Theoretical study of rare B/D decays

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Outline

- Introduction/Motivation
- Theory of non-leptonic B/D decays
- Factorization assisted topological diagram approach for hadronic B/D decays
- Summary
Flavor physics is important

Progress in flavour physics may help understand open questions in cosmology - SM CPV insufficient to explain matter/antimatter asymmetry

Flavour physics is a proven tool of discovery:

- \( \text{BR}(K^0_L \rightarrow \mu\mu) \) & GIM \( \rightarrow \) prediction of charm
- CP violation \( \rightarrow \) need for a third generation
- B mixing \( \rightarrow \) mass of top is very heavy

Lesson from history: precise measurements of processes suppressed in existing theories have high sensitivity to new physics (NP) contributions. An excellent way to look for the NP expected at the TeV scale!
CKM triangle measurement
The CKM (Cabibbo・Kobayashi・Maskawa) matrix

Another possible parametrisations (Chau and Keung parametrisation, adopted by PDG):

\[ U = \begin{pmatrix}
  c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{i\phi} \\
  -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\phi} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\phi} & s_{23} c_{13} \\
  s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\phi} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\phi} & c_{23} c_{13}
\end{pmatrix} \]
Well motivated:

Baryon asymmetry of the Universe:

\[
\frac{n_B}{n_\gamma}_{WMAP} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}
\]

SM expectation (KM CPV phase):

\[
\frac{n_B}{n_\gamma}_{SM} \approx 10^{-20}
\]
too small by 10 orders-of-mag.

Additional source of CPV is required:

lepton-sector (ν's)?
4th generation quarks)?
(SUSY has ~40 CPV phases)

New Physics CPV searches are ~QCD-uncertainty-free!
New physics probes

Search for deviations from SM predictions from virtual contributions of new heavy particles in loop processes

- Measure CP violating phases and study rare decays of heavy quarks
- Compare to very precise predictions of the SM
  - Uncertainties from QCD is main problem
- Most interesting processes those where SM contribution is suppressed (e.g. FCNC)
  - Effects of New Physics (NP) are large
- Discovery potential for NP extends to mass scales $\gg$ centre-of-mass energy of collision
Flavor physics at CEPC as a super Z factory

On the way to the CEPC proposed as a Higgs factory, it starts with a $Z^0$ factory & very high luminosity, which tests the detector.

Luminosity: $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$

Integrated: 40 ab$^{-1}$ in 2 years

Comparable with super B factory

Advantage at Bs/Bc, tau, D physics
It makes even more sense to measure CP asymmetries in many-body final states, especially in $B_s$ decays

\[
\Delta A_{CP}(B^\pm \rightarrow K^\pm \pi^+ \pi^-) = +0.032 \pm 0.008_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.007_{\psi K^\pm}
\]
\[
\Delta A_{CP}(B^\pm \rightarrow K^\pm K^+ K^-) = -0.043 \pm 0.009_{\text{stat}} \pm 0.003_{\text{syst}} \pm 0.007_{\psi K^\pm}
\]
\[
A_{CP}(B^\pm \rightarrow K^\pm \pi^+ \pi^-)_{\text{regional}} = +0.678 \pm 0.078_{\text{stat}} \pm 0.032_{\text{syst}} \pm 0.007_{\psi K^\pm}
\]
\[
A_{CP}(B^\pm \rightarrow K^\pm K^+ K^-)_{\text{regional}} = -0.226 \pm 0.020_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.007_{\psi K^\pm}
\]

data of even more CKM suppressed $B^+$ decays give [5]:

\[
\Delta A_{CP}(B^\pm \rightarrow \pi^\pm \pi^+ \pi^-) = +0.117 \pm 0.021_{\text{stat}} \pm 0.009_{\text{syst}} \pm 0.007_{\psi K^\pm}
\]
\[
\Delta A_{CP}(B^\pm \rightarrow \pi^\pm K^+ K^-) = -0.141 \pm 0.040_{\text{stat}} \pm 0.018_{\text{syst}} \pm 0.007_{\psi K^\pm}
\]
\[
\Delta A_{CP}(B^\pm \rightarrow \pi^\pm \pi^+ \pi^-)_{\text{regional}} = +0.584 \pm 0.082_{\text{stat}} \pm 0.027_{\text{syst}} \pm 0.007_{\psi K^\pm}
\]
\[
\Delta A_{CP}(B^\pm \rightarrow \pi^\pm K^+ K^-)_{\text{regional}} = -0.648 \pm 0.070_{\text{stat}} \pm 0.013_{\text{syst}} \pm 0.007_{\psi K^\pm}
\]
Recently many CP measurements for 3-body B decays

PHYSICAL REVIEW D 89, 092006 (2014)

Measurement of resonant and CP components in $\bar{B}_{s}^{0} \rightarrow J/\psi \pi^{+}\pi^{-}$ decays

R. Aaij et al.

(LHCb Collaboration)

(Received 25 February 2014; published 14 May 2014)

<table>
<thead>
<tr>
<th>Component</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{0}(980)$</td>
<td>$70.3 \pm 1.5^{+0.4}_{-5.1}$</td>
<td>$92.4 \pm 2.0^{+0.8}_{-16.0}$</td>
</tr>
<tr>
<td>$f_{0}(1500)$</td>
<td>$10.1 \pm 0.8^{+1.1}_{-0.3}$</td>
<td>$9.1 \pm 0.9 \pm 0.3$</td>
</tr>
<tr>
<td>$f_{0}(1790)$</td>
<td>$2.4 \pm 0.4^{+5.0}_{-0.2}$</td>
<td>$0.9 \pm 0.3^{+2.5}_{-0.1}$</td>
</tr>
</tbody>
</table>

$$\frac{\mathcal{B}(\bar{B}_{s}^{0} \rightarrow J/\psi \pi^{+}\pi^{-})}{\mathcal{B}(\bar{B}_{s}^{0} \rightarrow J/\psi \phi)} = (19.79 \pm 0.47 \pm 0.52)\%.$$
In perturbative QCD approach

\[ B^0_{(s)} \rightarrow J/\Psi \pi^+ \pi^- \]

S-wave resonant states .........
Bc Meson/Unique from super B factory

$B_c^+ \rightarrow J/\psi \pi^+$

PRL 109 (2012) 232001, LHCb

Relative production cross section
Consistent with theory calculations
EPJC 38 (2004) 267, Chang & Wu
PRD 89 (2014) 034008, Qiao et al.

