STATO ATTUALE DELLA TEORIA EFFICACE

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Sommario

1. Teoria di campo efficace per mesoni pesanti e leggeri
2. Mesoni pesanti di massa superiore
3. Applicazioni nella fisica delle violazioni di CP

Riferimenti

1. H. Georgi, Ann.Rev.Nucl.Part.Sci.43:209,1993
2. M. B. Wise hep-ph/9805468
3. R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, F. Feruglio. R. Gatto and G. N. Phys. Rep. 281 (1997) 145
4. P. Colangelo, F. De Fazio, G.N., hep-ph/0001200
5. P. Colangelo, F. De Fazio, G.N., N. Paver and Riazuddin, Phys.Rev. D60: 033002, 1999
6. A.Deandrea, R. Gatto, M.Ladisa, G.N., P.Santorelli hep-ph/0002038 Phys.Rev.D to appear.

MOTIVATIONS

Usefulness of an effective field theory for hadrons exhibiting (approximate) symmetries of QCD.
Starting from the lowest order, successive terms can be introduced, including corrections to the (approximate) symmetries and an increasing number of light meson derivatives
The simplest lagrangian should therefore

1. Exhibit symmetries of QCD
2. Contain the minimum number of light hadron fields derivatives

Remark: An effective way to take into account the behaviour for higher values of momentum is by form factors
These rules can be applied not only to light quark sector of QCD (chiral symmetry) but also to heavy sector (heavy flavour-spin symmetry of HQET)

Building blocks

1. Effective heavy and light hadron fields
2. Heavy quark symmetry: invariance under

   $SU(2)_{heavy\ flavor} \times SU(2)_{heavy\ spin}$
3. Invariance under the chiral group
4. Minimum number of derivatives of light hadron fields

Effective heavy meson fields

s_ℓ conserved together with the spin s_Q in the infinite quark mass limit ($\vec{J} = \vec{s}_\ell + \vec{s}_Q$). This can be used to organize the heavy states in multiplets

Low lying multiplet

$s_\ell^P = \frac{1}{2}^-$ comprises a 0^- and a 1^- degenerate state: B, B^* for beauty and D, D^* for charm. Explicit matrix representatio:

$$H = \frac{(1+\not{v})}{2}\left[P^*_\mu \gamma^\mu - P\gamma_5\right]$$

where v =heavy meson velocity, $v^\mu P^*_{a\mu} = 0$ and $M_H = M_P = M_{P^*}$); $\not{v} H = -H\not{v} = H$; if $\bar{H} = \gamma_0 H^\dagger \gamma_0$, then $\bar{H}\not{v} = -\not{v}\bar{H} = \bar{H}$.

$P^{*\mu}$ and P = annihilation operators normalized as follows:

$$\langle 0|P|Q\bar{q}(0^-)\rangle = \sqrt{M_H}$$
$$\langle 0|P^{*\mu}|Q\bar{q}(1^-)\rangle = \epsilon^\mu\sqrt{M_H}$$

Higher spin states

Multiplet $s_\ell^P = \frac{1}{2}^+$ comprises a 0^+ and a 1^+ degenerate states. For charm the 1^+ state may be identified with the broad $D_1'(2461)$ state recently seen at CLEO(allowing some mixing with the $D_1(2420)$ narrow state).

$$S = \frac{1}{2}(1+\not{v})[P_1^\mu \gamma_\mu \gamma_5 + P_0]$$

Multiplet $s_\ell^P = \frac{3}{2}^+$ comprises a 1^+ and a 2^+ degenerate states. For charm: $D_1(2420)$and $D_1(2460)$. For beauty a bunch of states B^{**} at 5697 ± 9 MeV:

$$T^\mu = \frac{(1+\not{v})}{2}\left[P_2^{\mu\nu}\gamma_\nu - \sqrt{\frac{3}{2}}\tilde{P}_{1\nu}\gamma_5\left(g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right)\right]$$

Multiplet $s_\ell^P = \frac{3}{2}^-$ comprises a 1^- and a 2^- degenerate states. Not yet discovered. Predictions from constituent quark models $\Delta = m_H - m_Q = 1.2 - 1.4$ GeV.

