Charmless Two-body $B \to PP$, VP Decays in Soft-Collinear-Effective-Theory (SCET)

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based on work: arXiv:0801.3123 [hep-ph]

Outline

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1. Motivation
2. Factorization of $B \longrightarrow M_1 M_2$ decays in SCET
   - SCET in heavy quark physics
   - Fields, Power counting in SCET
   - Form factor and Decay amplitudes at leading power
   - Chiraly enhanced penguin
3. SCET analysis in $B \longrightarrow M_1 M_2$ decays
4. Conclusion

Theoretical approaches in B decays

There are many comprehensive studies of $B \to PP$, VP, VV decays in recent years:

- Naive factorization (Generalized factorization):
  $\langle M_1\, M_2|\mathcal{O}|B\rangle \propto f_{M_1} F^{B\to M_2} + f_{M_2} F^{B\to M_1}$
- QCD factorization: naive factorization + vertex corrections + hard spectator + (annihilation)
- PQCD approach: k_T factorization+ Sudakov resummation
- Soft-Collinear Effective Theory (SCET)
- Final state interactions: short distance + long distance

Motivation

1. In SCET, factorization is easily to prove theoretically.

But in phenomenology, there are two different ways: one is very similar with QCDF (by M. Beneke etc.);

Only a few studies in the other way on $B \to PP$ decays :

C. W. Bauer, I. Z. Rothstein and I. W. Stewart, Phys. Rev. D **74**, 034010 (2006)

A. R. Williamson and J. Zupan, Phys. Rev. D **74**, 014003 (2006) [Erratum-ibid. D **74**, 03901 (2006)]

There are not too many studies on $B \to VP$ and $B \to VV$ decays up to now.

Motivation

2. Chiraly enhanced penguin is an important power correction which has been taken into account in QCDF and PQCD approach.

Recently, factorization analysis of chiraly enhanced penguin has also been studied.

A. Jain, I. Z. Rothstein and I. W. Stewart, arXiv:0706.3399 [hep-ph].

But this has not been included in the phenomenology study

Outline

SCET in heavy quark physics

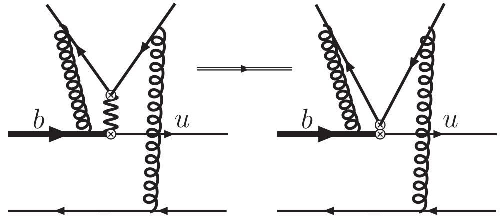


Figure: Typical Feynmann diagrams in the standard model

SCET in heavy quark physics

The starting point is the effective weak Hamiltonian at the scale $\mu \sim m_b$. We specify the weak effective Hamiltonian which describes $b \to D$ $(D = d, s)$ transitions :

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \Bigg\{ \sum_{q=u,c} V_{qb} V_{qD}^* \Big[C_1(\mu) O_1^q(\mu) + C_2(\mu) O_2^q(\mu)$$

$$+ \sum_{i=3}^{10,7\gamma,8g} C_i(\mu) O_i(\mu) \Big] \Bigg\} + \text{H.c.},$$

- current–current (tree) operators

$$O_1^q = (\bar{q}_\alpha b_\beta)_{V-A} (\bar{D}_\beta q_\alpha)_{V-A}, \qquad O_2^q = (\bar{q}_\alpha b_\alpha)_{V-A} (\bar{D}_\beta q_\beta)_{V-A},$$

QCD penguin operators and electro-weak penguin operators

$$O_3 = (\bar{D}_\alpha b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\beta q'_\beta)_{V-A}, \qquad O_4 = (\bar{D}_\beta b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\alpha q'_\beta)_{V-A},$$

$$O_5 = (\bar{D}_\alpha b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\beta q'_\beta)_{V+A}, \qquad O_6 = (\bar{D}_\beta b_\alpha)_{V-A} \sum_{q'} (\bar{q}'_\alpha q'_\beta)_{V+A},$$

$$O_7 = \frac{3}{2} (\bar{D}_\alpha b_\alpha)_{V-A} \sum_{q'} e_{q'} (\bar{q}'_\beta q'_\beta)_{V+A}, \quad O_8 = \frac{3}{2} (\bar{D}_\beta b_\alpha)_{V-A} \sum_{q'} e_{q'} (\bar{q}'_\alpha q'_\beta$$

$$O_9 = \frac{3}{2} (\bar{D}_\alpha b_\alpha)_{V-A} \sum_{q'} e_{q'} (\bar{q}'_\beta q'_\beta)_{V-A}, \quad O_{10} = \frac{3}{2} (\bar{D}_\beta b_\alpha)_{V-A} \sum_{q'} e_{q'} (\bar{q}'_\alpha q'$$

magnetic moment operators

$$O_{7\gamma} = -\frac{e m_b}{4\pi^2} \bar{D}_\alpha \sigma^{\mu\nu} P_R b_\alpha F_{\mu\nu}, \qquad O_{8g} = -\frac{g m_b}{4\pi^2} \bar{D}_\alpha \sigma^{\mu\nu} P_R T^a_{\alpha\beta} b_\beta G^a_{\mu\nu}, \quad (2)$$

