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DESY Theory Workshop
Quantum Chromodynamics
September 2002

Exclusive Heavy Quark Decays

I. Introduction

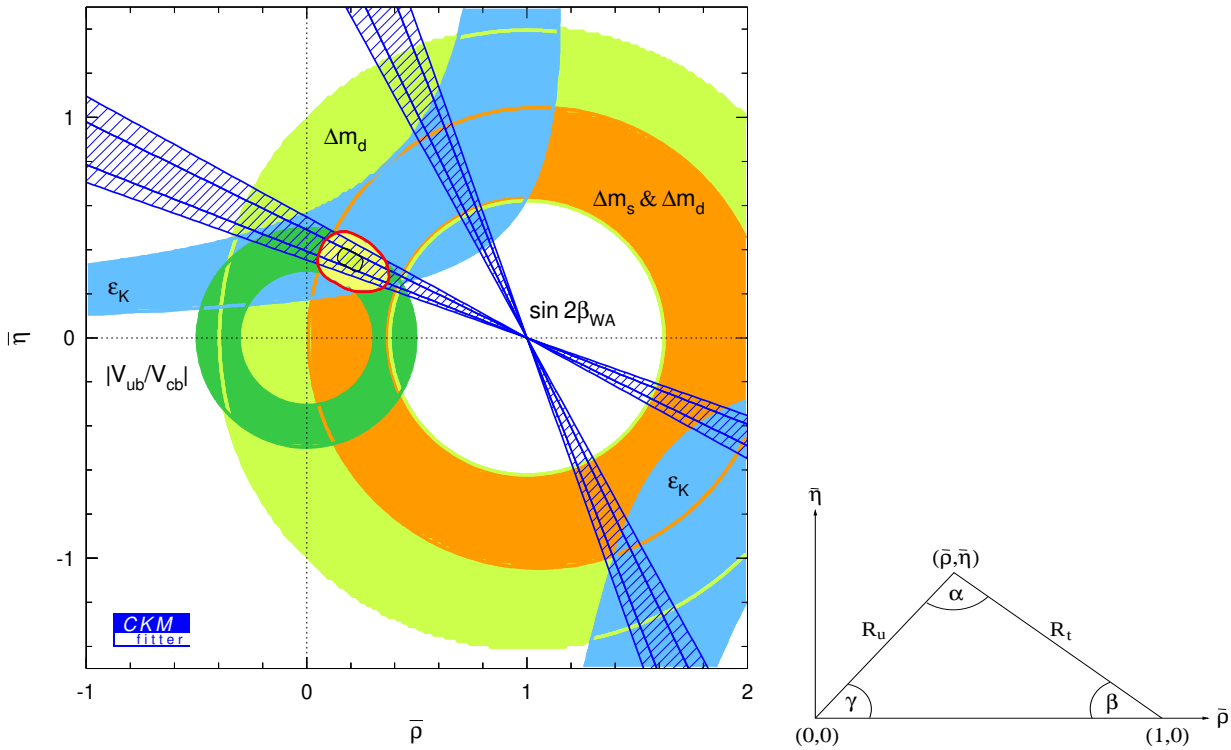
II. Two-body hadronic B decays

III. Rare and radiative B decays

IV. Conclusions

Introduction

Testing the quark flavour sector



Höcker, Lacker, Laplace, LeDiberder, Ocariz

Exclusive B Decays:

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

- Rich source of information (CKM angles, FCNC)
- Many new results from B factories
- Experimentally easier than inclusive channels
- Theoretical challenges: long-distance $\leftrightarrow$ short-distance QCD
- $m_b \gg \Lambda_{QCD} \to$ Factorization

