Heavy-to-Light Form Factors and Soft-Collinear Effective Theory

Thorsten Feldmann

$\longrightarrow$

"Colour Meets Flavour",
Siegen, 13./14. October 2011

Flavour Physics

CKM Elements and FCNCs

Exclusive Decays of (b, c)-Hadrons

Effective Theories → **Form Factors** ← QCD Factorization

Lattice QCD

Sum Rules

Light-Cone Distribution Amplitudes

Quantum Chromodynamics

$\longrightarrow$ A New Duality Transformation $\longrightarrow$

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Effective Theories $\longrightarrow$ **Form Factors** $\longleftarrow$ QCD Factorization

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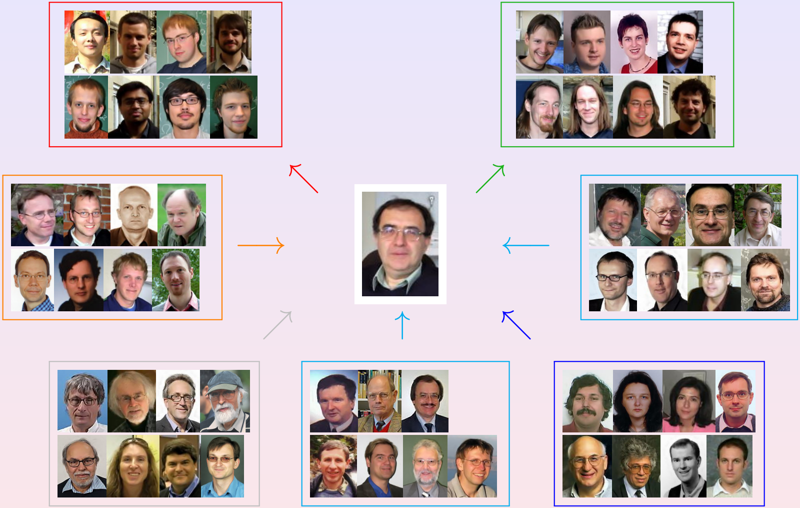
Friends



Physics

...but seriously ...

Transition Form Factors – Definitions and Conventions

- Lorentz Decomposition ? $\leftarrow$ polarization w.r.t. hadronic momentum transfer
- Normalization ? $\leftrightarrow$ "point-like" hadrons for $f_i \equiv 1$
  - $\to$ simple expressions for partial rates
  - $\to$ simple expressions for unitarity bounds
  - $\to$ simple symmetry relations in the HQET and SCET limit

Example: Vector Form Factors for $\Lambda_b \to \Lambda$

$$\langle \Lambda(p',s')|\bar q\,\gamma_\mu\, b|\Lambda_b(p,s)\rangle$$

$$= \bar u_\Lambda(p',s') \Big\{ f_0(q^2)\,(M_{\Lambda_b} - m_\Lambda)\,\frac{q_\mu}{q^2}$$

$$+ f_+(q^2)\,\frac{M_{\Lambda_b}+m_\Lambda}{s_+}\left(p_\mu + p'_\mu - \frac{q_\mu}{q^2}\,(M_{\Lambda_b}^2 - m_\Lambda^2)\right)$$

$$+ f_\perp(q^2)\left(\gamma_\mu - \frac{2m_\Lambda}{s_+}\,p_\mu - \frac{2M_{\Lambda_b}}{s_+}\,p'_\mu\right)\Big\}\, u_{\Lambda_b}(p,s)$$

with $s_+ = (M_{\Lambda_b}+m_\Lambda)^2 - q^2$

- $f_0, f_+, f_\perp$ correspond to time-like, longitudinal, transverse polarization
- For $f_0, f_+, f_\perp \to 1$, one obtains

$$\langle \Lambda(p',s')|\bar q\,\gamma_\mu\, b|\Lambda_b(p,s)\rangle = \bar u_\Lambda(p',s')\,\gamma_\mu\, u_{\Lambda_b}(p,s)$$

