4th International Workshop on CKM Unitarity Triangle 2006 Nagoya

Beauty Hadrons:

- **Lifetime Ratios:** $\tau(B^+)/\tau(B_d), \tau(B_s)/\tau(B_d), \tau(\Lambda_b)/\tau(B_d)$
- **Width Differences:** $\Delta\Gamma_d, \Delta\Gamma_s$
- **Semileptonic CP-Asymmetries:** A_{SL}^d, A_{SL}^s

Cecilia Tarantino
Technical University Munich

$B^0_q - \overline{B}_q^{\,0}$ SYSTEMS (q=d,s)

$$\hat{H} = \hat{M} - \frac{i}{2}\hat{\Gamma}$$

$$\hat{M} = \begin{pmatrix} M_{11} & M_{12} \\ M^*_{12} & M_{11} \end{pmatrix} \qquad \hat{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_{11} \end{pmatrix}$$

Oscillation — Decay

Eigenstates:

$$\left|B_q^{L,H}\right\rangle = p_q \left|B_q^0\right\rangle \pm q_q \left|\overline{B}_q^{\,0}\right\rangle$$

$$\Gamma^q_{11} \quad (\Delta B = 0)$$

•**Lifetimes:** $\Gamma_{B_q} = \Gamma^q_{11}$

$$\Gamma^q_{12} \quad (\Delta B = 2)$$

•**Width Differences:** $\Delta\Gamma_q = \Gamma_{B^q_L} - \Gamma_{B^q_H} \leftrightarrow \Gamma^q_{12}$

•**Semileptonic CP-Asymmetries:** $A^q_{SL} = -2\left(\left|\frac{q}{p}\right|_q - 1\right) \leftrightarrow \Gamma^q_{12}$

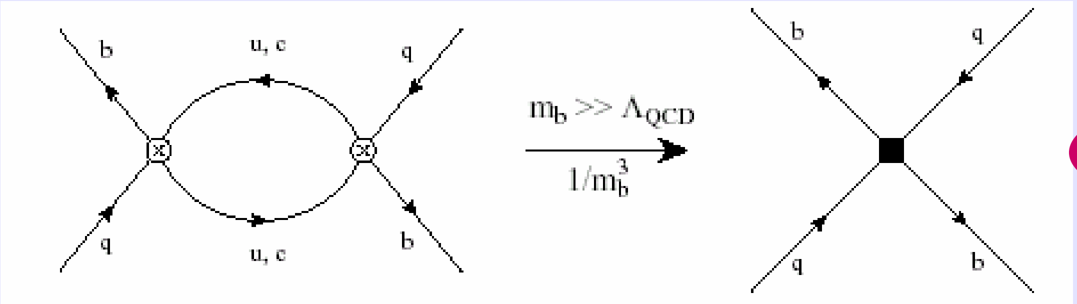
different V_{CKM}

$$\Gamma^q_{11} \propto \mathrm{Disc}\langle B^0_q | \mathcal{T} | B^0_q \rangle \qquad \Gamma^q_{12} \propto \mathrm{Disc}\langle B^0_q | \mathcal{T} | \overline{B}^0_q \rangle$$

$$\mathcal{T} = i \int d^4x \; T(H_{eff}^{\Delta B=1}(x) H_{eff}^{\Delta B=1}(0))$$

HQE $(m_b >> \Lambda_{QCD})$

Large energy release ⟺ contact interaction



SPECTATOR EFFECTS

$$\Gamma^q_{12} = \sum_k \frac{\vec{c}_k^{\,q}(\mu)}{m_b^k} \langle B^0_q | \vec{O}_k^{q\,\Delta B=2}(\mu) | \overline{B}^0_q \rangle$$

Scale separation

- $\vec{c}_k^{\,q}(\mu)$: short-distance (perturbative)
- $\langle B^0_q | \vec{O}_k^{q\,\Delta B=2}(\mu) | \overline{B}^0_q \rangle$: long-distance (non-perturbative)