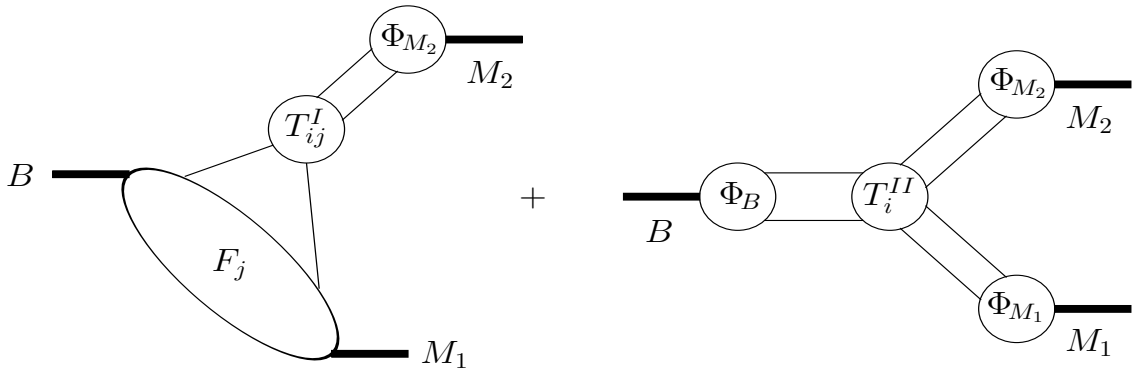
Exclusive Hadronic B Decays in QCD

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \lambda_{CKM}\, C_i Q_i$$

$B \to D\pi,\ B \to \pi\pi,\ B \to \pi K$

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

- $\Lambda_{QCD}/m_b \ll 1 \to$ power counting $\to$ 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 $\leftrightarrow$ long-distance (soft, collinear) separation: factorization formula

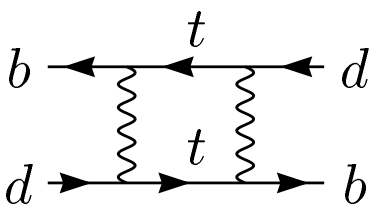
CP asymmetry in $B \to \pi\pi$

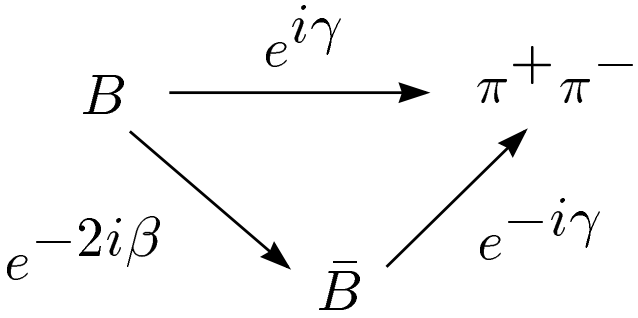
$$\mathcal{A}_{CP}(t) = \frac{\Gamma(B(t)\to\pi^+\pi^-) - \Gamma(\bar{B}(t)\to\pi^+\pi^-)}{+}$$

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

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

neglect of penguins
$\to S = \sin 2\alpha,\ C = 0$

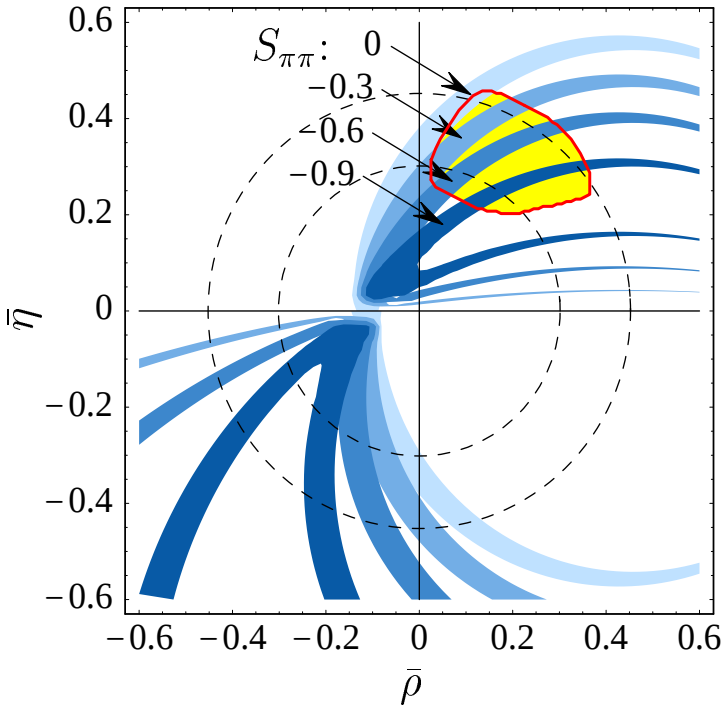




$$\exp(-2i(\beta + \gamma + \alpha - \alpha)) = \exp(2i\alpha)$$

$C = -0.94^{+0.31}_{-0.25} \pm 0.09(Belle)$, $\quad -0.30 \pm 0.25 \pm 0.04(Babar)$

$S = -1.21^{+0.38+0.16}_{-0.27-0.13}(Belle)$, $\quad +0.02 \pm 0.34 \pm 0.05(Babar)$



Beneke et al.

