Light-cone sum rules 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

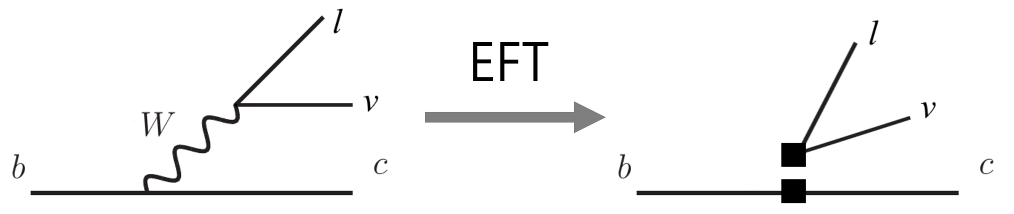
flavour changing neutral currents (FCNC) absent at tree level in the SM
FCNC are loop, GIM and CKM **suppressed in the SM**

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

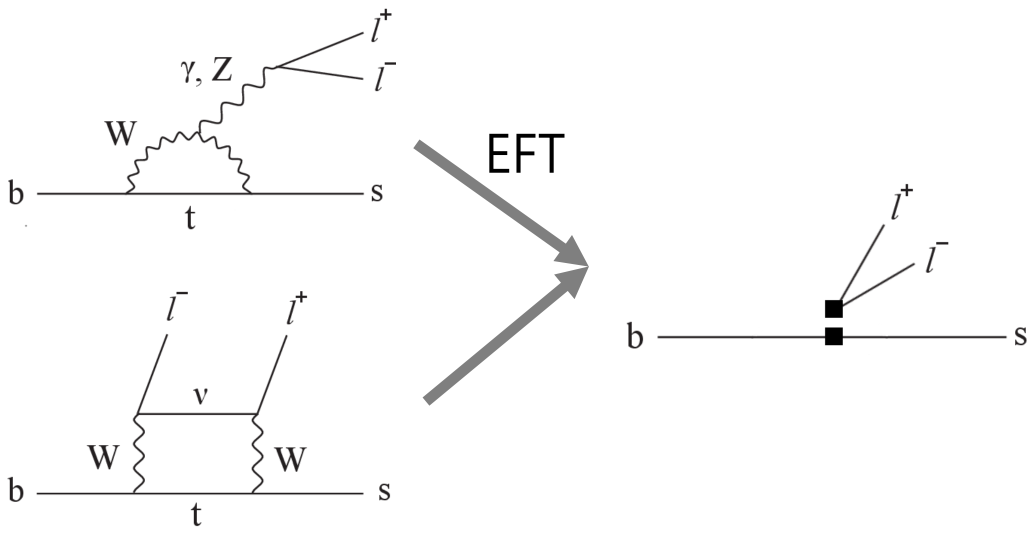
integrate out DOF heavier than the b

$\Downarrow$

weak effective field theory



FCCC



FCNC

Hadronic matrix elements

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

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

FCNC $\langle K^{(*)}\ell\ell|\mathcal{O}_{eff}|B\rangle = \langle \ell\ell|\mathcal{O}_{lep}|0\rangle\langle K^{(*)}|\mathcal{O}_{had}|B\rangle$ + 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)
  $\langle K^{(*)}|\mathcal{O}(0,x)|B\rangle$

