Recent Theory Developments in Flavor Physics

Belle II Germany Meeting – Munich – 19/09/2022

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Introduction

Two main experimental approaches to go **beyond the Standard Model** at Belle II:

Direct measurements:

- Dark Searches
- Light Higgs
- Lepton Flavor violation
- …

SM rates = 0

NP rates very small

Indirect measurements:

- CKM
- CP-violation
- Lepton Flavor Universality Violation
- Charm physics
- Spectroscopy
- …

SM rates are usually measurable
NP rates are small

Outline

I focus on **recent developments in B physics** (i.e. all citations are to be understood as "plus references therein"):

1) **Semileptonic decays**

2) **Nonleptonic decays**

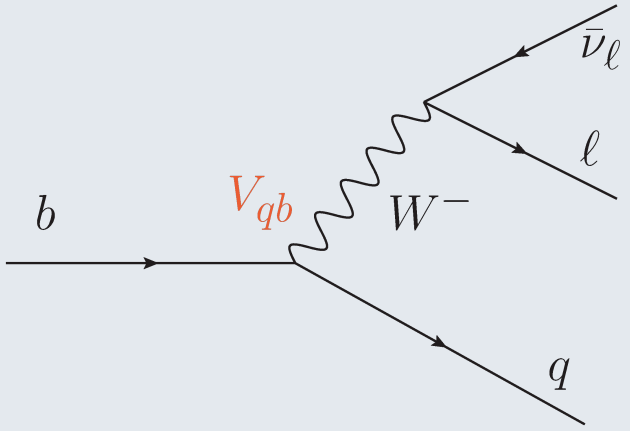
3) **Rare leptonic decays**

1) Semileptonic decays and the CKM

- $B_{(s)} \to D_{(s)}{}^{*} \ell \nu$
- $R(D)$, $R(D^{*})$
- $B \to X_c \ell \nu$
- ...

Main source of uncertainties

- **Tree-level process** mediated by the **weak interaction**
- As usual, the theory is simple with **quarks**…

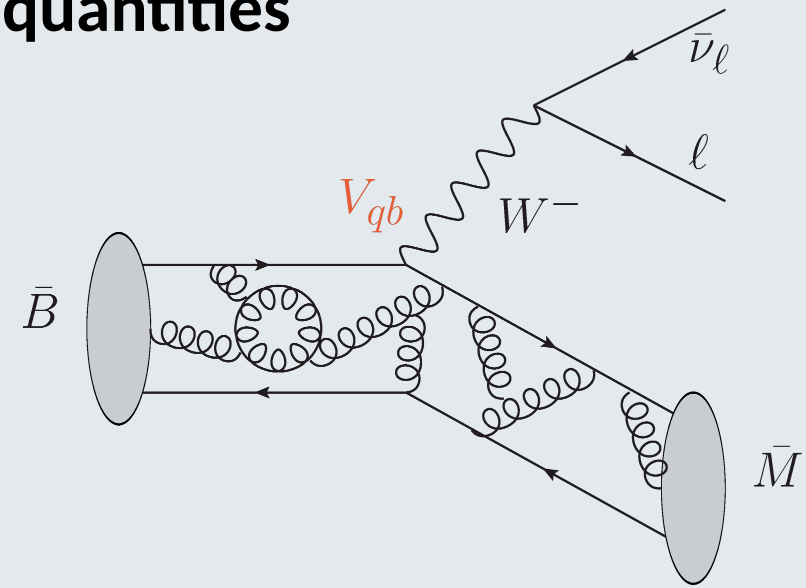


Main source of uncertainties

- **Tree-level process** mediated by the **weak interaction**
- As usual, the theory is simple with **quarks**...
- ...but we observe **hadrons**!