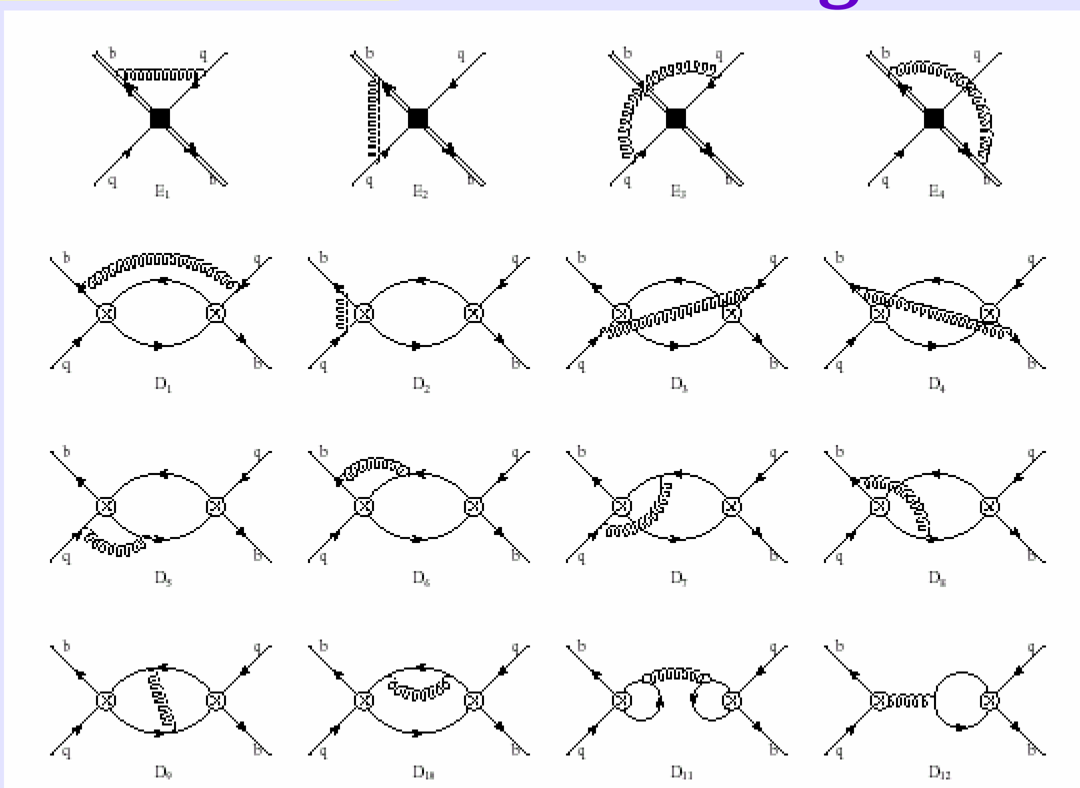
Wilson coefficients

$$\textbf{Disc}\langle T \rangle = \vec{\mathbf{c}}(\mu)\langle \vec{\mathbf{O}}(\mu) \rangle$$

Matching at NLO in QCD and $O(1/m_b)$ in the HQE

$\Delta B = 2(\Delta B = 0)$

NLO Diagrams



•Lifetime Ratios

$$\Gamma_{11}^{q} = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3 (2M_{B_q})}\left[c^{(3)}\langle \bar{b}b\rangle + c^{(5)}\frac{g_s}{m_b^2}\langle \bar{b}\sigma_{\mu\nu}G^{\mu\nu}b\rangle + \frac{96\pi^2}{m_b^3}\sum_k\left(c_k^{(6)}\langle O_k^{(6)}\rangle + \frac{c_k^{(7)}}{m_b}\langle O_k^{(7)}\rangle\right)\right]$$

$O(1)$ **(1996)** **[M. Neubert and C.T. Sachrajda]**

$O(\alpha_s)$ **(2002)**

- **[E. Franco, V. Lubicz, F. Mescia and C.T.]**
- **[M. Beneke, G. Buchalla, C. Greub, A. Lenz and U. Nierste]**

Spectator effects, explaining lifetime diversity, appear at $O(1/m_b^3)$

$O(1/m_b)$ **(2004)**

- **[F. Gabbiani, A. I. Onishchenko and A. A. Petrov]**

•Width Differences and ~~CP~~

$$\Gamma_{12}^{s} = -\frac{G_F^2 m_b^2}{12\pi(2M_{B_s})}(V_{cs}^* V_{cb})^2\left[C_1\langle O_1^s\rangle + C_2\langle O_2^s\rangle + \delta_{1/m_b}\right]$$

$O(\alpha_s)$ **(2003)**

- **[M. Ciuchini, E. Franco, V. Lubicz, F. Mescia and C.T.]**
- **[M. Beneke, G. Buchalla, A. Lenz and U. Nierste]**

