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QCD and Heavy Hadron Decays

I. Introduction

II. Tools and Applications

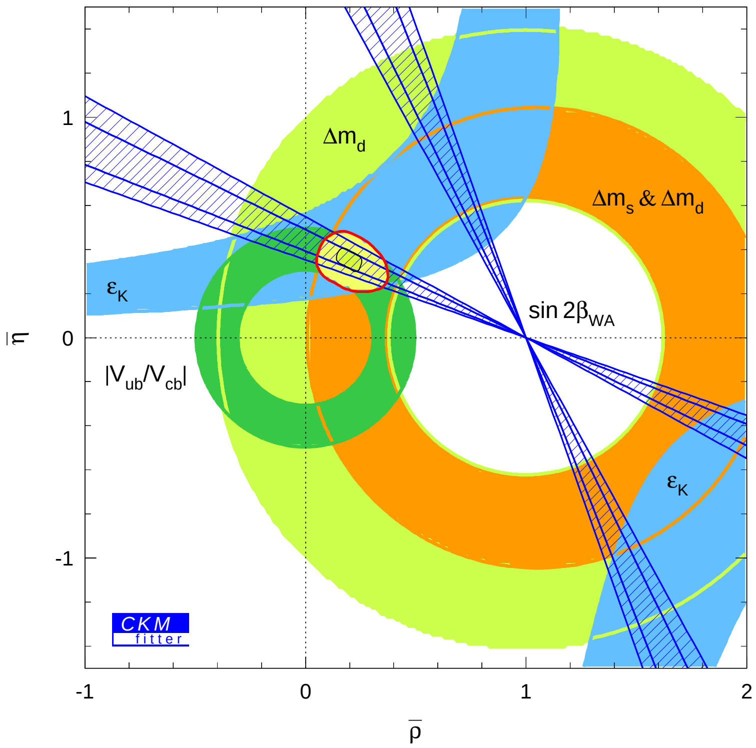
III. Two-body hadronic B decays

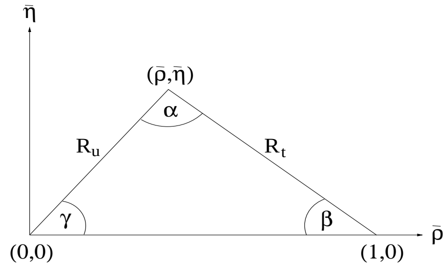
IV. Rare and radiative B decays

V. Conclusions

Introduction

Testing the quark flavor sector





Höcker, Lacker, Laplace, LeDiberder, Ocariz

Rare B Decays:

$B \to \pi\pi,\ \pi K,\ \pi\rho,\ \phi K_S,\ K^*\gamma,\ \rho\gamma,\ K^* l^+ l^-,\ l\nu\gamma$

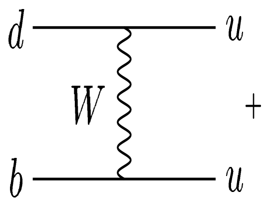
- Rich source of information (CKM angles, FCNC)
- Many new results from B factories
- Exclusive ↔ inclusive decays: experiment easier, theory harder
- Theoretical challenges: long-distance ↔ short-distance QCD
- $m_b \gg \Lambda_{QCD} \to$ Factorization
- flavor symmetries, SU(2), SU(3)

Gronau, London; Rosner; Fleischer

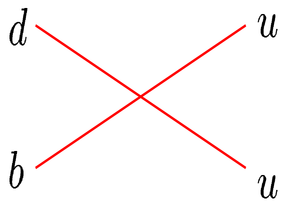
Tools and Applications

- short distance $\leftrightarrow$ long distance factorization
  $\rightarrow$ important simplifications

∘ $M_W, m_t \leftrightarrow m_b$: OPE, $\mathcal{H}_{eff}(\Delta B = 1, 2)$



$$+\text{QCD} \simeq C\left(\frac{M_W}{\mu}, \alpha_s\right) \cdot$$



$\mathcal{H}_{eff} \equiv$ Wilson coefficient $\cdot$local operator
factorization: high scales $> \mu >$low scales

∘ $m_Q \leftrightarrow \Lambda_{QCD}$: syst. exp. in $1/m_Q$, $\alpha_s(m_Q)$
HQET, HQE, QCD factorization, SCET

- HQET: static approximation for heavy quark;
  spin-flavor symmetry rel. form factors;
  m_Q-dependence explicit
  $B \rightarrow D^{(*)} l\nu$, f_B

- HQE: inclusive B decays, justifies parton model
  $B \rightarrow X_{c,u} l\nu$, $B \rightarrow X_s\gamma$, $B \rightarrow X_s l\bar{l}$, τ_B

- QCD factorization: exclusive hadronic B decays with fast light meson
  $B \rightarrow D\pi$, $B \rightarrow \pi\pi$, $B \rightarrow \pi K$, $B \rightarrow V\gamma$

- SCET: energetic light quarks
  $B \rightarrow P, V$; factorization proofs in $B \rightarrow M_1 M_2$

