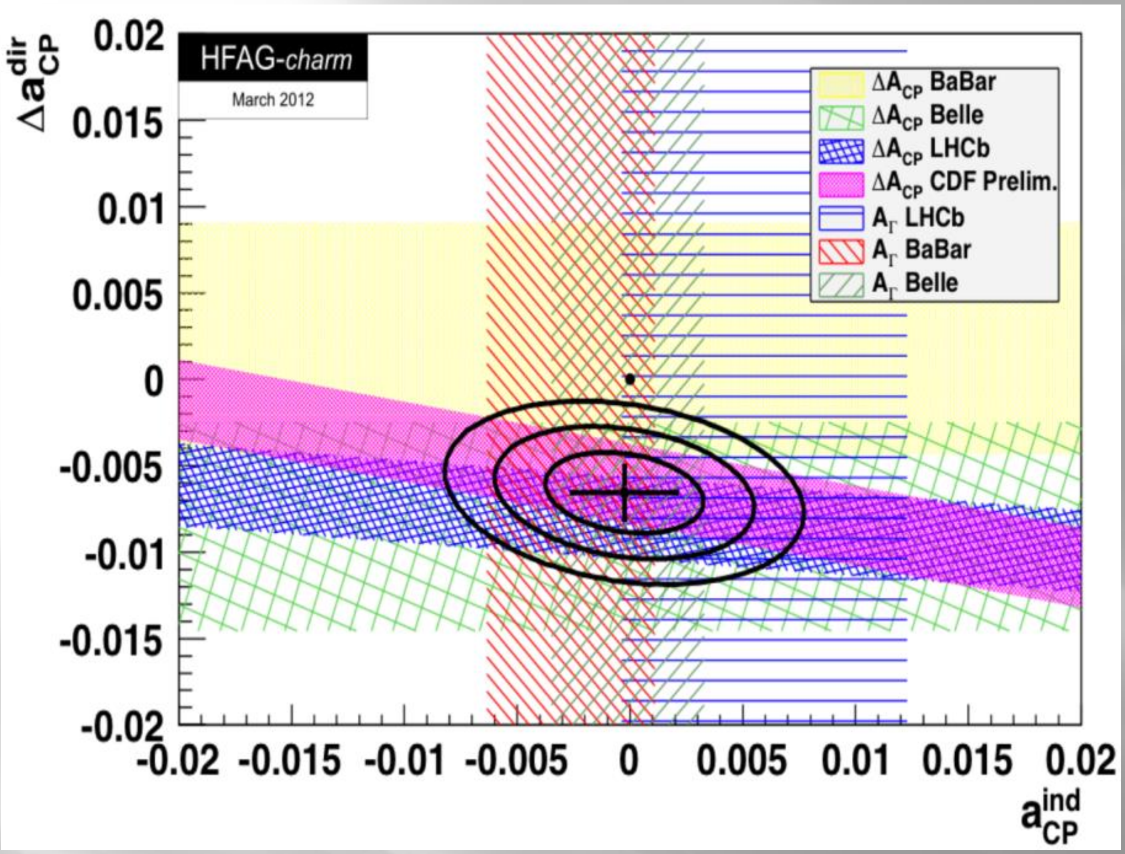
HADRONIC AND RADIATIVE CHARMED MESON DECAYS

Nita Sinha
The Institute of Mathematical Sciences
Chennai

Direct CPV in Charmed Meson Decays?

CHARM 2012



New world averages of LHCb + CDF + BaBar + Belle

Δa_{CP}^{dir} **= -(0.656±0.154)%, 4.3σ effect**

a_{CP}^{ind} **= -(0.025±0.235)%**

Isidori, Kamenik, Ligeti, Perez [1111.4987]

Brod, Kagan, Zupan [1111.5000]

Wang, Zhu [1111.5196]

Rozanov, Vysotsky [1111.6949]

Hochberg, Nir [1112.5268]

Pirtskhalava, Uttayarat [1112.5451]

Cheng, Chiang [1201.0785]

Bhattacharya, Gronau, Rosner [1201.2351]

Chang, Du, Liu, Lu, Yang [1201.2565]

Giudice, Isidori, Paradisi [1201.6204]

Altmannshofer, Primulando, C. Yu, F. Yu [1202.2866]

Chen, Geng, Wang [1202.3300]

Feldmann, Nandi, Soni [1202.3795]

Li, Lu, Yu [1203.3120]

Franco, Mishima, Silvestrini [1203.3131]

Brod, Grossman, Kagan, Zupan [1203.6659]

Hiller, Hochberg, Nir [1204.1046]

Grossman, Kagan, Zupan [1204.3557]

Cheng, Chiang [1205.0580] and many more!

Flurry of theory papers with models of New Physics that could explain the Direct CPV

PRESS RELEASE

MARCH 2007

SLAC today

Tuesday - March 13, 2007

New Form of Matter-antimatter Transformation Observed

by Kelen Tuttle

For the first time, BaBar researchers have observed the transition of one type of particle, the neutral D-meson, into its antimatter particle. This observation will now be used as a test of the Standard Model, the current theory that best describes all the universe's luminous matter and its associated forces.

"Achieving the large number of collisions needed to observe this D-meson transition is a testament to the tremendous capabilities of the laboratory's accelerator team," said Jonathan Dorfan. "The discovery of this long-sought-after process is yet another step along the way to a better understanding of the Standard Model and the physics beyond."

BaBar collaborators William Lockman, Ray Cowan, and Brian Aagaard Petersen inside the linac. (Click on image for larger version.)

大学共同利用機関法人 KEK 高エネルギー加速器研究機構

ホーム ニュース イベント ライブラリ キッズサイエンティスト サイトマップ 検索

>ホーム >ニュース >プレス >この記事

last update: 07/08/13

News@KEK プレス・リリース ~ 07-06 ~ For immediate release: 2007年08月13日

Belle実験の最新の結果について
ーD中間子の粒子・反粒子混合現象を発見ー

高エネルギー加速器研究機構

発表の骨子

小林・益川理論で説明される粒子・反粒子の混合現象*1については従来、中性の中間子*2のうちダウン型（電荷ー1/3e*3）のクォークを含むK中間子とB中間子のみで確認されていた。今回、高エネルギー加速器研究機構のKEK Bファクトリーを用いた実験により、アップ型（電荷＋2/3e）のクォークを含むD中間子の混合現象を世界で初めて捉えることができた。この発見により、標準理論を超える新しい理論に対する実験的知見が得られることが期待される。

Announcement by Babar and Belle collaborations of experimental evidence for $D^0 - \bar{D}^0$ mixing at Moriond conference on EW interactions

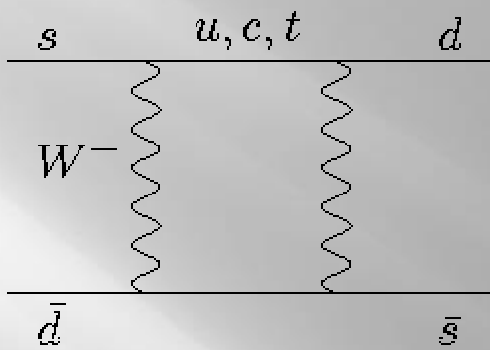
"D^0-$\bar{D}^0$ mixing is expected to be too small to measure with BaBar if the Standard Model is a complete description of physics."

