Project C2b
Exclusive non-leptonic and rare *b*-quark decays

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Outline

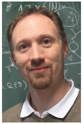
- Personnel
- Motivation
- Scope and work areas
- Role within SFB

Personnel

- Principal Investigators

Guido Bell

Thorsten Feldmann



Tobias Huber

- CRC-funded personnel

Marzia Bordone (SI)
from 10/2019

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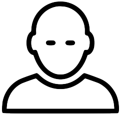
from 10/2019



N.N., PhD. (SI)
from 07/2019

- Additional personnel

Oscar Catà (SI)

Keri Vos (SI)

Motivation I

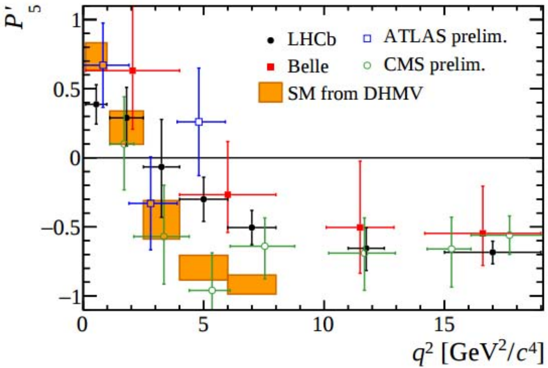
- Non-leptonic B decays, structure of amplitude

$$\mathcal{A}(\bar{B} \to f) = \lambda_u^{(D)}\, A_f^u + \lambda_c^{(D)}\, A_f^c = \sum_i \left[\lambda_{\rm CKM} \;\times\; C \;\times\; \langle f|\mathcal{O}|\bar{B}\rangle_{\rm QCD+QED}\right]_i$$

- Interplay between
  - Wilson coefficients C of tree ($C \sim 1$) or penguin ($C \sim 0.1$) operator
  - CKM factors $\lambda_p^{(D)} = V_{pb}\, V_{pD}^*$. Hierarchy of CKM elements, weak phase
  - Hadronic matrix elements $\langle f|\mathcal{O}|\bar{B}\rangle$ $\to$ C2a. Contain strong phases.
- Interplay offers rich and interesting phenomenology for non-leptonic and rare semi-leptonic decays
- Plethora of data, numerous observables (branching ratios, CP asymmetries, polarisations, Dalitz distributions, . . .)
- Test of CKM mechanism and indirect search for New Physics
- Challenging QCD dynamics !!

Motivation II

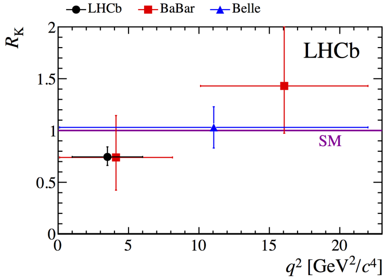
- Rare and radiative exclusive *B*-decays
  - Exhibit many of the current tensions in the flavour sector
    - E.g. angular observable P_5' in $\bar{B} \to K^* \ell\ell$

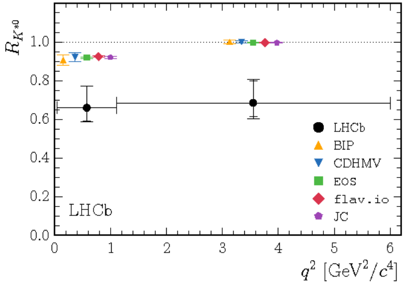


Motivation III

- Moreover: recent measurements w.r.t. the role of charged leptons in rare FCNC $\bar{B} \to K^{(*)}\ell\ell$ decays

$$R_{K^{(*)}} = \frac{\mathcal{B}(\bar{B} \to K^{(*)} ee)_{[q_1^2, q_2^2]}}{\mathcal{B}(\bar{B} \to K^{(*)} \mu\mu)_{[q_1^2, q_2^2]}}$$





Work areas in C2b

Scope of project C2b

- Precise and reliable predictions for non-leptonic and rare exclusive b-decays
- Calculate QFT effects and associated hadronic uncertainties using methods from EFT, factorization / -violation
- Test SM & constrain NP in non-leptonic and rare exclusive b-decays

Work areas

Work Area 1: NNLO QCD corrections (*Huber*)

Work Area 2: QED corrections (*Feldmann*)