Exclusive Hadronic B Decays in QCD

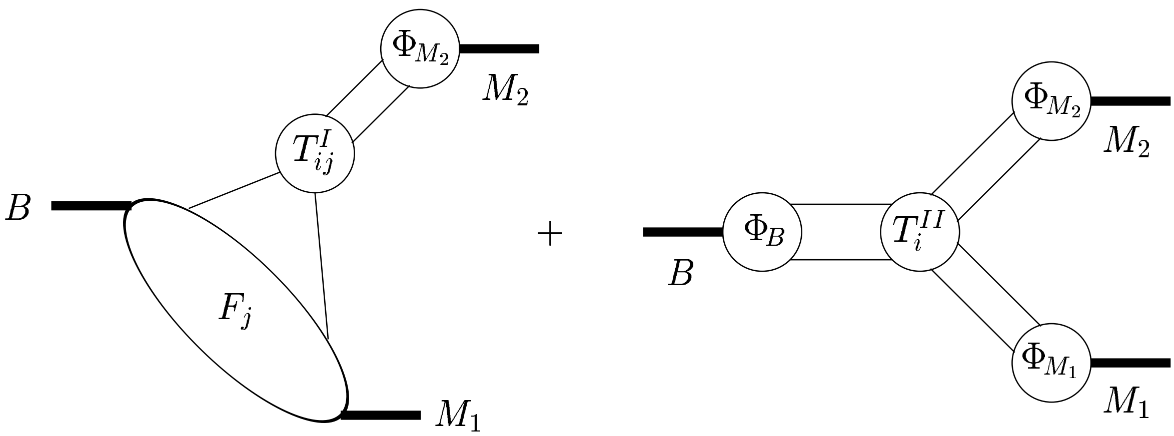
hamiltonian (e.g. for $B \to \pi\pi$)

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} \Big(\overset{(\bar{u}b)(\bar{d}u)\,\downarrow}{C_1 Q_1^u + C_2 Q_2^u} + \overset{(\bar{d}b)(\bar{q}q)\,\downarrow}{\sum_{penguins} C_p Q_p} \Big)$$
$$+ \frac{G_F}{\sqrt{2}} V_{cd}^* V_{cb} \Big(C_1 Q_1^c + C_2 Q_2^c + \sum_{penguins} C_p Q_p \Big)$$

similar for $B \to \pi K$, $B \to J/\Psi K_S$ $(d \leftrightarrow s)$

Stech et al.; Bjorken; Szczepaniak et al.; Dugan, Grinstein

problem:matrix elements $\langle Q_i \rangle$: $\langle \pi\pi | (\bar{u}b)_{V-A} (\bar{d}u)_{V-A} | B \rangle$



Politzer, Wise
Beneke, G.B., Neubert, Sachrajda
Bauer, Fleming, Pirjol, Stewart

- $\Lambda_{QCD}/m_b \ll 1$ → power counting → leading power
- light-cone dynamics
  $\langle \pi(p) | u(0) \bar{d}(z) | 0 \rangle = \frac{i f_\pi}{4} \gamma_5 \not{p} \int_0^1 dx\, e^{ixpz}\, \Phi_\pi(x)$
- colour transparency
- short-distance ↔ long-distance (soft, collinear) separation:
  factorization formula

CP asymmetry in $B \to \pi\pi$

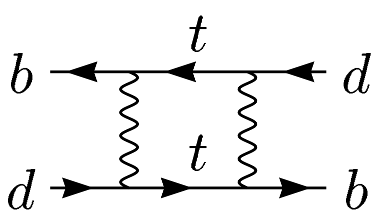
$$\mathcal{A}_{CP}(t) = \frac{\Gamma(B(t)\to\pi^+\pi^-)-\Gamma(\bar{B}(t)\to\pi^+\pi^-)}{+}$$

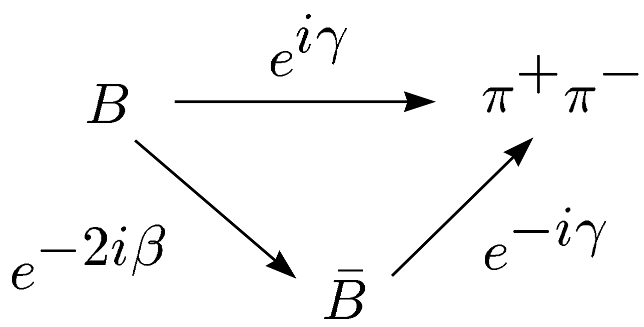
$$= -S\,\sin(\Delta M_d t) + C\,\cos(\Delta M_d t)$$

$$A(B \to \pi^+\pi^-) = V_{ub}^* V_{ud}(\text{up} - \text{top}) + V_{cb}^* V_{cd}(\text{charm} - \text{top})$$

