form factors for $\boldsymbol{B}$ decays and $\boldsymbol{V_{cb}}$ determination

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Based on
arXiv:1912.09335
in collaboration with
M. Bordone, M. Jung, D. van Dyk

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DFG Deutsche Forschungsgemeinschaft

Emmy Noether-Programm
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What’s new?

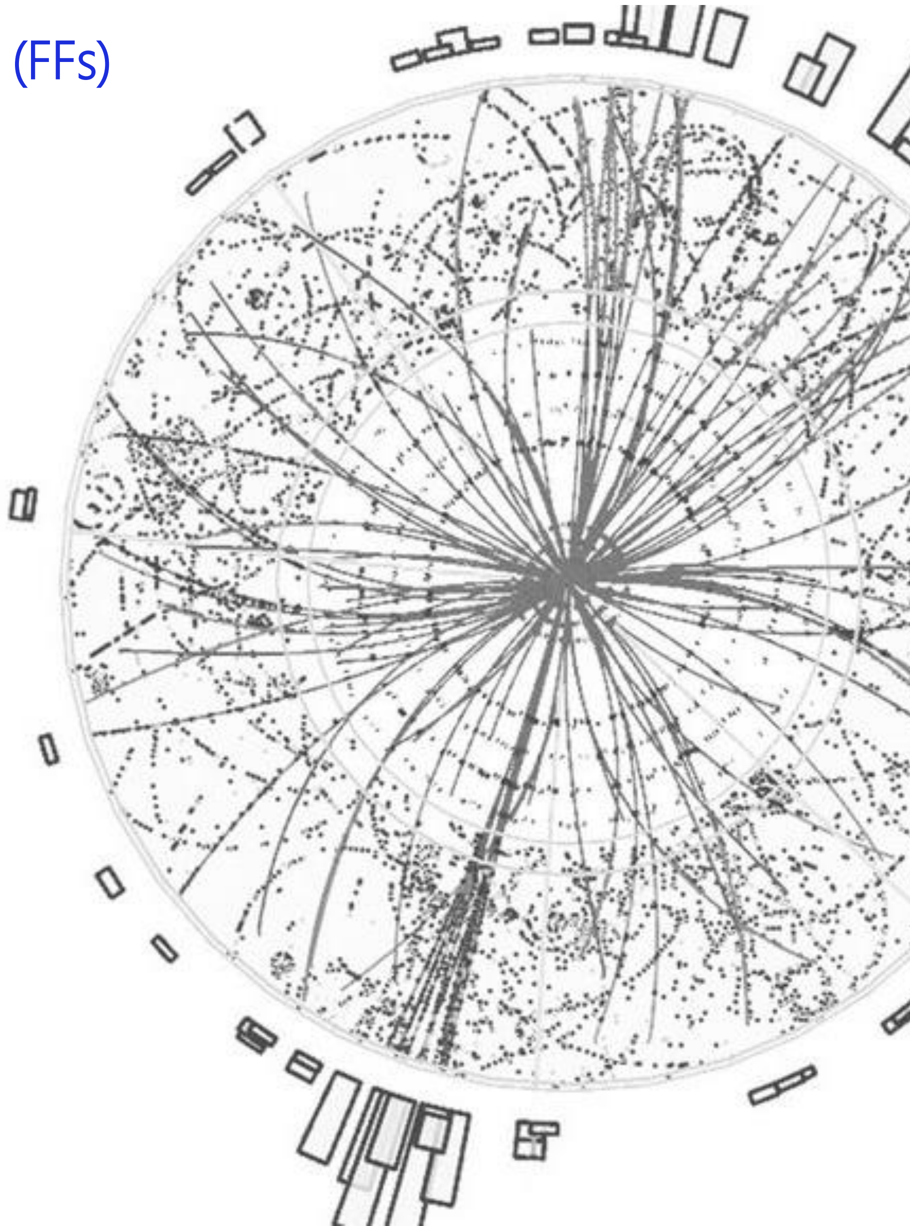
first simultaneous analysis of $\boldsymbol{B \to D^{(*)}}$ and $\boldsymbol{B_s \to D_s^{(*)}}$ form factors (FFs)
(use lattice QCD, light-cone sum rules, SVZ sum rules
and dispersive bounds **beyond $\boldsymbol{SU(3)_F}$ approximation**)

first theoretical prediction of all $\boldsymbol{B_s \to D_s^*}$ FFs
(except for A_1 at $\boldsymbol{q^2_{max}}$) using sum rules

high precision theoretical predictions in $B_{(s)} \to D_{(s)}^{(*)}$ decays of

- form factors (and BGL coefficients)
- angular observables
- LFU ratios $R(D_{(s)}^*)$
- ...