Work Area 3: Power corrections (*Bell*)

Work Area 4: Phenomenology of non-leptonic decays (*Bell, Huber*)

Work Area 5: Phenomenology of rare semilep. and radiative decays (*Feldmann*)

Work area 1

NNLO QCD corrections

- Penguin amplitude in QCD factorization ($p = u, c$)

$$\hat{\alpha}_4^p(M_1 M_2) = a_4^p(M_1 M_2) + \{1, -1\} \times r_\chi^{M_2} \, a_6^p(M_1 M_2) + \beta_3^p(M_1 M_2)$$

  - only leading-power piece is $a_4^p(M_1 M_2) \approx -0.03 - (0.01 \ldots 0.02)\, i$
  - Spin-dependent term $r_\chi^{M_2} \, a_6^p(M_1 M_2)$ is power-suppressed, but enhanced (and numerically important) for $M_2 = P$.
  - annihilation term $\beta_3^p(M_1 M_2)$ cannot be calculated in QCDF, estimate gives $|\beta_3^p(M_1 M_2)| \approx 0.03$

Preliminary work / QFET projects

- $a_4^p(M_1 M_2)$ to NNLO

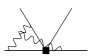
[Bell,Huber'14; Bell,Beneke,Huber,Li'15; Bell,Beneke,Huber,Li 190x.nnnnn]

[earlier work: Bell,'07,'09; Bell,Pilipp'09; Beneke,Huber,Li'09]

Work area 1

P³H tasks

- $a_6^p(M_1 M_2)$ to NNLO
  - Calculation shares some of the technical aspects of two-loop $a_4^p(M_1 M_2)$ calculation, but will be more involved
    - Expand loop integrands to sub-leading power in $p_\perp^\mu$
    - Infrared subtraction needs to be extended



$$\widetilde{T}_i^{(0)} = \widetilde{A}_{i1}^{(0)} ,$$

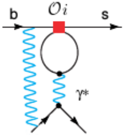
$$\widetilde{T}_i^{(1)} = \widetilde{A}_{i1}^{(1)\mathrm{nf}} + Z_{ij}^{(1)} \widetilde{A}_{j1}^{(0)} + \widetilde{A}_{i1}^{(1)\mathrm{f}} - A_{31}^{(1)\mathrm{f}} \widetilde{A}_{i1}^{(0)} - [\widetilde{Y}_{11}^{(1)} - Y_{11}^{(1)}] \widetilde{A}_{i1}^{(0)} - \sum_{b>1} \widetilde{H}_{ib}^{(0)} \widetilde{Y}_{b1}^{(1)} ,$$

$$\begin{aligned}
\widetilde{T}_i^{(2)} = {} & \widetilde{A}_{i1}^{(2)\mathrm{nf}} + Z_{ij}^{(1)} \widetilde{A}_{j1}^{(1)} + Z_{ij}^{(2)} \widetilde{A}_{j1}^{(0)} + Z_\alpha^{(1)} \widetilde{A}_{i1}^{(1)\mathrm{nf}} + (-i)\, \delta m^{(1)} \widetilde{A}_{i1}^{\prime(1)\mathrm{nf}} \\
& + Z_{ext}^{(1)} \left[\widetilde{A}_{i1}^{(1)\mathrm{nf}} + Z_{ij}^{(1)} \widetilde{A}_{j1}^{(0)}\right] - \widetilde{T}_i^{(1)} \left[C_{FF}^{(1)} + \widetilde{Y}_{11}^{(1)}\right] - \sum_{b>1} \widetilde{H}_{ib}^{(1)} \widetilde{Y}_{b1}^{(1)} + [\widetilde{A}_{i1}^{(2)\mathrm{f}} - A_{31}^{(2)\mathrm{f}} \widetilde{A}_{i1}^{(0)}] \\
& + (-i)\, \delta m^{(1)} [\widetilde{A}_{i1}^{\prime(1)\mathrm{f}} - A_{31}^{\prime(1)\mathrm{f}} \widetilde{A}_{i1}^{(0)}] + (Z_\alpha^{(1)} + Z_{ext}^{(1)}) [\widetilde{A}_{i1}^{(1)\mathrm{f}} - A_{31}^{(1)\mathrm{f}} \widetilde{A}_{i1}^{(0)}] \\
& - [\widetilde{M}_{11}^{(2)} - M_{11}^{(2)}] \widetilde{A}_{i1}^{(0)} - (C_{FF}^{(1)} - \xi_{45}^{(1)}) [\widetilde{Y}_{11}^{(1)} - Y_{11}^{(1)}] \widetilde{A}_{i1}^{(0)} - [\widetilde{Y}_{11}^{(2)} - Y_{11}^{(2)}] \widetilde{A}_{i1}^{(0)} \\
& - \sum_{b>1} \widetilde{H}_{ib}^{(0)} (\widetilde{Y}_{b1}^{(2)} + \widetilde{M}_{b1}^{(2)}) .
\end{aligned}$$