→ We have to **deal with QCD** (at different scales):

- Factorize the **non-perturbative quantities** and use:
  - Calculation: **Lattice**, **LCSR**...
  - Measures



Inclusive $|V_{cb}|$: state-of-the-art

- **Continuously improved** calculation:

[Fael, Schönwald, Steinhauser, '20 & '21]

$$\Gamma \propto |V_{cb}|^2 m_b^5 \left[\Gamma_0 + \Gamma_0^{(1)} \frac{\alpha_s}{\pi} + \Gamma_0^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \Gamma_0^{(3)} \left(\frac{\alpha_s}{\pi}\right)^3 + \frac{\mu_\pi^2}{m_b^2} \left(\Gamma^{(\pi,0)} + \frac{\alpha_s}{\pi}\Gamma^{(\pi,1)}\right)\right.$$

$$\left. + \frac{\mu_G^2}{m_b^2} \left(\Gamma^{(G,0)} + \frac{\alpha_s}{\pi}\Gamma^{(G,1)}\right) + \frac{\rho_D^3}{m_b^3} (\Gamma^{(D,0)} + \Gamma_0^{(1)} \left(\frac{\alpha_s}{\pi}\right)) + \mathcal{O}\left(\frac{1}{m_b^4}\right) + \cdots \right)$$

[Mannel, Pivovarov, '20]

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- Latest update:

$$|V_{cb}| = 42.16(30)_{th}(32)_{exp}(25)_\Gamma \; 10^{-3}$$

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- **Alternative method** using q^2 moments [Belle '21, Belle2 '22]

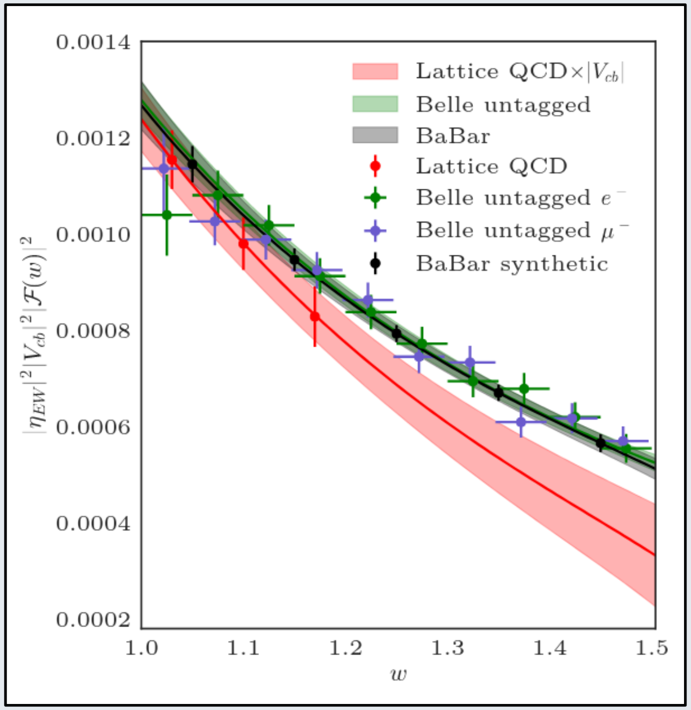
$$|V_{cb}| = (41.69 \pm 0.59|_{\text{fit}} \pm 0.23|_{\text{h.o.}}) \cdot 10^{-3}$$

[Bernlochner et al., '22]

[see also Martinelli, Simula, Vittorio, '22]

Lattice $B_{(s)} \to D_{(s)}^*$

- First **lattice QCD estimations** of $\overline{B}_{(s)} \to D_{(s)}^*$ form-factors at **non-zero recoil!** [HPQCD, '21][FNAL/MILC, '21]
- Results are in **agreement with HQE** [Bernlochner *et al.*, '22][Bordone, Gubernari, Jung, van Dyk, '20]



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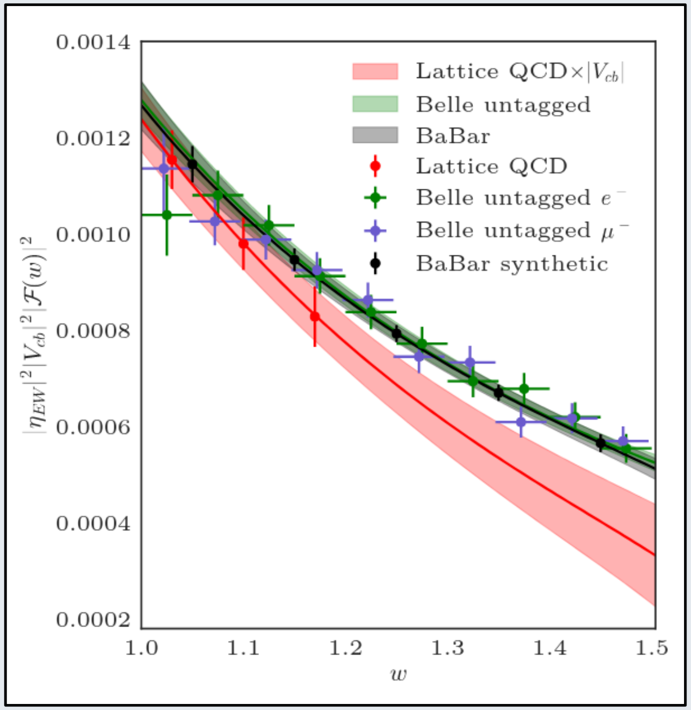
  → Extraction of **exclusive** |Vcb|:

