CP asymmetry in flavour-specific B decays

Ulrich Nierste
Fermilab

$B-\overline{B}$ mixing and a_{fs}

Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} |\,B(t)\,\rangle \\ |\,\overline{B}(t)\,\rangle \end{pmatrix} = \left(M - i\,\frac{\Gamma}{2}\right)\begin{pmatrix} |\,B(t)\,\rangle \\ |\,\overline{B}(t)\,\rangle \end{pmatrix}$$

3 physical quantities in $B-\overline{B}$ mixing:

$$|M_{12}|\,, \quad |\Gamma_{12}|\,, \quad \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

Two mass eigenstates:

Lighter eigenstate: $|\,B_L\,\rangle = p|\,B^0\,\rangle + q|\,\overline{B}^0\,\rangle.$

Heavier eigenstate: $|\,B_H\,\rangle = p|\,B^0\,\rangle - q|\,\overline{B}^0\,\rangle$ with $|p|^2 + |q|^2 = 1.$

with masses $M_{L,H}$ and widths $\Gamma_{L,H}$.
Here B represents either B_d or B_s.

To determine $|M_{12}|$, $|\Gamma_{12}|$ and ϕ measure

$$\Delta m = M_H - M_L \simeq 2|M_{12}|, \qquad \Delta\Gamma = \Gamma_L - \Gamma_H \simeq 2|\Gamma_{12}|\cos\phi$$

and

$$a_{\rm fs} = {\rm Im}\,\frac{\Gamma_{12}}{M_{12}} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi.$$

$a_{\rm fs}$ is the CP asymmetry in decays $B \to f$ which are flavour-specific, i.e.

$$\overline{B} \not\to f \text{ and } B \not\to \overline{f}.$$

Examples: $B_d \to X\ell^+\nu_\ell$ or $B_s \to D_s^- \pi^+$.

$$a_{\rm fs} = \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to \overline{f})}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to \overline{f})}$$

The time dependence of the decay rates $\Gamma(\overline{B}(t) \to f)$ and $\Gamma(B(t) \to \overline{f})$ drops out.

$a_{\rm fs}$ measures CP violation in mixing.

Standard Model expectation:

$$\frac{\Delta\Gamma}{\Delta m} \simeq \left|\frac{\Gamma_{12}}{M_{12}}\right| = \mathcal{O}\left(\frac{m_b^2}{M_W^2}\right) = 4 \cdot 10^{-3}$$

$$a_{\rm fs} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi = \begin{cases} -5 \cdot 10^{-4} & \text{for } B_d \\ 2 \cdot 10^{-5} & \text{for } B_s, \end{cases}$$

because

$$\phi = \mathcal{O}\left(\frac{m_c^2}{m_b^2}\right) = \begin{cases} -0.1 = -5^\circ & \text{for } B_d \\ 3 \cdot 10^{-3} = 0.2^\circ & \text{for } B_s. \end{cases}$$

New physics can affect M_{12} lifting the GIM suppression of ϕ.

$\Rightarrow$ large enhancement of $a_{\rm fs}$ possible

$\Rightarrow$ Even crude upper bounds constrain models of new physics.

Laplace,Ligeti,Nir,Perez,hep-ph/0202010

No tagging is necessary: With $\Gamma[f,t] = \Gamma(B(t) \to f) + \Gamma(\overline{B}(t) \to f)$,

$$a_{\rm fs}^{\rm untagged} = \frac{\Gamma[f,t] - \Gamma[\overline{f},t]}{\Gamma[f,t] + \Gamma[\overline{f},t]} = \frac{a_{\rm fs}}{2} \left[1 - \frac{\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2)} \right]$$

Relation to $|q/p|$:

$$\left| \frac{q}{p} \right|^2 = 1 - a_{\rm fs}$$

$\Rightarrow$ The time evolution of any decay $B \to f$ can be used to determine $a_{\rm fs}$

2001 world average of $a_{\rm fs}$ from $B_d \to X\ell^+\nu_\ell$ decays:

$$a_{\rm fs} = (2 \pm 14) \cdot 10^{-3}$$ Nir

Babar, hep-ex/0311037, decays with one fully reconstructed B_d:

$$a_{\rm fs}(B_d) = 2\left(1 - \left|\frac{q}{p}\right|\right) \in [-104 \cdot 10^{-3}, -2 \cdot 10^{-3}] \qquad @90\% CL$$

Any decay mode $B \to f$:

$$\lambda_f = \frac{q}{p} \frac{\langle f | \overline{B} \rangle}{\langle f | B \rangle}$$

E.g. $\lambda_f \simeq -\exp(-2i\beta) + \mathcal{O}(a_{\rm fs})$ for $B_d \to J/\psi K_S$.

