Exclusive *B* decays at the precision frontier

Using B-meson decays to probe the Standard Model and seek for New Physics

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Belle II Germany Meeting 2025

ROT building (Bonn), 8 September 2025

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Talk outline

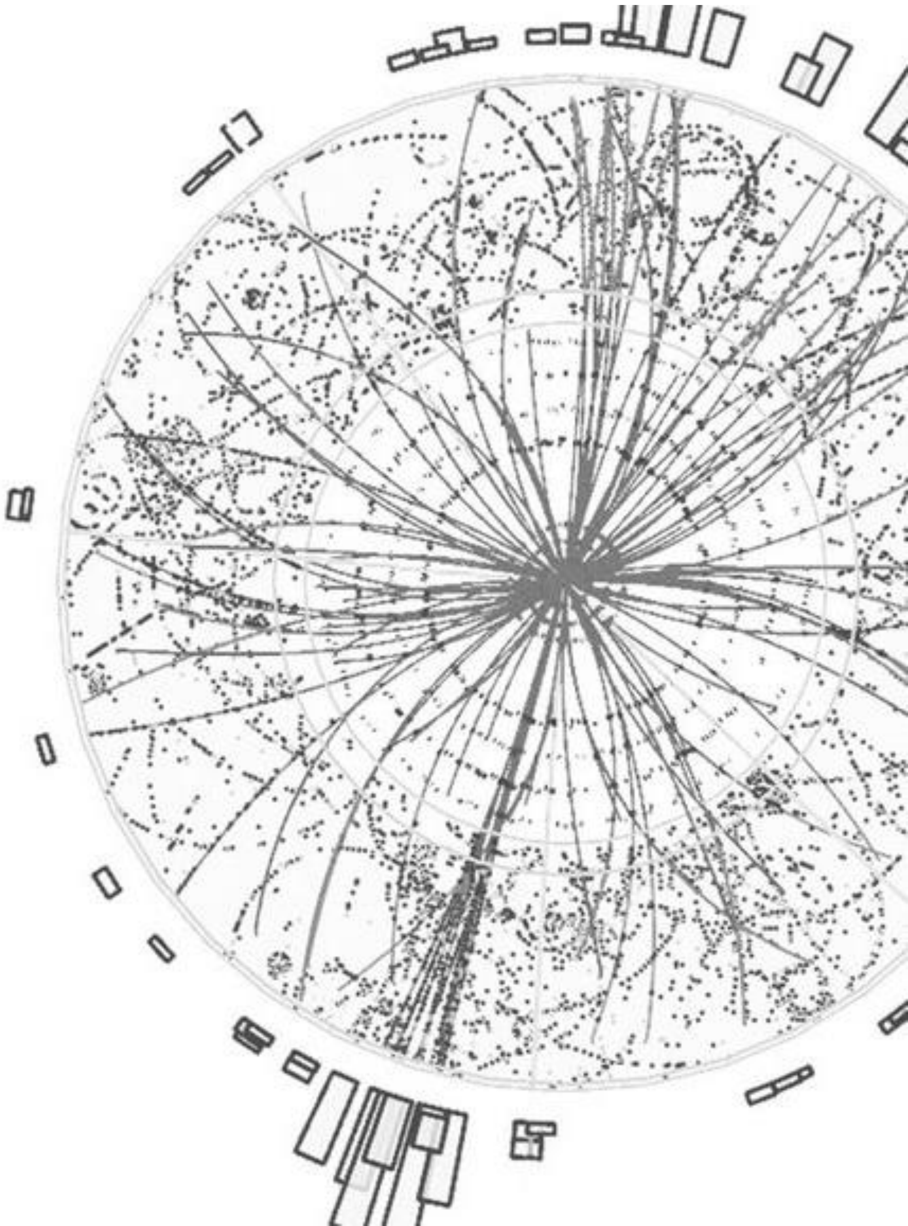
Introduction

Leptonic decays

Semileptonic decays

Hadronic decays

Summary and outlook



Introduction

Flavour physics and its goals

Flavour physics is a branch of particle physics that investigates the different quark and lepton flavours, their transitions, and their spectrum

Goals of flavour physics

Explain phenomena (understand the SM)

- spectroscopy
- extraction of CKM parameters

Search for New Physics (**indirect searches**)

- accurate study of leptonic and semileptonic B (and D) decays
- CP violation
- understand the origin of flavour

New Physics (**NP**) searches

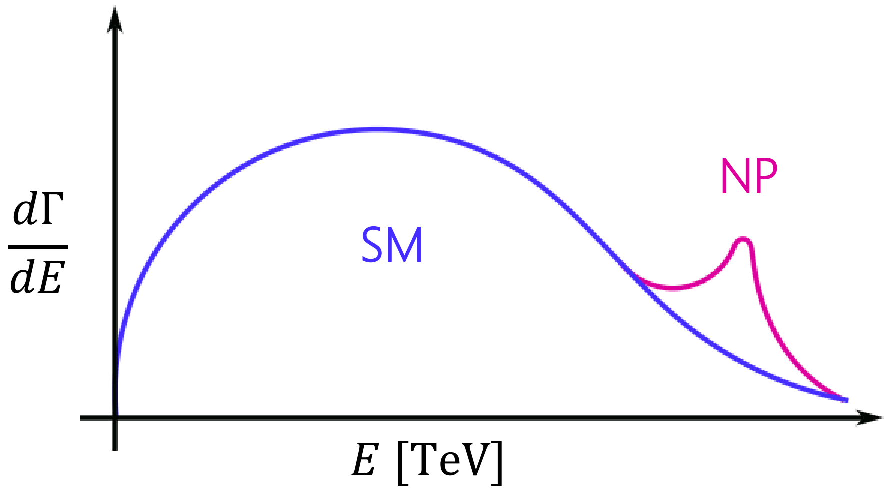
Direct searches

LHC has reached its maximum energy

No NP evidence so far (too heavy?)