[TF, M. Yip; in preparation]

(similar for 3 axial-vector and 4 tensor form factors)

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&= \bar u_\Lambda(p', s') \left\{ f_0(q^2) \, (M_{\Lambda_b} - m_\Lambda) \, \frac{q_\mu}{q^2} \right. \\
&\quad + f_+(q^2) \, \frac{M_{\Lambda_b} + m_\Lambda}{s_+} \left(p_\mu + p'_\mu - \frac{q_\mu}{q^2} \, (M_{\Lambda_b}^2 - m_\Lambda^2) \right) \\
&\quad \left. + f_\perp(q^2) \left(\gamma_\mu - \frac{2 m_\Lambda}{s_+} \, p_\mu - \frac{2 M_{\Lambda_b}}{s_+} \, p'_\mu \right) \right\} u_{\Lambda_b}(p, s)
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(similar for 3 axial-vector and 4 tensor form factors)

Kinematic Regimes and Symmetry Relations

HQET Regime:

- Heavy quark approximated by static source of colour with velocity

$$v^\mu = p^\mu / M$$

- Energy transfer to light hadron is small, $v \cdot p' \ll M$

$\Rightarrow$ HQET spin/flavour symmetries reduce number of independent form factors

For example, in case of $\Lambda_b \to \Lambda$

Reduction from 10 $\to$ 2 independent form factors,

$$\langle \Lambda(p', s') | \bar{q}\, \Gamma\, b | \Lambda_b(p, s) \rangle \simeq \bar{u}_\Lambda(p', s') \Big\{ A(v \cdot p') + \not{v}\, B(v \cdot p') \Big\} \Gamma\, u_{\Lambda_b}(p, s)$$

which implies

$$f_0(q^2) \simeq A(v \cdot p') + B(v \cdot p') , \qquad f_+(q^2) \simeq f_\perp(q^2) \simeq A(v \cdot p') - B(v \cdot p') \qquad \text{etc.}$$

[cf. Mannel/Recksiegel]

Kinematic Regimes and Symmetry Relations

SCET Regime:

- Energy of light hadron is large, (→ 2 light-like vectors $n_\pm^2 = 0$)

$$p'^\mu = (n_+p')\frac{n_-^\mu}{2} + (n_-p')\frac{n_+^\mu}{2} + p'^\mu_\perp \qquad \text{with} \quad (n_+p') \gg |p'_\perp| \gg (n_-p')$$

- Heavy quark still approximated by static source of colour
- Light quark fields can be approximated by SCET spinors ("Feynman mechanism")

⇒ Further reduction of number of independent form factors [Charles et al; Beneke/TF]

For example, in case of $\Lambda_b \to \Lambda$

Reduction from 10 → 1 independent form factor,

$$\langle \Lambda(p', s')|\bar{q}\,\Gamma\, b|\Lambda_b(p, s)\rangle \simeq \xi_\Lambda(n_+p')\,\bar{u}_\Lambda(p', s')\,\Gamma\, u_{\Lambda_b}(p, s)$$

which implies

$$f_0(q^2) \simeq f_+(q^2) \simeq f_\perp(q^2) \simeq \xi_\Lambda(n_+p') \qquad \text{etc.}$$

[TF/Yip]

Calculation of "soft" form factors $\xi_{\pi,K}$, ξ_{ρ,K^*}, $\xi_\Lambda \ldots$

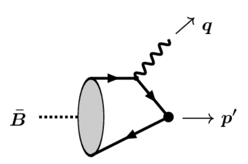
- Lattice QCD:
  - in principle: straight-forward
  - in practice: difficult/costly to simulate fast light hadrons on a lattice
  - typically: reliable predictions for *intermediate* momentum transfer
- QCD Factorization (BBNS):
  - Soft form factors as Non-Factorizable (i.e. irreducible, non-perturbative) ingredients in Factorization Theorems [Beneke/TF]
- (conventional) Light-cone Sum Rules:
  - Study Correlation Functions with interpolating current for *heavy* hadron
  - Non-perturbative input from Universal LCDAs for light hadron
  - Dispersion relations $\oplus$ Continuum Model [Alex + many others]
- **SCET Sum Rules:**
  - Exchange role of light and heavy hadrons [Alex, Mannel, Offen]
  - Factorization of hard scales ($\mu^2 \sim M_b^2$) from decay current matching.
  - Factorization of hard-collinear scales ($\mu^2 \sim \Lambda M_b$) and soft scales ($\mu^2 \sim \Lambda^2$) in SCET correlation functions.

