Anatomy of $B \to D\bar{D}$ Decays

Based on: L. Bel, K. De Bruyn, R. Fleischer, M. Mulder and N. Tuning, *Anatomy of $B \to D\bar{D}$ Decays*, to appear in JHEP, arXiv:1505.01361

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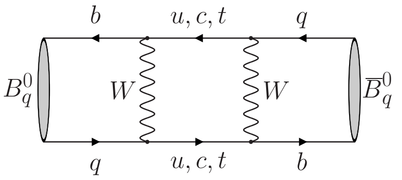
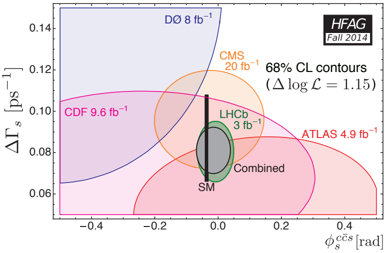
B2OC Time-Dependent Workshop – Padova
July 9th, 2015

New Physics Searches with ϕ_d and ϕ_s



- The *CP* phases $\phi_d = 2\beta + \phi_d^{\mathrm{NP}}$ and $\phi_s = -2\beta_s + \phi_s^{\mathrm{NP}}$ are sensitive probes for NP
- Predominantly studied with $B_d^0 \to J/\psi\, K_{\mathrm{S}}^0$ and $B_s^0 \to J/\psi\, \phi$

- Current Status: Possible NP effects are small
- Broaden our search area: $B \to D\overline{D}$
- Provides complementary information
- Important to explore in detail



HFAG, arXiv:1412.7515

The $B \to D\bar{D}$ Decays

Experimental Status:

- $B_d^0 \to D_d^- D_d^+$

BaBar, Phys.Rev.D79 (2009) 032002, arXiv:0808.1866
Belle, Phys.Rev.D85 (2012) 091106, arXiv:1203.6647

$$\mathcal{A}_{CP}^{\rm dir}(B_d \to D_d^- D_d^+) = \begin{cases} -0.07 \pm 0.23 \pm 0.03 & \text{(BaBar)} \\ -0.43 \pm 0.16 \pm 0.05 & \text{(Belle)} \end{cases} \tag{1}$$

$$\mathcal{A}_{CP}^{\rm mix}(B_d \to D_d^- D_d^+) = \begin{cases} +0.63 \pm 0.36 \pm 0.05 & \text{(BaBar)} \\ +1.06^{+0.14}_{-0.21} \pm 0.08 & \text{(Belle)} \end{cases} \tag{2}$$

- $\Rightarrow$ Access to ϕ_d

- $B_s^0 \to D_s^- D_s^+$

LHCb-PAPER-2014-051

$$\phi^{\rm eff}_{s,D_s^- D_s^+} = (1.1 \pm 9.7 \pm 1.1)^\circ \ , \qquad \left|\lambda_{D_s^- D_s^+}\right| = 0.91 \pm 0.18 \pm 0.02 \tag{3}$$

- $\Rightarrow$ Access to ϕ_s

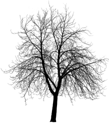
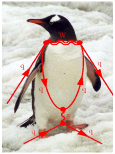
The $B \to D\bar{D}$ Decays

Decay Topologies:

- Need to be careful when relating these inputs with ϕ_d and ϕ_s
- We have additional decay topologies to worry about

Robert Fleischer, Eur.Phys.J.C10 (1999) 299, arXiv:hep-ph/9903455

Robert Fleischer, Eur.Phys.J.C51 (2007) 849, arXiv:0705.4421

$|A(B \to D\bar{D})|^2 = \Big|$  $+$  $+ \ \ldots \Big|^2$

- Deal with different decay dynamics (compared to $B \to J/\psi X$ modes)
- Constraining the effects from additional decay topologies requires complex study of many $B \to D\bar{D}$ decays.

Comparison with $B \to J/\psi X$

- Strategy is similar to the analysis of the $B \to J/\psi X$
- ... but different decay dynamics require separate treatement

Strategies for $B_d^0 \to J/\psi K_S^0$:

1. $B_s^0 \to \psi K_S^0$: Robert Fleischer, Eur.Phys.J.C10 (1999) 299, arXiv:hep-ph/9903455
   - Only possible for the LHCb Upgrade
2. $B_d^0 \to J/\psi \pi^0$: Sven Faller *et al*, Phys.Rev.D79 (2009) 014030, arXiv:0809.0842
3. Global fit to $B_d^0 \to J/\psi K_S^0$, $B^+ \to J/\psi K^+$, $B^+ \to J/\psi \pi^+$ and $B_d^0 \to J/\psi \pi^0$
   - $\Delta\phi_d^{J/\psi K_S^0} = -\left(1.03^{+0.69}_{-0.85}(\text{stat})\right)^\circ$

   Kristof De Bruyn & Robert Fleischer, JHEP 1503 (2015) 145, arXiv:1412.6834

Strategies for $B_s^0 \to J/\psi \phi$:

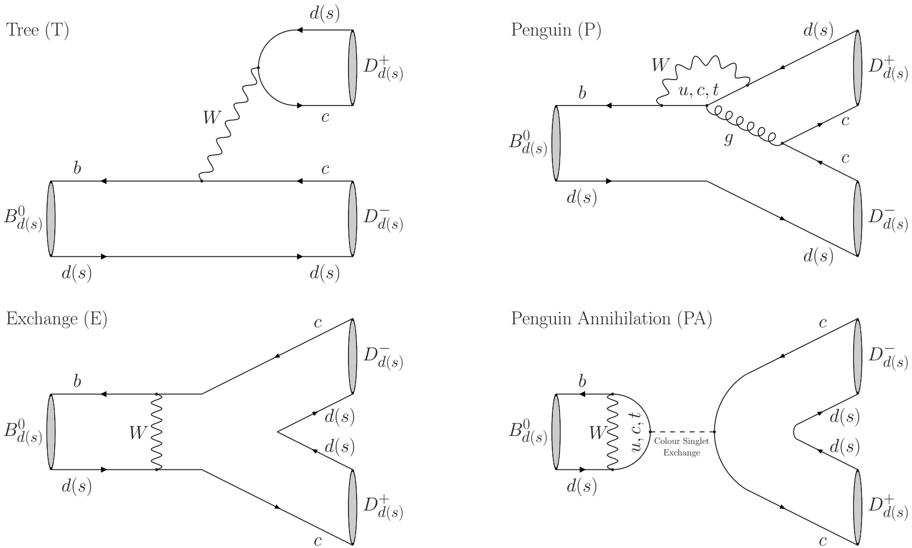
1. $B_d^0 \to J/\psi \rho^0$: Robert Fleischer, Phys.Rev.D60 (1999) 073008, arXiv:hep-ph/9903540
   - $\Delta\phi_s^{J/\psi \phi} = \left(0.12^{+0.56}_{-0.71}(\text{stat})^{+0.16}_{-0.13}(SU(3))\right)^\circ$ LHCb-PAPER-2014-058
2. $B_s^0 \to J/\psi \overline{K}^{*0}$: Robert Fleischer, Phys.Rev.D79 (2009) 014005, arXiv:0810.4248
   - Results expected for EPS LHCb-PAPER-2015-034
3. Combined fit of $B_d^0 \to J/\psi \rho^0$ and $B_s^0 \to J/\psi \overline{K}^{*0}$:
   - Results expected for EPS LHCb-PAPER-2015-034

Quick Overview

- Introduce the formalism & key observables
- Discuss hadronic physics
- Discuss the situation arising from the current data
- Discuss possible future scenarios
- Give my wishlist

Formalism & Key Observables

Decay Topologies



Decay Amplitudes for $B_d^0 \to D_d^- D_d^+$ and $B_s^0 \to D_s^- D_s^+$

General Structure:

$$A(B_d^0 \to D_d^- D_d^+) = -\lambda\mathcal{A}\left[1 - ae^{i\theta}e^{+i\gamma}\right] \quad (4)$$

$$A(B_s^0 \to D_s^- D_s^+) = \left(1 - \frac{\lambda^2}{2}\right)\mathcal{A}'\left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right] \quad (5)$$

