we learn from $B \to K^{(*)}\nu\bar{\nu}$?

- Remarks on $B \to K^{(*)}\nu\bar{\nu} / B \to K^{(*)}\mu\mu$
- **Implications beyond the SM**
- Probing hidden sectors?

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

- Low-energy EFT:

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

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

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

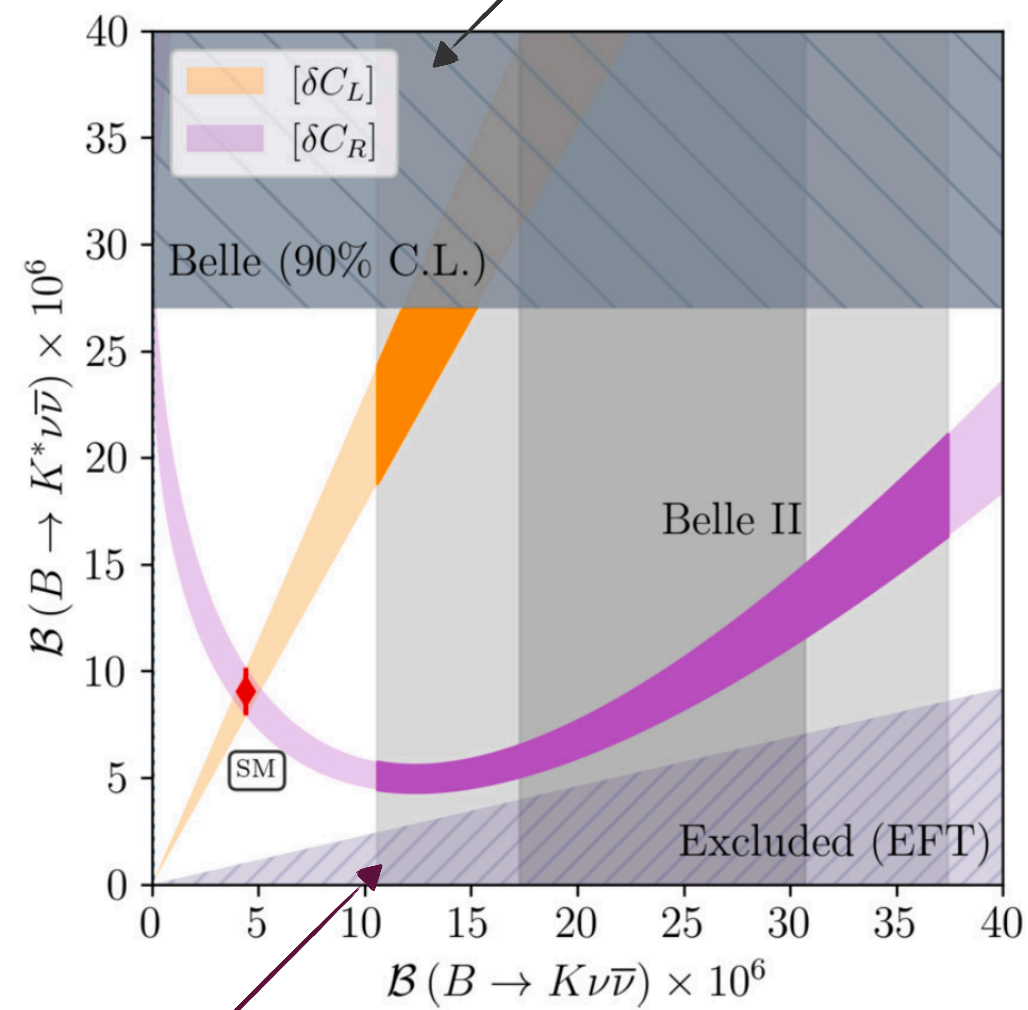
$$\frac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})^{\rm SM}} = 1 + \sum_i \frac{2\mathrm{Re}[C_L^{\rm SM}(\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3|C_L^{\rm SM}|^2} + \sum_{i,j}\frac{|\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j}|^2}{3|C_L^{\rm SM}|^2}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

$\eta_K = 0$

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

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

Exclusion from Belle/BaBar



Forbidden region in the EFT approach

[Bause et al. '23]

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

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

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

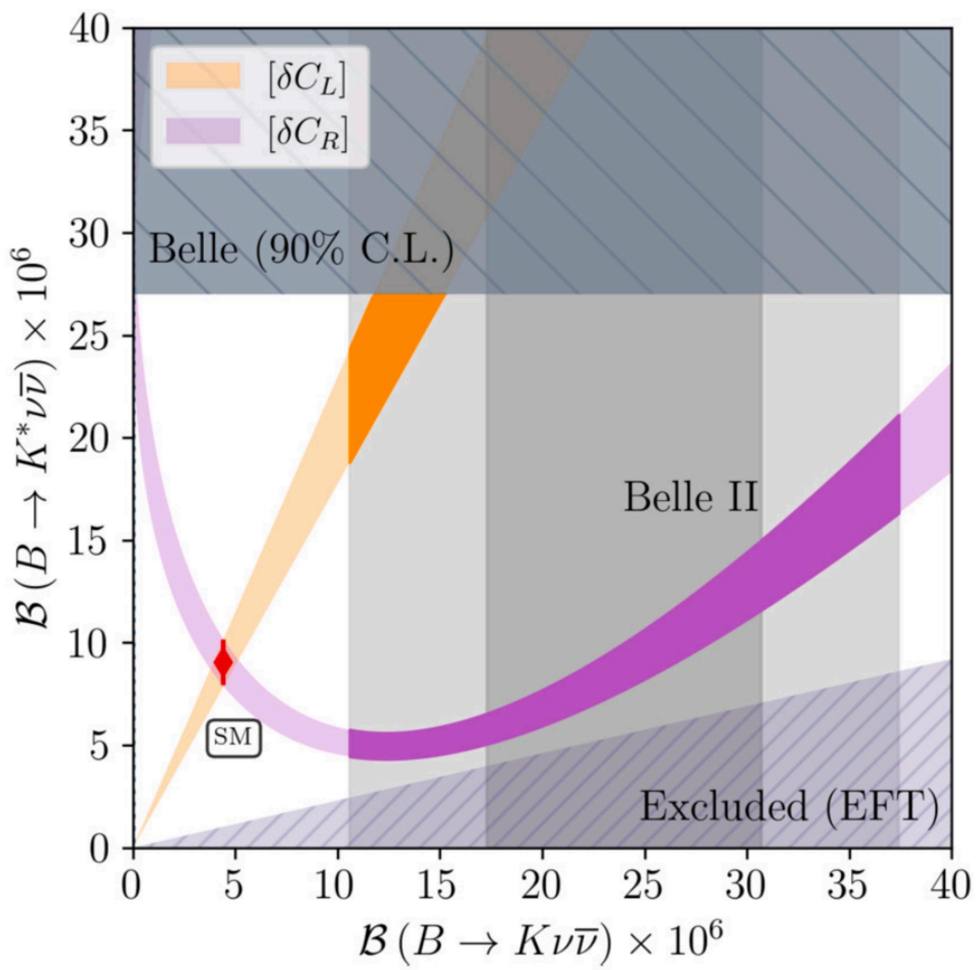
- Another observable to measure is the K^* longitudinal-polarisation asymmetry:

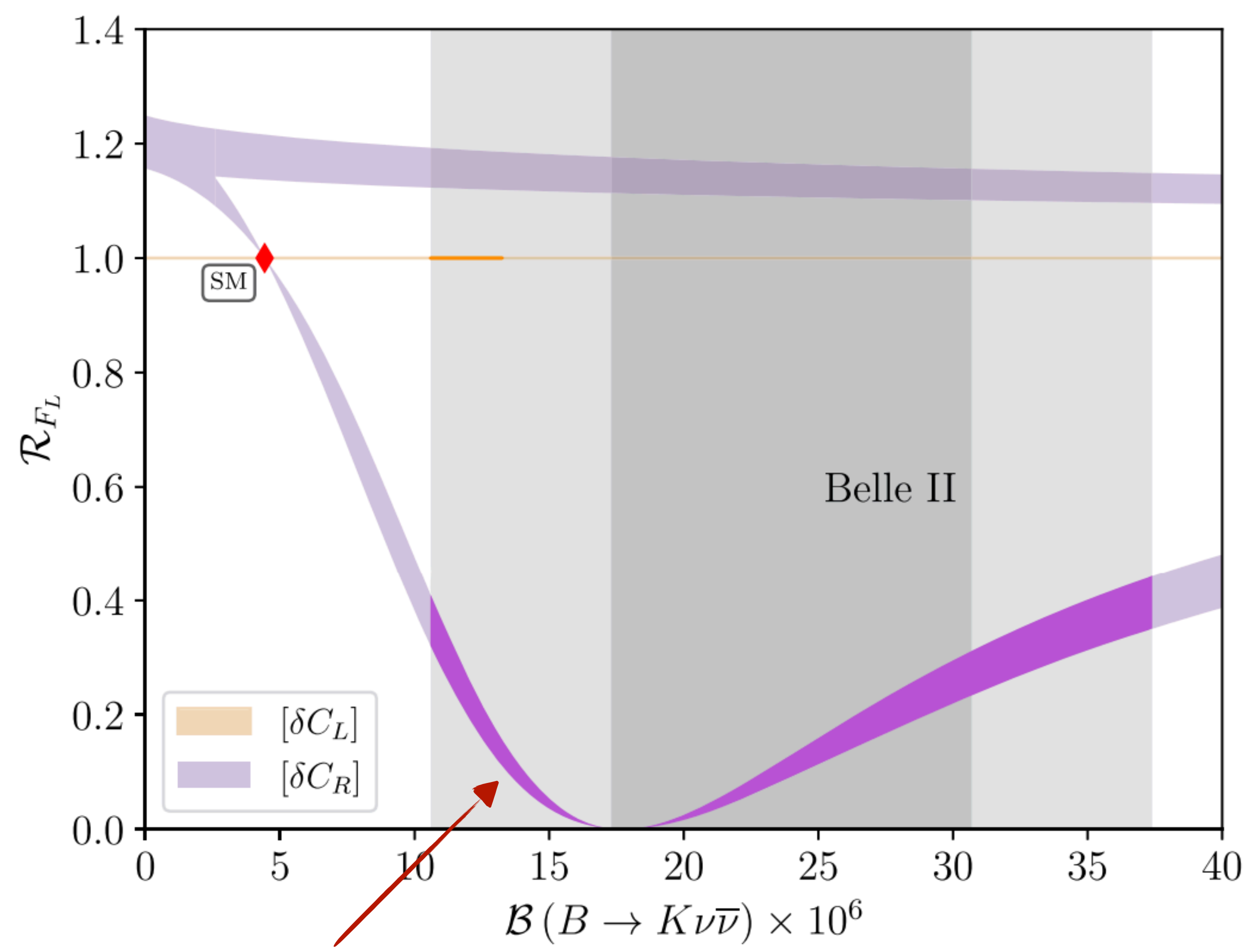
$$F_L \equiv \frac{\Gamma_L(B \to K^*\nu\bar{\nu})}{\Gamma(B \to K^*\nu\bar{\nu})}$$

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

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

[Altmannshofer et al. '09]





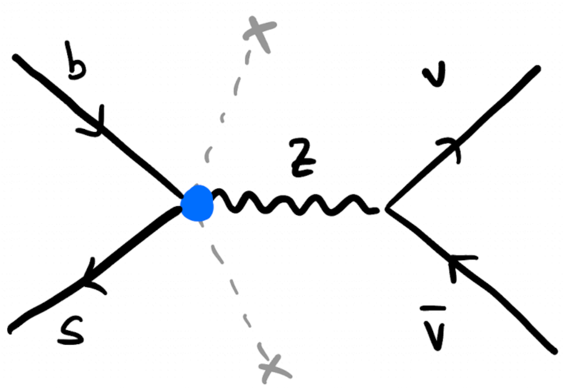
Depletion of SM prediction!

