Precise Standard Model predictions for $\boldsymbol{B}$ decays

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Introduction

Flavour changing currents

flavour changing charged currents (FCCC) occur at tree level (mediated by $W^{\pm}$) in the SM

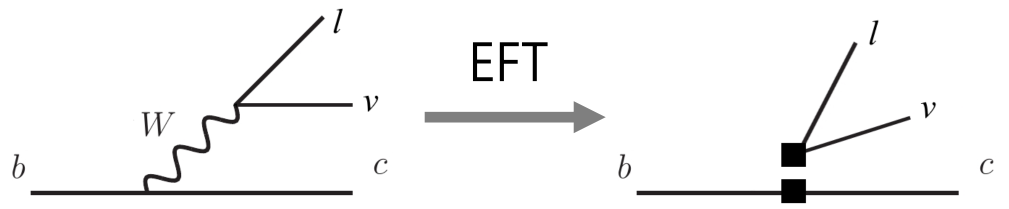
flavour changing neutral currents (FCNC) absent at tree level in the SM
FCNC are loop, GIM and CKM **suppressed in the SM**

FCNC **sensitive to new physics** contributions
probe the SM through **indirect searches**

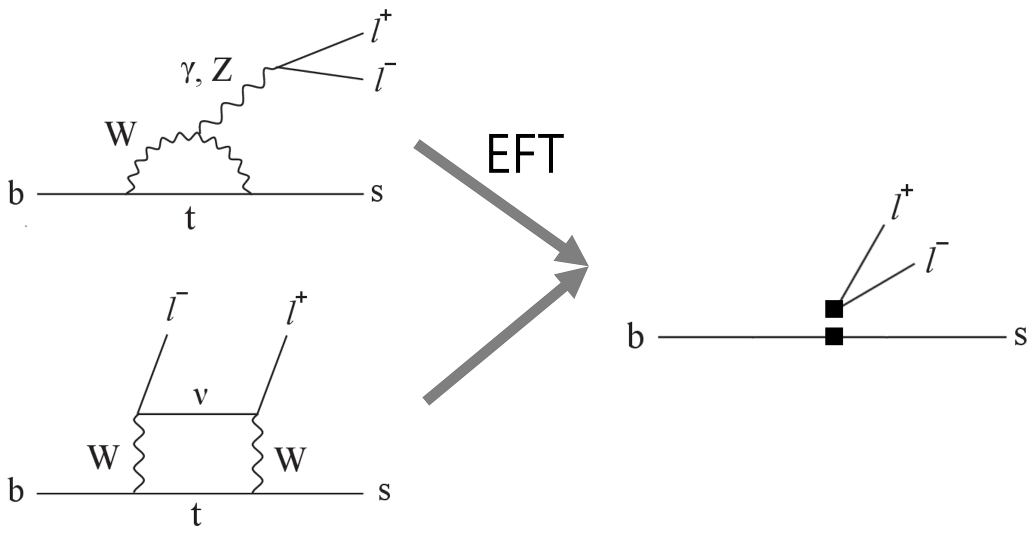
integrate out the W (and Z) boson

⇓

weak effective field theory



FCCC



FCNC

Hadronic matrix elements

study $\boldsymbol{B}$-meson decays to test the SM (neglect QED corrections)

$b \to c$ $\quad\quad \langle D^{(*)}\ell\nu_\ell|\mathcal{O}_{eff}|B\rangle = \langle \ell\nu_\ell|\mathcal{O}_{lep}|0\rangle\langle D^{(*)}|\mathcal{O}_{had}|B\rangle$

$b \to s$ $\quad\quad \langle K^{(*)}\ell\ell|\mathcal{O}_{eff}|B\rangle = \langle \ell\ell|\mathcal{O}_{lep}|0\rangle\langle K^{(*)}|\mathcal{O}_{had}|B\rangle$ + non–fact.

leptonic matrix elements: perturbative objects, high accuracy

hadronic matrix elements: non-perturbative QCD effects, usually large uncertainties

decay amplitudes depend on:

- local hadronic matrix elements
  (form factors)
  $\langle K^{(*)}|\mathcal{O}(0)|B\rangle$
  $\langle D^{(*)}|\mathcal{O}(0)|B\rangle$
- nonlocal hadronic matrix elements
  (soft gluon contributions
  to the charm-loop)
  $\langle K^{(*)}|\mathcal{O}(0,x)|B\rangle$

Interesting observables

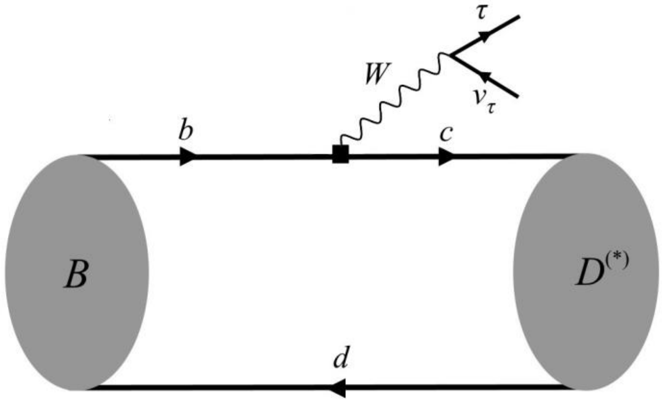
test the lepton flavour universality to test the SM

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

violations of lepton flavour universality $\Longrightarrow$ new physics

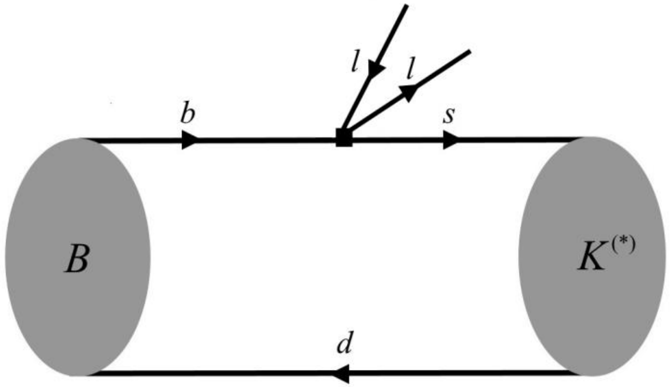
observables to test LFU

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)} \nu \tau)}{\Gamma(B \to D^{(*)} \nu \mu)} \qquad R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)} \mu^+ \mu^-)}{\Gamma(B \to K^{(*)} e^+ e^-)}$$