- $\boldsymbol{\lambda}$ $= V_{us} = 0.22548$ is a CKM factor,
- $\epsilon = \lambda^2/(1-\lambda^2) = 0.0536 \pm 0.0003$,
- $\boldsymbol{\mathcal{A}}$ represents (mainly) the tree topology,
- $\boldsymbol{a}$ the relative contribution from all other decay topologies,
- $\boldsymbol{\theta}$ the associated strong phase difference,
- $\boldsymbol{\gamma}$ the relative weak phase difference,

Decay Amplitudes for $B_d^0 \to D_d^- D_d^+$ and $B_s^0 \to D_s^- D_s^+$

Details:

- $\boldsymbol{\mathcal{A}}$ is a decay amplitude

$$\mathcal{A} \equiv \lambda^2 A \left[T + E + \left\{ P^{(c)} + PA^{(c)} \right\} - \left\{ P^{(t)} + PA^{(t)} \right\} \right] \tag{6}$$

- $\mathcal{A}$ is dominated by T
- . . . but also includes corrections from E, P and PA that have the same phase

- $\boldsymbol{ae^{i\theta}}$ is a ratio of decay amplitudes

$$ae^{i\theta} \equiv R_b \left[\frac{\left\{ P^{(u)} + PA^{(u)} \right\} - \left\{ P^{(t)} + PA^{(t)} \right\}}{T + E + \{P^{(c)} + PA^{(c)}\} - \{P^{(t)} + PA^{(t)}\}} \right] \tag{7}$$

- where

$$R_b \equiv \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| = 0.390 \pm 0.031 \tag{8}$$

- Expect $a \le R_b$: Tree dominates the penguin contributions.

Effective Mixing Phases

Penguin Shifts:

- Effective mixing phases

$$\frac{\mathcal{A}_{CP}^{\text{mix}}}{\sqrt{1-\left(\mathcal{A}_{CP}^{\text{dir}}\right)^2}} \equiv \sin\phi_q^{\text{eff}}\,, \qquad \phi_q^{\text{eff}} \equiv \underbrace{\phi_q}_{\text{POI}} + \underbrace{\Delta\phi_q(a^{(\prime)},\theta^{(\prime)})}_{\text{due to penguins}} \tag{9}$$

- where

$$\tan\Delta\phi_d^{D_d^- D_d^+} = \frac{-2a\cos\theta\sin\gamma + a^2\sin 2\gamma}{1-2a\cos\theta\cos\gamma + a^2\cos 2\gamma} \tag{10}$$

$$\tan\Delta\phi_s^{D_s^- D_s^+} = \frac{2\epsilon a'\cos\theta'\sin\gamma + \epsilon^2 a'^2\sin 2\gamma}{1+2\epsilon a'\cos\theta'\cos\gamma + \epsilon^2 a'^2\cos 2\gamma} \tag{11}$$

Strategy:

1. Determine $a^{(\prime)}$ and $\theta^{(\prime)}$ from experimental observables
2. Calculate the shift $\Delta\phi$ from $a^{(\prime)}$ and $\theta^{(\prime)}$
3. Determine ϕ_q from $\mathcal{A}_{CP}^{\text{mix}}/\phi_q^{\text{eff}}$

Experimental Observables: *CP* Asymmetries

CP Asymmetry:

$$a_{CP}(t) \equiv \frac{\Gamma(B(t)\to f) - \Gamma(\bar{B}(t)\to f)}{\Gamma(B(t)\to f) + \Gamma(\bar{B}(t)\to f)} = \frac{\mathcal{A}_{CP}^{\rm dir}\cos(\Delta m\, t) + \mathcal{A}_{CP}^{\rm mix}\sin(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)} \quad (12)$$

- where $\Delta m \equiv m_{\rm H} - m_{\rm L}$, $\Delta\Gamma \equiv \Gamma_{\rm L} - \Gamma_{\rm H}$ and

Tree Only:

- Situation for $a = 0$

$$\mathcal{A}_{CP}^{\rm dir}(B_d^0 \to D_d^- D_d^+) = 0 \quad (13)$$

$$\mathcal{A}_{CP}^{\rm mix}(B_d^0 \to D_d^- D_d^+) = \sin\phi_d \quad (14)$$

$$\mathcal{A}_{\Delta\Gamma}(B_d^0 \to D_d^- D_d^+) = -\cos\phi_d \quad (15)$$

- For $B_s^0 \to D_s^- D_s^+$, replace: $\phi_d \to \phi_s$
- Note: This is **not** the HFAG convention

Experimental Observables: *CP* Asymmetries

CP Asymmetry:

$$a_{CP}(t) \equiv \frac{\Gamma(B(t) \to f) - \Gamma(\overline{B}(t) \to f)}{\Gamma(B(t) \to f) + \Gamma(\overline{B}(t) \to f)} = \frac{\mathcal{A}_{CP}^{\rm dir} \cos(\Delta m\, t) + \mathcal{A}_{CP}^{\rm mix} \sin(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)} \tag{16}$$

- where $\Delta m \equiv m_{\rm H} - m_{\rm L}$, $\Delta\Gamma \equiv \Gamma_{\rm L} - \Gamma_{\rm H}$ and

Full Amplitude:

$$\mathcal{A}_{CP}^{\rm dir}(B_d^0 \to D_d^- D_d^+) = \frac{2\, a \sin\theta \sin\gamma}{1 - 2\, a \cos\theta \cos\gamma + a^2} \tag{17}$$

$$\mathcal{A}_{CP}^{\rm mix}(B_d^0 \to D_d^- D_d^+) = \left[\frac{\sin\phi_d - 2\, a \cos\theta \sin(\phi_d + \gamma) + a^2 \sin(\phi_d + 2\gamma)}{1 - 2\, a \cos\theta \cos\gamma + a^2}\right] \tag{18}$$

$$\mathcal{A}_{\Delta\Gamma}(B_d^0 \to D_d^- D_d^+) = -\left[\frac{\cos\phi_d - 2\, a \cos\theta \cos(\phi_d + \gamma) + a^2 \cos(\phi_d + 2\gamma)}{1 - 2\, a \cos\theta \cos\gamma + a^2}\right] \tag{19}$$

- For $B_s^0 \to D_s^- D_s^+$, replace: $\phi_d \to \phi_s$ and $a e^{i\theta} \to -\epsilon a' e^{i\theta'}$
- Note: This is **not** the HFAG convention

Experimental Observables: Branching Ratio Information

- If we want to have an independent measurement of ϕ_d from $B_d^0 \to D_d^- D_d^+$
- and simultaneously determine the penguin parameters a and θ

$\Rightarrow$ We will need yet a third, independent observable

- Use information from the untagged decay rate
- Can be accessed through the $B \to D\bar{D}$ branching ratios

H Observable:

- Definition

$$H \equiv \underbrace{\frac{1}{\epsilon}}_{\text{CKM}} \underbrace{\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2}_{SU(3)} \underbrace{\left[\frac{m_{B_d}}{m_{B_s}} \frac{\Phi(m_{D_s}/m_{B_s}, m_{D_s}/m_{B_s})}{\Phi(m_{D_d}/m_{B_d}, m_{D_d}/m_{B_d})} \frac{\tau_{B_s}}{\tau_{B_d}}\right]}_{\text{Phase-Space Factor}} \frac{\mathcal{B}\left(B_d \to D_d^- D_d^+\right)}{\mathcal{B}\left(B_s \to D_s^- D_s^+\right)_{\text{theo}}} \tag{20}$$

- Main challenge is the determination of $|\mathcal{A}'/\mathcal{A}|$
- Dependence

$$H = \frac{1 - 2\, a \cos\theta \cos\gamma + a^2}{1 + 2\epsilon a' \cos\theta' \cos\gamma + \epsilon^2 a'^2} \tag{21}$$

U-Spin Symmetry

Main Strategy:

- To determine the penguin shift from the experimental data, assume

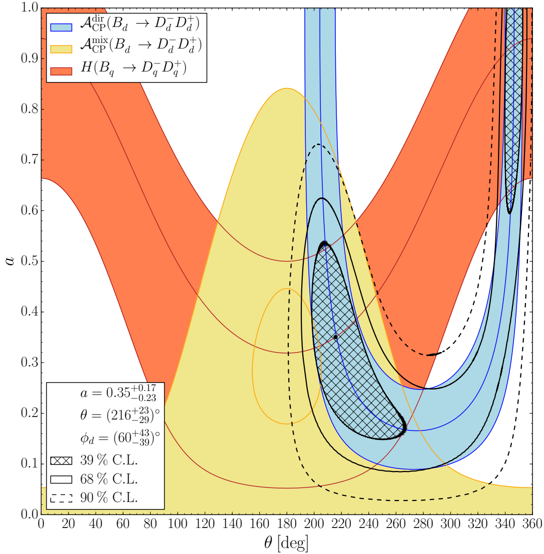
$$ae^{i\theta} = a'e^{i\theta'} \tag{22}$$

- Include external input on γ CKMfitter, Phys.Rev.D91 (2015) 073007, arXiv:1501.05013

$$\gamma = (73.2^{+6.3}_{-7.0})^\circ \tag{23}$$

- Use $\mathcal{A}_{CP}^{\rm dir}(a,\theta)$, $\mathcal{A}_{CP}^{\rm mix}(a,\theta,\phi)$, and $H(a,\theta)$ to determine a,θ (and ϕ)

Our Goal: Fit for a and θ



The Hadronic Amplitude Ratio $|\mathcal{A}'/\mathcal{A}|$

Breaking $|\mathcal{A}'/\mathcal{A}|$ into Bitesize Bits

- $|\mathcal{A}'/\mathcal{A}|$ is a crucial ingredient for the construction of the H observable
- Main limitation on precision on a, θ and $\Delta\phi_s$
- Need to control many different contributions to $|\mathcal{A}'/\mathcal{A}|$

$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right| = \left|\frac{T' + P^{(ct)'} + E' + PA^{(ct)'}}{T + P^{(ct)} + E + PA^{(ct)}}\right| \tag{24}$$

$$= \underbrace{\left|\frac{T'}{T}\right|}_{\text{Use Fact.}} \underbrace{\left|\frac{1 + P^{(ct)'}/T'}{1 + P^{(ct)}/T}\right|}_{\text{Neglect This}} \underbrace{\left|\frac{1+x'}{1+x}\right|}_{\text{From E+PA}} \tag{25}$$

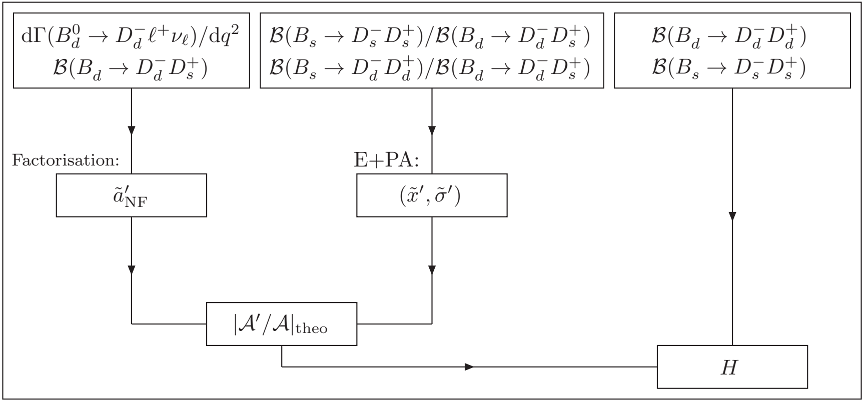
$$= \underbrace{\left|\frac{1+x'}{1+x}\right|}_{\text{Step 3}} \underbrace{\left|\frac{a_{\rm NF}^{(0)'}}{a_{\rm NF}^{(0)}}\right|}_{\text{Step 2}} \underbrace{\left|\frac{T'}{T}\right|_{\rm fact}}_{\text{Step 1}} \tag{26}$$

- Need input from many different $B \to D\bar{D}$ decays

The Many $B \to D\bar{D}$ Decays and their Purpose

Decay	$\mathcal{A}$	Topologies T	P	E	PA	A	Used for:
$B_d^0 \to D_d^- D_d^+$	$\mathcal{A}$	x	x	x	x		determination of a and θ (and ϕ_d)
$B_d^0 \to D_d^- D_s^+$	$\tilde{\mathcal{A}}'$	x	x				non-factorisable effect $\tilde{a}'_{\mathrm{NF}}$
$B_d^0 \to D_s^- D_s^+$	$\mathcal{A}_{EPA}$			x	x		quantify $E + PA$ contribution $\tilde{x}$
$B_s^0 \to D_s^- D_s^+$	$\mathcal{A}'$	x	x	x	x		physics goal ϕ_s
$B_s^0 \to D_s^- D_d^+$	$\tilde{\mathcal{A}}$	x	x				$SU(3)$ breaking non-fact. $\tilde{a}_{\mathrm{NF}}/\tilde{a}'_{\mathrm{NF}}$
$B_s^0 \to D_d^- D_d^+$	$\mathcal{A}'_{EPA}$			x	x		quantify $E + PA$ contribution $\tilde{x}'$
$B^+ \to \bar{D}^0 D_d^+$	$\tilde{\mathcal{A}}_c$	x	x			x	quantify A contribution r_{A} ...
$B^+ \to \bar{D}^0 D_s^+$	$\tilde{\mathcal{A}}'_c$	x	x			x	... and consistency of $a_{\mathrm{NF,c}}/a'_{\mathrm{NF,c}}$

Overview


$\mathrm{d}\Gamma(B_d^0 \to D_d^- \ell^+ \nu_\ell)/\mathrm{d}q^2$
$\mathcal{B}(B_d \to D_d^- D_s^+)$
$\mathcal{B}(B_s \to D_s^- D_s^+)/\mathcal{B}(B_d \to D_d^- D_s^+)$
$\mathcal{B}(B_s \to D_d^- D_d^+)/\mathcal{B}(B_d \to D_d^- D_s^+)$
$\mathcal{B}(B_d \to D_d^- D_d^+)$
$\mathcal{B}(B_s \to D_s^- D_s^+)$
Factorisation:
$\tilde{a}'_{\mathrm{NF}}$
E+PA:
$(\tilde{x}', \tilde{\sigma}')$
$|\mathcal{A}'/\mathcal{A}|_{\mathrm{theo}}$
H

Step 1: Factorisable Tree Contributions

- This is the most straight-forward part
- Expressed in terms of decay constants and form-factors

$$\left|\frac{T'}{T}\right|_{\text{fact}} = \left[\frac{m_{B_s}^2 - m_{D_s}^2}{m_{B_d}^2 - m_{D_d}^2}\right]\left[\frac{f_{D_s}}{f_{D_d}}\right]\left[\frac{F_0^{B_s D_s}(m_{D_s}^2)}{F_0^{B_d D_d}(m_{D_d}^2)}\right] = 1.356 \pm 0.076 \qquad (27)$$

- Input from Lattice/LCSR

Step 2: Non-Factorisable Corrections

Decay	$\mathcal{A}$	Topologies T	P	E	PA	A	Used for:
$B_d^0 \to D_d^- D_d^+$	$\mathcal{A}$	x	x	x	x		determination of a and θ (and ϕ_d)
$B_d^0 \to D_d^- D_s^+$	$\tilde{\mathcal{A}}'$	x	x				non-factorisable effect $\tilde{a}'_{\rm NF}$
$B_d^0 \to D_s^- D_s^+$	$\mathcal{A}_{EPA}$			x	x		quantify $E + PA$ contribution $\tilde{x}$
$B_s^0 \to D_s^- D_s^+$	$\mathcal{A}'$	x	x	x	x		physics goal ϕ_s
$B_s^0 \to D_s^- D_d^+$	$\tilde{\mathcal{A}}$	x	x				$SU(3)$ breaking non-fact. $\tilde{a}_{\rm NF}/\tilde{a}'_{\rm NF}$
$B_s^0 \to D_d^- D_d^+$	$\mathcal{A}'_{EPA}$			x	x		quantify $E + PA$ contribution $\tilde{x}'$
$B^+ \to \overline{D}^0 D_d^+$	$\tilde{\mathcal{A}}_c$	x	x			x	quantify A contribution $r_{\rm A}$ ...
$B^+ \to \overline{D}^0 D_s^+$	$\tilde{\mathcal{A}}'_c$	x	x			x	... and consistency of $a_{\rm NF,c}/a'_{\rm NF,c}$

