Massachusetts Institute of Technology

Technische Universität München

Theory Predictions for Rare B decays

Javier Virto

Massachusetts Institute of Technology

and

Technische Universität München

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Marie Skłodowska-Curie Actions

Rare Decays (of hadrons)

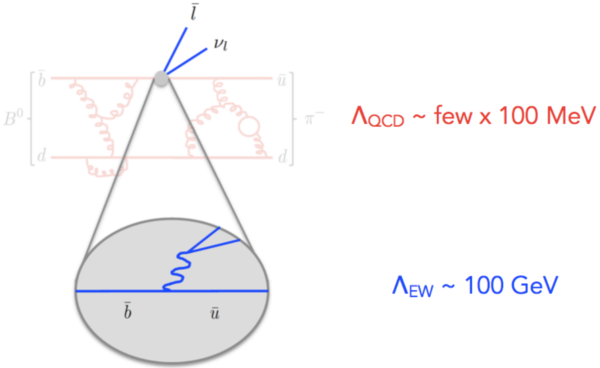
- Rare decays are those suppressed in the SM by e.g. loop, GIM, helicity, etc. They are very sensitive to BSM contributions.
- Rare decays have typically $\mathcal{B} < 10^{-6}$. Examples:

$$\mathcal{B}(K \to \pi\nu\bar{\nu}) \sim 10^{-11} \quad \mathcal{B}(K_S \to \mu^+\mu^-) \sim 10^{-12} \quad \mathcal{B}(K \to \pi\ell\ell) \sim 10^{-7}$$
$$\mathcal{B}(D \to \rho\ell\ell) \sim 10^{-9} \quad \mathcal{B}(B \to K^*\ell\ell) \sim 10^{-6} \quad \mathcal{B}(B_s \to \mu^+\mu^-) \sim 10^{-9}$$

- Nevertheless, some rare decays are no longer 'rare' at the LHC!
  E.g. $N(B \to K^*\mu\mu)_{\text{Run 1}} = 2398 \pm 57$
- Thus we require now theory predictions with $\sigma_{th} \lesssim 10\%$.

Effective Field Theory

- At scales $\mu \lesssim m_b$: $\mathcal{L}_{\rm (B)SM} \longrightarrow \mathcal{L}_{\rm WET} = \mathcal{L}_{\rm QED+QCD}^{e,\mu,\tau,u,d,s,c,b} + C_i(\mu)\, \mathcal{O}_i(\mu)$



- EFT is **convenient** but also **necessary**.

EFT Predictions

Thus predictions for hadron decay observables require **three** ingredients:

1. Construct the EFT (operators, matching conditions, Anomalous dimensions)

   Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06

   Aebischer, Crivellin, Fael, Greub '16, Aebischer, Fael, Greub, Virto '17, Jenkins, Manohar, Stoffer '17, ...

2. Calculate the decay amplitudes in the EFT, in terms of 'canonical' non-perturbative objects (matrix elements).

3. Deal with the non-peturbative matrix elements.

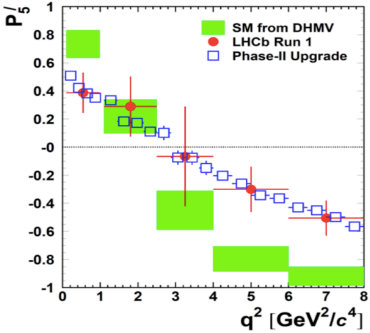
QCD anatomy of heavy-meson decays

Different non-pertubative objects and tools are needed :

1.	Inclusive semileptonic:	$B_q \to X\ell\nu$	HQE
2.	Exclusive leptonic:	$B_q \to \ell\ell$	f_B
3.	Inclusive rad./dileptonic:	$B_q \to X\gamma, X\ell\ell$	HQE + factorization
4.	Exclusive semileptonic:	$B_q \to M\ell\nu$	$F^{B\to M}$
5.	Exclusive rad./dileptonic:	$B_q \to V\gamma, M\ell\ell$	$F^{B\to M}$ + factorization
6.	Exclusive non-leptonic:	$B_q \to M_1 M_2$	factorization + $F^{B\to M}$ + Φ_M
	NIOBE®	$B_q \to M_1 M_2 M_3$	factorization + ???

Plan for the talk

Guidelines from the conveners: Instead of covering everything, focus on selected subtopics of high interest and discuss them in more depth.



CERN-LHCC-2017-003, LHCb EoI (LHCb ~ 2035)

☐ Bottleneck is SM uncertainties:

Assuming vanishing exp uncertainties

$\text{Pull}(P_5'^{[2.5,4.0]}) = 3.5\sigma$

$\text{Pull}(P_5'^{[4.0,6.0]}) = 6.5\sigma$

$\text{Pull}(P_5'^{[6.0,8.0]}) = 5.4\sigma$

This talk will focus on Exclusive $b \to s$ transitions. **Proxy for many others.**

Plan for the talk

1. Anatomy of $B \to K^{(*)}\ell\ell$ EFT Amplitudes

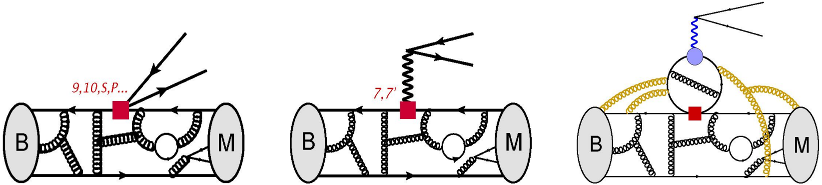
2. Local Form Factors
   - Lattice vs LCSRs
   - Large-recoil relations
   - Finite-width effects
   - q^2-dependence