extraction of $\boldsymbol{V_{cb}}$ using experimental data



theoretical framework

definition of the form factors

form factors (FFs) parametrize exclusive local hadronic matrix elements

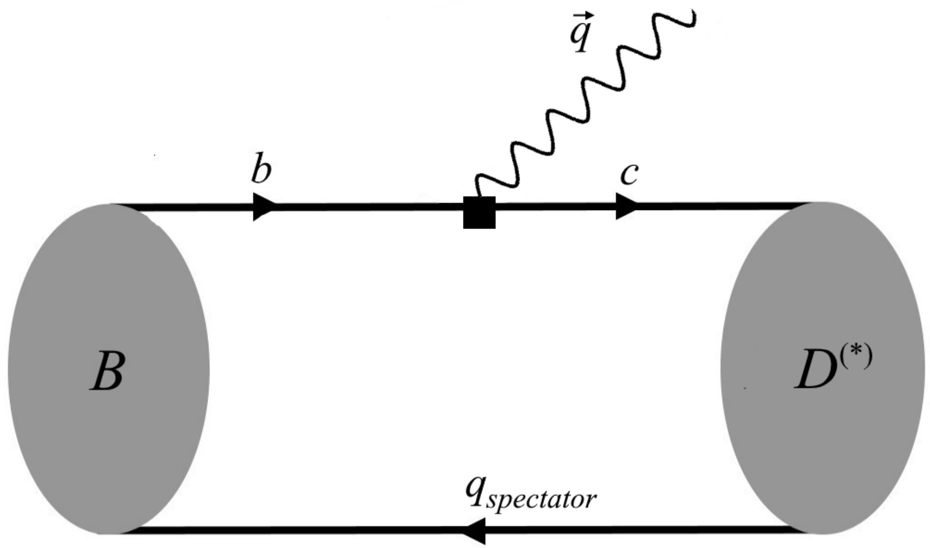
$$\langle D_{(s)}(k)|\bar{c}\,\gamma_\mu b|\bar{B}_{(s)}(q+k)\rangle = 2\,k_\nu f_+^{B_{(s)}\to D_{(s)}}(q^2) + q_\mu\left(f_+^{B_{(s)}\to D_{(s)}}(q^2) + f_-^{B_{(s)}\to D_{(s)}}(q^2)\right)$$

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

FFs are functions of the momentum transferred q^2

3 independent $B_{(s)} \to D_{(s)}$ FFs
7 independent $B_{(s)} \to D^*_{(s)}$ FFs

compute (non-perturbative) FFs
using lattice QCD or light cone sum rules



lattice QCD

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

Pros

based on first principles

small uncertainties
(few percent or below)

Cons

usually more effective at high q^2

excited states are problematic

long and expensive computations

state of the art

- $\boldsymbol{B \to D}$ FFs computed at high q^2 [Fermilab/MILC '15, HPQCD '15]
- $\boldsymbol{B_s \to D_s}$ FFs computed in the whole q^2 range [HPQCD '19]
- $\boldsymbol{B_{(s)} \to D^*_{(s)}}$ only A_1 computed at q^2_{max} [HFLAV '19, HPQCD '17 '19]

light-cone sum rules in a nutshell

light-cone sum rules (LCSRs) are a method to calculate form factors

method based on:

- dispersion relation
- quark-hadron duality assumption
- light-cone OPE

Pros

easy to adapt to different transitions

relatively faster than lattice QCD

effective at small q^2
(complementary to lattice QCD)

