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B Physics Workshop
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Nonleptonic Decays, Lifetimes and Mixing

1. Introduction
2. Inclusive Decays
   HQE ; lifetimes , other applications
3. $B - \bar{B}$ Mixing
4. Exclusive Decays
5. Summary

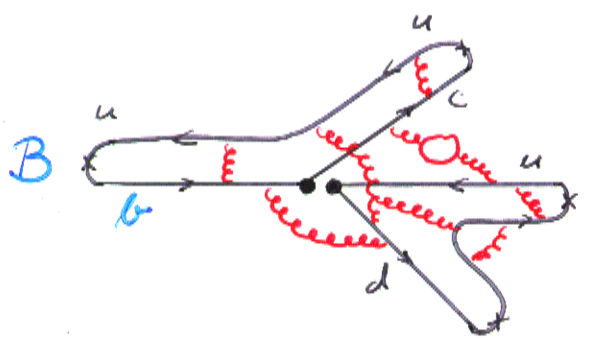
Introduction

nonleptonic B decays

- $\sim 75\%$ BR
- crucial for τ_B
- large and important field for CPV studies

  exclusive $B \to \psi K_s, \pi\pi, \pi K, \ldots$; inclusive channels

- theoretical challenge : all-hadronic final state



very difficult in general

boundstate dynamics, nonpert. QCD

- opportunity : large scale $m_b \gg \Lambda_{QCD}$

  $\to$ systematic extraction of short distance physics

short distance $\leftrightarrow$ long distance factorization

$\uparrow$ calculable

$\uparrow$ parametrize; $\leftrightarrow$ nonpert. input

tools: OPE, HQE, HQET, ...

$\to$ important simplifications

Inclusive Decays

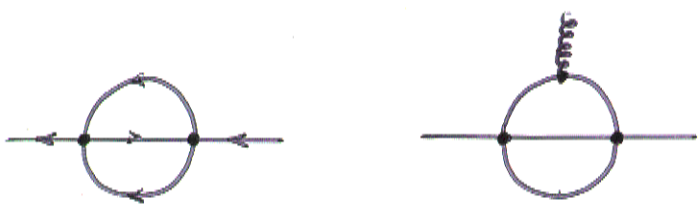
- optical theorem $\qquad \Gamma_H = \frac{1}{2M_H}\langle H|\,\mathcal{T}\,|H\rangle \equiv \langle \mathcal{T}\rangle$

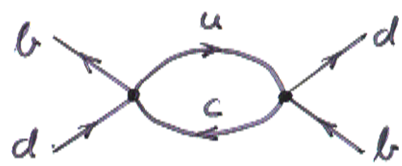
$$\mathcal{T} = \mathrm{Im}\; i\int d^4x\, T\, \mathcal{H}_{eff}(x)\,\mathcal{H}_{eff}(0) \qquad \Gamma_H \sim \langle H|\mathcal{H}_{eff}|X\rangle\langle X|\mathcal{H}_{eff}|H\rangle$$

- $\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{CKM}\, C_i\left(\frac{M_W}{\mu}, \alpha_s\right) Q_i$

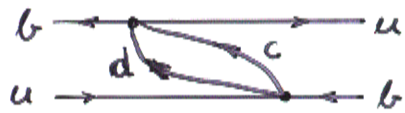
$\uparrow$ NLO $\qquad$ Buras et al., Ciuchini et al.

- $\mathcal{T} = \Gamma_b\, \bar{b}b + \frac{z_G}{m_b^2}\, \bar{b}\sigma G b + \sum \frac{z_i}{m_b^3}\, \bar{b}\Gamma_i q\, \bar{q}\Gamma_i b + \ldots$





WA (B_d)



PI (B_u)

OPE $\quad 1/m_b$

Bigi, Blok, Shifman, Uraltsev, Vainshtein, Voloshin

Chay, Georgi, Grinstein

- $\langle \bar{b}b\rangle = 1 + \frac{1}{2m_b^2}\langle \bar{h}(iD)^2 h\rangle + \frac{1}{4m_b^2}\langle \bar{h}\sigma G h\rangle$

$\quad\uparrow$ HQET $\qquad \hookrightarrow \frac{3}{2}(M_{B^*}^2 - M_B^2)$; B
$\qquad\qquad\qquad\qquad 0 \qquad\qquad \Lambda_b$

- asymptotically $\quad \Gamma_H = \Gamma_b \quad \leftarrow$ NLO ($\mathcal{O}(\alpha_s)$) $\quad$ Bagan et al.