$$H^\mu = \frac{(1+\not{v})}{2}[D_2^{*\mu\nu}\gamma_5\gamma_\nu$$
$$-\sqrt{\frac{3}{2}}\tilde{D}_{1\nu}^*\left(g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu + v^\mu)\right)]$$

Multiplet $s_\ell^P = \frac{5}{2}^-$ comprises a 2^- and a 3^- degenerate states. Not yet discovered. Predictions from constituent quark models. For charm: D_3: $2.76 - 2.83$ GeV. For beauty: 6.11 GeV:

$$H^{\mu\nu} = \frac{(1+\not{v})}{2}[D_3^{\mu\nu\sigma}\gamma_\sigma - \sqrt{\frac{5}{3}}\gamma_5 D_2^{*\prime\alpha\beta}$$

$$\left(g_\alpha^\mu g_\beta^\nu - \frac{\gamma_\alpha}{5}g_\beta^\nu(\gamma^\mu - v^\mu) - \frac{\gamma_\beta}{5}g_\alpha^\mu(\gamma^\nu - v^\nu)\right)]$$

Light meson fields

Octet of the pseudo Goldstone bosons

One uses the exponential form

$$\xi = \sqrt{\Sigma} = \exp \frac{iM}{f_\pi}$$

$$M = \begin{pmatrix} \sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

$f_\pi = 132\ MeV$.

Lagrangian for H, S and ξ with chiral and spin-flavour symmetry and at the lowest order in light mesons derivatives:

$$\mathcal{L}_0 + \mathcal{L}_1 = \frac{f_\pi^2}{8} < \partial^\mu \Sigma \partial_\mu \Sigma^\dagger > + i < H_b v^\mu D_{\mu ba} \bar{H}_a >$$
$$+ < S_b \, (i \, v^\mu D_{\mu ba} \; - \; \delta_{ba} \, \Delta) \bar{S}_a > +$$
$$i \, g < H_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba} \bar{H}_a > + i \, g' < S_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba} \bar{S}_a > +$$
$$[i \, h < S_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba} \bar{H}_a > \; + h.c.]$$

$< \ldots >=$ trace, $\Delta=$ mass splitting of the S states from the ground state H,

$$D_{\mu ba} = \delta_{ba}\partial_\mu + \mathcal{V}_{\mu ba} = \delta_{ba}\partial_\mu + \frac{1}{2}\left(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger\right)_{ba}$$

$$\mathcal{A}_{\mu ba} = \frac{1}{2}\left(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger\right)_{ba}$$

Under the chiral symmetry the fields transform as follows

$$\xi \to g_L \xi U^\dagger = U \xi g_R^\dagger$$

$$\Sigma \to g_L \Sigma {g_R}^\dagger$$

$$H \to H U^\dagger$$

$$\bar{H} \to U \bar{H}$$

where g_L, g_R are global $SU(3)$ transformations and U is a function of x, of the fields and of g_L, g_R.

Weak currents: Heavy→Heavy

Described in terms of universal form factors in the $m_Q \to \infty$ limit (corrections can also be included): $\xi = \xi_{IW}(v \cdot v')$, $\tau_{1/2}$, $\tau_{3/2}$, $\tau_{5/2}$.
They can be computed by non perturbative methods, e.g QCD Sum Rules (Neubert; Colangelo, De Fazio, G.N., Paver)

Typical effective currents

$$J^\mu = -\xi_{IW}(v \cdot v') < \bar{H}_c(v')\gamma^\mu(1-\gamma_5)H_b(v) >$$

$$J^{\mu\prime} = -\tau_{1/2}(v \cdot v') < \bar{S}_c(v')\gamma^\mu(1-\gamma_5)H_b(v) >$$

