Factorization assisted topology diagram approach for Hadronic B to D Decays

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Based on work collaborated with Ying Li, F-S. Yu, Qin Qin S-H. Zhou, Y.-B. Wei

Outline

- Introduction/Motivation
- Factorization assisted topological diagram approach for hadronic B to D decays
- Numerical results and discussions
- Summary
Rich physics in hadronic B decays

CP violation, FCNC, sensitive to new physics contribution...

The standard model describes interactions amongst quarks and leptons

In experiments, we can only observe hadrons

How can we test the standard model without solving QCD?
In principle, all hadronic physics should be calculated by QCD, provided you can renormalize the infinities and do all order calculations.

- Ultraviolet divergences $\rightarrow$ renormalization
- Infrared divergences? Infrared divergence in virtual corrections should be canceled by real emission
- In exclusive QCD processes $\rightarrow$ factorization
Factorization can only be proved in power expansion by operator product expansion. To achieve that, we need a hard scale $Q$

- In the certain order of $1/Q$ expansion, the hard dynamics characterized by $Q$ factorize from the soft dynamics
- Hard dynamics is process-dependent, but calculable
- Soft dynamics are universal (process-independent)
- Predictive power of factorization theorem
- Factorization theorem holds up to all orders in $\alpha_s$, but to certain power in $1/Q$
- In $B$ decays the hard scale $Q$ is just the $b$ quark mass
QCD-methods based on factorization work well for the leading power of $1/m_b$ expansion

Perturbative QCD approach based on $k_T$ factorization
[Keum, Li, Sanda, 00’; Lu, Ukai, Yang, 00’]
collinear QCD Factorization approach
Soft-Collinear Effective Theory
[Bauer, Pirjol, Stewart, 01’]

Unavailable for $1/m_b$ power corrections

- Work well for most of charmless B decays, except for pi K puzzle etc.
Hadronic decays with charm quark in the final states or initial state

- High precision measurements of $B$ to $D$ decays already by BaBar, Belle and LHCb, and to be pushed by LHCb upgrade and Belle-II.
- High precision in theoretical calculation is urged
- Theoretically, it is not satisfied, since there are mostly model calculations, some QCD sum rules calculation or rely on Lattice QCD: an ultimate tool but a formidable task now
- Charm quark mass is not large enough for heavy quark expansion
Topological diagrammatic approach

- Distinct by weak interaction and flavor flows with all strong interaction encoded, including non-perturbative ones. Model-independent
- Based on flavor SU(3) symmetry. Amplitudes with strong phases extracted from data. SU(3) breaking was lost.
- $DP$, $D^*P$ and $DV$ fitted separately, 5 parameters for each category of decay modes (15 in total). Less predictive.
We first apply our factorization assisted topological diagram approach in hadronic D decays

### Predictions of Direct CP asymmetries

<table>
<thead>
<tr>
<th>Modes</th>
<th>$A_{CP}(\text{FSI})$</th>
<th>$A_{CP}(\text{diagram})$</th>
<th>$A_{\text{tree}}^{CP}$</th>
<th>$A_{\text{tot}}^{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>0.02 ± 0.01</td>
<td>0.86</td>
<td>0</td>
<td>0.58</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+K^-$</td>
<td>0.13 ± 0.8</td>
<td>-0.48</td>
<td>0</td>
<td>-0.42</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^0$</td>
<td>0.54 ± 0.21</td>
<td>0.85</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^0\pi^0$</td>
<td>0.65 ± 0.08</td>
<td>0.37</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+\pi^-$</td>
<td>1.38 ± 0.05</td>
<td>1.53</td>
<td>0</td>
<td>1.38</td>
</tr>
</tbody>
</table>

First evidence of CP violation in charmed meson decays by LHCb, with 3.5 $\sigma$ [arXiv:1112.0938]

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})] \%$$

$\Delta_{CP} = -1 \times 10^{-3}$
LHCb combination

- The two measurements are compatible at the 3% level

\[ \Delta A_{CP} = (0.49 \pm 0.30\text{(stat.)} \pm 0.14\text{(syst.)}) \% \]

Semileptonic:

\[ \Delta A_{CP} = (-0.34 \pm 0.15\text{(stat.)} \pm 0.10\text{(syst.)}) \% \]

Prompt:

\( (\text{preliminary}) \)

NEW \( LHCb-PAPER-2015-055 \) to be submitted to PRL

\[ \Delta A_{CP \text{ prompt}} = (-0.10 \pm 0.08\text{(stat)} \pm 0.03\text{(syst)}) \% \]

compatible with the muon-tagged result

\[ \Delta A_{CP \text{ sec}} = (+0.14 \pm 0.16\text{(stat)} \pm 0.08\text{(syst)}) \% \] JHEP 07 (2014) 041

Both results are statistically and systematically uncorrelated
For the color favored diagram (T), it is proved factorization to all order of $\alpha_s$ expansion in soft-collinear effective theory,

The decay amplitudes is just the decay constants and form factors times Wilson coefficients of four quark operators. The SU(3) breaking effect is automatically kept.

\[
T_{c}^{DP} = i \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^{*} a_1(\mu) f_P (m_B^2 - m_D^2) F_0^{B \rightarrow D} (m_P^2),
\]
For other diagrams, we extract the amplitude and strong phase from experimental data by $\chi^2$ fit.