- QCD factorization to leading power shown for $B \to \pi\pi, \pi K$ at $\mathcal{O}(\alpha_s)$
- proof for $B \to D\pi$ (class-I) at two loops, all orders (SCET) *Bauer et al.*
- complete matrix elements at $\mathcal{O}(\alpha_s)$ (NLO), incl. EW penguins for $B \to \pi K$
- power corrections: $\sim \frac{m_\pi^2}{(m_u+m_d)m_b}$, annihilation $\leftrightarrow$ error estimate

but:

- many channels $\to$ cross checks
- use flavour symmetries, SU(2), SU(3)

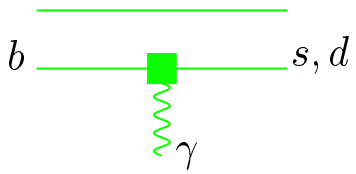
$B \to V\gamma$: Overview

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

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

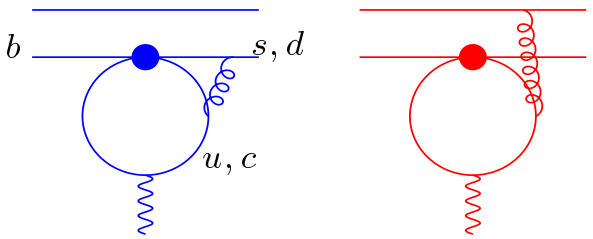
$$Q_1^p = (\bar{s}p)_{V-A}(\bar{p}b)_{V-A} \qquad Q_7 = \frac{e}{8\pi^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5) b \, F_{\mu\nu}$$

factorization formula:



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

Ball, Braun

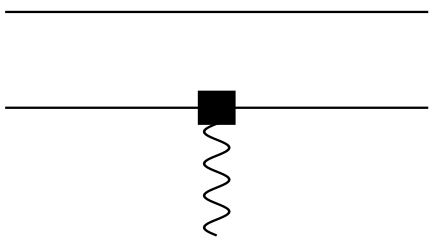


$$\langle V\gamma | Q_1^c | B \rangle = F(B \to V) \cdot T^I\left(\frac{m_c}{m_b}\right) +$$

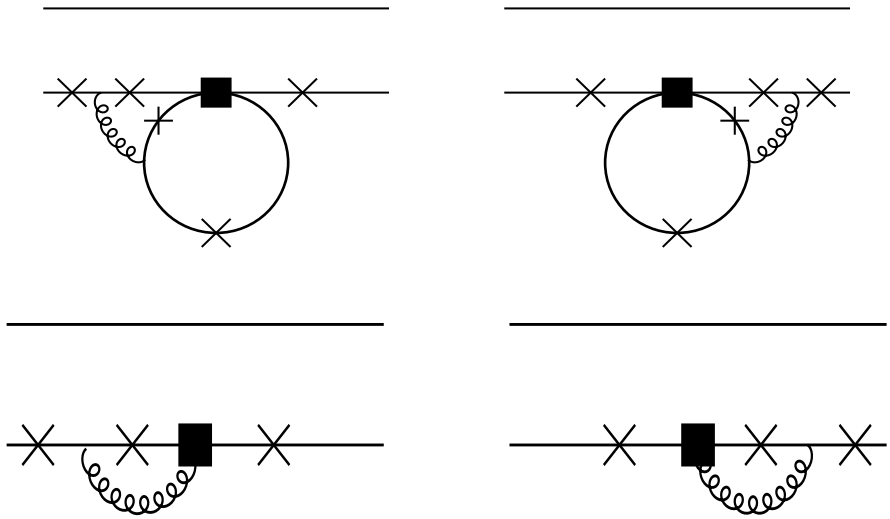
$$+ \int_0^1 d\xi \, dv \; T^{II}\left(\xi, v, \frac{m_c}{m_b}\right) \; \Phi_B(\xi) \, \Phi_V(v)$$