3. Non-Local Form Factors
   - Factorization
   - z-parametrization
   - Tests ‘a posteriori’

4. LCDAs (not covered today)

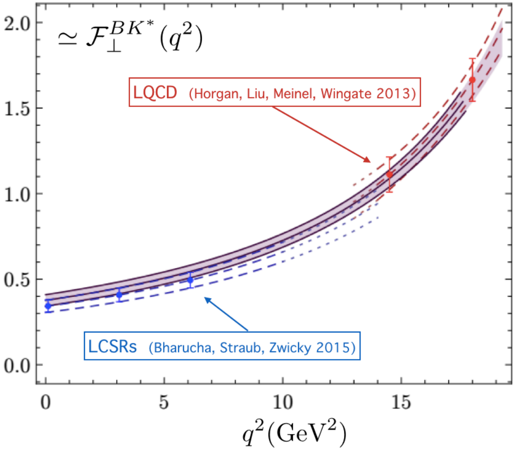
5. EM corrections (not covered today)

Anatomy of $B \to M_\lambda \ell^+ \ell^-$ EFT Amplitudes



$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

- Local (Form Factors) : $\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k) | \, \bar{s}\, \Gamma_\lambda^{(T)} \, b \, | \bar{B}(k+q) \rangle$
- Non-Local : $\mathcal{H}_\lambda(q^2) = i \mathcal{P}_\mu^\lambda \int d^4x \, e^{iq\cdot x} \langle \bar{M}_\lambda(k) | \, T\{ \mathcal{J}^\mu_{\rm em}(x), \mathcal{C}_i \, \mathcal{O}_i(0) \} | \bar{B}(q+k) \rangle$



q^2-dependence :

$\mathcal{F}(q^2) \propto \sum_k \alpha_k\, z(q^2)^k$

"z-parametrization"

Bourrely, Caprini, Lellouch

"Optimized" observables :

$P_1, P_2, \boldsymbol{P_5'}, \dots$ (a full *basis*)

Mescia, Matias, Ramon, JV, 1202.4266
Descotes-Genon, Matias, Ramon, JV, 1207.2753
Descotes-Genon, Hurth, Matias, JV, 1303.5794

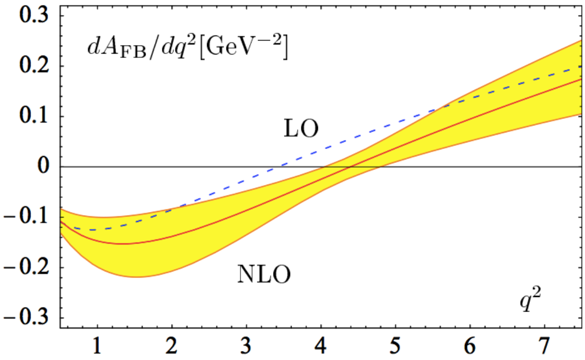
Finite width effects : $B \to K^*(\to K\pi)$

Accessible via LCSRs

Cheng, Khodjamirian, JV, 1701.01633
Cheng, Khodjamirian, JV, 1709.00173

$\mathcal{B}(B \to K^* \mu\mu)$ Forward-Backward Asymmetry Zero

Beneke, Feldmann, Seidel 2001



Partial cancellation of hadronic uncertainties in the zero-crossing

Hadronic Form Factors at Large Recoil

Beneke, Feldmann 2000; Descotes-Genon, Hofer, Matias, JV 2014

$$
\begin{aligned}
V(q^2) &= \frac{m_B + m_{K^*}}{m_B}\,\xi_\perp(q^2) + \Delta V^{\alpha_s}(q^2) + \Delta V^{\Lambda}(q^2)\,,\\
A_1(q^2) &= \frac{2E}{m_B + m_{K^*}}\,\xi_\perp(q^2) + \Delta A_1^{\alpha_s}(q^2) + \Delta A_1^{\Lambda}(q^2)\,,\\
A_2(q^2) &= \frac{m_B}{m_B - m_{K^*}}\left[\xi_\perp(q^2) - \xi_\parallel(q^2)\right] + \Delta A_2^{\alpha_s}(q^2) + \Delta A_2^{\Lambda}(q^2)\,,\\
A_0(q^2) &= \frac{E}{m_{K^*}}\,\xi_\parallel(q^2) + \Delta A_0^{\alpha_s}(q^2) + \Delta A_0^{\Lambda}(q^2)\,,\\
T_1(q^2) &= \xi_\perp(q^2) + \Delta T_1^{\alpha_s}(q^2) + \Delta T_1^{\Lambda}(q^2)\,,\\
T_2(q^2) &= \frac{2E}{m_B}\,\xi_\perp(q^2) + \Delta T_2^{\alpha_s}(q^2) + \Delta T_2^{\Lambda}(q^2)\,,\\
T_3(q^2) &= \left[\xi_\perp(q^2) - \xi_\parallel(q^2)\right] + \Delta T_3^{\alpha_s}(q^2) + \Delta T_3^{\Lambda}(q^2)\,,
\end{aligned}
$$