$$|V_{cb}| = (38.40 \pm 0.74) \times 10^{-3}.$$

  – The **exclusive vs inclusive tension** (~2σ) **remains**

    → Not NP friendly [Jung, Straub, '18]



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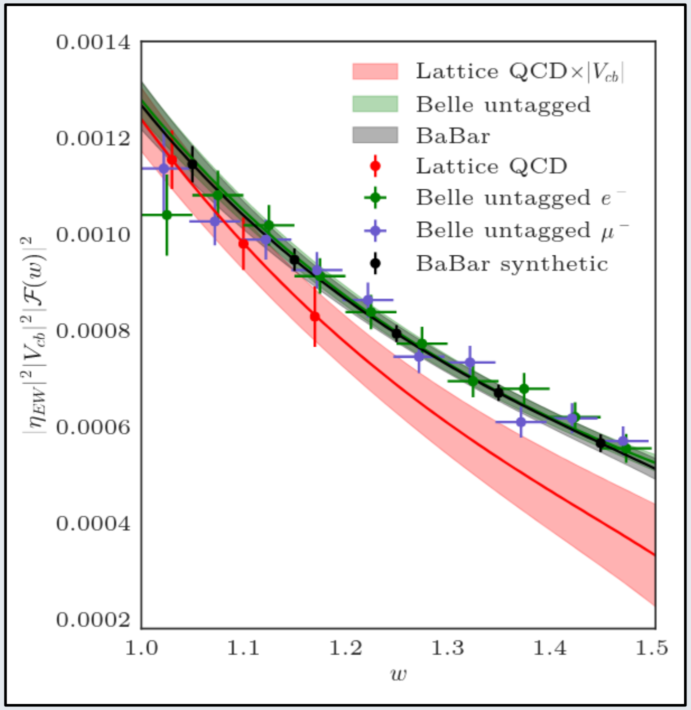
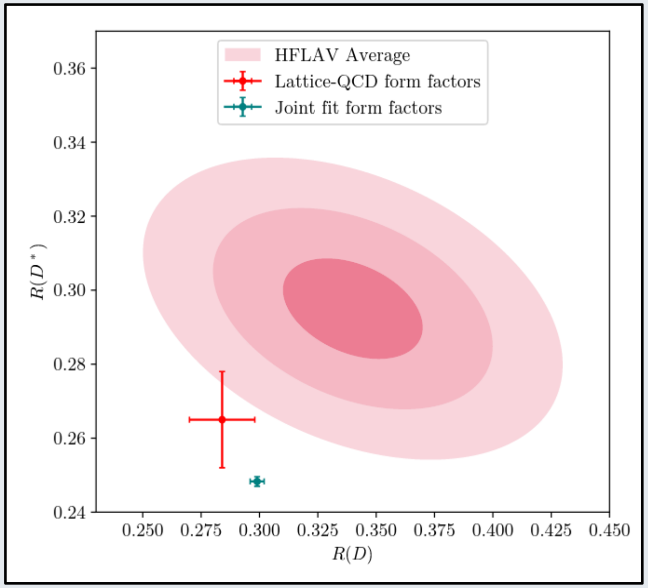
→ **Additional cross-check** for the test of lepton flavor universality