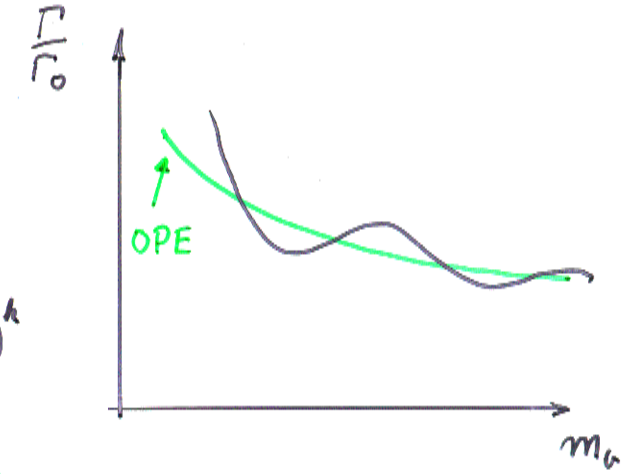
- no $1/m_b$ correction

- $1/m_b^3$ spectator effects : $\times 16\pi^2$ (phase space)

local duality

$$\Gamma/\Gamma_0 \overset{\text{OPE}}{\rightleftharpoons} 1 + \sum_{n=2}^{\infty} z_n \left(\frac{\Lambda}{m_b}\right)^n$$

missed by OPE : $\exp\left(-\left(\frac{m_b}{\Lambda}\right)^k\right) \sin\left(\frac{m_b}{\Lambda}\right)^k$



- Γ_B in 't Hooft model [$QCD_2 (N_c \to \infty)$]

  duality violation strongly suppressed

  Grinstein, Lebed
  Bigi, Shifman, Uraltsev, Vainshtein
  Bigi, Uraltsev

- resonance model, instanton model

  Shifman et al.

Lifetimes

	exp.	th.
$\tau(B^+)/\tau(B_d^0)$	1.07 ± 0.02	$\sim 1 - 1.1$
$\bar{\tau}(B_s)/\tau(B_d)$	0.94 ± 0.04	$1 \pm (<1\%)$
$\tau(\Lambda_b)/\tau(B_d)$	0.79 ± 0.05	$0.9 - 1.0$

Bigi et al.
Neubert, Sachrajda
Beneke, G.B., Dunietz

- uncertainties from $\langle \bar{b}\Gamma q \bar{q} \Gamma b \rangle$

Λ_b : Neubert, Sachrajda; Colangelo, De Fazio; Rosner; Voloshin

lattice (exploratory) : $\frac{\tau(\Lambda_b)}{\tau(B_d)} = \begin{cases} 0.91(1) & a\, m_\pi = 0.52(3) \\ 0.93(1) & 0.74(3) \end{cases}$ $\quad a = (1.1\,\text{GeV})^{-1}$

Di Pierro, Sachrajda, Michael

B_c HQE + NRQCD

$$\Gamma_{B_c} = \Gamma_b \left(1 - \frac{v_b^2}{2}\right) + \Gamma_c \left(1 - \frac{v_c^2}{2}\right) + \underbrace{\{PI, WA\}}_{}^{\sim v^3} + \mathcal{O}(v^4) = (0.4 - 0.7\ ps)^{-1}$$

Beneke, G.B.

Bigi

CDF $\tau_{B_c} = 0.46^{+0.18}_{-0.16} \pm 0.03$ ps

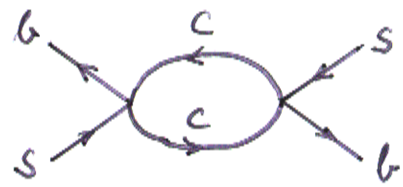
$(\Delta\Gamma/\Gamma)_{B_s}$ $\sim 16\pi^2 (\Lambda_{QCD}/m_b)^3$

- Lowest order estimates $\Delta\Gamma/\Gamma \approx 10\text{–}20\%$ — Bigi et al.
- Large $\Delta\Gamma$ → novel CPV studies w. untagged B_s — Dunietz; Fleischer, Dunietz
- with New Physics $\Delta\Gamma \leq \Delta\Gamma_{SM}$ — Grossman
- HQE test case

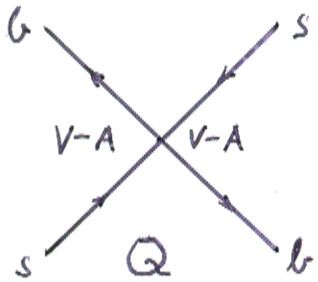
  $\Delta\Gamma_{B_s}$: local duality exact in large N_c + SV limit $\Lambda_{QCD} \ll m_b - 2m_c \ll m_b$

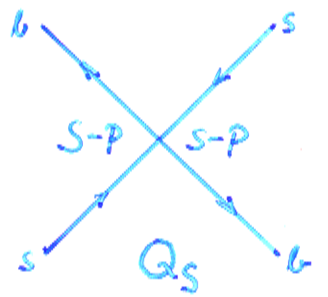
  Shifman, Voloshin ; Aleksan et al.