$B \to K^*\ell\ell$ "Optimized" observables

- The K^* helicity provides an extra valuable degree of freedom
- In the Heavy-Quark limit some relations among form factors arise:

$$\text{e.g.} \qquad \frac{\epsilon_-^{*\mu} q^\nu \langle K_-^* | \bar{s}\sigma_{\mu\nu} P_R b | B\rangle}{i m_B \langle K_-^* | \bar{s} \not{\epsilon}_-^* P_L b | B\rangle} = 1 + \mathcal{O}(\alpha_s, \Lambda/m_b)$$

- One can build observables that depend only on these ratios, e.g.:

$$P_5' = \sqrt{2}\, \frac{\mathrm{Re}(\mathcal{A}_0^L \mathcal{A}_\perp^{L*} - \mathcal{A}_0^R \mathcal{A}_\perp^{R*})}{\sqrt{|\mathcal{A}_0|^2 (|\mathcal{A}_\perp|^2 + |\mathcal{A}_\parallel|^2)}}$$

A full basis of "optimized" observables exists.

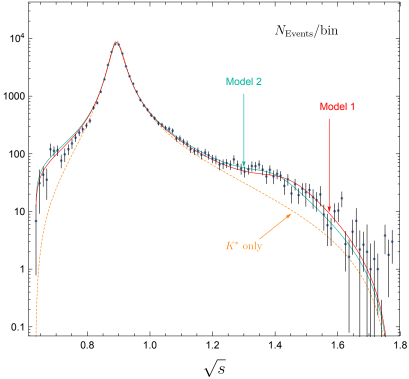
Mescia, Matias, Ramon, JV, 1202.4266
Descotes-Genon, Matias, Ramon, JV, 1207.2753

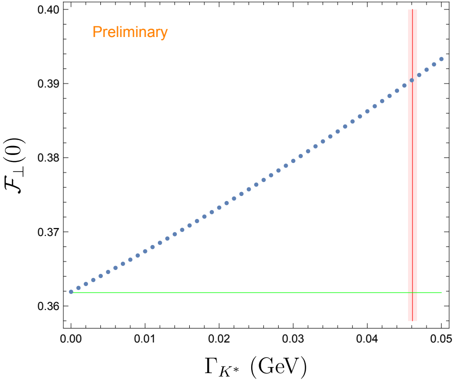
- These observables should be less sensitive to "miscalculations".

Finite-width effects (new)

Khodjamirian, Mannel, Offen 2006; Cheng, Khodjamirian, JV 2017, Descotes-Genon, Khodjamirian, JV, w.i.p.

$$\mathrm{Im}\langle 0|\,T\{j_{K^*},j_{sb}\}|B\rangle \sim \langle 0|j_{K^*}\underbrace{|K^*\rangle\langle K^*|}_{|K\pi\rangle\langle K\pi|}j_{sb}|B\rangle$$

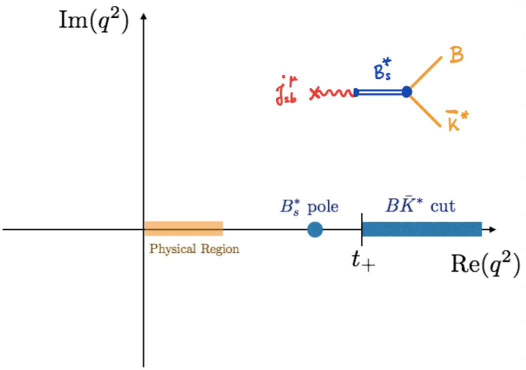




- Order 10% finite-width effects, similar to $B\to\rho$ form factors.

Form Factors : q^2-dependence from analyticity

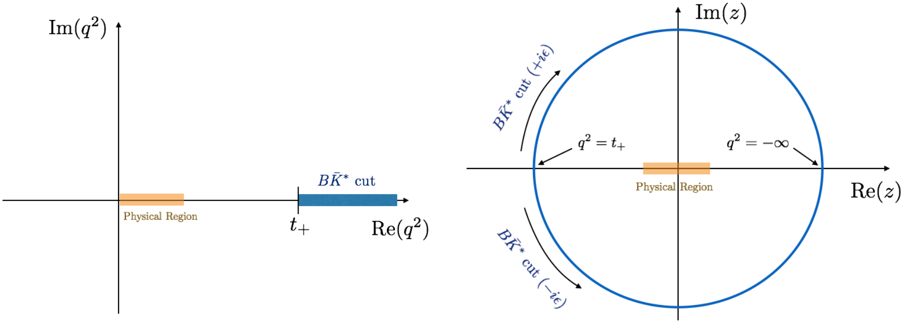
$\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k)|\,\bar{s}\,\Gamma_\lambda^{(T)}\,b\,|\bar{B}(k+q)\rangle$: Analytic structure in q^2 :



$\widehat{\mathcal{F}}_\lambda^{(T)}(q^2) \equiv (q^2 - m^2_{B_s^*})\,\mathcal{F}_\lambda^{(T)}(q^2)$ has no pole, only cut.