$$R(D^*) = 0.249(3) \qquad R(D^*)_{\mathrm{Lat}} = 0.265 \pm 0.013.$$



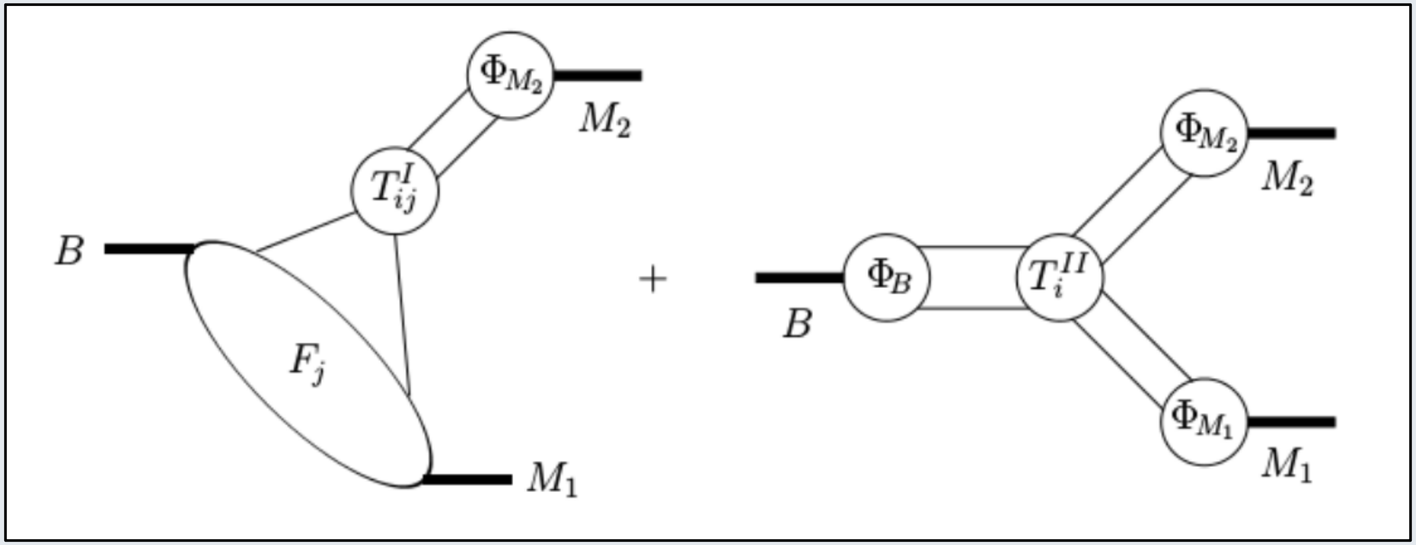


2) Nonleptonic decays and CP asymmetries

- $B \to K\pi$
- $B \to D^{(*)}K$
- $B_s \to D_s^{(*)}\pi$
- ...

Theory main approaches

- **QCD Factorization**: Separation of scales in the amplitude, **expansion in α_s and Λ_{QCD}/m_b**:
  - Computing the next order in α_s is doable but increasingly hard
  - However already the NLO in Λ_{QCD}/m_b requires another framework → 10-20% accuracy
  - Very active topic [Beneke *et al*, ‘20 & ‘21][Lü *et al*, ‘22][Chaï *et al*, ‘22] + …



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- **SU(3) symmetry**: Relates the decay channel to reduce the number of independent parameters:
  - Difficult implementation of flavour breaking effects
  - Approaches can be combined! [Huber, Tetlalmatzi-Xolocotzi, ‘21]

