Hadronic Uncertainties in Charmless Two-Body *B*-Decays

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Factorization

Symmetries

Non-perturbative Methods

summary.tmp

Sub-leading effects in SCET

FAQs (frequently answered questions)

Q: *What do we mean by hadronic uncertainties?*

A: Strong-interaction effects that cannot be calculated perturbatively, as a short-distance QCD sub-process!

Q: *How to disentangle?*

A: Factorization:

$$\langle \pi\pi | H_{\rm eff}^{\Delta B=1} | B \rangle = \sum \, [\text{pert. function}] \otimes [\text{hadronic quantities}]$$

Q: *Why is naive factorization incomplete?*

$$\langle \pi\pi | H_{\rm eff}^{\Delta B=1} | B \rangle = \sum_i \underbrace{C_i(\mu)}_{\text{Wilson coeff.}} \underbrace{\langle \pi_1 | J_1^i | B \rangle}_{\text{form factor}} \underbrace{\langle \pi_2 | J_2^i | 0 \rangle}_{\text{decay constant}}$$

A: No QCD cross-talk between $|\pi_2\rangle$ and other hadrons,
$\Rightarrow$ r.h.s. depends on factorization scale μ.

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Corrections to naive factorization

- 4 kinds of external momentum configurations
  - heavy b quark: $p_b \simeq m_b\,(1, 0_\perp, 0)$
  - soft spectators: $p_s \simeq (0, 0_\perp, 0)$
  - collinear pion$_1$: $p_{c1} \simeq m_b/2\,(1, 0_\perp, +1)$
  - collinear pion$_2$: $p_{c2} \simeq m_b/2\,(1, 0_\perp, -1)$

(in B rest frame)

- Interactions lead to the following internal modes:

	heavy	soft	coll$_1$	coll$_2$
heavy	–	heavy	hard	**hard**
soft	heavy	soft	hard-coll$_1$	**hard-coll$_2$**
coll$_1$	hard	hard-coll$_1$	coll$_1$	**hard**
coll$_2$	**hard**	**hard-coll$_2$**	**hard**	coll$_2$

where

- hard modes have invariant mass of order m_b
- hard-collinear modes have invariant mass $\sim \sqrt{\Lambda m_b}$

Q: *Are hard and hard-collinear interactions factorizable?*

QCD-improved factorization (BBNS)

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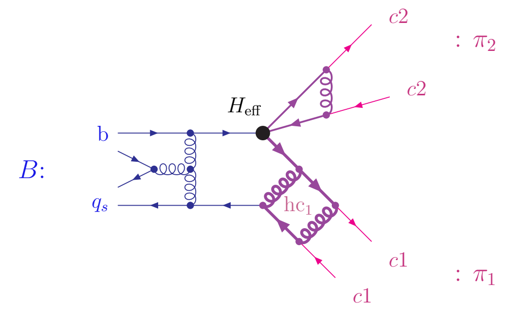
A: Not always, but at leading power in Λ/m_b expansion:



- Starting point: naive factorization, requires:
  - $B \to \pi_1$ form factor: $\boxed{F_+^{B\to\pi}(0)}$
    (already includes non-factorizable hard-collinear$_1$ dynamics!)
  - π_2 decay constant: $\boxed{f_\pi}$

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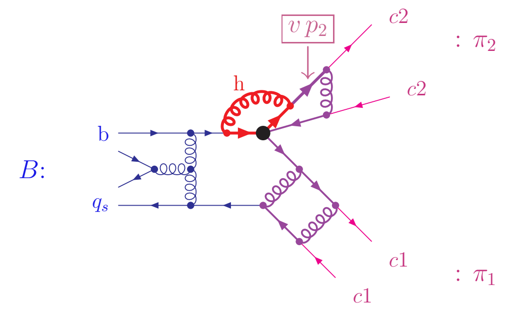

- hard vertex correction $\rightarrow T_{\rm I}(v; \mu, \mu_0)$
  - depends on factorization scale μ – matches $C_i(\mu)$ $\surd$
  - depends on momentum fraction v of collinear quark in π_2
    $\Rightarrow$ Needs LCDA for pion: $\boxed{\phi_\pi(v; \mu_0)}$

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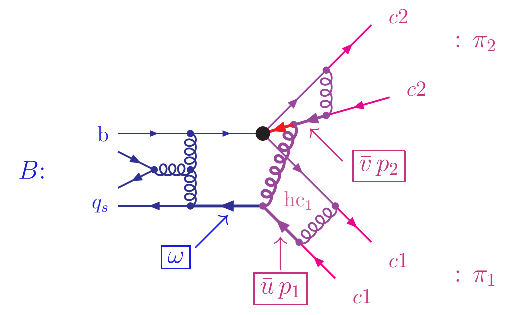

- hard-collinear spectator correction $\rightarrow T_{\rm II}(u, v, \omega; \mu, \mu_0)$
  - depends on factorization scale μ
  - depends on momenta of collinear quarks and soft spectators

  $\Rightarrow$ Also needs LCDA for B-meson: $\boxed{\phi_B(\omega; \mu_0)}$

Soft-collinear effective theory

Q: *What is the difference between*
QCD-improved factorization and SCET ?