Leading-Power Contributions

T^I, $\mathcal{O}(\alpha_s^0)$

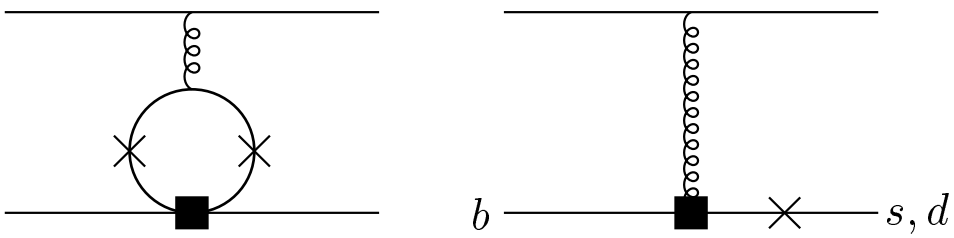


T^I, $\mathcal{O}(\alpha_s)$



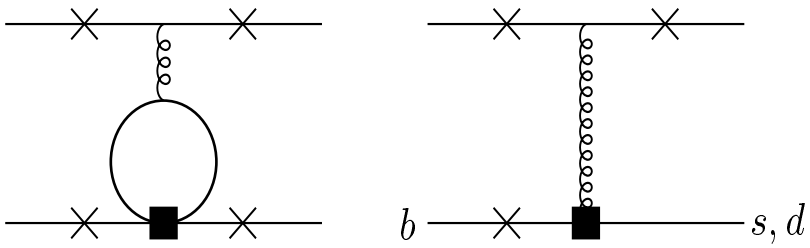
Greub, Hurth, Wyler
Buras, Czarnecki, Misiak, Urban

T^{II}, $\mathcal{O}(\alpha_s)$

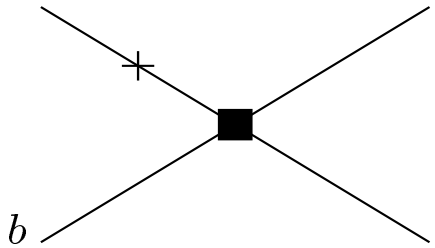


Beneke, Feldmann, Seidel; Bosch, G.B.
Ali, Parkhomenko

Subleading-Power Contributions



weak annihilation

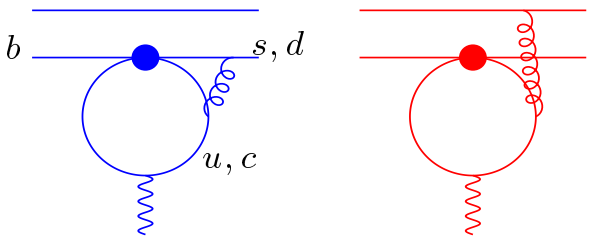


Grinstein, Pirjol
Ali, Handoko, London
Bosch, G.B.

- power suppression $\sim \Lambda/m_b$
- calculable
- sizeable effect from $Q_{1,2}$ in $B \to \rho\gamma$
  isospin breaking
- isospin breaking in $B^0 \to K^{*0}\gamma \leftrightarrow B^\pm \to K^{*\pm}\gamma$
  from Q_6 ($\sim 10\%$)

Kagan, Neubert

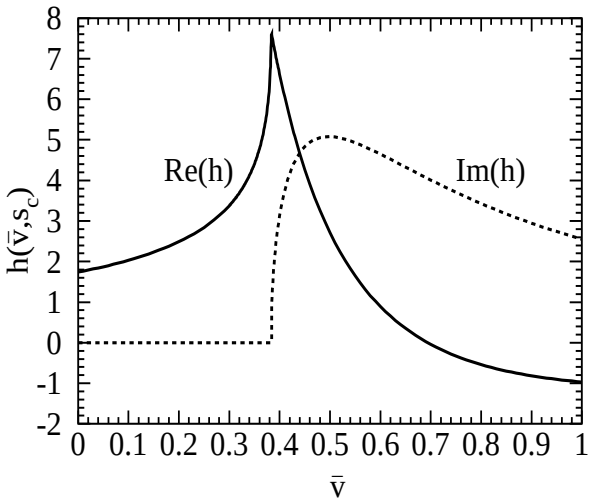
Up- and Charm-Quark Loops



- leading-power, short-distance effect, $\mathcal{O}(\alpha_s)$
- long-distance contributions power suppressed $\sim (\Lambda/m_Q)^n$

