Testing the SM with $B \to DD$ decays

Stefan Schacht

Karlsruhe Institute of Technology

CKM 2014

Vienna, 11/09/2014

based on work with M. Jung

Can we distinguish new physics in $B \to DD$ decays from the Standard Model?

Data from LHCb, Belle, BaBar, CDF, ...

Mode	$BR_{\text{theo}}/10^{-3}$	$A_{CP}/\%$	$S_{CP}/\%$
$B^- \to D^- D^0$	0.37 ± 0.04	3 ± 7	—
$B^- \to D_s^- D^0$	9.4 ± 0.9		—
$\bar{B}^0 \to D_s^- D^+$	7.6 ± 0.7	-1 ± 2	—
$\bar{B}_s \to D^- D_s^+$	0.30 ± 0.04		—
$\bar{B}^0 \to D^- D^+$	0.226 ± 0.023	(a) 31 ± 14	-98 ± 17
	BaBar :	(b) 7 ± 23	-63 ± 36
	Belle :	43 ± 17	-106^{+22}_{-16}
$\bar{B}_s \to D_s^- D_s^+$	4.6 ± 0.5		
$\bar{B}^0 \to D_s^- D_s^+$	≤ 0.036		
$\bar{B}_s \to D^- D^+$	0.27 ± 0.05		
$\bar{B}^0 \to \bar{D}^0 D^0$	0.013 ± 0.006		
$\bar{B}_s \to \bar{D}^0 D^0$	0.19 ± 0.04		

Red: First observation in 2013.

Symmetry analysis ⇒ Data-driven approach: Fit $SU(3)_F$ matrix elements to the data

States

- $\left(B^- = -\,|\bar{u}b\rangle\,, \bar{B}^0 = \left|\bar{d}b\right\rangle, \bar{B}_s = |\bar{s}b\rangle\right) = \bar{\mathbf{3}}$
- $\left(D^0 = -\,|c\bar{u}\rangle\,, D^+ = \left|c\bar{d}\right\rangle, D_s^+ = |c\bar{s}\rangle\right) = \bar{\mathbf{3}}$
- $\left(\bar{D}^0 = |\bar{c}u\rangle\,, \left|D^-\right\rangle = |\bar{c}d\rangle\,, \left|D_s^-\right\rangle = |\bar{c}s\rangle\right) = \mathbf{3}$

Product final states: $\mathbf{1}$ and $\mathbf{8}$.

Operators: $\Delta B = 1$, $\Delta C = 0$ Hamiltonian

[Zeppenfeld 1980]

- $\mathcal{H} \supsetsim V_{ub}V_{ud}^*(b\bar{u})(u\bar{d}) + V_{ub}V_{us}^*(b\bar{u})(u\bar{s}) + V_{cb}V_{cd}^*(b\bar{c})(c\bar{d}) + V_{cb}V_{cs}^*(b\bar{c})(c\bar{s})$
- $(b\bar{u})(u\bar{s}) \sim \mathbf{3} + \bar{\mathbf{6}} + \mathbf{15}$
- $(b\bar{c})(c\bar{s}) = \mathbf{3}$

Translation to Topological Amplitudes: Power Counting

- Match $SU(3)_F$ expressions ⇒ Equivalent topologic decomposition.

[Zeppenfeld 1981, Savage Wise 1989, Gronau Hernandez London Rosner 1994, Buras Silvestrini 1998, . . .]

- Enables power counting: Suppression of penguin and annihilation diagrams, $1/N_c$-counting and CKM structure.
- Alternative counting: No additional suppression of penguins.

- Neglect SU(3)-Xing corrections of penguins due to lack of sensitivity.