We factorize out the decay constants and form factor to keep the SU(3) breaking effect.

$$C_c^{DP} = i \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* f_D (m_B^2 - m_P^2) F_0^{B \rightarrow P} (m_D^2) \chi_C e^{i\phi_C^C},$$

$$E_c^{DP} = i \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* m_B f_B \frac{f_D^{(s)} f_P}{f_D f_\pi} \chi_C e^{i\phi_C^E},$$
Decay constants (Uncertainty 5 %) and form factors (Uncertainty 10%)

TABLE I. The decay constants of mesons (in units of MeV).

<table>
<thead>
<tr>
<th></th>
<th>$f_B$</th>
<th>$f_{B_s}$</th>
<th>$f_D$</th>
<th>$f_{D_s}$</th>
<th>$f_{D^*}$</th>
<th>$f_{D^*_s}$</th>
<th>$f_\pi$</th>
<th>$f_K$</th>
<th>$f_\rho$</th>
<th>$f_{K^*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>190</td>
<td>225</td>
<td>205</td>
<td>258</td>
<td>220</td>
<td>270</td>
<td>130</td>
<td>156</td>
<td>215</td>
<td>220</td>
</tr>
</tbody>
</table>

TABLE II. The transition form factors at maximum recoil and dipole model parameters used in this work.

<table>
<thead>
<tr>
<th></th>
<th>$F_0^{B \to \pi}$</th>
<th>$F_0^{B \to K}$</th>
<th>$F_{B_s}^{B \to K}$</th>
<th>$F_0^{B \to \eta_q}$</th>
<th>$F_{B_s}^{B \to \eta_q}$</th>
<th>$F_0^{B \to D}$</th>
<th>$F_{B_s}^{B \to D_s}$</th>
<th>$A_0^{B \to D^*}$</th>
<th>$A_{B_s}^{B \to D^*_s}$</th>
<th>$F_1^{B \to D}$</th>
<th>$F_{B_s}^{B \to D_s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.28</td>
<td>0.33</td>
<td>0.29</td>
<td>0.21</td>
<td>0.31</td>
<td>0.54</td>
<td>0.58</td>
<td>0.56</td>
<td>0.57</td>
<td>0.54</td>
<td>0.58</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>0.50</td>
<td>0.53</td>
<td>0.54</td>
<td>0.52</td>
<td>0.53</td>
<td>1.71</td>
<td>1.69</td>
<td>2.44</td>
<td>2.49</td>
<td>2.44</td>
<td>2.44</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>-0.13</td>
<td>-0.13</td>
<td>-0.15</td>
<td>0</td>
<td>0</td>
<td>0.52</td>
<td>0.78</td>
<td>1.98</td>
<td>1.74</td>
<td>1.49</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>$F_1^{B \to \pi}$</td>
<td>$F_1^{B \to K}$</td>
<td>$F_{B_s}^{B \to K}$</td>
<td>$F_1^{B \to \eta_q}$</td>
<td>$F_{B_s}^{B \to \eta_q}$</td>
<td>$B(s) \to V$</td>
<td>$A_0^{B \to \rho}$</td>
<td>$A_{0}^{B \to \omega}$</td>
<td>$A_{0}^{B \to \phi}$</td>
<td>$A_0^{B \to K^*}$</td>
<td>$A_{B_s}^{B \to K^*_s}$</td>
</tr>
<tr>
<td>Value</td>
<td>0.28</td>
<td>0.33</td>
<td>0.29</td>
<td>0.21</td>
<td>0.31</td>
<td>$A(0)$</td>
<td>0.30</td>
<td>0.26</td>
<td>0.30</td>
<td>0.33</td>
<td>0.27</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>0.52</td>
<td>0.54</td>
<td>0.57</td>
<td>1.43</td>
<td>1.48</td>
<td>$\alpha_1$</td>
<td>1.56</td>
<td>1.60</td>
<td>1.73</td>
<td>1.51</td>
<td>1.74</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>0.45</td>
<td>0.50</td>
<td>0.50</td>
<td>0.41</td>
<td>0.46</td>
<td>$\alpha_2$</td>
<td>0.17</td>
<td>0.22</td>
<td>0.41</td>
<td>0.14</td>
<td>0.47</td>
</tr>
</tbody>
</table>
Global Fit for all $B \rightarrow D_P$, $D^*P$ and $DV$ decays

$$\chi^2 = \sum_{i=1}^{n} \left( \frac{x_i^\text{th} - x_i}{\Delta x_i} \right)^2$$