The leading contribution in the HQE is of $O(1/m_b^3)$

$O(1/m_b)$ **(1996)**

- **[M. Beneke, G. Buchalla and I. Dunietz]**

$O(1/m_b^2)$ **(coming soon?)** ⇒ **+convenient change of basis**

- **[A. Lenz and U. Nierste]**

[appeared today: hep-ph/0612167]

Matrix Elements: ΔB=0 Operators

Leading spectator effect contribution: $O(1/m_b^3)$

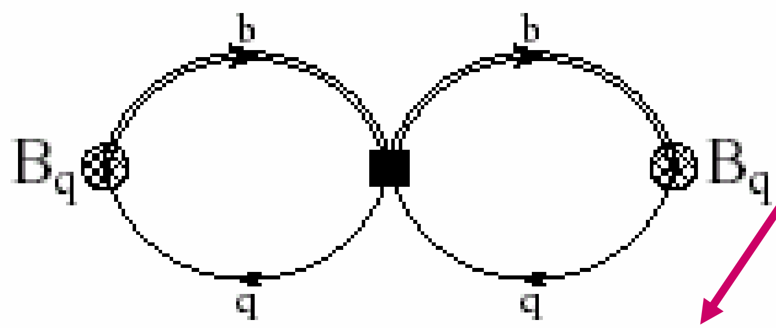
$$O_1^q = (\bar{b}q)_{V-A}(\bar{q}b)_{V-A} \leftrightarrow B_1^q, \qquad O_2^q = (\bar{b}q)_{S-P}(\bar{q}b)_{S+P} \leftrightarrow B_2^q,$$

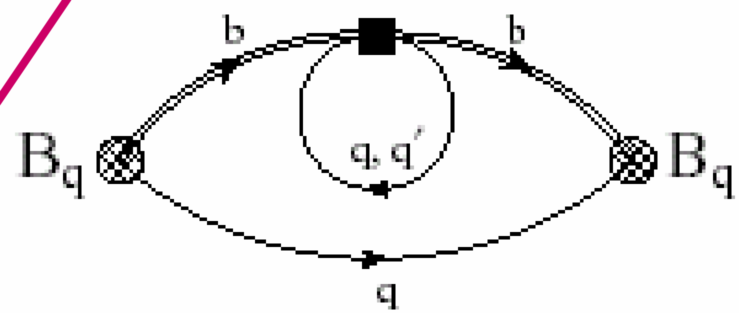
$$O_3^q = (\bar{b}T^a q)_{V-A}(\bar{q}T^a b)_{V-A} \leftrightarrow \varepsilon_1^q, \qquad O_4^q = (\bar{b}T^a q)_{S-P}(\bar{q}T^a b)_{S+P} \leftrightarrow \varepsilon_2^q,$$

$$O_P = (\bar{b}T^a b)_V \sum_{q=u,d,s,c} (\bar{q}T^a q)_V$$

not computed

$$\left[(\bar{q}q)_{V-A} = \bar{q}\gamma_L^\mu q, \quad (\bar{q}q)_{S\pm P} = \bar{q}(1\pm\gamma_5)q, \quad (\bar{q}q)_V = \bar{q}\gamma^\mu q\right]$$





not computed

These contributions are expected to be:
- negligible in $\tau(B^+)/\tau(B_d)$ [S~~U~~(2)-effect]
- small in $\tau(B_s)/\tau(B_d)$ [S~~U~~(3)-effect]
- significant in $\tau(\Lambda_b)/\tau(B_d)$

M.Ciuchini, E.Franco, V.Lubicz, F.Mescia, 2001]

B-parameters:

Λ_b Baryon

• Only one lattice calculation, in HQET ($m_b \to \infty$), evolved at LO
[M. Di Pierro, C.T. Sachrajda, C. Michael (UKQCD Collaboration), 1999]

(B_d,B_s,B^+) Mesons

• Lattice-HQET ($m_b \to \infty$)

$$B_1^d = 1.06 \pm 0.08, \quad B_2^d = 1.01 \pm 0.07,$$
$$\varepsilon_1^d = -0.01 \pm 0.03, \quad \varepsilon_2^d = -0.03 \pm 0.02.$$

[M. Di Pierro and C.T. Sachrajda, 1998]