Next experiments will probably focus on **precision**

Direct NP discovery difficult in coming decades

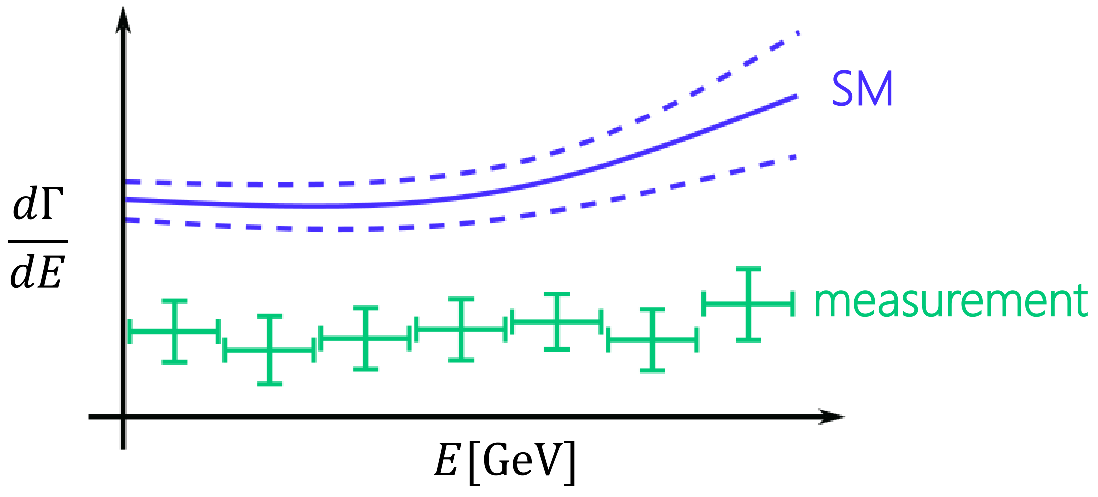


Indirect searches (with flavour)

Probe the SM at **higher energies** than direct searches

Compare precise measurements and calculations of flavour observables

$\Longrightarrow$ obtain constraints on NP (or new discovery?)



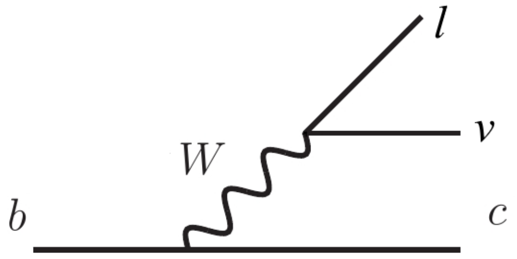
Flavour changing currents

Flavour changing charged currents (FCCC)

occur at tree level (mediated by $W^{\pm}$) in the SM

$b \rightarrow c$ most common transitions
(V_{cb} is relatively large)

$$\mathcal{B}(B \rightarrow D\ell\nu) \sim 5\%$$

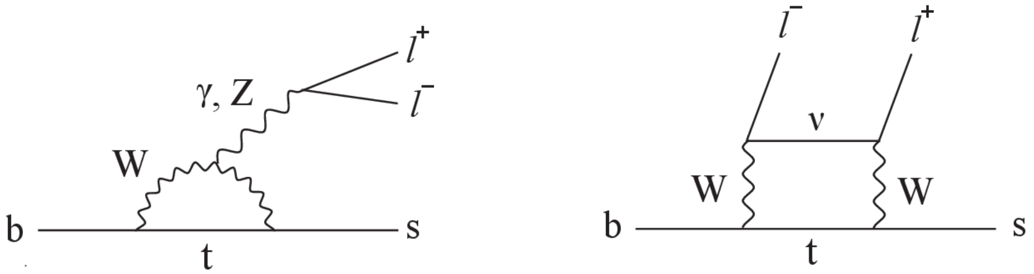


Flavour changing neutral currents (FCNC)

absent at tree level in the SM
FCNC are loop, GIM and CKM **suppressed in the SM**

FCNC **sensitive to new physics** contributions
Ideal for **indirect searches**

Focus on $b \rightarrow s\ell^+\ell^-$ **transitions**



Types of B meson decays

Exclusive B decays $\Longrightarrow$ golden channels $B_s \to \mu\mu$, $B \to D\mu\nu$, $B \to K\mu\mu$, …

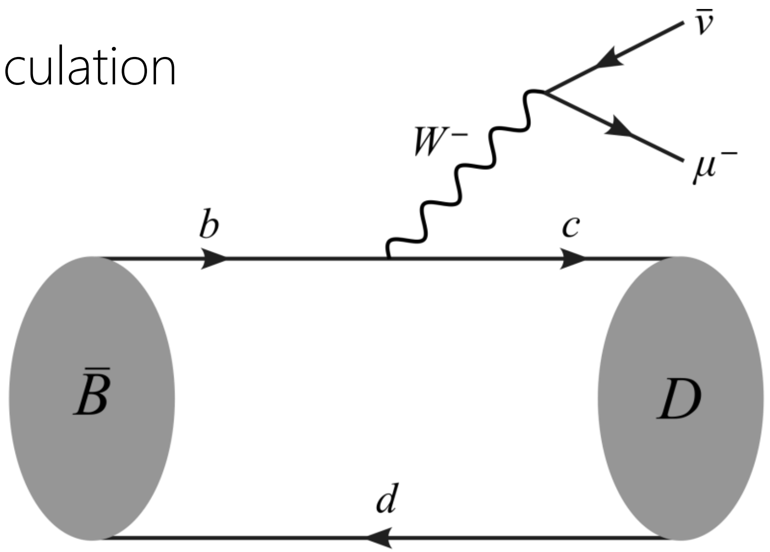
Inclusive B decays $\Longrightarrow$ see Tobias' talk

Focus on exclusive decays. Types of exclusive decays:

- leptonic decays: simplest hadronic matrix elements
- semileptonic decays: complicated hadronic effects
- hadronic (or non-leptonic) decays: no model independent calculation

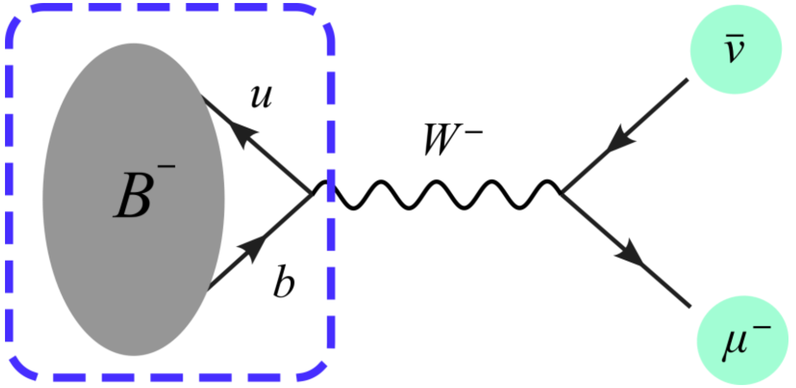
Additional subtypes

- radiative leptonic/semileptonic/hadronic decays:
  if γ is also present (e.g., $B \to \gamma\mu\nu$) see Max's talk
- rare leptonic/semileptonic/hadronic decays
  if mediated by FCNC (e.g., $B \to \mu\mu$, $B \to K\mu\mu$)