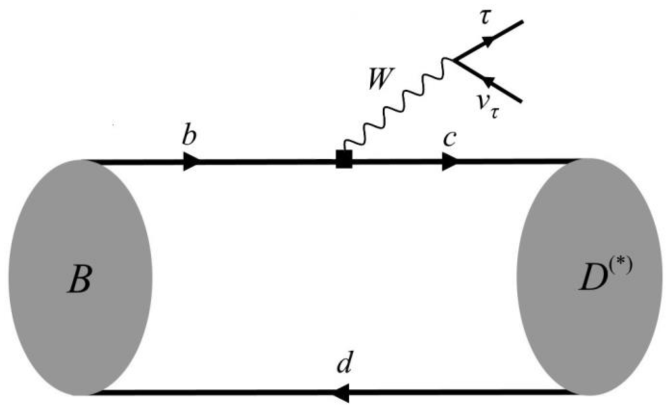
Interesting observables

test the lepton flavour universality to test the SM

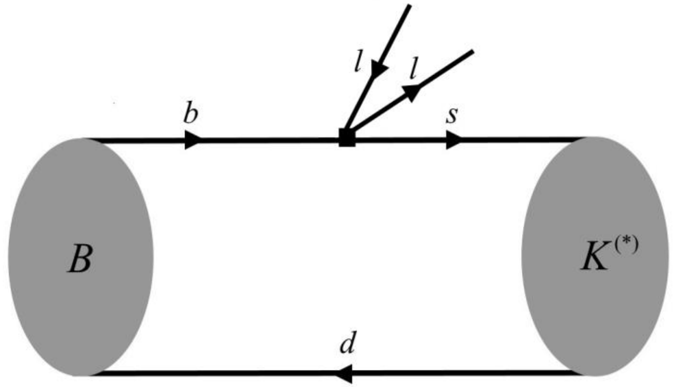
lepton flavour universality = the 3 lepton generations have the same couplings to the gauge bosons

violations of lepton flavour universality $\Longrightarrow$ new physics

observables to test LFU



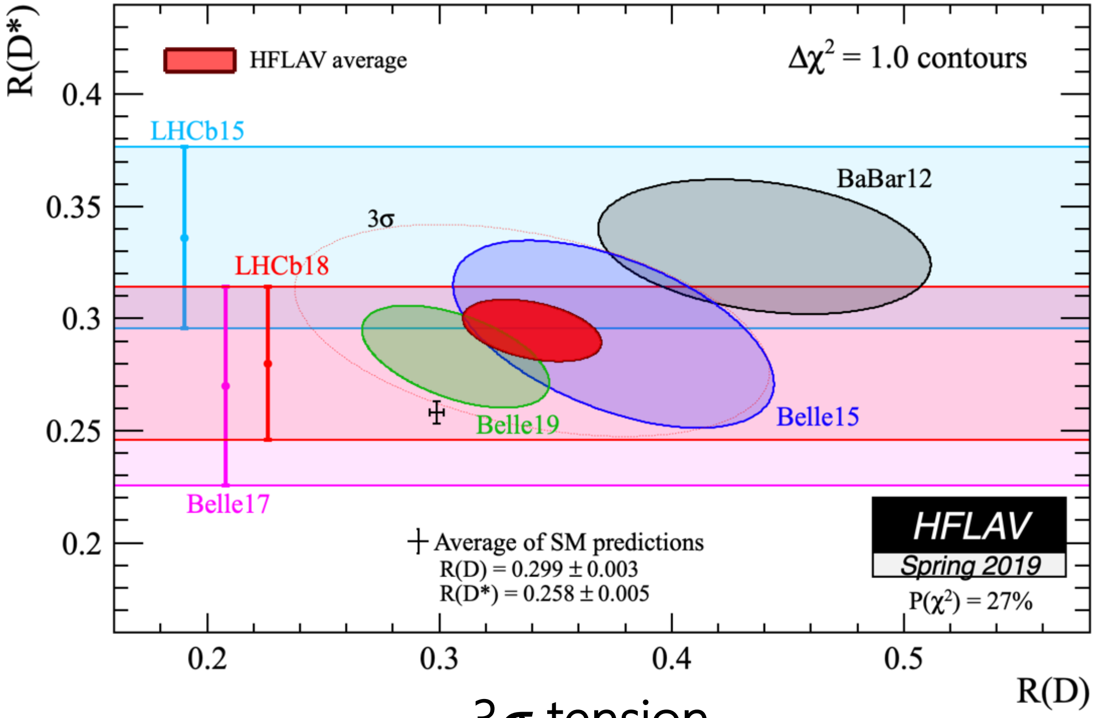
$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)} \nu \tau)}{\Gamma(B \to D^{(*)} \nu \mu)} \qquad R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)} \mu^+ \mu^-)}{\Gamma(B \to K^{(*)} e^+ e^-)}$$