neglect of penguins

$\to S = \sin 2\alpha,\ C = 0$



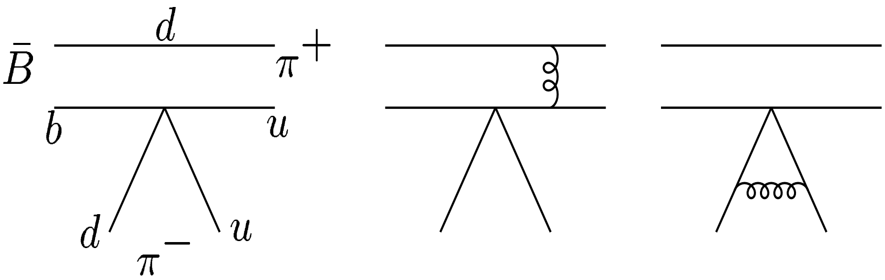


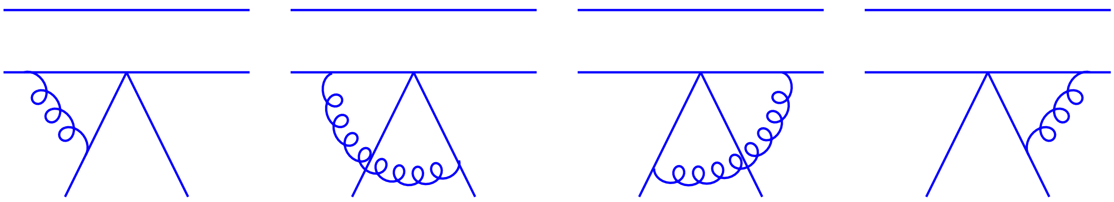
$$\exp(-2i(\beta + \gamma + \alpha - \alpha)) = \exp(2i\alpha)$$

$C = -0.77 \pm 0.27 \pm 0.08 (Belle)$, $\quad -0.30 \pm 0.25 \pm 0.04 (Babar)$

$S = -1.23 \pm 0.41^{+0.08}_{-0.07} (Belle)$, $\quad +0.02 \pm 0.34 \pm 0.05 (Babar)$

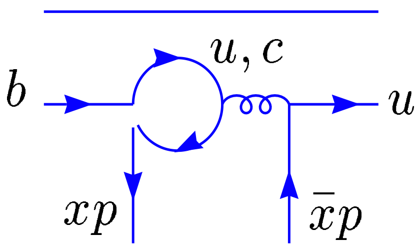
$B \to \pi\pi$ at NLO

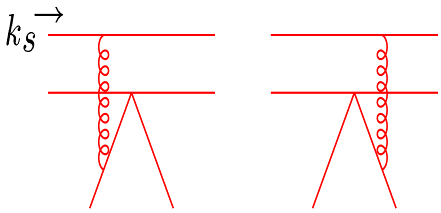




penguin contraction:

- gluon hard $k^2 = \bar{x} m_B^2$
- BSS mechanism
- $\langle G(k^2) \rangle = \int dx\, G(\bar{x})\, \Phi_\pi(x)$





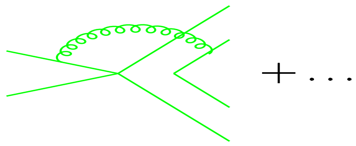
gluon hard $k^2 \sim \Lambda m_B$

$$\langle \pi\pi | Q | B \rangle = F(B \to \pi) \cdot \int_0^1 dx\ T^I(x)\ \Phi_\pi(x) +$$

$$+ \int_0^1 d\xi\, dx\, dy\ T^{II}(\xi, x, y)\ \Phi_B(\xi)\, \Phi_\pi(x)\, \Phi_\pi(y)$$

$$\xi = k_s^+ / p_B^+$$

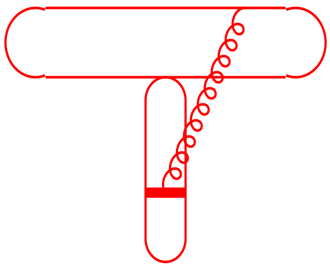
• annihilation

suppressed 

power corrections with chiral enhancement

$$\mu_\pi = \frac{m_\pi^2}{m_u+m_d} \approx 2\text{GeV} \sim \Lambda_{QCD}$$

• spectator hard scattering



pion w.f.: twist-2 and twist-3

$$\sim 1 + \frac{2\mu_\pi}{3m_b}\int_0^1 dy \frac{\Phi_p}{y} \qquad \Phi_p = 1$$

$$\int_0^1 \frac{dy}{y} = \ln\frac{m_B}{\Lambda}$$

• contribution $\sim a_6$

$$\langle\pi|(\bar{q}b)_{S-P}|B\rangle\langle\pi|(\bar{d}q)_{S+P}|0\rangle \sim \frac{\mu_\pi}{m_b}$$

