Beyond the LHCb Phase-1 Upgrade, Elba, 2017-05-29

Theory prospects: $b \to qll$

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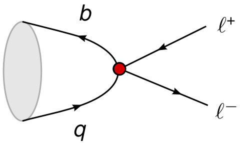
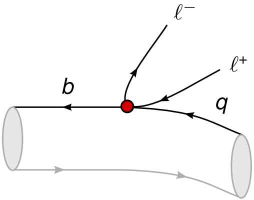
Processes sensitive to $b \to qll$

- Leptonic decays
  - $B_s \to \ell\ell$
  - $B^0 \to \ell\ell$
- Exclusive semi-leptonic decays
  - $B \to K^{(*)}\ell\ell$
  - $B \to (\rho, \pi, \omega, \eta^{(\prime)})\ell\ell$
  - $B_s \to \varphi\ell\ell$
  - $B_s \to K^{(*)0}\ell\ell$
  - $\Lambda_b \to \Lambda\ell\ell$

$q = s, d \quad \ell = e, \mu, \tau$



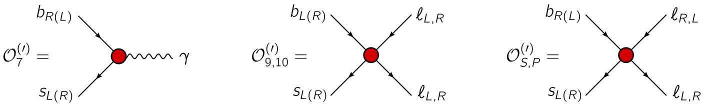


Will ignore:

- radiative decays Talk by A. Paul
- inclusive decays
- decays with >1 hadron in final state
- LFV decays Talk by J. Prisciandaro

Effective theory beyond the SM

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$



- Four-quark operators (many; enter through hadronic effects)
- Dipole operators (can be constrained by radiative decays)
- Semi-leptonic operators:

$$(Q_9^{(\prime)})_q^\ell = (\bar{q}_{L(R)}\gamma_\mu b_{L(R)})(\bar{\ell}\gamma^\mu\ell) \qquad (Q_{10}^{(\prime)})_q^\ell = (\bar{q}_{L(R)}\gamma_\mu b_{L(R)})(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$(Q_{S1}^{(\prime)})_q^\ell = m_b(\bar{q}_{L(R)} b_{R(L)})(\bar{\ell}_{R(L)}\ell_{L(R)})$$

$$(Q_{S2}^{(\prime)})_q^\ell = m_b(\bar{q}_{L(R)} b_{R(L)})(\bar{\ell}_{L(R)}\ell_{R(L)}) \qquad (Q_T^{(\prime)})_q^\ell = (\bar{q}_{R(L)}\sigma^{\mu\nu} b_{L(R)})(\bar{\ell}_{R(L)}\sigma_{\mu\nu}\ell_{L(R)})$$

Sensitivity to Wilson coefficients

Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X

- Different observables are complementary in constraining NP
- Leptonic decay uniquely sensitive to scalar operators

1. Introduction
2. Leptonic decays
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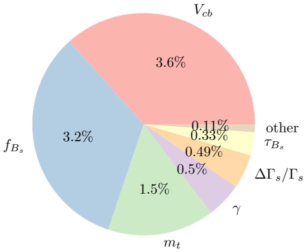
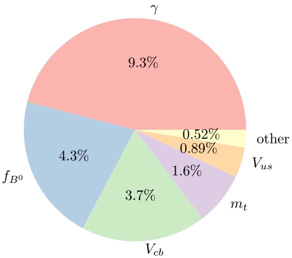
4. Semi-leptonic $b \to d$ decays

$B_q \to \mu^+\mu^-$: SM uncertainties

$\text{BR}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.60 \pm 0.19) 10^{-9}$ $\text{BR}(B^0 \to \mu^+\mu^-)_{\text{SM}} = (1.13 \pm 0.12) 10^{-10}$





- Hadronic uncertainty: only decay constants
  - LQCD: reduction by factor of a few in 10 years seems realistic
- Parametric uncertainty dominated by CKM (measure from trees!)
- Non-parametric uncertainty only 1.5% Bobeth et al. 1311.0903

