Effect of $\Delta\Gamma$ on the dimuon asymmetry in B decays

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Dimuon asymmetry

DØ has measured the CP-violating quantity

$$A_S = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

with N^{++} and N^{--} the number of (μ^+, μ^+) and (μ^-, μ^-) pairs, respectively, resulting from $(b, \bar{b})$ pairs produced in $p\bar{p}$ collisions.

Non-zero A_S requires that at least one of the $(b, \bar{b})$ quarks hadronises into a $B_{d,s}$ which oscillates into $\bar{B}_{d,s}$. The neutral-B sample consists of 58% B_d and 42% B_s mesons.

If all observed $\mu^\pm$ are from $b, \overline{b}$ decays, A_S is related to the *CP asymmetries in flavour-specific decays* $a_{\rm fs}^{d,s}$ (a.k.a as *semileptonic CP asymmetries*) as

$$A_S = 0.58 a_{\rm fs}^d + 0.42 a_{\rm fs}^s .$$

SM prediction: $A_S^{\rm SM} = -(2.0 \pm 0.3) \cdot 10^{-4}$

A. Lenz, UN, CKM2010, arXiv:1102.4272

DØ finds $A_S < A_S^{\rm SM}$. Deviations from SM prediction:

year	Ref.	deviation
2010	PRL 105, 081801 (2010)	3.2σ
2011	PRD 84, 052007 (2011)	3.9σ
2013	PRD 89, 012002 (2014)	3.6σ (*)

In (*) mixing-induced CP violation in $b \to c\bar{c}d$ is included.

$\longrightarrow$ topic of this talk

Discovery of Guennadi Borissov and Bruce Hoeneisen

(Phys.Rev. D87, 074020 (2013)):

$$\begin{array}{c} \bar{p}\ p \\ \downarrow \\ \mu^+ X \leftarrow \bar{b}\ b \rightarrow \bar{B}_d \xrightarrow{\text{mixes}} \frac{p}{q} g_-(t) B_d + g_+(t) \bar{B}_d \rightarrow D^+ D^- \\ \hookrightarrow \mu^+ X \end{array}$$

CP violation in the interference of B_d–$\bar{B}_d$ mixing and $\overset{(-)}{B}_d \rightarrow D^+ D^-$ creates and asymmetry w.r.t.

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This CP asymmetry is proportional to $\sin(2\beta)$, with 2β being the phase of the B_d–$\bar{B}_d$ mixing amplitude M_{12} (in the standard phase convention in which the $b \rightarrow c\bar{c}d$ decay amplitude is (essentially) real).

These $b \to c\bar{c}d$ decays create a contribution $A_S^{\rm int}$ to A_S.
CP-even and CP-odd final state contribute with opposite sign, but:

$$\Gamma(B_{\rm CP+} \to X_{c\bar{c}}) - \Gamma(B_{\rm CP-} \to X_{c\bar{c}}) \simeq \Delta\Gamma$$

Dunietz,Fleischer,UN 2001; Beneke,Buchalla,Lenz,UN 2003

so that

$$A_S^{\rm int} = -\, P_{c\to\mu}\, \frac{\Delta\Gamma}{\Gamma}\, \sin(2\beta) \frac{x_d}{1+x_d^2}$$

probability for $c \to \mu$ ↗ — CP phase ↑ — dilution from time integration. ↖

Here $x_d = \Delta m/\Gamma$ and Γ is the total B_d width.

Jarlskog criterion

Within the SM CP violation requires

$$(m_u - m_c)(m_c - m_t)(m_u - m_t)\times$$

$$(m_d - m_s)(m_s - m_b)(m_d - m_b)\,\mathrm{Im}\,(V_{11} V_{21}^* V_{22} V_{12}^*) \neq 0$$

$\Rightarrow$ CP asymmetries vanish for $m_c = m_u$.