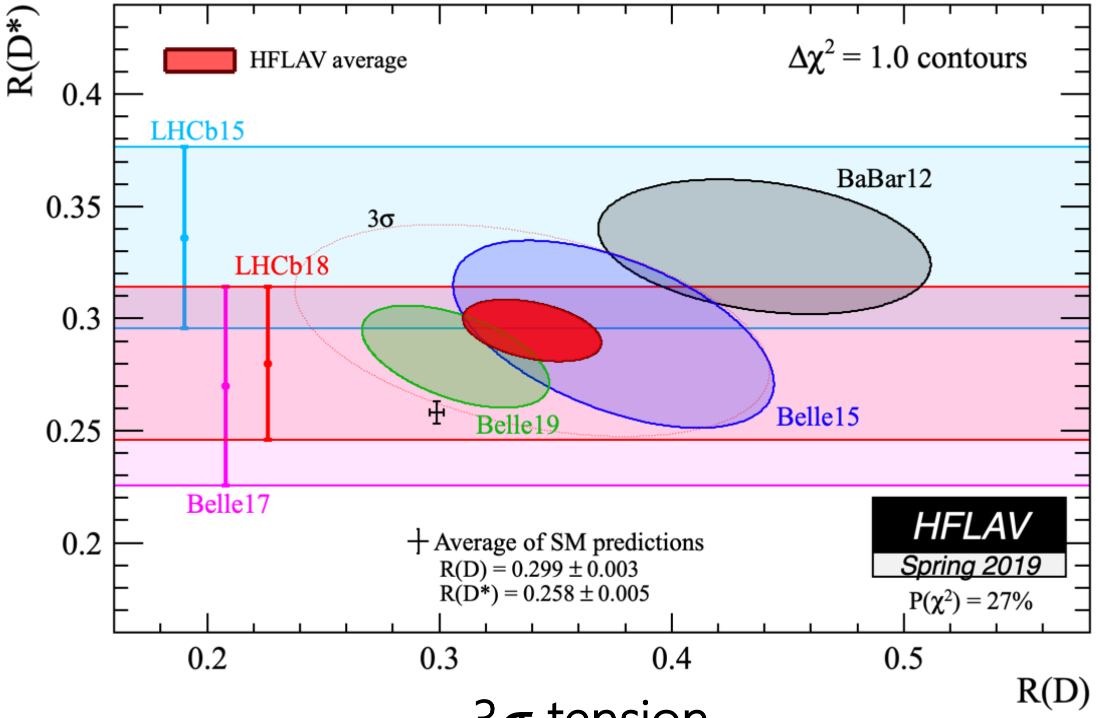


another test of the SM: angular observables in $B \to K^* \ell\ell$ (e.g. P_5')

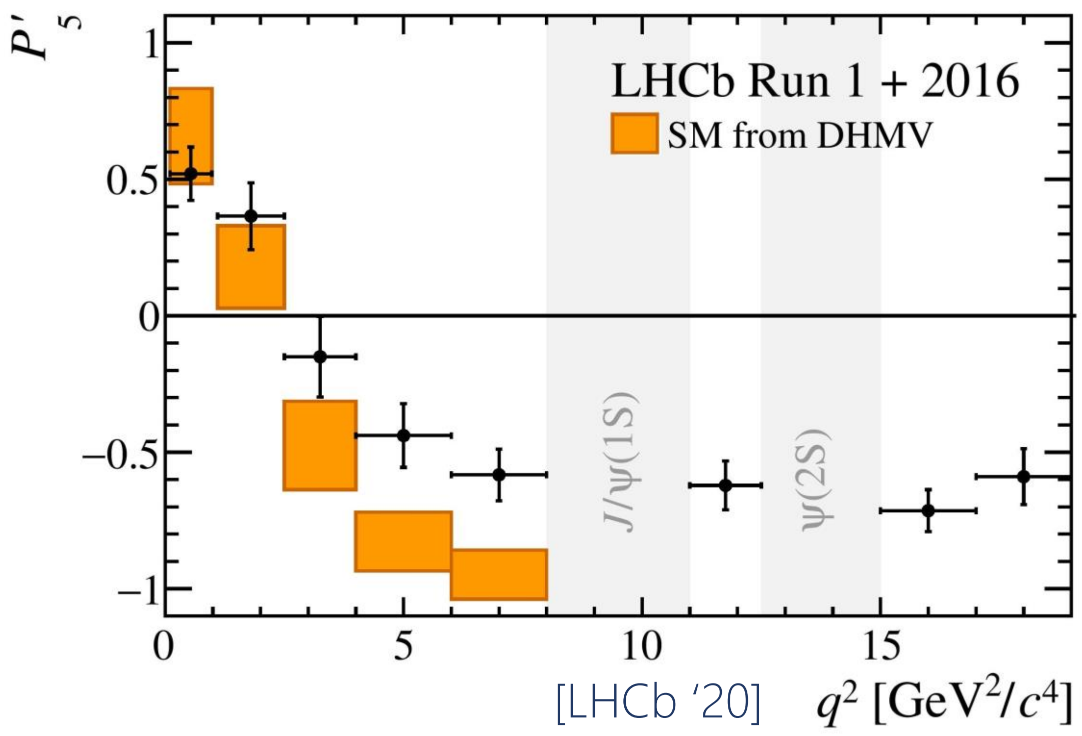
right choice of observables can reduce the hadronic uncertainties



B-anomalies



~3$\boldsymbol{\sigma}$ tension



[LHCb '20]

B-anomalies = tension between experimental measurements and theoretical predictions in B-meson decays involving different observables ($R_{D^{(*)}}, R_{K^{(*)}}, P_5'$ ...) and experiments