Weak currents: Heavy→light

At the lowest order in derivatives of the pseudoscalar fields and in the symmetry limit, weak interactions between light pseudoscalars and a heavy meson are described by[1]

$$L_a^\mu = \frac{i\alpha}{2} < \gamma^\mu (1-\gamma_5) H_b \xi^\dagger_{ba} >$$

where α is related to the pseudoscalar heavy meson decay constant f_H

$$< 0|\overline{q}_a \gamma^\mu \gamma_5 Q|P_b(p) >= ip^\mu f_H \delta_{ab}$$

$$\alpha = f_H \sqrt{M_H}$$

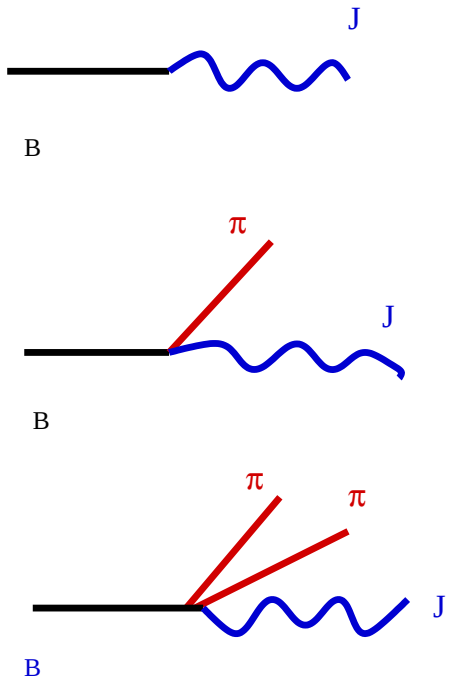
The current describing the weak interactions between pseudoscalar Goldstone bosons and the positive parity S fields:

$$\hat{L}_a^\mu = \frac{i\hat{\alpha}}{2} < \gamma^\mu (1-\gamma_5) S_b \xi^\dagger_{ba} >$$

and the current by which the H fields interact with the light vector mesons:

[1] Wise; Burdman-Donoghue; Casalbuoni, Deandrea, Di Bartolomeo, Feruglio, G.N., Gatto

$$L^{\mu}_{1a} = \alpha_1 < \gamma_5 H_b (\rho^{\mu} - V^{\mu})_{bc} \xi^{\dagger}_{ca} >$$



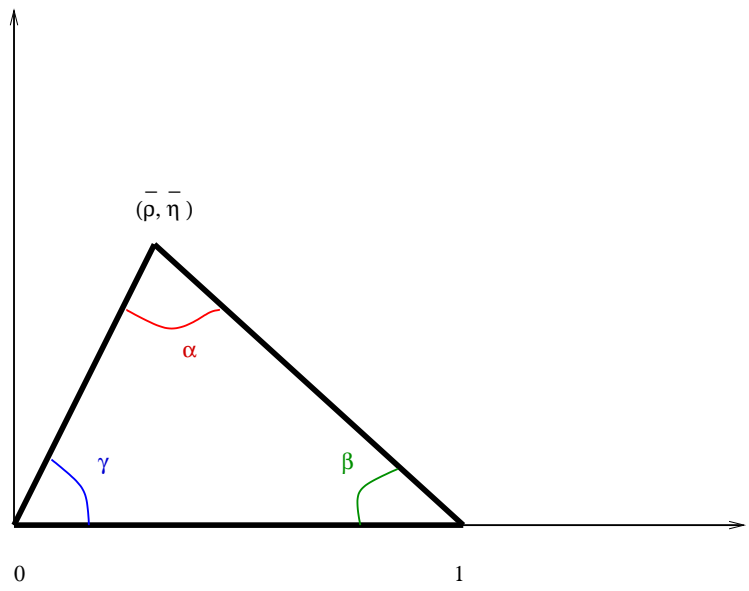
Applicazioni

1. Spettroscopia
2. Decadimenti forti
3. Decadimenti semileptonici $B \to D\pi\ell\nu$
4. Decadimenti semileptonici $B \to D^{**}\ell\nu$ (talk di Colangelo)
5. Decadimenti semileptonici $B \to \pi\pi\ell\nu$
6. Decadimenti radiativi $B^* \to B\gamma$
7. Decadimenti rari ($b \to s\gamma$, $c \to u\gamma$)
8. Splitting iperfini
9. Violazioni di CP: $B \to \rho\pi$ (talk di Deandrea)