Form Factors : q^2-dependence from analyticity

- Conformal mapping : $$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$



- "z-parametrization" : $\widehat{\mathcal{F}}_\lambda^{(T)}(q^2(z))$ is **analytic in** $|z| < 1$

$$\mathcal{F}_\lambda^{(T)}(q^2) = \frac{1}{(q^2 - m_{B_s^*}^2)} \sum_k \alpha_k \, z(q^2)^k$$

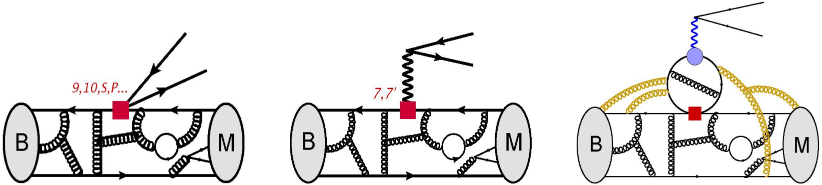
Bourrely, Caprini, Lellouch

E.g. $B \to K$ form factors $f_{0,+,T}$ from LQCD $(|z_{\rm phys}| < 0.15)$

	b_0^+	b_1^+	b_2^+	b_0^0	b_1^0	b_2^0	b_0^T	b_1^T	b_2^T
Mean	0.466	-0.885	-0.213	0.292	0.281	0.150	0.460	-1.089	-1.114
error	0.014	0.128	0.548	0.010	0.125	0.441	0.019	0.236	0.971
b_0^+	1	0.450	0.190	0.857	0.598	0.531	0.752	0.229	0.117
b_1^+		1	0.677	0.708	0.958	0.927	0.227	0.443	0.287
b_2^+			1	0.595	0.770	0.819	-0.023	0.070	0.196
b_0^0				1	0.830	0.766	0.582	0.237	0.192
b_1^0					1	0.973	0.324	0.372	0.272
b_2^0						1	0.268	0.332	0.269
b_0^T							1	0.590	0.515
b_1^T								1	0.897
b_2^T									1

Fermilab-MILC 1509.06235

Anatomy of $B \to M_\lambda \ell^+\ell^-$ EFT Amplitudes



$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2) \right] \right\}$$

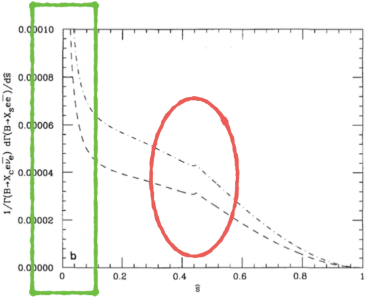
- Local (Form Factors) : $\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k) |\, \bar{s}\,\Gamma_\lambda^{(T)}\, b \,| \bar{B}(k+q) \rangle$
- Non-Local : $\mathcal{H}_\lambda(q^2) = i\mathcal{P}_\mu^\lambda \int d^4x\, e^{iq\cdot x} \langle \bar{M}_\lambda(k) | T\{\mathcal{J}_{\rm em}^\mu(x), \mathcal{C}_i\, \mathcal{O}_i(0)\} | \bar{B}(q+k) \rangle$

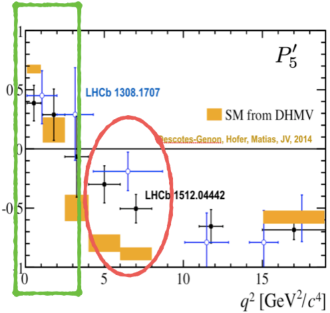
‘Non-local’ form factors

- **QCD Factorization** Beneke, Feldmann, Seidel 2001

$$\mathcal{H}_\lambda(q^2) \sim \Delta C_9^\lambda(q^2)\,\mathcal{F}_\lambda(q^2) + \frac{1}{q^2}\Delta C_7^\lambda(q^2)\,\mathcal{F}_\lambda^T(q^2) + HSS + \mathcal{O}(\Lambda/m_B, \Lambda/E)$$

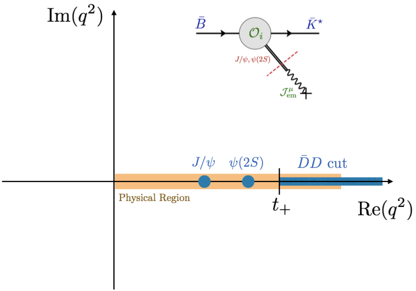
- It is assumed that the charm loop is dominated by short distances

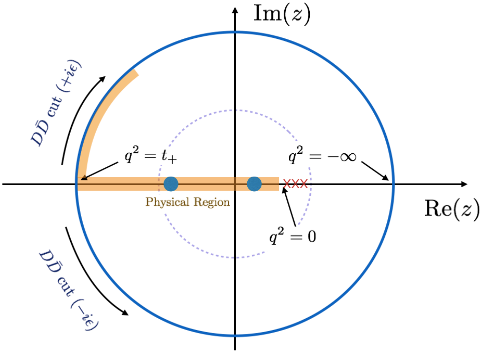




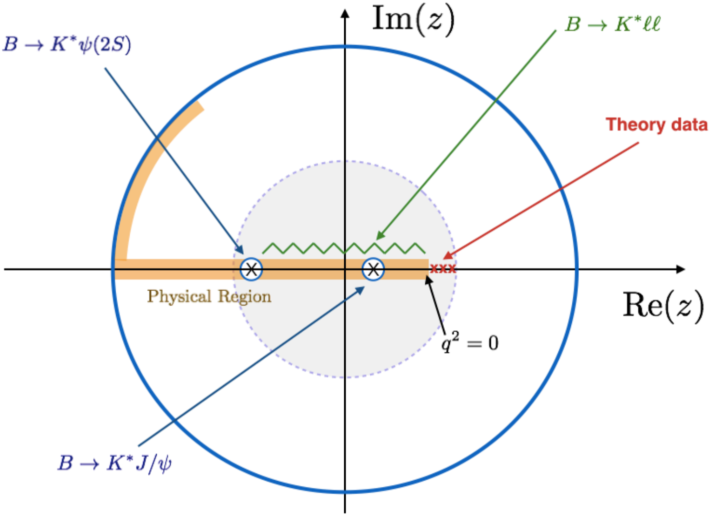
- Kink at $q^2 = 4m_c^2$ symptom of breaking of perturbativity

Same strategy as form factors!