SCET in heavy quark physics

The physics over scale $1/m_b$ can be computed using the operator product expansion. At the scale $\mu = m_b = 4.8$ GeV the Wilson coefficients C_i for tree and QCD penguin operators are

$$C_{1-6}(m_b) = \{1.110, -0.253, 0.011, -0.026, 0.008, -0.032\}, \quad (3)$$

while for electro-weak penguin (EWP) operators:

$$C_{7-10}(m_b) = \{0.09, 0.24, -10.3, 2.2\} \times 10^{-3}, \quad (4)$$

and for the magnetic operators $C_{7\gamma}(m_b) = -0.315$, $C_{8g}(m_b) = -0.149$.

Fields, Power counting in SCET

We can give the fields which appear in SCET with the corresponding **power** in expansion of $\lambda = \sqrt{\Lambda_{QCD}/m_B}$.

Heavy quark :

$$Q = e^{-imv\cdot x}(h_v + H_v), \tag{5}$$

with the definition for these two kinds of heavy fields:

$$h_v = \frac{1+\not{v}}{2} e^{imv\cdot x} Q \sim \lambda^3, \tag{6}$$

$$H_v = \frac{1-\not{v}}{2} e^{imv\cdot x} Q. \tag{7}$$

The component H_v will be integrated out.

Fields, Power counting in SCET

The power for soft quarks and soft gluons could be determined by the propagators:

Soft quarks $q(x)$: $k \sim (\lambda^2, \lambda^2, \lambda^2, \lambda^2)$

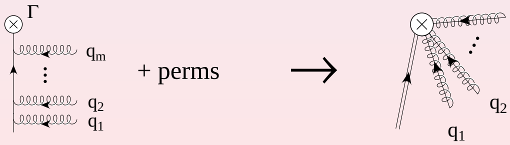
$$T[q(x)\bar{q}(y)] = \int d^4 k e^{-ik(x-y)} \frac{i\not{k}}{k^2} \sim \lambda^6 \rightarrow q \sim \lambda^3 \quad (8)$$

Soft gluons : $A_s \sim \lambda^2$.

Form factor and Decay amplitudes at leading power

An important feature of SCET is that we can very easily consider the interactions between the soft sector and collinear sector to all orders in α_s.

Here we take the interaction between a heavy quark and collinear gluons as an example:



$\text{SCET}_{I,II}$ and application to B to light form factors

These propagators will be integrated out and the gluons can be summed together. In effective theory, this can be achieved by making the following field redefinition:

$$h_v \longrightarrow W_{hc} h_v, \tag{9}$$

where W_{hc} is a Wilson line for hard-collinear gluons. Similarly, we can also redefine the hard-collinear fields:

$$\xi \longrightarrow Y_s \xi, \quad A_c \longrightarrow Y_s A_c Y_s^\dagger, \tag{10}$$

Y_s is a soft Wilson line. After these redefinitions, the hard-collinear sector and the soft sector will decouple with each other.

Form factor and Decay amplitudes at leading power

B to light form factors can be divided into two different kinds of contributions in SCET$_I$ up to next-to-leading power:

1. Quark bilinears (Two-body operators): $(\bar{\chi} W_{c1}) \not{n}_+ (1-\gamma_5) h_v$
2. Three-body operators: $(\bar{u} W_{c1})(W^\dagger_{c1} i\not{D}_{\perp c1} W_{c1})(s n_+)(1-\gamma_5) h_v$

$$\langle M_2 | T[(\bar{\chi} W_{c1}) \not{n}_+ (1-\gamma_5) h_v] | B \rangle = m_B \zeta,$$
$$\langle M_2 | T[(\bar{u} W_{c1})(W^\dagger_{c1} i\not{D}_{\perp c1} W_{c1})(s n_+)(1-\gamma_5) h_v] | B \rangle$$
$$= -m_B^2 \int dz e^{i m_B z \cdot s} \zeta_J(z), \quad (11)$$

$\zeta_J^{BM_2}(z)$ is given in terms of the jet functions as in SCET$_{II}$:

$$\zeta_J^{BM_2}(z) = \frac{f_B f_M}{m_B} \int dk_+ dx \phi_B^+(k_+) J(z, x, k_+) \phi_{M_2}(x). \quad (12)$$

