Project C2a

Hadronic Matrix Elements and Exclusive Semileptonic Decays

Thorsten Feldmann and Thomas Mannel

CRC Kick-Off Meeting, 18./19. March 2019

DFG TRR 257
particle **p**hysics **p**henomenology
after the **H**iggs discovery

UNIVERSITÄT SIEGEN

The Power of b-Hadron Physics

Many different decay modes, e.g.

- charged and neutral leptonic decays
  $(B_{u,c} \to \ell\nu,\ B_{s,d} \to \mu^+\mu^-,\ B \to \nu\nu,\ \ldots)$
- exclusive and inclusive semileptonic $b \to u(c)$ decays
  $(B \to X_{u,c}\ell\nu,\ B \to D^{(*)}\ell\nu,\ B \to \pi\ell\nu,\ B \to \pi\pi\ell\nu,\ B_s \to K\pi\ell\nu,\ \Lambda_b \to p\ell\nu,\ \ldots)$
- radiative and semileptonic FCNC decays
  $(B \to X_s\gamma,\ B \to \rho\gamma,\ B \to K^{(*)}\mu^+\mu^-,\ B_s \to \phi\mu^+\mu^-,\ \Lambda_b \to \Lambda\mu^+\mu^-,\ B \to K\nu\nu,\ \ldots)$
- non-leptonic decays with or without charm
  $(B \to J/\psi K,\ B \to \pi\pi,\ B \to K\pi,\ B \to \pi\pi\pi,\ \ldots)$

Many decay modes are suppressed by CKM- and/or loop factors
$\Rightarrow$ particular sensitivity to (indirect) NP effects !

The Power of b-Hadron Physics

Many different observables, e.g.

- lifetimes and mixing parameters
- (partially) integrated decay rates
- (moments of) decay spectra, Dalitz distributions
- forward-backward asymmetries
- direct and mixing-induced CP asymmetries
- angular distributions and polarization fractions

Some observables are small or even vanish in the SM
$\Rightarrow$ particular sensitivity to (indirect) NP effects !

The Challenges of b-Hadron Physics

Hadronic Uncertainties

- hadronic bound-state effects obscure underlying short-distance physics
- many process-dependent exclusive decay amplitudes that describe non-perturbative QCD dynamics

Idea: Factorization / EFT

- decaying b-quark is heavy compared to $\Lambda_{\rm QCD}$
- final states often involve (relatively) energetic particles (i.e. $E \sim m_b/2$)

$\Rightarrow$ different hadronic amplitudes can be expanded in terms of a handful of more fundamental (i.e. process-independent) quantities.

also: control large logarithms in QCD perturbation theory

Particularly important:

- Large energy $\leftrightarrow$ propagation close to the light-cone

$\Rightarrow$ hadronic matrix elements of non-local operators

Outline

1. Scope / Work Areas
2. Participating Scientists / Recruitment
3. Preliminary Work / Status of Subprojects
4. Recent Results – Example from WA1
5. Outlook

1. Scope / Work Areas

– reliable predictions for exclusive $b \to c\ell\nu$ and $b \to u\ell\nu$ transitions
– precision determinations of $|V_{cb}|$ and $|V_{ub}|$
– refined theoretical methods for hadronic input parameters

Work Area 1:	Factorization and light-cone distribution amplitudes
Work Area 2:	Theoretical development of QCD sum rules and related methods
Work Area 3:	New channels and multi-hadron final states
Work Area 4:	Inclusive rate from the sum over exclusive channels

- WA1 and WA3 will be coordinated by TF
- WA2 and WA4 will be coordinated by TM

2. Participating Scientists / Recruitment

Name	Position	Work Areas	Start – End	Affiliation
Yao Ji	Postdoc	WA1, WA4	Oct 19 –	SI
[N.N.]*	PhD Student	WA2, WA3	mid 19 –	SI
Björn O. Lange	Akad. Rat	WA1, WA4	permanent	SI

Additional personnel:

Alex Khodjamirian	Senior Prof.	WA2	– Dec 21	SI
Kevin Olschewsky	PhD Student	WA2, WA4	Feb 19 –	SI

* (candidate comes for a presentation talk in the first week of april . . .)