The measurement of $\mathcal{B}(B \to K^*\nu\bar{\nu})$ 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 $\Lambda \gg v_{\text{ew}}$ 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) $\psi^2 H^2 D$:

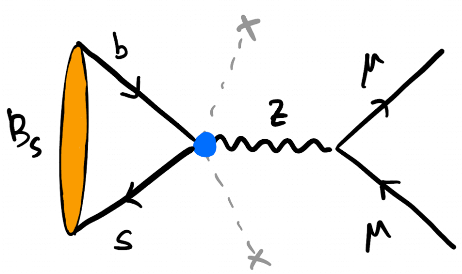


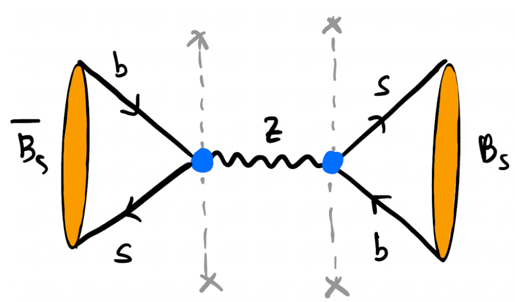
e.g.,

$\mathcal{O}_{Hl}^{(1)} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$

Lepton flavor universal!

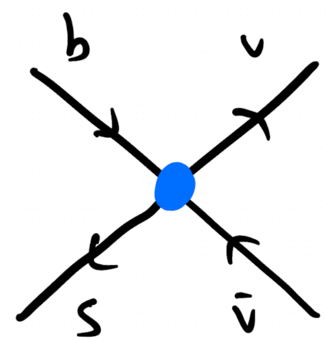
$\Rightarrow$ Severely constrained by $\mathcal{B}(B_s \to \mu\mu)$ and Δm_{B_s} :





✗

ii) ψ^4 :



e.g.,

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

$\Rightarrow$ **Only viable option!**

✓

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

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

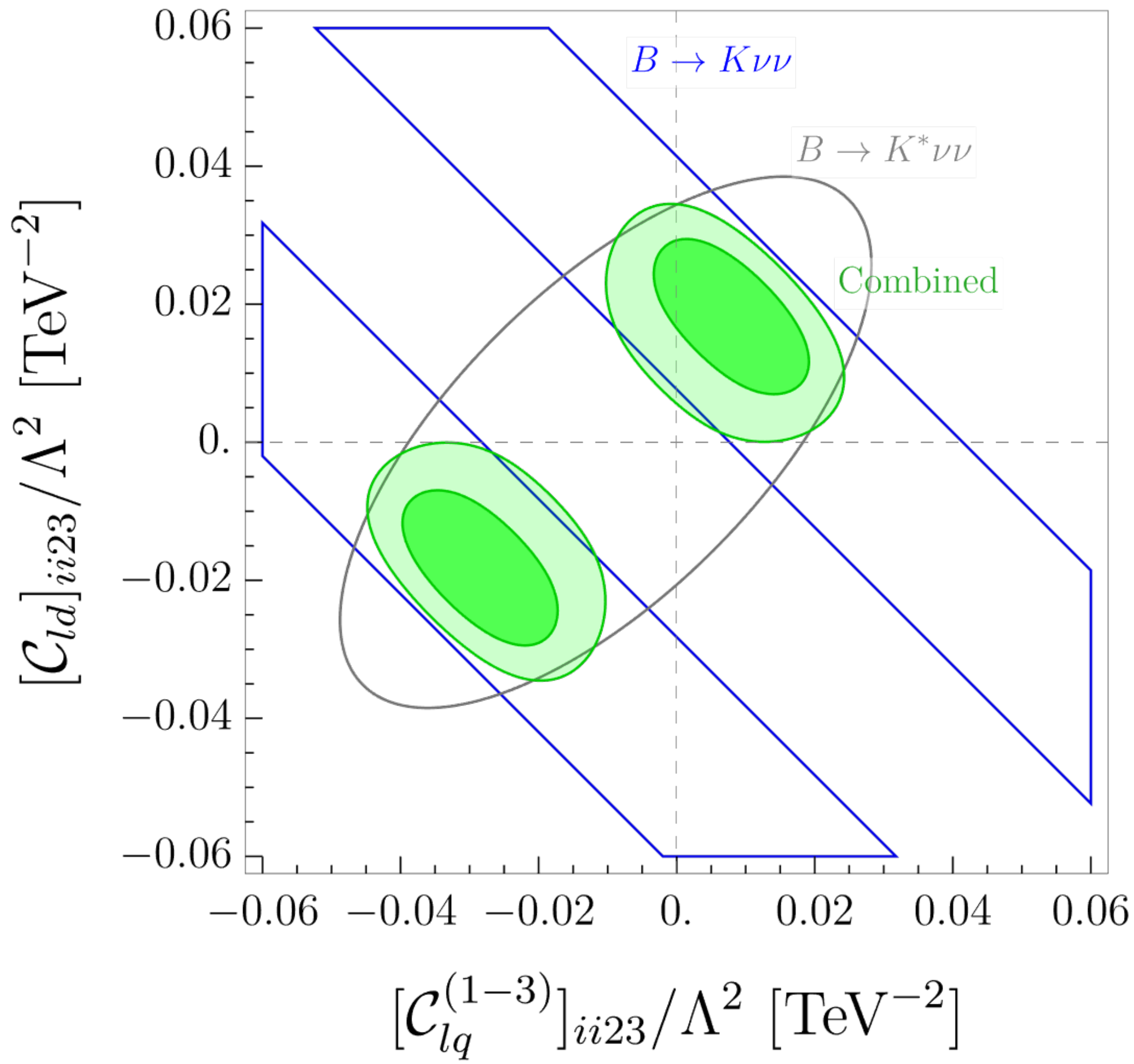
$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i \gamma^\mu L_j)(\overline{Q}_k \gamma_\mu Q_l)$$
$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i \gamma^\mu \tau^I L_j)(\overline{Q}_k \tau^I \gamma_\mu Q_l)$$
$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i \gamma^\mu L_j)(\overline{d}_k \gamma_\mu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

- SMEFT ⇔ LEFT matching:

$$\delta C_L^{\nu_i \nu_j} \propto \frac{v^2}{\Lambda^2}\left(\mathcal{C}_{\substack{lq \\ ij23}}^{(1)} - \mathcal{C}_{\substack{lq \\ ij23}}^{(3)}\right)$$

$$\delta C_R^{\nu_i \nu_j} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\substack{ld \\ ij23}}^{(1)}$$

Flavor $(i = j)$ fixed



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

[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 $SU(2)\times U(1)_Y$:

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

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

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

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

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

Which flavor?