Step 2: Non-Factorisable Corrections

- Ratios between non-leptonic decay rates and differential semileptonic rates are powerful tools to test factorisation

Daniela Bortoletto and Sheldon Stone, Phys.Rev.Lett.65 (1990) 2951

- Allows us to calculate the non-factorisable corrections

$$\tilde{R}_{D_d} \equiv \frac{\Gamma(B_d^0 \to D_d^- D_s^+)}{[\mathrm{d}\Gamma(B_d^0 \to D_d^- \ell^+ \nu_\ell)/\mathrm{d}q^2]|_{q^2=m_{D_q}^2}} \tag{28}$$

$$= 6\pi^2 |V_{cs}|^2 f_{D_s}^2 X_{B_d D_d}^{D_s} |\tilde{a}'_{\mathrm{NF}}|^2 \underbrace{\left[1 + 2\,\epsilon \tilde{a}' \cos\tilde{\theta}' \cos\gamma + \epsilon^2 \tilde{a}'^2\right]}_{\text{Neglect This}} \tag{29}$$

- where

$$X_{B_d D_d}^{D_s} = \frac{(m_{B_d}^2 - m_{D_d}^2)^2}{\left[m_{B_d}^2 - (m_{D_d} + m_{D_s})^2\right]\left[m_{B_d}^2 - (m_{D_d} - m_{D_s})^2\right]} \left[\frac{F_0^{B_d D_d}(m_{D_s}^2)}{F_1^{B_d D_d}(m_{D_s}^2)}\right]^2 \tag{30}$$

- Theory side: Input from Lattice/LCSR

Step 2: Non-Factorisable Corrections

- Experimental result

$$\tilde{R}_{D_d} = (2.90 \pm 0.41)\ \text{GeV}^2 \tag{31}$$

- leading to

$$|\tilde{a}'_{\rm NF}| = 0.756 \pm 0.085 \tag{32}$$

- Account for possible $SU(3)$-breaking using $\tilde{\xi}_{SU(3)}$

$$|\tilde{a}'_{\rm NF}| = 1 + \tilde{\Delta}'_{\rm NF}\,, \qquad |\tilde{a}_{\rm NF}| = 1 + \tilde{\Delta}'_{\rm NF}[1 - \tilde{\xi}_{SU(3)}] \tag{33}$$

- Leading to

$$\left|\frac{\tilde{a}'_{\rm NF}}{\tilde{a}_{\rm NF}}\right| = \frac{1+\tilde{\Delta}'_{\rm NF}}{1+\tilde{\Delta}_{\rm NF}} = 1 + \tilde{\xi}_{SU(3)}\tilde{\Delta}'_{\rm NF} + \mathcal{O}(\tilde{\Delta}'^2_{\rm NF}) \tag{34}$$

- NF corrections largely cancel in the ratio!
- Lastly, assume

$$\left|\frac{a^{(0)'}_{\rm NF}}{a^{(0)}_{\rm NF}}\right| = \left|\frac{\tilde{a}'_{\rm NF}}{\tilde{a}_{\rm NF}}\right| \tag{35}$$

Step 3: Exchange and Penguin-Annihilation Contributions

Decay	$\mathcal{A}$	Topologies					Used for:
		T	P	E	PA	A	
$B_d^0 \to D_d^- D_d^+$	$\mathcal{A}$	x	x	x	x		determination of a and θ (and ϕ_d)
$B_d^0 \to D_d^- D_s^+$	$\tilde{\mathcal{A}}'$	x	x				non-factorisable effect $\tilde{a}'_{\mathrm{NF}}$
$B_d^0 \to D_s^- D_s^+$	$\mathcal{A}_{EPA}$			x	x		quantify $E + PA$ contribution $\tilde{x}$
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$B_s^0 \to D_s^- D_d^+$	$\tilde{\mathcal{A}}$	x	x				$SU(3)$ breaking non-fact. $\tilde{a}_{\mathrm{NF}}/\tilde{a}'_{\mathrm{NF}}$
$B_s^0 \to D_d^- D_d^+$	$\mathcal{A}'_{EPA}$			x	x		quantify $E + PA$ contribution $\tilde{x}'$
$B^+ \to \bar{D}^0 D_d^+$	$\tilde{\mathcal{A}}_c$	x	x			x	quantify A contribution r_{A} ...
$B^+ \to \bar{D}^0 D_s^+$	$\tilde{\mathcal{A}}'_c$	x	x			x	... and consistency of $a_{\mathrm{NF,c}}/a'_{\mathrm{NF,c}}$

Step 3: Exchange and Penguin-Annihilation Contributions

Constraint 1: Theory Side

- Study the E+PA contributions using $B_s^0 \to D_s^- D_s^+$ and $B_d^0 \to D_d^- D_s^+$
- Has contributions from Tree and Penguin only

$$\frac{A(B_s^0 \to D_s^- D_s^+)}{A(B_d^0 \to D_d^- D_s^+)} = \left(\frac{\mathcal{A}'}{\tilde{\mathcal{A}}'}\right) \underbrace{\left[\frac{1+\epsilon a' e^{i\theta'} e^{i\gamma}}{1+\epsilon \tilde{a}' e^{i\tilde{\theta}'} e^{i\gamma}}\right]}_{\text{Neglect This}} \approx \left[\frac{T' + P^{(ct)'}}{\tilde{T}' + \tilde{P}^{(ct)'}} + \tilde{x}'\right] \tag{36}$$

- where

$$\tilde{x}' \equiv |\tilde{x}'| e^{i\tilde{\sigma}'} \equiv \frac{E' + PA^{(ct)'}}{\tilde{T}' + \tilde{P}^{(ct)'}} \tag{37}$$

- and

$$\varrho' \equiv |\varrho'| e^{i\omega'} \equiv \frac{T' + P^{(ct)'}}{\tilde{T}' + \tilde{P}^{(ct)'}} = \left[\frac{T'}{\tilde{T}'}\right] \underbrace{\left[\frac{1 + P^{(ct)'}/T'}{1 + \tilde{P}^{(ct)'}/\tilde{T}'}\right]}_{\text{Neglect This}} \tag{38}$$

- Which we can also get from Lattice/LCSR

$$\varrho'_{\text{fact}} = \left[\frac{m_{B_s}^2 - m_{D_s}^2}{m_{B_d}^2 - m_{D_d}^2}\right] \left[\frac{F_0^{B_s D_s}(m_{D_s}^2)}{F_0^{B_d D_d}(m_{D_s}^2)}\right] \tag{39}$$

Step 3: Exchange and Penguin-Annihilation Contributions

Constraint 1: Experimental Side

- Branching ratios give experimental access to $\tilde{x}'$

$$\Xi(B_s \to D_s^- D_s^+, B_d \to D_d^- D_s^+)$$
$$\equiv \left[\frac{m_{B_s}}{m_{B_d}} \frac{\Phi(m_{D_d}/m_{B_d}, m_{D_s}/m_{B_d})}{\Phi(m_{D_s}/m_{B_s}, m_{D_s}/m_{B_s})} \frac{\tau_{B_d}}{\tau_{B_s}}\right] \left[\frac{\mathcal{B}(B_s \to D_s^- D_s^+)_{\rm theo}}{\mathcal{B}(B_d \to D_d^- D_s^+)}\right] \quad (40)$$
$$= 0.647 \pm 0.049 \quad (41)$$

- In terms of ρ' and $\tilde{x}'$

$$\Xi(B_s \to D_s^- D_s^+, B_d \to D_d^- D_s^+) = |\varrho'|^2 + 2|\varrho'||\tilde{x}'|\cos(\omega' - \tilde{\sigma}') + |\tilde{x}'|^2 \quad (42)$$