$B_c^+ \rightarrow J/\psi \mu^+ \nu \chi$

arXiv: 1401.6932, LHCb

Most precise $B_c$ lifetime measurement

$\tau = 509 \pm 8 \pm 12$ fs
Current new physics signal in B physics

\[ \bar{B} \rightarrow D^{(*)} \tau \bar{\nu} \quad \text{Br} \sim 0.7+1.3 \% \text{ in the SM} \]

Not rare, but two or more missing neutrinos

Data available since 2007 (Belle, BABAR, LHCb)

Theoretical motivation

W.S. Hou and B. Grzadkowski (1992)

SM: gauge coupling
lepton universality

Type-II 2HDM (SUSY)
Yukawa coupling

\[ \propto m_b m_\tau \tan^2 \beta \]
\[ R(X) = \frac{\Gamma(B \rightarrow X\tau\bar{\nu})}{\Gamma(B \rightarrow X(e/\mu)\bar{\nu})} \]

\[ R(D) = 0.421 \pm 0.058 \]
\[ R(D^*) = 0.337 \pm 0.025 \]

\[ \sim 3.5\sigma \]

Y. Sakaki, M.T. A. Tayduganov, R. Watanabe

\[ R(D) = 0.391 \pm 0.041 \pm 0.028 \]
\[ R(D^*) = 0.322 \pm 0.018 \pm 0.012 \]

\[ \sim 3.9\sigma \]

HFAG
Standard model predictions

Theoretical uncertainty: form factors
data from $\bar{B} \to D(\ast) \ell \bar{\nu}$ ($\ell = e, \mu$)
+ HQET or pQCD
+ lattice QCD

$R(D) = 0.296 \pm 0.016$ (Fajfer, Kamenik, Nisandzic)
0.302 $\pm 0.015$ (Sakaki, MT, Tayduganov, Watanabe)
0.299 $\pm 0.011$ (Bailey et al.)

$R(D^\ast) = 0.337^{+0.038}_{-0.037}$ (Fan, Xiao, Wang, Li)
0.391 $\pm 0.041 \pm 0.028$ (Exp. HFAG)

$R(D^\ast) = 0.252 \pm 0.003$ (Fajfer, Kamenik, Nisandzic)
0.252 $\pm 0.004$ (Sakaki, MT, Tayduganov, Watanabe)

0.269$^{+0.021}_{-0.020}$ (Fan, Xiao, Wang, Li)
0.322 $\pm 0.018 \pm 0.012$ (Exp. HFAG)
Charged Higgs boson

predictions of 2HDM II

$\mathcal{R}(D)$

$\mathcal{R}(D^*)$

$\tan\beta/m_{H^+}$ (GeV$^{-1}$)

Charged Higgs excluded at 99.8% CL
How can we test the standard model without solving QCD?
Perturbative calculations

- In principle, all hadronic physics should be calculated by QCD.
- In fact, you can always use QCD to calculate any process, provided you can renormalize the infinities and do all order calculations.
Divergences

- Perturbation calculation means order by order
- Involving loop diagrams
- Therefore divergences unavoidable
- Ultraviolet divergences $\rightarrow$ renormalization
- Infrared divergences? Infrared divergence in virtual corrections should be canceled by real emission
- In exclusive QCD processes $\rightarrow$ factorization
It is very difficult for exclusive processes

- infrared finite seems not possible, no free gluon can be emitted
- Infrared divergence should be absorbed into meson wave function (distribution amplitude)
- This is called 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 $Q$ and the soft dynamic factorize
- The former into hard kernel $H$ and the latter into distribution amplitude $\phi$
- Factorization theorem holds up to all orders in $\alpha_s$, but to certain power in $1/Q$
- $H$ is process-dependent, but calculable
- $\phi$ are universal (process-independent) predictive power of factorization theorem
- In $B$ decays the hard scale $Q$ is just the $b$ quark mass
Hadronic matrix elements calculations

- QCD-methods based on factorization work well for many processes
  - 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**
  - Topological diagrammatic approach

- Work well for most of charmless B decays, except for pi K puzzle etc.
CP Violation in $B \rightarrow \pi \pi (K)$ (real prediction before exp.)

<table>
<thead>
<tr>
<th>CP(%)</th>
<th>FA</th>
<th>BBNS</th>
<th>PQCD</th>
<th>Exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ K^-$</td>
<td>$+9\pm3$</td>
<td>$+5\pm9$</td>
<td>$-17\pm5$</td>
<td>$-9.7\pm1.2$</td>
</tr>
<tr>
<td>$\pi^+ \pi^-$</td>
<td>$-5\pm3$</td>
<td>$-6\pm12$</td>
<td>$+30\pm10$</td>
<td>$+38\pm7$</td>
</tr>
</tbody>
</table>

Annihilation type diagram play a very important role in direct CP violation of B decays by providing the necessary strong phase.

For (V-A)(V-A), left-handed current

pseudo-scalar B requires spins in opposite directions, namely, helicity conservation

annihilation suppression $\sim \frac{1}{m_B} \sim 10\%$

Like $B \rightarrow e \nu_e$
Annihilation-Type diagrams

W annihilation

W exchange

Penguin type annihilation not suppressed

Time-like penguin

Space-like penguin
Pure annihilation type decay

\[ B_s \rightarrow \pi^+\pi^- \]

- Very rare decay predicted in PRD76, 074018 (2008)
- \( BR = (5.7 \pm 1.7) \times 10^{-7} \)
- No one expected to be measured

Time-like penguin
CDF Results

First evidence: $B^0_s \rightarrow \pi^+ \pi^-$

CDF Run II Preliminary $\int L dt = 6.11 \text{ fb}^{-1}$

Later also measured by LHCb

\[
\frac{f_s}{f_d} \times \frac{B(B^0_s \rightarrow \pi^+ \pi^-)}{B(B^0 \rightarrow K^+ \pi^-)} = 0.008 \pm 0.002 \ (\text{stat.}) \pm 0.001 \ (\text{syst.}) .
\]

\[
B(B^0_s \rightarrow \pi^+ \pi^-) = (0.57 \pm 0.15 \ (\text{stat.}) \pm 0.10 \ (\text{syst.})) \times 10^{-6}.
\]

Agreement with pQCD: $0.57^{+0.18}_{-0.16}$ PRD 76, 074018(2008), and $0.42 \pm 0.06$ from Y Li et al., PRD 70, 034009 (2004)
High precision measurements of $B/D$ decays already by BaBar, Belle, BESIII 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. Less predictive.