Standard Model predictions

Methods to compute hadronic matrix elements

non-perturbative techniques are needed
to compute hadronic matrix elements

Lattice QCD

numerical evaluation of correlators in a finite and discrete space-time

local matrix elements (usually at high q^2)

nonlocal matrix elements still work in progress

Light-cone sum rules (LCSRs)

based on unitarity, analyticity, and quark-hadron duality approximation

need universal B-meson matrix elements

applicable for both local and nonlocal matrix elements (at low q^2)

Definition of the form factors

form factors (FFs) parametrize exclusive hadronic matrix elements

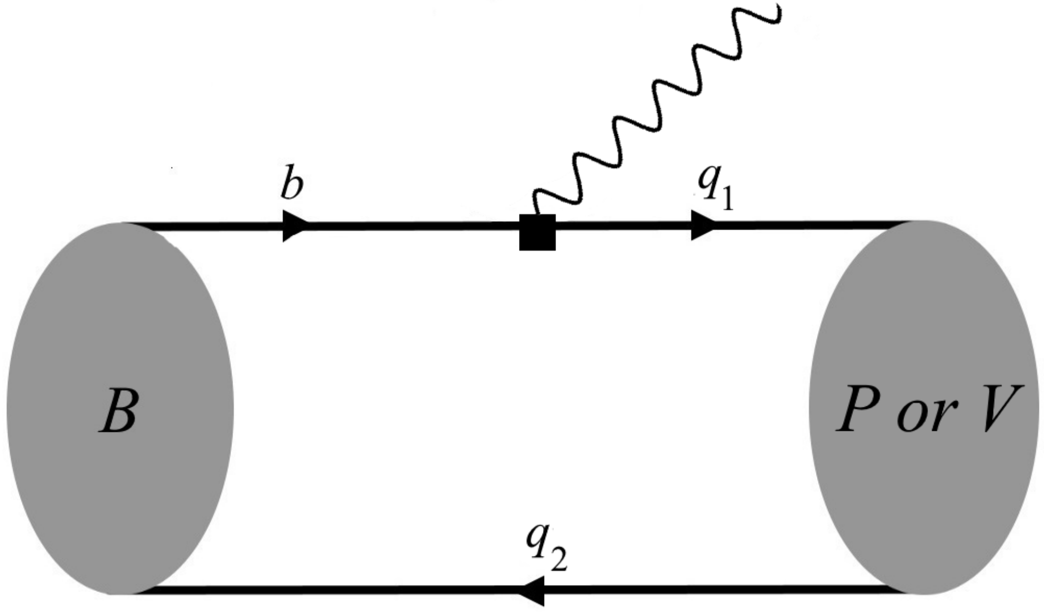
$$\langle P(k)|\bar{q}_1\gamma_\mu b|B(q+k)\rangle = 2\,k_\mu f_+(q^2) + q_\mu\big(f_+(q^2) + f_-(q^2)\big)$$

$$\langle P(k)|\bar{q}_1\sigma_{\mu\nu}q^\nu b|B(q+k)\rangle = \frac{i f_T(q^2)}{m_B+m_P}\left(q^2(2k+q)_\mu - (m_B^2 - m_P^2)q_\mu\right)$$