- where

$$\varrho'_{\rm fact} = 1.078 \pm 0.051 \quad (43)$$

Step 3: Exchange and Penguin-Annihilation Contributions

Constraint 2: Theory Side

- Study the E+PA contributions using $B_s^0 \to D_d^- D_d^+$
- Has contributions from Exchange and Penguin-Annihilation only

$$\frac{A(B_s^0 \to D_d^- D_d^+)}{A(B_d^0 \to D_d^- D_s^+)} = \left(\frac{\mathcal{A}'_{EPA}}{\tilde{\mathcal{A}}'}\right) \underbrace{\left[\frac{1+\epsilon a'_{EPA} e^{i\theta'_{EPA}} e^{i\gamma}}{1+\epsilon \tilde{a}' e^{i\tilde{\theta}'} e^{i\gamma}}\right]}_{\text{Neglect This}} \approx \varsigma' \tilde{x}' \tag{44}$$

- where

$$\varsigma' \equiv \frac{\hat{E}' + \hat{PA}'^{(ct)}}{E' + PA'^{(ct)}} \approx \left(\frac{f_{D_d}}{m_{D_d}} \frac{m_{D_s}}{f_{D_s}}\right)^2 = 0.700 \pm 0.042 \tag{45}$$

- and remember

$$\tilde{x}' \equiv |\tilde{x}'| e^{i\tilde{\sigma}'} \equiv \frac{E' + PA^{(ct)'}}{\tilde{T}' + \tilde{P}^{(ct)'}} \tag{46}$$

Step 3: Exchange and Penguin-Annihilation Contributions

Constraint 2: Experimental Side

- Branching ratios give experimental access to $\tilde{x}'$

$$\Xi(B_s \to D_d^- D_d^+, B_d \to D_d^- D_s^+)$$
$$\equiv \left[\frac{m_{B_s}}{m_{B_d}} \frac{\Phi(m_{D_d}/m_{B_d}, m_{D_s}/m_{B_d})}{\Phi(m_{D_d}/m_{B_s}, m_{D_d}/m_{B_s})} \frac{\tau_{B_d}}{\tau_{B_s}}\right] \left[\frac{\mathcal{B}(B_s \to D_d^- D_d^+)_{\mathrm{theo}}}{\mathcal{B}(B_d \to D_d^- D_s^+)}\right] \quad (47)$$
$$= 0.031 \pm 0.009 \quad (48)$$

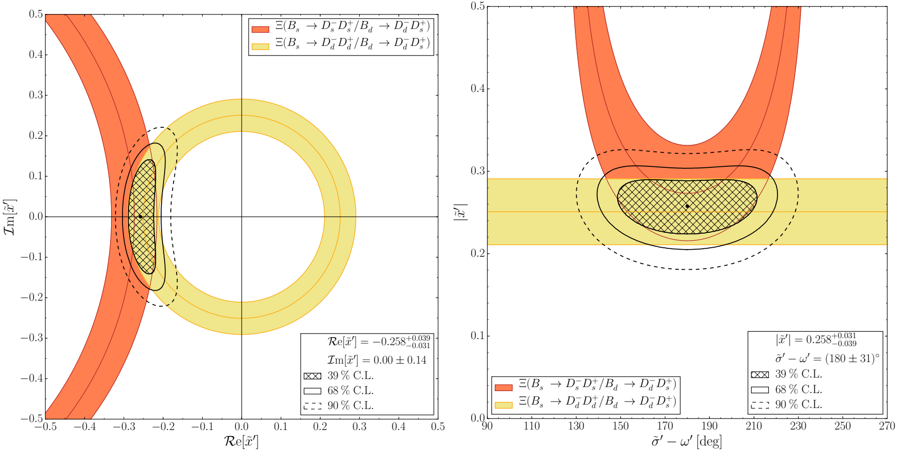
- In terms of ς' and $\tilde{x}'$

$$\Xi(B_s \to D_d^- D_d^+, B_d \to D_d^- D_s^+) = |\varsigma' \tilde{x}'|^2 \quad (49)$$

Fit for $\tilde{x}'$

- Combine the information from the two Ξ variables
- Intersection of both contours pins down $\tilde{x}'$

Step 3: Exchange and Penguin-Annihilation Contributions



Step 3: Exchange and Penguin-Annihilation Contributions

Fit Results:

- Better fit stability when fitting for

$$\mathcal{R}\text{e}(\tilde{x}') = -0.258^{+0.039}_{-0.031}\,, \qquad \mathcal{I}\text{m}(\tilde{x}') = 0.0 \pm 0.14 \tag{50}$$

- . . . which corresponds to

$$|\tilde{x}'| = 0.258^{+0.031}_{-0.039}\,, \qquad \tilde{\sigma}' - \omega' = (180 \pm 34)^\circ \tag{51}$$

Correction Factor:

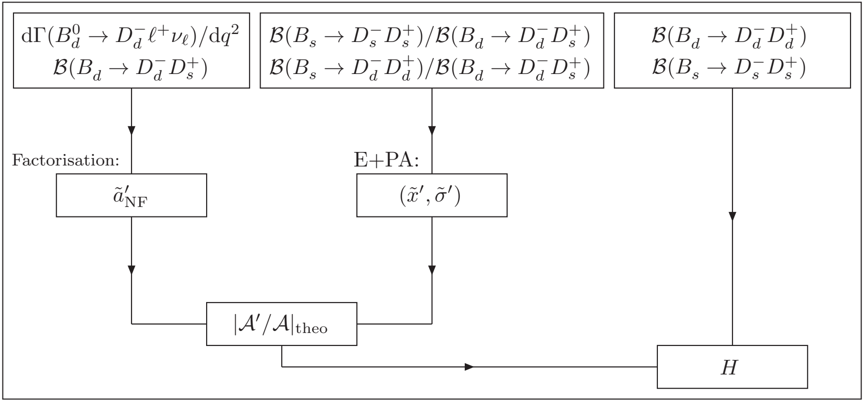
- Now relate that to what we need

$$x' = \frac{\tilde{x}'}{\varrho'}\,, \qquad x \approx \left(\frac{m_{B_s} m_{D_s}}{m_{B_d} m_{D_d}}\right)\left(\frac{f_{B_d} f_{D_d}}{f_{B_s} f_{D_s}}\right)\tilde{x}'\,, \tag{52}$$

- giving

$$\left|\frac{1+x'}{1+x}\right| = 0.930 \pm 0.020\,. \tag{53}$$

Putting it All Together



Putting it All Together

Recap:

- Need input from: Lattice/LCSR, $B_d^0 \to D_d^- D_s^+$, $B_d^0 \to D_d^- \ell^+ \nu_\ell$, $B_s^0 \to D_s^- D_s^+$, $B_s^0 \to D_d^- D_d^+$
- Hadronic amplitude ratio

$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right| = \underbrace{\left|\frac{1+x'}{1+x}\right|}_{\text{Step 3}} \underbrace{\left[\frac{a_{\rm NF}^{(0)'}}{a_{\rm NF}^{(0)}}\right]}_{\text{Step 2}} \underbrace{\left|\frac{T'}{T}\right|_{\rm fact}}_{\text{Step 1}} \tag{54}$$