HQE

$\mathcal{T} = \mathrm{Im}\, i$ 

$=$

$= C$ 

$+ \; C_S$ 

$+ \left(\text{dim 7 operators} \right)$

$$\left(\frac{\Delta\Gamma}{\Gamma}\right)_{B_s} = 16\pi^2 \frac{f_{B_s}^2 M_{B_s}}{m_b^3} \left[c\left(\alpha_s, \frac{m_c}{m_b}\right) \cdot B + c_S\left(\alpha_s, \frac{m_c}{m_b}\right) B_S \right] + R_{1/m_b}$$

$$= \left(\frac{f_{B_s}}{210\,\text{MeV}}\right)^2 \left[0.006\, B(m_b) + 0.150\, B_S(m_b) - 0.063 \right] \qquad (\text{NDR})$$

- R_{1/m_b} : rel. $1/m_b$ correction — Beneke, G.B., Dunietz
- c, c_S known at NLO — Beneke, G.B., Greub, Lenz, Nierste
- exploratory lattice study $B_S(m_b) = 0.75 \pm ??$

  Gupta, Bhattacharya, Sharpe

HQE - other applications

- $B_{SL} = \frac{\Gamma(B\to X e\nu)}{\Gamma_{tot}}$

  Bigi et al.
  G.B., Dunietz, Yamamoto
  Neubert, Sachrajda
  Lenz, Nierste, Ostermaier
  Dunietz et al.
  Kagan

  $n_c = 1 + B(b\to c\bar{c}s) - B(\text{no charm})$

- V_{ub} from $\frac{\Gamma(b\to u\bar{c}s)}{\Gamma(b\to c l\nu)} = K \left|\frac{V_{ub}}{V_{cb}}\right|^2 \left(1 + \mathcal{O}\left(\alpha_s, \frac{1}{m_c^3}\right)\right)$

  Beneke, G.B., Dunietz
  Falk, Petrov
  Chay et al.

  Lead. m_b, m_c dep. drops out

- CP violation in ...

  ... mixing $A_\ell(t) = \frac{\Gamma(\bar{B}(t)\to \ell^+) - \Gamma(B(t)\to\ell^-)}{+} = a = \mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}$

  SM: $a \lesssim 10^{-3}$ New Physics $a \sim 10^{-2}$ Cahn, Worah

  $$A_{all}(t) = \frac{\Gamma(B(t)\to all) - \Gamma(\bar{B}(t)\to all)}{+} = a\left[\frac{x}{2}\sin \Delta M t - \sin^2\frac{\Delta M t}{2}\right]; \quad x = \frac{\Delta M}{\Gamma}$$

  Beneke, G.B., Dunietz

  ... mixing-decay interference

  $$A(t) = \frac{\Gamma(B(t)\to f) - \Gamma(\bar{B}(t)\to f)}{+} \approx -0.1 \sin 2\alpha \sin \Delta M t$$

  $f = u\bar{u}d\bar{d}$

  Beneke, G.B., Dunietz

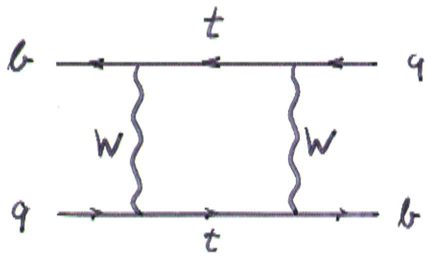
  ... decay (direct)

  $$\frac{\Gamma(B^+\to X) - \Gamma(B^-\to X)}{+} = \begin{cases} \left(2.0\,^{+1.2}_{-1.0}\right)\% & \Delta S = 0 \\ \left(-1.0\,^{+0.5}_{-0.5}\right)\% & \Delta S = 1 \end{cases} \quad \text{charmless}$$

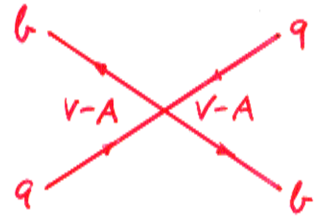
  Lenz, Nierste, Ostermaier

$B_q - B_q$ Mixing , ΔM_q

$q = d, s$



$= C\left(\frac{m_t}{M_W}, \mu\right) \cdot$



$+ \mathcal{O}\left(\frac{m_b^2}{M_W^2}\right)$

coefficient   matrix element

$$\Delta M_q = \frac{G_F^2 M_W^2}{6\pi^2} m_{B_q} |V_{tq}|^2 \; S_0\left(\frac{m_t}{M_W}\right) \eta_B \cdot B_{B_q} f_{B_q}^2$$