decomposition follows from Lorentz invariance

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

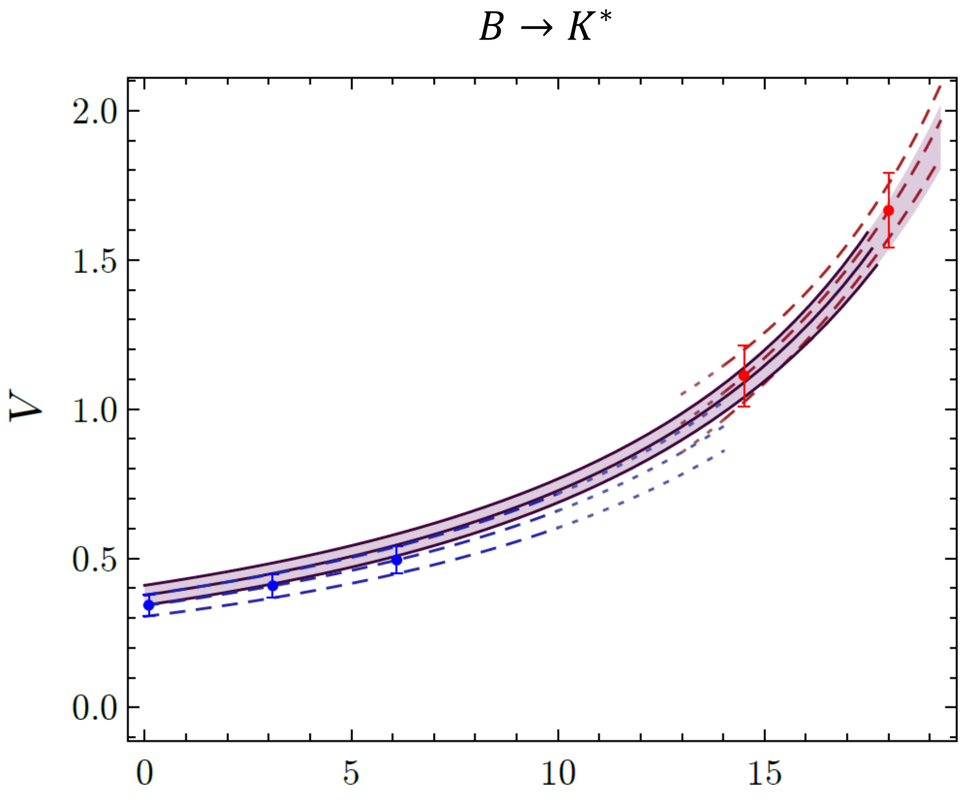
3 independent B to pseudoscalar meson (P) FFs
7 independent B to vector meson (V) FFs