[Chiang, Senaha, 07’]
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

$$T_c^{DP} = i \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* a_1(\mu) f_P (m_B^2 - m_D^2) F_0^{B \to D}(m_P^2),$$
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.

\[
C_{c}^{DP} = i \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* f_D (m_B^2 - m_P^2) F_0^{B \rightarrow P} (m_D^2) \chi_c e^{i \phi_c^C},
\]

\[
E_{c}^{DP} = i \frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* m_B^2 f_B \frac{f_D(s)}{f_D f_{\pi}} \chi_c e^{i \phi_c^E},
\]
Global Fit for all $B \to DP$, $D^*P$ and $DV$ decays (PRD92, 094016 (2015))

- 31 measured modes induced by $b \to c$ transitions

$$\chi_c^C = 0.48 \pm 0.01, \quad \phi_c^C = (56.6^{+3.2}_{-3.8})^\circ,$$
$$\chi_c^E = 0.024^{+0.002}_{-0.001}, \quad \phi_c^E = (123.9^{+3.3}_{-2.2})^\circ,$$

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

$\chi^2$ 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>$B_{\text{exp}}(\times10^{-4})$</th>
<th>$B_{\text{th}}(\times10^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</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>$D_s^+K^-$</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>$B^-$</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>$B_s^0$</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>$5.9 \pm 0.3 \pm 1.2 \pm 0.3$</td>
<td></td>
</tr>
</tbody>
</table>

| Cabibbo-suppressed $V_{cb}V_{us}^*$ |
|-------|------|------------|-------------------------------|-------------------------------|
| $B^0$ | $D^+K^-$ | $T$ | $1.97 \pm 0.21$ | $2.1 \pm 0.0 \pm 0.4 \pm 0.0$ |
|       | $D^0\bar{K}^0$ | $C$ | $0.5 \pm 0.1$ | $0.4 \pm 0.0 \pm 0.1 \pm 0.0$ |
| $B^-$ | $D^0K^-$ | $T + C$ | $3.70 \pm 0.17$ | $3.8 \pm 0.1 \pm 0.6 \pm 0.1$ |
| $B_s^0$ | $D_s^+K^-$ | $T + E$ | $2.1 \pm 0.0 \pm 0.4 \pm 0.0$ | |
|       | $D^0\eta$ | $\frac{1}{\sqrt{2}}E \cos \phi - C \sin \phi$ | $0.14 \pm 0.01 \pm 0.03 \pm 0.01$ | |
|       | $D^0\eta'$ | $\frac{1}{\sqrt{2}}E \sin \phi + C \cos \phi$ | $0.21 \pm 0.01 \pm 0.04 \pm 0.01$ | |
|       | $D^+\pi^-$ | $E$ | $0.011 \pm 0.001 \pm 0.000 \pm 0.001$ | |
|       | $D^0\pi^0$ | $\frac{1}{\sqrt{2}}E$ | $0.005^{+0.001}_{-0.000} \pm 0.000 \pm 0.001$ | |
\[ B \rightarrow D^*P \]

<table>
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<tr>
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<th>Amplitudes</th>
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<th>( B_{\text{th}}(\times10^{-4}) )</th>
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<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} ± 5.2 ± 0.1</td>
</tr>
<tr>
<td>( D^{*0}\pi^0 )</td>
<td>( \frac{1}{\sqrt{2}}(E - C) )</td>
<td>2.2 ± 0.6</td>
<td>2.8 ± 0.2 ± 0.6 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>( D^{*0}\eta )</td>
<td>( \frac{1}{\sqrt{2}}(C + E) \cos \phi )</td>
<td>2.3 ± 0.6</td>
<td>2.1 ± 0.1 ± 0.4 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>( D^{*0}\eta' )</td>
<td>( \frac{1}{\sqrt{2}}(C + E) \sin \phi )</td>
<td>1.40 ± 0.22</td>
<td>1.4 ± 0.1 ± 0.2 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>( D_{s}^{*+}K^- )</td>
<td>( E )</td>
<td>0.219 ± 0.030</td>
<td>0.22^{+0.03}_{-0.01} ± 0.00 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>( B^- )</td>
<td>( D^{*0}\pi^- )</td>
<td>( T + C )</td>
<td>51.8 ± 2.6</td>
<td>50.7^{+1.5}_{-1.8} ± 7.8 ± 1.4</td>
</tr>
<tr>
<td>( \bar{B}_{s}^0 )</td>
<td>( D_{s}^{*+}\pi^- )</td>
<td>( T )</td>
<td>20 ± 5</td>
<td>27.1 ± 0.0 ± 5.4 ± 0.1</td>
</tr>
<tr>
<td>( D^{*0}K^0 )</td>
<td>( C )</td>
<td></td>
<td>6.6^{+0.3}_{-0.4} ± 1.3 ± 0.7</td>
<td></td>
</tr>
</tbody>
</table>