Untagged decay rate (for $\Delta\Gamma = 0$):

$$\Gamma[f,t] \propto e^{-\Gamma t} \left[1 + \frac{a_{\rm fs}}{2} \left(1 - \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \cos(\Delta m\, t) + 2 \frac{\mathrm{Im}\, \lambda_f}{1+|\lambda_f|^2} \sin(\Delta m\, t) \right) \right]$$

So $a_{\rm fs}$ can be determined from tiny oscillatory terms in the untagged rate.

QCD corrections to a_{fs}

$$a_{\rm fs} = {\rm Im}\, \frac{\Gamma_{12}}{M_{12}}$$

Until recently: No QCD corrections to Γ_{12} were known.

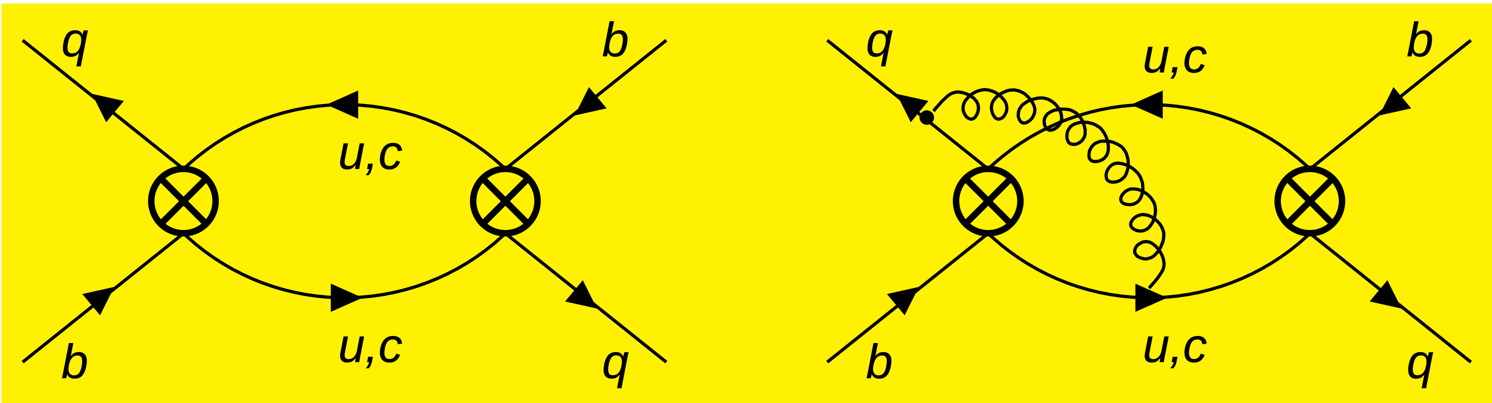
$a_{\rm fs} \propto m_c^2 \Rightarrow$ large uncertainities from uncontrolled definition of m_c

The calculation of next-to-leading order (NLO) QCD corrections reduces the uncertainty from 50% to 20%.

Ciuchini, Franco, Lubicz, Mescia, Tarantino, hep-ph/0307344

Beneke, Buchalla, Lenz, UN, hep-ph/0308029

LO and NLO sample diagram:



Results including both NLO QCD and $1/m_b$ corrections:

$$a_{\rm fs}(B_d) \;=\; 10^{-4}\left[-\frac{\sin\beta}{R_t}(12.0 \pm 2.4) + \left(\frac{2\sin\beta}{R_t} - \frac{\sin 2\beta}{R_t^2}\right)(0.2 \pm 0.1)\right]$$