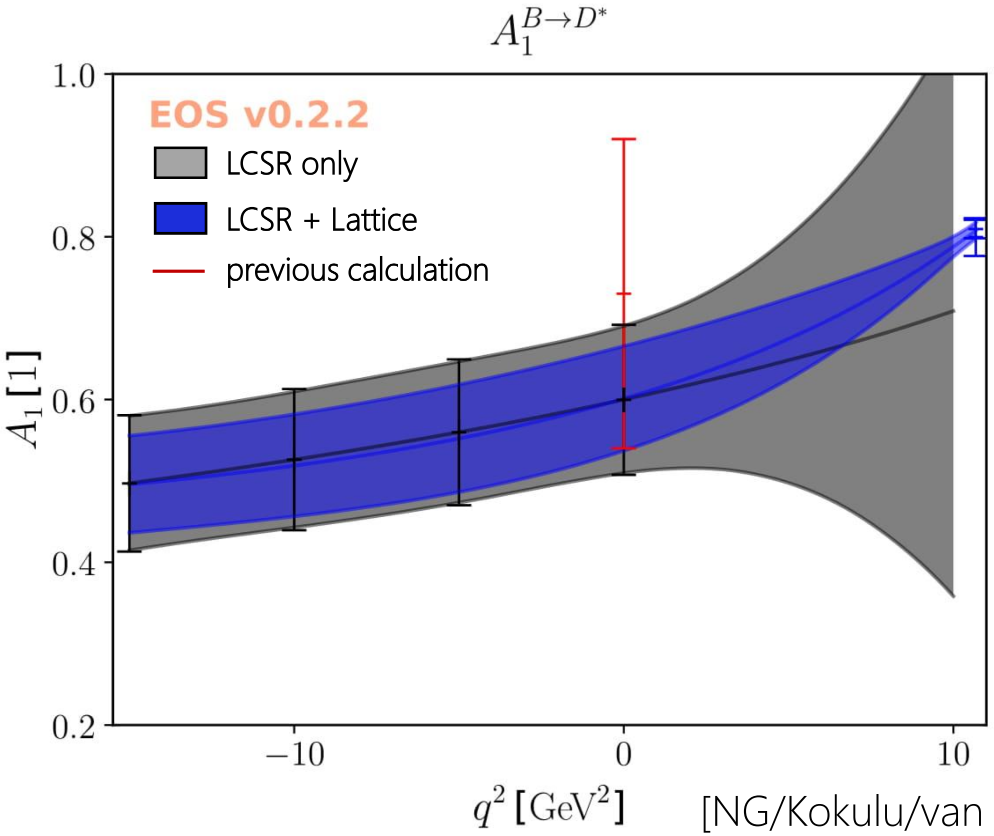
State of the art

	Transition	Lattice QCD	LCSR
$b \to s$	$B \to K$	high q^2	$q^2 < 12\ \mathrm{GeV}^2$
	$B \to K^*$	high q^2	$q^2 < 6\ \mathrm{GeV}^2$
	$B_s \to \phi$	high q^2	$q^2 < 6\ \mathrm{GeV}^2$
$b \to c$	$B \to D$	high q^2	$q^2 < 0\ \mathrm{GeV}^2$
	$B \to D^*$	only A_1 at max q^2	$q^2 < 0\ \mathrm{GeV}^2$
	$B_s \to D_s$	high q^2	$q^2 < 0\ \mathrm{GeV}^2$
	$B_s \to D_s^*$	only A_1 at max q^2	$q^2 < 0\ \mathrm{GeV}^2$

Combine lattice QCD and LCSRs for local FFs



[Bharucha/Straub/Zwicky '15]



[NG/Kokulu/van Dyk '18]

obtain the FF values to the whole spectrum (no additional assumptions required)

good agreement between lattice and LCSRs calculations

More on the $b \to c$ FFs

only one (A_1) out seven $B_{(s)} \to D^*_{(s)}$ FFs is known from lattice QCD

use Heavy Quark Effective Theory (HQET) to relate $B_{(s)} \to D_{(s)}$ FFs to $B_{(s)} \to D^*_{(s)}$ FFs

expand $B \to D^{(*)}$ FFs in the limit HQET ($m_{b,c} \to \infty$)

$$FF^{B\to D^{(*)}}(q^2) = c_0 \xi(q^2) + c_1 \frac{\alpha_s}{\pi} C_i(q^2) + c_2 \frac{1}{m_b} L_i(q^2) + c_3 \frac{1}{m_c} L_i(q^2) + c_4 \frac{1}{m_c^2} l_i(q^2)$$

$$FF^{B_s\to D_s^{(*)}}(q^2) = c_0 \xi^s(q^2) + c_1 \frac{\alpha_s}{\pi} C_i(q^2) + c_2 \frac{1}{m_b} L_i^s(q^2) + c_3 \frac{1}{m_c} L_i^s(q^2) + c_4 \frac{1}{m_c^2} l_i(q^2)$$