A: NONE! They are equivalent!

	QCD-F	SCET
factorization:	diagrammatic (method of regions) [Beneke/Smirnov 98]	perturbative matching (fields and operators)
resummation of Sudakov logs:	“by hand” [Korchemsky/Sterman 94] (not in BBNS 99)	renormalization group [Bauer et al. 2001]

A: still, SCET makes power-counting, emergence of approximative symmetries etc. more transparent . . .

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Soft-collinear effective phenomenology

Q: *What is the difference between*

- *BBNS* [Beneke/Buchalla/Neubert/Sachrajda 1999+]
- *and BPRS ?* [Bauer/Pirjol/Rothstein/Stewart 2004+]

A: Different assumptions about non-perturbative input:

	BBNS	BPRS
factorization formula:	reasonable values $\pm$ generous errors (form factor and LCDAs)	fit $T_{\rm I}$ and $T_{\rm II}$ to data (called ζ and ζ_J, real)
"charming penguins": [Ciuchini 97]	short-distance, (incl. in hard functions)	"charm-loop" left as phenomenological fit parameter (Δ^P)
non-factorizable power-corrections:	rough estimate of annihilation and sub-leading hard-scattering effects (X_A and X_H)	assumptions about systematic uncertainties

perturbative QCD approach (pQCD)

Q: *What is the difference between*

- *QCD Factorization*
- *and pQCD ?* [Keum/Li/Sanda]

A: non-factorizable terms in QCDF
$\longrightarrow$ perturbatively calculated in pQCD (systematics?)

- pQCD requires additional IR-regularization
  - exponentiation of Sudakov logarithms into form factor in transverse space
  - sensitive to endpoint behaviour of hadronic wave functions (model-dependent!)
  - neglect of higher Fock states
  - does not contain naive factorization as limiting case

$\Rightarrow$ non-factorizable effects and strong interaction phases are counted as $\mathcal{O}(1)$ in pQCD

Approximate symmetries

Q: *Is there a model-independent approach to $B \to \pi\pi$?*

A: Yes, use isospin symmetry!

- neglect sub-leading electroweak penguins
- isospin amplitudes, 5 independent real parameters

T(ree), $e^{i\theta_P}$ P(enguin), $e^{i\theta_C}$ C(olour suppressed tree)

- broken by photon radiation from charged hadrons
  ($\to$ experimental issue, see talk by E. Barbiero from Nov.05 and [Baracchini/Isidori 05])

Q: *Can $B \to \pi\pi$ data tell us WHICH assumptions about hadronic effects (e.g. in BBNS or BPRS) are justified?*

A: No! Very different assumptions about (possibly large) non-factorizable effects can accomodate (present) experimental data. [see, for instance TF/Hurth 2004]

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Approximate symmetries

- $SU(3)_F$ relations for $B \to \pi\pi,\ \pi K$ and $B_s \to KK$

  Q: *How large are corrections to symmetry limit?*
  A: Factorizable $SU(3)_F$ corrections can be estimated (f_K/f_π and $F^{B\to K}/F^{B\to\pi}$)

  Q: *What about non-factorizable $SU(3)_F$ corrections?*
  A: Probably not larger than 30%

  Needs experimental input (Tevatron, LHC) /
  cross-check with non-perturbative methods (see below)

Approximate symmetries

Q: *Can one use isospin-symmetry in $B \to \pi K$?*

A: Different situation than in $B \to \pi\pi$ because of different CKM structure:

- short-distance isospin violation included via EW penguins from SM or NP
- long-distance contributions from non-factorizable QED effects:
  WARNING! — Expansion parameter enhanced, if non-factorizable power corrections are numerically important

$$\alpha_{\rm QED} \longrightarrow \alpha_{\rm QED} \ln \frac{\Lambda}{m_b} \sim \frac{\alpha_{\rm QED}}{\alpha_s}$$

- "π-K puzzle"
  (somewhat too large deviations between charged and neutral decay modes)
  may partly be solved by QED corrections! [TF/Hurth 04]
  ...deserves further studies ...