- BaBar Physics Book (1998)

Moriond's new cocktail: the DDbar mix

Meson Mixing

$K - \overline{K}$



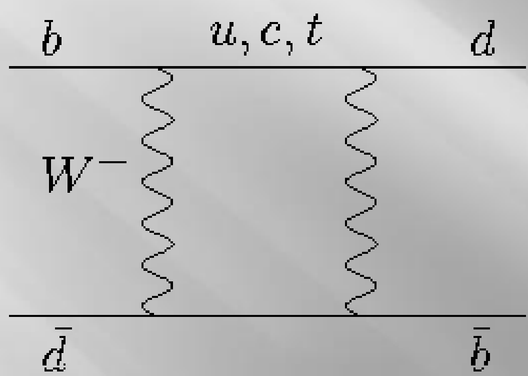
t: $(V_{ts}V^*_{td})^2 \sim \lambda^{10}$, m_t^2

c: $(V_{cs}V^*_{cd})^2 \sim \lambda^2$, m_c^2

u: $(V_{us}V^*_{ud})^2 \sim \lambda^2$, m_u^2

c dominates

$B - \overline{B}$



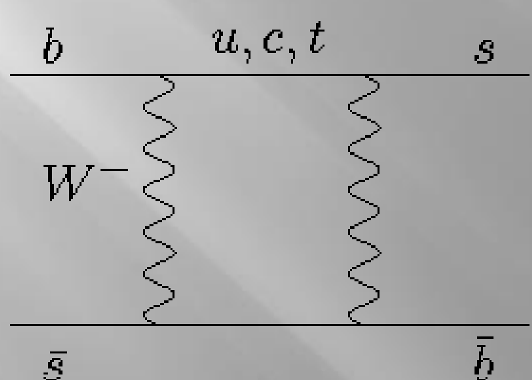
t: $(V_{tb}V^*_{td})^2 \sim \lambda^6$, m_t^2

c: $(V_{cb}V^*_{cd})^2 \sim \lambda^6$, m_c^2

u: $(V_{usb}V^*_{ud})^2 \sim \lambda^6$, m_u^2

top dominates

$B_s - \overline{B_s}$



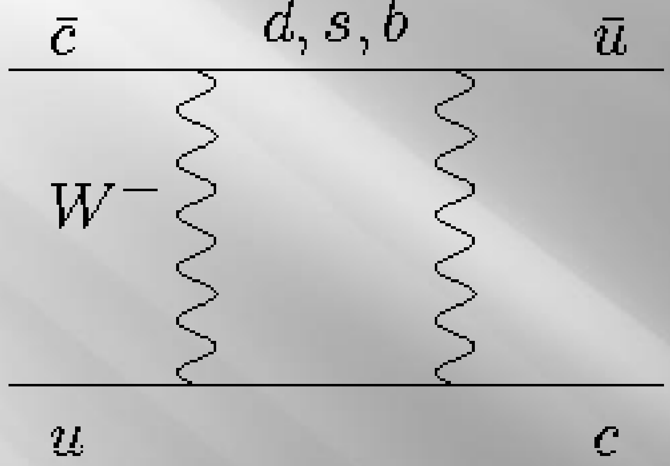
t: $(V_{tb}V^*_{ts})^2 \sim \lambda^4$, m_t^2

c: $(V_{cb}V^*_{cs})^2 \sim \lambda^4$, m_c^2

u: $(V_{ub}V^*_{us})^2 \sim \lambda^8$, m_u^2

Why are Charmed Mesons special?

$D - \bar{D}$



b quark not heavy enough to compensate for the large CKM suppression: $(V_{cb}V_{ub})^2 \sim \lambda^{10}$

Expect D mixing parameters to be small

Expect Any CPV-Direct or Indirect to be small within the SM

But SM calculation is very hard!

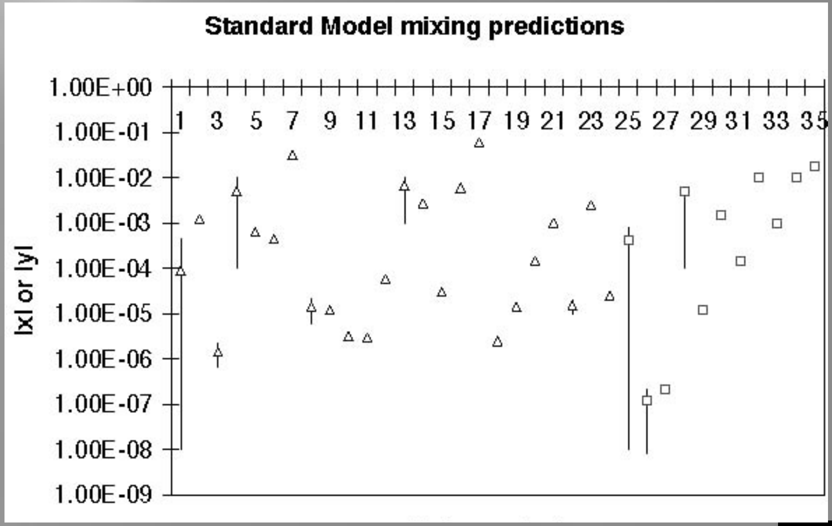
D is neither light nor heavy!!

Inclusive approach —OPE, expand in powers of Λ/m_c,

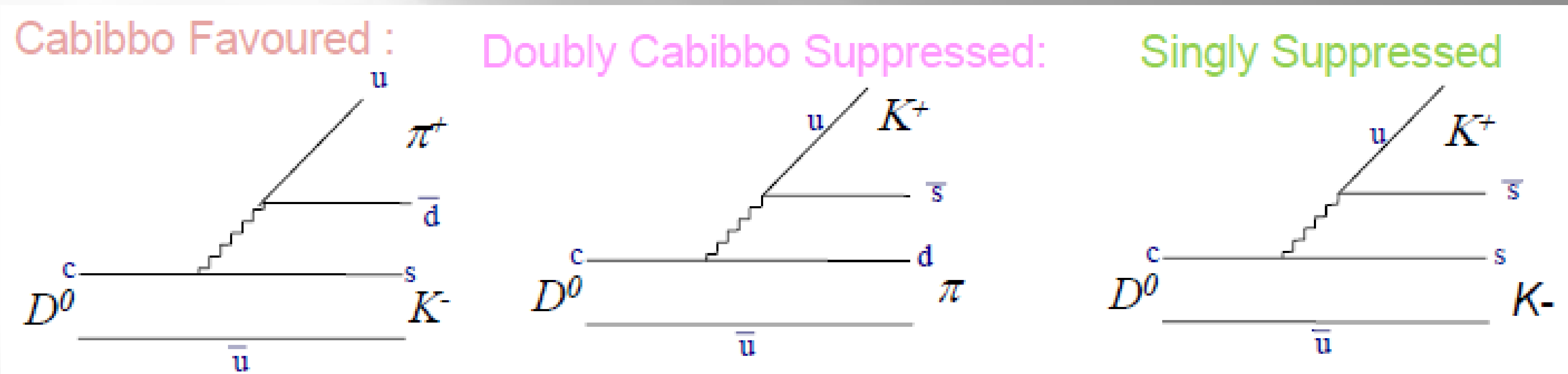
but m_c not large enough

Exclusive approach —sum over all hadronic final states, but m_D not Light enough -can't just sum over 2 body states

Predictions vary over many orders of magnitude!