- clean situation for OPE : top dominance , $M_W, m_t \gg \Lambda_{QCD}$

  C at NLO   Buras, Jamin, Weisz

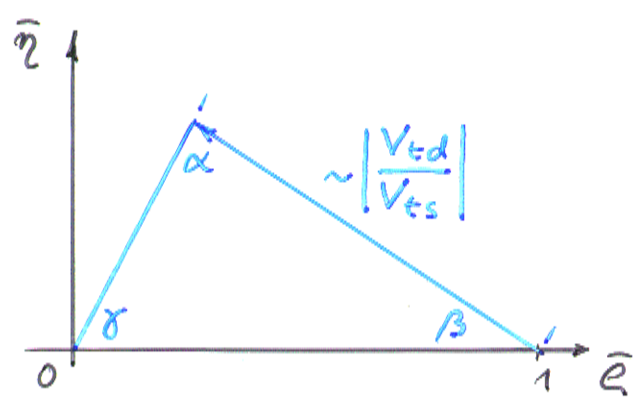
- theoretical uncertainty $\leftrightarrow B_{B_q} f_{B_q}^2$

$\hookrightarrow$ reduced in

$$\frac{\Delta M_{B_d}}{\Delta M_{B_s}} = \frac{m_{B_d}}{m_{B_s}} \underbrace{\frac{B_{B_d} f_{B_d}^2}{B_{B_s} f_{B_s}^2}}_{1 + SU(3)\text{ breaking}} \left|\frac{V_{td}}{V_{ts}}\right|^2$$

$B_{B_s}/B_{B_d} = 1.01\,(1)(3)$ $f_{B_s}/f_{B_d} = 1.16\,(4)$ Hashimoto lattice 99

- $\Delta M_d / \Delta M_s$ clean measure of $|V_{td}/V_{ts}|$



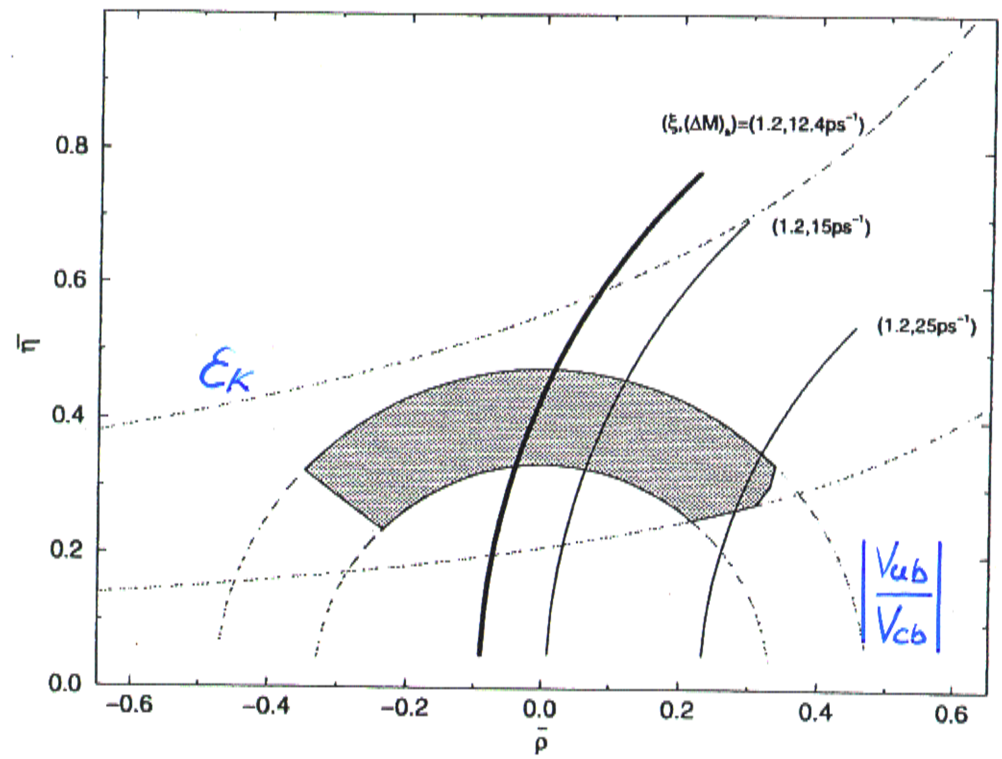
exp. avg. :