<p>| Cabibbo-suppressed ( V_{cb}V_{us}^* ) |
|-------|------|------------|-------------------------------|-------------------------------|
| ( \bar{B}^0 ) | ( D^{*+}K^- ) | ( T ) | 2.14 ± 0.16 | 2.0 ± 0.00 ± 0.4 ± 0.0 |
| ( D^{<em>0}\bar{K}^0 ) | ( C ) | 0.36 ± 0.12 | 0.45^{+0.02}<em>{-0.03} ± 0.09 ± 0.05 |
| ( B^- ) | ( D^{*0}K^- ) | ( T + C ) | 4.20 ± 0.34 | 3.8 ± 0.1 ± 0.6 ± 0.1 |
| ( \bar{B}</em>{s}^0 ) | ( D_{s}^{</em>+}K^- ) | ( T + E ) | 1.9 ± 0.0 ± 0.4 ± 0.0 |
| ( D^{*0}\eta ) | ( \frac{1}{\sqrt{2}}E \cos \phi - C \sin \phi ) | 0.15 ± 0.01 ± 0.03 ± 0.02 |
| ( D^{<em>0}\eta' ) | ( \frac{1}{\sqrt{2}}E \sin \phi + C \cos \phi ) | 0.23 ± 0.01 ± 0.04 ± 0.02 |
| ( D^{</em>+}\pi^- ) | ( E ) | &lt; 0.061 | 0.008 ± 0.001 ± 0.000 ± 0.001 |
| ( D^{*0}\pi^0 ) | ( \frac{1}{\sqrt{2}}E ) | | 0.004^{+0.004}_{-0.000} ± 0.000 ± 0.001 |</p>
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<tr>
<td>Cabibbo-favored</td>
<td>$V_{cb}V_{ud}^{*}$</td>
<td>$D^+\rho^-$</td>
<td>$T + E$</td>
<td>$78 \pm 13$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D^0\rho^0$</td>
<td>$\frac{1}{\sqrt{2}}(E - C)$</td>
<td>$3.2 \pm 0.5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D^0\omega$</td>
<td>$\frac{1}{\sqrt{2}}(E + C)$</td>
<td>$2.54 \pm 0.16$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D_s^+K^{*-}$</td>
<td>$E$</td>
<td>$0.35 \pm 0.10$</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$D^0\rho^-$</td>
<td>$T + C$</td>
<td>$134 \pm 18$</td>
<td>$105^{+2}_{-3} \pm 18 \pm 9$</td>
</tr>
<tr>
<td>$B_s^0$</td>
<td>$D_s^+\rho^-$</td>
<td>$T$</td>
<td>$70 \pm 15$</td>
<td>$78.6 \pm 0.0 \pm 15.7 \pm 7.9$</td>
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<td>$D^0K^{*0}$</td>
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<td>Cabibbo-suppressed</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>$D^0K^{*-0}$</td>
<td>$C$</td>
<td>$0.42 \pm 0.06$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D^{-}K^{*-}$</td>
<td>$T + C$</td>
<td>$5.3 \pm 0.4$</td>
</tr>
<tr>
<td>$B_s^0$</td>
<td>$D_s^+K^{*-}$</td>
<td>$T + E$</td>
<td></td>
<td>$4.0^{+0.04}_{-0.03} \pm 0.8 \pm 0.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D^0\phi$</td>
<td>$C$</td>
<td>$0.24 \pm 0.07$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D^+\rho^-$</td>
<td>$E$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D^0\rho^0$</td>
<td>$\frac{1}{\sqrt{2}}E$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D^0\omega$</td>
<td>$\frac{1}{\sqrt{2}}E$</td>
<td></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>$\mathcal{B}_{exp}(\times 10^{-5})$</th>
<th>$\mathcal{B}_{FAT}(\times 10^{-5})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>$V_{cb}V_{ud}$</td>
<td>$D_s^+ K^-$</td>
<td>$E$</td>
<td>$3.45 \pm 0.32$</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$V_{cb}V_{us}^*$</td>
<td>$D_s^*+ K^-$</td>
<td>$E$</td>
<td>$\propto \chi^E e^{i\phi^E}$</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$V_{cb}V_{us}^*$</td>
<td>$D_s^+ K^{*-}$</td>
<td>$E$</td>
<td>$3.5 \pm 1.0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meson</th>
<th>Mode</th>
<th>Amplitudes</th>
<th>$\mathcal{B}_{exp}(\times 10^{-3})$</th>
<th>$\mathcal{B}_{FAT}(\times 10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$</td>
<td>$V_{cb}V_{ud}$</td>
<td>$D_s^+ \pi^-$</td>
<td>$T$</td>
<td>$3.04 \pm 0.23$</td>
</tr>
<tr>
<td>$B_s^0$</td>
<td>$V_{cb}V_{us}^*$</td>
<td>$D_s^*+ \pi^-$</td>
<td>$T$</td>
<td>$2.0 \pm 0.5$</td>
</tr>
<tr>
<td>$B_s^0$</td>
<td>$V_{cb}V_{us}^*$</td>
<td>$D_s^+ \rho^-$</td>
<td>$T$</td>
<td>$7.0 \pm 1.5$</td>
</tr>
</tbody>
</table>

36
Global fit for hadronic D decays

- 12 free parameters are extracted from 28 experimental data of D->PP branching ratios

\[ \Lambda = 0.59 \text{ GeV}, \quad \chi_{n_f} = -0.84, \quad \chi_q^E = 0.09, \quad \chi_s^E = 0.19, \quad \chi_q^A = 0.10, \quad \chi_s^A = 0.16, \]
\[ S_\pi = -0.66, \quad \phi = -0.55, \quad \phi_q^E = 4.90, \quad \phi_s^E = 4.05, \quad \phi_q^A = 3.73, \quad \phi_s^A = 3.36, \]

\[ \chi^2/d.o.f = 8.1 \]

- \( \Lambda \) describes the soft momentum in D meson
- The value of Glauber phase is consistent with the value extracted from B->\( \pi K \) data, resolving the puzzle for direct CP asymmetry in this mode

[H.n Li, S. Mishima, 0901.1272]
Topology diagrams for BRs

- According to **weak interactions** and flavor flows
- Include **all strong interaction effects**, involving final state interaction (FSI) effects
- Magnitude and phase are introduced to each topology
- This is a **complete set**
- **Penguins are neglected for BRs** due to suppression of CKM matrix elements
Evolution scale

- Important flavor SU(3) breaking effects
- Non-negligible mass ratios $m_{K,\eta(1)}/m_D$
- Suggested by the PQCD approach, the scale is set to the energy release depending on masses of final states

$$
\mu = \sqrt{\Lambda m_D (1 - r_2^2)}, \quad r_2 = \frac{m_{P2}^2}{m_D^2}
$$

- $\Lambda$: the momentum of soft degrees of freedom, a free parameter to be determined

$$
a_1(\mu) = C_2(\mu) + \frac{C_1(\mu)}{N_c}, \\
a_2(\mu) = \left(C_1(\mu) + \frac{C_2(\mu)}{N_c} \chi_{nf}\right)e^{i\phi},
$$
Singly Cabibbo-suppressed decays $(10^{-3})$, better agreement with data