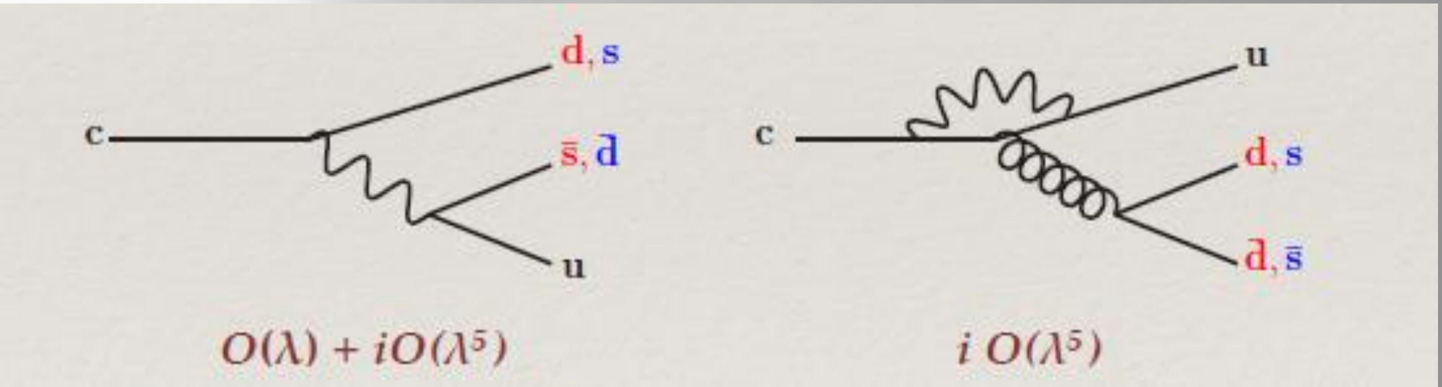


Different Types of Charmed Two Body decay modes



In B Meson Decays, a b quark transition will be at least λ^2 suppressed

Direct CPV can arise from the presence of Tree and Penguin Diagrams

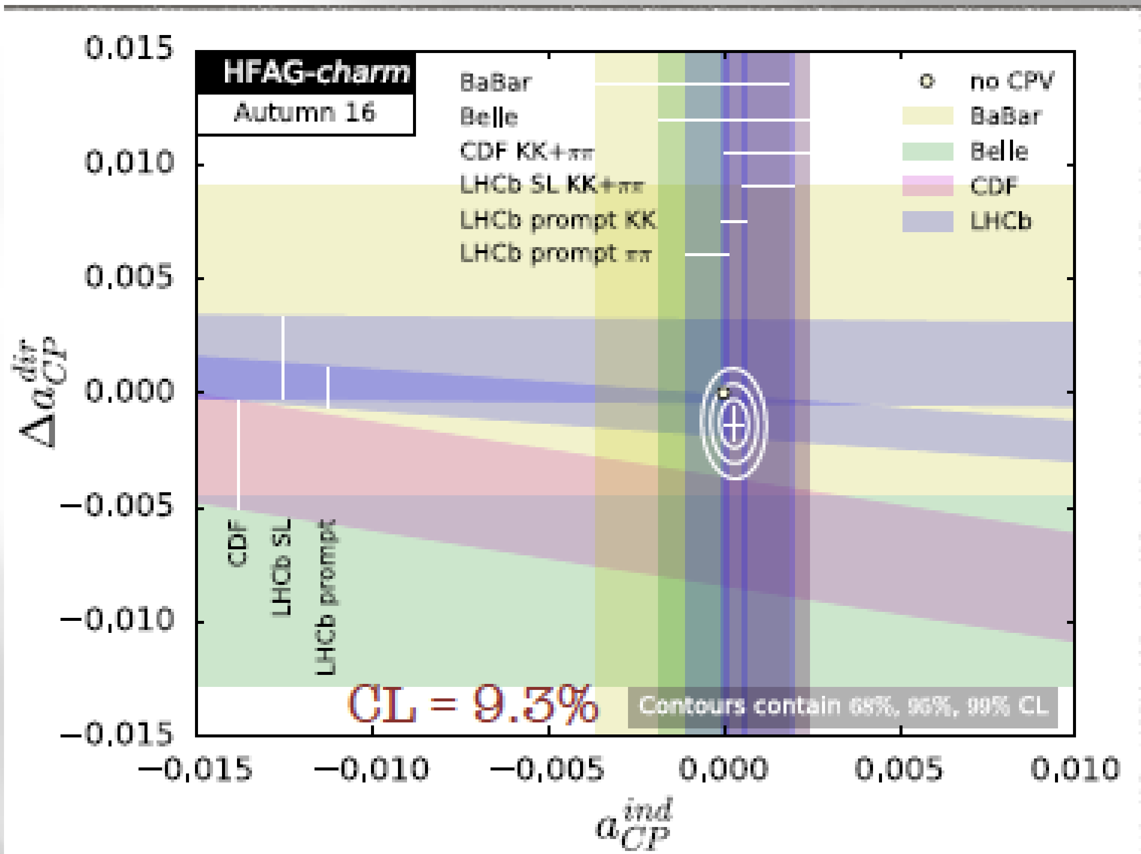


Feasible only in SCS modes, as a gluon (gluonic penguins) or γ/Z (EW penguins) will result in a $q\bar{q}$ pair

$$A = A_1 e^{i\delta_1} + A_2 e^{i\delta_2}\, e^{i\phi}$$

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{2A_1A_2 \sin\theta\ \sin\phi}{\left(A_1^2 + A_2^2 + 2\, A_1A_2 \cos(\delta_1 - \delta_2)\cos\phi\right)}$$

Status Now



$a_{CP}^{ind} = (3.0 \pm 2.6) \times 10^{-4}$

$\Delta a_{CP}^{dir} = (-1.3 \pm 0.7) \times 10^{-3}$

While at the moment there is no non-vanishing CP asymmetry measurement, a reliable SM estimate is required.

Need to see if can estimate the decay amplitudes and strong phases within the SM

Calculation of the Amplitudes

- ***The Charm quark mass ~$1.275\ GeV$ is neither heavy enough to allow use of Heavy quark effective theory, nor light enough for chiral perturbation theory to be applicable.***
- ***Factorization approach still one of the most successful and widely used for studying two-body charm meson decays. Non-factorizable corrections incorporated in the effective Wilson coefficients.***

Alternate approaches:

- ***Large $1/N_c$ approach-Dropping Fierz transformed terms characterized by $1/N_c$ improved predictions; supported by calculations based on QCD sum rules.***
- ***Quark diagram/topological approach- all 2 body NonLeptonic weak decays of heavy mesons are expressed in terms of distinct quark diagrams, these topologies include strong interaction effects and are based on SU(3) symmetry.***

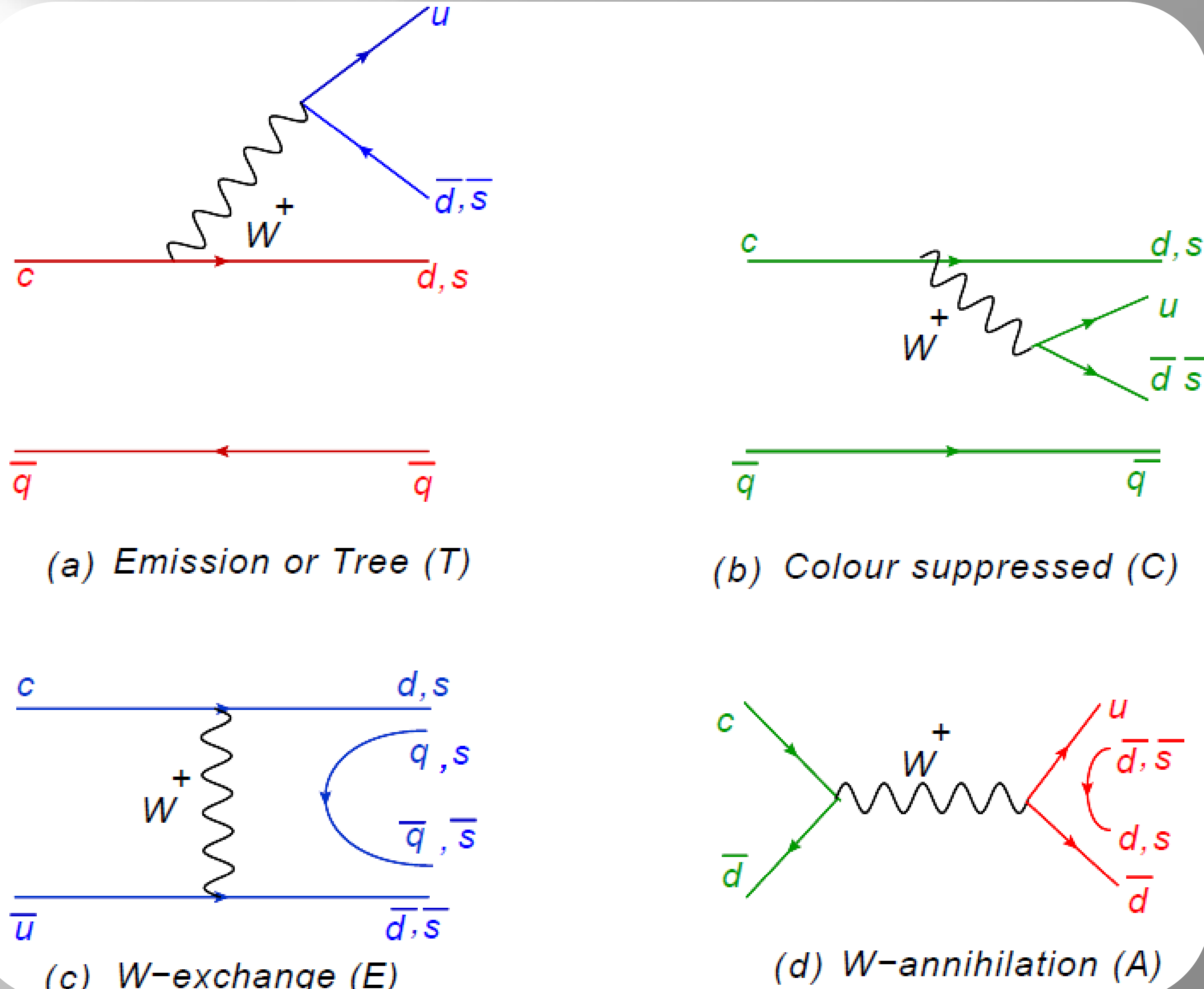
Final State Interactions

- ***Mass of the charmed mesons lie right in the heart of the resonance region.***
- ***Resonant final state rescattering bound to play a big role in two body charmed hadronic decays, needs to be evaluated.***
- ***Dynamical calculations of these long distance effects not possible, can only be incorporated phenomenologically.***
- ***Unitarity plays an important role.***