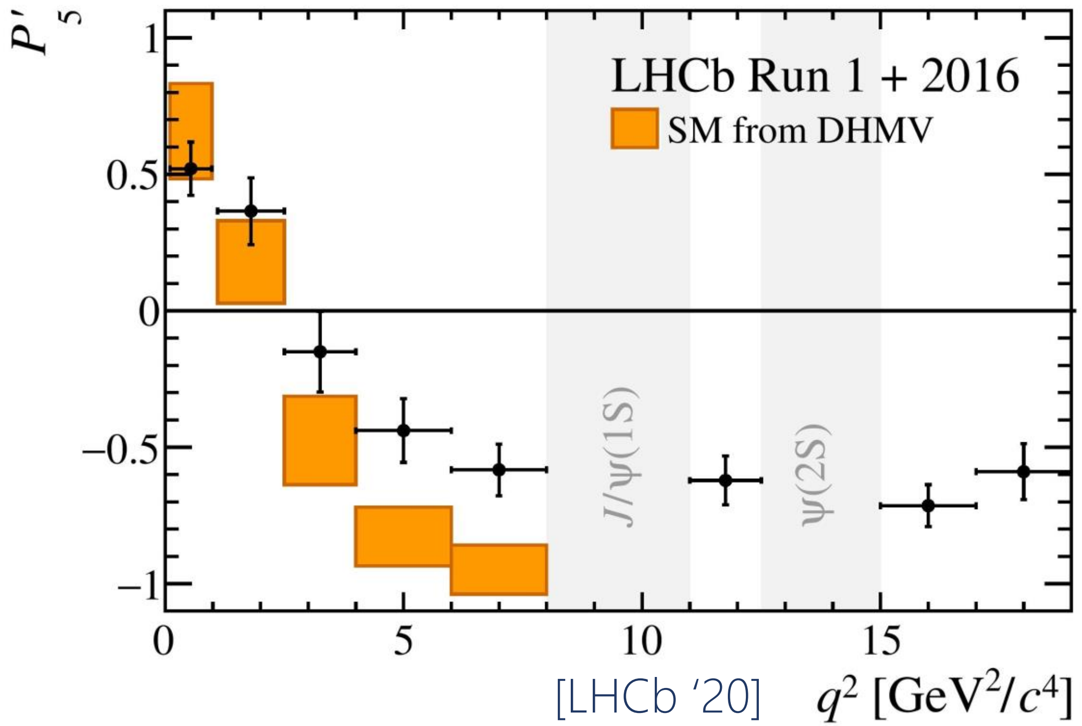
another test of the SM: angular observables in $B \to K^* \ell\ell$ (e.g. P_5')

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

Light-cone sum rules in a nutshell

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 non-perturbative inputs

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

Light-cone sum rules calculation

LCSRs are a method to calculate hadronic matrix elements

define a correlation function $\Pi(k,q)$

$$\Pi(k,q) = i\int \mathrm{d}^4x\, e^{ikx}\langle 0|T\{J_{int}(x), J_{weak}(0)\}|B(k+q)\rangle$$

compute the correlator in **two ways**

1

Hadronic representation
(using unitarity)

2

light-cone OPE for small q^2
(use also HQET)

the sum rule is obtained by matching the result of the two different calculations of $\Pi(k,q)$ and using semi-global quark-hadron duality

Light-cone sum rules results

sum rule

$$\mathcal{F}_\lambda(q^2) = \frac{f_B}{f_M} I(q^2) \otimes \langle 0 | \bar{d}(x) \dots h_v(0) | B(v) \rangle$$

factorize hard and soft contributions

- compute hard-scattering kernel $I(q^2)$ using **perturbative QCD** at leading order in α_s
- non-local *B*-to-vacuum matrix elements are a necessary **non-perturbative inputs**

method applicable for both local and nonlocal matrix elements

results for the local matrix elements complementary to lattice QCD results

access matrix elements not calculable with lattice QCD yet

Light-meson vs B-meson sum rules

light-meson LCSRs

light-meson distribution amplitudes (DAs)