Leptonic decays

Calculation of leptonic decays



Neglect QED corrections. The amplitude factorizes

$$\mathcal{A} \sim \langle \mu\bar{\nu} | \mathcal{O}_{4f} | B \rangle = \langle \mu\bar{\nu} | \mathcal{O}_{lep} | 0 \rangle \langle 0 | \mathcal{O}_{had} | B \rangle$$

Calculate the decay rate

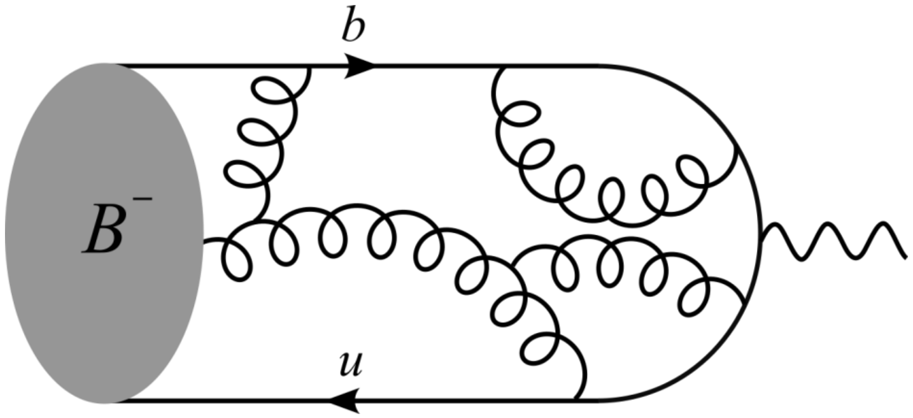
$$\Gamma(B \to \mu\bar{\nu}) = \frac{m_B}{8\pi} G_F^2 f_B^2 |V_{ub}|^2 m_\mu^2 \left(1 - \frac{m_\mu^2}{m_B^2}\right)^2$$

where

$$\langle 0 | \bar{u}\, \gamma^\mu \gamma_5\, b | B \rangle = i p^\mu f_B$$

Easy to get the decay rate, but how to get f_B?

Hadronic matrix elements: the “easy” ones



Decay constants are the simplest matrix elements appearing in B decays

QCD perturbation theory breaks down at low energies ($\mu \sim \Lambda_{\mathbf{QCD}}$)

Non-perturbative techniques are need to obtain hadronic matrix elements:

1. Lattice QCD (LQCD)
   numerically evaluate correlators
   systematically reducible uncertainties
   uncertainties $O(1\%)$

2. QCD sum rules
   based on a dispersion relation
   quantifiable but irreducible unc.
   uncertainties $O(10\%)$

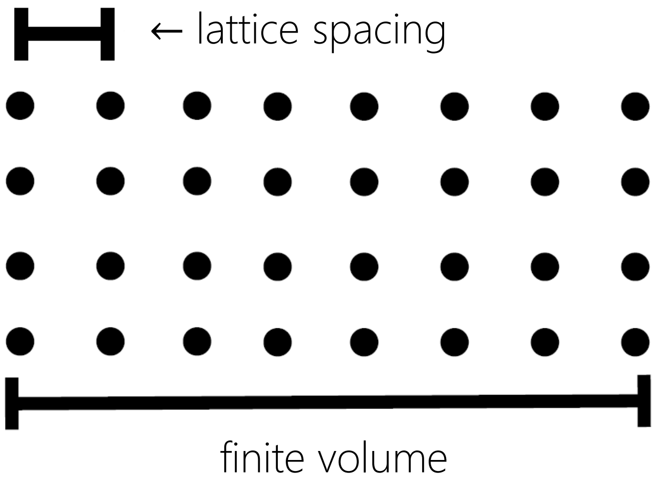
Lattice QCD in a nutshell

LQCD = evaluating path integrals numerically

$$\textbf{matrix element} = \int \prod_i \mathrm{d}\phi_i \, (\textbf{correlator})$$

to perform the calculation approximations are needed

1. nonzero lattice spacing
2. finite volume
3. Euclidian space time



Pros

first principles calculations

reducible systematic uncertainties

Cons

nonlocal matrix elements and unstable states, are still work in progress

computationally very expensive

QCD sum rules in a nutshell

QCD sum rules are a method to calculate hadronic matrix elements

method based on:

dispersion relation | quark-hadron duality assumption | OPE

Pros

compute hadronic matrix elements not accessible yet with LQCD

complementary w.r.t. LQCD

relatively faster

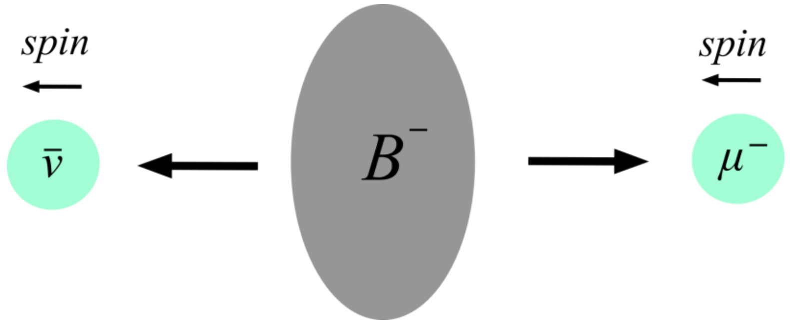
Cons

need universal non-perturbative inputs (QCD condensates or distribution amplitudes)

non-reducible (but quantifiable) systematic uncertainties

Results for leptonic decays

Leptonic two body decays are **helicity suppressed**



decay rate is proportional to the fermion masses squared, and hence suppressed

Only a few channels have been measured

$$\mathcal{B}(B^+ \to \tau^+\nu)_{\text{exp}} = (1.09 \pm 0.24) \cdot 10^{-4}$$

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\text{exp}} = (3.34 \pm 0.27) \cdot 10^{-9}$$

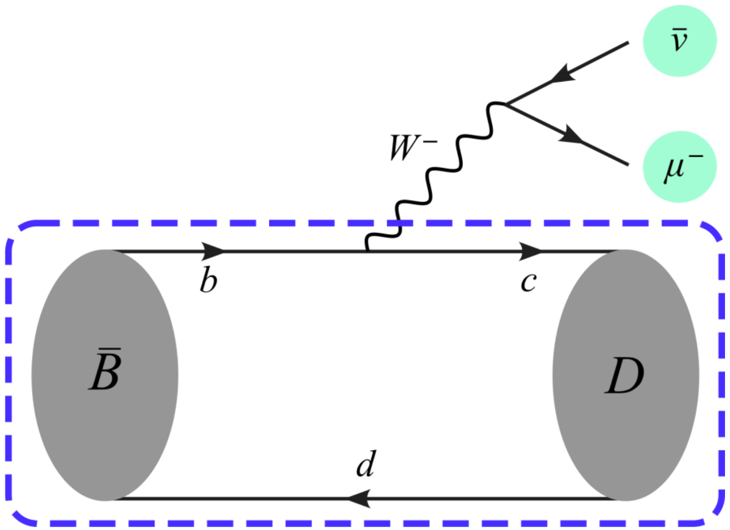
Theory (way) more precise than experiment

$$\mathcal{B}(B^+ \to \tau^+\nu)_{\text{SM}} = (0.87 \pm 0.05) \cdot 10^{-4}$$

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.57 \pm 0.17) \cdot 10^{-9}$$

