# Theoretical Aspects of $\gamma$ with $B \to D^0(^*)K(^*)$

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# OUTLINE

1. Introduction & basic ideas

2. Main points

   - Multitude of possible strategies

   - Potentially very clean and can have large CP asymmetries

   - An Illustrative numerical study

   - Possible role of charm factory

3. Summary and Outlook

Note $(\phi_1, \phi_2, \phi_3) \equiv (\beta, \alpha, \gamma)$

## Introducton: Clean unitarity angles from FS with $D^0(\bar{D}^0)$

In $B^{\pm}, B^0, \bar{B}^0$ decays final states containing $D^0(\bar{D}^0)$ are of crucial importance:

- $\gamma$ via (DIRCP) $B^{\pm} \to$ "$K^{\pm}$" $+ D^0, \bar{D}^0$ followed by $D^0$ and $\bar{D}^0$ decays to common final states (e.g. $K^+\pi^-$, $K_s\omega$...)
- $\alpha$ **AND** $\beta$ via (TDCP) $B^0(\bar{B}^0) \to$ "$K^0$" $D^0, \bar{D}^0$ (again) followed by $D^0$ and $\bar{D}^0$ decays to common FS.
- Multitude of common FS of $D^0$,$\bar{D}^0$ should greatly fecilitate the analysis esp. wrt the discrete ambiguities and the final error.
- Furthermore, "$K^{\pm}$" $\equiv K^{\pm}, K^{*\pm}$ and similarly for "$K^0$".
- Note charged and neutral B (in DIRCP and TDCP) are using the same common FS of $D^0, \bar{D}^0$,therefore needed information e.g. FS phases (possibly obtainable from charm factories) feciltates analysis in both cases.

## Basic Ideas

### Gronau-London-Wyler construction

Can extract $\gamma$ cleanly by measuring 5 of the following 6 quantities:

(1) A($B^+ \to D^0_{CP} K^+$); (2) A($B^+ \to D^0 K^+$)

(3) A($B^+ \to \bar{D}^0 K^+$); (4) A($B^- \to D^0_{CP} K^-$)

(5) A($B^- \to \bar{D}^0 K^-$); (6)A($B^- \to D^0 K^-$)

Flavor tagging of $\bar{D}^0$ in (say) $B^- \to \bar{D}^0 K^-$ is big challenge:

- semi-leptonic tag suffers from serious background from prompt semi-leptonic decays of B
- Hadronic tag receives significant contamination from doubly caibbo suppresed decays
- One may try to by-pass the difficulty by taking the needed BR from theory....This is a fine interim measure but NOT drsirable in the long-run as its extremely important that we prepare ourselves for small deviations from the SM

- The interference between direct and DCS $D^0$ decays is near maximal as its between $[CLA(B - decay)] \times [DCS(D^0 - decay)]$ versus $[CLS(B - decay)] \times [CBA(D^0 - decay)]$
  Crudely this goes as $\frac{V_{ub}}{N_c} \times \frac{1}{V_{cb}V_{cd}V_{us}} \approx 70\%$. Therefore, in the ADS approach one tries to cash on these DCS modes of $D^0$ that are expected to selectively exhibit largish CP asymmetries to extract a clean $\gamma$

- Grossman, Ligeti and Soffer [GLS] studied an important variation recently which uses singly-cabibbo-suppressed [SCS] (common) decay modes of $D^0$ and $\bar{D}^0$. This are expected to have larger BR but smaller asymmetries (compared to DCS)

- In principle any 2 common decay modes [say $F_1$ and $F_2$] of $D^0$ and $\bar{D}^0$ suffice as then there are 4 observables (i.e. BR's of $B^\pm \to$ "$K^\pm$"$[D^0(\bar{D}^0) \to F_1, F_2]$) and there are 4-parameters (i.e. the "unmeasurable" BR($B^- \to$ "$K^-$" $\bar{D}^0$, 2 strong phases and the GEM $\gamma$ that we are after). However,to overcome discrete ambiguities and improve determination redundacy is valuable