Mass matrix M, decay matrix Γ:

$$a_{\mathrm{fs}}^{d} = \operatorname{Im}\frac{\Gamma_{12}}{M_{12}} \propto \frac{m_c^2 - m_u^2}{m_b^2}$$

vanishes for $m_c = m_u$, while

$$\Delta\Gamma = -\Delta m \operatorname{Re}\frac{\Gamma_{12}}{M_{12}}$$

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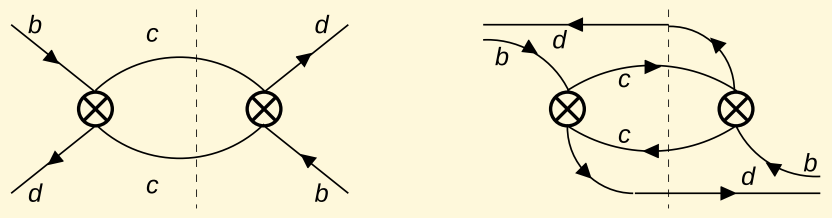
$\Rightarrow$ There should be a contribution with up quarks which contributes to $A_S^{\rm int}$ with opposite sign.

$$\Gamma_{12} = -\left[\lambda_c^2\,\Gamma_{12}^{cc} + 2\,\lambda_c\,\lambda_u\,\Gamma_{12}^{uc} + \lambda_u^2\,\Gamma_{12}^{uu}\right]$$

with $\lambda_c = V_{cd}^* V_{cb}$, $\lambda_u = V_{ud}^* V_{ub}$, and $\lambda_t = -\lambda_c - \lambda_u = V_{td}^* V_{tb}$.

In the SM the charm-charm contribution dominates

$$\Delta\Gamma = -\Delta m\,\mathrm{Re}\,\frac{\Gamma_{12}}{M_{12}} \approx 2|\lambda_c|^2\Gamma_{12}^{cc}$$



$$
\begin{aligned}
|B(t)\rangle &= \quad g_+(t)\,|B\rangle + \frac{q}{p}\,g_-(t)\,|\bar{B}\rangle\,, \\
|\bar{B}(t)\rangle &= \frac{p}{q}\,g_-(t)\,|B\rangle + \quad g_+(t)\,|\bar{B}\rangle.
\end{aligned}
$$

Time-dependent decay rate $\Gamma[B(t) \to f] = N_f |\langle f|B(t)\rangle|^2$ with phase-space factor N_f.

Interference term in $\Gamma[B(t) \to X_{c\bar{c}}]$:

$$
B_{cc}(t) = 2\,\mathrm{Re}\,\left[g_+^*(t)\frac{q}{p}g_-(t) \underbrace{\sum_{f \in X_{c\bar{c}}} N_f \langle B|f\rangle\langle f|\bar{B}\rangle}_{-\lambda_c^2 \Gamma_{12}^{cc}} \right]
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$$
B_{cc}(t) = \Gamma_{12}^{cc} e^{-\Gamma t} \sin(\Delta m t)\,\mathrm{Im}\left(\frac{q}{p}\lambda_c^2\right) = \Gamma_{12}^{cc} |\lambda_c|^2 e^{-\Gamma t} \sin(\Delta m t) \sin(2\beta)
$$

The interference term in $\Gamma[\overline{B}(t) \to X_{c\bar{c}}]$ has the opposite sign. Thus the charm-charm contribution to A_S^{int} is

$$A_S^{\mathrm{int},c\bar{c}} = -P_{c\to\mu} \int_0^\infty dt\, 2B_{cc}(t) = -P_{c\to\mu} \frac{2\Gamma_{12}^{cc}}{\Gamma} |\lambda_c|^2 \sin(2\beta) \frac{x_d}{1+x_d^2}$$

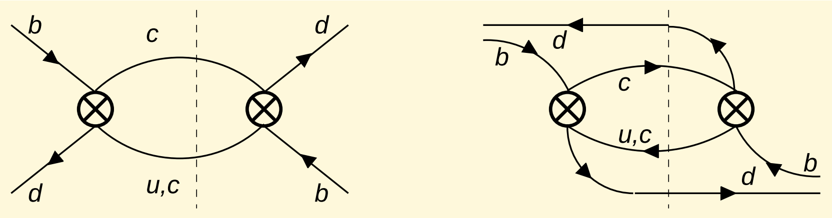
Add missing up contribution from up quark, taking $m_c = m_u$ here, so that $\Gamma_{12}^{cu} = \Gamma_{12}^{cc}$:

To find $A_S^{\mathrm{int},c\bar{c}} + A_S^{\mathrm{int},c\bar{u}}$ from $A_S^{\mathrm{int},c\bar{c}}$ simply replace

$$\mathrm{Im}\left(\frac{q}{p}\lambda_c^2\right) \to \mathrm{Im}\left(\frac{q}{p}\lambda_c(\lambda_c + \lambda_u)\right) = -\mathrm{Im}\left(\frac{q}{p}\lambda_c\lambda_t\right)$$

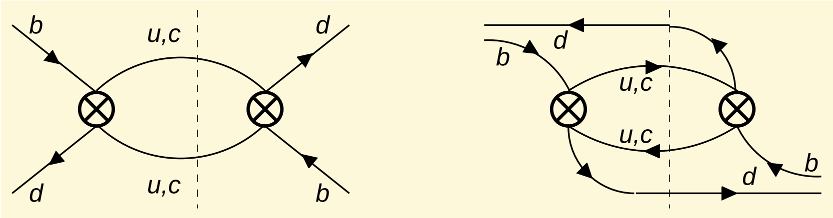
amounting to

$|\lambda_c|^2 \sin(2\beta) \to |\lambda_c\lambda_t| \sin\beta,$ smaller by factor of 0.49!



To comply with the Jarlskog criterion we also need to add $A_S^{\mathrm{int},u\bar{c}} + A_S^{\mathrm{int},u\bar{u}}$.
However, in our real world with $m_c \neq m_u$ the probabilities $P_{u\to\mu}$ and $P_{c\to\mu}$ are very different. μ's from the decay chain $b \to u \to \mu$ require that e.g. a K^+ or π^+ decays (semi-) muonically before reaching the detector.
In the considered limit $m_c = m_u$:

$$A_S^{\mathrm{int}} = -(P_{c\to\mu} - P_{u\to\mu})\,\frac{2\Gamma_{12}^{cc}}{\Gamma}\,|\lambda_c\lambda_t|\sin(\beta)\frac{x_d}{1+x_d^2}$$



Thus the estimate in Phys.Rev. D87, 074020 (2013)

$$A_S^{\rm int} = -(4.5 \pm 1.6)10^{-4}$$

gets reduced to

$$A_S^{\rm int} > -(2.2 \pm 0.8)10^{-4}$$

and the discrepancy between the DØ dimuon asymmetry and the SM prediction is actually *larger* than the 3.6σ quoted in Phys. Rev. D 89, 012002 (2014).

Important lesson: A_S^{int} depends on the individual components Γ_{12}^{cc}, Γ_{12}^{cu}, Γ_{12}^{uc}, and Γ_{12}^{uu} in a different way than a_{fs}^{d} and $\Delta\Gamma$!

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Thus the sensitivity to new physics is also different.

Important lesson: $A_S^{\rm int}$ depends on the individual components Γ_{12}^{cc}, Γ_{12}^{cu}, Γ_{12}^{uc}, and Γ_{12}^{uu} in a different way than $a_{\rm fs}^d$ and $\Delta\Gamma$!

Thus the sensitivity to new physics is also different. Consider a new contribution of the type

$$\text{real coefficient } \times \lambda_t \times \overline{d}b(\overline{u}u + \overline{c}c + \ldots),$$

i.e. new physics coming with a gluon/photon/Z penguin operator: The interference term with the SM tree amplitude amounts to (for $m_c = m_u$)

$$\delta a_{\rm fs}^d \propto \text{Im}\,\frac{\lambda_t(\lambda_u + \lambda_c)}{\lambda_t^2} = -\text{Im}\,\frac{\lambda_t^2}{\lambda_t^2} = 0$$

while

$$\delta A_s^{\rm int} \propto \text{Im}\,\frac{\lambda_t(P_{u\to\mu}\lambda_u + P_{c\to\mu}\lambda_c)}{\lambda_t^2} \neq 0.$$

Also $\Delta\Gamma$ will change from its SM value.

Conclusions

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- $$A_S^{\rm int} = -(P_{c\to\mu} - P_{u\to\mu}) \frac{|\Delta\Gamma|}{\Gamma} \frac{|\lambda_t|}{|\lambda_c|} \sin(\beta) \frac{x_d}{1 + x_d^2}$$

  is smaller in magnitude by at least a factor of 0.49 compared to the formulae used in the DØ analysis, so that the discrepancy with the SM is larger than the quoted 3.6σ.

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- $A_S^{\rm int}$ depends differently on new physics than $a_{\rm fs}^d$.