31 measured modes induced by $b \rightarrow c$ transitions

$$\chi_c^C = 0.48 \pm 0.01, \quad \phi_c^C = (56.6^{+3.2}_{-3.8})^\circ,$$

$$\chi_c^E = 0.024^{+0.002}_{-0.001}, \quad \phi_c^E = (123.9^{+3.3}_{-2.2})^\circ,$$

$$\chi^2 / \text{d.o.f.} = 1.4$$

$\chi^2$ is much smaller than previous topology diagram approach

Topological amplitudes

$$|T_c^{DP}| : |C_c^{DP}| : |E_c^{DP}| \sim 1 : 0.45 : 0.1$$
<table>
<thead>
<tr>
<th>Meson</th>
<th>Mode</th>
<th>Amplitudes</th>
<th>$\mathcal{B}_{\text{exp}}(\times 10^{-4})$</th>
<th>$\mathcal{B}_{\text{th}}(\times 10^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cabibbo-favored</td>
<td>$V_{cb}V_{ud}^*$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\overline{B}^0$</td>
<td>$D^+\pi^-$</td>
<td>$T + E$</td>
<td>$26.8 \pm 1.3$</td>
<td>$24.7^{+0.2}_{-0.1} \pm 5.1 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$D^0\pi^0$</td>
<td>$\frac{1}{\sqrt{2}}(E - C)$</td>
<td>$2.6 \pm 0.1$</td>
<td>$2.5^{+0.1}_{-0.2} \pm 0.5 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$D^0\eta$</td>
<td>$\frac{1}{\sqrt{2}}(C + E) \cos \phi$</td>
<td>$2.4 \pm 0.3$</td>
<td>$1.9 \pm 0.1 \pm 0.4 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$D^0\eta'$</td>
<td>$\frac{1}{\sqrt{2}}(C + E) \sin \phi$</td>
<td>$1.38 \pm 0.16$</td>
<td>$1.3 \pm 0.1 \pm 0.2 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$D^+_sK^-$</td>
<td>$E$</td>
<td>$0.345 \pm 0.032$</td>
<td>$0.30^{+0.04}_{-0.02} \pm 0.00 \pm 0.03$</td>
</tr>
<tr>
<td>$\overline{B}^-$</td>
<td>$D^0\pi^-$</td>
<td>$T + C$</td>
<td>$48.1 \pm 1.5$</td>
<td>$49.0^{+1.4}_{-1.7} \pm 7.6 \pm 0.6$</td>
</tr>
<tr>
<td>$\overline{B}_s^0$</td>
<td>$D^+_s\pi^-$</td>
<td>$T$</td>
<td>$30.4 \pm 2.3$</td>
<td>$30.2 \pm 0.0 \pm 6.0 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$D^0K^0$</td>
<td>$C$</td>
<td></td>
<td>$5.9 \pm 0.3 \pm 1.2 \pm 0.3$</td>
</tr>
<tr>
<td></td>
<td>Cabibbo-suppressed</td>
<td>$V_{cb}V_{us}^*$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\overline{B}^0$</td>
<td>$D^+K^-$</td>
<td>$T$</td>
<td>$1.97 \pm 0.21$</td>
<td>$2.1 \pm 0.0 \pm 0.4 \pm 0.0$</td>
</tr>
<tr>
<td></td>
<td>$D^0\overline{K}^0$</td>
<td>$C$</td>
<td>$0.5 \pm 0.1$</td>
<td>$0.4 \pm 0.0 \pm 0.1 \pm 0.0$</td>
</tr>
<tr>
<td>$\overline{B}^-$</td>
<td>$D^0K^-$</td>
<td>$T + C$</td>
<td>$3.70 \pm 0.17$</td>
<td>$3.8 \pm 0.1 \pm 0.6 \pm 0.1$</td>
</tr>
<tr>
<td>$\overline{B}_s^0$</td>
<td>$D^+_sK^-$</td>
<td>$T + E$</td>
<td>$2.1 \pm 0.0 \pm 0.4 \pm 0.0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^0\eta$</td>
<td>$\frac{1}{\sqrt{2}}E \cos \phi - C \sin \phi$</td>
<td></td>
<td>$0.14 \pm 0.01 \pm 0.03 \pm 0.01$</td>
</tr>
<tr>
<td></td>
<td>$D^0\eta'$</td>
<td>$\frac{1}{\sqrt{2}}E \sin \phi + C \cos \phi$</td>
<td></td>
