
Rescattering effects on

$B_{u,d,s} \rightarrow DP, \bar{D}P$ decays and the
extraction of the unitary angle $\gamma(\phi_3)$

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The Unitary Triangle

- The CKM picture in the SM is essentially correct:

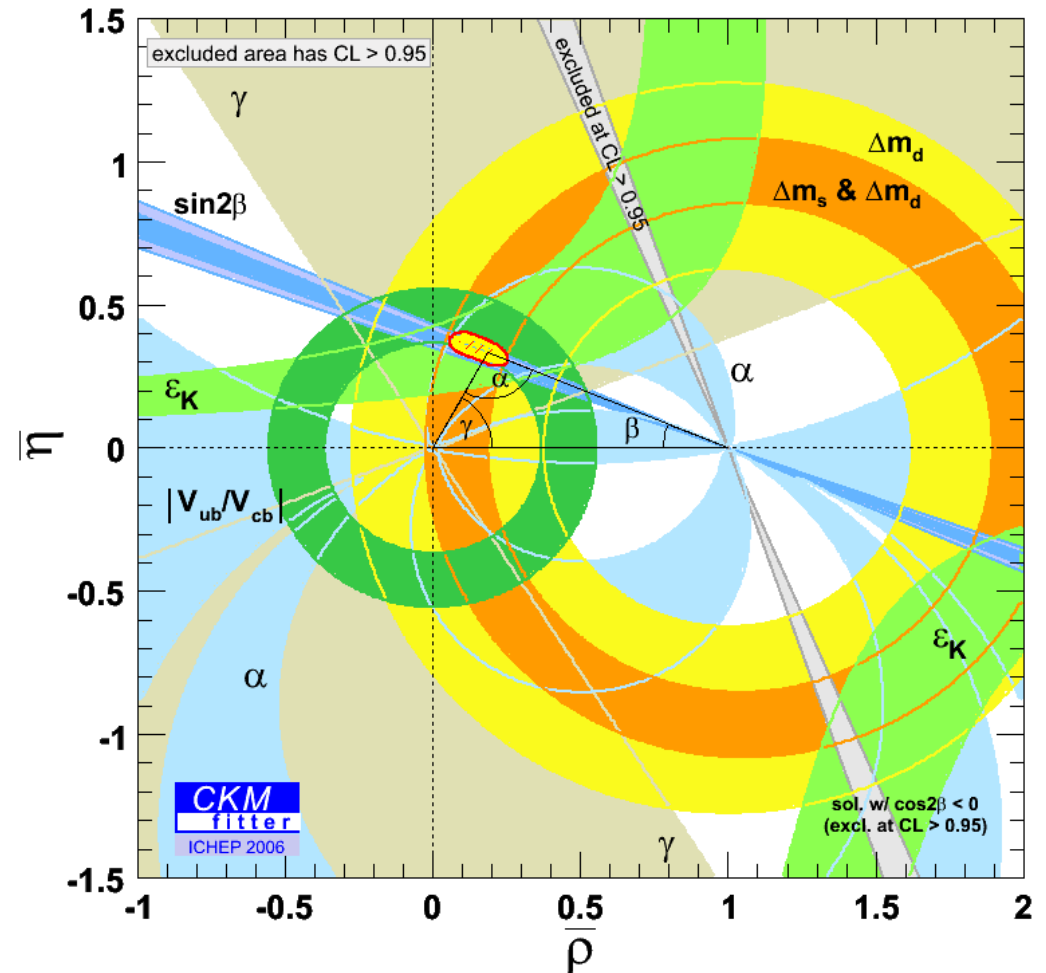
$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

$$V_{td} = |V_{td}| e^{-i\beta}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

The unitarity Triangle

Thanks to BaBar, Belle and others...



$$\beta = \phi_1, \gamma = \phi_3, \alpha = \phi_2$$

Present measurements on UT angles

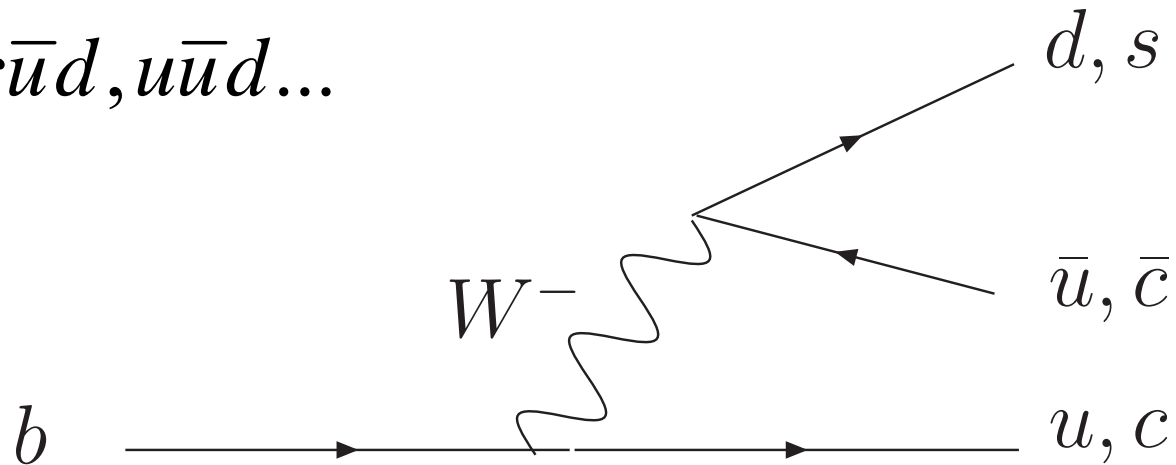
	World Average
$\alpha / \phi_2 (^\circ)$	$92.6^{+10.7}_{-9.3}$
$\beta / \phi_1 (^\circ)$	21.3 ± 1.0
$\gamma / \phi_3 (^\circ)$	62^{+38}_{-24}
$sum (^\circ)$	175.9 ± 32.6

- They should add up to 180° in the SM. Seems OK...
But we expect New Physics to account for DM, DE, ν mass...
New Interactions \Rightarrow New Phases.
- Presently, the errors are too large to check the sum rule.
- The largest error is from $\gamma(\phi_3)$: $\delta\beta(\phi_1) \sim 1^\circ$, $\delta\alpha(\phi_2) \sim 10^\circ$, $\delta\gamma(\phi_3) \sim 30^\circ$
- In this work, we (CKC, Hou) focus on $\gamma(\phi_3)$.