- *We assume that FSI effects are dominated by resonance states close to the mass of D mesons.*

- *In fact, there exist isospin $0, 1$ and $\frac{1}{2}$ resonances near the D mass, that may contribute to rescatterings among different channels in these respective isospin states and enhance/suppress some of the decay rates.*

Weak Annihilation and Exchange Contributions



- ✓ *Rosen (1980) proposed that these contributions may be large, since they appear only in D^0 and not D^+ decays, it could account for the difference in lifetime of these two mesons.*

- ✓ *Bigi and Fukugita had proposed several D and B meson decay modes that could be smoking gun signals of W-exchange contributions BUT when $D^0 \rightarrow \phi\overline{K^0}$ was observed, it was argued that it could have been generated from the decay mode $D^0 \rightarrow K^*\eta$, with this final state rescattering to the $\phi\overline{K^0}$ mode.*

- ✓ *Studies using the quark diagram approach had also indicated that annihilation type contributions are needed to explain the observed data.*

Weak Hamiltonian and Wilson Coefficients

Fermi Coupling constant

$$\mathcal{H}_w = \frac{G_F}{\sqrt{2}}[C_1(\mu)O_1(\mu) + C_2(\mu)O_2(\mu)] + h.c. \ .$$

Coefficient functions, which incorporate the strong interaction effects above the scale $\mu \sim m_c$

Current-current operators:

$$O_1 = (\bar{u}_\alpha q_{2\alpha})_{V-A}(\bar{q}_{1\beta} c_\beta)_{V-A}$$

$$O_2 = (\bar{u}_\alpha q_{2\beta})_{V-A}(\bar{q}_{1\beta} c_\alpha)_{V-A}$$

α, β colour indices; q_1, q_2 can be either the d or the s quark.

Penguin contributions in charmed meson decays are highly suppressed as the dominant down type quark contribution to the flavour changing neutral current $c \to u$ transition is from the b quark which is accompanied by the presence of the tiny product, $V^*_{cb}V_{ub}$ of the CKM matrix elements. $O_{1,2}$ sufficient for calculating the amplitudes and branching ratios of the $D \to PP$ modes.

Naive Factorization: the matrix element of the four-fermion operator in the heavy quark decay is replaced by a product of two currents—amplitudes for 2 body decay modes are product of a transition form factor and a decay constant.

Non-Factorizable Corrections

In the QCD factorization approach for B meson decays, these NF corrections are handled using the hard scattering approach, where the vertex corrections and the hard spectator interactions are added at the next to leading order in α_s and its accuracy is limited only by the corrections to the heavy quark limit.

But, in the case of charm decays, where the heavy quark expansion is not a very good approximation, it is best to parametrize these NF corrections and then determine them by fitting the theoretical branching ratios with the experimental data.

In the diagrammatic approach of Cheng et al also, either the Wilson coefficients themselves or the NF corrections appearing in the Wilson coefficients are determined from fits to data.

$$a_1(\mu) = C_1(\mu) + C_2(\mu)\left(\frac{1}{N_c} + \alpha(\mu)\chi_1 e^{i\phi_1}\right)$$

$$a_2(\mu) = C_2(\mu) + C_1(\mu)\left(\frac{1}{N_c} + \alpha(\mu)\chi_2 e^{i\phi_2}\right)$$

Where the scale,

$$\mu = \sqrt{\Lambda m_D(1 - r_2^2)}, \text{ where, } r_2^2 = m_{P_2}^2/m_D^2$$

For $D \to P_1 P_2$,
P_1 carries the spectator
P_2 is the meson emitted from the weak vertex

Included in both a_1, a_2 Hence appears in Tree and Color

The Un-Unitarized amplitudes

$$T(C) = \frac{G_F}{\sqrt{2}} V_{CKM} a_1(\mu)(a_2(\mu)) f_{P_2}(m_D^2 - m_{P_1}^2) F_0^{DP_1}(m_{P_2}^2)$$

Tree (Color)

$\Lambda, \chi_1, \chi_2, \phi_1, \phi_2$ are free parameters, taken to be universal for all the decay modes and are fitted from data

Initial Meson is annihilated
Final mesons are produced from the weak vertex

$$E_{q,s}(A_{q,s}) = \frac{G_F}{\sqrt{2}} V_{CKM} C_1(\mu)(C_2(\mu)) \chi_{q,s}^{E(A)} \frac{C_F}{N_c^2} f_D f_{P_1} f_{P_2}$$

$$\mu = \sqrt{\Lambda m_D (1 - r_1^2)(1 - r_2^2)}$$

Exchange (Annihilation)

Distinguish light $q\bar{q}$ from $s\bar{s}$ pair

Non-Perturbative Inputs: Form Factors and Decay Constants

For $D \rightarrow P_1$ transitions, m.e. of the vector current can be written in terms of form factors, F_+, F_0 as:

$$\langle P_1(p')|\bar{q}\gamma^\mu c|D(p)\rangle \equiv F_+(q^2)(p^\mu + p'^\mu - \frac{m_D^2 - m_{P_1}^2}{q^2}q^\mu) + F_0(q^2)\frac{m_D^2 - m_{P_1}^2}{q^2}q^\mu$$

The m.e. for the production of the 2[nd] meson P_2

$$\langle P_2(q)|\bar{q_1}\gamma_\mu q_2|0\rangle = i f_{P_2} q_\mu$$

Where $q \equiv p - p'$

Only F_0 appears

Transition form factors can be experimentally measured from semi-leptonic decays, however, in massless lepton limit, only the $F_+(q^2)$ contributes. At zero momentum transfer, $F_0(0) = F_+(0)$. The q^2 dependence of F_0 is accessible only with massive leptons in semileptonic decays or in lattice simulations.

Simple and modified pole models have been used-poor convergence! Recently the z-expansion has been used: Model independent over the entire kinematic range, improved convergence properties

The Z-expansion and Form factors Calculation

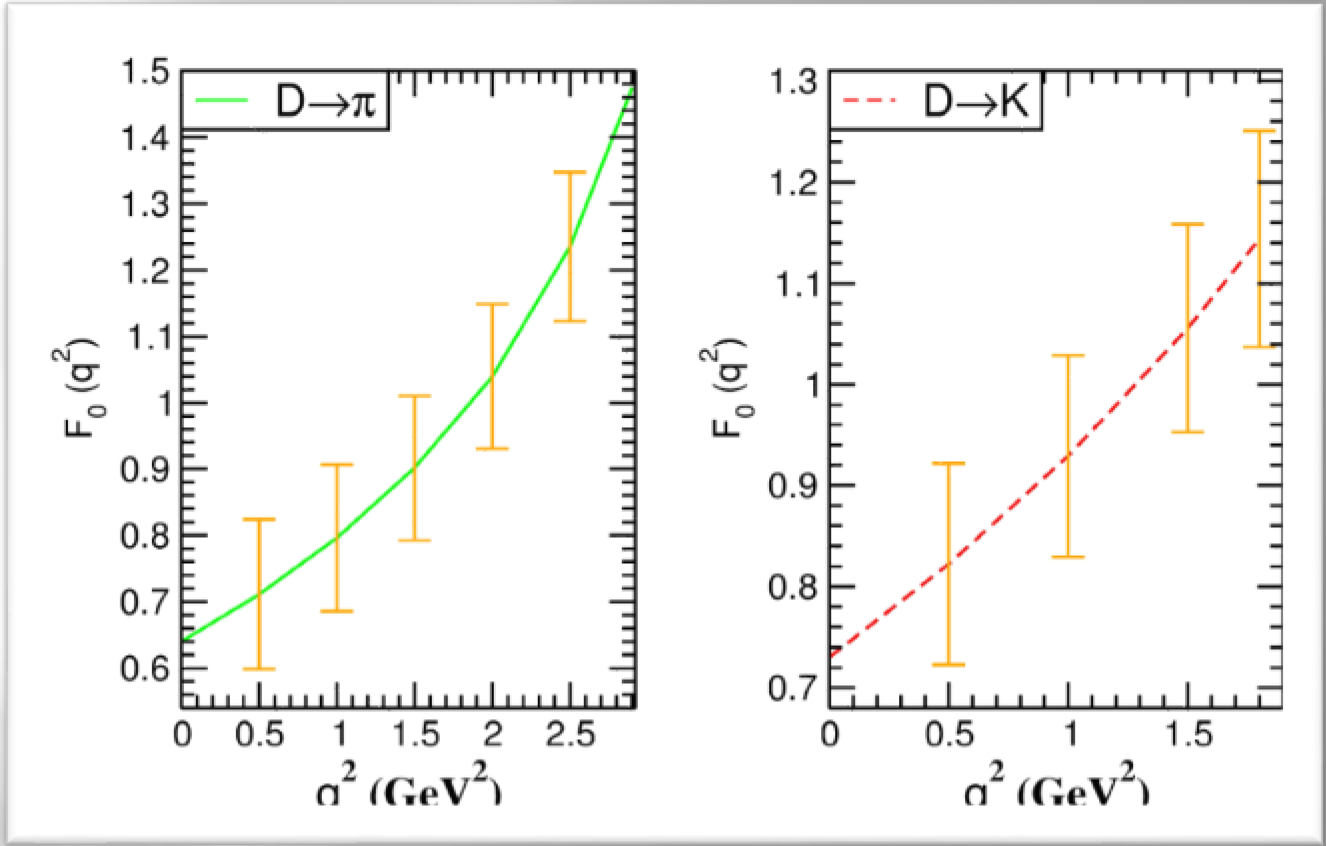
In this approach, based on analyticity and unitarity, the form factors are expressed as a series expansion in powers of z^n, where z is a non-linear function of q^2, with an overall multiplicative function accounting for the sub-threshold poles and branch cuts,