Electro-Weak Hamiltonian in SCET$_I$

In SCET$_I$, the leading power operators are given by

$$
\begin{aligned}
Q_{1s}^{(0)}(t) &= \left[(\bar{s}W_{c2})(tn_-)\frac{\not{n}_-}{2}(1-\gamma_5)(W_{c2}^\dagger u)\right][(\bar{u}W_{c1})\not{n}_+(1-\gamma_5)h_v]\,, \\
Q_{2s,3s}^{(0)}(t) &= \left[(\bar{u}W_{c2})(tn_-)\frac{\not{n}_-}{2}(1\mp\gamma_5)(W_{c2}^\dagger u)\right][(\bar{s}W_{c1})\not{n}_+(1-\gamma_5)h_v]\,, \\
Q_{4s}^{(0)}(t) &= \left[(\bar{s}W_{c2})(tn_-)\frac{\not{n}_-}{2}(1-\gamma_5)(W_{c2}^\dagger q)\right][(\bar{q}W_{c1})\not{n}_+(1-\gamma_5)h_v]\,, \\
Q_{5s,6s}^{(0)}(t) &= \left[(\bar{q}W_{c2})(tn_-)\frac{\not{n}_-}{2}(1\mp\gamma_5)(W_{c2}^\dagger q)\right][(\bar{s}W_{c1})\not{n}_+(1-\gamma_5)h_v]\,, \\
Q_{gs}^{(0)} &= m_b i\epsilon_{\perp\mu\nu}\mathrm{Tr}\left[[W_{c2}^\dagger iD_{\perp c2}^{\mu}W_{c2}][W_{c2}^\dagger iD_{\perp c2}^{\nu}W_{c2}]\right] \\
&\quad\times[(\bar{s}W_{c1})\not{n}_+(1-\gamma_5)h_v]\,.
\end{aligned}
$$

Electro-weak Hamiltonian in SCET_I

The next-to-leading power operators are given by:

$$
\begin{aligned}
Q_{1s}^{(1)}(t) &= -\frac{1}{m_b}\left[(\bar{s}W_{c2})(tn_-)\frac{\not{n}_-}{n_-v}P_L(W_{c2}^\dagger u)\right]\left[(\bar{u}W_{c1})(W_{c1}^\dagger i\not{D}_{\perp c1}W_{c1})P_L h_v\right], \\
Q_{2s,3s}^{(1)}(t) &= -\frac{1}{m_b}\left[(\bar{u}W_{c2})(tn_-)\frac{\not{n}_-}{n_-v}(1\mp\gamma_5)(W_{c2}^\dagger u)\right]\left[(\bar{s}W_{c1})(W_{c1}^\dagger i\not{D}_{\perp c1}W_{c1})P_L h_v\right] \\
Q_{4s}^{(1)}(t) &= -\frac{1}{m_b}\left[(\bar{s}W_{c2})(tn_-)\frac{\not{n}_-}{n_-v}(P_L(W_{c2}^\dagger q)\right]\left[(\bar{q}W_{c1})(W_{c1}^\dagger i\not{D}_{\perp c1}W_{c1})P_L h_v\right], \\
Q_{5s,6s}^{(1)}(t) &= -\frac{1}{m_b}\left[(\bar{q}W_{c2})(tn_-)\frac{\not{n}_-}{n_-v}(1\mp\gamma_5)(W_{c2}^\dagger q)\right]\left[(\bar{s}W_{c1})(W_{c1}^\dagger i\not{D}_{\perp c1}W_{c1})P_L h_v\right] \\
Q_{7s}^{(1)}(t) &= -\frac{1}{m_b}\left[(\bar{s}W_{c2})(tn_-)\not{n}_-\gamma_\mu^\perp P_R(W_{c2}^\dagger u)\right]\left[(\bar{u}W_{c1})(W_{c1}^\dagger iD_{\perp c1}^\mu W_{c1})P_L h_v\right], \\
Q_{8s}^{(1)}(t) &= -\frac{1}{m_b}\left[(\bar{s}W_{c2})(tn_-)\not{n}_-\gamma_\mu^\perp P_R(W_{c2}^\dagger q)\right]\left[(\bar{q}W_{c1})(W_{c1}^\dagger iD_{\perp c1}^\mu W_{c1})P_L h_v\right], \\
Q_{gs}^{(1)} &= -2m_b i\epsilon_{\perp\mu\nu}\mathrm{Tr}\left[[W_{c2}^\dagger iD_{\perp c2}^\mu W_{c2}][W_{c2}^\dagger iD_{\perp c2}^\nu W_{c2}]\right]\left[(\bar{s}W_{c1})(W_{c1}^\dagger i\not{D}_{\perp c1}W_{c1})\right.
\end{aligned}
$$