$\gamma(\phi_3)$ in a tree diagram:

- A tree diagram:

$$b \rightarrow c\bar{u}d, u\bar{u}d\dots$$

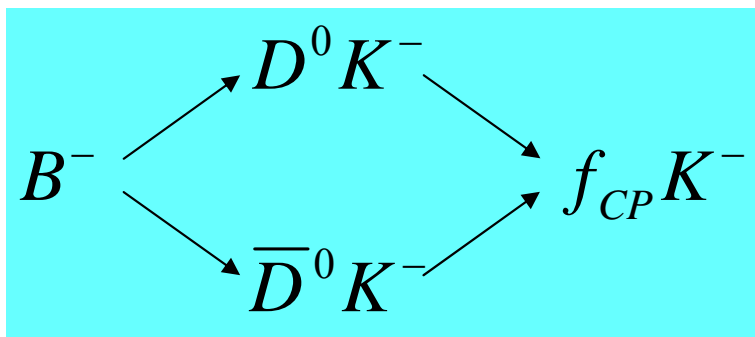


$$V_{ub} = |V_{ub}| e^{-i\gamma} \text{ (complex, } \gamma), V_{cb} \text{ (real)}$$

The color and CKM -suppressed $\bar{D}K^-$ mode is important in the γ extraction

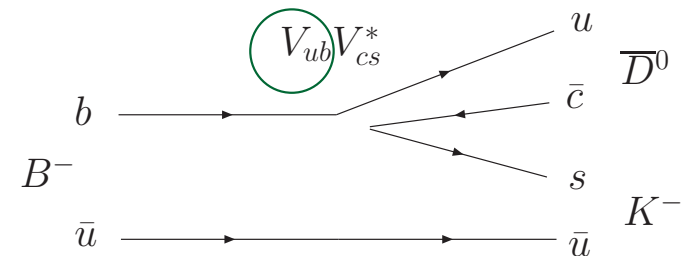
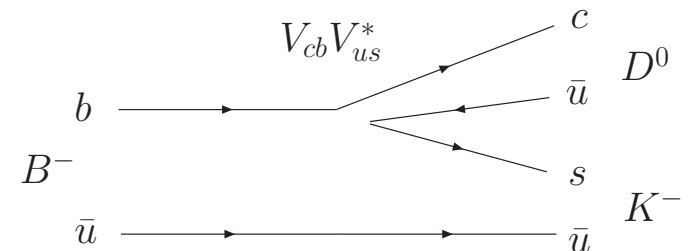
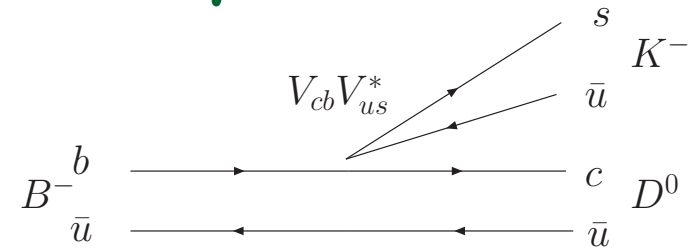
■ The γ determination methods:

- Gronau-London-Wyler
- Atwood-Dunietz-Soni
- DK Dalitz plot (Giri et al, Belle)



■ The interference effect is controlled by some common phases and parameters:

- $\gamma(\phi_3)$: the goal of the analysis.
- r_B : ratio of $D^0 K^- / \bar{D}^0 K^-$ amps.
- δ_B : relative phase of the amps.

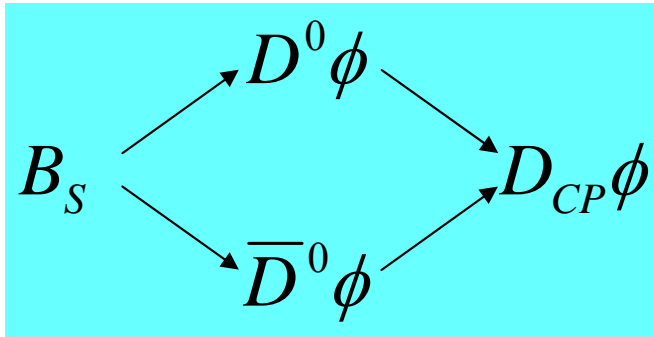


Extracting γ in B_s decays

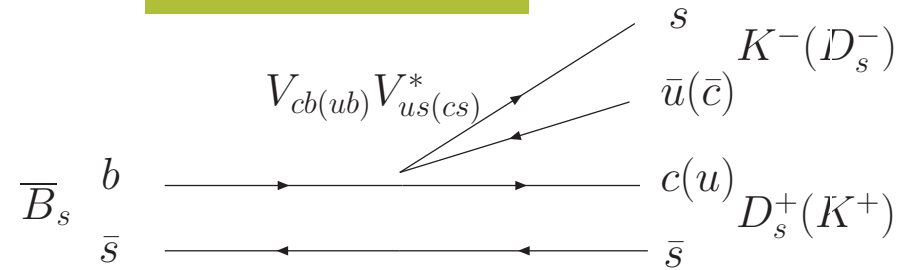
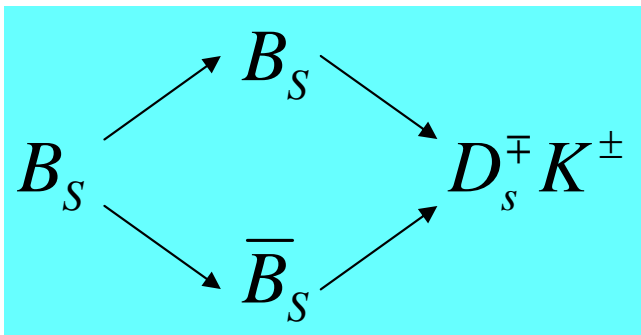
$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

■ The γ determination methods:

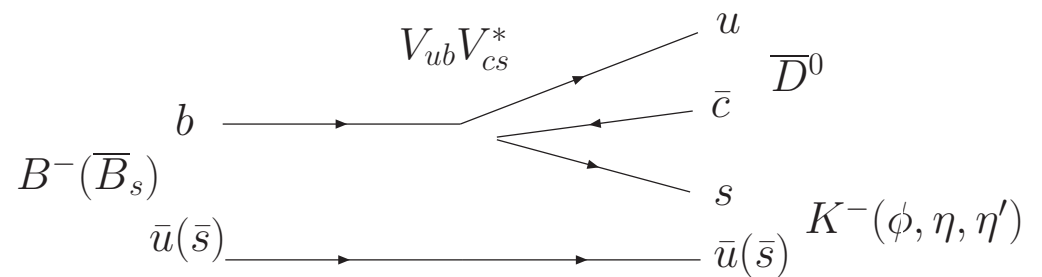
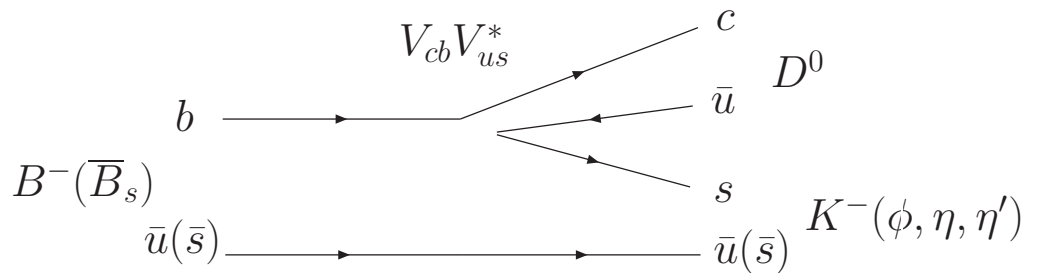
- Gronau-London (1991)