$B_s \to \mu^+\mu^-$: time dependence

Untagged time-dependent rate De Bruyn et al. 1204.1737

$$\Gamma(B_s(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s(t) \to \mu^+\mu^-) \propto$$
$$\left[\cosh\left(\frac{y_s t}{\tau_{B_s}}\right) + A_{\Delta\Gamma} \sinh\left(\frac{y_s t}{\tau_{B_s}}\right)\right] \times e^{-t/\tau_{B_s}}$$

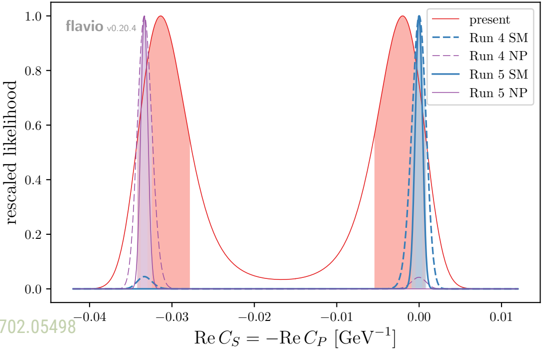
$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} = 0.065 \pm 0.005$$

$$A_{\Delta\Gamma}^{\rm SM} \equiv 1$$

$A_{\Delta\Gamma}$ is extremely **clean** and has **complementary** sensitivity to scalar op.s

Current & future constraints on C_S

scenario	$\sigma_{\text{exp}}(B_s \to \mu^+\mu^-)$	$\sigma_{\text{exp}}(A_{\Delta\Gamma})$
Run 4	0.19×10^{-9}	0.8
Run 5	0.08×10^{-9}	0.3



Altmannshofer et al. 1702.05498

Complementarity of $A_{\Delta\Gamma}$: MSSM

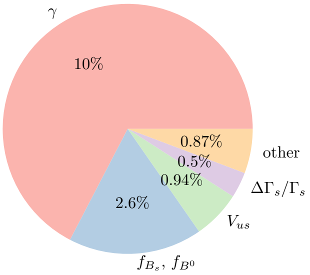
Altmannshofer et al. 1702.05498

$B_s \to \mu\mu$ vs. $B^0 \to \mu\mu$

Another very clean observable:

$$\frac{\text{BR}(B_s \to \mu^+\mu^-)}{\text{BR}(B^0 \to \mu^+\mu^-)} = \frac{\tau_{B_s^H} |V_{ts}|^2 f_{B_s}^2 m_{B_s}}{\tau_{B^0} |V_{td}|^2 f_{B^0}^2 m_{B^0}}$$

- Test of the SM and of all models with MFV
  Buras et al. hep-ph/0007085
- Current SM prediction 31 ± 3, uncertainty dominated by CKM
- Assuming the SM, can be used to extract $|V_{ts}/V_{td}|$



Comments on $B_q \to e^+e^-$ & $B_q \to \tau^+\tau^+$

- For new physics in scalar operators: no reason to expect lepton flavour universality!
- Models with LFU (e.g. to explain $R_{D^{(*)}}$) predict large effects in $B_q \to \tau^+\tau^-$
- Large enhancement of $B_q \to e^+e^-$ cannot be excluded model-independently

Leptonic decays: partial summary

- Theory uncertainties in $B_q \to \mu^+\mu^-$ branching ratios will be under control (expecting LQCD progress and improvements in CKM extractions)
- $A_{\Delta\Gamma}(B_s \to \mu^+\mu^-)$ is complementary to BR and extremely clean
- $\text{BR}(B_s \to \mu^+\mu^-)/\text{BR}(B^0 \to \mu^+\mu^-)$ tests SM & MFV
- Also important (whether observation at SM rate is feasible or not!):
  - $B_q \to e^+e^-$
  - $B_q \to \tau^+\tau^-$

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Exclusive semi-leptonic $b \to s$ transitions

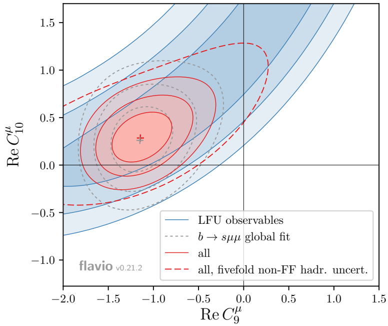
$B \to K\ell\ell$, $B \to K^*\ell\ell$, $B_s \to \varphi\ell\ell$, $\Lambda_b \to \Lambda\ell\ell$