Factorization of $B \longrightarrow M_1 M_2$ decays in SCET

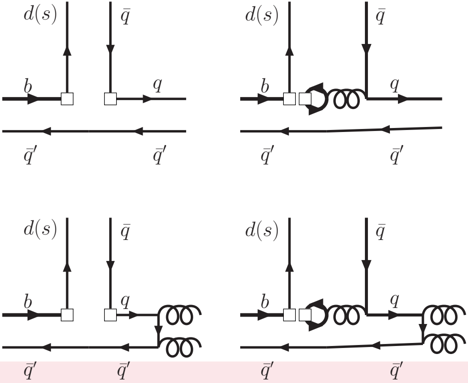
Power corrections are expected to be suppressed by at least the factor Λ_{QCD}/m_b, but chiraly enhanced penguins (operator O_6) are expected to be large enough as the suppression factor becomes $2\mu_P/m_b$, where μ_P is the chiral scale parameter.

Numerically, the chiral enhanced penguin can be comparable with contributions from leading power penguins, since $2\mu_P/m_b \sim 1$.

In SCET, the complete operator basis and the corresponding factorization formulae for the chirally enhanced penguin can be derived, which do not suffer from endpoint singularities.

This term will introduce a new form factor ζ_χ and a new light-cone distribution amplitude ϕ^{pp}.

The chiraly enhanced penguin has the same topology with charming penguin but different CKM matrix elements



Feynman diagrams for chiraly enhanced penguins (left) and charming penguins (right). The lower two diagrams only contribute to decays involving η or η', where $q = q'$.

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In SCET, the decay amplitudes of $B \to M_1 M_2$ can be written by:

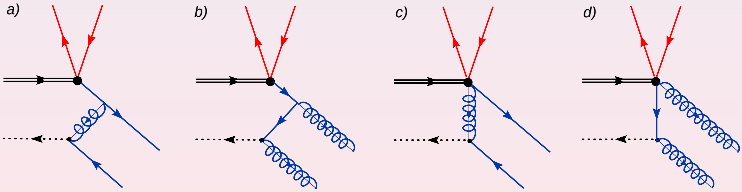
$$\begin{aligned} A(B \to M_1 M_2) &= \frac{G_F}{\sqrt{2}} m_B^2 \Big\{ f_{M_1} \int du \phi_{M_1}(u) T_1(u) \zeta^{BM_2} \\ &+ f_{M_1} \int du \phi_{M_1}(u) \int dz T_{1J}(u,z) \zeta_J^{BM_2}(z) \\ &+ f_{M_1} \int du \phi_{M_1}(u) T_{1g}(u) \zeta_g + \lambda_c^{(f)} A_{cc}^{M_1 M_2} \\ &+ f_{M_1} \int du \phi_{M_1}(u) \int dz T_{1Jg}(u,z) \zeta_{Jg}(z) + 1 \leftrightarrow 2 \Big\}, \end{aligned}$$

$$\begin{aligned} A^{\chi}(B \to M_1 M_2) &= \frac{G_F}{\sqrt{2}} m_B^2 \Big\{ -\frac{\mu_{M_1} f_{M_1}}{3 m_B} \int du \phi_{pp}^{M_1}(u) T_1^{\chi}(u) \zeta^{BM_2} \\ &\quad -\frac{\mu_{M_1} f_{M_1}}{3 m_B} \int dudz \phi_{pp}^{M_1}(u) T_{1J}^{\chi}(u,z) \zeta_J^{BM_2}(z) \Big\}, \end{aligned}$$

SCET analysis in $B \longrightarrow M_1 M_2$ decays

6 form factor like parameters

Figure: Factorizable and non-factorizable emission diagrams in SCET



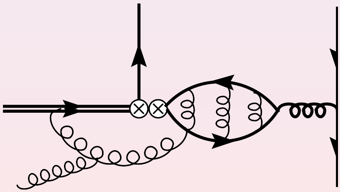
ζ^{BP}, ζ^{BV}, ζ_g, ζ_J^{BP}, ζ_J^{BV} ζ_{Jg}

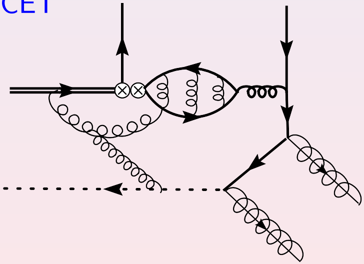
non-perturbative form factor perturbative part

SCET analysis in $B \to M_1 M_2$ decays

5 complex charming penguin parameters (10 real parameters)

Two kinds of charming penguins in SCET





A_{cc}^{PP}, A_{cc}^{PV}, A_{cc}^{VP}, A_{ccg}^{PP}, A_{ccg}^{VP}.