- Aleksan-Dunietz-Kayser (1992)



Color-allowed

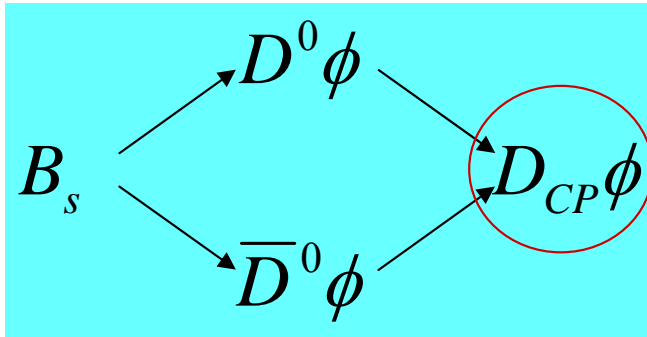


Color-suppressed

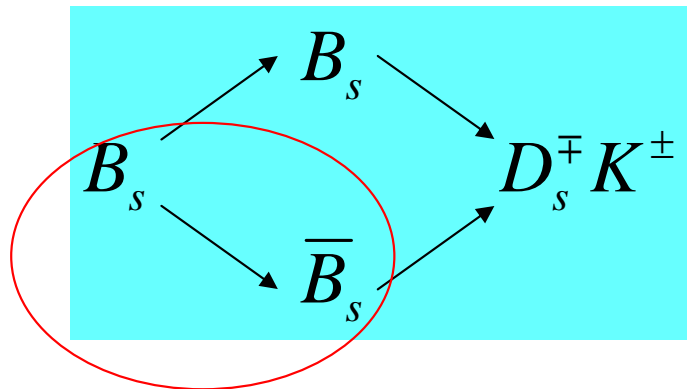
Extracting γ in B_s decays

■ The γ determination methods: ■ Interferences are needed

- Gronau-London (1991)



- Aleksan-Dunietz-Kayser (1992)



- $r \approx |V_{ub} V_{cs} / V_{cb} V_{us}| \approx 0.4$

■ Gronau-London

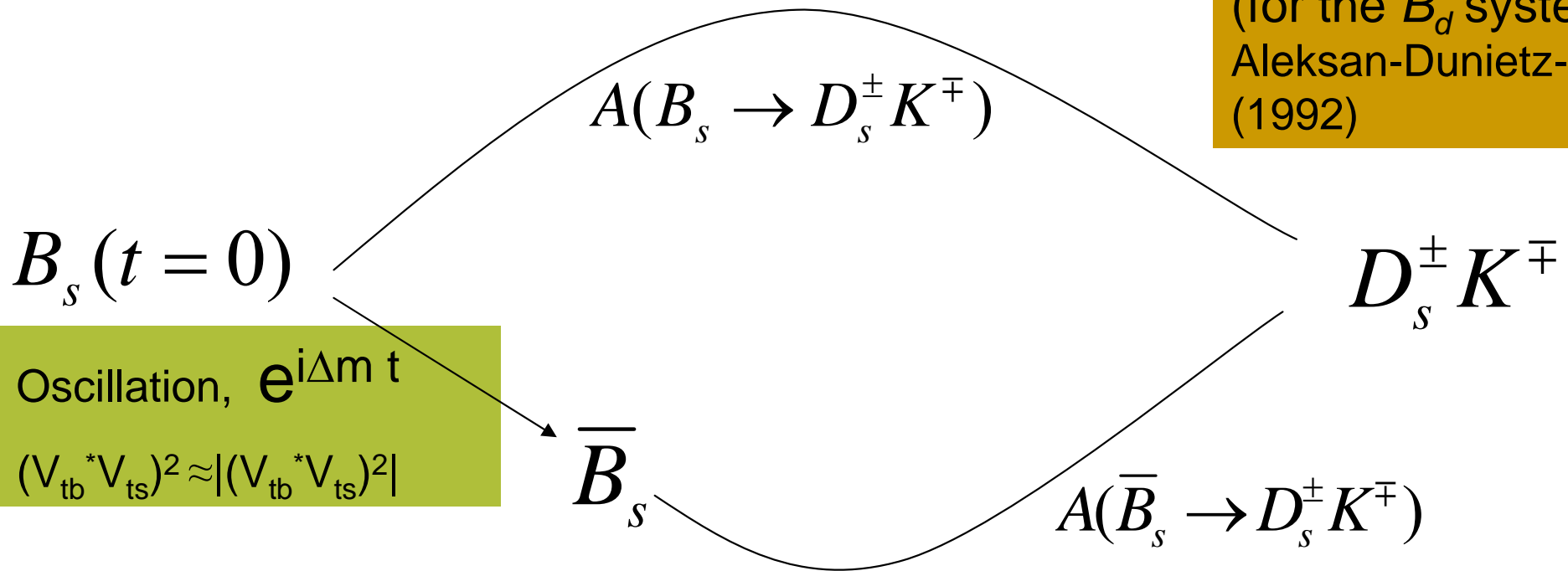
- Use same final state
- Rates are estimated to be of order 10^{-6}

■ Aleksan-Dunietz-Kayser

- Use B_s - B_s bar mixing
- Rates are estimated to be of order 10^{-4}
- **The favored method at LHC**

Mixing induced CP violation

Bigi, Sanda (1981)
 (for the B_d system)
 Aleksan-Dunietz-Kayser
 (1992)



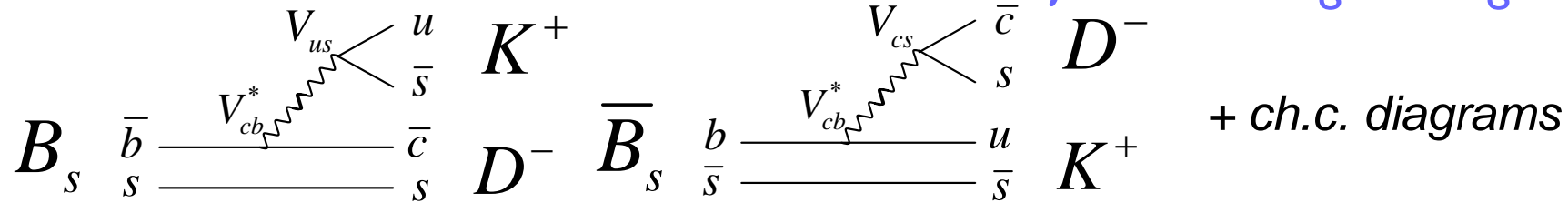
$$a_{f_{CP}}(t) = \frac{\Gamma(B_s(t) \rightarrow D_s^\pm K^\mp) - \Gamma(\bar{B}_s(t) \rightarrow D_s^\pm K^\mp)}{\Gamma(B_s(t) \rightarrow D_s^\pm K^\mp) + \Gamma(\bar{B}_s(t) \rightarrow D_s^\pm K^\mp)}$$