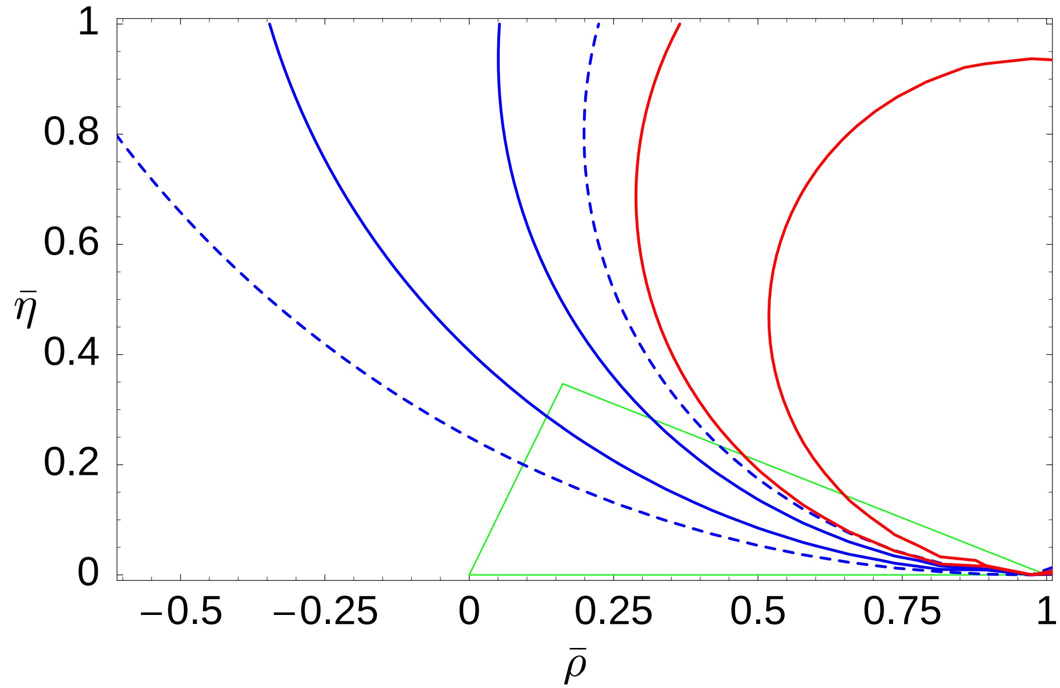
where β and R_t are one angle and one side of the unitarity triangle.
For the Standard Model fit to the unitarity triangle with $\beta = 22.4^\circ \pm 1.4^\circ$ and $R_t = 0.91 \pm 0.05$:

$$a_{\rm fs}(B_d) \;=\; -(5.0 \pm 1.1) \cdot 10^{-4}$$

For the B_s system:

$$\begin{aligned} a_{\rm fs}(B_s) \;&=\; (12.0 \pm 2.4) \cdot 10^{-4}\, |V_{us}|^2 R_t \sin\beta \\ &=\; (2.1 \pm 0.4) \cdot 10^{-5} \end{aligned}$$

Constraint on the $(\overline{\rho}, \overline{\eta})$ plane:



Solid curves: NLO

Area between red curves allowed for $a_{\mathrm{fs}} = -10^{-3}$

Area between blue curves allowed for $a_{\mathrm{fs}} = -5 \cdot 10^{-4}$

Area between dashed blue curves: LO range for $a_{\mathrm{fs}} = -5 \cdot 10^{-4}$

As a by-product we obtain the NLO QCD (and $1/m_b$ corrections) to $\Delta\Gamma$:

$$\frac{\Delta\Gamma}{\Delta m} = (4.0 \pm 1.6) \cdot 10^{-3} \qquad \text{for } B_d \text{ and } B_s$$
$$\frac{\Delta\Gamma}{\Gamma}(B_d) = (3.0 \pm 1.2) \cdot 10^{-3}$$

$\Delta\Gamma/\Delta m$ is proportional to the ratio $B_S/B = 1.4 \pm 0.2$ of two hadronic parameters which must be determined from lattice perturbation theory.

For $\Delta\Gamma/\Gamma$ in the B_s system NLO QCD corrections are known since 1998.

Beneke,Buchalla,Greub,Lenz,UN,hep-ph/9808385

Summary

Complete NLO QCD corrections are now known for the CP asymmetry in flavour-specific B decays and the width difference in $B\!-\!\overline{B}$ mixing.

In the Standard Model:

$$\begin{aligned} a_{\rm fs}(B_d) &= -(5.0 \pm 1.1) \cdot 10^{-4} \\ a_{\rm fs}(B_s) &= (2.1 \pm 0.4) \cdot 10^{-5} \\ \frac{\Delta\Gamma}{\Delta m} &= (4.0 \pm 1.6) \cdot 10^{-3} \qquad \text{for } B_d \text{ and } B_s \\ \frac{\Delta\Gamma}{\Gamma}(B_d) &= (3.0 \pm 1.2) \cdot 10^{-3} \end{aligned}$$

$a_{\rm fs}$ can be obtained from the decay distribution of any untagged decay $B \to f$ for which λ_f is known.