$$\langle 0|\bar{q}_1(x) \ldots q_2(0)|M\rangle$$

twist 6 accuracy

NLO corrections to the hard-scatt. kernel

DAs inputs well known

$B \to \pi, \rho, K^{(*)}$ … decays

~10% error

no much room for improvement

B-meson LCSRs

B-meson distribution amplitudes (DAs)

$$\langle 0|\bar{d}(x) \ldots h_v(0)|B\rangle$$

twist 4 accuracy

NLO corrections to the hard-scatt. kernel not known for all processes

poor knowledge of DAs inputs well known

$B \to \pi, \rho, K^{(*)}, D^{(*)}$ … decays

~30% error

room for big improvement

independent calculations, different inputs → results can be combined

Standard Model predictions

Definition of the form factors

form factors (FFs) parametrize exclusive hadronic matrix elements

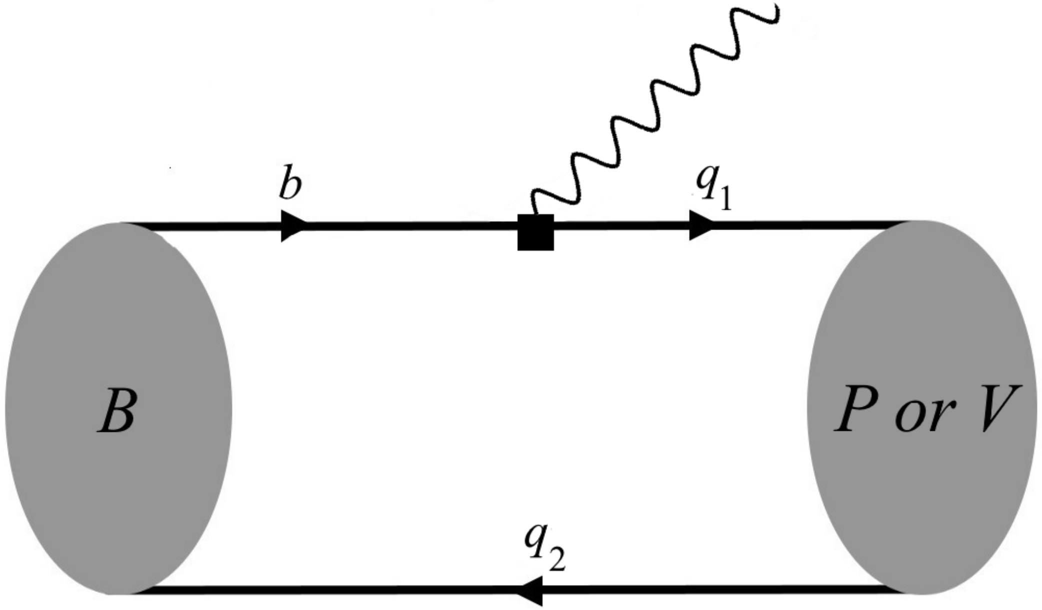
$$\langle P(k)|\bar{q}_1\gamma_\mu b|B(q+k)\rangle = 2\,k_\mu f_+(q^2) + q_\mu\big(f_+(q^2) + f_-(q^2)\big)$$