WA1: Factorization and LCDAs

Preliminary Work

- QCD factorization in exclusive B decays:
  [Böer 18 [thesis]] [Böer/TF/van Dyk 17] [Beneke/TF 04] [BOL/Neubert 04] [Beneke/TF 00]
- Properties of B-meson LCDAs:
  [TF/BOL/Wang 14] [Bell/TF/Wang/Yip 13] [Bell/TF 08]
  [Khodjamirian/TM/Offen 07] [BOL/Neubert 03]

Pending QFET Projects

- Resummation of rapidity logs in exclusive decays [Bell/TF/Böer/BOL]
- Renormalization of B-meson LCDA at 2-loop [Bell/Dehnadi/BOL/Piclum]

Current P3H Activities

- improved parametrizations of B-meson LCDA [TF/van Dyk]
  preliminary results (see below)
- parametrizations for higher-twist B-meson LCDAs [TF/van Dyk]

WA2: QCD sum rules and related methods

Preliminary Work

- $B \to \gamma\ell\nu$ transition: [Braun/Khodjamirian 13]
- $B \to \pi\ell\nu$ transition: [Imsong/Khodjamirian/TM/van Dyk 15] [Khodjamirian/TM/Offen/Wang 11] [De Fazio/TF/Hurth 07] [Khodjamirian/TM/Offen 06] [De Fazio/TF/Hurth 05]
- $B \to \pi\pi\ell\nu$ transition: [Cheng/Khodjamirian/Virto 17 (2x)] [Hambrock/Khodjamirian 16]
- semi-leptonic Λ_b decays: [Khodjamirian/Klein/TM/Wang 11] [TF/Yip 11]
- exclusive $b \to c$ transitions: [TM/van Dyk 15]

Pending QFET Projects

- isoscalar contribution to the $B \to \pi\pi$ form factor [Khodjamirian/Virto/Vos]
- vector contribution to the $B \to \pi K$ form factors [Khodjamirian/Virto]

Current P3H Activities

- phenomenological re-analysis of $B \to \gamma\ell\nu$ [TF/van Dyk; using results from WA1]
- a new QCD sum rule for B_c processes [Khodjamiran/TM]

WA3: New channels and multi-hadron final states

Preliminary Work

- phenomenology of $B_{(s)} \to M_1 M_2 \ell \nu$ decays
  [TF/van Dyk/Vos 18] [TF/Müller/van Dyk 15] [Faller/TF/Khodjamirian/TM/van Dyk 13]
- phenomenology of Λ_b decays
  [TM/Wang 11]

Current P3H Activities

- PhD project K. Olschewsky: "Multibody *B*-decays"
- phenomenological analysis of $B_c \to J/\Psi \ell \bar{\nu}$ [Khodjamiran/TM/Kellermann]

WA4: Inclusive rate from sum over exclusive rates

Preliminary Work

- phenomenological analysis of $B \to D, D^*, D^{**}$ effects:
  [TM/Rusov/Shahriaran 17] [Klein/TM/Shahriaran/van Dyk 15]
- differential decay spectra of charmless inclusive B decays:
  [BOL/Neubert/Paz 05]

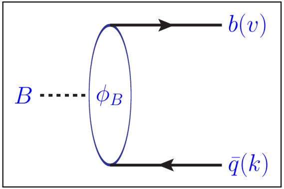
Current P3H Activities

- . . . waiting for postdoc to arrive in october . . .

4. Recent Results from WA1

“Systematic parametrization of the *B*-meson LCDAs”

[TF, van Dyk (in preparation)]



Parton picture: 2-particle Fock state

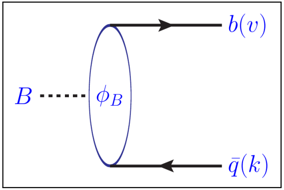
- Some external light-like momentum, e.g. $p_\gamma^\mu = E_\gamma n^\mu$, $n^2 = 0$
- with $\omega \equiv n \cdot k$ light-cone projection of light antiquark momentum
- $\phi_B(\omega)$ as probability amplitude