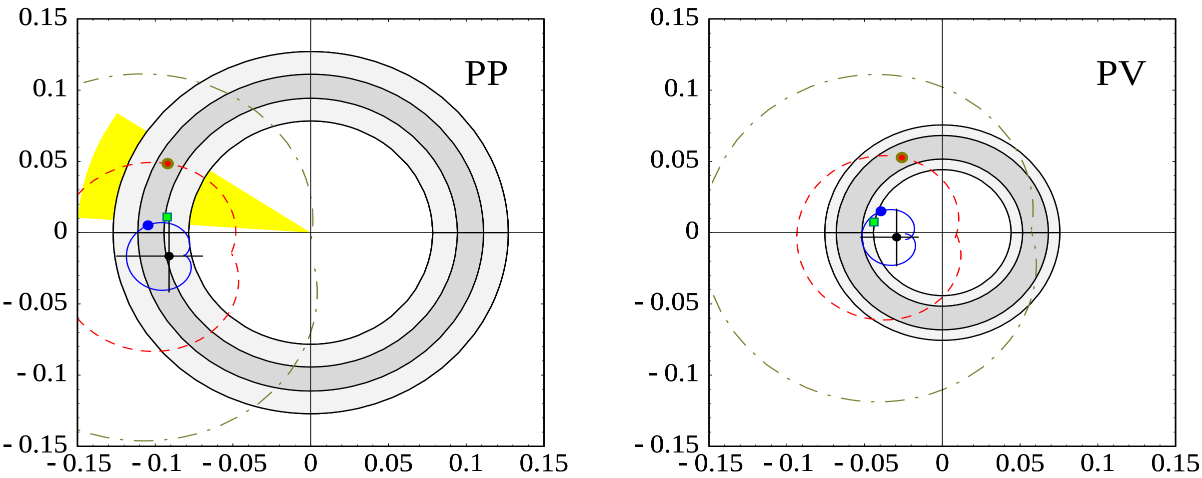
Phenomenology of $B \to PP$, PV

Beneke et al.; Beneke, Neubert

need to disentangle

- weak couplings (CKM)
- new physics
- QCD effects

1. $\left|\frac{penguin}{tree}\right| \sim \left|\frac{V_{ub}}{V_{cb}}\right| \frac{f_\pi}{f_K} \left[\frac{B(B^- \to \pi^- \bar{K}^0)}{2\, B(B^- \to \pi^- \pi^0)}\right]^{1/2}$



Beneke, Neubert

2. $\frac{\Gamma(B^- \to \pi^- \pi^0)}{d\Gamma(B \to \pi^+ l^- \nu)/dq^2|_{q^2=0}} = 3\pi^2 f_\pi^2 |V_{ud}|^2 |a_1 + a_2|^2$

Beneke, Neubert; Luo, Rosner

3. Direct CP asymmetries generally small ($\lesssim$ 10%)

4. Test: decays sensitive to annihilation

$$\bar{B}_d \to D_s^+ K^-, \; \bar{B}_d \to K^+ K^-$$

Hints of discrepancies (?)

- $\mathcal{A}_{CP}(B \to \pi^+\pi^-)$

$$C = 0.1 \pm 0.1\,[TH] \qquad = -0.51 \pm 0.23\,[EXP]$$

- $\mathcal{A}_{CP}(B \to \phi K_S, \quad \eta' K_S)$

Grossman, Isidori, Worah; Grossman, Ligeti, Nir, Quinn
Beneke, Neubert

$$S_{\phi K_S} - S_{\psi K_S} = 0.025 \pm 0.016\,[TH]$$
$$= -1.11 \pm 0.41\,[EXP]$$

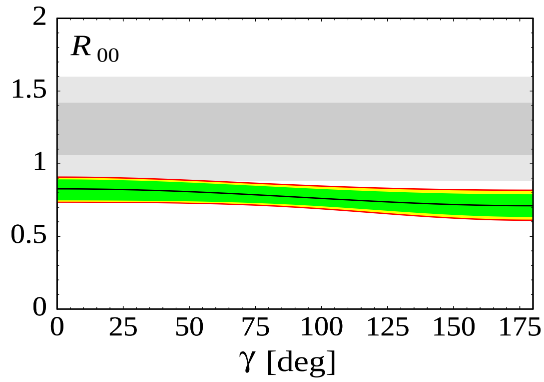
$$S_{\eta' K_S} - S_{\psi K_S} = 0.011 \pm 0.013\,[TH]$$
$$= -0.40 \pm 0.34\,[EXP]$$

- $B(B \to \pi^+\pi^-)_{exp}$ small

$\gamma > 90^\circ$? a_2 large, $F^{B\to\pi}$, m_s small ?

Beneke, Neubert

- $B(B \to \pi^0 K^0)_{exp}$ large $R_{00} = 2\Gamma(\pi^0 K^0)/\Gamma(\pi^\pm K^0)$