• Lattice-QCD ($m_c \leq m_Q < m_b$, $m_Q \to m_b$)

$$B_1^d = 1.2 \pm 0.2, \quad B_2^d = 0.9 \pm 0.1,$$
$$\varepsilon_1^d = 0.04 \pm 0.01, \quad \varepsilon_2^d = 0.04 \pm 0.01.$$

[APE (D. Becirevic et al.), 2001]

• Sum Rules, in HQET

$$B_1^d = 1.01 \pm 0.01, \quad B_2^d = 0.99 \pm 0.01,$$
$$\varepsilon_1^d = -0.08 \pm 0.02, \quad \varepsilon_2^d = -0.01 \pm 0.03.$$

[M.S. Baek et al., 1998]

Subleading spectator effect contribution: $O(1/m_b^4)$

8 operators, from the VSA (B-mesons) or the quark-diquark model (baryon)

Matrix Elements: ΔB=2 Operators

Leading contribution: $O(1/m_b^3)$

$$O_1^q = (\bar{b}q)_{V-A}(\bar{b}q)_{V-A} \leftrightarrow B_1^q, \qquad O_2^q = (\bar{b}q)_{S-P}(\bar{b}q)_{S-P} \leftrightarrow B_2^q,$$

B-parameters: From QCD *-sum rules* [J.G. Korner et al., 2003] and

Lattice:

• **HQET** $(m_b \to \infty)$

$B_1^s = 0.83(5)(6), \quad B_2^s = 0.81(2)(10)$ [V. Gimenez and J. Reyes, 2000]

• **NRQCD** $(O(1/m_b))$

$B_1^s = 0.85(3)(11), \quad B_2^s = 0.82(2)(11)$ [Hi-KEK (S. Hashimoto et al.), 2000]

• **Unquenched NRQCD** $(n_f=2)$

$B_1^s = 0.85(2)(6), \quad B_2^s = 0.84(6)(8)$ [JLQCD (S. Aoki et al.), 2001-2003]

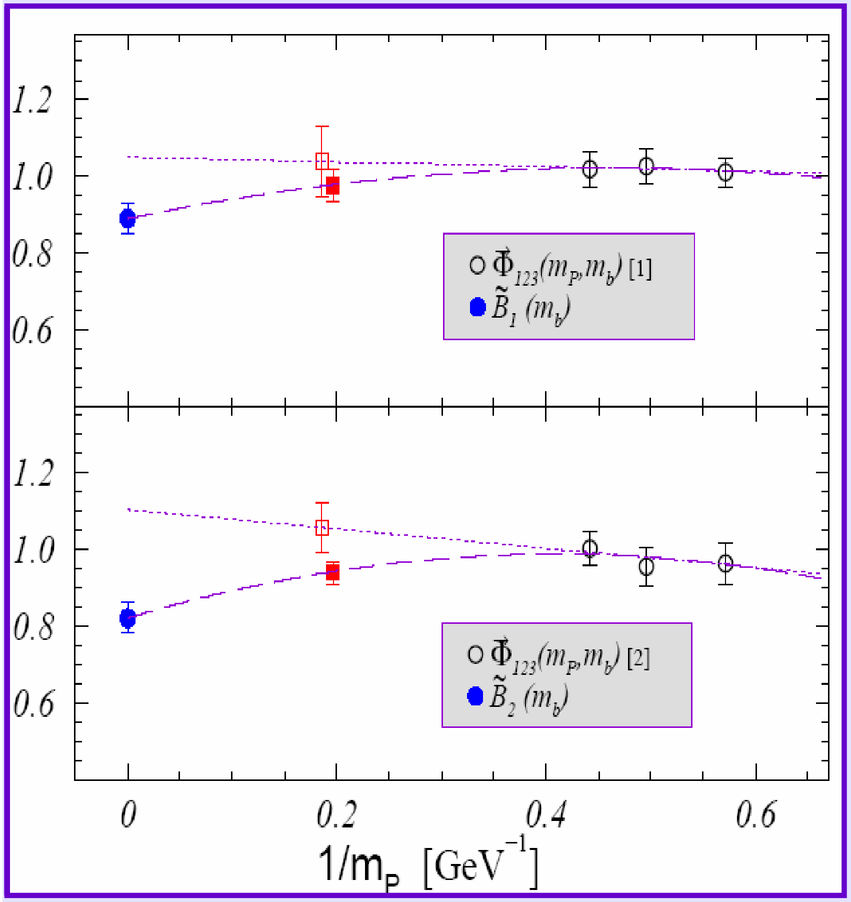
• **QCD** $(m_c \leq m_Q < m_b,\ m_Q \to m_b)$