- Field theoretical definition of $\phi_B^+(\omega)$ from light-cone operators in HQET:

$$m_B f_B^{(\mathrm{HQET})}\, \phi_B^+(\omega) = \int \frac{d\tau}{2\pi}\, e^{i\omega\tau}\, \langle 0|\, \bar{q}(\tau n)\, [\tau n, 0]\, \not{n}\gamma_5\, h_v^{(b)}(0)\, |\bar{B}(m_B v)\rangle$$

[Grozin/Neubert]

LCDA of the B-Meson



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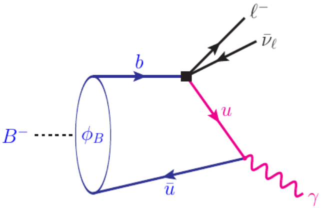
- Some external light-like momentum, e.g. $p_\gamma^\mu = E_\gamma n^\mu\,, \;\; n^2 = 0$
- with $\omega \equiv n \cdot k$ light-cone projection of light antiquark momentum
- $\phi_B(\omega)$ as probability amplitude

- in QCD factorization [Beneke et al.] one encounters **logarithmic moments**

$$L_n(\mu) \;=\; \int_0^\infty \frac{d\omega}{\omega}\, \ln^n\left(\frac{\mu}{\omega}\right) \phi_B^+(\omega) \qquad \text{(n=0,1,2, ...)}$$

- in QCD light-cone sum rules, one is sensitive to **low light-cone momenta**

$$\phi_B^{+\prime}(0)\,, \qquad \phi_B^{+\prime\prime}(0)\,, \qquad \text{etc.}$$



For large photon energy, $E_\gamma \sim m_b/2$:

$$(p_\gamma - p_{\bar{u}})^2 \simeq -2\, p_\gamma \cdot p_{\bar{u}} \equiv -2\, E_\gamma\, \omega$$

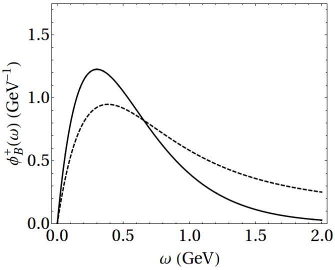
- Sensitive to light-cone projection ω of light antiquark momentum in B-meson

$$F^{B\to\gamma}(E_\gamma) \simeq \text{[kinematic factor]} \times \int_0^\infty \frac{d\omega}{\omega}\, \phi_B(\omega)$$

Experimental bound on BR $\longrightarrow$ bound on $\frac{1}{\lambda_B} \equiv \langle \omega^{-1} \rangle_B$

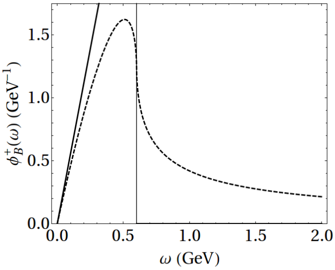
Simple Models for $\phi_B^+(\omega)$:

exponential model



$$\phi_B^+(\omega, \mu_0) = \frac{\omega}{\omega_0^2} \exp\left(-\frac{\omega}{\omega_0}\right)$$

free parton model



$$\phi_B^+(\omega, \mu_0) = \frac{\omega}{2\bar\Lambda^2}\, \theta(2\bar\Lambda - \omega)$$

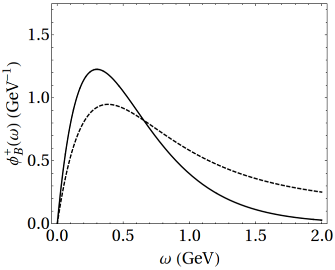
$$\bar\Lambda = M_B - m_b$$

— model LCDA at μ_0

– – effect of RG evolution towards higher scales

Simple Models for $\phi_B^+(\omega)$:

exponential model



$$\phi_B^+(\omega, \mu_0) = \frac{\omega}{\omega_0^2} \exp\left(-\frac{\omega}{\omega_0}\right)$$

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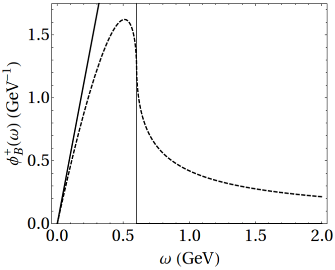

$$\phi_B^+(\omega, \mu_0) = \frac{\omega}{2\bar{\Lambda}^2}\, \theta(2\bar{\Lambda} - \omega)$$

$$\bar{\Lambda} = M_B - m_b$$

Can one do better?