Mode	Theory	S1	S2	S3	S4	Experiment
$B^- \to \pi^-\pi^0$	$6.0\,^{+3.0\,+2.1\,+1.0\,+0.4}_{-2.4\,-1.8\,-0.5\,-0.4}$	5.8	5.5	6.0	5.1	5.3 ± 0.8
$\bar{B}^0 \to \pi^+\pi^-$	$8.9\,^{+4.0\,+3.6\,+0.6\,+1.2}_{-3.4\,-3.0\,-1.0\,-0.8}$	6.0	4.6	9.5	5.2	4.6 ± 0.4
$\bar{B}^0 \to \pi^0\pi^0$	$0.3\,^{+0.2\,+0.2\,+0.3\,+0.2}_{-0.2\,-0.1\,-0.1\,-0.1}$	0.7	0.9	0.4	0.7	1.6 ± 0.7 (< 3.6)
$B^- \to \pi^-\rho^0$	$11.9\,^{+6.3\,+3.6\,+2.5\,+1.3}_{-5.0\,-3.1\,-1.2\,-1.1}$	14.2	12.6	12.2	12.3	9.4 ± 1.6
$B^- \to \pi^0\rho^-$	$14.0\,^{+6.5\,+5.1\,+1.0\,+0.8}_{-5.5\,-4.3\,-0.6\,-0.7}$	10.7	10.4	14.2	10.3	9.3 ± 1.3
$\bar{B}^0 \to \pi^+\rho^-$	$21.2\,^{+10.3\,+8.7\,+1.3\,+2.0}_{-8.4\,-7.2\,-2.3\,-1.6}$	18.6	11.0	22.2	11.8	13.9 ± 2.7
$\bar{B}^0 \to \pi^-\rho^+$	$15.4\,^{+8.0\,+5.5\,+0.7\,+1.9}_{-6.4\,-4.7\,-1.3\,-1.3}$	17.5	10.8	16.4	11.8	8.9 ± 2.5
$\bar{B}^0 \to \pi^\pm\rho^\mp$	$36.5\,^{+18.2\,+10.3\,+2.0\,+3.9}_{-14.7\,-8.6\,-3.5\,-2.9}$	36.1	21.8	38.6	23.6	24.0 ± 2.5
$\bar{B}^0 \to \pi^0\rho^0$	$0.4\,^{+0.2\,+0.2\,+0.9\,+0.5}_{-0.2\,-0.1\,-0.3\,-0.3}$	0.3	1.7	0.3	1.1	< 2.5
$B^- \to \pi^-\omega$	$8.8\,^{+4.4\,+2.6\,+1.8\,+0.8}_{-3.5\,-2.2\,-0.9\,-0.9}$	8.6	9.1	8.4	8.4	5.9 ± 0.9
$\bar{B}^0 \to \pi^0\omega$	$0.01\,^{+0.00\,+0.02\,+0.02\,+0.03}_{-0.00\,-0.00\,-0.00\,-0.00}$	0.01	0.07	0.01	0.01	< 1.9
$B^- \to \pi^-\bar{K}^0$	$19.3\,^{+1.9\,+11.3\,+1.9\,+13.2}_{-1.9\,-7.8\,-2.1\,-5.6}$	18.8	20.7	24.8	20.3	20.6 ± 1.3
$B^- \to \pi^0K^-$	$11.1\,^{+1.8\,+5.8\,+0.9\,+6.9}_{-1.7\,-4.0\,-1.0\,-3.0}$	14.0	11.9	14.0	11.7	12.8 ± 1.1
$\bar{B}^0 \to \pi^+K^-$	$16.3\,^{+2.6\,+9.6\,+1.4\,+11.4}_{-2.3\,-6.5\,-1.4\,-4.8}$	20.3	18.8	21.0	18.4	18.2 ± 0.8
$\bar{B}^0 \to \pi^0\bar{K}^0$	$7.0\,^{+0.7\,+4.7\,+0.7\,+5.4}_{-0.7\,-3.2\,-0.7\,-2.3}$	6.5	8.3	9.3	8.0	11.2 ± 1.4
$B^- \to \pi^-\bar{K}^{*0}$	$3.6\,^{+0.4\,+1.5\,+1.2\,+7.7}_{-0.3\,-1.4\,-1.2\,-2.3}$	3.4	2.2	7.3	8.4	13.0 ± 3.0
$B^- \to \pi^0K^{*-}$	$3.3\,^{+1.1\,+1.0\,+0.6\,+4.4}_{-1.0\,-0.9\,-0.6\,-1.4}$	5.5	2.6	5.4	6.5	< 31
$\bar{B}^0 \to \pi^+K^{*-}$	$3.3\,^{+1.4\,+1.3\,+0.8\,+6.2}_{-1.2\,-1.2\,-0.8\,-1.6}$	5.9	2.4	6.6	8.1	15.3 ± 3.8
$\bar{B}^0 \to \pi^0\bar{K}^{*0}$	$0.7\,^{+0.1\,+0.5\,+0.3\,+2.6}_{-0.1\,-0.4\,-0.3\,-0.5}$	0.6	0.4	2.1	2.5	< 3.6
$B^- \to \bar{K}^0\rho^-$	$5.8\,^{+0.6\,+7.0\,+1.5\,+10.3}_{-0.6\,-3.3\,-1.3\,-3.2}$	5.6	13.6	10.8	9.7	< 48
$B^- \to K^-\rho^0$	$2.6\,^{+0.9\,+3.1\,+0.8\,+4.3}_{-0.9\,-1.4\,-0.6\,-1.2}$	1.3	6.0	4.7	4.3	< 6.2
$\bar{B}^0 \to K^-\rho^+$	$7.4\,^{+1.8\,+7.1\,+1.2\,+10.7}_{-1.9\,-3.6\,-1.1\,-3.5}$	4.3	13.9	12.5	10.1	8.9 ± 2.2
$\bar{B}^0 \to \bar{K}^0\rho^0$	$4.6\,^{+0.5\,+4.0\,+0.7\,+6.1}_{-0.5\,-2.1\,-0.7\,-2.1}$	5.0	8.4	7.5	6.2	< 12
$B^- \to K^-\omega$	$3.5\,^{+1.0\,+3.3\,+1.4\,+4.7}_{-1.0\,-1.6\,-0.9\,-1.6}$	1.9	7.9	5.8	5.9	5.3 ± 0.8
$\bar{B}^0 \to \bar{K}^0\omega$	$2.3\,^{+0.3\,+2.8\,+1.3\,+4.3}_{-0.3\,-1.3\,-0.8\,-1.3}$	1.9	6.6	4.5	4.9	5.1 ± 1.1
$B^- \to K^-\phi$	$4.5\,^{+0.5\,+1.8\,+1.9\,+11.8}_{-0.4\,-1.7\,-2.1\,-3.3}$	4.4	2.5	10.1	11.6	9.2 ± 0.7
$\bar{B}^0 \to \bar{K}^0\phi$	$4.1\,^{+0.4\,+1.7\,+1.8\,+10.6}_{-0.4\,-1.6\,-1.9\,-3.0}$	4.0	2.3	9.1	10.5	7.7 ± 1.1