Mode	$\lambda_{cD}T$	$\lambda_{cD}A^c$	$\lambda_{uD}\tilde{P}_1$	$\lambda_{uD}\tilde{P}_3$	$\lambda_{uD}A_1^u$	$\lambda_{uD}A_2^u$
Counting	1	δ^2	$\delta^{3(5)}$ $\delta^{2(4)}$	$\delta^{4(6)}$ $\delta^{3(5)}$	$\delta^{3(5)}$	$\delta^{4(6)}$
$B^- \to D^- D^0$	1	0	-1	0	1	0
$B^- \to D_s^- D^0$	1	0	-1	0	1	0
$\bar{B}^0 \to D_s^- D^+$	1	0	-1	0	0	0
$\bar{B}_s \to D^- D_s^+$	1	0	-1	0	0	0
$\bar{B}^0 \to D^- D^+$	1	1	-1	-1	0	0
$\bar{B}^0 \to D_s^- D_s^+$	0	1	0	-1	0	0

Approximate Isospin Amplitude Sum Rules

Valid also for enhanced penguins, including SU(3)-Xing

For $b \to s$ decays: Test for $\Delta I = 1$ NP

[Gronau Hernandez London Rosner 1995, Jung Schacht 2014]

1. $\mathcal{A}\left(\bar{B}^0 \to D_s^- D^+\right) \simeq \mathcal{A}\left(B^- \to D_s^- D^0\right)$
2. $\mathcal{A}\left(\bar{B}_s \to D^- D^+\right) \simeq -\mathcal{A}\left(\bar{B}_s \to \bar{D}^0 D^0\right)$

- No SU(3)-Xing corrections.
- No penguin corrections.
- Corrections from annihilation $\sim \delta^{5(6)}$ and electroweak penguins only.

For $b \to d$ decays: Test for $\Delta I = 3/2$ NP

[Gronau Rosner Pirjol 2008, Sanda Xing 1997]

3. $\mathcal{A}(\bar{B}^0 \to D^- D^+) + \mathcal{A}(\bar{B}^0 \to \bar{D}^0 D^0) \simeq \mathcal{A}(B^- \to D^- D^0)$

- Annihilation $\sim \delta^3$ and electroweak penguin corrections only.

Approximate Isospin Rate Sum Rules

Valid also for enhanced penguins, including SU(3)-Xing

CP-averaged decay rate

$$\Gamma_D = \frac{\Gamma(\mathcal{D}) + \Gamma(\bar{\mathcal{D}})}{2} \qquad \Delta\Gamma_D = \frac{\Gamma(\mathcal{D}) - \Gamma(\bar{\mathcal{D}})}{2}$$

Precision relations

[Gronau Hernandez London Rosner 1995, Jung Schacht 2014]

1. $\Gamma(\bar{B}^0 \to D_s^- D^+) = \Gamma(B^- \to D_s^- D^0)\left(1 + \mathcal{O}(\delta^5)\right)$
2. $\Gamma(\bar{B}_s \to \bar{D}^0 D^0) = \Gamma(\bar{B}_s \to D^- D^+)\left(1 + \mathcal{O}(\delta^4)\right)$

3. $\Gamma(\bar{B}^0 \to D^- D^+) = \Gamma(B^- \to D^- D^0)\left(1 + \mathcal{O}(\delta^2)\right)$

➥ Model-independent test for isospin-breaking New Physics

Further Approximate Sum Rules

Valid also for enhanced penguins, including SU(3)-Xing

Up to $\mathcal{O}(\delta^3)$ or better

$$\mathcal{A}(\bar{B}^0 \to D_s^- D^+) - \mathcal{A}(\bar{B}_s \to D_s^- D_s^+) + \mathcal{A}(\bar{B}_s \to D^- D^+) =$$
$$\frac{\lambda_{cs}}{\lambda_{cd}} \left(\mathcal{A}(\bar{B}^0 \to D^- D^+) - \mathcal{A}(\bar{B}_s \to D^- D_s^+) - \mathcal{A}(\bar{B}^0 \to D_s^- D_s^+)\right) .$$

$$\mathcal{A}(\bar{B}^0 \to D_s^- D_s^+) = -\mathcal{A}(\bar{B}^0 \to D^0 \bar{D}^0)$$
$$\mathcal{A}(\bar{B}_s \to D^- D^+) = \frac{\lambda_{cs}}{2\lambda_{cd}} (\mathcal{A}(\bar{B}^0 \to D_s^- D_s^+) - \mathcal{A}(\bar{B}^0 \to D^0 \bar{D}^0))$$

➥Further general rules, but valid to less precision than isospin rules.