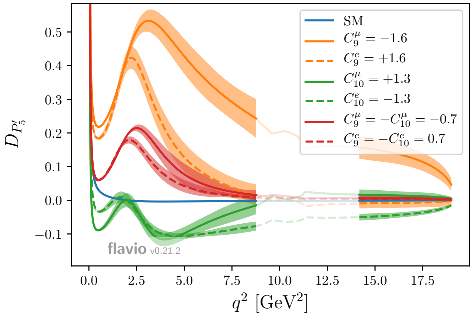
Observables:

- $\mu\mu$-ee LFU tests
  - extremely clean – no-brainer!
- $\mu\mu$ processes
  - some observables with significant hadronic uncertainties
- $\tau\tau$ processes
  - experimentally challenging but theoretically interesting (models with LFUV!)

Current tensions & future challenges

Altmannshofer et al. 1703.09189, Altmannshofer et al. 1704.05435





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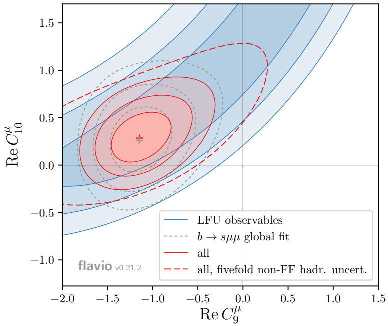

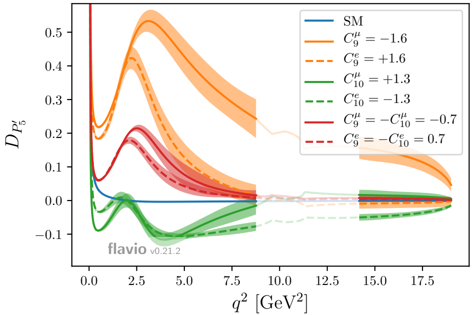

What if there is *no* violation of LFU?

Exclusive $b \to s\mu\mu$: null tests

Several observables are extremely clean

$B \to K^* \mu\mu$ & $B_s \to \varphi\mu\mu$

- T-odd angular CP asymmetries $A_{7,8,9}$
- CP-averaged angular coefficient $S_3 \propto P_1 \propto A_T^{(2)}$ at low q^2 (RH currents)

$B \to K\mu\mu$

- F_H and A_{FB}
  - NB, does not arise in weakly coupled high-scale models Alonso et al. 1407.7044, see however Catà and Jung 1505.05804

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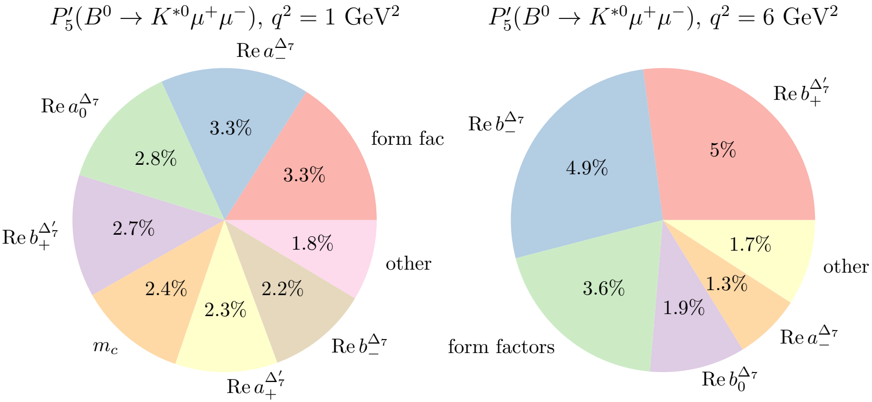
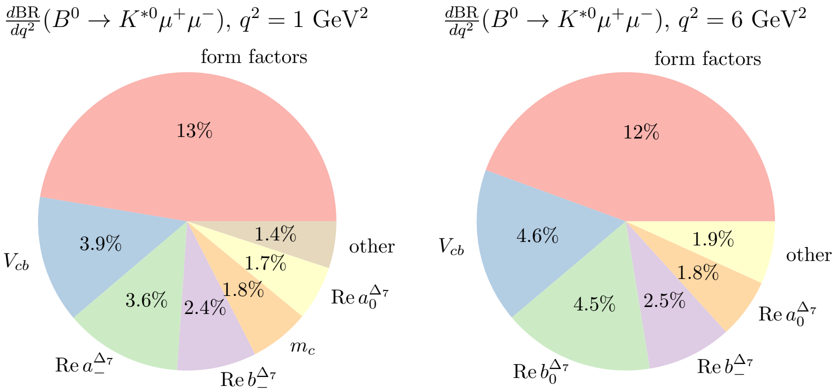
What if the null tests remain null?