$$\langle Q_1^p \rangle^{II} \sim \alpha_s \int_0^1 dv\, h(\bar{v}, s_p)\, \Phi_V(v)$$

$$p = u, c \qquad s_p = m_p^2/m_b^2 \qquad \bar{v} \equiv 1 - v$$



power counting for soft gluon $\bar{v} \sim \Lambda/m_b \ll 1$:

$$d\bar{v}\, \bar{v}\, h(\bar{v}, s_p) \sim (\Lambda/m_b)^2 \cdot h(\Lambda/m_b, s_p)$$

charm: $\dfrac{\Lambda^2}{m_b^2} \cdot \dfrac{1}{s_c} = \dfrac{\Lambda^2}{m_c^2}$ ($B \to X_s\gamma$: *Voloshin*)

up: $\dfrac{\Lambda^2}{m_b^2} \cdot \dfrac{1}{\bar{v}} = \dfrac{\Lambda}{m_b}$ ($B \to X_{s,d}\gamma$: *G.B., Isidori, Rey*)

Table 1: Summary of input parameters.

CKM parameters and coupling constants					
V_{us}	V_{cb}	$\lvert V_{ub}/V_{cb}\rvert$	$\Lambda^{(5)}_{\overline{MS}}$	α	G_F
0.22	0.041	0.085 ± 0.025	225 MeV	1/137	$1.166 \times 10^{-5}\text{GeV}^{-2}$

Parameters related to the B mesons				
m_B	f_B	λ_B	τ_{B^+}	τ_{B^0}
5.28 GeV	180 MeV	(350 ± 150) MeV	1.65 ps	1.56 ps

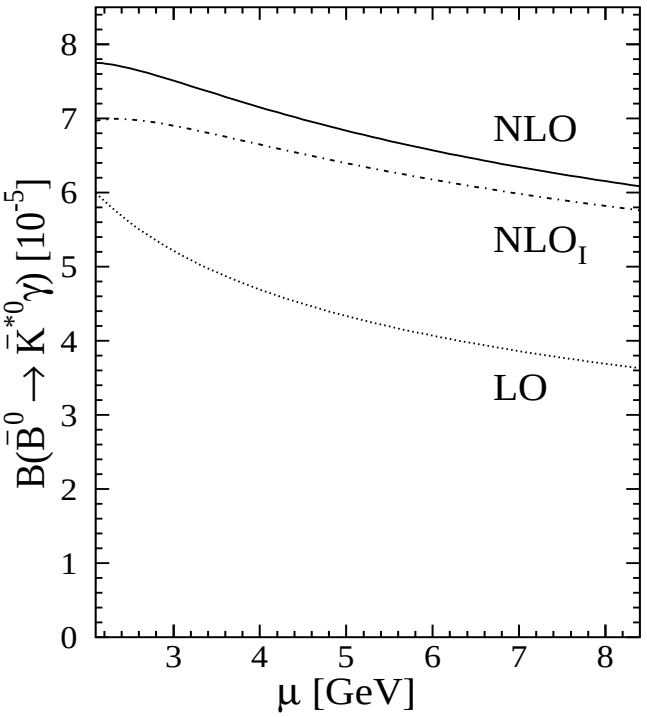
Parameters related to the K^* meson (*Ball, Braun*)					
F_{K^*}	$f^\perp_{K^*}$	m_{K^*}	$\alpha_1^{K^*}$	$\alpha_2^{K^*}$	f_{K^*}
0.38 ± 0.06	185 MeV	894 MeV	0.2	0.04	230 MeV