<td>$0.21 \pm 0.01 \pm 0.04 \pm 0.01$</td>
</tr>
<tr>
<td></td>
<td>$D^+\pi^-$</td>
<td>$E$</td>
<td></td>
<td>$0.011 \pm 0.001 \pm 0.000 \pm 0.001$</td>
</tr>
<tr>
<td></td>
<td>$D^0\pi^0$</td>
<td>$\frac{1}{\sqrt{2}}E$</td>
<td></td>
<td>$0.005^{+0.001}_{-0.000} \pm 0.000 \pm 0.001$</td>
</tr>
<tr>
<td>Meson</td>
<td>Mode</td>
<td>Amplitudes</td>
<td>$B_{\text{exp}} \times 10^{-4}$</td>
<td>$B_{\text{th}} \times 10^{-4}$</td>
</tr>
<tr>
<td>-------</td>
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<tr>
<td></td>
<td></td>
<td>Cabibbo-favored $V_{cb}V_{ud}^*$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{B}^0$</td>
<td>$D^{*-+}\pi^-$</td>
<td>$T + E$</td>
<td>27.6 ± 1.3</td>
<td>$24.9^{+0.2}_{-0.1} \pm 5.2 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$D^{*0}\pi^0$</td>
<td>$\frac{1}{\sqrt{2}}(E - C)$</td>
<td>2.2 ± 0.6</td>
<td>$2.8 \pm 0.2 \pm 0.6 \pm 0.3$</td>
</tr>
<tr>
<td></td>
<td>$D^{*0}\eta$</td>
<td>$\frac{1}{\sqrt{2}}(C + E)\cos \phi$</td>
<td>2.3 ± 0.6</td>
<td>$2.1 \pm 0.1 \pm 0.4 \pm 0.2$</td>
</tr>
<tr>
<td></td>
<td>$D^{*0}\eta'$</td>
<td>$\frac{1}{\sqrt{2}}(C + E)\sin \phi$</td>
<td>1.40 ± 0.22</td>
<td>$1.4 \pm 0.1 \pm 0.2 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$D^{*-+}K^-$</td>
<td>$E$</td>
<td>0.219 ± 0.030</td>
<td>$0.22^{+0.03}_{-0.01} \pm 0.00 \pm 0.03$</td>
</tr>
<tr>
<td>$B^-$</td>
<td>$D^{*0}\pi^-$</td>
<td>$T + C$</td>
<td>51.8 ± 2.6</td>
<td>$50.7^{+1.0}_{-1.8} \pm 7.8 \pm 1.4$</td>
</tr>
<tr>
<td>$\bar{B}_s^0$</td>
<td>$D^{*-+}\pi^-$</td>
<td>$T$</td>
<td>20 ± 5</td>
<td>$27.1 \pm 0.0 \pm 5.4 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$D^{*0}K^0$</td>
<td>$C$</td>
<td>6.6$^{+0.3}_{-0.4}$ ± 1.3 ± 0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cabibbo-suppressed $V_{cb}V_{us}^*$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{B}^0$</td>
<td>$D^{*-+}K^-$</td>
<td>$T$</td>
<td>2.14 ± 0.16</td>
<td>$2.0 \pm 0.00 \pm 0.4 \pm 0.0$</td>
</tr>
<tr>
<td></td>
<td>$D^{*0}\overline{K}^0$</td>
<td>$C$</td>
<td>0.36 ± 0.12</td>
<td>$0.45^{+0.02}_{-0.03} \pm 0.09 \pm 0.05$</td>
</tr>
<tr>
<td>$B^-$</td>
<td>$D^{*0}K^-$</td>
<td>$T + C$</td>
<td>4.20 ± 0.34</td>
<td>$3.8 \pm 0.1 \pm 0.6 \pm 0.1$</td>
</tr>
<tr>
<td>$\bar{B}_s^0$</td>
<td>$D^{*-+}K^-$</td>
<td>$T + E$</td>
<td>1.9 ± 0.0 ± 0.4 ± 0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^{*0}\eta$</td>
<td>$\frac{1}{\sqrt{2}}E\cos \phi - C\sin \phi$</td>
<td>0.15 ± 0.01 ± 0.03 ± 0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^{*0}\eta'$</td>
<td>$\frac{1}{\sqrt{2}}E\sin \phi + C\cos \phi$</td>
<td>0.23 ± 0.01 ± 0.04 ± 0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^{*-+}\pi^-$</td>
<td>$E$</td>
<td>&lt; 0.061</td>
<td>$0.008 \pm 0.001 \pm 0.000 \pm 0.001$</td>