## Multitude of Common Final States of $D^0$,$\bar{D}^0$

1. **CPES** [Gronau-London-Wyler],Cabibbo-allowed(CBA) or singly-Cabibbo- suppressed (SCBS) e.g. $K_s$ ($\pi^0$,$\eta$,$\eta'$,$\omega$, $\rho^0$); $\pi^+\pi^-$, $K^+K^-$.... Have smallish asymmetry but largish eff. BR
2. **CPNES** [Grossman-Ligeti-Soffer], SCBS, e.g. $K^+K^{*-}$,$\pi^+$($\rho^-$,$a_1^-$)... Have smallish asymmetries but largish eff. Br
3. **CPNES** [Atwood-Dunietz-Soni], doubly-Cabibbo-suppressed (DCBS) e.g. $K^+$($\pi^-$,$a_1^-$,$\rho^-$); $K^{*+}$($\pi^-$...)... Have largish asymmetry but smallish eff. Br

## Additional avenues for optimization

- In the original B decay, $K^\pm$ may be replaced with $K^{*\pm}$
- Furthermore, an even more interesting and potentially powerful possibilty is that $D^0$ may also be replaced by $D^{0*}$

Just these 2 generalizations improve the potential of the method dramatically; although many other variations are also possible.

## Additional Variations

1. **Three body modes via a Dalitz analysis**

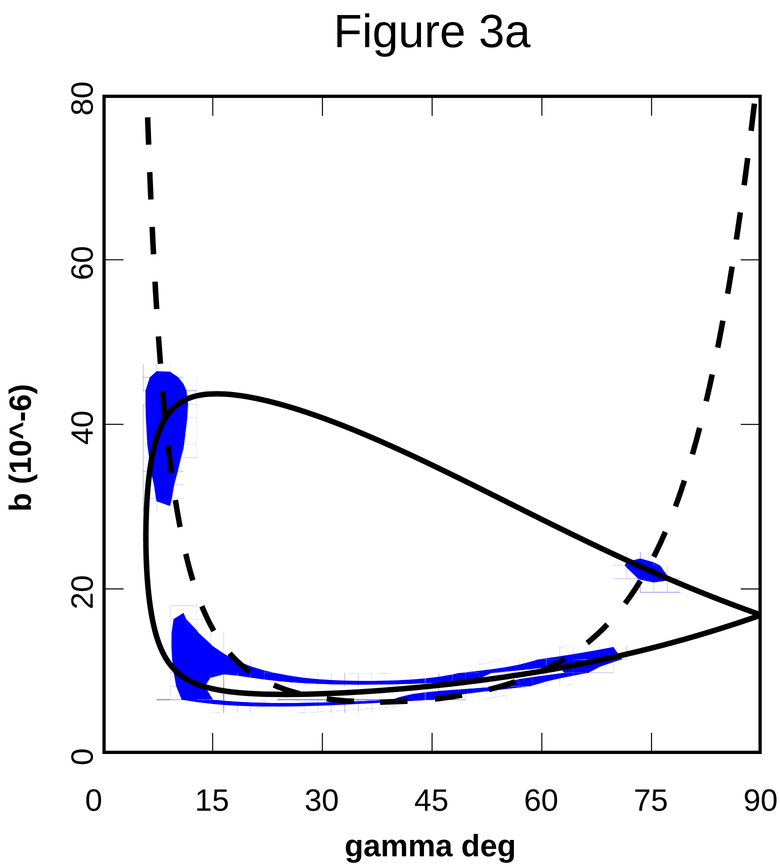
   Also intially suggested by ADS as a powerful way to get $\gamma$ as each point in the Dalitz plot can then be viewed as a distinct mode. For an explicit case study using $D^0 \to K^+\pi^-\pi^0$ as an example, see ADS, hep-ph/0008090

2. **Other multibody modes**

   - $B^\pm \to K^\pm D^0 \pi^0$ suggested by Aleksan,Petersen and Soffer, hep-ph/0209194
   - $B^\pm \to K^\pm [D^0 \to$ multibody], Giri, Grossman, Soffer and Zupan
   - $B^\pm \to K^\pm [D^0 \to$ **"moreclusive"**], Atwood and Soni hep-ph/0206045
   - Charm factory can be especially helpful for moreclusive analysis, see Atwood and Soni, hep-ph/0304085