Due applicazioni relative alla fisica delle violazioni di CP

Unitarity triangle

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



$$\bar{\rho} = \rho(1-\lambda^2/2)\ ;\ \bar{\eta} = \eta(1-\lambda^2/2)$$

$$\lambda \approx 0.22; \quad A \approx 0.83$$

Un metodo per estrarre informazioni sui CKM: mixing $\bar{B}^0 - B^0$ e $\bar{B}_s - B_s$

$$\Delta m_q = \frac{G^2}{6\pi^2}|V_{tb}|^2|V_{tq}|^2 m_{B_q} f_{B_q}^2 B_{B_q} \eta_B m_t^2 F(\frac{m_t^2}{m_W^2})$$

$$\Delta m_d \propto A^2\lambda^6[(1-\rho)^2+\eta^2]$$
$$\Delta m_s \propto A^2\lambda^4$$

Aleph

$$f_{D_s} = 284 \pm 62 MeV$$

Delphi

$$f_{D_s} = 329 \pm 97 MeV$$

L3

$$f_{D_s} = 309 \pm 77 MeV$$

World

$$f_{D_s} = 241 \pm 32 MeV$$

$$\frac{f_{D_s}}{f_D} = 1.1$$

(Teoria effettiva ad 1 loop : idem $D \to B$)

Risultati simili da QCD sum rules e reticolo.

Un parametro collegato e'

$$\frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.11^{+0.06}_{-0.04}$$

(fit: Parodi et al.)

Teoria effettiva chirale ad 1 loop (Grinstein et al.)

$$\frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}} = 1 - (\frac{7}{3} + 3g^2)\frac{m_K^2}{16\pi^2 f_\pi^2} ln \frac{m_K^2}{\mu^2}$$

che indica una correzione simile numericamente a quella trovato da Parodi et al.

$$\sin 2\beta = 0.79^{+0.41}_{-0.44}$$

from CDF: $B \to \psi K_s$

$$\Delta \sin 2\beta = 0.08 \text{ (B factories)}$$

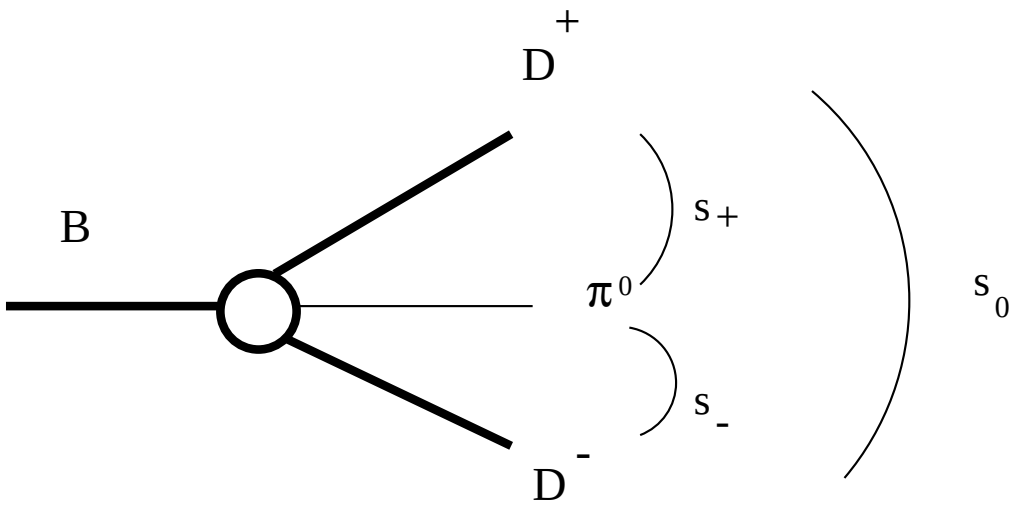
$$\Delta \sin 2\beta = 0.01 \text{ (LHC)}$$

Discrete ambiguity

$$\beta \to \frac{\pi}{2} - \beta$$

Possible way to solve the ambiguity:
$B \to DD\pi$ **channel**
An application of the effective theory