$B_1^s = 0.91(3)^{+0}_{-6}, \quad B_2^s = 0.86(2)^{+2}_{-3}$ [APE (D. Becirevic et al.), 2000]

•QCD +HQET

$B_1^s = 0.87(2)(5), \quad B_2^s = 0.84(2)(4)$

[APE (D. Becirevic et al.), 2001]



Relativistic QCD and static HQET results are combined

Matching between QCD and HQET is performed at NLO in perturbation theory

A new NRQCD study with nf=2+1(staggered) finds compatible results

$B_1^s = 0.76(11), \quad B_2^s = 0.84(13)$

[HPQCD (E.Dalgic et al.), 2006]

Subleading contribution: $O(1/m_b^4)$

4 Operators $\{R_1^q, R_2^q, R_3^q, R_4^q\}$:

- R_1^q, R_4^q are related to operators computed on the lattice, through Fierz Identities and equations of motion
- R_2^q, R_3^q are estimated in the Vacuum Insertion Approximation

A calculation with QCD-sum rules is in progress

[A.A. Pivovarov, private communication]

Lifetime Ratios

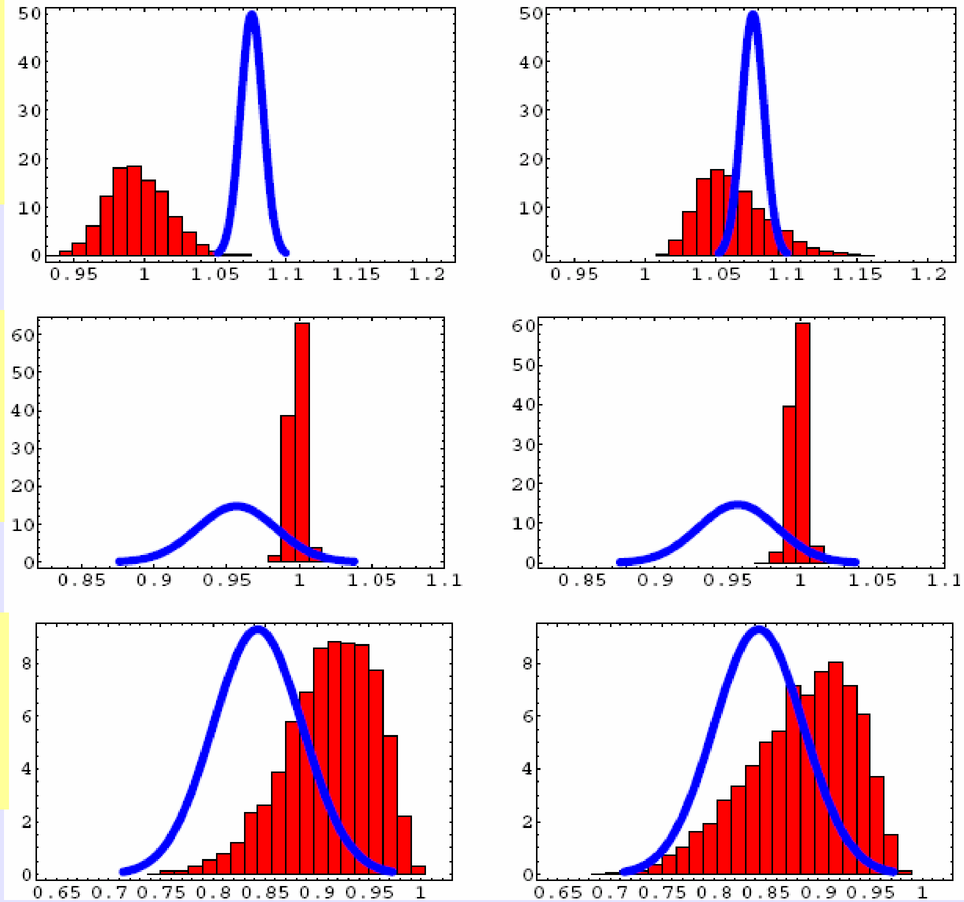
	$\frac{\tau(B^+)}{\tau(B_d)}$	$\frac{\tau(B_s)}{\tau(B_d)}$	$\frac{\tau(\Lambda_b)}{\tau(B_d)}$
LO	**1.01(3)**	**1.00(1)**	**0.93(4)**
NLO	**1.06(3)**	**1.00(1)**	**0.90(5)**
NLO+ O(1/m_b^4)	**1.06(2)**	**1.00(1)**	**0.88(5)**