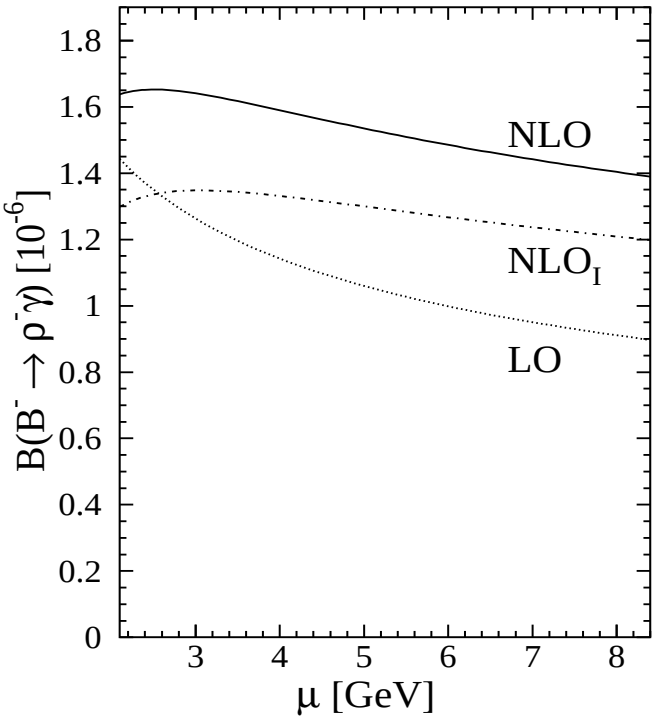
Parameters related to the ρ meson (*Ball, Braun*)					
F_ρ	$f^\perp_\rho$	m_ρ	α_1^ρ	α_2^ρ	f_ρ
0.29 ± 0.04	160 MeV	770 MeV	0	0.2	200 MeV

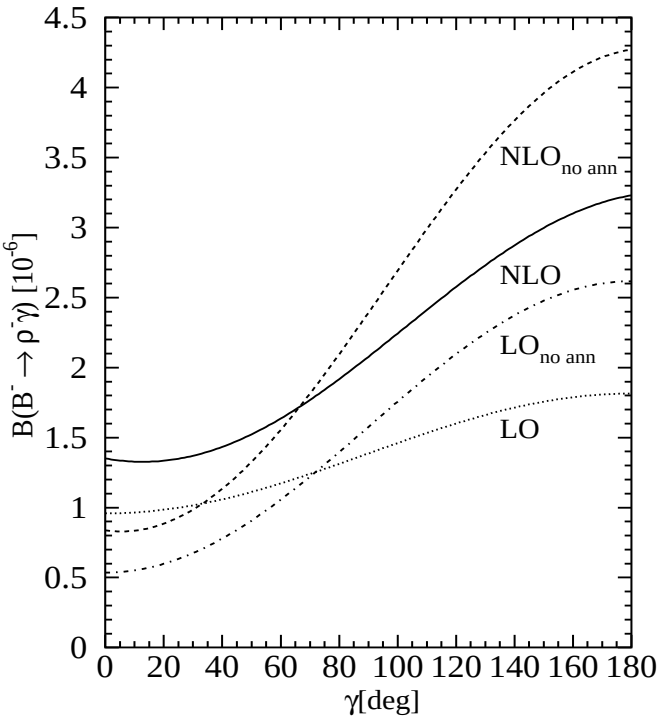
Quark and W-boson masses			
$m_b(m_b)$	$m_c(m_b)$	$m_{t,\text{pole}}$	M_W
4.2 GeV	(1.3 ± 0.2) GeV	174 GeV	80.4 GeV

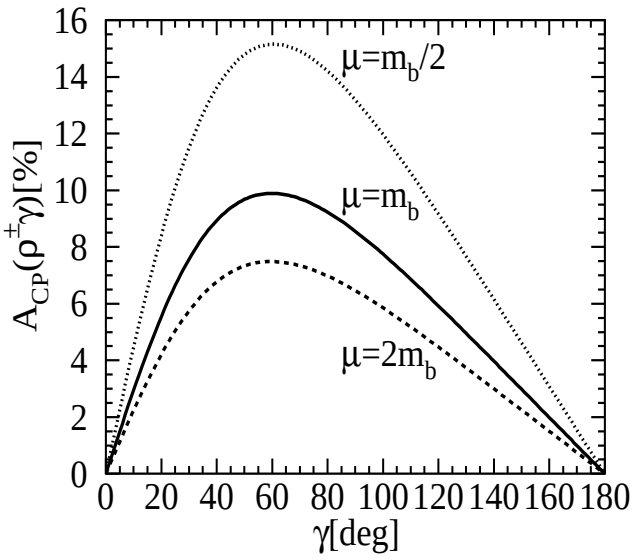
Table 2: Predictions for branching ratios and CP asymmetries with the errors from the individual input uncertainties.