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

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

ii. *LFV couplings* are *constrained* by searches for $\mathscr{B}(B_s \to \ell_i\ell_j)$ and $\mathscr{B}(B \to K^{(*)}\ell_i\ell_j)$. ✗

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

⇒ **Predictions:**

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

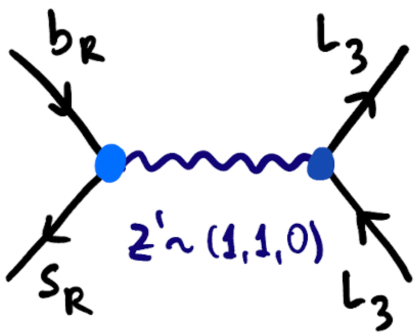
⇒ However, **experimentally challenging**...

Which concrete model?

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

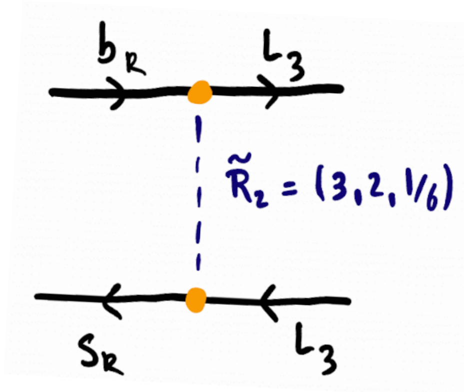
- More **correlations** between **observables** can arise in **concrete models**:

  - Z':



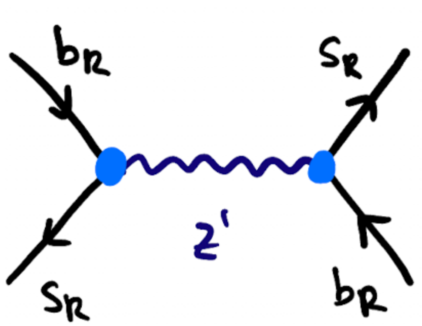
$$\mathcal{L}_{Z'} \supset g_{ij}^{\psi}\,(\bar\psi_i \gamma^\mu \psi_j) Z'_\mu$$

  - LQs:



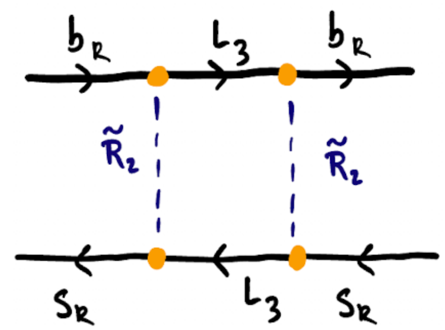
$$\mathcal{L}_{\widetilde{R}_2} \supset y_{ij}^{R}\,(\bar d_{Ri} \widetilde{R}_2 i\tau_2 L_j) + \text{h.c.}$$

- $\Delta F = 2$ 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.

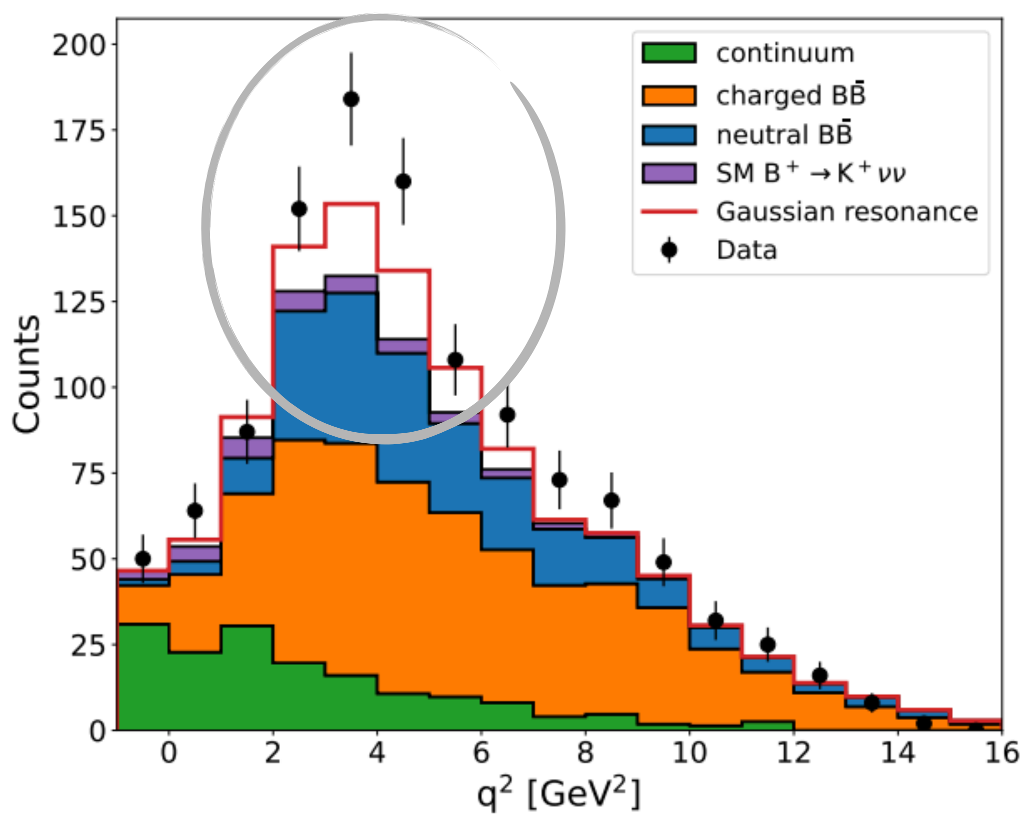
What can we learn from $B \to K^{(*)}\nu\bar{\nu}$?