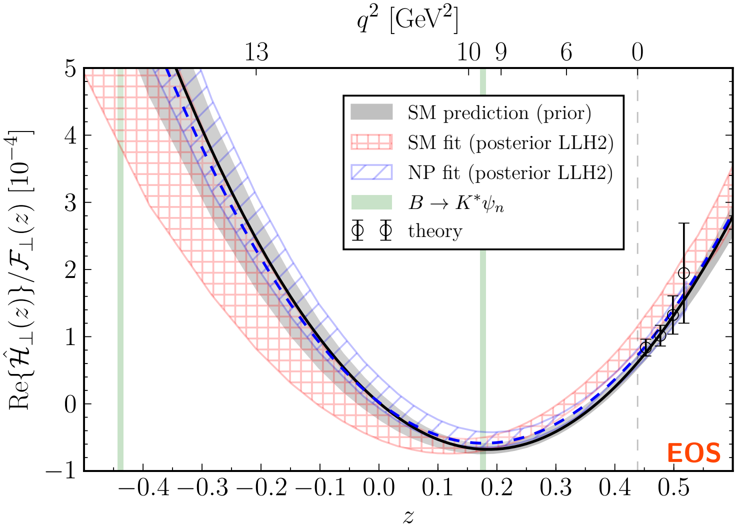




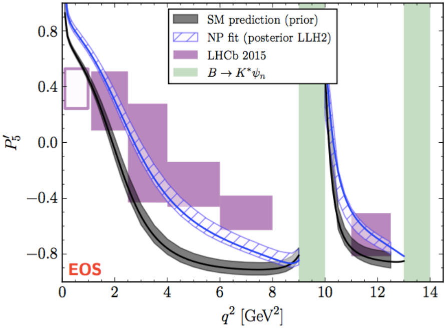
- $\hat{\mathcal{H}}_\lambda(q^2(z)) = (q^2 - M^2_{J/\psi})(q^2 - M^2_{\psi(2S)})\,\mathcal{H}_\lambda(q^2)$ is analytic in $|z| < 1$
- Taylor expand $\hat{\mathcal{H}}_\lambda(z)$ around $z = 0$: $\hat{\mathcal{H}}_\lambda(z) = \left[\sum_{k=0}^{K} \alpha_k^{(\lambda)}\, z^k\right] \mathcal{F}_\lambda(z)$
- Expansion needed for $|z| < 0.52$ $\left(-7\,\mathrm{GeV}^2 \leq q^2 \leq 14\mathrm{GeV}^2 \right)$

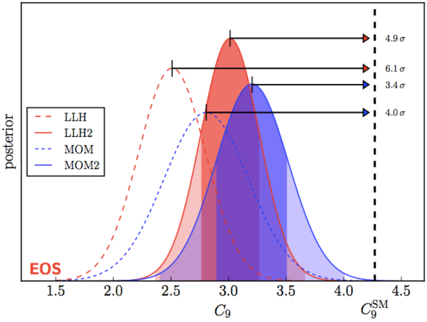

Im(z)
$B \to K^* \psi(2S)$
$B \to K^* \ell\ell$
Theory data
Physical Region
Re(z)
$q^2 = 0$
$B \to K^* J/\psi$

Bobeth, Chrzaszcz, van Dyk, JV, 1707.07305



SM predictions and Fit including $B \to K^* \mu^+ \mu^-$ data and $\mathcal{C}_9^{\rm NP}$:



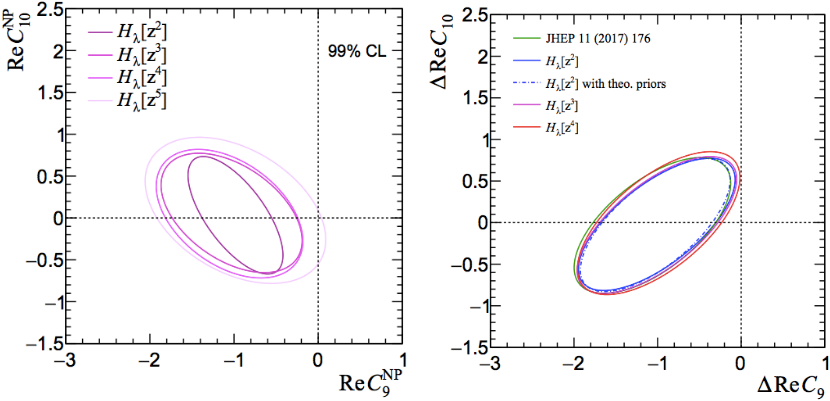


The NP hypothesis with $\mathcal{C}_9^{\rm NP} \sim -1$ is favored strongly in the global fit