[De Fazio, TF, Hurth]

SCET Sum Rules for Mesonic and Baryonic Transitions (Correlators)

$B \to \pi, \rho \ldots$ Form Factors

[De Fazio/TF/Hurth]



- For appropriate currents, correlator takes the form

$$\Pi(n_- p') = f_B m_B \int_0^\infty d\omega \, \frac{\phi_B^{(-)}(\omega,\mu)}{\omega - n_- p' - i\epsilon} + \mathcal{O}(\alpha_s)$$

- No large logarithms for: $\mu^2/n_+ p' \sim |n_- p'| \sim \langle\omega\rangle$.

$\Lambda_b \to \Lambda \ldots$ Form Factors

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$$\Pi(n_- p') = f_{\Lambda_b}^{(2)} \frac{\not{n}_-}{2} u_{\Lambda_b} \int_0^\infty d\omega \, \frac{\phi_{\Lambda_b}^{(4)}(\omega,\mu)}{\omega - n_- p' - i\epsilon} + \mathcal{O}(\alpha_s)$$

- At LO, only *sum* of spectator momenta appears, with

$$\phi_{\Lambda_b}^{(4)}(\omega) \equiv \omega \int_0^1 du \, \psi_{\Lambda_b}^{(4)}(\omega, u)$$

(LCDA of light scalar diquark component in Λ_b)

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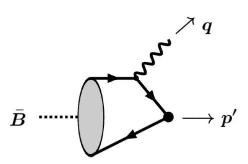

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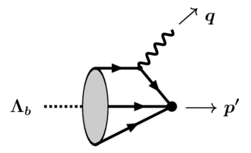

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After Borel transformation ($\to \omega_M$) and continuum subtraction ($\to \omega_s$):

$B \to X = \pi, \rho \ldots$ Form Factors

[De Fazio/TF/Hurth]

$$e^{-m_X^2/(n_+p')\omega_M}\,(n_+p')\,f_X\,\xi_X(n_+p',\mu) = M_B\,f_B \int_0^{\omega_s} d\omega\,\phi_B^{(-)}(\omega,\mu)\,e^{-\omega/\omega_M} + \ldots$$

$\Lambda_b \to \Lambda \ldots$ Form Factors

[TF/Yip]

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Theoretical Uncertainties / Hadronic Input:

- Values for light and heavy hadron decay constants.
- Shape of LCDAs for B and Λ_b.
- Reasonable choice of continuum threshold parameter $\omega_s = s_0/(n_+p')$.
- Reasonable range for Borel parameter $\omega_M = M^2_{\rm Borel}/(n_+p')$.
- Logarithmically enhanced radiative corrections $\sim \alpha_s \ln \omega_{s,M}/\omega$.
  ($\leftrightarrow$ endpoint divergences in QCDF $\leftrightarrow$ non-factorizable dependence on continuum model)

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Example: Numerical estimates for Baryonic Form Factor ξ_Λ (LO)

Input Parameters (default values) :

Threshold $s_0 = \omega_s\,(n_+p')$	2.55 GeV^2
Borel $M^2_{\text{Borel}} = \omega_M\,(n_+p')$	2.5 GeV^2
Decay constant f_Λ	$6 \cdot 10^{-3}$ GeV^2
Decay constant $f^{(2)}_{\Lambda_b}$	0.030 GeV^3
LCDA par. ω_0	300 MeV