Work area 2

QED corrections

- Precision studies require control over non-factorizing EM corrections (e.g. connecting hadronic and leptonic currents)
  - Can be logarithmically enhanced in certain corners of phase space
  - Relevant in the context of $R_K^{(*)}$ and other recent B-physics anomalies



Preliminary work / QFET projects

- QED corrections to inclusive $b \to s\ell\ell$ observables [Huber,Lunghi,Misiak,Wyler'05; Huber,Hurth,Lunghi'07; '15]
- EM effects and MC studies in exclusive $b \to s\ell\ell$ decays [Bordone,Isidori,Pattori'16]
- QED corrections to inclusive $b \to d\ell\ell$ observables [Huber,Hurth,Jankins,Lunghi,Qin,Vos in prep.]

Work area 2

P^{3}H tasks

- Start with matrix elements of semi-leptonic operators in $B \to K^{(*)}\ell^+\ell^-$
  - Generalization of QED analysis of the leptonic $B_s \to \ell^+\ell^-$ decay [Beneke,Bobeth,Szafron'18]
  - Extend to hadronic operators in $B \to K^{(*)}\ell^+\ell^-$ and penguin-dominated non-leptonic decays
  - Derive EM corrections to FF relations of decays into light mesons with different electric charges

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- Conceptual issues
  - New sources of non-factorizing effects ($\to$ factorization theorems)
    - Semi-leptonic 4-fermion operators don't factorize into hadr. and lept. current
    - Cancellation of IR divergences from QED loops and real-photon radiation has no analogue in the QCD factorization formula
  - Include QED Wilson lines to achieve gauge-invariance

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  - Include QED Wilson lines to achieve gauge-invariance
- Phenomenologially relevant aspects
  - Suppression by $\alpha_{\rm em}$ lifted by large logs, e.g. from interference of soft and collinear radiation at large recoil
  - Look at isospin-violating observables (sensitive to EW penguins)
  - QED effects contribute to lepton-flavour violating effects

Work area 3

Power corrections

- No systematic framework to compute Λ/m_b power corrections in QCDF approach
  - Breakdown of soft-collinear factorization, signalled by endpoint-divergent convolution integrals
  - Major source of uncertainty
- New developments in collider-physics applications of SCET
  - Collinear anomaly, rapidity RG [Becher,Neubert'11; Chiu,Jain,Neill,Rothstein'12]
  - Potentially help to solve problem of factorizing power corrections in exclusive B-decays

Preliminary work / QFET projects

- Factorization and resummation of soft-collinear dynamics in jet-broadening [Bell,Becher,Neubert'11]
- Study of non-relativistic transition form factors, all-order resummation of LL [Bell,Feldmann'05; Bell,Feldmann,Böer, w.i.p.]

Work area 3

P^3H tasks

- Transfer insights from collinear anomaly/rapidity RG to exclusive *B*-decays
- Start with simplified model for $B \to \pi$ transition FFs at large recoil
  - Initial and final states are nonrelativistic bound states
  - Allows to address the failure of the standard factorization approach in a perturbative setting
  - Goal: Extend resummation to sub-leading order, establish complete factorization theorem
- Generalize to realistic $B \to \pi$ transition form factors
- Extend method to exclusive non-leptonic and rare *B*-meson decays
  - Reduces theoretical uncertainties significantly

Work area 4

Work area 4

Phenomenology of Non-leptonic Decays

Preliminary work / QFET projects

- Branching ratios of tree-dominated decays [Bell,Pilipp'09; Beneke,Huber,Li'09]
- CP asymmetries of penguin-dominated transitions [Bell,Beneke,Huber,Li'15]
- Three-body decays $B \to \pi\pi\pi$ from QCD factorization [Kränkl,Mannel,Virto'15; Klein,Mannel,Virto,Vos'17]

P^{3}H tasks

- Complete phenomenological analysis of all two-body charmless non-leptonic decay channels at NNLO accuracy
  - $\sim$ 100 decay channels
  - Numerous observables (BRs, CP asymmetr., polarisation fractions, . . .)