SCET analysis in $B \to M_1 M_2$ decays

In the exact SU(3) limit, only two form factors are needed for $B \to PP$ decays without iso-singlet mesons:

$$\zeta_{(J)}^{BP} \equiv \zeta_{(J)}^{B\pi} = \zeta_{(J)}^{BK} = \zeta_{(J)}^{B_s K}. \tag{13}$$

Similarly, for $B \to V$ form factors:

$$\zeta_{(J)}^{BV} \equiv \zeta_{(J)}^{B\rho} = \zeta_{(J)}^{BK^*} = \zeta_{(J)}^{B\omega} = \zeta_{(J)}^{B_s K^*} = \zeta_{(J)}^{B_s \phi}. \tag{14}$$

There are non-perturbative, totally 16, inputs:

$$\zeta^{BP}, \quad \zeta_J^{BP}, \quad \zeta_g, \quad \zeta_{Jg}, \quad \zeta^{BV}, \quad \zeta_J^{BV}$$
$$A_{cc}^{PP}, \quad A_{cc}^{PV}, \quad A_{cc}^{VP}, \quad A_{ccg}^{PP}, \quad A_{ccg}^{VP}.$$

The χ^2 fit formula is

$$\chi_{BR}^2 = \sum_i \frac{(BR_i^{th} - BR_i^{exp})^2}{(BR_i^{err})^2}. \tag{15}$$

SCET analysis in $B \longrightarrow M_1 M_2$ decays

With 89 experimental data on $B \to PP$ and VP decays, the results for the non-perturbative inputs at leading power are:

$$
\begin{aligned}
\zeta^P &= (12.6 \pm 0.8) \times 10^{-2}, & \zeta_J^P &= (7.4 \pm 0.6) \times 10^{-2}, \\
\zeta^V &= (11.2 \pm 1.8) \times 10^{-2}, & \zeta_J^V &= (11.8 \pm 2.0) \times 10^{-2}, \\
\zeta_g &= (-5.3 \pm 2.4) \times 10^{-2}, & \zeta_{Jg} &= (-2.3 \pm 3.1) \times 10^{-2}, \\
|A_{cc}^{PP}| &= (48.0 \pm 0.6) \times 10^{-4}, & arg[A_{cc}^{PP}] &= (176.7 \pm 1.8)^\circ, \\
|A_{cc}^{VP}| &= (40.6 \pm 0.8) \times 10^{-4}, & arg[A_{cc}^{VP}] &= (2.9 \pm 4.5)^\circ, \\
|A_{cc}^{PV}| &= (30.9 \pm 1.2) \times 10^{-4}, & arg[A_{cc}^{PV}] &= (192.6 \pm 4.7)^\circ, \\
|A_{ccg}^{PP}| &= (38.6 \pm 2.0) \times 10^{-4}, & arg[A_{ccg}^{PP}] &= (90.1 \pm 3.7)^\circ, \\
|A_{ccg}^{VP}| &= (23.7 \pm 2.5) \times 10^{-4}, & arg[A_{ccg}^{VP}] &= (-23.7 \pm 11.0)^\circ,
\end{aligned}
$$

The form factors are then

$$F^{B\to P} = \zeta^P + \zeta_J^P = 0.198 \pm 0.004, \quad A_0^{B\to V} = \zeta^V + \zeta_J^V = 0.212 \pm 0.011$$

SCET analysis in $B \longrightarrow M_1 M_2$ decays

With chiraly enhanced penguin:

$$\begin{aligned}
\zeta^P &= (13.4 \pm 0.4) \times 10^{-2}, \quad \zeta_J^P = (7.2 \pm 0.3) \times 10^{-2}, \\
\zeta^V &= (11.3 \pm 1.0) \times 10^{-2}, \quad \zeta_J^V = (11.7 \pm 0.9) \times 10^{-2}, \\
\zeta_g &= (-5.2 \pm 1.1) \times 10^{-2}, \quad \zeta_{Jg} = (-2.5 \pm 1.3) \times 10^{-2}, \\
|A_{cc}^{PP}| &= (39.7 \pm 0.5) \times 10^{-4}, \quad arg[A_{cc}^{PP}] = (176.0 \pm 2.1)^\circ, \\
|A_{cc}^{VP}| &= (41.0 \pm 0.8) \times 10^{-4}, \quad arg[A_{cc}^{VP}] = (2.6 \pm 4.3)^\circ, \\
|A_{cc}^{PV}| &= (39.8 \pm 1.0) \times 10^{-4}, \quad arg[A_{cc}^{PV}] = (189.9 \pm 3.4)^\circ, \\
|A_{ccg}^{PP}| &= (38.3 \pm 1.4) \times 10^{-4}, \quad arg[A_{ccg}^{PP}] = (94.9 \pm 2.9)^\circ, \\
|A_{ccg}^{VP}| &= (24.4 \pm 2.3) \times 10^{-4}, \quad arg[A_{ccg}^{VP}] = (-17.6 \pm 13.2)^\circ,
\end{aligned}$$