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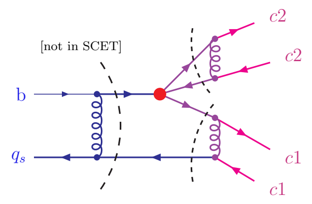
Non-perturbative methods

- No input from lattice (cannot simulate fast pions)

Non-perturbative methods

- Non-factorizable effects from light-cone sum rules:



  - Replace soft and/or collinear final states by appropriate interpolating currents
  - Dispersion relation for correlation function
  - ...
  - result in terms of sum-rule parameters and form factors, decay constants, LCDAs, condensates, quark masses ...

Non-perturbative methods

- Input to factorization formula from LCSRs:
  - form factor:

$$F_+^{B\to\pi}(0) = 0.26 \pm 0.03$$

$$\frac{F_+^{B\to K}(0)}{F_+^{B\to\pi}(0)} = 1.2 - 1.5$$ LCSR in QCD [→ talk by R. Zwicky]

$$\xi_{\rm soft}^{B\to\pi} \equiv \zeta = 0.27^{+0.09}_{-0.12}$$

$$\zeta_J \ll \zeta$$ LCSR in SCET [DeFazio/TF/Hurth 05]

  - inverse moment of pion LCDA:

$$\langle u^{-1}\rangle_\pi = 3.3 \pm 0.3 \qquad \text{(at } \mu = 1 \text{ GeV)}$$

  - inverse moment of the B-meson LCDA:

$$\langle \omega^{-1}\rangle_B = (2.15 \pm 0.50)\ \text{GeV}^{-1} \qquad \text{(at } \mu = 1 \text{ GeV)}$$

[Braun/Ivanov/Korchemsky 03, see also Lee/Neubert 05]

Non-perturbative methods

- Estimate of non-factorizable corrections in $B \to \pi\pi$:

[Khodjamirian et al. hep-ph/0509049]
[preliminary results from M. Melcher (work in preparation)]

$$\mathcal{A}(\bar{B}_d^0 \to \pi^+\pi^-) = \text{(naive)} \times \left\{ \lambda_u(c_1 + c_2/3) + \sum_{k,T} \lambda_k \tilde{c}_k r_{k,T}^{(\pi\pi)} \right\}$$

From LCSRs in QCD (finite m_b):

- "emission topologies":
  $10^2 \times r_E^{(\pi\pi)} = \left(1.8^{+0.5}_{-0.7}\right)_{1/m_b} + \left[\left(-1.9^{+0.5}_{-0.1}\right) + i\left(-3.6^{+1.0}_{-0.4}\right)\right]_{\alpha_s}$
- "charming penguin":
  $10^2 \times r_{P_c}^{(\pi\pi)} = -0.18^{+0.06}_{-0.68} + i\left(-0.80^{+0.17}_{-0.08}\right)$
- "annihilation":
  $10^3 \times r_A^{(\pi\pi)} = -0.67^{+0.47}_{-0.87} + i\left(3.6^{+0.5}_{-1.1}\right)$

Non-factorizable effects, including FSI phases, small (?)

Non-perturbative methods

- $SU(3)_F$ breaking in $B \to \pi K$ from LCSR:

  [Khodjamirian/Mannel/Melcher hep-ph/0407226]

  - in terms of m_s, $\langle \bar{s}s \rangle$ and a_1^K (kaon DA)
  - typical $SU(3)_F$ relation: (emission topology only)

$$A(B^- \to \pi^- \bar{K}^0) + \sqrt{2} A(B^- \to \pi^0 K^-)$$
$$= \sqrt{2} \left(\frac{V_{us}}{V_{ud}} \right) A(B^- \to \pi^- \pi^0) \{1 + \delta_{SU(3)}\}$$

  - Estimate: $\delta_{SU(3)} = (0.215^{+0.019}_{-0.016}) + (-0.009^{+0.009}_{-0.010})i$

    (consistent with naive expectation)

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- hadronic uncertainties as input to QCD factorization
- non-factorizable hadronic uncertainties at $\mathcal{O}(1/m_b)$
- symmetry constraints
- non-perturbative effects estimated via LCSRs
  (in QCD or in SCET)
- phenomenological situation not completely satisfactory
  - depends on particular channel/observable
  - may partly be improved by NNLO effects in QCDF

    [⟶ talk by S. Jäger]
  - more experimental feedback may help, too!

Q: *Can we do better?*

A: It may be worth looking at sub-leading effects from the SCET perspective …
[see also TF/Hurth 04]

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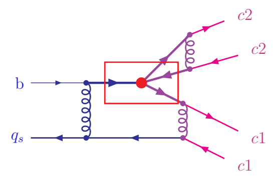
SCET classification of sub-leading operators

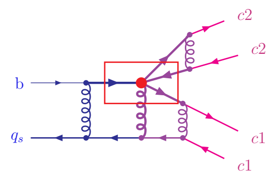
Q: *How do the leading (non-local) operators look like?*

A: (schematically, using light-cone gauge)

$(\bar\xi_L^{hc2}\,\Gamma\,\xi_L^{hc2})\,(\bar\xi_L^{hc1}\,h_v)$



$(\bar\xi_L^{hc2}\,\Gamma\,\xi_L^{hc2})\,(\bar\xi_L^{hc1}\,\not{A}_{hc1}^{\perp}\,h_v)$



QCD-factorizable

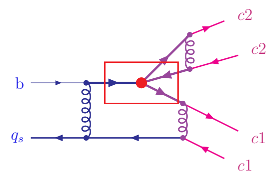
[see also Chay/Kim, Bauer et al.]