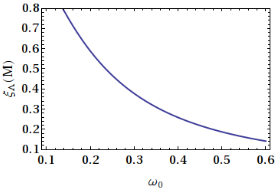
Model for the Λ_b LCDA:

$$\phi^{(4)}_{\Lambda_b}(\omega) := \frac{\omega}{\omega_0^2}\, e^{-\omega/\omega_0}$$

Central Value (LO, max. recoil)

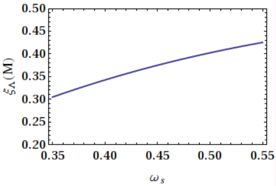
$$\xi_\Lambda(n_+p' = M_{\Lambda_b}) \approx 0.38$$

ω_0 dependence



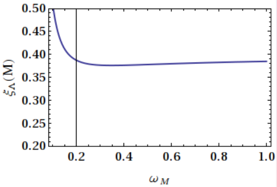
(very sensitive)

ω_s dependence



(moderate)

ω_M dependence

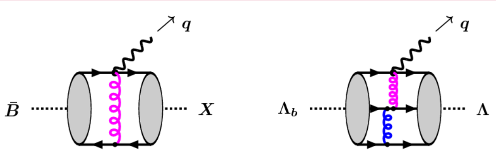


(weak)

[TF/Yip – preliminary]

Calculation of perturbative Corrections $\Delta\xi$

QCD Factorization: Convolution of LCDAs and spectator-scattering kernels

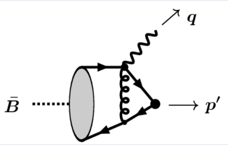


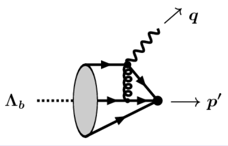
(improved version of Efremov-Radyushkin-Brodsky-Lepage picture)

- Factorization for $B \to X = \pi, \rho \dots$ in the large recoil limit [Beneke/TF]
- For $\Lambda_b \to \Lambda$ form factors, factorization spoiled by soft-gluon exchange between spectator quarks
  ...

SCET Sum Rules: Correlators involving "factorizable" part of SCET currents

$$\bar{q}\,\Gamma_i\,Q_v \longrightarrow C_{ij}\,\bar{\xi}\,\tilde{\Gamma}_j\,h_v \overbrace{-\frac{1}{n_+p'}\,\bar{\xi}\,g\not{A}_\perp\,\frac{\not{n}_+}{2}\,\Gamma_i\,h_v - \frac{1}{M_b}\,\bar{\xi}\,\Gamma_i\,\frac{\not{n}_-}{2}\,g\not{A}_\perp\,h_v} + \dots$$





- Reproduces QCDF for $B \to X$ in the large recoil limit [De Fazio/TF/Hurth]
- Predictions for violation of symmetry relations through $\Delta\xi_\Lambda \sim \mathcal{O}(\alpha_s)$

[TF/Yip]

Features of $\Delta\xi_\Lambda$

In the limit $\omega_{s,M} \ll \omega_0$, the sum rule takes the form

$$e^{-m_\Lambda^2/(n_+p')\omega_M}\, f_\Lambda\, m_\Lambda\, \Delta\xi_\Lambda$$

$$\simeq \frac{\alpha_s C_F}{2\pi} \underbrace{\frac{f_{\Lambda_b}^{(2)}}{M_{\Lambda_b}} \int_0^\infty \frac{d\omega}{\omega}\, F(\omega,1)} \times \underbrace{\omega_M \left(\omega_M - e^{-\omega_s/\omega_M}(\omega_M + \omega_s)\right)}$$

- Formally, $\Delta\xi_\Lambda$ and ξ_Λ scale with the same power of M_b.
- Dependence on Λ_b-Properties and Sum-Rule Parameters factorizes !
- Proportional to inverse moment of the effective LCDA

$$F(\omega,1) \equiv \int_0^\omega d\eta\, \frac{\eta}{\omega} \left(\tilde\psi_4(\eta,u=1) - \tilde\psi_2(\eta,u=1)\right)$$