$$F^{B\to P} = 0.206 \pm 0.003, \quad A_0^{B\to V} = 0.229 \pm 0.007 \qquad (16)$$

SCET analysis in $B \longrightarrow M_1 M_2$ decays

The inclusion of chirally enhanced penguin will mainly change the three charming penguins A_{cc}^{PP}, A_{ccg}^{PP}, A_{cc}^{PV}.

Predictions for branching fractions and CP asymmetries will not be changed sizably.

After including the chiraly enhanced penguin, the total χ^2 is smaller $\chi^2 = 331/(89-16)$ while $\chi^2 = 155$ for the 57 observables in $B \longrightarrow VP$ decays. (S1)

We also find another solution with the chiral enhanced penguin (S2)

The corresponding $\chi^2 = 305/(89-16)$, χ^2 for the 57 observables in all $B \longrightarrow VP$ decays is 118

SCET analysis in $B \longrightarrow M_1 M_2$ decays

S2

$$\begin{aligned}
\zeta^P &= (14.0 \pm 0.9) \times 10^{-2}, & \zeta_J^P &= (5.5 \pm 0.7) \times 10^{-2}, \\
\zeta^V &= (23.5 \pm 1.9) \times 10^{-2}, & \zeta_J^V &= (5.8 \pm 2.0) \times 10^{-2}, \\
\zeta_g &= (-10.4 \pm 0.7) \times 10^{-2}, & \zeta_{Jg} &= (5.4 \pm 0.8) \times 10^{-2}, \\
|A_{cc}^{PP}| &= (40.4 \pm 0.6) \times 10^{-4}, & arg[A_{cc}^{PP}] &= (176.0 \pm 1.7)^\circ, \\
|A_{cc}^{VP}| &= (29.0 \pm 0.8) \times 10^{-4}, & arg[A_{cc}^{VP}] &= (178.2 \pm 7.5)^\circ, \\
|A_{cc}^{PV}| &= (33.5 \pm 1.1) \times 10^{-4}, & arg[A_{cc}^{PV}] &= (-12.8 \pm 4.0)^\circ, \\
|A_{ccg}^{PP}| &= (38.3 \pm 1.8) \times 10^{-4}, & arg[A_{ccg}^{PP}] &= (95.2 \pm 3.8)^\circ, \\
|A_{ccg}^{VP}| &= (19.1 \pm 2.4) \times 10^{-4}, & arg[A_{ccg}^{VP}] &= (114.1 \pm 10.4)^\circ,
\end{aligned}$$

with the form factors:

$$F^{B \to P} = 0.196 \pm 0.016, \quad A_0^{B \to V} = 0.293 \pm 0.010 \qquad (17)$$

Form factors and tree dominated B decays

Branching Ratios (in units of 10^{-6}) of $B \to \pi\rho$ decays induced by the $b \to d$ ($\Delta S = 0$) transition.

Channel	Exp.	QCDF	S1	S2
$\bar{B}^0 \to \rho^+\pi^-$	8.9 ± 2.5	$15.4^{+8.0+5.5+0.7+1.9}_{-6.4-4.7-1.3-1.3}$	5.7	6.7
$\bar{B}^0 \to \rho^-\pi^+$	13.9 ± 2.7	$21.2^{+10.3+8.7+1.3+2.0}_{-\ 8.4-7.2-2.3-1.6}$	7.4	10.1
$\bar{B}^0 \to \rho^0\pi^0$	$1.8^{+0.6}_{-0.5}$	$0.4^{+0.2+0.2+0.9+0.5}_{-0.2-0.1-0.3-0.3}$	2.6	1.4

Our predictions on branching fractions are smaller than those in QCDF: they use much larger form factors $F^{B\to\pi} = 0.28$, $A_0^{B\to\rho} = 0.37$.