Complications:

Renormalization of light-cone operator in HQET non-trivial:

- local limit $\lambda \to 0$ and renormalization do not commute
- $\phi_B^+(\omega, \mu)$ exhibits a "radiative tail"
- non-negative moments of $\phi_B^+(\omega, \mu)$ become divergent

[Lange/Neubert, Lee/Neubert, Braun/Ivanov/Korchemsky]

What do we know:

- tree-level constraints from HQET parameters [Grozin/Neubert]
- dim-3 and dim-4 contributions to radiative tail [Lee/Neubert]
- dim-5 contributions to radiative tail (position space) [Kawamura et al.]
- simple hadronic models [Kawamura et al.,Khodjamirian et al., Braun et al.]
- eigenfunctions of the 1-loop RG equations [Bell/TF/Wang ; Braun/Manashov]

Our Approach:

Step 1: Generic parametrization for low-ω region

$$\phi_B^+(\omega, \mu_m) \equiv \frac{\omega\, e^{-\omega/\omega_0}}{\omega_0^2} \sum_{k=0}^{N} c_k(\mu_m)\, L_k^{(1)}\left(\frac{\omega}{\omega_0}\right) + \text{“radiative tail” @ } \mu_m$$

- (truncated) series of **associated Laguerre polynomials** $L_k^{(1)}$
- **exponential damping** for large momenta ω
- **hadronic information** encoded in
  - Laguerre coefficients $c_k(\mu_m)$
  - hadronic reference momentum $\omega_0 \sim \Lambda_{\rm had}$
  - reference renormalization scale $\mu_m \gg \Lambda_{\rm QCD}$
- radiative tail will be treated separately

Our Approach

Step 2: The generating function: (basically Mellin transform)

$$F_{[+]}(t,\mu_m) \equiv \frac{\Gamma(1-t)}{\Gamma(1+t)} \int_0^\infty \frac{d\omega}{\omega} \left(\frac{\mu e^{2\gamma_E}}{\omega}\right)^{-t} \phi_B^+(\omega)$$

$$= \frac{1}{\omega_0} \left(\frac{\mu_m e^{2\gamma_E}}{\omega_0}\right)^{-t} \sum_{k=0}^{N} c_k(\mu_m) \frac{\Gamma(1+k-t)}{\Gamma(1+k)} \quad + \text{radiative tail}$$

- Logarithmic moments can be obtained by expanding around $t=0$, e.g.

$$L_0(\mu_m) = \frac{1}{\omega_0} \sum_{k=0}^{N} c_k(\mu_m) \quad + \text{radiative-tail contribution}$$

- Low-momentum behaviour from setting $t=-1,-2,\ldots$, e.g.

$$\phi_B^{+\prime}(0,\mu_m) = \frac{1}{\omega_0^2} \sum_{k=0}^{N} k\cdot c_k(\mu_m) \quad + \text{radiative-tail contribution}$$

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$$= \frac{1}{\omega_0} \left(\frac{\mu_m e^{2\gamma_E}}{\omega_0}\right)^{-t} \sum_{k=0}^{N} c_k(\mu_m) \frac{\Gamma(1+k-t)}{\Gamma(1+k)} \quad + \text{radiative tail}$$

- The generating function has a simple RG evolution:

$$F_{[+]}(t,\mu) = e^V \left(\frac{\mu}{\mu_m}\right)^{-t} F_{[+]}(t+g,\mu_m)$$

where $V = V(\mu,\mu_m)$ and $g = g(\mu,\mu_m)$ are standard RG functions in SCET.