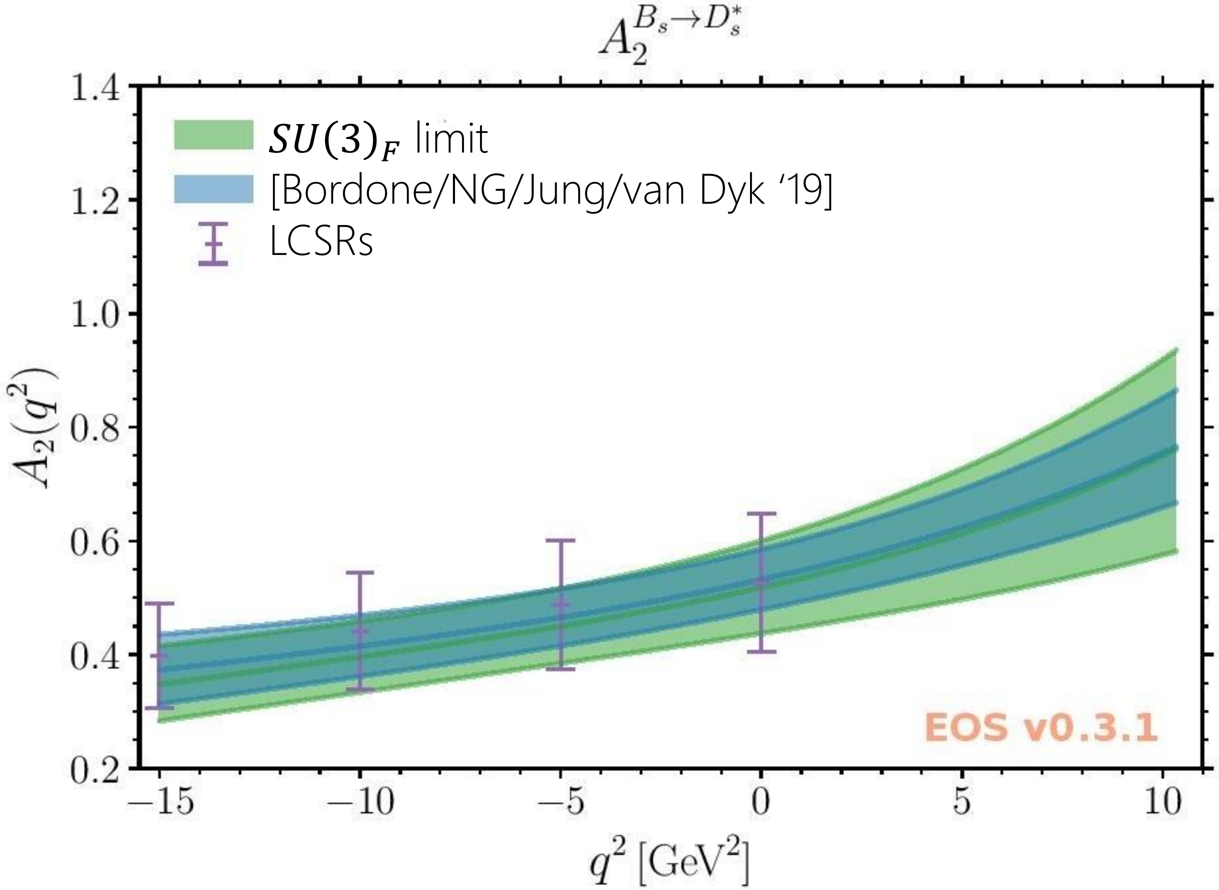
include $1/m_c^2$ corrections [Bordone/Jung/van Dyk '19]

all $B \to D^{(*)}$ and $B_s \to D_s^{(*)}$ FFs parametrized in terms of 14 Isgur-Wise functions

More on the $b \to c$ FFs

combine

- lattice QCD (where available)
- light-cone sum rules for the FFs
- dispersive bounds
- SVZ sum rules for Isgur-Wise functions
- with and w/o exp data



results for all $B \to D^{(*)}$ FFs and $B_s \to D_s^{(*)}$ FFs in the whole physical phase space

improved precision going beyond the $SU(3)_F$ limit

More on the $b \to s$ FFs

rare decays amplitude written in term of (local) FFs and non-local FFs

$$\mathcal{A}(B \to K^{(*)}\ell\ell) = \mathcal{N}\left[\left(C_9 L_V^\mu + C_{10} L_A^\mu\right) \boldsymbol{\mathcal{F}_\mu} - \frac{L_V^\mu}{q^2}\left(C_7\, \boldsymbol{\mathcal{F}_{T,\mu}} + \boldsymbol{\mathcal{H}_\mu}\right)\right]$$

(local) FFs:

- combine lattice QCD (high q^2) and LCSRs (low q^2) to get good precision $\sim 10\%$

non-local FFs (charm-loop effects):

- calculated using an Operator Product Expansion (OPE)
- large uncertainties → reduce uncertainties for a better understanding of rare B decays

Conclusions and outlook

Conclusion and outlook

$b \to c$ transitions:

- $B_{(s)} \to D_{(s)}$ FFs – lattice QCD (and LCSRs) calculations available
- $B_{(s)} \to D^*_{(s)}$ FFs – only LCSRs available except $A_1(q^2_{max})$ from lattice QCD (use HQET and dispersive bounds)
- non-local effects absent (neglect QED corrections)

$\Longrightarrow B_{(s)} \to D^*_{(s)}$ FFs from lattice are needed (and will come soon)!

$b \to s$ transitions:

$B \to K^{(*)}$ and $B_s \to \phi$ FFs – lattice QCD (and LCSRs) calculations available

$\Longrightarrow$ non-local effects implies large uncertainties – control these uncertainties (use dispersive bounds) [NG/van Dyk/Virto '20]

Thank you!