$\Rightarrow$ **Therefore very high degree of redundancy should become available.**

## Discrete ambiguities aglore with only 2 modes




The likelihood distribution is shown as a function of $\gamma$ and $b(K^*)$ assuming that $N_{B\bar{B}}(acceptance) = 10^8$ and assuming only the $K^+\pi^-$ and $K_s\pi^0$ modes of $D^0$,$\bar{D}^0$ are measured in $B^\pm \to K^\pm D^0, \bar{D}^0$ decays. The outer edge of the the shaded regions correspond to $90\%$ confidence while the inner edge corresponds to $68\%$ confidence. The solid line shows solution for $K^+\pi^-$ only and dashed one for $K_s\pi^0$ only. From Atwood,Dunietz,Soni,hep-ph/0008090

## Illustrative Study with $(4-8)\times 10^8$ $B\bar{B}\,pairs$

[See Atwood and Soni, AMES-HET-03-05; BNL-HET-03-23; **WIP** to be published]

**Aim: Explore effectiveness of combining various strategies**

With data samples likely to be available in the near future a single strategy is unlikely to work; besides fixed sample of $B\bar{B}\,pairs$ will contain CPES, DCS as well as SCS modes....

**ASSUME(1)**: detection efficiencies for $\pi^{\pm}$,$K^{\pm}$ and $\pi^0$ $(\eta)$ is 0.95,0.8 and 0.5 respectively

**ASSUME(2)**: Acceptance cuts to discriminate against continuum backgrounds will reduce the final acceptance by factor of $5-10$.

**ASSUME(3)**: For now ignore $D^0\bar{D}^0$ mixing (see Appendix to paper)

## Important features of the study

- Altogether four types of intial (charged) B decays are considered: (1) $B^\pm \to K^\pm D^0$; (2) $B^\pm \to K^{*\pm} D^0$; (3) $B^\pm \to K^\pm D^{0*}$; and (4) $B^\pm \to K^{*\pm} D^{0*}$
- When $D^{0*}$ is involved we take $D^{0*} \to D^0 + \gamma(\pi)$ before the $D^0$ goes to the hadronic FS
- The $D^0$ is considered to decay into 6 types of possible FS: (1) $K^+\pi^-$; (2) $K^{*+} + \pi^-$; (3) $K^+\pi^- + n\pi$; (4) CP odd FS; (5)$K^* + K^-$ and (6) $K^{*-}K^+$
- For each of the 4 $B^\pm$ decays we take the six subsequent $D^0$ decays to have the following number of events:
  $K^+\pi^-\,(25)$ ;$K^{*+}\pi^-\,(14)$ ;$CPES-\,(920)$ ;
  $K^+\pi^- + n\pi\,(106)$ ;$K^{*+}K^-\,(50)$ ; $K^{*-}K^+\,(50)$
- Whenever strong phase(s) are needed for numerical illustration we choose them (a) arbitrarily, (b) randomly.
  (In the quantities studied no appreciable differences were seen)

- In the case of $K^{*\pm}D^{0*}$ FS, **FOR NOW** no angular analysis is done; instead we assume that the 3 helicities are equally probable.

## Framework for analysis

For a given decay of the form $B^- \to K^{(*)-}[\mathbf{D}^{(*)0} \to F]$ where $F$ is in general an exclusive or inclusive final state, let us denote

$d = Br(B^- \to K^{(*)-}[D^{(*)0} \to F])$

$\bar{d} = Br(B^+ \to K^{(*)+}[D^{(*)0} \to \bar{F}])$

where in the case of $\mathbf{D}^*0$ it cascades down to $\mathbf{D}^0$ before a $\mathbf{D}^0 \to F$ decay. In terms of the $B$ and $D$ branching ratios and the strong and weak phases, these quantities are given by

$d = ac_F + b\bar{c}_F + 2R_F\sqrt{ac_F b\bar{c}_F}\cos(\zeta_B + \zeta_F + \gamma)$

$\bar{d} = ac_F + b\bar{c}_F + 2R_F\sqrt{ac_F b\bar{c}_F}\cos(\zeta_B + \zeta_F - \gamma)$

where $a = Br(B^- \to K^{(*)-}D^{(*)0})$, $b = Br(B^- \to K^{(*)-}\bar{D}^{(*)0})$, $\zeta_B$ is the strong phase difference of the $B^-$ decay, $\zeta_F$ is the strong phase difference for the $D^0$ decay, $c_F = Br(D^0 \to F)$; $\bar{c}_F = Br(\bar{D}^0 \to F)$ and $R_F$ is the coherence factor (needed for inclusive decays). See later. Also, $d_{av} = (d+\bar{d})/2$; $A_{CP} = (d-\bar{d})/(d+\bar{d})$ is thus the PRA.