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

decomposition follows from Lorentz invariance

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

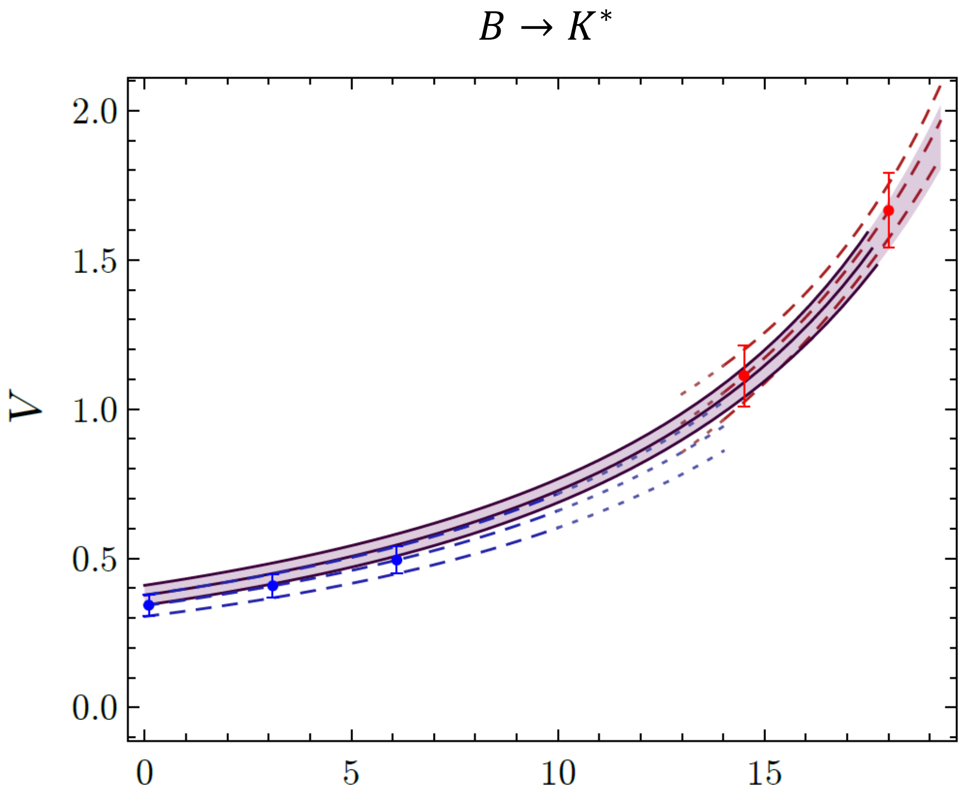
3 independent B to pseudoscalar meson (P) FFs
7 independent B to vector meson (V) FFs



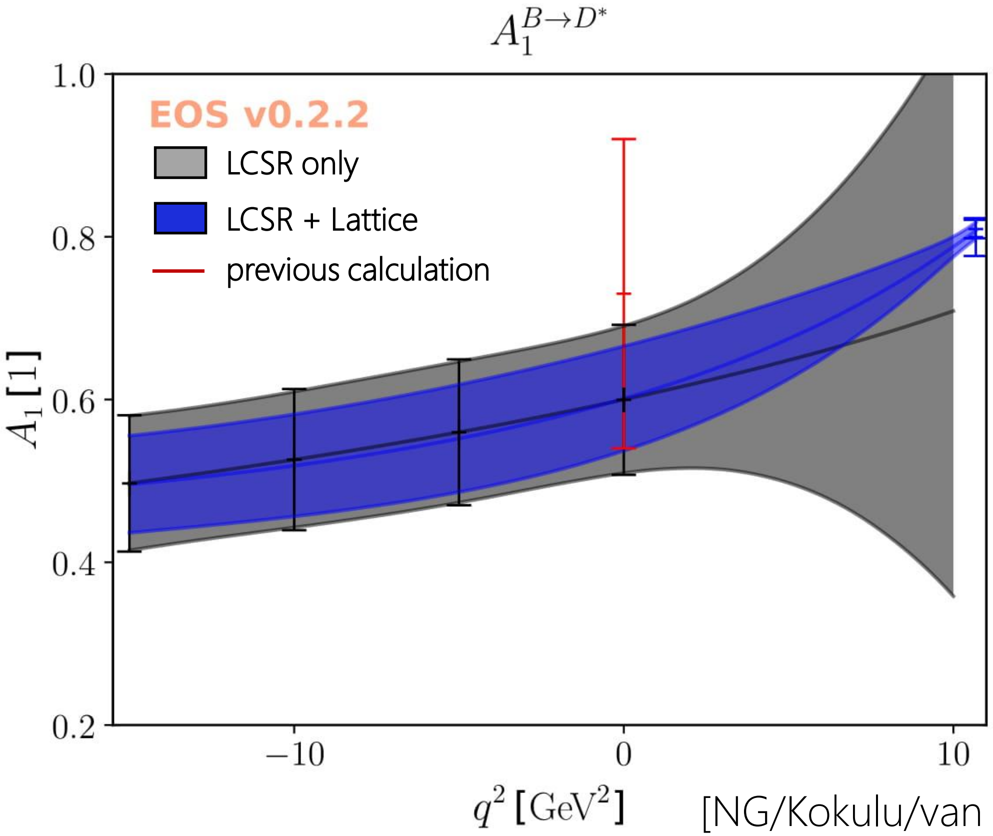
State of the art

	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	$q^2 < 0\ \mathrm{GeV}^2$
	$B \to D^*$	high q^2	$q^2 < 0\ \mathrm{GeV}^2$
	$B_s \to D_s$	whole q^2 range	$q^2 < 0\ \mathrm{GeV}^2$
	$B_s \to D_s^*$	whole q^2 range	$q^2 < 0\ \mathrm{GeV}^2$