$$= C \cos \Delta m t + S \sin \Delta m t$$

Contain γ

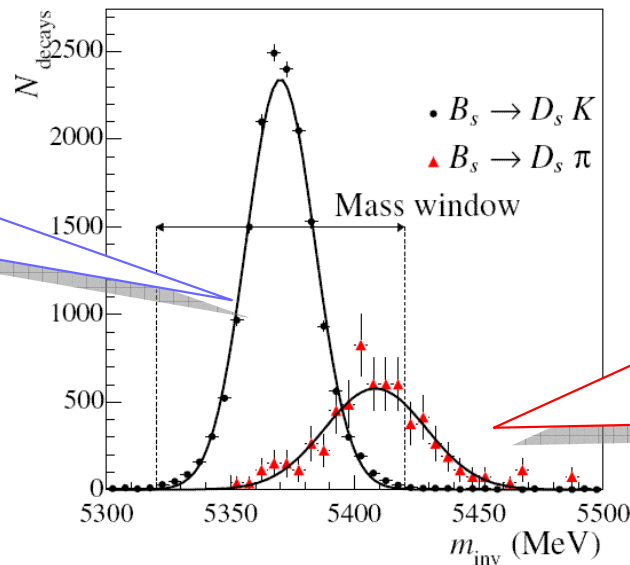
Need to measure the time dependents

γ from $B_s \rightarrow D_s K^\pm$



- Two tree decays ($b \rightarrow c$ and $b \rightarrow u$), which interfere via B_s mixing:
 - can determine $(\phi_s + \gamma)$, hence γ in a very clean way
- Fit 4 tagged, time-dependent rates
 - Extract $\phi_s + \gamma$, strong phase difference Δ , amplitude ratio
 - $B_s \rightarrow D_s \pi$ also used in the fit to constrain other parameters ($\omega, \Delta m_s, \Delta \Gamma_s$)

- Expect 6200 $D_s K$ events in 2 fb^{-1}
- $B/S < 0.5$



- Expect 140 000 $D_s \pi$
- 98% suppression achieved with RICH PID system in the analysis
- Used to measure Δm_s
- 2 fb^{-1} : $\sigma(\Delta m_s) \approx 0.012 \text{ ps}^{-1}$

- Study sensitivity by generating toy-experiments with experimental inputs derived from full MC (Decay time and mass resolution, reconstruction efficiency, tagging...)
 - Sensitivity with 2 fb^{-1} : $\sigma(\gamma) \sim 13^\circ$

Color-suppressed $\bar{B} \rightarrow D^0 h^0$ Decays

- Color-suppressed (CS) modes were observed:

$D^{(*)0}\pi^0, D^{(*)0}\eta, D^{(*)0}\omega,$ (Belle, CLEO, 2001)

$D_s K^-, D^0\bar{K}^0$ (Belle, BaBar, 2002)

$D^0\eta'$ (BaBar, Belle, 2004)

- Rates are significantly larger than (naive factorization) expectations.

[$B(D^0\pi^0) \times 10^4 \approx 0.5 \rightarrow 2.5, \dots$]

- Non vanishing strong phases ($D\pi$ triangle, $\delta \approx 30^\circ \dots$).
- Hint at the present of Final State Interactions (FSI).

(Xing, Cheng, CKC, Hou, Yang, Gronau, Fleischer, QCDF, SCET, pQCD groups, Soni, Chiang ...)

Final State Interaction

- Through FSI CS ($D^0 h^0$) rates can be easily fed from the CA ($D^+ \pi^-$) one.

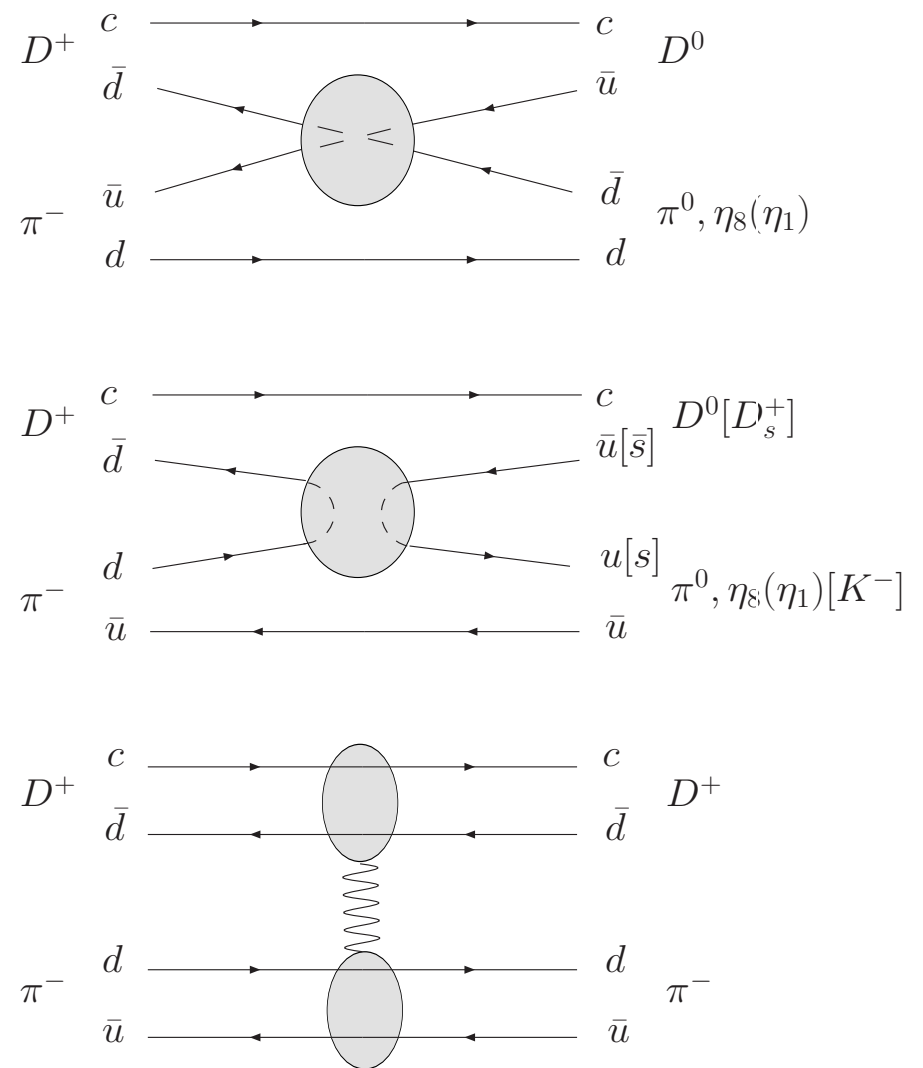
$$B(D^+ \pi^-) = (27.6 \pm 2.5) \times 10^{-4}$$

$$B(D^0 \pi^0) = (2.53 \pm 0.20) \times 10^{-4}$$

$$B(D^+ \pi^-) : B(D^0 \pi^0) \approx 10 : 1$$

- FSI generates strong phases. Watson Theorem.