SM error budgets: examples



$a_x^{\Delta_i}, b_x^{\Delta_i}, c_x^{\Delta_i}$: parametrisation of non-factorisable hadronic effects

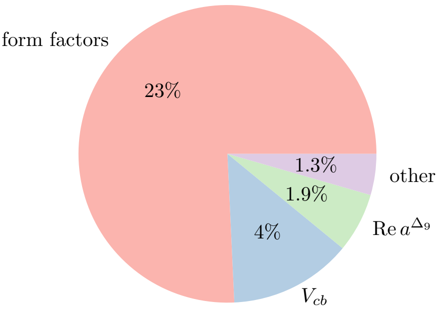
SM error budgets: examples



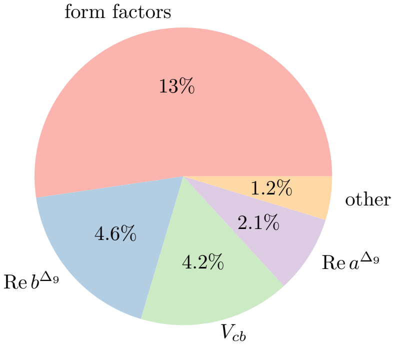
$a_x^{\Delta_i}, b_x^{\Delta_i}, c_x^{\Delta_i}$: parametrisation of non-factorisable hadronic effects

SM error budgets: examples

$\frac{d\text{BR}}{dq^2}(B^\pm \to K^\pm \mu^+\mu^-)$, $q^2 = 1\ \text{GeV}^2$

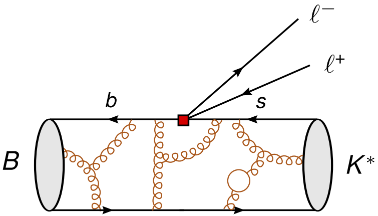


$\frac{d\text{BR}}{dq^2}(B^\pm \to K^\pm \mu^+\mu^-)$, $q^2 = 6\ \text{GeV}^2$



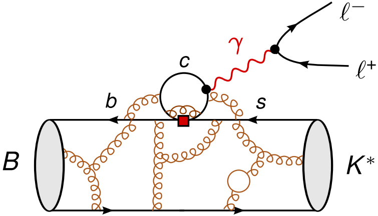
$a^{\Delta_i}, b^{\Delta_i}, c^{\Delta_i}$: parametrisation of non-factorisable hadronic effects

SM uncertainties: form factors



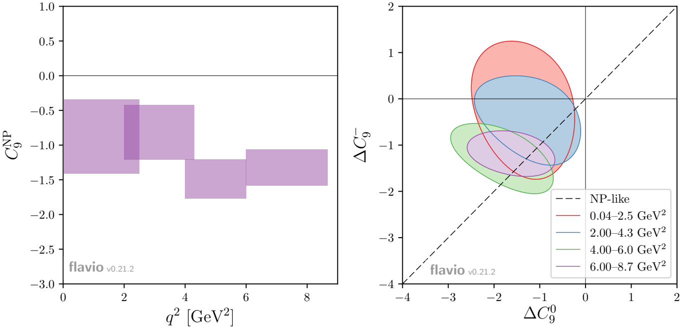
- Light-cone sum rules: already close to systematic limit
- LQCD:
  - $B \to K$: improvement by factor of a few in 10 years seems realistic (EM effects?)
  - $B \to K^*$: currently treated as stable, unknown (possibly sizable) systematic uncertainty. Solution possible see e.g. Agadjanov et al. 1605.03386
  - $B_s \to \varphi$: φ also treated as stable, possibly less problematic since narrow