- Dependence on decay constants cancels in ratio $\Delta\xi/\xi$.
- Contributions to individual form factors take the form

$$f_{0,\perp}(q^2) \simeq C_{f_{0,\perp}}\, \xi_\Lambda(n_+p') \mp \frac{2M}{n_+p'}\, \Delta\xi_\Lambda(n_+p')$$

$$f_+(q^2) \simeq C_{f_+}\, \xi_\Lambda(n_+p') - 2\left(2 - \frac{M}{n_+p'}\right) \Delta\xi_\Lambda(n_+p') \qquad \text{etc.}$$

[TF/Yip – preliminary]

Extraction of Matching Coefficients from Hard Vertex Corrections (Baryons)

Renormalization Scheme: $C_{f_+} = C_{g_+} \equiv 1$

- Using results from [Beneke/TF 2000]:

$$C_{f_\perp} = C_{g_\perp} = 1 + \frac{\alpha_s C_F}{4\pi} L \,,$$

$$C_{h_\perp} = C_{\tilde{h}_\perp} = 1 + \frac{\alpha_s C_F}{4\pi} \left(\ln \frac{M_b^2}{\mu^2} - 2 \right) \qquad \text{etc.}$$

with $L \equiv -\frac{M^2 - q^2}{q^2} \ln \left(1 - \frac{q^2}{M^2} \right)$.

Form Factor Relations *after* Inclusion of $\mathcal{O}(\alpha_s)$ Corrections ($\Delta\xi$ and C_i)

$$\frac{f_0 + h_+}{g_0 + \tilde{h}_+} = \frac{f_\perp - h_+}{g_\perp - \tilde{h}_+} = \frac{f_+ + h_+ - 2h_\perp}{g_+ + \tilde{h}_+ - 2\tilde{h}_\perp}$$

$$= -\frac{2(f_+ - f_\perp) + h_+ - h_\perp}{2(g_+ - g_\perp) + \tilde{h}_+ - \tilde{h}_\perp} = -\frac{M^2 - 2q^2}{M^2} \frac{h_+ - \tilde{h}_+}{f_+ - g_+} = 1 \,.$$

[TF/Yip – preliminary]

Application: FBA-Zero in $\Lambda_b \to \Lambda\mu^+\mu^-$

[TF/Yip – preliminary]

Zero of Forward-Backward Asymmetry, for values of q^2 satisfying

$$\mathrm{Re}\left[C_9^{\rm eff}(q^2)\right] + \frac{M_b\,(M_{\Lambda_b}+m_\Lambda)\,C_7^{\rm eff}}{q^2}\,\frac{h_\perp}{f_\perp} + \frac{M_b\,(M_{\Lambda_b}-m_\Lambda)\,C_7^{\rm eff}}{q^2}\,\frac{\tilde{h}_\perp}{g_\perp} \stackrel{!}{=} 0$$

- Symmetry Limit: Recover LO result from inclusive/mesonic case $\surd$
- Corrections from $\Delta\xi$ are additionally suppressed by m_Λ/M_{Λ_b} (!)
- Corrections from hard-vertex corrections C_i (model-independent)
- Power Corrections to form-factor relations ($\to$ SR/Lattice)
- Non-Factorizable Corrections from long-distance photons ($\to$ future work)

Conclusions

- Light-Cone/SCET Sum Rules provide a Universal and Efficient Framework to estimate (heavy-to-light) Transition Form Factors at Large Recoil Energy $\surd$
- Improved Estimates of Hadronic Input Parameters and LCDAs required, in particular for baryonic decays [see e.g. Alex, Klein, Mannel, Wang] !
- Better understanding of Endpoint Logarithms in Exclusive Matrix Elements ?

Still a lot to explore for ALEX and his Friends !

Conclusions

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All the best for the future, ALEX, **and** *Happy Birthday* **!**