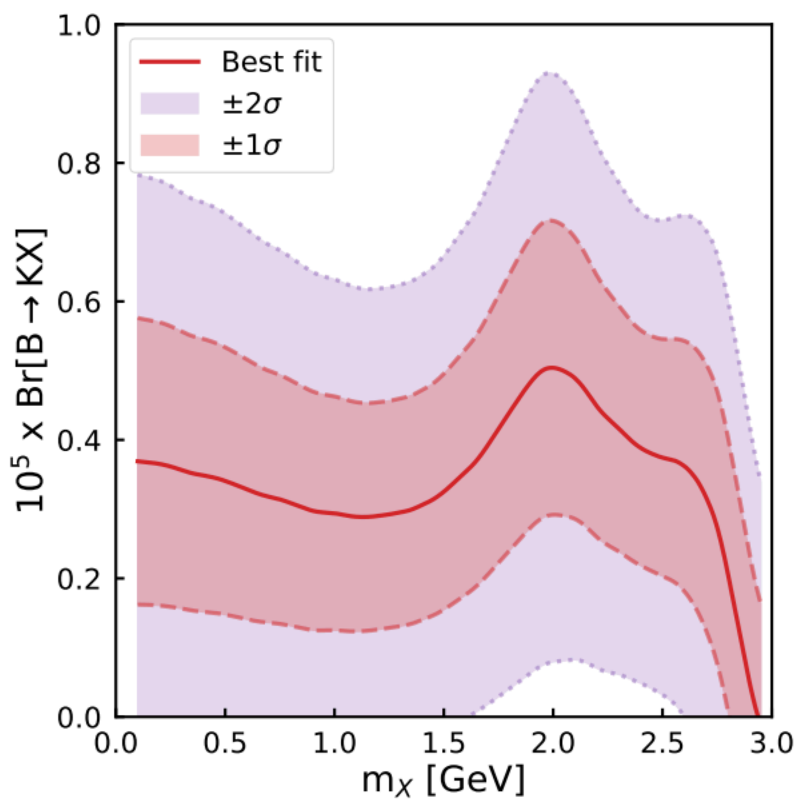
- Remarks on $B \to K^{(*)}\nu\bar{\nu} / B \to K^{(*)}\mu\mu$
- Implications beyond the SM
- Probing hidden sectors?

Hidden sectors?

[Altmannshofer et al. '23]

- What if the excess is due to $B \to KX(\to \text{inv})$, where $X \sim (\mathbf{1},\mathbf{1},0)$ is a light mediator produced on-shell *(i.e., with $m_X < m_B$)*?
- The main difference would be a **peak** in the **q^2-distributions** at $q^2 \simeq m_X^2$, smeared by the detector resolution.
- **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 $\mathcal{B}(B \to KX) = (5.1 \pm 2.1) \times 10^{-6}$

$\Rightarrow$ To be checked by **dedicated searches**!

Summary & Outlook

Summary

- $B \to K^{(*)}\nu\bar{\nu}$ decays are cleaner than $B \to K^{(*)}\mu\mu$, but one should remain **cautious** about the **uncertainties** from the **form factors** and **CKM** matrix elements, in view of the **future Belle-II sensitivity**:

  ⇒ *Binned data can be used to test these predictions — which are more reliable at high-*q^2.

  ⇒ *We propose to measure the ratio* $\mathrm{Br}(B \to K\nu\bar{\nu})_{\mathrm{low}}/\mathrm{Br}(B \to K\nu\bar{\nu})_{\mathrm{high}}$*, which is sensitive to the* q^2*-shape of the (extrapolated) vector form-factor.*

  ⇒ *The ambiguity in the CKM matrix-element determination is the dominant uncertainty for* $B \to K\nu\bar{\nu}$ *decays and it remains an open problem — which value to take?*

- The ratio $B \to K^{(*)}\nu\bar{\nu}/B \to K^{(*)}\mu\mu$ is independent of the CKM and only mildly dependent on the form-factors — **opportunity** to **extract** the $c\bar{c}$**-contributions** to $C_9^{\mu\mu}$ (i.e., for $b \to s\mu\mu$).

- The latest **Belle-II results** show an **excess** that can be accommodated, e.g., by **SMEFT** operators with τ**-flavor**. Many **cross-checks** of these results are **possible:**

  ⇒ *Semileptonic tagging analysis.*

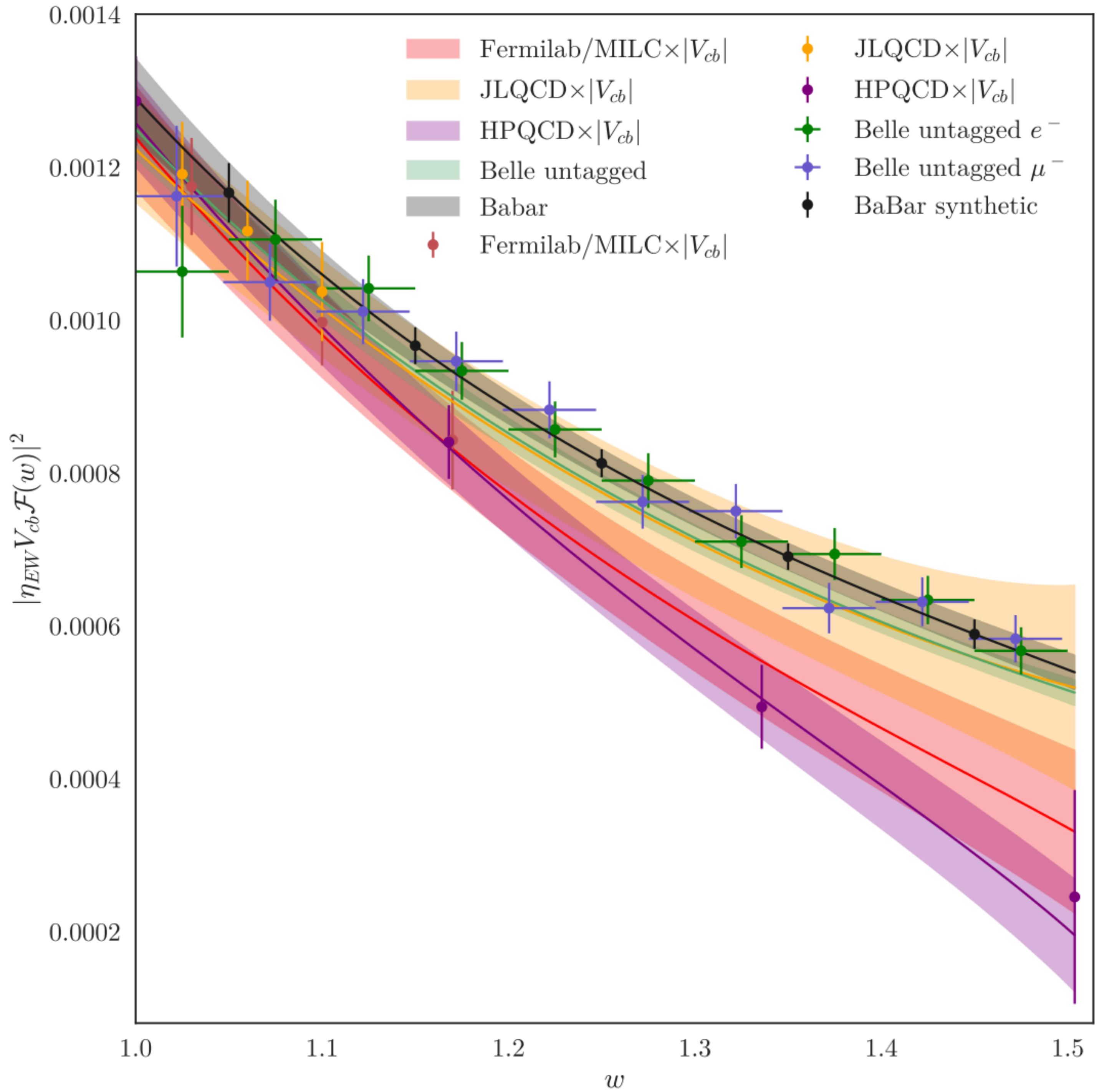
  ⇒ $\mathrm{Br}(B^0 \to K_S\nu\bar{\nu})$, $\mathrm{Br}(B \to K^*\nu\bar{\nu})$ *and* $F_L(B \to K^*\nu\bar{\nu})$.