LO **NLO**

$$\frac{\tau(B^+)}{\tau(B_d)}$$

$$\frac{\tau(B_s)}{\tau(B_d)}$$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)}$$



Theoretical predictions at the NLO + contribution of $O(1/m_b^4)$:

$$\frac{\tau(B^+)}{\tau(B_d)} = 1.06 \pm 0.02, \quad \frac{\tau(B_s)}{\tau(B_d)} = 1.00 \pm 0.01, \quad \frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.88 \pm 0.05$$

[E.Franco, V.Lubicz, F.Mescia, C.T., 2002-2004]

Experimental averages:

$$\frac{\tau(B^+)}{\tau(B_d)} = 1.076 \pm 0.008, \quad \frac{\tau(B_s)}{\tau(B_d)} = 0.957 \pm 0.027, \quad \frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.84 \pm 0.05$$

[HFAG, 2006]

…before new Tevatron measurements…

CDF

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 1.041 \pm 0.057$$

[CDF (A.Abulencia et al.), 2006]

D0 [PRELIMINARY]

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.870 \pm 0.102 \pm 0.041$$

[D0 (C.Ay talk@HQL06), 2006]

- differs from the world average by 2.5 σ
- single best measurement from fully reconstructed $\Lambda_b \to \Lambda^0 J_\psi$
- Is there a reversed Λ_b puzzle? Too early to answer!

Width Differences and Semileptonic CP-Asymmetries

$$\frac{\Delta\Gamma_q}{\Gamma_q} = -\frac{\Delta M_q}{\Gamma_q}\,\mathrm{Re}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) \qquad A_{SL}^q = \mathrm{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)$$

After the CDF measurement of ΔM_s
non-perturbative uncertainties
are only enclosed in B-parameters

$\Gamma_{12}{}^q$ describes decay (to SM particles only) ⇒ Insensitive to NP

$M_{12}{}^q$ describes oscillation through box-diagrams ⇒ Sensitive to NP ⇒ $M_{12}^q = \left(M_{12}^q\right)_{SM} C_{B_q} e^{2i\varphi_{B_q}}$

$$\frac{\Delta\Gamma_q}{\Gamma_q} = -\left(\frac{\Delta M_q}{\Gamma_q}\right)^{exp}\left[\mathrm{Re}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^{SM}\frac{\cos 2\varphi_{B_q}}{C_{B_q}} - \mathrm{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^{SM}\frac{\sin 2\varphi_{B_q}}{C_{B_q}}\right]$$

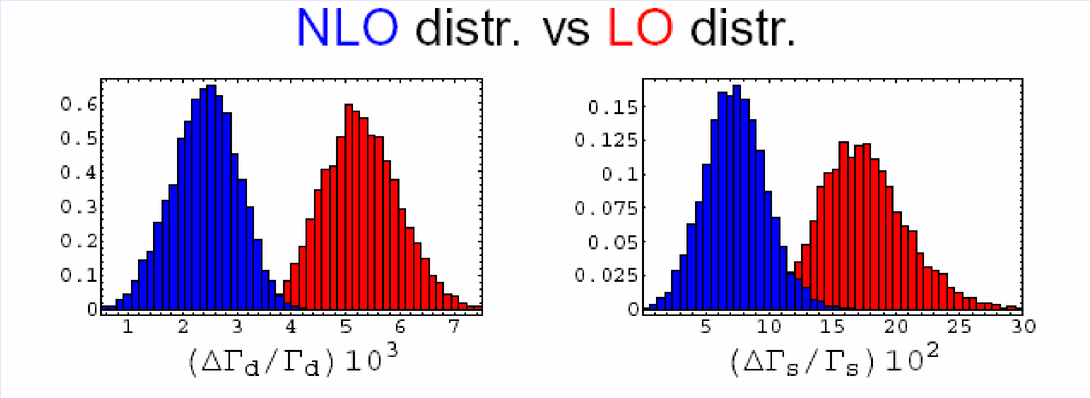
$$A_{SL}^q = \left[\mathrm{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^{SM}\frac{\cos 2\varphi_{B_q}}{C_{B_q}} - \mathrm{Re}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^{SM}\frac{\sin 2\varphi_{B_q}}{C_{B_q}}\right]$$