Cons

quark-hadron duality assumption

non-perturbative inputs (see next slide)

large uncertainties

light-cone sum rules results

sum rule

$$FF^{B_{(s)}\to D_{(s)}^{(*)}}(q^2) = \frac{f_B}{f_{D^{(*)}}}\int_0^{s_0} \mathrm{d}s \sum_{t\leq 4} I_t(s,q^2)\,\Psi_t(s)$$

factorize hard and soft contributions

- compute I_t using **perturbative QCD**
- *B*-meson distribution amplitudes Ψ_t are a necessary **non-perturbative inputs**

adapt the sum rules of NG/Kokulu/van Dyk '18 for $B \to D^{(*)}$ to $B_s \to D_s^{(*)}$
(LO in α_s and NNL twist)

first theoretical prediction of all $B_s \to D_s^*$ FFs (except for A_1 at q^2_{max})

HQET and SVZ sum rules

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

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

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

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

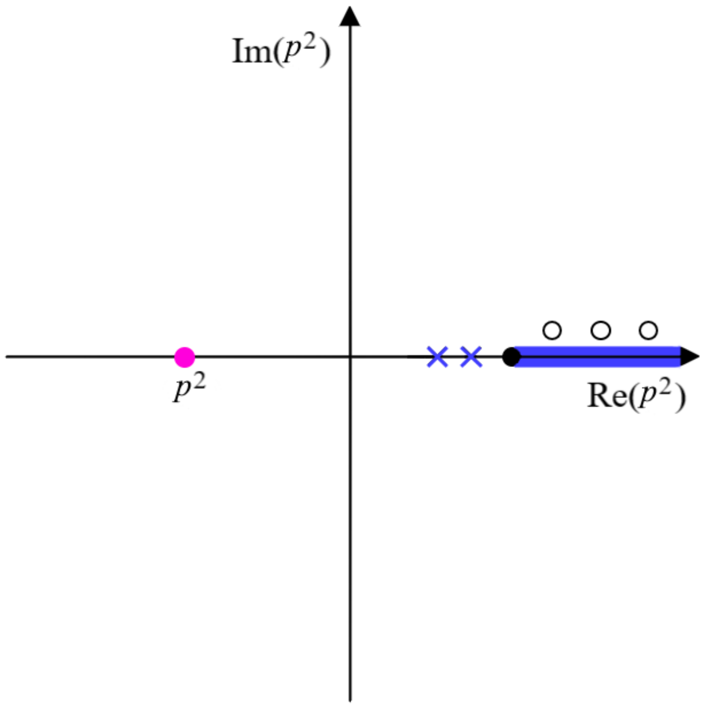
Isgur-Wise functions ξ and L_i computed using SVZ sum rules [Neubert/Ligeti/Nir, '93 '94]

we adapt this SVZ sum rules $B_s \to D_s^{(*)}$ case

dispersive (or unitarity) bounds

define correlator

$$\Pi^{\mu\nu}(p) = \int dx\, e^{ipx} \langle 0 | T\{\bar{c}\, \gamma^{\mu}(\gamma_5) b(x), \bar{b}\, \gamma^{\nu}(\gamma_5) c(0)\} | 0 \rangle$$



dispersion relation

$$\Pi(p^2) = \frac{1}{\pi} \int_0^{\infty} dt \frac{\mathrm{Im}\,\Pi(t)}{t - p^2}$$

express imaginary part $\mathrm{Im}\,\Pi(t)$ as a sum of all possible hadronic matrix elements

compute $\Pi(p^2)$ for $p^2 \ll m_b^2$ using an OPE

dispersive bounds

$$\Pi^{\mathrm{OPE}}(p^2 = 0) = \frac{1}{\pi} \int_0^{\infty} dt \frac{\sum_f g(t) \left(\left| FF_f^{B \to D^{(*)}}(t) \right|^2 + \left| FF_f^{B_s \to D_s^{(*)}}(t) \right|^2 \right)}{t} + \cdots$$

dispersive bounds 2

$$\Pi^{\text{OPE}}(p^2=0) > \frac{1}{\pi}\int_0^\infty dt \frac{\sum_f g(t)\left(\left|FF_f^{B\to D^{(*)}}(t)\right|^2 + \left|FF_f^{B_s\to D_s^{(*)}}(t)\right|^2\right)}{t}$$

z transformation

$$z(t) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

Taylor expand in z

$$B(z)\,\phi(z)\,FF^{B_{(s)}\to D_{(s)}^{(*)}}(t(z)) = \sum_n a_n z^n$$

the **(strong) dispersive bounds** can be written as [Caprini/Lellouch/Neubert '98]