$$F(t) = \frac{1}{P(t)\phi(t,t_0)} \sum_{\mathrm{k=0}}^{\mathrm{inf}} a_k(t_0) z(t,t_0)^k$$

The series coefficients and prefactors can only be determined from fits to lattice or experimental data.

In fact, CLEO collaboration has determined these coefficients for the $D \to \pi, K, \eta$ form factors from the semileptonic decays but, in the massless lepton limit.

Hence, for $F_0(q^2)$, we use lattice results to determine the first two coefficients



Our values at $q^2 = 0$, is consistent with other published results, including that from CLEO; the shape is also consistent

For, $D, D_s \rightarrow \eta, \eta'$ FFs not very well determined

Decay Constants

The f_π , f_K are taken from the Particle Data Group(PDG).

For the η and η', it is assumed that the decay constants in the quark flavour basis, follow the pattern of particle state mixing. The η and η' are expressed as linear combinations of the orthogonal flavor states,

$$\eta_q = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}), \quad \text{and} \quad \eta_s = s\bar{s}$$

The physical states η and η' are related to these flavour states by

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix}$$

where, the $\eta - \eta'$ mixing angle denoted by ϕ, represents the sum of the ideal mixing angle and the $\eta - \eta'$ mixing angle (θ) in the octet-singlet basis, $\phi = \theta + tan^{-1}\sqrt{2}$

Hence the decay constants (form factors) f_q and f_s (F_{0q} and F_{0s}) corresponding to that for η_q and η_s ($D \to \eta_q$ and $D \to \eta_s$) respectively, are given by:

$$f_\eta^q = f_q \cos\phi, \quad f_\eta^s = -f_s \sin\phi, \qquad F_{0_\eta}^q = F_{0_q} \cos\phi, \quad F_{0_\eta}^s = -F_{0_s} \sin\phi,$$

$$f_{\eta'}^q = f_q \sin\phi, \quad f_{\eta'}^s = f_s \cos\phi. \qquad F_{0_{\eta'}}^q = F_{0_q} \sin\phi, \quad F_{0_{\eta'}}^s = F_{0_s} \cos\phi.$$

Final State Interactions

In addition to the short distance effects incorporated in the modified Wilson coefficients, residual long distance effects can be particularly important for Charmed meson decays, due to presence of nearby resonances.

This residual scattering is considered among a limited set of $D \rightarrow PP$ decays

Writing this residual scattering matrix in terms of a real symmetric K matrix, Unitarized (final state interaction corrected amplitudes may be written as

$$\mathcal{A}_{\mathrm{i}}^{\mathrm{U}} = \sum_{\mathrm{k}=1}^{\mathrm{n}} ((1 - \mathrm{iK})^{-1})_{\mathrm{ij}} \mathcal{A}_{\mathrm{j}}^{\mathrm{fac}}$$

Factorized Amplitude, including NF corrections

K matrix parametrization has the advantage that the resonances coupling two-body channels are represented by poles in the K matrix.

For each of the SCS, CF as well as DCS modes, states with the same isospin are coupled together. In general the K matrix coupling three channels will have the form:

$$K(s) = \frac{1}{(m_{Res}^2 - s)} \begin{bmatrix} k_1\Gamma_{11} & \sqrt{k_1 k_2}\Gamma_{12} & \sqrt{k_1 k_3}\Gamma_{13} \\ \sqrt{k_2 k_1}\Gamma_{21} & k_2\Gamma_{22} & \sqrt{k_2 k_3}\Gamma_{23} \\ \sqrt{k_3 k_1}\Gamma_{31} & \sqrt{k_3 k_2}\Gamma_{32} & k_3\Gamma_{33}, \end{bmatrix}$$

K is real symmetric matrix

$$S = (1 - iK)^{-1}(1 + iK)$$

Coupling of different Isospin states and Resonances

The isospin zero combinations of the $\pi^+\pi^-$ and $\pi^0\pi^0$, K^+K^- and $K^0\overline{K^0}$ and $\eta\eta$ modes are coupled with the $f_0(1710)$ pole in the K matrix. k_i's are the cm momenta of the 3 decay modes. The Γ_{ii}'s are related to the partial decay width of the resonance to the ith channel.

$$\Gamma(f_0 \to \pi\pi) = \frac{\Gamma_{11}k_1}{m_{Res}}, \quad \Gamma(f_0 \to K\bar{K}) = \frac{\Gamma_{22}k_2}{m_{Res}}, \quad \text{and} \quad \Gamma(f_0 \to \eta\eta) = \frac{\Gamma_{33}k_3}{m_{Res}}.$$

Experimentally, only two of the ratios of the decay rates:

$$\Gamma(f_0 \to K\bar{K})/\Gamma(f_0 \to \pi\pi) \qquad \Gamma(f_0 \to K\bar{K})/\Gamma(f_0 \to \eta\eta)$$

have been measured. We keep $g_{pe} \equiv \Gamma(f_0 \to K\bar{K})$ as a parameter to be determined from fits of theoretical estimates to observed BR's.

Similarly, for the $I = 1$ case, we take the $a_0(1450)$) resonance with $m_{Res} = 1.474\ GeV$ to be responsible for the rescattering among the channels $K\overline{K}$, $\pi\eta$ and $\pi\eta'$, to which this resonance decays. Here again, $\Gamma(a_0 \to \pi\eta)$ is not accurately measured and is treated as a parameter (h_{pe}).

Note that the $K\bar{K}, \pi\eta$ and $\pi\eta'$ states appear as final states not only of SCS D^0 and D^+ decays, but also in the CF decays of the D_s^+ decays.

The same K matrix (apart from tiny modifications in the cm momenta and the mass-squared of the decaying meson) will suffice, and more importantly with the same one unknown parameter, while many additional observables will get added to the chisq fit.