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<tr>
<td></td>
<td>$D^{*0}\pi^0$</td>
<td>$\frac{1}{\sqrt{2}}E$</td>
<td>$0.004^{+0.004}_{-0.000} \pm 0.000 \pm 0.001$</td>
<td></td>
</tr>
<tr>
<td>Meson</td>
<td>Mode</td>
<td>Amplitudes</td>
<td>$B_{\text{exp}}(\times 10^{-4})$</td>
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</tr>
<tr>
<td>-------</td>
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<td>-------------------------------</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$D^+ \rho^-$</td>
<td>$T + E$</td>
<td>78 ± 13</td>
<td>$65.3^{+0.5}_{-0.3} ± 13.5 ± 6.6$</td>
</tr>
<tr>
<td></td>
<td>$D^0 \rho^0$</td>
<td>$\frac{1}{\sqrt{2}}(E - C)$</td>
<td>3.2 ± 0.5</td>
<td>2.6 ± 0.2 ± 0.6 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>$D^0 \omega$</td>
<td>$\frac{1}{\sqrt{2}}(E + C)$</td>
<td>2.54 ± 0.16</td>
<td>2.7 ± 0.2 ± 0.5 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>$D_s^+ K^{*-}$</td>
<td>$E$</td>
<td>0.35 ± 0.10</td>
<td>$0.38^{+0.05}_{-0.02} ± 0.00 ± 0.06$</td>
</tr>
<tr>
<td>$B^-$</td>
<td>$D^0 \rho^-$</td>
<td>$T + C$</td>
<td>134 ± 18</td>
<td>$105^{+2}_{-3} ± 18 ± 9$</td>
</tr>
<tr>
<td>$B^0_s$</td>
<td>$D_s^+ \rho^-$</td>
<td>$T$</td>
<td>70 ± 15</td>
<td>78.6 ± 0.0 ± 15.7 ± 7.9</td>
</tr>
<tr>
<td></td>
<td>$D^0 K^{*0}$</td>
<td>$C$</td>
<td>3.5 ± 0.6</td>
<td>4.9$^{+0.2}_{-0.3}$ ± 1.0 ± 0.2</td>
</tr>
<tr>
<td>Cabibbo-suppressed $V_{cb} V_{us}^*$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0$</td>
<td>$D^+ K^{*-}$</td>
<td>$T$</td>
<td>4.5 ± 0.7</td>
<td>3.9 ± 0.0 ± 0.8 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>$D^0 K^{*0}$</td>
<td>$C$</td>
<td>0.42 ± 0.06</td>
<td>0.37 ± 0.02 ± 0.07 ± 0.02</td>
</tr>
<tr>
<td>$B^-$</td>
<td>$D^0 K^{*-}$</td>
<td>$T + C$</td>
<td>5.3 ± 0.4</td>
<td>$6.0^{+0.1}_{-0.2} ± 1.0 ± 0.5$</td>
</tr>
<tr>
<td>$B^0_s$</td>
<td>$D_s^+ K^{*-}$</td>
<td>$T + E$</td>
<td>4.0$^{+0.04}_{-0.03}$ ± 0.8 ± 0.4</td>
<td>4.0$^{+0.04}_{-0.03}$ ± 0.8 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>$D^0 \phi$</td>
<td>$C$</td>
<td>0.24 ± 0.07</td>
<td>0.31$^{+0.01}_{-0.02}$ ± 0.06 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>$D^+ \rho^-$</td>
<td>$E$</td>
<td>0.019$^{+0.002}_{-0.001}$ ± 0.000 ± 0.003</td>
<td>0.019$^{+0.002}_{-0.001}$ ± 0.000 ± 0.003</td>
</tr>
<tr>
<td></td>
<td>$D^0 \rho^0$</td>
<td>$\frac{1}{\sqrt{2}}E$</td>
<td>0.010 ± 0.001 ± 0.000 ± 0.001</td>
<td>0.010 ± 0.001 ± 0.000 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>$D^0 \omega$</td>
<td>$\frac{1}{\sqrt{2}}E$</td>
<td>0.008 ± 0.001 ± 0.000 ± 0.001</td>
<td>0.008 ± 0.001 ± 0.000 ± 0.001</td>
</tr>
</tbody>
</table>
Nonperturbative parameters $\chi^C, \phi^C, \chi^E, \phi^E$ are universal for all the $DP, D^*P$ and $DV$ modes.