<table>
<thead>
<tr>
<th>Modes</th>
<th>Br(FSI)</th>
<th>Br(diagram)</th>
<th>Br(pole)</th>
<th>Br(exp)</th>
<th>Br(this work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to \pi^+\pi^-$</td>
<td>1.59</td>
<td>2.24±0.10</td>
<td>2.2 ± 0.5</td>
<td>1.45±0.05</td>
<td>1.44</td>
</tr>
<tr>
<td>$D^0 \to K^+K^-$</td>
<td>4.56</td>
<td>1.92±0.08</td>
<td>3.0 ± 0.8</td>
<td>4.07±0.10</td>
<td>4.19</td>
</tr>
<tr>
<td>$D^0 \to K^0\overline{K}^0$</td>
<td>0.93</td>
<td>0</td>
<td>0.3 ± 0.1</td>
<td>0.320±0.038</td>
<td>0.35</td>
</tr>
<tr>
<td>$D^0 \to \pi^0\pi^0$</td>
<td>1.16</td>
<td>1.35±0.05</td>
<td>0.8 ± 0.2</td>
<td>0.81±0.05</td>
<td>0.55</td>
</tr>
<tr>
<td>$D^0 \to \pi^0\eta$</td>
<td>0.58</td>
<td>0.75±0.02</td>
<td>1.1 ± 0.3</td>
<td>0.68±0.07</td>
<td>0.94</td>
</tr>
<tr>
<td>$D^0 \to \pi^0\eta'$</td>
<td>1.7</td>
<td>0.74±0.02</td>
<td>0.6 ± 0.2</td>
<td>0.91±0.13</td>
<td>0.64</td>
</tr>
<tr>
<td>$D^0 \to \eta\eta$</td>
<td>1.0</td>
<td>1.44±0.08</td>
<td>1.3 ± 0.4</td>
<td>1.67±0.18</td>
<td>1.48</td>
</tr>
<tr>
<td>$D^0 \to \eta\eta'$</td>
<td>2.2</td>
<td>1.19±0.07</td>
<td>1.1 ± 0.1</td>
<td>1.05±0.26</td>
<td>1.52</td>
</tr>
<tr>
<td>$D^+ \to \pi^+\pi^0$</td>
<td>1.7</td>
<td>0.88±0.10</td>
<td>1.0 ± 0.5</td>
<td>1.18±0.07</td>
<td>0.88</td>
</tr>
<tr>
<td>$D^+ \to K^+\overline{K}^0$</td>
<td>8.6</td>
<td>5.46±0.53</td>
<td>8.4 ± 1.6</td>
<td>6.12±0.22</td>
<td>5.97</td>
</tr>
<tr>
<td>$D^+ \to \pi^+\eta$</td>
<td>3.6</td>
<td>1.48±0.26</td>
<td>1.6 ± 1.0</td>
<td>3.54±0.21</td>
<td>3.37</td>
</tr>
<tr>
<td>$D^+ \to \pi^+\eta'$</td>
<td>7.9</td>
<td>3.70±0.37</td>
<td>5.5 ± 0.8</td>
<td>4.68±0.29</td>
<td>4.54</td>
</tr>
<tr>
<td>$D^+_S \to \pi^0K^+$</td>
<td>1.6</td>
<td>0.86±0.09</td>
<td>0.5 ± 0.2</td>
<td>0.62±0.23</td>
<td>0.65</td>
</tr>
<tr>
<td>$D^+_S \to \pi^+K^0$</td>
<td>4.3</td>
<td>2.73±0.26</td>
<td>2.8 ± 0.6</td>
<td>2.52±0.27</td>
<td>2.21</td>
</tr>
<tr>
<td>$D^+_S \to K^+\eta$</td>
<td>2.7</td>
<td>0.78±0.09</td>
<td>0.8 ± 0.5</td>
<td>1.76±0.36</td>
<td>1.00</td>
</tr>
<tr>
<td>$D^+_S \to K^+\eta'$</td>
<td>5.2</td>
<td>1.07±0.17</td>
<td>1.4 ± 0.4</td>
<td>1.8±0.5</td>
<td>1.92</td>
</tr>
<tr>
<td>Modes</td>
<td>diagrams</td>
<td>Br(FSI)</td>
<td>Br(diagrammatic)</td>
<td>Br(pole)</td>
<td>Br(FAT)</td>
</tr>
<tr>
<td>--------------</td>
<td>----------</td>
<td>----------</td>
<td>------------------</td>
<td>----------</td>
<td>---------</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^+ K^{*-}$</td>
<td>$T_V, E_P$</td>
<td>4.69</td>
<td>5.91 ± 0.70</td>
<td>3.1 ± 1.0</td>
<td>7.12</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^0 K^{*0}$</td>
<td>$C_P, E_P$</td>
<td>3.49</td>
<td>2.82 ± 0.34</td>
<td>2.9 ± 1.0</td>
<td>3.51</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^0 \rho^0$</td>
<td>$C_V, E_V$</td>
<td>0.88</td>
<td>1.54 ± 1.15</td>
<td>1.7 ± 0.7</td>
<td>1.28</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^0 \omega$</td>
<td>$C_V, E_V$</td>
<td>2.16</td>
<td>2.26 ± 1.38</td>
<td>2.5 ± 0.7</td>
<td>2.23</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^0 \phi$</td>
<td>$E_P$</td>
<td>0.90</td>
<td>0.868 ± 0.139</td>
<td>0.8 ± 0.2</td>
<td>0.818</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^- \rho^+$</td>
<td>$T_P, E_V$</td>
<td>11.19</td>
<td>10.8 ± 2.2</td>
<td>8.8 ± 2.2</td>
<td>9.80</td>
</tr>
<tr>
<td>$D^0 \rightarrow \eta K^0$</td>
<td>$C_P, E_P, E_V$</td>
<td>0.51</td>
<td>0.96 ± 0.32</td>
<td>0.7 ± 0.2</td>
<td>1.00</td>
</tr>
<tr>
<td>$D^0 \rightarrow \eta' K^0$</td>
<td>$C_P, E_P, E_V$</td>
<td>0.005</td>
<td>0.012 ± 0.003</td>
<td>0.016 ± 0.005</td>
<td>0.015</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^0 K^{*0}$</td>
<td>$C_P$</td>
<td>0.64</td>
<td>1.83 ± 0.49</td>
<td>1.4 ± 1.3</td>
<td>1.81</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^0 \rho^+$</td>
<td>$T_P, C_V$</td>
<td>11.77</td>
<td>9.2 ± 6.7</td>
<td>15.1 ± 3.8</td>
<td>6.0</td>
</tr>
<tr>
<td>$D^+_s \rightarrow \pi^+ \rho^0$</td>
<td>$A_P, A_V$</td>
<td>0.080</td>
<td>0.4 ± 0.4</td>
<td>0.026</td>
<td>0.02 ± 0.012</td>
</tr>
<tr>
<td>$D^+_s \rightarrow \pi^+ \omega$</td>
<td>$A_P, A_V$</td>
<td>0.0</td>
<td>0</td>
<td>0.25</td>
<td>0.25 ± 0.07</td>
</tr>
<tr>
<td>$D^+_s \rightarrow \pi^+ \phi$</td>
<td>$T_V$</td>
<td>2.89</td>
<td>4.38 ± 0.35</td>
<td>4.3 ± 0.6</td>
<td>3.1</td>
</tr>
<tr>
<td>$D^+_s \rightarrow \pi^0 \rho^+$</td>
<td>$A_P, A_V$</td>
<td>0.080</td>
<td>0.4 ± 0.4</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>$D^+_s \rightarrow K^+ K^{*-}$</td>
<td>$C_P, A_V$</td>
<td>3.86</td>
<td>4.2 ± 1.7</td>
<td>4.12</td>
<td>3.95 ± 0.2</td>
</tr>
<tr>
<td>$D^+_s \rightarrow K^0 K^{*+}$</td>
<td>$C_V, A_P$</td>
<td>3.37</td>
<td>1.0 ± 0.6</td>
<td>4.4</td>
<td>5.4 ± 1.2</td>
</tr>
<tr>
<td>$D^+_s \rightarrow \eta \rho^+$</td>
<td>$T_P, A_P, A_V$</td>
<td>9.49</td>
<td>8.3 ± 1.3</td>
<td>6.5</td>
<td>8.9 ± 0.8</td>
</tr>
<tr>
<td>$D^+_s \rightarrow \eta' \rho^+$</td>
<td>$T_P, A_P, A_V$</td>
<td>2.61</td>
<td>3.0 ± 0.5</td>
<td>2.3</td>
<td>12.5 ± 2.2</td>
</tr>
</tbody>
</table>