Many opportunities to **learn more** about physics **(B)SM**!

Thank you!

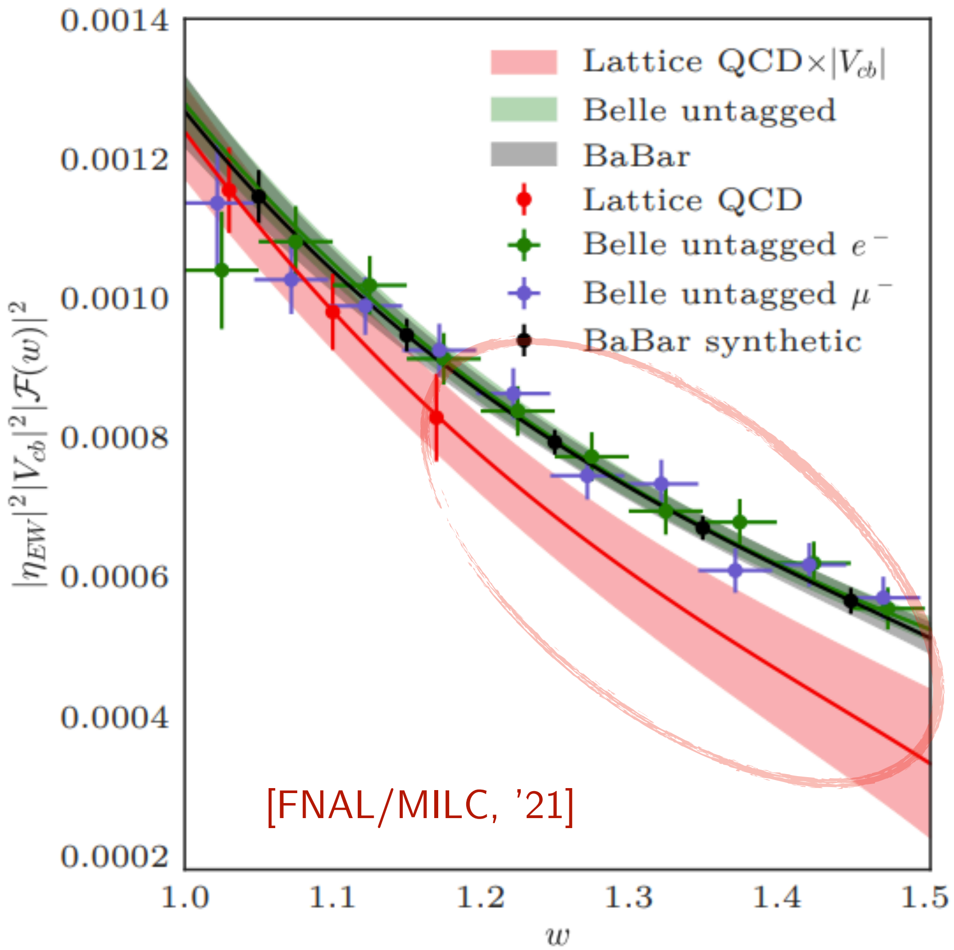
Back-up

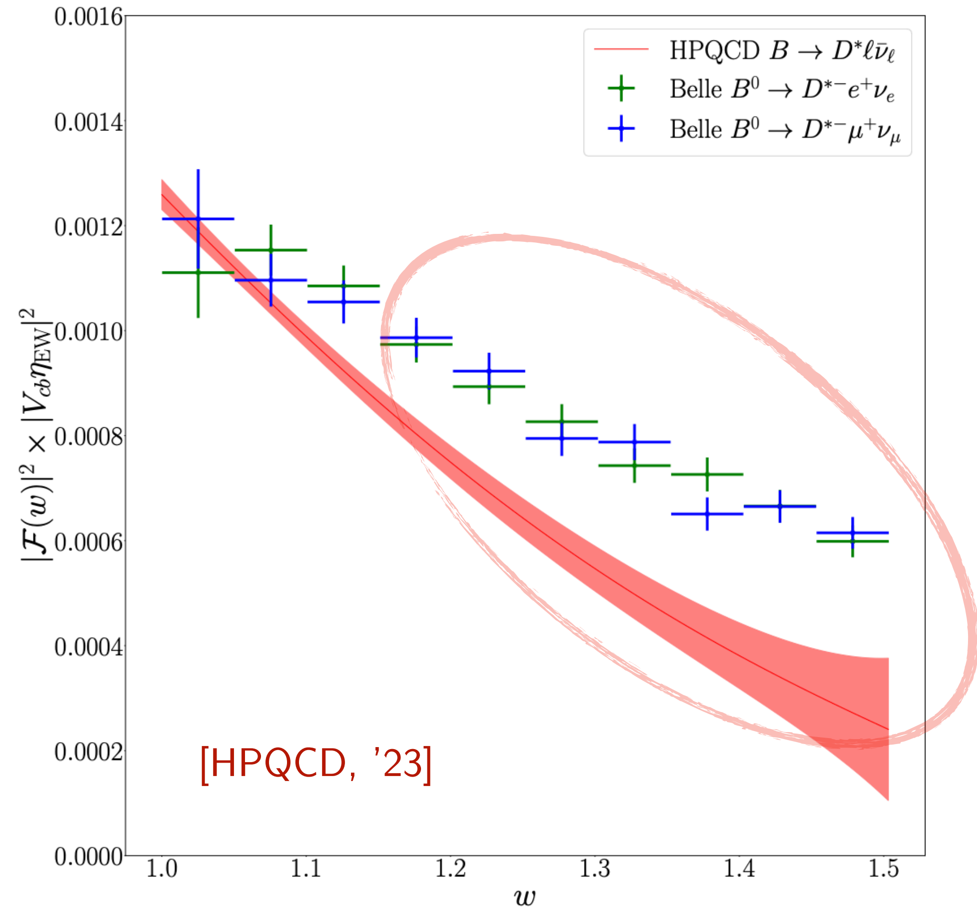
Comparison from A. Lytle talk



[Intermezzo]: Warning!

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

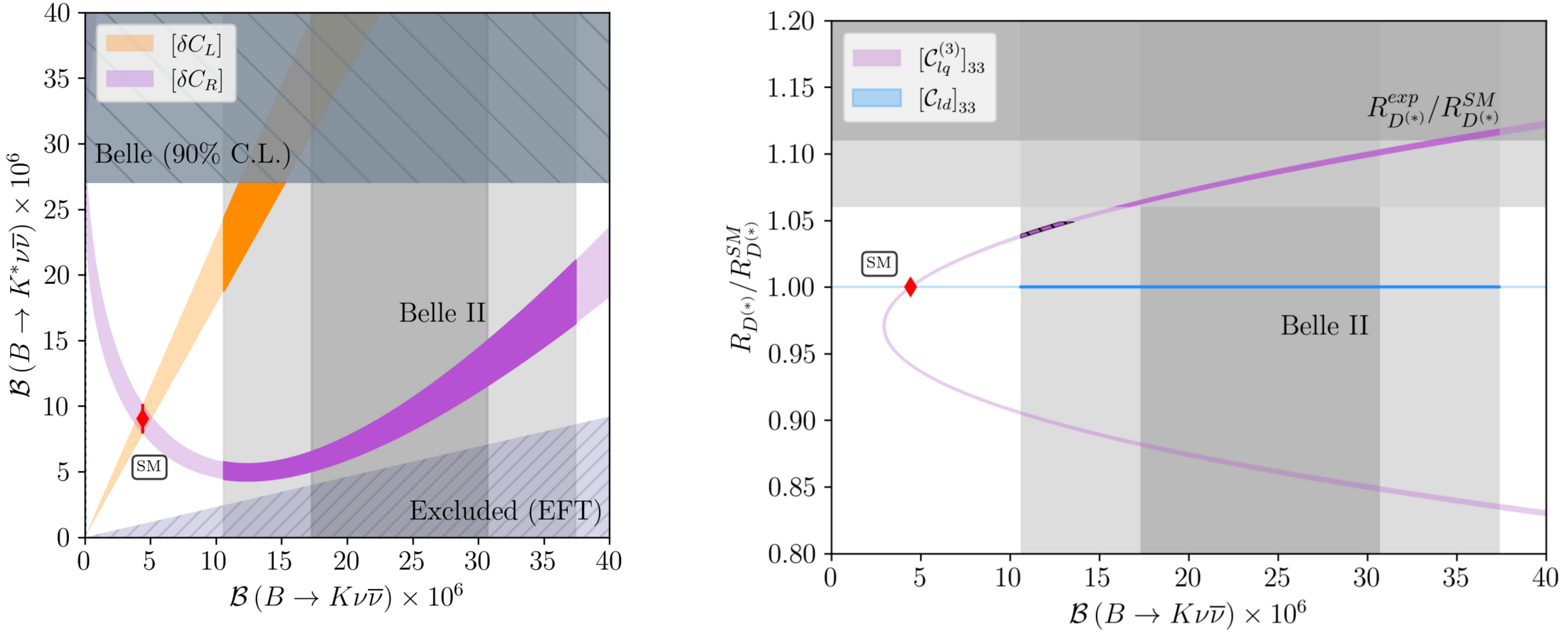




⇒ **Needs clarification** to reliably **extract** $|V_{cb}|$ from $B \to D^* \ell \bar{\nu}$...

NB. Recent JLQCD agrees well with exp. data!

Way out: independent LQCD results + Belle-II data!



$[\delta C_L]$
$[\delta C_R]$
Belle (90% C.L.)
Belle II
Excluded (EFT)
SM
$\mathcal{B}(B \to K^* \nu\bar{\nu}) \times 10^6$
$\mathcal{B}(B \to K \nu\bar{\nu}) \times 10^6$
$[\mathcal{C}_{lq}^{(3)}]_{33}$
$[\mathcal{C}_{ld}]_{33}$
$R^{exp}_{D^{(*)}}/R^{SM}_{D^{(*)}}$
Belle II
SM
$R_{D^{(*)}}/R^{SM}_{D^{(*)}}$
$\mathcal{B}(B \to K \nu\bar{\nu}) \times 10^6$