Expectations for CP Asymmetries

Without penguin enhancement

Tree-dominated $b \to s$ modes: $\mathcal{O}(\delta^5)$, *i.e.*, $\lesssim 1\%$

$B^- \to D_s^- D^0, \quad \bar{B}^0 \to D_s^- D^+, \quad \bar{B}_s \to D_s^- D_s^+$

Annnihilation-dominated $b \to s$ modes: $\mathcal{O}(\delta^4)$, *i.e.*, $\lesssim 3\%$

$\bar{B}_s \to D^- D^+, \quad \bar{B}_s \to \bar{D}^0 D^0$

Tree-dominated $b \to d$ modes: $\mathcal{O}(\delta^3)$, *i.e.*, $\lesssim 10\%$

$B^- \to D^- D^0, \quad \bar{B}_s \to D^- D_s^+, \quad \bar{B}^0 \to D^- D^+$

Annnihilation-dominated $b \to d$ modes: $\mathcal{O}(\delta^2)$, *i.e.*, $\lesssim 30\%$

$\bar{B}^0 \to D_s^- D_s^+, \quad \bar{B}^0 \to \bar{D}^0 D^0$

Assume a future enhanced CP asymmetry. . .

. . . then if due to penguins, sum rules between CP asymmetries should hold.

Up to $\mathcal{O}(\delta)$

$$
\begin{aligned}
A_{\rm CP}(\bar{B}^0 \to D_s^- D^+) &= A_{\rm CP}(B^- \to D_s^- D^0)\,[1 + \mathcal{O}(\delta)] \\
A_{\rm CP}(\bar{B}_s \to \bar{D}^0 D^0) &= A_{\rm CP}(\bar{B}_s \to D^- D^+)\,[1 + \mathcal{O}(\delta)]
\end{aligned}
$$

$$
\Delta\Gamma(\bar{B}_s \to D^- D_s^+) + \Delta\Gamma(\bar{B}_s \to D_s^- D_s^+) + \Delta\Gamma(\bar{B}^0 \to D^- D^+) = \\
\Big(2\Delta\Gamma(B^- \to D^- D^0) + \Delta\Gamma(B^- \to D_s^- D^0)\Big)\,[1 + \mathcal{O}(\delta)]
$$

➥ Crosscheck of power counting in case of enhanced penguins.

Experimental status of Isospin Sum Rules

1st Rule: 2σ Tension

$$\Gamma(\bar{B}^0 \to D_s^- D^+) = \Gamma(B^- \to D_s^- D^0)\left(1 + \mathcal{O}(\delta^5)\right)$$

Theory: $BR(B^- \to D_s^- D^0)/BR(\bar{B}^0 \to D_s^- D^+) \sim 1.08$ (including $\tau_{B^-,\bar{B}^0}$)

Experiment: $BR(B^- \to D_s^- D^0)/BR(\bar{B}^0 \to D_s^- D^+) = 1.22 \pm 0.07$ [LHCb 2013]

2nd rule: SM prediction

$$\begin{aligned} BR(\bar{B}_s \to \bar{D}^0 D^0) &= BR(\bar{B}_s \to D^- D^+) \\ &= (0.21 \pm 0.03) \times 10^{-3} \end{aligned}$$

Data: $BR(\bar{B}_s \to \bar{D}^0 D^0) = (0.19 \pm 0.04) \times 10^{-3}$

$BR(\bar{B}_s \to D^- D^+) = (0.27 \pm 0.05)$

Global Fit

➥Control Penguins and SU(3)-Xing at the same time !