<table>
<thead>
<tr>
<th>Meson</th>
<th>Mode</th>
<th>Amplitudes</th>
<th>$B_{\text{exp}} \times 10^{-5}$</th>
<th>$B_{\text{FAT}} \times 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td></td>
<td>$V_{cb}V_{ud}^*$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_s^+ K^-$</td>
<td>$E$</td>
<td>$\chi^E e^{i\phi^E}$</td>
<td>$3.45 \pm 0.32$</td>
<td>$3.0^{+0.4}_{-0.2} \pm 0.0 \pm 0.3$</td>
</tr>
<tr>
<td>$D_s^{*-} K^-$</td>
<td>$E$</td>
<td>$\chi^E e^{i\phi^E}$</td>
<td>$2.19 \pm 0.30$</td>
<td>$2.2^{+0.3}_{-0.1} \pm 0.0 \pm 0.3$</td>
</tr>
<tr>
<td>$D_s^+ K^-$</td>
<td>$E$</td>
<td>$\chi^E e^{i\phi^E}$</td>
<td>$3.5 \pm 1.0$</td>
<td>$3.8^{+0.5}_{-0.2} \pm 0.0 \pm 0.6$</td>
</tr>
<tr>
<td>$B^0$</td>
<td></td>
<td>$V_{cb}V_{us}^*$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_s^0 K^{*-0}$</td>
<td>$C$</td>
<td>$\chi^C e^{i\phi^C}$</td>
<td>$5.2 \pm 0.7$</td>
<td>$4.0 \pm 0.0 \pm 1.0 \pm 0.0$</td>
</tr>
<tr>
<td>$D_s^{*-0}$</td>
<td>$C$</td>
<td>$\chi^C e^{i\phi^C}$</td>
<td>$3.6 \pm 1.2$</td>
<td>$4.5^{+0.2}_{-0.3} \pm 0.9 \pm 0.5$</td>
</tr>
<tr>
<td>$D_s^{*-0}$</td>
<td>$C$</td>
<td>$\chi^C e^{i\phi^C}$</td>
<td>$4.2 \pm 0.6$</td>
<td>$3.7 \pm 0.2 \pm 0.7 \pm 0.2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meson</th>
<th>Mode</th>
<th>Amplitudes</th>
<th>$B_{\text{exp}} \times 10^{-3}$</th>
<th>$B_{\text{FAT}} \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td></td>
<td>$V_{cb}V_{ud}^*$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_s^+ \pi^-$</td>
<td>$T$</td>
<td>factorization</td>
<td>$3.04 \pm 0.23$</td>
<td>$3.02 \pm 0.00 \pm 0.6 \pm 0.01$</td>
</tr>
<tr>
<td>$D_s^{*-} \pi^-$</td>
<td>$T$</td>
<td>factorization</td>
<td>$2.0 \pm 0.5$</td>
<td>$2.71 \pm 0.00 \pm 0.54 \pm 0.01$</td>
</tr>
<tr>
<td>$D_s^+ \rho^-$</td>
<td>$T$</td>
<td>factorization</td>
<td>$7.0 \pm 1.5$</td>
<td>$7.86 \pm 0.00 \pm 1.57 \pm 0.79$</td>
</tr>
</tbody>
</table>
SU(3) breaking effects in amplitudes to be 10~20%.