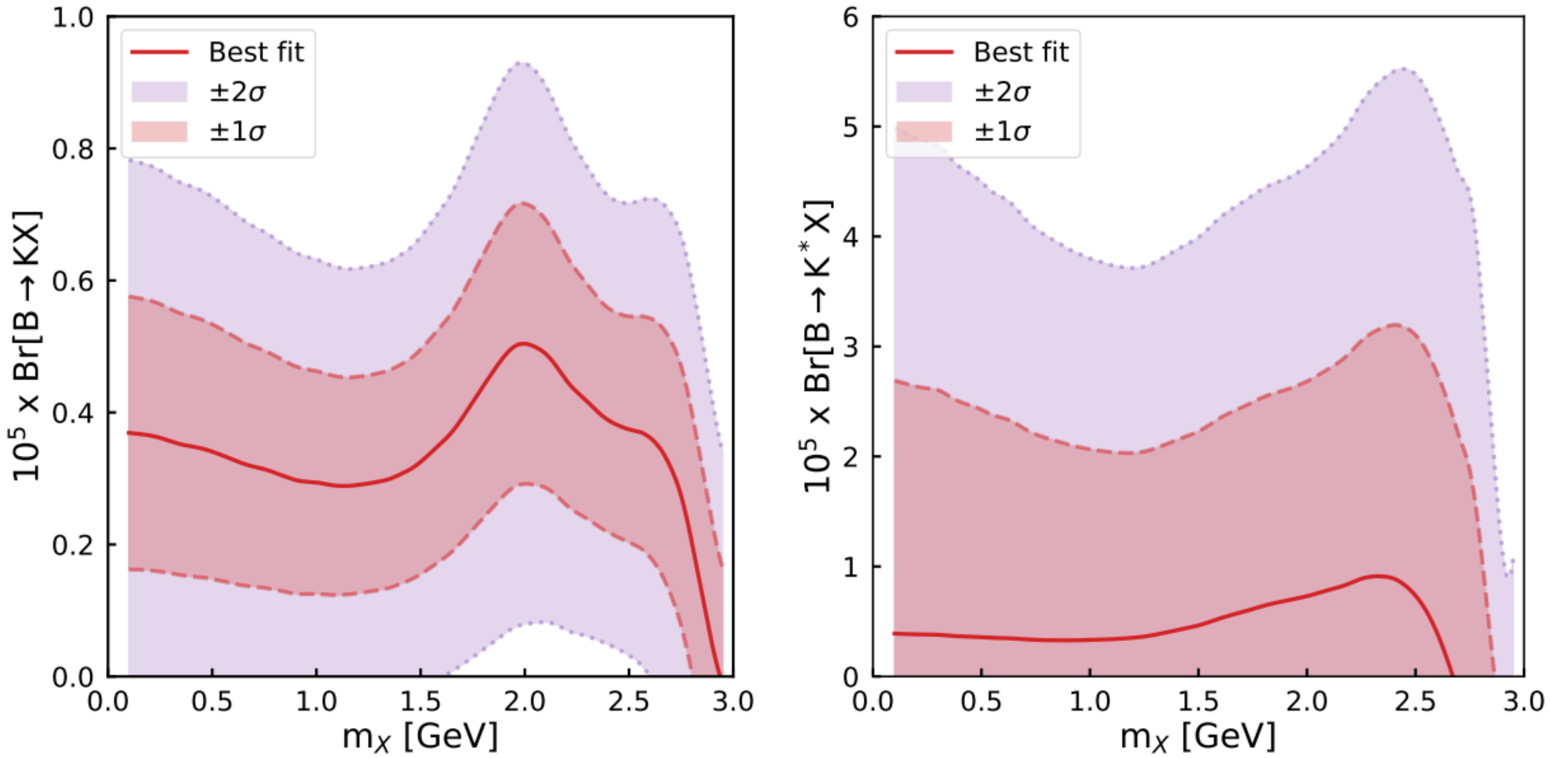


FIG. 1: Left: Combined fit to Br$[B \to KX]$ from Belle II and BaBar as a function of the mass of X. Right: Same for Br$[B \to K^*X]$ (only BaBar data available).

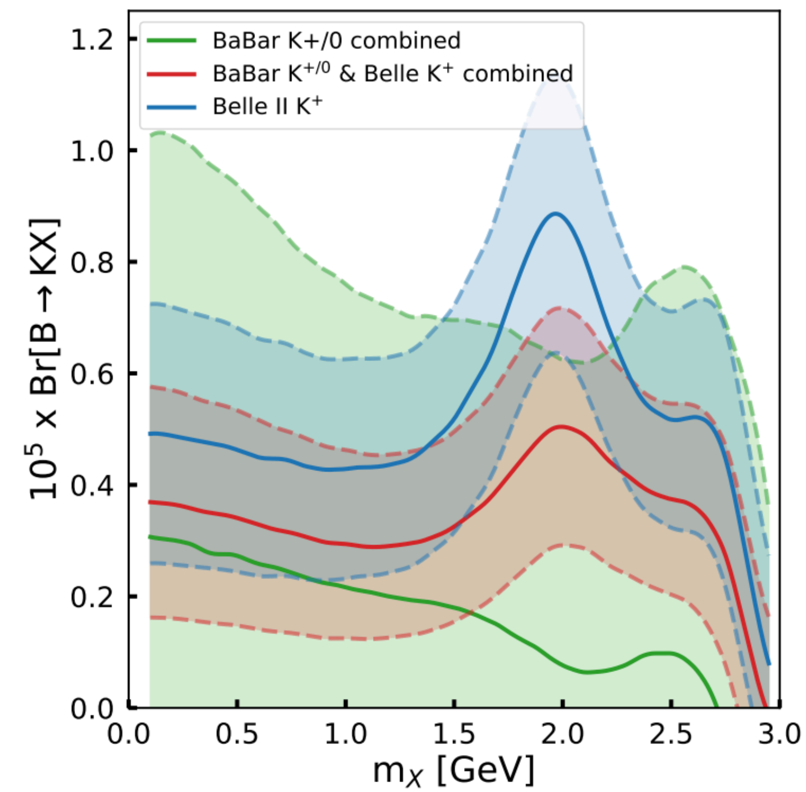


FIG. 5: Best fit and associated 1σ errors for Br$[B \to K^{(*)}X]$ as a function of m$_X$, for the fit to the BaBar distributions (green), the Belle II distribution (blue) and the combined fit to all data (red).