$$2 \operatorname{Im} B \begin{array}{c} \diagup p_1 \\ \circ \\ \diagdown p_2 \end{array} = \sum_k B \begin{array}{c} \diagup \\ \circ \\ \diagdown \end{array} \{q_k\} \begin{array}{c} \diagup p_1 \\ \circ T^\dagger \\ \diagdown p_2 \end{array}$$



Expt. Results from DK Dalitz method:

	<i>Belle</i>	<i>BaBar</i>
γ / ϕ_3	$(53_{-18}^{+15} \pm 3 \pm 9)^\circ$	$(92 \pm 41 \pm 11 \pm 12)^\circ$
r_B	$0.16 \pm 0.05 \pm 0.01 \pm 0.05$	$< 0.14 (1\sigma)$
δ_B	$(146_{-20}^{+19} \pm 3 \pm 23)^\circ$	$(118 \pm 63 \pm 19 \pm 36)^\circ$

HFAG

- Comparing Belle's and BaBar's results:
 - γ/ϕ_3 central values are off by a factor of 2 (but errors are large).
 - Belle $r_B >$ BaBar r_B
 - \Rightarrow Belle $\delta\gamma <$ BaBar $\delta\gamma$
- $r_B [\equiv A(\bar{D}^0 K^-) / A(D^0 K^-)]$ is important in the γ determination.
- Not much theoretical predictions on r_B .

What is the implication of $D^0 h^0$ on r_B ?

- Naïve factorization expectation: $r_B \approx 0.4 \times 0.2 \approx 0.08$.

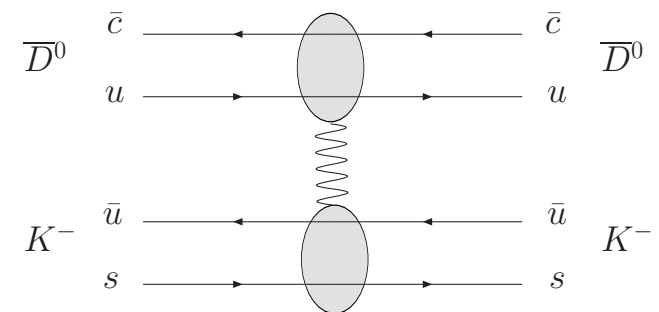
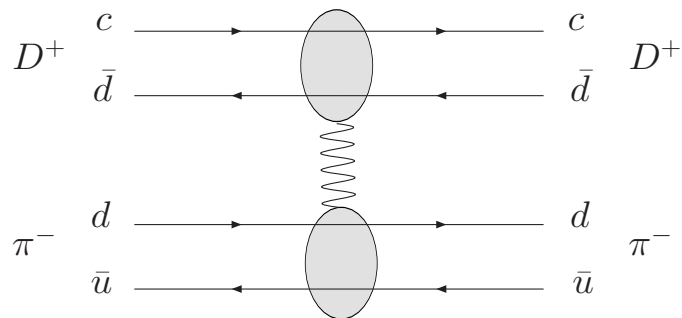
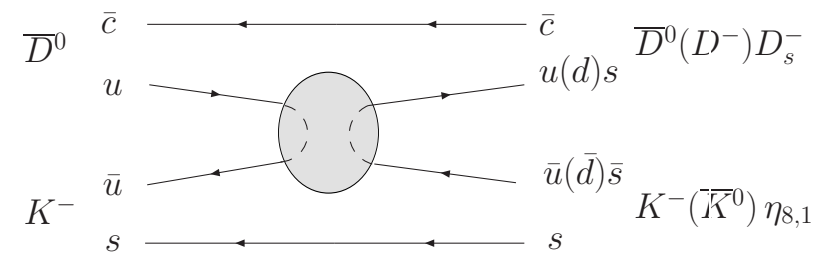
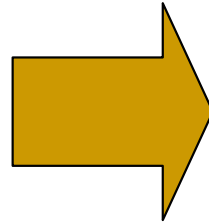
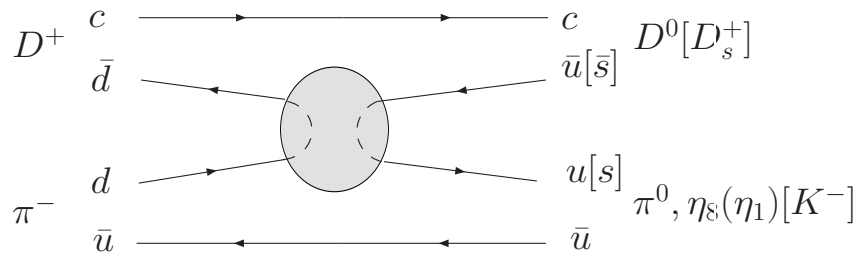
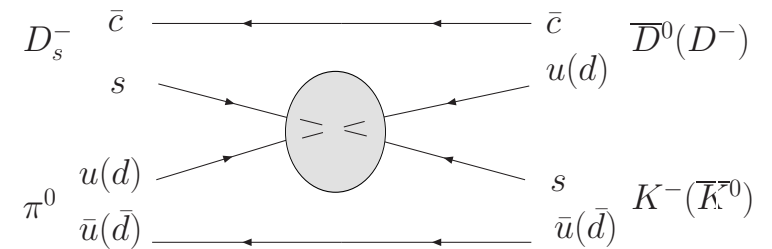
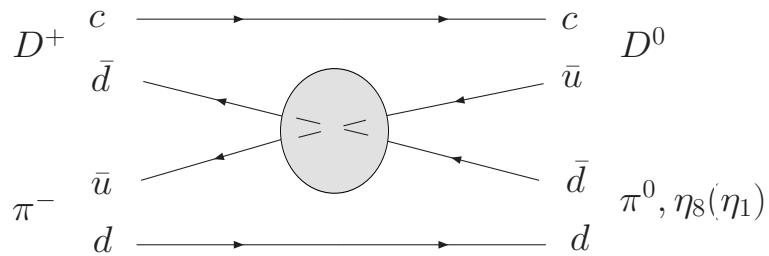
$$r_B \approx \left| \frac{V_{ub} V_{cs}^*}{V_{cd} V_{us}^*} \right| \times \left| \frac{a_2}{a_1} \right|$$

← CS, CA

(small correction from FF, decay constant ratio)

- The color suppressed $D^0 h^0$ rates are enhanced, perhaps $r_B [=|A(\bar{D}^0 K^-)/A(D^0 K^-)|]$ will also be enhanced. (Gronau, 2002)
- Question: “What is the implication of $D^0 h^0$ on r_B ?”