Work area 4

P^{3}H tasks cont'd

- Power corrections
  - Apply results from WA3
  - Exploit flavour-symmetries of the light quarks

$$
\begin{aligned}
P^{s0} &= f P^{d0}\Big[1 + (A^d_{KK}/P^{d0})\Big\{\delta\alpha^c_4 - \delta\alpha^c_{4EW}/2 \\
&\qquad + \delta\beta^c_3 + 2\delta\beta^c_4 - \delta\beta^c_{3EW}/2 - \delta\beta^c_{4EW}\Big\}\Big]
\end{aligned}
$$

  - consider entity of channels and observables, aim for (public) code containing all correlations
- Apply QCDF to three-body non-leptonic decays
  - Improve theoretical description of decays like $B \to \rho(\to \pi\pi)\pi$
    - allows to perform studies of two-body decays beyond quasi-particle approximation
    - Introduces new hadronic quantities (generalized FFs and light-cone DAs)
    - constrain new hadronic parameters with data

Work area 5

Work area 5

Phenomenology of rare semi-leptonic and radiative decays

Preliminary work / QFET projects

- QCDF in $B \to K^* \ell^+ \ell^-$ at large hadronic recoil [Beneke,Feldmann,Seidel'01]
- $B \to K^* \ell^+ \ell^-$ decay at large hadronic recoil [Khodjamirian,Mannel,Wang'13]
- Rare semi-leptonic baryonic decays like $\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$ [Böer,Feldmann,van Dyk'15]
- Charm-loop effects in exclusive $b \to s\ell^+\ell^-$ decays [Beylich,Buchalla,Feldmann'11; Khodjamirian,Mannel,Pivovarov,Wang'10]

P³H tasks

- Goal: combine new insights for higher-order terms in the EFT framework with phenomenological information from dedicated exclusive $b \to s(d)\ell^+\ell^-$ observables.

Work area 5

P^{3}H tasks cont'd

- Use results from WA1 and WA2 for improved predictions for observables at large hadronic recoil (differential decay rates, asymmetries, angular observables, . . .)
- Use results from WA3 for improved theoretical parametrizations of power corrections in annihilation and spectator-scattering topologies

Work area 5

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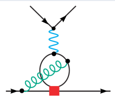
- Use results from WA3 for improved theoretical parametrizations of power corrections in annihilation and spectator-scattering topologies
- Study of charmonium resonances (J/ψ, $\psi(2S)$, . . .)
  - Effects of quark-hadron duality violation above and below the $c\bar{c}$-resonances
  - Inclusion of non-factorizable effects
    - Interactions between $b \to s(d)\gamma^*$ and $e^+e^- \to \gamma^*$ system
    - Interference with spectator particles
    - Non-trivial strong phases and interference effects.



Work area 5

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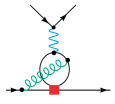

- Extend results for $B \to K^{(*)}\ell^+\ell^-$ to
  - decays of B_s or B_c mesons
  - baryonic decays like $\Lambda_b \to \Lambda\ell^+\ell^-$
  - multi-body decays like $B \to K\pi\ell^+\ell^-$ away from ($K^* \to K\pi$) resonance

The Role of C2b within the CRC

- Project C2b complements the research on
  - charged-current b-hadron decays in project C2a
  - inclusive decays and lifetimes/mixing in C1
- WA4 and WA5 will rely on hadronic matrix elements (generalized FFs, B-meson LCDAs) from project C2a
- Relate hadronic uncertainties from charged and neutral currents $\rightarrow$ C2a
- Perturbative corrections (WA1) have direct connections to first column
- WA3 directly profits from conceptual insights in SCET gained in project B2a
- Phenomenological aspects of this project can be used to rule out or motivate specific NP models $\rightarrow$ C3
- interesting links to projects A3a and B2b owing to sensitivity of $b \rightarrow s$ transitions to top-quark and extended Higgs sectors