SM uncertainties: hadronic effects



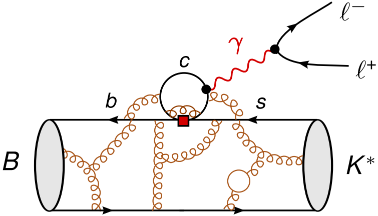
- currently dominant uncertainties for several $B \to K^* \ell\ell$ angular observables
- Making progress based on theory alone is hard ...
- ... but the huge dataset envisioned will allow to constrain these effects!

Example: q^2 dependence of C_9 best-fit



- Bin-by-bin fit to $B \to K^* \mu^+ \mu^-$ data Altmannshofer et al. 1703.09189
- NP in C_9 would give helicity and q^2 independent effect
- hadronic effect could be helicity and q^2 dependent
- See also more sophisticated Bayesian fits Ciuchini et al. 1512.07157, ...

Extracting hadronic effects from data



If no new physics in 4-quark operators, can extract/constrain hadronic effect from data cf. A. Khodjamirian et al. 1006.4945

- Use knowledge about analytic structure
- Use data on $B \to \psi^{(\prime)} K^{(*)}$
- Use data in region close to/between narrow $c\bar{c}$ resonances to determine relative strong phases

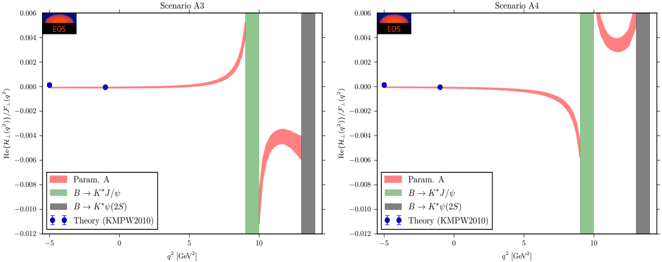
Current work in progress

:: Results Parametrization A

Preliminary

Bobeth, Chrzaszcz, van Dyk, Virto

Results for $\mathrm{Re}(\mathcal{H}_\perp/\mathcal{F}_\perp)$ **:**



Discrete ambiguity in phases of the residues : (only two shown)

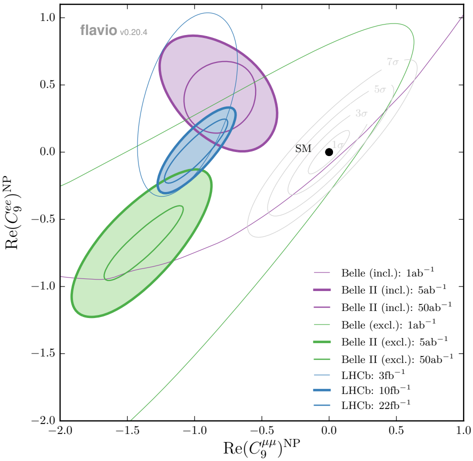
Left : $\phi_{J/\psi} = \pi$, $\phi_{\psi(2S)} = 0$ **Right :** $\phi_{J/\psi} = \phi_{\psi(2S)} = \pi$

Semi-leptonic $b \to s$: partial summary

- Plenty of very clean observables
  - $\mu\mu/ee$ LFU tests
  - null tests (S_3, $A_{7,8,9}$)
- Th. uncertainties in less clean observables will go down
  - LQCD progress both in $B \to P$ & $B \to V$ form factors expected
  - hadronic effects can be (partially) extracted from data

Currently large theory uncerainties are not showstoppers!