Penguin parameterization

- Use the long-distance hadronic parameters fixed by the data of branching ratios
- Try to formulate penguin contribution without introducing additional free parameters
- The tree operators are all $(V-A)(V-A)$
- For penguins, the hadronic matrix elements with $(V-A)(V-A)$ operators are the same as tree level operators
Predictions of Direct CP asymmetries

<table>
<thead>
<tr>
<th>Modes</th>
<th>(a_{\text{CP}}) (FSI)</th>
<th>(a_{\text{CP}}) (diagram)</th>
<th>(a_{\text{CP}}^{\text{tree}})</th>
<th>(a_{\text{CP}}^{\text{tot}}) ((\times 10^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^0 \to \pi^+ \pi^-)</td>
<td>0.02±0.01</td>
<td>0.86</td>
<td>0</td>
<td>0.74</td>
</tr>
<tr>
<td>(D^0 \to K^+ K^-)</td>
<td>0.13±0.8</td>
<td>-0.48</td>
<td>0</td>
<td>-0.54</td>
</tr>
<tr>
<td>(D^0 \to \pi^0 \pi^0)</td>
<td>-0.54±0.31</td>
<td>0.85</td>
<td>0</td>
<td>0.26</td>
</tr>
<tr>
<td>(D^0 \to K^0 \overline{K}^0)</td>
<td>-0.28 ± 0.16</td>
<td>0</td>
<td>0.69</td>
<td>0.90</td>
</tr>
<tr>
<td>(D^0 \to \pi^0 \eta)</td>
<td>1.43±0.83</td>
<td>-0.16</td>
<td>-0.29</td>
<td>-0.61</td>
</tr>
<tr>
<td>(D^0 \to \pi^0 \eta')</td>
<td>-0.98±0.47</td>
<td>-0.01</td>
<td>0.43</td>
<td>1.67</td>
</tr>
<tr>
<td>(D^0 \to \eta \eta)</td>
<td>0.50±0.29</td>
<td>-0.71</td>
<td>0.29</td>
<td>0.18</td>
</tr>
<tr>
<td>(D^0 \to \eta \eta')</td>
<td>0.28 ± 0.16</td>
<td>0.25</td>
<td>-0.30</td>
<td>0.97</td>
</tr>
<tr>
<td>(D^+ \to \pi^+ \pi^0)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-0.23</td>
</tr>
<tr>
<td>(D^+ \to K^+ \overline{K}^0)</td>
<td>-0.51±0.30</td>
<td>-0.38</td>
<td>-0.08</td>
<td>-0.93</td>
</tr>
<tr>
<td>(D^+ \to \pi^+ \eta)</td>
<td>-0.65</td>
<td>-0.46</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>(D^+ \to \pi^+ \eta')</td>
<td>0.41</td>
<td>0.30</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td>(D_S^+ \to \pi^0 K^+)</td>
<td>0.88</td>
<td>0.17</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>(D_S^+ \to \pi^+ K^0)</td>
<td>0.52</td>
<td>-0.01</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>(D_S^+ \to K^+ \eta)</td>
<td>-0.19</td>
<td>0.75</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>(D_S^+ \to K^+ \eta')</td>
<td>-0.41</td>
<td>-0.48</td>
<td>1.83</td>
<td></td>
</tr>
</tbody>
</table>
LHCb combination