In particular
Re>>Im in B_s
⇓
Even a small φ_{B_s}
can be seen in $A^s{}_{SL}$

A promising way to determine $\Delta M_s/(\Delta M_s)_{SM}$ is provided by: $\frac{\Delta M_s}{(\Delta M_s)_{SM}} = C_{B_s} = -\left|\mathrm{Re}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right)^{SM}\right| \frac{S_{\psi\varphi}}{A_{SL}^s}$

[M. Blanke, A.J. Buras, D. Guadagnoli, C.T., 2006]

Width Differences



Experimental averages:

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (9 \pm 37)\cdot 10^{-3}, \quad \frac{\Delta\Gamma_s}{\Gamma_s} = (14 \pm 6)\cdot 10^{-2}$$

[Unofficial world average, talk by R.Van Kooten@FP&CP2006]

[HFAG, 2006]

Theoretical predictions at the NLO + contribution of $O(1/m_b^4)$:

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (2.3 \pm 0.8)\cdot 10^{-3}, \quad \frac{\Delta\Gamma_s}{\Gamma_s} = (7 \pm 3)\cdot 10^{-2}$$

[M.Ciuchini, E.Franco, V.Lubicz, F.Mescia, C.T., 2003]

Quite large uncertainties for NLO and $O(1/m_b^4)$ predictions:

they are due to large NLO and $O(1/m_b^4)$ contributions that induce strong cancellations

A.Lenz's and U.Nierste's Idea: Change Basis!

[Today`s hep-ph/0612167]

$O_1^q = (\bar{b}_i q_i)_{V-A}(\bar{b}_j q_j)_{V-A} \leftrightarrow B_1^q,\quad O_2^q = (\bar{b}_i q_i)_{S-P}(\bar{b}_j q_j)_{S-P} \leftrightarrow B_2^q,\quad O_3^q = (\bar{b}_i q_j)_{S-P}(\bar{b}_j q_i)_{S-P} \leftrightarrow B_3^q,$

$\{O_1^q, O_2^q\} \rightarrow \{O_1^q, O_3^q\}$

Old basis $\rightarrow$ New basis

Using the NLO and O($1/m_b$) relation:

$$O_2^q + \alpha_1 O_3^q + \frac{\alpha_2}{2} O_1^q = R_0^q$$

O(1) O(α_s) O(1) O(α_s) O($1/m_b$)

$$\mathrm{Re}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right)^{OLD} = (-0.54 + 0.26)B_1^s + (-12.0 + 4.4)B_2^s + 4.0$$

$$\mathrm{Re}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right)^{NEW} = (-6.8 + 1.6)B_1^s + (-2.4 + 0.2)B_3^s + 1.6$$

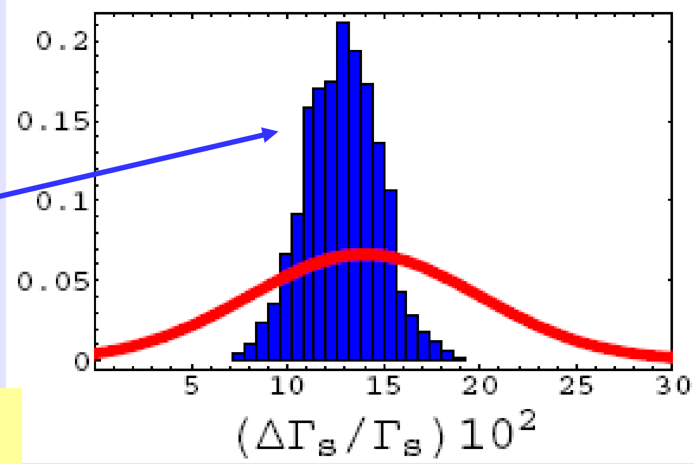
The series in both

α_s and $1/m_b$

behave better!

	Old basis	New basis
$\frac{\Delta\Gamma_d}{\Gamma_d}$	$2.3(8)10^{-3}$	$4.1(5)10^{-3}$
$\frac{\Delta\Gamma_s}{\Gamma_s}$	$7(3)10^{-2}$	$13(2)10^{-2}$

NEW th. vs exp.