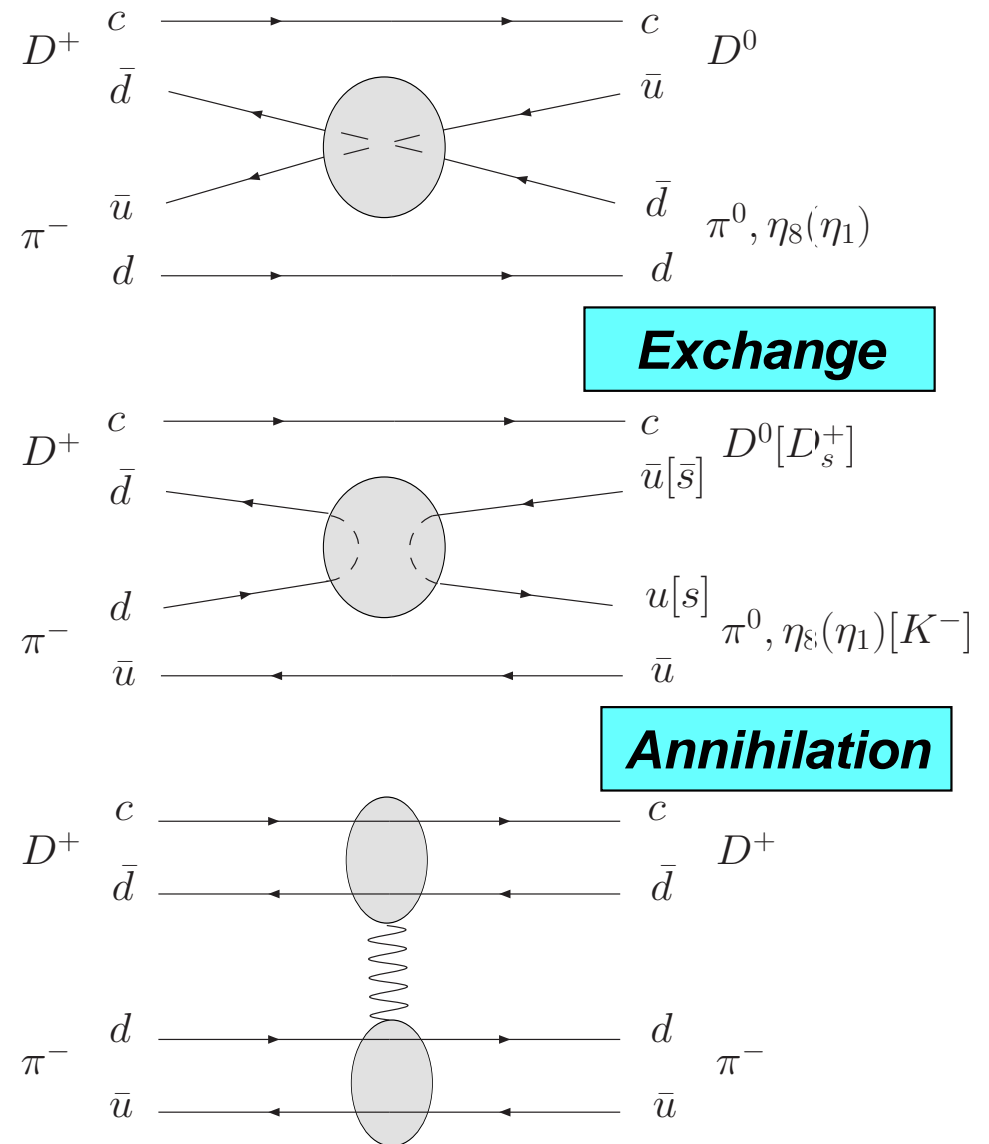
QCD respects Charge Conjugation [SU(3)]: Lessons learned from $D^0 h^0 \Rightarrow \bar{D} \bar{K}$



Quasi-elastic scattering

- FSI in B decays cannot be neglected. (non vanishing $D\pi$ triangle) (Donoghue et al, Cheng CKC Soni)
- May have cancellation in in-elastic rescattering.
 - Statistical approach. Random phase (Suzuki, Wolfenstein)
 - Fac. in $D^+\pi^-$, QCDF (BBNS)
- Concentrate on quasi-elastic rescattering (CKC, Hou, Yang),
 - The large source $D^+\pi^-$ is included
- The Flavor Flow analysis is equivalent to the SU(3) sym. approach.

Flavor Flow Diagram.



Singlet Exch.

In the light of $SU(3)$ decomposition:

- $DP = D(\bar{3})\Pi(8) = \bar{15} + \bar{6} + \bar{3}$, $D(\bar{3})\eta_1(1) = \bar{3}'$:

$$S = |\bar{15}\rangle\langle\bar{15}| + e^{2i\delta} |\bar{6}\rangle\langle\bar{6}| + (|\bar{3}\rangle \quad |\bar{3}'\rangle) \cdot U \cdot \begin{pmatrix} \langle\bar{3}| \\ \langle\bar{3}'| \end{pmatrix}$$

- $\bar{D}P = \bar{D}(3)\Pi(8)$, $\bar{D}(3)\eta_1(1)$:

$$S = |15\rangle\langle 15| + e^{2i\delta} |\bar{6}\rangle\langle\bar{6}| + (|3\rangle \quad |3'\rangle) \cdot U \cdot \begin{pmatrix} \langle 3| \\ \langle 3'| \end{pmatrix}$$

- Need three phases (δ, θ, σ) and one mixing angle (τ).

$\bar{6}, \sim 3, \sim 3'$

Use D^0h^0 rates (9) to extract $a_{1,2}^{\text{eff}}$ (2) and rescattering parameters (4):

parameter	result	parameter	result
χ_{min}^2	0.85	$\chi_{\text{min}}^2/\text{d.o.f.}$	0.28
a_1^{eff}	0.93 ± 0.02	a_2^{eff}	0.20 ± 0.04
δ	$\pm(53.8^{+1.6}_{-1.7})^\circ$	θ	$\pm(19.1^{+1.5}_{-1.3})^\circ$
σ	$\mp(95.5^{+17.6}_{-17.9})^\circ$	τ	$(8.7^{+2.2}_{-2.3})^\circ$
$1 + ir'_0$	$(0.80 \pm 0.01) \pm (0.40 \pm 0.01)i$	ir'_e	$(0.20 \pm 0.01) \mp (0.40 \pm 0.01)i$
ir'_a	$(0.07 \pm 0.01) \mp (0.09 \pm 0.01)i$	$i(\bar{r}'_a + \bar{r}'_e)$	$(-0.17^{+0.03}_{-0.02}) \mp (0.21 \pm 0.06)i$
$1 + i\tilde{r}'_0 + i\frac{\tilde{r}'_e + \tilde{r}'_a}{3}$	$(-0.07^{+0.31}_{-0.30}) \mp (0.96^{+0.01}_{-0.07})i$		
$1 + ir'_0 + i\frac{r'_e + r'_a}{3}$	$(0.89 \pm 0.01) \pm (0.24 \pm 0.01)i$	$i(r'_a + r'_e)$	$(0.27 \pm 0.02) \mp (0.49 \pm 0.02)i$

- **$\mathbf{A}=\mathbf{S}^{1/2}\mathbf{A}_0$, use naïve fac. amplitude as \mathbf{A}_0**
 - avoid double counting
 - $a_{1,2}^{\text{eff}}$ values ~ as expected
- **Exchange rescattering dominating $|r_e| > |r_a|$.**

Fitted rates (9 modes \Rightarrow 6 parameters)

Many modes are enhanced.