\[
\begin{align*}
\left| \frac{T^{\bar{B} \rightarrow DK}}{V_{cb} V_{us}^*} \right| : \left| \frac{T^{\bar{B} \rightarrow D\pi}}{V_{cb} V_{ud}^*} \right| : \left| \frac{T^{\bar{B}_s \rightarrow D_s K}}{V_{cb} V_{us}^*} \right| : \left| \frac{T^{\bar{B}_s \rightarrow D_s \pi}}{V_{cb} V_{ud}^*} \right| &= 1 : 0.83 : 1.10 : 0.90; \\
\left| \frac{C^{\bar{B} \rightarrow DK}}{V_{cb} V_{us}^*} \right| : \left| \frac{C^{\bar{B} \rightarrow D\pi}}{V_{cb} V_{ud}^*} \right| : \left| \frac{C^{\bar{B}_s \rightarrow DK}}{V_{cb} V_{us}^*} \right| : \left| \frac{C^{\bar{B}_s \rightarrow D\pi}}{V_{cb} V_{ud}^*} \right| &= 1 : 0.85 : 0.91; \\
\left| \frac{T^{\bar{B} \rightarrow DK^*}}{V_{cb} V_{us}^*} \right| : \left| \frac{T^{\bar{B} \rightarrow D\rho}}{V_{cb} V_{ud}^*} \right| : \left| \frac{T^{\bar{B}_s \rightarrow D_s K^*}}{V_{cb} V_{us}^*} \right| : \left| \frac{T^{\bar{B}_s \rightarrow D_s \rho}}{V_{cb} V_{ud}^*} \right| &= 1 : 0.83 : 1.07 : 0.89; \\
\left| \frac{C^{\bar{B} \rightarrow DK^*}}{V_{cb} V_{us}^*} \right| : \left| \frac{C^{\bar{B} \rightarrow D\rho}}{V_{cb} V_{ud}^*} \right| : \left| \frac{C^{\bar{B}_s \rightarrow DK^*}}{V_{cb} V_{us}^*} \right| : \left| \frac{C^{\bar{B}_s \rightarrow D\rho}}{V_{cb} V_{ud}^*} \right| &= 1 : 0.79 : 0.84; \\
\left| \frac{E^{\bar{B} \rightarrow D_s K}}{V_{cb} V_{us}^*} \right| : \left| \frac{E^{\bar{B}_s \rightarrow D_s \pi}}{V_{cb} V_{us}^*} \right| &= 1 : 0.81; \\
\left| \frac{E^{\bar{B} \rightarrow D_s K^*}}{V_{cb} V_{us}^*} \right| : \left| \frac{E^{\bar{B}_s \rightarrow D_s \rho}}{V_{cb} V_{us}^*} \right| &= 1 : 0.80.
\end{align*}
\]
SU(3) breaking effects can be described by decay constants