<table>
<thead>
<tr>
<th>Type</th>
<th>Expression</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semileptonic</td>
<td>$\Delta A_{CP} = (+0.49 \pm 0.30^{\text{stat.}} \pm 0.14^{\text{syst.}}) %$</td>
<td></td>
</tr>
<tr>
<td>Prompt (preliminary)</td>
<td>$\Delta A_{CP} = (-0.34 \pm 0.15^{\text{stat.}} \pm 0.10^{\text{syst.}}) %$</td>
<td></td>
</tr>
</tbody>
</table>

- The two measurements are compatible at the 3% level
  - $\chi^2 = 4.85$
- Naive average (neglecting indirect CP violation)
  \[
  \Delta A_{CP, LHCb} = (-0.15 \pm 0.16) \%
  \]
Charmless B decays

- **Famous pi K puzzle** not well explained
- **Tree + penguin contribution**, complicated

(a) $T$

(b) $C$

(c) $A$

(d) $E$

(c) $P_T$

(b) $P_C$

(c) $P_E$

(d) $P_A$
Large color suppressed tree diagram contribution together with large strong phase also expected

\[
\chi^C = 0.61 \pm 0.08, \phi^C = -1.73 \pm 0.09, \\
\chi^E = 0.068 \pm 0.004, \phi^E = 2.97 \pm 0.15, \\
\chi^A = 0, \phi^A = 0 \\
\chi^{PC} = 0.035 \pm 0.007, \phi^{PC} = -1.99 \pm 0.27, \\
\chi^{PE} = 0, \phi^{PE} = 0, \\
\chi^{PA} = -0.018 \pm 0.002, \phi^{PA} = -2.06 \pm 0.09 \\
\chi_{EW}^{PC} = 0.015 \pm 0.006, \phi_{EW}^{PC} = 2.02 \pm 0.39,
\]

\[
\chi^2/\text{d.o.f} = 16/(31 - 10) = 0.76
\]
## Preliminary results

<table>
<thead>
<tr>
<th>Modes</th>
<th>Amplitude</th>
<th>$B_r$</th>
<th>$B_r^{(exp)}$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \to \pi^- \pi^0$</td>
<td>$T + C + PT + PC_{EW}$</td>
<td>5.53232</td>
<td>5.5 ± 0.4</td>
<td>0.00652872</td>
</tr>
<tr>
<td>$B^- \to \pi^- \pi^0$</td>
<td>$Acp$</td>
<td>0.041999</td>
<td>0.03 ± 0.04</td>
<td>0.0899848</td>
</tr>
<tr>
<td>$B^- \to \pi^- \eta$</td>
<td>$T + C + PT + PC + PA + PC_{EW}$</td>
<td>3.92657</td>
<td>4.02 ± 0.27</td>
<td>0.11974</td>
</tr>
<tr>
<td>$B^- \to \pi^- \eta$</td>
<td>$Acp$</td>
<td>-0.151074</td>
<td>-0.14 ± 0.07</td>
<td>0.0250255</td>
</tr>
<tr>
<td>$B^- \to \pi^- \eta'$</td>
<td>$T + C + PT + PC + PA + PC_{EW}$</td>
<td>3.51146</td>
<td>2.7 ± 0.9</td>
<td>0.812914</td>
</tr>
<tr>
<td>$B^- \to \pi^- \eta'$</td>
<td>$Acp$</td>
<td>0.096414</td>
<td>0.06 ± 0.16</td>
<td>0.051796</td>
</tr>
<tr>
<td>$B^- \to \pi^- K^0$</td>
<td>$PT + PA$</td>
<td>23.4716</td>
<td>23.7 ± 0.8</td>
<td>0.0815354</td>
</tr>
<tr>
<td>$B^- \to \pi^- K^0$</td>
<td>$Acp$</td>
<td>0.00472197</td>
<td>-0.017 ± 0.016</td>
<td>1.84314</td>
</tr>
<tr>
<td>$B^- \to \eta K^-$</td>
<td>$T + C + PT + PC + PA + PC_{EW}$</td>
<td>12.5717</td>
<td>12.9 ± 0.5</td>
<td>0.431047</td>
</tr>
<tr>
<td>$B^- \to \eta K^-$</td>
<td>$Acp$</td>
<td>0.0470468</td>
<td>0.037 ± 0.021</td>
<td>0.228883</td>
</tr>
<tr>
<td>$B^- \to \eta' K^-$</td>
<td>$T + C + PT + PC + PA + PC_{EW}$</td>
<td>2.00155</td>
<td>2.4 ± 0.4</td>
<td>0.992275</td>
</tr>
<tr>
<td>$B^- \to \eta' K^-$</td>
<td>$Acp$</td>
<td>-0.231809</td>
<td>-0.37 ± 0.08</td>
<td>2.98385</td>
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<tr>
<td>$B^- \to \eta' K^-$</td>
<td>$T + C + PT + PC + PA + PC_{EW}$</td>
<td>70.4999</td>
<td>70.6 ± 2.5</td>
<td>0.00160229</td>
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<tr>
<td>$B^- \to \eta' K^-$</td>
<td>$Acp$</td>
<td>-0.000968861</td>
<td>0.013 ± 0.017</td>
<td>0.675187</td>
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<tr>
<td>$B^- \to K^- K^0$</td>
<td>$PT + PA$</td>
<td>1.35493</td>
<td>1.31 ± 0.17</td>
<td>0.0698523</td>
</tr>
<tr>
<td>$B^- \to K^- K^0$</td>
<td>$Acp$</td>
<td>-0.0788943</td>
<td>-0.21 ± 0.14</td>
<td>0.876974</td>
</tr>
<tr>
<td>$B^0 \to \pi^+ \pi^-$</td>
<td>$T + E + PT + PA$</td>
<td>5.08659</td>
<td>5.12 ± 0.19</td>
<td>0.0309292</td>
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<tr>
<td>$B^0 \to \pi^+ \pi^-$</td>
<td>$Acp$</td>
<td>0.273558</td>
<td>0.31 ± 0.05</td>
<td>0.531213</td>
</tr>
<tr>
<td>$B^0 \to \pi^+ \pi^-$</td>
<td>$Scp$</td>
<td>-0.619095</td>
<td>-0.66 ± 0.06</td>
<td>0.464778</td>
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<tr>
<td>$B^0 \to \pi^+ K^-$</td>
<td>$T + PT + PA$</td>
<td>20.0407</td>
<td>19.6 ± 0.5</td>
<td>0.77694</td>
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<tr>
<td>$B^0 \to \pi^+ K^-$</td>
<td>$Acp$</td>
<td>-0.0821164</td>
<td>-0.082 ± 0.006</td>
<td>0.000376224</td>
</tr>
<tr>
<td>$B^0 \to \pi^0 \pi^0$</td>
<td>$C + E + PT + PA + PC_{EW}$</td>
<td>2.01526</td>
<td>1.91 ± 0.22</td>
<td>0.228932</td>
</tr>
</tbody>
</table>
Charmless $B_c$ decays