Finally, the isospin ½ states of $K\pi, K\eta$ and $K\eta'$ are coupled with the $K_0^*(1950)$ resonance. Only one BR measured, 2 add. Parameters: appear in SCS D_s^+, CF of D^0 and DCS decays of D^0 and D^+

SCS Decays

$$) \equiv \sqrt{2}\mathcal{A}_2^{\pi\pi} + \sqrt{2}\mathcal{A}_0^{\pi\pi(U)}$$

$$\equiv 2\mathcal{A}_2^{\pi\pi} - \mathcal{A}_0^{\pi\pi(U)}$$

$$\equiv \sqrt{3}\mathcal{A}_1^{\pi\eta(U)}$$

$$\equiv \sqrt{3}\mathcal{A}_1^{\pi\eta'(U)}$$

$$\sqrt{3}\mathcal{A}_0^{\eta\eta(U)}$$

$$\equiv \sqrt{3}\mathcal{A}_0^{\eta\eta'}$$

$$^-) \equiv \sqrt{\frac{3}{2}}\left(\mathcal{A}_1^{KK(U)} + \mathcal{A}_0^{KK(U)}\right)$$

$$^0) \equiv \sqrt{\frac{3}{2}}\left(\mathcal{A}_1^{KK(U)} - \mathcal{A}_0^{KK(U)}\right)$$

$$) \equiv 3\mathcal{A}_2^{\pi\pi}$$

$$^0) \equiv \mathcal{A}_1^{K^+K(U)}$$

$$\equiv \mathcal{A}_1^{\pi^+\eta(U)}$$

$$) \equiv \mathcal{A}_1^{\pi^+\eta'(U)}$$

$$^0) \equiv \frac{1}{\sqrt{3}}\mathcal{A}_{\frac{3}{2}}^{\pi K} + \sqrt{\frac{2}{3}}\mathcal{A}_{\frac{1}{2}}^{\pi K(U)}$$

$$^+) \equiv \sqrt{\frac{2}{3}}\mathcal{A}_{\frac{3}{2}}^{\pi K} - \frac{1}{\sqrt{3}}\mathcal{A}_{\frac{1}{2}}^{\pi K(U)}$$

$$) \equiv \mathcal{A}_{\frac{1}{2}}^{K^+\eta(U)}$$

$$') \equiv \mathcal{A}_{\frac{1}{2}}^{K^+\eta'(U)}$$

CF Decays

$$A^{(U)}(D^0 \to K^-\pi^+) = \frac{1}{3}\mathcal{A}_{\frac{3}{2}}^{\bar{K}\pi} + \frac{2}{3}\mathcal{A}_{\frac{1}{2}}^{\bar{K}\pi(U)}$$

$$A^{(U)}(D^0 \to \bar{K}^0\pi^0) = \frac{\sqrt{2}}{3}(\mathcal{A}_{\frac{3}{2}}^{\bar{K}\pi} - \mathcal{A}_{\frac{1}{2}}^{\bar{K}\pi(U)})$$

$$A^{(U)}(D^0 \to \bar{K}^0\eta) = \sqrt{\frac{2}{3}}\mathcal{A}_{\frac{1}{2}}^{\bar{K}\eta(U)}$$

$$A^{(U)}(D^0 \to \bar{K}^0\eta') = \sqrt{\frac{2}{3}}\mathcal{A}_{\frac{1}{2}}^{\bar{K}\eta'(U)}$$

$$A^{(U)}(D^+ \to \bar{K}^0\pi^+) = \mathcal{A}_{\frac{3}{2}}^{\bar{K}\pi^+}$$

$$A^{(U)}(D_s^+ \to \bar{K}^0K^+) = \mathcal{A}_1^{K\bar{K}(U)}$$

$$A^{(U)}(D_s^+ \to \pi^+\eta) = \mathcal{A}_1^{\pi^+\eta(U)}$$

$$A^{(U)}(D_s^+ \to \pi^+\eta') = \mathcal{A}_1^{\pi^+\eta'(U)}$$

DCS Decay

$$A^{(U)}(D^0 \to K^+\pi^-) = \frac{\sqrt{2}}{3}\mathcal{A}_{\frac{3}{2}}^{K}$$

$$A^{(U)}(D^0 \to K^0\pi^0) = \frac{2}{3}\mathcal{A}_{\frac{3}{2}}^{K\pi} -$$

$$A^{(U)}(D^0 \to K^0\eta) = \mathcal{A}_{\frac{1}{2}}^{K\eta(U)}$$

$$A^{(U)}(D^0 \to K^0\eta') = \mathcal{A}_{\frac{1}{2}}^{K\eta'(U)}$$

$$A^{(U)}(D^+ \to K^0\pi^+) = \frac{\sqrt{2}}{3}\mathcal{A}_{\frac{3}{2}}^{K}$$

$$A^{(U)}(D^+ \to K^+\pi^0) = \frac{2}{3}\mathcal{A}_{\frac{3}{2}}^{K\pi}$$

$$A^{(U)}(D^+ \to K^+\eta) = \mathcal{A}_{\frac{1}{2}}^{K^+\eta(U}$$

$$A^{(U)}(D^+ \to K^+\eta') = \mathcal{A}_{\frac{1}{2}}^{K^+\eta'(}$$

$$A^{(U)}(D_s^+ \to K^+K^0) = \frac{1}{\sqrt{2}}(\mathcal{A}$$

Numerical Fits

The unknowns:

Four parameters representing the NF corrections, χ_1, χ_2 and their respective phases ϕ_1, ϕ_2

Four parameters : $\chi^E_{q,s}$ and $\chi^A_{q,s}$ depicting the strength of the W-exchange and W-annihilation amplitudes with distinct strengths for qq and ss pair production

One unknown in each of the isospin zero and isospin one K matrices coupling modes from decays of D^0 and D^+ mesons, two parameters in the isospin half K matrix coupling various decay modes of D_s^+

One parameter, representing the momentum of the soft degrees of freedom in the charmed mesons, that is used to define the scale for each of the individual decay modes

Numerical Results

Theoretical Errors:

Form factors, η and η' decay constants, $\eta - \eta'$ mixing angle, errors in measured decay widths of various resonances into the different channels.

Our best fit has a chisq/degree of freedom of 2.25, an improvement over previous results in the literature.

Our Branching Ratios for $D \to KK, D \to \pi\pi$ modes that have been a longstanding puzzle are in agreement with the measured values.

Name	Values	Name	Values	Name	Values
Λ	0.625645	j_{pe_1}	0.0000239368	χ_q^A	132.685
χ_1	-2.68215	j_{pe_2}	0.096456	χ_s^A	193.447
χ_2	2.23605	χ_q^E	-334.805	ϕ_1	0.302258
g_{pe}	0.0471262	χ_s^E	-81.3363	ϕ_2	2.87681
h_{pe}	0.118834				

We have evaluated the cosine of the strong phase difference between the unitarized amplitudes for $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^+\pi^-$ and obtain, $\cos\delta_{K\pi} = 0.94 \pm 0.027$. This result is consistent with the recently measured BESIII,