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

use heavy-quark limit ($m_{b,c} \to \infty$) to relate $B_{(s)} \to D_{(s)}$ FFs to $B_{(s)} \to D_{(s)}^{*}$ FFs

expand $B_{(s)} \to D_{(s)}^{(*)}$ FFs in the heavy-quark limit

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

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

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 (IW) functions

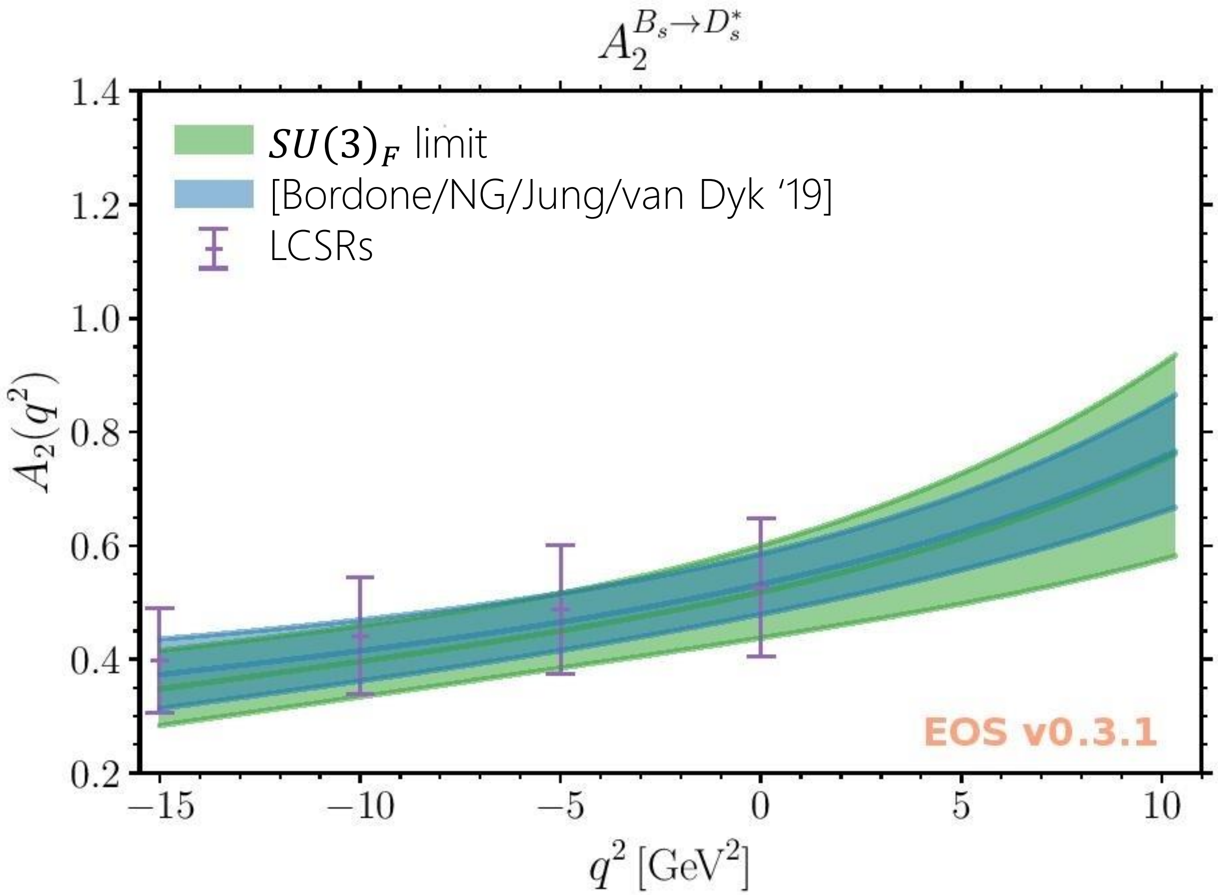
More on the $B_{(s)} \to D_{(s)}^{(*)}$ FFs