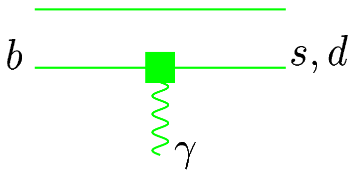
$B \to V\gamma$

Beneke, Feldmann, Seidel
Bosch, G.B.
Ali, Parkhomenko

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{ps}^* V_{pb} \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3,\ldots,8} C_i Q_i \right]$$

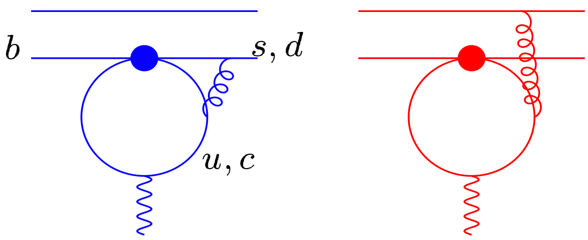
$$Q_1^p = (\bar{s}p)_{V-A}(\bar{p}b)_{V-A} \qquad Q_7 = \frac{e}{8\pi^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)b \, F_{\mu\nu}$$

factorization formula:



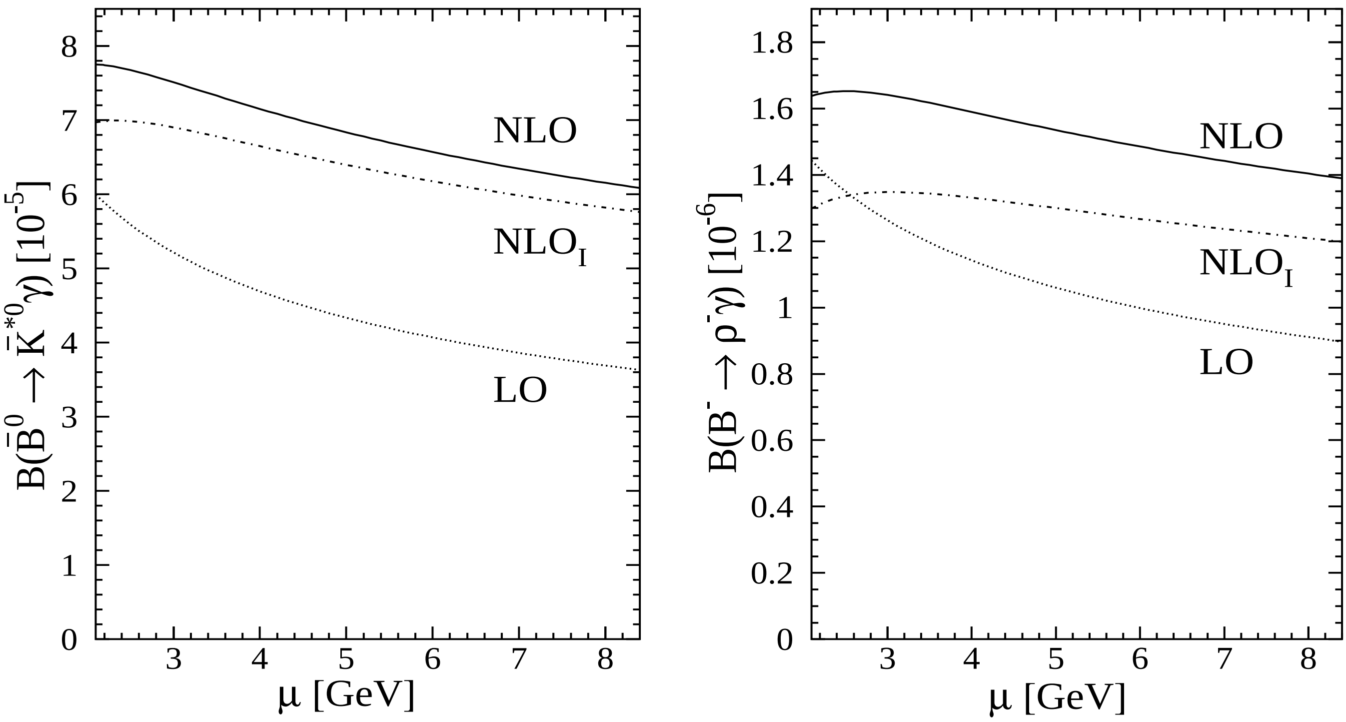
$$\langle V\gamma | Q_7 | B \rangle \sim F(B \to V)$$