value $\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06$

Table: $D \to PP$ SCS B.R.'s

Modes	With FSI	Without FSI	Without Annihilation	Experimental Value
$D^0 \to \pi^+\pi^-$	$(1.44 \pm 0.027) \times 10^{-3}$	$(4.35 \pm 1.67) \times 10^{-3}$	$(4.02 \pm 1.75\times) \times 10^{-3}$	$(1.402 \pm 0.026) \times 10^{-3}$
$D^0 \to \pi^0\pi^0$	$(1.14 \pm 0.56) \times 10^{-3}$	$(3.66 \pm 1.43) \times 10^{-3}$	$(2.04 \pm 0.79) \times 10^{-3}$	$(8.209 \pm 0.35) \times 10^{-4}$
$D^0 \to K^+K^-$	$(4.06 \pm 0.77) \times 10^{-3}$	$(4.27 \pm 2.34) \times 10^{-3}$	$(6.78 \pm 3.08) \times 10^{-3}$	$(3.96 \pm 0.08) \times 10^{-3}$
$D^0 \to K^0\bar{K}^0$	$(3.42 \pm 0.52) \times 10^{-4}$	$(5.61 \pm 0.00) \times 10^{-4}$	$(2.80 \pm 0.84) \times 10^{-4}$	$(3.4 \pm 0.8) \times 10^{-4}$
$D^0 \to \pi^0\eta$	$(1.47 \pm 0.90) \times 10^{-3}$	$(6.47 \pm 2.98 \times 10^{-3}$	$(3.25 \pm 1.51 \times 10^{-3}$	$(6.8 \pm 0.7) \times 10^{-4}$
$D^0 \to \pi^0\eta'$	$(2.17 \pm 0.65) \times 10^{-3}$	$(3.81 \pm 1.43) \times 10^{-3}$	$(1.85 \pm 0.79) \times 10^{-3}$	$(9.0 \pm 1.4) \times 10^{-4}$
$D^0 \to \eta\eta$	$(1.27 \pm 0.27) \times 10^{-3}$	$(1.32 \pm 0.41) \times 10^{-3}$	$(1.34 \pm 0.29) \times 10^{-3}$	$(1.67 \pm 0.20) \times 10^{-3}$
$D^0 \to \eta\eta'$	$(9.53 \pm 1.83) \times 10^{-4}$	$(1.04 \pm 0.27) \times 10^{-3}$	$(5.38 \pm 1.63) \times 10^{-4}$	$(1.05 \pm 0.26) \times 10^{-3}$
$D^+ \to \pi^+\pi^0$	$(8.89 \pm 4.51) \times 10^{-4}$	$(8.70 \pm 6.70) \times 10^{-4}$	$(9.73 \pm 3.94) \times 10^{-4}$	$(1.19 \pm 0.06) \times 10^{-3}$
$D^+ \to K^+\bar{K}^0$	$(3.75 \pm 0.63) \times 10^{-3}$	$(1.02 \pm 0.37) \times 10^{-2}$	$(1.99 \pm 0.56) \times 10^{-2}$	$(5.66 \pm 0.32) \times 10^{-3}$
$D^+ \to \pi^+\eta$	$(4.72 \pm 0.21) \times 10^{-3}$	$(2.34 \pm 1.26) \times 10^{-2}$	$(1.66 \pm 0.77) \times 10^{-2}$	$(3.53 \pm 0.21) \times 10^{-3}$
$D^+ \to \pi^+\eta'$	$(6.76 \pm 2.19) \times 10^{-3}$	$(3.00 \pm 0.76) \times 10^{-2}$	$(9.78 \pm 3.35) \times 10^{-3}$	$(4.67 \pm 0.29) \times 10^{-3}$
$D_s^+ \to \pi^+K^0$	$(1.96 \pm 0.90) \times 10^{-3}$	$(1.46 \pm 1.10) \times 10^{-3}$	$(1.32 \pm 1.01) \times 10^{-3}$	$(2.42 \pm 0.12) \times 10^{-3}$
$D_s^+ \to \pi^0K^+$	$(8.17 \pm 4.64) \times 10^{-4}$	$(1.74 \pm 1.00) \times 10^{-4}$	$(1.01 \pm 0.54) \times 10^{-3}$	$(6.3 \pm 2.1) \times 10^{-4}$
$D_s^+ \to K^+\eta$	$(1.50 \pm 0.75) \times 10^{-3}$	$(6.40 \pm 4.52) \times 10^{-3}$	$(2.23 \pm 1.82) \times 10^{-3}$	$(1.76 \pm 0.35) \times 10^{-3}$
$D_s^+ \to K^+\eta'$	$(7.07 \pm 0.49) \times 10^{-4}$	$(2.09 \pm 0.87) \times 10^{-3}$	$(0.57 \pm 0.47) \times 10^{-4}$	$(1.8 \pm 0.6) \times 10^{-3}$

Table: $D \to PP$ CF B.R.'s

es	With FSI	Without FSI	Without Annihilation	Experimental Value
$\to K^- \pi^+$	$(3.70 \pm 1.33) \times 10^{-2}$	$(8.83 \pm 2.47) \times 10^{-2}$	$(5.63 \pm 1.81) \times 10^{-2}$	$(3.88 \pm 0.05) \times 10^{-2}$
$\to \bar{K}^0 \pi^0$	$(1.88 \pm 0.99) \times 10^{-2}$	$(1.29 \pm 0.44) \times 10^{-1}$	$(3.30 \pm 1.47) \times 10^{-2}$	$(2.38 \pm 0.08) \times 10^{-2}$
$\to \bar{K}^0 \eta$	$(1.59 \pm 0.48) \times 10^{-2}$	$(0.97 \pm 0.33) \times 10^{-2}$	$(1.09 \pm 0.34) \times 10^{-2}$	$(0.958 \pm 0.06) \times 10^{-2}$
$\to \bar{K}^0 \eta'$	$(2.29 \pm 0.43) \times 10^{-2}$	$(2.06 \pm 0.30) \times 10^{-2}$	$(2.45 \pm 0.47) \times 10^{-2}$	$(1.88 \pm 0.1) \times 10^{-2}$
$\to \bar{K}^0 \pi^+$	$(3.42 \pm 1.78) \times 10^{-2}$	$(1.35 \pm 1.12) \times 10^{-1}$	$(5.25 \pm 3.34) \times 10^{-2}$	$(2.94 \pm 0.14) \times 10^{-2}$
$\to \bar{K}^0 K^+$	$(5.65 \pm 1.29) \times 10^{-2}$	$(1.70 \pm 0.79) \times 10^{-1}$	$(1.35 \pm 0.53) \times 10^{-1}$	$(2.95 \pm 0.14) \times 10^{-2}$
$\to \pi^+ \eta$	$(2.26 \pm 0.82) \times 10^{-2}$	$(0.78 \pm 0.56) \times 10^{-2}$	$(2.14 \pm 0.90) \times 10^{-2}$	$(1.69 \pm 0.10) \times 10^{-2}$
$\to \pi^+ \eta'$	$(2.64 \pm 0.78) \times 10^{-2}$	$(3.73 \pm 1.52) \times 10^{-2}$	$(2.52 \pm 0.85) \times 10^{-2}$	$(3.94 \pm 0.25) \times 10^{-2}$

Table: $D \to PP$ DCS B.R.'s

Modes	With FSI	Without FSI	Without Annihilation	Experimental Value
$D^0 \to K^+\pi^-$	$(1.77 \pm 0.88) \times 10^{-4}$	$(3.71 \pm 1.33) \times 10^{-4}$	$(2.48 \pm 1.07) \times 10^{-4}$	$(1.38 \pm 0.028) \times 10^{-4}$
$D^0 \to K^0\pi^0$	$(2.11 \pm 0.26) \times 10^{-4}$	$(3.70 \pm 1.35) \times 10^{-4}$	$(0.68 \pm 0.46) \times 10^{-4}$	–
$D^0 \to K^0\eta$	$(0.94 \pm 0.45) \times 10^{-4}$	$(0.28 \pm 0.10) \times 10^{-4}$	$(0.96 \pm 0.32) \times 10^{-4}$	–
$D^0 \to K^0\eta'$	$(8.02 \pm 3.32) \times 10^{-4}$	$(0.59 \pm 0.08) \times 10^{-4}$	$(9.22 \pm 1.61) \times 10^{-4}$	–
$D^+ \to K^0\pi^+$	$(3.27 \pm 1.86) \times 10^{-4}$	$(1.19 \pm 0.55) \times 10^{-3}$	$(3.51 \pm 2.11) \times 10^{-4}$	–
$D^+ \to K^+\pi^0$	$(3.07 \pm 1.02) \times 10^{-4}$	$(2.15 \pm 1.17) \times 10^{-4}$	$(3.27 \pm 1.39) \times 10^{-4}$	$(1.83 \pm 0.26) \times 10^{-4}$
$D^+ \to K^+\eta$	$(0.98 \pm 0.26) \times 10^{-4}$	$(1.04 \pm 0.23) \times 10^{-4}$	$(0.89 \pm 0.27) \times 10^{-4}$	$(1.08 \pm 0.17) \times 10^{-4}$
$D^+ \to K^+\eta'$	$(1.40 \pm 0.39) \times 10^{-4}$	$(1.82 \pm 0.18) \times 10^{-4}$	$(1.35 \pm 0.39) \times 10^{-4}$	$(1.76 \pm 0.22 \times 10^{-4})$
$D_s^+ \to K^+K^0$	$(7.84 \pm 2.31) \times 10^{-4}$	$(0.68 \pm 0.09) \times 10^{-4}$	$(0.72 \pm 0.44) \times 10^{-4}$	–

The mode $K^0\overline{K^0}$

The mode $D^0 \rightarrow K^0\overline{K^0}$ does not have any tree or colour suppressed contributions, but can come only from W-exchange.
In fact, there are two exchange contributions, one appearing with a $d\bar{d}$ and the other with an $s\bar{s}$, which under exact SU(3) symmetry would cancel each other, resulting in a null amplitude.

However, since our parameters for these two contributions are distinct, our bare amplitude for this mode is small but non-vanishing.
There have been speculations that this mode can arise just from final state interactions, even in the absence of a weak exchange contribution.

However, from our fits it is clear that without the exchange contribution we are unable to generate a large enough rate: both final state interaction and the exchangecontribution are necessary for consistency with the measured branching fraction.

Other Features

Apart from improved z-expansion form factors, clear distinction between different form factors results in additional contributions to our amplitudes.

A naive look at the colour suppressed diagrams for $D \to \pi^0\eta(\eta')$ will indicate that the contributions from the case where the spectator is part of the π^0, and that, where it constitutesthe $\eta(\eta')$ must cancel.