Lenz and Nierste quote $(12.7\pm2.4)\bullet10^{-2}$: perfect compatibility!

The non-perturbative uncertainties have a smaller impact in the new basis

BUT

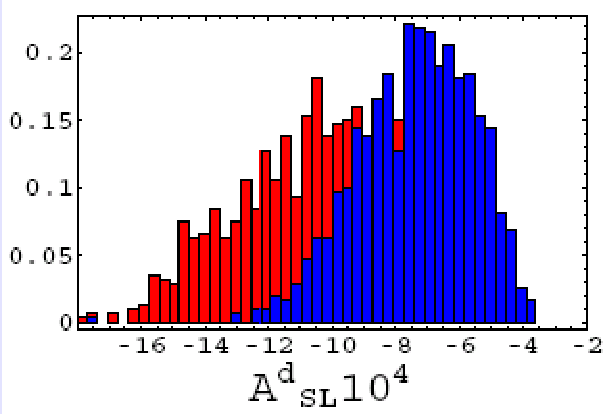
The shift of central values signal important (unknown) $O(\alpha_s^2)$ and $O(\alpha_s)\bullet O(1/m_b)$ corrections

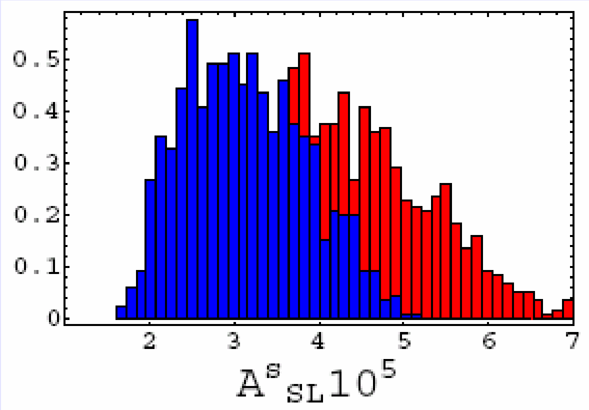
WHILE

$O(1/m_b^5)$ effects are small [A. Lenz and U. Nierste: private communication]

Semileptonic CP-Asymmetries

NLO distr.
vs
LO distr.





Experimental averages:

$$A^d_{SL} = -(30 \pm 78) \cdot 10^{-4}, \quad A^s_{SL} = (2450 \pm 1930(\text{stat.}) \pm 350(\text{syst.})) \cdot 10^{-5}$$

[HFAG, 2006] [D0, 2006]

Theoretical predictions at the NLO + contribution of $O(1/m_b^4)$:

$$A^d_{SL} = -(6.4 \pm 1.6) \cdot 10^{-4}, \quad A^s_{SL} = (2.7 \pm 0.6) \cdot 10^{-5}$$

[M.Ciuchini, E.Franco, V.Lubicz, F.Mescia, C.T., 2003]

In the combinations of Wilson coefficients entering here, the change of basis doesn't help

	Old basis	New basis
A^d_{SL}	$-6.4(16)10^{-4}$	$-6.6(17)10^{-4}$
A^s_{SL}	$2.7(6)10^{-5}$	$2.8(6)10^{-5}$

Outlook

We are waiting for updated experimental values of:

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} \qquad \frac{\Delta\Gamma_s}{\Gamma_s}$$

…and measurements with ~30% accuracy of:

$$\frac{\Delta\Gamma_d}{\Gamma_d} \qquad A^d_{SL} \qquad A^s_{SL}$$

2007

Meanwhile, from the theoretical side:

- Results for the perturbative $O(1/m_b^5)$ contribution to Γ_{12}^q [A.Lenz, U.Nierste]
- Results in QCD-sum rules for $\Delta B=2$ subleading operators [A.A.Pivarov et al.]
- Further Lattice studies of $\Delta B=2$ B-parameters [D.Becirevic et al,…]

…and hopefully soon:

- Improved lattice calculation of Λ_b B-parameters
- First Lattice calculation of $\Delta B=2$ subleading operators (R_2^q, R_3^q)
- Perturbative calculation of $O(\alpha_s^2)$ and $O(\alpha_s)O(1/m_b)$ corrections in Γ_{12}^q