Color-suppressed B decays in SCET

Our predictions for branching ratios of $\bar{B}^0 \longrightarrow \pi^0 \rho^0$ are larger than that in QCDF and consistent with experimental data:

1. Color-suppressed: $C_2 + \frac{C_1}{N_c} \sim 0.12 \ll C_1 + \frac{C_2}{N_c} \sim 1.$

2. Hard-scattering form factor ζ_J is large and comparable with the soft form factor ζ.

$$\zeta_J^P = (7.4 \pm 0.6) \times 10^{-2}, \quad \zeta_J^V = (11.8 \pm 2.0) \times 10^{-2}. \qquad (18)$$

3. ζ_J has a large correction in Wilson coefficient b_1^f, since $C_2 + \frac{1}{N_c}(1 - \frac{m_b}{\omega_3})C_1 \sim 1.23$ is large (even larger than the so-called color allowed Wilson coefficient $b_1 = C_1 + \frac{1}{N_c}(1 - \frac{m_b}{\omega_3})C_2 \sim 0.77$)

4. Two kinds of charming penguin almost cancel with each other, since they have similar magnitudes and but different phases

Penguin dominated B decays in SCET

The CKM matrix elements $b \to s$ transition are given as:

$|V_{ub}V_{us}^*| = 0.81\times 10^{-3}$, $|V_{cb}V_{cs}^*| = 39.41\times 10^{-3}$, $|V_{tb}V_{ts}^*| = 40.66\times 10^{-3}$.

The tree operator is suppressed, but the penguin operators are comparable with charming penguins.

$$A_t(B^- \to \pi^- \bar{K}^0) = 0.16 \times (-0.044\zeta^P - 0.036\zeta_J^P) \sim 15 \times 10^{-4},$$
$$A_t(B^- \to \rho^- \bar{K}^0) = 0.16 \times (0.0004\zeta^V + 0.004\zeta_J^V) \sim 1 \times 10^{-4},$$
$$A_t(B^- \to \pi^- \bar{K}^{*0}) = 0.217 \times (-0.022\zeta^P - 0.015\zeta_J^P) \sim 10 \times 10^{-4}.$$

Penguin dominated B decays in SCET

$$
\begin{aligned}
|A_{cc}^{PP}| &= (39.7 \pm 0.5) \times 10^{-4}, \quad arg[A_{cc}^{PP}] = (176.0 \pm 2.1)^\circ, \\
|A_{cc}^{VP}| &= (41.0 \pm 0.8) \times 10^{-4}, \quad arg[A_{cc}^{VP}] = (2.6 \pm 4.3)^\circ, \\
|A_{cc}^{PV}| &= (39.8 \pm 1.0) \times 10^{-4}, \quad arg[A_{cc}^{PV}] = (189.9 \pm 3.4)^\circ,
\end{aligned}
$$

Branching ratios (in units of 10^{-6}) for $\Delta s = 1$ processes.

Channel	Exp.	QCDF	PQCD	S 1	S 2
$B^- \to \bar{K}^{*0}\pi^-$	10.7 ± 0.8	$3.6^{+0.4+1.5+1.2+7.7}_{-0.3-1.4-1.2-2.3}$	$6.0^{+2.8}_{-1.5}$	8.5	9.9
$B^- \to \rho^- \bar{K}^0$	$8.0^{+1.5}_{-1.4}$	$5.8^{+0.6+7.0+1.5+10.3}_{-0.6-3.3-1.3-3.2}$	$8.7^{+6.8}_{-4.4}$	9.3	10.0

B_s decays in SCET

Most comparable with the other two approaches

But there are large differences in our predictions of $\mathcal{BR}(\bar{B}_s \to \phi\eta(\eta'))$ with QCDF and PQCD.

CP-averaged branching ratios ($\times 10^{-6}$) of $B_s \to PV$ decays

Modes	QCDF	PQCD	S 1	S 2
$\bar{B}_s^0 \to \phi\eta$	$0.12^{+0.02+0.95+0.54+0.32}_{-0.02-0.14-0.12-0.13}$	$3.6^{+1.5+0.8+0.0}_{-1.0-0.6-0.0}$	0.40	1.2
$\bar{B}_s^0 \to \phi\eta'$	$0.05^{+0.01+1.10+0.18+0.40}_{-0.01-0.17-0.08-0.04}$	$0.19^{+0.06+0.19+0.00}_{-0.01-0.13-0.00}$	7.7	4.2

B_s decays in SCET

In PQCD, the contribution from gluonic component of η and η' are small.