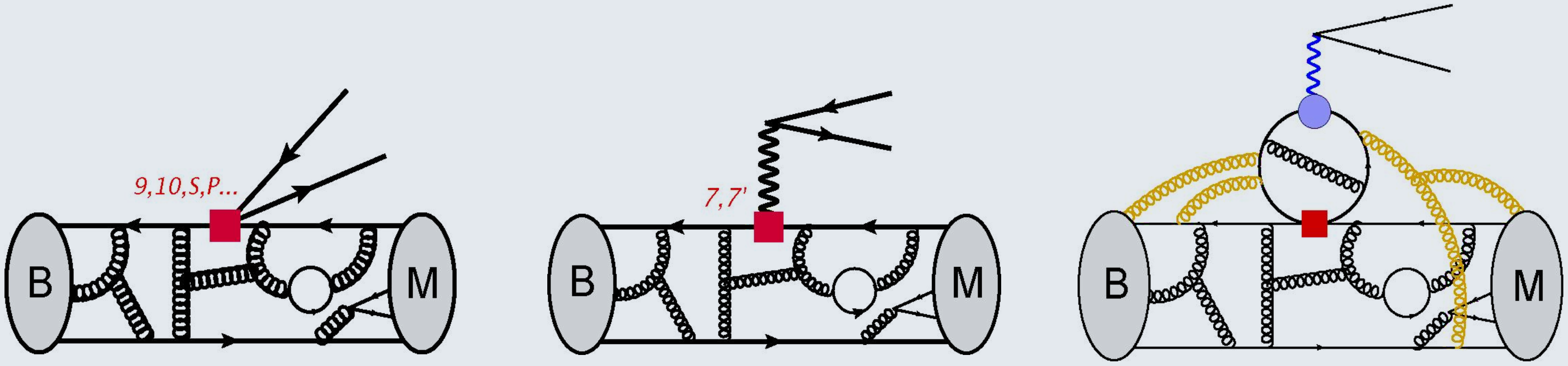
Puzzles in nonleptonic decays

- $B \to K\pi$
  - CP asymmetry measured **larger than predicted**
  - **Theoretically challenging** [Bell *et al.*, '20]
- $B \to D^{(*)}K$ and $B_s \to D_s^{(*)}\pi$
  - **"Cleaner"**: colour-allowed tree decays only
  - Latest update shows a **4σ deviation** with respect to data [Bordone *et al.*, '20]
  - Hardly due to QED [Beneke *et al.*, '21]
  - Hardly explained by NP [Endo, Iguro, Mishima, '21] [Bordone, Greljo, Marzocca, '21]
- Belle II can measure **more of these modes!**

3) Rare leptonic decays

- $b \to s\ell\ell$: $R(K)$, $R(K^*)$, P_5'…
- $b \to d\ell\ell$
- …

Form-factors in $b \to s\ell\ell$



$$\mathcal{A}_\lambda^{L,R}(B \to M_\lambda \ell\ell) = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

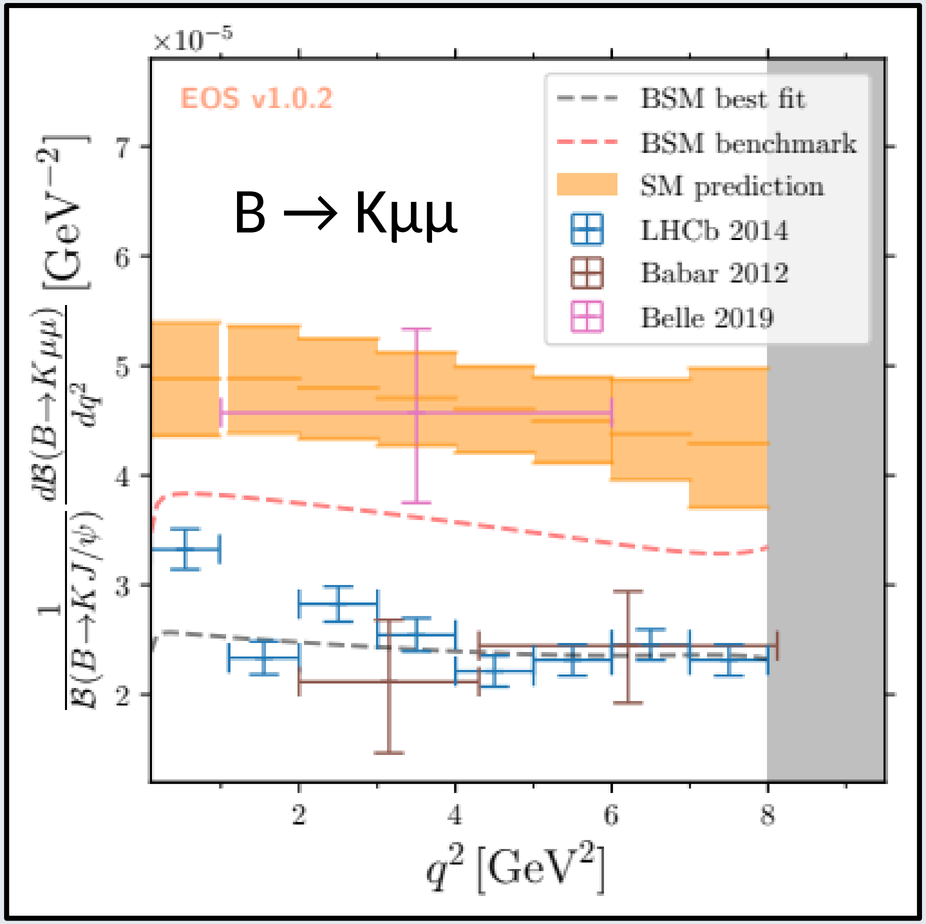
Local and non local form-factors (charm-loops)