Mode	$\mathcal{B}^{\text{exp}} (10^{-4})$	$\mathcal{B}^{\text{fac}} (10^{-4})$	$\mathcal{B}^{\text{FSI}} (10^{-4})$
$B^- \rightarrow D^0 \pi^-$	47.5 ± 1.9	$47.60^{+4.60}_{-4.66}$	$47.60^{+1.31}_{-1.06}$
$\bar{B}^0 \rightarrow D^+ \pi^-$	27.6 ± 1.9	$33.08^{+1.53}_{-1.68}$	$27.77^{+1.32}_{-1.52}$
$\bar{B}^0 \rightarrow D^0 \pi^0$	2.59 ± 0.26	$0.42^{+0.18}_{-0.15}$	$2.46^{+0.19}_{-0.16}$
$\bar{B}^0 \rightarrow D_s^+ K^-$	0.27 ± 0.05	0	0.26 ± 0.03
$\bar{B}^0 \rightarrow D^0 \eta$	2.02 ± 0.21	$0.24^{+0.11}_{-0.09}$	$2.03^{+0.18}_{-0.17}$
$\bar{B}^0 \rightarrow D^0 \eta'$	1.26 ± 0.21	$0.15^{+0.06}_{-0.05}$	$1.27^{+0.18}_{-0.16}$
$B^- \rightarrow D^0 K^-$	3.83 ± 0.45	3.71 ± 0.40	$3.71^{+0.15}_{-0.11}$
$\bar{B}^0 \rightarrow D^+ K^-$	2.04 ± 0.57	$2.39^{+0.11}_{-0.12}$	$1.92^{+0.08}_{-0.09}$
$\bar{B}^0 \rightarrow D^0 \bar{K}^0$	0.52 ± 0.07	0.10 ± 0.04	0.57 ± 0.03

Predictions on $\bar{B}_s \rightarrow DP$ decay rates

Mode	\mathcal{B}^{exp}	$\mathcal{B}^{\text{fac}} (10^{-4})$	$\mathcal{B}^{\text{FSI}} (10^{-4})$
$\bar{B}_s^0 \rightarrow D_s^+ \pi^-$	–	$32.28^{+1.49}_{-1.64}$	$26.02^{+1.13}_{-1.23}$
$\bar{B}_s^0 \rightarrow D^0 K^0$	–	$1.65^{+0.73}_{-0.61}$	$7.94^{+0.41}_{-0.45}$
Mode	$\mathcal{B}^{\text{exp}} (10^{-5})$	$\mathcal{B}^{\text{fac}} (10^{-5})$	$\mathcal{B}^{\text{FSI}} (10^{-5})$
$\bar{B}_s^0 \rightarrow D^+ \pi^-$	–	0	0.16 ± 0.02
$\bar{B}_s^0 \rightarrow D^0 \pi^0$	–	0	0.08 ± 0.01
$\bar{B}_s^0 \rightarrow D_s^+ K^-$	–	$23.33^{+1.08}_{-1.19}$	$19.52^{+0.93}_{-1.07}$
$\bar{B}_s^0 \rightarrow D^0 \eta$	–	$0.44^{+0.20}_{-0.16}$	$2.81^{+0.36}_{-0.35}$
$\bar{B}_s^0 \rightarrow D^0 \eta'$	–	$0.61^{+0.27}_{-0.22}$	$1.83^{+0.36}_{-0.40}$

- The $D^0 K^0$ rate is enhanced by a factor of 5 and reaches 10^{-3} .
- The $D_s K^-$ rate is 10^{-3} (LHC favored mode for γ).
- $D^0 \eta$ and $D^0 \eta'$ rates are enhanced to 10^{-4} .

Prediction for $B(\overline{DP})$

Mode	$\mathcal{B}^{\text{exp}} (10^{-5})$	$\mathcal{B}^{\text{fac}} (10^{-5})$	$\mathcal{B}^{\text{FSI}} (10^{-5})$
$B^- \rightarrow \overline{D}^0 K^-$	–	$0.17^{+0.08}_{-0.06}$	$0.29^{+0.06}_{-0.26}$
$B^- \rightarrow D^- \overline{K}^0$	< 0.5	0	0.04 ± 0.01
$B^- \rightarrow D_s^- \pi^0$	< 20	1.03 ± 0.05	$0.84^{+0.03}_{-0.04}$
$B^- \rightarrow D_s^- \eta$	< 50	0.59 ± 0.03	0.38 ± 0.07
$B^- \rightarrow D_s^- \eta'$	–	0.37 ± 0.02	$0.60^{+0.08}_{-0.09}$
$\overline{B}^0 \rightarrow D_s^- \pi^+$	1.4 ± 0.3	1.92 ± 0.09	$1.56^{+0.06}_{-0.07}$
$\overline{B}^0 \rightarrow \overline{D}^0 K^0$	–	$0.16^{+0.07}_{-0.06}$	$0.52^{+0.04}_{-0.03}$
$\overline{B}_s^0 \rightarrow D^+ \pi^-$	–	0	0.03 ± 0.00
$\overline{B}_s^0 \rightarrow \overline{D}^0 \pi^0$	–	0	0.01 ± 0.00
$\overline{B}_s^0 \rightarrow D_s^+ K^-$	–	$3.94^{+0.18}_{-0.20}$	$3.30^{+0.16}_{-0.18}$
$\overline{B}_s^0 \rightarrow \overline{D}^0 \eta$	–	0.07 ± 0.03	0.47 ± 0.06
$\overline{B}_s^0 \rightarrow \overline{D}^0 \eta'$	–	0.10 ± 0.04	$0.31^{+0.06}_{-0.07}$

- Several rates are enhanced.
- agreement of $D_s \pi$ rate with data improved.