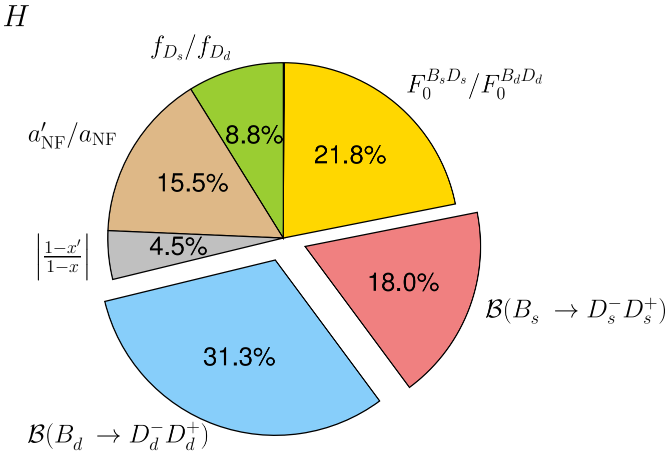
$$= 1.261 \pm 0.091 \tag{55}$$

- ...and finally our observable for the penguin fit

$$H \equiv \underbrace{\frac{1}{\epsilon}}_{\text{CKM}} \underbrace{\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2}_{SU(3)} \underbrace{\left[\frac{m_{B_d}}{m_{B_s}} \frac{\Phi(m_{D_s}/m_{B_s}, m_{D_s}/m_{B_s})}{\Phi(m_{D_d}/m_{B_d}, m_{D_d}/m_{B_d})} \frac{\tau_{B_s}}{\tau_{B_d}}\right]}_{\text{Phase-Space Factor}} \frac{\mathcal{B}\left(B_d \to D_d^- D_d^+\right)}{\mathcal{B}\left(B_s \to D_s^- D_s^+\right)_{\rm theo}} \tag{56}$$

$$= 1.30 \pm 0.26 \tag{57}$$

Error Budget



- Lot of improvement possible with more precise experimental input

Penguin Fit to the Current Data

Fit Setup for $B_d^0 \to D_d^- D_d^+$

Input:

- CP asymmetries

BaBar, Phys.Rev.D79 (2009) 032002, arXiv:0808.1866
Belle, Phys.Rev.D85 (2012) 091106, arXiv:1203.6647

$$\mathcal{A}_{CP}^{\rm dir}(B_d \to D_d^- D_d^+) = \begin{cases} -0.07 \pm 0.23 \pm 0.03 & \text{(BaBar)} \\ -0.43 \pm 0.16 \pm 0.05 & \text{(Belle)} \end{cases} \quad (58)$$

$$\mathcal{A}_{CP}^{\rm mix}(B_d \to D_d^- D_d^+) = \begin{cases} +0.63 \pm 0.36 \pm 0.05 & \text{(BaBar)} \\ +1.06^{+0.14}_{-0.21} \pm 0.08 & \text{(Belle)} \end{cases} \quad (59)$$

- Branching ratio information

$$H = 1.30 \pm 0.26 \quad (60)$$

- External input

CKMfitter, Phys.Rev.D91 (2015) 073007, arXiv:1501.05013

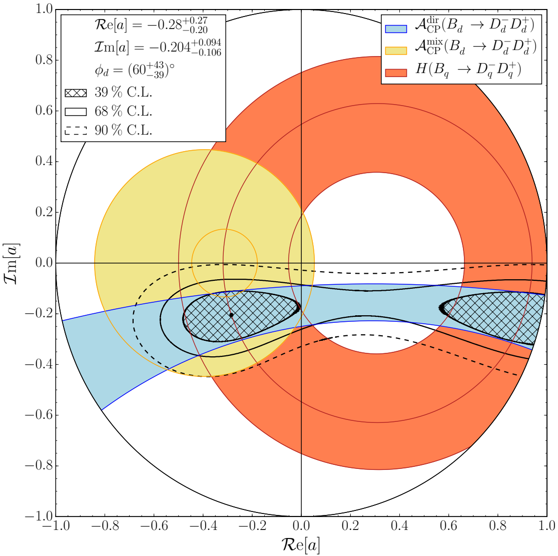
$$\gamma = (73.2^{+6.3}_{-7.0})^\circ \quad (61)$$

Change of Coordinate System:

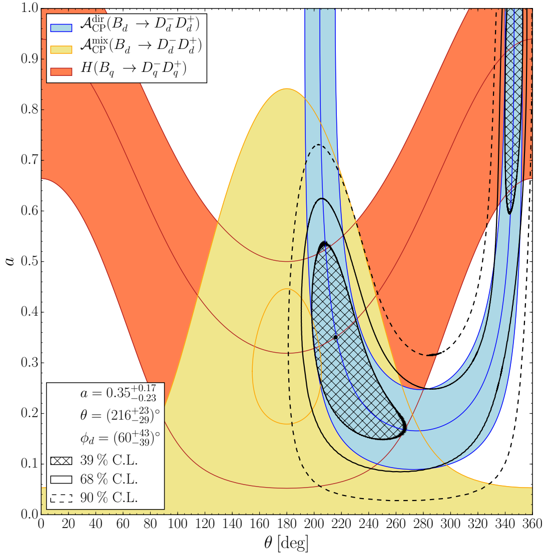
- Goal: a, θ and ϕ_d
- Better fit stability when fitting for

$$\mathcal{R}e[a] = a\cos\theta\,, \qquad \mathcal{I}m[a] = a\sin\theta \quad (62)$$

Confidence Level Contours: $\mathcal{R}\text{e}[a]$–$\mathcal{I}\text{m}[a]$



Confidence Level Contours: θ–a



Fit Results with Current Data

Results for $B_d^0 \to D_d^- D_d^+$:

- Cartesian coordinates

$$\mathcal{R}\mathrm{e}[a] = -0.29^{+0.27}_{-0.20}\,, \qquad \mathcal{I}\mathrm{m}[a] = -0.204^{+0.094}_{-0.105}\,, \qquad \phi_d = \left(60^{+43}_{-39}\right)^\circ \tag{63}$$

- ... which corresponds to

$$a = 0.35^{+0.19}_{-0.20}\,, \qquad \theta = \left(215^{+51}_{-17}\right)^\circ \tag{64}$$

- ... and a penguin shift

$$\Delta\phi_d^{D_d^- D_d^+} = \left(30^{+23}_{-32}\right)^\circ \tag{65}$$

- Unfortunately, the result on ϕ_d is not competitive with $B_d^0 \to J/\psi K_S^0$

Fit Results with Current Data

Results for $B_s^0 \to D_s^- D_s^+$:

- Allow for U-spin breaking, using $\xi = 1 \pm 0.2$ and $\delta = (0 \pm 20)^\circ$

$$a' = \xi a\,, \qquad \theta' = \theta + \delta \tag{66}$$

- The penguin shift on $B_s^0 \to D_s^- D_s^+$

$$\Delta\phi_s^{D_s^- D_s^+} = -\left(1.7^{+1.6}_{-1.2}\,(\text{stat})^{+0.3}_{-0.7}\,(U\text{-spin})\right)^\circ \tag{67}$$

- Resulting value for ϕ_s

$$\phi_s = -\left(0.6^{+9.8}_{-9.9}\,(\text{stat})^{+0.3}_{-0.7}\,(U\text{-spin})\right)^\circ \tag{68}$$

- Recall

$$\phi_{s,D_s^- D_s^+}^{\text{eff}} = (1.1 \pm 9.7 \pm 1.1)^\circ \tag{69}$$

Prospects for the LHCb Upgrade

Preliminaries

Conclusion from Current Data:

- Limited precision on ϕ_d obtained with the current $B_d^0 \to D_d^- D_d^+$ data

$$\phi_d(B_d^0 \to D_d^- D_d^+) = \left(60^{+43}_{-39}\right)^\circ \tag{70}$$

- compared to Kristof De Bruyn & Robert Fleischer, JHEP 1503 (2015) 145, arXiv:1412.6834

$$\phi_d(B_d^0 \to J/\psi K_S^0) = (43.9 \pm 1.7)^\circ \tag{71}$$

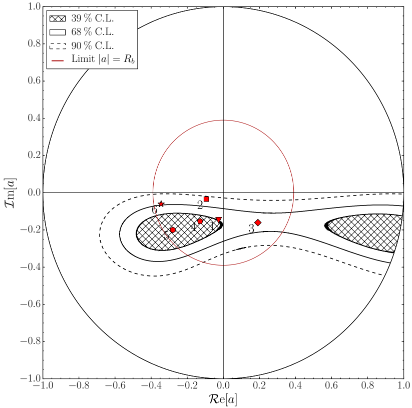
- $B_d^0 \to D_d^- D_d^+$ key strength is to provide important constraints on penguin contributions in $B_s^0 \to D_s^- D_s^+$