constrain IW functions with

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

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



The $B \to D^{**}$ FFs

why study $B \to D^{**}$ FFs? $D^{**} = \{D_0^*, D_1', D_1, D_2^*\}$

- alternative channel to study the (anomalous) $b \to c$ transitions
- important background for the $B \to D^{(*)}\ell\nu$ measurements
- improve the determination of $|V_{cb}|$ and $|V_{ub}|$

theoretical calculations of $B \to \{D_1', D_1\}$ FFs are very challenging (both with LQCD and LCSRs)

- same quantum numbers ($J^P = 1^+$)
- almost the same mass

difficult to disentangle

extend the LCSR method to disentangle D_1 and D_1'

[NG/Khodjamirian/Mandal/Mannel w.i.p.]

More on the $b \to s$ transitions

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 $\boldsymbol{q^2}$) and LCSRs (low $\boldsymbol{q^2}$) to get good precision $\boldsymbol{\sim 10\%}$

non-local FFs (charm-loop effects):

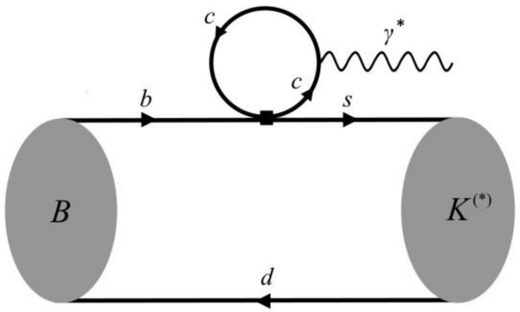
- calculated using an Operator Product Expansion (OPE)
- large uncertainties → reduce uncertainties for a better understanding of rare $\boldsymbol{B}$ decays

Soft-gluon contribution to the charm loop

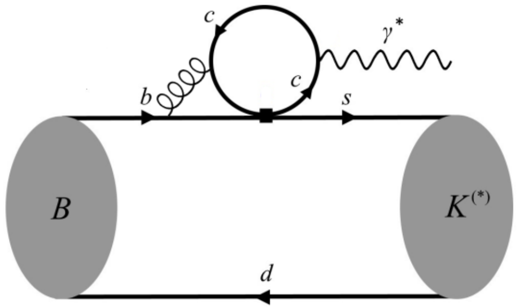
expand $\mathcal{H}_\lambda$ in a light-cone OPE for $q^2 \ll 4m_c^2$

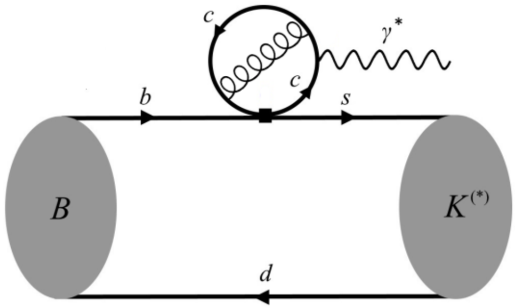
$$\mathcal{H}_\lambda(q^2) = C_\lambda(q^2)\mathcal{F}_\lambda(q^2) + \tilde{C}_\lambda(q^2)\mathcal{V}_\lambda(q^2) + \cdots$$

leading power (LO in α_s)