\[ A(B^- \rightarrow D^0 K^-) = V_{cb} V_{us}^* (T + C) \]
\[ A(B^- \rightarrow D^0 \pi^-) = V_{cb} V_{ud}^* (T + C) \]

\[ R_1^{\text{FAT}} = \frac{\mathcal{B}(B^- \rightarrow D^0 K^-)/|V_{us} f_K|^2}{\mathcal{B}(B^- \rightarrow D^0 \pi^-)/|V_{ud} f_\pi|^2} = 1.01 \pm 0.12 \]

\[ R_1^{\text{exp}} = 1.01 \pm 0.06 \]

SU(3) breaking (I)
CKM suppressed $b \to u$ transitions

- All modes predicted, with assumptions:
  - non-perturbative parameters are the same as those in the $b \to c$ transitions
  - W-annihilation A diagrams calculated in the pole model

$$|T_u| : |C_u| : |E_u| : |A_u| \sim 1 : 0.4 : 0.1 : 0.03$$
## Examples for decays induced by $b \to u$ transition

<table>
<thead>
<tr>
<th>Meson</th>
<th>Mode</th>
<th>Amplitudes</th>
<th>$B_{\text{exp}} \times 10^{-6}$</th>
<th>$B_{\text{th}} \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>Cabibbo favored $D^- \pi^+$</td>
<td>$V_{ub} V_{cs}^*$</td>
<td>21.6 ± 2.6</td>
<td>29.1 ± 0.0 ± 6.3 ± 1.0 ± 7.0</td>
</tr>
<tr>
<td></td>
<td>$D^0 K^0$</td>
<td>$T$</td>
<td>5.7 ± 0.3 ± 1.2 ± 0.3 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>$B^-$</td>
<td>$D^- \pi^0$</td>
<td>$\frac{1}{\sqrt{2}} T$</td>
<td>15.6 ± 0.0 ± 3.4 ± 0.6 ± 3.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^- \eta$</td>
<td>$\frac{1}{\sqrt{2}} T \cos \phi$</td>
<td>9.8 ± 0.0 ± 2.0 ± 0.3 ± 2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^- \eta'$</td>
<td>$\frac{1}{\sqrt{2}} T \sin \phi$</td>
<td>5.9 ± 0.0 ± 1.3 ± 0.2 ± 1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{D}^0 K^-$</td>
<td>$C + A$</td>
<td>5.8 ± 0.3 ± 1.3 ± 0.3 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>$\bar{B}^0_s$</td>
<td>$D^- K^+$</td>
<td>$A$</td>
<td>&lt; 2.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{D}^0 \eta$</td>
<td>$\frac{1}{\sqrt{2}} E \cos \phi - C \sin \phi$</td>
<td>2.0 ± 0.1 ± 0.4 ± 0.1 ± 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{D}^0 \eta'$</td>
<td>$\frac{1}{\sqrt{2}} E \sin \phi + C \cos \phi$</td>
<td>2.9 ± 0.1 ± 0.6 ± 0.1 ± 0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^- \pi^+$</td>
<td>$E$</td>
<td>0.14 ± 0.02 ± 0.00 ± 0.02 ± 0.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{D}^0 \pi^0$</td>
<td>$\frac{1}{\sqrt{2}} E$</td>
<td>0.07 ± 0.01 ± 0.00 ± 0.01 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>Cabibbo suppressed $\bar{B}^0$</td>
<td>$D^- \pi^+$</td>
<td>$V_{ub} V_{cd}^*$</td>
<td>0.78 ± 0.14</td>
<td>0.90 ± 0.01 ± 0.20 ± 0.04 ± 0.22</td>
</tr>
<tr>
<td></td>
<td>$D^0 \pi^0$</td>
<td>$\frac{1}{\sqrt{2}} (E - C)$</td>
<td>0.11 ± 0.01 ± 0.02 ± 0.01 ± 0.03</td>
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<tr>
<td></td>
<td>$\bar{D}^0 \eta$</td>
<td>$\frac{1}{\sqrt{2}} (E + C) \cos \phi$</td>
<td>0.07 ± 0.01 ± 0.01 ± 0.00 ± 0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{D}^0 \eta'$</td>
<td>$\frac{1}{\sqrt{2}} (E + C) \sin \phi$</td>
<td>0.05 ± 0.00 ± 0.01 ± 0.00 ± 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^- K^+$</td>
<td>$E$</td>
<td>0.011 ± 0.001 ± 0.000 ± 0.001 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>$B^-$</td>
<td>$D^0 \pi^-$</td>
<td>$C + A$</td>
<td>0.23 ± 0.01 ± 0.05 ± 0.01 ± 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^- \pi^0$</td>
<td>$\frac{1}{\sqrt{2}} (T - A)$</td>
<td>0.55 ± 0.00 ± 0.12 ± 0.03 ± 0.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^- \eta$</td>
<td>$\frac{1}{\sqrt{2}} (T + A) \cos \phi$</td>
<td>0.30 ± 0.00 ± 0.06 ± 0.02 ± 0.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^- \eta'$</td>
<td>$\frac{1}{\sqrt{2}} (T + A) \sin \phi$</td>
<td>0.20 ± 0.00 ± 0.04 ± 0.01 ± 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D^- K^0$</td>
<td>$A$</td>
<td>&lt; 800</td>
<td></td>
</tr>
<tr>
<td>$\bar{B}^0_s$</td>
<td>$D^- K^+$</td>
<td>$T$</td>
<td>1.05 ± 0.00 ± 0.24 ± 0.05 ± 0.25</td>
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</tr>
<tr>
<td></td>
<td>$\bar{D}^0 K^0$</td>
<td>$C$</td>
<td>0.24 ± 0.01 ± 0.05 ± 0.01 ± 0.06</td>
<td></td>
</tr>
</tbody>
</table>
$\bar{B}_s \to D_s^{\pm} K^{\mp}$

CP asymmetries

$C_f = C_{\bar{f}} = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2},$

$S_f = \frac{2\text{Im}(\lambda_f)}{1 + |\lambda_f|^2}, \quad S_{\bar{f}} = \frac{2\text{Im}(\bar{\lambda}_{\bar{f}})}{1 + |\bar{\lambda}_{\bar{f}}|^2},$

$D_f = \frac{2\text{Re}(\lambda_f)}{1 + |\lambda_f|^2}, \quad D_{\bar{f}} = \frac{2\text{Re}(\bar{\lambda}_{\bar{f}})}{1 + |\bar{\lambda}_{\bar{f}}|^2}.$

FAT predictions

$C_f = C_{\bar{f}} = 0.71 \pm 0.07$

$S_f = -S_{\bar{f}} = -0.63 \pm 0.06$

$D_f = D_{\bar{f}} = 0.32 \pm 0.03$

LHCb measurement

$C_f = 1.01 \pm 0.55,$

$S_f = -1.25 \pm 0.61, \quad S_{\bar{f}} = 0.08 \pm 0.74,$

$D_f = -1.33 \pm 0.65, \quad D_{\bar{f}} = -0.81 \pm 0.62,$

To be tested in the future
Summary

- $B \to D_P, D^*P$ and $DV$ decays are studied in the factorization-assisted topological-amplitude approach
- Only four universal non-perturbative parameters to be fitted for all $B \to D_P, D^*P$ and $DV$ decays (b $\to$ c transition), more predictive power than ever
- Results are consistent with data. SU(3) breakings are studied.
- Predictions for more than 100 channels (especially for all b $\to$ u transition) to be tested by future exp.
Summary

- $B \to DP$, $D^*P$ and $DV$ decays are studied in the factorization-assisted topological-amplitude approach.

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- Predictions for more than 100 channels (especially for all $b \to u$ transition) to be tested by future exp.

Thank you!