Future Wilson coefficient fits



- LHCb Run 4 & Belle-II uncertainty projections
- Factor of 2 reduction of form factor uncertainties assumed
- Different new physics hypothesis assumed for each experiment

J. Albrecht, F. Bernlochner, S. Reichart, DS (preliminary)

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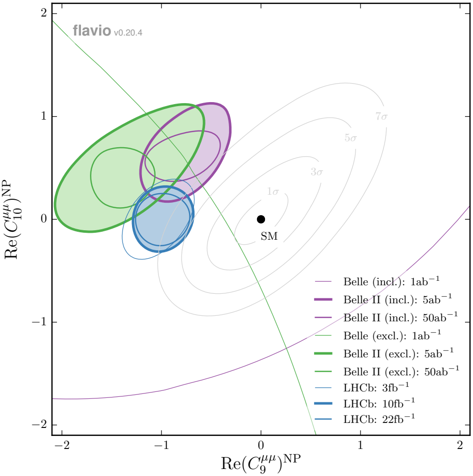

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Exclusive semi-leptonic $b \to d$ transitions

$B \to (\rho, \pi, \omega, \eta^{(\prime)})\ell\ell$, $B_s \to (K_S, K^{*0})\ell\ell$

What stays the same

- $\mu\mu/ee$ **LFU tests** are extremely clean
- $B_s \to K^*\ell\ell$ gives access to rich **angular distribution**

What changes

- **Form factors:** vector FFs can be extracted from charged-current decays $B \to (\rho, \pi, \omega, \eta^{(\prime)})\ell\nu$, $B_s \to K^{(*)+}\ell\nu$
- Different **CKM hierarchies** lead to more pronounced hadronic effects

CKM hierarchies: $b \to s$ vs. $b \to d$

$b \to s$

$$V_{tb}V_{ts}^* \approx -V_{cb}V_{cs}^* \gg V_{ub}V_{us}^*$$

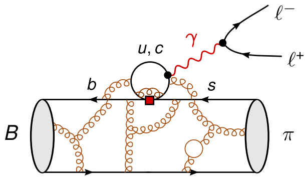
- tiny direct CP asymmetries
- hadronic uncertainties dominated by “charm loops”

$b \to d$

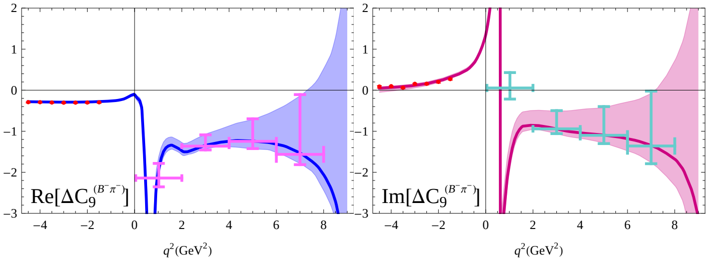
$$|V_{tb}V_{td}^*| \sim |V_{cb}V^*{}_{cd}| \quad \sim |V_{ub}V_{ud}^*|$$

- possibly sizable direct CP asymmetries
- additional hadronic uncertainties due to light-quark loops/light meson resonances

Hadronic effects in $b \to d\ell\ell$



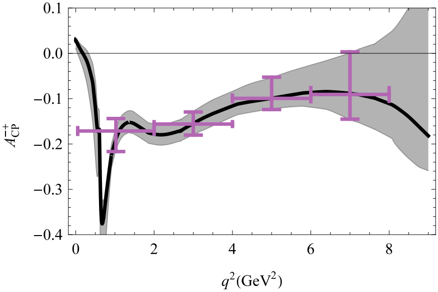
- Example: effective shift in C_9 for $B^- \to \pi^-\ell^+\ell^-$ Hambrock et al. 1506.07760



New observables

Given sizable strong phases, new observables become relevant that can be used to constrain hadronic effects

- Direct CP asymmetries Hambrock et al. 1506.07760, see also Khodjamirian and Rusov 1703.04765



- $B_s \to K^{*0}\ell^+\ell^-$ angular observables that are suppressed in $b \to s\ell\ell$
  - CP asymmetries $A_{3,4,5,6}$
  - CP-averaged $S_{7,8,9}$

Semi-leptonic $b \to d$: partial summary

- Main novel theory challenge: sizable hadronic effects $\propto V_{ub}V_{ud}^*$
- New observables (e.g. A_{CP}, $S_{7,8,9}$, ...) allow to constrain these effects