	$B(\bar{B}^0 \to \bar{K}^{*0}\gamma)[10^{-5}]$	$B(B^- \to \rho^-\gamma)[10^{-6}]$	$\mathcal{A}_{CP}(\rho^\pm\gamma)[\%]$
central	7.09	1.58	9.89
F_{K^*}	$+2.32/-1.99$	–	–
F_ρ	–	$+0.42/-0.37$	$+0.12/-0.13$
μ	$+0.67/-1.00$	$+0.07/-0.19$	$+5.25/-2.40$
λ_B	$+0.38/-0.15$	$+0.26/-0.09$	$+0.35/-0.28$
m_c	$+0.38/-0.43$	$+0.12/-0.12$	$+1.40/-1.52$
$\lvert V_{ub}/V_{cb}\rvert$	$+0.05/-0.05$	$+0.15/-0.13$	$+3.48/-3.30$





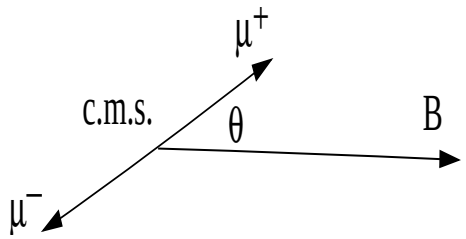


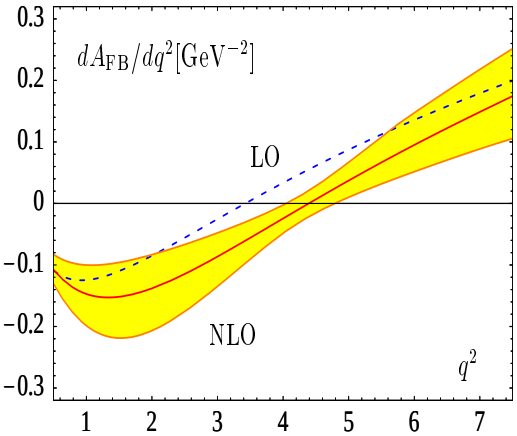


$$B(\bar{B}^0 \to \bar{K}^{*0}\gamma)/10^{-5} = 7.1 \pm 2.5 \qquad (4.44 \pm 0.35)$$

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

$B \to K^* l^+ l^-$: 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*

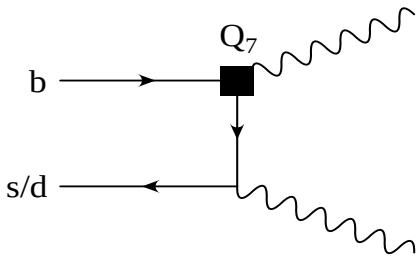
$$A(B \to K^* l^+ l^-) = c_i \xi_i + \Phi_B \otimes T \otimes \phi_{K^*}$$

SM: $dA_{FB}(\bar{B})/dq^2$ positive slope at q_0^2 *G.B., Hiller, Isidori*

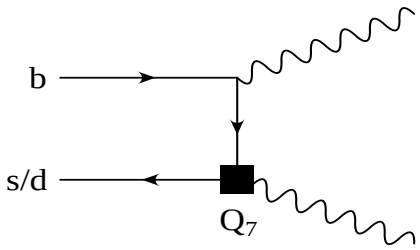
Factorization for $B \to \gamma\gamma$

Bosch, G.B.