However, in terms of the specific decay constants and form factors, one is proportional to $-f_\pi {F_0}^{D\eta_q}(m_\pi^2)$, while the other is proportional to $f_{\eta_q} F_0^{D\pi}(m_\eta^2)$ which are unequal and hence has to be non-vanishing.

We find the combination of U-spin breaking ratios proposed by Gronau to be indeed small.

Further Improvements possible with : Accurate measurements of widths of resonances, improvement in data (lattice) FFs, a more sophisticated statistical analysis.

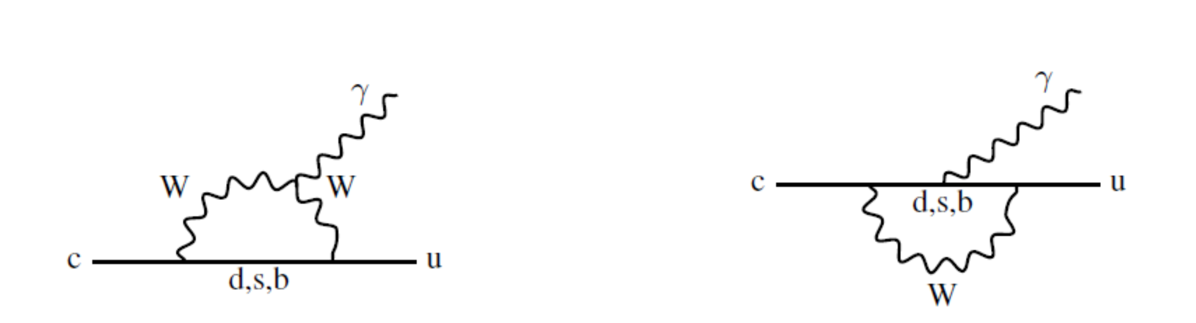
CONCLUSIONS

Before jumping to conclude presence of NP in Charm Decays, we need to ensure we understand the hadronic branching fractions within the SM

Weak Annihilation/Exchange, Final State interaction effects need to be incorporated.

With upcoming data from BESIII, LHCb and BelleII we hope to get an more clearer picture

Radiative Charmed Meson Decays



- FCNC absent at tree Level
- Appears at loop level, where virtual NP particles may be present
- Extensive studies of inclusive and exclusive radiative B meson decays have been performed.
- Less attention has been paid to the D meson radiative decays, smaller BRs expected due to almost complete GIM suppression.

- Moreover, charm radiative decays will be dominated by long distance contributions, which can hide the presence of new physics particles that may appear in the loop of the short distance penguin contributions.

D^0 to $V\gamma$

- Statistical error will scale as:

$$
\begin{array}{lcccc}
 & \text{Belle } (1\text{ab}^{-1}) & 5\text{ab}^{-1} & 15\text{ab}^{-1} & 50\text{ab}^{-1} \\
\mathcal{A}_{CP}(D^0 \to \rho^0\gamma) = +0.056 \pm 0.152 \pm 0.006 & \longrightarrow & 0.07, & 0.04, & 0.02 \\
\mathcal{A}_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001 & \longrightarrow & 0.03, & 0.02, & 0.01 \\
\mathcal{A}_{CP}(D^0 \to \overline{K}^{*0}\gamma) = -0.003 \pm 0.020 \pm 0.000 & \longrightarrow & 0.01, & 0.005, & 0.003
\end{array}
$$

Enhancement of rates:

with QCD Corrections

Within SM, there is an enhancement of the radiative decay rates in the presence of QCD corrections.

Enhancement by a factor of 2 in $\boldsymbol{b \to s\,\gamma}$. A more dramatic enhancement expected in the case of charm radiative decays.

Hence need to evaluate the corresponding Wilson coefficients within the RG improved perturbation theory.

with NP

Need to enhance the rate above that from long distance Effects OR need signals that can be observed even in the presence of the long distance effects.

- We work in $\overline{\text{MS}}$ scheme in accordance with 10.1007/JHEP08(2016)091.
- Hamiltonian for the scale $m_b < \mu < M_W$ is given by

$$\mathcal{H}_{eff}(m_b < \mu < M_W) = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s,b} V^*_{cq} V_{uq} [C_1(\mu) Q^q_1 + C_2(\mu) Q^q_2].$$

- Effective hamiltonian at the scale $m_c < \mu < m_b$ is given by

$$\mathcal{H}_{eff}(m_c < \mu < m_b) = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V^*_{cq} V_{uq} [C_1(\mu) Q^q_1 + C_2(\mu) Q^q_2 + \sum_{i=3}^{10} C_i(\mu) Q_i]$$

QCD corrections	SM
Bare	2.04×10^{-17}
LO	9.48×10^{-15}
NLO	1.86×10^{-9}

- Above the b scale, all quarks except the top are considered massless.
- This is in accordance with the factorization scale. Otherwise, spurious large logarithms are introduced
- The operators Q_1^q and Q_2^q are the only ones that contribute at $m_b < \mu < M_W$. Within SM, these are the only operators that contribute for $c \to u\gamma$. This is in contrast with radiative bottom decays.

$$Q_1^q = (\bar{u}^\alpha q^\beta)_{V-A}(\bar{q}^\beta c^\alpha)_{V-A}, \qquad Q_2^q = (\bar{u}q)_{V-A}(\bar{q}c)_{V-A}.$$

- Operators Q_3 to Q_8 are generated at $m_c < \mu < m_b$ due to the matching at scale m_b.

$$\begin{aligned} Q_3 &= (\bar{u}c)_{V-A}\sum_q(\bar{q}q)_{V-A}, \qquad Q_4 = (\bar{u}^\alpha c^\beta)_{V-A}\sum_q(\bar{q}^\beta q^\alpha)_{V-A}, \\ Q_5 &= (\bar{u}c)_{V-A}\sum_q(\bar{q}q)_{V+A}, \qquad Q_6 = (\bar{u}^\alpha c^\beta)_{V-A}\sum_q(\bar{q}^\beta q^\alpha)_{V+A}, \\ Q_7 &= \frac{e}{16\pi^2} m_c F_{\mu\nu}\bar{u}\sigma^{\mu\nu}P_R c, \qquad Q_8 = \frac{g_s}{16\pi^2} m_c G^a_{\mu\nu}\bar{u}\sigma^{\mu\nu}T^a P_R c. \end{aligned}$$

- The evolution can be schematically expressed as

$$C^{(O)}(\mu = m_c) = U^{(O)}_{(f=4)}(\mu = m_c, m_b) R^{(O)}_{match} U^{(O)}_{(f=5)}(m_b, M_W) C^{(O)}(M_W)$$

  with O ={LO, NLO} specifying the order in QCD corrections.

- $U^{(O)}_{(f=5)}(m_b, M_W)$ is 2×2 and $U^{(O)}_{(f=4)}$ is 8×8 matrix.
- At LO, $U^{(LO)}_{(f=5)}(m_b, M_W)$ and $U^{(LO)}_{(f=4)}$ are dependent on LO anomalous dimension matrix. For NLO, they dependent on NLO anomalous dimension matrix. Both are taken from 10.1007/JHEP08(2016)091.
- $R^{(LO)}_{match}$ is Identity matrix. $R^{(NLO)}_{match}$ taken from 10.1007/JHEP08(2016)091.
- LO initial conditions

$$C_1(M_W) = 0, \qquad C_2(M_W) = 1. \tag{1}$$

- NLO initial conditions

$$C_1(M_W) = \frac{15\alpha_s(M_W)}{4\pi}, \qquad C_2(M_W) = 1. \tag{2}$$

Rare decays: new physics

★ Can New Physics be "hiding" in the up-type quark transitions?
- explicit models can be constructed where it can be done
- long-distance effects complicate interpretation
- must use exp and theo tricks to sort out

$$\mathcal{O}_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1+\gamma_5) c,$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell,$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

$$\mathcal{O}'_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1-\gamma_5) c,$$

$$\mathcal{O}'_9 = \frac{e^2}{16\pi^2} \bar{u}_R \gamma_\mu c_R \bar{\ell} \gamma^\mu \ell,$$

$$\mathcal{O}'_{10} = \frac{e^2}{16\pi^2} \bar{u}_R \gamma_\mu c_R \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

Maybe correlations between different measurements can help sorting out NP in charm?

Thank You