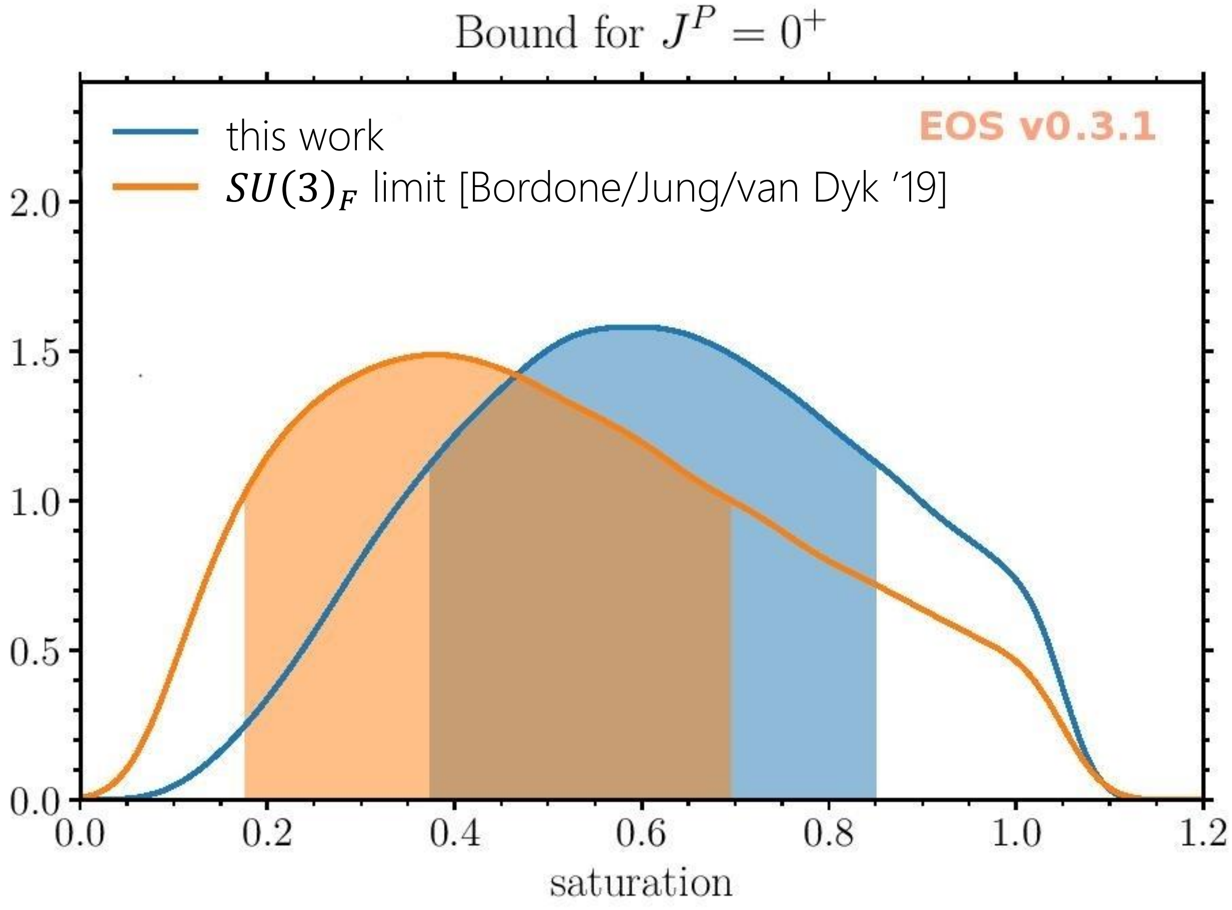
$$\sum_{FF}\sum_n \left|a_{FF,n}\right|^2 < 1$$

saturation of the bounds

lifting $SU(3)_F$ assumption
increases bounds saturation of $\sim 20\%$

stronger constrains on the FFs
smaller uncertainties

possible improvements including
additional contributions
($\Lambda_b \to \Lambda_c$ FFs w.i.p.)