Semileptonic decays

Calculation of FCCC semileptonic decays



Neglect QED corrections. The amplitude factorizes

$$\mathcal{A} \sim \langle D\mu\bar{\nu}|\mathcal{O}_{4f}|B\rangle = \langle \mu\bar{\nu}|\mathcal{O}_{lep}|0\rangle\langle D|\mathcal{O}_{had}|B\rangle$$

Calculate the (differential) decay rate (for $m_\mu \sim 0$)

$$\frac{d\Gamma(B \to D\mu\bar{\nu})}{dq^2} = \frac{G_F^2|V_{cb}|^2\lambda^{\frac{3}{2}}}{192\pi^3 m_B^3} f_+^{BD}(q^2)$$

Easy to get the decay rate, but how to get f_+^{BD}?

Definition of the form factors

Form factors (FFs) parametrize exclusive hadron-to-hadron matrix elements

$$\langle D(k)|\bar{c}\,\gamma_\mu b|B(q+k)\rangle = (2\,k_\mu + q_\mu)f_+(q^2) + q_\mu\, f_-(q^2)$$

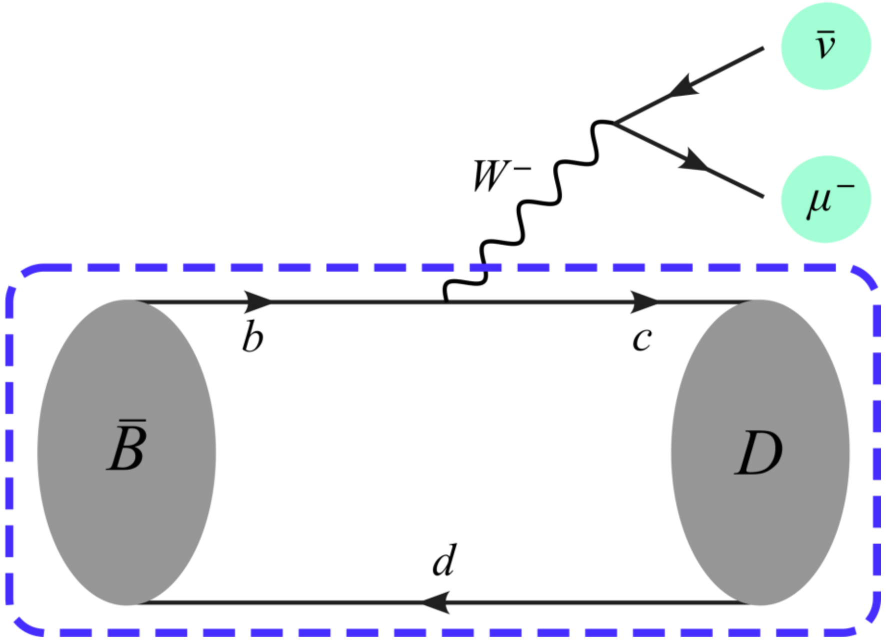
$$\langle D(k)|\bar{c}\,\sigma_{\mu\nu}q^\nu b|B(q+k)\rangle = \frac{i f_T(q^2)}{m_B + m_D}\left(q^2(2k+q)_\mu - (m_B^2 - m_D^2)q_\mu\right)$$

decomposition follows from Lorentz invariance

FFs are functions of the momentum transferred q^2
(q^2 is the dilepton mass squared)

2(+1) independent $B \to D$ FFs
4(+3) independent $B \to D^*$ FFs

Analogous definitions for different transitions



State of the art $B_{(s)} \to D_{(s)}^{(*)}$ FFs

- $B \to D$
  LQCD calculations available at **high** q^2
  [FNAL/MILC 2015] [HPQCD 2015]

- $B \to D^*$
  LQCD calculations available at **high** q^2
  [FNAL/MILC 2021] [JLQCD 2023]
  in the **whole** semileptonic region of q^2
  [HPQCD 2023]

- $B_s \to D_s$
  LQCD calculations available
  in the **whole** semileptonic region of q^2
  [HPQCD 2019]

- $B_s \to D_s^*$
  LQCD calculations available
  in the **whole** semileptonic region of q^2
  [HPQCD 2021] [HPQCD 2023]

LCSRs available for the four processes at **low** q^2

Methods to compute FFs

Combine LQCD (and LCSR) results to obtain the FF values in the whole semileptonic region

Fit results to a **parametrization**

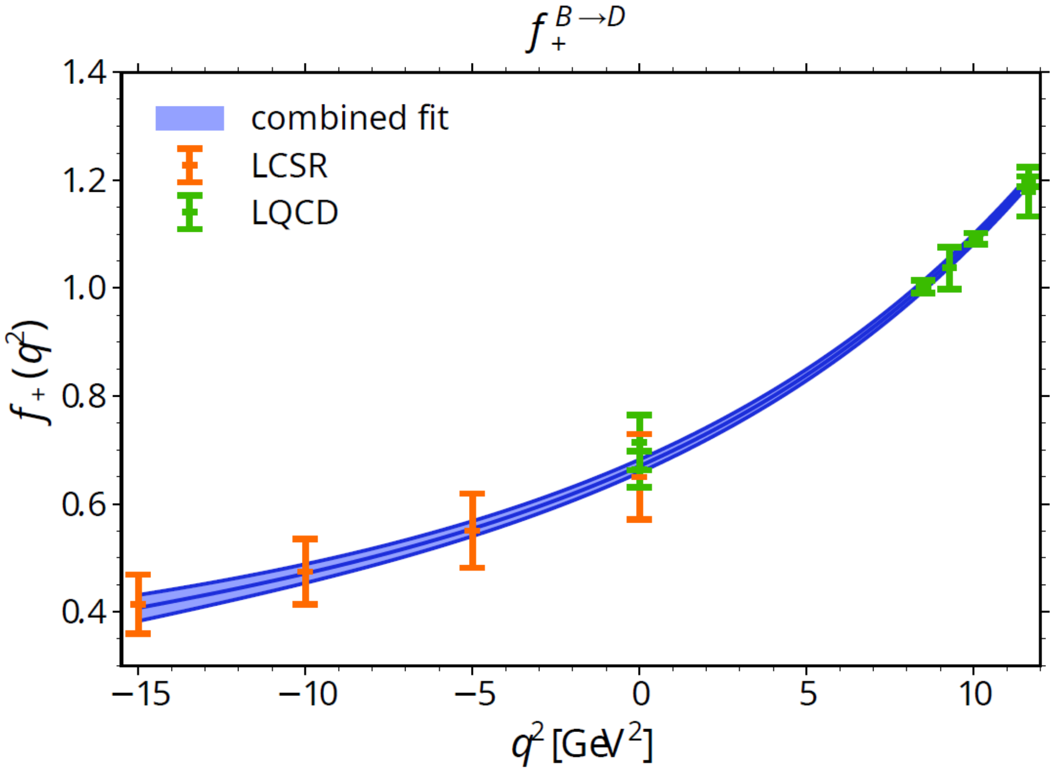
$$f(z) \propto \sum_{n=0}^{N} \alpha_n^f \, g_n(q^2)$$