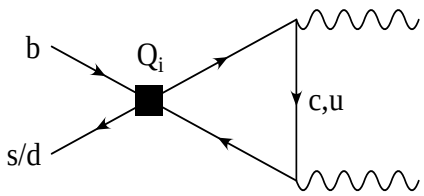
leading



Λ/m_b suppressed



Λ/m_b suppressed, calculable

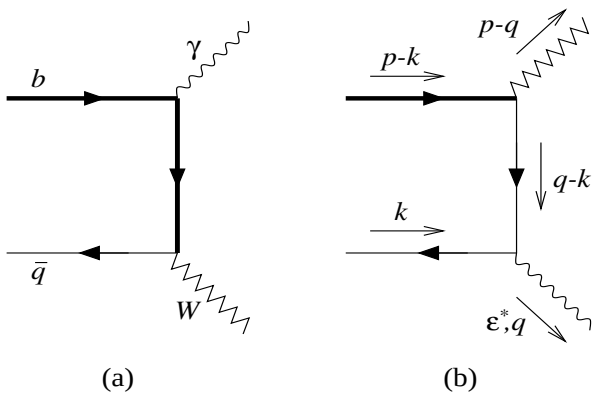


$B(\bar{B}_s \to \gamma\gamma) \sim 1.2 \cdot 10^{-6}$ $(< 1.48 \cdot 10^{-4}$ *L3*)

$B(B_d \to \gamma\gamma) \sim 3 \cdot 10^{-8}$ $(< 1.7 \cdot 10^{-6}$ *BABAR*)

$B \to l\nu\gamma$

Korchemsky, Pirjol, Yan



(b): leading power

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

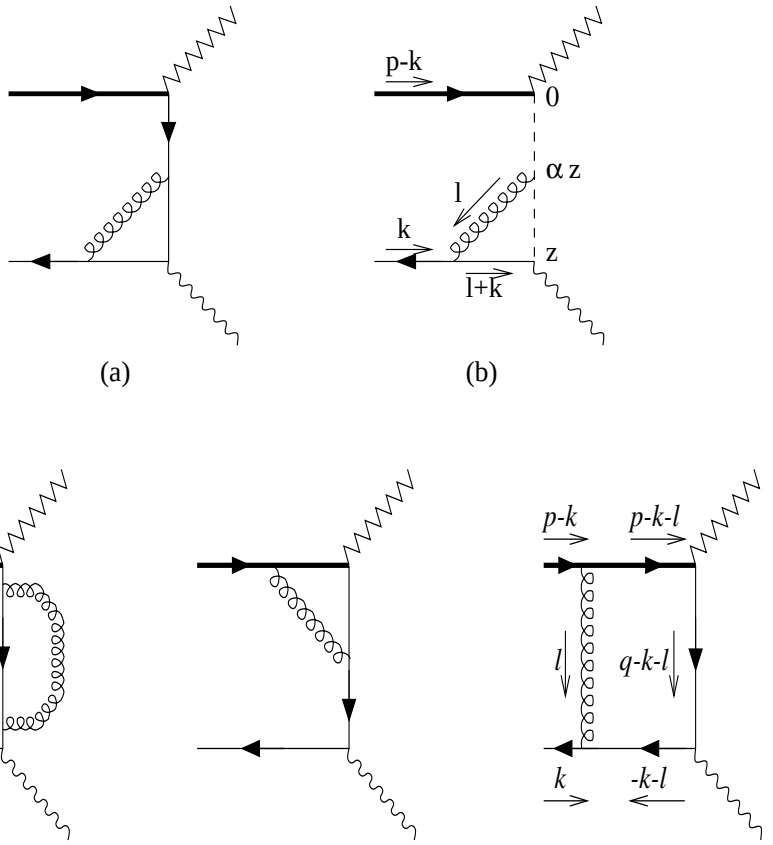
$$\Phi_B(\tilde{k}_+) = \int dz_- e^{i\tilde{k}_+ z_-} \langle 0|b(0)\bar{u}(z)|B\rangle|_{z_+=z_\perp=0}$$

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

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



future: generalization to higher orders

soft-collinear effective theory (SCET)

Bauer, Fleming, Pirjol, Stewart

SCET including power corrections

Beneke, Chapovsky, Diehl, Feldmann

Conclusions

- factorization formulas ($m_b \gg \Lambda$)
  for large class of exclusive B decays

- justify phenomenological factorization ansatz

- calculable corrections in α_s

- non-factorizable long-distance effects $\sim (\Lambda/m_b)^n$

- $B \to D^+\pi^-$ best understood

- $B \to \pi\pi,\ K^*\gamma,\ \rho\gamma,\ K^*l^+l^-,\ \ldots$
  hard spectator interaction

- new tools: SCET

- improved understanding of HSI
  from $B \to l\nu\gamma$ analysis

$\Rightarrow$ important applications:

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

CPV, CKM angles, FCNC