## Some numerical results **WIP**

### CP asymmetries in various channels [$\gamma = 60^\circ$]

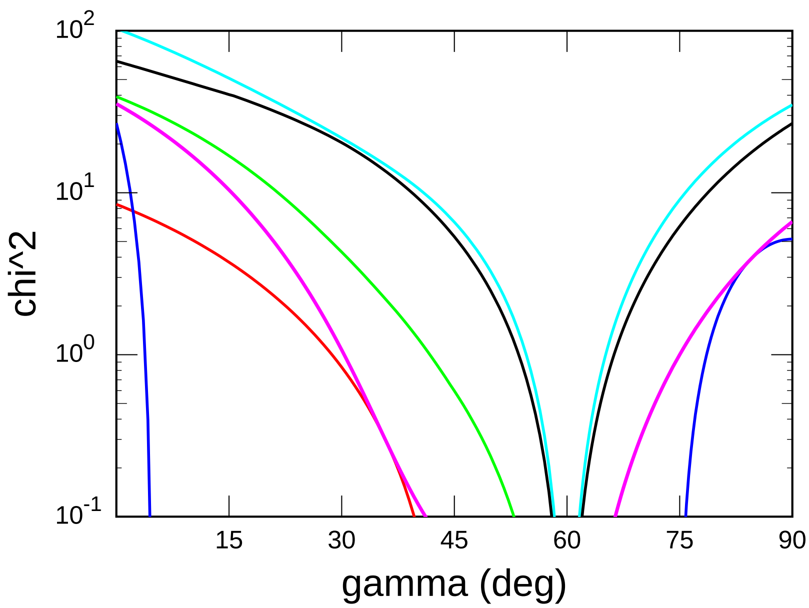
| | $K^+\pi^-$ | $K^{*+}\pi^-$ | $CPES-$ |
|---|---|---|---|
| $B^- \to K^- D^0$ | -58.2% | -8.1% | -17.1% |
| $B^- \to K^{*-} D^0$ | -54.3% | -63.3% | +11.6% |
| $B^- \to K^- D^{*0}$ | -76.9% | -39.4% | -4.1% |
| $B^- \to K^{*-} D^{*0}$ | +58.4% | -13.5% | +15.8% |

| | $K^+\pi^-$ | $K^{*+}\pi^-$ | $CPES-$ |
|---|---|---|---|
| $B^- \to K^- D^0$ | 53.4% | 47.7% | 14.6% |
| $B^- \to K^{*-} D^0$ | 53.4% | 47.7% | 14.6% |
| $B^- \to K^- D^{*0}$ | 53.4% | 47.7% | 14.6% |
| $B^- \to K^{*-} D^{*0}$ | 36.8% | 33.0% | 10.4% |

Improved determination with addition of more modes

$N_{B\bar{B}} = 4 - 8 \times 10^8$ (including efficiencies) see Atwood and Soni (to be published)

The minimum value of $\chi^2$ is shown as a function of $\gamma$ for various




combinations of data in the sample calculation. The blue line shows the result using just the $B^- \to K^-[D^0 \to CPES-]$ data. The red line shows the result using just $B^- \to K^-[D^0 \to K^+\pi^-]$ data. The purple curve shows the result taking both $B^- \to K^-[D^0 \to K^+\pi^-]$ and $B^- \to K^-[D^0 \to CPES-]$ data together. The green line shows the result using $B^- \to K^{(*)-}[D^{(*)0} \to K^+\pi^-]$. In the light blue curve, all four of the initial $B^-$ decays where the $D^0$ decays to the same two final states are considered. Thus this light blue curve results from taking together data of the form $B^- \to K^{(*)-}[D^{(*)0} \to K^+\pi^-]$ and $B^- \to K^{(*)-}[D^{(*)0} \to CPES-]$. The black curve only includes data from two parent $B^-$ decays, in particular it includes data of the form $B^- \to K^-[D^0 \to K^+\pi^-]$ and $B^- \to K^-[D^{*0} \to CPES-]$.**This combination seems to be very effective and gives a $3-\sigma$ determination of $\gamma$ to be about ($60 \pm 15$ deg)**