Relevance of $B \to D^+D^-\pi^0$ for determining β



$$H_{nl} = \frac{G}{\sqrt{2}} V_{cb} V_{cd}^* a_2 \bar{b}\gamma^\mu(1-\gamma_5)c\bar{c}\gamma_\mu(1-\gamma_5)d + h.c.$$

V_{cb} V_{cd}^* real: Weak phase only from t mixing $B^0 - \bar{B}^0$ (no penguins)

Time dependent amplitude for an oscillating state $|B^0(t)>$tagged as B meson at $t = 0$:

$$\mathcal{A}(s_+, s_-, t) = \mathcal{A}(s_+, s_-)\cos\frac{\Delta m t}{2}$$
$$+e^{-2i\beta}\bar{\mathcal{A}}(s_+, s_-)\sin\frac{\Delta m t}{2}$$

Time decay probability of a state $= B^0$ at $t = 0$:

$$P(t) = e^{-\Gamma t}\{G_0(s_+, s_-) + G_c(s_+, s_-)\cos\Delta m t$$
$$+G_s(s_+, s_-)\sin\Delta m t$$

$$G_0(s_+, s_-) = |\mathcal{A}(s_+, s_-)|^2 + |\bar{\mathcal{A}}(s_+, s_-)|^2$$
$$G_c(s_+, s_-) = |\mathcal{A}(s_+, s_-)|^2 - |\bar{\mathcal{A}}(s_+, s_-)|^2$$
$$G_s(s_+, s_-) = -2\sin 2\beta\, Re\mathcal{A}^*\bar{\mathcal{A}} + 2\cos 2\beta\, Im\mathcal{A}^*\bar{\mathcal{A}}$$

Knowledge of the term proportional to $\sin\Delta m t$ in the time-dependent decay probability, i.e.

$$G_s(s_+, s_-)$$

gives access to a $\cos 2\beta$ term.
Thus one can solve the

$$\beta \to \frac{\pi}{2} - \beta$$

ambiguity, which is inherent to any decay process producing asymmetries $\sim 2\beta$, for example $B \to J/\psi K_s$ time dependent CP asymmetry.

Remarks

1) The $\cos 2\beta$ term must be present.

Neglecting penguins, $Im\mathcal{A}^*\bar{\mathcal{A}} = 0$ ($\mathcal{A}$ has no weak phase) only if final state interactions could be neglected, which is not permitted, since they arise from resonance production of the $D\pi$ pairs ($D^*, D^{**} \to D\pi$) (Charles et al.)

2) The $\cos 2\beta$ term can be disentangled from the $\sin 2\beta$ term.

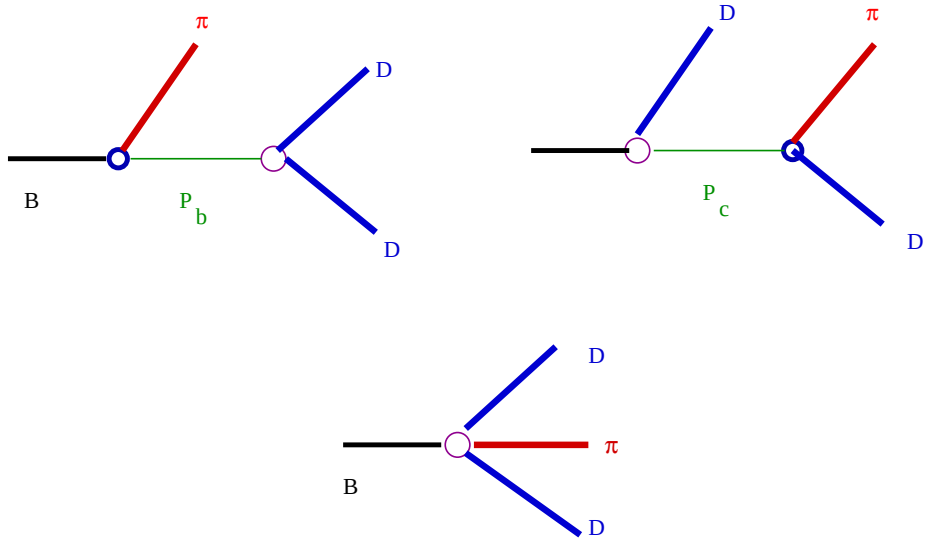
The coefficient $Re\mathcal{A}^*\bar{\mathcal{A}}$ of the latter is symmetric in $s_+ \to s_-$, while $Im\mathcal{A}^*\bar{\mathcal{A}}$ is antisymmetric.