choose optimal g_n, e.g.,

$$g_n = (q^2)^n$$

$$g_n = z^n \equiv \left(\frac{\sqrt{s_+ - q^2} - \sqrt{s_+ - s_0}}{\sqrt{s_+ - q^2} + \sqrt{s_+ - s_0}} \right)^n$$

$$g_n = polinomial$$



[Boyd/Grinstein/Lebed 1997]
[Bourrely/Caprini/Lellouch 2008]
[NG/van Dyk/Virto 2020] ...

Optimised observables and LFU

Test the lepton flavour universality to test the SM

lepton flavour universality (LFU) = the 3 lepton generations have the same couplings to the gauge bosons

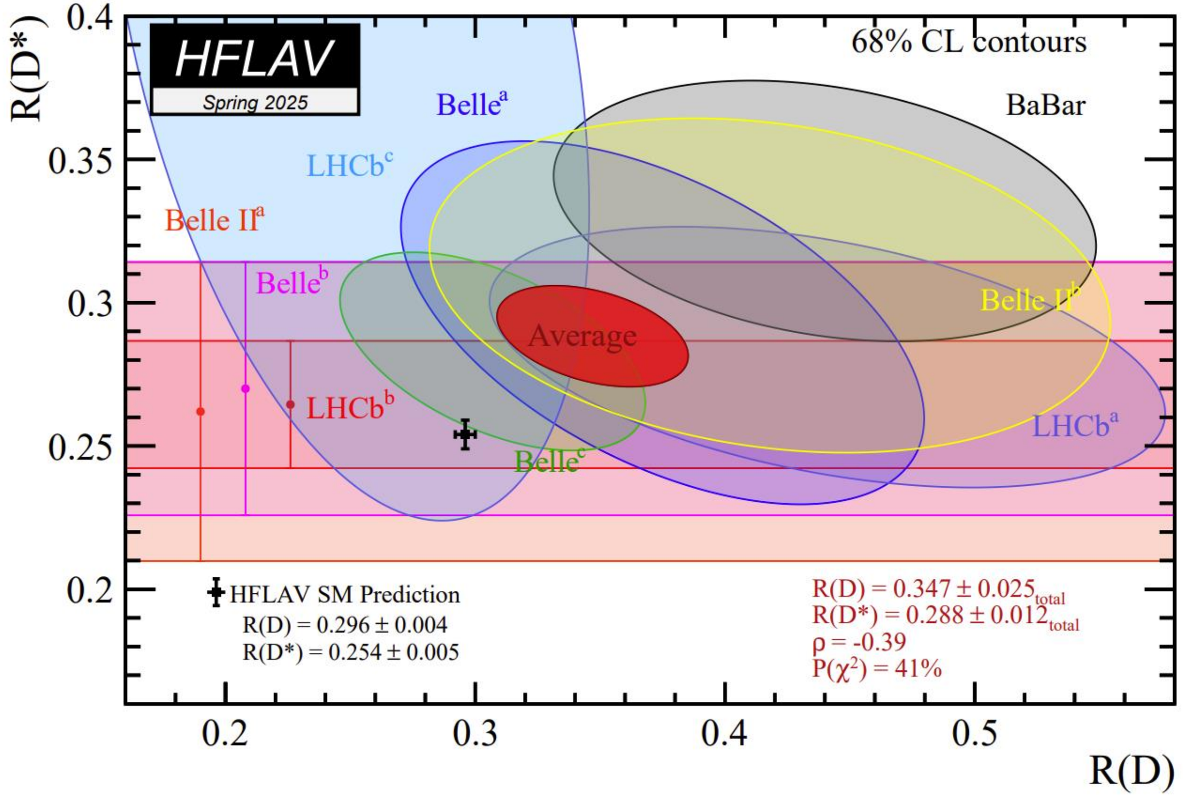
violations of LFU $\Longrightarrow$ new physics

Define observables smartly to reduce theory uncertainties and cancel V_{cb}

Observables to test LFU

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\,\nu)}{\Gamma(B \to D^{(*)}\ell\,\nu)}$$