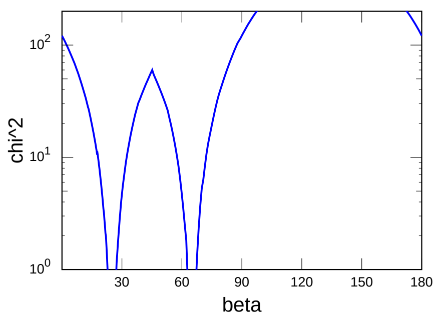
## $\delta = \beta - \alpha + \pi \equiv 2\beta + \gamma$ via TDCP in $B^0 \to$ "$K^0$" $D^0$

Attainable one sigma accuracy with various data sets given $N_{B\bar{B}}$ times acceptance $= 10^9$. [see Atwood and Soni,hep-ph/0206045]

| Case | Accuracy |
|---|---|
| CP- final states with $K_S$ and CP+ states i.e. $\pi^+\pi^-$,$K_S f_0$ and $K^+K^-$ | $\pm 18.2^\circ$ |
| The CPNES $K^-\pi^+$ together with CPES, both with $K_S$ only | $\pm 9.0^\circ$ |
| CPNES $K^-\pi^+$ with $K_S$ and with $K_L$ | $\pm 5^\circ$ |
| $K^- + X$ together with $K_S$ CPES | $\pm 2.5^\circ$ |

# $\beta(\phi_1)$ via TDCP in $B^0 \to$ "$K^0$" $D^0$

$\chi^2_{min}$ vs. $\beta(\phi_1)$ for the toy model calculation given $N_B\times$ acceptance $= 10^9$ $B\bar{B}$ pairs using $K^- + X$ with CPES containing $K_s$. [Note $\beta(\phi_1) = 25$ degrees is assumed.]



## Possible Role of Charm Factory

[see Atwood and Soni, hep-ph/hep-ph/0304085. For earlier works related to CF see: Soffer; ADS; Silva and Soffer; Gronau, Grossman and Rosner]

**Just about the most important application of a Charm Factory (CF) is to help in CKM determinations via BKD Modes**. There are a number of ways in which this can be done:

1. Measurements of the Br's of some of the D decay modes that enter the analysis; specifically determinations of the DCS D decays such as $K^+$ $(K^{*+})$ $[\pi^-, \rho^-, a_1^-]$.

2. Improving the constraints on the $D^0 - \bar{D}^0$ mixing parameters, $x_D$, $y_D$ can be very helpful.

3. Another very interesting application is to use a CF factory to determine two parameters needed for being able to use (exclusive and) **moreclusive** decays of $D^0, \bar{D}^0$

## Moreclusive states

**moreclusive $\equiv$ more general than inclusive; i.e sum over points in phase space of e.g. a 3 body (exclusive decay mode) (in say a Dalitz plot) is a sum over various quantum mechanical amplitudes and so is the case for (say) $D^0 \to K^- + X$ which represents a sum over many exclusive modes.**

Thus, a decay such as $D^0 \to K^-\pi^+$ would be an exclusive state while for a three body decay such as $D^0 \to K^-\pi^+\pi^0$, each point on the Dalitz plot must also be considered a distinct exclusive state.