phenomenological results

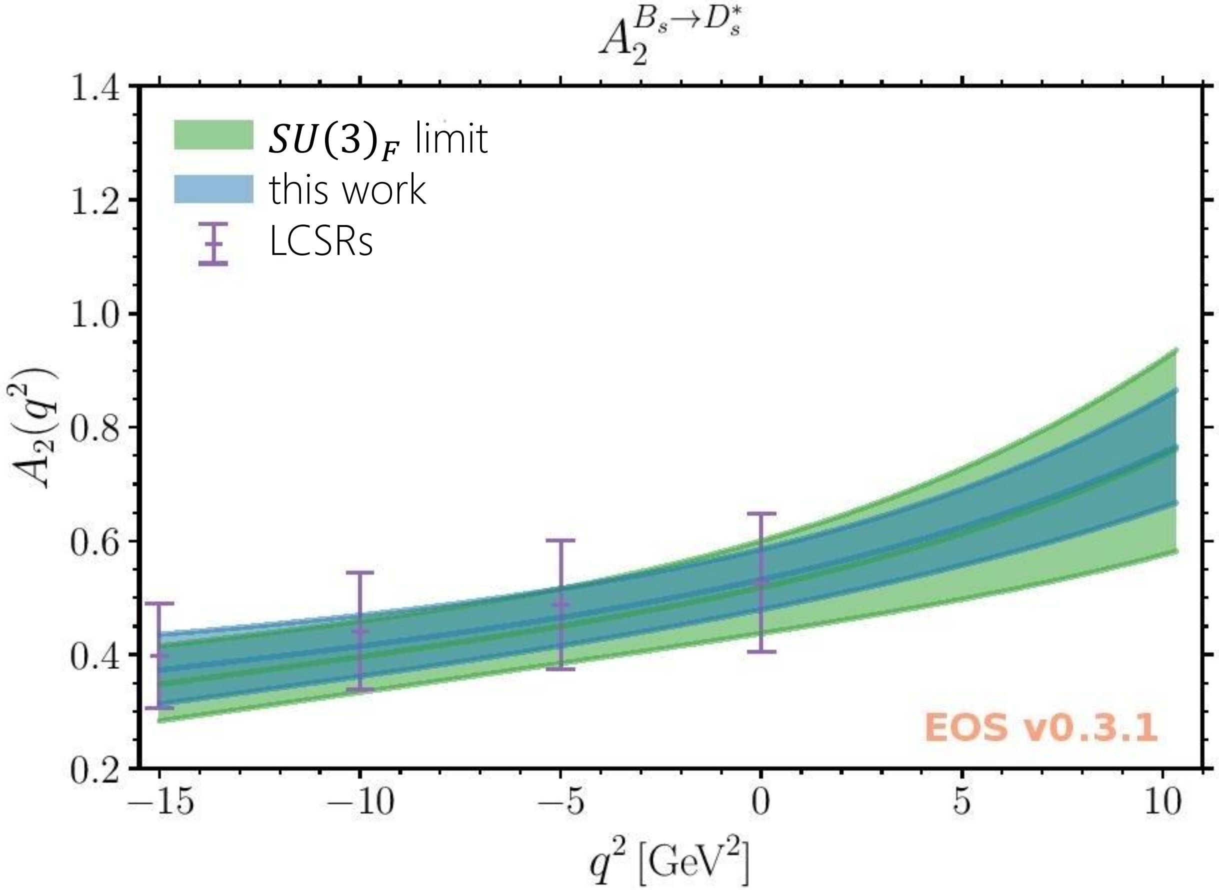
FFs predictions

combine

- lattice QCD (where available)
- light-cone sum rules for the FFs
- SVZ sum rules for Isgur-Wise functions
- dispersive bounds
- 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