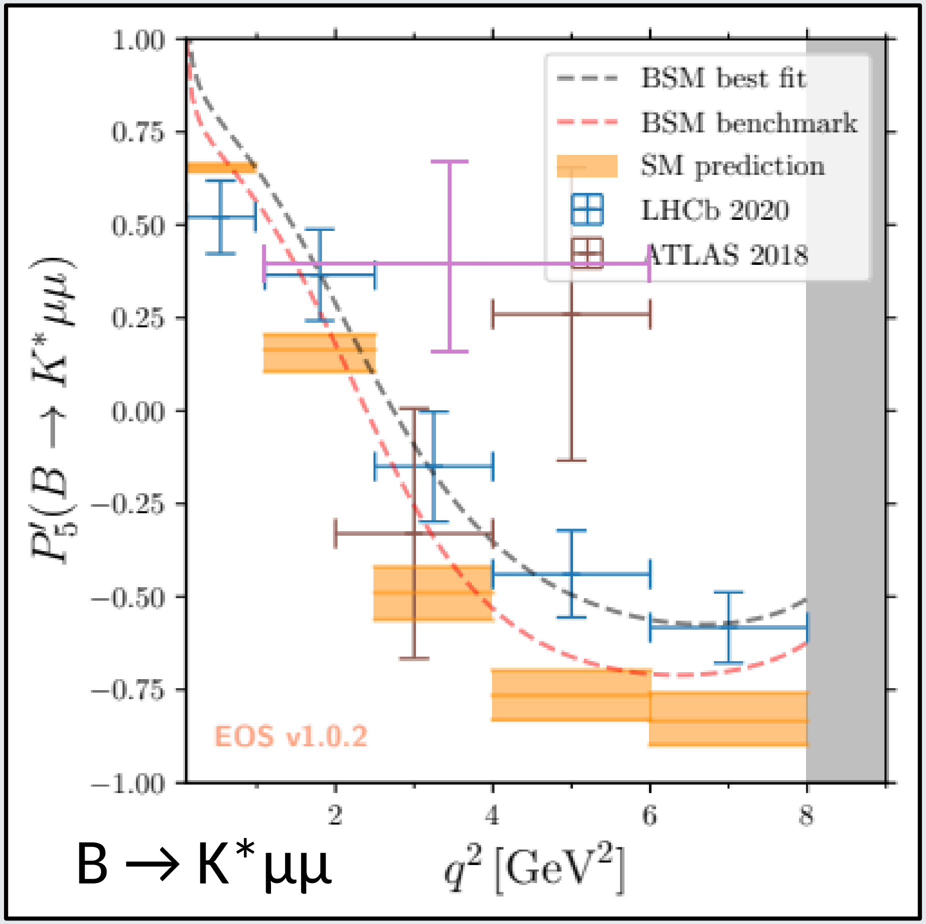
Predictions based on:

- **Lattice QCD** calculations (on the entire q^2 range for B→K! [HPQCD, '22])
- **Light-cone sum rules** estimates [Khodjamirian, Rusov, '17][Gubernari *et al.* '18 & '20]
- **Controlled** and **improvable uncertainties** due to **dispersive bounds** [Gubernari, MR, van Dyk, Virto '22]

b → sℓℓ anomalies

- Tension **increased** in the “non-ratio” observables – see also [Buras ‘22]
- **Consistent** new physics pattern
- Belle already gave **very promising results**