Moreclusive states are inclusive either because they are integrated over phase space or include states with different particle content. In particular, the determination of $\gamma$ using decays of the form $B^- \to K^- D^0$ where the $D^0$ subsequently decays to moreclusive final states is highly desirable. **For such an analysis CF is very valuable as it can be used to determine two crucial parameters: $R_F$ ("coherence coefficient") and**

$\zeta_F$ **(average strong phase)**) This can be done by exploiting the **entangled** state of $D^0\bar{D}^0$. The important point is that in $\psi(3770) \to D^0\bar{D}^0$ the D's have an antisymmeyrical wavefunction in flavor space: $(|D^0\rangle|\bar{D}^0\rangle - |\bar{D}^0\rangle|D^0\rangle)/\sqrt{2}$

## Numerical Results from an illustrative toy model

[Atwood and Soni hep-ph/0304085]

The modes used in the toy model for $D^0 \to K^- X$ where $X$ contains at most one $\pi^0$.

| Mode | Sub-mode | Br |
|---|---|---|
| $K^-\pi^+$ | | 3.8% |
| $K^-\pi^+\pi^0$ | | 13.1% |
| | $K^-[\rho^+ \to \pi^+\pi^0]$ | 8.64% |
| | $\pi^+[K^{*-} \to K^-\pi^0]$ | 5.02% |
| | $\pi^0[\bar{K}^{*0} \to K^-\pi^0]$ | 1.46% |
| $K^-\pi^-\pi^+\pi^+$ | | 7.46% |
| | $K - \pi^+[\rho^0 \to \pi^+\pi^-]$ | 4.7% |
| | $[K^{*0} \to K^-\pi^+][\rho^0 \to \pi^+\pi^-]$ | 0.97% |
| | $K^-[a_1^+ \to \pi^+\pi^+\pi^-]$ | 3.6% |
| | $[K_1^-(1270) \to K^-\pi^+\pi^-]\pi^+$ | 0.37% |
| | 4-body continuum | 1.74% |
| $K^-\pi^-\pi^+\pi^+\pi^0$ | | 4.0% |

The parameters for the three different inclusive modes resulting in our toy model.

| Mode | Br | $\zeta$ | R |
|---|---|---|---|
| $\mathcal{F}_1$ | 11.0% | $-34^\circ$ | 0.74 |
| $\mathcal{F}_2$ | 24.9% | $-86^\circ$ | 0.29 |
| $\mathcal{F}_3$ | 19.3% | $30^\circ$ | 0.91 |
| CP eigenstates | 5% | | 1 |

The 3-$\sigma$ error in degrees in the determination of $\gamma$ with $\hat{N}_B = 10^9$ for the various toy models considered, for $\gamma = 60^\circ$ and $\zeta_k = -50^\circ$. The first three rows refer to exclusive states where we take $\eta(K^+\pi^-) = 120^\circ$ and $\zeta(K^+\pi^-) = 60^\circ$ while the last two rows refer to the inclusive states $\mathcal{F}_i$.

| Input | $\gamma = 60^\circ$; $\zeta_k = -50^\circ$ |
|---|---|
| $K^{*+}\pi^-$ with CPES- | $10.0^\circ$ |
| $K^{*+}\pi^-$ and $K^+\pi^-$ with CPES- | $9.1^\circ$ |
| $K^{*+}\pi^-$ and $K^+\pi^-$ with CPES- using $\psi(3770)$ | $3.4^\circ$ |
| $\mathcal{F}$ with CPES- | $12.0^\circ$ |
| $\mathcal{F}_1$, $\mathcal{F}_2$ and $\mathcal{F}_3$ with CPES- | $2.3^\circ$ |

# Summary and Outlook

- $B \to KD^0$ methods with **DIRECT AND TDCP** provide a very clean way to extract CKM angles, with irreducible theory error $O(.1\%)$.
- However, unlike $\beta$ from $B \to \psi K_s$, BKD method will require intensive phenomenological studies, due to the multitude of possiblities, before we can develop optimal strategy.
- Current study suggests inclusion of $B \to$ "$K$" $D^{0*}$ followed by $D^{0*} \to \gamma(\pi) D^0$ may be quite helpful. With $(4-8) \times 10^8 B\bar{B}$ pairs, $\gamma$ may be determined with a $3-\sigma$ error of about 15 degrees. Background were not taken into account but also not all possible input has been used. (e.g. SCS)
- It should be emphasized that just about the best application of Charm Factory is to the physics of CKM via BKD. Info thus obtained can be very helpful both for DIRECT and for TD CP. CF data could lead to the best determination of CKM angles.