Compare with other results:

$\mathcal{B} (10^{-4})$	This work	CF	CS
$\overline{B}_s^0 \rightarrow D_s^+ \pi^-$	$26.02_{-1.23}^{+1.13}$	29 ± 6	22 ± 1
$\overline{B}_s^0 \rightarrow D^0 K^0$	$7.94_{-0.45}^{+0.41}$	8.1 ± 1.8	5.3 ± 0.3
$\mathcal{B} (10^{-5})$	This work	CF	CS
$\overline{B}_s^0 \rightarrow D^+ \pi^-$	0.16 ± 0.02	0.20 ± 0.06	0.14 ± 0.03
$\overline{B}_s^0 \rightarrow D^0 \pi^0$	0.08 ± 0.01	0.10 ± 0.03	0.07 ± 0.01
$\overline{B}_s^0 \rightarrow D_s^+ K^-$	$19.52_{-1.07}^{+0.93}$	18 ± 3	20 ± 1
$\overline{B}_s^0 \rightarrow D^0 \eta$	$2.81_{-0.35}^{+0.36}$	2.1 ± 1.2	1.4 ± 0.1
$\overline{B}_s^0 \rightarrow D^0 \eta'$	$1.83_{-0.40}^{+0.36}$	0.98 ± 0.76	2.9 ± 0.2

- CF: Colangelo and Ferrands
- CS: Chiang and Senaha
- Most predictions are similar except D0 eta, D0 eta', due to singlet contributions

The $D^0\phi$ rate is also enhanced ($10 \times$)

- In term of topological amplitudes (Chau Cheng, Gronau Rosner)

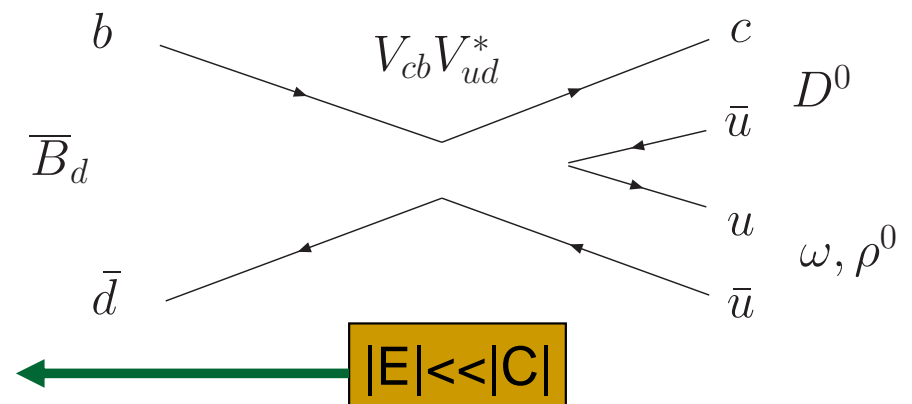
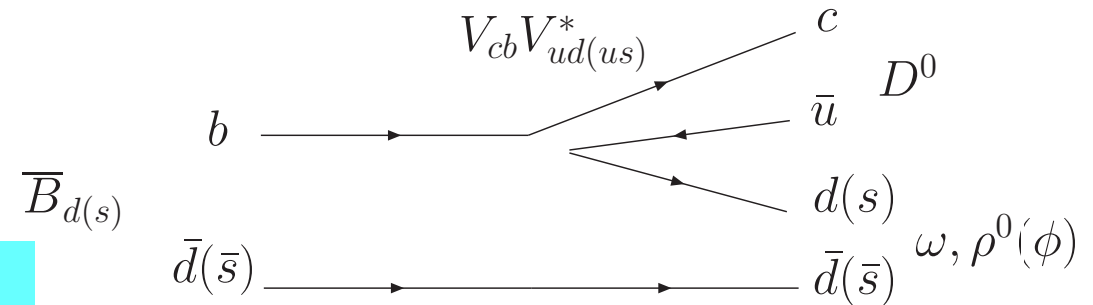
$$A(\bar{B}_s \rightarrow D^0 \phi) = V_{cb} V_{us}^* C$$

$$A(\bar{B}^0 \rightarrow D^0 \omega) = V_{cb} V_{ud}^* \frac{1}{\sqrt{2}} (C + E)$$

$$A(\bar{B}^0 \rightarrow D^0 \rho^0) = V_{cb} V_{ud}^* \frac{1}{\sqrt{2}} (-C + E)$$

- $B(D^0 \omega^0) = (2.5 \pm 0.6) \times 10^{-4}$,
 $B(D^0 \rho^0) = (2.9 \pm 1.1) \times 10^{-4}$

$$\mathcal{B}(\bar{B}_s \rightarrow D^0 \phi) \simeq \frac{\tau_{B_s}}{\tau_{B_d}} \left| \frac{V_{us}}{V_{ud}} \right|^2 [\mathcal{B}(\bar{B}^0 \rightarrow D^0 \rho^0) + \mathcal{B}(\bar{B}^0 \rightarrow D^0 \omega)] \simeq 3 \times 10^{-5}$$



Predictions on r_B and r_{B_s}

	Expt	fac	FSI
$r_B(D^0K^-)$	$0.16 \pm 0.05 \pm 0.01 \pm 0.05$ (Belle) < 0.14 (1σ) (BaBar)	0.07 ± 0.01	0.09 ± 0.01
$\delta_B(D^0K^-)$	$(146_{-20}^{+19} \pm 3 \pm 23)^\circ$ (Belle) $(118 \pm 63 \pm 19 \pm 36)^\circ$ (BaBar)	180°	$180^\circ \mp (35.2_{-8.6}^{+9.8})^\circ$
$r_B(D^0K^0)$	–	0.40 ± 0.00	0.30 ± 0.01
$\delta_B(D^0K^0)$	–	180°	$180^\circ \pm (7.7_{-1.2}^{+1.1})^\circ$
$r_{B_s}(D_s^+K^-)$	–	0.41 ± 0.00	0.41 ± 0.00
$\delta_{B_s}(D_s^+K^-)$	–	180°	$180^\circ \pm (0.1 \pm 0.0)^\circ$
$r_{B_s}(D^0\eta')$	–	0.40 ± 0.00	0.41 ± 0.00
$\delta_{B_s}(D^0\eta')$	–	180°	$180^\circ \mp (0.2 \pm 0.1)^\circ$

- $r_B(D^0K^-)$ slightly enhanced and prefers the BaBar result. (Belle r_B reduced).
- $r_B(D^0K^0)$ reduced by 25%. ■ r_{B_s} unaffected.

Conclusion

- The extractions of unitarity angles (sum= π ?) are in progress:

$$\delta\beta(\phi_1)\sim 1^\circ, \delta\alpha(\phi_2)\sim 10^\circ, \delta\gamma(\phi_3)\sim 30^\circ.$$

\Rightarrow Need to improve on the extraction of $\gamma(\phi_3)$.

- Rescattering effects on $B_{u,d,s} \rightarrow DP$, $D\bar{b} P$ decays are investigated using the quasi-elastic approach.
- Many decay rates are enhanced.
- Some of these modes will be useful to extract $\gamma(\phi_3)$.
- Combined analysis of these modes (with B and B_s decays, LHC) will be valuable (statistic) to reduce the error in $\gamma(\phi_3)$.