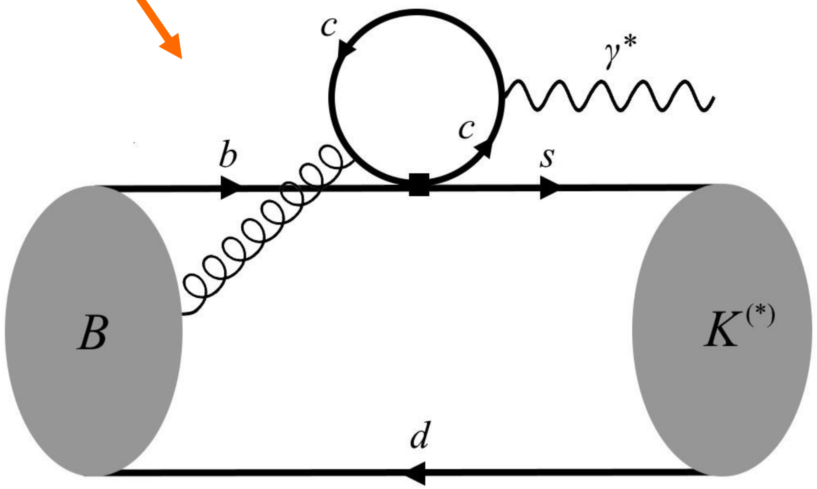


+ hard gluons (α_s) corrections





soft gluon correction
non-perturbative
$\Longrightarrow$ not α_s suppressed



Charm-loop results and comparison

$\Delta C_9(q^2 = 1\ \mathrm{GeV}^2)$		**KMPW2010**	**GvDV2019**
leading power (LO α_s)		0.27	0.27
$B \to K\ell\ell$	$\mathcal{V}_{\mathcal{A}}$	$-0.09^{+0.06}_{-0.07}$	$(1.9^{+0.6}_{-0.6}) \cdot 10^{-4}$
$B \to K^*\ell\ell$	$\mathcal{V}_1$	$0.6^{+0.7}_{-0.5}$	$(1.2^{+0.4}_{-0.4}) \cdot 10^{-3}$
	$\mathcal{V}_2$	$0.6^{+0.7}_{-0.5}$	$(2.1^{+0.7}_{-0.7}) \cdot 10^{-3}$
	$\mathcal{V}_3$	$1.0^{+1.6}_{-0.8}$	$(3.0^{+1.0}_{-1.0}) \cdot 10^{-3}$
$B_s \to \phi\ell\ell$	$\mathcal{V}_i$	—	see paper

[Khodjamirian/Mannel/Pivovarov/Wang 2010 (**KMPW2010**)]

- our results are **two orders of magnitude smaller** than in KMWP2010 ($\Longrightarrow$ **smaller unc.**)
- **we can reproduce the analytical results given in KMWP2010 and the differences are well understood**
- quick **convergence of the light-cone OPE**

Why such different results?

different inputs: LCDAs models depend on λ_H^2, λ_E^2 $\rightarrow$

KMPW10:
$\lambda_H^2 = \lambda_E^2 = 0.31 \pm 0.15\ \mathrm{GeV}^2$
$\Longrightarrow$ twist 3 does not contribute

we use $\lambda_E^2 = 0.03 \pm 0.02\ \mathrm{GeV}^2$
$\lambda_H^2 = 0.06 \pm 0.03\ \mathrm{GeV}^2$
$\Longrightarrow$ ~10 times smaller [Nishikawa/Tanaka 2014]

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three-particle LCDAs twist expansion $\rightarrow$

KMPW10: the 3-pt LCDAs twist expansion was not known

we use Braun/Ji/Manashov 2017

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independent 3-particle LCDAs considered $\rightarrow$

KMPW10: 4 Lorentz structures

all 8 independent Lorentz structures
$\Longrightarrow$partial cancelation (new structures come with an opposite sign)

Conclusions and outlook

Conclusion and outlook

$\boldsymbol{b \to c}$ transitions:

- $B_{(s)} \to D_{(s)}^{(*)}$ FFs – lattice QCD (and LCSRs) calculations available
- use HQET and dispersive bounds for better precision
- non-local effects absent (neglect QED corrections)
- computation $B \to \{D_1', D_1\}$ FFs with LCSRs w.i.p.

$\boldsymbol{b \to s}$ transitions:

- $B \to K^{(*)}$ and $B_s \to \phi$ FFs – lattice QCD (and LCSRs) calculations available
- non-local effects implies large uncertainties
- calculate non-local effects
- control these uncertainties (use dispersive bounds)

Thank you!