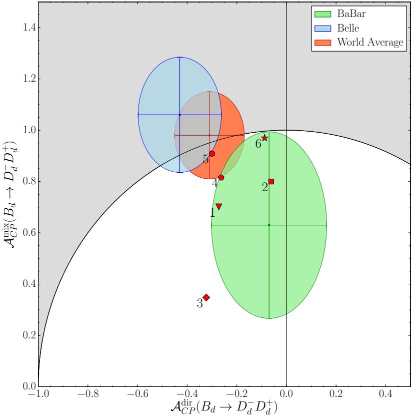
For Future Prospects:

- Better to focus purely on ϕ_s from $B_s^0 \to D_s^- D_s^+$
- Include external input on ϕ_d to improve knowledge on a and θ

Toy Studies

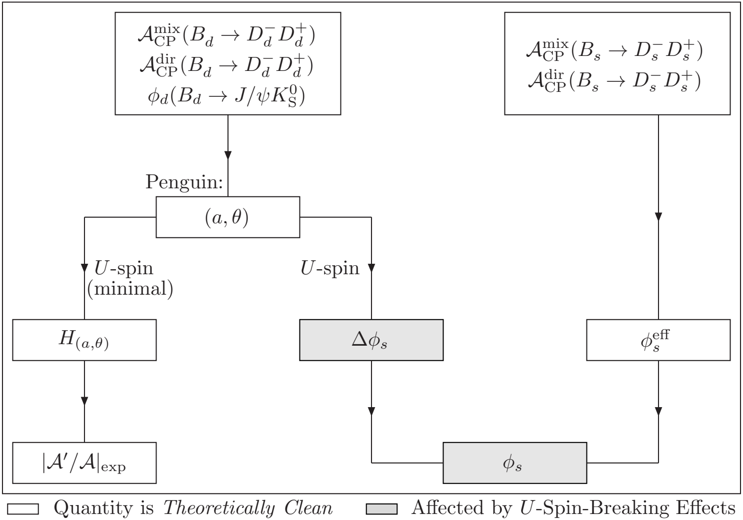
- Current situation allows for a large variety of possibilities
- Explored 6 different scenarios



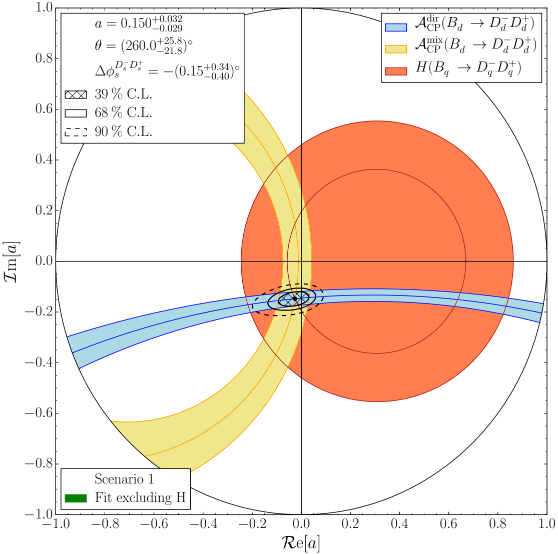


- End up with two possible situations

Situation 1: No Need for H



An Illustration: Scenario 1



Scenario 1

- Since H is not required for the fit, we can predict it from a and θ
- As a bonus we get experimental access to the hadronic amplitude ratio

$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right| = \sqrt{\epsilon H_{(a,\theta)} \left[\frac{m_{B_s}}{m_{B_d}} \frac{\Phi(m_{D_d^-}/m_{B_d}, m_{D_d^+}/m_{B_d})}{\Phi(m_{D_s^-}/m_{B_s}, m_{D_s^+}/m_{B_s})} \frac{\tau_{B_d^0}}{\tau_{B_s^0}}\right] \frac{\mathcal{B}\left(B_s \to D_s^- D_s^+\right)_{\text{theo}}}{\mathcal{B}\left(B_d \to D_d^- D_d^+\right)}} \quad (72)$$

Numerical Results:

$$a = 0.150^{+0.032}_{-0.029}\,, \qquad \theta = \left(260.0^{+25.8}_{-21.8}\right)^\circ \quad (73)$$

- leading to

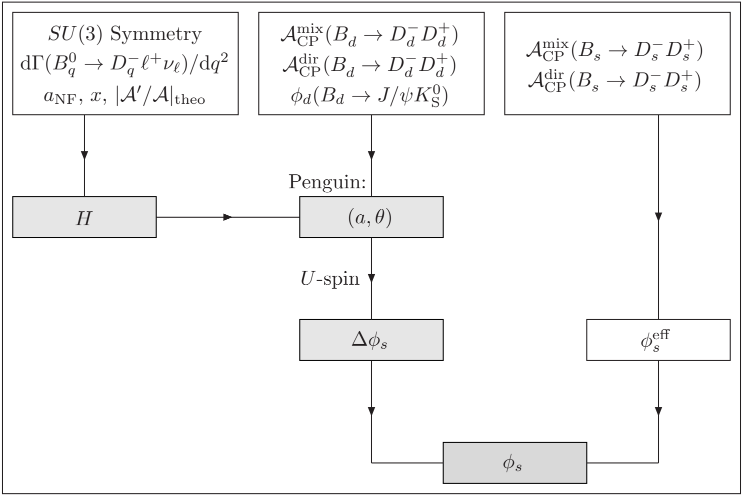
$$\Delta\phi_s = \left(-0.15^{+0.40}_{-0.34}(\text{stat})^{+0.32}_{-0.30}(U\text{-spin})\right)^\circ \quad (74)$$

- and

$$H = 1.038 \pm 0.039(a,\theta) \pm 0.002(\xi,\delta)\,, \qquad \left|\frac{\mathcal{A}'}{\mathcal{A}}\right| = 1.163 \pm 0.048 \quad (75)$$

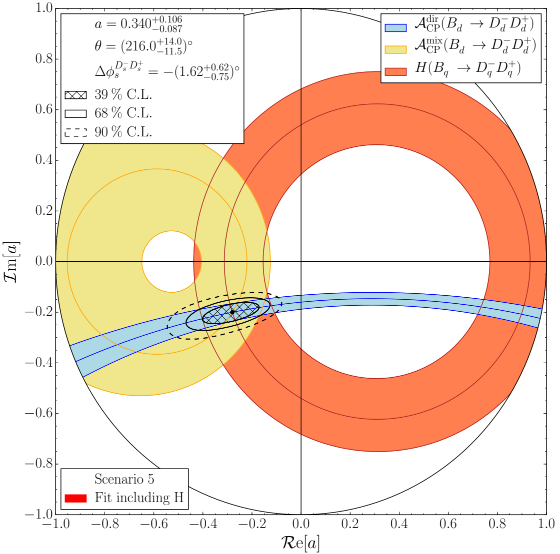
- (factor 2 smaller than current LCSR results)

Situation 2: Input from H is Necessary



Quantity is *Theoretically Clean* Affected by U-Spin-Breaking Effects

An Illustration: Scenario 5



Scenario 5

Numerical Results:

$$a = 0.340^{+0.106}_{-0.087}\,, \qquad \theta = \left(216.0^{+14.0}_{-11.5}\right)^\circ \tag{76}$$

- leading to

$$\Delta\phi_s = \left(-1.62^{+0.75}_{-0.62}(\text{stat})^{+0.62}_{-0.48}(U\text{-spin})\right)^\circ \tag{77}$$

- We can in all cases control the penguin effects, compared to expected experimental precision on $\phi_s^{\text{eff}}(B_s^0 \to D_s^- D_s^+)$ of 2°

Our Wishlist for LHCb

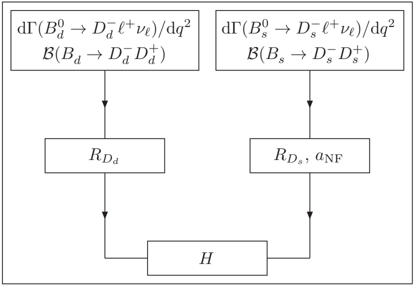
A New Suggestion for H

- To reduce the theoretical uncertainty on H from $|\mathcal{A}'/\mathcal{A}|$
- rely on information from semi-leptonic B_q^0 decays

$$H = \left|\frac{V_{cs}}{V_{cd}}\right|^2 \left[\frac{R_{D_d}}{R_{D_s}}\right] \left[\frac{f_{D_s}}{f_{D_d}}\right]^2 \left[\frac{X_{D_s}}{X_{D_d}}\right] \left|\frac{a_{\rm NF}^{(s)}}{a_{\rm NF}^{(d)}}\right|^2 \qquad (78)$$