Step 3: Determining the Radiative Tail

from perturbative analysis in the parton picture [Lee/Neubert] [Kawamura et al.]

$$\phi_B^+(\omega, \mu_m)\big|_{\text{radiative}} = \theta(\omega - \omega_t)\frac{\alpha_s C_F}{\pi\omega}\left\{\frac{1}{2} - \ln\frac{\omega}{\mu} + \frac{4\bar{\Lambda}}{3\omega}\left(2 - \ln\frac{\omega}{\mu}\right) + \frac{\ldots\bar{\Lambda}^2 + \ldots\lambda_E^2(\mu) + \ldots\lambda_H^2(\mu)}{\omega^2} + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^3}{\omega^3}\right) + \ldots\right\}$$

- HQET parameter $\bar{\Lambda} = m_B - m_b$ (pole-mass scheme)
- we also included the higher-order terms from dim-5 operators, with $\lambda_{E,H}^2(\mu)$ (chromoelectric and chromomagentic terms)
- forcing ϕ_B^+ to be continuous at $\omega = \omega_t$, one sets

$$\Rightarrow \qquad \omega_t = \sqrt{e}\,\mu_m + 2\,\bar{\Lambda} + \ldots$$

Step 4: Improved Grozin-Neubert Relations

Constraints on Laguerre coefficients $c_{0,1,2}$ to 1-loop accuracy, e.g.

$$c_0(\mu_m) = 1 + \frac{\alpha_s C_F}{4\pi}\left\{\frac{1}{2} - \frac{\pi^2}{12} - \frac{8\bar\Lambda}{3\sqrt{e}\mu_m} + \ldots\right\}$$

$$c_1(\mu_m) = \left(1 - \frac{2\bar\Lambda}{3\omega_0}\right)\left(1 + \frac{\alpha_s C_F}{4\pi}\left\{\frac{1}{2} - \frac{\pi^2}{12} + \ldots\right\}\right) + \frac{\alpha_s C_F}{4\pi}\left\{-\frac{2\sqrt{e}\mu_m}{\omega_0} + \ldots\right\}$$

- naive tree-level normalization [← Grozin/Neubert]
- radiative corrections [← Lee/Neubert]
- power corrections, requiring $\bar\Lambda \ll \mu_m$ [← Lee/Neubert] [← Kawamura et al.]
- power-enhanced terms ↔ renormalon ambiguity in def. of $\bar\Lambda$

⇒ switching to renormalon-free definition $\bar\Lambda_{\rm DA}(\mu_m)$ [Lee/Neubert]

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Step 5: Analytic Form for Generating Function

$t < 1$

$$F_{[+]}(t, \mu_m)\big|_{\text{radiative}} = \frac{\alpha_s C_F}{\pi} \frac{\Gamma(1-t)}{\Gamma(1+t)} \frac{e^{-2\gamma_E t}\, e^{t/2}}{\sqrt{e}\mu_m} \left\{ -\frac{1}{(t-1)^2} + \frac{\bar\Lambda}{3\sqrt{e}\mu_m} \frac{8-6t}{(t-2)^2} + \ldots \right\}$$

- Read off radiative contribution to logarithmic moments, e.g.

$$L_0(\mu_m)\big|_{\text{radiative}} = -\frac{\alpha_s C_F}{\sqrt{e}\mu_m \pi} \left\{ 1 - \frac{2\bar\Lambda}{3\sqrt{e}\mu_m} + \ldots \right\}$$

(suppressed by α_s/π and ω_0/μ_m compared to tree-level result)

- By construction, no contribution to low-momentum behaviour.

Step 6: Numerical Implications

. . . work in progress . . .

5. Outlook / ToDo List

WA1:

- generic parametrizations for higher-twist B-meson LCDAs
- implications for phenomenology, in particular for $B \to \gamma \ell \nu$ [$\to$ C2b]
- applying the same ideas to shape functions for inclusive decays [$\to$ WA4 + C1a]

WA2:

- new sum rules for B_c form factors [$\to$ WA3]
- sum rules for $1/m_{b,c}$ corrections in $B \to D \ell \bar{\nu}$

WA3:

- semileptonic processes with bottom baryons
- B_c phenomenology

WA4:

- study of non-resonant contributions in $b \to c$ and $b \to u$
- decays into excited hadrons