$\Delta M_d = 0.473 \pm 0.016\ ps^{-1}$

$\Delta M_s > 12.4\ ps^{-1}$

UT   Wolfenstein parameters $\bar\varrho, \bar\eta$

Buras



Quantity	Central	Error	Reference
$\lvert V_{cb}\rvert$	0.040	± 0.002	[8]
$\lvert V_{ub}\rvert$	$3.56 \cdot 10^{-3}$	$\pm 0.56 \cdot 10^{-3}$	[15]
$\hat{B}_K$	0.80	± 0.15	See Text
$\sqrt{B_d} F_{B_d}$	200 MeV	± 40 MeV	[48]
m_t	165 GeV	± 5 GeV	[50]
ΔM_d	0.471 ps^{-1}	± 0.016 ps^{-1}	[51]
ΔM_s	> 12.4 ps^{-1}	95%C.L.	[51]
ξ	1.14	± 0.08	[48, 52]

Exclusive Nonleptonic Decays

Problem: $\langle \pi\pi | Q_i | B \rangle$; $\neq$ incl.: $\sum_f |\langle f | Q | B \rangle|^2 \to \langle B | Q^\dagger(x) Q(0) | B \rangle$
$\to$ OPE

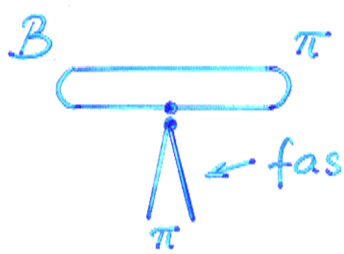
- eliminate matrix elements : use flavor symm. + combine modes
  - $B \to \pi\pi$ + SU(2) Gronau, London ; $B \to \pi^+\pi^-$, $B_s \to K^+K^-$ + SU(3) Dunietz ; Fleischer
- general parametrizations of m.e. Ciuchini et al.; Buras, Silvestrini

- naive factorization
- hard scattering approach Szczepaniak, Henley, Brodsky; Kroll et al.
- LEET for $B \to D\pi$ Dugan, Grinstein
- QCD sum rules Blok, Shifman ; Khodjamirian, Rückl
  (corrections to fact.) Donoghue, Petrov

new approach : QCD factorization Beneke, G.B., Neubert, Sachrajda

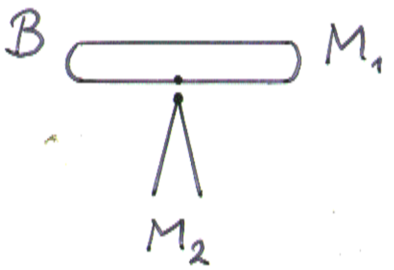
$m_B \gg \Lambda_{QCD} \Rightarrow$

$$A(B \to \pi\pi) \sim \underbrace{\langle \pi | j_1 | B \rangle \langle \pi | j_2 | 0 \rangle \left[1 + \mathcal{O}(\alpha_s) \right.}_{\text{calculable in terms of } f_+(0),\ f_\pi,\ \phi_\pi, \ldots} \left. + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_B}\right) \right]$$



← fast, collinear $q\bar{q}$ – decouples from IR int. to lead. power

includes : hard spectator int., penguins, rescatt. $\rightsquigarrow$
strong phases $\mathcal{O}(\alpha_s ; \frac{\Lambda}{m_B})$



approach valid for
$M_2 = \pi, \rho, K, J/\psi, \ldots$
not : $M_2 = D$

$$\frac{\Gamma(B \to D^*\pi)}{\Gamma(B \to D\pi)}$$
Politzer, Wise

Summary

theoretical framework for nonleptonic B decays

$$\langle f | \mathcal{H}_{eff} | B \rangle \sim C_i\left(\frac{M_W}{m_b}, \alpha_s\right) \cdot \langle f | Q_i | B \rangle$$

short distances
$M_W \to m_b$

short + long distances
$m_b \gg \Lambda_{QCD}$

HQE (inclusive); QCD fact. (exclusive)

- inclusive decays – HQE
  - local quark-hadron duality
    models ... ? ; test predictions $\leftrightarrow$ experiment
  - higher corrections : $1/m_b$, α_s $\Delta\Gamma_{B_s}$ ✓
  - nonpert. matrix elements ←
  - applications – b-hadron lifetimes
    – CPV , CKM

    ? τ_{Λ_b} , $B_{SL} \leftrightarrow n_c$

- exclusive decays (two-body)
  - QCD factorization – power corrections ?
    – exp. tests
  - phenomenological approaches

⇒ promising opportunities for physics with hadronic B decays