- where

$$R_{D_q} \equiv \frac{\Gamma(B_q \to D_q^- D_q^+)_{\rm theo}}{[{\rm d}\Gamma(B_q^0 \to D_q^- \ell^+ \nu_\ell)/{\rm d}q^2]|_{q^2=m_{D_q}^2}} \qquad (79)$$



A New Suggestion for H

- Get the non-factorisable corrections

$$R_{D_s} = 6\pi^2 |V_{cs}|^2 f_{D_s}^2 X_{D_s} \left| a_{\rm NF}^{(s)} \right|^2 \underbrace{+\mathcal{O}(\epsilon a)}_{\text{Neglect This}} \tag{80}$$

- and

$$X_{D_q} = \left[\frac{(m_{B_q}^2 - m_{D_q}^2)^2}{m_{B_q}^2 (m_{B_q}^2 - 4\, m_{D_q}^2)} \right] \left[\frac{F_0^{B_q D_q}(m_{D_q}^2)}{F_1^{B_q D_q}(m_{D_q}^2)} \right]^2 \tag{81}$$

- thus

$$|a_{\rm NF}^{(s)}| \equiv 1 + \Delta_{\rm NF}^{(s)} = \sqrt{\frac{R_{D_s}}{6\pi^2 |V_{cs}|^2 f_{D_s}^2 X_{D_s}}} \tag{82}$$

- and use

$$\left| \frac{a_{\rm NF}^{(s)}}{a_{\rm NF}^{(d)}} \right| = \frac{1 + \Delta_{\rm NF}^{(s)}}{1 + \Delta_{\rm NF}^{(s)} \left[1 - \xi_{SU(3)} \right]} = 1 + \Delta_{\rm NF}^{(s)}\, \xi_{SU(3)} + \mathcal{O}\left(\Delta_{\rm NF}^{(s)2} \right) . \tag{83}$$

A New Suggestion for H

- No theoretical show-stoppers to reach high precision on H
  $\rightarrow$ Large advantage over the classic formula using $|\mathcal{A}'/\mathcal{A}|$
- Dependence on f_s/f_d drops out of the expression
- But ... we need to measure $\Gamma(B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell)/\mathrm{d}q^2$
- Greg Ciezarek (who did the $B_d^0 \rightarrow D^{*-}\tau^+\nu_\tau$ analysis) claims this is doable, despite the additional difficulties to get a handle on D_s^* decays

Wishlist

CP Asymmetries:

- Measurement of $\mathcal{A}_{CP}^{\rm dir}$ and $\mathcal{A}_{CP}^{\rm mix}$ in $B_d^0 \to D_d^- D_d^+$:
  $\to$ resolve tension between BaBar and Belle

- Measurement of $\mathcal{A}_{CP}^{\rm dir}$ in $B_s^0 \to D_s^- D_d^+$:
  $\to$ allows us to further disentangle the contributions from different decay topologies

Branching Ratios:

- Observation of $B_s^0 \to D_d^- D_d^+$:
  $\to$ further information on exchange & penguin-annihilation contributions

- Many specific ratios of $B \to D\bar{D}$ decays:
  $\to$ increased precision as systematic uncertainties largely cancel

Wishlist: Ratios of Branching Fraction

Obs	Decay Ratio	Current Measurement of ratio of BRs	LHCb Uncertainty 2011	LHCb Uncertainty Upgrade
H	$B_d^0 \to D_d^- D_d^+ / B_s^0 \to D_s^- D_s^+$	0.048 ± 0.007	14%(12%)	8%
$\tilde{H}$	$B_s^0 \to D_s^- D_d^+ / B_d^0 \to D_d^- D_s^+$	$0.050 \pm 0.008 \pm 0.004$	18%	7%
H_c	$B^+ \to \bar{D}^0 D_d^+ / B^+ \to \bar{D}^0 D_s^+$	0.042 ± 0.006	15%(7%)	6%
Ξ	$B_s^0 \to D_s^- D_s^+ / B_d^0 \to D_d^- D_s^+$	$0.56 \pm 0.03 \pm 0.04$	9%	7%
Ξ	$B_d^0 \to D_d^- D_d^+ / B_s^0 \to D_s^- D_d^+$	0.59 ± 0.14	24%(20%)	6%
Ξ	$B_s^0 \to D_d^- D_d^+ / B_d^0 \to D_d^- D_s^+$	0.031 ± 0.009	24%(20%)	11%
Ξ	$B_d^0 \to D_s^- D_s^+ / B_s^0 \to D_s^- D_d^+$	Not observed		

- The value in brackets indicates the possible uncertainty if this ratio were determined directly.

Conclusion

- Performed an extensive theoretical analysis of the $B \to D\bar{D}$ decays
- Rich structure to explore
- Still large uncertainties $\to$ much room for improvement
- Current data suggests potentially large penguin and/or exchange+penguin-annihilation contributions
- Showed two possible future scenarios for $B_d^0 \to D_d^- D_d^+$
- We can control the penguin effects
- LHCb can make a large contribution to sharpen the current picture

Back-up

The Many $B \to D\bar{D}$ Decays and their Purpose

Decay	$\mathcal{A}$	Topologies					Used for:
		T	P	E	PA	A	
$B_d^0 \to D_d^- D_d^+$	$\mathcal{A}$	x	x	x	x		determination of a and θ (and ϕ_d)
$B_d^0 \to D_d^- D_s^+$	$\tilde{\mathcal{A}}'$	x	x				non-factorisable effect $\tilde{a}'_{\mathrm{NF}}$
$B_d^0 \to D_s^- D_s^+$	$\mathcal{A}_{EPA}$			x	x		quantify $E + PA$ contribution $\tilde{x}$
$B_s^0 \to D_s^- D_s^+$	$\mathcal{A}'$	x	x	x	x		physics goal ϕ_s
$B_s^0 \to D_s^- D_d^+$	$\tilde{\mathcal{A}}$	x	x				$SU(3)$ breaking non-fact. $\tilde{a}_{\mathrm{NF}}/\tilde{a}'_{\mathrm{NF}}$
$B_s^0 \to D_d^- D_d^+$	$\mathcal{A}'_{EPA}$			x	x		quantify $E + PA$ contribution $\tilde{x}'$
$B^+ \to \bar{D}^0 D_d^+$	$\tilde{\mathcal{A}}_c$	x	x			x	quantify A contribution r_{A} ...
$B^+ \to \bar{D}^0 D_s^+$	$\tilde{\mathcal{A}}'_c$	x	x			x	... and consistency of $a_{\mathrm{NF,c}}/a'_{\mathrm{NF,c}}$

The Many Observables of the $B \to D\bar{D}$ System

Var.	Amplitude ratio	Description
a	$(P^{(ut)} + PA^{(ut)})/(T+E+P^{(ct)}+PA^{(ct)})$	Penguin contribution wrt. total ampl.
x	$(E + PA^{(ct)})(T + P^{(ct)})$	Exchange and penguin annihil. contr.
r_P	$P^{(ct)}/T$	Penguin contribution wrt. tree
r_A	$A/P^{(ut)}$	Annihilation contr. (in charged B's)
r_{PA}	$PA^{(ut)}/P^{(ut)}$	Penguin-annihilation contribution
r_{PA}^A	$(1 + r_A)/(1 + r_{PA})$	Comparison between A and PA
$\|a_{NF}\|^2$	$\sim \Gamma(B \to DD')/\mathrm{d}\Gamma(B \to D\ell\nu)/\mathrm{d}q^2$	Non-factorisable effects
ρ		$SU(3)$-breaking in $T+P$ contributions
ς		$SU(3)$-breaking in $E+PA$ contributions
ξ, δ		$SU(3)$-breaking in a and θ