Prospects: LHC Run-2 unbinned fits to z-parametrization

Chrzaszcz, Mauri, Serra, Coutinho, van Dyk 1805.06378

Mauri, Serra, Coutinho 1805.06401

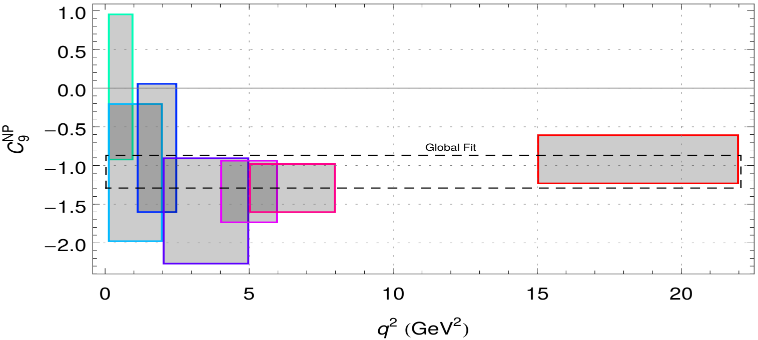


Unbinned fits to $B \to K^* \mu\mu$ (Left) and $B \to K^* \ell\ell$ (Right)

‘A posteriori’ test of non-local effect

☐ Testing the data : q^2-dependence

Descotes-Genon, Hofer, Matias, JV 1510.04239



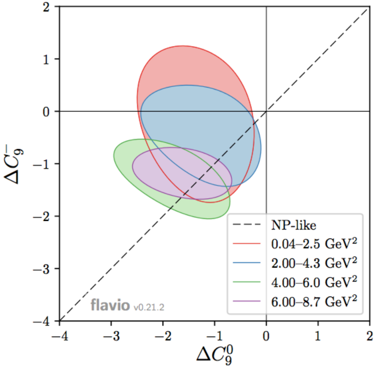
☐ Tiny uncertainites will allow to test hadronic contributions precisely

See also Altmannshofer, Straub 1503.06199, Ciuchini et al 1512.07157, Chobanova et al 1702.02234

‘A posteriori’ test of non-local effect

☐ Testing the data : K^*-helicity dependence

Altmannshofer, Niehoff, Stangl, Straub 1703.09189



☐ Tiny uncertainites will allow to test hadronic contributions precisely

Summary

- EFT Predictions for rare decays are limited by the determination of 'local' and 'non-local' form factors.
- For 'local' form factors LQCD is promising, but:
  1. Need LCSRs for q^2 interpolation
  2. Finite width effects can be sizeable (currently beyond LQCD)
  3. Optimize observables exist, but power corrections
- The 'non-local' form factors are the focus of most current efforts
  1. Need new ideas from LQCD
  2. Analyticity methods promising, but still rely on factorization @ $q^2 < 0$
  3. Unitarity bounds?
  4. 'A posteriori' tests / combined fits to NP and data promising @ Phase II.
- Many things left out (large q^2, baryonic, inclusive, EM corrections, …)

Thank you

Extra slides

Experimental constraints on z parametrisation $[B \to K^* \ell\ell]$

Bobeth, Chrzaszcz, van Dyk, Virto 2017

Experimental constraints :

- The residues of the poles are given by $B \to K^* \psi_n$:

$$\mathcal{H}_\lambda(q^2 \to M_{\psi_n}^2) \sim \frac{M_{\psi_n} f_{\psi_n}^* \mathcal{A}_\lambda^{\psi_n}}{M_B^2 (q^2 - M_{\psi_n}^2)} + \cdots$$

- Angular analyses Belle, Babar, LHCb determine :

$$|r_\perp^{\psi_n}|, \; |r_\parallel^{\psi_n}|, \; |r_0^{\psi_n}|, \; \arg\{r_\perp^{\psi_n} r_0^{\psi_n *}\}, \; \arg\{r_\parallel^{\psi_n} r_0^{\psi_n *}\},$$

where $\quad r_\lambda^{\psi_n} \equiv \underset{q^2 \to M_{\psi_n}^2}{\mathrm{Res}} \frac{\mathcal{H}_\lambda(q^2)}{\mathcal{F}_\lambda(q^2)} \sim \frac{M_{\psi_n} f_{\psi_n}^* \mathcal{A}_\lambda^{\psi_n}}{M_B^2 \, \mathcal{F}_\lambda(M_{\psi_n}^2)}$

- We produce correlated pseudo-observables from a fit (5+5).

Prior Fit to z parametrisation $[B \to K^*\ell\ell]$

Bobeth, Chrzaszcz, van Dyk, Virto 2017

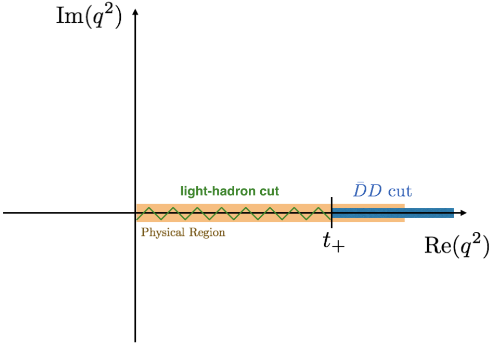
(Prior) Fit to Experimental and theoretical pseudo-observables :

k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

Table 1: Mean values and standard deviations (in units of 10^{-4}) of the prior PDF for the parameters $\alpha_k^{(\lambda)}$.