Ball, Braun



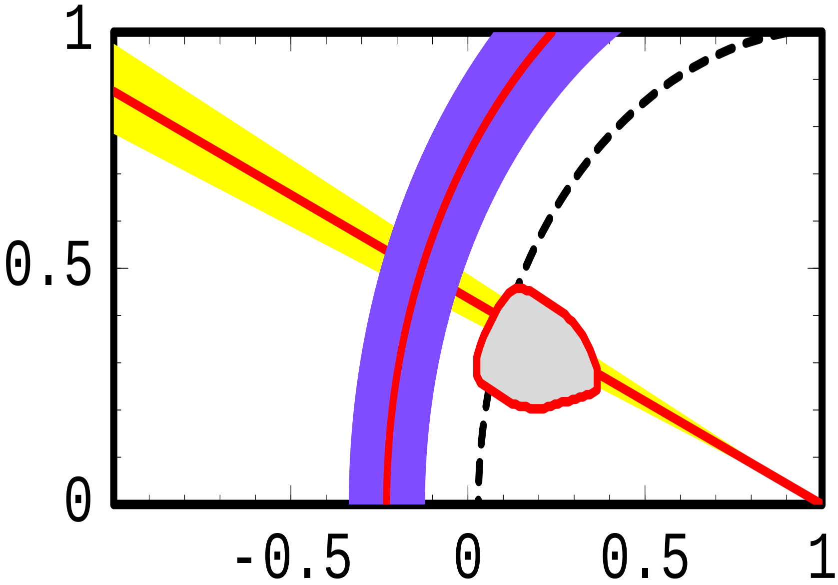
$$\langle V\gamma | Q_1^c | B \rangle = F(B \to V) \cdot T^I\left(\frac{m_c}{m_b}\right) +$$

$$+ \int_0^1 d\xi \, dv \; T^{II}\left(\xi, v, \frac{m_c}{m_b}\right) \; \Phi_B(\xi) \, \Phi_V(v)$$



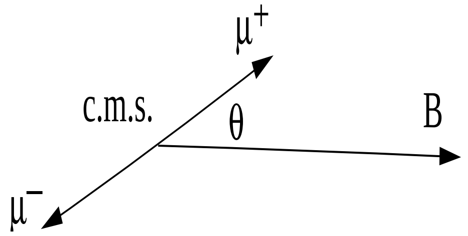
$$B(\bar{B}^0 \to \bar{K}^{*0}\gamma)/10^{-5} = 7.1 \pm 2.5 \qquad (4.44 \pm 0.35)$$

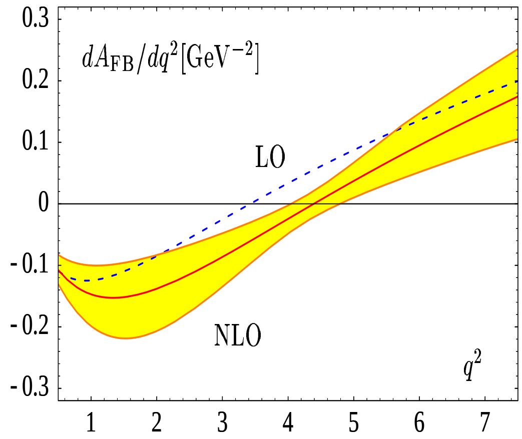
$$B(B^- \to \rho^-\gamma)/10^{-6} = 1.6 \pm 0.6 \qquad < 2.3$$



$(\bar{\rho}, \bar{\eta})$ constraint from $B(\rho^0\gamma)/B(K^{*0}\gamma)$

$B \to K^* l^+ l^-$: A_{FB}





$$\frac{q_0^2}{m_B^2} = -\alpha_+ \frac{m_b C_7}{m_B C_9^{eff}}$$

$\alpha_+ \approx 2$ *Burdman*

$B \to P, V$ form factor relations
for $m_b, E_{P,V} \gg \Lambda$ *Charles et al.*

$\Rightarrow \alpha_+ = 2$ in this limit *Ali, Ball, Handoko, Hiller*

valid beyond tree level *Bauer et al.*
NLO corrections to q_0^2 *Beneke, Feldmann, Seidel*

$$A(B \to K^* l^+ l^-) = c_i \xi_i + \Phi_B \otimes T \otimes \phi_{K^*}$$

SCET

$$p^\mu = \frac{1}{\sqrt{2}}(p_- n^\mu + p_+ \bar{n}^\mu) + p_\perp^\mu \qquad p_\pm = \frac{p^0 \pm p^3}{\sqrt{2}}$$

	p_-,	p_+,	$p_\perp$	p^2
$hard$	M,	M,	M	M^2
$hard-collinear$	M,	Λ,	$\sqrt{\Lambda M}$	ΛM
$collinear$	M,	Λ^2/M,	Λ	Λ^2
$soft$	Λ,	Λ,	Λ	Λ^2

$$\tilde{p} \equiv \frac{1}{\sqrt{2}} p_- n + p_\perp \qquad \psi(x) = \sum_{\tilde{p}} e^{-i\tilde{p}\cdot x} \psi_{n,p}$$

$$\xi_{n,p} = \frac{\not{n}\,\not{\bar{n}}}{4}\psi_{n,p} \qquad \xi_{\bar{n},p} = \frac{\not{\bar{n}}\,\not{n}}{4}\psi_{n,p}$$