3.3 σ tension between the SM and data

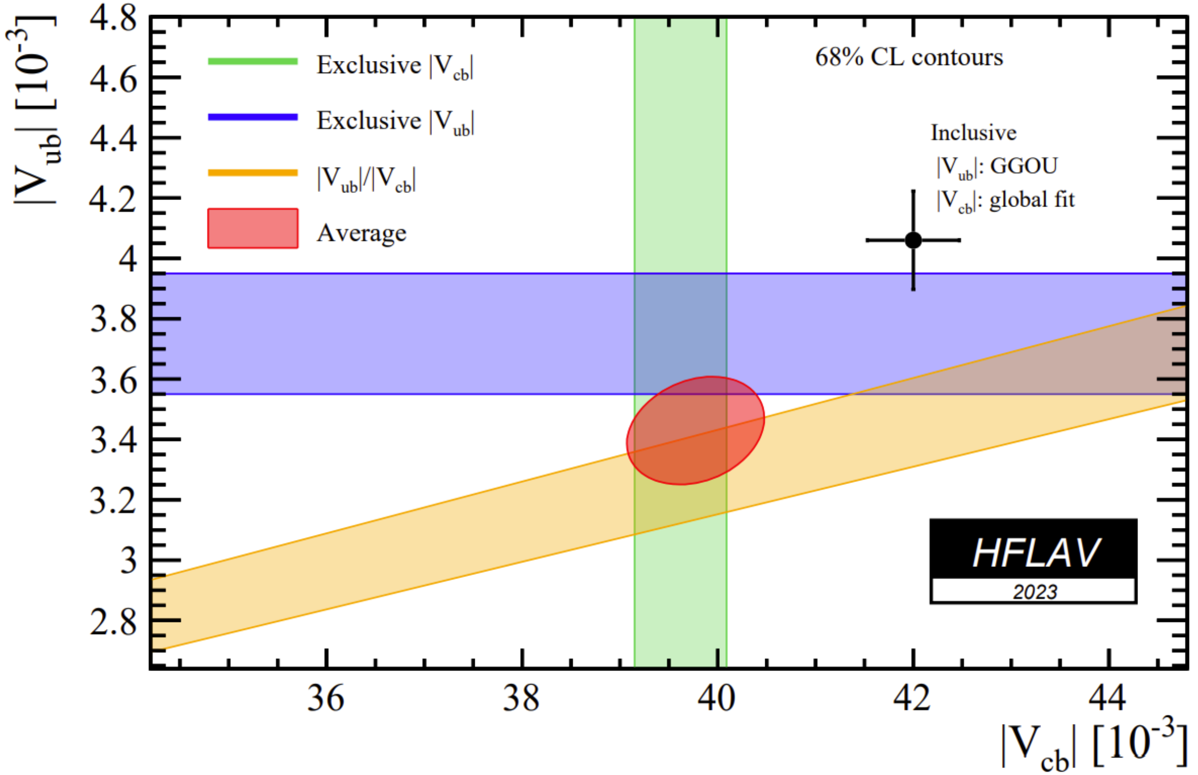


$|V_{cb}|$ extraction

Reminder:

$$\frac{d\Gamma(B\to D\mu\bar{\nu})}{dq^2} = \frac{G_F^2|V_{cb}|^2\lambda^{\frac{3}{2}}}{192\pi^3 m_B^3} f_+^{BD}(q^2)$$

Extract $|V_{cb}|$ by comparing theoretical predictions and experimental measurements
$\Longrightarrow$ fundamental parameter of the SM



Two different ways of extracting $|V_{cb}|$ (and $|V_{ub}|$)

- using inclusive $B\to X_c\ell\nu$ decays ($B\to X_u\ell\nu$)
- using exclusive $B\to D\ell\nu$ or $B\to D^*\ell\nu$ decays ($B\to\pi\ell\nu$)

$|V_{cb}|-|V_{ub}|$ puzzle

Calculation of FCNC semileptonic decays

Calculate decay amplitudes precisely to probe the SM

$$\mathcal{A} \sim \langle K^{(*)} \ell^+ \ell^- | O_{\text{eff}} | B \rangle = \langle \ell\ell | \mathcal{O}_{\text{lep}} | 0 \rangle \langle K^{(*)} | O_{\text{had}} | B \rangle + \text{non-local}$$

Easily obtain the (differential) branching ratio and angular observables from the amplitude

$$\frac{d\mathcal{B}}{dq^2} = \frac{1}{\Gamma_{\text{tot}}} \frac{d\Gamma}{dq^2} \propto |\mathcal{A}|^2$$

Calculation of FCNC semileptonic decays

Calculate decay amplitudes precisely to probe the SM

$$\mathcal{A} \sim \langle K^{(*)}\ell^+\ell^-|O_{\text{eff}}|B\rangle = \langle\ell\ell|\mathcal{O}_{\text{lep}}|0\rangle\langle K^{(*)}|O_{\text{had}}|B\rangle + \text{non-local}$$

Leptonic matrix elements (and constants $\boldsymbol{\alpha}$, $\boldsymbol{V_{CKM}}$…)

perturbative objects, small uncertainties

Calculation of FCNC semileptonic decays

Calculate decay amplitudes precisely to probe the SM

$$\mathcal{A} \sim \langle K^{(*)} \ell^+ \ell^- | O_{\rm eff} | B \rangle = \langle \ell\ell | \mathcal{O}_{\rm lep} | 0 \rangle \langle K^{(*)} | O_{\rm had} | B \rangle + \text{non-local}$$

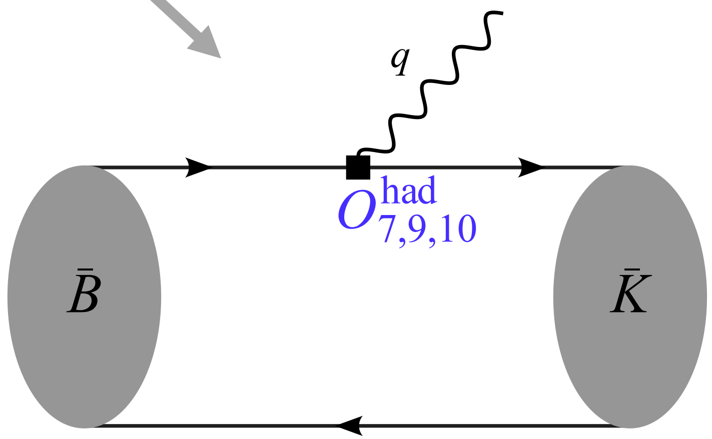
Local hadronic matrix elements (local **FFs**)

$$\langle K^{(*)} | O^{\rm had}_{7,9,10} | B \rangle \qquad O^{\rm had}_{7,9,10} = (\bar{s}\,\Gamma\, b)$$

leading hadronic contributions

non-perturbative QCD objects
$\Longrightarrow$ calculate with lattice QCD (or LCSR)

moderate uncertainties ($3\% - 15\%$)



Calculation of FCNC semileptonic decays

Calculate decay amplitudes precisely to probe the SM

$$\mathcal{A} \sim \langle K^{(*)} \ell^+ \ell^- | O_{\mathrm{eff}} | B \rangle = \langle \ell\ell | \mathcal{O}_{\mathrm{lep}} | 0 \rangle \langle K^{(*)} | O_{\mathrm{had}} | B \rangle + \text{non-local}$$