$R(D^*_{(s)})$ and V_{cb}

FFs from THEORY ONLY results

LFU ratios

$$R(D\ ) = 0.2989 \pm 0.0032$$
$$R(D^*) = 0.2472 \pm 0.0050$$
$$R(D_s^*) = 0.2970 \pm 0.0034$$
$$R(D_s^*) = 0.2450 \pm 0.0082$$

extract V_{cb} using FFs and experimental data

$B \to D\ \{e,\mu\}\bar{\nu}$ data $\Rightarrow$ $V_{cb} = 40.7 \pm 1.1 \cdot 10^{-3}$

$B \to D^*\{e,\mu\}\bar{\nu}$ data $\Rightarrow$ $V_{cb} = 38.8 \pm 1.4 \cdot 10^{-3}$

combined $\Rightarrow$ $V_{cb} = 40.0 \pm 0.9 \cdot 10^{-3}$

FFs from THEORY +
EXPERIMENTAL data shape $B \to D^{(*)}\ell\bar{\nu}$

arXiv:1702.01521 [hep-ex]
arXiv:1809.03290 [hep-ex]

LFU ratios

$$R(D\ ) = 0.2981 \pm 0.0029$$
$$R(D^*) = 0.2504 \pm 0.0026$$
$$R(D_s^*) = 0.2971 \pm 0.0034$$
$$R(D_s^*) = 0.2472 \pm 0.0077$$

extract V_{cb} using FFs and experimental data

$B \to D\ \{e,\mu\}\bar{\nu}$ data $\Rightarrow$ $V_{cb} = 40.7 \pm 1.1 \cdot 10^{-3}$

$B \to D^*\{e,\mu\}\bar{\nu}$ data $\Rightarrow$ $V_{cb} = 39.5 \pm 0.9 \cdot 10^{-3}$

combined $\Rightarrow$ $V_{cb} = 40.0 \pm 0.7 \cdot 10^{-3}$

angular observables and BGL coefficients

predictions of angular observables in $\bar{B} \to D^*\{\mu, \tau\}\,\bar{\nu}$ and $\bar{B}_s \to D_s^*\{\mu, \tau\}\,\bar{\nu}$ decays

ancillary files available with **BGL coefficients** and LCSRs results

observable \ transition	$\bar{B} \to D^* \mu^- \bar{\nu}$	$\bar{B} \to D^* \tau^- \bar{\nu}$	$\bar{B}_s \to D_s^* \mu^- \bar{\nu}$	$\bar{B}_s \to D_s^* \tau^- \bar{\nu}$
J_1^s	0.257 ± 0.007	0.279 ± 0.006	0.255 ± 0.012	0.277 ± 0.009
J_2^c	-0.399 ± 0.008	-0.128 ± 0.001	-0.402 ± 0.015	-0.127 ± 0.002
J_2^s	0.085 ± 0.002	0.047 ± 0.001	0.085 ± 0.004	0.047 ± 0.002
J_3	-0.133 ± 0.004	-0.082 ± 0.002	-0.135 ± 0.006	-0.082 ± 0.003
J_4	-0.230 ± 0.001	-0.105 ± 0.001	-0.231 ± 0.003	-0.105 ± 0.002
J_5	0.167 ± 0.008	0.207 ± 0.005	0.161 ± 0.012	0.204 ± 0.007
J_6^c	0.011 ± 0.001	0.277 ± 0.015	0.011 ± 0.001	0.282 ± 0.023
J_6^s	-0.203 ± 0.012	-0.163 ± 0.012	-0.194 ± 0.016	-0.155 ± 0.015

summary

first simultaneous analysis of $\boldsymbol{B} \rightarrow \boldsymbol{D}^{(*)}$ and $\boldsymbol{B_s} \rightarrow \boldsymbol{D_s^{(*)}}$ form factors (FFs)

dispersive bounds beyond $SU(3)_F$ approximation ⇒ $\sim\mathbf{20\%}$ closer to saturation

⇓

stronger constrains on the FFs

first calculation of $\boldsymbol{B_s} \rightarrow \boldsymbol{D_s^*}$ FFs (except for A_1 at q^2_{max})

high precision predictions for FFs and various observables in both $\boldsymbol{B} \rightarrow \boldsymbol{D}^{(*)}$ and $\boldsymbol{B_s} \rightarrow \boldsymbol{D_s^{(*)}}$

extract $V_{cb} = 40.0 \pm 0.09 \cdot 10^{-3}$

Thank you!