Only annihilation type diagrams contribute, and experimentally not accessible by super $B$ factory

FIG. 1. Typical Feynman diagrams for two-body nonleptonic charmless $B_c$ decays.
Results from pQCD based on $k_T$ factorization

<table>
<thead>
<tr>
<th>Decay modes ( (\Delta S = 0) )</th>
<th>BRs ( (10^{-8}) )</th>
<th>Decay modes ( (\Delta S = 1) )</th>
<th>BRs ( (10^{-8}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_c \to \pi^+ \pi^0 )</td>
<td>0</td>
<td>( B_c \to \pi^+ K^0 )</td>
<td>( 4.0^{+1.0}<em>{-0.6}(m_c)+0.5</em>{-0.3}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to \pi^+ \eta )</td>
<td>( 22.8^{+6.9}_{-4.6}(m_c)+7.2(a_i)+3.4(m_0) )</td>
<td>( B_c \to K^+ \eta )</td>
<td>( 0.6^{+1.0}<em>{-0.6}(m_c)+0.5</em>{-0.3}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to \pi^+ \eta' )</td>
<td>( 15.3^{+4.6}_{-3.1}(m_c)+4.8(a_i)+2.8(m_0) )</td>
<td>( B_c \to K^+ \eta' )</td>
<td>( 5.7^{+1.0}<em>{-0.9}(m_c)+0.5</em>{-0.3}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to K^+ \bar{K}^0 )</td>
<td>( 24.0^{+2.4}_{-0.0}(m_c)+7.3(a_i)+6.8(m_0) )</td>
<td>( B_c \to K^+ \pi^0 )</td>
<td>( 2.0^{+1.0}<em>{-0.5}(m_c)+0.5</em>{-0.3}(m_0) )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay modes ( (\Delta S = 0) )</th>
<th>BRs ( (10^{-7}) )</th>
<th>Decay modes ( (\Delta S = 1) )</th>
<th>BRs ( (10^{-8}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_c \to \pi^+ \rho^0 )</td>
<td>( 1.7^{+0.1}_{-0.0}(m_c)+0.1(a_i)+0.5(m_0) )</td>
<td>( B_c \to K^+ \rho^0 )</td>
<td>( 3.1^{+0.6}<em>{-0.8}(m_c)+0.5</em>{-0.3}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to K^0 K^{*+} )</td>
<td>( 1.8^{+0.7}_{-0.1}(m_c)+4.1(a_i)+0.5(m_0) )</td>
<td>( B_c \to K^0 \rho^+ )</td>
<td>( 6.1^{+1.3}<em>{-1.5}(m_c)+2.5</em>{-0.9}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to \pi^+ \omega )</td>
<td>( 5.8^{+1.4}_{-2.2}(m_c)+1.1(a_i)+0.5(m_0) )</td>
<td>( B_c \to K^+ \omega )</td>
<td>( 2.3^{+1.8}<em>{-1.2}(m_c)+0.5</em>{-0.3}(m_0) )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay modes ( (\Delta S = 0) )</th>
<th>BRs ( (10^{-7}) )</th>
<th>Decay modes ( (\Delta S = 1) )</th>
<th>BRs ( (10^{-8}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_c \to \rho^+ \pi^0 )</td>
<td>( 0.5^{+0.1}_{-0.2}(m_c)+0.5(a_i)+0.3(m_0) )</td>
<td>( B_c \to K^{*0} \pi^+ )</td>
<td>( 3.3^{+0.7}<em>{-0.4}(m_c)+0.5</em>{-0.2}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to \rho^+ \eta )</td>
<td>( 5.4^{+1.2}_{-1.4}(m_c)+2.1(a_i)+0.5(m_0) )</td>
<td>( B_c \to K^{*+} \pi^0 )</td>
<td>( 1.6^{+0.3}<em>{-0.0}(m_c)+0.5</em>{-0.2}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to \rho^+ \eta' )</td>
<td>( 3.6^{+1.4}_{-0.8}(m_c)+0.9(a_i)+0.5(m_0) )</td>
<td>( B_c \to K^{*+} \eta )</td>
<td>( 0.9^{+0.1}<em>{-0.0}(m_c)+0.5</em>{-0.2}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to K^{*0} K^+ )</td>
<td>( 10.0^{+5.0}_{-3.0}(m_c)+1.7(a_i)+0.8(m_0) )</td>
<td>( B_c \to K^{*+} \eta' )</td>
<td>( 3.8^{+1.1}<em>{-0.6}(m_c)+0.5</em>{-0.2}(m_0) )</td>
</tr>
<tr>
<td>( B_c \to K^{*0} K^+ )</td>
<td>( 10.0^{+5.0}_{-3.0}(m_c)+1.7(a_i)+0.8(m_0) )</td>
<td>( B_c \to \phi K^+ )</td>
<td>( 5.6^{+1.1}<em>{-0.9}(m_c)+0.5</em>{-0.3}(m_0) )</td>
</tr>
</tbody>
</table>
Summary

- High-energy QCD processes must involve both perturbative and nonperturbative dynamics.
- At leading power, the two dramatically different dynamics factorize.
- Theoretical study of non-leptonic D/B meson decays making great improvement with helping from rich experimental data.
- Flavor sector has only been tested at the 10% level and can be done much better.
- We are still waiting for a clear New physics signal in the heavy flavor sector.
Thanks!