Non-local FFs

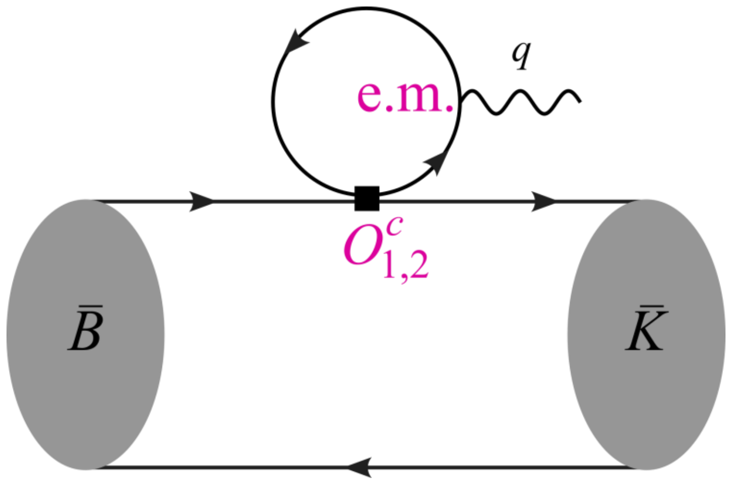
$$i \int d^4x \, e^{iq\cdot x} \langle K^{(*)} | T\{ j_\mu^{\mathrm{em}}(x), O_{1,2}^c(0) \} | B \rangle$$

$$O_{1,2}^c = (\bar{s}\,\Gamma\, b)(\bar{c}\,\Gamma\, c)$$

subleading (?) hadronic contributions

non-perturbative QCD objects
$\Longrightarrow$ very hard to calculate

large uncertainties



Methods to calculate non-local FFs

Non-perturbative techniques are needed to compute non-local FFs

- **lattice QCD** $\Longrightarrow$ work in progress [Frezzotti et al. 2025]

- **QCD factorization:** [Beneke/Feldmann/Seidel 2001]
  factorize hard and soft contributions
  $\Longrightarrow$ double expansion in $1/m_b$ and $1/E_{K^{(*)}}$
  valid for $q^2 < 7\ \mathrm{GeV}^2$
  How to calculate power corrections? How extend to Λ_b decays?
  Is the perturbative treatment of the charm loop reliable close to threshold?

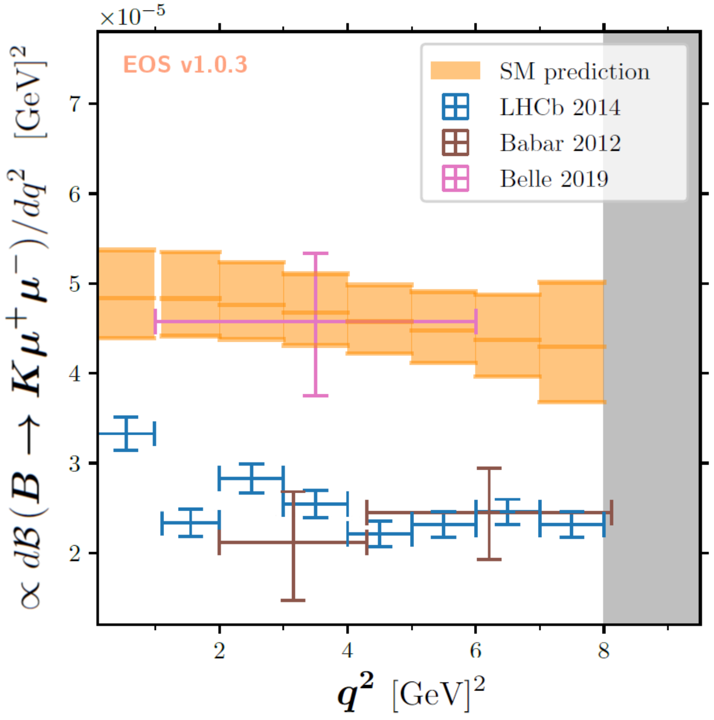
- **light-cone operator product expansion**

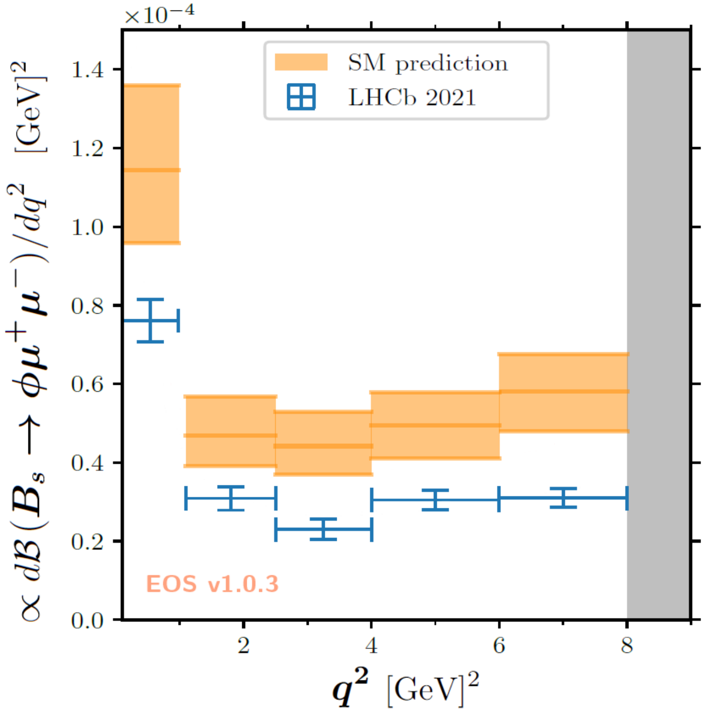
$$\mathrm{non-local\ FF} \propto \mathrm{local-FF} + \mathrm{non-fact.\ effects}$$

[Khodjamirian et al. 2010]
[NG/van Dyk/Virto 2020]

$b \to s\mu^+\mu^-$ anomalies

Predict observables using our local and non-local FFs results





Agreement between theory and experiment for LFU ratios R_K and R_{K^*},

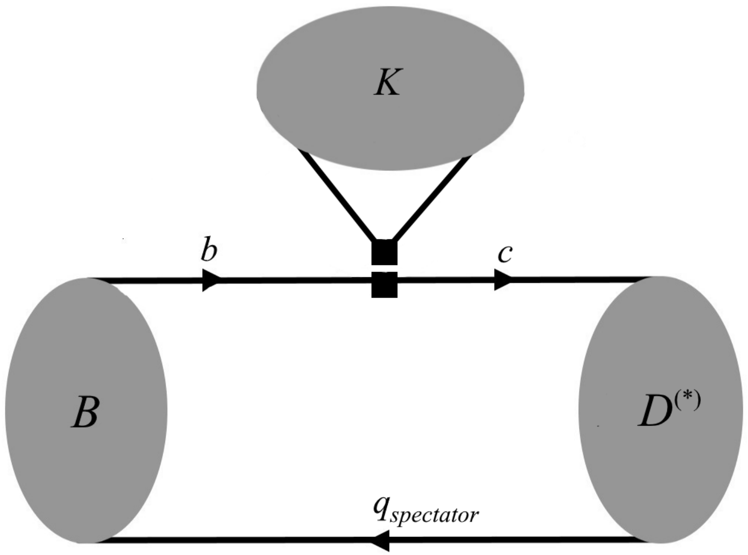
but **tension (or anomalies) remains for** $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$observables

$\Longrightarrow$ need to understand this tension

[NG/Reboud/van Dyk/Virto 2022]

Hadronic decays

Calculation of hadronic decays



The amplitude does not trivially factorize

$$\mathcal{A} \sim \langle D^+ K^- | O_i | \bar{B}_s^0 \rangle$$

Very complicated matrix element

$\Longrightarrow$ cannot be calculated directly

Is it possible to simplify it?