Light-hadron cut

The non-local ME of $O^c_{1,2}$ also contains a cut at low q^2 from intermediate "light-hadron" states:



$$\mathrm{Disc}[\mathcal{H}_\lambda(q^2 > t_+)] \sim \sum_X \langle 0|j_{\mathrm{em}}|X^{1^{--}}_{cc}\rangle\langle X^{1^{--}}_{cc} K^*|(\bar{s}c)(\bar{c}b)|\bar{B}\rangle$$

$$\mathrm{Disc}[\mathcal{H}_\lambda(0 < q^2 < t_+)] \sim \sum_X \langle 0|j_{\mathrm{em}}|X^{1^{--}}\rangle\langle X^{1^{--}} K^*|(\bar{s}c)(\bar{c}b)|\bar{B}\rangle$$

Light-hadron cut

⋆ Support for $\langle X^{1^{--}} K^* | (\bar{s}c)(\bar{c}b) | \bar{B}\rangle \ll \langle X_{cc}^{1^{--}} K^* | (\bar{s}c)(\bar{c}b) | \bar{B}\rangle$:

- OZI rule.
- $\mathcal{B}(B \to K^{(*)}\omega) \approx 2 \text{ - } 5 \cdot 10^{-6}$ (in agr. with QCDF from $[\bar{s}q][\bar{q}b]$)

$$\Rightarrow \langle K^*\omega | (\bar{s}c)(\bar{c}b) | \bar{B}\rangle \lesssim \underbrace{C_q/C_c}_{few\,\%} \langle K^*\omega | (\bar{s}q)(\bar{q}b) | \bar{B}\rangle$$

- Same argument for $\mathcal{B}(B \to K^{(*)}\phi)$
- In absence of OZI, the natural size of these BRs is 10^{-3} not 10^{-6} :

$$\mathcal{B}(B \to KJ/\psi) = 9 \times 10^{-4} \qquad \mathcal{B}(B \to K^* J/\psi) = 1.3 \times 10^{-3}$$
$$\mathcal{B}(B \to K[D^*\bar{D}]) = 6 \times 10^{-3} \qquad \mathcal{B}(B \to K[D^*\bar{D}^*]) = 8 \times 10^{-3}$$
$$\mathcal{B}(B \to K[D\bar{D}]) = 5 \times 10^{-4}$$

- Note also the **total** BR: $\mathcal{B}(B \to K^{(*)}[\bar{K}K]) \sim 10^{-5} \ll 10^{-3}$
- Test: $\mathcal{B}(B \to K^{(*)} X^{1^{--}}(\text{high mass})) \ll 10^{-3}$

Light-hadron cut

Conclusion: OZI $\rightarrow$ Two order of magnitude suppression.

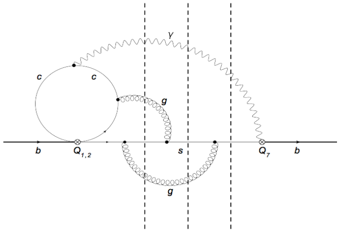
- But CKM- and penguin-suppressed light-quark loops are there.
- Not OZI suppressed.
- Must be constrained if precision is sought (but rough estimate might suffice).
- Can do dispersive analysis Khodjamirian, Mannel, Wang 2012 ...
- Could use $b \rightarrow d$ analogues + U-spin.

Inclusive Heavy Meson Decay:

☐ Optical Theorem

☐ Heavy-Quark Expansion

☐ Subleading Shape Functions



$$\Gamma(\bar{B} \to X_s\gamma)_{E_0} = \underbrace{\Gamma(b \to s\gamma) + \Gamma(b \to sg\gamma)}_{\text{Known @ NNLO}^{(1)}} + \underbrace{\Gamma(b \to sq\bar{q}\gamma)}_{\text{Known @ NLO}^{(2)}} + \cdots + \underbrace{\mathcal{O}(1/m_b)}_{\sim 5\%^{(3)}}$$

(1) Misiak et al (many papers) and a tiny few w/o Misiak

(2) Huber, Poradzinski, JV, 1411.7677

(3) For $E_0 \sim 1.6$ GeV, Benzke, Lee, Neubert, Paz, 1003.5012

$$\mathcal{B}^{\text{th}}_{s\gamma} = (3.36 \pm 0.23) \cdot 10^{-4}\ (7\%)^{(4)} \quad \text{vs.} \quad \mathcal{B}^{\text{exp}}_{s\gamma} = (3.43 \pm 0.22) \cdot 10^{-4}\ (6\%)^{(5)}$$

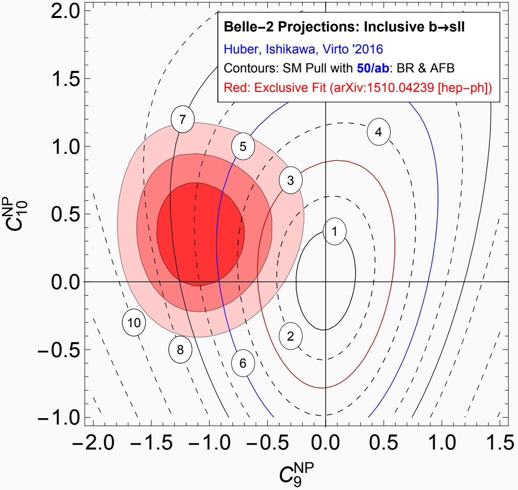
(4) Misiak, JV, et al, 1503.01789

(5) CLEO + BaBar + Belle

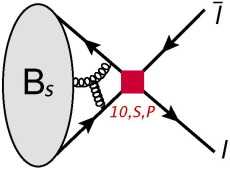
Note : $\Gamma_{LO} \sim |\mathcal{C}_7|^2 + |\mathcal{C}'_7|^2$