$B_s \to \phi\eta_q$: $2(a_3 - a_5)$, with $q = u, d$
$B_s \to \phi\eta_s$: $a_4 - 2r_\chi a_6 + a_3 - a_5$ (η_s emission) or $a_4 + a_3 - a_5$ (ϕ emission).

$$\eta = \eta_q \cos\theta - \eta_s \sin\theta, \quad \eta' = \eta_q \sin\theta + \eta_s \cos\theta \tag{19}$$

Numerical values of the Wilson coefficients at different scales (μ).

μ (GeV)	2.5	2.0	1.5	1.0
$a_3(\times 10^{-3})$	6.2	7.5	9.7	14.4
$a_4(\times 10^{-3})$	-32.0	-35.8	-41.4	-51.3
$a_5(\times 10^{-3})$	-5.6	-7.4	-10.5	-17.6
$a_6(\times 10^{-3})$	-46.8	-54.9	-68.2	-95.6

B_s decays in SCET

In SCET, the charming penguins A_{cc}^{VP} almost cancels with A_{cc}^{PV}. Thus the contribution to $B_s \to \phi\eta(\eta')$ are from the gluonic charming penguin and the penguin operators which are proportional to $V_{tb}V_{ts}^*$. Neglecting the latter, we have :

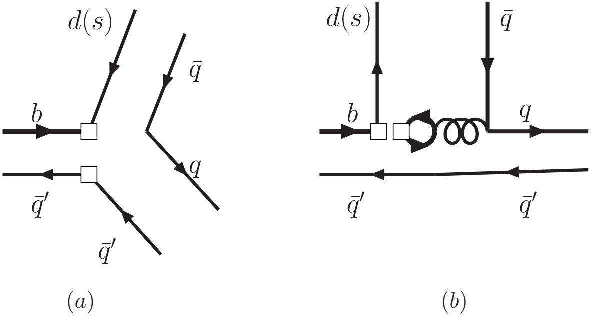
$$A_{cc}^{B_s\to\phi\eta} = \cos(\theta)\sqrt{2}A_{ccg}^{VP} - \sin(\theta)A_{ccg}^{VP} \sim (\sqrt{2}-1)A_{ccg}^{VP},$$
$$A_{cc}^{B_s\to\phi\eta'} = \sin(\theta)\sqrt{2}A_{ccg}^{VP} + \cos(\theta)(A_{ccg}^{VP}) \sim (\sqrt{2}+1)A_{ccg}^{VP}.$$

These two equations can explain the large branching fraction for $B_s \to \phi\eta'$ together with the small one for $B_s \to \phi\eta$.

The gluonic charming penguin are essential to explain the hierarchy of $B \to K\eta^{(\prime)}$ and $B \to K^*\eta^{(\prime)}$ branching ratios

Charming penguin in SCET and annihilation in PQCD

CKM matrix elements: The $(S-P)(S+P)$ penguin annihilation is proportional to $V_{tb}V_{tD}^*$, while charming penguin is proportional to $V_{cb}V_{cD}^*$.



They have the same topology, play very important role in each approach

Charming penguin in SCET and annihilation in PQCD

besides the CKM, they play the same role for strong phases required by direct CP asymmetry

The annihilation is dynamically enhanced to be of the same order with penguins in emission diagrams in PQCD.

But in SCET, it is larger than the contribution from penguin operators.

In PQCD approach, the dominant part of annihilation is imaginary.

Strong phase in charming penguin in SCET is not too large but large enough for the direct CP asymmetry

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Charming penguin in SCET and annihilation in PQCD

PQCD:

$$V_{tb} V_{td}^* \sim e^{i\beta} \longrightarrow S_f = -\sin(2\beta + 2\epsilon), \quad S_f = -\cos(2\beta + 2\epsilon), \quad (20)$$

SCET:

$$V_{cb} V_{cd}^* 1 \longrightarrow S_f = -\sin(+2\epsilon) \sim 0, \quad S_f = -\cos(+2\epsilon) \sim -1, \quad (21)$$

Mixing-induced CP asymmetries $(S_f)_{B_s}$ and $(H_f)_{B_s}$ in $B_s \longrightarrow PV$ decays are quite different

Modes	PQCD	SCET1	SCET2
$\overline{B}_s^0 \longrightarrow K_S \phi$	-0.72	0.09	-0.13
	-0.69	-1.00	-0.99

Outline

Summary

1. SCET is an very effective theory to deal with two-body charmless B decays.
2. Hard kernels can be simplified. Chiraly enhanced penguin can also be included.
3. Using the experimental data to fit the 16 non-perturbative inputs, we find two different kinds of results.
4. A number of decays are compared with QCDF, PQCD and experimental data.
5. Charming penguin in SCET and penguin annihilations in PQCD play similar role, but not exactly the same

Thank you!