QCD factorization

Compute systematically α_s corrections, neglect power corrections $\frac{\Lambda_{\text{QCD}}}{m_b}$

[Beneke/Buchalla/Neubert/Sachrajda 2000]

for M_1 and M_2 both light

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = \sum_j F_j^{B\to M_1}(m_2^2) \int_0^1 du\, T_{ij}^I(u) \Phi_{M_2}(u) \; + (M_1 \leftrightarrow M_2)$$
$$+ \int_0^1 d\xi du dv\, T_i^{II}(\xi, u, v) \Phi_B(\xi) \Phi_{M_1}(v) \Phi_{M_2}(u)$$

for M_1 heavy, and M_2 light

$$\langle M_1 M_2 | O_i | \bar{B} \rangle = \sum_j F_j^{B\to M_1}(m_2^2) \int_0^1 du\, T_{ij}^I(u) \Phi_{M_2}(u)$$

$T_{ij}^I(u)$ computed at NNLO in α_s

[Huber/Kränkl/Li '16]

Comparison between theory and exp.

source	PDG	QCDF prediction
scenario	—	—
χ^2/dof	—	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)$	3.00 ± 0.23	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	0.186 ± 0.020	0.326 ± 0.015
$\mathcal{B}(\bar{B}^0 \to D^+\pi^-)$	2.52 ± 0.13	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^{*+}\pi^-)$	2.0 ± 0.5	$4.3^{+0.9}_{-0.8}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$	0.212 ± 0.015	$0.327^{+0.039}_{-0.034}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$	2.74 ± 0.13	—

- consistent measurements
- discrepancy between measurements and theoretical predictions:

$\bar{B}_s^0 \to D_s^+\pi^- \quad \to 4\sigma$
$\bar{B}^0 \to D^+K^- \quad \to 5\sigma$
$\bar{B}_s^0 \to D_s^{*+}\pi^- \quad \to 2\sigma$
$\bar{B}^0 \to D^{*+}K^- \quad \to 3\sigma$

[Bordone el al. 2019]

Summary and outlook

Summary

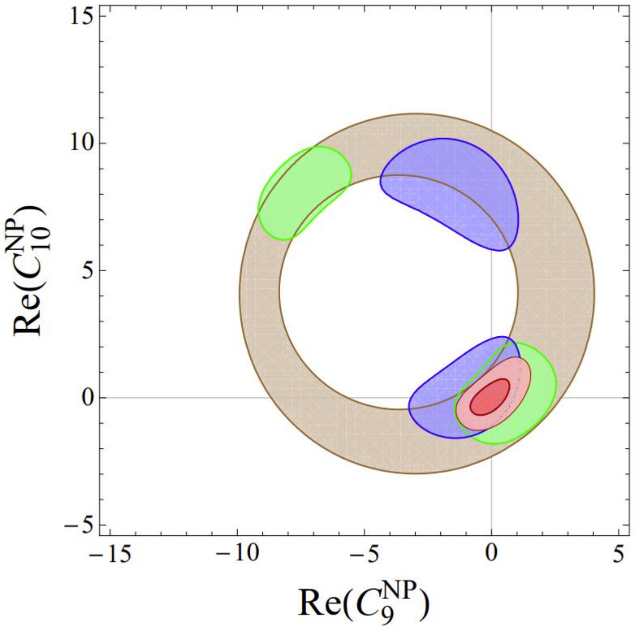
- Leptonic decays (e.g., $B \to \mu\nu$)
  Easiest to calculate (simplest hadronic matrix elements)
  Hard experimentally (neutrinos in the final state, backgrounds, low branching ratios)
  Theory more precise than experiment

- Semileptonic decays (e.g., $B \to D\mu\nu$, $B \to K\mu\mu$)
  Complicated hadronic effects (form factors)
  Good progress both theoretical and experimental side (similar uncertainties, $5 - 10\%$)
  Ideal for indirect searches!

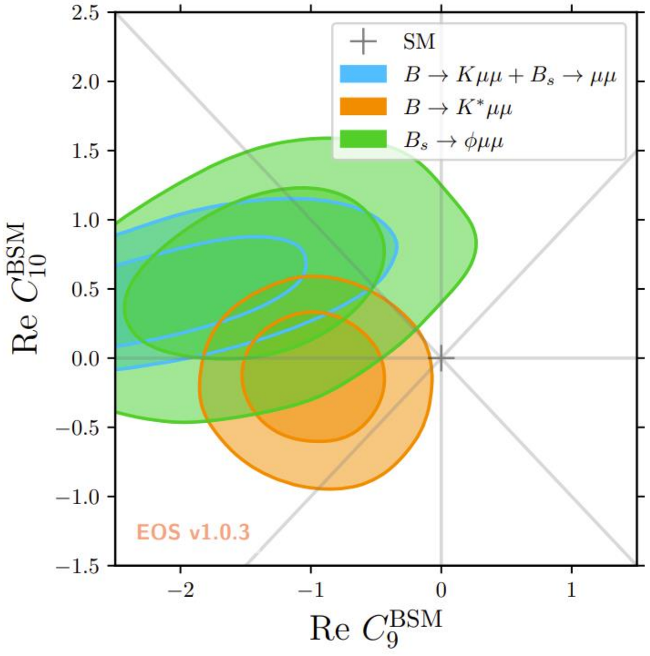
- Hadronic (or non-leptonic) decays (e.g., $B \to \pi\pi$)
  Hardest to calculate (no model independent calculation)
  Precise measurements available ($< 5\%$ uncertainties)
  Experiment way more precise than theory

Outlook

Community concern: no clear BSM signals, slow progress, ...



[Altmannshofer/Paradisi/Straub 2011]



[NG/Reboud/van Dyk/Virto 2022]

Precision and reach are improving rapidly

Right now: new data (LHC Run III and Belle II) + better theory sharpen the picture

$\Longrightarrow$ strong potential for discoveries in B decays

Thank you!