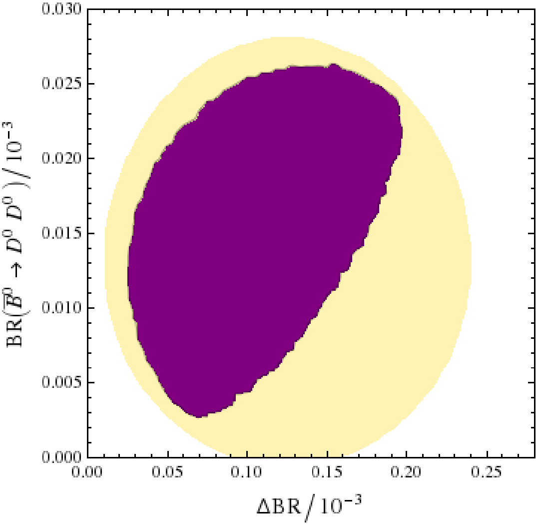
- Power counting works quite well.
- $\Gamma(\bar{B}^0 \to D^- D^+) = \Gamma(B^- \to D^- D^0)$ holds only marginally.
  ➥Sizable annihilation, $|A^c|/T \in [0.1, 0.27]$ (95%). [agreeing with Eeg Fajfer Hiorth 2003]
- Small to moderate $(10 - 30\%)$ SU(3) breaking sufficient.
- Current data: No competitive extraction of $\phi_{d,s}$ possible.
- Two data sets.

Mode	$BR_{\text{theo}}/10^{-3}$	$A_{\text{CP}}/\%$	$S_{\text{CP}}/\%$
$\bar{B}^0 \to D^- D^+$	$0.226 \pm 0.023^{\S}$	**(a)** 31 ± 14 (HFAG)	-98 ± 17 (HFAG)
	BaBar :	**(b)** 7 ± 23	-63 ± 36
	Belle :	43 ± 17	-106^{+22}_{-16}

Correlations of Branching Ratios

- 3rd Isospin rule: $\mathcal{A}(\bar{B}^0 \to D^- D^+) + \mathcal{A}(\bar{B}^0 \to \bar{D}^0 D^0) \simeq \mathcal{A}(B^- \to D^- D^0)$.
- $\Delta BR \equiv BR(B^- \to D^0 D^-) - r_{\tau,\mathrm{PS}} BR(\bar{B}^0 \to D^- D^+)$.
- SU(3)-limit: $BR(\bar{B}^0 \to \bar{D}^0 D^0) = (1.19 \pm 0.16) \times 10^{-5}$.
- Contours: 95% C.L.

[Jung Schacht 2014]



Yellow: Data. Violet: Scenario and data set independent fit result.

CP Violation

Time dependent CP Violation

$$a_{\mathrm{CP}}(\mathcal{D};t) \equiv \frac{\Gamma(\mathcal{D};t) - \Gamma(\bar{\mathcal{D}};t)}{\Gamma(\mathcal{D};t) + \Gamma(\bar{\mathcal{D}};t)} = \frac{S_{\mathrm{CP}}(\mathcal{D})\sin(\Delta m t) + A_{\mathrm{CP}}(\mathcal{D})\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) - A_{\Delta\Gamma}(\mathcal{D})\sinh(\Delta\Gamma t/2)}$$

Penguin pollution

[Fleischer 1999, 2007, Ciuchini Pierini Silvestrini 2005, Faller Jung Fleischer Mannel 2008, ...]

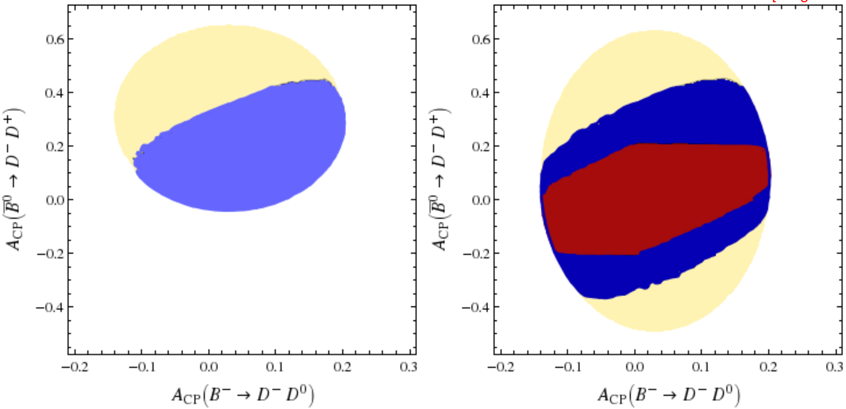
$$\Delta S_{\mathrm{CP}}(\mathcal{D}) \equiv -\eta^{f}_{\mathrm{CP}} S_{\mathrm{CP}}(\mathcal{D}) - \sin\phi(\mathcal{D}), \qquad \phi(\mathcal{D}) = \phi_d(\phi_s)$$

➥ How large can the penguin shift become?