collinear quark $\xi_{n,p}$
heavy quark h_v; soft, collinear gluons

$$\mathcal{L}_{QCD} \to \mathcal{L}_{SCET}$$

matching $\bar{q}\,\Gamma\, b \to C_i\, \bar{\xi}_{n,p} \tilde{\Gamma}_i h_v$

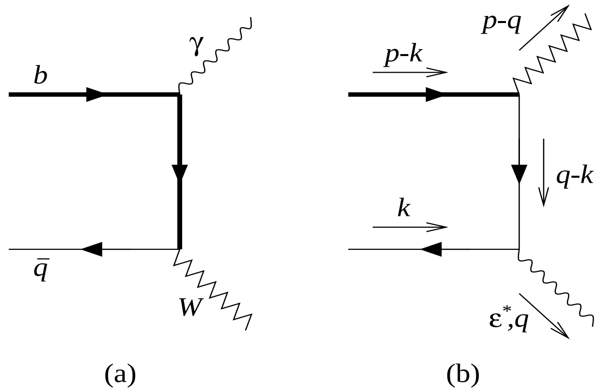
$$\not{v} h_v = h_v \qquad \not{n}\xi_{n,p} = 0 \Rightarrow$$

$B \to P, V$ form factors: 10 in QCD $\to$ 3 in SCET

Bauer, Fleming, Pirjol, Stewart
Beneke, Chapovsky, Diehl, Feldmann
Descotes, Sachrajda; Lunghi, Pirjol, Wyler et al.
Neubert et al.; Chay, Kim

$B \to l\nu\gamma$

Korchemsky, Pirjol, Yan



(b): leading power

$(q-k)^2 \approx -2q\cdot k \sim q_- k_+$

$$\Phi_B(\tilde{k}_+) = \int dz_- e^{i\tilde{k}_+ z_-} \langle 0|b(0)\bar{u}(z)|B\rangle|_{z_+=z_\perp=0}$$

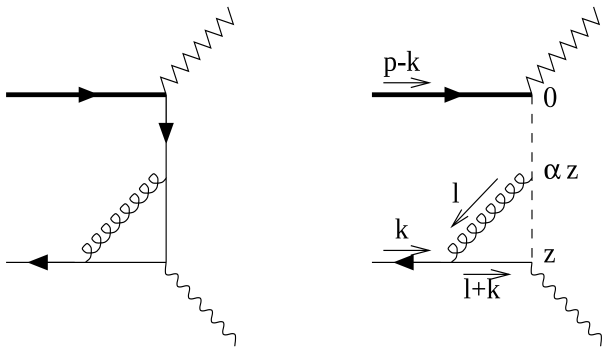
Grozin, Neubert; Beneke et al.; Kodaira et al.; Lange, Neubert

$$F = \int d\tilde{k}_+ \Phi_B(\tilde{k}_+)\, T(\tilde{k}_+)$$

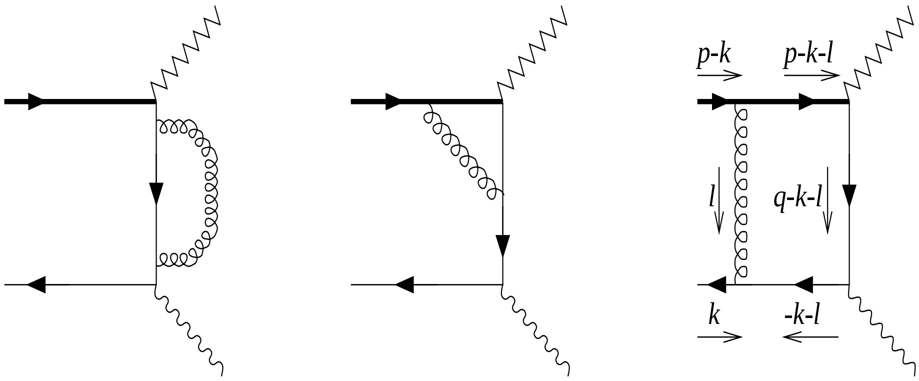
Descotes-Genon, Sachrajda

- holds at $\mathcal{O}(\alpha_s)$
- $F^{(0)} \sim \int d\tilde{k}_+ \Phi_B(\tilde{k}_+)/\tilde{k}_+ = 1/\lambda_B$
- hard scale $\mu_F \sim \sqrt{m_b \Lambda}$
- resummation of $\alpha_s^n \ln^{n+1}(m_b/\tilde{k}_+)$, $\alpha_s^n \ln^n(m_b/\tilde{k}_+)$ (SCET)
- NLO corrections typically few $\times 10\%$

Descotes-Genon, Sachrajda



(a) (b)



generalization to higher orders

soft-collinear effective theory (SCET)

Bauer, Fleming, Pirjol, Stewart
Lunghi, Pirjol, Wyler
Bosch, Hill, Lange, Neubert

SCET including power corrections

Beneke, Chapovsky, Diehl, Feldmann

Conclusions

- $m_b \gg \Lambda$
  short distance $\leftrightarrow$ long distance factorization

- important tools for heavy hadron decays:
  HQE, HQET, SCET,
  factorization formulas for exclusive B decays

- hadronic modes: $B \to D^+\pi^-$ best understood

- $B \to \pi\pi$, $K^*\gamma$, $\rho\gamma$, $K^* l^+ l^-$, ... more complicated

- complete proofs

- hard spectator interaction

- power corrections

- test reliability of $m_b \gg \Lambda$ limit

$\Rightarrow$ important applications:

$B \to \pi^+\pi^-$, $B \to \pi K$, $B \to \rho\gamma$

CPV, CKM angles, FCNC