Performing symmetric (antisymmetric) integrations in the Dalitz plot (s_+, s_-) one gets rid of $\sim Im\mathcal{A}^*\bar{\mathcal{A}}$ ($\sim Re\mathcal{A}^*\bar{\mathcal{A}}$) part. Therefore the two contributions can be disentangled

$$\cos 2\beta = \pm\sqrt{1 - \sin^2 2\beta}$$

For an accurate evaluation of the strong phases, arising from both resonant and non-resonant interactions, the effective field theory for light and heavy mesons is particularly useful.

Evaluating $B \to DD\pi$



Resonant diagrams

$$P_c = D^*(2.01),\ D_1(2.42),\ D_1'(2.461),\ D_2(2.46)$$

$$P_b = B^*(5.33),\ B^{**}(5.7)$$

All strong coupling constants given in terms of three coupling constants

$$g\ , h,\ h'$$

Weak non leptonic effective lagrangian

with pions and heavy mesons interacting weakly.

It has the *current*×*current* and implements factorization of the amplitudes

$$\mathcal{L}_{eff} = \frac{G}{\sqrt{2}} a_2 V_{cb} V_{cd}^* < (L+L')^\mu (J+J'+J'')_\mu >$$

$$L^\mu = \frac{i\alpha}{2} < \gamma^\mu (1-\gamma_5) H_c \xi^\dagger >$$

$$L^{\mu\prime} = \frac{i\alpha^+}{2} < \gamma^\mu (1-\gamma_5) S_c \xi^\dagger >$$

α, α^+ describe pseudoscalar heavy meson decays $D \to \mu\nu$, $D_0 \to \mu\nu$, $D_1 \to \mu\nu$etc.

$$J^\mu = -\xi_{IW}(v \cdot v') < \bar{H}_c(v') \gamma^\mu (1-\gamma_5) H_b(v) >$$
$$J^{\mu\prime} = -\tau_{1/2}(v \cdot v') < \bar{S}_c(v') \gamma^\mu (1-\gamma_5) H_b(v) >$$
$$J^{\mu\prime\prime} = -\tau_{3/2}(v \cdot v') < v_\lambda \bar{T}_c^\lambda(v') \gamma^\mu (1-\gamma_5) H_b(v) >$$

Simple parametrizations of the IW ffs (QCDsr)

$$\xi_{IW}(y) = \left(\frac{2}{1+y}\right)^2$$
$$\tau_{1/2}(y) = 0.3\,[1 - 0.5(-1+y)]$$
$$\tau_{3/2}(y) = 0.3\,[1 - 0.8(-1+y)]$$

Complete calculation includes 9 contributions with their interferences.

Results

$$\Gamma(\bar{B}^0 \to D^+ D^- \pi^0) = 5 \times 10^{-16} GeV$$

$$BR(\bar{B}^0 \to D^+ D^- \pi^0) \sim 1 \times 10^{-3}$$

should be detectable at B factories (for comparison $BR(B \to D^{*+} D^{*-}) = (6.2^{+4.0}_{-2.9} \pm 1.0) \times 10^{-4}$ at CLEO II)

$SU(3)$ related process

$$B^0 \to D^+ D^- K_s$$

Fairly large BR

$$B(B^0 \to D^+ D^- K_s) \approx 9 \times 10^{-3}$$

Appealing channel for experimental analyses (see T.E. Browder et al.)

Chiral effective lagrangian for heavy hadrons:

Useful tool

1) Allows to implement corrections to light and heavy quarks systematically
2) Allows a systematic expansion in light meson momenta
3) Helps in organizing diagrams for various exclusive decays.

As an example, its usefulness in computing contributions relevant for the study of CP violations in B decays has been shown.

Its kinematical range is however limited
To extend the validity a number of couplings and/or form factors have to be introduced and measured.
Some (many?) of them will be hopefully measured at future B factories and at LHC.