SCET classification of sub-leading operators

Q: *What, if one changes the chirality of light quarks?*

A: same kind of diagrams, . . .

$(\bar{\xi}_L^{hc2}\,\Gamma\,\xi_R^{hc2})\,(\bar{\xi}_R^{hc1}\,h_v)$



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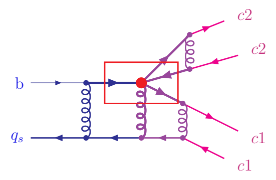


- different hard-matching coefficient functions

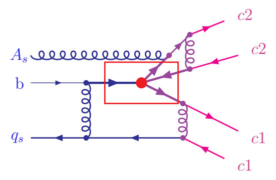
$\longrightarrow$ chirally enhanced power corrections $\sim m_\pi^2/(2m_q m_b)$ (X_H in BBNS)

SCET classification of sub-leading operators

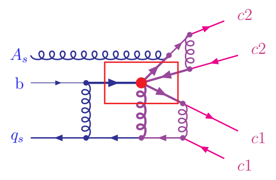
Q: *What about different colour projection?*

A: requires additional soft gluon radiation

$(\bar{\xi}_L^{hc2} \Gamma T^A \xi_L^{hc2}) (\bar{\xi}_L^{hc1} T^A h_v)$



$(\bar{\xi}_L^{hc2} \Gamma T^A \xi_L^{hc2}) (\bar{\xi}_L^{hc1} \not{A}^{\perp}_{hc1} T^A h_v)$



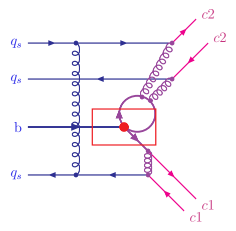
- sensitive to higher Fock states with additional soft gluon

$\longrightarrow$ power corrections to “colour-suppressed tree”

SCET classification of sub-leading operators

- change isospin projection of light quark pair
  $\rightarrow$ power corrections to “penguin” amplitude

$(\bar{\xi}_L^{hc2}\Gamma\,\xi_L^{hc2})_{I=0}\,(\bar{\xi}_L^{hc1}\,h_v)$



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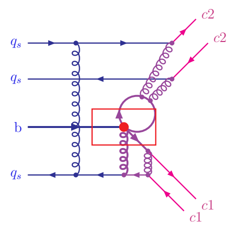


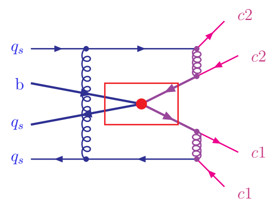
- Sensitive to higher Fock states with additional $q\bar{q}$ pairs.
- Count $\sqrt{\Lambda m_b} \sim m_c \ll m_b \quad \Rightarrow \quad (I=0)$ can also be $c\bar{c}$
  $\Rightarrow$ charm and light-quark loops on the same footing!

SCET classification of sub-leading operators

Q: *What about annihilation of soft spectator quark?*

A: requires additional $q\bar{q}$ pair

$(\bar{\xi}_L^{hc2}\Gamma T^A \xi_L^{hc2})_{l=0}\,(\bar{\xi}_L^{hc1}\, T^A h_v)$



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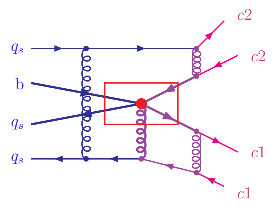


- Sensitive to higher Fock states with additional $q\bar{q}$ pairs.

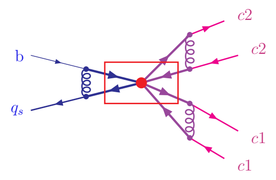
$\longrightarrow$ soft contribution to annihilation (power-suppressed)

SCET classification of sub-leading operators

Q: *Are there operators with more than 4 quarks?*

A: Yes, via pair production from hard gluons ...

$$(\bar\xi^{hc2}\Gamma\xi^{hc2})\,(\bar\xi^{hc1}\Gamma'\xi^{hc1})\,(\bar q_s\Gamma'' h_v)$$



$\longrightarrow$ hard contribution to annihilation (X_A in BBNS)