$b \to s\ell\ell$ wishlist

- Improve on $B \to K^{(*)}\ell\ell$ angular analysis, branching ratios…
  - Reconstruction of neutrals → **high q^2**
  - **Electron and tau** channels!
- $B \to K^{(*)}\nu\nu$
  - Theoretically **very clean** (limited by the form-factors and CKM)
  - Theoretically **very well motivated**
- **LFV** modes $B \to K^{(*)}\ell\ell'$

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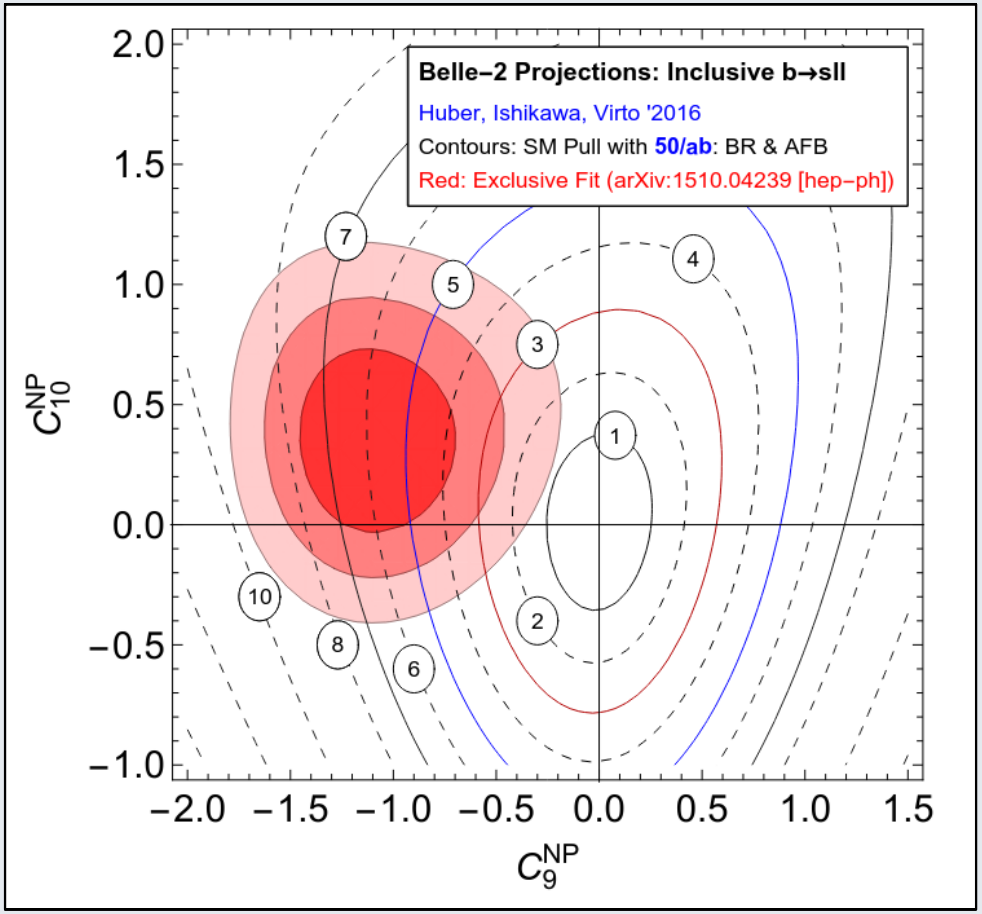

Conclusion

- Belle II is in a leading position to improve on many puzzles, **both directly and indirectly**.
- I restricted this talk to B-physics, but there have been a **lot of theoretical interest** in
  - Charm physics
  - Tau decays
  - Quarkonium physics
  - Dark/Invisible searches
  - ...

Thanks!

Backup

Bottom-up approach

Complete models: link to other open questions (DM, hierarchy, flavor structure…)

Λ_{NP}

Simplified models:
1 or 2 new particles

WET/SMEFT: Model independent, global fits

$\Lambda \sim M_Z$

Experimental measurements
(Belle II, LHCb…)

$\Lambda \sim m_b$

Top-down constraints

Complete models: link to other open questions (DM, hierarchy, flavor structure…)

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Experimental measurements
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New observables:

- **Direct searches** (ATLAS, CMS)
- **pT searches**
- **DM, ALP**
- …

The CKM triangle

- > 20 years of **experimental and theory efforts**
- The pulls are more or less **stable**
- Can it hold 10 other years?