Study possible penguin enhancement in CPV observables.
CP Violation beyond that ⇒ NP.

Disentangling the two data sets

[Jung Schacht 2014]



Yellow: (a) HFAG input

Yellow: (b) BaBar input

Red: Standard counting. Blue: Enhanced penguins.

Outside of blue (red): NP.

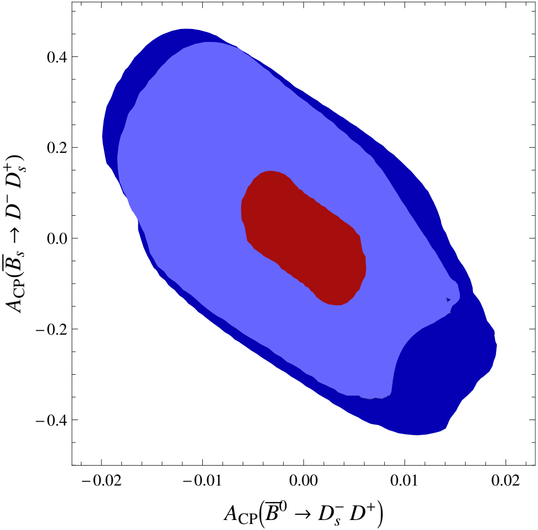
↳Largish Belle CPV measurement difficult for standard counting.

SM Prediction for Flavor-Specific CP Asymmetries

How much can the penguins pollute NP tests?

- Red: Standard counting.
- Blue: Enhanced penguins.
- Light: HFAG input.
- Dark: BaBar input.
- Outside of blue (red): NP.

[Jung Schacht 2014]

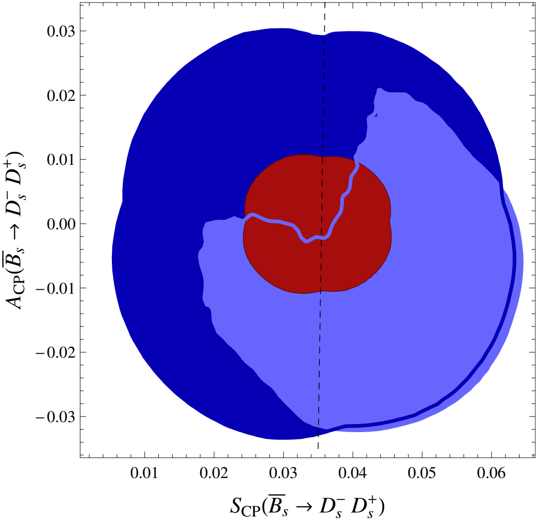


SM Prediction for Time-dependent CP Asymmetries

Measurement at 17:05 CEST [Talk by C. Fitzpatrick, LHCb]

How much can the penguins pollute NP tests?

- ϕ_s fixed to SM value.
- Line: $S_{CP} = \sin\phi_s$.
- Red: Standard counting.
- Blue: Enhanced penguins.
- Light: HFAG input.
- Dark: BaBar input.
- Outside of blue (red): NP.



Conclusion

- Very exciting time for decays of beauty to charm !
- Isospin sum rules enable precision tests of the SM, already with branching ratios.
  ➥Currently, 2σ tension in $BR(B^- \to D_s^- D^0)/BR(\bar{B}^0 \to D_s^- D^+)$.
- Penguin pollution and SU(3)$_F$ breaking controlled in a global fit.
  ➥Predictions of CP asymmetries.
- Much room for NP to be tested @LHC and Belle II !