Complementarity with inclusive measurements at Belle-2

- Belle-II is directly sensitive to the $b \to s$ anomaly with $B \to X_s\, \mu^+\mu^-$



Huber, Ishikawa, JV, "The Belle II Physics Book"



$\propto \langle 0|\bar{s}\gamma^\mu\gamma_5\, b|B_s\rangle \equiv f_{B_s}\, p_B^\mu$ (Decay Constant)

	LQCD [1]	QCDSRs [2]
f_B	186(4)	207(17)
f_{B_s}	224(5)	242(17)

[1] FLAG 1607.00299 ; [2] Gelhausen, Khodjamirian, Pivovarov, Rosenthal 1305.5432

$$BR(B_s \to \ell\bar{\ell}) = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s}^3}{2\pi}\sqrt{1-\frac{4m_\ell^2}{m_{B_s}^2}}\,|\mathcal{C}_S^-|^2 + \left|\mathcal{C}_P^- + \frac{2m_\ell}{m_{B_s}}(\mathcal{C}_{10}-\mathcal{C}'_{10})\right|^2$$

$\bar{\mathcal{B}}_{s\mu}^{\rm th} = (3.65 \pm 0.23)\cdot 10^{-9}\ (6.4\%)$[3] vs. $\bar{\mathcal{B}}_{s\mu}^{\rm exp} = (2.9 \pm 0.7)\cdot 10^{-9}\ (24\%)$[4]

(main th. uncertainties: f_B and CKM ; exp: statistic-dominated)

[3] Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser'2014 ; [4] CMS+LHCb 1411.4413

$b \to s\ell\ell$ Observables – Total ~ 174

$B_s \to \mu^+\mu^-$	$B \to X_s\mu^+\mu^-$	$B \to K^*\gamma$	$B \to X_s\gamma$
$B \to K\mu\mu$	$B \to K^*\mu\mu$	$B_s \to \Phi\mu\mu$	$\Lambda_b \to \Lambda\mu\mu$
BRs	AOs	Low q^2	Large q^2
R_K	R_{K^*}	LFU	LFUV
LHCb	Belle/BaBar	ATLAS	CMS

“Anomalies”

- Observables with larger pulls:

Largest pulls	$\langle P_5' \rangle_{[4,6]}$	$\langle P_5' \rangle_{[6,8]}$	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$	$\mathcal{B}^{[2,5]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[5,8]}_{B_s\to\phi\mu^+\mu^-}$
Experiment	-0.30 ± 0.16	-0.51 ± 0.12	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$	0.77 ± 0.14	0.96 ± 0.15
SM prediction	-0.82 ± 0.08	-0.94 ± 0.08	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01	1.55 ± 0.33	1.88 ± 0.39
Pull (σ)	-2.9	-2.9	+2.6	+2.3	+2.6	+2.2	+2.2
Prediction for $\mathcal{C}_{9\mu}^{\rm NP}=-1.1$	-0.50 ± 0.11	-0.73 ± 0.12	0.79 ± 0.01	0.90 ± 0.05	0.87 ± 0.08	1.30 ± 0.26	1.51 ± 0.30
Pull (σ)	-1.0	-1.3	+0.4	+1.9	+1.2	+1.8	+1.6

Effective Theory for $b \to s$ Transitions

For $\Lambda_{\rm EW}, \Lambda_{\rm NP} \gg M_B$: General model-indep. parametrization of NP :

$$\mathcal{L}_W = \mathcal{L}_{\rm QCD} + \mathcal{L}_{\rm QED} + \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^\star \sum_i \mathcal{C}_i(\mu)\, \mathcal{O}_i(\mu)$$

$$\mathcal{O}_1 = (\bar c \gamma_\mu P_L b)(\bar s \gamma^\mu P_L c) \qquad \mathcal{O}_2 = (\bar c \gamma_\mu P_L T^a b)(\bar s \gamma^\mu P_L T^a c)$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar s \sigma_{\mu\nu} P_R b) F^{\mu\nu} \qquad \mathcal{O}_{7'} = \frac{e}{16\pi^2} m_b (\bar s \sigma_{\mu\nu} P_L b) F^{\mu\nu}$$

$$\mathcal{O}_{9\ell} = \frac{\alpha}{4\pi} (\bar s \gamma_\mu P_L b)(\bar\ell \gamma^\mu \ell) \qquad \mathcal{O}_{9'\ell} = \frac{\alpha}{4\pi} (\bar s \gamma_\mu P_R b)(\bar\ell \gamma^\mu \ell)$$

$$\mathcal{O}_{10\ell} = \frac{\alpha}{4\pi} (\bar s \gamma_\mu P_L b)(\bar\ell \gamma^\mu \gamma_5 \ell) \qquad \mathcal{O}_{10'\ell} = \frac{\alpha}{4\pi} (\bar s \gamma_\mu P_R b)(\bar\ell \gamma^\mu \gamma_5 \ell),$$

SM contributions to $\mathcal{C}_i(\mu_b)$ known to NNLL Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06

$$\mathcal{C}_{7\rm eff}^{\rm SM} = -0.3,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3,\ \mathcal{C}_1^{\rm SM} = 1.1,\ \mathcal{C}_2^{\rm SM} = -0.4,\ \mathcal{C}_{\rm rest}^{\rm SM} \lesssim 10^{-2}$$